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HL-LHC Accelerator Physics Challenges

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Thanks to G. Arduinig, O. Brüning and S. Fartoukh for the material provided
Content

- HL-LHC goal and performance optimisation
- HL-LHC challenges
  - Triplet magnets
  - Optics challenges: the ATS
  - Beam-Beam aspects
  - Crab-cavities
  - Collimation
  - Vibrations
- Performance projections
From LHC to HL-LHC

Technical limits (in experiments, too) like:

- Cryogenic limit & Radiation Damage of triplet magnets
- Splices fixed ➔ Energy
- Injectors upgrade
- e-cloud UFOs!

Run I
- Splices fixed ➔ Energy
- Lumi

Run II
- Injectors upgrade
- LS1
- 25 fb⁻¹
- 0.75 \(10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
- 50 ns bunch
- high pile up \(\sim 40\)

Run III
- LS2
- Injector upgrade
- LIU
- 300 fb⁻¹
- 1.5 \(10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
- 25 ns bunch
- very high pile up \(> 60\)

- 1.5 - 2.2 \(10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
- 25 ns bunch
- very high pile up \(> 60\)
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:

- Prepare machine for operation beyond 2025 and up to 2035
- Devise beam parameters and operation scenarios for:
  - enabling a total integrated luminosity of \(3000 \text{ fb}^{-1}\)
  - implying an integrated luminosity of \(250 \text{ fb}^{-1}\) per year,
  - design oper. for \(\mu \delta 140\) (\(\Rightarrow\) peak luminosity \(5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}\))

\(\Rightarrow\) Operation with levelled luminosity!

\(\Rightarrow\) 10 times the luminosity reach of first 10 years of LHC operation

Y. Papaphilippou - Thessaloniki, 04/09/2016
LHC upgrade goals: Performance optimisation

Luminosity recipe (round beams):

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

- 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
- Upgrade LIU
- triplet aperture
- Crab Cavities
- minimize number of unscheduled beam aborts

Y. Papaphilippou - Thessaloniki, 04/09/2016
LHC Limitations and HL-LHC Challenges

- Technical bottle necks (e.g. cryogenics) ➔ New addit. Equipment
- Insertion magnet lifetime and aperture:
  ➔ New insertion magnets and low-β with increased aperture
- Geometric Reduction Factor: ➔ SC Crab Cavities
  ➔ New technology and a first for a hadron storage ring!
- Performance Optimization: Pileup density ➔ Lumi levelling
  ➔ devise parameters for virtual luminosity >> target luminosity
- Beam power & losses ➔ additional collimators in DS region
- Machine efficiency and availability:
  # R2E ➔ removal of all electronics from tunnel region
  # e-cloud ➔ beam scrubbing (conditioning of surface)
  # UFOs ➔ beam scrubbing (conditioning of surface)
HL-LHC Upgrade Ingredients: Triplet Magnets

- Nominal LHC triplet: 210 T/m, 70 mm coil aperture
  - ca. 8 T @ coil
  - 1.8 K cooling with superfluid He (thermal conductivity)
  - current density of 2.75 kA / mm$^2$
- At the limit of NbTi technology (HERA & Tevatron ca. 5 T @ 2kA/mm$^2$)!!!

LHC Production in collaboration with USA and KEK

Critical Surface for NbTi
HL-LHC technical bottleneck

Radiation damage to triplet magnets at 300 fb-1

Peak dose longitudinal profile

- 7+7 TeV proton interactions
- IT quadrupoles
- MCBX-1
- MCBX-2
- MQSX
- MCTX nested in MCBX-3
- MCSOX

Distance from IP [m]

Peak dose [MGy / 300 fb-1]

- Q2 27 MGy
- MCBX3 20 MGy

Cold bore insulation ≈ 35 MGy

Y. Papaphilippou - Thessaloniki, 04/09/2016
Radiation damage to triplet magnets

Need to replace existing triplet magnets with radiation hard system (shielding!) such that the new magnet coils receive a similar radiation dose @ 10 times higher integrated luminosity!!!!

➡ Shielding!
➡ Requires larger aperture!

➡ New magnet technology

➡ 70mm at 210 T/m ➔ 150mm diameter 140 T/m
➡ 8T peak field at coils ➔ 12T field at coils (Nb$_3$Sn)!!!
New Interaction Region layout

Longer Quads; Shorter D1 (thanks to SC)

Thick boxes are magnetic lengths -- Thin boxes are cryostats

Y. Papaphilippou - Thessaloniki, 04/09/2016
Optics Challenges & the ATS scheme

→ Lowering $\beta^*$ needs magnets of larger aperture, but also new hardware or sophistication (crab-cavity, flat optics,...) to mitigate the luminosity loss due to the Piwinsky angle.

→ How to produce this $\beta^*$ ???

This is the aim of the ATS scheme which solves many optics limitations coming from the overall LHC ring.

1. Optics matchability to the arcs:
   – Some IR quads going to 0 T/m, others to max. field (200T/m).
   – Simply the matching section becomes too short at some point.

2. Correctability of the chromatic aberrations induced, not only $Q'$, but also $Q''$, $Q'''$,..., and off-momentum $\beta$-beating:
   – Limitations from the arc sextupole strength (<600A).

S. Fartoukh, PRSTAB 16, 111002, 2013
The ATS scheme
S. Fartoukh, PRSTAB 16, 111002, 2013

- **A new injection optics** (~π/2 FODO lattice → new integer tunes)
- **A squeeze in 2 steps**

1) An “almost” standard squeeze, the **Pre-squeeze**:
   → acting on the matching quads of IR1 and IR5,
   → with new matching constraints on the left/right IR phase
   → till reaching some limits (sextupoles, matching quadrupoles)

2) A further reduction of β*, the **Squeeze**:
   → acting on IR2/8 for squeezing IR1 and IR4/6 for IR5,
   → inducing β-beating bumps in sectors 81/12/45/56 to boost the sextupole efficiency at constant strength.

\[
\beta_{\text{Squeeze}}^* = \beta_{\text{Pre-Squeeze}}^* \times \frac{\left(\hat{\beta}_{\text{Arc}}\right)_{\text{FODO}}}{\left(\hat{\beta}_{\text{Arc}}\right)_{\text{Mismatched}}}
\]
**HL-LHC optics using the ATS**

**Injection optics $\beta^* = 5.5\ m$ at IP1 and IP5 (150 T/m IT gradient)**

S. Fartoukh

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**Diagram:**

- $\beta_x, \beta_y, D_x$
- $s (m)$
- $D (m)$
- $[\times 10^{**3}]$
Pre-squeezed optics $\beta^* = 40$ cm at IP1 and IP5 (150 T/m IT gradient)
HL-LHC optics using the ATS

Round Squeezed optics $\beta^* = 10 \text{ cm}$ at IP1 and IP5 (150 T/m IT gradient)

S. Fartoukh

![Graph showing HL-LHC optics parameters](image-url)
HL-LHC optics using the ATS

Flat Squeezed optics $\beta^* = 20/5 \text{ cm}$ at IP1 and IP5 (150 T/m IT gradient)

S. Fartoukh

$\beta_{\text{max}} = 55 \text{ km}$
a factor of 12 above nominal!
Parasitic bunch encounters:

Operation with ca. 2800 bunches @ 25ns spacing ⇒ approximately 30 unwanted collision per Interaction Region (IR).

⇒ Operation requires crossing angle

Non-linear fields from long-range beam-beam interaction:

efficient operation requires large beam separation at unwanted collision points ⇒ Separation of 10 -12 σ ⇒ large triplet apertures for HL-LHC!!
New tools and new theory

- The beta aspect ratio at the wire(s) is fundamental
- $\beta_x/\beta_y = 1$ is a poor compromise with 1 wire/IP
- With 2 wires $\beta_x/\beta_y \sim 2$ and $1/2$ is optimal for all driving terms!

Provide new credit to the ``HL-LHC Plan B’’ (back up w/o crab-cavity)

- Based on flat optics and BBLR compensation, with similar(+/- 10 %) data quantity and quality w.r.t. the baseline
- Installing the wires between Q4 and Q5, where the optimal $\beta$ aspect ratio can easily be realized and the integration are quite relaxed (if any!)
Crab Cavities: Geometric Luminosity Reduction Factor:

- Reduces the effect of geometrical reduction factor
- Independent for each IP

\[ F = \frac{1}{\sqrt{1 + \frac{Q^2}{Q^*}}}; \quad \frac{c}{z} \]

- Noise from cavities to beam?!?
- Challenging space constraints:
  - requires novel compact cavity design
3 Advanced Design Studies with Different Coupler concepts

Concentrate on two designs in order to be ready for test installation in SPS in 2016/2017 TS

Present baseline: 4 cavity/cryomod TEST in SPS under preparation for 2017
And excellent first results: RF Dipole
Recent results from Measurements @ CERN

Initial goal was 3.5 MV however $\Delta V > 5$-6 MV would ease integration
Testing Crab Cavities with Beams

Crab Cavity Test Installation in the SPS:
• Vital to gain feedback from operation with beam before launching of cavity production for HL-LHC ➔ need results before LS2!!!
• Tight and ambitious schedule but doable!
  ➔ Visualization and planning now
  ➔ Preparation in EYETS 16/17
  ➔ Installation YETS 17/18

➔ vital for project to be able to launch Carb cavity production by LS2!!! (international partners!!!)
SPS beam test: a critical step for Crab Cavities
LHC Challenges: Beam Power

Unprecedented beam power:

Worry about beam losses:

Failure Scenarios ➔ Local beam Impact

➔ Equipment damage
➔ Machine Protection

Lifetime & Loss Spikes ➔ Distributed losses

➔ Magnet Quench
➔ R2E and SEU
➔ Machine efficiency
Baseline upgrades

56 new collimators to be produced by LS3 in the present baseline!

Ion physics debris: DS collimation

Low-impedance, high robustness secondary collimators

Cleaning: DS coll. + 11T dipoles, 2 units per beam

Completely new layouts
Novel materials.
IR1+IR5, per beam:
4 tertiary collimators
3 physics debris collimators
fixed masks

4 tertiary collimators
3 physics debris collimators
fixed masks

56 new collimators to be produced by LS3 in the present baseline!

S. Redaelli, Chamonix 2016, 28-01-2016

Y. Papaphilippou - Thessaloniki, 04/09/2016
DS collimators – 11 T Dipole

LHC PROJECT

halo

Q7 MB.A8R7 MB.A9R7 MB.B8R7 MB.B9R7 MB.A10R7 MB.B10R7 MB.B11R/L MB.B11R/L

Point 5

Point 4

Point 2

Point 1

missing dipole

ALICE

ATLAS

Y. Papaphilippou - Thessaloniki, 04/09/2016

6.18 m (L_CM)

5.3 m (L_max)

2.27 m (collimator)

5.3 m (L_max)

6.18 m (L_CM)
Prototyping of the by-pass crystostat (QTC) for the installation of a warm collimator in the cold dispersion

Magnet: prototypes reached 11 T field in March 2013!
IR1 & IR5 Underground Civil Engineering

P. Fessia, HL-LHC TDR
Lessons from Civil Engineering Test Drills and Earth Quakes On Vibration Tolerances:

- Driven by worries about vibrations from the HL-LHC civil engineering

- **GEOTHERM2020**
  a renewable energy production project by the Canton of Geneva
Vibration Tolerances for Operation

Lessons from Civil Engineering Test Drills and Earthquakes

On Vibration Tolerances:

• From Noise to Beam

- $O(100)$ amplification to cold-mass for certain modes ($H_0$)
- $O(10^{-100})$ attenuation $H_1$ and $H_2$
- Order of micrometer tolerance for vibrations!
- Schedule that allows CE construction during LS2!!
- Hollow electron lens for halo depletion!

Y. Papaphilippou - Thessaloniki, 04/09/2016
## New Schedule: HL-LHC CE during LS2

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Legend:
- **ShUTDOWN/TECHNICAL STOP**
- **PROTONS PHYSICS**
- **COMMISSIONING**
- **IONS**

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Legend:
- **LS3**

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Legend:
- **LS5**
Performance Projections up to HL-LHC

- **Run I**: Splices fixed
- **Run II**: Injectors upgrade
- **Run III**: New Low-\(\beta^*\) quads

**Technical limits** (in experiments, too) like:
- Cryogenic limit, Radiation & Damage of triplet magnets
- 5 \(10^{34}\) cm\(^{-2}\)s\(^{-1}\) levelled
- 5 \(10^{34}\) cm\(^{-2}\)s\(^{-1}\) very high pile up
- e-cloud UFOs!

- **Energy**: 6.5 TeV
- **Intensity Upgrade**
- **Crab Cavity Phase2**
- **25 fb\(^{-1}\)**
- **1000 fb\(^{-1}\)**
- **3000 fb\(^{-1}\)**
- **300 fb\(^{-1}\)**

**Performance Projections**
- **Run I**
- **Run II**
- **Run III**

**Y. Papaphilippou - Thessaloniki, 04/09/2016**
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal LHC (design report)</th>
<th>HL-LHC 25ns (standard)</th>
<th>HL-LHC 25 ns (BCMS)</th>
<th>HL-LHC 50ns</th>
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<td>Beam energy in collision [TeV]</td>
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<td>$N_b$</td>
<td>$1.15E+11$</td>
<td>$2.2E+11$</td>
<td>$2.2E11$</td>
<td>$3.5E+11$</td>
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<tr>
<td>$n_b$</td>
<td>2808</td>
<td>2748</td>
<td>2604</td>
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<td>Number of collisions at IP1 and IP5</td>
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<td>2736</td>
<td>2592</td>
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<td>$N_{tot}$</td>
<td>$3.2E+14$</td>
<td>$6.0E+14$</td>
<td>$5.7E+14$</td>
<td>$4.9E+14$</td>
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<td>Beam current [A]</td>
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<td>x-ing angle [µrad]</td>
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<td>590</td>
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<td>beam separation [σ]</td>
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<td>$β^*$ [m]</td>
<td>0.55</td>
<td>0.15</td>
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<td>$ε_n$ [µm]</td>
<td>3.75</td>
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<td>$ε_L$ [eVs]</td>
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<td>r.m.s. energy spread</td>
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<td>r.m.s. bunch length [m]</td>
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<td>IBS horizontal [h]</td>
<td>80 -&gt; 106</td>
<td>18.5</td>
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<td>17.2</td>
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<tr>
<td>IBS longitudinal [h]</td>
<td>61 -&gt; 60</td>
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<td>Piwinski angle</td>
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<td>Geometric loss factor R0 without crab-cavity</td>
<td>0.836</td>
<td>0.305</td>
<td>0.305</td>
<td>0.331</td>
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<tr>
<td><strong>Geometric loss factor R1 with crab-cavity</strong></td>
<td>(0.981)</td>
<td><strong>0.829</strong></td>
<td><strong>0.829</strong></td>
<td><strong>0.838</strong></td>
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<td>beam-beam / IP without Crab Cavity</td>
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<td>3.3E-03</td>
<td>3.3E-03</td>
<td>4.7E-03</td>
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<tr>
<td>beam-beam / IP with Crab cavity</td>
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<td><strong>1.1E-02</strong></td>
<td><strong>1.1E-02</strong></td>
<td><strong>1.4E-02</strong></td>
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<td>Peak Luminosity without crab-cavity [cm$^2$ s$^{-1}$]</td>
<td>$1.00E+34$</td>
<td>$7.18E+34$</td>
<td>$6.80E+34$</td>
<td>$8.44E+34$</td>
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<tr>
<td>Virtual Luminosity with crab-cavity: $L_{peak}^*R1/R0$ [cm$^2$ s$^{-1}$]</td>
<td>(1.18E+34)</td>
<td><strong>19.54E+34</strong></td>
<td>18.52E+34</td>
<td>21.38E+34</td>
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<tr>
<td>Events / crossing without levelling w/o crab-cavity</td>
<td>27</td>
<td>198</td>
<td>198</td>
<td>454</td>
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<tr>
<td>Levelled Luminosity [cm$^2$ s$^{-1}$]</td>
<td>-</td>
<td><strong>5.00E+34</strong></td>
<td>5.00E34</td>
<td>2.50E+34</td>
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<tr>
<td>Events / crossing (with levelling and crab-cavities for HL-LHC)</td>
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<td>138</td>
<td>146</td>
<td>135</td>
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<tr>
<td>Peak line density of pile up event [evt/mm] (max over stable beam)</td>
<td>0.21</td>
<td>1.25</td>
<td>1.31</td>
<td>1.20</td>
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<td>Levelling time [h] (assuming no emittance growth)</td>
<td>-</td>
<td>8.3</td>
<td>7.6</td>
<td>18.0</td>
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Reserve slides
R2E SEU Failure Analysis - Actions

- **2008-2011**
  - Analyze and mitigate all safety relevant cases and limit global impact

- **2011-2012**
  - Focus on equipment with long downtimes; provide shielding

- **LS1 (2013/2014)**
  - Relocation of power converters

- **LS1 – LS2:**
  - Equipment Upgrades

- **LS3 -> HL-LHC**
  - Remove all sensitive equipment from underground installations

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Y. Papaphilippou - Thessaloniki, 04/09/2016
The critical zones around IP1 and IP5

1. New triplet $\text{Nb}_3\text{Sn}$ required due to:
   - Radiation damage
   - Need for more aperture

2. We also need to modify a large part of the matching section e.g. Crab Cavities & D1, D2, Q4 & corrector

3. For collimation we also need to change the DS in the continuous cryostat: 11T $\text{Nb}_3\text{Sn}$ dipole

More than 1.2 km of LHC!!
Plus technical infrastructure (e.g. Cryo and Powering)!!