Two Scenarios for the LHC Luminosity Upgrade

Walter Scandale, Frank Zimmermann

Special PAF meeting 10.04.2007

We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" programme (CARE, contract number RII3-CT-2003-506395)
outline

- beam parameters
- features, IR layouts, merits and challenges of both scenarios
- luminosity evolution
- bunch structures
- luminosity leveling
- summary & recommendations
- appendix - LUMI’06 outcome, effect of off-center collisions, shorter bunches vs crab cavities, Super-LHCb, leveling equations
luminosity reduction factor from crossing angle

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

Piwinski angle

 nominal LHC
<table>
<thead>
<tr>
<th>parameter</th>
<th>symbol</th>
<th>nominal</th>
<th>ultimate</th>
<th>12.5 ns, short</th>
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</thead>
<tbody>
<tr>
<td>transverse emittance</td>
<td>$\varepsilon$ [(\mu\mathrm{m})]</td>
<td>3.75</td>
<td>3.75</td>
<td>3.75</td>
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<tr>
<td>protons per bunch</td>
<td>$N_b$ [10^{11}]</td>
<td>1.15</td>
<td>1.7</td>
<td>1.7</td>
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<td>bunch spacing</td>
<td>$\Delta t$ [ns]</td>
<td>25</td>
<td>25</td>
<td>12.5</td>
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<tr>
<td>beam current</td>
<td>$I$ [A]</td>
<td>0.58</td>
<td>0.86</td>
<td>1.2</td>
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<tr>
<td>longitudinal profile</td>
<td></td>
<td>Gauss</td>
<td>Gauss</td>
<td>Gauss</td>
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<tr>
<td>rms bunch length</td>
<td>$\sigma_z$ [cm]</td>
<td>7.55</td>
<td>7.55</td>
<td>3.78</td>
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<tr>
<td>beta* at IP1&amp;5</td>
<td>$\beta^*$ [m]</td>
<td>0.55</td>
<td>0.5</td>
<td>0.25</td>
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<tr>
<td>full crossing angle</td>
<td>$\theta$ [(\mu\mathrm{rad})]</td>
<td>285</td>
<td>315</td>
<td>445</td>
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<td>Piwinski parameter</td>
<td>$\phi=\varepsilon \sigma_z / (2 \sigma_x^*)$</td>
<td>0.64</td>
<td>0.75</td>
<td>0.75</td>
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<td>peak luminosity</td>
<td>$L$ [10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}]</td>
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<td>88</td>
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<tr>
<td>initial lumi lifetime</td>
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<td>14</td>
<td>7.2</td>
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<td>0.91</td>
<td>2.7</td>
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<td></td>
<td>$T_{\text{run,opt}}$ [h]</td>
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<td>17.0</td>
<td>12.0</td>
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<td>effective luminosity (T_{turnaround}=5 h)</td>
<td>$L_{\text{eff}}$ [10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}]</td>
<td>0.56</td>
<td>1.15</td>
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<td></td>
<td>$T_{\text{run,opt}}$ [h]</td>
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<td>12.0</td>
<td>8.5</td>
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<td>e-c heat SEY=1.4(1.3)</td>
<td>$P$ [W/m]</td>
<td>1.07 (0.44)</td>
<td>1.04 (0.59)</td>
<td>3.34 (7.25)</td>
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<td>SR heat load 4.6-20 K</td>
<td>$P_{\text{SR}}$ [W/m]</td>
<td>0.17</td>
<td>0.25</td>
<td>0.5</td>
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<tr>
<td>image current heat</td>
<td>$P_{\text{IC}}$ [W/m]</td>
<td>0.15</td>
<td>0.33</td>
<td>1.87</td>
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<td>gas-s. 100 h (10 h) $\tau_b$</td>
<td>$P_{\text{gas}}$ [W/m]</td>
<td>0.04 (0.38)</td>
<td>0.06 (0.56)</td>
<td>0.113 (1.13)</td>
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<tr>
<td>extent luminous region</td>
<td>$\sigma_1$ [cm]</td>
<td>4.5</td>
<td>4.3</td>
<td>2.1</td>
</tr>
</tbody>
</table>

**Comment**: 
Total heat far exceeds max. local cooling capacity of 2.4 W/m

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**Baseline upgrade parameters 2001-2005**

- Abandoned at LUMI’06
- (SR and image current heat load well known)
<table>
<thead>
<tr>
<th>parameter</th>
<th>symbol</th>
<th>25 ns, small (\beta^*)</th>
<th>50 ns, long</th>
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<td>transverse emittance</td>
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<td>(\sigma_z) [cm]</td>
<td>7.55</td>
<td>11.8</td>
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<td>beta* at IP1&amp;5</td>
<td>(\beta^*) [m]</td>
<td>0.08</td>
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<td>(\theta) [(\mu\text{rad})]</td>
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<td>381</td>
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<td>Piwinski parameter (\phi=0_c\sigma/(2*\sigma_x^*))</td>
<td>0</td>
<td>2.0</td>
<td></td>
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<td>hourglass reduction</td>
<td></td>
<td>0.86</td>
<td>0.99</td>
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<tr>
<td>peak luminosity</td>
<td>(L) ([10^{34}\text{ cm}^{-2}\text{s}^{-1}])</td>
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<td>effective luminosity (T_{\text{turnaround}=10\text{ h}})</td>
<td>(L_{\text{eff}}) ([10^{34}\text{ cm}^{-2}\text{s}^{-1}])</td>
<td>2.4</td>
<td>2.5</td>
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<tr>
<td></td>
<td>(T_{\text{run, opt}}) [h]</td>
<td>6.6</td>
<td>9.5</td>
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<tr>
<td>effective luminosity (T_{\text{turnaround}=5\text{ h}})</td>
<td>(L_{\text{eff}}) ([10^{34}\text{ cm}^{-2}\text{s}^{-1}])</td>
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<td>(\sigma_t) [cm]</td>
<td>3.7</td>
<td>5.3</td>
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<tr>
<td>comment</td>
<td>D0 + crab (+ Q0)</td>
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</table>

two new upgrade scenarios

compromises between heat load and \# pile up events

wire comp.
for operation at beam-beam limit with alternating planes of crossing at two IPs, luminosity equation can be written as

\[
L \approx \pi \gamma (n_b) \frac{(\gamma \varepsilon) f_{rev}}{r_p^2 \beta^*} \Delta Q_{bb}^2 \sqrt{1 + \phi^2 F_{profile} F_{h - g}}
\]

where \( \Delta Q_{bb} = \) total beam-beam tune shift (hourglass effect is neglected above)
25-ns low-\(\beta\) upgrade scenario

- stay with ultimate LHC beam (1.7x10^{11} protons/bunch, 25 spacing)
- squeeze \(\beta^*\) to \(\sim 10\) cm in ATLAS & CMS
- add early-separation dipoles in detectors starting at \(\sim 3\) m from IP
- possibly also add quadrupole-doublet inside detector at \(\sim 13\) m from IP
- and add crab cavities (\(\phi_{\text{Piwinski}} \sim 0\), and/or shorten bunches with massive addt’l rf

\(\rightarrow\) new hardware inside ATLAS & CMS detectors, first hadron-beam crab cavities

(J.-P. Koutchouk et al)
CMS & ATLAS IR layout for 25-ns option

- D0 dipole
- Q0 quad's
- ultimate bunches & near head-on collision
- stronger triplet magnets
- small-angle crab cavity
25-ns scenario assessment

**merits:**
- negligible long-range collisions,
- no geometric luminosity loss,
- no increase in beam current beyond ultimate

**challenges:**
- D0 dipole deep inside detector (~3 m from IP),
- Q0 doublet inside detector (~13 m from IP),
- crab cavity for hadron beams (emittance growth),
  - or shorter bunches (requires much more RF)
- 4 parasitic collisions at 4-5$\sigma$ separation,
  - “chromatic beam-beam” $Q_{\text{eff}}^{\prime} \sim \sigma_z/(4\pi\beta^*\sigma_\delta)$,
- poor beam and luminosity lifetime $\sim \beta^*$.
50-ns higher $\beta^*$ upgrade scenario

- double bunch spacing
- longer & more intense bunches with $\phi_{\text{Piwinski}} \approx 2$
- keep $\beta^* \approx 25$ cm (achieved by stronger low-$\beta$ quads alone)
- do not add any elements inside detectors
- long-range beam-beam wire compensation

$\rightarrow$ novel operating regime for hadron colliders
CMS & ATLAS IR layout for 50-ns option

long bunches & nonzero crossing angle & wire compensation

text with diagrams and labels
50-ns scenario assessment

**merits:**
no elements in detector, no crab cavities,
lower chromaticity,
less demand on IR quadrupoles (NbTi possible),
could be adapted to crab waist collisions (LNF/FP7)

**challenges:**
operation with large Piwinski parameter unproven for hadron beams,
high bunch charge,
beam production and acceleration through SPS,
“chromatic beam-beam” \( Q'_{\text{eff}} \approx \sigma_z/(4\pi\beta*\sigma_\delta) \),
larger beam current,
wire compensation (almost established)
IR upgrade optics

“compact low-gradient” NbTi, $\beta^*=25$ cm
<75 T/m (Riccardo De Maria, Oliver Bruning)

“modular low gradient” NbTi, $\beta^*=25$ cm
<90 T/m (Riccardo De Maria, Oliver Bruning)

“low $\beta_{\text{max}}$ low-gradient” NbTi, $\beta^*=25$ cm
<125 T/m (Riccardo De Maria, Oliver Bruning)

standard Nb$_3$Sn upgrade, $\beta^*=25$ cm
~200 T/m, 2 versions with different magnet parameters
(Tanaji Sen et al, Emmanuel Laface, Walter Scandale)

+ crab-waist sextupole insertions? (LNF/FP7)

early separation with $\beta^*=8$ cm, Nb$_3$Sn
includes D0; either triplet closer to IP or Q0;
being prepared for PAC’07 (Jean-Pierre Koutchouk et al)
crab waist scheme

Hamiltonian

\[ H_I = -\frac{1}{4} p_y^2 \left( \frac{2x}{\theta_c} \right) \]

minimizes \( \beta \) at \( s = -x/\theta_c \)

initiated and led by LNF in the frame of FP7;
first beam tests at DAFNE later in 2007

realization:
add sextupoles at right phase distance from IP
IP1& 5 luminosity evolution for 25-ns and 50-ns spacing

![Graph showing luminosity evolution for 25-ns and 50-ns spacing.](image)

- **Luminosity** \([10^{34} \text{ cm}^{-2} \text{ s}^{-1}]\)
- **Time** \([\text{h}]\)
- **Initial luminosity peak** may not be useful for physics (set up & tuning?)
IP1 & 5 event pile up for 25-ns and 50-ns spacing

events per crossing

W. Scandale/F. Zimmermann, 10.04.2007
old upgrade bunch structure

nominal

ultimate

25 ns

12.5-ns upgrade

12.5 ns

abandoned at LUMI’06
new upgrade bunch structures

nominal

new alternative!
ultimate & 25-ns upgrade

50-ns upgrade, no collisions @S-LHCb!

new baseline!
50-ns upgrade with 25-ns collisions in LHCb

W. Scandale/F. Zimmermann, 10.04.2007
luminosity leveling in IP1&5

experiments prefer more constant luminosity, less pile up at the start of run, higher luminosity at end

*how could we achieve this?*

**25-ns low-β scheme:**
- dynamic β squeeze

**50-ns higher-β scheme:**
- dynamic β squeeze, and/or
- dynamic reduction in bunch length
  (less invasive)
dynamic $\beta$ squeeze for 25-ns option

$\beta^* [m]$

$\Delta N_{75}$

75 evts/Xing

$\Delta N_{150}$

150 evts/Xing

$N_b [10^{11}]$
dynamic $\beta$ squeeze for 50-ns option

we might also reduce the charge/bunch and go for shorter bunches

F. Zimmermann, W. Scandale, 10.04.2007
dynamic bunch length change for 50-ns option

\[ l_b \text{ [m]} \]

\[ N_b \text{ [10^{11}]} \]

75 evts/Xing
150 evts/Xing
300 evts/Xing

F. Zimmermann, W. Scandale, 10.04.2007
<table>
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<tr>
<th></th>
<th>25 ns, low $\beta^*$, with leveling</th>
<th>50 ns, long bunches, with leveling</th>
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<tr>
<td>events/crossing</td>
<td>300</td>
<td>300</td>
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<tr>
<td>run time</td>
<td>N/A</td>
<td>2.5 h</td>
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<tr>
<td>av. luminosity</td>
<td>N/A</td>
<td>$2.6 \times 10^{34} \text{s}^{-1} \text{cm}^{-2}$</td>
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<tr>
<td>events/crossing</td>
<td>150</td>
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<td>run time</td>
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<td>$1.7 \times 10^{34} \text{s}^{-1} \text{cm}^{-2}$</td>
</tr>
</tbody>
</table>

assuming 5 h turn-around time
IP1& 5 luminosity evolution for 25-ns and 50-ns spacing with leveling
IP1 & 5 event pile up for 25-ns and 50-ns spacing with leveling.

Events per crossing

25 ns spacing

50 ns spacing

Time [h]
example tune shifts with luminosity leveling
average luminosity & run time vs. final $\beta^*$ for 25-ns option with dynamic $\beta^*$ squeeze

average luminosity [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]

$\beta^*$ [m]

optimum run time [h]

F. Zimmermann, W. Scandale, 10.04.2007
average luminosity & run time vs. final $\beta^*$ for 50-ns option with dynamic $\beta^*$ squeeze

average luminosity $[10^{34} \text{cm}^{-2} \text{s}^{-1}]$

![Graph showing average luminosity vs. $\beta^*$ for different event rates.]

optimum run time [h]

![Graph showing optimum run time vs. $\beta^*$ for different event rates.]

F. Zimmermann, W. Scandale, 10.04.2007
average luminosity & run time vs. final $\sigma_z$ for 50-ns option with dynamic $\sigma_z$ change

average luminosity [10$^{34}$ cm$^{-2}$ s$^{-1}$]

![Graph showing average luminosity vs. $I_b$ for different event rates.

F. Zimmermann, W. Scandale, 10.04.2007
summary

- two scenarios of $L \sim 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ for which heat load and #events/crossing are acceptable

- 25-ns option: pushes $\beta^* ;$ requires slim magnets inside detector, crab cavities, & Nb$_3$Sn quadrupoles and/or Q0 doublet; attractive if total beam current is limited; transformed to a 50-ns spacing by keeping only $\frac{1}{2}$ the number of bunches

- 50-ns option: has fewer longer bunches of higher charge ; can be realized with NbTi technology if needed ; compatible with LHCb ; open issues are SPS & beam-beam effects at large Piwinski angle; luminosity leveling may be done via bunch length and via $\beta^*$
recommendations

• **luminosity leveling** should be seriously considered: → higher quality events, moderate decrease in average luminosity

• it seems **long-bunch 50-ns option** entails less risk and less uncertainties; however not w/o problems

• leaving the **25-ns option as back up** until we have gained some experience with the real LHC may be wise

• needed for both scenarios are **concrete optics solutions, beam-beam tracking studies, and beam-beam machine experiments**
appendix
Reminder of LUMI’06 Outcome

IR upgrade and beam parameters

1) quadrupole 1st preferred over dipole 1st
2) pushed NbTi or Nb$_3$Sn still pursued, or hybrid solution – new
3) slim magnets inside detector (“D0 and Q0”) – new
4) wire compensation ~established; electron lens – new
5) crab cavities: large angle rejected; small-angle – new
6) 12.5-ns scenario strongly deprecated
7) e-cloud/pile-up compromise: 25-ns w $\beta^*\sim$8 cm, or 50-ns spacing, $\beta^*$=0.25 m, long bunches – new
4 parasitic collisions at 4-5σ offset in 25-ns low-β case

cconcerns:

• poor beam lifetime
• enhanced detector background

discouraging experience at RHIC, SPS, HERA and Tevatron
RHIC experiments in 2005 and 2006

single off-center collision

one collision with $5-6\sigma$ offset strongly reduces RHIC beam lifetime; worse at smaller offsets

(W. Fischer et al.)
proton background with 1 head-on and 1 off-center collision vs beam-beam separation (K. Cornelis, LHC99); significantly affected by single LR collision at $3\sigma$ (W. Herr); see also PhD thesis M. Meddahi, CERN SL/91-30, Fig. 22
HERA ~1992

proton beam lifetime drops from 50 h to 1-5 h for single off-center collision with beam-beam separation between 0.3 and 2 \(\sigma\) (F. Willeke & R. Brinkmann, PAC 93; T. Limberg, LHC’99)

Tevatron 2006

removal of the four closest long-range collisions at about 6.2\(\sigma\) separation has increased integrated Tevatron luminosity per run by up to 30% (V. Shiltsev, private communication)
shorter bunches for 25 ns?

- reduced longitudinal emittance
  2.5 eVs $\rightarrow$ 1.78 eVs (loss of Landau damping if $\sigma_z^5 f_r f^3 V_{rf} < \text{const} N_b \text{ Im}(Z_\parallel/n)$; also stronger IBS)
- 43 MV rf voltage at 1.2 GHz
  (nominal LHC: 16 MV at 400 MHz)
- not sufficient to avoid large luminosity loss
  (for which crab cavities are needed anyhow)
bunch shortening rf voltage:

\[
V_{rf} \approx \left[ \frac{\varepsilon_{||,\text{rms}}^2 c^3 C \eta}{E_0 2\pi f_{rf}} \right] \frac{1}{\sigma_z^4} \approx \left[ \frac{\varepsilon_{||,\text{rms}}^2 c^3 C \eta}{E_0 2\pi f_{rf}} \right] \frac{\theta_c^4}{0.7^4 16 \sigma_x^{*4}}
\]

unfavorable scaling as 4\textsuperscript{th} power of crossing angle and inverse 4\textsuperscript{th} power of IP beam size; can be decreased by reducing the longitudinal emittance; inversely proportional to rf frequency

crab cavity rf voltage:

\[
V_{\text{crab}} = \frac{c E_0 \tan(\theta_c / 2)}{e 2\pi f_{rf} R_{12}} \approx \frac{c E_0}{e 4\pi f_{rf} R_{12}} \theta_c
\]

proportional to crossing angle & independent of IP beam size; scales with 1/R\textsubscript{12}; also inversely proportional to rf frequency
$V_{rf} \ [MV]$.

$\sigma^* = 11.7 \ \mu m, \ R_{12} = 30 \ m$

bunch shortening rf

2.5 eVs, 400 MHz
1.75 eVs, 400 MHz
1.75 eVs, 1.2 GHz

200 MHz
400 MHz
800 MHz

$\theta_c \ [rad]$
LHCb recipe for 50-ns scenario

• add satellites at 25 ns spacing
• these can be produced by highly asymmetric bunch splitting in the PS (possibly large fluctuation)
• in LHCb satellites collide with main bunches
• satellite intensity should be lower than $3 \times 10^{10}$ p/bunch to add <5% to beam-beam tune shift and to avoid e-cloud problems;
  $3 \times 10^{10} \sim 1/16^{th}$ of main-bunch charge
• $\beta$ function of $\sim 3$ m would result in desired luminosity equivalent to $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$; easily possible with present IR magnets & layout
LHCb schemes for 25-ns scenario

• here head-on collisions unavoidably contribute to beam-beam tune shift of the bunches colliding in ATLAS & CMS

• two potential ways out:
  – collisions with transverse offset; concerns: offset stability, interference with collimation, poor beam lifetime, detector background
  – collide at LHCb only in later part of each store, when the beam-beam tune shift from IP1 & 5 has decreased (H. Dijkstra)
LHCb collisions with transverse offset $d$

luminosity: \[ L = L_0 \exp\left(-\frac{d^2}{4\sigma^2}\right) \] (for Gaussian distribution)

\[ \Delta Q_{LHCb} = 2 \cdot \frac{\Delta Q_{IP1or5}}{(d/\sigma)^2} \]

suppose tune shift from LHCb should be less than 10% of that from CMS or ATLAS $\rightarrow d > 4.5 \sigma$; then luminosity $L \sim 0.006 L_0$

if we wish $L_{LHCb} \sim 0.01 \cdot L_{IP1or5} \sim 1-2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
we need $\beta^* \sim 0.08 \text{ m} \rightarrow \text{IR triplet upgrade!}$

offset collisions w/o IR upgrade $L_{LHCb} \sim 4 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$
LHCb luminosity for 25 ns with offset & 50 ns spacing,

luminosity $[10^{32} \text{cm}^{-2} \text{s}^{-1}]$

LHCb 50-ns luminosity decays 2x more slowly than 25-ns luminosity or that at ATLAS and CMS

F. Zimmermann, W. Scandale, 10.04.2007
tune shift during store for 25-ns & 50-ns spacing

total tune shift $\Delta Q$ (without LHCb)

LHCb 25-ns collisions from middle of each store?! $\beta^* \sim 3$ m

(5 h turnaround time is assumed)
LHCb luminosity for 25-ns late collisions & 50 ns spacing,

\[ \text{luminosity } [10^{32} \text{cm}^{-2} \text{s}^{-1}] \]

- 25 ns spacing, \( \beta^* \sim 3 \text{ m} \), no transverse offset
- 50 ns spacing, \( \beta^* \sim 3 \text{ m} \), satellites

(5 h turnaround time is assumed)

F. Zimmermann, W. Scandale, 10.04.2007
<table>
<thead>
<tr>
<th>parameter</th>
<th>symbol</th>
<th>25 ns, offset</th>
<th>25 ns, late collision</th>
<th>50 ns, satellites</th>
</tr>
</thead>
<tbody>
<tr>
<td>collision spacing</td>
<td>$T_{coll}$</td>
<td>25 ns</td>
<td>25 ns</td>
<td>25 ns</td>
</tr>
<tr>
<td>protons per bunch</td>
<td>$N_p$ [10^{11}]</td>
<td>1.7</td>
<td>1.7</td>
<td>4.9 &amp; 0.3</td>
</tr>
<tr>
<td>longitudinal profile</td>
<td></td>
<td>Gaussian</td>
<td>Gaussian</td>
<td>flat</td>
</tr>
<tr>
<td>rms bunch length</td>
<td>$\sigma_z$ [cm]</td>
<td>7.55</td>
<td>7.55</td>
<td>11.8</td>
</tr>
<tr>
<td>beta* at LHCb</td>
<td>$\beta*$ [m]</td>
<td>0.08</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>rms beam size</td>
<td>$\sigma_{x,y}^*$ [$\mu$m]</td>
<td>6</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>rms divergence</td>
<td>$\sigma_{x',y'}^*$ [$\mu$rad]</td>
<td>80</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>full crossing angle</td>
<td>$\theta_c$ [urad]</td>
<td>550</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>Piwinski parameter</td>
<td>$\phi=\theta_c\sigma_z/(2\sigma_{x}^*)$</td>
<td>3.3</td>
<td>0.18</td>
<td>0.28</td>
</tr>
<tr>
<td>peak luminosity</td>
<td>$L$ [10^{33} cm^{-2}s^{-1}]</td>
<td>1.13</td>
<td>2.1</td>
<td>2.4</td>
</tr>
<tr>
<td>effective luminosity</td>
<td>$L_{eff}$ [10^{33} cm^{-2}s^{-1}]</td>
<td>0.25</td>
<td>0.35</td>
<td>0.67</td>
</tr>
<tr>
<td>initial lumi lifetime</td>
<td>$\tau_L$ [h]</td>
<td>1.8</td>
<td>2.8</td>
<td>9</td>
</tr>
<tr>
<td>length of lum. region</td>
<td>$\sigma_l$ [cm]</td>
<td>1.6</td>
<td>5.3</td>
<td>8.0</td>
</tr>
</tbody>
</table>

rms length of luminous region:

$$\frac{1}{\sigma_l^2} \approx \left( \frac{2}{\sigma_z^2} + \frac{\theta_c^2}{2\sigma_{x,y}^*} \right)$$

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leveling equations

\[
\frac{\text{events}}{\text{Xing}} = \frac{L_0 \sigma_{\text{inel}}}{n_b} \approx \text{const} \quad L = L_0 \approx \text{const}
\]

\[
N = N_0 - \frac{L_0 \sigma_{\text{tot}} n_{\text{IP}}}{n_b} t
\]

beam intensity decays linearly

length of run

\[
t_{\text{run}} = \frac{\Delta N_{\text{max}} n_b}{L \sigma_{\text{tot}} n_{\text{IP}}}
\]

average luminosity

\[
L_{\text{ave}} = \frac{L_0}{1 + \frac{L_0 \sigma_{\text{tot}} n_{\text{IP}}}{\Delta N_{\text{max}} n_b} T_{\text{turn-around}}}
\]