Accelerators - 1

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significant input from Mike Lamont & Lucio Rossi

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outline

• a brief history of high-energy accelerators
• LHC basics and run 1 (2010-13)
• what has changed for run 2?
  - is it really a "new machine"?
• run 2 highlights & challenges
• planned upgrades – LIU and HL-LHC
• LHeC option
energy frontier over 70 years

new technologies: 

- $Nb$-$Ti$ SC magnets
- colliders

repeated jumps from saturation to new emerging technologies

storage rings have been the frontrunner technology for the last $\sim$50 years
colliding beams

centre-of-mass energy:

\[ E_{\text{c.m.}} = \sqrt{2E_{\text{beam}} M_{\text{target}}}c^2 \]

beam hits a “fixed target”

\[ E_{\text{c.m.}} = 2E_{\text{beam}} \]

two beams collide

colliding two beams against each other can provide much higher centre-of-mass energies than fixed target!
superconducting magnets

2 T
SPS MBA, 6.5 m long, 360 dipoles
SPS MBB, 6.5 m long, 384 dipoles

4.5 T
HERA,
9 m, 75 mm
416 dipoles

5.3 T
Tevatron,
6 m, 76 mm
774 dipoles

3.5 T
RHIC,
9 m, 80 mm
264 dipoles

8.3 T
LHC,
15 m, 56 mm
1276 dipoles

normal conducting warm magnets
1st cyclotron, ~1930
E.O. Lawrence
11-cm diameter
1.1 MeV protons

LHC, 2015
9-km diameter
~7 TeV protons

after ~80 years
~$10^7$ x more energy
~$10^5$ x larger
remarkable advance in accelerator cost/energy thanks to new technologies

Specific cost vs center-of-mass energy of CERN accelerators

Specific cost \[\text{[2008 MCHF/GeV c m]}\]

\[\text{cost} \sim E_{cm}^{0.28}\]

P. Lebrun, RFTech 2013
accelerator size, energy, cost ... 

what else is there?
reaction rate \( R = \sigma L \)

**luminosity**

- Cross section \( \sigma \)
- Luminosity \( L \)


**Graph Details**

- **Cross section (mb)**
- **\( P_{\text{lab}} \) GeV/c**
- **\( \sqrt{s} \) GeV**

- **Total cross section** \( \sigma_{\text{tot}} \approx 100 \text{ mbarn} \approx 10^{-25} \text{ cm}^2 \)
- **Proton consumption** (beam lifetime) determined from cosmic rays

**LHC**
LHC run 1 (2012-13) accumulated more integrated luminosity than all previous hadron colliders together!
2010: 0.04 fb\(^{-1}\)
- 7 TeV CoM
- Commissioning

2011: 6.1 fb\(^{-1}\)
- 7 TeV CoM
- Exploring the limits

2012: 23.3 fb\(^{-1}\)
- 8 TeV CoM
- Production

\(\sigma_{\text{Higgs}} \sim 20\text{–}50 \text{ pb} \rightarrow \text{with 300 fb}^{-1} \text{ LHC produces} \sim 10 \text{ million Higgs} \)
luminosity

\[ L = \frac{N^2 n_b f}{4\pi\sigma_x \sigma_y} \quad F = \frac{N^2 n_b f\gamma}{4\pi\varepsilon_n \beta^*} \]

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<thead>
<tr>
<th>N</th>
<th>number of particles per bunch</th>
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<tr>
<td>(n_b)</td>
<td>number of bunches / beam</td>
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<tr>
<td>f</td>
<td>revolution frequency</td>
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<td>(\sigma^*)</td>
<td>beam size at interaction point</td>
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<td>F</td>
<td>reduction factor due to crossing angle</td>
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<td>(\varepsilon)</td>
<td>emittance</td>
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<td>(\varepsilon_n)</td>
<td>normalized emittance = (\varepsilon\gamma\beta)</td>
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<td>(\beta^*)</td>
<td>beta function at IP</td>
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Round beams, beam 1 = beam 2

\[ * = \sqrt{\frac{\pi\varepsilon}{n}} \]

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Large Hadron Collider (LHC) - design

- c.m. energy: 14 TeV (pp)
- luminosity: $10^{34}$ cm$^{-2}$s$^{-1}$
- 1.15x10$^{11}$ p/bunch
- 2808 bunches/beam
- ~16 μm IP beam size
- 360 MJ / beam
- dipole field 8.33 T
## LHC peak performance in run 1 (2010-12)

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<th>2010</th>
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<th>2012</th>
<th>Nominal</th>
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<tr>
<td><strong>bunch spacing [ns]</strong></td>
<td>150</td>
<td>50</td>
<td>50</td>
<td>25</td>
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<tr>
<td><strong>no. of bunches</strong></td>
<td>368</td>
<td>1380</td>
<td>1380</td>
<td>2808</td>
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<td><em><em>beta</em> [m]</em>* ATLAS and CMS</td>
<td>3.5</td>
<td>1.0</td>
<td>0.6</td>
<td>0.55</td>
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<tr>
<td><strong>max bunch intensity [protons/bunch]</strong></td>
<td>$1.2 \times 10^{11}$</td>
<td>$1.45 \times 10^{11}$</td>
<td>$1.7 \times 10^{11}$</td>
<td>$1.15 \times 10^{11}$</td>
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<td><strong>normalized emittance [mm.mrad]</strong></td>
<td>~2.0</td>
<td>~2.4</td>
<td>~2.5</td>
<td>3.75</td>
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<td><strong>peak luminosity [cm^{-2}s^{-1}]</strong></td>
<td>$2.1 \times 10^{32}$</td>
<td>$3.7 \times 10^{33}$</td>
<td>$7.7 \times 10^{33}$</td>
<td>$1.0 \times 10^{34}$</td>
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</table>
Huge efforts over last months to prepare for high lumi and pile-up expected in 2012:

- Optimized trigger and offline algorithms (tracking, calorimeter noise treatment, physics objects) → mitigate impact of pile-up on CPU, rates, efficiency, identification, resolution
- In spite of x2 larger CPU/event and event size → we do not request additional computing resources (optimized computing model, increased fraction of fast simulation, etc.)

$Z \rightarrow \mu\mu$ event from 2012 data with 25 reconstructed vertices

Pile up will increase at higher energy → experiments request 25 ns operation in 2015

M. Lamont, IPAC’13
luminosity levelling for LHCb

Luminosity decay in ATLAS and CMS and levelled luminosity at LHCb – typical example from LHC run 1 (C. Gaspar).

Luminosity levelling at around $4 \times 10^{32}$ cm$^{-2}$s$^{-1}$ via transverse separation (with tilted crossing angle)
Long Shutdown 1 – SC circuit consolidation
Following sector by sector cool-down

Powering tests were completed at 8 am on Friday 3 April 2015

Since 15 September 2014:

1566 superconducting circuits commissioned through execution and analysis of more than 10,000 test steps (≈13,800 test steps including re-execution)

172 training quenches on 8 dipole circuits
dipole training for 6.5 TeV

- 154 dipoles per sector, powered in series
- ramp the current until single magnet quenches - “training quench”
- usually quench 3 – 4 other dipoles at the same time
- cryogenics recovery time: 6 – 8 hours

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• assume all 412 firm 3 dipoles need re-training
  – some will require several re-training quenches
• firm 2 (≈5% to 6.5 TeV) and firm 1 (≈1% to 6.5 TeV) will also play a part
• detailed analysis ongoing
  – clearly hundreds further t-quenches required
  – could type test 1 sector in 2015 YETS...

**target energy for 2015: 6.5 TeV**
LHC 2015

• target energy: 6.5 TeV
  – looking good
• bunch spacing: 25 ns
  – strongly favored by experiments (pile-up limit around 50)
• \( \beta^* \) in ATLAS and CMS: 80 to 40 cm

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energy 6.5 TeV (raised from 4 TeV)
• lower quench margins
• lower tolerance to beam loss
• hardware closer to maximum (beam dumps, power converters etc.)

25 ns (decreased from 50 ns)
• electron cloud
• UFOs
• more long range collisions
• larger crossing angle, higher beta*
• higher total beam current
• higher intensity per injection
LHC bunch structure - 2015

- 25 ns bunch spacing
- \( \approx 2800 \) bunches
- nominal bunch intensity \( 1.15 \times 10^{11} \) protons per bunch

1 PS batch (72 bunches)  
1 SPS batch (288 bunches)

Abort gap

26.7 km 2800 bunches

new limits of \( \approx 2 \) PS batches per injection from the injection protection absorbers – will reduce maximum number of bunches to \( \approx 2500 \)
25 ns & electron cloud

possible consequences:
- instabilities, emittance growth, poor lifetime, desorption – bad vacuum
- excessive energy deposition in the cold sectors

electron bombardment of a surface has been proven to reduce drastically the secondary electron yield (SEY) of a material, this technique, known as scrubbing, provides a means to suppress electron cloud build-up

electron cloud significantly worse with 25 ns
crossing angle & long-range collisions
work with a crossing angle to avoid parasitic collisions.

25 ns, 7.5 m
12.5 ns, 3.75 m

separation: 10 - 12 σ

at 25 ns
≈30 long-range collisions per IP
(50 ns: ≈15)

diagram showing the geometric luminosity reduction factor:

\[ F = \frac{1}{\sqrt{1 + \Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x} \]
2015: beta* in IPs 1 and 5

• many things have changed - starting carefully and pushing performance later
• start-up: $\beta^* = 80 \text{ cm} – (\text{very}) \text{ relaxed}$
  – 2012 collimator settings
  – 11 sigma long range separation
  – aperture, orbit stability... checks ongoing
• ultimate in 2015: $\beta^* = 40 \text{ cm}$
  – possible reduction later in the year
2015 commissioning strategy

- low intensity commissioning of full cycle – 8 weeks
- pilot physics – low number of bunches
- special physics run: LHCf and luminosity calibration
- scrubbing for 50 ns
- intensity ramp-up with 50 ns
  - characterize vacuum, heat load, electron cloud, losses, instabilities, UFOs, impedance
- scrubbing for 25 ns
- ramp-up 25 ns operation with relaxed beta*
- possibly commission lower beta*
- 25 ns operation

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## 2015 Q2

### Timeline:

- **April 5th:** First beam
- **June 3rd:** First stable beam
- **Scrubbing for 50 ns:** June 23rd

### Schedule:

- **8 weeks beam commissioning**
- **Pilot physics** – up to at least 40 bunches per beam
- **5 days special physics at beta* = 19 m** (VdM, LHCf, TOTEM & ALFA)
- **Start technical stop** – 15th June

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2015 milestones so far

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<th>circulating beam</th>
<th>Sunday 5\textsuperscript{th} April</th>
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<tr>
<td>ramp to 6.5 TeV</td>
<td>Friday 10\textsuperscript{th} April</td>
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<td>first 13 TeV collisions</td>
<td>Wednesday 20\textsuperscript{th} May</td>
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<td>first “Stable beams”</td>
<td>Wednesday 3\textsuperscript{rd} June</td>
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working throughout with:
- probes (5e9 protons per bunch) or
- 1 or 2 nominal bunches (1.2e11 protons per bunch)

THIS IS NOT BAD!

M. Lamont
6.5 TeV for the first time
# Q3/Q4 2015

## July

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**Scrubbing for 25 ns operation**

## August

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**Intensity ramp-up with 50 ns beam**

## September

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**Intensity ramp-up with 25 ns beam**

**Scrubbing for 25 ns**

## October

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**Special physic run**

## November

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**TS3 setup**

## December

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**End physics [06:00]**

**Technical stop**

**Xmas**
Run 2 impressions till now

• *it’s not a new machine*
  – a lot of lessons learnt from Run 1
• excellent and improved system performance
  – beam Instrumentation, transverse feedback, RF, collimation, injection and beam dump systems, vacuum, machine protection
• improved software & analysis tools
• experience!
• magnetically reproducible as ever, excellent optics
• **behaving well at 6.5 TeV**
  – only one additional training quench so far
• operationally under control
  – injection, ramp, squeeze, de-squeeze

still have to face the intensity ramp-up
• UFOs, e-cloud, vacuum, beam induced heating, instabilities
optics $\beta^* = 40$ cm – before correction

$\sigma = \sqrt{\varepsilon \beta}$

Peak $\beta$ beating of $\approx 120\%$
slightly lower $\beta$ beating in 2015 (IP2 not squeezed)
$\Delta \beta / \beta$ vs $\beta^*$ after local corrections - 2015 vs 2012

LHCB1 6.5TeV

LHCB2 6.5TeV

$\Delta \beta / \beta_x$

$\Delta \beta / \beta_y$

R. Tomas

15% $\beta$ beating for beam 1 horizontal
two warm cleaning insertions, 3 collimation planes

IR3: Momentum cleaning
1 primary (H)
4 secondary (H)
4 shower abs. (H,V)

IR7: Betatron cleaning
3 primary (H,V,S)
11 secondary (H,V,S)
5 shower abs. (H,V)

local cleaning at triplets
8 tertiary (2 per IP)

passive absorbers for warm magnets
physics debris absorbers
transfer lines (13 collimators)
injection and dump protection (10)

total of 108 collimators
(100 movable);
two jaws (4 motors) per collimator!

S. Redaelli
Novel features of collimation system – BPM equipped tertiary collimators, automatic beam based set-up, …
- multiple loss events after a short time at 6.5 TeV compatible with micron-size particles falling into the beam
  - loss patterns point to a specific position in the middle of a dipole magnet
  - quenched twice, numerous BLM triggered dumps...
aperture restriction in 15R8

ULO (Unidentified Lying Object)

- aperture restriction measured at injection and 6.5 TeV
- presently running with orbit bumps
  - -3 mm in H, +1 in V, to optimize available aperture
  - aperture probably not limiting for operation
- behaviour with higher intensities and bunch trains still unknown
- MUFOs went away for several weeks, but returned in mid-June
UFOs in 15R8 back ?!

Dump 1: 5.1 TeV with two bunches
Dump 2: 4.3 TeV with one bunch

somewhat worrying
LHC strategy against electron cloud

1) warm sections (20% of circumference) coated by TiZrV getter developed at CERN; low secondary emission

2) outer wall of beam screen (at 4-20 K, inside 1.9-K cold bore) has sawtooth surface (30 μm over 500 μm) to reduce photon reflectivity to ~2% so that photoelectrons are only emitted from outer wall & confined by dipole field

3) pumping slots in beam screen are shielded to prevent electron impact on cold magnet bore

4) rely on surface conditioning (‘scrubbing’)
evolution of secondary emission yield (lab meas.)

- Cu as received
- Cu partially scrubbed
- Cu fully scrubbed
- Contribution of secondaries to $\delta$
- Contribution of reflected electrons to $\delta$

Primary Energy (eV)

yield

$\delta$
**Goal:** accumulate $e^-$ dose on the beam chambers to mitigate e-cloud effects with 50 ns and 25 ns beams

**Strategy:** gradually increase the $e^-$ flux (50 ns $\rightarrow$ 25 ns $\rightarrow$ doublets) while keeping under control vacuum, heat loads and beam degradation.
Goal: accumulate e⁻ dose on the beam chambers to mitigate e-cloud effects with 50 ns and 25 ns beams

Strategy: gradually increase the e⁻ flux (50 ns → 25 ns → doublets) while keeping under control vacuum, heat loads and beam degradation
**Goal:** accumulate $e^-$ dose on the beam chambers to mitigate e-cloud effects with 50 ns and 25 ns beams

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**Strategy:** gradually increase the $e^-$ flux (50 ns $\rightarrow$ 25 ns $\rightarrow$ doublets) while keeping under control vacuum, heat loads and beam degradation

---

### Graphical Data

- **50 ns beam**
  - Approximately 1400 bunches
  - $1.7 \times 10^{11}$ p/b

- **25 ns beam**
  - Approximately 2800 bunches
  - $1.15 \times 10^{11}$ p/b

- **Doublet beam**
  - Approximately 900 doublets
  - $0.7 \times 10^{11}$ p/b

---

G. Iadarola, G. Rumolo
last 5 days: LHC Scrubbing Run at 450 GeV

- **Thursday**: Scrubbing with 25 ns beams, trains of 24 bunches: 
  - 698b. in beam 1,
  - 444b. in beam 2

- **Friday**: then moved to trains of 48 bunches

- **Monday**: trains of 36 bunches
  - 1020
  - 870

- **Tuesday**: trains of 36 bunches
  - 1200
  - 1177

G. Rumolo, G. Iadarola
scrubbing - heat load on arc beam screens

50 ns scrubbing  25 ns scrubbing

switching to 25 ns is the key for efficient scrubbing, although it makes beam operation more challenging!!!
beam observations: coherent e-cloud instabilities

due to e-cloud, the 25 ns beam often unstable at injection (mainly in the vertical plane)

recipe to accumulate 25 ns beam in LHC:

- high chromaticity settings at injection ($Q'_{H,V} \approx 15$), but trim $Q'_{H,V} \approx 10$ later to improve beam lifetime
- octupoles (knob value=-1.5)
- high damper gain

steady improvement fill after fill

- Beam 1 (which has more accumulated dose) hardly showed any sign of coherent instability at injection in the last fills
25 ns beams stored in the LHC still show a strong degradation

- transverse emittance blow up along batches and from batch to batch
- beam 2 worse than beam 1

G. Rumolo, G. Iadarola
first doublet beams in the LHC
**Two scrubbing runs:** Week 26 (followed by 50 ns operation), Weeks 31-32 (followed by 25 ns operation)

<table>
<thead>
<tr>
<th>Week</th>
<th>April</th>
<th>May</th>
<th>June</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo</td>
<td>14</td>
<td>18</td>
<td>22</td>
</tr>
<tr>
<td>Tu</td>
<td></td>
<td>19</td>
<td>Whit</td>
</tr>
<tr>
<td>We</td>
<td>16</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td>Th</td>
<td>17</td>
<td>21</td>
<td>25</td>
</tr>
<tr>
<td>Fr</td>
<td>15</td>
<td>23</td>
<td>26</td>
</tr>
<tr>
<td>Sa</td>
<td>13</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>Su</td>
<td>6</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

**Setup time mainly for injection and ADT**

- Scrubbing for 50 ns operation
- Scrubbing with 25 ns
- Special physics run
- Setup
- Scrubbing with 50 ns

**July**

- Leap second 1

**August**

- Scrubbing with doubles
- Tests with 25 ns at 6.5 TeV
- Intensity ramp-up with 25 ns beam

**September**

- Intensity ramp-up with 50 ns beam
2015: ATLAS and CMS performance

- conservative beta* to start
- nominal bunch population
- reasonable emittance into collisions
- assume same machine availability as 2012

<table>
<thead>
<tr>
<th></th>
<th>Nc</th>
<th>Beta *</th>
<th>ppb</th>
<th>EmitN</th>
<th>Lumi [cm⁻²s⁻¹]</th>
<th>Days (approx)</th>
<th>Int lumi</th>
<th>Pileup</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 ns</td>
<td>1300</td>
<td>80</td>
<td>1.2e11</td>
<td>2.5</td>
<td>4.8e33</td>
<td>21</td>
<td>≈1 fb⁻¹</td>
<td>25</td>
</tr>
<tr>
<td>2015.1</td>
<td>2448</td>
<td>80</td>
<td>1.2e11</td>
<td>3.1</td>
<td>7.1e33</td>
<td>35</td>
<td>≈4 fb⁻¹</td>
<td>21</td>
</tr>
<tr>
<td>2015.2</td>
<td>2448</td>
<td>40</td>
<td>1.2e11</td>
<td>3.1</td>
<td>1.2e34</td>
<td>30</td>
<td>≈5 fb⁻¹</td>
<td>35</td>
</tr>
</tbody>
</table>

official luminosity target for the year was 10 fb⁻¹ now on the challenging side – revised estimate 5-10 fb⁻¹
**Run 2**

- **EYETS** – Extended Year End Technical Stop – 19 weeks – CMS pixel upgrade
- **Mid-year 2018 stop will be pushed towards year end (not yet official?)**
Run 2 performance

- aim to start 2016 in production mode
  - 6.5 TeV, machine scrubbed for 25 ns operation
  - $\beta^* = 40$ cm in ATLAS and CMS
  - new injection protection absorbers – full injection
  - peak lumi limited to $1.7 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ by inner triplets

<table>
<thead>
<tr>
<th>Year</th>
<th>Peak lumi $10^{34} \text{cm}^{-2}\text{s}^{-1}$</th>
<th>Days proton physics</th>
<th>Approx. int lumi [fb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>1.2</td>
<td>70</td>
<td>5 - 10</td>
</tr>
<tr>
<td>2016</td>
<td>1.5</td>
<td>160</td>
<td>35</td>
</tr>
<tr>
<td>2017</td>
<td>1.7</td>
<td>160</td>
<td>45</td>
</tr>
<tr>
<td>2018</td>
<td>1.7</td>
<td>40</td>
<td>10</td>
</tr>
</tbody>
</table>
LHC roadmap: 20-yr schedule beyond LS1

LS2  starting in 2018 (July)  =>  18 months + 3 months BC
LS3  LHC: starting in 2023  =>  30 months + 3 months BC
Injectors: in 2024  =>  13 months + 3 months BC

(Extended) Year End Technical Stop: (E)YETS

30 fb⁻¹

Q1  | Q2  | Q3  | Q4  | Q1  | Q2  | Q3  | Q4  | Q1  | Q2  | Q3  | Q4  | Q1  | Q2  | Q3  | Q4  | Q1  | Q2  | Q3  | Q4  | Q1  | Q2  | Q3  | Q4  | Q1  | Q2  | Q3  | Q4  | Q1  | Q2  | Q3  | Q4

LHC Injectors: YETS

Run 2 - LS 2 - Run 3

2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028
Q1  | Q2  | Q3  | Q4  | Q1  | Q2  | Q3  | Q4  | Q1  | Q2  | Q3  | Q4  | Q1  | Q2  | Q3  | Q4  | Q1  | Q2  | Q3  | Q4  | Q1  | Q2  | Q3  | Q4  | Q1  | Q2  | Q3  | Q4  | Q1  | Q2  | Q3  | Q4

LHC Injectors: YETS

LS 3 - Run 4 (HL-LHC)

300 fb⁻¹

2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035
Q1  | Q2  | Q3  | Q4  | Q1  | Q2  | Q3  | Q4  | Q1  | Q2  | Q3  | Q4  | Q1  | Q2  | Q3  | Q4  | Q1  | Q2  | Q3  | Q4  | Q1  | Q2  | Q3  | Q4  | Q1  | Q2  | Q3  | Q4  | Q1  | Q2  | Q3  | Q4

LHC Injectors: LS 4

Run 5 (HL-LHC) - LS 5

3'000 fb⁻¹

F. Bordry
• 3000 fb\(^{-1}\) delivered in the order of 10 years
• high “virtual” luminosity with levelling anticipated
• challenging demands on the injector complex
  – major upgrades foreseen in LS2

\[ L [10^{34} \text{ cm}^{-2}\text{s}^{-1}] \]

- no leveling w/ peak \(2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}\)
- leveling at \(5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
- nominal

\[ t [\text{h}] \]

\[ 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]

levelled luminosity

pile-up \(\approx 140\)

3 fb\(^{-1}\) per day

\(\approx 250\) fb\(^{-1}\) /year
the technical trigger for the upgrade: radiation damage of final triplet quadrupoles

![Peak dose longitudinal profile](image)

- **Q2**: 27 MGy
- **Cold bore insulation**: \(\approx 35\) MGy

**Graph Details**
- **7+7 TeV proton interactions**
- **IT quadrupoles**
- **MCBX-1**
- **MCBX-2**
- **MQSX**
- **MCTX nested in MCBX-3**
- **MCBXSX**

**Axes**
- **Y-axis**: Peak dose [MGy / 300 fb\(^{-1}\)]
- **X-axis**: Distance from IP [m]

L. Rossi
technology transition: $Nb-Ti \rightarrow Nb_3Sn$
1. New quadrupole triplet based on Nb$_3$Sn (12 T at coil) 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: 11-T Nb$_3$Sn dipole

→ more than 1.2 km of LHC
→ plus technical infrastructure (e.g. Cryo and Powering)

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

O. Brüning, L. Rossi
FNAL: $Nb_3Sn$ dipole demonstrators

MBHSP02 (1 m) passed 11 T field during training at 1.9 K with $I = 12080$ A on 5 March 2013
squeeze in ATLAS: LHC vs. HL-LHC

<table>
<thead>
<tr>
<th></th>
<th>$\beta_{\text{triplet}}$</th>
<th>sigma triplet</th>
<th>$\beta^*$</th>
<th>sigma*</th>
</tr>
</thead>
<tbody>
<tr>
<td>nominal</td>
<td>$\sim 4.5$ km</td>
<td>1.5 mm</td>
<td>55 cm</td>
<td>17 $\mu$m</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>$\sim 20$ km</td>
<td>2.6 mm</td>
<td>15 cm</td>
<td>7 $\mu$m</td>
</tr>
</tbody>
</table>
Luminosity loss due to crossing angle is related to the effective increase of the transverse beam size, $\sigma \rightarrow \sigma \sqrt{1 + \phi^2}$.

**Geometric luminosity loss** as a function of the Piwinski angle.

\[ \phi \equiv \frac{\theta_c \sigma_z}{2\sigma_x} \]

Piwinski angle
“Crab-crossing” configuration in the crossing plane
HL-LHC compact crab-cavity prototypes

LARP-BNL
LARP-ODU-JLAB
Uni.Lancaster-CI-CERN
crab cavity test results: RF dipole > 5 MV

Goal is 3.3 MV
ΔV > 5 MV would be an asset

J. Delayen, L. Rossi
Large Hadron electron Collider (LHeC)

RR LHeC: new ring in LHC tunnel, with bypasses around experiments

ERL LHeC: recirculating linac with energy recovery

e-/e+ injector 10 GeV, 10 min. filling time

At 2012 CERN-ECFA-NuPECC LHeC workshop ERL-LHeC was selected as baseline (RR LHeC issues: HL-LHC schedule, tunnel work, interference)
LHeC CDR published in

http://cern.ch/lhec

LHeC Study Group


About 150 Experimentalists and Theorists from 50 Institutes

Thanks to all and to
CERN, ECFA, NuPECC

~600 pages
two 10-GeV SC linacs, 3-pass up, 3-pass down; 6.4 mA, 60 GeV e-’s collide w. LHC protons/ions

(C=1/3 LHC allows for ion clearing gaps)

A. Bogacz, O. Brüning, M. Klein, D. Schulte, F. Zimmermann, et al
<table>
<thead>
<tr>
<th>parameter [unit]</th>
<th>( e^- )</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>species</td>
<td></td>
<td></td>
</tr>
<tr>
<td>beam energy (/nucleon) [GeV]</td>
<td>60</td>
<td>7000</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>bunch intensity (nucl.) ([10^{10}])</td>
<td>0.1 → 0.4</td>
<td>17 → 22</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>6.4 → 25.6</td>
<td>860 → 1110</td>
</tr>
<tr>
<td>normalized rms emittance [µm]</td>
<td>50 → 20</td>
<td>3.75 → 2.5</td>
</tr>
<tr>
<td>geometric rms emittance [nm]</td>
<td>0.43 → 0.17</td>
<td>0.50 → 0.34</td>
</tr>
<tr>
<td>IP beta function ( \beta_{x,y} ) * [m]</td>
<td>0.12 → 0.10</td>
<td>0.10 → 0.05</td>
</tr>
<tr>
<td>IP rms spot size [µm]</td>
<td>7.2 → 4.1</td>
<td>7.2 → 4.1</td>
</tr>
<tr>
<td>lepton ( D ) &amp; hadron ( \xi )</td>
<td>6 → 23</td>
<td>0.0001 → 0.0002</td>
</tr>
<tr>
<td>hourglass reduction factor ( H_{hg} )</td>
<td></td>
<td>0.91 → 0.80</td>
</tr>
<tr>
<td>pinch enhancement factor ( H_D )</td>
<td></td>
<td>1.35</td>
</tr>
<tr>
<td>luminosity/nucl. ([10^{33}\text{cm}^{-1}\text{s}^{-1}])</td>
<td></td>
<td>1.3 → 14.4</td>
</tr>
</tbody>
</table>
**Higgs physics at an LHeC**

**h-e Higgs-boson production and decay,**
precision measurements of the **$H$–$bb$ coupling** in **$WW$–$H$ production**

M. Klein and H. Schopper, CERN Courier June 2014
LHC Run 2 is looking good at 6.5 TeV
- impressive progress so far
- fabulous job done in LS1 and during powering tests
- lot of lessons learnt in Run 1, not a “new machine”

next challenge - higher intensity and e-cloud (ongoing!)

sound fundamentals, no show-stoppers for the moment
- some irritants – resolution cost time

2015 will be a short year for proton physics but lay foundations for production for the rest of Run 2

it takes a remarkable effort by a large number of teams to prepare and exploit the LHC
Conclusions – HL-LHC

- LHC Injector Upgrade and High-Luminosity LHC Upgrade will increase annual integrated luminosity by factor 10
- New ingredients: a few tens of novel \( Nb_3Sn \) quadrupoles and dipoles (11-12 T peak field), novel compact crab cavities, SC link, luminosity leveling, ...
- LHC exploitation until \( \approx 2036 \), goal: 3000 fb\(^{-1}\)
- Proposed option of Large Hadron electron Collider (LHeC) running concurrently with HL-LHC

HL-LHC will prepare the technology for future proton colliders of even higher energy
RESTART THE ONE ON THE LEFT. IT’S LESS COMPLICATED.

LARGE HADRON COLLIDER

THE ECONOMY

seen on the internet
appendix
LHC Injector Upgrade (LS2) – 72 b trains

<table>
<thead>
<tr>
<th>25 ns</th>
<th>$N_b \ [10^{11} \text{ p/b}]$</th>
<th>$\varepsilon \ [\mu\text{m}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>achieved in 2012</td>
<td>1.2</td>
<td>2.6</td>
</tr>
<tr>
<td>HL-LHC goal</td>
<td>2.3</td>
<td>2.1</td>
</tr>
</tbody>
</table>
LIU-BCMS scheme (48 bunch trains)

Linac4 – BCMS scheme – 2GeV – 25ns

- PSB brightness: 5.8e–13μm/(p/b)
- PS bunch splitting factor: 6
- PS bunch length: 135ns
- PS momentum spread: 1.1e–03
- PS injection energy: 2GeV
- LHC number of bunches: 2592

higher beam brightness than HL-LHC target
LHC beam generation in the PS

Standard scheme:
(maximum number of bunches in LHC)

Triple splitting up to 2013 at 1.4 GeV
(moved to 2.5 GeV after LS1)

BCMS scheme:
(less bunches in LHC but higher brightness)

PS batches with 72 (36) bunches for 25ns (50ns)

Y. Papaphilippou
"Doublet" scrubbing beam - generation in the SPS

Scrubbing with 25 ns beam allowed to lower the SEY of the dipole chambers well below the multipacting threshold for 50 ns \(\rightarrow\) e-cloud free operation with 50 ns beams

\(\rightarrow\) Can we go to lower bunch spacing (e.g. 12.5 ns) to scrub for 25 ns operation?

- Due to RF limitations in the PS it is impossible to inject bunch-to-bucket into the SPS with spacing shorter than 25 ns
- An alternative is to inject long bunches into the SPS and capturing each bunch in two neighboring buckets obtaining a \((5+20)\) ns “hybrid” spacing

Non adiabatic splitting at SPS injection

G. Iadarola
Scrubbing with 25 ns beam allowed to lower the SEY of the dipole chambers well below the multipacting threshold for 50 ns \( \rightarrow \) e-cloud free operation with 50 ns beams

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Non adiabatic splitting at SPS injection

- Doublet scrubbing beam - generation in the SPS

G. Iadarola
New Optics: Achromatic Telescopic Squeeze

- Small $\beta^*$ is limited by aperture but also by optics matching & flexibility, chromatic effects, spurious dispersion from X-angle,..

- A novel optics scheme (ATS) reaches un-precedent $\beta^*$ w/o chromatic limit based on a generalized squeeze involving 50% of the ring

Beam sizes [mm] @ 7 TeV from IR8 to IR2 for typical ATS “pre-squeezed” optics (left) and “telescopic” collision optics (right)

The new IR is sort of 8 km long!
"crab kissing" scheme

Illustration of "crab kissing" configuration for luminosity levelling in the plane orthogonal to the crossing plane. A newly proposed scheme based on additional crab cavities deflecting the two beams in the non-crossing plane in anti-phase; this scheme does not reduce the longitudinal extent of the luminous region during the levelling process [S. Fartoukh, Phys. Rev. ST Accel. Beams 17, 111001 (2014)]