6 Addendum

6.1 Community

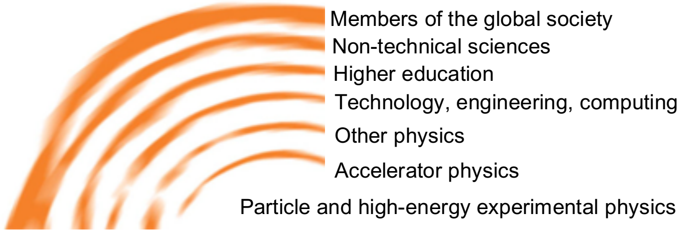

Figure 6: The "onion" model of involvement of and impact for different communities.

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.

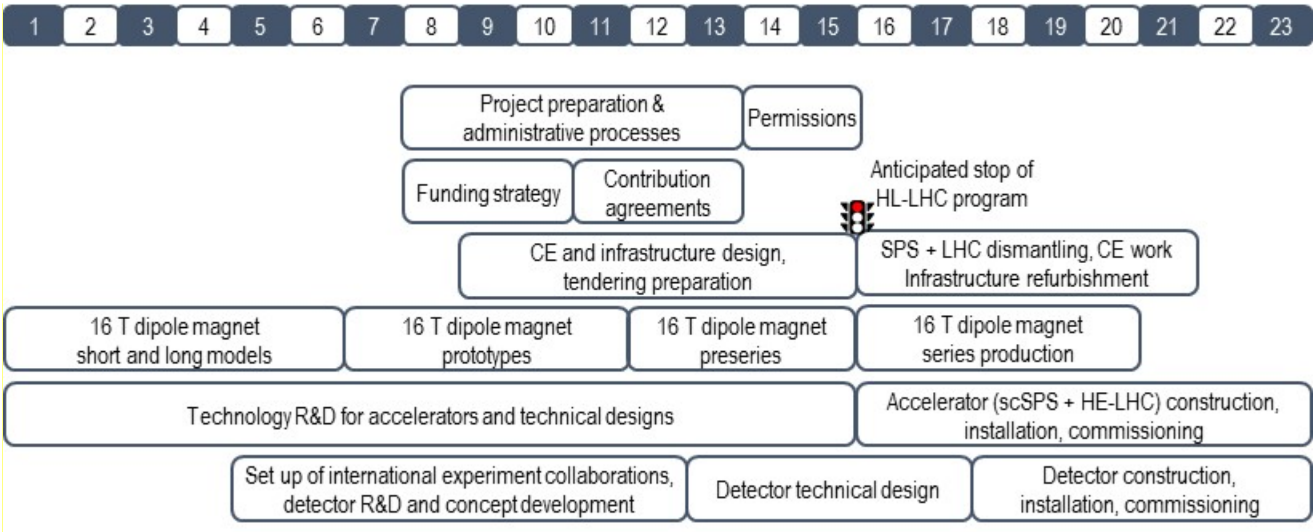

Figure 7: Overview of implementation timeline for the HE-LHC project starting in 2020. Numbers in the top row indicate the year. Physics operation would start in the mid 2040ies.

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.

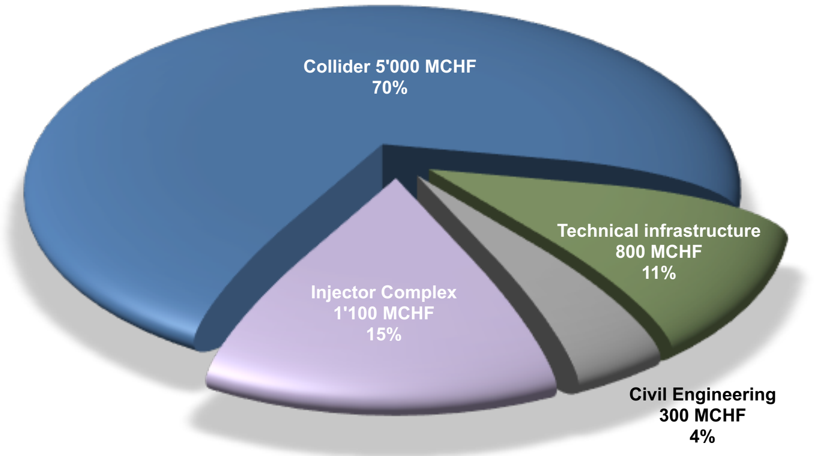

Figure 8: HE-LHC capital cost per project domain.

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.**