Exciting year 2010 for us! Would it work?
Can only see with beam!

... the 2003 Ash Wednesday talk!
LHC Beam Momentum: \( \times 3.5 \) WR
LHC Stored Energy: \( \times 15 \) WR*  

* Here taking world record in super-conducting accelerators.

Only 1 beam-induced quench (at 450 GeV), except quench test.
Content

• Hardware performance, collimation setup, impedance and verification

• Intensity reach from collimation

□ $\beta^*$ reach from orbit & collimation

• Luminosity reach at 3.5 TeV from collimation

• Conclusion

See also Evian talks in “Beam Loss” session, in particular Daniel Wollmann and Roderik Bruce!
Includes short synthesis and summary of these Evian presentations!
LHC Collimators Position sensors performance: drift evaluation over 1 year operation

Differences between end-stops measurements (both inner and outer) performed with LVDT in January 2011 and reference values used in 2010 operational calibrations

The 2011 measurements of the mechanical end stops are averages of 5 repeated measurements

Only few axes have shown deviations above 20-30 μm. Accurate investigations have shown that these are caused by a higher uncertainty on the mechanical end stops approaching experienced on some calibrations and not by a higher drift of the sensor reading over the year

The typical value of the position sensors reading drift over the entire 2010 operation year is lower than 30 μm
The LHC collimators system downtime over an operation period of 8184 hours (341 days * 24 h) has been of only 37.55 hours. Only 10.45 h of these ones provoked an LHC downtime (access to the tunnel and/or interlocks activated). The other failure types provoked an operation downtime of some and/or several LHC collimators.

- Many important failures experienced in the 2010 operation have been definitively fixed:
  - The middleware communication problems have been fixed by the RDA team thanks to an accurate review of the operator clients (slow clients) and the installation of a proxy to limit the connections toward the FESA gateways.
  - A proper recovery tool has been developed and tested to recover LHC collimators operation after a power cut in only 20 minutes.

99.5 % uptime.

Thanks a lot to BE/CO for the precious support.

Comment (RA): Work on maximum robustness and reliability of collimators paid off! Excellent work on mechanics, actuation, sensors, controls, quality control.
## Settings End of 2010 p Run

<table>
<thead>
<tr>
<th>Condition</th>
<th>Unit</th>
<th>Plane</th>
<th>Set 1</th>
<th>Set 2</th>
<th>Set 3</th>
<th>Set 4</th>
<th>Set 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>[GeV]</td>
<td>n/a</td>
<td>450</td>
<td>3500</td>
<td>3500</td>
<td>3500</td>
<td>3500</td>
</tr>
<tr>
<td>IP beta function $\beta^*$</td>
<td>[m]</td>
<td>n/a</td>
<td>10-11</td>
<td>10-11</td>
<td>10-11</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Crossing angle $\alpha_c$</td>
<td>[$\mu$rad]</td>
<td>n/a</td>
<td>170</td>
<td>170</td>
<td>100-110</td>
<td>100-110</td>
<td>100-110</td>
</tr>
<tr>
<td>IR separation</td>
<td>[mm]</td>
<td>n/a</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Primary cut IR7</td>
<td>[\sigma]</td>
<td>H, V, S</td>
<td>5.7</td>
<td>5.7</td>
<td>5.7</td>
<td>5.7</td>
<td>5.7</td>
</tr>
<tr>
<td>Secondary cut IR7</td>
<td>[\sigma]</td>
<td>H, V, S</td>
<td>6.7</td>
<td>8.5</td>
<td>8.5</td>
<td>8.5</td>
<td>8.5</td>
</tr>
<tr>
<td>Quartiary cut IR7</td>
<td>[\sigma]</td>
<td>H, V</td>
<td>10.0</td>
<td>17.7</td>
<td>17.7</td>
<td>17.7</td>
<td>17.7</td>
</tr>
<tr>
<td>Primary cut IR3</td>
<td>[\sigma]</td>
<td>H</td>
<td>8.0</td>
<td>12.0/10.0</td>
<td>12.0/10.0</td>
<td>12.0/10.0</td>
<td>12.0/10.0</td>
</tr>
<tr>
<td>Secondary cut IR3</td>
<td>[\sigma]</td>
<td>H</td>
<td>9.3</td>
<td>15.6</td>
<td>15.6</td>
<td>15.6</td>
<td>15.6</td>
</tr>
<tr>
<td>Quartiary cut IR3</td>
<td>[\sigma]</td>
<td>H, V</td>
<td>10.0</td>
<td>17.6</td>
<td>17.6</td>
<td>17.6</td>
<td>17.6</td>
</tr>
<tr>
<td>Tertiary cut experiments</td>
<td>[\sigma]</td>
<td>H, V</td>
<td>15-25</td>
<td>40-70</td>
<td>40-70</td>
<td>15.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Physics debris collimators</td>
<td>[\sigma]</td>
<td>H</td>
<td>out</td>
<td>out</td>
<td>out</td>
<td>out</td>
<td>out</td>
</tr>
<tr>
<td>TCSG/TCDQ IR6</td>
<td>[\sigma]</td>
<td>H</td>
<td>7-8</td>
<td>9.3-10.6</td>
<td>9.3-10.6</td>
<td>9.3-10.6</td>
<td>9.3-10.6</td>
</tr>
<tr>
<td>TDI/TCLIA/TCLIB</td>
<td>[\sigma]</td>
<td>V</td>
<td>7.0</td>
<td>out</td>
<td>out</td>
<td>out</td>
<td>out</td>
</tr>
<tr>
<td>Protection margin W coll</td>
<td>[\sigma]</td>
<td>H, V</td>
<td>1.5</td>
<td>7.6</td>
<td>7.6</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Protection margin W coll</td>
<td>[mm]</td>
<td>H, V</td>
<td>0.8</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

A few 100,000 values drive and control system.

Settings verified with loss maps!

Generate low intensity beam losses with H, V and energy errors (induced).

Check that response of system is correct. If incorrect then fix. Only then declare system operational.

Stringent approach caught a few mistakes without impact on operation.

---

R. Assmann
Time for Beam-Based Setup & Check

- LHC collimation operates very differently from other previous systems:
  - Tevatron, RHIC: Collimators adjusted at start of each physics.
  - LHC: Not possible for high power. **Infrequent but very precise setups which are then kept for months (reliability & precisions allows this).** Requires special fills.

- Each change of orbit, energy and/or optics requires new setup:

<table>
<thead>
<tr>
<th>Activity</th>
<th>Shifts</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>450 GeV setup:</td>
<td>3 x 8 h</td>
<td>16 h</td>
</tr>
<tr>
<td>450 GeV check:</td>
<td>1 x 8 h</td>
<td>8 h</td>
</tr>
<tr>
<td>High energy setup:</td>
<td>5 x 8 h</td>
<td>40 h</td>
</tr>
<tr>
<td>High energy check:</td>
<td>6 – 10 fills</td>
<td>30 – 50 h</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>94 – 114 h</td>
</tr>
</tbody>
</table>

- Several measures to speed up under way but no miracles \(\rightarrow\) Stefano!
Content

• Hardware performance, collimation setup, impedance and verification

• **Intensity reach from collimation**
  - $\beta^*$ reach from orbit & collimation

• Luminosity reach at 3.5 TeV from collimation

• Conclusion
Measured Cleaning Efficiency
(linear scale, overall sums)

Protons (shown here):
- Sum cleaning ins.: 99.93 %
- Sum SC magnets: 0.07 %

Ions (not shown):
- Sum cleaning ins.: 98.1 %
- Sum SC magnets: 1.9 %

betatron losses B1 3.5TeV ver ocorr stable beams (20101004, 162853)
Losses in SC magnets understood: location and magnitude

Protons: Simulations vs Measurement
B1v, 3.5TeV, $\beta^*=3.5m$, IR7

Cleaning Inefficiency

10,000

Simulated (ideal)

Measured

R. Assmann
Ions: Beam 2 Leakage from IR7 Collimation (much worse, as expected)

Correction of Cleaning Inefficiency: Reduce by Factor 2 (BLM Response)

Factor 2 better performance reach!

Included now.

Data show BLM response for full beam lost, while collimator is being closed.
Stability Versus Time

Analysis: Daniel Wollmann, see Evian talk!
Compare Observation to Model from 2008

Model is OK!

R. Assmann
Loss rate at hor. TCP in IR7 during high luminosity run, 150ns, 312b (24.10.2010)

- 150ns, 312 bunches
- BLM signal RS04 (640us)
- Significant loss increase when in collisions
- Loss spike during the whole run

Analysis: Daniel Wollmann, see Evian talk!
Loss rates and instantaneous life time for the 8 high luminosity fills

Range of highest (lowest) loss rates (life times) during high luminosity proton runs for different integration times of BLM signal:

<table>
<thead>
<tr>
<th>Integration times</th>
<th>Runs 312 bunches (3 runs)</th>
<th>Runs 368 bunches (5 runs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS02 (80us)-lifetime [h]</td>
<td>0.3&lt;τ&lt; 2.6</td>
<td>0.6&lt;τ&lt; 6.8</td>
</tr>
<tr>
<td>Loss rate [p/s]</td>
<td>3.3e10&gt; R &gt; 2.8e9</td>
<td>1.6e10 &gt; R &gt; 1.64e9</td>
</tr>
<tr>
<td>RS04 (640us)-lifetime [h]</td>
<td>0.5 &lt;τ&lt; 5.5</td>
<td>1.0&lt;τ&lt; 7.7</td>
</tr>
<tr>
<td>Loss rate [p/s]</td>
<td>2.0e10 &gt; R &gt; 1.3e9</td>
<td>1.2e10 &gt; R &gt; 1.4e9</td>
</tr>
<tr>
<td>RS06 (10.24ms)-lifetime [h]</td>
<td>2.3 &lt;τ&lt; 6.2</td>
<td>1.3 &lt;τ&lt; 21.6</td>
</tr>
<tr>
<td>Loss rate [p/s]</td>
<td>4.2e9 &gt; R &gt; 1.6e9</td>
<td>7.3e9 &gt; R &gt; 5.5e8</td>
</tr>
<tr>
<td>RS09 (1.3s)-lifetime [h]</td>
<td>6.0 &lt;τ&lt; 26.5</td>
<td>1.6 &lt;τ&lt; 40.6</td>
</tr>
<tr>
<td>Loss rate [p/s]</td>
<td>1.4e9 &gt; R &gt; 3.8e8</td>
<td>7.2e9 &gt; R &gt; 3.0e8</td>
</tr>
</tbody>
</table>

Remarks:
- RS02 and RS04: transient losses (1-7 turns)
- RS06 and RS09: steady state losses (115 – 14600 turns)
- B2 less loss spikes in 80us BLM signals, although the overall life time during fills is better in B1
- B2: IR7 TCSG.A6R7 at same loss level as TCPs for some fills
- Error (loss rate, life time < 20%)

Analysis: Daniel Wollmann, see Evian talk!
Result: Intensity Limit vs Loss Rate 7 TeV

Model LMC March 2009 – Same Plot

- Tight
- Intermediate

2010 analysis

Peak Fractional Loss Rate \([s^{-1}]\)

Maximum Intensity \([p]\)

better → worse
Intensity Reach
(from collimation)

<table>
<thead>
<tr>
<th>Energy</th>
<th>p Intensity (max)</th>
<th>Ion intensity (max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5 TeV</td>
<td>9.1e14</td>
<td>1.5e13 (q)</td>
</tr>
<tr>
<td>5.0 TeV</td>
<td>2.3e14</td>
<td></td>
</tr>
<tr>
<td>7.0 TeV</td>
<td>0.9e14</td>
<td></td>
</tr>
</tbody>
</table>

No predicted collimation limit on intensity at 3.5 TeV and 4 TeV!

Can imagine up to 2808 nominal or even ultimate bunches, if we only look at cleaning!

Analysis: Daniel Wollmann & Ralph Assmann, see Daniel’s Evian talk!
Content

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**Reach from Orbit & Collimation**

*accepting ≤ 1/30,000 y risk for triplet, ≤ 1/300 y for TCT*

- Reduce the separation at the IPs to its nominal value of 0.7 mm
- Measure the triplet aperture locally
- β-beating below 10%, reproducibility 5%, bias at TCTs/triplets
- Interlocks, warnings to reduce damage risk further
- New settings to be qualified with loss maps and async. dump tests. Problems => margins and β* to be increased
- Verify cleaning hierarchy on a regular basis
- Detailed study to correlate n1 calculation and measurements

### Table

<table>
<thead>
<tr>
<th></th>
<th>3.5 TeV</th>
<th>4 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>β* (m)</td>
<td>α (μrad)</td>
</tr>
<tr>
<td>2010 margins</td>
<td>2.3</td>
<td>125</td>
</tr>
<tr>
<td>2011 proposal</td>
<td><strong>1.6</strong></td>
<td><strong>150</strong></td>
</tr>
</tbody>
</table>

Analysis: Roderik Bruce, see Roderik’s Evian talk!
Proposed Margins and Settings

• Summing *linearly* we get the margins

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th></th>
<th>2011</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(σ)</td>
<td>(mm)</td>
<td>(σ)</td>
<td>(mm)</td>
</tr>
<tr>
<td>triplet–TCT</td>
<td>2.5</td>
<td>0.9–2.1</td>
<td>2.3</td>
<td>1.1–2.7</td>
</tr>
<tr>
<td><strong>TCT–TCSG IR6</strong></td>
<td><strong>5.7</strong></td>
<td><strong>3.5–4.4</strong></td>
<td><strong>2.5</strong></td>
<td><strong>1.3–1.8</strong></td>
</tr>
<tr>
<td>TCSG IR7–TCP</td>
<td>2.8</td>
<td>0.6–1.6</td>
<td>2.8</td>
<td>0.5–1.5</td>
</tr>
</tbody>
</table>

• and the settings

<table>
<thead>
<tr>
<th></th>
<th>TCP IR7</th>
<th>TCS IR7</th>
<th>TCS IR6</th>
<th>TCT</th>
<th>aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.70</td>
<td>8.50</td>
<td>9.30</td>
<td>11.80</td>
<td>14.10</td>
</tr>
</tbody>
</table>

• Assuming IP2 remains at larger margins. Proposed settings very similar to what was used in 2010 run with $\beta^*=2.0$ m
Content

- Hardware performance, collimation setup, impedance and verification
- Intensity reach from collimation
  - $\beta^*$ reach from orbit & collimation
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Emittance Limit from Collimation

\[ \mathcal{L} = \frac{1}{4\pi m_0 c^2} \cdot \frac{f_{rev} \cdot F}{\gamma \cdot \beta^*} \cdot \frac{N_p}{\epsilon} \cdot E_{stored} \]

5.3 \times 10^8 \text{ J}^{-1}

- \text{Proton rest mass}
- \text{Light velocity}
- \text{Revolution frequency}
- \text{Geometric correction factor}
- \text{IP beta function}
- \text{Stored energy}
- \text{Number of bunches per beam}
- \text{Number of protons per bunch}
- \text{Relativistic Lorentz factor}
- \text{Transverse (round) emittance (geom)}

\[ \frac{N_p}{\epsilon} \leq 3.4 \times 10^{20} \text{ m}^{-1} \]

Conservative limit but gives peace of mind! Injectors cannot do better anyway!
Luminosity at Collimation Limit @ 3.5 TeV (50 ns)

- Best performance reach parameters while respecting robustness limit:
  - Bunch intensity: $1.7 \times 10^{11}$ p (ultimate)
  - Norm. emittance: $1.9 \, \mu m$ (half nominal)
  - Geom. emittance: $0.5 \, nm$ (nominal value at 7 TeV)
  - Number of bunches: 1404 (50 ns)
  - $\beta^*$: 1.6 m

- We then get:
  - Stored energy: 133 MJ

- Luminosity reach with collimation limits:
  - Theoretically: $< 4.5 \times 10^{33} \, \text{cm}^{-2} \, \text{s}^{-1}$

...not reachable due to other limits... Thursday session!

\[
\mathcal{L} \lesssim \frac{10^{40}}{\gamma \cdot \beta^*} \cdot \frac{E_{\text{stored}}}{500 \, \text{MJ}}
\]

...have to add F correction ...
• Hardware performance, collimation setup, impedance and verification
• Intensity reach from collimation
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Conclusion: Disclaimer

- **Other beam dynamics limits** do exist: fold in → Thursday session.
- **Our life is much easier at 3.5 TeV** than it will be later:
  - Operation with low emittance beams (primary collimators at 10 $\sigma_{\text{real}}$ instead of 5.7 $\sigma_{\text{real}}$).
  - Losses reduced by skipping chromaticity measurements.
  - Impedance much lower than later (intermediate coll. settings & 3.5 TeV gaps).
  - Operation with 150 ns was far away from instabilities (e.g. e-cloud).
  - Long-range beam-beam much weaker than later.
  - Magnets far away from their limits (much more quench margin).
  - Efficiency of collimation is better at lower beam energy (less effect from single-diffractive scattering).
  - Transverse damper is easier.
  - Aperture might get worse with time due to ground motion.
- **Be careful with extrapolation to higher intensities and energies!**
Conclusion

- **Collimation behaves as predicted, including cleaning efficiency → no need to change performance models.**
- **Good surprise:** 6 times better beam lifetime than specified.
- **Collimation:**
  - \[ N_{\text{tot}}(p) \leq 2808 \times 1.7 \times 10^{11} \quad \text{(3.5 & 4 TeV)} \]  
  - (cleaning only)
  - \[ N_{\text{tot}}(\text{ion}) \leq 1.5 \times 10^{13} \quad \text{(charges)} \]
- **Essentially: No intensity limit from collimation at 3.5 TeV and 4 TeV.**
  - \[ \frac{N_p}{\epsilon} \leq 3.4 \times 10^{20} \, \text{m}^{-1} \]
  - \[ T_{\text{setup}} \approx 94 - 114 \, \text{h} \]
  - \[ T_{\text{validity}} \approx 4 - 5 \, \text{months} \]
  - \[ T_{\text{uptime}} = 99.5 \% \]
- **Orbit & coll.:** \[ \beta^* \geq 1.6 \, \text{m} \quad \text{(1.4 m @ 4 TeV)} \]
- **Coll. cannot help for UFO cleaning (localized losses away from coll).**
- **Limit for 7 TeV now estimated at ~ 30% of nominal intensity.**
- **Ongoing upgrade program should guarantee nominal intensity @ 7 TeV.**
Thank You
Microphone Detection of Unstable Beam

Spectrogram of Microphone Data at TCP.D6L7, Oct 27th, 2010

- upper sidebands of Amplitude Modulation:
  \[bf + \text{glissf}\]
- beam frequency:
  \[bf = 11.2\text{kHz}\]
- lower sidebands of Amplitude Modulation:
  \[bf - \text{glissf}\]
- AM sidebands of 2nd beam harmonic:
  \[2^*bf - \text{glissf}\]
- 2nd and 3rd harmonic of glissando:
  \[2^*\text{glissf}, 3^*\text{glissf}\]
- glissando:
  \[\text{glissf} = 3.4\text{kHz} \ldots 3.5\text{kHz}\]
- Injection
- Beam Dump