Machine Protection &
LHC Beam Operation

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Outline

1. Introduction
2. LHC beam is a dangerous beam
3. LHC Beam Operation /Machine protection
4. Conclusions
CERN Accelerator Complex

- Large Hadron Collider (LHC)
- Super Proton Synchrotron (SPS)
- Proton Synchrotron (PS)
LHC milestones

- August 2008: First Injection
- September 10, 2008: Both beams circulating
- November 29, 2009: Beams back
- October 14, 2010: 248 bunches
- November, 2011: Higgs candidates
- February, 2012: highest energy

- September 19, 2008: Incident
- March 30, 2010: First collisions at 3.5 TeV
- November 2010: Ion run
- June 28, 2011: 1380 bunches
- July, 2012: 5 fb⁻¹
A schematic view of the **26.7 km-long LHC ring** composed of 8 arcs and 8 long straight sections (LSSs)

A **two-in-one magnet design**, the counter-rotating proton beams circulate in separated vacuum chambers and **cross each other** only in the experimental interaction regions.
LHC Parameters

- LHC parameters for proton operation 2012

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy [TeV]</td>
<td>7.0</td>
<td>3.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Peak luminosity [$10^{33}$ cm$^{-2}$s$^{-1}$]</td>
<td>10</td>
<td>3.6</td>
<td>6.6</td>
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<tr>
<td>Stored energy [MJ]</td>
<td>362</td>
<td>112</td>
<td>115</td>
</tr>
<tr>
<td>Bunch intensity [$10^{10}$ p]</td>
<td>11.5</td>
<td>14.5</td>
<td>15</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2808</td>
<td>1380</td>
<td>1380</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>25</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Norm. transv. emittance [$\mu$m]</td>
<td>3.5</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>$\beta^*$ in IR1/IR5 [m]</td>
<td>0.55</td>
<td>1.0</td>
<td>0.6</td>
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</tbody>
</table>
LHC beam journey

Emittance measurement at 1.4 GeV

Bunch splitting at 1.4 GeV

Single bunch intensity at 26 GeV

Booster & CPS
1.4GeV/26 GeV

SPS injection
26 GeV

SPS extraction
450 GeV

LHC Injection
450 GeV

LHC Ramp
4 / 7 TeV

Total intensity $2 \times 10^{14}$/beam

Beam losses end of ramp warning

Luminosity adjustments
Operating machine

- Filling
- Squeezing
- Collisions
- Beams dumped
- STABLE BEAMS

- Pre-injection flat bottom
- Injection
- Ramp up
- Ramp down

R. Giachino
Cern OP experience

- **LHC machine operation**
  - 2006 one OP group working in the Cern Control Centre
  - Direct line to the Injectors chain (Booster, CPS, SPS)
  - Share PPbar and Electron Positron collider experience

*‘80 Ppbar beam operation challenge*
  - Collisions 270 GeV, Intensity $P_{10^{13}}$, $\overline{P}_{10^{12}}$
  - Old fashion control but already Sequence driven

*‘90 Electron positron collider dimension challenge*
  - Injection energy 3.5 GeV, Collisions 45/90 GeV
  - Control software redesigned by Op

*2000 LHC PP collider energy & power challenge*
  - Injection energy 450 GeV, Collisions 4/7 TeV
  - Intensity $2\cdot10^{14}$
Kinetic Energy of 200m Train at 155 km/h

Kinetic Energy of Aircraft Carrier at 50 km/h

Stored energy per beam is 360 MJ

Stored energy in the magnet circuits is 9 GJ
Beam Protection: Beam Energy → Beam Dump

100x energy of TEVATRON
0.000005% of beam lost into a magnet = quench
0.005% beam lost into magnet = damage

Failure in protection – complete loss of LHC is possible

Beam is ‘painted’ diameter 35cm

Concrete Shielding

Strong absorber Graphite = 800°C
Killer beam & downtime

- **LHC operation is several orders of magnitude more dangerous.**

<table>
<thead>
<tr>
<th>LHC 50 ns</th>
<th>Intensity x bunch</th>
<th>Nr bunches</th>
<th>Energy [GeV]</th>
<th>Intensity</th>
<th>Energy [MJ]</th>
</tr>
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<tbody>
<tr>
<td>flat bottom PSB</td>
<td>9.50E+11</td>
<td>1</td>
<td>0.5</td>
<td>9.50E+11</td>
<td>0.0001 x4</td>
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<td>1.4</td>
<td>9.50E+11</td>
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<tr>
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<tr>
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<td>450.0</td>
<td>2.10E+14</td>
<td>15.1389 x2</td>
</tr>
<tr>
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<td>1380</td>
<td>4000.0</td>
<td>2.07E+14</td>
<td>132.6456 x2</td>
</tr>
</tbody>
</table>

- **Magnet quench** (or a few magnets): a few hours
- **Collimator replacement**: a few days to 2 weeks (including bake out if needed)
- **Superconducting magnet replacement**: 2 months (warming up, cooling down)
- **Damage to an LHC experiment**: many months

- Beam accidents could lead to damage of superconducting magnets, and to a release of the energy stored in the magnets (coupled systems)
- **Experience with the accident in sector 34 in 2008**: one year downtime!!
When the MPS is not fast enough...

- At the SPS the MPS was been ‘assembled’ in stages over the years, but not following a proper failure analysis.
- As a consequence the MPS cannot cope with every situation! It is now also covered by the Machine Protection WG but would require new resources...
- Here an example from .... 2008 ! The effect of an impact on the vacuum chamber of a **400 GeV beam of 3x10^{13} p (2 MJ)**.
- Vacuum to atmospheric pressure, Downtime ~ 3 days.
LHC machine protection Interlock

- **LHC Beam interlock** system
  - Interact with all **LHC systems** involved in the protection of the machine.
  - Safe Machine Parameters, Safe Beam Flag, Beam Presence Flag, Mask and Unmasking mechanism
  - Interface with the **Beam dumping** system and the **SPS extraction system**.

- **SPS Extraction / LHC Injection Beam** interlock system
  - Protects the transfer lines from SPS to the LHC.
  - Protects the LHC against bad injection.

- **Software Interlock system**
  - Detailed surveillance of many machine parameters

- **Machine Protection Diagnostics**
  - Detailed post mortem analysis

- **Remote Base Access Control system**
  - Token assigned to change parameters
Safe Machine Parameters

receives accelerator information

generates flags & values

directly transmitted and / or broadcast

Injection procedure

Extraction Interlocks

Beam Interlocks
Collimation
Beam Loss Monitors...

*fast *safe *reliable *available
Extraction Interlocks

Transfer Lines
Beam-1 = TT60 + TI2
Beam-2 = TT40 + TI8

Super Proton Synchrotron

Extraction Master Beam Interlock Controllers

Large Hadron Collider
Extraction Interlocks

Super Proton Synchrotron

Large Hadron Collider
Extraction Interlocks

Beam presence flag = False Only Safe beam can be injected ($1 \times 10^9$)

Beam presence flag = True Any beam can be injected into LHC

three beam transfer conditions:

- probe
- set-up
- nominal

Super Proton Synchrotron

Directly Transmitted Interlock Signals

SPS Machine Parameters

Safe Machine Parameter Controller

LHC Machine Parameters

Large Hadron Collider
Safe beam flag evolution

- **The Safe Beam Flag** depends:
  - on the beam energy and intensity

Estimated damage level for fast losses

- at 450GeV $\Rightarrow \sim 2 \cdot 10^{12}$ protons
- at 7 TeV $\Rightarrow \sim 1 \cdot 10^{10}$ protons

In this intensity range, a safe beam becomes unsafe during acceleration
On large accelerators it is not always possible to cover all failure mechanisms with a hardware system:
- It needs something more flexible like adding a new interlock if not too time critical
- Survey the control system components relevant for machine protection
  - as additional protection layer, with possibility to abort beam if necessary
- Provide additional protection for complex but less critical conditions
  - (> 12 BPMs over 6 mm for beam 2 horizontal plane (too large RF frequency change)

![Graph showing orbit excursion and threshold]

**Trigger orbit excursion >>**

**Threshold**
LHC Post Mortem system is an automated post-operational analysis of transient data recordings from LHC equipment systems.

Meant to support machine protection by helping the operations crews and experts in understanding the machine performance and beam dump events and answer fundamental questions:

- **What happened?** (ie the initiating event / event sequence leading to dump/incident)
- **Did the protection systems perform as expected** (automated Post operational checks) ?
- **Assist in trend analysis, statistics of machine performance,** ...

Each beam dump generates ~ 1GB of PM data which is automatically analysed in typically < 1 min.
Transient data recording after a beam dump (PM)
Analysis modules for beam PM

RF/ADT data

COLL hierarchy

MP3 expert system

BBQ/Tune signal
Who’s operating the LHC

- **LMC LHC machine committee** (50)
  - Responsible for **strategic decision** short & long-term
  - Highest organ for **accelerator technical decisions**

- **LHC Coordinators** (6)
  - Senior accelerator physicists responsible for the **weekly LHC performances**

- **LHC Machine protection committees** (6-12)
  - Responsible for approval of energy or intensity increase

- **LHC Engineers In Charge** (7)
  - Responsible **day to day operation** when in charge or during his/her special activity.

**All of them**

*The entire operation team in the control centre is sharing the stressful moments as well as the records achievement*
Since the accident of September 2008 the LHC has been operated at ½ its nominal energy.

In March 2013 the LHC will be stopped for approximately 1 ½ years to perform a complete repair of the defect soldering.

Towards the end of 2014 the LHC will come back online at its full energy for the next adventure of particle physics.
• LHC Machine Protection Systems have been working well during 2011 run thanks to a lot of loving care and rigor of operation crews and MPS experts.
• No quenches with circulating beam.
• No evidence of major loopholes or uncovered risks, additional active protection will provide further redundancy.
• LHC is a stressfully operation, we are confident on our Machine Protection System which capture most failure before effect on the beam are seen.
• We have to remain vigilant to maintain current level of safety of MPS systems while increasing efforts on increasing MPS availability.
CERN experiments observe particle consistent with long-sought Higgs boson

“We observe in our data clear signs of a new particle, at the level of 5 sigma, in the mass region around 126 GeV. The outstanding performance of the LHC and ATLAS and the huge efforts of many people have brought us to this exciting stage,” said ATLAS experiment spokesperson Fabiola Gianotti, “but a little more time is needed to prepare these results for publication.”

“The results are preliminary but the 5 sigma signal at around 125 GeV we’re seeing is dramatic. This is indeed a new particle. We know it must be a boson and it’s the heaviest boson ever found,” said CMS experiment spokesperson Joe Incandela. “The implications are very significant and it is precisely for this reason that we must be extremely diligent in all of our studies and cross-checks.”