The Future of the Large Hadron Collider

A Super-Accelerator with Multiple Possible Lives

Editors: Oliver Brüning • Max Klein
Lucio Rossi • Paolo Spagnolo

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Foreword

Particle physics is in a remarkable situation. It has the wonderful Standard Model which summarizes almost all experimentally known data, but is only a model put together, with 26 parameters and including 'by hand' any new experimental discoveries or many constants taken from data. It unites the electromagnetic interaction with the weak interaction, however, the strong force is just attached to it. For example, there is no theoretical relation between all the coupling constants. The last missing building block of that Standard Model, the Higgs particle, was found by the LHC experiments ATLAS and CMS ten years ago. The SM, however, does not give any hints about which direction it could be extended and where to experimentally look for new physics. Particle physics is not yet based on a united, comprehensive theory derived from fundamental assumptions.

In the first decade of operation, as described in this book, the LHC experiments have provided an enormous amount of data in support of the SM while not observing further new particles predicted, for example, by Supersymmetry. The situation reminds me of the late 1960's and early 1970's when we had nice theories, like Regge poles, dispersion relations etc., and a lot of experimental data representing a particle zoo, but no deeper understanding of its origin nor symmetry. Initially a change towards the SM came by the more or less unexpected discoveries of partons, quarks and gluons in 1968 and the J/ψ particle in 1973, as well as with the application of Yang Mills theory and the prediction of asymptotic freedom of the strong interaction as described by Quantum Chromodynamics.

Where should we look today? The main particle physics instruments to investigate nature at higher energies, which is equivalent to looking for finer details of the structure of matter, are electron (e) and proton (p) based colliders of three types; e^+-e^-, e-p, p-p (or hadrons instead of protons or antiparticles), which are complemented by a few special experiments such as those looking for axions or cosmic radiation observations. However, not only are higher energies necessary, greater collision rates are required at the same time since the quantum mechanical interaction cross sections decrease with the square of the center of mass energies. This is the principal reason for the huge experimental, technical, and theoretical effort, described in all its facets in this book dedicated to the largest hadron collider built so far, the LHC at CERN, and its future exploitation. The LHC at high luminosity (HL-LHC) is now scheduled to operate from the end of the 2020's until about 2040, possibly beyond. The technical upgrade of the facility opens prospects for its utilization for a further phase of collider and fixed target experiments, depending on the perspectives of high energy physics at CERN and worldwide.

The quest for new, higher energy colliders is perhaps not surprisingly focused on colliding the same kind of particles, e^+-e^- or p-p. Known examples are the future circular collider (FCC) project at CERN, a similar project in China or the international linear collider (ILC) in Japan. The technologies for producing large beam currents are quite different for electrons and protons since synchrotron radiation losses increase with the fourth power of the inverse of particle mass and are thus much bigger for electrons while they become noticeable only at extreme high energies for protons heaving a much greater mass. A special possibility for a next, higher energy hadron collider consists in developing and building magnets at industrial scale of about 20 T field strength, tripling the LHC achievement. The book describes an interesting further option of using the LHC infrastructure by inserting such high field magnets, should they become available by about 2040, into the LHC tunnel, a project called HE-LHC. Besides the like particle e^+-e^- and p-p colliders, a special interest is raised by the possibility to collide electrons off protons as was realized with HERA at DESY. HERA produced unique results especially on the distribution functions of quarks and gluons inside the nucleon in a much extended phase space.

During the last decade, a large community of physicists and engineers, partly enthusiasts from HERA, came together to study the advantages and possibilities which an energy frontier e-p facility based on the intense hadron beams of the LHC would offer from the view of new physics and at the same time exploring the practical and technical challenges.

In order to make a considerable step beyond HERA, an electron energy in the range of 50 to 100 GeV is necessary. Since the physics of this new e-p collider demanded very high luminosity, the preferred electron accelerator solution would not be a storage ring but rather the application of a new technology which reuses the energy stored in the decelerated beam. Such a 'beam energy recovery technology' is under development in various laboratories in the USA, Asia, and Europe. For advancing this technology to be used directly for an e-p collider, a test facility is being built, which could be used also for other purposes, by an international collaboration, including CERN, with the main installation of the PERLE facility at IJCLab Orsay (France).

Under the assumption that this beam energy recovery can be applied, detailed configurations for an added electron racetrack have been worked out, both for the HL-LHC, possibly the HE-LHC, and the FCC p-p version. This work included not only characteristics of the electron ring such as lattice or civil engineering but also detailed designs of the asymmetric e-p interaction region. The addition of an electron-proton and electron-ion experiment to the LHC, and later possibly the FCC, opens new horizons as to the investigation of the Higgs boson properties or the reliable precision determination of the complete set of parton distributions as is required for fully exploiting the physics of the hadron colliders.

All new collider projects under discussion require not only a scientific but also political decision. It currently is very difficult to guess what the chances of a particular facility might be. The LHC has been the most successful and the largest enterprise of particle physics so far. In this book, the striking knowledge and colossal work which has been performed by many colleagues, sometimes voluntarily and often in addition to their normal job, has been collected which illustrates the LHC achievements as well as several options for a further future of the LHC based on its ongoing upgrade to enhanced luminosity. I am convinced that the material, partly scientific, partly technical, will find useful applications in one form or another while it may also be instrumental to lead particle physics beyond the Standard Model.

Herwig Schopper
University Hamburg, former CERN Director General

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