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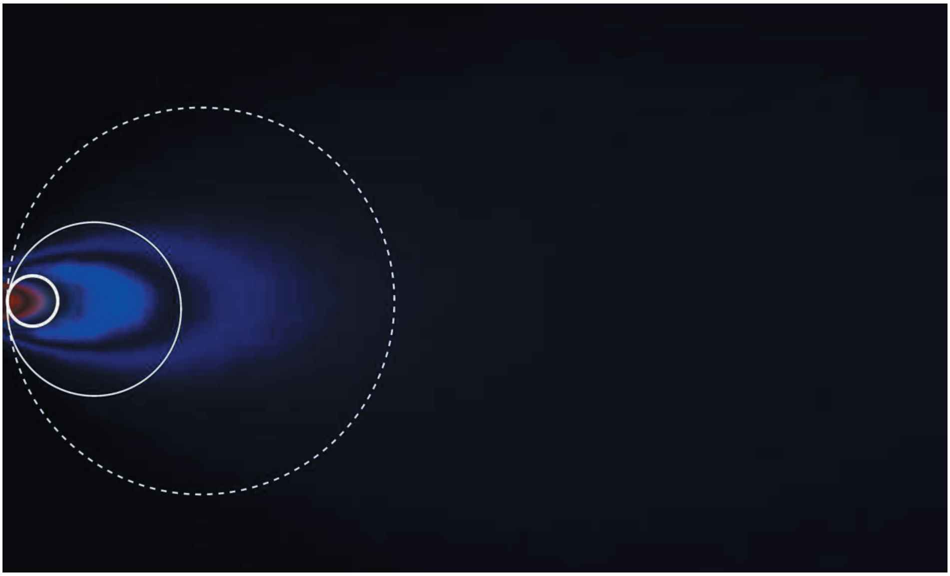
# STRATEGY FOR FUTURE EXTREME BEAM FACILITIES

EDITED BY F. ZIMMERMANN



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Cover image:
"Artist's view of past and future circular colliders",
courtesy CERN FCC Study Office

## Abstract:

Over a period of 4 years EuCARD-2 XBEAM has organized, or co-organized 35 workshops addressing key topics of future (circular) particle colliders, storage rings for intense beams, superconducting hadron linacs, and polarization challenges.

The present deliverable report summarizes the state of the art, discusses emerging new developments, and highlights a large number of upcoming and proposed projects, which will certainly push the existing boundaries. The report also underlines the important role played by the European accelerator networks, and it presents some tantalizing future perspectives, including large circular colliders, cold muon beams, crystals and nanotubes.

Edited by F. Zimmermann

# STRATEGY FOR FUTURE EXTREME BEAM FACILITIES

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# 1. EXECUTIVE SUMMARY

*During four years from May 2013 to April 2017 EuCARD-2 Work Package 5 "Extreme Beams" (XBEAM) organized or co-organized 35 workshops on extreme colliders, extreme rings, extreme linacs and extreme polarization.*

*In 2016 XBEAM delivered four reports describing preliminary strategies for future hadron & lepton colliders, for future high-performance hadron rings, for future high-power high-current SC linacs, for future polarized beam, respectively.*

*In this final XBEAM report, we present an overall overview, draw our final conclusions and issue recommendations regarding the short-term, medium-term and long-term future of accelerator facilities pushing the frontiers of energy, intensity, power and precision.*

*For future large projects, efficiency and cost minimization become ever more important. Various novel technologies and concepts – such as ionization-cooling-free muon colliders and crystal/nanobeam acceleration – and tools – e.g. multi-purpose electron lenses – may help reduce these expenses.*

*Much will be learnt from upcoming new facilities and test facilities, such as SuperKEKB, IOTA, CBETA, ESS, NICA, MESA, FAIR, LIU and HL-LHC.*

*Strengthening pan-European and global collaboration is another recipe for future success.*

*European accelerator networks continue to play a key role in all the aforementioned areas, and they provide key ingredients for the future accelerator development.*

# 2. INTRODUCTION

EuCARD-2 XBEAM has proven a highly successful network activity, resonating with the European accelerator community. During four years, and often driven by community demands, XBEAM organized or co-organized 35 workshops, mini-workshops or conferences [1-35]. Noteworthy are, in particular, in the final couple of months, a joint workshop of XBEAM – XCOLL and WP7 EuroNNAc "Focus: Future Frontiers in Accelerator (F3iA)" [18], in Germany from December 2016, and a concluding XBEAM strategy workshop held at the University of Valencia in February 2017 [35]. The following sections are based on the conclusions from the Valencia workshop, and consider, successively, colliders, hadron rings, hadron linacs and polarisation issues. The report closes with an outlook, a list of references, and a glossary of acronyms.

# 3. EXTREME COLLIDERS

## 3.1. COLLIDER LANDSCAPE AND EUCARD-2 XCOLL ACTIVITIES

Thanks to the discovery at the Large Hadron Collider (LHC) of the Higgs boson in 2012, and signs of new physics in 2015, interest in future colliders has reached a new level. Various proposals have appeared – especially in Europe, the United States, and China – for new highest-luminosity $e^+e^-$ colliders, with sensitivity up to tens of TeV and direct discovery potential for rare decays, for higher-luminosity hadron colliders, and even for next-generation lepton-hadron colliders. In addition, recently proposed novel concepts which do not require ionization cooling have revived the idea of a muon collider.

EuCARD-2 WP5.2 XCOLL was active at the center of this exciting R&D evolution. In total, XCOLL organized and co-organized 18 workshops [1-18], i.e. six times as many as originally foreseen in the EuCARD-2 proposal.

In the framework of XBEAM task 5.2 “Extreme colliders, XCOLL” the following eighteen dedicated or semi-dedicated workshops were held:

- XCOLL workshop on future circular $e^+e^-$ colliders, TLEP6, CERN, 16-18 Oct. 2013 [1].
- SuperKEKB Commissioning Workshop, KEK, Japan, November 2013 [2].
- XCOLL workshop on LHC crab cavities LHC-CC13, CERN, 9-11 December 2014 [3].
- International Workshop on Future High Energy Circular Colliders”, IHEP, Beijing, China, 16-17 December 2013 [4].
- Workshop on the LHeC lepton-hadron collider, Chavannes-de-Bogis, 20-21 January 2014 [5].
- Future Circular Collider Study Kick-Off Meeting", U. Geneva, 12-15 February 2014 [6].
- Workshop on “Electromagnetic wake fields and impedances in particle accelerators”, Erice, Italy, 23-29 April 2014 [7].
- International Workshop on “Multipactor, Corona and Passive Intermodulation (MULCOPIM)”, Valencia, 19-21 September 2014 [8].
- International Conf. on Charged & Neutral Particles Channeling Phenomena – “Channeling 2014”, Capri, Italy 5-10 October 2014 [9].
- Higgs Factory ICFA workshop HF2014, IHEP, China, October 2014 [10].
- XCOLL/XRING joint workshop on Advanced Optics Control (AOC), CERN, February 2015 [11].
- FCC Week 2015, Washington, United States, March 2015 [12].
- Workshop on the LHeC (and future electron–hadron colliders at CERN), CERN and Chavannes-de-Bogis, 24-26 June 2015 [13].
- XCOLL workshop on “Tracking for Collimation”, CERN, 30 October 2015 [14].
- FCC Week 2016, Rome (Italy), April 11-15 2016 [15].
- International Conference on Charged & Neutral Particles Channeling Phenomena - Channeling 2016”, Sirmione, Italy, 25-30 September 2016 [16].
- ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular $e^+e^-$ Colliders – “eeFACT2016,” Daresbury, 24-27 October 2016 [17].
- XCOLL/EuroNNAc joint workshop “Focus: Future Frontiers in Accelerator (F3iA)”, Scharbeutz, Germany, 5-9 December 2016 [18].

These workshops covered basically all aspects of the newly proposed circular colliders, and helped shape and improve the respective designs. In the following we briefly describe the state of the art plus strategic elements for circular $e^+e^-$ colliders, muon colliders, hadron colliders, and lepton-hadron colliders, respectively, before briefly comparing their respective merits with those of other approaches (e.g. linear $e^+e^-$ and plasma colliders) and formulating a roadmap for the future.

## 3.2. CIRCULAR $e^+e^-$ COLLIDERS

In order to reach high luminosity and high energies in future circular lepton colliders, several key technical and design issues must be mastered. A number of workshops were held to discuss the design strategies. Figure 1 shows the luminosity as a function of center of mass energy for past, present and (proposed) future lepton colliders around the world. It is clear that the future relies on achieving much higher luminosities. Figure 2 presents the peak luminosity of circular $e^+e^-$ lepton colliders versus time, illustrating an impressive, unabated progress over several decades, thanks to continuous innovation, which is expected to continue.

At present, our strategy plan for the future can be based on the commissioning results of the high luminosity SuperKEKB B-Factory in Japan, an upgrade of the KEKB B-Factory, and on the work being done for the "Higgs and beyond" Factories at CERN for FCC-ee and in China for the twin project CEPC. These accelerators represent the luminosity frontier at medium energy (SuperKEKB) and at high energies ranging from 45 to 175 GeV/beam (FCC-ee, CEPC). Future colliders will profit from the lessons learnt at past and present colliders, including: (1) possibility of high beam currents thanks to the control of Higher Order Modes (HOMs) and electron cloud; (2) the feasibility of the crab-waist collision scheme, as demonstrated at DAFNE, requiring a special lattice; (3) the need for top-up injection, calling for a reliable injection complex; (4) the possibility of electron-cloud mitigation through solenoids, clearing electrodes, grooves and vacuum surfaces of low secondary emission yield thanks to a-C coating, TiN coating, NEG coating or scrubbing; (5) the benefit of bunch-by-bunch feedbacks plus upgrades thereof; (6) handling of background increases with beam current, luminosity and beam energy by means of masking, shielding, and beamstrahlung control; (7) essential emittance tuning, machine error minimization (girders), fast online procedures for orbit/beta /dispersion/ coupling correction; (8) the necessity of IP orbit control and IP feedback; (9) vibration control of final-focus quadrupoles of the collision of "nano-beams".

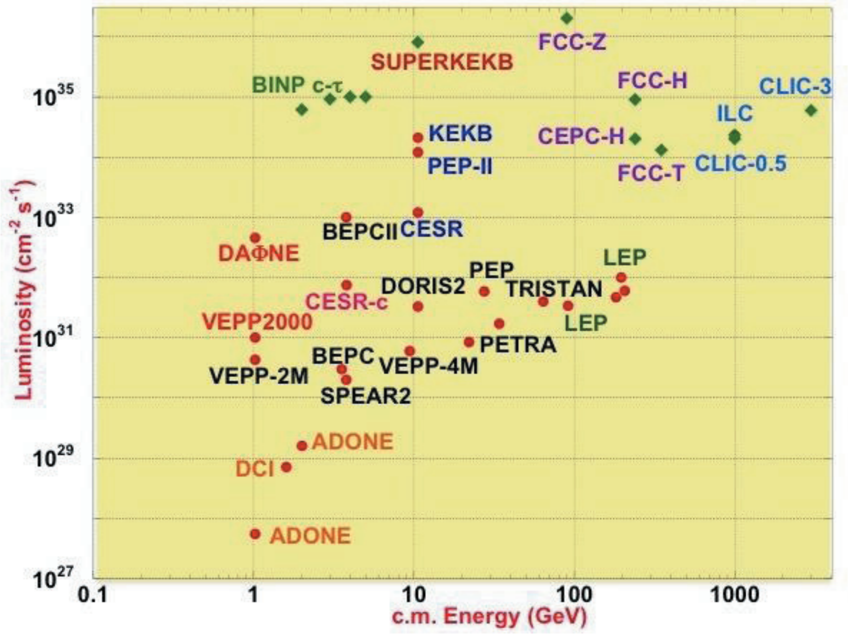


Figure 1: Luminosity vs. centre-of-mass energy for past [orange, black, green centre-right], present (2015) [red] and future lepton colliders [blue, purple, green top-left] around the world.

The choice of the beam/ring parameters is crucial. The experience gained from the past circular $e^+e^-$ colliders gives confidence in the attainable parameters. LEP was the highest energy $e^+e^-$ collider so far, and its experience offers plenty of suggestions and operational clues. The highly successful B-Factories PEP-II in the US and KEKB in Japan have demonstrated the possibility of storing high beam currents (up to 3.2 A of positrons in PEP-II), together with the ability to continuously inject small amounts of beams ("top-up injection"), in order to maintain a constant luminosity, equal to the peak luminosity, and, thereby, to increase the integrated luminosity, but also to overcome the low beam lifetime due to collision physics processes (e.g. radiative Bhabha scattering). Top-up injection requires an injection system capable of providing, reliably and at a sufficiently high rate, the needed electrons and positrons.

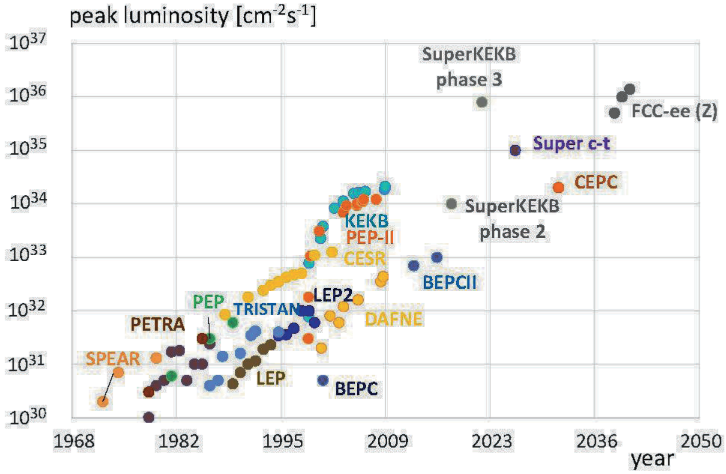


*Figure 2: Peak luminosity of circular $e^+e^-$ colliders as a function of year – for past, operating, and proposed facilities including the Future Circular Collider [historical data courtesy Y. Funakoshi].*

For high energy lepton colliders, the synchrotron radiation is an issue since it quickly drives up the operational costs. For this reason, in both FCC-ee and CEPC designs the synchrotron power loss is limited by design to 50 MW per beam. The synchrotron radiation ultimately limits the energy reach of a circular collider at a given circumference.

Table 1 compares a few primary beam parameters for three future colliders: SuperKEKB (built), FCC-ee and CEPC (both proposed).

*Table 1: Design beam parameters for three state-of-the-art circular colliders. Preliminary revised CEPC parameters were provided by C. Yu on 6 March 2017.*

| | SuperKEKB | FCC-ee | CEPC |
|---|---|---|---|
| c.m. energy [GeV] | 10.58 | 90 → 350 | 90 → 240 |
| circumference [km] | 3. | 100 | 100 |
| luminosity/IP [$cm^{-2}s^{-1}$] | $8\times10^{35}$ | $2.1\times10^{36} \rightarrow 1.3\times10^{34}$ | $>10^{35} \rightarrow 2.0\times10^{34}$ |
| hor. emittance [nm] | 5 (HER) 3 (LER) | 0.2 → 1.3 | 1.5 → 1.3 |
| vert. emittance [pm] | 13 (HER) , 9 (LER) | 1→ 2.5 | 7.8→ 4.0 |
| beam current (mA) | 3600 (LER) 2600 (HER) | 1450 → 6.6 | <466 → 19.2 |
| SR power (MW)/beam | 6.5 | 50 | <16→ 32 |

Modern colliders all feature two separate beam pipes crossing at an angle in one or several Interaction Points (IPs). The same layout has been chosen for FCC-ee and, recently, also for CEPC.

For all projects the lattice design effort is focused on achieving low emittances, both horizontally and vertically. In recent years, the community of the synchrotron-light source designers has progressed towards the realization of lower emittance rings, because an emittance reduction by 1-2 orders of magnitude would enable synchrotron radiation experiments in the diffraction limited regime. Since the pioneering design of the MAX-IV 3 GeV storage ring in Sweden, based on novel multibend achromat lattice, a generational change is taking place in this field, as is impressively depicted in Fig. 3. By contrast, for large high-energy accelerators a FODO cell lattice remains the most suitable and cheapest choice for the arc optics. In particular, such a lattice maximizes the dipole filling factor, a crucial parameter for any highest-energy collider. For this reason, FODO cell arcs were adopted by both the FCC and CEPC designs. Indeed, the latter two designs are converging towards almost identical parameters and layouts (Fig. 4), except for a different maximal c.m. energy (≥350 GeV for FCC-ee, and 240 GeV for CEPC, respectively).

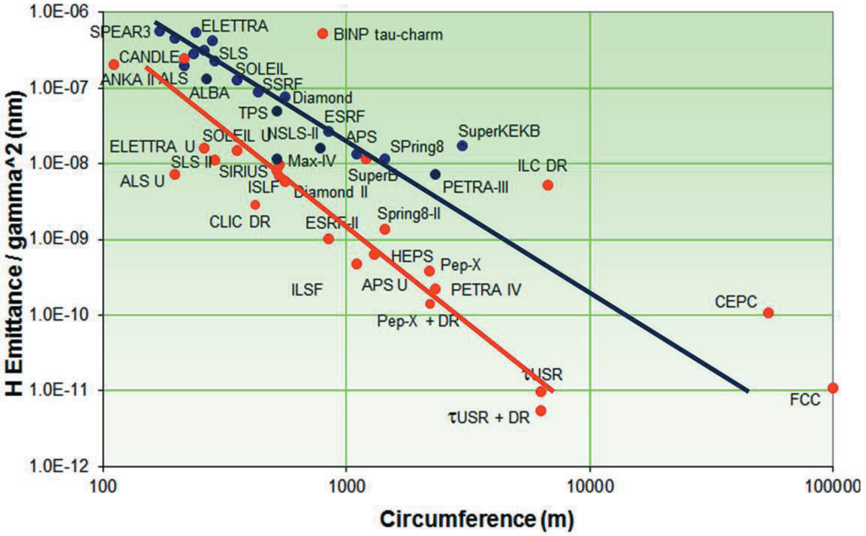


*Figure 3: Emittance normalized to beam energy vs. circumference for storage rings in operation (blue dots) and under construction or being planned (red dots). The ongoing generational change is indicated by the transition from the blue line to the red line (R. Bartolini, LER-2014 workshop, updated 2016)*

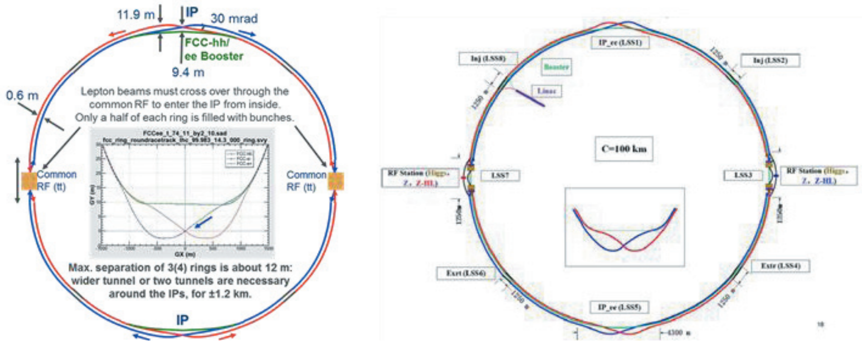


Figure 4: Layouts of FCC-ee (K. Oide, 2015) and CEPC (J. Gao, LCWS2016)

Achieving the target values for the vertical emittance requires the use of established optics correction techniques such as dispersion-free steering and local coupling correction. Such techniques are highly refined for modern storage-ring light sources. Differently from the light sources, in colliders the small vertical emittance must be attained with colliding beams. Figure 5 documents some historical accomplishments and future goals.

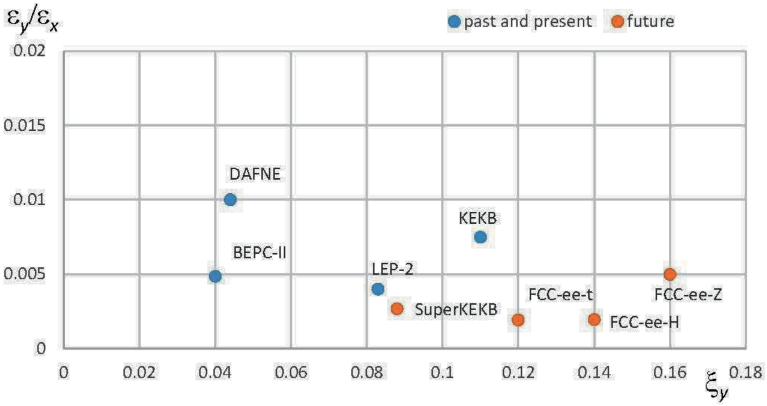


*Figure 5: Vertical-to-horizontal emittance radios achieved in various past $e^+e^-$ colliders (blue) along with target values for future machines (orange) as a function of beam-beam parameter (per IP); past values were extracted from [36].*

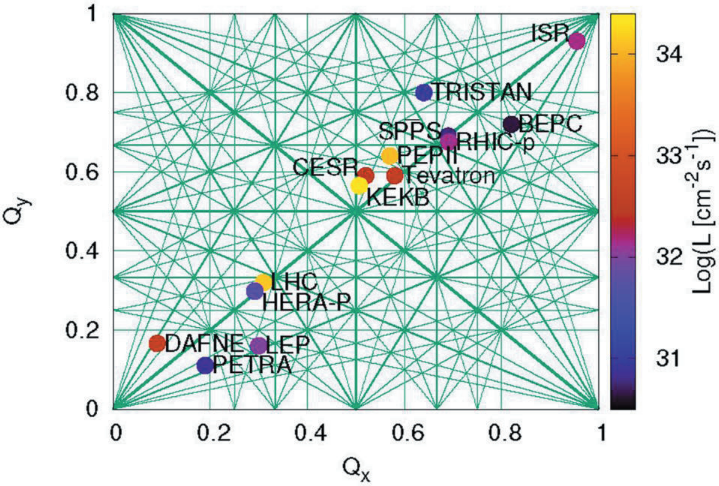


*Figure 6: Operating points in the tune diagram and luminosity performance of past colliders (R. Tomas, Valencia workshop [35]).*

The beam-beam performance (and minimum) vertical blow up also depends on the choice of working point in the tune diagram and on the collision scheme. Figure 6 attempts to correlate performance with the tune choices for various electron-positron and hadron colliders. A new collision scheme, known as "Large Piwinski Angle with Crab Waist Sextupoles", was developed in 2007 at LNF Frascati for the DAΦNE Φ-Factory by P. Raimondi. This collision scheme allows overcoming the limitations of colliding with a large crossing angle, by suppressing betatron resonances arising from the crossing angle, and at the same time increasing the luminosity. In addition, the resonance-free area in the tune diagram is also increased, leaving more operational freedom, and enabling operation at higher beam-beam tune shift. This scheme has practically been adopted by all future collider designs, even if for SuperKEKB at the moment the use of the actual crab waist sextupoles is not foreseen due to lack of a suitable sextupole location. However, SuperKEKB is designed with a large Piwinski angle.

For the SuperKEKB collider a very low β* IR has been designed, with a complicated arrangement of quadrupoles, correcting coils and solenoids in order to suppress the coupling induced by the detector solenoid and to reduce the emittance growth due to the solenoidal fringing field. These and other future IR designs (for FCC-ee and CEPC) must all achieve a large momentum acceptance (or ±1.5% to 2 %) and, therefore, require a careful correction of chromaticity and geometrical aberrations. For this purpose, a "local" compensation scheme, with a vertical chromaticity correction section (CCSY) close to the IP doublet, has been generally adopted, and optionally also a subsequent horizontal correction system (CCSX). For FCC-ee the requirement of having only low-energy photons hitting the IP region (with a critical photon energy $E_\gamma$<100 keV over the last 500 m upstream of the IP) has given rise to an asymmetric IR design. This has some implications for the tunnel layout, separating the lepton collider IP from the collision point of the hadron collider (FCC-hh), but it facilitates the bypassing of the lepton detector with the lepton top-up injector (the latter can follow the footprint of the hadron collider) transversely offset by about 10 m at the IP.

The complex IR design for SuperKEKB is shown in Fig. 7, the one for FCC-ee in Fig. 8. The synchrotron radiation (SR) hitting the detector and the IP doublets is the main constraint for the IR optics and layout. The IP quadrupoles, with high gradients, should fit within the minimum possible space, compatible with the detector request for the largest possible solid angle. Compensation of the detector solenoidal field should be provided in order to minimize the impact on the beam x-y coupling and to minimize any depolarizing effect (in case resonant depolarization is used for energy calibration). Luminosity monitors should also be placed close to the IP. The design of masks and SR shielding is part of the effort to evaluate and minimize detector background.

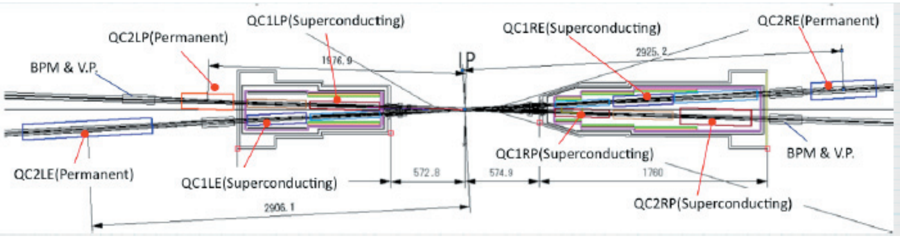


*Figure 7: SuperKEKB Interaction Region.*

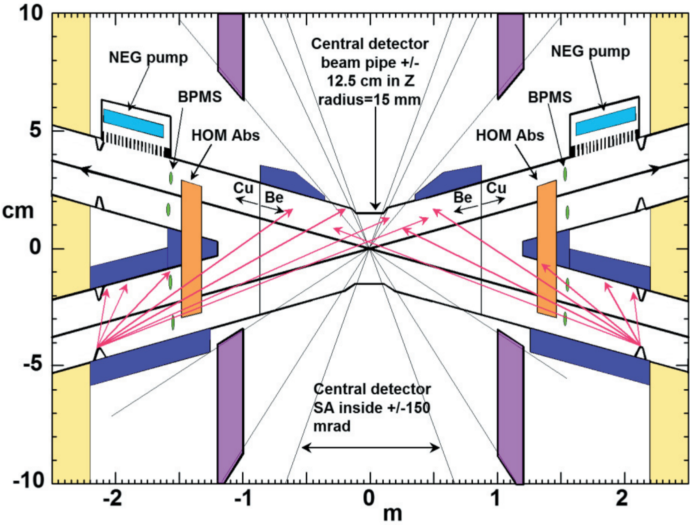


*Figure 8: FCC-ee Interaction Region (M. Sullivan, FCC-ee MDI review, January 2017)*

*Table 2: Key optics parameters for final-focus systems of various linear and circular lepton colliders, compared with parameters reachable at the ATF2 test facility.*

| | $L^*$ [m] | $\beta_y^*$ [μm] | $\xi \sim L^* / \beta_y^*$ |
|---|---|---|---|
| CLIC | 3.5 | 70 | 50000 |
| ILC | 4.5 | 480 | 9000 |
| ATF2 | 1 | 100 | 10000 |
| ATF2 ultralow | 1 | 25 | 40000 |
| SuperKEKB LER | 0.9 | 270 | 3460 |
| FCC-ee | 2 | 1000 | 2000 |

The difficulty of the final-focus optics for extremely low $\beta_y^*$ roughly scales with the chromaticity of the final quadrupole. Table 2 illustrates that linear-collider final-focus systems are extremely challenging, and that SuperKEKB is optically more demanding than FCC-ee, so that the successful operation of SuperKEKB would serve as a proof of principle. The ATF2 test facility in Japan can operate over a large range of chromaticity of interest for linear colliders. After roughly ten years of operation spot sizes close to design are achieved, but only with a bunch intensity reduced by a factor of 5 compared with the design (which lowers the effects of wake fields and also the incoming beam emittances) and with a ten-fold increase of the horizontal IP beta function, $\beta_x^*$ (which greatly decreases optical aberrations affecting the vertical beam size). Detailed measurement and benchmarking campaigns indicate the presence of much larger-than-expected optical aberrations (Fig. 9), the origin and nature of which have not yet been identified [37]. The original performance predictions for the ATF2 design were clearly too optimistic, as was the case for the final focus system of the first (and so far only operating) linear collider, the SLAC Linear Collider [38].

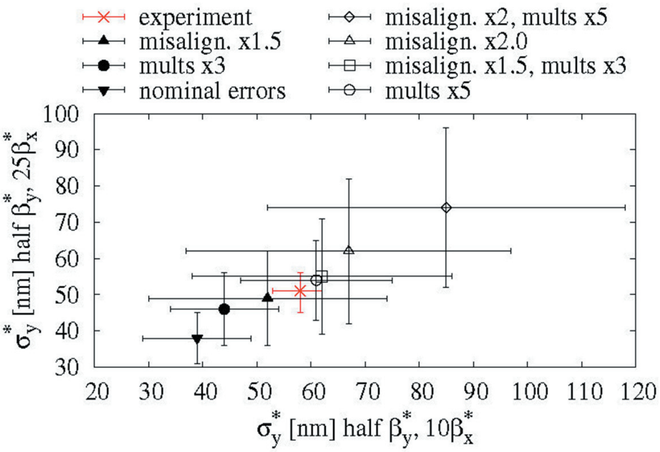
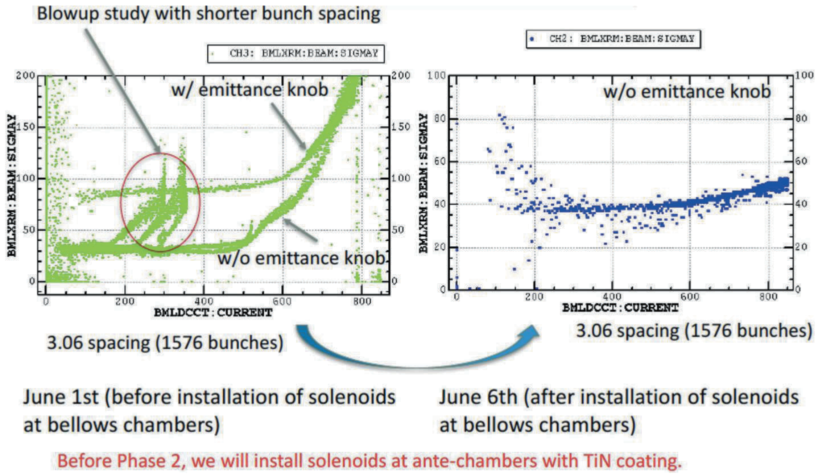


*Figure 9: ATF-2 vertical beam size at low bunch intensity with 25x increased $\beta_x^*$ versus vertical beam size with 10× increased $\beta_x^*$, comparing measurements and simulations making various error assumption [37]; the measurements can be reproduced by assuming unreasonably large field errors and misalignments (R. Tomas, Valencia, 2017 [35]).*

For FCC-ee and CEPC, beamstrahlung, i.e. the radiation emitted during the collision by particles of one beam experiencing the field of the other beam, will increase the energy spread and bunch length, especially at low beam energy ($Z$ and $W$ operation). In addition, at high energy ($t\bar{t}$ running, 175 GeV beam energy) it has an impact on the beam lifetime if the momentum acceptance of the rings is not large enough. The lifetime effect of beamstrahlung at high energy can be mitigated by relaxing the horizontal IP beta function, or by adjusting other beam parameters, and it does not seem to introduce any serious performance limitation. At lower collision energies multi-turn beamstrahlung leads to a bunch lengthening, which can counteract a violent higher-order strong-strong beam-beam instability in the *x-z* plane, which might be encountered at the Z pole if the horizontal IP beta function is too large (this novel type of higher-order coherent beam-beam instability in the *x-z* plane appearing for collisions with a large crossing angle was recently discovered by K. Ohmi and confirmed by D. Shatilov; it seems to be different from other coherent beam-beam instabilities studied in the past).

Technological issues are common to all projects: The impedance budget needs careful simulations of each hardware component in order to reduce the beam pipe impedance. For high current operation, such as in SuperKEKB, the ultra-low vacuum is a challenge. The cure of the electron cloud instability in the positron ring requires a variety of mitigation techniques (e.g. solenoidal windings, grooves, clearing electrodes, coatings with a low secondary emission yield) depending on the ring region. The efficiency of several such countermeasures can be studied at SuperKEKB, where electron-cloud related vertical emittance blow up of the positron beam has been observed, and suppressed, already during the phase 1 beam commissioning in 2017; see Fig. 10. Clearing electrodes successfully reduced the growth rates of electron-cloud driven coupled-bunch instabilities in DAFNE (Fig. 11); however, after 5 years of operation, 80% of these clearing electrodes are damaged and no longer functioning.



June 1st (before installation of solenoids at bellows chambers)

June 6th (after installation of solenoids at bellows chambers)

Before Phase 2, we will install solenoids at ante-chambers with TiN coating.

*Figure 10: Vertical beam size versus beam current in the SuperKEKB HER during the first commissioning run, showing the effect of adding solenoids at the bellows chambers (M. Biagini, Valencia, 2017 [35]).*

For both high-energy and high-current operation the main challenge is the RF system required to compensate the energy loss from synchrotron radiation. For FCC-ee at highest energy a sufficiently high voltage is needed, preferably achieved with multi-cell cavities. For high current operation at lower energy, single-cell cavities are preferred. In either case, a high efficiency is desired. Efficiency expressed as effective beam power per interaction point IP or in terms of luminosity per unit wall-plug power is a key motive in Table 3, which compares key design parameters of FCC-ee with those of two proposed linear colliders. This table suggests that roughly up to the top-quark threshold the circular collider is the preferred choice.

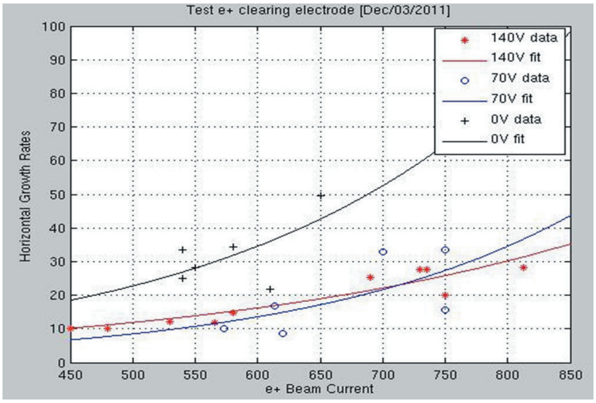


*Figure 11: Horizontal instability growth rate at DAFNE for different voltages on clearing electrodes (A. Drago, Valencia, 2017 [35]).*

*Table 3: Key optics parameters for final-focus systems of various linear and circular lepton colliders (A. Yamamoto, Hong Kong 2017; corrected and completed by M. Biagini and F. Zimmermann).*

| | **Unit** | **ILC - TDR** | | | **CLIC – CDR+** | | **FCC-ee** | | |
|---|---|---|---|---|---|---|---|---|---|
| technology | | linear<br>SRF, klystron driven | | | linear<br>NRF, 2-beam | | circular (2 IPs) | | |
| energy | GeV | 250 | **500** | 1,000 | 380 | 3,000 | 91 | **240** | **350** |
| acc. length | km | ~21 | 31 | 50 | 11 | 48 | 100 | | |
| **total luminosity** | $10^{34}$ cm$^{-2}$ s$^{-1}$ | **0.82** | **1.8** | **3.6** | **1.5** | **5.9** | **300** | **10** | **2.6** |
| acc. gradient | MV/m | 31.5 | 31.5 | 31.5 /45 | 72 | 100 | 7 | 10 | 10 |
| RF frequency | GHz | 1.3 | 1.3 | 1.3 | 12 | 12 | 0.4 | | |
| IR, v. size | nm | 7.7 | 5.9 | 2.7 | 2.9 | 1 | 32 | 49 | 70 |
| beam power (/beam /IP) | MW | 2.9 | 5.2 | 10.6 | 2.8 | 14 | 66000 | 3600 | 1160 |
| SR loss | MW | 4 | 4 | 4 | 3 | 2 | 100 | | |
| **AC power** | MW | **129** | **163** | **300** | **252** | **589** | **275** | 308 | **364** |
| **L / AC** | [nb$^{-1}$s$^{-1}$/ MW] | 0.06 | 0.11 | 0.12 | 0.06 | 0.1 | 11.1 | 0.3 | 0.07 |

## 3.3. MUON COLLIDERS

Since several decades muon colliders are being proposed. A renewed interest in future muon colliders was triggered by first results from the MICE cooling experiment in the UK, by ideas for further improved cooling schemes, and, mostly, by novel proposals to produce the muons already with a low emittance – avoiding the need for cooling.

Muons are commonly produced by sending a high-power proton beam on a target, resulting in pion generation and pion decay. A technique called ionization cooling could improve the quality of such muon beam through lowering their emittance and energy spread by several orders of magnitude. The proof-of-principle experiment MICE at Rutherford Laboratory in the UK has so far collected and analyzed 10 million individual muon tracks (Fig. 12), without any RF system, and detected a cooling effect of about 10 per cent (as expected). The next step of this experiment, foreseen for 2018, will include the reacceleration of the muons.

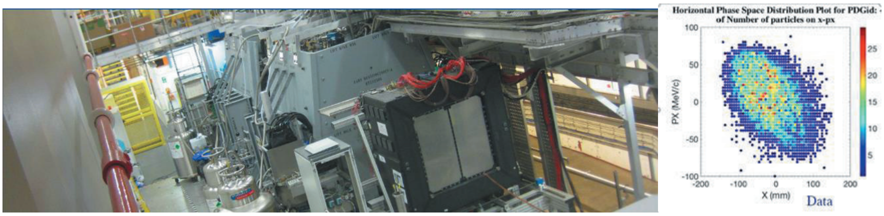


*Figure 12: MICE Experiment for the demonstration of muon ionization cooling (left) and example of muon-track data (right) (V. Shiltsev, Valencia, 2017 [35]).*

For the actual application at a future muon collider the ionization cooling channel and its operational principles can be further optimized. In particular, the so-called parametric resonance ionization cooling (PIC), proposed by Y. Derbenev, offers a potential improvement (Fig. 12), and is of interest for a muon-collider-based Higgs factory.

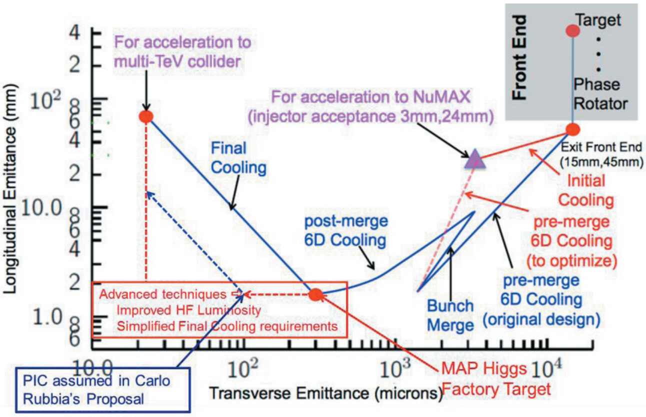


*Figure 12: Parametric resonance ionization cooling (PIC) offering enhanced cooling path and better performance (M. Boscolo, Valencia, 2017 [35]).*

An alternative modern approach is to generate the muons already with a low emittance. This can be achieved by producing the muons close to threshold either in the annihilation of positrons $e^+e^- \rightarrow \mu^+\mu^-$ (P. Raimondi), or when colliding laser photons with a high-energy proton beam that is circulating in the LHC or FCC-hh (L. Serafini). Advantages are the initial low emittance and low energy spread, allowing for lower intensity, low detector background, and reduced losses from decay. The main disadvantage (key challenge) is the low rate due to the much smaller cross section (1 μbarn at most for $e^+e^- \rightarrow \mu^+\mu^-$) compared with muon production by protons. An $e^+e^-$ luminosity of $10^{40}$ $cm^{-2}$ $s^{-1}$ would yield muon rates of $10^{10}$ Hz. Such luminosities can be obtained only in fixed target collisions. One proposal is using an $e^+$ ring, with a thin internal target, in order to reduce the demands on the positron source (M. Boscolo). The needed $e^+$ rate from the source is of order $10^{15}$ $e^+$ / second, and hence more than the rate required for the ILC and similar to the $e^+$ rate desired for positron operation of a high-luminosity LHeC. The tremendous simplification of the muon collider thanks to using positrons for muon production is evident from Fig. 14. We caution, however, that competing processes in the target such as bremsstrahlung and $e^+e^-$ pair production may contribute to the depletion of the stored $e^+$ beam without producing any additional muons.

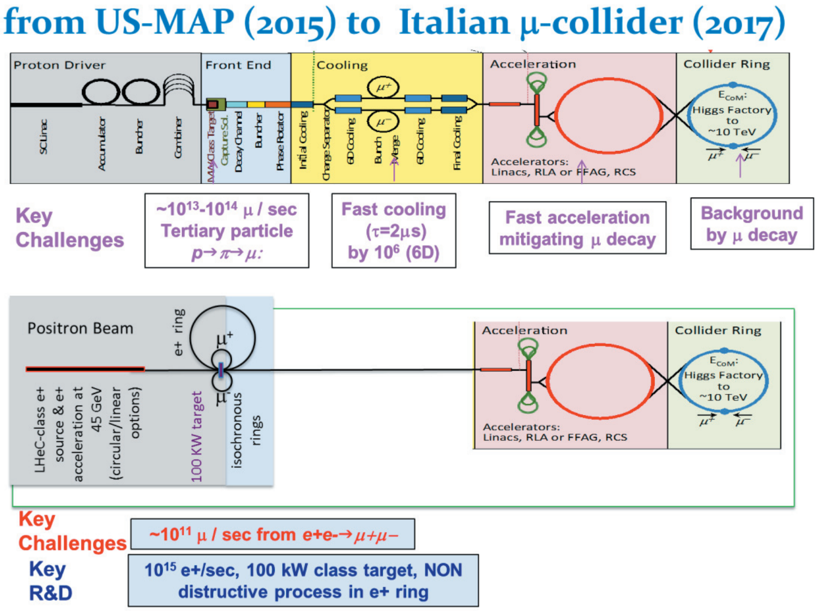


*Figure 14: From the US MAP based on a proton driver to the slimmer Italian muon collider based on an e+ storage ring with internal target (M. Boscolo, Valencia, 2017 [35]).*

In the long term, once low-emittance muon beams are available, the 26.7 km LHC tunnel can be filled with ~5 km of 16 T SC magnets and ~20 km of ±3.5 T pulsed magnets plus an additional 7 GeV of new pulsed SRF in the straight sections, to construct a 14 TeV muon collider (Fig. 15). This option also allows for efficiently reusing the existing tunnels of the SPS (6.9 km) and PS (0.7 km) and therefore to lower the price of such a collider to a level comparable to the cost of the LHC.

The ultimate dream lepton collider is an X-ray driven muon crystal linear collider, with an accelerating gradient of up to 10 TeV/m and a final crystal funnel, as sketched in Fig. 16. A variant would replace the various crystals with carbon nanotube accelerator modules and carbon nanotube funnels, respectively (V. Shiltsev).

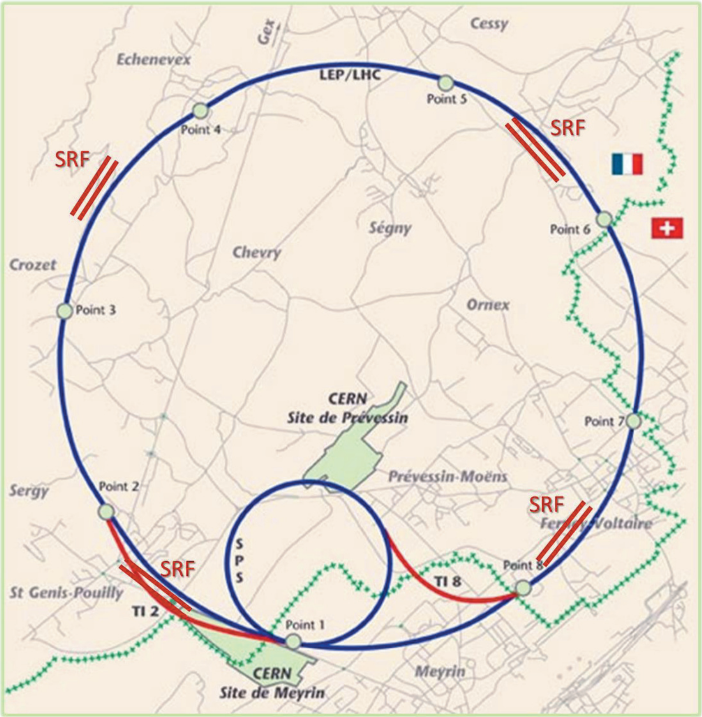


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*Figure 15: CERN 14 TeV muon collider based on the LHC (V. Shiltsev, Valencia, 2017 [35]).*

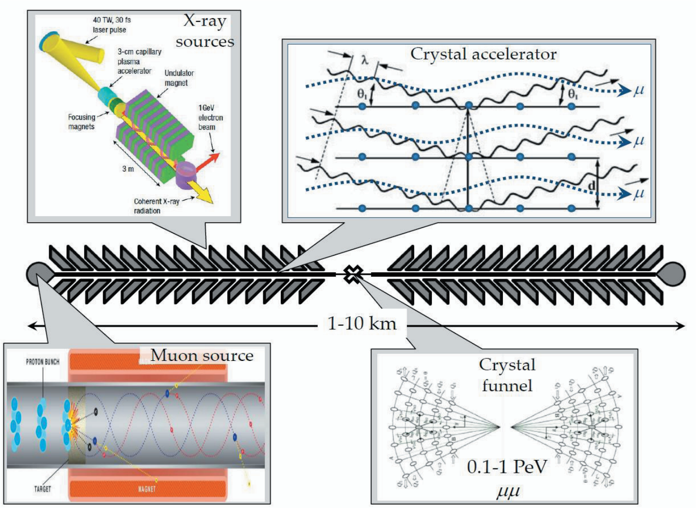


*Figure 16: 1000 TeV muon crystal collider [39] (V. Shiltsev, Valencia, 2017 [35]).*

## 3.4. HADRON COLLIDERS

Circular hadron colliders are known as discovery machines. Their discovery reach is determined by the beam energy, which depends on only two parameters: the dipole magnetic field and the size of the collider. Therefore, historically new colliders always were larger and used stronger magnets than their predecessors. For example, the Tevatron near Chicago was the first hadron collider based on superconducting magnet technology installed in a 6.3 km ring. The LHC uses 8.3 T dipoles in a 26.7 km tunnel. The 100 TeV Future Circular Collider (hadron version "FCC-hh", addressed in several XCOLL workshops requires 16 Tesla dipole magnets in a 100 km ring. No other proposed concept, not even a muon collider, appears technically ready to provide collision energies in the 10s of TeV energy range during the 21st century.

The collider luminosity ideally increases with the square of the energy since the cross sections decrease as the inverse square of energy. Due to the nonlinear parton distribution inside the colliding protons also a lower luminosity can produce exciting physics, and the most important parameter is energy. Nevertheless, at a given energy the discovery reach grows with higher luminosity. The LHC design has greatly increased the luminosity compared with previous machines. This can be seen in Fig. 17, which is the hadron-collider analogue of Fig. 1, and also in Fig. 18. Much higher luminosities still are expected for the approved HL-LHC, as well as for the proposed HE-LHC and FCC-hh. The luminosity for the latter two machines will profit from the significant radiation damping at the associated high beam energies and magnetic fields.

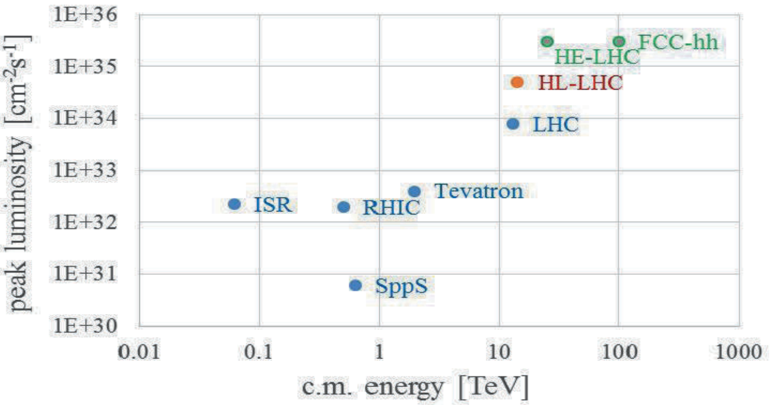


*Figure 17: Luminosity vs. centre-of-mass energy for past and present [blue], upcoming [red], and longer-term future hadron (pp or $p\bar{p}$) colliders [green] around the world.*

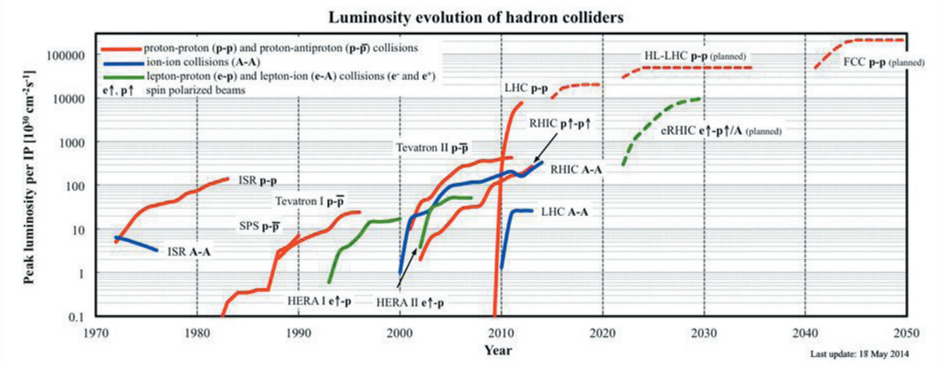


*Figure 18: Hadron collider peak luminosity as a function of year – for past, operating, and proposed facilities including the Future Circular Collider [courtesy W. Fischer].*

Higher luminosity can be achieved by reducing the beta function at the interaction point (IP), $\beta_{x,y}^*$. However, until now all hadron colliders, starting from the ISR, have operated with similar beta functions, with minimum values of about 0.3 m; see Table 4. With 0.15 (or even 0.10) m the HL-LHC will set a new record. An ongoing study aims at pushing the FCC-hh $\beta^*$ down to 5 cm (R. Martin et al., submitted to PRAB). For proton-proton colliders with many bunches, such as HL-LHC and FCC-hh, a crossing angle is required to avoid or mitigate parasitic beam-beam collisions. Unfortunately, this crossing angle needs to be increased as $\beta_{x,y}^*$ is reduced. Without countermeasures this would dramatically degrade the overlap of the colliding bunches and all but eliminate any benefit from reducing the IP beam size. To avoid this degradation both the HL-LHC and FCC-hh phase 2 will use novel crab cavities. These are transversely deflecting RF cavities, which impart kicks of opposite sign to the head and the tail of each bunch, so as to maintain the crossing angle of the bunch centroid motion, and at the same time to restore an effectively full bunch overlap during the collision. One of the EuCARD-2 WP5 XCOLL workshops was devoted to the crab cavities for the FCC-hh [3].

*Table 4: Beta* at hadron colliders (R. Tomas, Valencia, 2017 [35]).*

| collider | $\beta_x^*$ [m] | $\beta_y^*$ [m] |
|---|---|---|
| ISR | 0.3 | 3.0 |
| Sp$\bar{p}$S | 0.15 | 0.6 |
| HERA-p | 0.18 | 2.4 |
| RHIC | 0.50 | 0.50 |
| Tevatron | 0.28 | 0.28 |
| LHC | 0.4 | 0.4 |
| HL-LHC | 0.15 | 0.15 |
| FCC-hh | 1.1→0.3<br>(0.05?) | 1.1→0.3<br>(0.05?) |

Present and future hadron colliders are characterized by a large amount of stored beam energy, which render machine protection a paramount concern. A multi-stage collimation system is needed to avoid local beam loss spikes near cold magnets, which would induce magnet quenches. The collimation system of the LHC works according to specification. For the planned and proposed future colliders – HL-LHC, HE-LHC and FCC-hh – collimation remains a serious concern. A topical XCOLL workshop reviewed the modelling tools used for validating the collimation-system performance and their benchmarking against beam measurements [14]. The proceedings of this XCOLL workshop will be published as a CERN Yellow Report.

Beam injection and beam extraction are particularly sensitive operations, as the injection or dump kickers belong to the fastest elements in the machine. The collider design must be robust against the sudden asynchronous firing of a kicker unit. The collimators are likely to be the first element to be hit by the beam in case of any fast failure. They must withstand the impact of one or a few bunches. The LHC collimators are based on CFC carbon. For HL-LHC and farther future machines, even stronger materials or composites are being developed and examined. More advanced options include the use of short bent crystals as primary collimators (reviewed at an XCOLL co-organized workshop [9]), and the deployment of hollow electron-beam lenses as non-destructible collimators.

An acceptable performance of the collimation system and small IP beta function can be achieved only with an excellent optics control, supported by another topical XCOLL workshop [11].

## 3.5. TECHNOLOGIES

The primary technology of future hadron colliders are high-field magnets, both dipoles and quadrupoles. The HL-LHC will use, for the first time in a collider, some tens of dipole and quadrupole magnets based on a new high-field magnet technology using $Nb_3Sn$ superconductor, instead of $Nb$-$Ti$ (which had been used in the present LHC, Tevatron, RHIC and HERA), with a peak field of 11-12 Tesla. This will prepare the ground for the development of 16 Tesla $Nb_3Sn$ magnets, and the later production of about 5000 $Nb_3Sn$ magnets required by the FCC-hh.

Another important technology is the cryo beam vacuum system, which has to cope with unusually high levels of synchrotron radiation in a cold environment (about 5 MW in total for FCC-hh). The design of the beam screen intercepting the radiation inside the cold bore of the magnets and the choice of its operating temperature are key ingredients of the hadron collider design. First hardware prototypes will be tested with synchrotron radiation from an electron beam at the KIT ANKA facility at Karlsruhe in 2017.

Further key technologies of the hadron collider include the collimators, the kicker and septa required for the extremely high beam energy, and the superconducting radiofrequency systems, e.g. for acceleration and compensation of synchrotron-radiation energy losses, as well as for the ever more demanding crab cavities.

Hadron beam intensity may be limited by conventional instabilities, in particular – due to the very large circumference and low momentum compaction – by resistive wall instability (low revolution frequency) and transverse mode coupling at injection. These limitations were examined at a dedicated workshop [7]. Another intensity limit may arise from the electron cloud (which is driving a different type of instability or creating additional significant heat loads on the beam screen inside the cold magnets), as is currently experienced at the LHC. A joint workshop with ESA-ESTEC developed synergies between the accelerator and space-satellite communities for the modelling tools and understanding of relevant surface properties [8]. Indeed, the electron cloud is a primary source of beam instability in the LHC (especially with a proton bunch spacing of 25 ns). The beam performance tends to improve in time thanks to beam-induced surface conditioning ("scrubbing"). In addition, at the LHC occasional losses of transverse or longitudinal Landau damping arise due to the classical machine impedance with contributions from vacuum chamber, RF cavities, and transitions. Concerning instability mitigation, the following lessons have been learnt in operating the LHC: There exists a narrow range of machine settings for which the beam remains stable all along the cycle; instabilities occur if the transverse betatron coupling exceeds a certain threshold value (different at different stages); chromaticity settings are crucial along the cycle and cannot be relaxed; the octupole-magnet settings have to be adapted according to beam emittance; the transverse damper is indispensable to preserve beam stability all along the cycle.

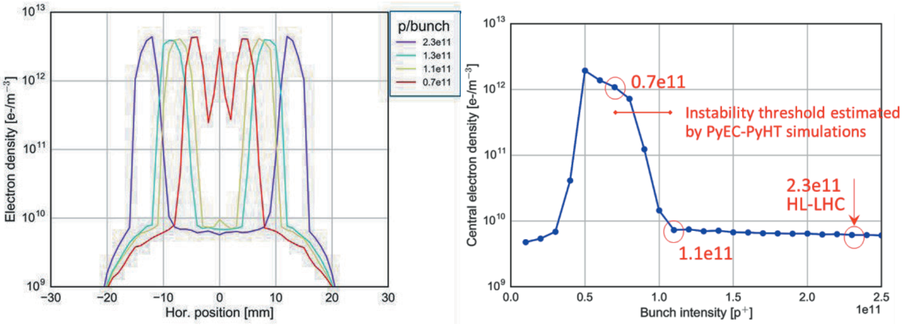


*Figure 19: Electron cloud distribution in an LHC dipole magnet for varying proton bunch population (left) and central electron density versus bunch intensity (right) (A. Romano et al., PRAB paper in preparation; and G. Rumolo, Valencia, 2017 [35]).*

Interestingly, the electron cloud can drive coherent instabilities even when beams are in collision (providing strong Landau damping). Simulations and earlier measurements at the SPS show that, for lower bunch intensities, the electron cloud in the dipoles tends to form a central stripe; at the LHC the central density threshold of the electron-cloud driven single-bunch head-tail instability (~$5\times10^{11}$ $m^{-3}$ at Q'=15) is crossed when the bunch intensity decreases – as is illustrated in Fig. 19; for Q'>20 the threshold becomes much higher. This explanation of the beam instabilities observed towards the end of LHC physics fills also is consistent with the disappearance of the phenomenon after "scrubbing".

## 3.6. LEPTON-HADRON COLLIDERS

Following the success of HERA in Germany, there are proposals for two future high-energy lepton-hadron colliders, which would greatly extend the reach in the Bjorken $1/x$ and $Q^2$ parameter plane: The Large Hadron electron Collider (LHeC) based on colliding a 60 GeV electron beam, from an energy-recovery linac, with one of the circulating 7 TeV LHC proton beams, and FCC-he, realized by colliding an electron beam from the same, or a similar, ERL with a 50 TeV proton beam stored in the FCC-hh. Two XCOLL co-supported workshops advanced the design of, and examined alternative options for, these two facilities [5,13].

## 3.7. EFFICIENCY AND COST OF FUTURE COLLIDERS

A possible figure of merit is the beam power at the collision point(s) divided by the total electrical power of the facility [suggestion by J. Stadlmann, GSI]. As shown in Table 5, this figure of merit clearly reveals the advantages of circular design approaches, where the same particles are made to collide again and again over many turns. Another sensible figure of merit can be the luminosity per electrical input power [P. Janot, CERN; A. Yamamoto, KEK]. The table illustrates why linear colliders must operate with dramatically smaller IP spot sizes to achieve luminosity levels competitive with circular machines. Energy recovery linacs improve the efficiency compared with single-pass linacs, but by far do not reach the efficiency of storage rings. On the other hand, future circular lepton and hadron colliders offer outstanding ratios of luminosity to input power. Figures of merit computed for plasma linear colliders are highly uncertain.

*Table 5: Parameters of selected circular, linear, & linac-ring colliders[*], including two figures of merit: IP beam power per electrical input power, and luminosity per input power. Excellent figures of merit are highlighted in green, good ones in blue, those at the bottom end in red. The parameters for a 3 TeV μ collider are taken from a recent presentation (M. Palmer "Muon Collider: Physics and Accelerator Technology", Higgs-Maxwell Particle Physics Workshop, Royal Society of Edinburgh, 17 February 2016) and include ionization cooling.*

| **collider** | c.m. energy [TeV] | $P_{el}$: tot. el. power [MW] | $P_b$: IP beam power [GW] | luminosity $L$ [$nb^{-1}s^{-1}$] / IP | $P_b/P_{el}$ | $L/P_{el}$ (/IP) [$nb^{-1}s^{-1}$/MW] |
|---|---|---|---|---|---|---|
| **CEPC** | 0.24 | ~500 | 4.0 | 20 | **8000** | **0.04** |
| **FCC-ee** | 0.091 | 276 | 132 | 1500 | **500000** | **5.4** |
| **FCC-ee** | 0.24 | 308 | 7.2 | 50 | **23000** | **0.16** |
| **FCC-ee** | 0.35 | 364 | 2.3 | 13 | **6300** | **0.04** |
| **LHeC** | 1.3 | 75 (e- only) | 0.4 (e-only) | 1 | **5** | **0.01** |
| **LHeC-HF** | 1.3 | 100 (e- only) | 1.5 | 16 | **15** | **0.16** |
| **ILC** | 0.25 | 122 | 0.0059 | 7.5 | **0.05** | **0.06** |
| **ILC** | 0.5 | 163 | 0.0105 | 18 | **0.06** | **0.11** |
| **CLIC** | 0.5 | 271 | 0.009 | 23 | **0.03** | **0.08** |
| **CLIC** | 3.0 | 582 | 0.028 | 59 | **0.05** | **0.10** |
| **μ collider** | 6.0 | 270 | 100 | 120 | **370** | **0.44** |
| **laser-plasma**[**] | 3.0 | 282 | 0.045 | 100[**] | **0.05??** | **??** |
| **LHC** | 13.0 | ~150 | 8000 | 10 | **50000** | **0.07** |
| **HE-LHC** | 25.0 | ~200 (guess) | 30000 | 300 | **100000** | **1.5** |
| **FCC-hh** | 100.0 | 500 (target) | 50000 | 300 (phase 2) | **100000** | **0.6** |
| **SPPC** | 70.2 | 600 (guess) | 53000 | 120 | **90000** | **0.2** |

[*] The CEPC values were extracted from the CEPC-SPPC pre-CDR (IHEP-CEPC-DR-2015-01, 2015), FCC-ee values from an IPAC'16 paper (F. Zimmermann et al., Electrical Power Budget for FCC-ee, Proc. IPAC'16 Busan), ILC values from the ILC TDR (2013), CLIC values from the CLIC CDR (2012) and a RAST article (A. Yamamoto and K. Yokoya, in Reviews of Accelerator Science and Technology: Volume 7: Colliders, 2015), LHeC baseline numbers from the CDR (J. Abelleira et al., A Large Hadron Electron Collider at CERN, J. Phys. G: Nucl. Part. Phys. 39 (2012) 075001), LHeC Higgs factory numbers from IPAC'13 (F. Zimmermann et al., The LHeC as a Higgs Boson Factory, Proc. IPAC'13 Shanghai). The FCC-hh and SPPC values are educated estimates based on the literature and published design parameter sets.

[**] Several challenges will still need to be overcome to achieve the advertised performance of laser-plasma colliders (see, e.g., D. Schulte, "Application of Advanced Accelerator Concepts to Colliders", invited contribution to RAST issue 2016). This technology might not be available before the end of the century.

The annual operation cost of a collider does not only depend on the accelerator efficiency. Figure 20 illustrates that the electricity price varies by up to a factor of four between facilities, and especially between countries. The lowest electricity prices exist in the U.S. and Russia, closely followed by CERN and the large facilities in Sweden. On the other hand, accelerators in Italy, Japan, Germany, Spain, and China face particularly high electricity costs. To give an example, in the era of the High-Luminosity LHC (HL-LHC) and, similarly, for the proposed FCC-ee lepton collider, the entire CERN will consume about 1400 GWh per year, which at present prices would correspond to an operational cost of about 70 MEuro per year, i.e. a rather small fraction of the actual or expected construction cost. Based on the prices from 2014/15, operating the same machine in China would require 160 MEuro per year, and in Japan, assuming KEK's electricity cost, it would be about 200 MEuro per year.

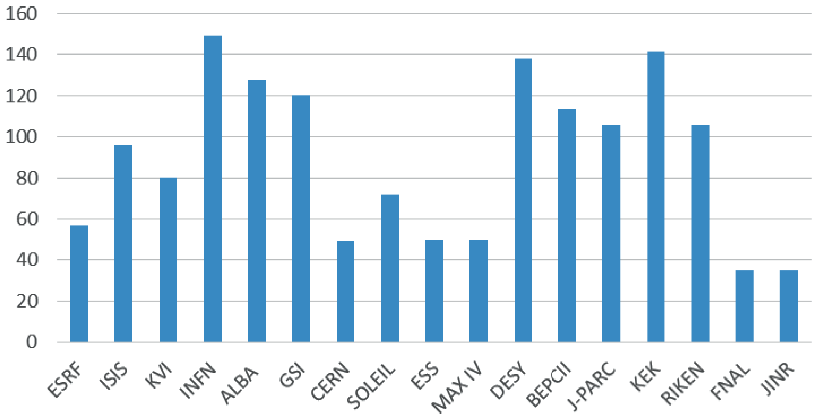


Figure 20: Facility electricity price 2014/15 in units of Euro/MWh (courtesy Q. Qin, K. Oide, M. Seidel, J. Toberntsson [EuCARD-2 Deliverable D3.1], V. Shiltsev, and G. Trubnikov)

Figure 21 shows that within +/-30%, the construction prices of a large number of built or costed accelerator projects is well described by the αβγ model of V. Shiltsev [40], where the cost varies with square roots of system length $L$, of energy E and of total electric power $P$ as:

$$\text{cost (TPC)} = \alpha L^{1/2} + \beta E^{1/2} + \gamma L^{1/2} \ .$$

Technology is the cost driver: the RF is the most expensive technology ever invented with a beta coefficient of $\beta \approx 10\mathrm{B\$}/\sqrt{\mathrm{TeV}}$, about five times higher than for SC high-field magnets. Only plasma acceleration is even (2-3×) more expensive than RF. The αβγ model allows estimating the cost of future collider projects, and studying approached for cost-saving. Figure 22 indicates that with present technologies and technology prices only the HE-LHC and the FCC-ee/CEPC may be considered affordable (with a cost of about or below 10 B$ in the US accounting). The cost of a 100 TeV hadron collider, FCC-hh, can be reduced by three steps: (1) build this collider on site with an existing injector complex, such as CERN; (2) consider staging ($e^+e^-$ 1st, pp 2nd), and (3) reduce the superconductor/magnet cost. Arguably, the FCC-hh would be affordable in a staged approach (i.e. following the FCC-ee in the same tunnel), or if cost coefficients can be reduced. Figure 23 illustrates that reducing the magnet cost has a bigger impact on the FCC-hh cost than reducing the tunneling cost. For the long term the crystal muon collider might offer an affordable path to 1000 TeV c.m., albeit with a high error bar on the cost estimate (Fig. 22).

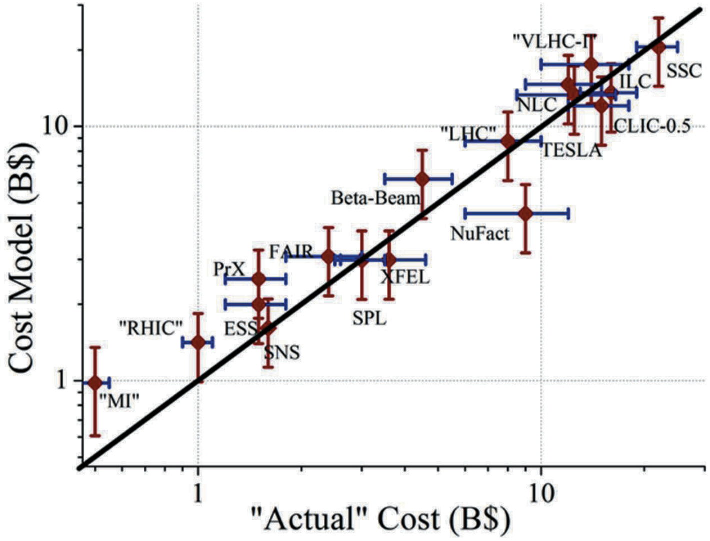


*Figure 21: Actual or forecast project costs fitted by αβγ model [39] (V. Shiltsev, Valencia, 2017 [35]).*

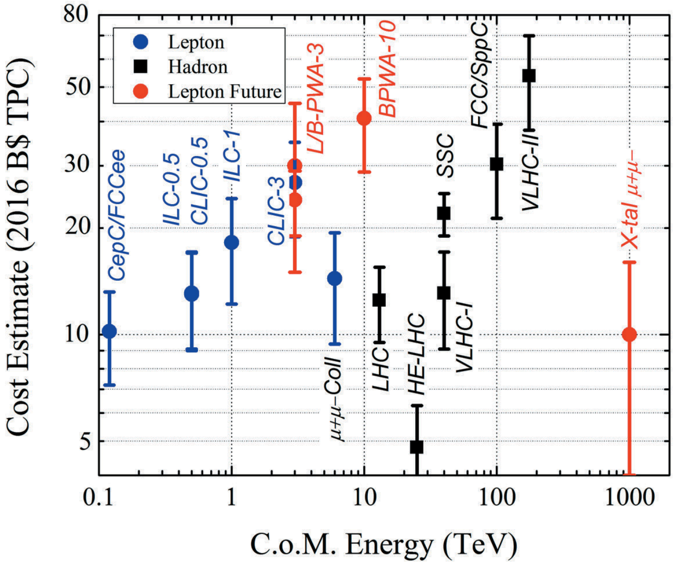


*Figure 22: Estimated prices of various proposed collider projects at present technology prices based on the αβγ model with historical coefficients (V. Shiltsev, Valencia, 2017 [35]).*

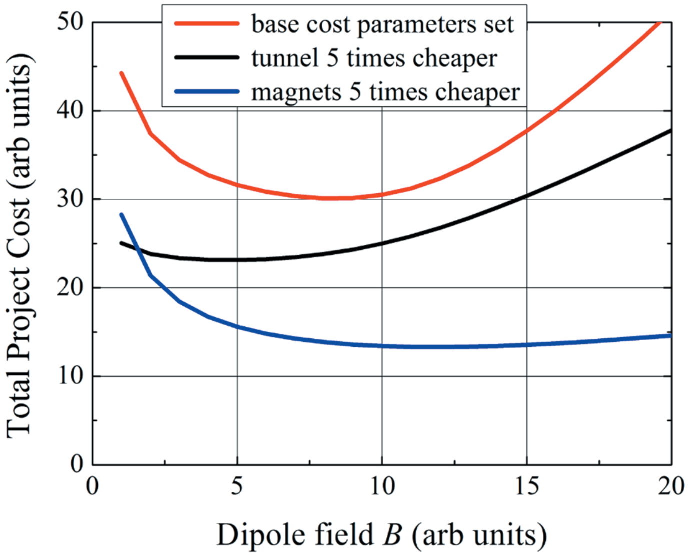


*Figure 23: Qualitative cost dependencies of a 100 TeV pp collider (V. Shiltsev, Valencia, 2017 [35]).*

### 3.8. COLLIDER STRATEGIES

In this section, some main findings and key strategies for future high-performance lepton, hadron and lepton-hadron colliders have been discussed.

Two figures of merits underline the efficiency of circular colliders. A suite of colliders for the next 70 years has been presented. Highest-luminosity circular lepton colliders and highest-energy hadron collider can greatly extend the search for new physics far into yet unexplored territories. For the longer-term future, muon colliders and crystal (or nanotube) colliders hold some promises; for these numerous technical and physical obstacles still need to be overcome. Cost minimization and development of cheaper accelerator technologies are essential ingredients on the way forward.

The close collaboration among international accelerator laboratories is mandatory in order to profit from the experience gained with the operation of highly successful past and present colliders, and with the ongoing worldwide studies for future machines. For example, in Europe, Russia, USA, Japan, and China, experts have coped with many of the issues related to high current, and small beams in circular colliders, which allows the design of better future machines.

EuCARD-2 has proven the natural environment where such competences could be collected and fruitful collaborations be established.

# 4. EXTREME RINGS

## 4.1. HADRON-RING LANDSCAPE AND EUCARD-2 XRING ACTIVITIES

Future hadron rings in Europe can be divided into three different categories: (1) Upgrade of existing facilities, i.e. the upgrade of existing rings in order to reach higher performance. The major upgrade presently underway is the LHC injector upgrade (LIU project). Other upgrades concern the SIS18 at GSI, and the ISIS at RAL; also the upgrade of the J-PARC facility in Japan belongs to this same category. (2) Completion of construction and commissioning of approved projects, i.e. the construction of new hadron rings; here the FAIR project plays a major role with the SIS100 synchrotron, the construction of the Collector Ring and the HESR. (3) Next generation hadron rings, related to the quest for even higher intensity.

At CERN the need for higher luminosity at the LHC (HL-LHC project) is the major factor for requiring higher intensity in the injectors (LIU project). At GSI the nuclear physics experiments require higher intensity to speed up the measurement process. Following the SIS100 commissioning, subsequent upgrades are already foreseeable. Similarly, at RAL the ISIS2 is set to replace the present ISIS. The NICA ion collider at JINR (Dubna) requires the upgrade of the existing Nuclotron facility (SC proton/ion accelerator). The long-term future also holds a large high-energy Future Circular Collider (FCC) together with its injector complex.

For the upgrade of existing facilities (LIU, SIS18, ISIS) XRING enhanced the synergies between the efforts of large laboratories, smaller institutes and universities. The network activity of XRING established a connected community capable of further advancing the technical realization and scientific exploitation of the European high-power hadron-ring facilities.

One recommended strategy for supporting the present construction projects and planned future upgrades in Europe is to maintain and solidify the XRING initiative, which successfully boosted the collaboration of major European laboratories, such as CERN, GSI, and RAL. Indeed, the European XRING network is playing a fundamental role as a community organizer and as a catalyzer for a broad range of activities on hadron rings across Europe. This activity will be pursued and extended by the proposed ARIES project. It is evident that only the mandate deriving from an authoritative European network can act as the glue for joint efforts by national laboratories and universities, each of which otherwise tends to act only with an internal focus on “domestic” problems.

Specifically, XRING has made great strides in five complementary directions, by addressing the interplay of beam dynamics with magnets, beam instrumentation, high-intensity effects, user demands in fixed-target operation, and beam vacuum plus collimation, respectively. These five directions were motivated by practical demands from actual construction projects. Concrete aims included (1) understanding and overcoming the FAIR beam intensity limitations in theory, simulations, & experiments; (2) optimizing the LHC injector upgrade path, including a mitigation of SPS limits; (3) supporting the PSI-HIPA and ISIS upgrade projects, in particular with regard to beam dynamics, e.g. space charge effects; (4) advancing the beam instrumentation and diagnostics for all the present and future extreme performance rings; and (5) addressing the vacuum, beam-stability and machine-protection requirements linked to high-intensity and high-power hadron beams.

In total, XRING organized and co-organized 9 workshops [11,19-26], i.e. three times as many as originally foreseen in the EuCARD-2 proposal. These were:

- XRING workshop "Beam Dynamics meets Magnets”, Darmstadt, December 2013 [19]
- Space Charge Collaboration Meeting 2014, CERN, May 2014 [20]

- XRING workshop "Beam Dynamics meets Magnets – II", Bad Zurzach, December 2014 [21]
- XCOLL/XRING joint workshop on Advanced Optics Control (AOC), CERN, February 2015 [11].
- International workshop "Space Charge 2015", Oxford, 23-27 March 2015 [22].
- XRING/XLINAC joint workshop, "Beam Dynamics meets Diagnostics," Firenze, November 2015 [23].
- XRING workshop on Slow Extraction, Darmstadt, June 2016 [24].
- XRING GSI-FZJ mini-workshop, 18 November, 2016, Jülich, Germany [25].
- XRING workshop "Beam Dynamics meets Vacuum, Collimations, and Surfaces", Karlsruhe, March 2017 [26].

Synthesizing the main conclusions from the above workshops, in the following we can formulate a tentative roadmap for the future development of extreme hadron rings.

### 4.2. FUTURE HIGH-PERFORMANCE HADRON RINGS, LIMITS AND RECIPES

A number of hadron facilities are under construction or being upgraded around the world; see the photographs in Fig. 24. Several of these facilities are found in Europe.

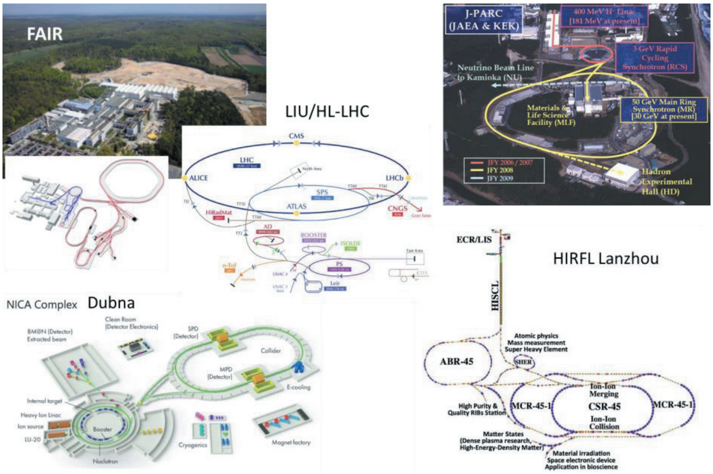


*Figure 24: Important hadron facilities under instructions or being upgraded around the world (G. Franchetti, Valencia, 2017 [35])*

The injector upgrade at CERN is well advanced and an on track for completion by 2019. The path of this upgrade is set by the major hardware construction of Linac4, already achieved, and by the planned subsequent upgrade of the PS booster. A second major project in Europe is the ongoing construction of the FAIR facility at Darmstadt. Mitigations of high intensity effects in the CERN PS booster, in the CERN PS, and in the various FAIR rings have been studied and developed in a collaborative effort under the umbrella of XRING.

Considering the major hadron facilities in Europe, the respective paths forward are as follows.

**CERN:** The beam parameters of the CERN LHC injector complex will be upgraded in the frame of the LIU project [41] (~2019) with HL-LHC [42] (~2025) as ultimate goal, according to Table 6 (G. Rumolo), which also indicates the present status. Achieving the ambitious target value of about 0.7 for the space charge tune-shift in the PS booster (PSB) will be critical for the LIU and in particular for the HL-LHC.

April 24, 2017 – Beam parameters at injection of each accelerator

**PSB** (H$^-$ injection from Linac4)

| | | $N$ ($10^{11}$ p) | $\epsilon_{x,y}$ ($\mu$m) | $E$ (GeV) | $\epsilon_z$ (eVs) | $B_l$ (ns) | $\delta p/p_0$ ($10^{-3}$) | $\Delta Q_{x,y}$ |
|---|---|---|---|---|---|---|---|---|
| Achieved | Standard | 17.73 | 2.14 | 0.05 | 1.0 | 1100 | 2.4 | (0.51, 0.59) |
| | BCMS | 8.48 | 1.15 | 0.05 | 0.9 | 1000 | 2.2 | (0.46, 0.56) |
| LIU target | Standard | 34.21 | 1.72 | 0.16 | 1.4 | 650 | 1.8 | (0.58, 0.69) |
| | BCMS | 17.11 | 1.36 | 0.16 | 1.4 | 650 | 1.8 | (0.35, 0.43) |

**PS** (Standard: 4b+2b – BCMS: 2× 4b)

| | | $N$ ($10^{11}$ p/b) | $\epsilon_{x,y}$ ($\mu$m) | $E$ (GeV) | $\epsilon_z$ (eVs/b) | $B_l$ (ns) | $\delta p/p_0$ ($10^{-3}$) | $\Delta Q_{x,y}$ |
|---|---|---|---|---|---|---|---|---|
| Achieved | Standard | 16.84 | 2.25 | 1.4 | 1.2 | 180 | 0.9 | (0.25, 0.30) |
| | BCMS | 8.05 | 1.20 | 1.4 | 0.9 | 150 | 0.8 | (0.24, 0.31) |
| LIU target | Standard | 32.50 | 1.80 | 2.0 | 3.00 | 205 | 1.5 | (0.18, 0.30) |
| | BCMS | 16.25 | 1.43 | 2.0 | 1.48 | 135 | 1.1 | (0.20, 0.31) |

**SPS** (Standard: 4 × 72b – BCMS: 5 × 48b)

| | | $N$ ($10^{11}$ p/b) | $\epsilon_{x,y}$ ($\mu$m) | $p$ (GeV/c) | $\epsilon_z$ (eVs/b) | $B_l$ (ns) | $\delta p/p_0$ ($10^{-3}$) | $\Delta Q_{x,y}$ |
|---|---|---|---|---|---|---|---|---|
| Achieved | Standard | 1.33 | 2.36 | 26 | 0.35 | 4.0 (3.0) | 0.9 (1.5) | (0.05, 0.07) |
| | BCMS | 1.27 | 1.27 | 26 | 0.35 | 4.0 (3.0) | 0.9 (1.5) | (0.07, 0.12) |
| LIU target | Standard | 2.57 | 1.89 | 26 | 0.35 | 4.0 (3.0) | 0.9 (1.5) | (0.10, 0.17) |
| | BCMS | 2.57 | 1.50 | 26 | 0.35 | 4.0 (3.0) | 0.9 (1.5) | (0.12, 0.21) |

**LHC** (≈10 injections)

| | | $N$ ($10^{11}$ p/b) | $\epsilon_{x,y}$ ($\mu$m) | $p$ (GeV/c) | $\epsilon_z$ (eVs/b) | $B_l$ (ns) | bunches/train |
|---|---|---|---|---|---|---|---|
| Achieved | Standard | 1.20 | 2.60 | 450 | 0.45 (0.50) | 1.65 (1.21) | 288 |
| | BCMS | 1.15 | 1.39 | 450 | 0.35 (0.39) | 1.50 (1.05) | 96 |
| LIU target | Standard | 2.32 | 2.08 | 450 | 0.50 | 1.65 | 288 |
| | BCMS | 2.32 | 1.65 | 450 | 0.50 | 1.65 | 240 |

** Longitudinal emittance $\epsilon_z$ ($2\sigma$), momentum spread $\delta p/p_0$ ($1\sigma$), bunch length $B_l$ ($4\sigma$): values are given at injection (first turn), values in parentheses are after filamentation ($V_{SPS}$=4 MV, $V_{LHC}$=6 MV). Longitudinal emittances at SPS injection and after filamentation are the same because they are measured with different conventions

*Table 6: Present and future beam parameters in the CERN injector complex (courtesy G. Rumolo)*

**GSI/FAIR:** The planned parameters for a future SIS100 upgrade are: 1) For the radioactive beam program about $10^{12}$ uranium ions should be delivered per second at energies from 400 to 2700 MeV/u either with a long duty cycle of approximately 100% or in a single short bunch with pulse lengths from 50 to 100 ns. 2) For plasma physics research, at least $10^{12}$ uranium ions should be provided in a single short bunch (50 to 100 ns length) at energies from 400 to 1000 MeV/u. 3) For the antiproton facility 2.5x$10^{13}$ protons per pulse at 29 GeV are required every 5 seconds. A future FAIR hadron ring is the SIS300. It will be operated in two different modes: firstly, in a so-called stretcher mode and secondly in a high-energy mode. In the stretcher mode SIS300 shall provide non-interrupted slowly extracted beams of high intensity in the energy range of the SIS100. In order to achieve the maximum number of particles per second, intermediate charge states have to be chosen. E.g. it is planned to provide slowly extracted $U^{28+}$ beams with an intensity of $10^{12}$ ions/s at an energy of 1 GeV/u in order to produce radioactive beams for experiments with fixed targets behind the Super-FRS. In the second operation mode, SIS300 will be supplied with fully stripped heavy ion beams from SIS100. The fully stripped heavy ions will be generated by means of a stripper foil located in the transfer channel between SIS100 and SIS300. In this mode, the fully stripped heavy ions will be accelerated up to the maximum magnetic rigidity of 300 Tm. E.g. $U^{92+}$ beams will be accelerated up to a maximum energy of 34 GeV/u and then slowly extracted with spill durations of up to 100 s.

**RAL:** A new 3.2 GeV synchrotron connected to the 800-MeV ISIS has been designed, raising the beam power by a factor of 4. A new 800 MeV linac also already designed will inject into this new ring at a later stage (decommissioning of the existing machine), to further increase the beam power to about 5 MW. This scenario represents a progressive transformation of ISIS. However, at the present ISIS proper nowadays still the effects of half-integer resonances, the injection efficiency and acceleration cycles are under study and or under improvement.

A future strategy plan for RAL considers developing a completely new spallation source in 10-15 years' time. This spallation source would be based on a single FFAG, of energy ~3 GeV, and produce a beam power of up to 10 MW [42]. This new source will be fully independent of any old machine. The FFAG should be extremely flexible and is designed to meet all the demands of the neutron users. Design options include a novel optics scheme (patent pending), and using proton injection (not $H^-$). A small proto-type FFAG, at 3-10 MeV, installed in the front-end test stand (FETS), will be used for the essential R&D towards the multi-MW machine. The high-power beam may be distributed to several targets and also serve for other applications. This concept expands on the experience from ISIS' new low-power target station (40 kW), which has been remarkably successful in terms of new science generated. Since the FFAG15 workshop, a more formal study is being conducted, for example using a tilted septum injection scheme for the protons as in the HIDIF study (which the Chinese have adopted for HIAF).

**PSI:** The beam power of the PSI cyclotron was continually increased while complying with the boundary condition of keeping the uncontrolled losses at extraction below 200 W, corresponding to relative losses of $1\text{-}2\times10^{-4}$. The improvements were achieved by tuning, collimation of beam tails, and mainly by reducing the number of turns in the cyclotron, resulting in reduced impact of space charge effects. With a CW power of 1.4 MW the PSI-HIPA facility remains at the forefront of high intensity proton accelerators in the world. Other efforts have focused on improving the target efficiency, which is as important as the proton beam power.

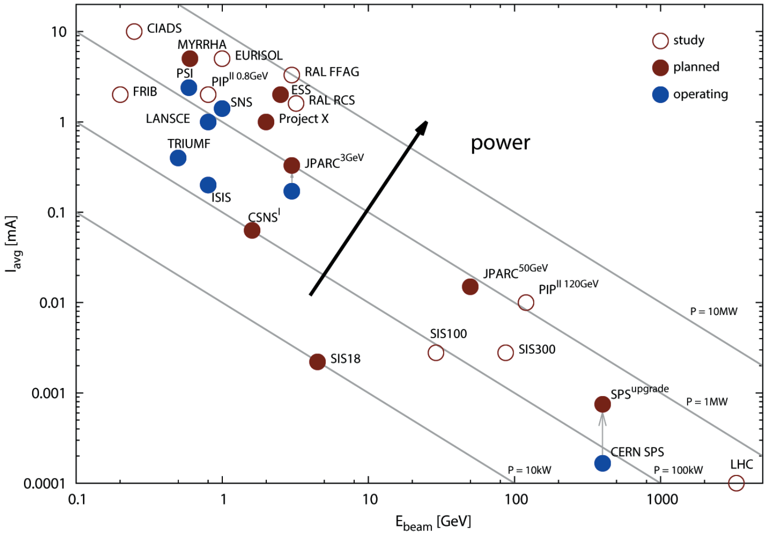


*Figure 25: Operating points of various extreme-ring an extreme-linac facilities in the plane spanned by average beam current and beam energy (Courtesy M. Seidel).*

*Table 7: Key parameters of present, planned and proposed extreme-ring facilities around the world. NICA parameters were taken from S. Kostromin et al., Optics Design for NICA Collider, Proc. RuPAC-2010.*

| Facility | circum-ference [m] | beam energy (species) | av. beam current / intensity | beam power |
|---|---|---|---|---|
| CERN PS | 628 | 26 GeV (p) | $2\times10^{13}$ /pulse at 0.83 Hz | 70 kW |
| CERN SPS | 6911 | 400 GeV (p) | 0.15 μA, 0.75 μA | 67 kW (in operation),<br>300 kW (proposed$^*$) |
| LHC fixed target (FCC era) | 26700 | 3.3 TeV (p) | 2×0.1 μA | 2×270 kW (proposed) |
| SIS18 | 217 | 4.5 GeV (p),<br>200 MeV/u(U) | 2.2 μA (p) | 10 kW |
| SIS100 | 1084 | 29 GeV (p),<br>2.7 GeV/u (U) | 2.8 μA (p), or $1.5\times10^{11}$ U ions at 2.7 Hz | 80 kW (planned) |
| SIS300 | 1084 | 87 GeV (p)? | 2.8 μA (p)?, or $5\times10^{11}$ U ions at 0.7 Hz | 240 kW (proposed) |
| PSI SINQ | 45 | 590 MeV | 2.4 mA | 1.4 MW (operation)<br>1.8 MW (planned) |
| EMMA FFAG | 16.6 | acc. from 10.5 to 20.5 MeV/c | 2 nA | 0.04 W (achieved) |
| KURRI-FFAG | 28.5 | 150 MeV | 1 nA (achieved),<br>1 μA (design) | 0.15 W (achieved),<br>150 W (goal) |
| JINR NICA | 454 | 4.5 GeV/n ($Au^{79+}$), 12.6 GeV (p) | 2×1.1 A (design) | [collider, effective IP power 20 GW for $Au^{79+}$] |
| RAL ISIS | 163 | 800 MeV | $2.8\times10^{13}$ /pulse at 50 Hz | 0.2 MW (achieved) |
| RAL RCS | ~320 | 3.2 GeV | 1.6 mA | 4 MW? (proposed) |
| RAL FFAG | ? | 3 GeV | 3.3 mA | 10 MW (proposed) |
| LANL PSR | 90 | 800 MeV | 100 μA | 0.1 MW |
| SNS | 248 | 1.3 GeV | 2.3 mA | 1.4 MW (achieved),<br>3 MW (planned) |
| J-PARC JSNS | 348 | 3.0 GeV | $8.3\times10^{13}$ /pulse at 25 Hz | 0.5 MW (achieved),<br>1 MW (design) |
| CSNS I | 231 | 1.6 GeV | 62.5 μA | 100 kW |
| CSNS II | 228 | 1.6 GeV | 125 μA | 500 kW |
| HIAF ICR-35 | 804 | 9.5 GeV (p),<br>0.8GeV/u ($U^{34+}$) | $1.0\times10^{12}$(p) 2Hz,<br>$2.4\times10^{11}$ ($U^{34+}$) | 3 kW (p) |

Figure 25 illustrates the beam power on target of various operating, planned or proposed extreme ring facilities, in a beam-current/beam-energy plane. Table 7 compiles values of circumference, beam energy, beam species, beam intensity/current and beam power for several present and future extreme ring facilities. We are tempted to infer that the FFAG concept is not a promising way to achieve a high beam power. High beam power can be achieved both with fairly fast cycling machines at high energy well above 1 GeV, as well as with close to CW beam current at energies around 1 GeV.

Figure 26 illustrates that hadron storage rings become ever more extreme, not only in terms of beam power, but also in terms of space-charge tune shift and the number of turns the beam is stored. Not surprisingly then, the key topics and trends for extreme rings include the space charge limit and its various mitigations (resonance compensation, improved optics control, e-lenses …). Other related R&D topics are magnet alignment, more accurate field models, dynamic vacuum pressure and ion beam lifetimes, multi-turn injection and extraction (novel loss-free or septum less schemes based on resonance islands), slow extraction with reduced micro-spill structure (spill feedback), electron cooling, stochastic cooling, laser cooling, advanced schemes (opt. stochastic cooling, coherent el. cooling) – beam tests and developments at FNAL and BNL, beam stabilization (e.g. by e-lenses for Landau damping, or by forming integrable systems – to be tested at FNAL's IOTA), isochronous operation mode, and transition crossing (by means of tune jump, optics change, or islands).

In the case of slow extraction, the spill quality is a key parameter Table 8 compares spill uniformity achieved at large laboratories and small medical facilities worldwide, as collected by XRING. For faster beam extraction, e.g. within a few revolution periods, sextupole and octupole magnets can be excited so as to generate stable islands in phase space (Fig. 27). Nowadays such a scheme is used in routine operation at the CERN SPS and allows for an almost loss-free multi-turn extraction. A multitude of other advanced applications is being proposed.

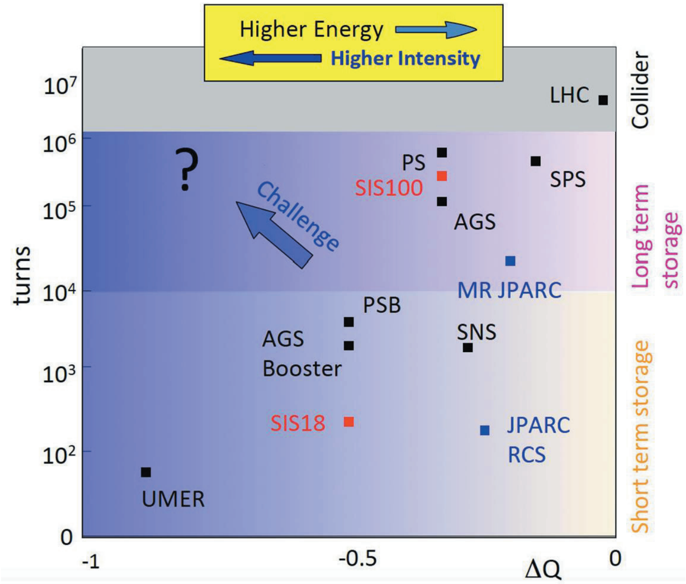


*Figure 26: Storage time and space-charge tune shifts in some past and future machine (G. Franchetti, Valencia, 2017 [35]).*

*Table 8: Extraction spill performance at various large and small facilities around the world (G. Franchetti, based on data compiled for the XRING Slow Extraction Workshop, Darmstadt, 2016).*

| Name, Institution | spill duration | particles in spill | original bin length | Particles Per Bin, av. (orig.) ($PPB_{av}$) | $\frac{\Delta PPB_{rms}}{PPB_{av}}$ | Particles Per Bin, av. (1 ms) ($PPB_{av}$) | $\frac{\Delta PPB_{rms}}{PPB_{av}}$ (1 ms) |
|---|---|---|---|---|---|---|---|
| M. Fraser, CERN | 4.0 s | $4.0 \cdot 10^{13}$ | 0.4 ms | $4.0 \cdot 10^{9}$ | 0.158 | $10^{10}$ | 0.157 |
| C. Krantz, MIT | 8.0 s | $2.7 \cdot 10^{8}$ | 0.05 ms | 1700 | 0.25 | 34000 | 0.17 |
| K. Brown, BNL (*) | 2.4 s | $7.6 \cdot 10^{13}$ | 0.04 ms | $1.3 \cdot 10^{9}$ | 0.21 | $3.2 \cdot 10^{10}$ | 0.19 |
| C. Schömers, HIT | 5.0 s | $1.5 \cdot 10^{8}$ | 0.05 ms | 1500 | 0.31 | 30000 | 0.21 |
| H. Stockhorst, FZJ (+) | 3.5 s | $1.3 \cdot 10^{7}$ | 1.0 ms | 3700 | 0.28 | 3700 | 0.28 |
| S. Ivanov, IHEP | 1.3 s | $(2 - 10) \cdot 10^{12}$ | 0.04 ms | $(6.0 - 30.0) \cdot 10^{8}$ | 0.45 | $(1.5 - 7.5) \cdot 10^{9}$ | 0.329 |
| P. Forck, GSI (x) | 1.5 s | $1.4 \cdot 10^{6}$ | 0.02 ms | 18 | 0.58 | 900 | 0.334 |
| A. Wastl, MedAustron | 5.0 s | $1.8 \cdot 10^{10}$ | 0.02 ms | 72000 | 0.90 | $3.6 \cdot 10^{6}$ | 0.54 |
| K. Brown, BNL (**) | 1.6 s | $6.2 \cdot 10^{13}$ | 0.04 ms | $1.5 \cdot 10^{9}$ | 0.87 | $3.0 \cdot 10^{10}$ | 0.57 |
| M. Tomizawa, J-PARC | 2.1 s | $4.8 \cdot 10^{13}$ | 0.01 ms | $2.3 \cdot 10^{8}$ | 0.91 | $2.3 \cdot 10^{10}$ | 0.637 |
| P. Forck, GSI (xx) | 2.0 s | $1.1 \cdot 10^{6}$ | 0.02 ms | 11 | 0.81 | 550 | 0.642 |
| P. Forck, GSI (xxx) | 2.1 s | $2.1 \cdot 10^{6}$ | 0.02 ms | 20 | 1.4 | 1000 | 0.73 |
| H. Stockhorst, FZJ (++) | 3.0 s | $4.3 \cdot 10^{6}$ | 1.0 ms | 1400 | 1.1 | 1400 | 1.1 |

K. Brown (*) – empty 93 MHz bucket
K. Brown (**) – no empty bucket filtering
H. Stockhorst (+) – stochastic extraction
H. Stockhorst (++) – quadrupole driven extraction
P. Forck (x) – bunched beam, KO extraction
P. Forck (xx) – bunched beam, quadrupole driven extraction
P. Forck (xxx) – unbunched beam, quadrupole driven extraction

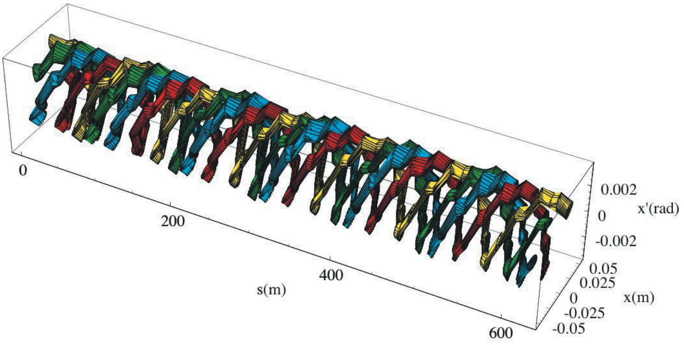


*Figure 27: Measured orbit of SPS beam trapped in a resonance island (M. Giovannozzi, Valencia, 2017 [35]).*

Optics control needs for extreme rings are also extreme. Computer simulations like the one shown in Fig. 28 suggest that space-charge limited rings would benefit from sub-% optics control and that even small optics errors must be taken into account in the simulations. Desirable new diagnostics includes an AC version of the orbit-response matrix technique.

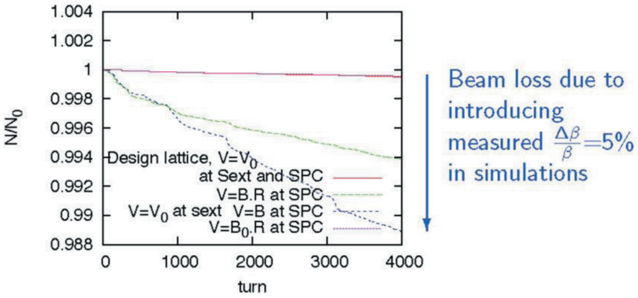


*Figure 28: Simulation of beam decay in a J-PARC ring by K. Ohmi showing the importance of excellent optics control (R. Tomas, Valencia, 2017 [35]).*

Several simulation studies have demonstrated the feasibility of space-charge compensation using electron lenses. In a 2007 study for the FNAL booster (400 MeV, 474 m, periodicity=24, $N_p$~4.5x$10^{12}$ $\Delta Q_{sc}$=-0.3), Y. Alexahin and V. Kapin concluded that “space charge compensation with e-lenses works” and “the more compensators the better” (24→12→3 minimum). As early as 2001, simulating the KEK PS (500 MeV, 340 m, $N_p$~$10^{12}$, $\Delta Q_s$=−0.2). S. Machida found that “space charge compensation with e-lenses works” and that +0.1-0.2 sigma e-p displacement is tolerable. Finally, in 2007 M. Aiba et al. (PAC’07, Albuquerque) performed simulations of electron-lens compensation for the CERN PS booster (50 MeV, 157 m P=16, $\Delta Q_s$=-0.5), showing that “space charge compensation with e-lenses works in principle… deserves further studies”, and found no evidence for any coherent mode limitations in PSB and PS. Aiba et al. highlighted a concern about overcompensation in the bunch head and tail. Consistent with Alexahin and Kapin, also for the PS booster it was demonstrated that the more compensators the better (8 better than 4). Soon the first experimental studies of space-charge compensation using electron lenses will become possible, at FNAL’s new IOTA beam test facility (Fig. 29), which is scheduled to see first beam in 2018. In addition to space-charge compensation IOTA beam tests can address other electron lens applications such as using electron lenses for generating an integrable beam optics or the use of electron lenses for enhancing Landau damping.

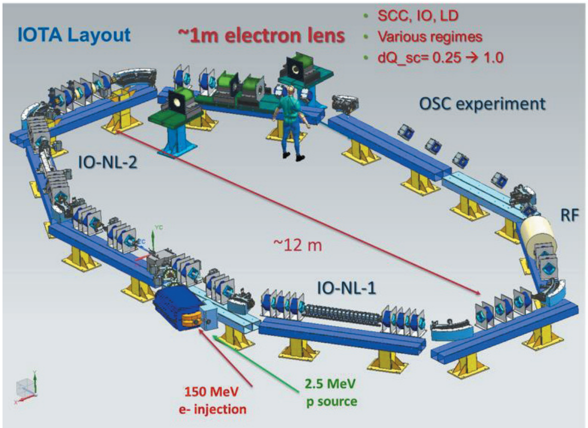


*Figure 29: IOTA beam test facility at FNAL-FAST (V. Shiltsev, Valencia, 2017 [35]).*

## 4.3. XRING STRATEGY FOR EXTREME HADRON RINGS

Raising the performance of hadron storage rings requires better optics control, possibly even completely novel types of optics, space-charge mitigation, and advanced tools like electron lenses. The beam test facility IOTA soon to start operation may shed new light on many of these issues. LHC and LIU also provide invaluable experience.

For four years, the EuCARD-2 Task 5.3 on extreme performance rings (XRING) coordinated and integrated the activities of the accelerator, nuclear and particle physics communities towards reaching the optimum performance of FAIR, ISIS and PSI-HIPA, and helping guide the upgrade strategy for the LHC injector complex. Identifying and overcoming ultimate performance limitations for the aforementioned facilities were primary topics. XRING also supported studies on critical beam diagnostics (e.g. continuous emittance control, beam-loss and halo measurements) and supported FFAGs development in the UK.

XRING created several strong new synergies across communities, countries and continents. XRING also catalyzed community discussions on the various performance limitations of high-intensity high-brightness hadron rings. Preliminary roadmaps for the upgrade of several European facilities were developed and validated. In particular, XRING brought together beam dynamicists, magnet specialists, and beam instrumentation experts in order to arrive at optimum upgrade solutions including risk mitigation. The integration of the efforts of large laboratories, smaller institutes and universities, was advanced though joint fora involving universities and laboratories.

A sustained effort of forming and maintaining a European multi-domain accelerator community requires a follow-up network with consolidated scope and goals. Such a network, already set up in the frame of the ARIES work package APEC, will further advance the technical realization of the next generation of high-power hadron-ring facilities in Europe, and help optimize their scientific exploitation.

APEC should ultimately become the seed for a self-sustained transnational European working group on future hadron rings (the equivalent of the ICFA panels for colliders and advanced accelerator concepts).

## 5. EXTREME LINACS

### 5.1. EXTREME LINAC LANDSCAPE AND EUCARD-2 XLINAC ACTIVITIES

High-current high-power superconducting linear accelerators are becoming the work horses for advanced material, biological, and nuclear research, as well as for accelerator-driven systems. Several superconducting linacs are under planning and construction, others already in operation, including SNS (U.S.A.), LCLS-II (U.S.A.), PIP-II SRF linac at FNAL (U.S.A.), the European XFEL (Germany), ESS (Sweden), FRIB (U.S.A.), MYRRHA (Belgium), CAS-IHEP ADS (China), and the ILC (Japan).

In a series of five workshops [23,27-30], motivated by actual questions at ongoing projects, e.g. from the ESS, a wide range of topics were treated:

- XLINAC workshop “Commissioning of Proton Linacs”, ESS, April 2014 [27].
- XLINAC workshop “LLRF and Beam Dynamics Mutual Needs in Hadron Linacs”, Lund, June 2015 [28].
- XRING/XLINAC joint workshop, "Beam Dynamics meets Diagnostics," Firenze, November 2015 [23].
- 57th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams - HB2016,” Malmö, July 2016 [29].
- XLINAC workshop “Upgrading Existing High Power Proton Linacs,” Lund, November 2016 [30].

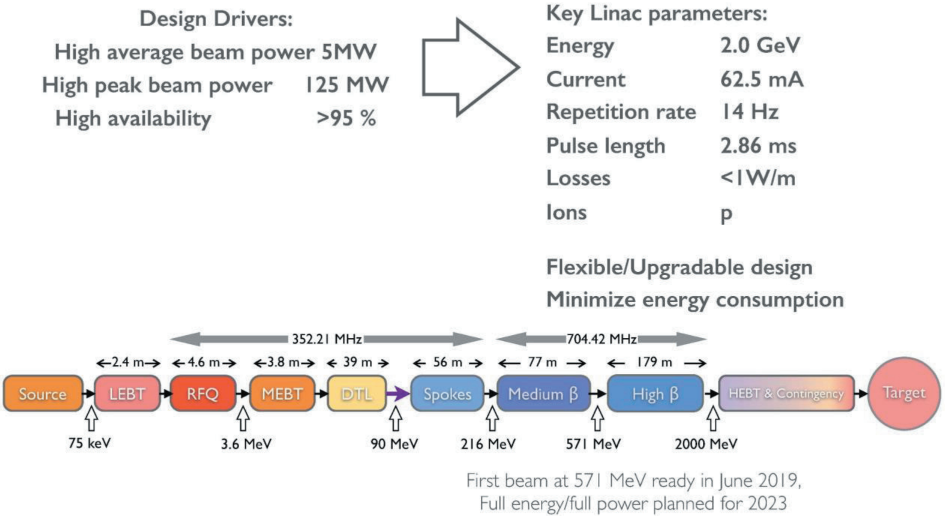
### 5.2. EXTREME LINACS – ISSUES AND DIRECTIONS

Quite a number of “extreme” superconducting linacs are already in operation. Even more are under construction or being proposed, for a variety of applications. Table 9 shows some parameters of major superconducting hadron and electron linacs. Figure 30 presents the layout and some details of the ESS linac, as a typical modern example.  A recent upgrade proposal – still under discussion - is shown in Fig. 31.

Among the key issues of extreme linac facilities are (1) cost reduction, (2) more efficient production of SC cavities (large grain, hydroforming), (3) beam halo and losses, (4) HOM couplers, and (5) pushing the 1 MW limit of the fundamental power couplers.

*Table 9: Key parameters of "extreme" superconducting linear accelerators in operation (blue), under construction (green), or being proposed (red).*

| | Particle | Duty factor | Energy/Nucleon resp. energy per e- [MeV] | (Pulse) Current [mA] | Av. power [kW] |
|---|---|---|---|---|---|
| ATLAS at ANL | ions | up to CW | 10 to 20 | 0.0002-0.06 | 2 |
| ELBE | e | CW | 40 | 1 | 40 |
| SNS | H$^-$ | 8% | 1000 | 38 | 1400 |
| SPIRAL-2 | p, d, ions | up to CW | 8 to 33 | 1 to 6 | 200 |
| CEBAF Upgr. | e | CW | 12000 | 0.1 | 1000 |
| ESS | P | 4% | 2000 | 62.5 | 5000 |
| FRIB | ions | up to CW | 200 to 320 | 0.65 | 400 |
| LCLS-II | e | CW | 4000 | 0.06-0.3 | 300-1200 |
| Europ. XFEL | e | 0.7% | 17500 | 5 | 900 |
| PIP-II | H$^-$/p | up to CW | 800 | 2 | >16 |
| Chinese ADS | P | CW | 1500 | 10 | 15000 |
| MESA Mainz | E | CW | 105-155 | 1-10 | 1600 |
| MYRRHA | P | CW | 600 | 4 | 2400 |
| eRHIC (ERL) | E | CW | 20000 | 50 | 1000,000 |
| LHeC (ERL) | E | CW | 60000 | 6.6 | 400,000 |
| SPL at CERN | H$^-$ | 4% | 5000 | 20 (40) | 4000 |
| ESS+ESSnuSB | p | ~9% | 2000 | 62.5 | 10000 |
| ILC | e | 0.4% | 250 | 5.8 | 2×5200 |



**Design Drivers:**

| | |
|---|---|
| High average beam power 5MW | |
| High peak beam power | 125 MW |
| High availability | >95 % |

**Key Linac parameters:**

| | |
|---|---|
| Energy | 2.0 GeV |
| Current | 62.5 mA |
| Repetition rate | 14 Hz |
| Pulse length | 2.86 ms |
| Losses | <1W/m |
| Ions | p |

Flexible/Upgradable design
Minimize energy consumption

First beam at 571 MeV ready in June 2019,
Full energy/full power planned for 2023

*Figure 30: The ESS linac (M. Eshraqi and A. Jansson, Valencia, 2017 [35]).*

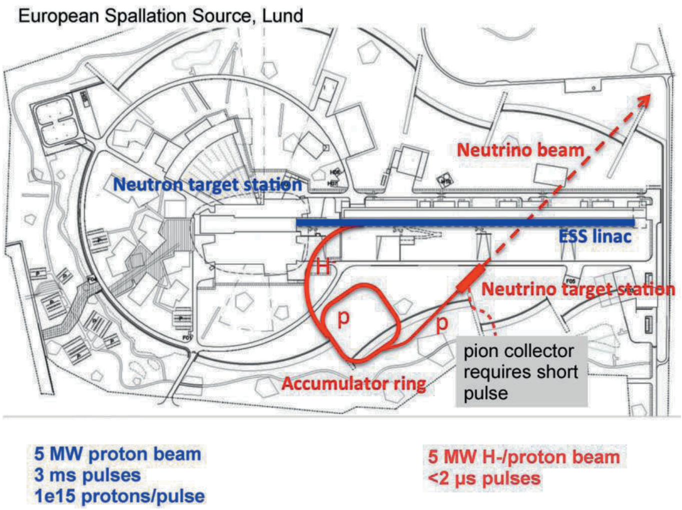


*Figure 31: ESSnuSB proposal (M. Olvergard, Uppsala; M. Eshraqi and A. Jansson, Valencia, 2017 [35]).*

One of the primary challenges of high power accelerators, such as the ESS, is their efficient and timely commissioning, considering the delicacy of the components as well as their high beam power and significant RF power. The commissioning is an important step in the life of an accelerator, which can significantly affect its performance over the following years of operation. The increased number of linear accelerators under design or at the verge of commissioning, especially in Europe, call for increased collaboration on commissioning of proton linacs.

In preparation for the commissioning and operation of future extreme linacs, appropriate beam diagnostics suites need to be chosen and included already from the early design phases onward. For beam commissioning, the emphasis is on reliability, simplicity and redundancy of the diagnostics tools.

The commissioning phase could extend well beyond the traditional commissioning times. For example, the SNS and J-PARC facilities are still improving the performance, as is illustrated in Figs. 32 and 33.

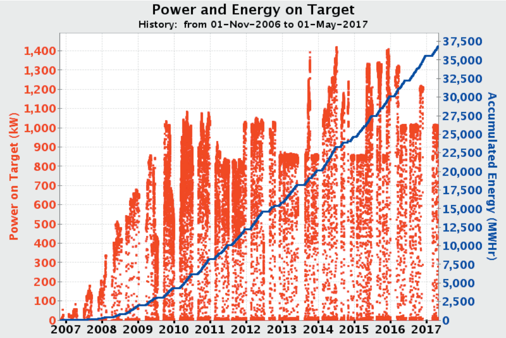


*Figure 32: Beam power at SNS as a function of year (from* https://ics-web.sns.ornl.gov/chico/beam.jsp*).*

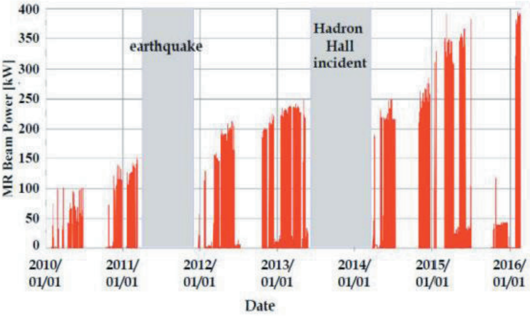


*Figure 33: Beam power from J-PARC Main Ring as a function of year (M. Kinsho, IPAC16)*

Beam loss and activation is a major concern for extreme hadron linacs. Profile and halo monitors are important diagnostics devices for controlling and limiting this beam loss. The linac beam dynamics must be optimized (e.g. choosing between equipartition and equal tune depression lattices).

To make accurate predictions, computer simulations require a realistic representation of the static and dynamic RF errors, including their dependencies and the effects of feedback/feedforward systems. A good temperature control of the timing reference lines is mandatory. Advanced low-level RF systems can minimize the overall electric power consumption of extreme linac facilities, and so could more efficient klystrons or better inductive output tubes (IOTs). The LLRF systems must meet the tight error tolerances set by the beam dynamics in order to keep beam losses along the linac under control.

Beam diagnostics for high-power proton linacs includes 3 or 4 "B's" – beam current monitors (BCMs), beam loss monitors (BLMs), beam position monitors (BPMs), and beam phase monitors – for controlling beam loss and to trigger fast aborts in case of failure, profile measurements as minimally invasive diagnostics (wire scanner, ionization monitor, beam-induced fluorescence (BIF) monitor [w. pump laser?]), advanced beam instrumentation such as fast neutron monitor, differential BCMs, bunch shape monitors, gas jets, electron-beam scanner, or 6D emittance measurements, and advanced use of 3B instrumentation, like the "Shishlo method" (BPM sum & cavity scan [see Fig. 34]). The ESS contains about 500 diagnostics systems of about 20 different types. Planned pioneering 6D emittance measurements (Fig. 35) will provide additional insight into linac performance and allow for more reliable computer simulations of the linac beam dynamics.

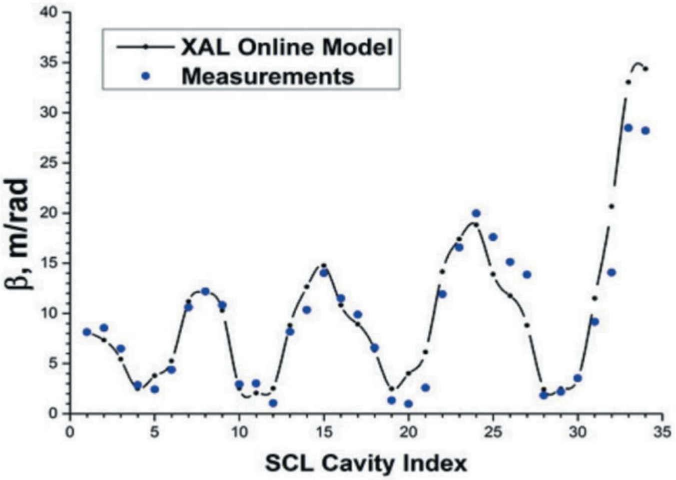
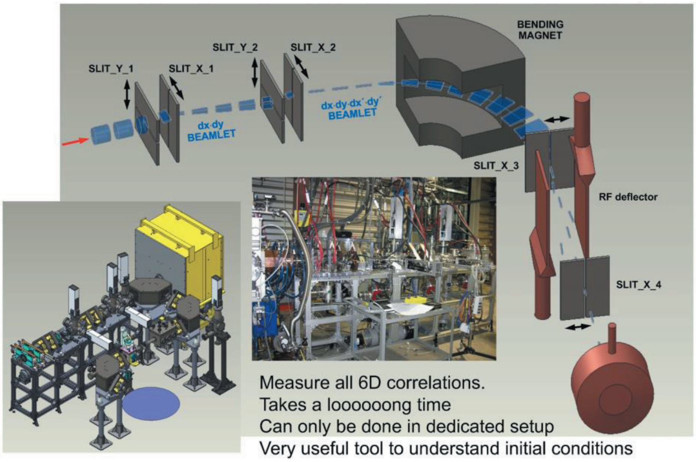


*Figure 34: Longitudinal beta function measurement obtained by the "Shishlo method" (A. Shishlo and A. Aleksandrov, Phys. Rev. ST Accel. Beams 16, 062801) at the SNS SC linac (A. Jansson, Valencia, 2017 [35])*



Measure all 6D correlations.
Takes a loooooong time
Can only be done in dedicated setup
Very useful tool to understand initial conditions

*Figure 35: 6D Emittance measurement station at the SNS developed by A. Aleksandrov (A. Jansson, Valencia, 2017 [35])*

### 5.3. XLINAC STRATEGY FOR EXTREME HADRON LINACS

Concerning the future strategy, the XLINAC workshop discussions give rise to the following conclusions.

(1) An enhanced collaboration and sharing of expertise and equipment between similar projects in Europe and around the world are essential for fast progress at minimum cost.

(2) An early, thorough preparation for beam commissioning with special attention to (redundant) important diagnostics will greatly facilitate the running-in of new linear accelerators.

(3) Beam-loss minimization is crucial for achieving the desired levels of availability and hands-on maintenance of high-power proton linacs. A properly specified and well-functioning low-level radiofrequency system (LLRF), along with good temperature control of the timing reference lines, is the key for meeting beam-dynamics tolerances and keeping the losses under control. In addition, advanced LLRF systems also help minimizing the overall electric power consumption. Static and dynamic LLRF errors need to be properly modelled in simulations.

(4) Planned pioneering 6D emittance measurements will provide additional insight into linac performance. In particular, they will determine the initial beam parameters, and, thereby, improve the predictive power of computer simulations.

In particular, we see the following main areas where networking and R&D activities are needed for a period defined approximately by the next decade:

- beam commissioning strategies fur future extreme linacs;
- low-level RF development for future high-power accelerators, targeted at beam-loss control and electric-power reduction;
- beam diagnostics tools for commissioning and operation, allowing beam halo control, loss minimization and further improved simulations; and
- enhancing the reliability and availability of future high-current linear accelerators.

## 6. EXTREME POLARIZATION

### 6.1. POLARIZATION LANDSCAPE AND EUCARD-2 XPOL ACTIVITIES

Over the past 40 years beam polarization has proven a powerful additional tool for colliders and precision measurements. Colliders like LEP, SLC and HERA have operated with highly polarized lepton beams, either obtained by self-polarization (Sokolov-Ternov effect) or from a polarized source (strained GaAs photocathode). RHIC has steadily increased the level of proton polarization. Polarized protons are successfully accelerated in the AGS and RHIC storage rings through numerous spin resonances using (partial) Siberian snakes. Various types of purely transverse or transverse-longitudinal spin rotators have proven their respective merits. At lower energy and in fixed target experiments, e.g. at CEBAF or MAMI, electron beam polarization has long been an essential quality. Future machines like MESA or future storage rings to measure the electric dipole moment will rely on advanced spin dynamics and pertinent measurement techniques.

In a series of four workshops and seminars [31-34], EuCARD-2 XPOL addressed polarization in upcoming accelerator projects, the role of the polarization measurement, accelerator-based measurement of electric dipole moments, and advances in polarimetry:

- XPOL workshop "Spin Optimization at Lepton Accelerators", Mainz, February 2015 [31].
- XPOL workshop "Search for the Electron EDM in an Electrostatic Storage Ring", Mainz, September 2015 [32].

- XPOL workshop “Polarization Issues in Future High Energy Circular Colliders," Rome, April 2016 [33].
- XPOL seminar “New Polarimeter Techniques for Symmetry Breaking Experiments at Accelerators,” Mainz, 2 December 2016 [34].

These workshops revealed that polarization in future experiments involves two main branches:

(1) low-energy “small” accelerators (EDM JEDI, MESA), for the purpose of discovery (strong CP and T violation) and precision experiments (weak parity violation); and

(2) high-energy “big” accelerators: precision measurements at the ILC (polarized e+ source technologically challenging, polarization measurement via Compton backscattering promising ($\Delta p/p \sim 0.1\%$), precision beam parameters at the FCC-ee (absolute energy calibration by resonant depolarization at the level of $\Delta E/E \sim 10^{-6}$; high-energy polarized proton beam at the FCC-hh (not completely impossible), fixed target polarization at LHC or FCC-hh (possible!), and LHeC with polarized $e^-$ beam (feasible).

## 6.2. EXTREME POLARIZATON IN LINEAR COLLIDERS

For linear colliders, polarized particles have to be generated in particle sources which represent the spin polarized quantum ensemble that is used at the experiment to investigate spin-dependent effects. In a linear system, the preservation of polarization is not a major concern, though subtle effects contribute in the collision region.

In addition, precision polarimetry is available, since Laser-Compton backscattering can be applied, a technique which can be pushed to a few per-mille accuracy in determining the magnitude of the polarization vector.

For the electron arm of the collider the particle source is based on photoemission from suitable semiconductor nanostructures. The physics of these processes is well understood and the technological challenges are demanding, but can be kept under control if sufficient resources are available. A comparatively small additional R&D effort is needed to adapt existing designs to the requirements. For instance, specific laser systems have to be developed to meet exactly the time structure of the linear colliders for polarized-beam operation. This may require some effort, but is not considered critical.  Beam polarization of up to 90% can be expected which is well within the target specifications of the designs.

Polarized positrons can be generated by pair conversion from circular polarized Gamma radiation. The magnitude of polarization depends on the positron momentum range that is accepted. At the end point of the positron energy spectrum it is identical to the photon helicity and can therefore reach a magnitude comparable to the electron polarization. As in the case of a conventional positron source a main issue is to obtain a sufficient photon flux that allows achieving a sufficient yield of positrons. For lepton colliders, two approaches towards realizing a circularly polarized photon source were pursued and the operating principles of both methods successfully demonstrated. The first method is Compton backscattering of circularly polarized laser photons off intense electron beams in the GeV range – an option considered for CLIC. The second, which was adopted for the ILC baseline, is using a helical undulator driven by an electron beam at even higher energies of about 200 GeV.

Since pair production is associated with strong heat dissipation, the long-term availability of the positron conversion target is of concern, in particular in view of the repeatedly varying thermal stress induced in the material. The problem is not completely treatable by modelling and therefore calls for experimental investigation. Unfortunately, this experimental regime is also not easily accessible since the photon sources corresponding to the parameters envisaged for the ILC do not exist yet. This problem is one of the remaining technology challenges of the ILC design. A promising approach for testing the target environment under realistic conditions was proposed, based on the discussions at the first XPOL workshop [31]. It consists of using the ionization caused by electron beams as a surrogate for the not yet available gamma source. Existing c.w. electron accelerators can be modulated with the required time structure and the available beam intensity is large enough to create the required ionization density, albeit in small volumes of target material. First tests have been done in the spring of 2016 at the MAMI facility in Mainz [44]. With the input from such experiments and improved simulations more reliable answers can be expected.

## 6.3. EXTREME POLARIZATION IN CIRCULAR COLLIDERS

Polarization issues for circular colliders were addressed at the third XPOL workshop [33].

Spin polarized beams (SPBs) at circular machines are subject to a more complex environment if compared to a linear accelerator. As an advantage, one may in some cases profit from the effect of self-polarization ("Sokolov-Ternov-Effect") which allows avoiding the problems associated with the production of the polarized positron beam. On the other hand, hadron as well as lepton circular machines suffer from depolarization effects which are due to a synchronization of spin motion with the characteristic orbital frequencies in the accelerator, a phenomenon referred to as "depolarizing resonances". In lepton machines strong synchrotron radiation increases the possibility to excite such resonances which makes the problem more severe. Spin rotators which are integrated into the ring ("Siberian Snakes") or improved orbit control can mitigate the problem, but they require additional effort and cost, which have to be justified by the resulting increase of physics output.

The future circular lepton collider FCC-ee, as well as a similar machine CEPC, proposed by CAS-IHEP in China, will be operated at centre-of-mass energies ($E_{CM}$) up to a few hundred GeV. Higher energies are not reasonable due to the ever increasing synchrotron-radiation losses in a circular system. At lower energies (for instance $E_{CM}$ =160.7 GeV, which corresponds to the production of W boson pairs) the particle physicists currently have a strong opinion that it is more advantageous to optimize the luminosity of the FCC compared to an availability of polarization in the direction of particle momentum ("longitudinal"). This longitudinal orientation is necessary to investigate the spin dependent effects, but it causes considerable complications due to the complex set-up implied by the requirement of longitudinal spin orientation.

The contribution of polarization to the physics output of FCC-ee is nevertheless significant and lies in the possibility of accurate determination of $E_{CM}$ – as it is indicated by the accurate number "160.7 GeV" above. The method of "resonant depolarization" is best suited for measuring $E_{CM}$. It uses a Compton backscattering polarimeter for detecting the loss of polarization which occurs when the accelerator energy approaches a value that corresponds to a spin resonance. Obviously, the method also requires some magnitude of polarization, but in this case the polarization can be perpendicular to momentum and is therefore attainable "for free" due to self-polarization. Since the process of self-polarization is rather slow at low energies, an enhancement of the polarization rate is advisable which can be achieved by introducing polarization wigglers. Moreover, improved experimental ingredients - more powerful laser systems and higher resolution detectors, were demonstrated at ELSA, a 4 GeV synchrotron at University of Bonn/Germany. Such advancements reduce the required magnitude of polarization, hence creating opportunities to obtain both faster and more accurate determinations of the beam energy (through resonant depolarization). Indeed, extrapolating from ELSA and assuming a state-of-the-art laser system, at the FCC-ee a Compton polarimeter can measure the beam polarization with a precision of 0.1-0.2% turn-by-turn and bunch-by-bunch [33] (W. Hillert). This means that polarization levels of only a few percent may be required for precise energy calibration using resonant depolarization.

The FCC-ee will deliver beams with center of mass energies ranging from the Z pole ($E_{CM}$=91 GeV) up to the top mass ($E_{CM}$=350 GeV). Extrapolating from LEP suggests that achieving significant polarization levels at energies above the W threshold ($E_{CM}$>160 GeV) may be difficult as a result of the increased energy spread due to synchrotron radiation. Further improvements of the optical lattice with regard to polarization, and the development of suitable spin manipulation techniques, including e.g. spin matching in the presence of errors or the addition of Siberian snakes, will aim at achieving polarization also in the highest-energy operation of this proposed future $e^+e^-$ collider.

Due to the very high beam energy in the future circular hadron collider FCC-hh – up to 50000 GeV – the fixed absolute energy difference between two resonances (0.523 GeV in case of the so-called "imperfection resonances" for the proton) creates additional problems. A large number of resonances need to be crossed during acceleration, and the spin resonance strengths increase with beam energy. Successfully preserving polarization under these conditions requires a high level of spin control. Interestingly, the experts in the field do not consider this task as hopeless. The installation of a large number of "partial Siberian snakes" could be a starting point to solve the problem, as first simulations indicate [33] (V. Ptitsyn). Example results are presented in Fig. 36. Though the number of snake devices is high and the individual snake length is about 10 meter, the overall length increase of the 100 km long FCC would only be of order 1%. However, further R&D effort will be needed to come to reliable conclusions. In any case the inclusion of such a large number of devices has to be justified by additional return on investment by physics output.

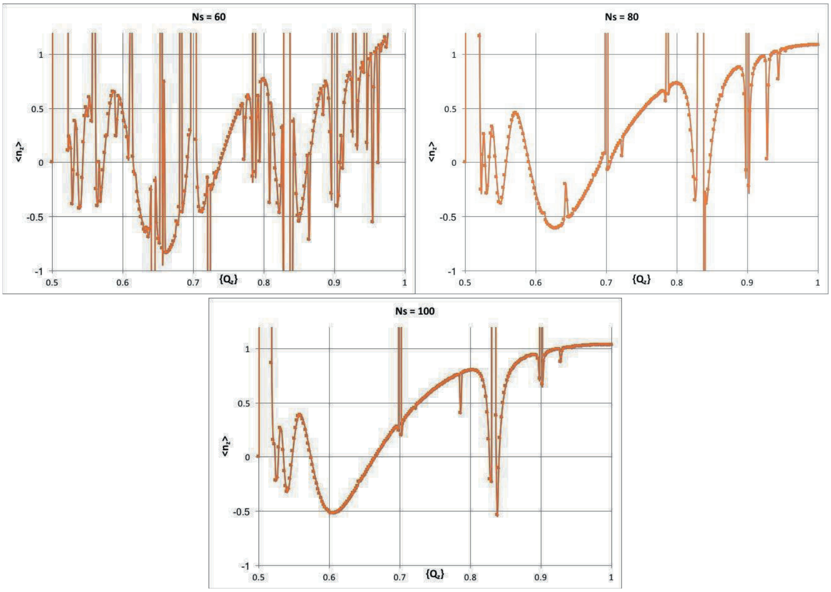


*Figure 36: Simulated snake resonances in FCC-hh for varying number of snakes: 60 snakes (top left), 80 snakes (top right) and 100 snakes (bottom); shown is the vertical polarization averaged over the betatron phase for protons with 3$\sigma$ vertical betatron amplitude versus the fractional part of the vertical betatron tune; irregular areas characterize the snake resonance width; the snakes could consist of four helical dipoles each, with a snake length of about 10 m (V. Ptitsyn, 3rd XPOL workshop [33], Rome, 2016).*

It can also be mentioned that present day research has demonstrated that it is possible to introduce small amounts of gas in the vicinity of the LHC-b detector. Since polarized gas targets also have low densities this can be an option to provide polarized fixed targets as attractive add-on to the collider program of the LHC or the FCC-hh.

## 6.4. SPIN POLARIZED BEAMS AT THE PRECISION FRONTIER

SPB's are an expedient means to increase the physics reach of smaller scale accelerators, which are not able to contribute to experiments at the energy frontier. Observables include fundamental constants such as the electroweak mixing angle, the observation of physics beyond the Standard Model such as an increased magnitude of the electric dipole moment of fundamental particles, and also double polarization experiments which allowing for precision measurements of hadron physics observables such as the magnetic form factor of the nucleon or polarization-dependent parton structure functions.

The latter is a part of the motivation for medium-size colliders (eRHIC, LHeC) because it addresses one of the great mysteries in strong interaction physics, namely the "spin puzzle" – the problem that present day theory cannot completely motivate the magnitude of the spin of the proton.

The accelerators used for this purpose comprise fixed target machines such as CEBAF, MAMI/MESA, ELSA, but also colliders like eRHIC, LHeC, or FCC-he. The following topics were addressed during several EuCARD-2 workshops and in particular at the second [32].

Parity violating electron scattering is one of the methods in use at the precision frontier. It is currently pursued at JLAB/CEBAF in the US and at MAMI/MESA in Mainz, Germany. Typically, the observable is a change in cross section under reversal of the longitudinal polarization (helicity) of the electron beam. This effect is small – typically the cross sections vary by a few ppm at most, and in some cases even much lower. In addition, the observed cross section difference is proportional to the beam polarization. To illustrate the magnitude of the problem one may consider a 1% accuracy measurement of a 1ppm cross section variation. The total error resulting from counting statistics and all other error sources should then be smaller than 10ppb. The statistical requirement means that high intensity sources are needed to create luminosities in the range $10^{38}$ -$10^{39}$ $cm^{-2}s^{-1}$, which can only be realized with external beams created by linear accelerators impinging on relatively thick targets. High intensity in this context means beam currents of up to several hundred microampere. In this current range the lifetime of photocathodes is sufficient to guarantee for an acceptably high beam availability. One can therefore state that the critical issue for existing projects is not intensity, but beam parameter control.

Figure 37 illustrates the precision goal for MESA, namely „elastic electron scattering on proton measuring $1\text{-}4\sin^2\Theta_W$ (small asymmetry in the scattering has a high sensitivity); supressing hadronic contributions favours low momentum transfer and low beam energy.

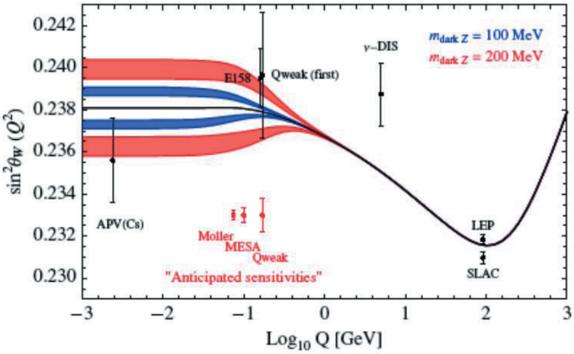


*Figure 37: Running Weinberg angle versus Q (log scale) and targeted measurement presentation of MESA at low momentum transfer; MESA would be sensitive to a "dark Z boson", which also contributes to the muon anomalous magnetic moment (K. Aulenbacher, Valencia, 2017 [35]).*

The first critical parameter is the magnitude of beam polarization, since the accuracy of the result is directly proportional to the accuracy obtained in the polarization measurement. The other one is to minimize the fluctuation of accelerator parameters under helicity reversal. To illustrate this, one should recall that the extracted cross section is proportional to the beam current in each helicity state. For the example discussed here, this results in the requirement that the helicity correlated beam current modulation must be measured with much less than 10 ppb accuracy. Similar requirements follow for the control of other helicity correlated parameter fluctuations such as position, energy and angle. This presents a formidable task for the non-invasive measurement of such parameters. Experience shows that the developments in beam diagnostic devices and feedback systems which are applied to solve these issues help to increase the accelerator performance in general.

In the future, "linac-ring" type colliders which are planned at CERN and at Brookhaven National Laboratory (LHeC, FCC-eh, eRHIC) do not have such stringent requirements on the electron beam parameter control. The main reason is that the parity-violation (PV) signal increases essentially with the square of the beam energy, so that parameter fluctuations become less important. On the other hand, colliders need very high beam currents to achieve sufficient luminosity. In a "linac-ring" system with polarization in the linac arm this has two consequences, namely the need for extremely highly polarized electron currents and the need for recovery of the beam energy (ERL principle). Presently average currents of ~1 mA are considered as feasible in long term operation, while ion back bombardment from the residual gas progressively destroys the semiconductor nanostructure of the photocathode. The future projects require about an order of magnitude higher intensities. Several approaches to increase the photocathode lifetimes exist, one of the most promising may be to immerse the photocathode in a vacuum vessel at cryogenic temperatures. In conjunction with RF operation of the source the number of ions created will be minimized in twofold fashion, first by the reduced gas pressure, second by the low attainable ion-energy compared to a dc source. In order to guarantee the reliable operation of such colliders R&D in this direction will be indispensable.

Accurate spin control in a storage ring enables the search for a charged particle electric dipole moment (EDM). The existence of such an EDM is violating the CP symmetry in nature and a sufficiently large violation (which is not foreseen in the present standard model of physics) can help explain the existence of matter in the universe – a truly fundamental question. With the exception of neutron experiments, EDM searches have so far been carried out only on complex systems such as heavy atoms or molecules. The sensitivity of these experiments is very high, which means that considerable R&D effort is needed for the accelerator experiments to become competitive. However, the effort could pay off since the elementary nature of the particles investigated (electrons, protons or deuterons) will reduce the ambiguities in the interpretation of a non-zero finding of an EDM of a complex system, even if the accelerator based experiments do not achieve a sufficiently steep learning curve to overtake the other techniques until the time of discovery.

A necessary ingredient is to conserve the polarisation during free precession in the accelerator plane. This will lead to a spin precession which differs from the orbital (revolution) frequency. The additional change in frequency, given in units of the orbital frequency, is called the “spin tune”. Based on techniques developed at Brookhaven National Laboratory in the U.S.A. considerable progress has been made in experiments at the COSY storage ring. A spin lifetime in free precession of thousand seconds has been achieved which enabled a measurement of the spin tune with a relative accuracy of about $10^{-10}$ – one of the most accurate determinations of an accelerator parameter ever.

The EDM will be observed as an occurrence of a vertical spin polarization component. Since such components can also be generated spuriously, for instance by radial magnetic fields, it is necessary to take precautions. One of the most effective would be to build an electrostatic storage ring with frozen spin, i.e. spin tune zero and zero magnetic fields in the lab frame. Such a system would be rather compact for electrons, and much more demanding for the proton. The proton is the more interesting species to study since larger effects are expected, but the electron storage ring can help to develop and improve the necessary techniques, in particular polarimetry, see below. Figures 38 and 39 relate to EDM measurements of protons and possibly deuterons in a dedicated storage ring. For protons, a purely electrostatic storage ring can do the job. Precision is improved and the effects of residual magnetic stray field minimized by comparing the behaviour and orbits of two counter-rotating beams. Deuterons require a combination of electric and magnet fields.

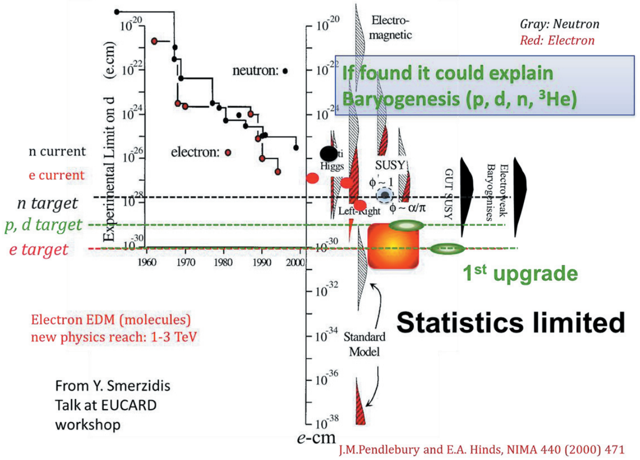


*Figure 38: Jülich Electric Dipole Moment Investigation „JEDI” aims at discovering proton EDM in an electrostatic storage ring (K. Aulenbacher, Valencia, 2017 [35])*

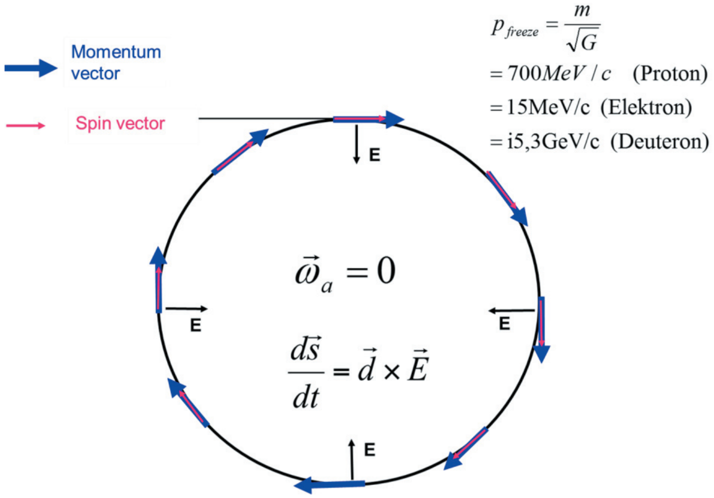


*Figure 39: Electrostatic storage ring with frozen spin to measure the proton EDM (K. Aulenbacher, Valencia, 2017 [35])*

### 6.5. “INVASIVE” VS “NON-INVASIVE” POLARIMETRY

The detection of polarization by analysing the spin dependent rates in scattering processes is well established for leptonic and hadronic probes. Achieving a good statistical accuracy is of no concern for accelerators with external beams. On the other hand, storage rings like those used for the EDM experiment need to make efficient use of the very limited number of particles stored. In this case it is necessary to optimize the sensitivity of the device. For the example of the EDM rings just discussed it can be found that the effectiveness for hadronic scattering (protons on carbon targets) is by far superior compared to the effectiveness for leptons (Mott or Möller scattering).

For “non-invasive” techniques the situation is almost reversed. For leptonic particles in the ultra-relativistic regime (>1 GeV) one can use Compton backscattering, a method which is suitable for external as well as for stored beams. In the lower energy region (<1 GeV) the Compton process is less effective. In this region a promising method is Electron-Electron Scattering, a double polarization experiment which is commonly called Möller polarimeter. In its present appearance, it is limited in accuracy due to the application of solid magnetized iron as polarized electron-electron target, which creates systematic uncertainties due to solid state effects. Significant progress in accuracy may be achieved if it becomes possible to use a completely polarized hydrogen gas, longitudinally trapped in a magnetic bottle. The radial trapping is provided by a superfluid helium film at a temperature of 0.3 K, on which the hydrogen atoms are reflected. This device is called the “Hydro-Möller” polarimeter since it employs Möller scattering on the completely polarized electrons of the trapped hydrogen atoms. The Hydro-Möller can be operated online because of its low target density and the windowless trap. Moreover, it has the potential to achieve extremely high accuracies since the target polarization of the electrons is known with a relative error $<10^{-4}$. However considerable R&D effort is required to develop this type of polarimeter.

It has been suggested that one can use the Stern-Gerlach force in a cavity [45] that is integrated in a storage ring to obtain a signal that is related to individual polarisation components. This kind of signal pick up would be as "non-invasive" as possible. The suggestions for such devices are very elaborate, in particular for reducing the non-spin correlated noise in the pick-ups. Nevertheless, the associated proposals contain ideas how to deal with these problems, and a successful development would be rewarded with a huge increase in sensitivity, in particular for an electron EDM experiment, where conventional polarimetry is inefficient. Again, a large R&D effort is needed in the future.

## 6.6. XPOL STRATEGY FOR FUTURE POLARIZED BEAM AND PRECISION EXPERIMENTS

We see the following main lines where networking and R&D activities are needed for a period defined approximately by the next half decade:

(1) **Future large scale machines** (FCC, etc.): These accelerator projects are still in a phase where networking and R&D can have a significant impact on the overall layout. It is mandatory to optimize the modelling tools and to update the technological achievements occurred since the LEP era in order to make reliable predictions of what can (and what cannot) be achieved with respect to polarization performance. If the realization of polarization degrees of freedom is only a matter of additional technical effort clear statements should be worked out by groups with well-defined responsibilities why (or why not) polarization is (not) desirable for the individual machine.

(2) **Technical subcomponents:** It is evident that improving the capabilities of hardware and software tools will have to go on in the future. Important issues are the improvement of spin polarized electron sources for linac-ring colliders, and measures to increase the accuracy of polarimetry. On the software side, it seems that a coordinated effort to modernize and standardize the existing software packages would be helpful, in order to optimize the reliability of the results, to do benchmarking and to compare the results obtained by different groups.

(3) **High risk projects**: Significant breakthroughs can be obtained by techniques which are out of the scope of established methods. Examples are using a superconducting RF source to get rid of the ion back-bombardment problem for high intensity spin polarized sources or the non-invasive resonant polarimeter under discussion for the EDM experiments. As in all projects with significant risk one has to take into account the possibility of failure, but given the moderate cost and the high gain, a pursuit of such research is recommended.

## 7. OUTLOOK

Circular colliders and storage rings work well and advance further thanks to new concepts (crab waist, top up, monochromatization,...) and tools (e-lenses, e-cloud mitigation, novel beam-cooling schemes, …).

One attractive route forward starts from a circular e+e- collider (FCC-ee/CEPC), proceeds to a 100 TeV hadron collider (FCC-hh/SPPC), and culminates in a 100 TeV muon collider ("FCC-μμ"). An alternative path could be 25 TeV hadron collisions (HE-LHC) followed by a 25 TeV muon collider.

Common to all facilities is that the technology cost must be reduced.

Advanced crystal and nanotube concepts should be explored for the long-term future. These may well turn out to be more attractive than plasma-based acceleration schemes.

The beam power of rings and linacs is ever more increasing, which calls for better beam control and better diagnostics.

Polarization offers additional handles for discovery and precision studies at lower energy.

Several tantalizing projects are upcoming during the next couple of years, such as SuperKEKB, IOTA, ESS, NICA, HEPS, HL-LHC, and MESA. They are certain to teach us new lessons. Many other machines – ESSnuSB, JEDI, FCC, CEPC, LHC-based Gamma-Factory, γγ colliders,...– are being proposed.

Enhanced by possible novel uses of storage rings, e.g. for the detection or generation of gravitational waves (R. D'Agnolo, Valencia, 2017 [35]), and by new methodologies for modelling actual accelerator performance and pushing availability to unprecedented levels (A. Apollonio, Valencia, 2017 [35]; Fig. 40), these next-generation facilities are offering an exciting perspective for the future.

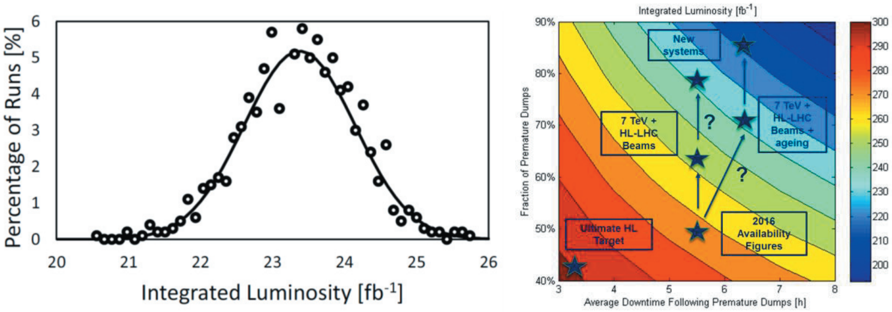


*Figure 40: Prediction of 2012 LHC integrated luminosity from 1000 rounds of Monte-Carlo simulation using LHC availability/reliability model (left picture); for comparison the actual luminosity was 23.27 fb$^{-1}$; integrated annual luminosity forecast for HL-LHC in units of fb$^{-1}$ [colour code] (right picture; A. Apollonio, Valencia, 2017 [35])*

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[8] XCOLL co-sponsored workshop on “Multipactor, Corona and Passive Intermodulation (MULCOPIM)”, Valencia, 19-21 September 2014; http://www.mulcopim.org/ .

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[19] 1st XRING workshop "Beam Dynamics meets Magnets", Darmstadt, 2-4 December 2013; https://indico.gsi.de/conferenceDisplay.py?confId=2352 ;
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[23] 3rd XRING/XLINAC joint workshop "Beam Dynamics meets Diagnostics," Firenze, 4-6 November 2015; https://indico.gsi.de/conferenceDisplay.py?confId=3509 ; EuCARD-2 Milestone Report MS38 and MS39, https://edms.cern.ch/ui/file/1325177/1/EuCARD2-Mil-MS38and39_Final.pdf .

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# ANNEX: GLOSSARY

| **Acronym** | **Definition** |
|---|---|
| ADS | Accelerator Driven Sub-critical system (for nuclear power generation) |
| BPM | Beam Position Monitor |
| BCT | Beam Current Transformer |
| BDS | Beam Delivery System |
| BNL | Brookhaven National Accelerator Laboratory in New York State, U.S.A. |
| CAS | Chinese Academy of Science |
| CBETA | Cornell-BNL FFAG-ERL Test Accelerator, an ERL test facility with FFAG arcs under construction at Cornell University, U.S.A. |
| CEBAF | Electron beam facility based on a recirculating SC linac, at Jefferson Lab U.S.A. |
| CEPC | Circular Electron Positron Collider at the Higgs energy, proposed by IHEP in China |
| CERN | Centre Européen pour la Recherche Nucléaire, in Geneva, Switzerland and France |
| CLIC | Compact Linear Collider, proposed in the Geneva region |
| c.m. | centre of mass |
| COSY | Cooler Synchrotron at FZ Jülich, Germany |
| DAΦNE | Φ-Factory in operation at Frascati INFN National Laboratories, Italy |
| dc | direct current, the opposite of alternating current (ac) |
| DESY | Deutsches Elektronen Synchrotron, Hamburg, Germany |
| DTL | Drift Tube Linac |
| $E_{CM}$ | Centre of Mass energy |
| EDM | Electric Dipole Moment |
| ELSA | Elektronen Stretcher Anlage in Bonn, Germany |
| eRHIC | Electron Relativistic Heavy Ion Collider proposed at BNL, U.S.A. |
| ERL | Energy Recovery Linac |
| ESA | European Space Agency |
| ESS | European Spallation Source, in Lund, Sweden |
| ESTEC | European Space Research and Technology Centre operated by ESA in Noordwijk, the Netherlands |
| European XFEL | European X-Ray Free-Electron Laser, in Hamburg, Germany |
| FAIR | Facility for Antiproton and Ion Research, at GSI |
| FCC | Future Circular Collider, a 100-km collider in the Lake Geneva basin, under design by an international collaboration, with focus on 100-TeV hadron collisions (FCC-hh), and including a possible intermediate $e^+e^-$ factory (FCC-ee), a lepton-hadron option (FCC-he), and a High-Energy LHC (HE-LHC) |

| | |
|---|---|
| FCC-ee | Future Circular Collider (electron-positron version), proposed in the Geneva region |
| FCC-he | Future Circular Collider (hadron-electron/positron version), proposed in the Geneva region |
| FCC-hh | Future Circular Collider (hadron-hadron version), proposed in the Geneva region |
| FFAG | Fixed Field Alternating Gradient |
| FNAL | Fermi National Accelerator Laboratory in Illinois, U.S.A. |
| FZJ | Forschungszentrum Jülich in Germany |
| GANIL | Accelerator Complex in Caen, France |
| GeV/MeV/TeV | Giga/Mega/Tera-Electron-Volt |
| GSI | Gesellschaft für Schwerionenforschung, Darmstadt, Germany |
| HE-LHC | A 25-TeV collider in the LHC tunnel based on FCC-hh magnet technology |
| HIAF | High-Intensity Heavy Ion Accelerator Facility in Lanzhou, China |
| HIDIF | Heavy Ion Driven Inertial Fusion |
| HL-LHC | High Luminosity LHC (expected to operate from 2025 onwards) |
| ICFA | International Committee for Future Accelerators |
| IHEP | Institute of High Energy Physics, Beijing, P.R. China |
| ILC | International Linear Collider proposed in North-East Japan |
| IOTA | Integrable Optics Test Accelerator at Fermilab, U.S.A. |
| INFN | National Institute for Nuclear Physics, Italy |
| IP / IR | Interaction Point / Interaction Region |
| ISIS | Synchrotron-based pulsed neutron and muon source at RAL, U.K. |
| JGU | Johannes Gutenberg-Universität Mainz, Germany |
| JINR | Joint Institute of Nuclear Research, Dubna, Russia |
| JLEIC | Electron-ion collider proposed by Jefferson Lab, U.S.A. |
| J-PARC | Accelerator complex at Tokai in Japan |
| KEK | High Energy Accelerator Research Organization at Tsukuba, Japan |
| KEKB | Former B factory at KEK, Tsukuba, Japan |
| LANL | Los Alamos National Laboratory, New Mexico, U.S.A. |
| LEP | Former Large Electron Positron collider at CERN |
| LHC | Large Hadron Collider at CERN, Geneva, Switzerland |
| LHeC | Large Hadron electron Collider, proposed electron-hadron collider based on the LHC |
| LINAC | Linear Accelerator |
| LIU | LHC Injectors Upgrade |
| LLRF | Low Level Radio-Frequency (system) |
| MAMI | Mainz Microtron |

| | |
|---|---|
| MESA | Mainz Energy-recovering Superconducting Accelerator, in Mainz, Germany |
| MIT | Massachusetts Institute of Technology |
| MYRRHA | European accelerator-driven fission project at CEN, Belgium |
| NICA | Nuclotron-based Ion Collider fAcility is a new international accelerator complex hosted at the Joint Institute for Nuclear Research (Dubna, Russia) for the purpose of studying properties of dense baryonic matter. NICA will provide a variety of beam species ranging from protons and polarized deuterons to very massive gold ions. |
| PEP-II | Former e+e- B factory at SLAC, Stanford, U.S.A. |
| PIP-II | Proton Improvement Plan II, at FNAL, U.S.A. |
| ppm/ppb | Parts per million/parts per billion |
| PS | (CERN) Proton Synchrotron |
| PSB | (CERN) Proton Synchrotron Booster |
| PSI | Paul-Scherrer Institut, Villingen, Switzerland |
| PV | Parity Violation |
| RAL | Rutherford Appleton Laboratory, U.K. |
| R&D | Research and development |
| RF | Radiofrequency (system), normal- or superconducting |
| RFQ | Radiofrequency quadrupole |
| RHIC | Relativistic Heavy Ion Collider at BNL, U.S.A. |
| SIS18 | Existing ion synchrotron at GSI (protons up to 4.5 GeV; uranium ions up to 1 AGeV) |
| SIS100 | New high-energy ion synchrotron to be built in the first phase of FAIR (protons up to 30 GeV) |
| SIS300 | New higher-energy ion synchrotron to be built in a later stage of FAIR (protons up to 90 GeV, and heavy ions (fully stripped) to an order of magnitude higher energy per nucleon than at SIS100 (partially stripped) |
| SLAC | Stanford Linear Accelerator Center in California, U.S.A. |
| SLC | SLAC Linear Collider at Stanford, U.S.A., providing e+e- collisions at a centre-of-mass energy of 91 GeV, in operation from 1987 to 1998 |
| SNS | Spallation Neutron Source in Oak Ridge, U.S.A. |
| SPB | Spin Polarized Beam |
| SPIRAL-2 | Linear accelerator at GANIL, Caen, France |
| SPS | Super Proton Synchrotron at CERN, accelerating protons to up to 450 GeV/c for injection into the LHC, or to 400 GeV for fixed-target experiments. Heave ions are brought to the equivalent energies. |
| SuperKEKB | Super B factory under commissioning at KEK, Tsukuba, Japan |
| XFEL | X-ray Free Electron Laser |