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LHC, HL-LHC and beyond

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A brief overview of LHC operations over the last 3 years is given. Luminosity performance has been satisfactory and the factors that have been exploited are outlined. Availability and operational efficiency are discussed. An overview of the planned long shutdown is given and estimates of the potential post shutdown performance briefly enumerated. Finally a brief survey of future options for the LHC and other possible circular colliders at CERN is presented.

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1. Introduction

The LHC has four main experiments: ATLAS, CMS, ALICE and LHCb. Of these, ATLAS and CMS are general purpose detectors (GPD) designed for high luminosity and searches in a wide variety of channels. In the following the focus is on the delivery of instantaneous and integrated luminosity to the GPDs. ALICE and LHCb have also operated successfully at lower luminosities and are briefly referenced.

The LHC re-started initial commissioning with beam at the end of 2009. Since then the LHC has had three years of operations as summarized in table 1.

Table 1: LHC operations 2010 to 2012

Year	Overview	Energy [TeV]	Integrated luminosity [fb^{-1}]
2010	Commissioning	3.5	0.04
2011	Exploring limits	3.5	6.1
2012	Production	4.0	23.1

The integrated luminosity performance over the 3 years can be regarded as satisfactory, with the LHC delivering enough integrated luminosity to enable ATLAS and CMS to announce the discovery of a Higgs boson on July 4th 2012. The total integrated proton-proton luminosity delivered to ATLAS at 3.5 and 4 TeV by the end of 2012 can be seen in table 1.

2012 was a production year at an increased beam energy of 4 TeV. The choice was made to continue to exploit 50 ns and run with a total number of bunches of around 1380. Based on the experience of 2011, the decision was taken to operate with tight collimator settings. The tighter collimator hierarchy shadows the inner triplet magnets more effectively allowing a more aggressive squeeze to a β^* of 0.6 m. The price to pay was increased sensitivity to orbit movements, particularly in the squeeze, and increased impedance. The latter having a clear effect on beam stability as expected. Peak luminosity was rapidly brought close to its peak. This was followed by a determined and long running attempts to improve peak performance. 2012 was very long operational year and included the extension of the proton-proton run until December resulting in the shift of a four week proton-lead run to 2013. Integrated rates were healthy at around the 1 fb^{-1} per week level and this allowed a total for the year of about 23 fb^{-1} to be delivered to both ATLAS and CMS.

1.1 Other users

Besides the delivery of high instantaneous and integrated proton-proton luminosity to ATLAS and CMS, the LHC team was also able to fulfil a number of other physics programs.

- 2010 and 2011 saw lead-lead ion runs which delivered 9.7 and 166 μb^{-1} respectively at an energy of 3.5Z TeV [1]. Here the clients were ALICE, ATLAS and CMS.
- Luminosity levelling at around 4×10^{32} cm^{-2}s^{-1} via transverse separation, with a tilted crossing angle to make life difficult, enabled LHCb to collect 1.2 and 2.2 fb^{-1} in 2011 and 2012 respectively.
- ALICE enjoyed some sustained proton-proton running in 2012 at around 5×10^{30} cm^{-2}s^{-1} with collisions between enhanced satellite bunches and the main bunches.

- There was a successful β^* = 1 km run for TOTEM and ALFA [2]. With t_{min} of approximately 0.0004 GeV^2 this was the first LHC measurement in Coulomb-Nuclear Interference region.
- The three years operational period culminated in successful proton-lead run at the start of 2013 [3]. Here the clients were ALICE, ATLAS, CMS and LHCb.

2. Performance

One of the main features of operations in 2011 and 2012 was the use of the high bunch intensity with 50 ns bunch spacing offered by the injectors. The injector complex has succeeded in delivering beam with significantly higher bunch intensities with lower emittances than nominal. This is particularly significant for the 50 ns beam. Happily the LHC has proven capable of absorbing these brighter beams, notably from a beam-beam perspective. This fact has lead to the LHC choosing to operate with 50 ns in both 2011 to 2012 and pushing hard at this bunch spacing. The clear cost has been increased pile-up for the high luminosity experiments.

In short the LHC has achieved good luminosity performance between 2010 and 2012 via the following.

- Exploiting the important advantage that high bunch intensities bring (luminosity proportional to N_b^2). Here the bunch intensity has been up to 150% of nominal with the 50 ns bunch spacing.
- The normalized emittance going into collisions has been around 2.5 mm.mrad i.e. 67% of nominal. Again this is thanks to very good injector performance and ability to conserve the emittance through the Booster, PS, and SPS. Some systematic blow-up at injection and in the ramp is seen in the LHC [4]
- It has proved possible to squeeze to a β^* of 60 cm thanks to the measurement of good aperture in the interaction regions (credit to alignment, respect of mechanical tolerances, optics measurement and correction, and orbit correction and stability).

The corresponding values for the main luminosity related parameters at the peak performance of the LHC through the years are shown in table 2. The design report values are shown for comparison. Remembering that the beam size is naturally larger at lower energy, it can be seen that the LHC has achieved 77% of design luminosity at 4 sevenths of the design energy with a β^* of 0.6 m (cf. design value of 0.55 m) with half nominal number of bunches.

3. Overview of machine characteristics

The performance described above is on the back of some excellent system performance and some fundamental characteristics of the LHC.

- The LHC has excellent single beam lifetime at 4 TeV before collisions of over 300 hours and on the whole the LHC enjoys excellent vacuum conditions in both warm and cold regions.
- With a peak luminosity of around 7×10^{33} $cm^{-2}s^{-1}$, the start of a fill the luminosity lifetime was initially in the range 6 to 8 hours increasing as the fill develops. There is minimal drifts in beam overlap during physics and the beams are generally very stable.

Table 2: Performance related parameter overview

Parameter	2010	2011	2012	Design value
Beam energy [TeV]	3.5	3.5	4	7
β^* in IP 1 and 5 [m]	2.0/3.5	1.5/1.0	0.6	0.55
Bunch spacing [ns]	150	75/50	50	25
Number of bunches	368	1380	1380	2808
Max. bunch intensity [protons per bunch]	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}	1.15×10^{11}
Normalized emittance at start of fill [mm.mrad]	≈2.0	≈2.4	≈2.5	3.75
Peak luminosity [cm^{-2}s^{-1}]	2.1×10^{32}	3.7×10^{33}	7.7×10^{33}	1×10^{34}
Max. mean number of events per bunch crossing	4	17	37	19
Stored beam energy [MJ]	≈28	≈110	≈140	362

- There is excellent field quality, coupled with good correction of non-linearities. Certainly dynamic aperture appears not to be an issue.
- There is low tune modulation, low power converter ripple, and low RF noise.
- Head-on beam-beam is not a limitation although long range has to taken reasonably seriously with enough separation at the long range encounters guaranteed by sufficiently large crossing angles. The linear beam-beam parameter achieved in operations is around 0.02.
- Collective effects have been seen with the high bunch intensities. Single and coupled bunch instabilities have been suppressed using a range of tools (high chromaticity, Landau damping octupoles and transverse feedback).

Very good understanding of the beam physics and a good level of operational control has been established.

- The linear optics is well measured and remarkably close to the machine model. The bare β beating is acceptable and has been corrected to excellent [5]. The availability of measurement and impressive analysis tools should be noted.
- The magnetic machine is well understood. The modelling of all magnet types by the FIDEL team has delivered an excellent field description at all energies [6]. This model includes persistent current effects which have been fully corrected throughout the cycle. A long and thorough magnet measurement and analysis campaign meant that the deployed settings produced a machine remarkable close to the untrimmed model.
- There is better than expected aperture due excellent alignment and respect of mechanical tolerances.
- The β^* reach has been established and exploited. Reduction has been pursued aggressively, exploiting: the better than specified available aperture; tight collimator settings; and very good stability and reproducibility.

The complex operational cycle is now well established and is robust.

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- The pre-cycle, injection process, 450 GeV machine, ramp, squeeze, and collide are largely sequencer driven. The sequence is generally reliable and good beam lifetime is maintained throughout the whole process.
- A strict pre-cycling regime means that the magnetic machine is remarkably reproducible. This is reflected in the optics, orbit, collimator set-up, tune and chromaticity. Importantly orbit stability (or the ability to consistently correct back to a reference) means that collimator set-up remains good for a year's run [7].
- The total intensity has reached 2.2×10^{14} i.e. 70% of nominal. Here a fully trustworthy machine protection system (detailed below) has been instrumental in providing the confidence to routinely deal with 140 MJ beams.

4. Availability and issues

Availability has, in general, been pretty good considering the size, complexity and operating principles of the LHC. Of note is the good availability of the critical LHC cryogenics system. Issues, outlined below, have seen vigorous follow-up and consolidation has been performed. A 257 day run included around 200 days dedicated to proton-proton physics. 36.5% of the time was spent in Stable Beams with an overall Hübner factor of around 0.18. This is encouraging for a machine only 3 years into its operational lifetime. There have inevitably been a number of issues arising during the exploitation of the LHC. A brief outline is provided below.

Initially single event effects (SEEs) caused by beam induced radiation to tunnel electronics was a serious cause of inefficiency. However this problem had been foreseen and its impact was considerably reduced following a sustained program of mitigation measures coordinated by the R2E (Radiation to Electronics) team [8]. There were several shielding campaigns prior to the 2011 run including relocations "on the fly" and equipment upgrades. The 2011/12 Christmas stop saw some "early" relocation and additional shielding and further equipment upgrades. This has resulted in the reduction of premature dumps from $\approx$12 per fb^{-1} to $\approx$3 per fb^{-1} in 2012, going a long way to helping the efficiency of integrated luminosity delivery.

UFOs (Unidentified Falling Objects) have now been well studied and simulated [9]. There were occasional dumps in 2012 following adjustment of BLM thresholds at the appropriate time-scales (the beam loss spike caused by a UFO is typically of order 200 μs). With the increase in energy to 6.5 TeV and the proposed move to 25 ns there is potentially serious problem with the UFOs become harder (energy) and potentially more frequent (25 ns). Investigations have continued and potentially encouraging results from the 2013 quench test program are noted.

Beam induced heating has been an issue and essentially all cases have been local and in some way due to non-conformities either in design or installation. The guilty parties have been clearly enumerated [10]. Design problems have affected the injection protection devices (TDI) and the mirror assemblies of the synchrotron radiation telescopes. Installation problem have occurred in a low number of vacuum assemblies.

Beam instabilities are an interesting problem that dogged operations through 2012. Although never debilitating there were times when they cut into operational efficiency. It should be noted that these problems paralleled a gentle push in bunch intensity with the peak going into stable beams reaching around 1.7×10^{11} protons per bunch i.e. ultimate bunch intensity. Cofactors included increased impedance from tight collimator settings; smaller than nominal emittance; and operation with low chromaticity during the first half of the run [11].

The final issue to be discussed here is that of electron cloud. Although this has not been a serious issue with the 50 ns beam, there are potential problems with the 25 ns foreseen for post LS1 operation. During the scrubbing run with 25 ns beams at 450 GeV between 6 and 9 December 2012, scrubbing effects in the arcs saw quite rapid initial conditioning. The secondary electron yield (SEY) evolution significantly slowed down during the last scrubbing fills and preliminary conclusions [12] are that an electron cloud free environment with 25 ns beam after scrubbing at 450 GeV seem not be reachable in a reasonable time. Operation with high heat load and electron cloud density (with blow-up) seems to be unavoidable with a corresponding slow intensity ramp-up.

5. Long shutdown 1 (LS1)

The primary aim of LS1 is the consolidation of the superconducting splices in the magnet interconnects following the incident of 2008. This will allow the current in the main dipole and quadrupole circuits to be increased to the 6.5 and then 7 TeV level. Besides this a huge amount of maintenance and other consolidation work is to be performed. Key LS1 work packages are outlined below.

- Measure all splices and repair the defective ones. Repeat for the 6 splices per interconnect (2 splices for the main dipoles and 4 for the 2 main quadrupole circuits). There are approximately 1700 interconnects in the machine. The interconnects will be consolidated with shunts and an insulation box.
- Finish installation of pressure release mechanisms on cryostats not yet so equipped
- Magnet consolidation: the exchange of weak cryo-magnets
- Consolidation of the current lead feed-boxes (DFBAs)
- Measures to further reduce SEE (R2E) via a combination of: equipment relocations at 4 LHC points; additional shielding; and critical system upgrades (QPS, FGC)
- Install collimators with integrated button BPMs (tertiary collimators and a few secondary collimators)
- Plus a lot of other maintenance work covering cryogenics, quench protection, electrical infrastructure, cooling and ventilation, radio frequency, beam dump absorber and magnet, change of dump switches (radiation), electron cloud mitigations

6. Post LS1

6.1 Energy

The magnets coming from the damaged sector 34 do not show degradation of performance, and the best estimates to train the LHC (with large errors) are: 30 quenches to reach 6.25 TeV; and 100 quenches to reach 6.5 TeV [13]. With two quenches/day this would mean between 2 to 5 days of training per sector. The proposed plan is to try to reach 6.5 TeV in four sectors in mid 2014. Based on that experience, the decision can then be made to go at 6.5 TeV or step back to 6.25 TeV.

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6.2 Beam from the injectors LS1 to LS2 and potential performance

50 ns proved a good choice in 2011 and 2012 opening the way to an increased number of bunches and the excellent performance in terms of emittance and bunch intensity. The best that was taken into collisions in 2012 was around 1.7 $\times 10^{11}$ protons per bunch with an emittance of around 2.5 μm going into collision. Further imaginative developments on the PS side have lead to the creation of the so-called BCMS (Batch Compression and (bunch) Merging and (bunch) Splittings) scheme [14] which offer remarkably low emittance coupled with healthy bunch intensity. The 25 ns BCMS option is at present offering nominal bunch intensity and a normalized emittance of 1.9 μm going into collision.

This scheme should open the way to well above nominal performance in the post LS1 era. Major upgrades of the injectors, including the increase of the Booster to PS transfer energy, and the connection of LINAC4 to the Booster will only take place during LS2. These upgrades should open the way towards ultimate LHC performance (i.e. peak luminosity of order 2.3×10^{34} cm^{-2}s^{-1}). LHC limitations could keep the luminosity below this value.

50 ns offers: lower total beam current; higher bunch intensity (at the cost of having to wrestle with beam instablities); and lower emittance. However the perhaps crippling cost at 6.5 TeV is the very high pile-up which will certainly required levelling to be operationally useful. On the other hand 25 ns has a number of negative points which include: more long range collisions: requiring a larger crossing angle and thus higher β^*; higher emittance; seriously more electron cloud with the need for scrubbing; higher UFO rate; higher injected bunch train intensity; and higher total beam current. The push will be to go for 25 ns to avoid the inefficiencies and cost of high pile-up.

The potential performance for the 25 ns BCMS option is shown in table 3. The estimate assumes: a beam energy of 6.5 TeV; a 1.1 ns bunch length (nominal); a scheduled 160 days of proton physics with a reasonable optimistic availability (Hübner factor $\approx$ 0.2); 85 mb visible cross-section. The 25 ns BCMS scheme gives a healthy 1.7×10^{34}cm^{-2}s^{-1} with peak <mu> of around 50 with 83% of the nominal intensity.

Table 3: Post LS1 performance estimates for a full year - usual caveats apply

Scheme	Number of bunches	Protons per bunch [10^{11}]	β_x^*[cm]/β_y^*[cm]/ half crossing angle [μrad]	Emittance [μm]	Peak luminosity	Pile-up	Int. lumi fb^{-1}
25 ns BCMS	2590	1.15	45/43/149	1.9	1.7e34	49	45

7. 10 year plan

An outline of the baseline 10 year plan is presented below. Some adjustments will surely be made over the coming years.

- **2015 - 2017** Physics operation, initially at 6.5 TeV. One might hope for a peak luminosity in the region of 1.7×10^{34} cm^{-2}s^{-1}. 2015 will be a re-commissioning year and will deliver less integrated luminosity than a nominal year at 6.5 TeV.

- **2018** Long shutdown 2 - here the main focus will the injector complex upgrade including connection of LINAC4 to the booster.
- **2019 - 2021** Given the increased performance of the injectors, it might possible to approach a luminosity of 2.0×10^{34} cm^{-2}s^{-1}.
- **2022 - 2023** Long shutdown 3: this is essentially for the HL-LHC upgrade and will include the installation of new inner triplet magnet assemblies.

8. HL-LHC

A very brief overview of the HL-LHC follows. For more details see [15, 16]. The project is based around an upgrade of the experiments' insertion regions. The upgrade will include the installation of wide aperture triplets allowing a reduction of β^* to around 15 cm. This will be combined with beam with high bunch population and low emittances, the demands for which place challenging demands on the injector complex where major upgrades are foreseen (Linac 4, Booster, PS and SPS).

The HL-LHC foresees the delivery of around 3000 fb^{-1} in the order of 10 years. High "virtual" luminosity with levelling is anticipated. The levelled luminosity is planned to be 5×10^{34} cm^{-2}s^{-1}. With good availability this should allow the delivery of around 250 fb^{-1} a year. The main features of the upgrade are listed below.

- Wide aperture niobium-tin (Nb_3Sn) quadrupoles will be used to replace the present inner triplet magnets.
- The wider aperture and revision of the insertion optics and layout will allow a squeeze to β^* of 15 cm.
- 11 T Nb_3Sn dipoles will be used to make room for collimators in the cold dispersion suppressors.
- Large aperture niobium-titanium (NbTi) separator magnets (the first twin aperture magnets moving away from the interaction point) are also required.
- Crab cavities will be employed to reduce the luminosity reduction caused by the large crossing angle.
- Enhanced collimation is required for the 500 MJ beams.

The key peformance parameters are shown in table 4. The project has been firmly established under leadership of Lucio Rossi and Oliver Brüning and now represents an international collaboration with a solid research and development program.

9. Beyond

A brief review of potential future circular colliders at CERN is given below. It should be noted that at present these must be regarded as options.

Large Hadron Electron Collider: LHeC Quoting from the LHeC's conceptual design report (CDR) [17]: "The LHeC is an electron-proton (ep) and electron-ion (eA) complement of the LHC, with which lepton-quark interactions can be explored at the TeV energy scale. In summer 2012

Table 4: Key HL-LHC performance parameters (25 ns beam)

Parameter	Value
Protons per bunch	2.2×10^{11}
Normalized emittance	2.5 mm.mrad
β^*	15 cm
Crossing angle	590 μrad
Geometrical reduction factor	0.305
Peak luminosity	7.3×10^{34} cm^{-2}s^{-1}
Virtual luminosity	24×10^{34} cm^{-2}s^{-1}
Levelled luminosity	5.0×10^{34} cm^{-2}s^{-1}
Levelled pile-up	140

an extensive report was published, in which a new electron beam accelerator was designed, as a ring mounted on top of the LHC (RR option) and as a multiple pass, energy recovery linac in a racetrack configuration (LR option). The LHeC is designed to run simultaneously with pp (or AA) collisions." The LHeC plans for 60 GeV electrons on 7 TeV protons.

High Energy LHC: HE-LHC The HE-LHC foresees re-equipping the existing LHC tunnel with high field (20 T) magnets. It is envisaged that these magnets will combine high temperature superconductor (HTS), Nb_3Sn and NbTi. It should be noted that intense R&D will be required to approach these field levels. The key performance parameters are shown in table 5.

Table 5: Key HE-LHC performance parameters

Parameter	Value
Circumference	26.7 km
Maximum dipole field	20 T
Injection energy from superconducting SPS	1.3 TeV
Maximum c.o.m. energy	33 T
Peak luminosity	5×10^{34} cm^{-2}s^{-1}

Very High Energy LHC: VHE-LHC Very early sketches are in place for a 80 to 100 km ring which could house the VHE-LHC. The VHE-LHC foresees the use of very high field magnets which would allow a maximum beam energy of 50 TeV. The key performance parameters are shown in table 6.

Among the many challenges such a project would face are: a significant synchrotron radiation heat load; collimation of very high stored beam energy; design of insertion region quadrupoles; and design of arc quadrupoles.

To avoid the need for a high energy injector, injection could be achieved from a low energy ring in the same tunnel (the so-called VHE-LHC-LER). Initial studies suggest the use of the “Pipetron" concept using transmission line magnets [18]. This solution could be relatively cheap and, via the use of HTS, require limited cryogenic power. The magnet field swing to bring the beams from 450 GeV to 4.1 TeV would be something like 0.167 to 1.5 T.

Table 6: Key VHE-LHC performance parameters

Parameter	Value
Circumference	80 to 100 km km
Maximum dipole field	20 to 16 T
Injection energy from sperconducting SPS	> 3 TeV
Maximum c.o.m. energy	100 TeV
Peak luminosity	5×10^{34} cm^{-2}s^{-1}
Stored beam energy	5500 MJ

The LER would also be suitable for electrons-positrons opening the way for possible synergy with very large electron-positron collider.

TLEP The TLEP project envisages a circular electron-positron collider in a new 80 to 100 km tunnel [19]. A storage ring would have separate beam pipes for electrons and positrons for multi-bunch operation up to 350 GeV c.o.m. Top-up injection would take place from an ancillary accelerator (potentially the LER described above). The concept foresees very high luminosity at Z pole and above WW threshold with operation up to t-t threshold. The essential synergy would be to use the same tunnel as that proposed for the VHE-LHC before installation of said.

Future Circular Colliders A design study team has been set up during 2013. Pre-studies have been launched for hadron colliders (VHE-LHC/HE-LHC), lepton colliders (TLEP) and hadron-lepton colliders (VHE-LHeC). Studies and R&D for high field magnets as well as high-gradient and high beam power superconducting RF cavities for the HL-LHC, HE-LHC, VHE- LHC (and TLEP) will enhance common efforts and exploit synergies.

10. Conclusions

There has been reasonably good performance from commissioning through run I. After a lengthy false start, it took 2 years 3 months from first collisions to the announcement of the Higgs discovery The foundations have been firmly laid for run II. The LHC carries forward a wealth of experience from operation at 3.5 and 4 TeV, and is anticipating operation at 6.5 TeV in 2015 following a two year shutdown. There are potential issues. Measures to address and mitigate these are under examination.

The HL-LHC project is well established and is seen as the way to fully exploit the LHC's significant potential. Beyond this, several options are under investigation. One (the LHeC) has already a CDR in place. A formal study process is being prepared for the other, longer term, options.

11. Acknowledgements

The LHC is enjoying benefits of the decades long international design, construction, installation effort. Progress with beam represents phenomenal effort by all the teams involved.

References

[1] J. Jowett et al, First run of the LHC as a heavy-ion collider, CERN-ATS-2011-143.

[2] H. Burkhardt et al, Commissioning and operation at beta* = 1000 m in the LHC, IPAC13, Shanghai, 2013.

[3] J. Jowett et al, Proton-nucleus collisions in the LHC, these proceedings.

[4] M. Kuhn et al, Investigations of the LHC Emittance Blow-up during the 2012 Proton Run, IPAC13, Shanghai, 2013.

[5] P.K. Skowronski, Optics performance of the LHC during the 2012 run, IPAC13, Shanghai, 2013.

[6] E. Todesco et al, The Magnetic Field Model of the Large Hadron Collider: Overview of Operation at 3.5 and 4 TeV, proceedings of IPAC2012, New Orleans, LA, USA, May 2012.

[7] B. Salvachua, Cleaning performance of the LHC collimation system up to 4 TeV, IPAC13, Shanghai, 2013.

[8] G. Spiezia, R2E Experience and Outlook, proceedings of LHC Beam Operation workshop Evian 2012.

[9] T. Baer, UFOs, proceedings of LHC Beam Operation workshop Evian 2012.

[10] B. Salvant et al, Update on beam induced RF heating in the LHC, IPAC13, Shanghai, 2013.

[11] E. Metral, Review of the instabilities observed during the 2012 run and actions taken, proceedings of LHC Beam Operation workshop Evian 2012.

[12] G. Iadarola et al, Electron cloud and scrubbing studies for the LHC, IPAC13, Shanghai, 2013.

[13] E. Todesco, What is the maximum reasonable energy?, Proceedings of Chamonix 2012 workshop on LHC performance, CERN-ATS-2012-069.

[14] R. Steerenberg, Post LS1 25 ns and 50 ns options from the injectors, Proceedings of the LHC Beam Operation workshop - Evian 2012.

[15] http://cern.ch/HiLumiLHC/index.html

[16] F. Bordry, Research on high-field superconducting magnets and prospects for higher-energy hadron colliders, these proceedings.

[17] O. Bruning, M. Klein The Large Hadron Electron Collider, LHeC-Note-2013-001 GEN, Geneva, May 9, 2013.

[18] G. W. Foster, The Pipetron a Low-Field Approach to a Very Large Hadron Collider, Snowmass ’96.

[19] Katsunobu Oide, The Circular Road to a Higgs Factory and Beyond, these proceedings.