Accelerator physics and technology challenges for the HL-LHC

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- From LHC to HL-LHC ➔ HL-LHC goal
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  - Levelling
  - Triplet magnets
  - Optics challenges: the ATS
  - Beam-Beam aspects
  - Crab-cavities
  - Beam power
  - Civil engineering
- 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

25 fb⁻¹
300 fb⁻¹

0.75 \(10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
50 ns bunch
high pile up ~40

1.5 \(10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
25 ns bunch
high pile up ~40

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

e-cloud UFOs!
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 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...
HiLumi LHC landmarks: a project for Physics and Technology jump

**CIVIL ENGINEERING**
- 2 new caverns and two new 300-metre service galleries,
- two new large shafts,
- 16 new technical buildings on surface in P1 and P6 (ATLAS and CMS)

**CRYOGENICS**
- 2 new large 1.9 K helium refrigerators for HiL-LHC near ATLAS and CMS

**FOCUSING MAGNETS**
- 12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.

**“CRAB” CAVITIES**
- 8 superconducting “crab” cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.

**BENDING MAGNETS**
- 2 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

**SUPERCONDUCTING LINKS**
- Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service galleries to the LHC tunnel.

**COLLIMATORS**
- 16 to 20 new collimators and 60 replacement collimators to reinforce machine protection.
HiLumi collaboration: pushing the boundaries of the LHC

HL-LHC in-kind contributors
A global effort

Under discussion with Canada, Georgia, Japan, Russia, USA

Total
LHC upgrade goals: Performance optimisation

Luminosity recipe (round beams):

$$L = \frac{n_b \times N_1 \times N_2 \times f_{rev}}{4 \times \times n} \times F(\ , \ , \ )$$

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
- 25ns
- Crab Cavities
- minimize number of unscheduled beam aborts

Y. Papaphilippou - Corfu, 02/09/2018
Goal of High-Luminosity LHC

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:
  1. Enabling at total integrated luminosity of $3000 \text{ fb}^{-1}$
  2. Implying an integrated luminosity of $250 \text{ fb}^{-1} \text{ per year}$,
  3. Design operation for $\mu \delta 140$ ($\Rightarrow$ peak luminosity $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)

- Operation with levelled luminosity!
- 10 times the luminosity reach of first 10 years of LHC operation

Y. Papaphilippou - Corfu, 02/09/2018
- Introduced separation levelling for all experiments (Separation levelling is used since many years for ALICE and LHCb)
- Dynamic orbit bump changes overlap of colliding bunches
- Initial spike before leveling reaching $2.2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$

![Graph showing LHC 2017: separation levelling]
β* levelling

Levelling luminosity by β* should be the main levelling technique for HL-LHC

Succesfull β* levelling in LHC MDs

implementation of β* levelling steps during LHC operation

Luminosity evolution during β* levelling, moving back and forth between 30 cm and 40 cm. The beams remained head-on within ~ 2 µm!
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 / mm²
- At the limit of NbTi technology (HERA & Tevatron ca. 5 T @ 2kA/mm²)!!!

LHC Production in collaboration with USA and KEK
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

Cold bore insulation ≈ 35 MGy

Q2 27 MGy

MCBX3 20 MGy

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Radiation damage to triplet magnets

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

⇒ Shielding!

⇒ Requires larger aperture!

⇒ New magnet technology

⇒ 70 mm @ 210 T/m ⇒ 150 mm diameter @ 140 T/m
8 T peak field @ coils ⇒ 12 T field at coils (Nb$_3$Sn)!!!
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 b-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 \((\sim \pi/2\) FODO lattice \(\rightarrow\) new integer tunes\)
- A squeeze in 2 steps

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

2) A further reduction of \(\beta^*\), \textbf{the Squeeze}:
\(\rightarrow\) acting on IR2/8 for squeezing IR1 and IR4/6 for IR5,
\(\rightarrow\) inducing \textit{\(\beta\)-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

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

S. Fartoukh

- LHC operating **smoothly** with ATS optics since 2017
- Several **HL-LHC options** tested in MDs (flat optics, beam-beam long range compensation with DC wires and octupoles)
Parasitic bunch encounters:

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

\(\Rightarrow\) Operation requires crossing angle

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

efficient operation requires large beam separation at unwanted collision points \(\Rightarrow\) Separation of 10 - 12 \(\sigma\) \(\Rightarrow\) large triplet apertures for HL-LHC!!
Crab Cavities

- Reduce the effect of geometrical reduction factor
- Independent for each IP
- Noise from cavities to beam???
- Challenging space constraints:
  - requires novel compact cavity design
HL-LHC Crab Cavities designs

2 Designs with Different Coupler concepts and Deflection planes

RF Dipole: Waveguide or waveguide-coax couplers

DQW crab-cavity Cryomodule for SPS tests

Double ¼-wave: Coaxial couplers with hook-type antenna

Present baseline: 4 cavities / IP / side → 16 total
First proton crabbing ever!

TEST in SPS ongoing since 2018

Crabbing Voltage from Head-Tail Monitor
2018-05-23 17:02:39

Study and R&D has been very useful to obtain this result
LHC Challenges: Beam Power

Unprecedented beam power:
Potential equipment damage in case of failures.

In case of failure the beam must never reach sensitive equipment!

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

- New collimators and absorbers for the HL-LHC
- Remove all active components from the LHC tunnel [requiring new space underground]

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Baseline upgrades

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

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

Ion pair production: DS collimation

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

Low-impedance, high robustness secondary collimators

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DS collimators – 11 T Dipole

11 T Nb₃Sn
IR1 & IR5 Civil Engineering

Vibrations of Civil Engineering Work affects operation!!!

- CE work needs to be done when LHC is not operating
- main work needs to be carried out during LS2 in order to finish work in time for LS3
Underground Constructions

⇒ HL-LHC CE work started in June

Point 5) Awarded and signed in March 2018!
15 June 2018: Groundbreaking Ceremony

Launch of the civil engineering work for the High Luminosity LHC Project
Friday, 15 June 2018

Inauguration des travaux de génie civil du projet LHC à Haute Luminosité
Vendredi 15 juin 2018
Work is progressing fast...

P5: capping beam

Temporary building above the shaft
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 the LHC will be upgraded!!

Plus technical infrastructure (e.g. Cryo and Powering)!!

Changing the triplet region is not enough for reaching the HL-LHC goal!
Schedule

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Performance Projections up to HL-LHC

- Peak luminosity
- Integrated luminosity

Run I
- Splices fixed
- Energy 6.5 TeV

Run II
- Injectors upgrade
- e-cloud UFOs!

Run III
- New Low-β* quads
- Crab Cavity Phase 2

- Technical limits (in experiments, too) like:
  - Cryogenic limit, Radiation & Damage of triplet magnets

- Performance Projections up to HL-LHC

- 0.75 \(10^{34}\) cm\(^{-2}\)s\(^{-1}\)
  - 50 ns bunch high pile up ~40

- 1.5 \(10^{34}\) cm\(^{-2}\)s\(^{-1}\)
  - 25 ns bunch high pile up ~40

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

- 5 \(10^{34}\) cm\(^{-2}\)s\(^{-1}\)
  - Levelled 25 ns bunch very high pile up ~140

Y. Papaphilippou - Corfu, 02/09/2018
Ευχαριστώ για την προσοχή σας

Corfu Summer Institute on Elementary Particle Physics and Gravity 2018

URL Address: http://physics.ntua.gr/corfu2018
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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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!