The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of $L_{\text{peak}} = 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ with levelling, allowing:

An integrated luminosity of $250 \text{ fb}^{-1}$ per year, enabling the goal of $L_{\text{int}} = 3000 \text{ fb}^{-1}$ twelve years after the upgrade. This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

Ultimate performance established 2015-2016: with same hardware and same beam parameters: use of engineering margins:

$L_{\text{peak ult}} \approx 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and Ultimate Integrated $L_{\text{int ult}} \sim 4000 \text{ fb}^{-1}$

LHC should not be the limit, would Physics require more...

Project approved by CERN Council in June 2016
Partecipants HiLumi Collaboration Meetings

HiLumi LHC CM participants

# participants

YEAR


FP7-HiLumi DS

CERN internal kick off meeting
Project management full steam ahead

Technical Coordination Committee

- Installed in 2016 (replacing TC and PLC of HiLumi DS)
- Chaired by O. Bruning
  - M. Zerlauth, Y. Papaphilippou, A. Apollonio
- In total 59 meetings (20/y)
- 267 presentations
- A few critical decisions 2018
  - Optics configuration change, new perf. Table
  - ATLAS shielding, CMS beam pipe support
  - Circuit layout and local 120 A CL
  - Cold Diodes (subj.to final confirmation)
  - FQ of IT quads ↔ HOC magnet length
  - Loss of reversibility (no second set CC)
- Average attendance: >35 people

PSM Project Steering Committee

- Started in 2017
- Scope: review of each WP by HLPO with GL & Dep. Head concerned, of: budget, MS & DLV, procurement and plan
  - With template
  - So far 67 PSMs (~1/week)
    - Max 5 times WP3-6A-8-11-15
    - Min 1 for WP18 (recent set up)
Production Readiness Reviews & Manufacturing Reviews (Quality)

- **PRR** – for each equipment (~20) is assessed:
  - Scope of work: is there a clear definition and clear interfaces?
  - Procedures, construction specifications, executive drawings: are all in approved status, verified by due authority, and well documented?
  - Is Quality Assurance correctly in place: procedures, documentation, check/holding points, etc.?
  - Components, Assembly tools, Availability, qualifications
  - Production planning robustness.

- **MR** – to ensure the quality is kept during production:
  - Adequateness and validity of certifications
  - Correct implementation and application of QP and MIP
  - Site organization (manufacturing, storage of components, finished product)
  - Implementation of document managing system
  - Actual training for documentation and of personnel

- Review panel with few permanent members and a few appointed *ad hoc*:
  - Chair PRR: D. Perini (EN/MME); Reviewed: TDIS, TANB, 11 T dipole coils and cold mass
  - Chair MRR: I. Bejar Alonso (HLPO); to start in January ‘19 (TDIS, DQW-CC, Collimators…)
  - When the case, organized with Collaborating Institutes for in-kind
Non binding MoU for HL-LHC

The time for “booking” in-kind contributions is shrinking! Certain items require a long qualification process for companies and also for Labs.

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Recent signed collaborations and in-kinds
The HL-LHC IT STRING in the crowdly SM18
The String gives the clock to many WPs!
Recent internal review of the IT string

HL LHC IT STRING is foreseen to study the collective behaviour of the IT zone

- The main components are: Q1-D1 with complete cold and warm powering
- The test stand will be integrated into SM18
- Infrastructure upgrade is well advanced
- P5L will be reproduced without slope
- 180 quenches/or power aborts are planned
- 400 W heat extraction possibility exist

ID CARD of the TEST STAND: HL-LHC IT STRING

TEST Facility LOCATION: SM18 (b. 2173)
TEST DATE: 2021-2022
OPERATIONAL TEMPERATURE: 1.9 K
OPERATIONAL CURRENT: Ultimate (108% $I_{\text{nominal}} = 18 \text{ kA}$)
MAGNETS: Q1, Q2a, Q2b, Q3, CP, D1
COLD POWERING: SC link, HTS leads DFH and DFX,
WARM POWERING: 1 x PC for 18 kA + 3 Trim for Q1-Q3 + 6 x 2 kA + 1 x 12 kA + 9 x 0.1 kA + WCC
PROTECTION: CLIQ and QH; EE where is baseline

Talk of Marta Bajko THU morning
Risk register: new feature from 2017
Are we too optimistic?

- Risks related to Delivery on mission
- Risks related to Strategy & Planning

See presentation by I. Bejar Alonso on Thursday
Main changes affecting Baseline since 2015!
From C&S Review 2015 to C&S Review 2016

- New WP: WP18 - Control Technologies
- Confirmation of dedicated resources to WP16 – Hardware Commissioning, including the... String test;

Main baseline changes:
- WP3: keep 70 mm aperture Q4 magnets (MQY) in the HI LHC instead of 90 mm aperture Q4 magnets (MQYY);
- WP3: decision to adopt laminated structure in triplet magnets;
- WP4: reduction by half of the number of crab cavities to be installed during LS3;
- WP5: reduction of number of secondary low impedance collimators (TCTs) and decision to use tertiary collimators (TCTPMs);
- WP6A: reduction of superconducting length thanks to implementation of the so-called 'double-decker' solution for underground infrastructures;
- WP6B: reduction of number of circuits and amperage;
- WP11: redefined scope: 11T dipole magnets around LHC-P7 (2 sets of dipoles) and connection cryostats in LHC P2 (2 sets of connection cryostats);
- WP17: Integration inside the Budget At Completion of a new cost estimate (increased!), as provided during an internal C&S review of this WP in May 2016.

AND

- CERN Accelerator Master Schedule change: Long Shutdown 2 delayed by 6 month and extended by 6 month. Long Shutdown 3 delayed by one year while maintaining its duration.

Rebaselining of August 2016 to recover 120 MCHF (re-evaluation of C.E. – extra cost and extra-scope - and T.I.) ~80 MCHF on WP1-16 by re-scoping ~ 40 MCHF on C.E.-T.I.

Full performance all recovered (but less margin!)
Main changes affecting Baseline since 2015! From C&S Review 2016 to C&S Review 2018

Main baseline changes:

- WP3: Additional proto for orbit correctors, no PIT R&D, reduced scope for Warm Magnets
- WP5: Contribution to low impedance material in primary collimators
- WP6A: Link design change (R&D needs), additional copper stabilizer
- WP6B: New R2E 120A converters and adding redundancy
- WP7: R&D on cold diodes
- WP9: New refrigerator at LHC P4 replaced by upgrade of existing refrigerator + purchase of mobile refrigerator for RF (Big saving! WP9)
- WP11: No PIT R&D, No PIT prototype, No tooling in industry
- WP12: New Tungsten supporting system (impact of CLIQ), coating of Q5&Q6 during LS2, alignment capabilities of +/- 2.5mm
- WP13: Implementation of final design on BGV proto, no cryo BLMs
- WP14: new design for MKI beam screens
- WP17: Cancellation of activities for CE, CV, EL for LHC-P4 (see WP9)
HL-LHC has passed the cap of 180 MCHF in expenditure >350 MCHF in commitment.
HL-LHC established in summer 2010 in view of FP7-Hilumi LHC DS. Installation of equipment will start in 2024 and HWC in 2026; today Oct. 2018 we are HALF WAY through the project duration!
ULTIMATE HL-LHC performance

Performance fully recovered after rebaselining 2016: reviewed by CMAC (Chamonix 2017 and 2018) & by CSR2 – CSR3

LHC is projecting ~ 400 fb⁻¹: delaying HL is not an option!

In collaboration with M. Lamont

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# Updated table of parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Nominal LHC (Design report)</th>
<th>LHC 2018 max values</th>
<th>HL-LHC (standard)</th>
<th>HL-LHC 8b+4e</th>
<th>HL-LHC (Ultimate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy in collision [TeV]</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>$N_b$</td>
<td>1.15E+11</td>
<td>1.15E+11</td>
<td>2.2E+11</td>
<td>2.2E+11</td>
<td>2.2E+11</td>
</tr>
<tr>
<td>$n_b$</td>
<td>2808</td>
<td>2556</td>
<td>2760</td>
<td>1972</td>
<td>2760</td>
</tr>
<tr>
<td>Number of collisions in IP1 and IP5 (^1)</td>
<td>2808</td>
<td>2544</td>
<td>2748</td>
<td>1967</td>
<td>2748</td>
</tr>
<tr>
<td>$N_{tot}$</td>
<td>3.2E+14</td>
<td>2.9E+14</td>
<td>6.1E+14</td>
<td>4.3E+14</td>
<td>6.1E+14</td>
</tr>
<tr>
<td>Beam current [A]</td>
<td>0.58</td>
<td>0.52</td>
<td>1.1</td>
<td>0.79</td>
<td>1.1</td>
</tr>
<tr>
<td>x-ing angle [μrad]</td>
<td>285</td>
<td>320 ==&gt; 260</td>
<td>500</td>
<td>470 (^{10})</td>
<td>500</td>
</tr>
<tr>
<td>Beam separation [$\sigma$] (^{11})</td>
<td>9.4</td>
<td>10.3 ==&gt; 6.8</td>
<td>10.5</td>
<td>10.5 (^{10})</td>
<td>10.5</td>
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<tr>
<td>$\beta^*$ [m]</td>
<td>0.55</td>
<td>0.50 ==&gt; 0.25</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>$\varepsilon_n$ [μm]</td>
<td>3.75</td>
<td>2 ==&gt; 2.5</td>
<td>2.50</td>
<td>2.0</td>
<td>2.50</td>
</tr>
<tr>
<td>r.m.s. bunch length [m]</td>
<td>7.55E-02</td>
<td>8.25E-02</td>
<td>7.61E-02</td>
<td>7.61E-02</td>
<td>7.61E-02</td>
</tr>
<tr>
<td>Total loss factor R0 without crab-cavity</td>
<td>0.342</td>
<td>0.342</td>
<td>0.342</td>
<td>0.342</td>
<td>0.342</td>
</tr>
<tr>
<td>Total loss factor R1 with crab-cavities</td>
<td>0.716</td>
<td>0.749</td>
<td>0.716</td>
<td>0.716</td>
<td>0.716</td>
</tr>
<tr>
<td>Virtual Luminosity (max over stable beams)</td>
<td>1.70E+35</td>
<td>1.44E+35</td>
<td>1.70E+35</td>
<td>1.70E+35</td>
<td>1.70E+35</td>
</tr>
<tr>
<td>r.m.s. bunch length [m] ((\text{max over stable beams for HL-LHC})^{8})</td>
<td>1.00E+34</td>
<td>2.00E+34</td>
<td>5.0E+34 (^{5})</td>
<td>3.82E+34</td>
<td>7.5E+34 (^{5})</td>
</tr>
<tr>
<td>$P_{r.m.s.}$ bunch length [m]</td>
<td>27</td>
<td>55</td>
<td>131</td>
<td>140</td>
<td>197</td>
</tr>
<tr>
<td>Probability of events [event/mm] (max over stable beams)</td>
<td>0.21</td>
<td>0.38</td>
<td>1.3</td>
<td>1.3</td>
<td>1.9</td>
</tr>
<tr>
<td>Leveling time [h] (assuming no emittance growth) (^{8,13})</td>
<td>7.2</td>
<td>7.2</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>

---

**Flat optics very promising!!**

HiLumi Plan B that may be «upgraded» to main line.

See talk of S. Fartoukh Thu morning.
Avancement from 7th Collaboration Meetign of Madrid

- CC into SPS with new cryogenic infrastructure anf first prton crabbing! Mission accomplished!
- USA: good quench perfomance of 1st Nb$_3$Sn IT QUAD Proto; Second proto, full length 4.2 m IT quad under test; Coils for series started.
- CERN 7.2 m IT near completion; starting coils for series!
- 1st proto 5.5 m 11 T dipole tested, **under revamping (one coil not good)**!
- 2 exceptional good short magnets in Nb$_3$Sn (11 T and QXF)
- Low impedance collimator proto tested in LHC!
Avancement from previous CM – 2
Two large C.E. contracts signed - groundbreaking 15 June 2018!!!
WP17.1: Civil-engineering work at Point 1

See specific presentation by P. Mattelaer on Wednesday
Technical visit on Friday

~ 30 m excavated
Travaux Point 5
Chantier Point 5: almost 25 m excavated
Avancement from previous CM – 3

- First important contracts for HiTech equipment construction issued!
  - All Nb$_3$Sn conductor placed: at budget cost (RRP)
  - Industrial service for 11 T collared coils: high overcost
  - CC DQW, (dressed cavities) supply (pre and series): moderate undercost
  - Low impedance collimators (first batch for LS2): moderate undercost
- Launching last purchase of MgB2 and all cabling for SC links!
- Simple 2-wall cryostat validated (only 1.5 W/m losses!)
- Last call for in-kinds! And securing it. All final opportunity for options
Avancement from previous CM – 4

- Final optimization approved, or almost:
  - Magnet powering & circuits
  - Integration
  - **Optimization of MS (full remote alignment; simplification of correctors; shorter cryogenics...)** Task force P. Fessia & S. Claudet, looks very positive!! See talk by P. Fessia on TUE. (and by H. Mainaud Durand on THU on remote alignment)
  - Decision on many options (see talk by O. Bruning on Tuesday).
- De-installation and installation: List of tasks and costs and interfaces completed in bottom up approach
- **First «detailed» technical evaluation of de-installation** (M. Modena)
- Readiness of installation with margin assessed (P. Fessia)
Integration: the puzzle that is – almost – solved!

- > 1.2 km of new accelerator
- > 1 km of new underground galleries to fill!
- 10 new buildings
And also surface building integration is coming nicely...
LS3 DE-INSTALLATION studies started!

Working on a Vers.0 of “de-installation sequence”, analyzing sub- and co-activities and any other main boundary conditions.

TARGET: a De-Install Planning Vers.0 for the next C&S Review

Modification of the TAS and VAX @ ATLAS:

- VAX removal
  - Simple operation done via the tunnel
  - Several objects with a couple of kg
  - Activity in the tunnel

Starting series of “ad-hoc” meetings with main WPs + Transport + RP + Planning teams etc.

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V1.4 Optics and Layout

Major changes with respect to previous baseline:

- Q4: reusing existing cold mass (MQY+3MCBY) @ 4.5 K
- Q5: reusing existing cold mass (MQML+1MCBC) @ 4.5 K
- Possible thanks to the deployment of a fully remote alignment system to be used with safe beam.
- Apertures compatible with Round Optics with $\beta^* = 15$ cm and Flat optics $\beta^* = 7.5/18-30$ cm

Optics

- Improved Point 4 optics for Beam Instrumentation and e-lens.
- Further reduction of Q5.R6 required strength to avoid 1.9 K upgrade at 7.5 TeV

Possible optimization

- Crab angle increase for 7 TeV operations if Q7 can reach ultimate current
- TAXN aperture could be reduced by few mm \(\Rightarrow\) useful to reduce radiation to the matching section elements
BBLR compensation

- Successful demonstration of the compensation of the Beam-Beam Long Range effects (for flat and round beams) in machine studies both with octupoles and wires in IR1 and IR5
- Important tools to further enhance performance (virtual luminosity, pile-up density, lifetime)

Octupoles

\[
\sigma_{\text{eff}, i} \text{ (mb)} = \frac{|dN_i/dt|}{E_i}\frac{d\varphi}{dt} 
\]

Beam 1

\[
\sigma_{\text{burn-off}} \approx 80 \text{ mb}
\]

Wires

On this and other options (beyond baseline) see talk of Oliver Bruning TUE morning

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HL-LHC SPS Test stand for crab-cavities

Compressor

80m long cryo distribution line

Cryo-service-box

Transfer-table

RF passive equipment

510 mm movement in/out

Articulated vacuum Y-chamber with carbon coating

V-shaped coupling for RF waveguides

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HL-LHC SPS Test stand for crab-cavities

Compressor

80m long cryo distribution line

Cryo-service-box

Transfer-table

Radio frequency passive equipment

510 mm movement in/out

Articulated vacuum Y-chamber with carbon coating

V-shaped coupling for RF waveguides

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SPS-BA6, CC operation in 2018
Cryogenic operation facts for 1st year after completion of this new facility

0.00 1.00 1.50 2.00 2.50 3.00 3.50 4.00 4.50 5.00
0.00 10.00 20.00 30.00 40.00 50.00 60.00 70.00 80.00 90.00 100.00

- Phase1 @ 4.5K
- Phase2 @ 2K
- LN2 Consolidation
- 2K commissioning
SPS-DQW MDs with Beam

First injection – 12:55, May 23
2 × 10^{11} protons / bunch, 26 GeV

RF phase scan w.r.t the beam phase with cavity 1
CERN-RFD Fabrication Ongoing
IT Quad model MQXFS4 – final RRP Nb₃Sn

Courtesy E. Todesco & P. Ferracin
Progress of long IT Quad at CERN

Assembly with 4 practice coils

4 first Nb$_3$Sn coils for the 7.4 m long proto

USA: talk by S. Rolli today and G. Apollinari tomorrow
Cold Power: effort for 60 m DEMO1 validation by end of the year
11 T dipole (and new connection cryostat)

First cold mass of the LEP connection cryostats

1st 5.5 m long 11 T dipole before testing July ‘18

Model SP107 (new layout – taskforce)
WP5: first HL-LHC hardware in the LHC

First TCLD jaw prototype at the company (courtesy of EN/STI)

Samples of MoGr (Molybdenum-Graphite) from producer (courtesy of EN/MME)

Dedicated talk by S. Gilardoni
WP5: Update on crystal collimation

Scope: further improvement of ion cleaning after 2016 re-baselining. Studying if, for ions, this can be an “adiabatic” upgrade of the IR7 system.

2017: improved by up to x60 collimation cleaning of Xe beams!

4 mm = 50 μrad, or 10 x 15m long LHC dipoles or 300 T at 7 TeV

Two goniometers installed on B1 in LS2; two more on B2 in 2017, upgraded in 2018.

4 operational crystals for collimation.

All details: special workshop organised this Friday!
https://indico.cern.ch/event/752062

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WP5: pushing even further accelerator technology

It would allow controlling actively the halo, through a hollow electron beam (overlapped over three meters to the proton/ion beams) that selectively excites halo particles.

Design nearly complete. Surpassed target e-beam current of 5A, now final cathode design (smaller) under test at FNAL.

Ready to built it if integrated into the baseline.
- Selection of Technology for Energy Storage for the 18kA Lithium titanium oxide batteries (LTO),

LTO: the most suitable but also the safest and cheapest

- ADC development for Class 0
  New HPM7177 (based on commercial ADC): first prototype of signal conditioning and ADC tested. Noise up to 0.1 Hz better than 0.05 ppm rms: well within HL-LHC specs 😊

- Linearity better than 0.5 ppm

- Max settling error of about 0.1 ppm
Irradiation test of triplet cold by-pass diodes

- Cold diode irradiation cryostat installed in CHARM on 10.04.2018
- Two stacks of four diodes (77K, 4K), weekly measurement of forward characteristic up to 18 kA, turn on voltage, reverse blocking voltage and capacitance.
- Measurements to be continued until November (end of protons in injectors), expected to reach total ~ 10 kGy and ~ 2e14 1MeVneq/cm²
- Annealing tests will be performed after the end of the irradiation period
WP12: *in-situ* a-C coating system ready for LS2

- Fabrication of the coating system for the production in the tunnel during LS2.
- First coating in a real magnet with a beam screen already exposed to the LHC beam (SSS#243, removed from the LHC in LS1 and stored in air since then) with:
  - No impact on cold bore kapton insulation
  - No impact on button BPM response
  - Good adhesion
  - Maximal Secondary Electron Yield along the 6 meters: \(<\delta_{\text{max}}\> = 1.01 \pm 0.04\)
- TE-VSC is ready for the coating campaign in LS2 (Q5 + Q6 in IR2R and IR8L)

---

**Modular sputtering source**

**SSS#243 during coating**

**a-C deposition in SSS#243**

**Spools for the electrical and mechanical cables**
WP14: first TDIS module tested in HiRadMat

- Full TDIS module tested under high intensity beam impact
- **Test completed successfully on 24th August 2018**
- Jaws tested for high impact parameters.
- Intensities/position producing equivalent thermal loads as HL beams
  - Impacts with $1.2E11 \text{ p/b x 288b} \rightarrow \text{total intensity per pulse} = 3.5E13 \text{ p}$
- Two different material options tested for the back-stiffener:
  - TZM (baseline)
  - Aluminium (back-up)
- Cooling circuit performed well → room temperature reached after ~10 min
- Post Irradiation Examinations to be performed soon…
On time or small delays; typically 3-6 months.
Largest is 6-9 months on WP6a also because of change of scope (cable layout following Circuit review);
All is well within margin. Most critical: 11 T (NO MARGIN) and TDIS since they are for LS2!

Courtesy of M. Barberan Marin & M. Alcaide Leon
Thanks to the WPLs, GLs, HLPO, and all those who provided inputs and materials.