HL-LHC: Performance and Availability

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Acknowledgements: R. Schmidt, G. Spiezia, B. Todd, S. Uznanski, J. Wenninger, D. Wollmann, M. Zerlauth
Outline

- Introduction to the HL-LHC project
- Performance and Availability: Monte Carlo model
- Example: requirements for radiation-induced failures
- Luminosity optimization
Qualitative definitions

- Availability is a measure of the useful time for user experiments during the accelerator run.

- For particle colliders the key performance indicator is integrated luminosity $[\text{fb}^{-1}]$.

See talk B. Todd on Monday.
High Luminosity LHC (HL-LHC)

- Starting in 2025
- HL-LHC aims at producing 250-300 fb\(^{-1}\) per year (400 for ultimate parameters)
- 3000 fb\(^{-1}\) over about 10 years of operation
- The total integrated luminosity produced by the LHC in 2010-2012 is around 30 fb\(^{-1}\)
- First accelerator with an explicit integrated luminosity goal
Given a target integrated luminosity, life-cycle operational costs decrease with increasing availability.

Source: “Reliability in Automotive and Mechanical Engineering”, B. Bertsche
HL-LHC: New systems

- New $\text{Nb}_3\text{Sn}$ Triplets
- Cryo-plants
- Machine Protection Systems
<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHC (design report)</th>
<th>HL-LHC (25 ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>7 TeV</td>
<td>7 TeV</td>
</tr>
<tr>
<td>Total Intensity</td>
<td>$3.2 \times 10^{14}$</td>
<td>$6 \times 10^{14}$</td>
</tr>
<tr>
<td>Peak Luminosity (PL)</td>
<td>$1 \times 10^{34}$</td>
<td>$7 \times 10^{34}$</td>
</tr>
<tr>
<td>Virtual PL (Crab Cavities)</td>
<td>-</td>
<td>$19 \times 10^{34}$</td>
</tr>
<tr>
<td>Events per crossing</td>
<td>27</td>
<td>138</td>
</tr>
<tr>
<td>Levelled Luminosity</td>
<td>-</td>
<td>$5 \times 10^{34}$</td>
</tr>
</tbody>
</table>
Beam dump implies on average 5.5 hours of turnaround – impacting availability!
Machine Failure Rate (MFR) = fraction of premature dumps = 70%

Monte Carlo model for integrated luminosity estimates (MATLAB):
- Based on observed failure distributions
- The model accurately reproduces 2012 operation (1% accuracy)
- Extrapolated distributions for future LHC runs and HL-LHC
Luminosity vs Availability: MC Model

$L(t)$

\[ 19 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1} \]

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

Peak Lumi

Lumi Lifetime

Stable Beams Time

\[ \sim 5.5 \text{ h} \]

End of p-p Operation
Luminosity Predictions for HL-LHC

ASSUMPTIONS:
- Extrapolated distribution of fault time
- MFR = 59%
- Average turnaround = 6.2 h
- Virtual peak luminosity: \(1.954 \times 10^{35} \text{ [cm}^{-2}\text{s}^{-1}]\)
- Levelled luminosity: \(5 \times 10^{34} \text{ [cm}^{-2}\text{s}^{-1}]\)
- 4.7 h luminosity lifetime
- 160 days of p-p physics
- 1000 years of simulated HL-LHC operation

Availability is one of the key factors to reach the target 250-300 fb\(^{-1}\)/year of the HL-LHC project
Sensitivity Analysis: HL-LHC

- Identification of requirements for system upgrades

Fault time:
- Diagnostics
- Logistics
- Repair
Fault Time Distributions in 2012

*Faults: registered in the eLogbook*
R2E Effects

- **Total Ionizing Dose Effects (TID) and Displacement Damage (DD):**
  - Cumulative effects, easier to predict
  - LHC absolute values typically not critical (especially in shielded areas)
  - Scaling of components positive for TID (smaller oxides)

- **Single Event Effects (SEEs):**
  - Stochastic events, which can happen “any time” and are therefore harder to predict
  - Absolute levels are high, even in shielded areas (neutrons still make it through!)
  - Most effects are constant with scaling (smaller volumes compensate lower critical charges) but they can also increase (proton direct ionization, etc.)

See talk S. Uznanski on Wednesday
Extrapolation of R2E-induced faults

**ASSUMPTION:**

- Expected number of faults: linear scaling with HEH fluence (>20 MeV)

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of dumps per year</th>
<th>Total Downtime [h]</th>
<th>Average Downtime [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>56</td>
<td>250 - 300</td>
<td>4.5 – 5.3</td>
</tr>
<tr>
<td>2015 (~2012)</td>
<td>10 - 12</td>
<td>44</td>
<td>4.4</td>
</tr>
<tr>
<td>Run 2 (&gt;2015)</td>
<td>9 - 12</td>
<td>35</td>
<td>3.9</td>
</tr>
<tr>
<td>Run 3</td>
<td>15 - 20</td>
<td>55</td>
<td>3.7</td>
</tr>
<tr>
<td>HL-LHC (2025)</td>
<td>25 - 40</td>
<td>84</td>
<td>3.4</td>
</tr>
</tbody>
</table>

- Average downtime consistently decreases in the 3 phases, as the longest failure modes were mitigated during LS1
R2E failure ‘budget’

- Requirements:
  - 35% further reduction of R2E-induced downtime
    - reduce the total number of dumps by 5-10% (~9 dumps)
    - reduce the average fault time by 50% (3.5 h)
  - Same proportion of R2E dumps among systems observed in 2012

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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>QPS</td>
<td>31</td>
<td>~ 80 h</td>
<td>9</td>
<td>32 h</td>
</tr>
<tr>
<td>PC</td>
<td>14</td>
<td>~ 60 h</td>
<td>4</td>
<td>14 h</td>
</tr>
<tr>
<td>CRYO</td>
<td>4</td>
<td>~ 70 h</td>
<td>1</td>
<td>3.5 h</td>
</tr>
<tr>
<td>Vacuum</td>
<td>4</td>
<td>~ 20 h</td>
<td>1</td>
<td>3.5 h</td>
</tr>
<tr>
<td>Other</td>
<td>3</td>
<td>~ 30 h</td>
<td>1</td>
<td>3.5 h</td>
</tr>
</tbody>
</table>

- A lot of effort already in these 2 directions:
  - Shielding, relocation, use of radiation tolerant components
  - Introduction of remote resets, hot spares, …
Luminosity Optimization

Parameters to consider:
- Fault time
- Turnaround time
- Luminosity lifetime
- Levelling!

\[ L(t) \]

\[ t \]

\[ t_{\text{OPT}} \]
Optimization of Stable Beams Length

Balance between:
- Turnaround time
- Luminosity exponential decay

Non-linear constrained optimization:
- Number of fills
- Stable beams length

Input parameters:
- Luminosity lifetime
- Peak luminosity
- Fault time
- Turnaround time
Conclusions

- System faults prevent luminosity production both causing downtime and requiring an additional turnaround time.

- **Availability** will be one of the **key parameters** for the success of HL-LHC.

- A **Monte Carlo model** was developed to assess the impact of availability on integrated luminosity.

- The model allows for the identification of **individual systems requirements**.

- As an example, requirements for R2E-failures were derived for all affected systems.

- The **approach will be extended** to all other new systems.
“Reliability approach for machine protection design for particle accelerators”, THPFI045, proceedings of IPAC’13, Shanghai, China.

“HL-LHC: integrated luminosity and availability”, TUPFI012, proceedings of IPAC’13, Shanghai, China.

“Reliability and availability modelling for accelerator driven facilities”, THPRI019, proceedings of IPAC’14, Dresden, Germany.

“Update on predictions for yearly integrated luminosity for HL-LHC based on expected machine availability”, TUPRO015, proceedings of IPAC’14, Dresden, Germany.


“Quantitative reliability analysis in the design of interlock systems for machine protection”, in preparation.
Extrapolation of radiation levels

### FLUENCE AND DOSE / LHC PHASE

#### ANNUAL RADIATION LEVELS

<table>
<thead>
<tr>
<th>Area Assumptions</th>
<th>HEH Fluence [cm⁻²]</th>
<th>Dose [Gray]</th>
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</thead>
<tbody>
<tr>
<td>TurboFlash (TFL)</td>
<td>3E+08</td>
<td>0.3</td>
</tr>
<tr>
<td>TurboFlash 1</td>
<td>3E+08</td>
<td>1.0</td>
</tr>
<tr>
<td>TurboFlash 2</td>
<td>3E+08</td>
<td>1.0</td>
</tr>
<tr>
<td>TurboFlash 3</td>
<td>3E+08</td>
<td>2.9</td>
</tr>
<tr>
<td>TurboFlash 4</td>
<td>2E+09</td>
<td>4.0</td>
</tr>
<tr>
<td>TurboFlash 5</td>
<td>2E+09</td>
<td>8.0</td>
</tr>
</tbody>
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#### ULTIMATE HL

<table>
<thead>
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</tr>
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<tr>
<td>TurboFlash 5</td>
<td>2E+09</td>
<td>8.0</td>
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#### 2012 ~ 2015 as increased energy is compensated by an expected lower luminosity

#### 2015

<table>
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<tr>
<th>Location</th>
<th>HEH Fluence [cm⁻²]</th>
<th>Dose [Gray]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULTRA 1</td>
<td>1E+07</td>
<td>0.1</td>
</tr>
<tr>
<td>ULTRA 2</td>
<td>2E+08</td>
<td>0.3</td>
</tr>
<tr>
<td>ULTRA 3</td>
<td>2E+08</td>
<td>0.3</td>
</tr>
<tr>
<td>ULTRA 4</td>
<td>5E+08</td>
<td>1.0</td>
</tr>
<tr>
<td>ULTRA 5</td>
<td>1E+09</td>
<td>2.0</td>
</tr>
<tr>
<td>ULTRA 6</td>
<td>2E+09</td>
<td>4.0</td>
</tr>
<tr>
<td>ULTRA 7</td>
<td>4E+09</td>
<td>8.0</td>
</tr>
</tbody>
</table>

#### ULTIMATE HL

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<td>ULTRA 7</td>
<td>4E+09</td>
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2012 LHC Dump Causes

- Operations: End of Fill: 30.1%
- Operations: Test and Development: 10.9%
- Operations: Error: 1.0%
- Equipment Failure: Machine: 22.6%
- Equipment Failure: Machine Protection: 14.0%
- Equipment Failure: Controls: 2.1%
- Equipment Failure: Safety: 0.3%
- Beam: Losses (UFO): 2.6%
- Beam: Losses: 9.9%
- Beam: Orbit: 0.2%
- TOTEM: 0.7%
- CMS: 0.5%
- LHCb: 0.3%
- ALICE: 0.3%
- ATLAS: 0.0%
Peak luminosity and lifetime

![Graph showing peak luminosity and lifetime as functions of fill number.]

The graph displays the peak luminosity and lifetime trends over different fill numbers. The peak luminosity is represented in units of $10^{30}$ Hz/cm², while the lifetime is given in hours. The data points are scattered across the graph, with distinct clusters indicating variations in luminosity and lifetime with fill number.
2005 – Reliability Sub-Working Group
Predicted false dumps and safety of Machine Protection System

safety: no events
false dumps: used to determine whether predictions were accurate

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</thead>
<tbody>
<tr>
<td>LBDS</td>
<td>6.8 ± 3.6</td>
<td>9</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td>BIS</td>
<td>0.5 ± 0.5</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>BLM</td>
<td>17.0 ± 4.0</td>
<td>0</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>PIC</td>
<td>1.5 ± 1.2</td>
<td>2</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>QPS</td>
<td>15.8 ± 3.9</td>
<td>24</td>
<td>48</td>
<td>56</td>
</tr>
<tr>
<td>SIS</td>
<td>-</td>
<td>4</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

radiation induced effects are included in the figures above
false dumps – in line with expectations...
safety – therefore in line with expectations... if ratio false dumps to safety is ok.
Stable beams distribution

![Histogram of stable beams distribution]

- Occurrence on the y-axis.
- Hours on the x-axis.

The distribution shows a peak around the first few hours, with a gradual decrease as hours increase.
Optimization of Stable Beams Length

- Ideal length, balance between:
  - Turnaround time
  - Luminosity exponential decay
- Non-linear constrained optimization:
  - Number of fills
  - Stable beams length
- Input parameters:
  - Luminosity lifetime
  - Peak luminosity
  - Fault time
  - Turnaround time

Online tool for dynamic optimization of stable beams in the control room