LHEC AND HE-LHC: ACCELERATOR LAYOUT AND CHALLENGES

F. Zimmermann, CERN, Geneva, Switzerland

Abstract

This paper presents a concise description of the layouts of the proposed Large Hadron electron Collider (LHeC) and the High-Energy Large Hadron Collider (HE-LHC), discusses their main accelerator-physics and technology challenges, details the required LHC modifications, and describes the associated global schedules with decision points.

LARGE HADRON ELECTRON COLLIDER (LHEC)

The Large Hadron electron Collider is a proposed new facility at CERN which will collide the 7-TeV protons circulating in the Large Hadron Collider (LHC) with a high-energy lepton beam at a single collision point. The high-energy lepton beam is provided either by a new ring in the LHC tunnel, similar to LEP, which would also require a new injector complex of about 10 GeV, or by a novel recirculating 6-pass energy recovery linac. The two LHeC options are illustrated in Fig. 1.

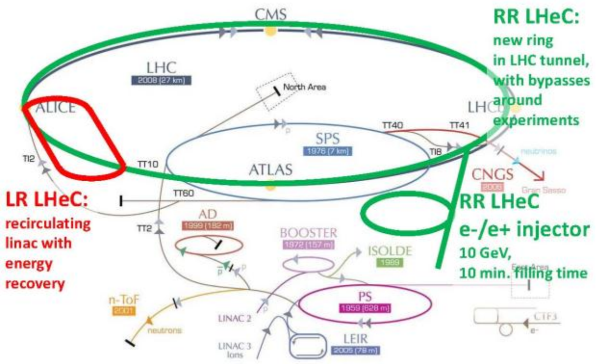

Fig. 1: Schematic of a Large Hadron electron Collider (LHeC) based on the LHC: option 1 consists of a new lepton ring in the LHC tunnel together with a 10-GeV injector complex (green color), option 2 of a Racetrack-shape multiple-pass recirculating energy-recovery linac placed in a new, smaller separate tunnel (red).

In September 2011 a draft Conceptual Design Report (CDR) for a future Large Hadron electron Collider based on the LHC was completed and published as a CERN LHeC Note [1]. This draft CDR was coauthored by about 150 experimentalists and theorists from approximately 50 institutes around the world, and features roughly 600 pages. It has been sent to a panel of distinguished expert referees, whose reports and feedbacks are used to improve and finalize the CDR, which is expected to be complete by March 2012. The further schedule foresees the composition of a Technical Design Report (TDR) by 2014, after which the LHeC construction could start.

The main performance targets are set by the physics goals and are summarized as follows: The electron energy beam should be at least 60 GeV and the electron-proton luminosity at least 10^{33} cm^{-2}s^{-1}; the total electrical power needed for the electron branch of the LHeC should be less than 100 MW; the LHeC should also provide positron-proton collisions with similar luminosity; the LHeC should operate simultaneously with *pp* physics collisions in 2 to 4 of the present LHC experiments; both electron and positron beams should be polarized; and the particle-physics detector acceptance should extend down to 1°.

Design lepton-beam parameters are listed in Table 1, for the ring-ring (RR) LHeC, for the linac-ring (LR) LHeC based on a recirculating energy-recovery linac (ERL), and for a third option of a future higher-energy LHeC based on a straight pulsed linac. Table 2 shows the assumed parameters for the LHC proton beam at the *ep* collision point.

Table 1: Design electron-beam parameters for the ring-ring (RR) LHeC, for the cw Linac-Ring (LR) LHeC with energy recovery, and for a pulsed straight higher-energy LR LHeC without energy recovery.

electron beam	**RR**	**LR**	**LR***
e^- energy at IP[GeV]	60	60	140
luminosity [10^{32} cm^{-2}s^{-1}]	17	10	0.44
polarization [%]	40	90	90
bunch population [10^9]	26	2.0	1.6
e- bunch length [mm]	10	0.3	0.3
bunch interval [ns]	25	50	50
transv. emit. $\gamma\varepsilon_{x,y}$ [mm]	0.58, 0.29	0.05	0.1
rms IP beam size $\sigma_{x,y}$ [μm]	30, 16	7	7
e- IP beta funct. $\beta^*_{x,y}$[m]	0.18, 0.10	0.12	0.14
full crossing angle [mrad]	0.93	0	0
geometric reduction H_{hg}	0.77	0.91	0.94
repetition rate [Hz]	N/A	N/A	10
beam pulse length [ms]	N/A	N/A	5
energy recovery efficiency	N/A	94%	N/A
average current [mA]	131	6.6	5.4
tot. wall plug power[MW]	100	100	100

For the proton beam a bunch spacing of 50 ns and a bunch population of N_b=1.7x10^{11} are assumed together with an rms normalized rms emittance of 3.75 μm. These numbers are conservative, since the LHC has already been operated with proton beams of two times higher brightness. The proton IP beta function considered for the linac-ring LHeC of β*~0.1 m can be achieved by reducing the free length between the last proton quadrupole and the interaction point (IP) to 10 m, down from 23 m for the *pp* IP, by squeezing only one of the two proton beams, and by using stronger larger-aperture quadrupole magnets made from Nb_3Sn instead of Nb-Ti, as are in the process of being developed for the High Luminosity LHC (HL-LHC) project. Indeed an even smaller β^* of 0.025 m may be possible in LHC IPs 3 or 7 using the ATS optics [3], as well as a smaller emittance of 2 μm [4,5]. Using these numbers a luminosity of up to L~10^{34} cm^{-2}s^{-1} may be within reach for the R-L LHeC.

In addition to *ep* collisions, the LHeC design also foresees lepton-deuteron and lepton-lead collisions.

Table 2: Design proton-beam parameters for both the riong-ring and linac-ring versions of the LHeC.

proton beam	RR	LR
bunch population [10^{11}]	1.7	1.7
transvserse emittance $\gamma\varepsilon_{x,y}$ [μm]	3.75	3.75
spot size $\sigma_{x,y}$ [μm]	30, 16	7
$\beta^*_{x,y}$ [m]	1.8, 0.5	0.1
bunch spacing [ns]	25	25

The primary challenges for the ring-ring LHeC are [6]:

- bypassing the main LHC detectors (CMS: 20 cm distance to cavern, 1.3 km bypass, 300 m for RF installation; ATLAS: using the survey gallery, 1.3 km bypass, 170 m for RF installation; similar schemes for LHCb & ALICE);
- integration into the LHC tunnel (cryo jumpers taken into account in the arc-cell design);
- installation matching LHC circumference (avoiding Hirata-Keil resonances [7]; arcs with about 4000 magnets; no show stopper found, but 3D integration needed; compact magnet design & prototypes at BINP and CERN);
- installation within LHC shutdown schedule.

The linac-ring LHeC faces the following challenges:

- two 10 GeV SC Energy Recovery Linacs (SC linac: synergies with ESS, SPL, XFEL, JLAB, ILC, eRHIC; linac size similar to XFEL at DESY; cryo power ~1/2 LHC; less current than other ERL designs such as CESR-ERL or eRHIC);
- the return arcs (total circumference ~9 km, 3 passes; same magnet design as for RR option, >4500 magnets; installation fully decoupled from LHC operation);
- e^+p luminosity: e^+ production & recycling (IP e+ rate ~100 times higher than for CLIC or ILC; several schemes proposed to achieve this).

Figure 2 presents a schematic of the ERL for the linac-ring LHeC. The total circumference is chosen to be exactly equal to one third of the LHC circumference. This allows, if necessary, the introduction in the linac of ion-clearing gaps which coincide for all 6 passes and always encounter the same proton bunches in the LHC. As a result an LHC proton bunch either always or never collides with an electron bunch, which is expected to minimize proton beam emittance growth.

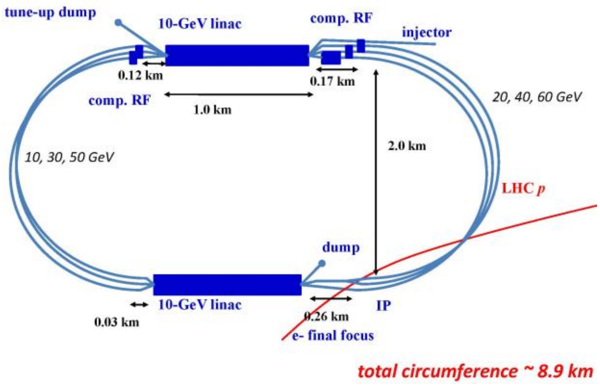

Fig. 2: Schematic ERL configuration for the linac-ring LHeC.

A preliminary civil engineering study has been performed. Figures 3 and 4 illustrate the underground layout and integration with the LHC for the example of *ep* collisions at Point 2. Key components of the ring and linac electron accelerators are compiled in Table 2.

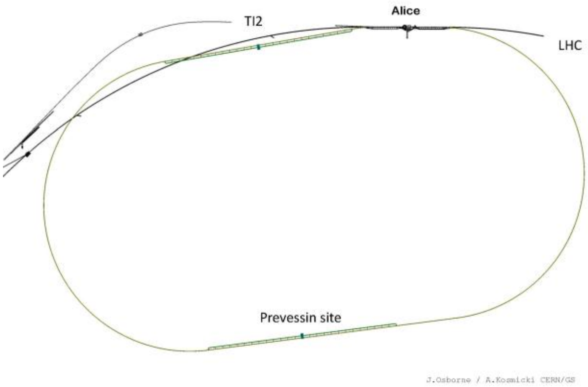

Fig. 3: Example underground layout and LHC integration of a linac-ring LHeC for the example of *ep* collisions in Point 2 – overall view [7].

Table 2: Components of LHeC electron accelerators.

	ring	**linac**
magnets		
beam energy	60 GeV	
no. magnets	3080	3600
dipole field [T]	0.013-0.076	0.046-0.264
no. quadrupoles	866	1588
RF & cryogenics		
no. cavities	112	944
gradient [MV/m]	11.9	20
RF power [MW]	49	39
cavity voltage [MV]	5	21.2
cavity R/Q [Ω]	114	285
cavity Q_0	-	$2.5\cdot10^{10}$
cooling power [kW]	5.4 at 4.2 K	30 at 2 K

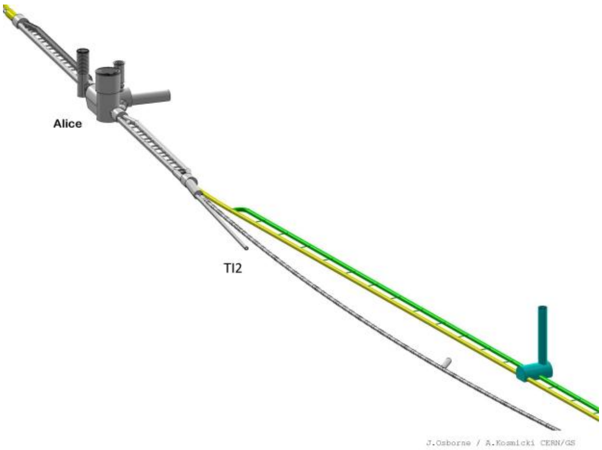

Fig. 4: Example underground layout and LHC integration of a linac-ring LHeC for the example of ep collisions in Point 2 – close-up view around the IR [7].

The linac-ring and ring-ring LHeC options face joint challenges for the interaction region (IR}:

- interaction region layout for 3 beams (exit holes & optics);
- final quadrupole design (e.g. Q1 half quadrupole design, synergy with HL-LHC developments such as Nb_3Sn magnets);
- IR synchrotron radiation (SR) shielding (SR from last quadrupoles and/or combination dipole; minimizing backscattering into the detector; shielding of SC quadrupoles; SR masking to be further optimized with regard to vacuum & detector background)

A draft LHeC IR layout with three beams for the linac-ring version is shown in Fig. 5. To align the incoming electron beam with the colliding proton beam a detector-integrated dipole field of 0.3 T extends over ± 9 m around the IP.

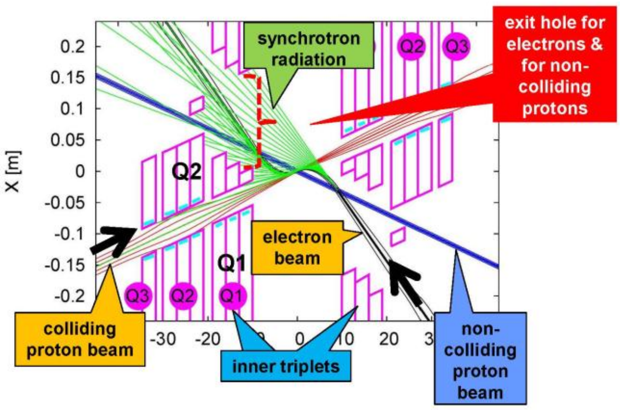

Fig. 5: Schematic of linac-ring 3-beam LHeC IR including synchrotron radiation fan from detector-integrated dipole magnet [R. Tomas].

In case of the linac-ring LHeC, the final two high-gradient SC proton IR quadrupoles for the colliding proton beam are based on Nb_3Sn superconductor and feature low-gradient exit hole(s) for the electron beam and the non-colliding proton beam, as illustrated in Fig. 6. Tentative parameters of these two quadrupoles are listed in Table 3.

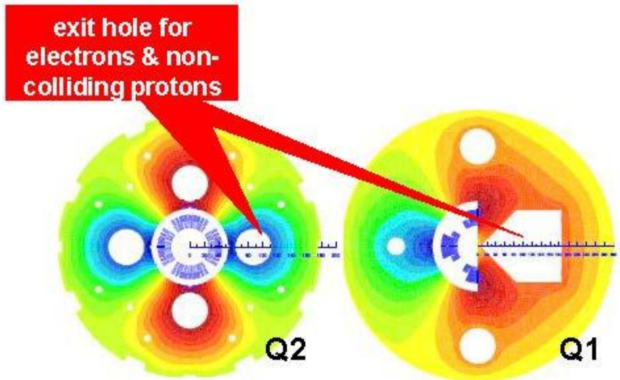

Fig. 6: Cross section of final two proton quadrupoles of the linac-ring LHeC with parameters as listed in Table 3 [S. Russenschuck].

Table 3: Design parameters of the last two quadrupoles for the colliding proton beam in the linac-ring LHeC [S. Russenschuck].

quadrupole	Q1	Q2
superconductor	Nb_3Sn (HFM46)	Nb_3Sn (HFM46)
coil current, gradient and dipole field, proximity to quench level	5700 A, 175 T/m & 4.7 T at 82% on the load line (4 layers), 4.2 K	8600 A, 311 T/m at 83% on the load line, 4.2 K
colliding proton beam 1 aperture and separation between proton beams 1 and 2	46 mm (half aperture), 73 mm beam separation	23 mm (half aperture), 87 mm beam separation
field in exit hole	0.5 T, 25 T/m	0.09 T, 9 T/m

A big challenge for the ring-ring design is achieving significant radiative polarization in the 60-GeV storage ring given the large energy spread at this beam energy.

The biggest challenge for the linac-ring design is to provide positron-proton collisions at comparable luminosity. The required positron rate at the collision points is 6666 times higher than what had been achieved at the SLC and a factor 100-400 larger than those foreseen in the CLIC and ILC designs, respectively. The improvement needed is highlighted in Table 4.

Various approaches have been proposed to meet the formidable positron-rate requirement, including:

- recycling the e^+ together with their energy [F. Zimmermann];
- colliding e^+ several times before decelerating [D. Schulte];
- installing a wiggler-dominated cooling ring in the SPS tunnel with a transverse radiation damping time of $\tau_\perp$~2 ms [Y. Papaphilippou];

- e^+ production using a Compton ring [E. Bulyak, T. Omori];
- e^+ production using a Compton ERL [V. Yakimenko];
- e^+ generation by coherent pair production [H. Braun];
- e^+ production by sending the high-energy (60-GeV) e^+ (or e^-) beam through an undulator [L. Rinolfi];
- 3-ring transformer with cooling ring [E. Bulyak] – see the illustration in Fig.7; and
- fast asymmetric laser cooling [E. Bulyak] [9].

A combination of several of the above schemes is likely to produce the required rate of positrons at the collision point (at possibly significant cost).

Table 4: Positron production rate at the SLC (achieved) compared with the rates required for CLIC, ILC and the linac-ring LHeC (planned) [L. Rinolfi].

collider	SLC	CLIC (3 TeV)	ILC (RDR)	L-R LHeC
beam energy (at DR)	1.19 GeV	2.86 GeV	5 GeV	-
e^+/bunch at IP	$40\cdot 10^9$	$3.72\cdot10^9$	$20\cdot10^9$	$2\cdot10^9$
e^+/bunch before DR injection	$50\cdot 10^9$	$7.6\cdot10^9$	$30\cdot10^9$	N/A
bunches. macropulse	1	312	2625	N/A
macropulse repetition rate	120	50	5	CW
bunches/second	120	15600	13125	$20\cdot10^6$
e^+/second	$0.06\cdot10^{14}$	$1.1\cdot10^{14}$	$3.9\cdot10^{14}$	$400\cdot10^{14}$

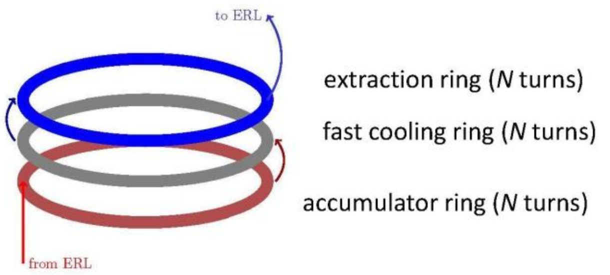

Fig. 7: Schematic of 3-ring transformer with central cooling ring [E. Bulyak]. Beam is injected for N turns into the accumulator ring which transforms the initial CW beam into a pulsed beam. The latter is cooled for N turns in the cooling ring, before being transformed back into a CW beam during another N turns using slow extraction.

Concerning the LHeC planning and time line, the CERN medium term plan for the next 10 years is recalled in Fig. 8, including LHeC installation during the LHC long shutdown no. 3 (LS3) in 2022 [6]. There are only two long shutdowns before 2022, and only 10 years from the completion of the LHeC CDR (in 2012) to the planned start of LHeC operation. The tight time line implies that R&D must start as soon as possible. In parallel a detailed TDR will be developed with feedback from the CDR review. Figure 9 presents the baseline LHeC time schedule in greater detail.

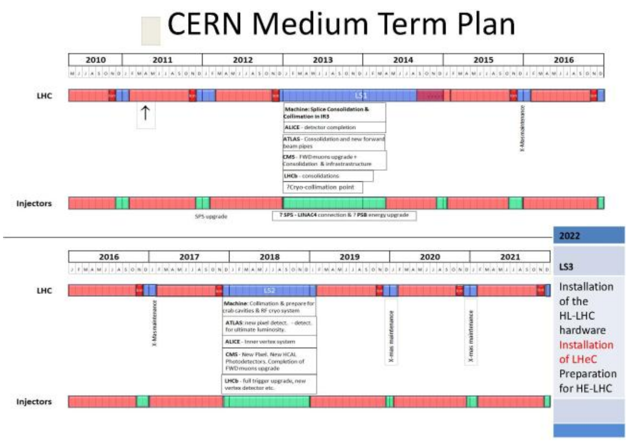

Fig. 8: CERN medium term plan including LHeC installation during LS3 [6].

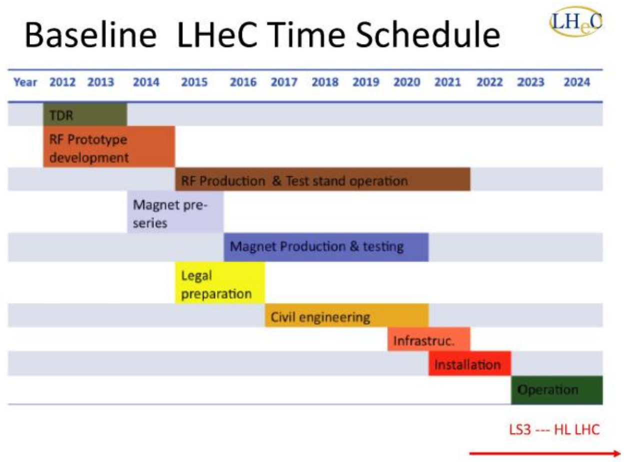

Fig. 9: Baseline LHeC schedule [6]

Future effort should be concentrated on only one LHeC option: either linac-ring or ring-ring. Some arguments in favor of the energy-recovery linac option are:

- novel far-reaching energy-efficient technology;
- no interference with LHC operation and HL-LHC work in the LHC tunnel;
- synergies w SPL, CEBAF+, ESS, XFEL, eRHIC, SPL, ILC, …;
- new technology, great investment for future (e.g. neutrino factory, linear collider, muon collider, 20-GeV SC proton linac, HE-LHC injector, higher-energy LHeC, proton-driven plasma acceleration,…)

Arguments for the ring-ring option include:

- conventional, little risk, less demanding p optics;

- strong synergies with a LEP3 Higgs factory in LHC tunnel – see the next parenthetic section.

The LHeC priority R&D activities include:

- superconducting RF with high Q & strategic partnerships, including the choice between 1.3 GHz and 720 MHz for the ERL RF frequency;
- normal conducting compact magnet design (completed!);
- superconducting 3-beam IR magnet design, in synergy with HL-LHC triplet magnet R&D;
- test facility for energy recovery operation and/or for compact injector complex of the ring-ring option;
- R&D on high intensity polarized positron sources.

PARENTHESIS: LEP3 HIGGS FACTORY

Following the evidence for a 126-GeV Higgs particle presented by the ATLAS and CMS in December 2011, a high-luminosity e^+e^- factory in the LHC tunnel (or in a new tunnel of twice the circumference) has been proposed [10]. Such collider would feature only few bunches / beam. With SR power limited to 50 MW per beam (as for the LHeC ring-ring collider), and using as an example the LHeC ring optics, a luminosity in excess of 10^{34} cm^{-2}s^{-1} could be delivered to the (upgraded) ATLAS and CMS detectors, resulting in more than 10^4 Z-H events per year in each of the two experiments. At this luminosity the beam lifetime would be only a few minutes. Therefore, top up injection from a second accelerator ring is considered as depicted in Fig. 10. Table 5 compares the LEP3 parameters with those of LEP2 and the LHeC ring-ring design. The LEP3 e^+e^- Higgs factory ring could be designed and configured so as to also (either before or later) provide LHeC *ep* collisions and vice versa.

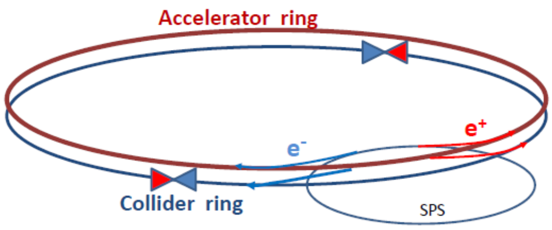

Fig. 10: LEP3 two ring scheme with top-up injection into the collider ring [10].

Table 5: Parameters of LEP, the LHeC ring design, and LEP3 - a new electron-positron collider in the LHC tunnel, extrapolated from the LHeC design.

	LEP [11,12]	LHeC ring design [1]	LEP3
beam energy E_b	104.5 GeV	60 GeV	120 GeV
beam current	4 mA	100 mA	7.2 mA
#bunches	4	2808	3
total #e- / beam	2.3e12	5.6e13	4.0e12
horiz. emittance	48 nm	5 nm	20 nm
vertical emittance	0.25 nm	2.5 nm	0.15 nm
dip. bend radius	3096 m	2620 m	2620 m
partit. number J_ε	1.1	1.5	1.5
momentum comp.	1.85x10^{-4}	8.1x10^{-5}	8.1x10^{-5}
SR power / beam	11 MW	44 MW	50 MW
$\beta_{x,y}$*	1.5, 0.05 m	0.18,0.10 m	150, 1.2 mm
rms IP beam size	270,3.5 μm	30,16 μm	55, 0.4 μm
hourglass factor	0.98	0.99	0.65
energy loss/ turn	3.408 GeV	0.44 GeV	6.99 GeV
total RF voltage	3641 MV	500 MV	9000 MV
beam-beam tune shift (/IP)	0.025, 0.065	N/A	0.126, 0.130
synchr. frequency	1.6 kHz	0.65 kHz	2.98 kHz
average acc.field	7.5 MV/m	11.9 MV/m	18 MV/m
eff. RF length	485 m	42 m	505 m
RF frequency	352 MHz	721 MHz	1300 MHz
rms energy spr'd	0.22%	0.116%	0.232%
rms bunch length	1.61 cm	0.688 cm	0.30 cm
pk luminosity / IP	1.3x10^{32}cm^{-2}s^{-1}	N/A	1.3x10^{34} cm^{-2}s^{-1}
number of IPs	4	1	2
beam lifetime	6.0 h	N/A	12 minutes

HIGH-ENERGY LHC (HE-LHC)

The High-Energy Large Hadron Collider is a future energy upgrade of the LHC. It foresees new 20-T dipole magnets in the LHC arcs, providing a *pp* c.m. energy of 33 TeV. The HE-LHC also requires correspondingly stronger arc quadrupoles., upgraded or new detectors in LHC interaction points 1 and 5, as well as a new higher-energy injector, for which a Superconducting SPS, S-SPS, accelerating protons up to about 1.3 TeV, is one of the options considered. The HE-LHC and its main ingredients are sketched in Fig. 11. Aside from a proton beam energy of 16.5 TeV in the LHC tunnel, other performance targets include a peak luminosity of 2x10^{34} cm^{-2}s^{-1}, heavy ion collisions at an equivalent energy, and eventually high-energy *ep* collisions.

The key component of the HE-LHC is the 20-T dipole magnet. Figure 12 presents the field in SC accelerator dipole magnets achieved, or predicted, for three types of superconductor, illustrating that in order to reach the target field of 20-T the HE-LHC magnets must contain high-temperature superconductor (HTS). The high-field magnet proposed for the HE-LHC is a hybrid design design [13] optimized for production cost, consisting of an outer layer of Nb-Ti, a next layer of high-flux Nb_3Sn, a third layer of low-flux Nb_3Sn, and an inner layer of HTS [14], as indicated in Table 6 and Fig. 13. The SC part of the magnet is arranged in the form of block coils for optimum stress management [13,14]. The complete 2-in-1 magnet for the two beams, including common iron yoke is presented in Fig. 14.

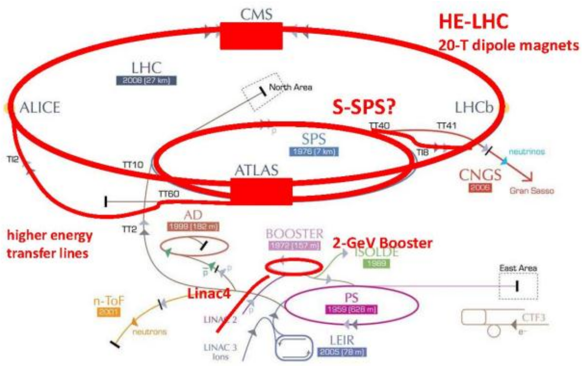

Fig. 11: Schematic of a High-Energy LHC in the LHC tunnel; new components are shown in bold red color.

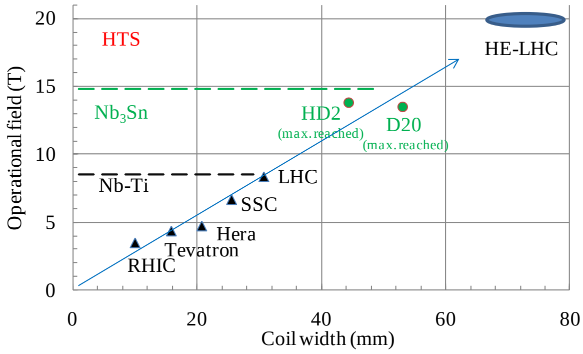

Fig. 12: Operational field of SC dipole magnets based on three different SC materials, as a function of coil width for various accelerators (Nb-Ti) and a few prototype magnets (Nb_3Sn) and the HE-LHC (HTS).

Table 6: Relative weight distribution of 4 types of SC in the HE-LHC hybrid design [E. Todesco].

Nb-Ti	26%
Nb_3Sn – high *j*	35%
Nb_3Sn – low *j*	23%
HTS (Bi2212)	17%

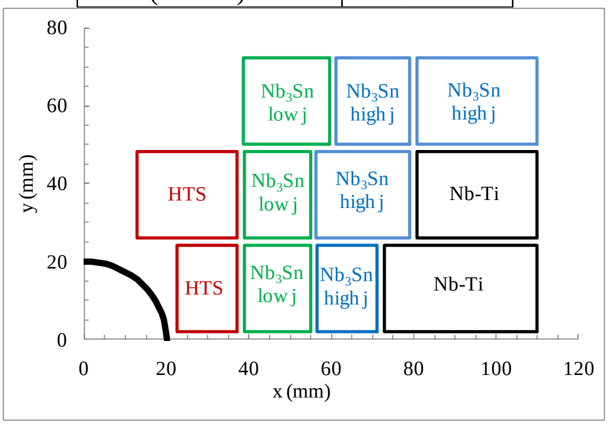

Fig. 13: SC block coil layout for the HE-LHC dipole [14].

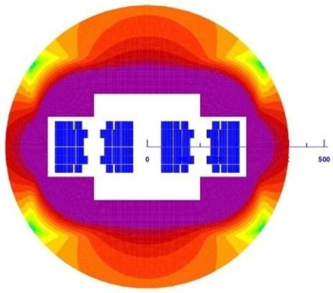

Fig. 14: HE-LHC 2-in-1 dipole[14].

The HE-LHC activities so far included a CERN working group in 2010 [15], and EuCARD AccNet workshop HE-LHC'10 in October 2010 [16]. Key topics discussed on these occasions were the choice of beam energy (16.5 TeV), the design of the 20-T magnets, cryogenics and synchrotron-radiation heat, radiation damping and emittance control (Fig. 15; revealing a new "easy" beam-dynamics regime), vacuum system with desorption from synchrotron radiation, the new injector and its energy, and the HE-LHC beam parameters (Table 7).

Table 7: HE-LHC beam parameters compared with those of the LHC.

	LHC	HE-LHC
beam energy [TeV]	7	16.5
dipole field [T]	8.33	20
dipole coil aperture [mm]	56	40
#bunches	2808	1404
number of IPs contributing to tune shift	3	2
beam circulating current [A]	0.584	0.328
IP beta function [m]	0.55	1 (x), 0.43
SR power per ring [kW]	3.6	65.7
arc SR heat load dW/ds [W/m/aperture]	0.17	2.8
events per crossing	19	76
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	1.0	2.0

Among the HE-LHC challenges are the following:

- 20-T dipole magnets: cost & feasibility; "acrobatic" price estimates for 2025 (Nb3Sn is 4x more expensive than Nb-Ti; HTS is 4x more expensive than Nb_3Sn; price for 1200 magnets: 5-6B$ [18]); choice between 20 T and 15 T (the latter being available today); stored energy and magnet protection;
- injector: S-SPS w 5-6 T dipole or 2-T superferric ring in LHC tunnel; will the LHC injector complex still be working in 2030-40?;
- synchrotron radiation handling & heat load: the HE-LHC beam screen experiences 6 times more

heat load than at the LHC (as a mitigation one could operate the HE-LHC beam screen at 40-60 K); the cold mass heat load is 50% higher than for the LHC; the total heat-load will be near the limit of the present LHC cryogenics capacity [19].

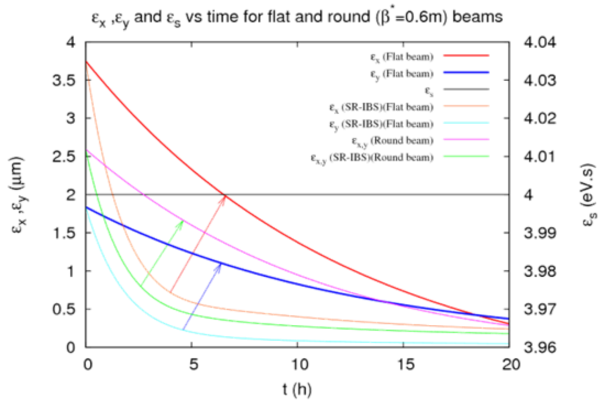

Fig. 15: HE-LHC emittance evolution in store with (bold) and without (faint) controlled emittance blow up [17].

TIME LINE & DECISION POINTS

The time line of LHC-related CERN projects is illustrated in Fig. 16. LHeC will run in parallel to HL-LHC and, due to its later start, it faces a very tight R&D schedule. HE-LHC will follow the HL-LHC. The time available for HE-LHC R&D and prototyping is less than the corresponding time spent for the LHC.

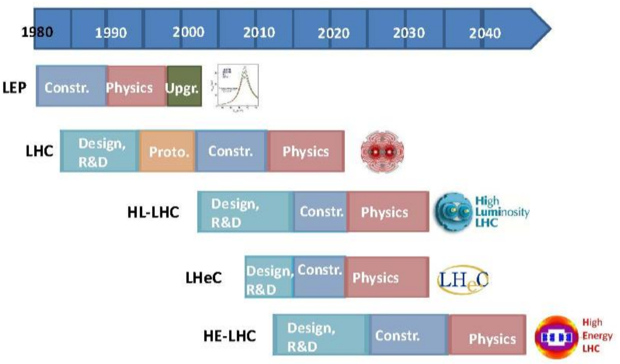

Fig. 16: Time line of LHC-related projects at CERN [20].

The future key decision points are, for the LHeC, the choice between linac and ring (in 2012), the choice of IR (Point 2, 7 or 3?, by 2013) and the decision to go ahead with production (2014) and, for HE-LHC, the decision to use or not to use HTS (in 2016), and the decision to go ahead with production (by 2024).

“LHC” PROJECTS FOR NEXT 50 YEARS

During the last 30 years the Fermi distance scale was explored by a family of complementary *p*bar-*p*, e^+e^- and *ep* colliders, as sketched in Fig. 17. Prospects are good that over the next 30 years the sub-Fermi scale will be probed by a similar set of complementary colliders, as suggested in Fig. 18. It appears that all of these colliders could be based on the LHC and/or the LHC tunnel.

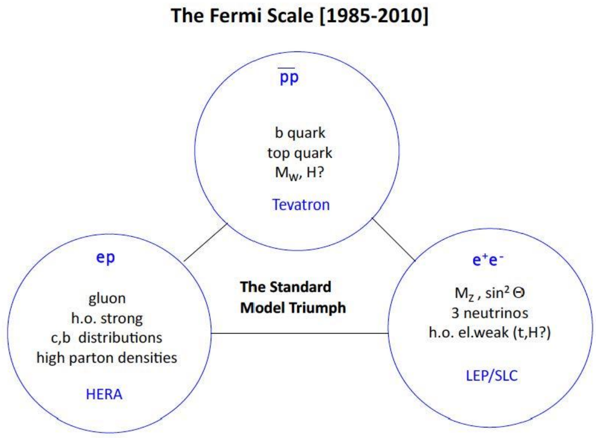

Fig. 17: The three pillars of high-energy physics in the last three decades [21].

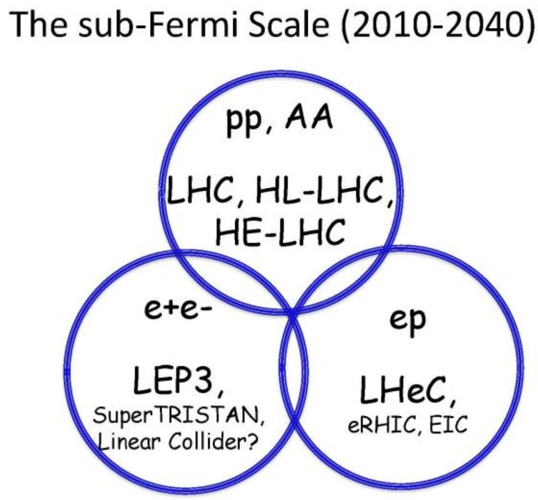

Fig. 18: The possible three pillars of high energy physics for the next three decades until 2040.

Beyond 2040, further great upgrades appear on the horizon, such as obvious extensions of the projects in Fig. 16, for example an HL-HE-LHC (with 10^{35} $cm^{-2}s^{-1}$ luminosity at 33 TeV c.m. energy), and an HE-LHeC (150 GeV e^- x 16.5 TeV p^+). The latter could be realized in the form of a straight enery recovery linac consisting of an accelerating and a decelerating half, where the energy is transferred back from the latter to the former using 10 GeV “drive beams,” making use of technology developed for the CLIC project.

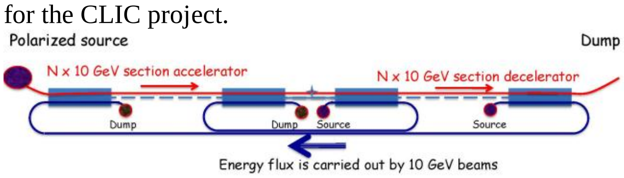

Fig. 19: High energy ERL using “CLIC” technology [22].

ACKNOWLEDGEMENTS

The accelerator layouts and concepts presented in this paper owe much to Jose Abelleira, Ralph Assmann, Nathan Bernard, Alex Bogacz, Chiara Bracco, Oliver Brüning, Helmut Burkhardt, Swapan Chattopadhyay, Ed Ciapala, John Dainton, Octavio Dominguez, Anders Eide, Miriam Fitterer, Brennan Goddard, Friedrich Haug, Bernhard Holzer, Miguel, Jimenez, John Jowett, Max Klein, Peter Kostka, Vladimir Litvinenko, Peter McIntyre, Karl Hubert Mess, Steve Myers, Alessandro Polini, Louis Rinolfi, Lucio Rossi, Stephan Russenschuck, GianLuca Sabbi, Daniel Schulte, Mike Sullivan, Laurent Tavian, Ezio Todesco, Rogelio Tomas, Davide Tommasini, Joachim Tückmantel, plus many others.

REFERENCES

[1] LHeC Study Group (C. Adolphsen et al.), “A Large Hadron Electron Collider at CERN,'' CERN LHeC-Note-2011-003 GEN (2011)

[2] E. Todesco, High Energy LHC, 2nd EuCARD Meeting, Paris, 11.05.2011

[3] S. Fartoukh, private communication at Chamonix ’12.

[4] H. Damerau, “Performance Potential of the Injectors after LS1,” Proc. 2012 LHC Performance Workshop, Chamonix (2012).

[5] W. Herr, “Performance Reach of LHC after LS1,” Proc. 2012 LHC Performance Workshop, Chamonix (2012).

[6] O. Brüning, “LHeC Accelerator,” presentation at ECFA Meeting, CERN, 25.11.2011

[7] K. Hirata, E. Keil, “Barycenter Motion of Beams due to Beam-Beam Interaction in Asymmetric Ring Colliders,” Nucl. Instrum. Meth. A 292: 156-168 (1990).

[8] J. Osborne, A. Kosmicki, private communication; see also ref. [1] (2011).

[9] E. Bulyak, J. Urakawa, F. Zimmermann, “Compton Ring with Laser Radiative Cooling,” Proc. POSIPOL2011, 28-30 August 2011, IHEP Beijing, to be published by WSPC (2011).

[10] A. Blondel, F. Zimmermann, “A High Luminosity e^+e^- Collider in the LHC tunnel to study the Higgs Boson,” CERN-OPEN-2011-047, arXiv: 1112. 2518 v1 [hep-ex]

[11] R.W. Assmann, “LEP Operation and Performance with Electron-Positron Collisions at 209 GeV,” Proc. LHC Workshop, Chamonix 15 - 19 January 2001, CERN-SL-2001-003 DI (2001).

[12] A. Butterworth et al, “The LEP2 superconducting RF system,” NIM A Vol. 587, Issues 2-3, 21 March 2008, Pages 151-177

[13] A. Sattarov, P. McIntyre, “On the Feasibility of a Tripler Upgrade for LHC,” Proc. PAC’05, Knoxville, 16-20 May 2005, pp. 634 (2005)

[14] L. Rossi, E. Todesco, “Conceptual Design of 20 T Dipoles for High-Energy LHC,” in ref. [16], pp.13-19 (2011).

[15] R. Asssmann, R. Bailey, O. Brüning, O. Dominguez, G. de Rijk, J.M. Jimenez, S. Myers, L. Rossi, L. Tavian, E. Todesco, F. Zimmermann, “First Thoughts on a Higher-Energy LHC,” CERN-ATS-2010-177 (2010).

[16] Proc. of HE-LHC’10 (Eds. E. Todesco, F. Zimmermann), Malta, 14-16 October 2010, CERN Yellow Report 2011-3

[17] O. Dominguez, F. Zimmermann, “Luminosity Optimization for a Higher-Energy LHC,” Proc. IPAC’11 San Sebastian (2011)

[18] L. Rossi, 18 April 2006, CERN EDMS Nr 754391 (2006).

[19] D. Delikaris, L. Tavian, “Heat Loads and Cryogenics for HE-LHC,” ref. [16], pp.75-78 (2011)

[20] L. Rossi, “Report of HiLumi Collaboration Meeting 16-18 November 2011,” CERN LMC meeting #117, 30 November 2011 (modified) (2011).

[21] M. Klein, “Steering Group Report,” 1st ECFA-CERN LHeC workshop, Divonne-les-Bains, 1-3 September 2008.

[22] V. Litvinenko, “LHeC with ~100% Energy Recovery Linac,” 2nd CERN-ECFA-NuPECC Workshop on the LHeC, Divonne-les-Bains, 1-3 September 2009.