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High-Energy Particle Physics and Accelerator Studies

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ABSTRACT

High Energy particle physics is the study of the building blocks of matter and their interactions on the smallest scales, whilst accelerator studies is the study of the development and optimisation of the machines in which these sociabilities can be explored. In this article the theory of particle physics is reviewed and the most important highlights of the development of this field are presented along with the technology of accelerators from radio frequency (RF) cavities to plasma wake field accelerators. We provide a method that is used for design of experiments and accelerators, discuss representative data and performance metrics, discuss some of the scientific and technological issues, and make some concrete recommendations about future research and facility development. The work involves synthesis of the theory, instrumentation, data analysis and computation techniques that are pertinent to modern high energy physics programs.

Introduction

High energy particle physics (HEPP) attempts to discover the fundamental constituents of the matter, and the forces which control them, by looking at the interactions at the shortest possible distance scales and at the highest possible energies in the laboratory. The Standard Model (SM) of particle physics is an extraordinary combination of quantum field theory and the dignity of the principle of symmetry which provides an encoding of three of the four known fundamental forces (electromagnetic, weak, and strong), as well as a grouped structure of the known elementary particles (quarks, leptons, gauge bosons, the Higgs boson) to a compact theoretical structure which has been spectacularly successful in providing an explanation for the data of experiments (Peskin & Schroeder, 1995; Olive et al., 2014). But there are nonetheless puzzles both empirically and theoretically like neutrino masses and oscillations, the nature of dark matter and dark energy, the baryon asymmetry of the Universe, the hierarchy problem etc. The answers to these questions are only to be found in a combination of theoretical innovation and the use of powerful experimental facilities.

The engines of Experimental HEPP are particle accelerators. From the first cyclotron and synchrotron, to the present multi-TeV colliders and creative accelerator designs, development in the technology of accelerators have allowed discoveries ranging from the muon and pion to the W and Z bosons and the Higgs boson 1-3 (Wilson, 2001; Wiedemann, 2015). Colliders such as the Large Hadron Collider (or LHC) at Cern promise us leads to enormous integrated luminosities and unprecedented center of mass energies as well as not only the precision testing of the Standard Model, but also searching for new physics very powerfully (Evans & Bryant, 2008). Fixed-target experiments, neutrino beamlines and dedicated intensity frontier facilities are a complementary part of collider experiments, from which the potential for high statistics and high-precision measurements as well as the study of rare processes is expected.

Experimental success requires the combination of a tight sequence of capabilities: accelerator design and beam dynamics to produce the beams that are bright stable beams, systems to place and focus the beam and the interactions with the target systems, highly sophisticated detector arrays to record the products of the interaction, trigger systems, data acquisition systems and computing systems to capture, store and analyze the information contained in the hundreds of petabytes of data (Knoll, 2010; Green, 2017). Beam instrumentation (beam position monitors, profile monitors, emittance diagnostics), radio-frequency (RF) systems to accelerate the beam and vacuum and cryogenic systems to envelop superconducting components are all necessary essential technical components which must all be in synch to produce the luminosities and energies needed for frontier physics.

Beyond the traditional RF accelerators, novel acceleration techniques (plasma wakefield acceleration, or PWFA, laser wakefield acceleration, or LWFA) could be helpful to achieve larger gradients than conventional cavities by orders of magnitudes, developing the way to compact high energy machines as well as new experimental opportunities (Esarey, Schroeder, & Leemans, 2009). However, there are still major challenges related to beam quality preservation, efficiency, staging and repetition rate to make plasma accelerators a practical collider application. Similarly, energy recovery linac (ERL), muon collider and advanced superconducting RF (SRF), are emerged possibilities for the development of next generation facilities.

High energy particle physics is at the centre of our understanding of the Universe at the tiniest of scales possible and has a track record of providing transformative scientific knowledge as well as enabling technology spinoffs (e.g superconducting RF, medical imaging). The importance of accelerator studies is the possibility to extend the experimental reach in the energy scale as well as in the precision, that will hopefully allow the test of the Standard Model and the search of new phenomena such as the supersymmetry, dark matter candidates or signs for the existence of compositeness. Accelerator research also lead to developments in materials science, cryogenic, RF technology and control systems which are useful to society in general. The objectives of this article are to: (1) provide a comprehensive overview of HEPP concepts and accelerator technologies related to the current and future generation of experiments; (2) present the methodology for structured design of accelerator experiments and profiling of the machine performance; (3) analyze representative results on performance and results on detector performance to provide information for design decisions related to energy vs. luminosity vs. detector performance; and (4) point to technical challenges and strategic recommendations regarding future development of the facility with a strong emphasis on the combination of novel acceleration technologies with advanced detectors and machine obesity based optimization to maximize a science return (Peskin &

Literature Review

The literature of high energy particle physics and studies at accelerators covers theoretical developments in quantum field and phenomenology, discovery process and decades of technical innovation in the field of accelerator science. Theory of colliders - such as Peskin and Schroeder in 1995,Halzen and Martin in 1984 the basics of theoretical texts on quantum field theory and particle phenomenology that underpanies collider experiments. The experimental confirmation of the Standard Model other than precision electroweak physics measurements in LEP, top quark discovery from Tevatron and disappearing Higgs boson from LHC have brought both confirmation and also the motivation for new questions (ALEPH et al., 2006; Abbott et al., 1995; Aad et al., 2012; Chatrchyan et al., 2012). The Particle Data Group (PDG) compendia have been used as the authoritative source for properties of particles and reviews of experimental techniques (Olive et al., 2014). Accelerator physics reached maturity with such seminal works, describing beam dynamics, effects of behaviors of collective motion and RF technology (Wiedemann, 2015, Courant, Snyder, 1958, Sands, 1970). The design and operation of large colliders (like the LHC and its predecessors) is covered in technical design reports and review articles which deal with the technology of both the magnets, vacuum systems, cryogenics, control of beam losses, collimation and optimization of luminosity (Evans & Bryant, 2008; Rossi & Bruning, 2004). The research on synchrotron radiation and synchrotron radiation mitigation of electron machine was put into storage ring (Sands, 1970). Superconducting RF (SRF) technology and cavity design literature returned with a vengeance with applications to energy efficient acceleration (Padamsee, Knobloch, & Hays, 1998). In the field of beam instrumentation and diagnostics a great amount of texts and reviews on beam position monitors, profile monitors, methods for measurement of emittance and non-invasive diagnostics necessary for modern machines were published (Wanzeberg, 2003; Keil, Zotter 1993). High intensity frontier machines and neutrino facilities has lead to Targetry development (Barton, 1965), Radiation shielding and remote handling (Kirk et al., 2013). Novel acceleration techniques came to the fore through theoretical and experimental studies based on plasma wakefield acceleration techniques, laser wakefield acceleration techniques and dielectric wakefield structures for much greater gradients than classical RF accelerating structures (Tajima & Dawson, 1979; Esarey & Schroeder & Leemans, 2009; Leemans et al, 2014). These concepts have come of age with the demonstration experiments yielding GeV scale electron beam over centimeter scales to meters and led to roadmaps for staged applications towards light sources and high energy colliders (Schroeder et al., 2010). Another focal point of the accelerator science community has been on advanced simulation tools which are used for simulating the dynamics of the beam, collective effects and multi-physics modeling, and codes such as MAD-X, Elegant, Warp and IMPACT are used in design and commissioning (Reiser, 2008; Borland, 2000). The detector development literature in silicon pixels and strips, in the case of calorimetry (homogeneous and sampling), gaseous detectors (TPC, RPC) and photodetectors, occurs with the problems of spatial resolution, radiation hardness, time resolution and connecting readout electronics (Spieler, 2005; Kleinknecht, 1998). A literature based on low-latency and high-bandwidth data acquisition (T/DAQ) systems to do with the interaction rate of the LHC (Grunberg et al, 2012). Advances in computing architectures, distributed data grids and machine learning all have become increasingly incorporated in the accelerator operations and physics analysis: works describing applications of machine learning for beam tuning, anomaly detection and real-time optimization are testament to real performance improvements12. Conceptual and technical studies of future facilities including International Linear Collider (ILC), Compact Linear Collider (CLIC), Future Circular Collider (FCC), circular electron positron Higgs factories, muon colliders and neutrino factories are massive (Baer et al., 2013; Linssen et al., 2012; Zimmermann et al., 2014); they discuss physics range and machine design, cost drivers and R&D requirements. The community is also busy in study of policy, impact on the society and international collaboration models for large facilities (Cern council reports, 2010s). Finally there is the cross-disciplinary literature relating to the applications of accelerator technologies in medicine, industry and materials science and the greater societal benefits of accelerator R&D (Wilson, 2001). Collectively, it is this body of work that has provided a landscape of co-evolving theoretical ambition, experimental capability and engineering innovation and a continuing programme of research and development that is focused on meeting a tough pressure to stretch the limits of energy and intensities, enhance beam quality and detector performance alongside exploiting new acceleration concepts and exploring cost and sustainability.

Methodology

This section describes the methodology applied for the synthesis of physics objectives, accelerator design requirements, detector requirements and data analysis strategies, in an extensive study of high energy particle physics and accelerator studies. The methodology combines a combination of theoretical considerations with machine principles, detector design principles, simulation and modeling working procedures and data analysis working procedures.

Defining Physics objectives and performance (metrics)The starting point is to define requirements driven by physics which are e.g. center of mass energy to be reached, luminosity integrated, measurement error precision (e.g. Higgs couplings at percent level), measurement of rare processes, or discovery potential for new particles with some cross section and some decay signature. From these objectives are derived machine objectives, by way of machine metrics: peak luminosity , bunch repetition rate, beam emittance, beta, , at the interaction point, bunch population and acceptable background rates. The relevant detector requirements such as momentum resolution , vertexing capabilities, time resolution, calorimeter energy resolution and radiation tolerance are determined by the physics targets.

Accelerator design - Beam dynamics modelling. For proposed facility (collider or fixed target) require creation of accelerator lattice using established codes (MAD-X, Elegant) with the aim of simulating beam optics, section & interaction region match. Simulate single particle dynamics into the function of the dynamic aperture and chromaticity Include Collective effects - space charge for low energy machines, wake fields & beam induced heating for high current beams, intra beam scattering and Touschek effects for lepton machines. For hadron colliders the beam-beam effects, the long range interactions and effects of the electron clouds are taken into consideration. Perform tracking studies (Multi-particle tracking) in order to simulate the growth and stability of the emittance in operational cycles;

RF Systems, Cryogenics & Magnet Design. Energy frontier machines Design RF acceleration systems(Dfrequency choice, cavity gradient-couplers) & superconducting magnet systems (dipole/quadrupole fields, fields quality) Modelling of cryogenic loads on SRF cavities and superconducting magnets, quantification of refrigeration needs, thermal losses etc. Evaluate Options of Magnet Technology (NbTi, Nb_3Sn and HTS) for Field Strength and Cryogens

Novel concepts of accelerating and staging. For advanced concept (PWFA/LWFA) model Wakefield generation, Beam loading, Transformer ratio/ staging efficiency. Rule 2 Propose measurement of injection, emittance preservation and beam quality by means of particle-in-cell (PIC) simulations e.g. Warp, OSIRIS Establish experimental situations to create the following: Demonstration of GeV acceleration, beam capture and focusing, controlling of energy spread, coupling to the conventional beamlines or injectors.

Design & integration of detector. With respect to python, some units have different names inside the matching ones, namely (:) some postfixes ("Root") are dropped, and units that are like lists see actually NumPyArrays ("pyarray", "array"). Pure-Pyro based The Baculum algorithm ("baculum.array"), a direct Python based implementation of the Baculum array does not have an index initialization (nith so: Construction of units with properties that are similar to NumPyArrays (e.g. "pyarray", "array") arepired by the object as mmol id. detector object is always object detectorrals sometimes id. Based on physics signatures, design Conduct Geant4 based a full detector simulations, in order to model energy deposition and secondary interactions and backgrounds from radiation induced from beam. Gamification & Optimization Segmentation materials budget and readout channel speeds to achieve tracking and calorimetry performance minimise it material in front of calorimps

Ship instruments and controls (Beam). Beam position and profile, current and loss detection diagnostics can be specified. Integrate Fast feedback system for orbit stabilisation and fast feedback for transverse /longitudinal damping Develop control strategies for luminosity levelling monopolies and machine protection systems for the protection of the detectors and components from unexpected beam loss events

Simulation pipeline & Performance evaluation. Roach There is need to construct a simulation pipeline coupling beam dynamics, the RF/Magnet models, response of detectors and background generation. Hard scattering On the hard scattering processes physics event generators (PYTHIA, Madgraph) and detector simulation (full-trigger) should be used for reconstruction studies. Define metrics for Performance - luminosity UPtIme Background occupancy Trigger accept rates (Significdirect & background efficiency) systematic uncertainties.

Model for acquiring data, Computing model. Design trigger/Data acquisition (DAQ) architecture with expected rates of event rates from the heel handling. For the collider experiments Multi-level trigger hierarchies, high bandwidth read out implementation. Define off-line computing requirements such as data storage requirements, reconstruction farms and distributed analytics workflows The real-time processing and machine learning role for low latency decision taking.

Experimental programme and programme of commissioning. Develop staged commissioning plans - injector characterisation, first stage beam commissioning, firststage delivery of functionality of the optics, Progressive ramping up of current and luminosity stored. plan to go to machine studies to beat emittance, collimate and run detector calibration

Sensitivity & Uncertainty quantification. For physics reach studies, signal and background modelling, selection and expected significance calculation by using the normal hypothesis testing (profile likelihood, CLS) may then be undertaken. Assess the systematic errors from the calibration of the detector and luminosity measurement and theoretical predictions on cross sections. Estimating Sensitivity to Beam and Machine Parameters by Variances from Modelling?

Risk Assessment and Research agenda development (R&D agenda). Identify technological (i.e. not being able to achieve the required SRF gradients, insufficient beam quality from plasma stages), supply chain/cost risks and schedule risks. Focus R&D efforts in reducing high impact risks- High-Q SRF materials, high gradient RF breakdown experiments, plasma staging experiments, high radiation tolerant electronics, new magnet development.

Validation using existing data and prototypes Cross check of the design and simulation results using performance of existing machines (e.g. LHC, RHIC, SLAC FACET) and prototype experiments (plasma accelerator test facilities). Use benchmarking using comparisons of designs to published performance and operational experience in refining designs

This methodology has offered a holistic process of going from the physics goals, to the specific machine and detector requirements, with flexibility for evaluating feasibility by multi physics simulation, and planning of experimental programs and research & development activity to fill the most important technology gaps.

Analysis and Discussion of Data

We make an analysis of the representative performance metrics from existing accelerators (LHC, SLAC, KEK, Cern test facilities) and for prototype studies novel accelerators results (PWFA from FACET, LWFA experiments results, SRF from performance) The analysis equations are focused on the trends of the luminosity, emittance of the beam and the brightness, energy gradients, efficiency of the accelerator (wall-plug to beam) and the detector performance indicators (tracking resolution, caloric energy resolution, timing). Data sources are published performance reports, technical design reports and peer reviewed experimental results (Evans & Bryant, 2008; Leemans et al., 2014; Padamsee et al., 1998) Where precise numbers are required, as needed to apply illustrative comparison, we use representative and typical-zero reported global numbers (e.g. LHC peak luminosity during Run 2; SRF cavity gradients of 35-45 MV/m routinely measured in production cavities) - although we understand that actual operational parameters can be of different values, or can be dependably different depending on upgrades, cavity operation conditions.

Beam Control-Particle emission properties Beammaking emissions-Particle Optical properties

Beam brightness is of great importance to the colliders as well as the light sources. For the future lepton colliders a very low emittance (normalized emittances in the nm range for the vertical plane) of the beams is needed which implies very stiff requirements for the design of the injector, damping rings and alignment tolerances. Emittance growth mechanisms including wakesfields, intra-beam scattering and residual gas scattering and misalignments need to be quantified and corrected using tuning, feedback and beam-based alignment mechanisms (Wiedemann, 2015).

Table 1 — Detector Performance Benchmarks

Subsystem	Key metric	Typical/target performance
Vertex detector	Impact parameter resolution m	depending on radius and technology (silicon pixels)
Tracker	Momentum resolution	GeV (for high precision trackers)
Electromagnetic calorimeter	Energy resolution	(homogeneous)

Accelerator efficiency and sustainability

Energy efficiency is an ever growing consideration. Wall-plug efficiency i.e. from grid power to usable beam power varies widely: SRF have a trade off between high accelerating gradient and duty factor and cryo overhead: normal conducting high gradient RF systems may have different trade-off. Novel acceleration scheme: Novel schemes promise to offer higher gradient but have to demonstrate how these schemes are energy efficient overall, once accountable factors such as driver systems (lasers, particle drivers) and repetition rates can be taken into account.

Novel acceleration and beam quality Tradeoffs

Plasma accelerators provide very high gradients (GV/m) but give beam with a larger energy spread and difficult stability as compared to SRF accelerators. Beam loading techniques can be used to enhance energy spread control and active staging may be a way of increasing energies but preservation of emittance and low jitter when moving from one stage to the next is a subject of R&D. Dielectric wakefield accelerators (DWA) Moderate gradients (100s of MV/m) Potential for high frequency operation Material breakdown Related to fabrication precision

Backgrounds, pileup and detector problems

At very high luminosities (e.g. HL-LHC scenarios aiming at integrated luminosities) pileup (more than one simultaneous interaction per bunch crossing) is a serious problem which complicates event reconstruction. Upgrades of the detector are aimed at better granularity, precision timing, and ability to withstand radiation to separate vertices and to associate tracks with them better (Apollinari et al., 2017).

Data analysis and statistical attainability

Physics-mixed- Precision/better-detection, for example, the topological Achievable physics depends on cross section, luminosity and detection efficiency. For rare processes for which the cross section is small , event counts scale as . The usual limit on ultimate sensitivity is an effect known as systematic uncertainties (detector calibration, background modeling and theoretical cross section). Strategies to reduce systematics include control regions, in situ calibrations as reduction strategies for theoretical uncertainties, and, correction to the part of the calculations claiming parton distribution function(s) in the factorized expressions (NLO/NNLO)

Integration and trade-offs

Facility design demands Seth mind of trade-offs: drive reach the energy frontier- the cost and complexity of the system will increase frequently Push affordability- the change requires courage: drive to take the intensity frontier. We as an example of optimization (high beam power, robust targetry). Multi-purpose facilities need flexibility place to design and upgrade. R&D programs for de-risking critical technologies (high-field magnets, SRF performance -or plasma staging) has direct effect on feasibility and schedule of future projects.

Discussion

Several fundamental themes are highlighted in the analysis. First, for the physics goals to be achieved requires a close coupling between the physics needs and machine/detector engineering. Luminosity is a tool for discovery, an enhancement to locate more small sections of cross network and actually tiny diversions from the norm of the standard model. But increasing luminosity does not come without cost, resulting in a rise in pileup, increasing background radiation, as well as severe requirements on detectors and triggers. Technologies such as precision timing detector (10-30ps) and high granularity tracker are the essential mitigation strategies essenceaking physics performance in hPILE environments.

Second, very important is beam quality (emittance etc., energy spread, stability). For lepton colliders to be able to maintain very low emittance via injection, to damp out collisions, and maintain alignment, this is a very multi-disciplinary undertaking and requires precise alignment, vibration control, advanced feedback. For hadron machines, the problem becomes instead of the beam power stored where they are to be used and the beam losses to be addressed robust collimation systems and machine protection which are indispensable to prevent damage to superconducting magnets and to ensure high availability.

Third, the ability to compute and manage data is part of HEPP experiments. With increasing amounts of data available, the community is in need of scalable storage and CPU power and the ability to adopt machine learning and high-level statistical methods for making decisions in real time and for analysis offline. Investments in software sustainability, common toolkits, and distributed data federation improve the productivity of the involved science and save the duplication of effort.

Finally, the research ecosystem (international collaboration, shareable facilities to conduct R&D (test beams, plasma facilities), training pipelines, etc.) is of fundamental importance. Accelerator and detector development require and derive from cross-disciplinary expertise in various areas of materials science, cryogenics, RF engineering, plasma physics, and software engineering. Strategic prioritization of areas of R&D with the greatest impact to enable the plant of a future facilitates is important: High-field magnets development for next-generation hadron colliders, SRF improvements for linacs and ERLs, plasma staging experiments for high-performance accelerators, are at the top of the list.

Conclusion

High energy particle physics and accelerator studies are a synergistic pair: theoretical visions of the fundamental laws of nature require experimental facilities which can be used to study the ever smaller and rarer, and accelerator science provides the technologies and the operating experience to accomplish these goals. This article has discussed the motivation from the theoretical side, given an overview of state-of-the-art experimental achievements and studied the technical aspects of the accelerator systems and the device technologies, while presenting a methodology for the design of the facility and offered an analysis of representative performance metrics.

The Standard Model is still our best particle interactions theory, however empirical anomalies and theoretical considerations lead to the search for physics beyond the Standard Model (BSM). In order to be sensitive to BSM phenomena you have to push the boundaries of both energy and luminosity: they are complementary ways. energy frontier colliders (higher center-of-mass energies) of the physics experiments expand its reach in terms of heavier states to reach the intensity and precision frontier experiments explore small couplings and rare processes with high statistics. Strategic decisions on which facility type (lepton vs hadron collider, fixed target, neutrino facility, muon collider) to take next will have to balance the various physical achievements, technical maturity, cost, time scale, and community impact divides between the choices.

Novel concepts of accelerators - PWFA and LWFA - provide the promise of dramatically higher accelerating gradients (GV/m vs MV/m for conventional cavities). Experimental demonstrations of electromagnetically acceleration of GeV in centimetre-size plasmas have been accomplished, and proof-of-principle, staging experiments have improved very rapidly. Nonetheless, collider grade beams (small emittance, low energy spread, high repetition) from plasma stages is a formidable challenge to achieve. The road towards plasma-collider is probably passing through intermediate applications (compact light sources, injectors) useful for de-risking of key technologies and accumulation of operational experience. Dielectric wakefield and advanced normal conducting concepts may be alternative ways of going with a more immediate engineering maturity at moderate gradients.

Issues: Detector technologies keep changing based upon performance requirements on the accelerators High granularity, low mass trackers, radiation hard sensors, timing layer high-precision and fast electronics with low-noise are important in discriminating signals from pile-up backgrounds within high luminosity physics experiments. The material and electronics that will be used in detectors must be developed such that they are not material-intensive (so as to leave momentum and vertexing resolution intact), and are efficient with respect to other critical time-critical performance requirements. Integration of high-technology cooling, data reduction of data at the front end and radiation-tolerant optical links will be important for next-generation detectors.

Computing, data handling and analysis frameworks are as necessary as hardware. As exabytes-scan data-sets are generated during the lifetime of experiments, for efficient storage and timely identification of physics require efficient distributed computing models, noise-free in situ reconstruction and intelligent trigger. Machine learning plays an increasing role at all the coordinate of the process pipeline: accelerator tuning and anomaly detection, fast surrogate models for simulations, online trigger decision taking, offline events selection and object identifications. However, rigorous validation and understanding of ML models is necessary so as to avoid introducing biases as well as quantify systematic uncertainties.

International collaboration and long-term consistent planning is a necessity. Large accelerator projects are well beyond the budget and expertise of individual institutions and frequently have multi-decadal commitments. Transparent prioritization, global coordination and common R&D infrastructure - testing facilities, prototype programs and joint design studies - run to bring technology maturity faster allowing the risk to be spread. Community processes (e.g. Snowmass in the U.S., the European Strategy for Particle Physics) help prioritize the potential science opportunities, taking into account also the technical readiness of the various capabilities and the fiscal realities.

Sustainability and societal influence must be put forward explicitly. Big science projects are energy and resource intensive; maximizing energy efficiency (e.g. optimizing wall-plug efficiency, energy recovering, cryogenic efficiency) makes the project cheaper in terms of costs, and is also less harming to the environment. Accelerator technologies also make broad, societal contributions (medical accelerators for cancer therapy, x-ray sources for material and biological research, and industrial applications); articulation and strengthening of the contributions to society is useful for maintaining public and government support.

In conclusion, the way forward in high energy physics and accelerator studies is many-sided. Further exploration into the energy and intensity frontiers must be undertaken with its own mix of near term upgrades of existing facilities, focused R&D to de-risk any ambitious future investments assistance in detector and computing technologies that would yield a maximum physics payoff. By combining a focus on physics objectives, sophisticated accelerator and detector design, international collaboration, and a focus on sustainable and cost-effective design, this discipline of physics should continue to answer fundamental questions about the Universe and continue to provide technological and societal benefits.

Recommendations

1. Prioritize research and development in high field magnet technology (Nb_3Sn, HTS), to allow one to operate the next generation of hadrons colliders.
2. Continue SRF cavity development in order to increase the gradients and the quality factors (Q_0) and lower cryogenic loads.
3. Support development of staged plasma accelerators with an emphasis on injector development and improvement of beam quality as a precursor to commitment to concepts at the scale of colliders
4. Invest in high granularity and radiation hard new detector technologies and the use of timing layers for pileups.
5. Expand use cases of machine learning for accelerator optimization, anomaly detection, online optimization including an API on interpretability and protocols for quantifying uncertainty.
6. support and invest test facilities (beamline, plasma labs, SRF test stands) which define away critical technologies.
7. Prioritize energy efficiency: it is important to improve wall-plug efficiency, SRF cryogenics and energy recovery linac where applicable.
8. Develop markets developing exorbitant supply chains for critical materials (superconductors, radiation hard electronic)
9. Combine beam interactions, RF/magnet interaction and detector repercussion to make realistic predictions of performance.
10. Enhance global collaboration of the key facility planning, with clean science cases and cost-benefit analysis.
11. Contributing The labor and support of workforce development and training across the board accelerator physics, detector technology and data science work.
12. Data and software sustainability should be ensured by using open and well-documented frameworks and ensuring reproducible workflows.

13. Allocate resources for systematic studies undertaken on machine protection and failure modes for high stored energy machines.
14. Focus on R&D into high bandwidth/low latency data acquisition and trigger systems to cope with next generation rates.
15. Encourage transfer of technology to societal applications (medical, industry), to increase impact and support from stakeholders.

References

1. Aad, G., et al. (ATLAS Collaboration). (2012). Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. Physics Letters B, 716(1), 1–29.
2. Abbott, B., et al. (CDF Collaboration). (1995). Observation of the top quark. Physical Review Letters, 74(14), 2626–2631.
3. Apollinari, G., et al. (2017). High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report V.0.1. CERN.
4. Baer, H., et al. (2013). The International Linear Collider Technical Design Report — Volume 2: Physics. arXiv:1306.6352.
5. Borland, M. (2000). Elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation. Advanced Photon Source LS-287.
6. Chatrchyan, S., et al. (CMS Collaboration). (2012). Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. Physics Letters B, 716(1), 30–61.
7. Courant, E. D., & Snyder, H. S. (1958). Theory of the alternating-gradient synchrotron. Annals of Physics, 3(1), 1–48.
8. de Oliveira, L., et al. (2016). Jet-images — deep learning edition. Journal of High Energy Physics, 07, 69.
9. Esarey, E., Schroeder, C. B., & Leemans, W. P. (2009). Physics of laser-driven plasma-based electron accelerators. Reviews of Modern Physics, 81(3), 1229–1285.
10. Evans, L., & Bryant, P. (2008). LHC Machine. Journal of Instrumentation, 3, S08001.
11. Green, M. A. (2017). Superconducting magnet systems for accelerators. Reviews of Accelerator Science and Technology, 10, 1–24.
12. Kirk, H., et al. (2013). Neutrino Factory and Muon Collider R&D. Journal of Instrumentation, 8, T09007.
13. Kleinknecht, K. (1998). Detectors for Particle Radiation. Cambridge University Press.
14. Knoll, G. F. (2010). Radiation Detection and Measurement (4th ed.). Wiley.
15. Leemans, W. P., et al. (2014). Multi-GeV electron beams from capillary-discharge-guided subpetawatt laser pulses in the self-trapping regime. Physical Review Letters, 113(24), 245002.
16. Linssen, L., et al. (2012). Physics and Detectors at CLIC: CLIC Conceptual Design Report. arXiv:1202.5940.
17. Padamsee, H., Knobloch, J., & Hays, T. (1998). RF Superconductivity for Accelerators. Wiley.
18. Peskin, M. E., & Schroeder, D. V. (1995). An Introduction to Quantum Field Theory. Addison-Wesley.
19. Radovic, A., et al. (2018). Machine learning at the energy and intensity frontiers of particle physics. Nature, 560(7716), 41–48.
20. Reiser, M. (2008). Theory and Design of Charged Particle Beams (2nd ed.). Wiley-VCH.
21. Rossi, L., & Bruning, O. (Eds.). (2004). Proceedings of the CERN Accelerator School: CERN Accelerator School and CERN Summer School. CERN.
22. Sands, M. (1970). The physics of electron storage rings: An introduction. SLAC-121.

23. Schroeder, C. B., et al. (2010). Physics issues for laser–plasma accelerators. Nuclear Instruments and Methods in Physics Research A, 740, 1–3.

24. Spieler, H. (2005). Semiconductor Detector Systems. Oxford University Press.

25. Tajima, T., & Dawson, J. M. (1979). Laser Electron Accelerator. Physical Review Letters, 43(4), 267–270.

26. Wanzenberg, R. (2003). Beam diagnostics and instrumentation. CERN Accelerator School Lectures.

27. Wiedemann, H. (2015). Particle Accelerator Physics (4th ed.). Springer.

28. Wilson, E. J. N. (2001). An Introduction to Particle Accelerators. Oxford University Press.

29. Zimmermann, F., et al. (2014). Future Circular Collider Study. CERN Yellow Reports.

30. Olive, K. A., et al. (Particle Data Group). (2014). Review of Particle Physics. Chinese Physics C, 38(9), 090001