The LHC: Status and Outlook

Islamabad

October 15, 2009

Sergio Bertolucci

CERN
Our agony and ecstasy: the LHC

- Status
- Schedule
- Commissioning plans
- Early Physics
- The future
The LHC repairs in detail

1. 14 quadrupole magnets replaced
2. 39 dipole magnets replaced
3. 54 electrical interconnections fully repaired. 150 more needing only partial repairs
4. Over 4 km of vacuum beam tube cleaned
5. A new longitudinal restraining system is being fitted to 50 quadrupole magnets
6. Nearly 900 new helium pressure release ports are being installed around the machine
7. 6500 new detectors are being added to the magnet protection system, requiring 250 km of cables to be laid
Magnet protection and anchoring

- DN200 on dipoles 732/1344 installed
- DN200 on ITs 24/24 installed
- SSS anchoring 104/104 installed
- DN160 on SAM 92/96 installed

First School on LHC Physics
Magnet protection and anchoring

DN 200 on DFBL
5/5 installed

DN 230 on DFBA HCM
40/64 installed

DN 200 on DFBA LCM
7/9 installed

DN 200/100 on DFBM link
25/29 installed

DFBA anchoring
6/6 installed
DSLC protection

DN160 on DSLC
2/2 installed

DN160 on DSLC
2/2 installed

DN200 on DSLC
2/2 installed
Enhanced QPS
Role of the Enhanced QPS System

To protect against the new ‘problems’ discovered in 2008:
- The Aperture-Symmetric Quench feature in the Main Dipoles and
- Defective Joints in the Main Bus-bars, inside or in-between the magnets.

QPS Upgrade also allows:

- Precision measurements of the joint resistances at cold (sub-nΩ range) of every Busbar segment. This will allow complete and continuous mapping of the splice resistances (the bonding between the s.c. cables)
- To be used as the basic monitoring system for future determination of busbar resistances at warm (min. 80 K), to measure regularly the continuity of the copper stabilizers.
The nQPS project

DQAMG-type S controller board
1 unit / crate, total 436 units

DQQBS board for busbar splice detection
5 such boards / crate, total 2180 units

DQQDS board for SymQ detection
4 boards / crate, total 1744

DQTE board for ground voltage detection
(total 1308 boards, 3 units/crate)

DQLPUS Power Packs
2 units / rack (total 872 units)

DQLPU-type S crate
total 436 units

‘Internal’ and ‘external’ cables for sensing, trigger, interlock, UPS power, uFIP (10'400 + 4'400)

2 UPS Patch Panels / rack & 1 Trigger Patch Panel / rack
total 3456 panel boxes
Sc cable Splices
missing electrical contact on at least one side of the connection

lack of solder within the joint
# Number of splices in RB, RQ circuits

<table>
<thead>
<tr>
<th>circuit</th>
<th>splice type</th>
<th>splices per magnet</th>
<th>number of units</th>
<th>total splices</th>
</tr>
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<tbody>
<tr>
<td>RB</td>
<td>inter pole</td>
<td>2</td>
<td>1232</td>
<td>2464</td>
</tr>
<tr>
<td>RB</td>
<td>inter aperture</td>
<td>1</td>
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<td>1232</td>
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<td>RB</td>
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<td>4928</td>
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<tr>
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<td>1232</td>
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<tr>
<td>RB</td>
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<tr>
<td>RQ</td>
<td>Inter pole</td>
<td>6</td>
<td>394</td>
<td>2364</td>
</tr>
<tr>
<td>RQ</td>
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<td>1576</td>
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<td>4</td>
<td>1686</td>
<td>6744</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td></td>
<td></td>
<td>23912</td>
</tr>
</tbody>
</table>

Mike Koratzinos - Splices update
Methods for testing splices

- The methods we have at our disposal to measure spice resistances (either directly or indirectly) are four:
  - The ‘Keithley’ method
  - The ‘QPS snapshot’ method
  - The calorimetric method
  - *The ultrasound method*
Decision: Beam Energy at Start-up (August 2009)

- **Avoidance of thermal runaway** (during a quench)
  - **Maximum safe current flowing in joint** (beam energy)
    - Electro-magnetic, thermo-dynamic simulations
    - Probability of simultaneous quench in magnet and joint (?beam losses FLUKA)
    - Quench propagation time from the magnet to the joint
  - **Resistance of the copper stabilizers** (measurements)
  - **Quality of the copper in the sc cable and the Cu stabiliser** (RRR)
  - **Energy extraction time** (modification of dump resistors quads and dipoles)
  - **Gaseous cooling of the joint?**

**Choices**
- Stick to 5TeV/beam and repair all necessary Cu stabilizer joints => warm up of several sectors and delay start of physics till 2010
- Aim for **maximum safe energy** with no additional repairs on CU stabilizers => allows us to gain experience up to this maximum energy (accelerator and detectors)
Simultaneous busbar and magnet quench?

**FLUKA Simulations**

- Combined busbar and magnet quench cannot be excluded but is highly unlikely.
- Magnet will quench at a significantly lower level of beam loss than adjacent bus bars (in inter-connects or the empty cryostat):
  - $10^6$ protons sufficient to quench the magnets
  - $10^9$-$10^{10}$ protons required to quench the busbars
- According to the present studies it is very unlikely to quench the busbar only (not observed in these studies)
New RQ dump resistors; preparation was launched immediately
RB: case 1 (instantaneous quench in busbar/magnet)

Quench of RB joint due to beam loss
QPS delay=0 s, RRR\textsubscript{cable}=80, RRR\textsubscript{bus}=100 with self-field, cable without bonding at one bus extremity, no contact between bus stabiliser and joint stabiliser.

- \(\tau=68\) s, adiab.
- \(\tau=68\) s, bus cooling to 1.9 K
- \(\tau=50\) s, adiab.
- \(\tau=50\) s, bus cooling to 1.9 K

Max. safe current [A]

R\textunderscore additional [microOhm]
Thermal propagation time (for case 2)

Experience from HWC for RB quenches at 7-11 kA.

Assume that the joint quenches after half the MB-MB thermal propagation time, so $t_{tQ}=0.5*(70-I_Q/300)$

Maybe possible to get more accurate value from thermal analysis....
RB: case 2 (quench propagation from magnet to busbar)

Quench of RB joint due to warm He
QPS delay=0 s, $RRR_{\text{cable}}=80$, $RRR_{\text{bus}}=100$, with self-field, cable without bonding at one bus extremity, no contact between bus stabiliser and joint stabiliser. $t_{\text{JQ}}=35-I_Q/600$. 

Max. safe current [A]

R_additional [microOhm]

Arjan Verweij, TE-MPE, 23 July 2009

A. Verweij, TE-MPE. 5 Aug 2009, LMC meeting
Decision on Initial Beam Operating Energy
(August 2009)

- Highest measured value of excess resistance ($R_{\text{long}}$) in 5 sectors measured at 300K was $53\mu\Omega$.
- Operating at 7TeV cm with a energy extraction times of 50s, 10s (dipoles and quadrupoles)
  - Simulations show that resistances of $\leq 120\mu\Omega$ are safe from thermal runaway under conservative assumed conditions of worst case conditions for the copper quality (RRR) and no cooling to the copper stabilizer from the gaseous helium.
- Operating at 10TeV cm with a dipole energy extraction time of 68s
  - Simulations show that resistances of $\leq 67\mu\Omega$ are safe from thermal runaway under conservative assumed conditions of worst case conditions for the copper quality (RRR), and with estimated cooling to the stabilizer from the gaseous helium.

**Decision:**
- Operation initially at 7TeV cm (energy extraction time of 50s, 10s) with a safety factor or more than 2 for the worst stabilizers.
  - During this time
    - Monitor carefully all quenches to gain additional information.
    - Continue simulations and validation of simulations by experimentation (FRESCA)
- Then operate at around 10TeV cm.
Since August

- Start of re-establishment of spares situation as it was before the incident
- Helium leak (flexible in the DFBs) in S45, S23, and S81. All repaired
- Super-insulation fire in S67 (minimum damage)
- Magnet/busbar short to earth in S67 (detected and repaired)
LHC Schedule
Cool down status on 14th October 2009
Sector 1-2 splice measurement with the nQPS

Measured Segment Resistances

Normalized to Number of Splices

Splice Resistance statistics

- Gaussian Center: 324pOhm
- Gaussian Std Dev: 52pOhm
- Sum: 848
- Mean: 322pOhm
- Standard Deviation: 61pOhm

A12.RQD/RQF, 2009/09/24, 17:15:00–21:44:11, I_{max} = 2000A
This is the present plan:

- It will almost certainly be modified on a daily/weekly basis, once we start with beam commissioning.

- …BUT we need a plan!
LHC beam commissioning

- Global machine checkout
- Essential 450 GeV commissioning
- Machine protection commissioning 1
- 450 GeV collisions
- Ramp commissioning to 1 TeV
- System/beam commissioning
- Machine protection commissioning 2
- 3.5 TeV beam & first collisions
- Full machine protection qualification
- System/beam commissioning
- Pilot physics

~one month to first collisions

<table>
<thead>
<tr>
<th>Energy</th>
<th>Safe</th>
<th>Very Safe</th>
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<tbody>
<tr>
<td>450</td>
<td>1 e12</td>
<td>1 e11</td>
</tr>
<tr>
<td>1 TeV</td>
<td>2.5 e11</td>
<td>2.5 e10</td>
</tr>
<tr>
<td>3.5 TeV</td>
<td>2.4 e10</td>
<td>probe</td>
</tr>
<tr>
<td>Week</td>
<td>Oct</td>
<td>Nov</td>
</tr>
<tr>
<td>------</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>Mo</td>
<td>28</td>
<td>5</td>
</tr>
<tr>
<td>Tu</td>
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<td>12</td>
</tr>
<tr>
<td>We</td>
<td>HWC</td>
<td>26</td>
</tr>
<tr>
<td>Th</td>
<td>DSO</td>
<td>2</td>
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<tr>
<td>Fr</td>
<td>INJ</td>
<td>9</td>
</tr>
<tr>
<td>Sa</td>
<td>TEST</td>
<td>47</td>
</tr>
<tr>
<td>Su</td>
<td></td>
<td>48</td>
</tr>
</tbody>
</table>

- All dates approximate…
- Reasonable machine availability assumed
Possible evolution

Physics at 3.5 TeV
beta* = 2 m
no crossing angle, 156 bunches

Step up in energy

Ramp, squeeze, ramp to 4-5 TeV
beta* = 2 m
no crossing angle, 156 bunches

Ramp, squeeze at 4-5 TeV
beta* = 2 m
crossing angle, 50 ns
## LHC 2010 – very draft

<table>
<thead>
<tr>
<th>Week</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
</tr>
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<td>Mo</td>
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<td></td>
</tr>
<tr>
<td>Su</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**2009:**
- 1 month commissioning

**2010:**
- 1 month pilot & commissioning
- 3 month 3.5 TeV
- 1 month step-up
- 5 month 4 - 5 TeV
- 1 month ions

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### Calendar

#### 2009:
- **March 3:** 1 month commissioning

#### 2010:
- **April 1:** 1 month pilot & commissioning
- **June 1:** 3 month 3.5 TeV
- **July 1:** 1 month step-up
- **September 1:** 5 month 4 - 5 TeV
- **October 1:** 1 month ions

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**Technical Step**
- **Recommissioning with beam**
- **SPS et al Physics Program**

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**LHC 2009 - 2010**
# Plugging in the numbers with a step in energy

<table>
<thead>
<tr>
<th>Month</th>
<th>OP scenario</th>
<th>Max number bunch</th>
<th>Protons per bunch</th>
<th>Min beta*</th>
<th>Peak Lumi [pb⁻¹]</th>
<th>Integrate d</th>
<th>% nominal</th>
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<tbody>
<tr>
<td>1</td>
<td>Beam commissioning</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2</td>
<td>Pilot physics combined with commissioning</td>
<td>43</td>
<td>3 x 10¹⁰</td>
<td>4</td>
<td>8.6 x 10²⁹</td>
<td>~200 nb⁻¹</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>43</td>
<td>5 x 10¹⁰</td>
<td>4</td>
<td>2.4 x 10³⁰</td>
<td>~1 pb⁻¹</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>156</td>
<td>5 x 10¹⁰</td>
<td>2</td>
<td>1.7 x 10³¹</td>
<td>~9 pb⁻¹</td>
<td>2.5</td>
</tr>
<tr>
<td>5a</td>
<td>No crossing angle</td>
<td>156</td>
<td>7 x 10¹⁰</td>
<td>2</td>
<td>3.4 x 10³¹</td>
<td>~18 pb⁻¹</td>
<td>3.4</td>
</tr>
<tr>
<td>5b</td>
<td>No crossing angle – pushing bunch intensity</td>
<td>156</td>
<td>1 x 10¹¹</td>
<td>2</td>
<td>6.9 x 10³¹</td>
<td>~36 pb⁻¹</td>
<td>4.8</td>
</tr>
<tr>
<td>6</td>
<td>Shift to higher energy: approx 4 weeks</td>
<td></td>
<td></td>
<td></td>
<td>Would aim for physics without crossing angle in the first instance with a gentle ramp back up in intensity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>4 – 5 TeV (5 TeV luminosity numbers quoted)</td>
<td>156</td>
<td>7 x 10¹⁰</td>
<td>2</td>
<td>4.9 x 10³¹</td>
<td>~26 pb⁻¹</td>
<td>3.4</td>
</tr>
<tr>
<td>8</td>
<td>50 ns – nominal Xing angle</td>
<td>144</td>
<td>7 x 10¹⁰</td>
<td>2</td>
<td>4.4 x 10³¹</td>
<td>~23 pb⁻¹</td>
<td>3.1</td>
</tr>
<tr>
<td>9</td>
<td>50 ns</td>
<td>288</td>
<td>7 x 10¹⁰</td>
<td>2</td>
<td>8.8 x 10³¹</td>
<td>~46 pb⁻¹</td>
<td>6.2</td>
</tr>
<tr>
<td>10</td>
<td>50 ns</td>
<td>432</td>
<td>7 x 10¹⁰</td>
<td>2</td>
<td>1.3 x 10³²</td>
<td>~69 pb⁻¹</td>
<td>9.4</td>
</tr>
<tr>
<td>11</td>
<td>50 ns</td>
<td>432</td>
<td>9 x 10¹⁰</td>
<td>2</td>
<td>2.1 x 10³²</td>
<td>~110 pb⁻¹</td>
<td>12</td>
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</table>
New and exciting physics expected at 7TeV cm (3.5 times the energy of the Tevatron)
What do we need to do to match the Tevatron, which aims for 9 fb⁻¹ by 2010? What is the minimum amount of data at a given energy that is needed to make the 2009 physics run useful? (assuming CM energy 8 < s < 10 TeV)
Top quark

- Background to new physics searches – must measure cross-section & properties in data
- Expected Tevatron statistics provide a benchmark:
  - Cross-section statistical precision will then be comparable to other uncertainties
  - High-precision top physics will be underway

\[ \text{ATLAS estimate} \quad \text{Tevatron } \ell+\text{jets w. } 8 \text{ fb}^{-1} \]

\[ \text{Tevatron } \ell\ell\text{bb w. } 8 \text{ fb}^{-1} \]

\[ \text{\ell+jets} \]

\[ \text{\ell\ell\text{bb}} \]

\[ \approx 50 \text{ pb}^{-1}@14 \text{ TeV would match full Tevatron sample} \]
- lose \( \approx \text{factor } 2 \) in cross-section dropping to 10 TeV
- lose \( \approx \text{another factor } 2 \) dropping to 8 TeV

Below 8 TeV samples will be rather small, with a few tens of pb\(^{-1}\)

Catch up with Tevatron with \( s^{1/2} = 8\text{-}10 \text{ TeV} \) and \( \approx 200\text{-}100 \text{ pb}^{-1} \text{ g.d.} \)
Z': Heavy partner of the Z (SSM)

- Very clean experimental signal: $Z' \rightarrow \ell \ell$
- Tevatron 95% CL limit at $m_{Z'} = 1$ TeV

**ATLAS fast simulation**

Needed luminosity for 95%CL exclusion at $m_{Z'} = 1$ TeV:

- $s^{1/2}$: 14 → 10 → 6 TeV
- Lumi: 13 → 30 → 110 pb$^{-1}$
SUSY, an example

- \( \ell + \text{jets} + \text{missing-}E_T \) channel
  - Not most sensitive, but will be usable before inclusive jets + missing-\( E_T \) analysis

- Tevatron limit currently is 380 GeV in this model (\( m_{\tilde{q}} = m_{\tilde{g}} \))
  - plot shows 3 masses above this

- We will be sensitive to a region overlapping with ultimate Tevatron reach

- Below \( E_{\text{cm}} \approx 8 \text{ TeV} \), the sensitivity collapses

---

5\( \sigma \) discovery beyond current Tevatron limits is possible with \( s^{1/2} = 8-10 \text{ TeV} \) and \( \sim 30-15 \text{ pb}^{-1} \text{ g.d.} \)
Higgs 95% CL at LHC GPD, $H \rightarrow$ weak bosons, indicative

**Combined $H \rightarrow WW + H \rightarrow ZZ$: lumi for 95% CL**

<table>
<thead>
<tr>
<th>$m_H$ (GeV/c$^2$)</th>
<th>Luminosity for 95% CL exclusion (fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$HZZ+HW\nu$ (6 TeV)</td>
<td><img src="graph1.png" alt="Graph" /></td>
</tr>
<tr>
<td>$HZZ+HW\nu$ (10 TeV)</td>
<td><img src="graph2.png" alt="Graph" /></td>
</tr>
<tr>
<td>$HZZ+HW\nu$ (14 TeV)</td>
<td><img src="graph3.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

- **Energy** $s^{1/2}$: 14 → 10 → 6 TeV
- **Lumi needed**: 0.1 → 0.2 → 0.6 fb$^{-1}$

**Compare sensitivity to Tevatron with 8 fb$^{-1}$**

- Tevatron expect 1.9σ sensitivity at $m=160$ with 8 fb$^{-1}$ (one expt)

**Massive loss of sensitivity below 6 TeV**

To challenge Tevatron with $s^{1/2} = 8-10$ TeV, we need $\sim 300-200$ pb$^{-1}$ g.d.
Physics reach for $\text{BR}(B_s^0 \to \mu^+\mu^-)$

- as function of integrated luminosity (and comparison with Tevatron)

At $s^{1/2} = 8 \text{ TeV}$, need $\sim 0.3-0.5 \text{ fb}^{-1} \text{ g.d.}$ to improve on expected Tevatron limit

Collect $\sim 3 \text{ fb}^{-1}$ for $3\sigma$ observation of SM value
Heavy Ions: Flow at LHC

- one of the first and most anticipated answers from LHC
  - 2nd RHIC paper: Aug 24, 22k MB events, flow surprise (v_2)
    - Hydrodynamics: modest rise (Depending on EoS, viscosity, speed of sound)
      increase of flow

BNL Press release, April 18, 2005:
Data = ideal Hydro
"Perfect" Liquid
New state of matter more remarkable than predicted – raising many new questions

LHC will either
confirm the RHIC interpretation
(and measure parameters of the QGP EoS)
OR
.................................
Summary of beam commissioning

- First injection test – 24/25 October
- With a bit of luck - first high energy collisions just before Christmas
- Step up in energy would take ~4 weeks physics to physics
- Would start at higher energy with a flat machine before bringing on crossing angle and exploiting 50 ns.
- Interesting times.
Preparations for the Future

Operational Consolidation
1. we have prepared an inventory of
   a) the existing spares and spare components for the LHC
   b) the existing spare components of the LHC infrastructure
   c) Consolidation needed to increase the efficiency of safe
      operation of the machine in the longer term
2. we have prepared a preliminary estimate of the total materials cost
3. In the MTP, we have planned a budget of 25MCHF/year to carry out this programme
4. The time prioritization of the operational consolidation work is being done by Risk Ranking of the inventory. Two passes finished and the “final” ranking in a few weeks
5. The manpower needed to carry out this programme has not yet been identified
How will the next few years develop?

- Through a sequence of long runs alternated to relative long shutdowns

- Initial runs to tune and get to know machine and experiments (7 TeV -> 10 TeV -> 14 TeV)

- Shutdowns to upgrade the energy to 7 TeV (probably in steps, fix known problems, re-train magnets,...), but also to increase luminosity and machine protection (collimation upgrade)

- 200-300 fb\(^{-1}\) is the integrated Luminosity level where the pp experiments expect some aging of the present pixel innermost layer and when new hardware might become necessary

New discoveries will eventually influence this path
The CERN accelerator complex: injectors and transfer

Beam size of protons decreases with energy: area $\sigma^2 \propto 1/E$

Beam size largest at injection, using the full aperture

Simple rational fractions for synchronization based on a single frequency generator at injection

<table>
<thead>
<tr>
<th>machine</th>
<th>circum [m]</th>
<th>relative</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS</td>
<td>628.318</td>
<td></td>
</tr>
<tr>
<td>SPS</td>
<td>6911.56</td>
<td>11 $\times$ PS</td>
</tr>
<tr>
<td>LHC</td>
<td>26658.883</td>
<td>27/7 $\times$ SPS</td>
</tr>
</tbody>
</table>
The CERN accelerators complex upgrade

The LHC-imposed beam brightness ($N_b / \varepsilon_{x,y}$) must be present from the lowest energy on (Liouville’s theorem)

- Beam loss is higher than foreseen: ultimate beam characteristics ($N_b = 1.7 \times 10^{11}$ p/b, $\varepsilon_{X,Y} = 3.5 \text{ mm.mrad}$) cannot be obtained. Nominal $N_b = 1.15 \times 10^{11}$ p/b achieved in the SPS

- Operation is complicated and involves the control of many RF systems: risk of drift and of long duration of repair/re-adjustment

- Reliability is uncertain: many equipments are old (e.g. PS magnets) and used at the limit of their capability
Maximum beam intensity LHC year 1

Design LHC intensity: \(3.23 \times 10^{14}\) protons / beam

1st years, limited by magnet quench / collimation

Maximum beam loss rate \(\sim 10^{-3}\) /s fraction or \(\sim 4 \times 10^{11}\) p/s

Examples for 0.001/s Loss Rate

- It is really the loss rate that matters above a few ms. So what counts is the ratio of loss amount over loss duration (short loss spikes are very dangerous). We get the peak loss rate 0.001/s from:
  - 1% of beam lost in 10 s.
  - 0.1% of beam lost in 1 s.
  - 0.01% of beam lost in 100 ms.
  - 0.001% of beam lost in 10 ms.
- Stick with the official loss rate 0.001/s from now on, adding some evolution.
- Assume 0.002/s is achieved in the first year of LHC operation at 5 TeV, as shown in following slides.

Result: Intensity Limit vs Loss Rate 5 TeV

# bunches: nominal is 2808 bunches, 25 ns spacing

LHC year 1: Important to go in small steps - minimize beam losses. Max. total intensity at 5 TeV roughly \(\sim 1/10\) nominal.

Start of physics run: \(I < 2 \times 10^{13}\) p with intermediate coll. settings

Later: \(I < 5 \times 10^{13}\) p with tight coll. settings.

3.5 TeV intensities could be a bit higher - details remain to be worked out.
Scaling of beam parameters with energy

Baseline beam parameters for $E_b = 5$ TeV have been worked out, discussed and agreed, LPC 7/5/09. Details for 3.5 TeV still need to be defined.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scale Factor 3.5 to 5 TeV</th>
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<tbody>
<tr>
<td>intensity</td>
<td>more critical at high $E$</td>
</tr>
<tr>
<td>emittance</td>
<td>$E^{-1}$</td>
</tr>
<tr>
<td>$\beta^*$</td>
<td>$\sim E^{-1}$ triplet aperture</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$\sim E^{-2}$</td>
</tr>
<tr>
<td>beam-beam tune shift</td>
<td>constant</td>
</tr>
</tbody>
</table>

Luminosity estimates: roughly 2× less at 3.5 TeV compared to 5 TeV. This should be conservative and does not take into account that lower energies are less critical for protection, shorter ramp time and faster turnaround.

Beam-beam tune shift parameter $\xi$ for head-on collisions depends only on intensity (not energy, $\beta^*$):

$$\xi = \frac{\tau_2 N}{\sqrt{\pi} \epsilon_N}$$

$N$ is the number of interacting particles, and $\epsilon_N$ is the normalized emittance at the design emittance.

<table>
<thead>
<tr>
<th>$N$</th>
<th>$\xi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5 \times 10^9$</td>
<td>0.000163</td>
</tr>
<tr>
<td>$4 \times 10^{10}$</td>
<td>0.00130</td>
</tr>
<tr>
<td>$1.15 \times 10^{11}$</td>
<td>0.00374</td>
</tr>
</tbody>
</table>

Nominal LHC: round beams and constant $\epsilon_N$.
Luminosity road map in 2 phases

LHC peak luminosity ($10^{34}$ cm$^{-2}$s$^{-1}$)

- No phase II
- Phase II

- New injectors + IR upgrade, phase 2
- Collimation phase 2
- Linac4+IR upgrade phase 1

- sLHC
- LHC

Year:
- 2010
- 2012
- 2014
- 2016
- 2018
- 2020
- 2022
Phase I upgrade brings us to end of the LHC mandate

Linac4 higher performance:

Space charge decreased by a factor of 2 in the PSB, factor 2 gain in $\beta \gamma^2$

⇒ potential to double the beam brightness at constant tune shift and fill the PS with the LHC beam in a single pulse

✓ Linac-4 approved and construction work has started
✓ Allows to increase the LHC current to “ultimate” which is 2.3 times the nominal
✓ New Inner Triplet focusing magnets. Larger aperture, allows $\beta^*$ of 0.25 m, L x 2 !
✓ The expectation is that these two improvements will allow a ramp-up to 3 x nominal Luminosity, 120-180 fb^{-1} /year
**Why should we go beyond 600 fb\(^{-1}\): sLHC?**

10 times more statistics, is there a physics motivation for 3000 or more fb\(^{-1}\)?

Whatever the decision will be, in 8-9 years from now the pp detectors will need a major upgrade; some components like the Inner Detectors will be suffering from aging and radiation damage.
The lesson from the Tevatron is that once data are available, the experimental ingenuity can deliver the "impossible" (M. Mangano)

..but it also says that it takes time
Beam at sLHC injection shall have up to twice the ultimate brightness
\((N_b = 3.4 \times 10^{11} \text{ p/b, } \varepsilon_{X,Y} = 3.7 \text{ mm.mrad})\)

⇒ Simple operating mode
⇒ Margin in beam performance
⇒ Margin in equipment ratings
⇒ Advantage of shorter LHC filling time

✓ Linac4 project has started, ready in 2014 for phase I
Peak Luminosity also depends on the IR properties

\[ L = \frac{N_b^2 n_b f_r \gamma}{4 \pi \varepsilon_n \beta^*} F \]

- \( N_b \) number of particles per bunch
- \( n_b \) number of bunches
- \( f_r \) revolution frequency
- \( \varepsilon_n \) normalised emittance
- \( \beta^* \) beta value at Ip
- \( F \) reduction factor due to crossing angle

**F** beam-beam tune (\( \Delta Q \)) shift proportional to F and beam brightness (beam stability)

**F** = \[ \frac{1}{\sqrt{1 + \frac{\phi^2}{2 \sigma_x^2}}} \]

\( \phi \equiv \frac{\theta_c z}{\sigma_x} \) “Piwinski angle”

- \( N_b, \varepsilon_n \) injector chain
- \( \beta^* \) LHC insertion
- \( F \) beam separation schemes
- \( n_b \) electron cloud effect

nominal LHC
crossing angle reduces the luminosity AND the beam-beam tune shift
effective beam size \( \sigma \rightarrow \sigma/F \)
Crossing angle: the LHC solution!

~30 long range beam beam interaction per IP

tune shift would increase 30 times without crossing angles

To increase Luminosity choose between head-on collisions, large beam brightness, minimize transverse emittance .... or a combination of them ...

... but minimize beam beam tune shift $\Delta Q_{bb}$
Several solutions still possible!!

**Large Piwinski angle (LPA)**

- Larger-aperture triplet magnets
- 50ns, flat intense bunches, $\theta_c \sigma_z >> 2 \sigma_x$

**Low transverse emittance (LE)**

- Stronger triplet magnets
- Constraint on new injectors, $\gamma \epsilon \sim 1-2 \mu m$

**Early separation + crab cavities (ES)**

- D0 dipole, stronger triplet magnets
- Small-angle crab cavity
- Dipoles inside the experiments

**Full crab crossing (FCC)**

- Stronger triplet magnets
- Small-angle crab cavity
- Crab cavities with 60% higher voltage

*First School on LHC Physics*
Possible Luminosity Upgrade road map

nominal?

make LHCb and ALICE transparent

increase bunch intensity (to maximal 1.7-2.4 x 10^{11})

IR-1: reduce $\beta^*$ to 25 cm & increase $\theta_c$

IR-2: reduce $\beta^*$ to <15 cm & install local crab cavities

50 ns spacing & increase bunch intensity to 5x10^{11}, flat shape

F. Zimmerman 2009

First School on LHC Physics
**Luminosity life time**

Very inefficient way to use the beam, very difficult experimental environment at the very beginning of the fill, short cycles (5-6 hours)

Expected very fast decay of luminosity (few hours) dominated by proton burn-off in collisions

\[ \tau_{eff} = \frac{N_b n_b}{n_{IP} \hat{L} \sigma_{tot}} \]
**The solution: Luminosity Leveling**

Flat luminosity profile (~80 events per crossing, ~10 h fill lifetime for leveling with crossing angle)

Optimize Integrated Luminosity vs. Peak Luminosity

**Luminosity leveling** (changing dynamically $\theta_c$, $\beta^*$ or $\sigma_z$ in store to keep luminosity constant) becomes a powerful strategy to reduce event pile up in the detector & peak power deposited in IR magnets

**Leveling with crossing angle has distinct advantages:**
- increased average luminosity if beam current not limited
- operational simplicity

**Natural option for early separation or crab cavities**

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Planning the future

- Workshop on new injectors (Chamonix 2010?)
- Tests/studies on the different IP schemes
- Tests on the luminosity leveling
- ......
....and for the experiments

- Improve detector and background modeling, based on the real LHC environment experience
- Minimize cavern background (new TAS, forward shielding)
- Assess and understand detectors performances as luminosity grows
- Improve the trigger capabilities to cope with ~ factor 5-10 higher amount of hard collisions, in particular at level 1 (µseconds scale)
- Build new low mass beam pipes
- Prepare to rebuild the inner detectors (tracking), mostly using silicon technology
To conclude

- By year 2013, **experimental results** will be dictating the agenda of the field.
- Early discoveries will greatly accelerate the case for the construction of the next facilities (sLHC, Linear Collider, \( \nu \)-factory …)
- No time to idle, no time to be shy!
Very exciting years are ahead of us!

LHC ring:
27 km circumference

CMS

ALICE

LHCb

ATLAS