STRATEGY AND ISSUES FOR THE LHC UPGRADES AND FAIR, INCLUDING LONGER-TERM PROSPECTS

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Abstract:

This report discusses the time line, goals and key ingredients for the next ten years of LHC operation, including injector upgrade, for the following High Luminosity LHC (HL-LHC), and for the FAIR project. Results from pertinent EuCARD-WP4 workshops on optics, space charge, crab cavities, crystal collimation, and electron cloud are summarized in this context.

A Large Hadron electron Collider, LHeC, would be an additional upgrade, further expanding the physics scope of the LHC, to eventually include both *ep* and γγ Higgs factories (LHeC-HF and SAPPHiRE). Results from relevant topical WP4 workshops are highlighted.

The development of magnet and cable technology based on Nb_3Sn, and *HTS*, for the HL-LHC prepares the ground for a future higher-energy hadron collider, either in the LHC tunnel, “HE-LHC” (33 TeV c.m.), or in a new 80- or 100-km tunnel, “VHE-LHC” (100 TeV c.m.). A large new tunnel could also host an ultimate highest-precision e^+e^- Higgs factory collider, “TLEP,” exhibiting many synergies and sharing components with VHE-LHC and LHeC/SAPPHiRE. As a possible back-up option, “LEP3” would be an e^+e^- Higgs factory in the LHC tunnel. WP4 AccNet organized the first ever workshops on HE-LHC, VHE-LHC, LEP3, TLEP, and SAPPHiRE, respectively.

FAIR is advancing the development of fast cycling superconducting magnets. Such magnets, as well as alternative designs based on the transmission-line concept, are of interest for the injector ring of the VHE-LHC or HE-LHC.

Putting the various elements together, EuCARD-AccNet has developed a coherent vision for future accelerator-based high-energy physics in form of a sequence of circular high-performance colliders leading up to the 100-TeV energy scale and extending over most of the 21st century.

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1. EXECUTIVE SUMMARY

WP4.2 AccNet-EuroLumi supported the development of SC magnets, crab cavities, and crystal collimators for the HL-LHC, and it catalysed new European as well as international collaborations, including on topics of joint interest with FAIR. WP4.2 AccNet-EuroLumi also initiated and organized a series of targeted mini-workshops exploring possible collider options beyond the LHC, notably HE-LHC, VHE-LHC, LEP3, TLEP, and SAPPHiRE. The result is a coherent synergetic strategy proposed for future accelerator-based high-energy physics consisting of a series of circular high-performance colliders, leading up to the 100-TeV energy scale and supporting an energy-frontier physics programme for the coming 80 or more years.

Over the next 10 years LHC operation will be ramped up to ultimate performance and close to nominal energy. Reaching the nominal beam parameters with 25-ns bunch spacing requires suppressing the electron-cloud build up either by continued surface conditioning ("scrubbing" – the present baseline) or, if needed, by more aggressive means.

An upgrade of the LHC injector complex is scheduled for about 2018. It will overcome present limitations due to space-charge effects in the injector chain.

An excellent optics control is one of the keys for the success of both this and the following stages of the LHC.

The LHC luminosity upgrade "HL-LHC," is planned for around 2022, which comprises larger-aperture final-triplet quadrupoles made from Nb_3Sn*, a few high-field dipole magnets in the dispersion suppressors, crab cavities, superconducting links, improved detectors capable of handling higher event pile up, a new "achromatic telescopic squeeze" optics, and as a fundamental feature – luminosity levelling. In addition, hollow electron lenses, coherent electron cooling, or crystal collimators can further improve the HL-LHC performance.*

A Large Hadron electron Collider, LHeC, can be realized by adding a 9-km long recirculating electron linac to the LHC. The LHeC would further expand the physics output of the LHC. A high-luminosity version of the LHeC would render this machine an interesting ep Higgs factory. The LHeC can also be reconfigured as a $\gamma\gamma$ *Higgs factory, by accelerating electrons in both directions with a collision point at the centre of the highest-energy arc. The required high repetition-rate high-power laser system is expected to soon be available.*

As an essential part of the proposed strategy, the development of new Nb_3Sn*, magnets together with superconducting links for the HL-LHC will provide the technology required for a higher-energy hadron collider, either in the LHC tunnel, called HE-LHC (33 TeV c.m..) or in a new 80- or 100-km tunnel, called VHE-LHC (100 TeV c.m.). A large new 80-100 km tunnel could also host an ultimate highest-precision e+e- Higgs factory collide "TLEP". TLEP might share the magnets, cryo-plants and parts of the particle-physics detectors with the VHE-LHC, and the (identical) RF system with LHeC. The construction of a SC RF test facility at CERN will boost the technology base for LHeC, LHeC-HF, SAPPHiRE and TLEP.*

FAIR and GSI are pushing the development of fast cycling superconducting magnets, as well as many other technologies of relevance for future higher-energy hadron colliders, e.g. remote handling, cryogenic collimators, advanced cooling, and dynamic vacuum issues. FAIR-type fast ramping SC magnets, or alternative designs based on the transmission-line concept, will be needed for the injector ring of the VHE-LHC or HE-LHC.

2. INTRODUCTION

FP7 EuCARD WP4.2 “AccNet-Eurolumi” was a network activity running for 51 months, from 1 April 2009 to 31 July 2013. Building on the success of the earlier FP6-CARE-HHH network, AccNet-EuroLumi quickly became the international platform where accelerator scientists discussed hadron machine performance, upgrades, and future colliders/accelerators – in particular Higgs factories – beyond the LHC and FAIR, in efficient topical mini-workshops attracting many of the best experts.

WP4.2 also supported short-term exchanges of renowned specialists between institutes. An impressive result is the 78 documents published by WP4.2, which are listed in Chapter 12. However, the primary “tool” of the network was the organization of, or contribution to, workshops.

A total of 27 workshops and mini-workshops were held in the frame of EuroLumi. A full list including dates, topics, number of participants, location, and “activity index” is given in Chapter 11.

Workshops were organized either by EuroLumi alone or in collaboration with EU and non-EU partners wherever relevant. Important EuroLumi partners from outside Europe were the consortium of US national accelerator laboratories US-LARP, the KEK accelerator laboratory and Hiroshima University in Japan, and the Mexican CINVESTAV. Topical EuroLumi workshops typically aimed at assembling 30 to 40 world experts for brainstorming on advanced topics. In most cases, the attendance exceeded this goal, demonstrating the added value of this format of networking. In all workshops, the fraction of participants originating from outside EuCARD was significant, typically 25%, sometimes above 50%. Events were often organized at CERN in view of its numerous facilities, lower costs and easy air flight connections to most world destinations, and since the main topic of EuroLumi – the LHC upgrade – was directly linked to CERN.

Topics of the EuroLumi workshops included HL-LHC crab cavities, electron-cloud mitigation, electron-cloud modelling and diagnostics, crystal collimation, beam-driven plasma acceleration, accelerator simulations, LHC & HL-LHC optics measurements and corrections, modelling and mitigation of space-charge effects, and the designs of the High-Luminosity LHC, High-Energy LHC, Very High Energy LHC, circular e^+e^- Higgs factories (LEP3 and TLEP), as well as $\gamma\gamma$ Higgs factories (SAPPHiRE based on LHeC).

The sum of the EuroLumi workshops delivered a coherent long-term vision for HEP accelerators, aimed at ultimate-precision tests of the standard model and searches for New Physics at the highest collision energies attainable with near-term technologies. EuroLumi workshops also prepared the ground for the wider use of crystals and plasmas in accelerators.

References:

- List of EuCARD-AccNet Workshops
- List of EuCARD-AccNet papers and presentations

3. LHC UNTIL 2022

3.1. TOWARDS ULTIMATE PERFORMANCE

In 2011-12 the LHC has delivered about 30 fb^{-1} in *pp* luminosity to each of the two high-luminosity experiments, ATLAS and CMS, at a beam energy of 3.5 (2011) and 4 TeV (2012). In 2015, after the first long shutdown (LS1), including a magnet-interconnect splice consolidation, the beam energy will be raised to about 6.5 TeV (limited by the expected re-training of magnets), while the bunch spacing will be reduced from 50 ns to the nominal value of 25 ns, and LHC will run for about 3 years in luminosity production. Around 2018, in long shutdown no. 2 (LS2), the injector complex will be upgraded, which will make a higher-brightness beam available for the LHC, and will certainly allow surpassing the "ultimate" luminosity of 1.7×10^{34} $cm^{-2}s^{-1}$, if this will not have happened already before. By 2021 the LHC will have delivered about 400 fb^{-1} to ATLAS and to CMS, and this will be the right time for a larger upgrade, namely the HL-LHC.

Two of the key elements for past and future LHC performance are optics control and electron-cloud mitigation. Both of these have been explored in several dedicated EuCARD-WP4 workshops, with some primary results reported below.

3.1.1. Optics

Excellent beam-optics control has been one of the foundations for the outstanding LHC performance in 2010-13. An example is shown in Fig. 1. In 2011 the reproducibility of the measured β function after the β* squeeze was better than the measurement error.

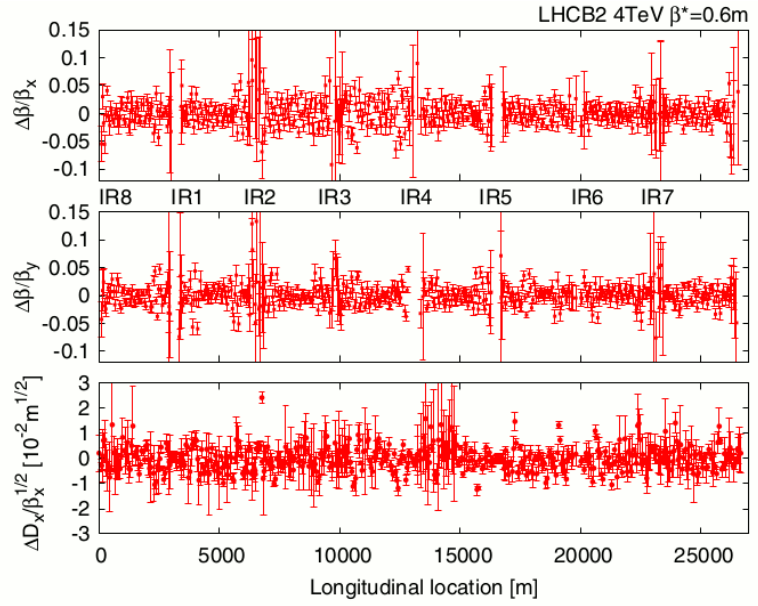

Figure 1: Measured beta-beating & normalized dispersion beating for LHC beam 2 after global correction at β* = 0.6 m, in 2012 [R. Tomas et al, Phys. Rev. ST Accel. Beams 15, 091001 (2012)]

A first EuroLumi workshop on Optics Measurement, Corrections and Modelling in High Performance Rings (OMCM) was organized from 20 to 22 June 2011. The workshop scope, though targeted at the LHC, included the experience from light sources and lepton colliders and had an international reach. Two years later, on 17-18 June 2013, a more targeted review of LHC Optics Measurement and Corrections (OMC) reviewed the status and progress on all fronts to ensure the high resolution measurement and correction in view of the LHC start up after the Long Shutdown 1 (LS1) in 2015 and looking further ahead at HL-LHC requirements. In 2015 the LHC will resume operation with increased collision energy, around 13 TeV c.m., and new operational scenarios galore. At the higher beam energy of 6.5 TeV increased snapback and larger saturation effects are expected. Optics measurement and corrections will be challenged by planned new dynamic beam processes such as “combined energy ramp & squeeze”, “combined collide & squeeze” and “beta* levelling”. Furthermore the correction accuracy and the measurement resolution will continue to be stressed by the desired precise emittance measurements and by the particle detector requirements. In 2015, beta* levelling may be tested in normal operation, at a single IP at first. Many different configurations are required for the LHC physics programme, including Van der Meer scans at different values of beta*. New algorithms for automatic local corrections will support rapid optics changes.

There is a need for highly accurate optics measurements in order to more precisely determine the beam emittance. Specifically, a resolution of 3.5% in the beta functions is requested. This is a factor 2-3 better than what was achieved in 2012 for the wire scanners and other elements in regular locations, reflecting the uncertainty from interpolation to a particular element when propagating the measured error bars from the beam position monitors (BPMs) to the location in question. The requested better resolution is particularly important in view of an apparent 40% emittance growth observed during the 2012 LHC run, possibly arising during the energy ramp. Also for the beta* a resolution of 3.5% would be desirable, though even more difficult, with errors so far at the 10-20% level.

Improved optics measurements will be achieved with the help of various instrument upgrades, such as longer AC dipole excitations, longer BPM acquisitions, new BPMs with improved resolution and including correction of BPM non-linear aberrations. The requested 3.5% resolution then does not seem out of reach with a proposed modified algorithm to measure the beta functions from the phase advances between 7 BPMs. Automatic correction of coupling seems possible at all energies by using the new higher-resolution BPMs. The correction of chromatic coupling was demonstrated experimentally already, and it should be used routinely from 2015 onward. Various correction strategies exist for the dispersion. The target value for the spurious dispersion in 2015 is still being discussed.

A first measurement of amplitude detuning by means of the AC dipoles was successful. This technique will be used operationally from 2015 onward in order to avoid any unwanted values of amplitude detuning, addressing a concern from the 2012 run. Namely, in 2012 during half of the year, the amplitude detuning for LHC beam 2 at injection had been twice as large as expected and then, during the other half of the year, unexpectedly small – about zero.

In 2014-15 sector tests will be performed prior to circulating beam in the LHC. Following this a two months period is allocated for commissioning with circulating beam.

Another optics measurement and corrections workshop is planned towards the end of 2015, possibly in the frame of EuCARD-2, to review the achievements at the higher beam energy and to assess the possible problems and limitations, especially in view of the HL-LHC.

Looking further ahead, in the longer term the improvements in the resolution of the beam position monitors will allow for weak and safe betatron excitation. The AC dipole operation in this regime will not pose any threat for machine protection, enabling its more flexible deployment, including long excitation periods for on-line monitoring and improved resolution. This will allow for frequent optics measurements and corrections during normal operation which should lead to a new level of unprecedented optics control in hadron colliders. Future colliders like HL-LHC, VHE-LHC or even TLEP should take this into account during the design phase by targeting a very accurate optics (a few per cent beta-beating) so as to maximize the design luminosity, and, in the case of TLEP, to minimize the vertical emittance, and also by incorporating in the design all the required correction knobs to allow for efficient local corrections.

References:

- EuCARD-AccNet Workshop on Optics Measurement, Correction & Modelling "OMCM", CERN, 20-21 June 2011
- R. Bartolini, O. Bruning, R. Calaga, D. Einfeld, M. Giovannozzi, J.-P. Koutchouk, C. Milardi, J. Safranek, R. Tomas, J. Wenninger, F. Zimmermann, Summary of the AccNet EuCARD Workshop on Optics Measurements, Corrections and Modelling for High-Performance Storage Rings "OMCM," CERN, Geneva 20-22 June 2011, EuCARD-CON-2012-004
- EuCARD-AccNet co-organized LHC Optics Measurement and Corrections Review, CERN, 17-18 June 2013
- O. Brüning et al, Summary of the 2013 LHC Optics Measurement and Correction Review, EuCARD-REP-2013-003

3.1.2. Electron cloud

Under the auspices of EuCARD-WP4-AccNet a strong synergy between space-charge studies and electron-cloud studies was realized and exploited.

The joint GSI-CERN EuCARD-WP4 workshop on electron-cloud effects highlighted the possibility of utilizing the synchrotron phase shift resulting from the energy loss of proton bunches to the electron cloud as a diagnostics tool for the integrated electron-cloud density and its build up along bunch trains, with first experimental results presented from the LHC. Various items for future collaborative studies were identified, including simulating long-term behavior of the beam under the action of an electron cloud; 3D self-consistent calculation of single-bunch electron-cloud wake fields, in particular quantifying the energy loss, and studying the influence of the electron magnetic field on the transverse wake; electron-cloud build-up simulations with the CERN ECLOUD code, in particular for the LHC warm-warm transitions with the present pressure-rise data, and benchmarking with a GSI code for SIS18 bunches; the effect of a wide-band transverse feedback; an exploration of coupled-bunch higher-order head-tail wakes and the resulting instability rise times; specific studies on electron-cloud fluctuations; the question of primary (ionization) electrons generated outside the beam and the emergence of electron stripes at high magnetic field; scrubbing optimization or artificial graphitization; benchmarking of the measured synchronous phase shift with cryogenic heat load and simulations; open questions pertaining to α-C coating of the SPS (little effect on vacuum pressure rise, and aging); and the role and parameterization of re-diffused secondary electrons.

Collaborations with the European Space Agency and its partners were intensified at the EuCARD-AccNet workshop AEC'09 and at the EuCARD co-sponsored MulCoPim2011. Joint efforts focused on electron-mitigation studies (e.g. advanced coatings, magnetized surfaces) and on simulation-code developments (e.g .modelling the effect of microwaves on the accelerator electron cloud).

The interplay of space charge with machine nonlinear magnets is an important topic for beam survival over long-term storage in FAIR. In joint CERN-GSI studies it was recognized that, with regard to incoherent effects, for the LHC and the SPS as LHC injector the electron cloud plays a similar role as the beam space charge does in FAIR, the PS and the PS Booster.

In particular for the electron cloud the effect of the pinch inside magnets is relevant. The electron pinch in field-free regions and dipole fields was studied for several years. A more recent investigation investigated the pinch effect in a quadrupole field, especially when the closed orbit is shifted, which represents a new level of beam modeling. Figure 2 shows the effect of the closed orbit distortion (right) with respect to the case of a corrected COD (left).

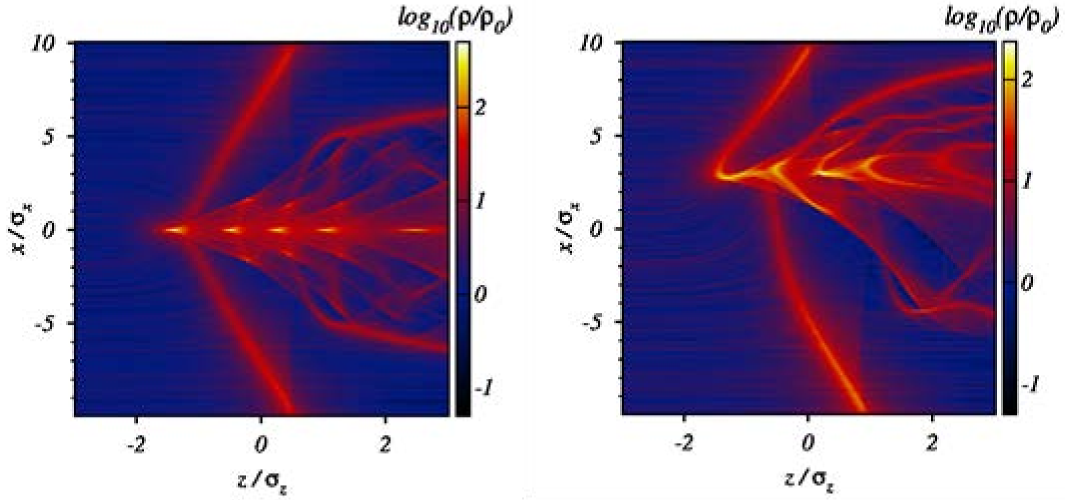

Figure 2: Electron pinch during a bunch passage inside a quadrupole field for a perfect central orbit (left) and in the presence of a closed orbit distortion (right). The left picture shows the electron density enhancement for an LHC proton bunch traversing an electron cloud localized inside a quadrupole. The colour code represents the logarithmic relative electron density as seen from the proton bunch reference frame. The dynamics of the electrons yields a complex electron density pattern responsible for incoherent effects experience by the proton bunch. The right picture on the right shows the same bunch passing now off center through the quadrupole at $x=3\sigma_r$, y=0. The electron pinch is affected by the quadrupolar forces, which are no longer centred on the bunch longitudinal axis. The resulting pinch is a distorted version of the left picture. Note that the pinch calculation starts at $-3\sigma_r$. The structure of the pinch is now asymmetric with respect to the bunch center. The resulting incoherent effects experienced by the proton beam is more difficult to predict.

Complex electron dynamics lies at the base of anomalous LHC performances, and adequate modelling, measurements and mitigation of these effects is the cornerstone for high luminosity performance of LHC after LS1. The assessment of this pinch effect was subject of many studies and was implemented in a model for LHC (presented at the EuCARD-WP4 workshop ECLOUD12 and at the special EuCARD-AccNet session of ICAP12. The complexity of the nonlinear detuning created by the pinched electrons remains difficult to assess with regard to long-term effects. In particular the phenomenon of resonance crossing is of crucial importance. The regime of non-adiabatic resonance crossing was studied in the context of the pinched electron cloud. A simplified mathematical model, developed in the frame of AccNet, has allowed substantial progress in the fundamental understanding of the trapping process. In particular, the usual nonlinear dynamics concepts of fix points and trapping, traditionally invoked for adiabatic processes, was extended to general non-adiabatic resonance crossing. This study has laid the foundations for future studies exploiting analytically derived and numerically demonstrated scaling laws. A primary conclusion of the pertinent WP4 studies is that understanding and controlling the incoherent effect of the electron cloud requires continued modeling effort and further targeted benchmarking between simulations and measurements.

The baseline scenario with-25 ns operation in the LHC after LS1 may still face some difficulties related to electron cloud if the latter cannot be fully eliminated by conditioning.

A likely obstacle could be yet unpredicted (e.g. incoherent) electron-cloud effects, which may occur even if the planned “scrubbing runs” reduces the secondary emission yield and suppresses beam-induced electron multipacting, given that the production rate of photo-electrons alone is not insignificant at 6.5 or 7 TeV. A strategic preparation of future experimental studies appears essential for successfully mastering the electron cloud at 7 TeV beam energy with 25-ns bunch spacing in the LHC.

Residual electron cloud activity may be correlated with the occurrence of unidentified falling objects (UFOs), inducing local beam losses, and occasionally triggering a beam dump. Like the severity of the electron cloud, also the rate of such UFOs is empirically expected to increase at higher beam energy and at shorter bunch spacing (see below).

For future machines, the use of metallic foams has been proposed as an interesting new concept to improve the vacuum conditions and to suppress the electron cloud.

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- O. Dominguez, F. Zimmermann, Electron-Cloud Maps for the LHC Scrubbing Optimization, Proc. IPAC'13 Shanghai, 12-17 May 2013, EuCARD-CON-2013-011

3.1.3. UFOS

About 20 beam dumps each, in 2011 and 2012, were caused by so-called UFOs, presumably macroparticles (“dust”) falling into the beam from the top of the beam pipe, and causing a local beam loss. The events occur on a fast time scale, ranging from 50-200 μs to 1-2 ms. Many more UFO events were observed below the dump threshold. A conditioning during the year was observed, with about 20 UFOs events per hour in physics seen at the start of 2011, and only about 2 per hour at the end of the year. However, there also was some deconditioning during the Christmas shutdown 2011/12.

About 10 times higher UFO rate was seen after switching from 50 ns to 25 ns operation for a few days at the end of 2012, which is a concern with regard to possible 25-ns operation in 2015. The strong sensitivity to the bunch spacing could indicate that the electron cloud plays a role in triggering the UFOs event, e.g. by charging up the macroparticles.

Another concern arises from the higher beam energy, which in 2015 will be 6.5 and ultimately 7 TeV instead of 4 TeV. This higher energy implies a 4 times higher energy peak deposition, and a 5 times reduced quench margin. On the positive side, beam quench tests at the end of the 2012/13 LHC run indicated a factor 3 margin in the beam dump threshold for the relevant time scale, which will be made use of in 2015. An additional mitigation measure consists in a more uniform deployment of beam-loss monitors along the arc cells, rather than concentrating them at the quadrupole magnets. This will allow a further relaxation of the beam-dump threshold. It is hoped that with these countermeasures the beam-dump rate due to UFOs at the higher beam energy and shorter bunch spacing will stay comparable to the dump rates from 2011 and 2012.

References:

- T. Baer et al, UFOs in the LHC: Observations, Studies and Extrapolations, IPAC'12 New Orleans
- F. Zimmermann, LHC Status & Plan, LAL Orsay, 28 June 2013, EuCARD-PRE-2013-008

3.1.4. Radiation to Electronics

Certain electronics in the tunnel is sensitive to radiation induced by halo beam particles interacting with the LHC collimators or arising from the collision debris. Resulting single-event upsets are the biggest concern. A concerted program of mitigation measures (shielding, relocation…) has been put in place. Actions taken so far have reduced the premature dump rate down from 12/fb^{-1} in 2011 to 3/fb^{-1} in 2012. Further activities are underway to cope with higher beam energy and higher luminosity in 2015-17. For the HL-LHC a "SC link" (see below) will allow relocating the power converters at a safe distance.

References:

- M. Brugger, Radiation Damage to Electronics at the LHC, IPAC'12 New Orleans
- F. Zimmermann, LHC Status & Plan, LAL Orsay, 28 June 2013, EuCARD-PRE-2013-008

3.1.5. New Beam Production Scheme & 2015 Luminosity Forecast

In the second half of 2012 a new beam production scheme was developed in the LHC injector complex, the so-called BCMS (= Batch Compression and Merging and Splitting). Here batches are at first compressed, and then two bunches from the booster are merged into one, following which the standard LHC bunch production scheme with bunch tripling and double splitting is applied. The result is up to two times higher brightness than considered in the LHC design, at 25 ns bunch spacing, limited primarily by space charge in the booster, but with a smaller number of bunch per batch (i.e. bunch train).

For the 2015-17 run, the low-emittance beam available with this scheme could be used to achieve the luminosity performance projected in Table 1, at a beam energy of 6.5 TeV (dictated by magnet retraining), with a bunch spacing of 25 ns. Pile-up considerations are relevant. The injectors are potentially able to offer nominal intensity with even lower emittance. The maximum luminosity is expected to be limited by the inner triplet heat load from collision debris at about 1.7×10^{34} cm^{-2}s^{-1}±20%. Table 1 shows possible parameters.

Table 1: Luminosity projection for 2015 LHC run with BMCS low-emittance beam at 25 ns bunch spacing and with a beam energy of 6.5 TeV.

Bunch spacing	Number of bunches	N_b LHC FT[1e11]	Emit LHC [μm]	Peak Lumi [cm^{-2}s^{-1}]	Event pile-up	Int. Lumi per year [fb^{-1}]
25 ns	2520	1.15	1.9	**$1.7\text{x}10^{34}$**	52	~45

References:

- M. Lamont, The First Years of LHC Operation for Luminosity Production, IPAC'13 Shanghai (slides)
- EuCARD-AccNet co-organized workshop SPACE CHARGE 2013, CERN, 16-19 April 2013 (in particular talks by S. Gilardoni and G. Rumolo)

3.2. INJECTOR UPGRADE

3.2.1. Linac4

The new Linac4 is under construction and commissioning at CERN. It will accelerate H^- ions to 160 MeV, replacing the existing 50-MeV proton linac. The Linac4 could double the beam brightness injected into the booster, for equal space-charge tune shift. In addition, the charge exchange injection with H^- beam will allow for greater flexibility with the injection scheme and possibly higher brightness, than with the present proton injection. It also means that the connection of Linac4 will require substantial changes for the PS booster injection region, and cannot easily be reversed. The Lianc4 may become operational in 2015, but, except for an emergency (e.g. a problem in Linac2), it will only be connected during the long Shutdown 2, scheduled for 2018. To profit from the higher brightness available other bottlenecks, e.g. at injection from the booster into the PS also need to be addressed.

References:

- EuCARD-AccNet co-organized workshop SPACE CHARGE 2013, CERN, 16-19 April 2013 (in particular talks by S. Gilardoni and G. Rumolo)

3.2.2. PS Booster & SPS

To remove the second space-charge bottleneck, namely at injection into the PS, the transfer energy from the PS booster will be increased from 1.4 to 2 GeV, gaining about a factor two with regard to brightness. This change, also scheduled for the LS2, will enable the full exploitation of the higher brightness provided by Linac4. Remarkably this will be the third time that the extraction energy of the PS booster will be upgraded, with earlier upgrades having raised the extraction energy from 800 MeV to 1 GeV, and from 1 to 1.4 GeV, respectively. The pioneers building the PS booster had left sufficient margin in the magnet design. The expensive part of the upgrade will be the new power converter. The SPS will also need to be improved, including an upgrade of the 200-MHz RF system, impedance reduction, and possibly electron-cloud mitigation (e.g. carbon coating, wideband feedback, etc.).

References:

- EuCARD-AccNet co-organized workshop SPACE CHARGE 2013, CERN, 16-19 April 2013 (in particular talks by S. Gilardoni and G. Rumolo)

4. HL-LHC

4.1. MOTIVATION & SCOPE

At an integrated luminosity around 400/fb, forecast for about 2021, the low-beta quadrupoles around the LHC Points 1 and 5 are expected to be damaged by radiation so that they need to be replaced. This “opportunity” will be used to replace these quadrupoles by better-performing new ones, which together with a series of complementary improvements, and also profiting from the higher brightness of the injector complex upgraded earlier, will significantly boost the LHC luminosity performance to a “virtual” level that is more than 20 times higher than the original design value. This performance improvement will greatly extend the discovery reach of the LHC, and will be needed to reduce the statistical errors, and e.g. to measure the self-coupling of the Higgs boson. The experiments will also be upgraded to “cope” with higher luminosity. However, they will be limited to a maximum event pile up (i.e. number of events per bunch crossing) of at most 200 with luminosity decay. Since the potential luminosity of the HL-LHC could provide more than 400 events per crossing, luminosity levelling will be mandatory. The HL-LHC design aims at a constant luminosity of 5x10^{34} $cm^{-2}s^{-1}$ at a bunch spacing of 25 ns, which would correspond to about 140 events per crossing. Figures 3 and 4 illustrate the scope of the HL-LHC upgrade.

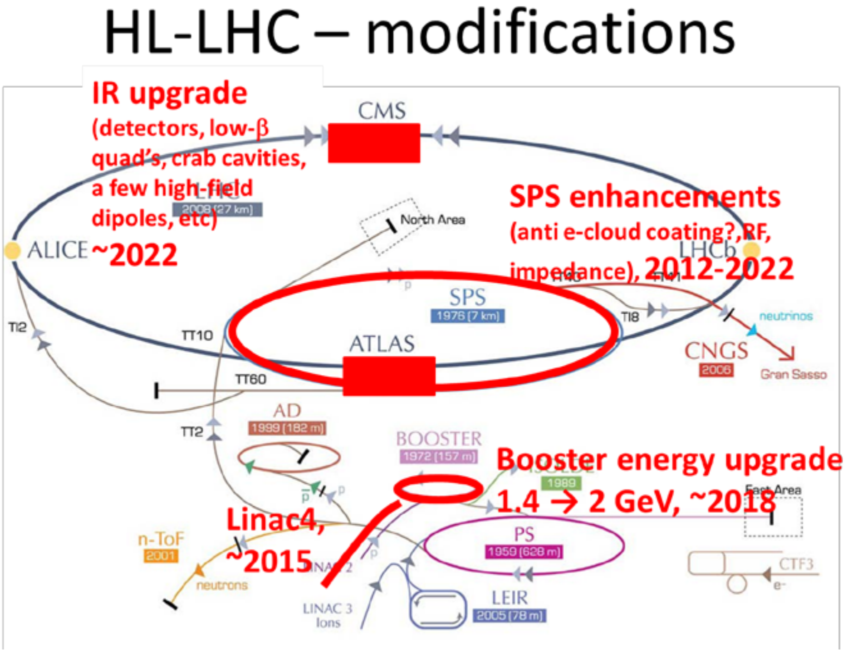


Figure 3: LHC-complex upgrades for the HL-LHC. In addition to the new Linac4, energy upgrade of the PS Booster, and SPS enhancements, all foreseen for LS2 (2018), the HL-LHC in 2022 entails major upgrades of the interaction regions (new final quadrupoles, crab cavities, high-field dipoles) at the high-luminosity insertions as well as upgraded detectors.

References:

- EuCARD’13 Final Annual Workshop “Visions for the Future of Particle Accelerators, CERN, 10-14 June 2013 (in particular the talk by L. Rossi).

- F. Zimmermann, O. Brüning, Parameter Space for the LHC Luminosity Upgrade, Proc. IPAC'12 New Orleans, 20-25 May 2012, p. 127, EuCARD-CON-2012-009

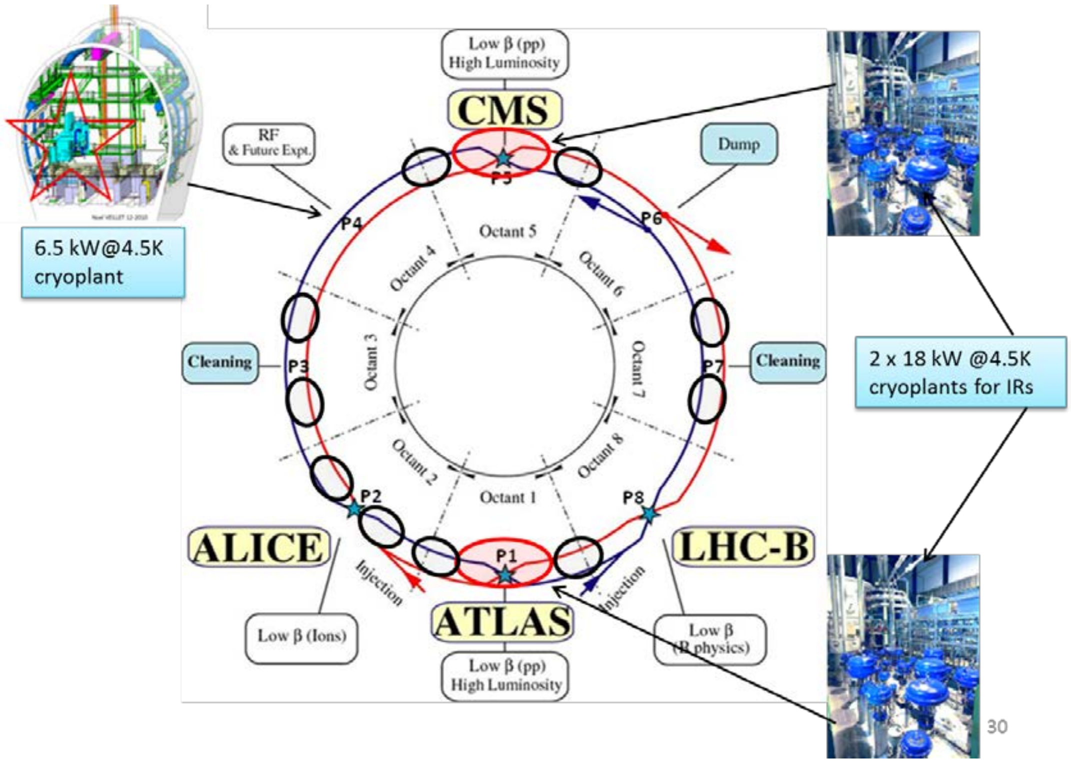


Figure 4: Schematic of HL-LHC modifications in the LHC ring proper [L. Rossi]. In total there will be 1.2 km of new equipment. The RF in Point 4 and the high-luminosity interaction region will be cooled by new separate independent cryoplants, which will provide the maximum cooling capacity for electron cloud in the adjacent arc sectors. Larger-aperture Nb_3Sn quadrupoles will be installed in IPs 1 and 5. Shorter high-field Nb_3Sn dipole magnet will replace a few existing *Nb-Ti* dipoles in the dispersion suppressors of IPs 1 (ATLAS), 2 (ALICE) and 5 (CMS) and around the cleaning insertions of Points 3 and 7 so as to free space for new collimators capturing off-energy particles originating from the collision points or from the main collimators.

4.2. INGREDIENTS

The new final-triplet quadrupoles will be based on a different superconductor, Nb_3Sn instead of *Nb-Ti*, and with larger aperture, allowing for a better performance, specifically for a smaller β^* at the collisions points. The new quadrupoles need to accompanied by novel crab cavities to fully benefit from a reduced IP beta function. Other expected bottlenecks will be addressed with a few additional stronger dipole magnets, replacing existing ones, to make space for new collimators in the dispersion suppressors of three experimental IPs and the collimation insertions, and by additional cryo plants, which will separate the cryogenics of the RF system and of the interaction region for the high-luminosity insertions from the cryogenics of the adjacent arc sectors, thereby providing a maximum and equal cooling capacity to all 8 octants of the LHC.

4.2.1. *Nb_3Sn* Magnets

The existing final-triplet quadrupoles, made from *Nb-Ti*, which are expected to be damaged after a total integrated luminosity around 400 fb^{-1}, should be replaced by new quadrupoles based on Nb_3Sn. Since Nb_3Sn can sustain up to two times higher field, the new quadrupoles can feature a much larger aperture, allowing for smaller β^*. The existing LHC quadrupoles have a coil aperture of 70 mm and provide a maximum operational gradient of 215 T/m at 1.9 K. A number of prototype quadrupoles on the path towards the HL-LHC have been built in the frame of the US-LARP collaboration. In 2012, the LQS03 (90 mm aperture, 3.7 m long) achieved a gradient of 208 T/m at 4.6 K, and 210 T/m at 1.9 K. In June 2013 the HQ02a (120 mm, 1.5 m long) reached 150 T/m at 4.6 K, and 170 T/m at 1.9 K. For comparison the HL-LHC goal is quadrupoles with a 150 mm gap, and 140 T/m at 1.9 K.

In 10 of the LHC dispersion suppressors existing *Nb-Ti* dipoles (maximum field 8.3 T) will be replaced by stronger dipoles based on Nb_3Sn to liberate space for new collimators catching off-energy protons or ions around ALICE, ATLAS, CMS and the two cleaning insertions. In April 2013, in the US a 1-m long prototype model achieved the nominal field of 11 T. The next steps include a longer 2-m single bore prototype, followed by 2-in-1 test magnets.

References:

- EuCARD-AccNet HE-LHC'10, Mini-Workshop on High-Energy LHC, Malta, 14-16 October 2010 (in particular talks by G.L. Sabbi, S. Caspi, T. Nakamoto, G. de Rijk, A. Zlobin, S. Gourlay)
- EuCARD’13 Final Annual Workshop “Visions for the Future of Particle Accelerators, CERN, 10-14 June 2013 (in particular talks by L. Rossi, G. de Rijk, and S. Caspi).

4.2.2. Magnet Quenches

The quench modelling, detection and protection of the individual superconducting magnets for LHC upgrades and future machines are important R&D issues, which were reviewed at the EuCARD co-sponsored WAMSDO2013 workshop (see Fig. 5).

Future work should be directed principally to three fronts. Firstly, the “allowables”; the allowable hot-spot temperature, the allowable voltages and, for HTS, the allowable temperature gradients. Secondly, precise knowledge of key properties like the quench propagation speeds for the different materials and in various conditions. Thirdly, new technologies for high fields and high current density magnets: novel quench heaters, new detection techniques and advanced protection methods. For the first two items some modelling effort, but foremost experiments are needed. For the last one, new ideas and R&D are called for.

Figure 5: Snapshot from WAMSDO2013.

References:

- EuCARD-AccNet co-sponsored WAMSDO workshop on Magnet Quenches, CERN, 15-16 January 2013

4.2.3. SC Link

Radiation to electronics causing single-event upsets is a critical issue for the LHC and even more for the higher-luminosity HL-LHC. The ultimate mitigation strategy consists in moving the radiation sensitive power converters further away from machine. In order to do so a SC high-current link needs to be developed to connect the then remote converters to the local SC circuits in the tunnel. A first prototype of such a link – from EuCARD WP7 –, 20 m long and carrying a maximum current of 20 kA, is under test at CERN. Future tests will compare cables based on the novel and inexpensive conventional SC MgB_2 and HTS cables made from *YBCO* and *BSCCO*. This development is also of great interest for electrical power companies, as it could provide for loss-free power distribution over long distances.

References:

- EuCARD’13 Final Annual Workshop “Visions for the Future of Particle Accelerators, CERN, 10-14 June 2013 (in particular the talk by A. Ballarino).

4.2.4. Crab cavities

In order to profit from a small β* at the HL-LHC, crab cavities are essential. As β* is decreased the crossing angle must be increased as $1/\beta^{*1/2}$ to maintain adequate transverse beam-beam separation at the parasitic encounters. Therefore, without crab cavities, when decreasing β* by a factor 5 below nominal, the geometric loss factor would decrease by almost the same factor (see Fig. 6), cancelling any luminosity gain from the smaller spot size. Crab cavities, i.e. transverse RF deflectors acting on the head and tail of a bunch with opposite sign, restore the ideal geometric overlap of the colliding bunches (Fig 7), and thereby allow harvesting the full benefit of the lower β*. At the same time the crossing angle of the bunch centroids and the associated strength of the long-range beam-beam interaction are unaffected. Crab cavities were first proposed in 1988, initially for linear colliders, and actually used in operation at the KEKB circular e^+e^- collider since 2007.

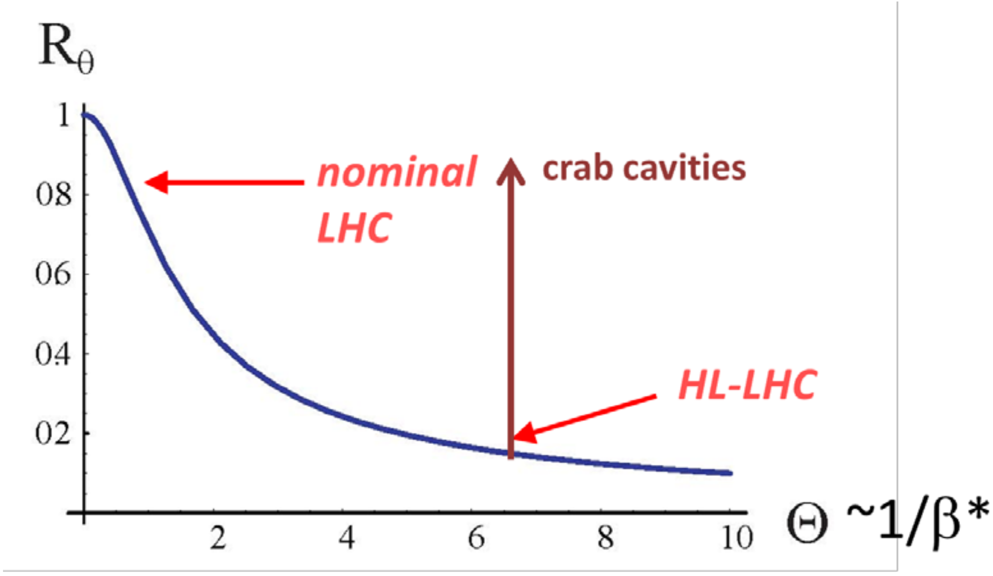


Figure 6: Geometric luminosity reduction factor as a function of Piwinski angle, illustrating a factor of 5 recovery of luminosity for the HL-LHC thanks to the crab cavities.

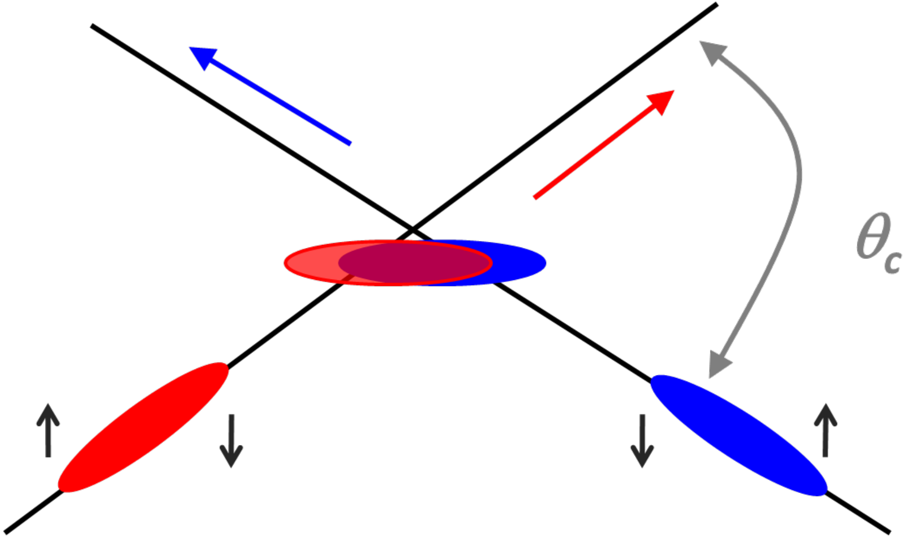


Figure 7: Illustration of crab crossing.

In the frame of EuCARD-AccNet a series of LHC crab-cavity workshops was organized, continuing an effort which had already been driven forward by the CARE-HHH EU programme (in 2004-2008). While in 2008 the crab cavities were still regarded to be on the "imaginary axis," it is thanks to these EuCARD-AccNet workshops that they have become part of the HL-LHC baseline design. Meanwhile successful prototypes for three different designs, down-selected at the EuCARD-AccNet workshops, have demonstrated the technical feasibility of these devices.

EuCARD-AccNet workshop LHC-CC09 concluded that the crab-cavity infrastructure should be included in all other LHC upgrades scenarios, since crab cavities can increase the LHC luminosity without an accompanying increase in beam intensity, thereby avoiding negative side effects associated with high intensity and high stored beam energy. This opinion had been endorsed by the general-purpose high-luminosity experiments. At LHC-CC09 one possible show-stopper was highlighted: machine protection, which is critical for LHC. The effect of fast cavity changes is being looked at with high priority. Mitigation schemes such as raising the *Q* value of the cavity have subsequently been studied.

At the EuCARD-AccNet workshop LHC-CC10, local crab crossing with the aid of 400 MHz deflecting SRF cavities was identified as the baseline tool for geometric luminosity-loss compensation and luminosity levelling for the HL-LHC. Also at LHC-CC10, the decision was taken not to install a retired KEK-B crab cavity in the SPS. However, it was recommended that all measures to test future LHC prototype cavities with and without beam outside the LHC be taken in order to ensure robust operation of future crab RF structures in the LHC.

Following the EuCARD-AccNet LHC-CC11 workshop (Fig. 8), detailed specifications for compact cavities were prepared based on an initial set of HL-LHC parameters.

Figure 8: Snapshots from Joint EuCARD-AccNet – LARP – KEK – CI/DL workshop on LHC crab cavities, LHC-CC11, 14-15 November 2011, CERN

One challenge for the LHC is the close transverse distance (19 cm) between the two beams, which together with the rms bunch length (~8 cm, determining 400 MHz crab RF frequency) excludes the installation of a conventional elliptical crab cavity as had been used at KEKB. Unconventional "compact" cavity shapes had thus been called for. During the course of the three EuCARD crab-cavity workshops three concrete types of alternative compact cavity designs emerged, as shown in Fig 9.

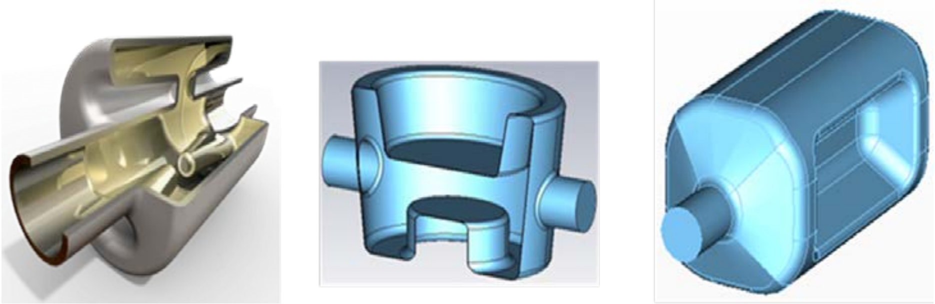


Figure 9: Final down-selected compact cavity designs for the LHC upgrade: 4-rod cavity design by Cockcroft I. & JLAB (left), l/4 TEM cavity by BNL (centre), and double-ridge l/2 TEM cavity by SLAC & ODU (right).

Prototypes for all three designs have been built, some of which in the frame of EuCARD WP7 (and all by the same company, Niowave), and successfully tested. Photos from two of these prototypes are shown in Fig. 10. In its very first test the double-ridge cavity reached more than twice the nominal RF voltage before tripping, which is extremely encouraging in view of future stable operation.

Figure 10: Prototype compact *Nb-Ti* crab cavities for the LHC: 4-rod cavity (left) and double-ridge cavity (right).

References:

- EuCARD-ACCNET Workshop on LHC Crab Cavities "LHC-CC09", organized jointly with CERN, US-LARP, DL/CI, and KEK, at CERN, CERN, 16-18 September 2009
- R. Calaga, F. Zimmermann et al, Summary of the 3rd LHC Crab Cavity Workshop (LHC-CC09) , EuCARD-PUB-2010-007
- LHC-CC10, 4th LHC Crab Cavity Workshop, CERN, 15-17 December 1010
- R. Calaga, LHC Crab Cavities, AccNet Highlight Talk at First Annual EuCARD Meeting, RAL, UK, 14 April 2010
- R. Calaga, S. Myers, F. Zimmermann, Summary of the 4th LHC Crab Cavity Workshop "LHC-CC10", EuCARD-REP-2011-001 (2011)
- LHC-CC11- 5th LHC Crab Cavity Workshop, CERN, 14-15 September 2011

- G. Arduini, R. Calaga, E. Ciapala, P. Collier, M. Giovannozzi, E. Jensen, J.-P. Koutchouk, P. McIntosh, E. Metral, S. Myers, V. Parma, J. Wenninger, F. Zimmermann, 5th LHC Crab Cavity Workshop, LHC-CC11 Workshop Summary Report, CERN-ATS-2012-055, EuCARD-PUB-2012-001, 5 April 2012
- Y.-P. Sun, R. Assmann, R. Tomas, and F.Zimmermann, Crab dispersion and its impact on the CERN Large Hadron Collider collimation, Phys. Rev. ST Accel. Beams 13, 031001 (2010), EuCARD-PUB-2009-030
- K. Ohmi, R. Tomás, Y. Funakoshi, R. Calaga, T. Ieiri, Y. Morita, K. Nakanishi, K. Oide, Y. Ohnishi, Y. Sun, M. Tobiyama, F. Zimmermann, Response of colliding beam-beam system to harmonic excitation due to crab-cavity rf phase modulation, Phys. Rev. Spec. Top. Accel. Beams 14 (2011) 111003, and EuCARD-PUB-2012-002
- G. Burt, Joint Highlight Talk of WPs 4&10: Compact Crab Cavities for LHC, 3rd EuCARD Annual Meeting, WUT, Warsaw, Poland, 25 April 2012

4.2.5. Luminosity leveling

In 2012 the present LHC experiments demonstrated that they can analyse data with 40 events per crossing, twice the design value. The detector upgrades aim at improving the experiment capacity so as to work with 140 events per crossing, corresponding to a luminosity around $5x10^{34}$ $cm^{-2}s^{-1}$ at 25 ns spacing. Since the HL-LHC could provide much higher peak luminosity – beyond $2x10^{35}$ $cm^{-2}s^{-1}$ –, the “pile up,” e.g. the number of events per crossing, will need to be limited by “levelling.”

Luminosity levelling by varying either the β^* (or the bunch length for the co-called “LPA scheme”) during a physics store for *pp* collisions in the context of the LHC luminosity upgrade was first proposed in early 2007 [F. Zimmermann, FP6 CARE-HHH co-organized “PAF/POFPA” meeting, 13.02.2007]; so was levelling by crossing angle variation in the “early separation scheme” [G. Sterbini & J.-P. Koutchouk, LHC-Project-Note-403 (2007)], as well as levelling using the crab RF voltage [W. Scandale, F. Zimmermann, “Scenarios for sLHC and vLHC,” FP6 CARE-Conf-07-011-HHH].

Since then the HL-LHC plan indeed was to vary the crab cavity voltage for levelling purpose, but recently it was highlighted that this would change the size of luminous region during a physics store, which is disliked by the LHC experiments. Therefore, at the HL-LHC, the luminosity at ATLAS and CMS will likely be levelled by varying the transverse separation or the beta* during the physics store. Levelling with transverse separation was used routinely for LHCb and ALICE in the 2011-12 physics operation, and first successful tests of β^* levelling have been performed as part of the 2012 machine development.

Figure 11 illustrates the HL-LHC luminosity evolutions with and without levelling, and compares these with the luminosity decay of the nominal LHC. The integrated luminosity corresponds to the area under the respective curves. The ideal time-averaged luminosity is only about 20% lower with levelling (with the benefit of much higher-quality data than without).

Reference:

- F. Zimmermann, O. Brüning, Parameter Space for the LHC Luminosity Upgrade, Proc. IPAC'12 New Orleans, 20-25 May 2012, p. 127, EuCARD-CON-2012-009

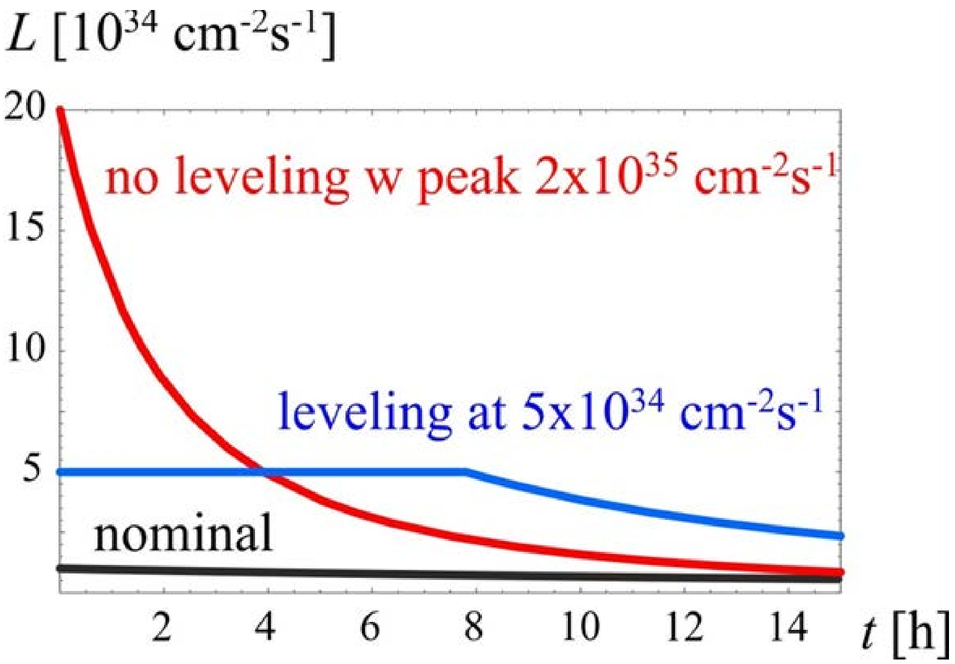


Figure 11: schematic of luminosity levelling at the HL-LHC (blue), and comparison with the luminosity decay in physics for the nominal LHC (black) and with a hypothetical unlevelled HL-LHC (red) . The integrated luminosity corresponds to the area under the curve.

4.3. ENHANCEMENTS

A number of additional enhancements are considered for further boosting the HL-LHC performance. These include hollow electron beam lenses for improved collimation and crab-cavity related machine protection, and various schemes of coherent electron cooling to increase the LHC proton beam brightness.

The original idea of coherent electron cooling was proposed by Y. Derbenev in 1980. A novel scheme with full evaluation has been developed over the past years by V. Litvinenko. The coherent electron cooling would provide a fast cooling of high energy hadron beams. It is made possible by the availability of high-brightness electron beams and state-of-the-art FEL technology. A prototype is being developed for eRHIC. A proof-of-principle experiment is planned with 40 GeV/*n Au* beam at RHIC in about 2015. In 2013 a variation of this scheme has been proposed by D. Ratner, where the FEL amplifier for the electron beam is replaced by a simpler micro-bunching amplifier.

In the following we highlight two other enhancement concepts which have been explored in the frame of EuCARD-AccNet: long-range beam-beam compensation and crystal collimation.

References:

- LHC-CC10, 4th LHC Crab Cavity Workshop, CERN, 15-17 December 1010 (in particular the talk by J. Wenninger)

- Joint Snowmass-EuCARD/AccNet-HiLumi LHC meeting 'Frontier Capabilities for Hadron Colliders 2013', CERN, 21-22 February 2013 (in particular the talk by V. Litvinenko).
- EuCARD'13 Final Annual Workshop "Visions for the Future of Particle Accelerators, CERN, 10-14 June 2013 (in particular the talk by P. Ostroumov).

4.3.1. Long-Range Beam-Beam Compensation

The performance of the LHC and the minimum crossing angle at the LHC interaction points are limited by long-range beam-beam collisions. DC "wire compensators" can mitigate part of the long-range effects. Computer simulations were performed to explore the efficiency of the compensation at possible wire locations by examining the tune footprint and the dynamic aperture. Starting from the weak-strong simulation code BBTrack a new calculation tool for Lyapunov indicators was developed. Different wire positions (longitudinal and transverse), varying wire currents, several wire shapes, and a range of beam-beam crossing angles were investigated, preparing for a prototype wire installation in the LHC foreseen for 2014/15. According to the simulations, the prototype wires can provide a good compensation, including for reduced crossing angle. Among the benefits of an LHC wire compensator are a better overlap of colliding bunches, as well as the possibility of smaller β^* or higher beam current. EuCARD-AccNet recommends including the wire compensator in the HL-LHC baseline design.

References:

- G. Sterbini, An Early Separation Scheme for the LHC Luminosity Upgrade, PhD thesis Lausanne EPFL, 2009, EuCARD-DIS-2009-003.
- T. Rijoff, R. Steinhagen, F. Zimmermann, Simulation studies for LHC long-range beam-beam compensators, Proc. IPAC'12 New Orleans, 20-25 May 2012, p. 2002, EuCARD-CON-2012-012
- T. Rijoff, Testing Long Range Beam-Beam Compensation for the LHC Luminosity Upgrade, Master Thesis, University of Milano, July 2012, EuCARD-DIS-2012-003
- EuCARD-AccNet co-sponsored conference ICAP 2012, Warnemünde, 19-25 September 2012, special AccNet sessions

4.3.2. Crystal Collimation

Crystal collimators offer the perspective to increase the impact parameter, and to obtain less nuclear events, lower losses, and a reduced collimator impedance.

The underlying physics is the following. Charged particles entering a crystal at sufficiently small angles with respect to the crystal planes can be captured in channeling states, performing quasi-harmonic oscillations between the crystal planes. Trajectory confinement is determined by the average electric field of the ordered atoms, equivalent to a magnetic field of a few 1000 T. Particle channeling is still possible if the crystal is moderately bent up to a critical radius. Particles channeled in a bent crystal are deflected by the crystal's bend angle. This provides a powerful method to steer particle beams that has been investigated and already occasionally exploited for several decades.

In a high-intensity high-energy hadron collider halo particles surrounding the beam core produce losses in sensitive areas of the accelerator hindering its operation. At the LHC, a multi-stage collimation system is employed to remove & absorb the beam halo. Using a bent crystal instead of an amorphous solid target as a primary collimator should further improve of the performance of the collimation system, The bent crystal would act as a knife excising the incoming halo, by deflecting halo particles at large angles and directing them into a secondary collimator-absorber, which would almost fully absorb the beam halo, with the promise of reduced losses outside the collimation regions.

For the past couple of years, the UA9 Collaboration supported by CERN, INFN, Imperial College, LAL, PNPI, IHEP and JINR has been investigating how tiny bent crystals could assist and improve collimation process in modern hadron colliders, such as the LHC, in view of ultra-high luminosity operation. The launch of this collaboration and the preparation of SPS beam experiments were fostered by several workshops organized in the frame of EuCARD WP4, i.e. the AccNet-EuroLumi Workshops on Crystal Collimation held at CERN on 9-10 November 2009, and on 25-26 October 2010.

From 2009 onwards the UA9 Collaboration successfully tested silicon crystals at the SPS measuring collimation efficiencies with various methods and detectors. A part of these studies was done by INFN in the frame of EuCARD WP8. The experimental layout is shown in Fig. 12. Some example results are displayed in Figs. 13 and 14. The UA9 results with protons and *Pb* ions at 120 GeV/c and 270 GeV/c per charge collected from 2009 to 2012 provides strong indication that crystal assisted collimation is well mastered and understood. The main findings of the UA9 experiments at the SPS are as follows:

1) With a 1-mm long crystal in channeling orientation the loss rate close to the crystal is reduced by a factor close to 20 and the far off-momentum halo population is reduced by a factor of 7.
2) The miscut angle between the crystal planes and its surface plays an important role. Taking this miscut into account, the UA9 experimental data are in excellent agreement with simulation results.
3) The beneficial effect of a crystal primary collimator is global, i.e. the losses all around the SPS circumference show a strong reduction of losses with the crystal in channeling orientation.
4) A first industrial goniometer compliant with the LHC specification is now available.

All these indications lend confidence that the UA9 beams tests results can readily be extrapolated to the LHC.

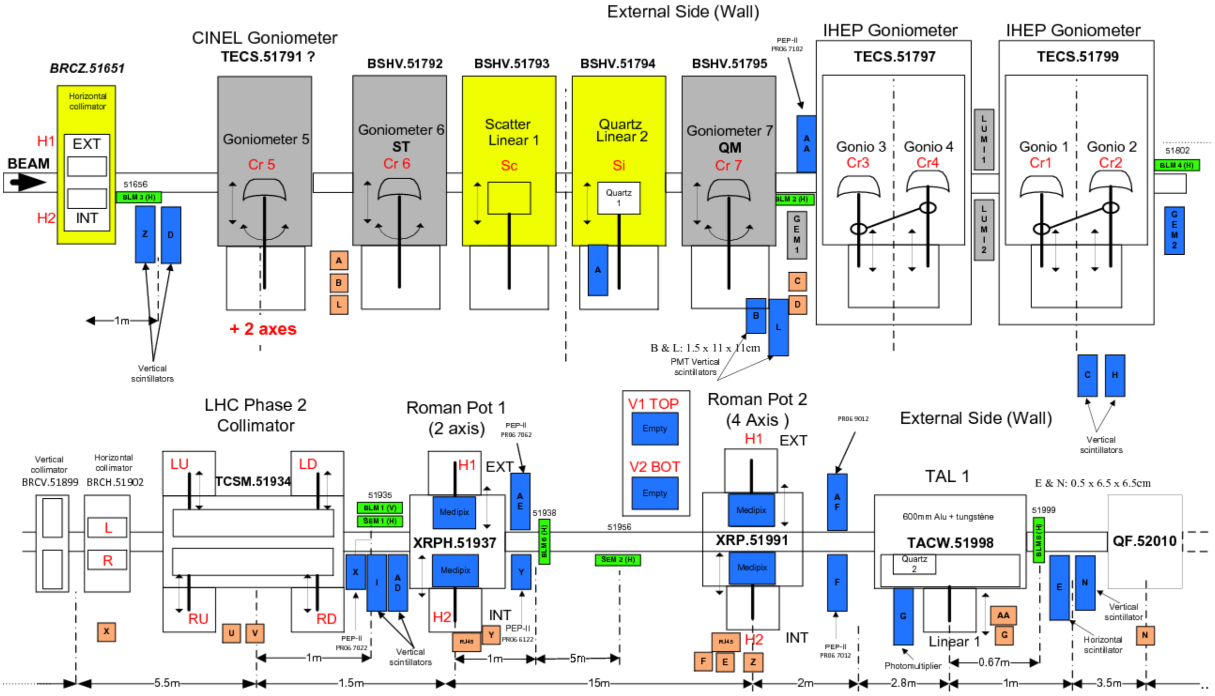


Figure 1a

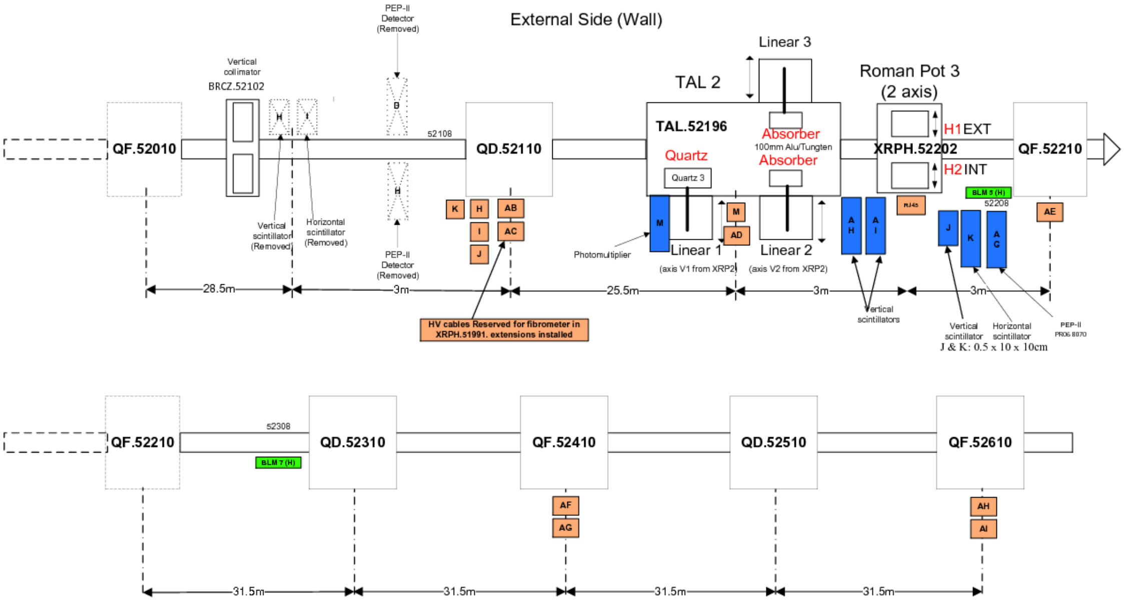


Figure 1b

Figure 12: Layout of the UA9 experiment in the SPS environment. (a) Crystal-collimator area of UA9. (b) High dispersion area of UA9.

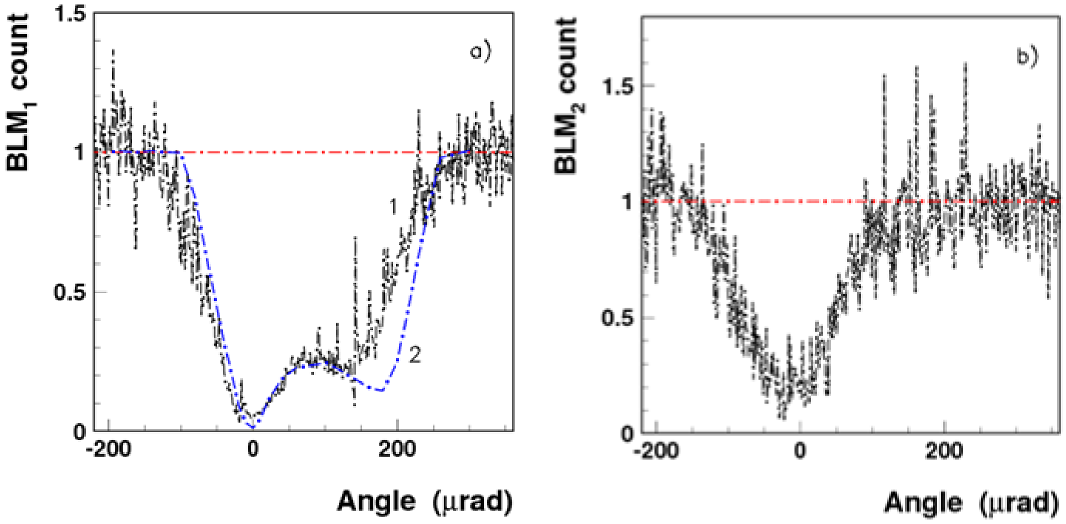


Figure 13: Beam of 270 GeV/c protons. Curves (1) show the dependencies of the beam loss observed at the crystal (a) and in the HD area target (b) on the angular position of the crystal C4. Curves (2) show the dependence of the number of inelastic nuclear interactions of protons in the crystal on its orientation angle obtained by a simulation taking into account the crystal miscut.

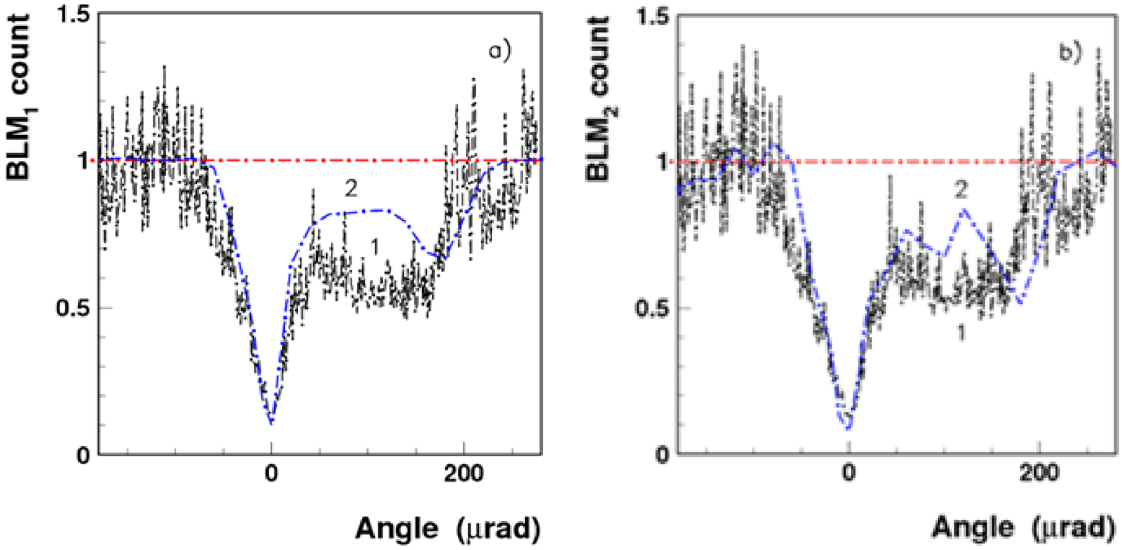


Figure 14: Beam of *Pb* ions with 270 GeV/c per charge. Curves (1) show the dependencies of beam losses observed at the crystal (a) and in the HD area target (b) on the angular position of the crystal C4. Curves (2) show the dependence of the number of inelastic nuclear interactions of protons in the crystal on its orientation angle obtained by a simulation taking into account the crystal miscut.

The plan for the near-term future is installing two crystals in one of the two LHC rings, one horizontal and one vertical, in order to initially assist proton and *Pb*-ion collimation during test runs. The orientation of the crystal with respect to the beam envelope will be controlled using a piezoelectric driven goniometer. To detect the deflected beam, an in-vacuum Cherenkov radiator will be used.

Two medium-term steps have been identified The first is conceiving a secondary absorber that could sustain the nominal flux of the extracted halo particles without damage. The second is staging two crystals per plane in order to guarantee the halo extraction even in the presence of small orbit deviations. Development of a simulation code through adding a crystal model description to a particle tracking programme such as SIXTRACK also is in progress.

The final usage of crystals for collimation purposes in routine operation at the LHC will pose novel challenges: In steady conditions, a bent crystal could deposit up to 0.5 MW power during several seconds in a small spot on the collimator-absorber that should sustain it without suffering any damage. The angular acceptance for channeling is reduced with increasing particle energy. Alignment mechanisms with angular accuracy beyond the state of the art are therefore required and are being developed in partnership with industrial companies. The growth rate of the beam halo is so slow that the first impacts on the crystal occur in a region not exceeding a few atomic layers. This requires a flat surface parallel to the crystal planes with an unprecedented tolerance. The global needs for crystal-assisted collimation call for technological breakthroughs in a multidisciplinary range of issues related to beam manipulation, particle detectors, computing and data analysis. UA9 intends to achieve the necessary breakthroughs.

In a long-term view bent crystals could replace high-field magnets in transport systems and storage rings, opening up a new path to push the highest-energy frontier. In view of this exciting perspective, the R&D on crystal applications for accelerators should be pursued with a high priority.

References:

- EuCARD-AccNet-EuroLumi mini-Workshop on Crystal Collimation, CERN, 9-10 November 2009
- EuCARD-AccNet-EuroLumi Workshop on Crystal Collimation, CERN, 25-26 October 2010
- W. Scandale, UA9 Status Report, EuCARD-REP-2012-002
- W. Scandale, UA9 Results from Crystal Collimation Tests in the SPS & Future Strategy, EuCARD-REP-2013-002.

5. FAIR

FAIR aims to extend the existing GSI beam facilities in various directions and by several orders of magnitude. It will increase the primary beam intensity by a factor of 100–1000, the secondary beam intensity by an even larger factor of 10000, and the heavy ion energy by a factor of 30. In addition it will newly provide cooled pbar beams (15 GeV) as well as intense cooled radioactive beams. Plus it will allow for parallel operation of various types of beams.

Figure 15 shows a modularized start version of FAIR. The super fragment separator (Super FRS, module 2) will operate with primary beams of 3×10^{11} of $^{238}U^{28+}$/s (slow extr.) at 1.5

GeV/u or 4x10^{11} $^{238}U^{28+}$ (pulsed) at 1 GeV/u**,** which corresponds to a factor of 10 increase in intensity over the present SIS18 performance, and with a broad range of radioactive secondary beams up to 1.5 GeV/u in energy and with 10000 times higher intensity than available at present. Antiprotons (module 2) are produced by accelerating protons to 29 GeV in the new SIS100 (module 0) and shooting them on an antiproton-production target.

Achieving the targeted FAIR performance requires an upgrade of the GSI injector complex: Higher ion beam intensities are obtained with an 28-GHz ECRIS source. The UNILAC heavy-ion linac will be upgraded for high power (high intensity), and short pulses, increasing the beam brilliance (beam current / emittance) and the transported beam currents, with associated improvements of high current beam diagnostics and operation. The four 35-year old Alvarez linear accelerator tanks will be replaced by a new linac structure with modern interdigital H-type cavities. The SIS18 will be upgraded for fast ramping, enhanced intensity per pulse, increased injection acceptance, improved lifetime for low-charged U-ions (UHV upgrade, in particular addressing dynamic vacuum issues), and increased beam intensity per time due to a reduction of the SIS18 cycle time. The FAIR antiproton physics program is based on a rate of 7x10^{10} cooled antiprotons per hour. To provide the primary proton intensities a new proton linac will be operated independently of the existing UNILAC for heavy ions. The proposed linac comprises an ECR proton source, a RFQ, and a DTL. Its operation frequency of 352 MHz allows for an efficient acceleration to up to 70 MeV using normal conducting Crossed-bar H-cavities (CH-DTL)

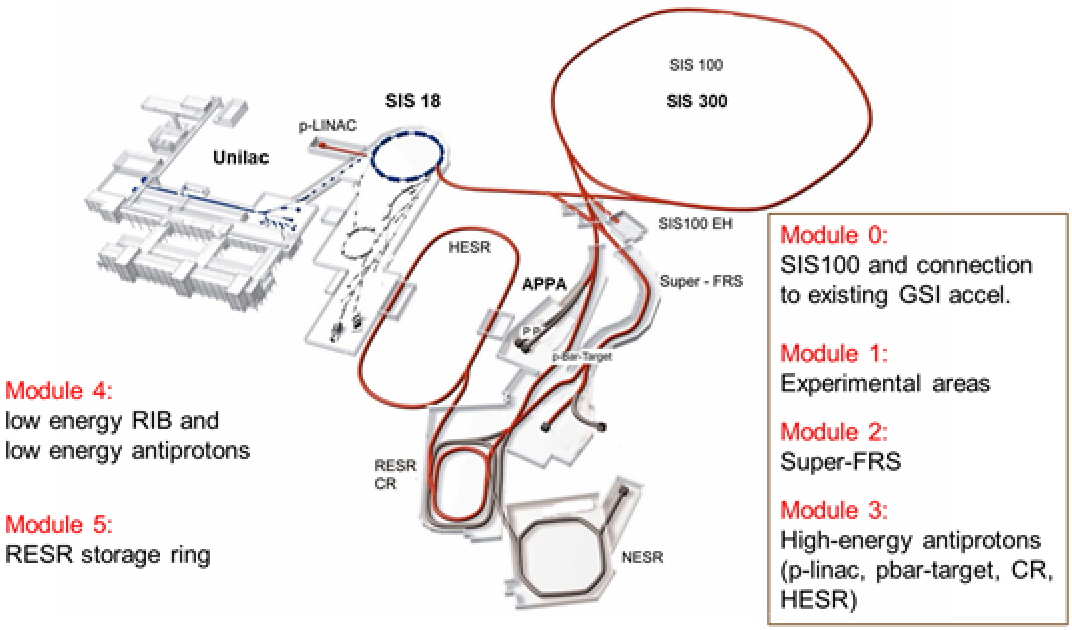


Figure 15: Modularized start version of the FAIR accelerator complex [O. Kester].

References:

- EuCARD-AccNet co-organized workshop SPACE CHARGE 2013, CERN, 16-19 April 2013 (in particular the talk by P. Spiller)

- EuCARD'13 Final Annual Workshop "Visions for the Future of Particle Accelerators, CERN, 10-14 June 2013 (in particular the talks by B. Sharkov and P. Ostroumov).

5.1. FAST CYCLING MAGNETS

SIS100 requires fast ramped SC magnets with $B\rho$= 100 Tm, B_{max}= 1.9 T, and dB/dt= 4 T/s. Challenges are the dynamic load and the AC heat losses, as well as the required high field quality and small multipole field errors. R&D goals are the reduction of eddy / persistent current effects, and the guarantee of long term mechanical stability ($\geq 2x10^8$ cycles), for which the mechanical stress must be mitigated by appropriate coil restraint.

The fast ramping dipoles for SIS300 represent the second generation of SC dipole magnets. The SIS-300 model magnet DISCORAP reached the nominal current with only one training quench. The magnet has been operated in pulsed regime, up to $dB_0/dt = 0.7$ T/s (the upper limit of the station). The magnet has demonstrated to work in fast ramp rate up to the ultimate field (B_0=4.5 T) with some limitations. As primary evident limitation of the design, the maximum variation of field allowed is confined to ΔB_0=1.5 T - 2 T for fast ramp rate, independently of the final field or of the sign of the ramp. Preliminary results show that the losses are very low (at least a factor 2 below the estimated value, even if the region at the nominal ramp rate has not yet been explored). The CRISP programme aims at the development and manufacturing of an upgraded collared coil of a SIS300 type dipole with an enhanced 2D-coil block design to minimize field errors, a better design of the coil ends, also to reduce field errors, and a new low loss conductor (Bruker EST wire). A full (second) magnet could be built with appropriate funding. Table 2 indicates how the SIS300 magnet design could be adapted for the SC injector ring of a higher-energy hadron collider.

Table 2: SIS300 dipole magnet parameters and proposed (HE-)LHC injector dipole based on SIS300 magnet technology [P. Fabbricatore]

Parameters	**SIS300 dipole** 100 mm bore, 1.5 T to 4.5 T at 1 T/s	**(HE-)LHC injector dipole** 4 T, 100 mm bore, 1.5 T/s
Injection magnetic field [T] and b_3	1.5/ -0.75	0.4/ -4.5
Maximum/ Peak magnetic field [T]	4.5/4.9	4.0/4.4
Temperature Margin (K)	0.97	1.46
AC losses in SC cable during ramp [W/m]	3.5	5.6
AC losses during ramp (eddy currents & magnetization) [W/m]	3.5	5.9
Weight [T/m]	1.28	1.28
Constr. cost [K€/m] on 60 magnets	60-70	60-70

References:

- EuCARD-AccNet-EuroLumi workshop HE-LHC'10, Mini-Workshop on High-Energy LHC, Malta, 14-16 October 2010 (in particular the talk by P. Spiller)
- E. Todesco and F. Zimmermann (eds), The Higher-Energy Large Hadron Collider, Proceedings of the EuCARD-AccNet HE-LHC workshop, Malta, 14-16 October 2010, CERN, EuCARD-CON-2011-001
- EuCARD-AccNet co-organized workshop SPACE CHARGE 2013, CERN, 16-19 April 2013 (in particular the talk by P. Spiller)
- EuCARD'13 Final Annual Workshop "Visions for the Future of Particle Accelerators, CERN, 10-14 June 2013 (in particular the talks by P. Fabbricatore, B. Sharkov and P. Ostroumov).

5.2. OTHER CHALLENGES

The accelerator challenges of FAIR proper include, aside from the superconducting magnets, the curved dipole vacuum chamber, cold collimators ("cryo catchers", in EuCARD WP8), diagnostics and extremely high vacuum at higher ion-beam intensities, advanced RF cavities (metallic-alloy core cavities for generation of RF barriers), and beam cooling.

Developments for the SuperFRS comprise remote handling (pillow seal development), radiation-resistant normalconducting dipoles (1.6 T, using mineral insulating cable), and superferric multiplets.

References:

- EuCARD-AccNet co-organized workshop SPACE CHARGE 2013, CERN, 16-19 April 2013 (in particular the talk by P. Spiller)
- O. Kester. Subproject FAIR accelerators and FAIR@GSI, 3 June 2013

5.3. SPACE CHARGE AND FIELD ERRORS

The subject of adiabatic or non-adiabatic resonance crossing and trapping [13] is relevant not only for the pinched electron cloud, but also for the space-charge studies, as the occurrence of the same phenomena in the presence of space charge was previously established. For the FAIR project the control of long-term space charge induced beam loss is essential and the EuCARD-WP4 Space Charge workshop in 2013 has reviewed the community state of the art for code development and ongoing studies. Reliably predicting the long-term beam loss requires a code able to mitigate for unphysical spurious results introduced by numerical noise. The closely related issue of code validation to assure the reliability of the simulations for ongoing projects is still an important topic. Of particular interest is the joint GSI-CERN experimental campaign that merges LHC/LIU and FAIR activities. In 2012 two weeks of beam measurements were performed in the PS synchrotron with the goal to acquire new data for code benchmarking. The effect of the third order coupling resonance as $2Q_x + Q_y = n$ are dramatic and of substantial relevance for FAIR. Figure 16, taken from the EuCARD-WP4

Space Charge 2013 workshop (presentation by G. Franchetti, R. Wasef, A. Huschauer, F. Schmidt, and S. Gilardoni), shows a typical scenario (PS measurement) of storage of high intensity bunched beam. Close to the resistance the emittance increase is significant.

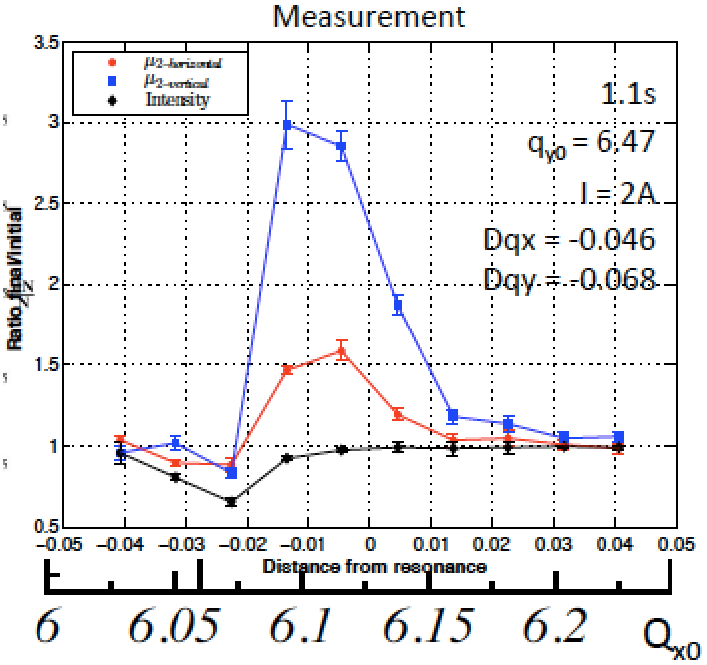


Figure 16: Space-charge induced emittance growth factor as a function of the horizontal betatron tune, as observed in an experiment at the CERN PS.

The results of the studies performed/supported in the frame of EuCARD-WP4-AccNet suggest the following strategies, which will be integrated in the future EuCARD-2 XBEAM activities:

1) Space charge effects require an efficient modeling of the machine. Different strategies are being pursued at the different laboratories and projects:
    a. For the FAIR project, in the future synchrotron SIS100, a strong interplay is expected between space charge and the nonlinear field of super-ferric dipoles. The strategy to achieve a successful operation relies on a thorough measurement of the magnet properties after their delivery to GSI. The subject is delicate as dipole magnets in SIS100 feature an elliptic cross-section that creates problems in retrieving a reliable multipole set. The strategy in this area is to consolidate the experimental procedure for measuring the SIS100 magnet multipole field errors through a review and cross collaboration among laboratories. This task is inherited by EuCARD-2 XBEAM and will be subject of an upcoming meeting.
    b. At the moment, resonance compensation is the best method to mitigate beam loss. This method relies on the knowledge and localization of magnet errors. However, so far no experimental proof exists that high-intensity beams can survive in a compensated lattice. Here, the strategy for the FAIR project is to continue the collaboration between GSI and CERN in a synergetic experimental program that advances the understanding and procedure of resonance compensation in presence of space charge.

c. The effectiveness of the resonance compensation is also of relevance with regard to magnet sorting: if the compensating magnets within their operating range do not allow for a perfect compensation, or if the applied perturbation theory used to compute the compensation scheme breaks down, a sorting strategy needs to be adapted. The magnet sorting is an expensive option that requires a significant effort on the logistics level. Joint studies associated with a) and b) will have to be carried out to arrive at a cost-effective and viable overall solution.

d. In the context of the aforementioned issues, it becomes essential to develop experimental methods allowing the retrieval of high order components in an existing operating machine. For the measurement of quadrupole errors, and skew-quadrupole components, as well as for sextupolar resonance driving terms, experimental techniques are being applied successfully (e.g. the beta-beating control at the LHC), but localization and quantitative measurements of octupolar components are not available at the moment (some related studies wered performed at RHIC in 2000). The development of such techniques is part of the strategy for the LIU program at CERN, in particular for the PS. For FAIR it prepares the laboratory for the post-commissioning era, in which SIS100 will possibly have to be analyzed with beam-based methods to retrieve a higher-order machine model.

e. Simulation modeling needs to be improved so as to obtain reliable beam loss predictions. This aspect requires modeling improvements complementing the more accurate parameters describing the accelerator. In particular, issues like self-consistency in long term simulations with space charge remain to be addressed.

2) Beam diagnostics should be carefully developed to support machine studies aimed at upgrades programs. This involves IPM as well as flying wire and tune measurement techniques. The reliability of these devices is relevant for machine operation as well as for beam/machine studies. Especially important is the assessment of the uncertainties in these devices so that error bars can be provided to users. In particular the effect of space charge in the IPM is an ongoing subject of study (which will be continued in EuCARD-2).

References:

- EuCARD-AccNet co-organized workshop SPACE CHARGE 2013, CERN, 16-19 April 2013
- G. Franchetti and F. Schmidt, Summary of the Space Charge Workshop 2013 (SC-13), CERN, Geneva, 16-19 April 2013, EuCARD-REP-2013-001
- G. Franchetti and F. Zimmermann, New Approach to Resonance Crossing, published in PRL 109, 234102 (2012), EuCARD-PUB-2012-009
- G. Franchetti, F. Zimmermann, Space Charge and Electron Cloud Simulations, Proc. ICAP'12 Warnemünde, 19-24 August 2012, p. 130, EuCARD-CON-2012-020

6. LHEC, LHEC-HF AND SAPPHIRE

The Large Hadron electron Collider (LHeC) is studied as a possible future facility colliding a 60-GeV electron beam from an energy recovery linac with one of the two proton beams circulating in the LHC. The nominal design luminosity is 10^{33} cm^{-2}s^{-1}. The Higgs discovery at the LHC in 2012 has triggered enhanced interest in using the LHeC as a Higgs factory. Boosting its luminosity to above 10^{34}cm^{-2}s^{-1} would allow precision Higgs coupling measurements (Hb$\bar{b}$, Hgg, H4l,…), the reduction of theoretical QCD-related uncertainties in *pp* Higgs physics, and the potential to find new physics at the cleanly accessible WWH (and ZZH) vertices. It has also been suggested to reconfigure the LHeC, by accelerating electrons in either direction through the linac, into a gamma-gamma collider Higgs factory known under the name SAPPHiRE.

6.1. LHEC

A Conceptual Design Report for the LHeC CDR was published in 2012 [J. Phys. G: Nucl. Part. Phys. 39 075001 (2012)], describing the physics case, the detector and the accelerator.

Figure 17 shows the CERN complex including the LHeC, and Fig. 18 a zoomed view of the LHeC energy recovery linac, considering of two SC linacs, with 3 passes of acceleration, collision, and 3 passes of deceleration; the nominal electron current is 6.4-mA, the RF gradient about 20 MV/m, and the RF frequency choice 800 MHz.

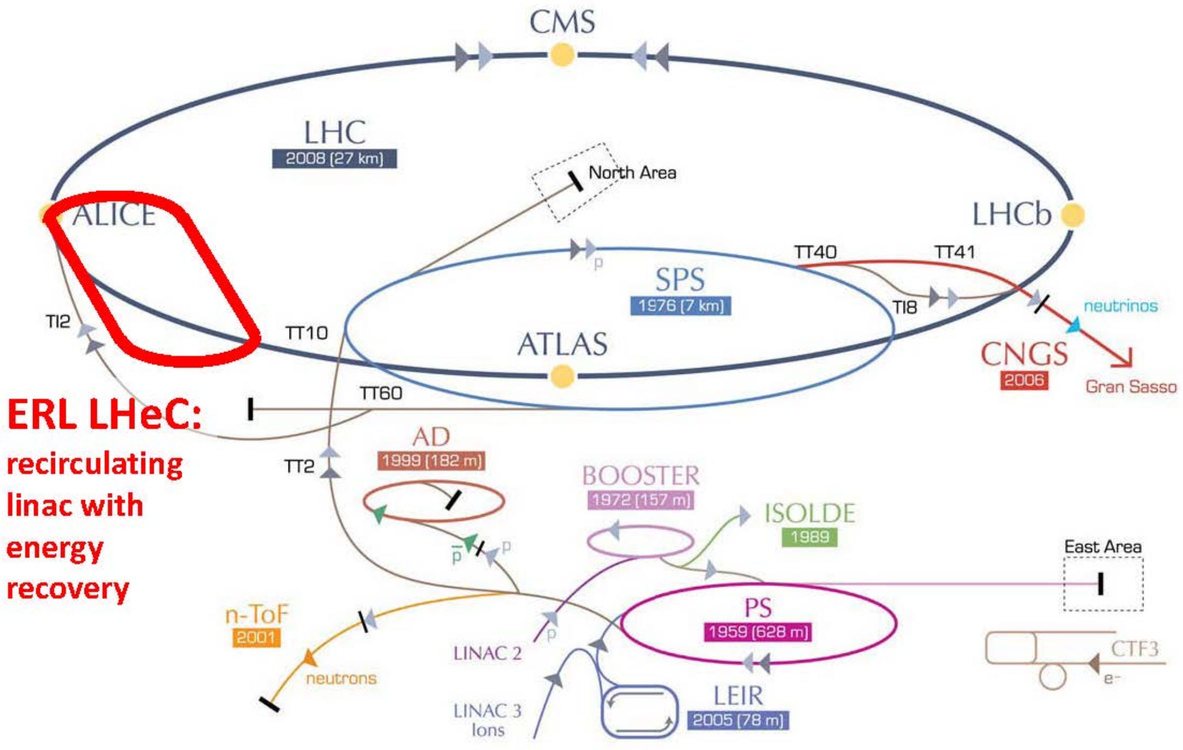


Figure 17: Schematic sketch of the LHeC on the CERN site.

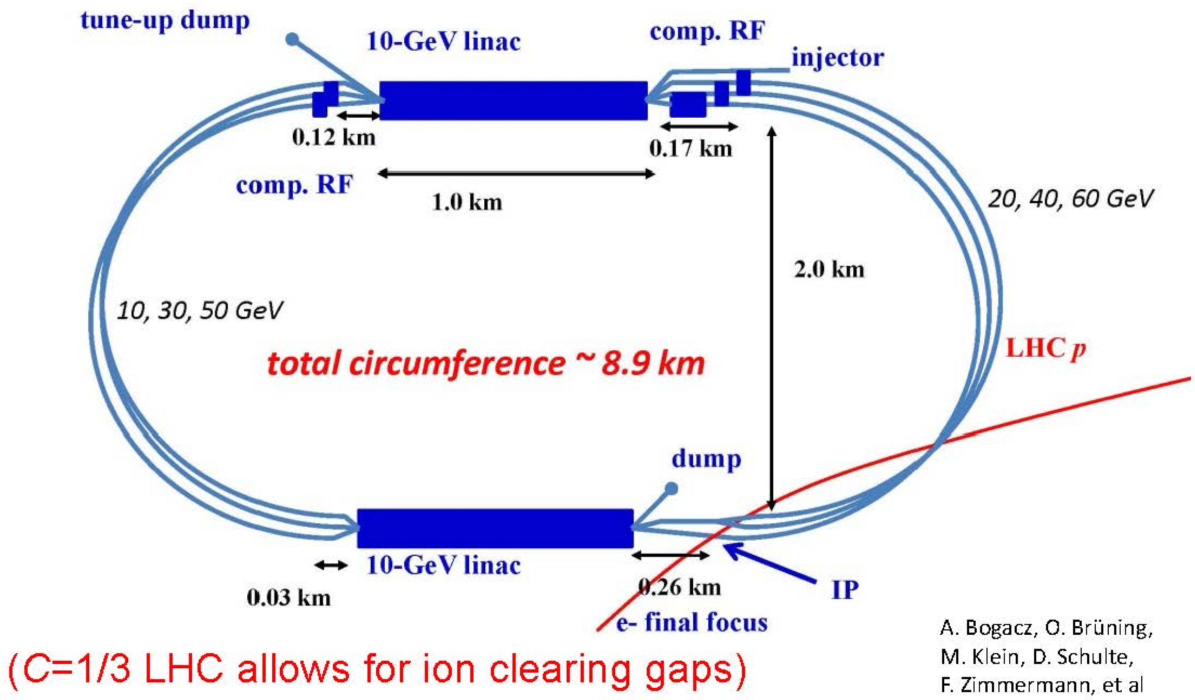


Figure 18: LHeC ERL layout including dimensions.

6.2. LHEC-HF

The luminosity of the LHeC is proportional to the electron beam current and to the proton beam brightness and scales with the inverse of the proton β*, which singles out all the parameters to be pushed in order to raise the LHeC luminosity up to $2x10^{34}cm^{-2}s^{-1}$, a machine which we call LHeC Higgs Factory, or short LHeC-HF.

6.3. SAPPHIRE

Figure 19 shows a sketch of the gamma-gamma collider Higgs factory, ``SAPPHiRE,'' based on the LHeC layout. The collision point is located at the center of the highest-energy arc. At the gamma-gamma collider the Higgs would be produced directly in the *s*-channel from two gammas. Due to the physics of Compton backscattering, the electron energy required is about 80 GeV, to be compared with 60 GeV for the LHeC. Therefore, one open question is whether for SAPPHiRE the linac should be operated in cw mode as for the LHeC (requiring additional arcs) or be pulsed with higher gradient.

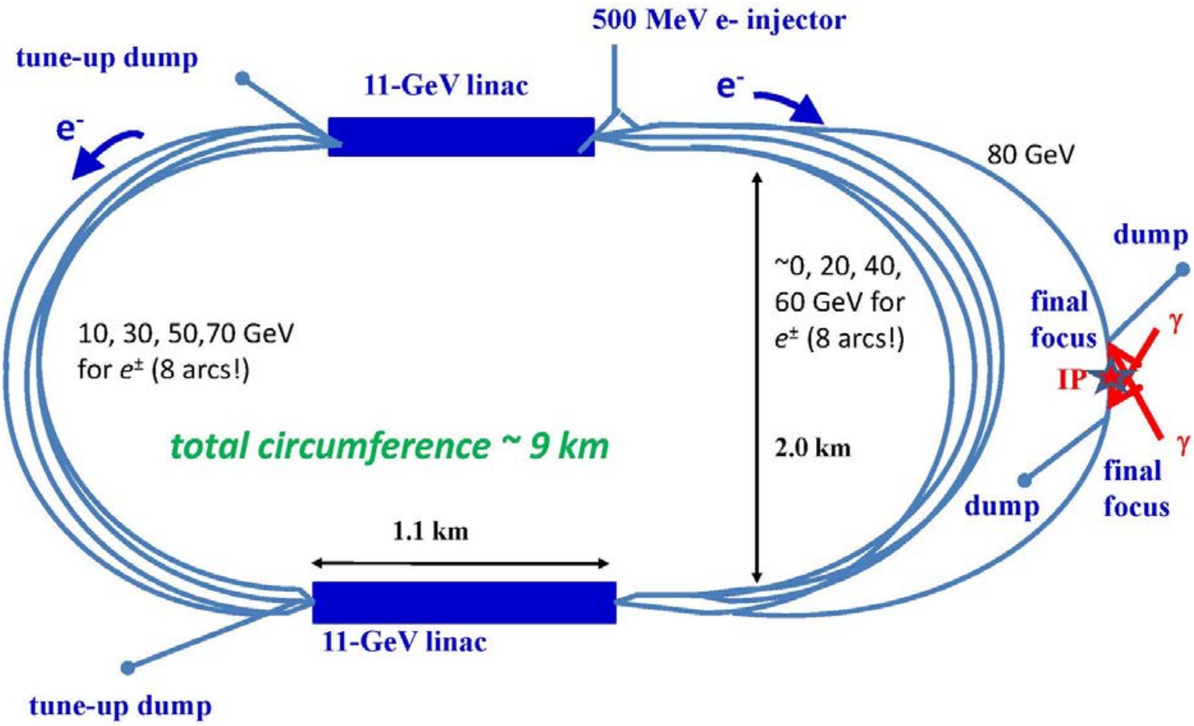


Figure 19: Sketch of a layout for a $\gamma\gamma$ collider, “SAPPHiRE,” based on the LHeC recirculating SC linacs.

In the frame of EuCARD-AccNet a first mini-workshop on SAPPHiRE was organized, focusing on laser and FEL technologies. Figure 20 presents two of the proposed solutions for the SAPPHiRE laser system, presented at this workshop. The optical stacking cavity was identified as the highest risk element. It is interesting that the recent proposal for a coherent amplifier network based on fibre laser by G. Mourou et al. (FP7 ICAN), would provide a high enough repetition rate (1 J at 10 kHz) that an optical stacking cavity might no longer be needed.

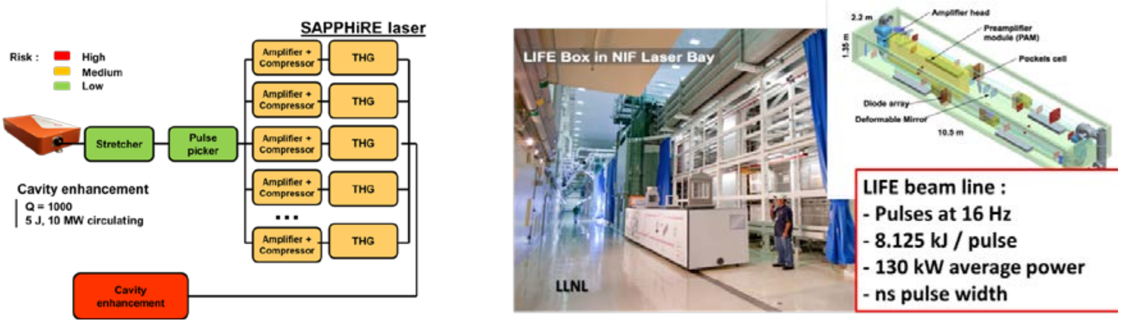


Figure 20; Laser options for SAPPPHiRE from Y. Zaouter (Amplitude Systems) [left] and from J. Gronberg (LLNL) [right] presented at the EuCARD-AccNet “SAPPHiRE Day”.

References:

- EuCARD-AccNet SAPPHiRE Day, CERN, 19 February 2013
- EuCARD'13 Final Annual Workshop "Visions for the Future of Particle Accelerators, CERN, 10-14 June 2013 (in particular the talks by J.-P. Koutchouk and F. Zimmermann).

6.4. PERFORMANCE SUMMARY

Table 3 compares the projected performances of LHeC, LHeC-HF and SAPPHiRE with regard to Higgs physics.

Table 3: LHeC baseline and Higgs factory parameters.

machine	**LHeC**	**LHeC-HF**	**SAPPHiRE**
luminosity $[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	0.1 (*ep*)	2 (*ep*)	0.06 ($\gamma\gamma$ >125 GeV)
cross section	~200 fb	~200 fb	>1.7 pb
no. Higgs/yr	2k	40k	>10k

.

References:

- EuCARD-AccNet SAPPHiRE Day, CERN, 19 February 2013
- Joint Snowmass-EuCARD/AccNet-HiLumi LHC meeting 'Frontier Capabilities for Hadron Colliders 2013', CERN, 21-22 February 2013 (in particular the second talk by F. Zimmermann)

7. HE-LHC AND VHE-LHC

The High-Energy LHC (HE-LHC) is a proposed new hadron collider in the existing 27-km LHC tunnel; see Fig. 21 (left). Utilizing new dipole magnets with a nominal field up to 20 T (2.5 times the LHC field), it can provide *pp* collisions with a c.m. energy of 33.5 TeV, assuming the same main-bend filling factor as in the present LHC (about 66% of the circumference). In the fall of 2010 EuCARD-AccNet organized the first and so far only workshop on HE-LHC. The workshop proceedings covering most aspects of such a machine constitute an important reference for the future design work.

The Very High Energy LHC (VHE-LHC) is an alternative proposal based on a larger ring circumference, which would allow exploring much higher beam energies still, up to 100 TeV in the centre-of-mass; see Fig. 21 (right). This VHE-LHC would be installed in a new tunnel of 80 km circumference, which could also accommodate a high-luminosity circular e^+e^- Higgs factory (TLEP). The larger tunnel would enable *pp* collisions of 42 TeV c.m. with the present 8.3-T LHC magnets, of 75 TeV with 15-T magnets, and of 100 TeV with 20-T HE-LHC type magnets. An even larger, 100-km tunnel would allow reaching 100 TeV c.m. with 15 or 16-T dipole magnets. In 2013 EuCARD-AccNet co-organized the first ever (two-day) working meeting on the VHE-LHC.

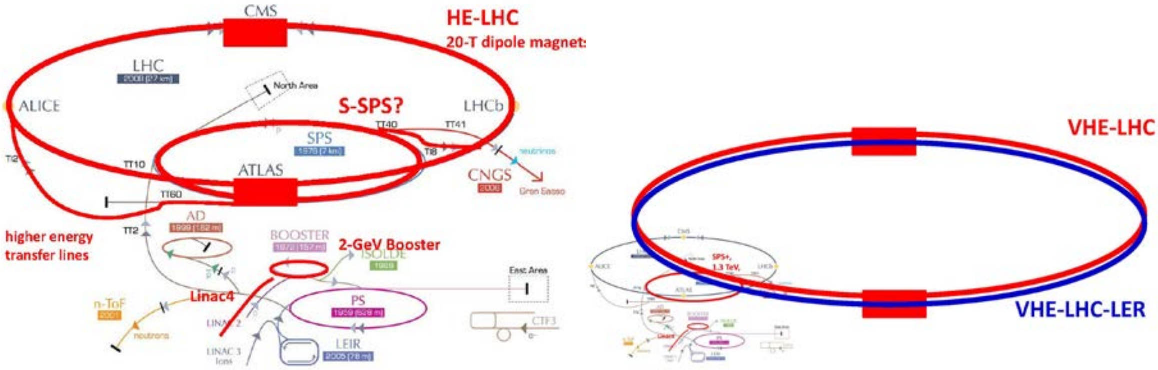


Figure 21: Bird’s eye views of the HE-LHC [left] and VHE-LHC [right].

References:

- EuCARD-AccNet-EuroLumi workshop HE-LHC'10, Mini-Workshop on High-Energy LHC, Malta, 14-16 October 2010
- E. Todesco and F. Zimmermann (eds), The Higher-Energy Large Hadron Collider, Proceedings of the EuCARD-AccNet HE-LHC workshop, Malta, 14-16 October 2010, CERN, EuCARD-CON-2011-001
- Joint Snowmass-EuCARD/AccNet-HiLumi LHC meeting 'Frontier Capabilities for Hadron Colliders 2013’, CERN, 21-22 February 2013

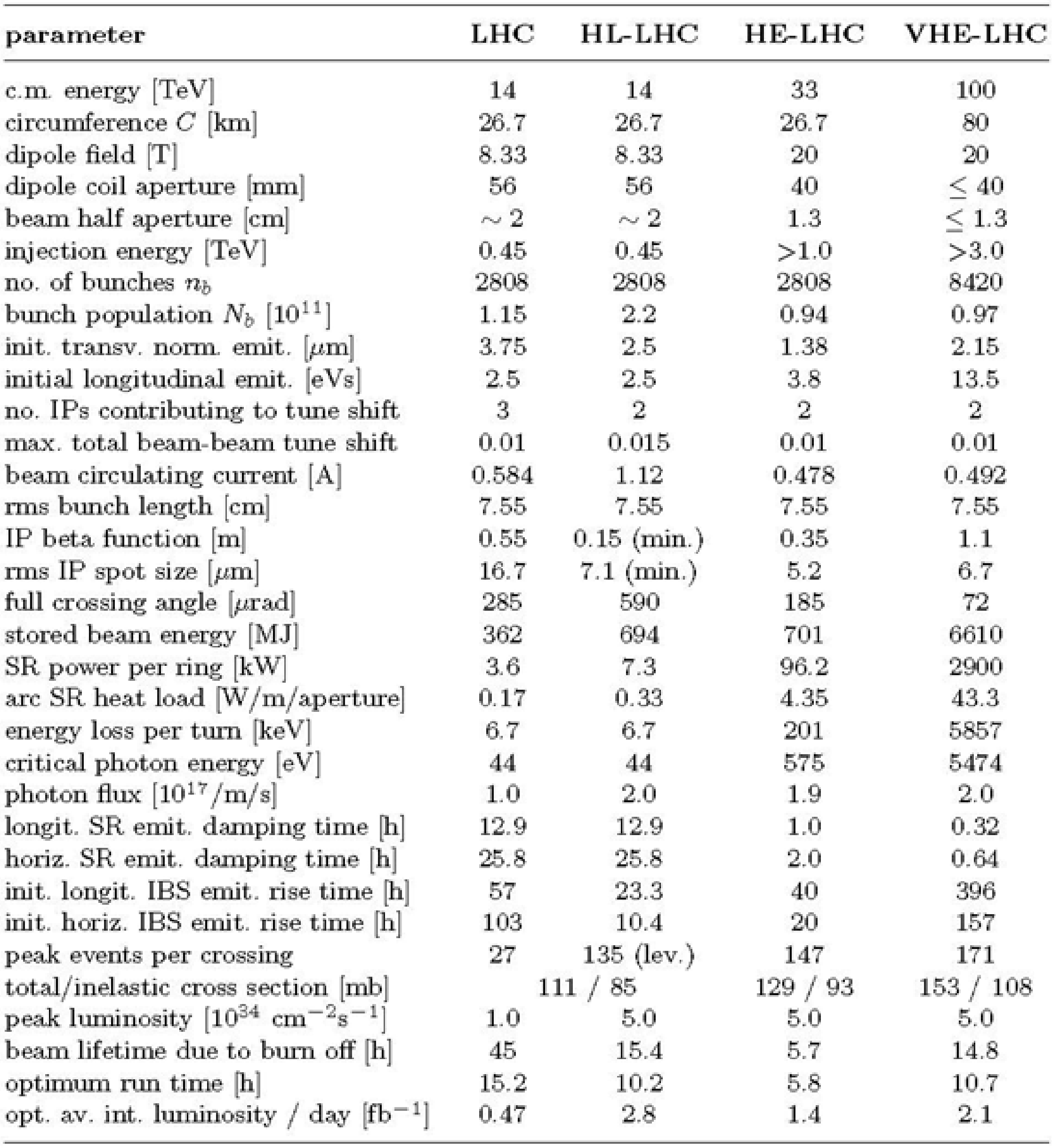
7.1. PARAMETERS

In Table 4, key parameters for HE-LHC and VHE-LHC are compiled and compared with those of the LHC and its high-luminosity upgrade (HL-LHC). For the HE-LHC and VHE-LHC, tentatively an initial luminosity value of $5\text{x}10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$ has been chosen, i.e., the same value as for the HL-LHC. At the higher energy this luminosity is easily attained. The interaction regions need to be adequately shielded against the more energetic luminosity debris. In Table 4 the bunch spacing has been kept at the nominal LHC design value of 25 ns, taking into account event pile up, electron cloud and machine protection. However, for HE-LHC and VHE-LHC much shorter bunch spacings, e.g. 5 ns or 2.5 ns, can also be considered. Thanks to the strong radiation damping, at these bunch spacings even higher luminosities could be attained as for 25 ns, with a reduced event pile up in the experimental detectors. For bunch spacings below 5 ns the electron-cloud build up becomes more benign again (see Fig. 22), while additional mitigation measures (coatings and clearing electrodes) are also being considered.

References:

- EuCARD-AccNet-EuroLumi workshop HE-LHC'10, Mini-Workshop on High-Energy LHC, Malta, 14-16 October 2010
- E. Todesco, F. Zimmermann (eds), The Higher-Energy Large Hadron Collider, Proc. EuCARD-AccNet HE-LHC’10, Malta, 14-16 Oct. 2010, EuCARD-CON-2011-001
- Joint Snowmass-EuCARD/AccNet-HiLumi LHC meeting 'Frontier Capabilities for Hadron Colliders 2013’, CERN, 21-22 February 2013
- O. Dominguez, F. Zimmermann, Beam Parameters and Luminosity Time Evolution for an 80-km VHE-LHC, EuCARD-CON-2013-010.

Table 4: Parameters for HE-LHC and VHE-LHC compared with those of LHC and HL-LHC.



parameter	LHC	HL-LHC	HE-LHC	VHE-LHC
c.m. energy [TeV]	14	14	33	100
circumference C [km]	26.7	26.7	26.7	80
dipole field [T]	8.33	8.33	20	20
dipole coil aperture [mm]	56	56	40	≤ 40
beam half aperture [cm]	~ 2	~ 2	1.3	≤ 1.3
injection energy [TeV]	0.45	0.45	>1.0	>3.0
no. of bunches n_b	2808	2808	2808	8420
bunch population N_b [10^{11}]	1.15	2.2	0.94	0.97
init. transv. norm. emit. [μm]	3.75	2.5	1.38	2.15
initial longitudinal emit. [eVs]	2.5	2.5	3.8	13.5
no. IPs contributing to tune shift	3	2	2	2
max. total beam-beam tune shift	0.01	0.015	0.01	0.01
beam circulating current [A]	0.584	1.12	0.478	0.492
rms bunch length [cm]	7.55	7.55	7.55	7.55
IP beta function [m]	0.55	0.15 (min.)	0.35	1.1
rms IP spot size [μm]	16.7	7.1 (min.)	5.2	6.7
full crossing angle [μrad]	285	590	185	72
stored beam energy [MJ]	362	694	701	6610
SR power per ring [kW]	3.6	7.3	96.2	2900
arc SR heat load [W/m/aperture]	0.17	0.33	4.35	43.3
energy loss per turn [keV]	6.7	6.7	201	5857
critical photon energy [eV]	44	44	575	5474
photon flux [10^{17}/m/s]	1.0	2.0	1.9	2.0
longit. SR emit. damping time [h]	12.9	12.9	1.0	0.32
horiz. SR emit. damping time [h]	25.8	25.8	2.0	0.64
init. longit. IBS emit. rise time [h]	57	23.3	40	396
init. horiz. IBS emit. rise time [h]	103	10.4	20	157
peak events per crossing	27	135 (lev.)	147	171
total/inelastic cross section [mb]	111 / 85		129 / 93	153 / 108
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	5.0	5.0	5.0
beam lifetime due to burn off [h]	45	15.4	5.7	14.8
optimum run time [h]	15.2	10.2	5.8	10.7
opt. av. int. luminosity / day [fb^{-1}]	0.47	2.8	1.4	2.1

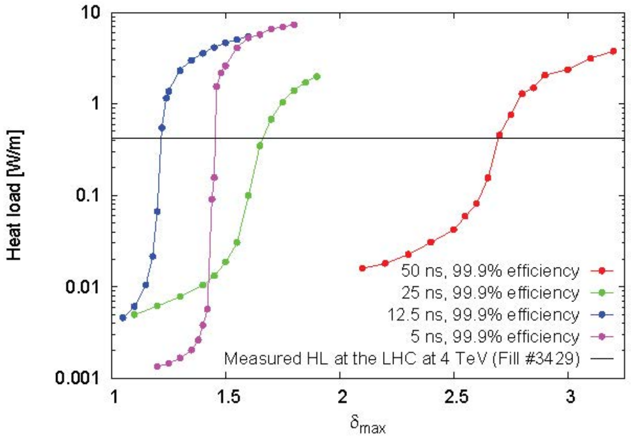


Figure 22: Simulated electron-cloud heat load in the VHELHC arc dipoles as a function of the maximum secondary emission yield for different bunch spacings, considering a chamber half aperture of 13 mm, and assuming that 99.9% of the synchrotron radiation photons are absorbed in dedicated photon stops and do not contribute to the primary photoelectrons initiating the EC build up [O. Dominguez].

7.2. MAGNETS

The 20-T dipole magnets for HE-LHC or VHE-LHC are based on an optimized hybrid-coil design, comprising blocks made from *Nb-Ti*, two types of *Nb_3Sn*, and *HTS*, respectively, which minimizes the cost while maximizing the performance. Figure 23 illustrates the block layout of such a dipole. Without the *HTS* the maximum field would be only about 15 or at most 16 T.

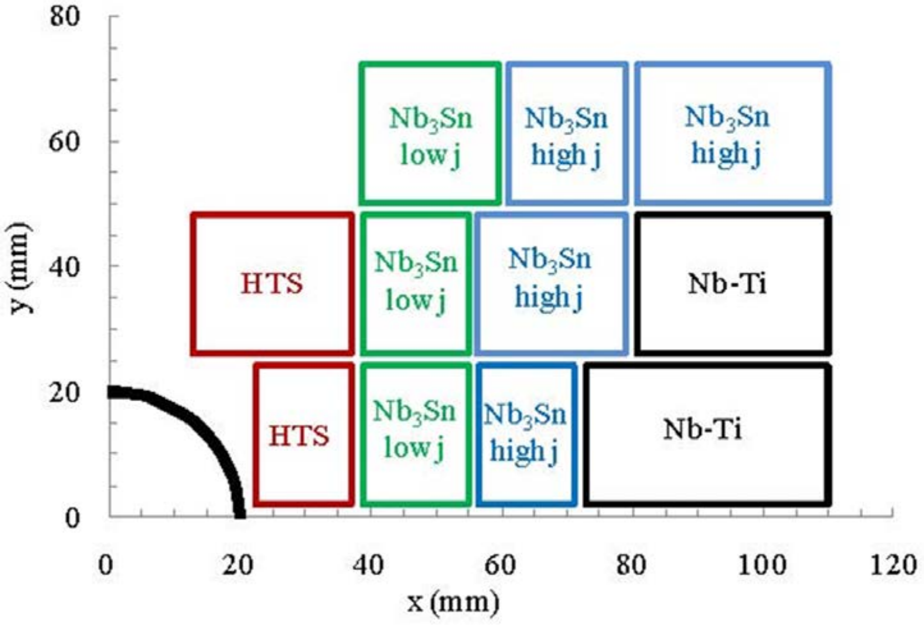


Figure 23: Schematic of a 20-T hybrid dipole magnet for HE-LHC or VHE-LHC [E. Todesco, L. Rossi, P. McIntyre, EuCARD-AccNet HE-LHC'10 workshop]

References:

- Joint Snowmass-EuCARD/AccNet-HiLumi LHC meeting 'Frontier Capabilities for Hadron Colliders 2013', CERN, 21-22 February 2013
- EuCARD-AccNet-EuroLumi workshop HE-LHC'10, Mini-Workshop on High-Energy LHC, Malta, 14-16 October 2010
- E. Todesco and F. Zimmermann (eds), The High-Energy Large Hadron Collider, Proceedings of the EuCARD-AccNet HE-LHC workshop, Malta, 14-16 October 2010, CERN, EuCARD-CON-2011-001

7.3. 80 OR 100-KM TUNNEL

Preliminary geological and environmental studies for identifying the best locations in the Geneva area for such a large infrastructure have been performed. Figure 24 presents one of the possible locations identified.

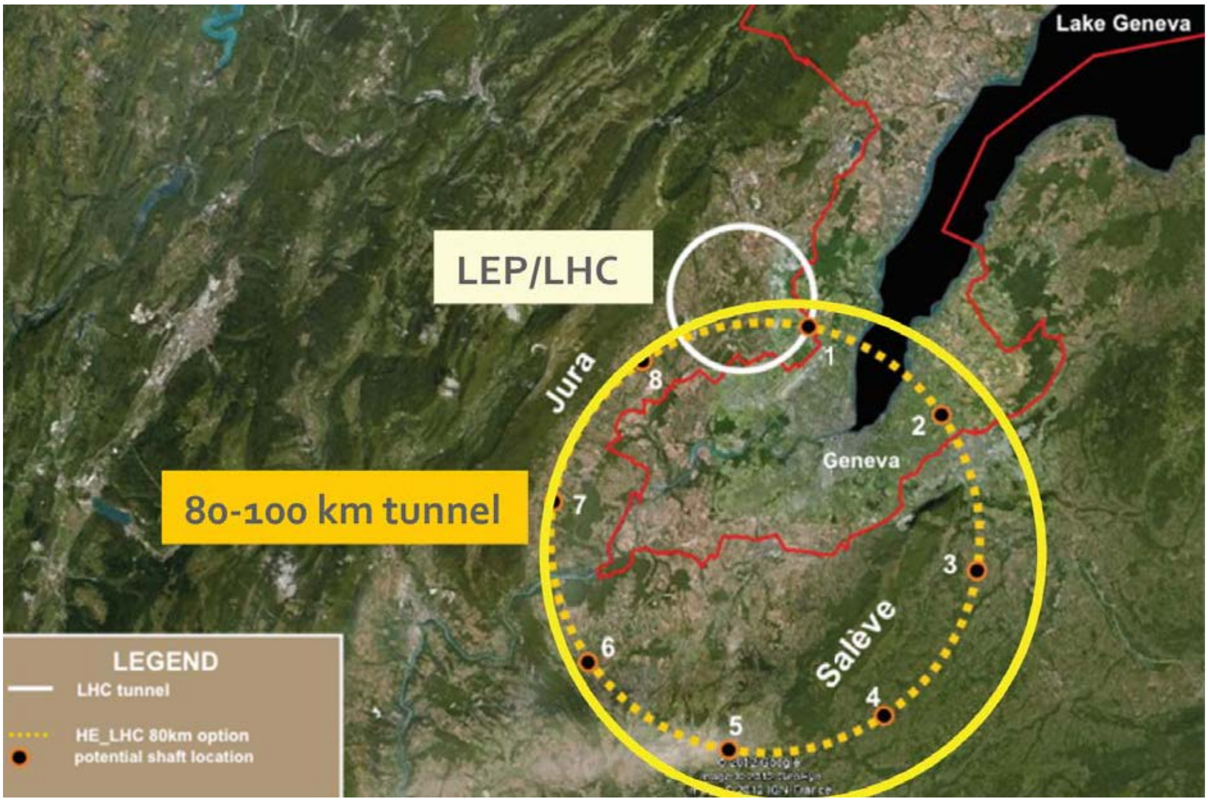


Figure 24: A possible implementation of the VHE-LHC/TLEP tunnel (dashed: 80 km, full: 100 km) in the Geneva area.

References:

- 1st EuCARD-AccNet LEP3 Day, CERN, 18 June 2012 (in particular the talk by J. Osborne)
- Joint Snowmass-EuCARD/AccNet-HiLumi LHC meeting 'Frontier Capabilities for Hadron Colliders 2013', CERN, 21-22 February 2013

7.4. SYNCHROTRON RADIATION & ELECTRON CLOUD

One important novel feature of highest-energy proton storage rings is the high synchrotron radiation power of close to 100 and 3000 kW for HE-LHC and VHE-LHC, respectively, to be contrasted with a few kW at the LHC or HL-LHC. This power translates into a heat load per meter and aperture of 4.4 W/m or 43 W/m for HE-LHC and VHE-LHC, respectively. For the HE-LHC, this heat load could be absorbed on a beam screen (BS) inside the cold magnets as for the present LHC, but at a higher BS temperature of 40-60 K instead of 4.6-20 K . Under this assumption, the existing LHC cryoplants would provide approximately the required cooling capacity. Compared with the LHC, the resistivity of the *Cu*-coated beam screen is enhanced due to its higher temperature (about a factor 4-8 in resistivity for RRR values of 100-200) and due to the larger magnetoresistance (at 20 T field a factor 2.5 compared with zero field, or a factor 1.6 compared with 8.33-T field of the LHC). Since the longitudinal and transverse impedances scale as $\rho^{1/2}$, and considering the high beam energy, the larger copper resistivity is not expected to be a problem for the HE-LHC beam stability. Vacuum considerations, e.g. the proper cryopumping of hydrogen, require an operating temperature below 2-3 K for the cold magnets, surrounding the beam screen. With the anticipated smaller aperture of the beam pipe and enhanced photon desorption, in order to provide sufficient pumping and to avoid pressure instabilities, either the transparency of the beam screen must be significantly increased compared with the LHC or warm photon absorbers be introduced in the magnet interconnections. Coating with open metallic foams has been suggested as a possible means to reduce the secondary emission yield and to improve the vacuum stability.

The approach of a cooled beam screen no longer works for synchrotron-radiation power levels above about 10 W/m. For the VHE-LHC the absorption of the much higher synchrotron-radiation power is more easily done at warm temperature, e.g. by using dedicated photon stops protruding into the beam tube at the end of each dipole magnet. Such photon stops are routinely used in storage-ring light sources. They were also being considered for the VLHC [9], for which a photon-stop cryo-experiment demonstrated the concept. From a vacuum point of view the photon stops would allow removing the beam screen from inside the magnet, gaining precious aperture. In addition a 100-V bias voltage applied to the photon stops would suppress electron emission and electron-cloud formation. The total longitudinal and transverse impedance is expected to remain acceptable despite the large number of photon stops. A small fraction of photons reemitted by X-ray fluorescence and escaping from the stops can be minimized by appropriate surface coating.

References:

- EuCARD-AccNet-EuroLumi workshop HE-LHC'10, Mini-Workshop on High-Energy LHC, Malta, 14-16 October 2010 (in particular the talk by P. Spiller)

- E. Todesco and F. Zimmermann (eds), The High-Energy Large Hadron Collider, Proceedings of the EuCARD-AccNet HE-LHC workshop, Malta, 14-16 October 2010, CERN, EuCARD-CON-2011-001
- Joint Snowmass-EuCARD/AccNet-HiLumi LHC meeting 'Frontier Capabilities for Hadron Colliders 2013', CERN, 21-22 February 2013

8. TLEP

With a maximum centre-of-mass energy of 209 GeV, LEP2, in operation at CERN until 2001, has been the highest energy e^+e^- collider so far. The discovery, in 2012, by two LHC experiments, of a Higgs-like boson at an energy reachable by a collider slightly more energetic than LEP2, together with the excellent performance achieved in the two B factories PEP-II and KEKB during the first decade of the 21st century, have led to new proposals for a next-generation circular e^+e^- collider at the energy frontier. In order to serve as a Higgs factory such a collider needs to be able to operate at least at a centre-of-mass energy of 240 GeV (for efficient $e^+e^- \rightarrow ZH$ production), i.e. 15% above the LEP2 peak energy. Reaching even higher energies, e.g. up to 350 GeV centre of mass, for t-tbar production, would also be possible for a new ring of larger circumference. In 2011 and 2012, several concrete proposals of high-energy circular e^+e^- colliders have emerged. For example, as least expensive option, “LEP3,” is proposed to be installed in the LEP-LHC tunnel, the existence of which, together with the associated infrastructure and the LHC detectors, is an attractive and economical starting point. Another option is a machine with three times the LEP or LHC conference, a triple LEP, or “TLEP,” which could deliver extremely high luminosities for c.m. energies below 240 GeV and could also operate above the t-tbar threshold at a c.m. energy of 350 GeV, with a luminosity still close to 10^{34} cm^{-2}s^{-1} at up to four collision points. The same two machines could deliver an unprecedentedly high luminosity of up to 10^{36} cm^{-2}s^{-1} for TLEP, at the Z pole (91 GeV c.m.), and also operate at the WW threshold (160 GeV c.m.). Starting in the summer of 2012 EuCARD-AccNet has organized 5 targeted workshops on TLEP and LEP3, advancing the basic design, helping to set up an international design study including working groups, and informing the community.

In view of the short beam lifetime at the high target luminosity, due to radiative Bhabha scattering, to achieve a high average luminosity the circular Higgs factory should be a double ring, as sketched in Fig. 25. Namely the collider ring operating at constant energy is complemented by a second ring installed in the same tunnel to “top up” the collider current continuously. Top-up injection is, or has been, routinely done in modern synchrotron light sources and in the two high-luminosity B factories PEP-II and KEKB.

For both TLEP and LEP3 at the Z pole significant longitudinal polarisation of both beams, up to 80%, may be possible, but this requires further investigation, especially when operating with very high luminosity. In TLEP some transverse polarization, allowing for precise energy calibration, may be obtained also at the WW threshold. Following the idea of LEP3 and TLEP, similar studies of circular e^+e^- Higgs factories have begun in Japan (SuperTRISTAN), China, Russia, and in the US.

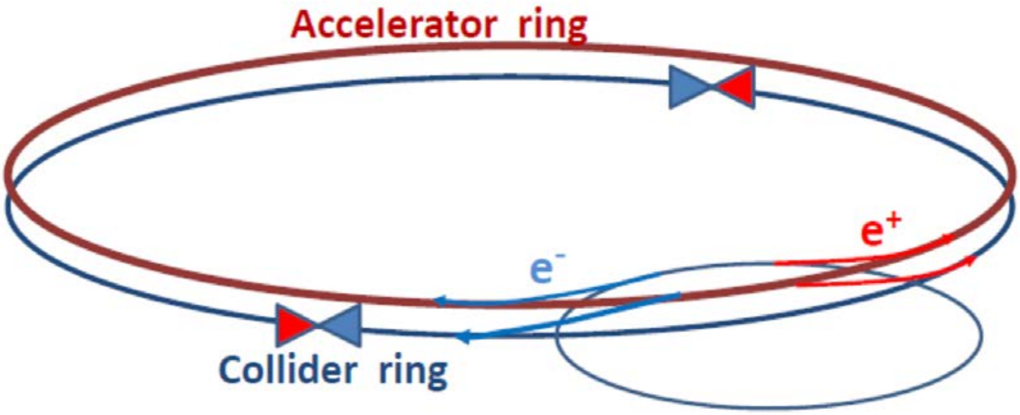


Figure 25: Schematic of circular highest-luminosity Higgs-factory with top-up injection [A. Blondel].

References:

- 1st EuCARD-AccNet LEP3 Day, CERN, 18 June 2012
- 2nd EuCARD-AccNet LEP3 workshop, CERN, 23 October 2012
- 3rd EuCARD-AccNet TLEP workshop, CERN, 10 January 2013
- 4th EuCARD-AccNet TLEP workshop, CERN, 4-5 April 2013
- 5th EuCARD-AccNet TLEP workshop, FNAL, 25-26 July 2013

8.1. PARAMETERS

Table 5 compares parameters for LEP3 and TLEP with those of LEP2. Important design constraints are the synchrotron radiation power, the total beam-beam tune shift, the minimum β_y^* (which is 50 times smaller than for LEP2), and the additional beam lifetime limitations and bunch lengthening due to beamstrahlung.

8.2. R&D

The most critical hardware component of TLEP is the radio-frequency (RF) system. At the t-tbar threshold an RF voltage of 12 GV needs to be provided. The 700-800 MHz SC cavity technology being developed for eRHIC, SPS, and ESS seems to be a good choice. Pertinent R&D is ongoing at BNL, CERN, and ESS for 704 MHz cavities and components. A similar frequency, 802 MHz, would be synergetic with SPS and LHC harmonic systems and LHeC. With 20 MV/m cavity gradient, for TLEP at 175 GeV beam energy the total cryomodule length is estimated to be about 902 m, which is similar to the 812 m of cryomodule length at LEP2. With a cavity Q_0 value of $2x10^{10}$ the total dynamic heat load at 1.9 K would be 25 kW, comparable to the existing LHC cryoplant capacity.

The large beam energy loss from synchrotron radiation implies that close to 200 kW need to be provided for each ~1-m long cavity. This appears well within reach of present technology:

Water and air-cooled fundamental power couplers developed for ESS and SPL have been tested up to 1.2 MW with 10% duty cycle. LHC windows are routinely tested above 500 kW in cw. The average HOM power per cavity would be of order 5 kW for TLEP at 240 GeV c.m. A design and prototype exists for eRHIC which can handle up to 7.5 kW, and for KEKB with 15 kW. A possible RF power source would be klystrons, which are available on the market in the 500-800 MHz frequency range from three different companies, with 62-65% efficiency. The high voltage power converters for the RF system could be thyristor-based with 95% efficiency, but non-optimum AC power quality, or be switched-mode converters with better quality, but only 90% efficiency. The klystron efficiency of about 65% is reached only if the klystron is run at saturation without headroom for RF feedback as in LEP2.

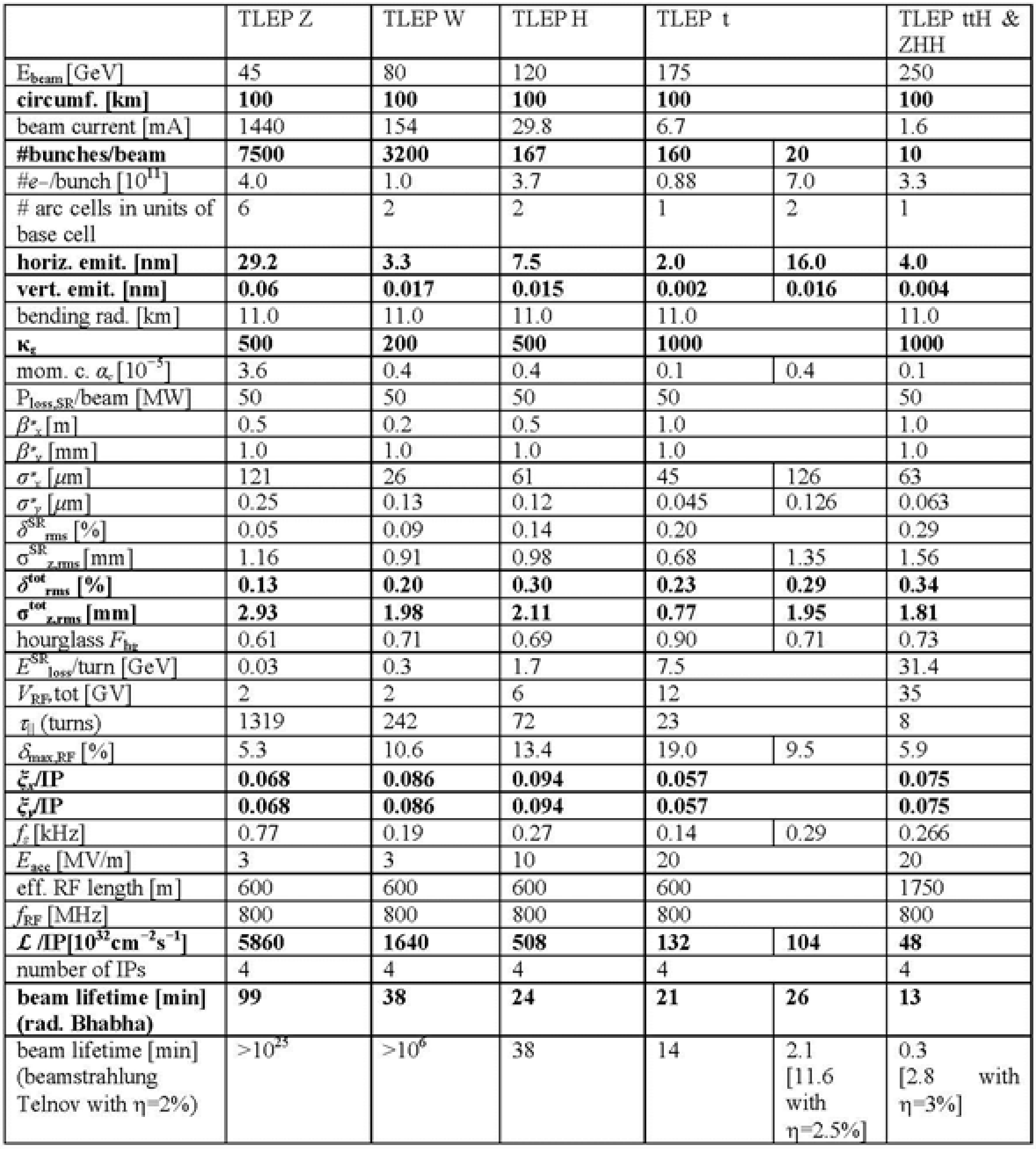
Also taking into account the RF distribution losses of 5 to 7% in waveguides and circulators, the overall RF efficiency (wall to beam) is estimated to be between 54% and 58%. The total electric power for the RF system and the cryo system combined is then extrapolated at about 210-220 MW for TLEP at the t-tbar threshold, and potentially less at lower energies. At energies of 240 GeV (c.m.) and below, where the maximum voltage does not exceed 6 GV, the RF system could be decoupled between the two beams, allowing for a complete separation, with no parasitic collisions anywhere in the machine.

SuperKEKB, the beam commissioning of which will start in 2015, is set to explore and demonstrate many of the key concepts of a circular Higgs factory: Its β^*_y is only 0.3 mm, 3-4 times smaller than the TLEP or LEP3 design value. Its beam lifetime – limited by Touschek scattering – will be about 5 minutes, even shorter than for TLEP, and maintained by top-up injection. To achieve this SuperKEKB will need to establish a sufficiently large off-momentum dynamic aperture of ±1.5%. The SuperKEKB design emittance ratio $\varepsilon_x/\varepsilon_y$ of about 400 is a factor of 2 better than obtained at LEP2 and close to the value assumed for TLEP.

References:

- 1st EuCARD-AccNet LEP3 Day, CERN, 18 June 2012
- 2nd EuCARD-AccNet LEP3 workshop, CERN, 23 October 2012
- 3rd EuCARD-AccNet TLEP workshop, CERN, 10 January 2013
- 4th EuCARD-AccNet TLEP workshop, CERN, 4-5 April 2013
- 5th EuCARD-AccNet TLEP workshop, FNAL, 25-26 July 2013

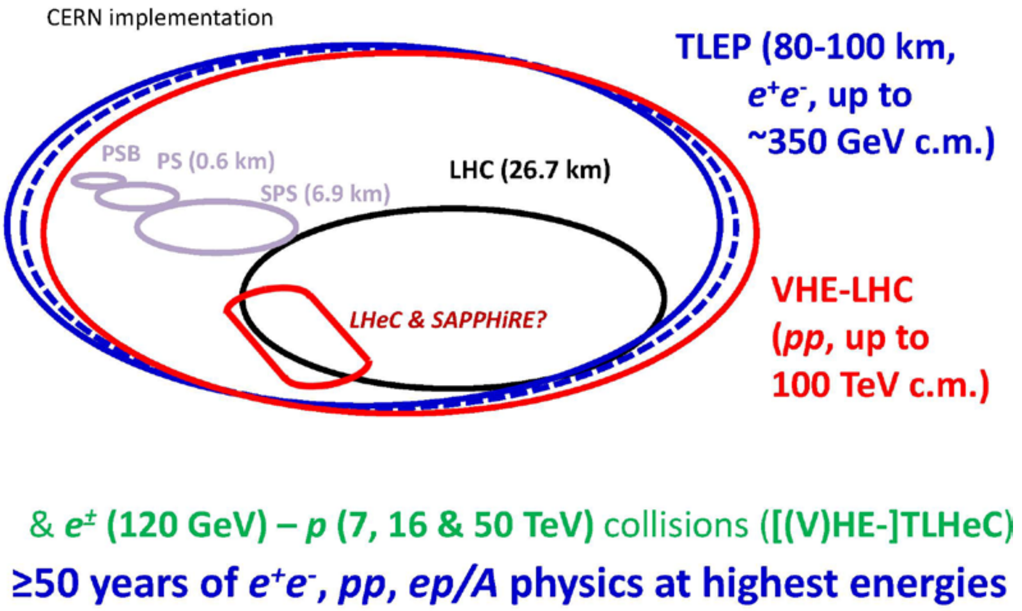
Table 5: Parameters for different operation modes of TLEP, ranging from the *Z* pole (45 GeV beam energy), over the *W* threshold (80 GeV), and Higgs production (120 GeV) to the t-tbar threshold (175 GeV). A possible future extension to a c.m. energy of 500 GeV (250 GeV beam energy) for studies of the *ttH* and *ZHH* coupling strengths is also indicated.



	TLEP Z	TLEP W	TLEP H	TLEP t		TLEP ttH & ZHH
E_{beam} [GeV]	45	80	120	175		250
circumf. [km]	**100**	**100**	**100**	**100**		**100**
beam current [mA]	1440	154	29.8	6.7		1.6
#bunches/beam	**7500**	**3200**	**167**	**160**	**20**	**10**
$\#e-$/bunch [10^{11}]	4.0	1.0	3.7	0.88	7.0	3.3
# arc cells in units of base cell	6	2	2	1	2	1
horiz. emit. [nm]	**29.2**	**3.3**	**7.5**	**2.0**	**16.0**	**4.0**
vert. emit. [nm]	**0.06**	**0.017**	**0.015**	**0.002**	**0.016**	**0.004**
bending rad. [km]	11.0	11.0	11.0	11.0		11.0
κ_ε	**500**	**200**	**500**	**1000**		**1000**
mom. c. α_c [10^{-5}]	3.6	0.4	0.4	0.1	0.4	0.1
$P_{loss,SR}$/beam [MW]	50	50	50	50		50
β^*_x [m]	0.5	0.2	0.5	1.0		1.0
β^*_y [mm]	1.0	1.0	1.0	1.0		1.0
σ^*_x [μm]	121	26	61	45	126	63
σ^*_y [μm]	0.25	0.13	0.12	0.045	0.126	0.063
δ^{SR}_{rms} [%]	0.05	0.09	0.14	0.20		0.29
$\sigma^{SR}_{z,rms}$ [mm]	1.16	0.91	0.98	0.68	1.35	1.56
δ^{tot}_{rms} **[%]**	**0.13**	**0.20**	**0.30**	**0.23**	**0.29**	**0.34**
$\sigma^{tot}_{z,rms}$ **[mm]**	**2.93**	**1.98**	**2.11**	**0.77**	**1.95**	**1.81**
hourglass F_{hg}	0.61	0.71	0.69	0.90	0.71	0.73
E^{SR}_{loss}/turn [GeV]	0.03	0.3	1.7	7.5		31.4
V_{RF},tot [GV]	2	2	6	12		35
$\tau_{\parallel}$ (turns)	1319	242	72	23		8
$\delta_{max,RF}$ [%]	5.3	10.6	13.4	19.0	9.5	5.9
ξ_x**/IP**	**0.068**	**0.086**	**0.094**	**0.057**		**0.075**
ξ_y**/IP**	**0.068**	**0.086**	**0.094**	**0.057**		**0.075**
f_s [kHz]	0.77	0.19	0.27	0.14	0.29	0.266
E_{acc} [MV/m]	3	3	10	20		20
eff. RF length [m]	600	600	600	600		1750
f_{RF} [MHz]	800	800	800	800		800
$\mathcal{L}$ **/IP[10^{32}cm^{-2}s^{-1}]**	**5860**	**1640**	**508**	**132**	**104**	**48**
number of IPs	4	4	4	4		4
beam lifetime [min] (rad. Bhabha)	**99**	**38**	**24**	**21**	**26**	**13**
beam lifetime [min] (beamstrahlung Telnov with η=2%)	>10^{25}	>10^6	38	14	2.1 [11.6 with η=2.5%]	0.3 [2.8 with η=3%]

9. COHERENT VISION BEYOND LHC

Figure 25 illustrates a proposed coherent strategy for the future accelerator-based high-energy physics emerging from the EuCARD-AccNet workshops. It is based on a sequence continuing the historical success route of (ISR-)PS-SPS-LEP/LHC, with the possible intermediate Higgs factories of LHeC and SAPPHiRE, towards TLEP and VHE-LHC, including a VHE-TLHeC. This offers the panorama of an exciting frontier physics programme until the end of the 21st century.



& $e^{\pm}$ (120 GeV) – *p* (7, 16 & 50 TeV) collisions ([(V)HE-]TLHeC)

≥50 years of e^+e^-, *pp*, *ep/A* physics at highest energies

Figure 25: Possible long-term strategy for HEP and CERN, based on a continued sequence of circular machines, exploring the Higgs boson, searching for new physics, and pushing the energy frontier.

9.1. SYNERGIES

There are numerous obvious synergies in the proposed strategy. We present a few examples.

The Nb_3Sn magnet and *HTS* cable developments for HL-LHC open up the path for the VHE-LHC (see Fig. 26).

TLEP could re-use the RF system and cryogenics of LHeC and SAPPHiRE, if the latter were built. By design, the RF system of TLEP is identical to the one of LHeC. A low-energy version of LHeC could also serve as pre-injector for TLEP.

Another strong synergy is between TLEP and VHE-LHC. TLEP would share the tunnel, the cryogenics, the detectors (Fig. 27), and possibly the magnets with the VHE-LHC or its injector ring. In addition, running both machines together could realize the highest-energy highest-luminosity lepton-hadron collider.

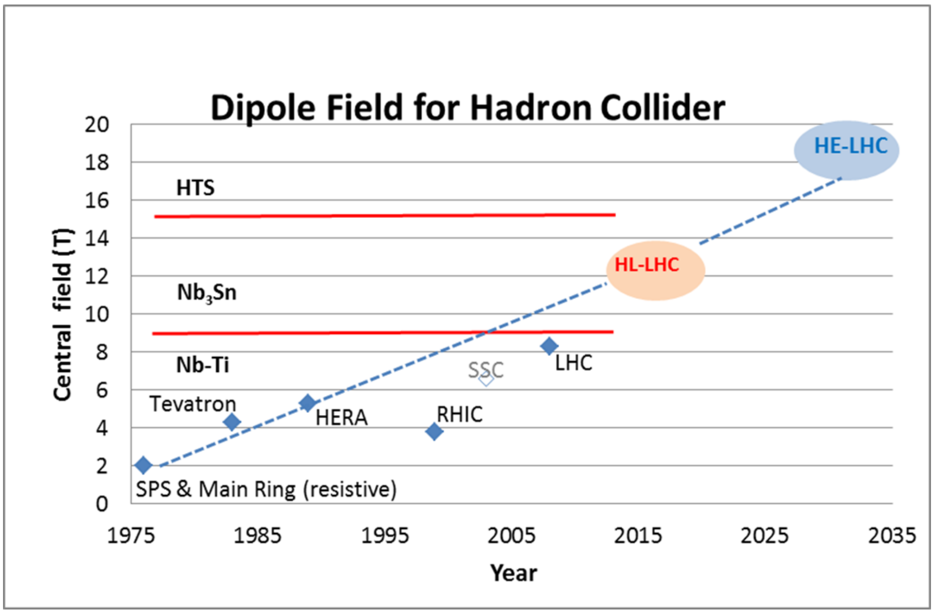


Figure 26: Accelerator dipole field versus year [L. Rossi]

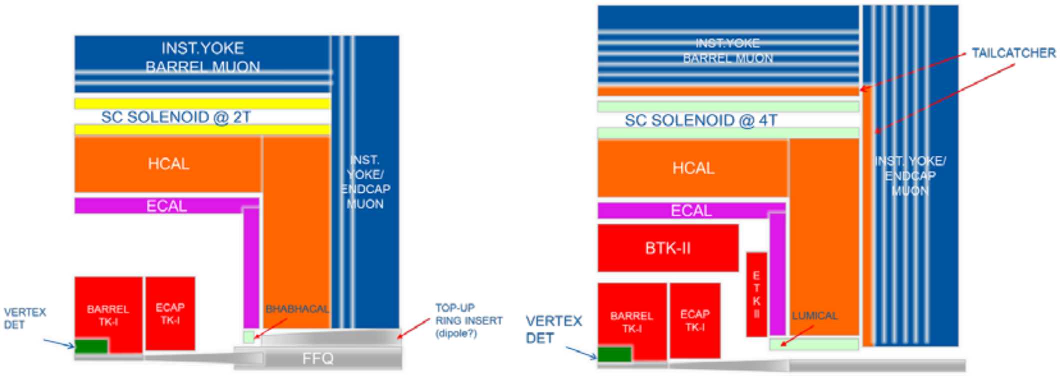


Figure 27: Schematic of modular detector for TLEP (left) and VHE-LHC (right) [E. Meschi].

References:

- 3^{rd} EuCARD-AccNet TLEP workshop, CERN, 10 January 2013
- Joint Snowmass-EuCARD/AccNet-HiLumi LHC meeting 'Frontier Capabilities for Hadron Colliders 2013', CERN, 21-22 February 2013
- 4th EuCARD-AccNet TLEP workshop, CERN, 4-5 April 2013

9.2. POSSIBLE TIME LINES

Possible time lines for FAIR and LHeC/SAPPHiRE/TLEP/VHE-LHC are illustrated in Figs. 28 and 29.

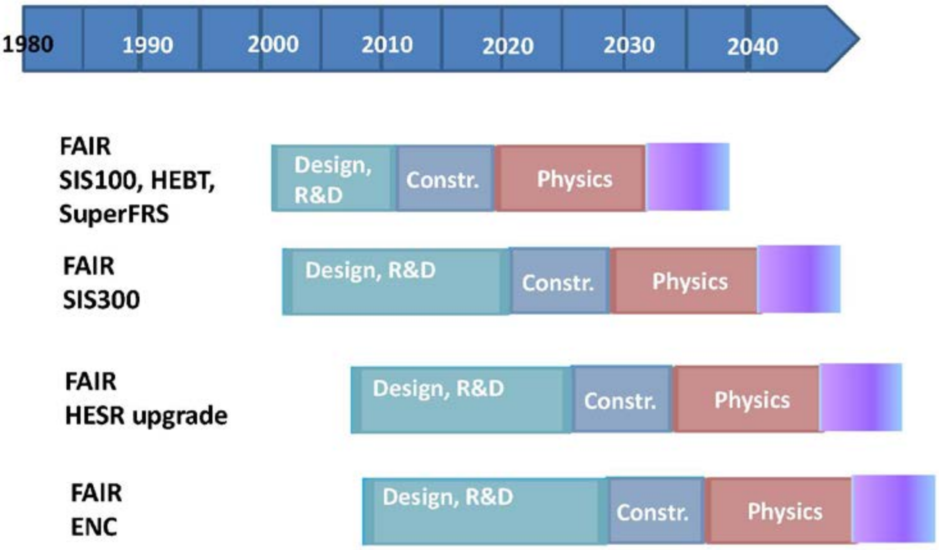


Figure 28: Possible (purely speculative) time line for FAIR project and its extensions.

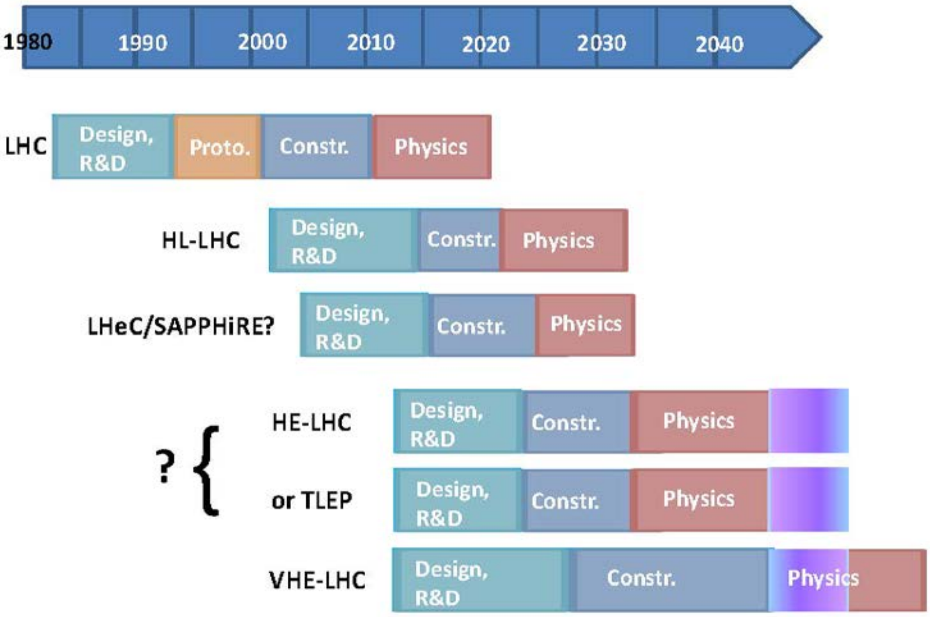


Figure 29: Possible time line for future colliders at CERN.

9.3. R&D PRIORITIES

EuCARD-AccNet identified the following key R&D priorities for the high-energy or high-intensity accelerators of the 21st century.

- high-gradient SC RF cavities for high-current CW operation in view of LHeC/SAPPHiRE/TLEP, including construction of an SRF test facility at CERN
- high-field magnet development for Hl-LHC, HE-LHC and VHE-LHC
- crab cavities for HL-LHC
- fast cycling SC (transmission-line or FAIR-type) magnets for VHE-LHC injector ring
- efficient RF power sources for TLEP and LHeC
- SR handling for TLEP and VHE-LHC
- design of low-beta IR optics with large momentum acceptance
- high-power high-repetition rate laser for SAPPHiRE (R&D performed by ICAN)
- crystal collimators and further studies of crystal channeling
- advanced cooling techniques, such as microbunching amplified electron cooling

10. CONCLUSIONS

EuCARD-AccNet-EuroLumi helped defining the HL-LHC, elucidated the staged FAIR programme, and contributed concepts and ideas for several key items – SC magnets, crab cavities, and crystal collimation.

After the launch of the LHC HiLumi project, and partly stimulated by the 2012 discovery of the Higgs boson at the LHC, AccNet has been looking beyond the HL-LHC, and organized the first-ever workshops on HE-LHC, VHE-LHC, LEP3, TLEP, and SAPPHiRE, respectively – all of which promising accelerator concepts for high-energy physics in the medium and longer-term future.

In total 27 workshops were held in the frame of AccNet-EuroLumi, which have given rise to a long-term vision for accelerator-based high-energy particle physics and identified the associated key R&D items.

A characteristic feature of the emerging strategy is a stepwise approach, with plenty of synergies, where each machine relies on components of the former and also prepares the following ones. This strategy provides for highest-precision tests of the standard model and represents the only conceivable path to reach the 100-TeV energy scale with near state-of-the-art technology.

11. WORKSHOPS ORGANIZED OR CO-ORGANIZED BY WP4.2 EUCARD-EUROLUMI

Table 6: Workshops and mini-workshops held in the frame of EuroLumi, showing the topic, partner organizers (if any), date, location, number of registered participants, and the activity index ("AI"). The latter is defined as the ratio of the number of registrants and the number of speakers. It is meant to be an indicator of the dynamic interactivity. For comparison, at a typical IPAC conference the AI is about 12.

#	Topic	Organizers	Time	Place	Registrants	AI
1	LHC Crab cavities "LHCC09"	EuroLumi, CERN, KEK, US-LARP	16-18 Sep 2009	CERN	54 from EU, USA, Japan	~1.2
2	Anti e-cloud coatings	EuroLumi	12-13 Oct 2009	CERN	41 from EU, USA, Japan, Pakistan	~1.6
3	Crystal Collimation	EuroLumi	9 Nov 2009	CERN	~29 from EU, Russia, USA	~1.3
4	*p* driven plasma acceleration	EuroLumi	17-18 Dec 2009	CERN	24 from EU. USA, Russia	~2.0
5	Health applications	CERN, EuCARD, EuroLumi	2-4 Feb 2010	CERN	~160 from EU, USA	~4.0
6	*p* driven plasma acceleration	EruoLumi	11-12 Mar 2010	CERN	16 from EU	2.3
7	Higher energy LHC	EuroLumi	14-16 Oct. 2010	U. Malta	56 from EU, US, Japan	1.6
8	Crystal collimation	EuroLumi	25-27 Oct. 2010	CERN	32 from EU, Russia and US	1.0
9	LHC Crab cavities "LHCC10"	EuroLumi, CERN, KEK, US-LARP	15-17 Dec. 2010	CERN	50 from EU, US, Japan	1.1
10	Electron cloud at CERN and GSI	EuroLumi	7–8 Mar. 2011	CERN	28 from EU, Japan, Mexico	1.4
11	Optics Measurements, Corrections and Modeling	EuroLumi	20-22 Jun. 2011	CERN	56 from EU, US, Japan	1.3
12	MulCoPim'11	ESA & U.	21-23	Valencia	~120 from EU,	~1.5

		Valencia EuroLumi	Sep. 2011		US	
13	LHC crab cavities, "LHC-CC11"	EuroLumi, KEK, US-LARP, UK CI/DL	14-15 Nov. 2011	CERN	52	~1.4
14	Electron Cloud	INFN-LNF, INFN-Pisa CERN LER, EuroLumi	5-9 Sep. 2012	La Biodola, Italy	62 from EU, US, Japan	~1.2
15	Computing in Accelerator Physics	U. Rostock, EuroLumi, RFTech, CST	19-25 Sep 2012	Warnemünde, Germany	about 100 from EU, US, Russia, and Japan	~1.2
16	LEP3 & TLEP	EuroLumi	18 June 2012	CERN	~30 from EU, US, Russia, Japan	~1.7
17	LEP3 & TLEP	EuroLumi	23 Oct. 2012	CERN	~30 from EU, US, Japan	~2.0
18	HL-LHC	EuroLumi, LARP, HiLumi LHC	14-16 Dec. 2012	Frascati	130 from EU, US, Japan	~1.5
19	TLEP	EuroLumi	10 Jan. 2013	CERN	~40 from EU, US, Russia, Japan	~2.2
20	SC Magnet Quenches	HiLumi LHC, EuCARD WP7 (HFM), EuroLumi	15-16 Jan. 2013	CERN	50 from EU, US, Japan	~3.2
21	SAPPHiRE	EuroLumi	19 Feb. 2013	CERN	25 from EU, US, Japan, Russia	1.6
22	VHE-LHC	HiLumi, EuroLumi, US-Snowmass	21-22 Feb. 2013	CERN	~50 from EU, US	~2.2
23	TLEP	EuroLumi	4 May 2013	CERN	27 from EU, US, China	1.2
24	Space Charge	EuroLumi, ICFA, HICforFAIR, LIU	16-19 Apr. 2013	CERN	83 from EU, US, Japan, China, Mexico, Russia	1.9

25	Future of accelerators	EuCARD, EuroLumi	10-14 Jun 2013	CERN	186 from EU, US, Japan, Israel	3.7
26	LHC Optics	EuroLumi, HiLumi	17-18 Jun 2013	CERN	53 from EU, US	1.7
27	TLEP	EuroLumi, LPC, FNAL	25-27 Jul. 2013	FNAL	60 from US, EU, Russia, Japan, Mexico	2.3

12. PUBLICATIONS AND EUCARD DOCUMENTS OF WP4.2 EUCARD-EUROLUMI

Table 7: EuCARD-WP4.2 documents, publications and presentations.

1.	O. Brüning et al, *Summary of the 2013 LHC Optics Measurement and Correction Review*, EuCARD-REP-2013-003
2.	W. Scandale, *UA9 Results from Crystal Collimation Tests in the SPS & Future Strategy*, EuCARD-REP-2013-002
3.	F. Zimmermann, *Bending and Focusing with Plasmas and Crystals - Potential and Challenges*, EuCARD'13 "Visions for the Future of Particle Accelerators," CERN, 11 June 2013.
4.	M. Koratzinos, A.P. Blondel, R. Aleksan, O. Brunner, A. Butterworth, P. Janot, E. Jensen, J. Osborne, F. Zimmermann, J. R. Ellis, M. Zanetti, *TLEP: A High-Performance Circular e+e- Collider to Study the Higgs Boson*, Proc. IPAC'13 Shanghai, 12-17 May 2013, EuCARD-CON-2013-013
5.	K. Ohmi, F. Zimmermann, *Simulated Beam-Beam Limit for Circular Higgs Factories*, Proc. IPAC'13 Shanghai, 12-17 May 2013, EuCARD-CON-2013-012
6.	O. Dominguez, F. Zimmermann, *Electron-Cloud Maps for the LHC Scrubbing Optimization*, Proc. IPAC'13 Shanghai, 12-17 May 2013, EuCARD-CON-2013-011
7.	O. Dominguez, F. Zimmermann, *Beam Parameters and Luminosity Time Evolution for an 80-km VHE-LHC*, Proc. IPAC'13 Shanghai, 12-17 May 2013, EuCARD-CON-2013-010
8.	G.H.I. Maury Cuna, D. Sagan, G. Dugan, F. Zimmermann, *Synchrotron-Radiation Photon Distributions for Highest Energy Circular Colliders*, Proc. IPAC'13 Shanghai, 12-17 May 2013, EuCARD-CON-2013-009
9.	O. Brüning, M. Klein, S. Myers, J. Osborne, L. Rossi, C. Waaijer, F. Zimmermann, *Civil Engineering Feasibility Studies for Future Ring Colliders at CERN*, Proc. IPAC'13 Shanghai, 12-17 May 2013, EuCARD-CON-2013-008
10.	B. Yee-Rendon, R. Lopez-Fernandez, T. Baer, J. Barranco, R. Calaga, A. Marsili, R. Tomas, F. Zimmermann, *Machine Protection Studies for a Crab Cavity in the LHC*, Proc. IPAC'13 Shanghai, 12-17 May 2013, EuCARD-CON-2013-007
11.	G. Franchetti and F. Schmidt, *Summary of the Space Charge Workshop 2013 (SC-13)*, CERN, Geneva, 16-19 April 2013, EuCARD-REP-2013-001
12.	R. Cimino, G. Rumolo, F. Zimmermann (eds.), *Proceedings of ECLOUD'12: Joint INFN-CERN-EuCARD-AccNet Workshop on Electron-Cloud Effects*, La Biodola, Isola d'Elba, Italy, 5-9 June 2012, EuCARD-CON-2013-001
13.	K. Ohmi, *Beam-Beam Simulations: Dynamical Effects and Beam-Beam Limit for LEP3*, CERN, 4 December 2012, EuCARD-PRE-2012-004
14.	K. Ohmi, *Beam-Beam Synchro-Beta Resonance*, CERN, 4 December 2012, EuCARD-PRE-2012-005
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