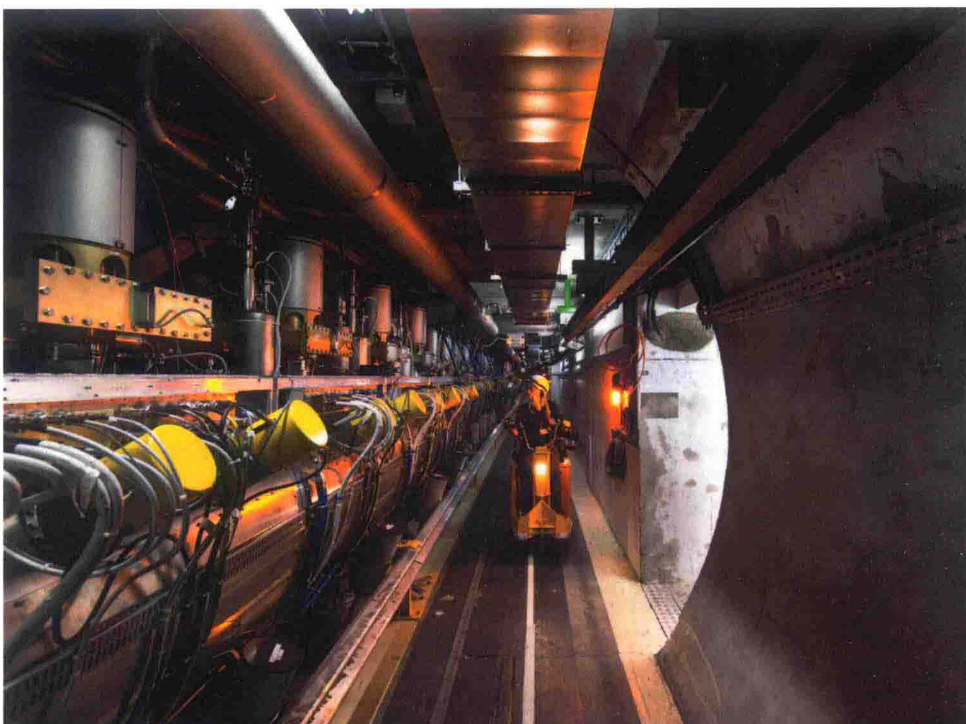
ISSN 1793-1339

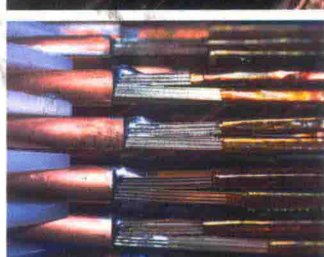
Advanced Series on
Directions in High Energy Physics — Vol. 24

THE HIGH LUMINOSITY LARGE HADRON COLLIDER

The New Machine for Illuminating the Mysteries of Universe

Editors
Oliver Brüning and **Lucio Rossi**





World Scientific

Advanced Series on
Directions in High Energy Physics — Vol. 24

THE HIGH LUMINOSITY LARGE HADRON COLLIDER

The New Machine for Illuminating the Mysteries of Universe

Editors

Oliver Brüning and **Lucio Rossi**

CERN

World Scientific

NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI • TOKYO

Published by

World Scientific Publishing Co. Pte. Ltd.
5 Toh Tuck Link, Singapore 596224
USA office: 27 Warren Street, Suite 401-402, Hackensack, NJ 07601
UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

Library of Congress Cataloging-in-Publication Data
The High Luminosity Large Hadron Collider : the new machine for illuminating the mysteries of universe / edited by Oliver Brüning (CERN) and Lucio Rossi (CERN).
pages cm -- (Advanced series on directions in high energy physics ; vol. 24)
Includes bibliographical references and index.
ISBN 978-9814675468 (hardcover : alk. paper) -- ISBN 978-9814678148 (pbk. : alk. paper)
1. Large Hadron Collider (France and Switzerland). I. Brüning, O., editor. II. Rossi, Lucio, 1955– editor. III. Series: Advanced series on directions in high energy physics ; v. 24.
QC787.P73H54 2015
539.7'36--dc23

2015022489

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Printed in Singapore

THE HIGH LUMINOSITY LARGE HADRON COLLIDER

The New Machine for Illuminating the Mysteries of Universe

ADVANCED SERIES ON DIRECTIONS IN HIGH ENERGY PHYSICS

ISSN: 1793-1339

Published

Vol. 1 – High Energy Electron–Positron Physics (*eds. A. Ali and P. Söding*)
Vol. 2 – Hadronic Multiparticle Production (*ed. P. Carruthers*)
Vol. 3 – CP Violation (*ed. C. Jarlskog*)
Vol. 4 – Proton–Antiproton Collider Physics (*eds. G. Altarelli and L. Di Lella*)
Vol. 5 – Perturbative QCD (*ed. A. Mueller*)
Vol. 6 – Quark–Gluon Plasma (*ed. R. C. Hwa*)
Vol. 7 – Quantum Electrodynamics (*ed. T. Kinoshita*)
Vol. 9 – Instrumentation in High Energy Physics (*ed. F. Sauli*)
Vol. 10 – Heavy Flavours (*eds. A. J. Buras and M. Lindner*)
Vol. 11 – Quantum Fields on the Computer (*ed. M. Creutz*)
Vol. 12 – Advances of Accelerator Physics and Technologies (*ed. H. Schopper*)
Vol. 13 – Perspectives on Higgs Physics (*ed. G. L. Kane*)
Vol. 14 – Precision Tests of the Standard Electroweak Model (*ed. P. Langacker*)
Vol. 15 – Heavy Flavours II (*eds. A. J. Buras and M. Lindner*)
Vol. 16 – Electroweak Symmetry Breaking and New Physics at the TeV Scale (*eds. T. L. Barklow, S. Dawson, H. E. Haber and J. L. Siegrist*)
Vol. 17 – Perspectives on Higgs Physics II (*ed. G. L. Kane*)
Vol. 18 – Perspectives on Supersymmetry (*ed. G. L. Kane*)
Vol. 19 – Linear Collider Physics in the New Millennium (*eds. K. Fujii, D. J. Miller and A. Soni*)
Vol. 20 – Lepton Dipole Moments (*eds. B. Lee Roberts and William J. Marciano*)
Vol. 21 – Perspectives on Supersymmetry II (*ed. G. L. Kane*)
Vol. 22 – Perspectives on String Phenomenology (*eds. B. Acharya, G. L. Kane and P. Kumar*)
Vol. 23 – 60 Years of CERN Experiments and Discoveries (*eds. H. Schopper and L. Di Lella*)
Vol. 24 – The High Luminosity Large Hadron Collider: The New Machine for Illuminating the Mysteries of Universe (*eds. O. Brüning and L. Rossi*)

Forthcoming

Vol. 8 – Standard Model, Hadron Phenomenology and Weak Decays on the Lattice (*ed. G. Martinelli*)

Foreword

CERN management usually changes once every five years. In January 2009, the new management of CERN had three high priority tasks.

1. To repair the LHC following the damage resulting from a serious technical accident in September 2008 (this work had already been started in collaboration with the outgoing management in October 2008). It was also clear that this repair should also ensure that, in the longer term, repetition of such an accident could never occur.
2. To commission the collider and begin operation with relatively high luminosity as soon as possible to provide the possibility for the experiments to make new discoveries in particle physics.
3. To prepare the upgrades of the LHC for the longer term future.

Priority 1 was reviewed during "Chamonix" 2009 and a clear plan was proposed for the repair and subsequent operation for the period 2010–2013.

During 2009, in parallel with the repair and redesign of the defected parts of the LHC, discussions started on the future upgrades of the collider (priority 3). During 2009, several reviews were made of the existing proposals, which involved building new injectors (a new Proton Synchrotron, PS2, and a Superconducting Proton Linac, SPL), upgrading the Super Proton Synchrotron, as well as phased new insertions for the LHC interaction points.

In January 2010, the results of these discussions were globally reviewed at the "Chamonix" meeting. Following this meeting, a new injector upgrade program for the LHC was born which did not necessitate the construction of new injectors. This new proposal involved upgrading of the **existing** injectors: increasing the energy of the PS booster and faster pulsing of the PS. The new scheme was considered to be less demanding on CERN manpower and financial resources as well as being much better matched to the requirements on "useful integrated luminosity" in the detectors.

In addition, based on experience on upgrades from previous colliders (where the beam down time needed for the implementation of the upgrade was barely compensated in integrated luminosity in the years following the upgrade), it was decided not to perform the upgrade of the insertions in two phases but in a single project using the newer superconducting technologies. The development of these newer technologies also paves the way for higher energy in a future collider such as the Future Circular Collider (FCC).

For optimization of the "useful integrated luminosity", it was realized that luminosity "leveling" was needed since the luminosity lifetime was comparable with the "physics to physics" turn-round time. A new scheme emerged using crab cavities with a crossing angle at the interaction points. The luminosity could be maintained constant for several hours either by changing the crossing angle or by reducing the beam size by increasing the focusing. This new scheme allowed a very high "constant" luminosity and therefore a constant "event pile-up" and lower radiation in the detectors.

Following Chamonix 2010, two new CERN major projects were created: LHC Injectors Upgrade (LIU), and High Luminosity LHC (HL-LHC). Since then, HL-LHC has become a multi-continent project (inclusion of the USA and Japan), involving research and development of many new cutting edge technologies such as very high field superconducting magnets, crab cavities, superconducting power links, new materials for collimators, etc. These technologies are not only necessary for the HL-LHC but are critical for future High Energy Physics projects.

The successful completion of the HL-LHC is CERN's flagship project and will allow the LHC to continue data taking at fantastic and constant collision rates until the middle of the 2030s. It will also serve as a critical test bed for future HEP projects such as the CERN Future Circular Colliders (FCC) project which was first proposed in 2012 in preparation for the European HEP strategy update.[a]

Steve Myers
Former CERN Director for Accelerator & Technology

[a]O. Brüning, B. Goddard, M. Mangano, S. Myers, L. Rossi, E. Todesco and F. Zimmerman, "High Energy LHC", CERN-ATS-237.

Preface

The High Luminosity LHC (HL-LHC) Project was set up in 2010 by the then CERN Director for Accelerator and Technology, Dr. Steve Myers, following a change of the CERN plan resulting in a down scoping of the previous LHC injector upgrade plan and a merging of the LHC upgrade Phase I and Phase II into one unique project. To this end CERN in consortium with 15 European Institutions applied in November 2010 to the call for European funding under the 7th Framework Programme, Design Study category: the application was approved with full budget in 2011 with the name FP7 High Luminosity Large Hadron Collider Design Study (nicknamed as HiLumi LHC, Grant No. 284404).

The book gives a fairly detailed description of the project, covering both project structure, governance, physics goals, accelerator layouts and key technologies like: new generation superconducting magnets, beam deflecting superconducting cavities, new materials for collimators, new high current superconducting links, etc. The book is structured in such a way that each of the 22 contributions can be read as an independent paper, although cross-references among papers are numerous. The emphasis is more on highlighting the accelerator challenges, the machine layout and required technology advances, rather than giving complete and detailed technical descriptions. The most conventional parts on infrastructure and civil engineering are not treated as a consequence of this approach, while the interplay with the companion LIU (LHC Injector Upgrade) project and review of operation modes and challenges are discussed.

This book reflects the work done in the first part of the HiLumi LHC Design Study, from November 2010 up to the end of 2014. Meanwhile in the first part of 2015, a few fine tunings have been carried out. For instant, a small change of the operating parameters of the inner triplet quadrupole magnets and a revision of the number of collimators in the Dispersion Suppressor associated with the 11 T dipole magnets have been implemented. However, these and other minor changes, which will likely continue until the end of 2016, do not affect the substance of the layout or of the importance of the technological advances needed for the ambitious HL-LHC project that, with its 1.2 km replacement of the existing LHC infrastructure is one of the most ambitious "new accelerator" projects approved for construction during the next ten years.

Editors:
Oliver Brüning (HL-LHC Deputy Project Leader)
Lucio Rossi (HL-LHC Project Leader)

List of Authors

C. Adorisio (CERN, TE Department, Genève 23, CH-1211, Switzerland)
G. Ambrosio (Fermi National Accelerator Laboratory, Batavia, IL 60510, USA)
R. B. Appleby (University of Manchester and the Cockcroft Institute, UK)
G. Arduini (CERN, BE Department, Genève 23, CH-1211, Switzerland)
T. Baer (CERN, TE Department, Genève 23, CH-1211, Switzerland)
A. Ballarino (CERN, TE Department, Genève 23, CH-1211, Switzerland)
M. Barnes (CERN, TE Department, Genève 23, CH-1211, Switzerland)
I. Bejar (CERN, Accelerator and Technology Sector, Genève 23, CH-1211, Switzerland)
A. Bertarelli (CERN, EN Department, Genève 23, CH-1211, Switzerland)
E. Bravin (CERN, BE Department, Genève 23, CH-1211, Switzerland)
K. Brodzinski (CERN, TE Department, Genève 23, CH-1211, Switzerland)
R. Bruce (CERN, BE Department, Genève 23, CH-1211, Switzerland)
M. Brugger (CERN, TE Department, Genève 23, CH-1211, Switzerland)
O. Brüning (CERN, Accelerator and Technology Sector, Genève 23, CH-1211, Switzerland)
H. Burkhardt (CERN, BE Department, Genève 23, CH-1211, Switzerland)
J. P. Burnet (CERN, TE Department, Genève 23, CH-1211, Switzerland)
G. Burt (University of Lancaster, STFC, Lancaster, UK)
R. Calaga (CERN, BE Department, Genève 23, CH-1211, Switzerland)
F. Caspers (CERN, BE Department, Genève 23, CH-1211, Switzerland)
F. Cerutti (CERN, TE Department, Genève 23, CH-1211, Switzerland)
S. Claudet (CERN, TE Department, Genève 23, CH-1211, Switzerland)
B. Dehning (CERN, BE Department, Genève 23, CH-1211, Switzerland)
L. S. Esposito (CERN, TE Department, Genève 23, CH-1211, Switzerland)
S. Fartoukh (CERN, BE Department, Genève 23, CH-1211, Switzerland)
G. Ferlin (CERN, TE Department, Genève 23, CH-1211, Switzerland)
P. Ferracin (CERN, TE Department, Genève 23, CH-1211, Switzerland)
P. Fessia (CERN, TE Department, Genève 23, CH-1211, Switzerland)
R. Garoby (CERN, BE Department, Genève 23, CH-1211, Switzerland)
B. Goddard (CERN, TE Department, Genève 23, CH-1211, Switzerland)
E. Jensen (CERN, BE Department, Genève 23, CH-1211, Switzerland)
R. Jones (CERN, BE Department, Genève 23, CH-1211, Switzerland)
J. M. Jowett (CERN, BE Department, Genève 23, CH-1211, Switzerland)
M. Lamont (CERN, BE Department, Genève 23, CH-1211, Switzerland)
A. Lechner (CERN, EN Department, Genève 23, CH-1211, Switzerland)

T. Lefevre (CERN, BE Department, Genève 23, CH-1211, Switzerland)
J. Lettry (CERN, BE Department, Genève 23, CH-1211, Switzerland)
R. Losito (CERN, EN Department, Genève 23, CH-1211, Switzerland)
M. Mangano (CERN, PH Department, Genève 23, CH-1211, Switzerland)
D. Manglunki (CERN, TE Department, Genève 23, CH-1211, Switzerland)
V. Mertens (CERN, TE Department, Genève 23, CH-1211, Switzerland)
E. Métral (CERN, BE Department, Genève 23, CH-1211, Switzerland)
N. Mounet (CERN, BE Department, Genève 23, CH-1211, Switzerland)
T. Nakamoto (KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan)
T. Pieloni (CERN, BE Department, Genève 23, CH-1211, Switzerland)
A. Ratti (Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA)
S. Redaelli (CERN, BE Department, Genève 23, CH-1211, Switzerland)
J. M. Rifflet (CERN, TE Department, Genève 23, CH-1211, Switzerland)
S. Roesler (CERN, TE Department, Genève 23, CH-1211, Switzerland)
L. Rossi (CERN, Accelerator and Technology Sector, Genève 23, CH-1211, Switzerland)
G. Rumolo (CERN, BE Department, Genève 23, CH-1211, Switzerland)
G. L. Sabbi (Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA)
B. Salvant (CERN, BE Department, Genève 23, CH-1211, Switzerland)
M. Schaumann (CERN and RWTH Aachen University, D-52056 Aachen, Germany)
H. Schmickler (CERN, BE Department, Genève 23, CH-1211, Switzerland)
R. Schmidt (CERN, TE Department, Genève 23, CH-1211, Switzerland)
M. Segreti (CEA, Saclay, 91400, France)
L. Tavian (CERN, TE Department, Genève 23, CH-1211, Switzerland)
E. Todesco (CERN, TE Department, Genève 23, CH-1211, Switzerland)
R. Tomas (CERN, BE Department, Genève 23, CH-1211, Switzerland)
C. Urscheler (Bundesamt fuer Gesundheit, Direktionsbereich Verbraucherschutz, Zchwarzenburgstrasse 165, 3003 Bern, Switzerland)
J. Uythoven (CERN, TE Department, Genève 23, CH-1211, Switzerland)
R. van Weelderen (CERN, TE Department, Genève 23, CH-1211, Switzerland)
R. Versteegen (CERN, BE Department, Genève 23, CH-1211, Switzerland)
H. Vincke (CERN, TE Department, Genève 23, CH-1211, Switzerland)
M. Vretenar (CERN, Accelerator and Technology Sector, Genève 23, CH-1211, Switzerland)
U. Wagner (CERN, TE Department, Genève 23, CH-1211, Switzerland)
J. Wenninger (CERN, BE Department, Genève 23, CH-1211, Switzerland)
D. Wollmann (CERN, TE Department, Genève 23, CH-1211, Switzerland)
Q. Xu (KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan)
M. Zerlauth (CERN, TE Department, Genève 23, CH-1211, Switzerland)
F. Zimmermann (CERN, BE Department, Genève 23, CH-1211, Switzerland)

Contents

Chapter 1

Introduction to the HL-LHC Project*

L. Rossi and O. Brüning

CERN, Accelerator and Technology Sector, Genève 23, CH-1211, Switzerland

The Large Hadron Collider (LHC) is one of largest scientific instruments ever built. It has been exploring the new energy frontier since 2010, gathering a global user community of 7,000 scientists. To extend its discovery potential, the LHC will need a major upgrade in the 2020s to increase its luminosity (rate of collisions) by a factor of five beyond its design value and the integrated luminosity by a factor of ten. As a highly complex and optimized machine, such an upgrade of the LHC must be carefully studied and requires about ten years to implement. The novel machine configuration, called High Luminosity LHC (HL-LHC), will rely on a number of key innovative technologies, representing exceptional technological challenges, such as cutting-edge 11–12 tesla superconducting magnets, very compact superconducting cavities for beam rotation with ultra-precise phase control, new technology for beam collimation and 300-meter-long high-power superconducting links with negligible energy dissipation.

HL-LHC federates efforts and R&D of a large community in Europe, in the US and in Japan, which will facilitate the implementation of the construction phase as a global project.

1. Context and Objectives

The Large Hadron Collider (LHC) was successfully commissioned in March 2010 for proton–proton collisions with a 7 TeV center-of-mass energy and has delivered 8 TeV center-of-mass proton collisions since April 2012. The LHC is pushing the limits of human knowledge, enabling physicists to go beyond the Standard Model: the enigmatic Higgs boson, mysterious dark matter and the world of supersymmetry are just three of the long-awaited mysteries that the LHC might unveil. The announcement given by CERN on 4 July 2012 about the discovery of new

*The project is partially supported by the EC as *FP7 HiLumi LHC Design Study* under grant no. 284404. In addition to the FP7-Hilumi LHC consortium, the Project relies on the special contributions by: USA (LARP), Japan (KEK), France (CEA), Italy (INFN-Milano and Genova) and Spain (CIEMAT).

boson at about 125 GeV, the long awaited Higgs particle, is hopefully the first fundamental discovery of a series that LHC can deliver. Thanks to the LHC, Europe has decisively regained world leadership in High Energy Physics, a key sector of knowledge and technology. The LHC can act as catalyst for a global effort unrivalled by other branches of science: out of the 10,000 CERN users, more than 7,000 are scientists and engineers using the LHC, half of which are from countries outside the EU.

The LHC baseline programme till 2025 is schematically shown in Fig. 1. After entering in the near-to-nominal energy regime of 13 TeV center-of-mass energy in 2015, (hoping to reach the 14 TeV in the subsequent year) it is expected that the LHC will reach the design peak **luminosity**[1] of 10^{34} $cm^{-2}s^{-1}$ and a total integrated luminosity over a one year of about 40 fb^{-1}. Then in the period 2015–2022 LHC will hopefully increase the peak luminosity: indeed margins have been taken in the design to allow, in principle, to reach about two times the nominal design performance. The baseline programme for the next ten years is depicted in Fig. 1, while Fig. 2 shows the graphs of the possible evolution of peak and integrated luminosity.

After 2020 the statistical gain in running the accelerator without an additional considerable luminosity increase beyond its design value will become marginal. The running time necessary to half the statistical error in the measurements will be more than ten years after 2020. Therefore to maintain scientific progress and to explore its full capacity, the LHC will need to have a decisive increase of its luminosity. That is why, when the CERN Council adopted the European Strategy for Particle Physics in 2006 [1], its first priority was agreed to be: "*to fully exploit the physics potential of the LHC. A subsequent major luminosity upgrade, motivated by physics results and operation experience, will be enabled by focused R&D*". The European Strategy for Particle Physics has been integrated into the ESFRI Roadmap of 2006 and its update of 2008 [2]. The priority to fully exploit the potential of the LHC has been recently confirmed as *first priority* among the "High priority large-scale scientific activities" in the new European Strategy for Particle Physics – Update 2013 [3], approved in Brussels on 30 May 2013 with the following wording: "*Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.*"

[1]**Luminosity** is the number of collisions per square centimeter and per second, $cm^{-2}s^{-1}$.

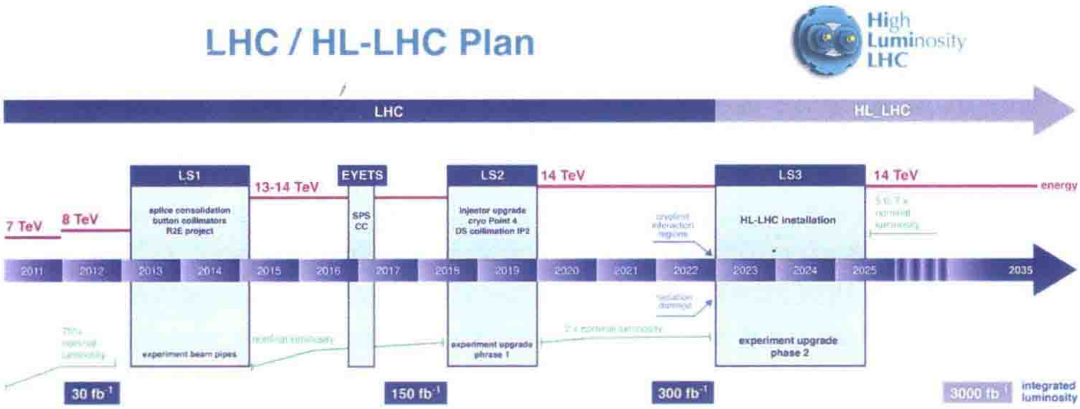


Fig. 1. LHC baseline plan for the next decade and beyond. In terms of energy of the collisions (upper line) and of luminosity (lower lines). The first long shutdown (LS1) 2013–14 is to allow design parameters of beam energy and luminosity. The second one, LS2 in 2018–19, is for securing luminosity and reliability as well as to upgrade the LHC Injectors. After LS3, in 2025 the machine should have the High Luminosity configuration (HL-LHC).

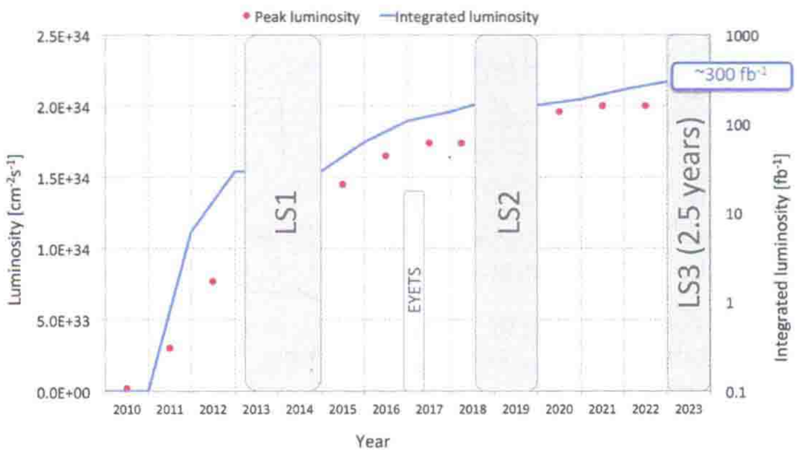


Fig. 2. Possible peak luminosity evolution (till the so-called "ultimate" limit) with consequent best forecast for integrated luminosity for the first decade of operation of LHC. Superimposed are the three long shutdowns (LS1, LS2, LS3) and the Extended Year End Technical Stop, as proposed in RLIUP and approved by CERN management and endorsed by CERN Council of December 2013. Also indicated the integrated luminosity goal of the LHC baseline program: 300 fb^{-1}.

The importance of the LHC upgrade in luminosity for the future of High Energy Physics has been also recently re-affirmed by the May 2014 resolution of the so-called P5 panel in the USA [4], a critical step in updating the USA strategy for HEP, with the following wording: "*Recommendation 10: ... The LHC upgrades constitute our highest-priority near-term large project.*"

In this context, CERN has put in place, at the end of 2010, the High Luminosity LHC (HL-LHC) project [5, 6]. Started as a Design Study, HL-LHC has become CERN's major construction project for the next decade after the approval of CERN

Council of 30 May 2013 and the insertion of the budget in the CERN Medium Term Plan approved by Council in the June 2014.

The main objective of High Luminosity LHC is to determine a set of beam parameters and the hardware configuration that will enable the LHC to reach the following targets:

(1) A peak luminosity of 5×10^{34} $cm^{-2}s^{-1}$ with leveling, allowing:
(2) An integrated luminosity of 250 fb^{-1} per year, enabling the goal of 3000 fb^{-1} in about a dozen years after the upgrade. This luminosity is about ten times the luminosity reach of the first twelve years of the LHC lifetime.

The time horizon foresees the installation of the main hardware for HL-LHC during LS3 and commissioning the new machine configuration in the period 2023–2025.

All hadron colliders in the world have so far produced a total combined integrated luminosity of about 10 fb^{-1}; LHC has delivered nearly 30 fb^{-1} at the end of 2012 and should reach 300 fb^{-1} in its first 10–12 years of life. The High Luminosity LHC is a major and extremely challenging upgrade. For its successful realization, a number of key novel technologies have to be developed, validated and integrated. The work is initiated with the FP7 Design Study HiLumi LHC which, approved by EC in the Seventh Framework Programme (FP7-INFRA) in 2011 with the highest mark [7], is instrumental in initiating a new global collaboration for the LHC that matches the spirit of the worldwide user community of the LHC experiments.

The High Luminosity LHC project is working in close connection with the companion ATLAS and CMS upgrade projects of 2018–2023 and the upgrade foreseen in 2018 for both LHCb and Alice, as discussed in [8]. Furthermore, the performance of the high luminosity machine will depend on the performance of the injector chain, which is also being upgraded by a companion program, the LHC Injector Upgrade (LIU) program [9].

2. Approach for the Upgrade

The (instantaneous) luminosity L can be expressed as:

$$L = \gamma \frac{n_b N^2 f_{\text{rev}}}{4\pi \beta^* \varepsilon_n} R;\ R = 1 \Big/ \sqrt{1 + \frac{\theta_c \sigma_z}{2\sigma}}$$

where:

γ is the proton beam energy in unit of rest mass;

n_b is the number of bunches in the machine: 1380 for 50 ns spacing and 2808 for 25 ns;

N is the bunch population. $N_{\text{nominal 25 ns}}$: 1.15×10^{11} p ($\Rightarrow$ 0.58 A of beam current at 2808 bunches);
f_{rev} is the revolution frequency (11.2 kHz);
β^* is the beam beta function (focal length) at the collision point (nominal design 0.55 m);
ε_n is the transverse normalized emittance (nominal design: 3.75 μm);
R is a luminosity geometrical reduction factor (0.85 at 0.55 m of β^*, down to 0.5 at 0.25 m);
θ_c is the full crossing angle between colliding beam (285 μrad as nominal design);
σ, σ_z are the transverse and longitudinal r.m.s. size, respectively (16.7 μm and 7.55 cm).

2.1. *Present luminosity limitations and hardware constraints*

There are various expected limitations to a continuous increase in luminosity, either in beam characteristics (injector chain, beam impedance and beam-beam interactions in the LHC) or in technical systems. Mitigation of potential performance limitations arising from the LHC injector complex are addressed by the LIU project, which should be completed in 2019 (LS2). Any potential limitations coming from the LHC injector complex put aside, it is expected that the LHC will reach a performance limitation from the beam current, from cleaning efficiency at 350 MJ beam stored energy and from the acceptable pile-up level. The ultimate value of bunch population with nominal LHC beam parameters should enable to reach $L = 2 \times 10^{34}$ cm^{-2}s^{-1}. Any further performance increase of the LHC will require significant hardware and beam parameter modifications with respect to the designed LHC configurations.

Before discussing the new configuration, it is useful to recall the systems that need to be changed, and possibly improved, just because they become more vulnerable to breakdown and accelerated wear out. This goes well beyond the on-going basic consolidation.

(1) *Inner Triplet Magnets*: At about 300 fb^{-1} some components of the low-beta triplet quadrupoles and their corrector magnets, we will have received a dose of 30 MGy, entering in the region of radiation damage. The quadrupoles may withstand 400–700 fb^{-1} but some corrector magnets of nested type are likely to wear out are already above 300 fb^{-1}. Damage must be anticipated because the most likely way of failing is through sudden electric breakdown, entailing serious and long repairs. That is why replacement of the triplet must be envisaged before damage. Replacement of the low-beta triplet is a long intervention, requiring one to two years shutdown and must be coupled with a major detector upgrade.
(2) *Cryogenics*: To increase flexibility of intervention and then availability (i.e. integrated luminosity) we plan to install a new cryo-plant in P4 for a full