CERN accelerator complex: present and future
(mainly LHC, HL-LHC and Post-LHC accelerators)

Frédérick Bordry
CERN accelerator complex: present and future
Frédérick Bordry
Joint Annual Meeting of the Swiss Physical Society and Austrian Physical Society
22nd August 2017

CERN’s scientific diversity programme

AD: Antiproton Decelerator for antimatter studies
AWAKE: proton-induced plasma wakefield acceleration
CAST, OSQAR: axions
CLOUD: impact of cosmic rays on aerosols and clouds → implications on climate
COMPASS: hadron structure and spectroscopy
ISOLDE: radioactive nuclei facility
NA61/Shine: heavy ions and neutrino targets
NA62: rare kaon decays
NA63: radiation processes in strong EM fields
NA64: search for dark photons
Neutrino Platform: ν detectors
R&D for experiments in US, Japan
n-TOF: n-induced cross-sections
UA9: crystal collimation

~20 experiments, > 1200 physicists
LHC (Large Hadron Collider)

14 TeV proton-proton accelerator-collider built in the LEP tunnel

**Lead-Lead (Lead-proton) collisions**

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1983</td>
<td>First studies for the LHC project</td>
</tr>
<tr>
<td>1988</td>
<td>First magnet model (feasibility)</td>
</tr>
<tr>
<td>1994</td>
<td>Approval of the LHC by the CERN Council</td>
</tr>
<tr>
<td>1996-1999</td>
<td>Series production industrialisation</td>
</tr>
<tr>
<td>1998</td>
<td>Declaration of Public Utility &amp; Start of civil engineering</td>
</tr>
<tr>
<td>1998-2000</td>
<td>Placement of the main production contracts</td>
</tr>
<tr>
<td>2004</td>
<td>Start of the LHC installation</td>
</tr>
<tr>
<td>2005-2007</td>
<td>Magnets Installation in the tunnel</td>
</tr>
<tr>
<td>2006-2008</td>
<td>Hardware commissioning</td>
</tr>
<tr>
<td>2008-2009</td>
<td>Beam commissioning and repair</td>
</tr>
</tbody>
</table>

2010-2035... **Physics exploitation**

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010 – 2012</td>
<td>Run 1 ; 7 and 8 TeV</td>
</tr>
<tr>
<td>2015 – 2018</td>
<td>Run 2 ; 13 TeV</td>
</tr>
<tr>
<td>2021 – 2023</td>
<td>Run 3 (14 TeV)</td>
</tr>
<tr>
<td>2024 – 2025</td>
<td>HL-LHC installation</td>
</tr>
<tr>
<td>2026 – 2035...</td>
<td>HL-LHC operation</td>
</tr>
</tbody>
</table>

A 27 km circumference collider...
LHC: technological challenges

The specifications of many systems were over the state of the art. Long R&D programs with many institutes and industries worldwide.

- The highest field accelerator magnets: 8.3 T (1232 dipole magnets of 15 m)
- The largest superconducting magnet system (~10’000 magnets)
- The largest 1.9 K cryogenics installation (superfluid helium, 150 tons of LHe to cool down 37’000 tons)
- Ultra-high cryogenic vacuum for the particle beams (10^{-13} atm, ten times lower than on the Moon)
- The highest currents controlled with high precision (up to 13 kA)
- The highest precision ever demanded from the power converters (ppm level)
- A sophisticated and ultra-reliable magnet quench protection system (Energy stored in the magnet system: ~10 Gjoule, in the beams > 700 MJ)
Energy management challenges

Energy stored in the magnet system: \( \sim 10 \) GJoule

10 GJoule \( \cong \) flying 700 km/h

Energy stored in the two beams: 720 MJ \( \left[ 6 \times 10^{14} \text{ protons (1 ng of H\textsuperscript{+}) at 7 TeV} \right] \)

700 MJ melt one ton of copper

700 MJoule dissipated in 88 \( \mu \)s

\[
700 \times 10^6 / 88 \times 10^6 \cong 8 \text{ TW}
\]

World Electrical Installed Capacity \( \cong 3.8 \text{ TW} \)

1 electron volt = 1,602\( \times 10^{-19} \) joule
LHC 2010-2012: a rich harvest of collisions

Σ ~30 fb⁻¹
~ 2 \(10^{15}\) collisions

2010: 0.04 fb⁻¹
- 7 TeV CoM
- Commissioning

2011: 6.1 fb⁻¹
- 7 TeV CoM
- ... exploring limits

2012: 23.3 fb⁻¹
- 8 TeV CoM
- ... production

7 TeV and 8 TeV in 2012

Up to 1380 bunches with \(1.5 \times 10^{11}\) protons
From individual theoretical physicist idea... to collective innovation!
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2013 - 2015

April ‘13 to Sep. ‘14

Dipole training campaign

5th April

3rd June
First Stable Beams

10th April
Beam at 6.5 TeV

28th October
Physics with record number of bunches
Peak luminosity $5 \times 10^{33}$ cm$^{-2}$s$^{-1}$
2016 LHC

Peak luminosity > $1.4 \times 10^{34}$ cm$^{-2}$s$^{-1}$

OVER 25 fb$^{-1}$ in both ATLAS and CMS 😊
2017 LHC

Very steep performance ramp up, … some problems last ten days peak luminosity $\sim 1.75 \times 10^{34}$ cm$^{-2}$s$^{-1}$ with 2460 bunches, both figures are new records at 13 TeV.
### Run 2 and Run 3

<table>
<thead>
<tr>
<th></th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
</table>

- **Shutdown/Technical stop**
- **Protons physics**
- **Commissioning**
- **Ions**

**2015**
- EYETS

**2017**
- >120 fb⁻¹ (13 TeV)
- Σ 300 fb⁻¹ (14 TeV)

<table>
<thead>
<tr>
<th></th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
</tr>
</thead>
</table>

**2019**
- LS2

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Why High-Luminosity LHC? (LS3)

Goal of HL-LHC project:
- 250 – 300 fb\(^{-1}\) per year
- 3000 fb\(^{-1}\) in about 10 years

By implementing HL-LHC
Almost a factor 3
By continuous performance improvement and consolidation

Around 300 fb\(^{-1}\) the present Inner Triplet magnets reach the end of their useful life (due to radiation damage) and must be replaced.
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. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.

**HL-LHC from a study to a PROJECT**

\[300 \text{ fb}^{-1} \rightarrow 3000 \text{ fb}^{-1}\]

including LHC injectors upgrade **LIU**

(Linac 4, Booster 2GeV, PS and SPS upgrade)
Near-term & Mid-term High-energy Colliders

**LARGE HADRON COLLIDER**

- The HL-LHC is strongly supported and is the first high-priority large-category project in our recommended program. It should move forward without significant delay to ensure that accelerator and experiments can continue to function effectively beyond the end of this decade and meet the project schedule.

- **Recommendation 10:** Complete the LHC phase-1 upgrades, and continue the strong collaboration in the LHC with the phase-2 (HL-LHC) upgrades of the accelerator and both general-purpose experiments (ATLAS and CMS). The LHC upgrades constitute our highest-priority near-term large project.
LHC Upgrade Goals: Performance optimization

Luminosity recipe:

\[ L = \frac{n_b \times N_1 \times N_2 \times f_{\text{rev}}}{4 \times b^* \times n} \times F(f, b^*, e, s) \]

- 1) maximize bunch intensities
- 2) minimize the beam emittance
- 3) minimize beam size (constant beam power);
- 4) maximize number of bunches (beam power);
- 5) compensate for ‘F’;
- 6) Improve machine ‘Efficiency’

- Injector complex
- LIU ⇔ IBS
- triplet aperture
- 25ns
- Crab Cavities
- minimize number of unscheduled beam aborts
Luminosity Levelling, a key to success

- High peak luminosity
- Minimize pile-up in experiments and provide “constant” luminosity

- Obtain about 3 - 4 fb\(^{-1}\)/day (40% stable beams)
- About 250 to 300 fb\(^{-1}\)/year
- Levelling:

- Integrated luminosity:
  - Average Fill length (must be larger than levelling time)
  - Average Turnaround time (must be small with respect to fill length)
  - Number of operation days
  - Overall machine efficiency (fraction of physics over scheduled time)
Goals and means of the LHC Injectors Upgrade: LIU project

Increase injector reliability and lifetime to cover HL-LHC run (until ~2040) closely related to consolidation program

- Upgrade/replace ageing equipment (power supplies, magnets, RF…)
- Improve radioprotection measures (shielding, ventilation…)

Increase intensity/brightness in the injectors to match HL-LHC requirements

Enable Linac4/PSB/PS/SPS to accelerate and manipulate higher intensity beams (efficient production, space charge & electron cloud mitigation, impedance reduction, feedbacks, etc.)

Upgrade the injectors of the ion chain (Linac3, LEIR, PS, SPS) to produce beam parameters at the LHC injection that can meet the luminosity goal

<table>
<thead>
<tr>
<th></th>
<th>$\mathcal{N}$ (x (10^{21}) p/b)</th>
<th>$\varepsilon$ ((\mu m))</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIU Baseline</td>
<td>2.3</td>
<td>2.2</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>2.3</td>
<td>2.1</td>
</tr>
</tbody>
</table>
LINAC4 – PS Booster:
- $^1H^-$ injection and increase of PSB injection energy from 50 MeV to 160 MeV, to increase PSB space charge threshold
- New RF cavity system, new main power converters
- Increase of extraction energy from 1.4 GeV to 2 GeV

PS:
- Increase of injection energy from 1.4 GeV to 2 GeV to increase PS space charge threshold
- Transverse resonance compensation
- New RF Longitudinal feedback system
- New RF beam manipulation scheme to increase beam brightness

SPS
- Electron Cloud mitigation – strong feedback system, or coating of the vacuum system
- Impedance reduction, improved feedbacks
- Large-scale modification to the main RF system

These are only the main modifications and this list is far from exhaustive


The PIMS section
Installation of the last beam line element, August 2016
October 2016
160 MeV
June 2016
107 MeV
November 2017
50 MeV

LINAC4 Inauguration 9th May 2017
The HL-LHC Project

New IR-quads Nb$_3$Sn (inner triplets)

► New 11 T Nb$_3$Sn (short) dipoles
► Collimation upgrade
► Cryogenics upgrade
► Crab Cavities
► Cold powering
► Machine protection

Major intervention on more than 1.2 km of the LHC
Squeezing the beams: High Field SC Magnets

Quads for the inner triplet
Decision 2012 for low-\(\beta\) quads
Aperture \(\varnothing\) 150 mm – 140 T/m
\((B_{\text{peak}} \approx 12.3 \text{ T})\)
operational field, designed for 13.5 T

\(\Rightarrow\) \(\text{Nb}_3\text{Sn}\) technology
\((LHC: 8 \text{ T}, 70 \text{ mm})\)
The « new » material : Nb$_3$Sn

- Recent 23.4 T (1 GHz) NMR Magnet for spectroscopy in Nb$_3$Sn (and Nb-Ti).
- 15-20 tons/year for NMR and HF solenoids. Experimental MRI is taking off
- ITER: 500 tons in 2010-2016!
  It is comparable to LHC (1200 tons of Nb-Ti but HL-LHC will require only 20 tons of Nb$_3$Sn)
- HEP ITD (Internal Tin Diffusion):
  • High Jc., 3xJc ITER
  • Large filament (50 µm), large coupling current...
  • Cost is 5 times LHC Nb-Ti
**Nb$_3$Sn quadrupole: complexity increase vs Nb-Ti**

- Development of Nb3Sn Conductor with $J_c$ almost 3 times of ITER
- Laminated structure for series production
- Section of MQXF mechanical model
- Second long (4 m) Nb3Sn coil

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The 11 T dipole 2 m long model reached a $B_{\text{max}}$ of 12.5 T

Test of the first full cross-section (150 mm aperture) Triplet Quadrupole, 1.5 m long, half CERN, half USA: it went beyond ultimate ($B_{\text{max \, eq.}}$ of 12.5 T)
Crab Cavity: Proton machine (HL-LHC)

- LHC Luminosity upgrade requires larger bunch charge and smaller $\beta^*$.  
- To prevent parasitic bunch crossings, a larger crossing angle is needed.  
- This leads to geometric luminosity loss at small $\beta^*$.  
- A crab cavity is a deflecting cavity that kicks the head of each bunch one way, the tail the opposite way, such that the crossing angle is compensated for the bunch overlap in the collision point.

![Diagram of bunches colliding with and without crab cavity](image)

Luminosity vs. $\beta^*$ for a non-zero crossing angle (lower curve) and possible luminosity for complete bunch overlap (upper curve).

Two bunches colliding with a non-zero crossing angle. Left: without crab cavity, right: with crab cavity.
February 2017 three (naked) Crab Cavities were tested: all went well beyond the operating voltage of 3.4 MV
- One US-LARP DQW (tested at JLab) went up to 5.4 MV
- One US-LARP RFD (tested at Jlab) reached 4.03 MV.
- One CERN DQW (test at SM18) went up to 5.04 MV

Good results for the CC testing in the SPS in 2018
LHC plan and HL-LHC (High Luminosity LHC)

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In-kind contributions and collaborations for design, prototypes, production and tests

Discussions are ongoing with other countries, e.g. India, Canada, Russia, China, ...

Q1-Q3 : R&D, Design, Prototypes and in-kind USA
D1 : R&D, Design, Prototypes and in-kind JP
MCBX : Design and Prototype ES
HO Correctors: Design and Prototypes IT
Q4 : Design and Prototype FR

CC : R&D, Design and in-kind USA
CC : R&D and Design UK
“to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update”

CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.

HFM

HGA

R&D on Proton-Driven Plasma Wakefield Acceleration (AWAKE Expt at CERN)
Advanced Proton Driven Plasma Wakefield Acceleration Experiment

- Proof-of-concept experiment to demonstrate a novel acceleration technique that accelerates particles up to three orders of magnitude stronger than conventional methods.
  - Accelerate electrons of several GeV/m
- Use the SPS proton beam to generate powerful wakefields in a 10m long plasma.
- Wakefields accelerate externally injected electron beam.
- Experiment has started end 2016.

First proton beam sent to AWAKE for proton beam line tests (16 June 2016)
Facility considerably modified for the AWAKE experiment.
Proton and laser beam line installed and commissioned, matching all specifications.
Experiment diagnostics installed and tested.
Plasma cell installed and hardware commissioned.
Synchronization of SPS beam with AWAKE laser with 20 ps accuracy.
CLIC Multi-TeV Linear Collider

A Multi-TeV Linear Collider based on CLIC Technology
CLIC Conceptual Design Report

Geneva 2012

Central MDI & Interaction Region

Tunnel implementations (laser straight)
Compact Linear Collider (CLIC)

- Direct discovery potential and precise measurements of new particles (couplings to Z/γ*) up to m~ 1.5 TeV
- Indirect sensitivity to E scales Λ ~ O(100) TeV
- Measurements of "heavy" Higgs couplings: \( t\bar{t}H \) to ~ 4%, \( HH \) ~ 10%

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>380 GeV</th>
<th>3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre-of-mass energy</td>
<td>TeV</td>
<td>0.38</td>
<td>3</td>
</tr>
<tr>
<td>Total luminosity</td>
<td>( 10^{34}) cm(^{-2})s(^{-1})</td>
<td>1.5</td>
<td>5.9</td>
</tr>
<tr>
<td>Luminosity above 99% of ( \sqrt{s} )</td>
<td>( 10^{34}) cm(^{-2})s(^{-1})</td>
<td>0.9</td>
<td>2.0</td>
</tr>
<tr>
<td>Repetition frequency</td>
<td>Hz</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Number of bunches per train</td>
<td></td>
<td>352</td>
<td>312</td>
</tr>
<tr>
<td>Bunch separation</td>
<td>ns</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Acceleration gradient</td>
<td>MV/m</td>
<td>72</td>
<td>100</td>
</tr>
</tbody>
</table>

Most recent operating scenario: start at \( \sqrt{s}=380 \) GeV for H and top physics

Linear e\(^+\)+e\(^-\) collider \( \sqrt{s} \) up to 3 TeV

100 MV/m accelerating gradient needed for compact (~50 km) machine → based on normal-conducting accelerating structures and a two-beam acceleration scheme
CLIC Collaborations
31 Countries – over 70 Institutes
CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.

“to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update”
Magnet design (20 T): very challenging but not impossible.

300 mm inter-beam
Multiple powering in the same magnet (and more sectioning for energy)
Work for 4 years to assess HTS for 2X20T to open the way to 16.5 T/beam.
Otherwise limit field to 15.5 T for 2x13 TeV
Higher INJ energy is desirable (2xSPS)

The synchrotron light is not a stopper by operating the beam screen at 60 K.

The beam stability looks «easier» than LHC thanks to dumping time.

Collimation is possibly not more difficult than HL-LHC. Reaching $2 \times 10^{34}$ appears reasonable.

beam handling for INJ & beam dump: new kicker technology is needed since we cannot make twice more room for LHC kickers.
Future Circular Collider

First studies on a new 80 km tunnel in the Geneva area

- **42 TeV** with **8.3 T** using present LHC dipoles
- **80 TeV** with **16 T** based on Nb$_3$Sn dipoles
- **100 TeV** with **20 T** based on HTS dipoles

High Energy-LHC : 33 TeV with 20T magnets
International FCC collaboration (CERN as host lab) to study:

- **pp-collider (FCC-hh)**
  - main emphasis, defining infrastructure requirements
  - $\sim 16$ T $\Rightarrow$ 100 TeV pp in 100 km

- **80-100 km tunnel infrastructure** in Geneva area, site specific

- **$e^+e^-$ collider (FCC-ee)**, as potential first step

- **p-e (FCC-he) option**, integration one IP, FCC-hh & ERL

- **HE-LHC** with FCC-hh technology
collaboration & industry relations

111 Institutes
25 Companies
32 Countries
EC H2020
Short model magnets (1.5 m lengths) will be built from 2017 - 2021
Implementation - footprint baseline

Optimisation in view of accessibility surface points, tunneling rock type, shaft depth, etc.

Tunneling
- Molasse 90%, Limestone 5%, Moraines 5%

Shallow implementation
- ~ 30 m below lakebed
- Reduction of shaft length and technical installations
- One very deep shaft F (RF or collimation), alternatives being studied, e.g. inclined access
Push Technologies

High-field Magnets

Novel Materials and Processes

Large-scale Cryogenics

Power Efficiency

Reliability & Availability

Global Scale Computing

F. Bordry
• Energy Management at Laboratories
• Energy Efficiency
• Energy Recovery
• Advanced Energy Technologies and Future R&D
CERN is presently exploiting the physics potential of the LHC and operating a large accelerator complex with a scientific diversity programme.

After the long shutdown LS1 the LHC operates at 13 TeV (2015-2018) and later to increase towards 14 TeV (2021-2023).

=> Goal 300 fb⁻¹

The approved high luminosity project HL-LHC will allow to collect ten times more data (2026 - mid 2030ies) => Goal of 3’000 fb⁻¹

Depending on the physics findings of the LHC “precision” e+e- linear colliders might be built in Japan (ILC) or at CERN (CLIC: 380 GeV,…, 3 TeV)

CERN is hosting a study performed in international collaboration for a Future Circular Colliders in the Geneva area with a circumference of 80 – 100km:
- hh-collider (FCC-hh) defining the infrastructure requirements
- e+e- collider (FCC-ee) as potential intermediate step
- e-h (FCC-eh) option
- HE-LHC is also a possible option (staged approach): 16T-20T High Field Magnets in the present LHC tunnel

Conclusion
PHYSICS BEYOND COLLIDERS

Kick-off workshop of the Physics Beyond Colliders study to be held at CERN, Geneva, on 6-7 September 2016.

The aim of the study is to explore the opportunities offered by the non-collider part of the CERN complex to tackle some of the outstanding questions in fundamental physics.

The kick-off workshop is intended to survey the possibilities and stimulate new ideas.

> 300 participants (75% from outside CERN)

Details on the workshop programme, registration and abstract submission, as well as the mandate of the Study Group, can be found on the workshop web site: https://indico.cern.ch/event/523655/

Organizing Committee: Joerg Jaeckel, Mike Lamont, Connie Potter, Claude Vallée.
Contact: PBC2016.cittee@cern.ch, +41754113293
Final Conclusion: CERN Technology Roadmap

Important milestone: 2019-2020 update of the European Strategy for Particle Physics
Thanks for your attention

"The task of the mind is to produce future"
Paul Valéry