HL-LHC Parameter Space and Scenarios

Many thanks to:

O. Brüning BE-ABP
Performance optimization for the LHC

Luminosity (round beams):

\[ L = \frac{n_b \cdot N_1 \cdot N_2 \cdot f_{rev}}{4\pi \cdot \beta^* \cdot \varepsilon_n} \cdot R(\phi, \beta^*, \varepsilon_n, \sigma_s) \]

- 1) maximize bunch brightness (beam-beam limit) \( \Rightarrow [N_b/\varepsilon_n] \)
- 2) minimize beam size (constant beam power; aperture)
- 3) maximize number of bunches (beam power; e-cloud)
- 4) compensate for ‘R’

Operation at performance limit

- choose parameters that allow higher than design performance
- leveling mechanisms for controlling performance during run
Potential Performance Limitations for the LHC

Bunch Intensity:

1) Beam-Beam interaction $\Rightarrow$ limit for beam brightness and $\Theta$? $\Rightarrow$ no limit found yet for head-on $\Rightarrow$ $\Delta Q = 0.02 - 0.03$

2) Collective effects (e.g. TMCI) $\Rightarrow$ ca. $3.5 \times 10^{11}$ ppb (single bunch) [Elias Metral]

3) e-cloud effect $\Rightarrow$ depends on bunch spacing and SEY

$\Rightarrow$ 50ns operation requires SEY < 2.1!
$\Rightarrow$ e-cloud with 50ns bunch spacing has larger bunch limit than single bunch TMCI limit for all SEY values!

$\Rightarrow$ 25ns requires SEY < 1.3 for $2 \times 10^{11}$ ppb
25-ns bunch spacing

- e-cloud heat load limit for 50ns larger than TMCI limit

50-ns bunch spacing

- e-cloud heat load limit for 25ns compatible with bb limit if

\[ \delta_{\text{max}} < 1.3 \]

or with special bunch patterns that minimize e-cloud

(e.g. micro batches or satellite bunches)
**Potential Performance Limitations for the LHC**

**beta*: 

1) Aperture ➔ interaction with WP3 of the HL-LHC: $\beta* < 0.2m$

2) Chromatic aberrations & optics matchability
   ➔ OK for $\beta* \geq 0.3m$ (Phase 1 solution)
   ➔ ATS squeezing mechanism for $\beta* < 0.3m$

3) Geometric reduction factor:
   ➔ moderate increase of L with reduced $\beta*$
   ➔ margin for L leveling with Crab Cavities

**Presentation by Stephane Fartoukh on Monday**
Geometric Reduction Factor: $R$

Geometric luminosity reduction factor:

$$R_{\theta} = \frac{1}{\sqrt{1 + \Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2 \sigma_x}$$

large crossing angle:

- reduction of long range beam-beam interactions
- reduction of head-on beam-beam parameter
- reduction of the mechanical aperture
- reduction of instantaneous luminosity
  - inefficient use of beam current (machine protection!)

Piwinski angle

effective cross section

Chamonix, 9 February 2012
Luminosity versus $\beta^*$:

Geometric reduction factor

small $\beta^*$: ➔ moderate increase of $L$ with decreasing $\beta^*$

- ca. 40% for $\beta^* \ 0.5m \to 0.25m$
- ca. 15% for $\beta^* \ 0.3m \to 0.2m$
- ca. 10% for $\beta^* \ 0.2m \to 0.1m$

➔ gain in virtual luminosity reach with Crab Cavities
Summary of LHC Intensity Limits (7 TeV)

Ideal scenario: no imperfections included!

Note: Some assumptions and conditions apply…
For given luminosity $\tau_{\text{eff}}$ scales with total beam current.

\[ \tau_{\text{eff}} [\text{h}] = \frac{N_{\text{tot}}}{n_{\text{evt}} \sigma_{\text{tev}}} \]

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

$\sigma = 100 \text{ mbarn}$

$\tau_{\text{eff}} = 13.9$ hours for $5 \times 10^{14} \text{ p/beam}$:

→ argument for HL-LHC scenarios with maximum beam current.

F. Zimmermann, Chamonix 2011

Upgrade Considerations: Beam Lifetime
Upgrade Considerations: Beam Lifetime

Run length assuming leveled luminosity:

- virtual luminosity of $k \times 5 \times 10^{34}$ cm$^{-2}$ sec$^{-1}$ \(\Rightarrow\) \(T_{\text{level}} = (1 - 1/\sqrt{k}) \ast \tau_{\text{eff}}\)

Assuming: $1.8 \times 10^{11}$ ppb @ 25ns & $3.5 \times 10^{11}$ ppb @ 50ns (\(\Rightarrow\) \(\approx 5 \times 10^{14}\) p/beam)

\(\Rightarrow\) \(\tau_{\text{eff}} = 13.9\) hours for $5 \times 10^{14}$ p/beam:

- # \(k = 2:\) \(\Rightarrow\) \(T_{\text{level}} = 4.1\) h
- # \(k = 3:\) \(\Rightarrow\) \(T_{\text{level}} = 5.9\) h
- # \(k = 4:\) \(\Rightarrow\) \(T_{\text{level}} = 7.0\) h
Upgrade Considerations: Integrated Luminosity

Integrated luminosity: run with luminosity decay

\[ L_{\text{int}} = \text{ca 0.4 fb}^{-1} \text{ over 3 h for a luminosity decay to } 2.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \]

assuming no emittance growth over the fill \( \rightarrow \) the emittance growth due to IBS and beam-beam is compensated by radiation damping
Upgrade Considerations: Integrated Luminosity

**Integrated luminosity**: leveling to constant luminosity

\[ L_{\text{int}} = L_{\text{level}} \times T_{\text{level}} \]

\[ (\sigma=100 \text{ mbarn}) \]

Integrating luminosity directly proportional to total current

\[ L_{\text{int}} = 0.4 \text{ fb}^{-1} \text{ per fill for } N_{\text{tot}} = 5 \times 10^{14} \text{ ppb over 3h and } k = 1 \]

\[ L_{\text{int}} = 0.4 + 0.73 \text{ fb}^{-1} \text{ per fill for } N_{\text{tot}} = 5 \times 10^{14} \text{ ppb over 7h and } k = 2 \]

\[ L_{\text{int}} = 0.4 + 1.25 \text{ fb}^{-1} \text{ per fill for } N_{\text{tot}} = 5 \times 10^{14} \text{ ppb over 10h and } k = 4 \]

Argument for HL-LHC scenarios with maximum ‘k’
HL-LHC Performance Goals

- **Leveled peak luminosity:** \( L = 5 \times 10^{34} \, \text{cm}^{-2} \, \text{sec}^{-1} \)

- **Virtual peak luminosity:** \( L > 10 \times 10^{34} \, \text{cm}^{-2} \, \text{sec}^{-1} \)

- **Integrated luminosity:** 200 fb\(^{-1}\) to 300 fb\(^{-1}\) per year

- **Total integrated luminosity:** ca. 3000 fb\(^{-1}\)
# HL-LHC Performance Estimates

**nominal bunch length and minimum $\beta^*$**: ‘HL-LHC Kickoff+’

<table>
<thead>
<tr>
<th>Parameter</th>
<th>25ns</th>
<th>50ns</th>
<th>100ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>1.15E+11</td>
<td>2.0E+11</td>
<td>3.3E+11</td>
</tr>
<tr>
<td>$n_b$</td>
<td>2808</td>
<td>2808</td>
<td>1404</td>
</tr>
<tr>
<td>beam current [A]</td>
<td>0.58</td>
<td>1.02</td>
<td>0.84</td>
</tr>
<tr>
<td>x-ing angle [μrad]</td>
<td>300</td>
<td>475</td>
<td>520</td>
</tr>
<tr>
<td>beam separation [σ]</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>$\beta^*$ [m]</td>
<td>0.55</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>$\varepsilon_n$ [µm]</td>
<td>3.75</td>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td>$\varepsilon_L$ [eVs]</td>
<td>2.51</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>energy spread</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>bunch length [m]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IBS horizontal [h]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IBS longitudinal [h]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piwinski parameter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>geom. reduction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>beam-beam / IP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Luminosity</td>
<td>5.6 $10^{14}$ and 4.6 $10^{14}$ p/beam</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Events / crossing: 19, 141, 257, 95, 190

- If luminosity (25ns) of $L = 7.4 / 0.37 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ ($'k' = 4$)
  - Virtual luminosity: $20 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

- If luminosity (25ns) of $L = 8.4 / 0.37 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ ($'k' = 4.5$)
  - Virtual luminosity: $22.7 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

(Leveled to $5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$)

**OK for HL goals ('$k' = 4$)**

- (Even better if emittances can be further reduced: still a factor 1.2 to 2.5 wrt beam-beam limit)

- Results in maximum fill length of 7 + 3 h and 1.7 fb$^{-1}$ per fill
Emittance Margin for SPS to HL-LHC

IBS growth @ injection: ca. 10% in 20min after loss of $9 \times 10^{10}$ ppb/mrad

(Fill 2028: Bunch intensity 1.26e+11; Bunch length ~ 1.1 ns; Emittance ~ 1.4 μm)

- density close to HL-LHC goals
- expect similar growth for HL-LHC

Growth @ ramp: related to damper gain and tune feedback

Growth @ squeeze: varies between zero and 10% depending on beam and plane

Assume for now 10% to 20% emittance growth between SPS extraction and HL-LHC luminosity production

should be able to find better solution for HL-LHC
HL-LHC Parameter Space

\[ \varepsilon_n [\text{\mu m rad}] \]

- Aperture
- head-on beam-beam without R
- head-on beam-beam with R
- single bunch TMCI

IBS \( \approx 15h \)
Fill 2028 from 2011

Chamonix, 9 February 2012
Oliver Brüning BE-ABP
HL-LHC Parameter Space: 25ns

\[ \varepsilon_n [\mu m \text{rad}] \]

Aperture

variation example

beam life limit for \( \delta = 1.2 \)

IBS \( \approx \) 15h

virtual performance reach

head-on beam-beam without R

head-on beam-beam with R

single bunch TMCI

\[ N_{\text{bunch}} [10^{11}] \]
HL-LHC Parameter Space: 50ns

εₚ [μm rad]

Aperture

variation example

virtual performance reach

IBS ≈ 15h

head-on beam-beam without R

head-on beam-beam with R

single bunch TMCI

N_{bunch} [10^{11}]
### HL-LHC Performance Estimates

**variation examples:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>nominal</th>
<th>25ns</th>
<th>50ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>1.15E+11</td>
<td>2.0E+11</td>
<td>2.5E+11</td>
</tr>
<tr>
<td>( n_b )</td>
<td>2808</td>
<td>2808</td>
<td>1404</td>
</tr>
<tr>
<td>beam current ([ A])</td>
<td>0.58</td>
<td>1.02</td>
<td>0.64</td>
</tr>
<tr>
<td>x-ing angle ([ \mu \text{rad}])</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>beam separation ([ \sigma])</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \beta^* ) ([\text{m}])</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \varepsilon_n ) ([\mu\text{m}])</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \varepsilon_L ) ([\text{eVs}])</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>energy spread</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>bunch length ([\text{m}])</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IBS horizontal ([\text{h}])</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IBS longitudinal ([\text{h}])</td>
<td>61 -&gt; 60</td>
<td>35</td>
<td>24</td>
</tr>
<tr>
<td>Piwinski parameter</td>
<td>0.68</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>geom. reduction</td>
<td>0.83</td>
<td>0.37</td>
<td>0.37</td>
</tr>
<tr>
<td>beam-beam / IP</td>
<td>3.10E-03</td>
<td>2.7E-03</td>
<td>3.4E-03</td>
</tr>
<tr>
<td>Peak Luminosity</td>
<td>1 10^{34}</td>
<td>5.6 10^{34}</td>
<td>4.4 10^{34}</td>
</tr>
<tr>
<td>Events / crossing</td>
<td>19</td>
<td>106</td>
<td>165</td>
</tr>
</tbody>
</table>

**5.6 10^{14} and 3.5 10^{14} \( \text{p/beam} \)**

➡️ Not sufficient room for leveling (with Crab Cavities)

At limit for HL goals

➡️ implies maximum fill length of 4h+3h and

ca. 1.1 \( \text{fb}^{-1} \) per fill

'irtual luminosity (25ns) of

\[
= \frac{5.6}{0.37} 10^{34} \text{cm}^{-2} \text{s}^{-1}
\]

\[
= 15 10^{34} \text{cm}^{-2} \text{s}^{-1} ('k' = 3)
\]

'irtual luminosity (50ns) of

\[
= \frac{4.4}{0.37} 10^{34} \text{cm}^{-2} \text{s}^{-1}
\]

\[
= 11.9 10^{34} \text{cm}^{-2} \text{s}^{-1} ('k' = 2.4)
\]

Chamonix, 9 February 2012
Upgrade Considerations: Integrated Luminosity

<table>
<thead>
<tr>
<th>Phase</th>
<th>Days</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commissioning</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>Scrubbing run</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>5 MDs</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>6 Technical stops</td>
<td></td>
<td>(3 days TS plus 1 day recovery with beam)</td>
</tr>
<tr>
<td>Special requests</td>
<td></td>
<td>TOTEM/ALPHA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Intermediate energy run</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Luminosity scans</td>
</tr>
<tr>
<td>Intensity ramp up</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Total high intensity</td>
<td>~130</td>
<td></td>
</tr>
<tr>
<td>Ion setup</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>24</td>
<td></td>
</tr>
<tr>
<td></td>
<td>290</td>
<td></td>
</tr>
</tbody>
</table>

Can hope for ca. 150 days / year for HL-LHC operation

⇒ requires between 150 and 230 fills per year to reach 250 fb⁻¹ per year!

⇒ implies 1 to 1.5 fills per day for previous scenarios
Machine Efficiency:

Upgrade Considerations: Integrated Luminosity

Efficiency = number of fills per day * fill-length / 24 h

Example 1: k = 4
1 fill per day with run length of 10h:
221 fills for reaching 250 fb
fill-length = 3h + 7h = 10h
Efficiency = 42%

Example 2: k = 2
1.5 fills per day with run length of 7h:
151 fills for reaching 250 fb
fill-time = 3h + 4h = 7h
Efficiency = 43%
LHC Availability and Performance in 2011

Hubner factor: \( H = 11.57 \times L_{\text{Del}}/(D \times L_{\text{Peak}}) \)  

**p-p (LP):** 81.4 days  
\( L_{\text{Peak}} = 2572 \text{ (µb.s)}^{-1} \)  
\( L_{\text{Del}} = 4.01 \text{ fb}^{-1} \)  
\( H = 0.22 \)

**Pb-Pb:** 24.1 days  
\( L_{\text{Peak}} = 512 \text{ (b.s)}^{-1} \)  
\( L_{\text{Del}} = 167.6 \text{ µb}^{-1} \)  
\( H = 0.24 \)
Upgrade Considerations: Integrated Luminosity

Machine Efficiency:

- Hübner Faktor: H
- integrated luminosity = H * L_{peak} * days

250 fb^{-1} in 150 days with L_{peak} = 5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}

- requires H = 0.4; independent on run length; Turnaround etc.

compared to Hübner factor of 0.2 – 0.24 in ATLAS and CMS and 0.26 – 0.32 with leveling

250 fb^{-1} per year is very ambitious with L_{peak} = 5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}

maximize peak performance reach for HL-LHC!
Machine Efficiency:

- average Turnaround time of ca. 5 hours
- minimum fill-to-fill time = leveling time + 3h + turnaround time
- Efficiency = number of fills per day * fill-to-fill time / 24 h

allows comparison with LHC operation: Efficiency = \( \frac{L_{\text{oper}}}{L_{\text{theor}}} \)

Example 1: \( k = 4 \) \( \rightarrow \) 1 fill per day with run length of 10h:

- fill-to-fill time = 3h + 7h + 5h = 15h
- Efficiency = 1 * 15 / 24 = 63%

Example 2: \( k = 2 \) \( \rightarrow \) 1.5 fills per day with run length of 7h:

- fill-to-fill time = 3h + 4h + 5h = 12h
- Efficiency = 1.5 * 12 / 24 = 75%
Using LHC data from 2011 one obtains:
- average run length = 4.6 hours
- most probable turnaround time = 5.23 hours
  ➔ average Fill-to-Fill time = 9.8 hours
- total number of physics fills = 99
- total number of physics days = 80 (luminosity production period)
  ➔ LHC efficiency in 2011 = \(99 \times \frac{9.8}{80/24} = 50\%\)
    (compared to 63% to 75% for the HL-LHC scenarios!)

One should demonstrate in LHC operation that average fill length can be larger than desired fill length for HL-LHC (> 7 hours) and that average Turnaround time can be ≤ 5 hours
Ion Operation during HL-LHC:

ALICE is preparing an upgrade bid for 10\( \text{nb}^{-1} \)
-scaling 2011 and 2012 performance to 7 TeV
ca. 500 \( \mu \text{b}^{-1} \) per year for a four week running period.

Doubling number of bunches:
-will double the injection time for existing injector performance
-resulting emittance growth due to IBS at injection might reduce performance reach

\( @ 7 \) TeV can partially compensate
stochastic cooling a la RHIC might help

Deuterons:
-In case a run with Deuterons is requested by ALICE, it will most likely
be scheduled after LS3 (development of source and injector
will be challenging before LS2).

Oliver Brüning BE-ABP
Chamonix, February 2012
Summary:

Small $\beta^*$ optics solutions open the door for HL-LHC performance with leveling ➔ we need Crab cavities!

➔ optics design requires information on required configurations (ALICE; LHCb)!

Bunch intensities: assuming total limit of 1 A in the LHC
2 $10^{11}$ ppb for 25ns and 3.5 $10^{11}$ ppb for 50ns operation

Bunch spacing:
- 25ns clearly preferred for event pileup but requires larger current wrt 50ns
- 50ns is a very attractive backup scenario for avoiding e-cloud problems (in the SPS and the LHC!)

Integrated luminosity:
- 250 fb$^{-1}$ is extremely challenging; requires high availability and reliability

➔ how much time can one assume for HL-LHC physics! (MDs, TS, Pb etc.)
150d; average fill length of 7h to 10h and average Turnaround time of ca. 5h
➔ ca. 70% efficiency [time required for physics fills / run time]!
Potential limitations: General worries

How confident are we that average fill times are longer than 7h?

- RF trips
- QPS and PC trips
- beam abort due to R2E
- UFO rate

\[ \rightarrow \text{aging after 15+ years of operation?} \]

\[ \rightarrow \text{losses for operation with } > 1A? \]

\[ \rightarrow \text{cleaning?} \]

\[ \rightarrow \text{Very few operator initiated EOFs in 2010 and 2011 operation!!!!!!} \]

How confident are we that we can overcome e-cloud for 25ns?

- HL-LHC goals require above ultimate intensities with sub-nominal $\varepsilon_n$
  - requires SEY of less than 1.3!
  - keep 50ns option alive!
  - apart from pile-up, 50ns has a high performance potential!
Bunch Intensity:

1) Beam-Beam interaction $\Rightarrow$ limit for beam brightness and $\Theta$?

$\Rightarrow$ no limit found yet for head-on
$\Rightarrow$ long range:
  $\Rightarrow$ losses for $d < 6\sigma$
  $\Rightarrow$ instabilities for tight settings with $d < 10\sigma$

Presentation by
Werner Herr on Monday
LHC Challenges: Long-Range Beam-Beam

Tune spread due to head-on beam-beam interaction wo x-ing:

$$\xi_{\text{beam-beam}} = \frac{r_p}{4\pi} \cdot \frac{N_b}{\varepsilon_n}$$

Long range interactions:

Crossing angle configurations:
Top Left: only head-on
Top right: $= 200\mu\text{rad} \approx 7\sigma$
Bottom left: $= 285\mu\text{rad} \approx 10\sigma$
Bottom right $= 400\mu\text{rad} \approx 13\sigma$

Werner Herr et al, LPN 416
LHC Challenges: Beam-Beam Interaction

Design report: $\Delta Q_{\text{beam-beam}} < 0.01$

3 head-on/bunch $\Rightarrow \xi_{\text{beam-beam}} < 3.3 \times 10^{-3} \Rightarrow N < 1.2 \times 10^{11}$

2 head-on/bunch $\Rightarrow \xi_{\text{beam-beam}} < 5 \times 10^{-3} \Rightarrow N < 1.7 \times 10^{11}$

@ nominal emittance: $\varepsilon_n = 3.75 \ \mu\text{m rad}$

Operation experience: $\Delta Q_{\text{beam-beam}} < 0.02 - 0.03$

3 head-on/bunch $\Rightarrow \xi_{\text{beam-beam}} < 10^{-2} \Rightarrow N < 3.6 \times 10^{11}$

@ $\varepsilon_n = 3.75 \ \mu\text{m rad}$

$\Rightarrow N < 2.4 \times 10^{11}$

@ $\varepsilon_n = 2.5 \ \mu\text{m rad}$

Assuming head-on collisions!
LHC Challenges: Beam-Beam Interaction

Design report: \( \Lambda \Omega < 0.01 \)

**Maximum beam brightness of** \( 10 \times 10^{10} \) ppb/\( \mu \text{m rad} \)
(compared to \( 8 \times 10^{10} \) ppb/\( \mu \text{m rad} \) in Rende’s presentation on Tuesday)

**Minimum emittance of** \( \varepsilon_n = 3.75 \, \mu \text{m rad} \) for \( 3.6 \times 10^{11} \) ppb
(single bunch TMCI limit)

**Minimum emittance of** \( \varepsilon_n = 2.5 \, \mu \text{m rad} \) for \( 2.4 \times 10^{11} \) ppb
(e-cloud limit for 25ns)

**Long-range BB separation > 10 \( \sigma \)**

(geometric reduction factor from crossing angle will affect BB tune shift)

Chamonix, 9 February 2012

Oliver Brüning BE-ABP
Potential Performance Limitations for the LHC

Number of bunches:

1) electron cloud effect $\Rightarrow$ limit depends on bunch spacing

2) Total beam power $\Rightarrow$ dedicated task in HL-LHC project $\Rightarrow$ for now we assume a limit of ca. 1 A per beam

1) Cleaning efficiency $\Rightarrow$ cryo collimators

2) Long range beam-beam: ca. 30+ /IP for 25ns bunch spacing

5) Injector performance depends on bunch spacing $\Rightarrow$ different brightness for 25ns & 50ns bunch spacing options
Performance: Turnaround

Turnaround Time after Stable Beams

Average Turn Around Times
- SB -> INJ = 6.46 hrs
- SB -> SB = 12.62 hrs
- Lumi Production: SB -> SB = 13.81 hrs
- Most Probable: SB -> SB = 5.23 hrs

SB->SB Speed records
- Top 5 Turnaround times
  1st: 2h07
  2nd: 2h13
  3rd: 2h28
  4th: 2h29
  5th: 2h29
Upgrade Considerations: Machine Efficiency

LHC Operation: theoretical maximum integrated luminosity

- average Turnaround time of ca. 5 hours @ 3.5 TeV (2.5 h minimum)
- Peak luminosity: $1.1 \times 10^{33}$ cm$^{-2}$ sec$^{-1}$
- Luminosity lifetime: ca. 20h ($35h$) exponential ($[1 + t/\tau]^2$) decay
  Can’t be explained by burn off (ca. 30h from DR restgas and IBS)!
- optimum fill length of ca. 14h with rather broad peak
- minimum fill-to-fill length: $2.5h + 14h = 16.5h$
- integrated luminosity / fill: ca. $40$ pb$^{-1}$ ($40$ pb$^{-1}$) (fill 1883) ($44$ pb$^{-1}$)
- integrated luminosity / day: ca. $58$ pb$^{-1}$ ($58$ pb$^{-1}$) ($65$ pb$^{-1}$)
- integrated luminosity / week: $405$ pb$^{-1}$ ($405$ pb$^{-1}$) ($450$ pb$^{-1}$)
LHC Operation:

- 650 pb\(^{-1}\) in last 4 weeks
- 800 pb\(^{-1}\) in last 5 weeks

Upgrade Considerations: Integrated Luminosity

Obtained integrated luminosity per week over last month: ca. 163 pb\(^{-1}\)

LHC Efficiency: ca. 163 / 405 \(\Rightarrow\) 40%
Potential limitations: high brightness operation:

No Leveling:

- ca. 0.6 fb\(^{-1}\) in 7 hours for start luminosity of 5 \(10^{34}\) cm\(^{-2}\) s\(^{-1}\):
  
  - 12 hour minimum fill-to-fill time for 5 h turnaround time
  - need 2.8 fills per day
  - 1.7 fb\(^{-1}\) per day
  - 250 fb\(^{-1}\) in 150 days
  - requires 100% efficiency to reach HL goals!

Chamonix, 9 February 2012
HL-LHC running scenarios:

- Assume average run length is reduced to premature end of fills
  - assume on average 25% shorter than ideal fill length
  - average fill time of 5h to 7.5h

- \( 1.33 \times 1 \) fills per day for \( k = 4 \)
  
  Efficiency = \( 1.33 \times 1 \times (0.75 \times [3h+7h]+5h) / 24 \) = 70% (63%)

- \( 1.33 \times 1.5 \) fills per day for \( k = 2 \)
  
  Efficiency = \( 1.33 \times 1.5 \times (0.75 \times [3h+4h]+5h) / 24 \) = 85% (75%)

Chamonix, 9 February 2012
LHC 2011 Run: Efficiency

Hubner factor

\[ H = 11.57 \times \frac{L_{\text{Del}}}{(D \times L_{\text{Peak}})} \]

\[ => H = 0.22 \]

- NB: based on Access (EIS Beam Status)
- All other categories use:
  - Beam mode
  - Beam presence
  - Lumi Production => 1380b

\[ D = 89.15 \text{ days} \]
\[ L_{\text{Peak}} = 2572.0 \text{ (µb.s)}^{-1} \]
\[ L_{\text{Del}} = 4.006 \text{ fb}^{-1} \]