Future Circular Collider - European Strategy Update Documents

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Future Circular Collider
The High-Energy LHC (HE-LHC)

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Abstract:

This report contains the description of a novel research infrastructure based on a high-energy hadron collider, which extends the current energy frontier by almost a factor 2 (27 TeV collision energy) and an integrated luminosity of at least a factor of 3 larger than the HL-LHC. In connection with four experimental detectors, this infrastructure will deepen our understanding of the origin of the electroweak symmetry breaking, allow a first measurement of the Higgs self-coupling, double the HL-LHC discovery reach and allow for in-depth studies of new physics signals arising from future LHC measurements. This collider would directly produce particles at significant rates at scales up to 12 TeV. The project re-uses the existing LHC underground infrastructure and large parts of the injector chain at CERN. This particle collider would succeed the HL-LHC directly and serve the world-wide physics community for about 20 years beyond the middle of the 21st century.

The FCC Conceptual Design Report volumes are available for download at
http://fcc-design-report.web.cern.ch.

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1 Scientific Context

Particle Physics has arrived at an important moment of its history. The discovery of the Higgs boson, with a mass of 125 GeV, completes the matrix of particles and interactions that has constituted the “Standard Model” for several decades. This model is a consistent and predictive theory, which has so far proven successful at describing all phenomena accessible to collider experiments. However, **several experimental facts do require the extension of the Standard Model** and **explanations are needed for observations** such as the abundance of matter over antimatter, the striking evidence for dark matter and the non-zero neutrino masses. Theoretical issues such as the hierarchy problem, and, more in general, the dynamical origin of the Higgs mechanism, do point to the existence of physics beyond the Standard Model.

While at least some of the new particles and phenomena needed to solve the open problems are anticipated to exist at the TeV scale, their masses could well be too large, or their couplings too small, to be observed at the LHC. Future indications or discoveries of new physics at the TeV scale, by the LHC and other facilities, will most certainly require increased sensitivity to pin down their origins. In addition to looking for well-hidden new physics, progress in our exploration also demands looking for phenomena appearing at energy scales beyond the current reach of direct detection and indirect evidence. A significant increase in the mass reach for direct discovery, with respect to the LHC, is an essential component of this research programme.

How big should this increase in mass reach be, to be rewarding? With the HL-LHC saturating the discovery potential via direct detection of new particles at the highest masses, even a modest increase in centre-of-mass energy could open the door to surprises. **Increasing** the **LHC collision energy by a factor of 2** and **increasing** the **peak luminosity by a factor of 15** (a factor of 3 with respect to the levelled HL-LHC luminosity), would allow the discovery reach at the highest masses to be doubled, and the precision and sensitivity of many measurements to be increased. In addition to extending the direct discovery reach, **a future high energy hadron collider (HE-LHC) with a total integrated luminosity exceeding 10 ab^{-1}** at a pp centre-of-mass energy of 27 TeV would allow incremental progress to be made towards addressing key quantitative and conceptual questions, such as: how does the Higgs particle couple to itself? Do the light generations of fermions get their mass from the Higgs boson? What was the nature of the electroweak phase transition? Are weakly interacting massive particles (WIMPs) a component of Dark Matter (DM)? Does the hierarchy problem admit a natural solution at the TeV scale? The HE-LHC may not have sufficient energy to guarantee conclusive answers to all these questions, but it will get us closer to opening cracks in the Standard Model. With flavour physics playing an increasingly important role among the accessible probes of new physics, special attention to dedicated high-luminosity interaction regions and experiments would significantly extend the ongoing and future flavour programme of the LHC. The HE-LHC precision and sensitivity can be further enhanced by a programme of ep collisions, yielding e.g. accurate determinations of the partonic luminosities. Furthermore, the HE-LHC could provide the most affordable and timely way to confirm preliminary signs of new physics at the LHC, or to begin the exploration of future LHC discoveries.

The thermodynamic behaviour of Quantum Chromodynamics (QCD) presents features that are unique among all other interactions. Their manifestations play a key role in fundamental aspects of the study of the universe, not least in cosmology and astrophysics. The studies of collisions with heavy nuclei (N) at RHIC and LHC have exposed novel features, beyond the standard quark-gluon plasma (QGP) paradigm, adding new questions to the set of open issues: how is thermal equilibrium reached? What is the origin of the collective phenomena that have been seen also in pp and pN collisions? Collisions of heavy ions at higher than LHC energies and luminosities, as delivered by the HE-LHC, will allow build further on the knowledge that future LHC heavy ion runs will reveal.

High-energy physics requires a powerful, but sustainable and versatile hadron collider at the energy frontier. While 27 TeV is well below the 100 TeV target of the FCC-hh, the increase of energy and luminosity with respect to the HL-LHC nevertheless represents a significant improvement over the HL-LHC reach. The discussion of the HE-LHC physics potential, therefore, should not be done through a direct comparison with the obviously more powerful and ambitious FCC project, but in consideration of the expected costs and benefits that it will bring after the HL-LHC has finished operation. Such a machine could expand the physics reach with multiple synergies and complementarities for the world-wide fundamental physics research community, until the second half of the 21st century.

2 Objectives

The objective is to **develop, build and operate a hadron collider, which extends the current energy frontier** by almost a factor 2 (27 TeV collision energy), with an integrated luminosity at least a factor 3 higher than the HL-LHC. With four experiment detectors, this infrastructure will **deepen our understanding of the origin of the electroweak symmetry breaking, allow first measurements of the Higgs self-coupling, double the HL-LHC discovery reach and allow in-depth studies of new physics signals arising from future LHC measurements**. This collider would **directly produce particles at significant rates at scales up to 12 TeV**. The project re-uses the existing LHC underground infrastructure and large parts of the injector chain at CERN. This collider would succeed the HL-LHC directly and **serve the global physics community for about 20 years, taking it beyond the middle of the 21st century.**

2.1 Scientific Objectives

The European Strategy for Particle Physics **(ESPP) 2013 unambiguously recognized the importance of *"a proton-proton high-energy frontier machine…coupled to a vigorous accelerator R&D programme…in collaboration with national institutes, laboratories and universities worldwide"***. Complying with this guideline, the international **FCC** collaboration has **developed a concept for a high-energy hadron collider (HE-LHC) that can be installed in the existing LHC tunnel, using large parts of the CERN accelerator complex as injector chain.** With respect to the HL-LHC, the HE-LHC offers a significant extension of the discovery potential and increased sensitivity to so far enigmatic processes. Together with a heavy ion operation programme and with a lepton-hadron interaction point, it provides broad perspectives for research at the energy frontier. A rich physics programme of about 20 years described in this section requires collision energies and luminosities that can only be delivered within a reasonable amount of time by a circular collider with several interaction regions.

The main objectives of the HE-LHC physics programme can be grouped in four areas:

1. Extending the HL-LHC direct search for new particles, approximately doubling its mass reach;
2. Establishing firm evidence for the structure of the symmetry-breaking Higgs potential, which lies at the heart of the Standard Model's (SM) electroweak (EW) sector;
3. Improving the precision of the HL-LHC measurements, with a consequent better indirect sensitivity to new physics at high mass scales, and better direct sensitivity to elusive final states such as dark matter (DM);
4. Exploring future LHC discoveries in greater detail, confirming preliminary signs of discovery from the LHC, or identifying the underlying origin of new phenomena revealed indirectly (e.g. the flavour anomalies currently under discussion) or in experiments other than those of the LHC (e.g. DM or neutrino experiments).

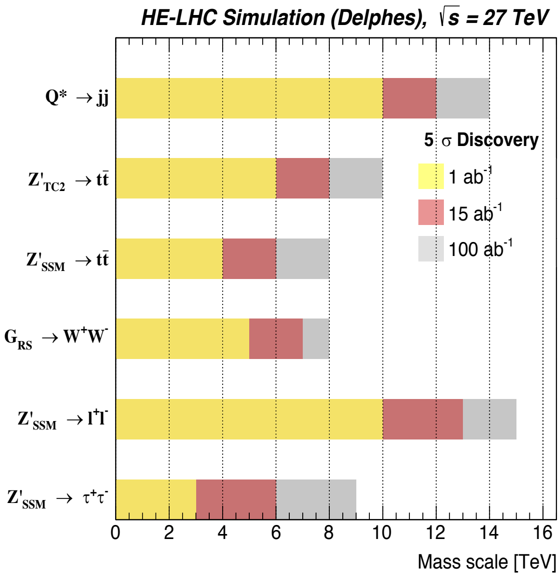

Figure 1: Discovery reach for heavy resonances.

Since cross sections for the production of a state of mass M scale like $1/M^2$, the integrated luminosity should be 4 times that of the HL-LHC (3 ab^{-1}), i.e. about 12 ab^{-1} after 20 years of operation, to be sensitive to two times larger masses. The HE-LHC baseline design aiming at 15 ab^{-1} meets this target. Fig. 1 shows discovery reach examples for the production of several types of new particles, including Z' gauge bosons carrying new weak forces and decaying to various SM particles, excited quarks Q*, and massive gravitons G_{RS} present in theories with extra dimensions. Other scenarios for new physics, such as supersymmetry and composite Higgs models, will likewise see a great increase of high-mass discovery reach. An example of the added value of HE-LHC is given in Fig. 2. The points in the plots correspond to parameter configurations of several supersymmetric models inspired by the requirement of a natural solution to the hierarchy problem. While HL-LHC can only cover part of the parameter space of the illustrated models, HE-LHC covers it entirely. With the exception of the models labeled by red (green) dots, where the gluino (stop) mass is typically larger than the HE-LHC reach, all other models would allow the 5σ discovery via the observation of both gluino and stop.

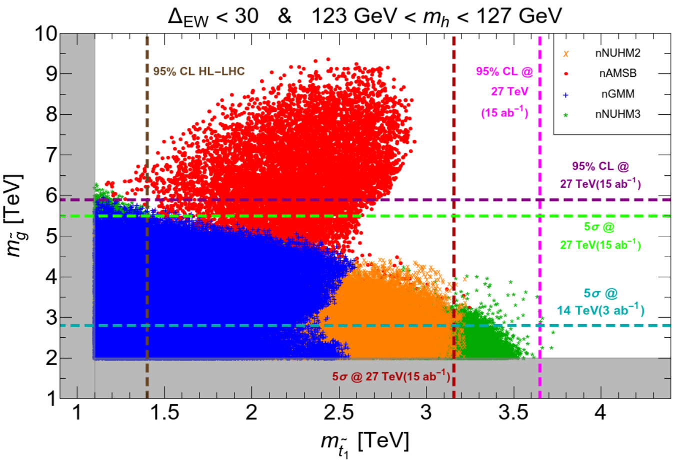

Figure 2: Discovery reach at the HE-LHC for gluinos and stops in various supersymmetric models, compared to the HL-LHC reach. The relevant areas lie under the horizontal lines (for the gluino) and to the left of the vertical lines (for the stop).

Until new physics is found, one of the key issues that will likely remain open after the HL-LHC, at the top of the HE-LHC physics objectives priority list, is: **how does the Higgs couple to itself?** Today, neither the fundamental origin of the SM scalar field nor the origin of the mass and self-interaction parameters in the Higgs scalar potential are known. The next stage of exploration for any high-energy physics programme is to determine these microscopic origins. With Higgs sample increases by a factor between 10 and 25 due to the higher cross sections and luminosity, the statistical uncertainties for the measurement of Higgs properties can be reduced by factors 3 to 5. The biggest improvements arise for the channels in which the HL-LHC is statistically limited, i.e. ttH and HH (see Table 1 below). In particular, **the trilinear Higgs self-coupling can be measured with a 15% precision**, at the 68% confidence level (CL). The large statistics could also allow HE-LHC to be the first to detect the **Higgs coupling to the charm quark**.

Table 1: Higgs production event rates for selected processes at 27 TeV (N_{27}) and statistical increase with respect to the statistics of the HL-LHC ($N_{27} = \sigma_{27TeV}$ x 15 ab^{-1} and $N_{14} = \sigma_{14TeV}$ x 3 ab^{-1}).

	gg→H	**WH**	**ZH**	**$t\bar{t}H$**	**HH**
N_{27}	2.2 x 10^9	5.4 x 10^7	3.7 x 10^7	4 x 10^8	2.1 x 10^7
N_{27}/N_{14}	13	12	13	23	19

The mass of higgsino and wino-like WIMP DM candidates is theoretically constrained to be below 1 and 3 TeV, respectively. A disappearing charged track analysis at the HE-LHC can probe Higgsino-like (wino-like) **DM candidates with a mass of up to 500 GeV (1.8 TeV)** at the 95% CL (Fig. 3). These results improve on the expected reach of HL-LHC, namely 300 GeV (900 GeV). While these results at the HE-LHC come short of saturating the full range of masses for possible DM WIMPs (which are achievable at the FCC-hh), the mass range accessible to HE-LHC greatly extends the HL-LHC potential.

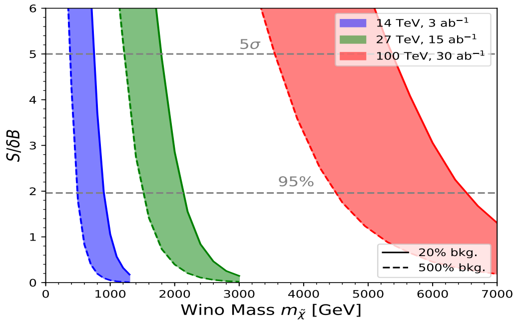

Figure 3: Sensitivity reach for wino-like DM WIMP candidates.

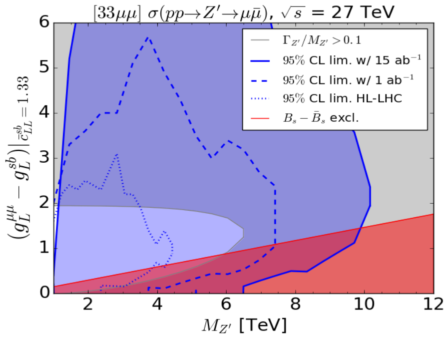

Figure 4: Sensitivities for narrow-width Z' models explaining the B anomaly.

In the near future, flavour phenomena may reveal new physics beyond the LHC reach, as suggested by the current flavour anomalies in B decays. Interpretations of these anomalies point to mediators of these interactions (leptoquarks or Z' bosons) whose mass might be in the sensitivity reach of a hadron collider in the 27 TeV energy range, as shown, for a specific class of models, in Fig. 4.

The HE-LHC collider can be enhanced with an **electron-hadron collider** with a centre of mass energy of 1.7 TeV, collecting up to 1 ab^{-1} of integrated luminosity in parallel with the HE-LHC operations. Deep inelastic scattering can determine the partonic luminosities of gg, gq and qq initial states with a few per mille precision, throughout the large range of masses relevant to HE-LHC's precise measurements and searches of new physics. A HE-LHeC also covers a rich programme of Higgs and electroweak precision measurements, as well as searches for new physics. The Higgs boson will be studied through the well-known neutral and charged vector boson fusion channels, providing precision measurements complementary in sensitivity and systematics to HE-LHC.

2.2 Strategic Objectives

The ESPP 2013 stated *"To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update"*. The **FCC study has implemented the ESPP recommendation** by **developing a vision for an *"accelerator project in a global context"***. This document **proposes, as a first step, the detailed design and preparation of a construction project** for a post-LHC circular hadron collider *"**in collaboration with national institutes, laboratories and universities worldwide**"*, and enhanced by a **strong participation of industrial partners**. The **coordinated preparation effort** can be based on a core of already more than 130 collaborating institutes worldwide.

The window of opportunity for a post-LHC collider-based research infrastructure is narrow: on one hand, the HL-LHC project provides a limited period to attract new scientists until the mid-twenty-thirties. These researchers may also dedicate part of their time to the development of the next machine and its experiments. On the other hand, the ever-faster pace of development of a large-scale particle-collider in Asia, which could already materialise during the next five years, introduces a serious risk of diverting resources and expertise built up in Europe. Hence, no time should be lost to profit from the current momentum, driven by a well-founded interest in building an infrastructure capable of addressing the open questions of particle physics in a sustainable and evolutionary way.

The existence of the HL-LHC underground infrastructure, a fully operational hadron injector complex, numerous technical infrastructures and well-established administrative services at CERN creates an opportunity. Through the active participation of both member and non-member states, CERN can establish a sustainable organisation and funding for a project, the scope of which extends far beyond national research centres, single nations, or even consortia of a few organisations. An endeavour like the HE-LHC is an ideal case to continue and expand the cooperative effort of nations in and beyond the European Research Area (ERA), including all regions of the world, especially North America and Asia. It should also engage regions without a historically strong record of particle-accelerator based research (e.g. Africa, Middle and South America, Middle East and Oceania). The Future Circular Collider study, launched in 2014, has so far attracted more than 130 universities and institutes from around the globe. In addition, the FCC study has spawned several important R&D activities with dedicated funding from national agencies (e.g. US DOE high-field magnet program and the Swiss CHART R&D program) and from the European Commission (e.g. EC H2020 projects EuroCirCol and EASITrain; further FCC developments are included in other EC projects such as ARIES and RI-Paths). These substantial achievements demonstrate that developing a common vision for the worldwide research community is of utmost importance for the field.

2.3 Socio-economic Impact

A large-scale, international fundamental research infrastructure, tightly involving industrial partners and providing training at all education levels, **will be a strong motor of economic and societal development in the CERN member states and beyond**. Indeed, **its positive impact**, beyond the increase of scientific knowledge, has been **quantitatively measured by taking the HL-LHC project as a case study**. This project can be taken as a direct baseline for a societal impact assessment of an HE-LHC project. The cost-benefit analysis of the LHC/HL-LHC programmes shows that the **construction and operation of a particle collider will pay back handsomely, through the numerous socio-economic benefits** they generate; the collider infrastructure **can even generate additional returns**, **in the billions of euro range over twenty years**. Therefore, for the HE-LHC the main question is not how much the construction of the machine and its experiments will cost, but rather **if sufficient long-term interest of early stage researchers and industrial partners can be raised, how much in terms of new open software and standards such a project can generate, how the continued creation of cultural goods in form of news about the physics research and potential findings can be planned and how many synergies with other science, technology and engineering domains can be created ab initio.** Long-term sustainability of this research infrastructure is another topic that is high on the agenda of funding agencies.

A quantitative cost-benefit assessment of the LHC/HL-LHC programme was carried out to provide a foundation for planning the socio-economic impact of a new particle-collider facility. This assessment revealed that, even for combined capital and operation expenditures in excess of 20 billion CHF, a surplus of more than 5 billion CHF in socio-economic benefits can be created at the level of today's activities over long time periods. In other words, the research infrastructure is not only paid for by its socio-economic value, but it even generates additional value for the society. Improving the quality of training, increasing the coordination of ICT technology developments for maximum impact, strengthening the cooperation with industry, and streamlining the creation of cultural products can increase the benefits further. A rough forecast for HE-LHC socio-economic benefits, taking the HL-LHC project as a direct case study points to a break-even of the combined capital and operation expenditures from the start of construction to the end of operation. The highest uncertainty for this project is the committed long-term interest of a significantly large early stage researcher community over several decades. This is because it is the single largest contributor to socio-economic benefits through the creation of a lifetime salary premium on top of a regular academic degree ranging from 5% to 13% for early stage researchers who participated in the programme. **For LHC/HL-LHC, the earnings effects for industrial suppliers and the value of openly accessible standards, software and tools exceeds 10 billion CHF today,** but this path remains largely underexplored due to there being too many ad-hoc developments with limited societal penetration. Industrial partners will profit the most from a research infrastructure project if co-developments are carried out and services are developed in the hi-tech domain. This includes the engagement of small and medium-size companies for all types of developments and operational tasks. Today's utility/sales ratio[1] of about 3 can be increased further. The benefits for industry are directly proportional to the investment volume, the level of involvement (co-development vs. commercial-off-the-shelf) and to the period of time during which an industry is involved. With the pervasiveness of media-rich web and social-media contents, the value of cultural goods has increased. Cultural impact correlates directly with the quality and reach of the products. For a new research project, sufficient materials need to be available upfront so that continuous information about the project discovery and knowledge, scientific findings, technology advances and, most important, stories about individual researchers can be produced. Streamlining of the contents distributed by media partners and focusing on active engagement of the public make it likely that today's benefits in this category can be maintained at a yearly value between 75 and 120 million CHF per year.

3 Methodology

An efficient **method to extend our current understanding of nature** consists of **extending the direct discovery reach and the direct measurement precision with a particle collider that directly succeeds the HL-LHC and which re-uses part of its existing infrastructure at CERN.** By rapidly bringing the key enabling technologies to series production grade, which are currently being developed for a 100 TeV hadron collider, the **energy frontier can be extended to the 27 TeV range**. This is achieved by improving significantly the Nb_3Sn superconductor technology, which will also be used for the HL-LHC in limited quantities, and by developing a more efficient cryogenic refrigeration infrastructure. The entire particle and high-energy physics community is called upon to combine their efforts in order to **define a research programme that makes best use of such a circular hadron collider**. A machine of that kind is **technically feasible** and **it can be built within an acceptable time frame and controlled project risks. Since the collider has to be built for the existing infrastructure at CERN, several constraints need to be considered in the design and for the operation. Continuous increase of the luminosity permits a gradual in-depth exploration up to the design performance specifications in a way that ensures sustainability and availability of infrastructure**. The experimental research at the HE-LHC will be **based on international collaborations** with **open access** to detector data and on a **community-based scientific analysis** supported by a worldwide data processing infrastructure, as has been best practice in high-energy physics for almost two decades. This **programme is complementary to other on-going research activities** (e.g. long-baseline neutrino experiments in the US and Japan) and it leverages cross-disciplinary synergies to expand our understanding of the universe (e.g. dark matter searches complementing astroparticle physics research projects). The HE-LHC could also provide the basis for a lepton-hadron collider, the HE-LHeC, a higher energy version of the proposed LHeC.

This project can begin addressing the open questions of the Standard Model with an effective and versatile direct observation tool: a large high-energy circular collider with multiple interaction points. The HE-LHC can host several experiment detectors designed, built and operated by international research collaborations. A global data processing infrastructure will enable the necessary powerful data analysis, naturally extending today's mode of operation in high-energy and particle physics. Collaboration members will benefit from unrestricted open access. The LHC experience demonstrates the need for long-term data maintenance. For the HE-LHC, the data conservation will be ensured by a consortium of national partners, which recognises a common long-term research interest. Such a consortium will emerge naturally from the HL-LHC project.

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[1] The secondary economic "utility" is the sum of increased turnover and cost savings generated by a company due to orders placed. The utility/sales ratio expresses the benefit (the "utility") that the company perceives due to the "sales" to CERN.

Transparency is key when it comes to designing and building a large-scale research infrastructure project based on a collaborative approach. The HE-LHC project profits from the lessons learnt at the LHC and HL-LHC. International collaborations will generate technical detector designs linked to common services provided by CERN. For the collider, joint developments with universities, research institutes and industry will be re-enforced to render the construction process sustainable and to maximise the economic impacts on industry and society. More than 50 years of successful accelerator and experiment projects coordinated by CERN are proof of its capacity to design and build the proposed HE-LHC machine. The implementation section below sheds more light on the planned governing model and organisational structures, which should help ensure transparency and credibility from the early design onwards.

The HE-LHC collider and its physics programme are complementary to other programmes in particle physics, high-energy physics and astrophysics. The HE-LHC infrastructure will permit concurrent operation of proton and ion fixed-target beams at CERN, thereby ensuring the continuation of a diverse and vibrant elementary particle-physics research programme beyond colliders. In addition, it will include a comprehensive ion-beam based physics programme and offers the possibility for complementary research at a lepton-hadron interaction point.

The improved exploration of the Higgs boson, the start of exploration of the quantum structure of the Higgs potential, probing of the electroweak phase transition, progress in understanding Dark Matter and the research concerning the origin of the matter/antimatter asymmetry that are all likely to emerge from these investigations will lead to a better understanding of nature. The HE-LHC project is complementary to the neutrino research programme mentioned in the last ESPP and it will also create new synergies between the various communities.

The HE-LHC design study already involves the EC, the US DOE and several national research agencies in Europe, which are co-funding research and innovation aimed at developing the key technologies for the proposed future research infrastructures. This successful multi-pronged approach, by now well established and with functioning administrative support, will be continued during the technical design and preparatory phases. Concrete examples are the submission of design studies in the frame of H2020 and Horizon Europe, a successfully targeted Swiss technology programme (CHART), the U.S. and Russian high-field superconducting magnet development programmes and converging world-wide technology R&D initiatives on superconductors in Germany, Finland, Japan, South Korea and the US.

4 Readiness

The **technology** for constructing a High-Energy LHC **can be brought to the technology readiness level required for construction within the coming ten years through a committed and focused R&D programme**. **Reuse of the LHC underground civil infrastructure** worth about 500 million CHF at the time of its construction, **extension of the surface sites and use of the existing injector chain,** which also serves a concurrent physics programme, are levers to come to a sustainable research infrastructure at the energy frontier.

Strategic R&D for HE-LHC aims at minimising construction cost and energy consumption, while maximising the socio-economic impact. The R&D should mitigate technology-related risks and ensure that industry can benefit from an acceptable economic utility. A **preparatory phase of about eight years is both necessary and adequate** from 2020 onwards. It will involve establishing the project governing and organisational structures, building the international consortia for the machine and experiments, developing a territorial implementation plan allowing for the constraints emerging from the use of the existing infrastructure and the host state requirements, optimising the use of land and resources, and finally preparing the construction project.

4.1 Technical Feasibility

A circular hadron collider with centre-of-mass energies **achieving 27 TeV in the existing 27 km long LHC circular tunnel is technically achievable with low temperature superconductors by the end of the HL-LHC operation period**. Such a machine **requires high-quality accelerator magnets with a 16 T field**. A **focused R&D programme has been running since 2014** aiming to bring Nb_3Sn conductors, already pioneered for the HL-LHC project, to the required current density of 1500 A/mm^2 at 4.2 K temperature (presently 1200 A/mm^2 are achieved). A US DOE magnet development programme is working to demonstrate a 15 T **superconducting accelerator magnet**. Collaboration agreements have been signed with the French CEA, the Italian INFN, the Spanish CIEMAT, the Swiss PSI and the Russian BINP organisations, to build short model magnets based on the designs that have been developed in the EuroCirCol H2020 EC funded project.

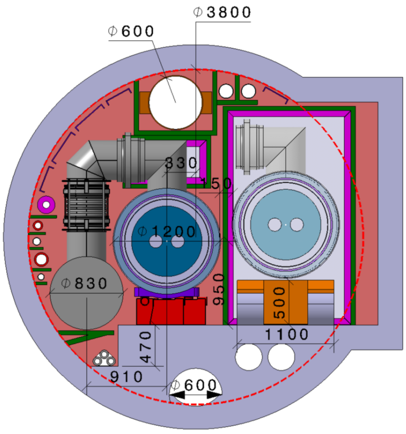

Figure 5: Cross section showing the superconducting magnet (1.2 m), the cryogen distribution line (0.83 m), the free space for installing the magnet (1.1 m) and the tunnel break-out for creating a safety compartment in the existing LHC tunnel (3.8 m).

The primary constraint comes from the limited space in the existing underground infrastructure (see Fig. 5; certain tunnel areas may provide even less space than shown). If an HE-LHC is the preferred scenario to be explored in more detail, work during the coming years must focus on developing a 16 T high-field accelerator magnet that is tailored to the specific needs of this machine and to the existing underground structures. The current "generic" 16 T magnet designs already aim at reduced weight and diameter of the cold mass by permitting a stray field in the tunnel. However, the effort required to produce an optimised design, to validate the concepts with model magnets and to build real-scale prototypes are only justifiable for one specific particle collider scenario.

To host a new collider, the **LHC machine (accelerator, underground technical infrastructure systems and detectors) must be decommissioned and dismantled**. Other infrastructure on the surface, such as cooling and ventilation, electricity and the cryogenic refrigeration, need to be extended. The equipment must be split into different classes of radioactive and non-radioactive waste. The host states must accept the radioactive materials as they become available after dismantling according to a "fair share" agreement to be developed in the coming years. The entire process is expected to take about three years, starting at the end of the HL-LHC operation.

In terms of **civil engineering**, sector 3-4 of the LHC tunnel needs to be reinforced with a 600 m long, internal steel structure. Additional underground caverns and alcoves need to be constructed at each access point to house the additional cryogenics, electricity and ventilation equipment. This also includes two new access shafts to lower the new equipment, in particular the cryogenic cylinders and the superconducting magnets, which are longer than those of the LHC. A safety concept based on fire compartments becomes necessary due to the greater amount of equipment in the tunnel, requiring the installation of separations every 548 m. For this purpose, the tunnel lining needs to be broken and the tunnel needs to be locally enlarged. On the surface, existing buildings will be reused where possible. Additional new cryogenic refrigeration plants, the refurbishment and addition of cooling and ventilation plants require site extensions at points 3 and 7 and new buildings at points 1, 2, 4, 6 and 8.

Luminosity increases with the beam energy. Compared to the HL-LHC, although the choice of a higher β^* function at the collision point leads to a partial loss of the luminosity gain, **HE-LHC delivers higher-luminosity** without the HL-LHC type luminosity levelling, which limits the peak luminosity at the start of the collision phase of each cycle. At the HE-LHC a different levelling naturally arises thanks to emittance shrinkage during each physics fill, due to enhanced radiation damping. A crossing angle of about 165 µrad limits the impact of parasitic beam-beam crossings and the associated luminosity reduction is compensated by using crab cavities. Electron lenses and current carrying wire compensators may further improve the performance of the machine.

The cryogenic system reuses the existing LHC helium refrigerators, which will be upgraded by doubling the number of 1.8 K refrigeration units (2 units per sector) and by adding specific 50 K refrigeration units based on neon-helium mixture cycle (so called nelium cycle) with a specific efficiency above 40%. The capacity of the 50 K refrigeration units is about a tenth of those required for FCC-hh and represents only 30% of the total entropic load. This technology is expected to lead to an electrical energy reduction of about 10% of the electrical energy consumption of the HE-LHC cryogenic system. The existing LHC cryogenic distribution line (the QRL) is not reusable; consequently, a new **Invar**-based cryogenic distribution infrastructure, leading to high reliability and low losses, is proposed. Both the QRL and the 50 K refrigeration units are being developed in synergy with the ongoing R&D programme for FCC-hh.

Many technical systems and operating concepts can be scaled up from HL-LHC or can be based on technology demonstrations carried out in the frame of a diverse set of ongoing R&D projects. A **robust collimation and beam extraction system** to protect the machine from the energy stored in the beam (factor 4 more than the LHC) can be constructed with the technologies that are being developed for the HL-LHC project. The momentum collimation system in LHC straight IR3 and the betatron collimation system in LHC straight IR7 can only accommodate normal conducting magnets due to the high beam losses. Increasing the magnet lengths to the maximum possible leads to a workable solution within the available space, based on a multi-stage system similar to the LHC's. Like the HL-LHC, additional collimators catching off-energy particles are needed in the dispersion suppressors of

IRs 1, 3, 5 and 8. A new **beam extraction system in IP6** will be based on a highly segmented, dual plane dilution kicker system that distributes all bunches of the beam onto a multi-branch spiral. With respect to the LHC, the kicker system has to be stronger and faster, to dilute the beam further and the absorber block has to be larger. Superconducting septa to deflect the rigid beams are currently being developed. The system is fault tolerant at design level, with limited effects from erratic firing of a single kicker element. Investigations of suitable absorber materials, including 3D carbon composites and foams, are ongoing in the HL-LHC project.

The cryogenic beam vacuum system is a key element of the hadron collider. It controls the heat power deposition resulting from the synchrotron radiation produced by the high energy beams. Early investigations revealed that the approach taken for the LHC would not lead to a workable solution due to the higher power density. The photon flux at the HE-LHC is even higher than that of a 100 TeV hadron collider (FCC-hh). This challenge has been taken up in the H2020 funded EuroCirCol project. A novel beamscreen geometry has been developed, which hides large pumping slots inside an ante-chamber, absorbs the synchrotron radiation with a saw-tooth surface and prevents electron-cloud build-up by carbon coating or laser treatment. This system, to be operated at 50 K, effectively shields the cold bore of the magnets, suppresses electron-cloud formation, and minimises resistive impedance effects. Several prototypes are currently being validated experimentally in the KARA synchrotron radiation test facility at KIT (Germany).

The RF system is the heart of any particle accelerator. It would operate at a frequency of 400.8 MHz, similar to the LHC, delivering up to 16 MV. Crab cavities are required for the HE-LHC. The RF power requirements for the main system are similar to those of the HL-LHC; up to 2 MW of total RF power will be required during acceleration. It is sufficient to install a single system at LHC point 4. In order to improve the energy efficiency, high-power conversion klystrons are currently being developed in an R&D programme. This creates synergies with other linear collider and circular lepton collider studies. There are no concerns about the technical feasibility.

HE-LHC injection at 450 GeV, re-using the existing SPS accelerator, would be extremely challenging. Only tight margins remain between the beam, the primary collimators, and the machine aperture in every arc cell, compromising machine protection and operational efficiency. In addition, assuming optimistic field errors based on 20 μm Nb3Sn filament sizes plus artificial flux pinning with 50% efficiency, the simulated dynamic aperture at 450 GeV appears insufficient. Therefore, the **baseline has injection at an energy in the range 900 GeV to 1.3 TeV from a new, superconducting SPS**. A study needs to be carried out to develop an optimum injection scenario. Injecting at 1.3 TeV simplifies the beam extraction in IR6, but requires more space for injection elements in IRs 2 and 8, potentially impacting the luminosity reach of secondary experiments in these IRs (length reduction by 20 to 40 m depending on the kicker rise time). Re-using Linac 4, PS, PSB and a new SPS as pre-accelerators permits the continuation of CERN's rich and diverse fixed-target physics programme in parallel with HE-LHC operation. Reliability and availability studies have confirmed that the operation and cycles can be chosen such that the HE-LHC collider will have an availability for luminosity production comparable to that of the LHC, i.e. > 70%.

To best serve the research community, the **HE-LHC experiment collaborations** will develop designs for complementary detectors. They might be similar to ATLAS or CMS with challenges related to radiation effects and pile-up. On the other hand, the trigger and readout strategies are closer to experiments for a 100 TeV hadron collider (FCC-hh). To what extent the magnet systems of ATLAS and CMS can be reused will depend on the subdetector concepts and on the lifetimes of these magnets. As the physics community advances with the definition of a physics research programme for this machine, a concept needs to be developed that can be based on a set of common infrastructure and services, avoiding overlaps and duplication of development and leveraging common technology research wherever possible. Common topics of interest span all domains of particle detection technologies, detector magnets, mechanical supports, computing and communication technologies, the trigger/data acquisition and on-line/off-line processing path. In particular, the development of a common simulation and analysis software environment, for future colliders which has been in place for five years, will be continued as a highly synergetic activity between collider studies and lepton/hadron physics communities.

4.2 Sustainable and Energy-Efficient Operation

The HE-LHC collider has been conceived with an emphasis on sustainability and energy efficiency. A storage ring maximises the energy efficiency for stepwise acceleration with the same RF system and for use of the accelerated beam through recirculation and by colliding the same beam many times. Combined with a high beam current and avoiding luminosity levelling, this beam recirculation results in an excellent figure-of-merit for luminosity per electrical input power. The most power-hungry element is the cryogenics refrigeration system needed to cool the superconducting magnets down to 1.9 K. Compared to the LHC systems, which would for an HE-LHC collider consume 55 MW of electrical power, nelium technology leads to a reduction to 50 MW in the baseline configuration, which corresponds to the cryogenic power consumption projected for HL-LHC operation. Cooperating with industry to bring medium voltage DC distribution systems to market grade so that they can power the accelerator subsystems helps dimensioning the electrical infrastructure, facilitates the integration of renewable energy sources and energy storage systems and suppresses the need of a power quality system. In order to avoid peak energy consumption during the ramp phase of the cycle, the energy stored in the magnets will be recovered for local buffering and re-use during the subsequent cycle with a constant power ramp, keeping total energy consumption at around 135 MW. The RF system will be optimised by increasing the peak electric to radiofrequency power conversion efficiency from 65% to above 80% in the scope of a klystron R&D programme carried out in close cooperation with the linear collider and circular lepton collider community. Superconducting thin-film coating technology will allow RF cavities to be operated at higher temperatures, thereby lowering the electricity need for cryogenics, or by reducing the required number of cavities by having an increased acceleration gradient. Higher-temperature high-gradient Nb/Cu accelerating cavities and highly-efficient RF power sources will find numerous other applications; they could greatly improve sustainability and performance for accelerators of nearly all types and sizes around the world. These combined efforts lead to a yearly power consumption forecast of the order of 1.2 TWh, slightly lower than the one projected for the HL-LHC.

The comprehensive resource-saving strategy includes studies to avoid water cooling wherever possible and by developing schemes to supply the waste heat to nearby consumers. A pilot programme, which is successfully integrated into a new, ecological residential and commercial district in the nearby French territory has recently been launched in the frame of the LHC programme. The detailed technical design of the HE-LHC will also investigate energy recovery opportunities within the accelerator infrastructure, for example, by working with industrial partners on either storing heat for later use or its conversion into mechanical or electrical energy.

4.3 Implementation Model

Assuming 2035 as the end date of the HL-LHC physics programme, dismantling of the LHC can be completed by around 2037/38. This brings the start of the HE-LHC physics programme to the mid-2040s. However, a legal framework for the project needs to be agreed by the host states due to the surface site extensions, the dismantling of the LHC, a new construction project in the region and new regulations in place with respect to waste management, environmental impact assessments and resource optimisation. A minimum period of eight-years for project preparation and administrative processes with the host states is required and therefore starting in the mid-2020s is sufficient. Joint studies with the host state authorities to develop a workable schedule have already begun.

The first step of the implementation model is to establish governing and management structures for a lean and effective organisation, which is needed to advance at a good pace. The design period includes a detailed cost analysis and the development of a sustainable funding strategy. It will establish the necessary legal framework to manage the commitment of contributions from member and non-member states and to create a suitable procurement and in-kind supply framework based on competitive performance of suppliers leading to control of the overall total-cost-of-ownership. It will create the framework to employ human resources under conditions corresponding to the needs of sustainable project preparation and construction. This phase concludes with the set-up of an appropriate auditing scheme, ensuring transparency to all stakeholders.

In parallel, focused R&D will be carried out to make sure that the key enabling technologies, namely the high performance Nb_3Sn superconducting wire, the 16 T accelerator magnet and the nelium-based cryogenic refrigeration **are available from industry at affordable cost when needed**. For the experiments, it includes the development of novel detector technologies and a significant improvement of existing concepts so that large pile-up can be managed effectively and the large amounts of data provided by the machine can be recorded and processed in an optimum way. **Detailed detector designs** can commence **with established experiment collaborations.** This activity needs to start as soon as the required expert researchers and engineers become available at the end of the current HL-LHC design activities. **The evolution of the off-line and on-line computing services along with the world-wide data processing infrastructure** will be orchestrated in a way that creates unified computing services, which serve the entire community. **Common software developments and code sharing** will **increase the overall efficiency**, avoiding parallel or even redundant developments. Construction of the experiments can begin when the accelerator design is finalised. **Installation** can start **as soon as experiment sites become available.** Experience with LEP, LHC and the B factories suggests that **a two-year commissioning period for the machine, including injectors, and experiments** will be adequate.

5 Challenges

The HE-LHC entails **a number of uncertainties** that can adversely impact the project implementation. They **need to be addressed in a timely manner during the project preparatory phase**. The greatest technical challenges are related to the availability of large amounts of superconducting Nb_3Sn wire at the required performance and cost levels. Other relevant challenges emerging from the re-use of the existing infrastructure are a) the need to refurbish and extend the underground and surface infrastructure, b) the integration of the machine in the existing tunnel, c) the availability of a workable injection scheme. Finally, a well-focused physics research programme, backed up by a committed world-wide consortium of scientific contributors needs to be defined in order to be able to develop a suitable detailed machine design and suitable experiment detectors.

Uncertainty	**Impacts**	**Mitigation**
Technical challenges		
Nb_3Sn wire performance or cost target not attainable in time.	Target field level and quality not achievable. Reduced collider performance.	Intensify Nb_3Sn magnet R&D programme. Invest in building up a co-development with industries worldwide to avoid a vendor-locked-in situation and to prevent price limitation.
Inefficient magnet series manufacturing, limited availability of companies with necessary capacities and quality management.	Increased cost, reduced performance and reliability of machine, unsustainable operation due to downtimes and excessive repair/maintenance.	Invest in R&D of easy to manufacture, test and install magnet designs. Optimise system interfaces. Launch studies to improve assembly efficiency and speed, reduce production steps. Invest in automation of production, assembly, testing and integration allowing for a geographically distributed process.
Cryogenic refrigeration system unsustainable.	Lower collider performance. Higher energy consumption.	Bring nelium-based refrigeration technology to a higher technological readiness level.
Particle detection technologies do not meet the performance, reliability and cost needs.	Under use of the collider's potential can lead to loss of interest in the worldwide community.	Launch a world-wide coordinated strategic R&D on detector technologies and software ecosystems, which engages the entire community in the definition of the physics programme and in the design of the detectors.
Injection from SPS at 450 GeV not feasible.	Need to replace the existing SPS with a superconducting synchrotron.	Perform a detailed study to confirm or rule out the use of the SPS as injector. Develop a cost-optimised design for a new, superconducting SPS accelerator.
Implementation challenges		
Funding of construction project and sustained operation throughout the entire physics programme.	Insecure funding will delay or prohibit construction. Insufficient operation funding will lead to below optimum exploitation of the facility.	Early negotiations with member states to set up a funding strategy for the preparatory phase. Construction cost profile with a staged implementation scheme permitting co-funding from the CERN budget. Timely production of a cost/benefit assessment will catalyse negotiations with host states and the EU bodies for regional developments.
Governing and project organisation including effective administration services.	Insufficient project management and resources to execute a decades-spanning, international hi-tech project can lead to runaway costs, significant delays, loss of scope and loss of community support.	Create a high-level international support group. Establish a dedicated organisational unit, adequately staffed with experienced personnel. Establish the legal framework for contributions from member and non-member states. Create a suitable procurement and in-kind supply framework, human resource conditions which provide for sustainable project preparation and construction.
Timely availability of rights of way on land plots and underground volumes. Acceptance of infrastructure development impact in the region.	Delays or unforeseen needs to adjust the project scope can stretch the preparation and construction phases or result in project re-scoping.	Winning the host states through timely involvement as partners is the key. Work has already started and a preparatory phase schedule has been developed. Adequate project governance, organisation and resources must be invested in early on with the host states, even if a decision about the construction will be taken at a later stage. Optimisation of resource usage (water, real estate) and limitation of urban impacts (traffic, noise, visual impacts) are tasks during this phase.

6 Addendum

6.1 Community

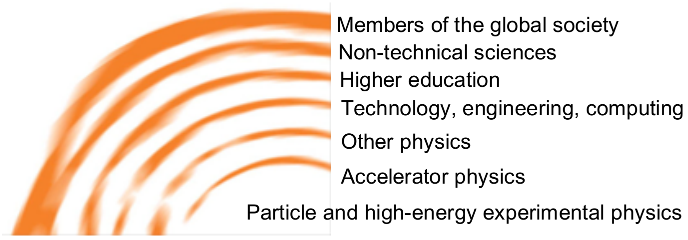

Figure 6: The "onion" model of involvement of and impact for different communities.

The impact on the community can be presented in terms of an "onion" type model, starting with the innermost layer comprising the **core scientific communities**, which need, conceive and use such a facility. Further communities in the European Research Area and beyond, which will benefit throughout the entire lifecycle, starting with the early design phase, include: **other sciences, engineering communities**, **higher education**, **industrial partners**, **researchers from non-technical domains**, and ultimately **all members of society**.

Community	**Impact potentials**
Particle physics	The HE-LHC increases the physics discovery potential. It will address the high energy frontier, electroweak, Higgs, Dark Matter and heavy flavour physics communities as well as the heavy ion and lepton-hadron communities, presently working on the LHC, flavour factories, Dark Matter experiments and other particle collider experiments worldwide. The theory community is needed to develop scenarios that can be tested well at this future collider. Together with the experimental physics community they need to define a comprehensive programme for such a frontier collider.
Experimental physics	The detectors for this machine will have to be highly versatile. Requirements include the measurement of multi-TeV jets, leptons and photons with masses up to 12 TeV. At the same time, detectors must be highly sensitive to known SM processes. Precision tracking and calorimetry are further fields of activity. The high occupancy and pile-up calls for unprecedented time resolution and advances in data reduction. The need for high spatial resolution due to boosted objects needs novel approaches for particle identification techniques, and precision tracking. Additional experimental physics communities will be attracted by this research infrastructure through the concurrent fixed target experiment programme and the heavy ion operation programme.
Accelerator physics	With its unprecedented collision energy and luminosity, the HE-LHC will attract a world-wide community of accelerator physicists. Fully automated operating procedures ensuring the concurrent operation of CERN's injector complex and the future high-energy collider, integrating luminosity optimisation, are topics that call for the integration of diverse domains of competence.
Other physics communities	The research at the HE-LHC will have implications for astrophysics and cosmology, offering an unprecedented opportunity to federate these scientific fields.
Technology, Engineering, Computing	The project will drive the development of superconductors for high-field magnet applications including large series production and precision machinery. The collider requires a novel approach to cryogenic refrigeration on a large-scale. The project also involves the development of systems for higher efficiency electrical to radio-frequency power conversion. The development of cost-effective, high-performance thin-film coated, superconducting cavities needs material scientists and requires expertise from manufacturing experts. Specific engineering areas include precision mechanics, surface treatment, superconductivity, novel materials, electronic engineering and reliability engineering to improve the particle accelerator efficiency. Electrical engineering communities will be involved in bringing medium voltage DC technology to the market, to conceive lower-loss electricity distribution systems which are more reliable and develop environmentally friendly and sustainable energy recovery and buffering systems. Designers will be needed for the development of waste-heat recovery and reuse systems.

	To design and construct the underground infrastructure in a cost-effective way, the civil engineering community is needed to advance tunnelling technologies and to develop ways for the recovery and re-use of excavation materials. This work will be carried out as a joint endeavour with material scientists, geologists and chemists. Information and communication technology communities will be involved everywhere. Their activities include simulation algorithms and software infrastructure; parallel and high-performance computing; distributed computing; real-time and embedded systems; mechatronics to conceive new standards and technologies for low-maintenance and easy-to-repair systems in the areas of protection, access, remote handling and autonomous interventions; data acquisition, data visualisation, modelling and operation optimisation,; the introduction of artificial intelligence in machine and detector operation; radiation and fault tolerant systems; environmental information systems; data mining technologies; wireless communications including safety-related functions; data and document management facilities; worldwide computing infrastructures; long-term data stewardship; open access data models and infrastructures and much more.
Higher education	The design and construction of the accelerator and the detectors will offer many opportunities for science teachers and students at master, doctorate and post-doc levels. Eventually the findings from all the scientific activities will enrich the academic curricula: state-of-science today will become state-of-the art tomorrow. This project will enlarge the impact potentials of higher education to highly qualified personnel (HQP) and apprentices.
Industry	A project of such scale must be designed, constructed, operated and maintained with strong involvement of industrial partners from all of the participating nations. Where reasonably possible, a gradual shift towards co-development will lead to a research infrastructure which is sustainable in the long-term on one hand and which has greater impact for industry on the other hand. A specific initiative during the detailed design phase will focus on identifying the fields of cooperation, also elucidating where companies can best profit from enhanced learning to increase their competitiveness and improve the quality of their product and internal processes.
Non-technical sciences	This project will engage a variety of scientific communities, beyond physics, technology and engineering domains. Examples include, but are not limited to research in logistics and systems engineering around the world-wide production chain for the accelerator and detectors (logistics, operations, sales, HR, procurement, accounting, management and organisation, business administration). Media and visual arts as well as museums and marketing experts are needed to efficiently engage the public and to communicate with institutional stakeholders. Radiation protection, technical risk management and waste management experts will facilitate the control of hazards and risks in all areas throughout the entire lifecycle. Environmental and urbanistic sciences will help avoiding, reducing and mitigating impacts. Economics, innovation management and political sciences form another group of non-technical sciences, which have already shown during the FCC study phase that they are essential for the successful preparation of a future project.
Members of the global society	The continued deep exploration of our universe tackles fundamental questions that intrigue everyone: What is the origin of the universe? What is the nature of the matter that we are all made of? Where do we come from? Why is there something and not nothing? This project addresses these questions directly and created opportunities to engage everyone who is interested. During the preparatory phase, an effort will be made to intensify such involvement through community science and a modern communications plan. The conceptual study phase has revealed that the greatest challenge is, however, to create interest among the majority of people who are unaware. HE-LHC needs to address the challenge well to raise awareness on a global scale and to strengthen the support for continued investment in this research by policy makers, funding agencies and ultimately, by every member of society.

6.2 Timeline

The overall project schedule is dominated by accelerator and technology R&D, in particular by the time needed to develop and industrialise 16 T Nb_3Sn superconducting magnets. Another key input for the HE-LHC schedule is the anticipated stop of HL-LHC. The construction phase requires then at least 8 years, from stop of HL-LHC operation to start of HE-LHC physics.

The preparation phase has to be launched at least 8 years before project start and includes:

- all administrative procedures with the host states, ultimately leading to the building permit and provision of the required surface and underground rights of way;
- development of project financing, organisation and governing structures;
- site investigations, civil engineering design, and tendering for consultant and construction contracts.

The construction phase has a duration of 8 years and includes construction of:

- all underground and surface structures;
- technical infrastructure;
- HE-LHC collider and detectors,
- superconducting SPS and associated transfer lines to HE-LHC;

as well as hardware and beam commissioning. The implementation time line for the HE-LHC is shown in Fig. 7.

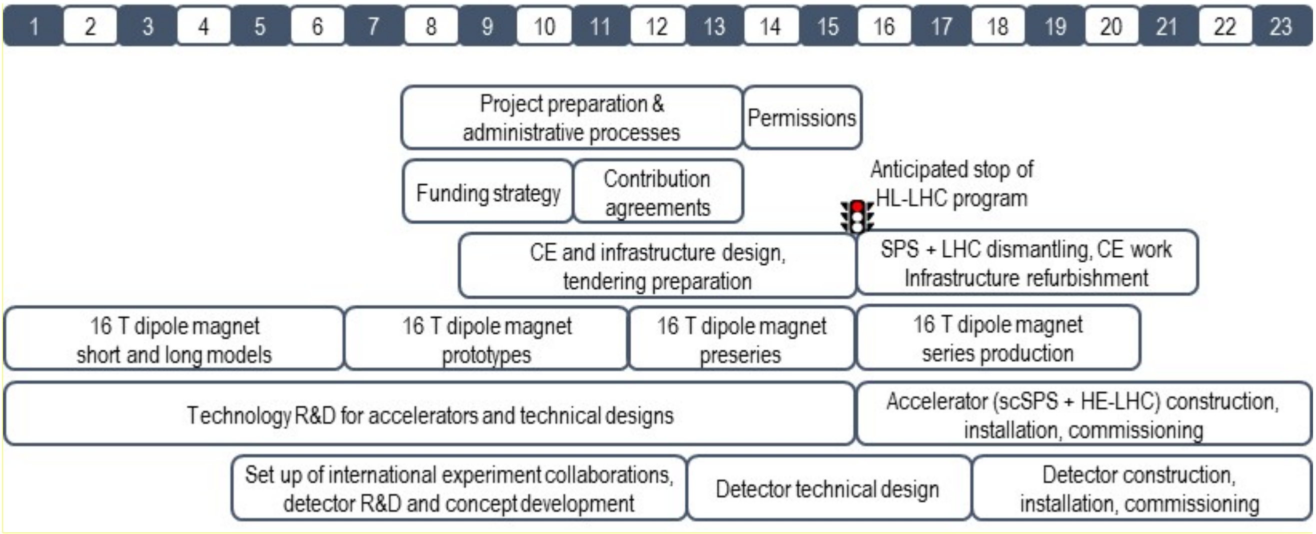

Figure 7: Overview of implementation timeline for the HE-LHC project starting in 2020. Numbers in the top row indicate the year. Physics operation would start in the mid 2040ies.

6.3 Construction and operational costs

6.3.1 Capital Cost

A cost study was performed based on the conceptual design of HE-LHC. The capital cost for construction of the project is summarised in Table 2. The precision of the overall cost estimate is at ±30% level.

Domain	**Cost in MCHF**
Collider	5,000
Injector complex	1,100
Technical infrastructure	800
Civil Engineering	300
TOTAL cost	**7,200**

Table 2: Summary of capital cost for implementation of the HE-LHC project.

The **total construction cost amounts to 7,200 MCHF** as shown in Fig. 5, and is dominated by 69% or 5,000 MCHF for the collider. The major part of the accelerator cost corresponds to the 1,250 Nb_3Sn 16 T main dipole magnets, with a cost target of 2.3 MCHF/magnet, totalling 2,900 MCHF. The collider cost also includes 260 MCHF for LHC disposal.

The cost for construction of a new superconducting SPS, with an energy around 1 TeV, and associated transfer lines (1,100 MCHF) was derived from scaling from SPS, LHC and HE-LHC systems and needs to be confirmed by a specific scSPS design study.

The construction cost for surface and underground civil engineering modifications and new structures is 300 MCHF or 4% of the total. The capital cost for the technical infrastructures is 800 MCHF corresponding to 11% of the total construction cost.

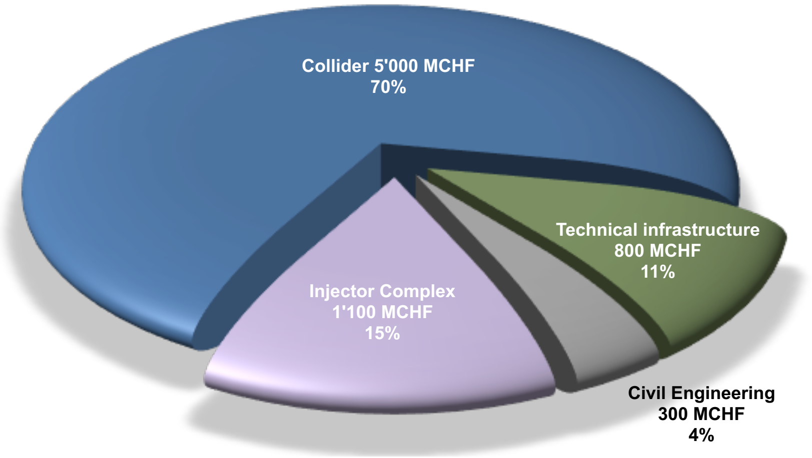

Figure 8: HE-LHC capital cost per project domain.

6.3.2 Operating Costs

The general concept for operation of the HE-LHC will be an evolution of the HL-LHC approach, streamlined to guarantee sustainable operation and maintenance: The machine design will put **an emphasis on a modular approach while conceiving the individual systems and subsystems so that they can be monitored, maintained and repaired by service suppliers as much as reasonably possible**.

The **electric power consumption** is an important operational expenditure and to arrive at a long-term, sustainable highest-luminosity collider, the HE-LHC conceptual design already integrates a number of energy saving measures:

- Use of **power-saving superconducting magnets and circuit layout optimisation**.
- A novel beamscreen design with an optimised temperature working point that permits efficient removal of the synchrotron radiation heat and minimises the load on the cryogenic refrigeration infrastructure.
- Use of an innovative cryogenic refrigeration system based on a neon-helium (nelium) light gas mixture, which reduces the electricity consumption and waste heat generation by about 10% with respect to traditional plants.
- **Recovery and buffering of the energy stored in the superconducting magnets** at the end of the cycle for reuse during the subsequent ramp in order to save energy and to control the peak electricity demand.
- Using **medium-voltage DC electricity distribution** to optimise the size of the powering infrastructure, enabling the introduction of renewable energy and storage systems and supressing the need for a power quality system.
- **Waste-heat recovery and re-use** inside the facility, and for storage and provision to district services (heating and air conditioning).

The above measures result in a total electrical energy consumption per year of nominal HE-LHC operation of 1.2 TWh/year, directly comparable to the 1.2 TWh/year consumed by CERN today and the expected 1.4 TWh/year for HL-LHC. With the CERN electricity prices from 2014/15, the electricity cost for HE-LHC collider operation would be about 55 Meuro per year.

Considering the total luminosity production of 15 ab^{-1} over 20 years, about 70 keuro for electricity would need to be invested to produce 1 fb^{-1} of integrated luminosity. With more than 2.5×10^{9} Higgs bosons and 5×10^{10} top-pairs produced in total, this translates into an **electricity cost of about 43 cents per Higgs boson and per 20 top quark pairs**.

6.4 Computing requirements

The LHC operation era has shown that computing has evolved into a **service for a world-wide user community.** The existence of a large-world wide computing and data service infrastructure for the LHC programme today with a need for committed enlargement tomorrow will lead to a long-term sustainable, world-wide scientific computing and data management infrastructure for the physics community. Involving further **partners beyond the high-energy physics community** will facilitate this endeavour. Concrete examples include astronomy and astrophysics projects like SKA and ESO operated facilities, life-sciences via advanced medical imaging, microscopy and bio-molecular data processing as supplied by EMBL and ELIXIR, photon and neutron sciences such as crystallography, and a long tail of scientific domains with more limited requirements, but with a need for affordable access to computing and data processing. Carrier neutrality, vendor and operator independence as well as the continued availability of **open standards, hardware and software technologies** are essential ingredients to guarantee independent and effective progress of science and education on a long time scale.

Specifically, for the HE-LHC, the **computing capacity requirements outpace those of the HL-LHC for event generation, detector performance simulation, data acquisition, on-line event filtering and off-line reconstruction**. Detectors would be similar to ATLAS and CMS with significantly greater challenges due to radiation and pile-up. Pile-up increase from 130 to 500, raises the need to migrate sophisticated off-line algorithms all the way up to the trigger level. Trigger rates will be closer to FCC-hh than to HL-LHC and event sizes will be larger, too, increasing by some factor with respect to ATLAS/CMS phase II scenarios. This creates new data handling challenges. The possibility **to exploit the particle collider's capabilities fully depends much on the capability to** record as much data as possible, to buffer them and process them in a sustainable fashion. The experimental physics and information technology communities will need to be fully engaged from an early phase to develop approaches and solutions that can come up to these new performance requirements.

For the detector design, the high beam energies and the development of new detector materials creates a need for a new, common high-performance detector simulation and event generation ecosystem. The FCC study spawned such a development at a very early point in time. The **FCC detector software, integrating detector description, detector models, event generation and simulation as well as radiation-impact forecast is an active programme today** that federates contributors from numerous high-energy physics experiments. The software has also started to be in used for the HL-LHC upgrade project. For the coming detector design phases, processing capacities need to make significant jumps and data from detector developments and irradiation facilities need to be integrated on a continuous basis. This involves the **development of new event generation techniques**, in particular involving novel algorithms, ongoing adaptation to underlying processing platforms to be able to exploit the hardware well, standardised ways to describe detector models and to integrate real data from test beams, irradiation facilities and laboratory measurement campaigns.

Furthermore, **tools need to be developed to compare the experimental results and the theoretical predictions**. Such an activity is expected to **strengthen the cooperation between theoretical and experimental physicists**, leading to a more coherent world-wide community by developing common goals and a sense of shared responsibility. This work will be the **result of a world-wide collaborative effort of theoretical and experimental physicists and contributors from related relevant information technology** disciplines.

The HE-LHC project also needs computing infrastructure that supports the operation of the detectors over long periods of time. As demonstrated in domains such as detector controls and readout electronics of the LHC project, the **development of common services will further improve the cost-efficiency** of such a project, **during the cost-intense operation phase**. As the separation between off-line and on-line computing gradually vanishes, common services which were traditionally purpose-built by each collaboration, become attractive.

Embedded and real-time computing are of interest **for an infrastructure that is characterised by its longevity** and thus dominated by maintenance costs. Given the significant increase in the number of devices for a future collider, **standardisation**, **coordinated testing, certification**, **procurement** and **maintenance/repair** services, available to all users, will improve sustainability. These activities can create impact far beyond the particle accelerator community, if properly set up and coordinated with ICT communities.

Cyber-security plays an increasingly important role and scientific computing is no exception to this. Intensified support to ensure adequate coverage of this domain is an important requirement for a future project. The use of COTS operating systems and embedded Web servers in all kind of equipment ranging from simple I/O devices, over measurement instruments to autonomous robots require an effective but lean infrastructure.

Cooperation on ICT standards, technology developments and relations with other research facilities with similar requirements (e.g. DESY, ESRF, ESS, Fermilab) needs to be strengthened. Synergies with other scientific domains (e.g. astronomy and radio astronomy facilities, light sources and FELs, neutrino and gravitational wave observatories, particle accelerators for medical applications and nuclear fusion experiments) can be developed to lead to more effective operation of **various IT services for research**. Activities spawned by DESY on front-end computing hardware and CERN's openlab are examples for such initiatives.

Considering the fast pace of information technology evolution, the long-term cost impact of in-house developments and their potentially limited industrial reach, it is prudent to base designs for a future project on widely accessible hardware, software and service infrastructures. The particular needs of an FCC-scale facility may also represent attractive test-beds for emerging technologies. Co-innovation projects with industrial partners during the early construction phase, permitting pre-commercial procurement initiatives that can lead to high-performance infrastructure services at competitive costs.

Finally, **long-term data availability** has become an important feature to ensure the lasting impact of the facility. The accessibility of several decades of LHC data, metadata and analysis results has turned out to be a major topic for the community. With a future particle collider, the time span will extend to the second half of the 21st century, calling for **evolving data storage and management systems that serve the core community** for long periods of time. Considering the continuous evolution of data formats, the ever-evolving particle detectors and a user community with significant turnover, **data quality management is a chief topic to be addressed. The value of a particle collider research facility depends directly on its data quality and long-term, world-wide open accessibility for as large a community of scientists as possible.**

7 Change Track

Revision	Date	Description
3.0	2018-12-18	Upload to site of European Particle Physics Strategy
3.01	2019-01-01	Section 2, page 6: clarification of educational value impact figures. 5% to 13% on top of regular academic training instead of 9% to 17% including academic training. 10 billion CHF of benefits are the sum of industrial spillovers and ICT. The industrial spillovers were missing and are now included as "earnings effects for industrial suppliers".
4.00	2019-01-11	For RF focus on power saving via klystrons rather than thin-film cavities. Removed dashed between figures and K unit in 4.1. Upload as a single document to the public website.