CAN WE AFFORD TO WAIT? DESIGNING THE COLLIDER OF THE FUTURE

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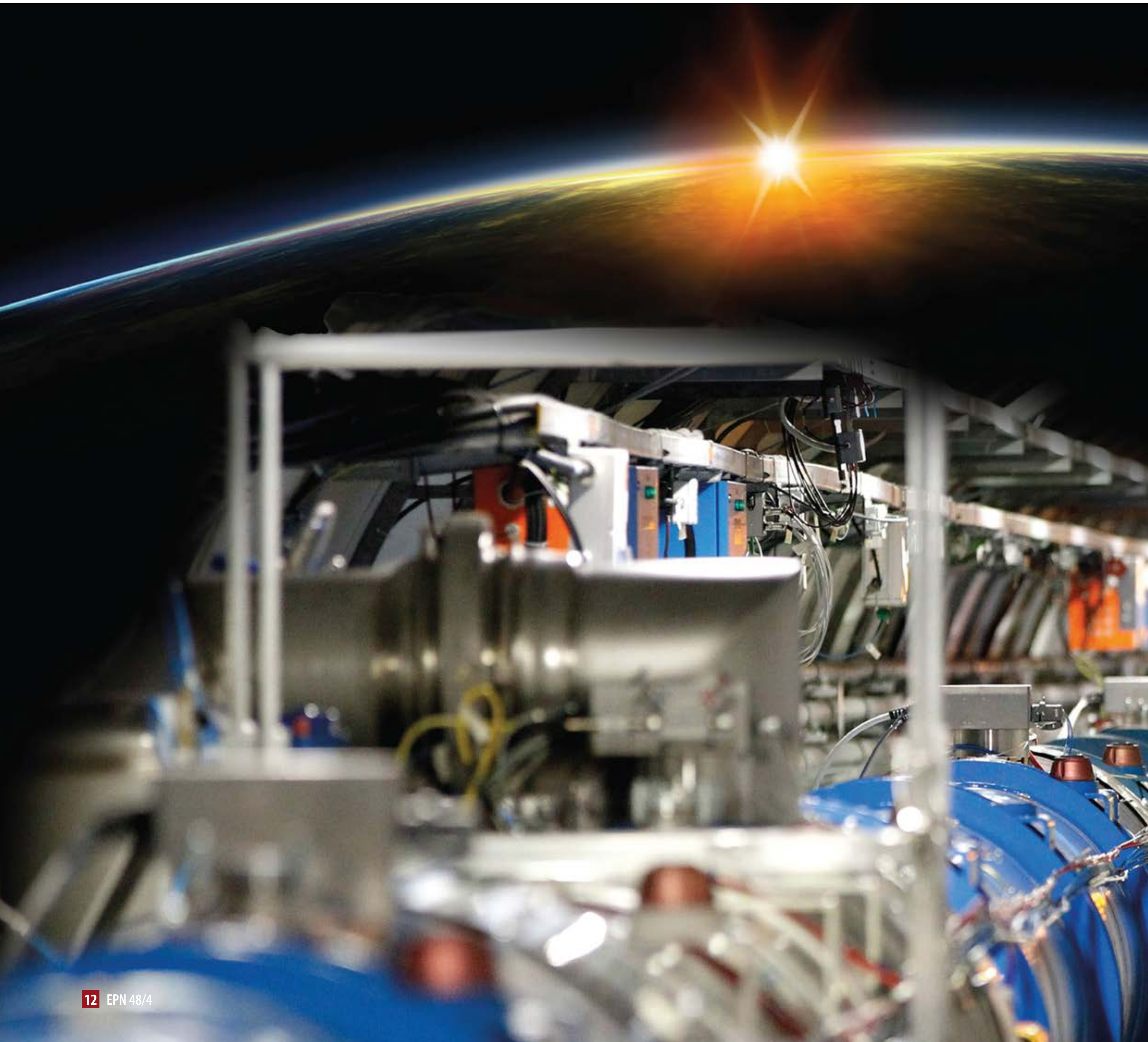
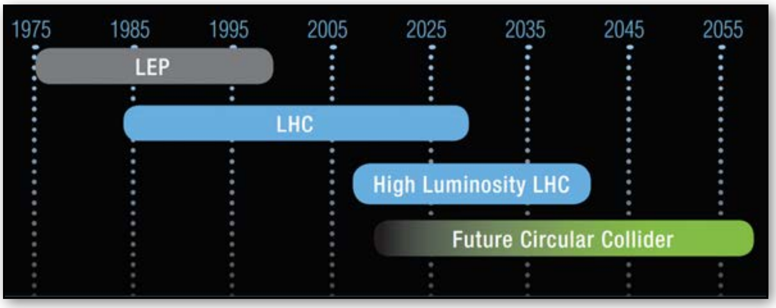
Designing a future circular collider is a next step in humanity's quest to explain the world. This effort is not only about striving for a profound understanding of nature, but also about creating an exciting perspective for future generations.



On 4 July 2012, during a special seminar in the main auditorium of the European Organization for Nuclear Research (CERN), the discovery of the Higgs boson was announced under the eyes of the world. This long elusive enigma had been the most sought-after particle in modern science, since the formulation of the Brout–Englert–Higgs mechanism back in 1964. Its discovery was a historical milestone not only for the Large Hadron Collider (LHC), but for the worldwide physics community, and resulted in the award of the 2013 Nobel Prize for Physics to Peter Higgs and François Englert.

The Higgs discovery, marking the end of a fifty years' adventure, completes the so-called Standard Model of particle physics, which describes the fundamental building blocks of matter and their interactions (except for



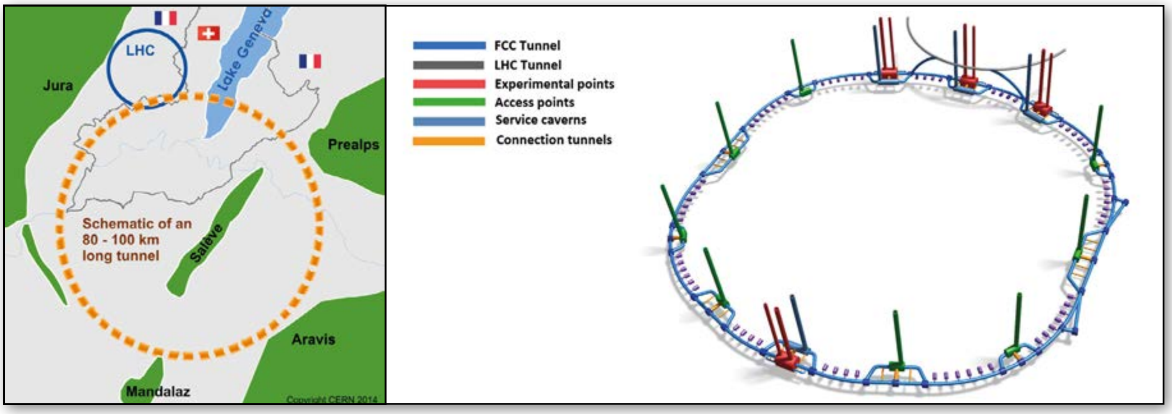
▲ FIG. 1: The goal of the FCC study is to explore post-LHC scenarios for a circular collider in order to ensure the seamless continuation of the world's particle physics programme after the LHC era. The significant lead time of approximately twenty years for the design and construction of a large-scale accelerator calls for a coordinated effort.

gravity). It is one of many instances in the history of science where more than a working life passed between the initial formulation of a theory and its final experimental confirmation. Often enormous patience is required for ultimate success. The discovery of gravitational waves, first predicted by Einstein's theory of general relativity in 1916, but only detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO) collaboration in 2016, offers another glaring example. These two recent discoveries - of the Higgs boson and of gravitational waves - are linked to the two great theoretical frameworks of modern physics: quantum mechanics and general relativity, respectively. Unfortunately, with so far no signs of supersymmetry at the LHC, these two fundamental theories remain fully disconnected. A future high-energy collider might be the tool required to unravel this great mystery.

Presently, we are in an intermediate period, waiting for more data from the high-energy physics experiments at the LHC and elsewhere. At the same time the increased volume and precision of the data, being collected since 2012, confront the Standard Model with more exquisite tests.

Now that the Standard Model is almost complete we are free to focus on the big questions beyond it, such as the properties of dark matter, the mechanism behind the expansion of the universe, the origin of the matter-antimatter asymmetry, the hierarchy problem, and the naturalness of the mass of the Higgs boson. These questions, and the need to study the recently-discovered Higgs boson in greater detail, call for the full exploitation of the LHC including its high-luminosity phase (HL-LHC), whose rich physics programme extends up to around 2035.

A future energy and intensity frontier circular collider coming into operation soon after the completion of the HL-LHC research programme will offer unprecedented physics possibilities and could herald a profound change of scientific paradigm in modern physics. Given the long lead times of at least 20 years (see Figure 1) required to design, develop and build such a complex machine it is more than timely to start thinking about a post-LHC accelerator facility. Such is the purpose and scope of the Future Circular Collider (FCC) study [1] (fcc.web.cern.ch), which was launched as a direct response to the 2013 update of the European Strategy for Particle Physics.



▸ FIG. 2: (a) Sketch of a future 80–100-km-long tunnel in the Geneva area, which would allow for a 100-TeV, energy-frontier proton collider and also, as a potential intermediate step, a high-luminosity e^+e^- collider serving as a W, Z, H and $t\bar{t}$ factory. (Image credit: CERN) (b) Schematic of the underground infrastructure preliminary layout. FCC study envisages a 100 km in circumference tunnel, nearly four times the size of the present LHC (Image credit: CERN/FCCstudy)

A large-scale research infrastructure for Europe

Presently we are testing our theories in the new energy regime opened up by the LHC. If new physics is uncovered at the LHC we will surely need to study it and further push the intensity and energy frontiers. But what if there is no sign of new physics at the LHC? In that case new experiments at higher energies but also of greater precision will be required to unravel the many unsolved mysteries of the Universe.

To prepare for either case, CERN has initiated the FCC study for a future large-scale research infrastructure centred on a new-generation circular hadron collider with a circumference of about 100 kilometres, able to reach proton-proton collision energies of 100 TeV [5] – about 8 times above the LHC – and a corresponding energy in heavy-ion collisions. A future high-luminosity electron-positron collider, which could be housed in the same tunnel, is being considered as a possible first step [6]. A high-energy LHC upgrade is yet another option.

The FCC study explores the feasibility and reliability of all these possible future machines and associated options such as ion operation and lepton-hadron collisions (FCC-he); it also develops key-enabling technologies and examines the various physics opportunities. These efforts will culminate in a Conceptual Design Report and a cost review that will inform the next Update of the European Strategy for Particle Physics expected around 2020.

Investment in frontier research will reinforce and revive European competitiveness, employment, and prosperity, while preparing the next generation of accelerators. However, the FCC study extends well beyond Europe: it is organized as an international collaboration, bringing together as of today 116 institutes from 33 countries. This is in line with CERN's long standing tradition. LHC is but the latest example in a series of ambitious, and successful global accelerator projects and scientific discoveries that have rewritten the particle physics textbooks.

At CERN for more than fifty years, scientists from all around the world have peacefully been working together to develop new technologies and the necessary infrastructure for answering some of the most puzzling questions of mankind, greatly advancing technologies and scientific understanding in parallel. Can we afford not to prepare a future for the next generation?

The discovery of the Higgs boson was only the beginning

It is often stated that the Higgs boson concludes a long-standing effort of describing the building blocks that make up our Universe. However one should not neglect the peculiarity of the discovered boson per se. The Higgs is a unique particle – starting already from its rather low mass – and its properties could be a portal to new physics. It is a keystone of the Standard Model and everything we learn about it may be linked to the deepest laws of nature.

There are two complementary paths that should be further explored: precision measurements of the Higgs properties where new physics can manifest itself as tiny deviations from Standard-Model predictions, and searches for new particles and new processes beyond the Standard-Model.

A 100 TeV proton-proton collider could produce conclusive answers to various open questions surrounding the Higgs boson and, in addition, solve some of the most tantalizing puzzles related to the matter-antimatter asymmetry, to dark matter and to dark energy [2]. This machine would offer a bold leap into completely uncharted territory, probing energy scales where fundamentally new physics principles might come into play.

In addition, a future circular electron-positron collider reaching c.m. energies up to 350 GeV (serving as W, Z, Higgs and top factory), will allow for the highest precision measurements ever, of many of the key parameters of the Standard Model [3]. These high-precision measurements in the clean environment of a lepton machine could unveil rare processes and deliver hints for new physics.

Finally, the potential of heavy-ion physics [4] at the hadron collider, and the additional option of hadron-lepton collisions illustrate the enormous versatility and richness of the FCC facility. This multi-faceted research infrastructure would offer profound insights into how matter and the universe behave under extreme conditions.

The various scenarios explored within the framework of the FCC study can be compounded into a research continuum well extending through the end of the 21st century. While preparing for this future collider complex, we should heed a lesson from science history: even, or especially, if our presently favoured theories are proven wrong we may discover something unanticipated, and possibly truly revolutionary, as was the case, *e.g.*, with the Geiger-Marsden experiments.

The brave new world

The development of a future circular 100 TeV collider requires significant advancements of numerous technologies. The FCC study has launched long-term R&D programmes in partnership with many outstanding research centres and universities. As demonstrated by past endeavours, the effective interplay between fundamental science and technological R&D has a great transformative potential for our daily lives.

Successful technology R&D relies on interdisciplinary synergies, taking into account the experience from past and present accelerator projects. Ranging from superconducting technologies to new electronics and from novel coolants to reliability studies, the FCC study develops innovative approaches with a great potential impact on industry and society.

The quest for higher energies requires a new magnet technology. Magnets based on Nb_3Sn superconductor can reach magnetic fields of 16 T (almost doubling the magnetic field of the LHC Nb-Ti dipole magnets). Such magnet development is supported by the European Commission through the EuroCirCol project (https://fcc.web.cern.ch/eurocircol). Small Nb_3Sn test coils at Lawrence Berkeley National Laboratory and at CERN have already achieved dipole fields around 16 Tesla [7]. The HL-LHC itself will include a few tens of real Nb_3Sn accelerator magnets (though with a field of "only" 11 or 12 Tesla), thus helping advance the technology for a future circular hadron collider.

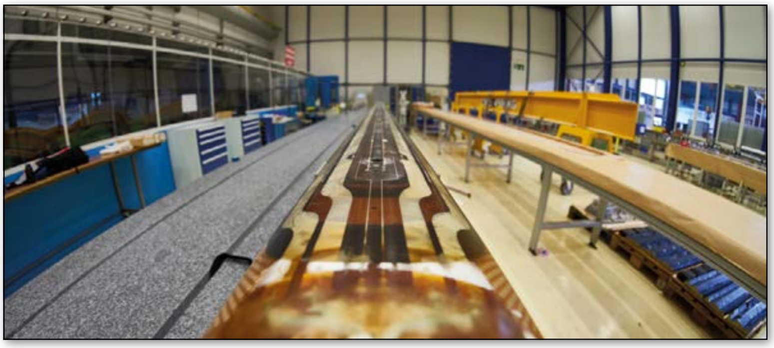
▲ FIG. 3: FCC Collaboration brings together 116 institutes from 33 countries as of June 2017 (Image credit: CERN)

The key element of the future electron-positron collider is a 100 MW RF system [8], for which advanced cavity production techniques and highly efficient RF power sources are being developed. In addition, an ultra-high vacuum and beam screen system [9] for the hadron collider along with a sustainable large-scale cryogenics infrastructure [10] are further examples of key technologies developed in the frame of the FCC study.

The FCC R&D technology programme is aiming not only at demonstrating the basic feasibility but also at reducing the associated costs and at guaranteeing a sustainable operation. The future circular collider will be much more than a scaled-up version of existing machines.

Fundamental research endeavours often bring about unexpected, life-changing results — as in the case of the basic research that led to the development of magnetic resonance imaging and PET tomography. It was also at CERN that the world-wide-web was invented, changing the lives of billions of people. Present research efforts in superconductivity – to name but one of the many different areas covered by the FCC study – can equally find many life-changing opportunities from transportation to medical applications. Although the benefit of any particular scientific endeavour is unpredictable, there is no doubt that investing in basic research has always paid off over time. Basic science research may transform our world.

◂ FIG. 4: The FCC study offers the opportunity to young researchers from all over Europe to develop now the technologies that will shape our future (Image credit: (left) Robert Hradil & Monika Majer, (right) CERN)



▲FIG. 5. Photo of the Nb_3Sn magnet coil that will be used in future high-field magnets allowing to reach 12 T for the High Luminosity upgrade of the LHC. The same material (Nb_3Sn) is also studied for the 16 T for a future circular collider (Image credit: CERN).

Concluding remarks and future directions

The fact that we need more complex machines to reach higher energies and intensities, poses a challenge not only to the scientific community but also for a society based on knowledge and innovation. We need to use our creative minds to invent and develop new technologies, or to push the existing ones, within the bounds of technical and financial feasibility.

The FCC collaboration is now moving to prepare a design report and cost estimates for all collider options to be delivered by the end of 2018. The vibrant and global R&D programme of FCC paves the way for future energy and intensity-frontier colliders that could replace the LHC by the end-2030s.

New large-scale research facilities are important to explore more deeply, and to push further, the boundaries of our knowledge. Over the past 50 years, high-energy colliders have been one of the most successful roads of exploration, leading to great discoveries such as the W and Z bosons, top quark and most recently the Higgs particle.

To remain a key player in science and innovation, in a world that is becoming ever more competitive, Europe should try to secure its current pole position in high-energy physics. Designing and building new machines implies investing in fundamental R&D on novel technologies. The effective collaboration between researchers and industrial partners from an early stage onward is one of the important cornerstones of the FCC study.

Looking at the present physics landscape, we can recognise an ocean of challenges and opportunities not only for physicists, but also for engineers, innovators, and early-stage researchers, and for the future of our societies. Despite the lack of clear evidence for the next big discovery we can't afford to ignore the many fundamental unanswered questions about the nature of our universe. The future is ours to shape! ■

▼FIG. 6: First hardware for FCC: Designing a novel beam screen system. The first prototypes of a new beam screen vacuum system to cope with the requirements of a 100 TeV collider are currently tested. (Image credit: CERN)

About the Authors

Dr. Michael Benedikt was appointed CERN study leader for the Future Circular Collider (FCC) study in 2013. He started his career with a PhD on medical accelerator design, as a member of the CERN Proton-Ion Medical Machine Study group. After obtaining his degree, in 1997, he joined CERN's accelerator operation group. He led the PS2 design study from 2005 to 2008 for a new high-performance synchrotron as potential replacement of CERN's Proton Synchrotron. From 2008 until 2013 he was project leader for the design and construction of the accelerator complex for the Austrian hadron therapy centre MedAustron in Wiener Neustadt

Dr. Frank Zimmermann is the deputy leader of the Future Circular Collider (FCC) study. A senior accelerator scientist at CERN, he also serves as the Editor of the journal "Physical Review Accelerators and Beams" (PRAB). He has earlier worked at SLAC, USA, and DESY, Germany. In 2002 he received the EPS-IGA accelerator prize. He is a fellow of the American Physical Society.

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