LHC Upgrade Plan and Ideas

scenarios & constraints from the machine side

Frank Zimmermann
LHCb Upgrade Workshop
Edinburgh, 11 January 2007
(1) **life expectancy of LHC IR quadrupole magnets** <10 years due to high radiation doses

(2) **CMS (&ATLAS?) inner detector layers** to be replaced after ~5 years

(3) **statistical error halving time** likely to exceed 5 years by 2011-2012

→ **machine luminosity upgrade based on new low-β IR magnets around ~2014-2015; goal is 10x higher luminosity (**$10^{35} \text{ cm}^{-2}\text{s}^{-1}$**) in IP1&5**
limitations of present LHC

- triplet aperture, $l^* \ & \ crossing \ angle \ limit \ min. \ \beta^*$
- head-on beam-beam tune shift
- long-range beam-beam effect, $\rightarrow$ dynamic aperture at $\sim 6\sigma$ for nominal LHC
- e- cloud $\rightarrow$ heat-load in s.c. magnets, CB & SB instabilities, poor beam lifetime (all seen @ SPS)
- geometric luminosity loss due to crossing angle, $\sim 20\%$ for nominal LHC
- intensity limits from collimation (impedance, diffractive scattering in primary collimators)
- number of detector pile-up events per crossing (RHIC p-p <1, Tevatron Run-II $\sim 2$, nominal LHC $\sim 20$)

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upgrade “toolbox”

- reducing $\beta^*$ in IP1&5 by stronger larger-aperture low-beta quadrupoles based on Nb$_3$Sn, pushed NbTi, or hybrid scheme, closer to the IP
- limiting # IPs to two
- detector-integrated slim s.c. quadrupole doublet in IP1&5 (effective decrease of $l^*$)
- detector-integrated slim early-separation dipole in IP1&5
- long-range beam-beam compensators
- small-angle crab cavities
- adaptation of filling pattern and beam parameters
- e-cloud cures for LHC, SPS, and PS(2)
Towards a Roadmap for the Upgrade of the LHC and GSI Accelerator Complex
IFIC, Valencia (Spain), 16-20 October 2006
→ strong synergy with US-LARP mini collaboration meeting 25-27 Oct. 2006

IR scheme, beam parameters, injector upgrade
<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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<tbody>
<tr>
<td>transverse emittance</td>
<td>$\varepsilon$ [(\mu m)]</td>
<td>3.75</td>
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<tr>
<td>protons per bunch</td>
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<td>longitudinal profile</td>
<td>Gauss</td>
<td>Gauss</td>
<td>Gauss</td>
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<td>rms bunch length</td>
<td>$\sigma_z$ [cm]</td>
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<td>beta* at IP1&amp;5</td>
<td>$\beta^*$ [m]</td>
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<td>Piwinski parameter</td>
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<td>peak luminosity</td>
<td>$L$ [10^{34} cm^{-2}s^{-1}]</td>
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<td>9.2</td>
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<td>peak events per crossing</td>
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<td>initial lumi lifetime</td>
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<td>effective luminosity</td>
<td>$L_{eff}$ [10^{34} cm^{-2}s^{-1}]</td>
<td>0.56</td>
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<td>(T_{turnaround}=10 h)</td>
<td>$T_{run,opt}$ [h]</td>
<td>15.0</td>
<td>12.0</td>
<td>15.5</td>
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<tr>
<td>effective luminosity</td>
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<td>3.6</td>
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<tr>
<td>(T_{turnaround}=5 h)</td>
<td>$T_{run,opt}$ [h]</td>
<td>15.0</td>
<td>12.0</td>
<td>15.5</td>
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<tr>
<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>13.34 (7.85)</td>
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<tr>
<td>SR heat load 4.6-20 K</td>
<td>$P_{SR}$ [W/m]</td>
<td>0.17</td>
<td>0.25</td>
<td>0.05</td>
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<td>image current heat</td>
<td>$P_{IC}$ [W/m]</td>
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<tr>
<td>gas-s. 100 h (10 h) $\tau_b$</td>
<td>$P_{gas}$ [W/m]</td>
<td>0.04 (0.38)</td>
<td>0.06 (0.56)</td>
<td>0.113 (1.13)</td>
</tr>
</tbody>
</table>
| comment                         |         |          |          | partial wire c.

**baseline upgrade parameters 2001-2005**

**abandoned at LUMI’06**

**total heat load far exceeds maximum local cooling capacity of 2.4 W/m**

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<table>
<thead>
<tr>
<th>parameter</th>
<th>symbol</th>
<th>25 ns, small $\beta^*$</th>
<th>50 ns, long</th>
</tr>
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<tbody>
<tr>
<td>transverse emittance</td>
<td>$\varepsilon , [\mu m]$</td>
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<td>3.75</td>
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<tr>
<td>protons per bunch</td>
<td>$N_h , [10^{11}]$</td>
<td>1.7</td>
<td>4.9</td>
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<tr>
<td>bunch spacing</td>
<td>$\Delta t , [ns]$</td>
<td>25</td>
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<tr>
<td>beam current</td>
<td>$I , [A]$</td>
<td>0.86</td>
<td>1.22</td>
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<tr>
<td>longitudinal profile</td>
<td>Gauss</td>
<td>Flat</td>
<td></td>
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<td>rms bunch length</td>
<td>$\sigma_z , [cm]$</td>
<td>7.55</td>
<td>11.8</td>
</tr>
<tr>
<td>beta* at IP1&amp;5</td>
<td>$\beta^* , [m]$</td>
<td>0.08</td>
<td>0.25</td>
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<tr>
<td>full crossing angle</td>
<td>$\theta , [\mu rad]$</td>
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<td>381</td>
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<tr>
<td>Piwinski parameter</td>
<td>$\phi = \theta_c \frac{\sigma_z}{(2*\sigma_x^*)}$</td>
<td>0</td>
<td>2.0</td>
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<tr>
<td>hourglass reduction</td>
<td></td>
<td>0.86</td>
<td>0.99</td>
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<tr>
<td>peak luminosity</td>
<td>$L , [10^{34} , cm^{-2},s^{-1}]$</td>
<td>15.5</td>
<td>10.7</td>
</tr>
<tr>
<td>peak events per crossing</td>
<td></td>
<td>294</td>
<td>403</td>
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<td>initial lumi lifetime</td>
<td>$\tau_L , [h]$</td>
<td>2.2</td>
<td>4.5</td>
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<td>effective luminosity (T_{turnaround} $=10$ h)</td>
<td>$L_{eff} , [10^{34} , cm^{-2},s^{-1}]$</td>
<td>2.4</td>
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<td></td>
<td>$T_{run, opt} , [h]$</td>
<td>6.6</td>
<td>9.5</td>
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<tr>
<td>effective luminosity (T_{turnaround} $=5$ h)</td>
<td>$L_{eff} , [10^{34} , cm^{-2},s^{-1}]$</td>
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<td>3.5</td>
</tr>
<tr>
<td></td>
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<td>6.7</td>
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<td>$P_{IC} , [W/m]$</td>
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<td>0.78</td>
</tr>
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<td>gas-s. 100 h (10 h) $\tau_b$</td>
<td>$P_{gas} , [W/m]$</td>
<td>0.06 (0.56)</td>
<td>0.09 (0.9)</td>
</tr>
<tr>
<td>comment</td>
<td>D0 + crab (+ Q0)</td>
<td>wire comp.</td>
<td></td>
</tr>
</tbody>
</table>

two new upgrade scenarios in 2006

compromises between heat load and # pile up events

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

$$L \approx \pi \gamma (n_b) \left( \gamma \epsilon \right) f_{rev} \frac{\Delta Q_{bb}^2}{r_p^2 \beta^*} \sqrt{1 + \phi^2} F_{profile}$$

where $\Delta Q_{bb} = \text{total beam-beam tune shift}$
25-ns upgrade scenario

- stay with ultimate LHC beam (1.7x10^{11} protons/bunch, 25 spacing)
- squeeze β* to ~10 cm in ATLAS & CMS
- add early-separation dipoles in detectors starting at ~ 3 m from IP
- possibly also add quadrupole-doublet inside detector at ~13 m from IP
- and add crab cavities (ϕ_{Piwinski} ~ 0)

→ new hardware inside ATLAS & CMS detectors, possible interference

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

D0 dipole

Q0 quad’s

stronger triplet magnets

small-angle crab cavity

ultimate bunches & near head-on collision

merits:

negligible long-range collisions,
no geometric luminosity loss

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)
Are there slots for a “D0” dipole in ATLAS?

- We cannot put the D0 in the inner detector
- **BUT** there are potential slots starting at 3.5 m and 6.8 m (ATLAS)

*Courtesy of M. Nessi, ‘Machine upgrade, ATLAS considerations’, June 2006*
Where would we put the D0 in ATLAS?

G. Sterbini, J.-P. Koutchouk, LUMI’06
The same strategy in CMS

G. Sterbini, J.-P. Koutchouk, LUMI’06
50-ns upgrade scenario

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

→ new operating regime for hadron colliders
CMS & ATLAS IR layout for 50-ns option

merits:
no elements in detector, no crab cavities,
lower chromaticity

challenges:
operation with large Piwinski parameter unproven for
hadron beams, high bunch charge, larger beam current

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IP1 & 5 luminosity evolution for 25-ns and 50-ns spacing

Luminosity \left[ 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \right]

25 ns spacing

50 ns spacing

Average luminosity

Time [h]

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IP1&5 event pile up for 25-ns and 50-ns spacing

![Graph showing event pile up for 25-ns and 50-ns spacing.]

Frank Zimmermann, LHCb Upgrade Workshop
what about LHCb?
LHC Luminosity and Energy Upgrade: A Feasibility Study

O. Brüning$, R. Cappi‡, R. Garoby‡, O. Gröbner†, W. Herr§, T. Linnecar§, R. Ostojic†, K. Potter*, L. Rossi†, F. Ruggiero§ (editor), K. Schindl‡, G. Stevenson¶, L. Tavian†, T. Taylor†, E. Tsesmelis*, E. Weisse§, and F. Zimmermann§
from 2001 upgrade feasibility study

The tune footprint for the nominal configuration is shown in Fig. 2. In both planes the overall tune spread is about 0.01 by design. A higher luminosity can only be obtained with a reduced number of experiments. In earlier deliberations [2] a single experiment was considered for luminosities close to $7 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$. We aim at an increase of a factor two and want to allow for two high luminosity experiments. The footprint with ...

3.4.2 Ultimate LHC scheme

Operating the LHC with higher luminosities in special configurations was first discussed in Ref. [2]. An important issue is the reduction of the number of experiments. The configuration with two experiments opposite in azimuth and with crossings in orthogonal planes allows a re-optimization of the parameters. The parameters are shown in Table 8

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Nominal parameters</th>
<th>Ultimate parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta^*$ in high-$L$ experiments</td>
<td>2 high-$L$ + 2 low-$L$</td>
<td>2 (maximum)</td>
</tr>
<tr>
<td>Full crossing angle $\theta_c$</td>
<td>0.5 m</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Bunch intensity</td>
<td>300 $\mu$rad</td>
<td>300 $\mu$rad</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>$1.10 \times 10^{11}$ p/bunch</td>
<td>$1.67 \times 10^{11}$ p/bunch</td>
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<tr>
<td>Normalised emittance ($\varepsilon_\beta^2$)</td>
<td>25 ns</td>
<td>25 ns</td>
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<tr>
<td>Beam-beam parameter $\xi_0$</td>
<td>3.75 $\mu$m</td>
<td>3.75 $\mu$m</td>
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<tr>
<td>Luminosity ($\theta_c = 0$ $\mu$rad)</td>
<td>0.00343</td>
<td>0.00545</td>
</tr>
<tr>
<td>Reduction factor $F$</td>
<td>$1.2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$</td>
<td>$2.78 \times 10^{34}$ cm$^{-2}$ s$^{-1}$</td>
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<tr>
<td>Luminosity ($\theta_c = 300$ $\mu$rad)</td>
<td>0.81</td>
<td>0.81</td>
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<tr>
<td>Beam lifetime $\tau_b$</td>
<td>$1.0 \times 10^{34}$ cm$^{-2}$ s$^{-1}$</td>
<td>$2.27 \times 10^{34}$ cm$^{-2}$ s$^{-1}$</td>
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<tr>
<td>Luminosity lifetime $\tau_L$</td>
<td>78 h</td>
<td>49 h</td>
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<tr>
<td></td>
<td>29 h</td>
<td>18 h</td>
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</tbody>
</table>

(note: 2006 nominal and ultimate parameters are slightly different)
from 2001 upgrade feasibility study

nominal tune footprint up to $6\sigma$ with 4 IPs

$L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

tune footprint up to $6\sigma$ with 2 IPs

tune footprint up to $6\sigma$ with 2 IPs at ultimate intensity

$L = 2.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

SPS, Tevatron, RHIC experience: beam-beam limit ↔ total tune shift $\Delta Q \sim 0.01$

going from 4 to 2 IPs we can increase ATLAS&CMS luminosity by factor 2.3

this and all following upgrade studies were based on assumption of only 2 IPs

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can we make (upgraded) LHCb compatible with upgraded LHC?!

- aim to minimize contribution to beam-beam tune shift (note: \( \Delta Q \) is independent of \( \beta^* \))

- aim to provide optimum LHCb luminosity of \( 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}/2808 \) per bunch crossing, or \( 1/50^{\text{th}} \) of luminosity in IP1 & 5
bunch structures

nominal

ultimate & 25-ns upgrade

50-ns upgrade, no collisions in LHCb!

50-ns upgrade with 25-ns collisions in LHCb
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

[simpler alternative with lower rate: collide displaced 50-ns bunch trains in LHCb @ $\beta^* \sim 25$ m (R. Garoby)]
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
  - 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)

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

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

offset collisions w/o IR upgrade $L_{LHCb} \sim 4 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$
other concerns for 4-5σ offset collisions:

• offset stability
• interference with LHC collimation
• effect on beam lifetime
• effect on detector background

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

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

(W. Fischer et al.)

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SPS collider ~1980s

proton background with 1 head-on and 1 off-center collision vs beam-beam separation (K. Cornelis, LHC99)
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 6.2σ separation has increased integrated Tevatron luminosity per run by up to 30%

(V. Shiltsev, private communication)
LHCb luminosity for 25 ns with offset & 50 ns spacing, 4.5σ offset, β*~0.08 m

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

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tune shift during store for 25-ns & 50-ns spacing

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

change $\Delta Q \sim -0.0033$

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,

$\beta^* \sim 3 \text{ m}$,

no transverse offset

50 ns spacing, $\beta^* \sim 3 \text{ m}$, satellites

25 ns spacing, $\beta^* \sim 3 \text{ m}$, no transverse offset

(5 h turnaround time is assumed)
<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>
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<tbody>
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<td>collision spacing</td>
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<td>25 ns</td>
<td>25 ns</td>
<td>25 ns</td>
</tr>
<tr>
<td>protons per bunch</td>
<td>$N_b [10^{11}]$</td>
<td>1.7</td>
<td>1.7</td>
<td>4.9 &amp; 0.3</td>
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<tr>
<td>longitudinal profile</td>
<td></td>
<td>Gaussian</td>
<td>Gaussian</td>
<td>flat</td>
</tr>
<tr>
<td>rms bunch length</td>
<td>$\sigma_z [\mu m]$</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>
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<tr>
<td>full crossing angle</td>
<td>$\theta_c [\mu rad]$</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>
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<tr>
<td>peak luminosity</td>
<td>$L [10^{33} \text{ cm}^{-2}\text{s}^{-1}]$</td>
<td>1.13</td>
<td>2.1</td>
<td>2.4</td>
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<tr>
<td>initial lumi lifetime</td>
<td>$\tau_L [\text{h}]$</td>
<td>1.8</td>
<td>2.8</td>
<td>9</td>
</tr>
<tr>
<td>length of lum. region</td>
<td>$\sigma_l [\text{cm}]$</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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**summary**

- two paths to 10x higher luminosity in IP1&5: based on 25-ns and 50-ns bunch spacing
- early LHC experience may determine choice
- original upgrade plans did not consider LHCb
- however LHCb can be made compatible
- for 50-ns upgrade: satellite bunches at 25 ns could yield desired LHCb luminosity and be nearly transparent with respect to other IPs
- for 25-ns upgrade: LHCb collisions with large transverse offset + LHCb IR upgrade not too promising; better: late collisions with $\beta^* \sim 3$ m
Thank you for your attention!

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