Upgrade of LHC, R&D and impact on LHC detectors

- LHC performance limitations
- Commissioning and nominal parameters
- Upgrade options and phases:
  - Phase 0: no hardware modifications
  - Phase 1: Interaction Region upgrade
  - Phase 2: major hardware modifications
The time scale of an LHC luminosity upgrade is set by the statistical error “halving time” for the experiments and by the radiation damage limit for the Interaction Region (IR) quadrupoles, currently estimated to about 700 fb$^{-1}$. The error “halving time” is defined as the machine running time required to multiply the integrated luminosity by a factor four.

- Due to the high radiation doses to which they will be submitted, the life expectancy of LHC IR quadrupole magnets is estimated to less than 10 years.
- Depending on the luminosity evolution, the error “halving time” will exceed 5 years by 2011-2012.
- Therefore it is reasonable to plan a machine luminosity upgrade based on new low-$\beta$ IR magnets before $\sim$2014.
Chronology of LHC Upgrade Studies


- **March 2002**: LHC IR Upgrade collaboration meeting
  [http://cern.ch/lhc-proj-IR-upgrade](http://cern.ch/lhc-proj-IR-upgrade)

- **October 2002**: ICFA Seminar at CERN on “Future Perspectives in High Energy Physics”

- **March 2003**: LHC Performance Workshop, Chamonix

- **2004**: CARE-HHH European Network on **High Energy**
  **High Intensity**
  **Hadron Beams**
Constraints for LHC commissioning parameters

- Only 8 of the 20 LHC dump dilution kickers will be available during the first two years of operation. This limits the total beam intensity in each LHC ring to 1/2 of its nominal value.

- According to SPS experience and to electron cloud simulations, the initial LHC bunch intensity can reach and possibly exceed its nominal value for 75 ns bunch spacing, while it may be limited to about 1/3 of its nominal value for 25 ns spacing.

- Machine protection and collimation favours initial operation with lower beam power and lower transverse beam density. Simple graphite collimators may limit maximum transverse energy density to about 1/2 of its nominal value.

- Emittance preservation from injection to physics conditions will require a learning curve → do not assume transverse emittance lower than nominal, even for reduced bunch intensity.

- Initial operation with relaxed parameters is strongly favoured → higher $\beta^*$, reduced crossing angle, and fewer parasitic collisions.
Challenge of a Cold Machine

Magnet Quench:
- beam abort
- several hours of recovery

LHC nominal beam intensity:
\[ I = 0.5 \text{ A} \quad \Rightarrow \quad 3 \cdot 10^{14} \text{ p/beam} \]

Quench level:
\[ N_{\text{lost}} < 7.0 \cdot 10^8 \text{ m}^{-1} \quad \Rightarrow \quad 2.2 \cdot 10^{-6} N_{\text{beam}} \]

(compared to 20% to 30% in other superconducting proton storage rings)

- remove stray particles and maximize aperture

Courtesy Oliver Bruning
Collimation & Machine Protection

- **Beam core**: ca. 2σ
- **Primary beam halo**: generated by: non-linearities (beam-beam) noise
  ca. 2σ – 6σ
  IBS can damage equipment
- **Secondary beam halo**: generated by: primary collimator
  ca. 6σ – 8σ can quench cold equipment

Courtesy Oliver Bruning
Stored beam energy for different accelerators (courtesy R. Assmann). The energy stored in the nominal LHC beam at 7 TeV is 10000 times that in the LEP2 beam and 200 times that in the Tevatron beam. Machine protection and collimation at the LHC is challenging, since the transverse energy density is even a factor 1000 larger.
impedance is a function of collimator jaw opening and thus imposes limits on total intensity AND the minimum beam size at the IP ($\beta^*$).

Impedance is a function of collimator jaw opening and thus imposes limits on total intensity AND the minimum beam size at the IP ($\beta^*$).

**Vertical plane**

Stability diagram for closure to 6 $\sigma$

**All the machine**

**Collimators**

**RW without collimators**

**BB impedance**

---

**E. Metral & F. Ruggiero**

Courtesy Oliver Bruning
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>75 ns spacing</th>
<th>25 ns spacing</th>
<th>nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of bunches</td>
<td>(n_b)</td>
<td>936</td>
<td>2808</td>
<td>2808</td>
</tr>
<tr>
<td>protons per bunch</td>
<td>(N_b [10^{11}])</td>
<td>0.9</td>
<td>0.4</td>
<td>1.15</td>
</tr>
<tr>
<td>norm. tr. emittance</td>
<td>(\varepsilon_n [\mu m])</td>
<td>3.75</td>
<td>3.75</td>
<td>3.75</td>
</tr>
<tr>
<td>r.m.s. bunch length</td>
<td>(\sigma_s [cm])</td>
<td>7.55</td>
<td>7.55</td>
<td>7.55</td>
</tr>
<tr>
<td>r.m.s. energy spread</td>
<td>(\sigma_E [10^{-4}])</td>
<td>1.13</td>
<td>1.13</td>
<td>1.13</td>
</tr>
<tr>
<td>IBS growth time</td>
<td>(\tau_x^{IBS} [h])</td>
<td>135</td>
<td>304</td>
<td>106</td>
</tr>
<tr>
<td>beta at IP</td>
<td>(\beta^* [m])</td>
<td>1.0</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>full crossing angle</td>
<td>(\theta_c [\mu \text{rad}])</td>
<td>250</td>
<td>285</td>
<td>285</td>
</tr>
<tr>
<td>luminosity lifetime</td>
<td>(\tau_L [h])</td>
<td>22</td>
<td>26</td>
<td>15</td>
</tr>
<tr>
<td>peak luminosity</td>
<td>(L [10^{34} \text{ cm}^{-2} \text{ s}^{-1}])</td>
<td>0.12</td>
<td>0.12</td>
<td>1.0</td>
</tr>
<tr>
<td>events/crossing</td>
<td></td>
<td>7.1</td>
<td>2.3</td>
<td>19.2</td>
</tr>
<tr>
<td>lumi over 200 fills</td>
<td>(L_{\text{int}} [\text{fb}^{-1}])</td>
<td>9.3</td>
<td>9.5</td>
<td>66.2</td>
</tr>
</tbody>
</table>

Possible scenarios with 75 ns and 25 ns bunch spacing for an early LHC luminosity run with integrated luminosity of \(\sim 10 \text{ fb}^{-1}\) in about 200 fills, assuming an average physics run time \(T_{\text{run}} = 14 \text{ h}\) and \(T_{\text{turnaround}} = 10 \text{ h}\).
In their present configuration, the CMS and ATLAS detectors can accept a maximum luminosity of $3 \div 5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

An increase in luminosity may require positioning the low-$\beta$ quadrupoles closer to the IP.

An ultimate bunch intensity of $1.7 \times 10^{11} \text{ p/bunch}$ is compatible with the present beam dumping system. Further increases, e.g. to $2 \times 10^{11} \text{ p/bunch}$ or slightly higher, could still be tolerated accepting somewhat reduced safety margins or implementing moderate upgrades. Machine protection and collimation will be challenging.

A possibility being considered also for CNGS beams is to upgrade the proton linac from 50 to $120 \div 160 \text{ MeV}$, to overcome space charge limitations at injection in the booster. Then the ultimate LHC intensity would become easy to achieve and a further 30% increase would be possible with same emittance and same LHC filling time.

If nominal (ultimate) luminosity is reached by 2011, the radiation damage limit for IR quads ($\sim 700 \text{ fb}^{-1}$) is reached by 2017 (2013).
Luminosity optimization

peak luminosity for round beams colliding with full crossing angle $\theta_c$

$$L = \frac{N_b^2 f_{\text{rep}}}{4\pi \sigma^*^2} F$$ reduced by a factor $F \simeq 1/\sqrt{1 + \left( \frac{\theta_c \sigma_z}{2\sigma^*} \right)^2}$

$f_{\text{rep}} = n_b f_o$: average bunch repetition frequency,

$\sigma^* = \sqrt{\varepsilon \beta^*}$: r.m.s. transverse beam size at the IP (16 $\mu$m for LHC)

maximum luminosity below beam-beam limit $\implies$ short bunches and minimum crossing angle (baseline scheme)

H-V crossings in two IPs $\implies$ no linear tune shift due to long range total linear beam-beam tune shift also reduced by a factor $F_{bb} \simeq F$

$$\Delta Q_{bb} = \xi_x + \xi_y = \frac{N_b r_p}{2\pi \varepsilon_n} F$$
if bunch intensity and brilliance are not limited by the injectors or by other effects in the LHC (e.g. electron cloud) \( \implies \) luminosity can be increased without exceeding the beam-beam limit \( \Delta Q_{bb} \sim 0.01 \) by increasing the crossing angle and/or the bunch length.

express beam-beam limited brilliance \( N_b/\varepsilon_n \) in terms of maximum total beam-beam tune shift \( \Delta Q_{bb} \), then

\[
L \simeq \gamma \Delta Q_{bb}^2 \frac{\pi \varepsilon_n f_{rep}}{r_p^2 \beta^*} \sqrt{1 + \left( \frac{\theta_c \sigma_z}{2 \sigma^*} \right)^2}
\]

luminosity is proportional to collision energy and normalized transverse emittance \( \varepsilon_n = \gamma \varepsilon \implies \) an increased injection energy (Super-SPS) allows a larger normalized emittance and thus more intensity and more luminosity at the beam-beam limit.

Another possibility to achieve significant luminosities with large crossing angles consists in colliding very long ‘super-bunches’.
Schematic of long-range collisions on either side of the main interaction point. (Courtesy F. Zimmermann)
Schematic of a super-bunch collision, consisting of ‘head-on’ and ‘long-range’ components. The luminosity for super-bunches having flat longitudinal distribution is $\sqrt{2}$ times higher than for conventional Gaussian bunches with the same beam-beam tune shift and identical bunch population (see LHC Project Report 627).
**Minimum crossing angle**

\[ d_{\text{sep}}/\sigma \simeq \theta_c/\sigma_\theta: \text{relative beam separation} \]
\[ \sigma_\theta = \sqrt{\varepsilon/\beta^*}: \text{r.m.s. angular beam divergence at the IP} \]

scaling law for 'diffusive aperture' \( d_{\text{da}} \) with long range collisions

\[
(d_{\text{sep}} - d_{\text{da}})/\sigma \propto \sqrt{k_{\text{par}} N_b/\varepsilon_n}
\]

The ratio \((d_{\text{sep}} - d_{\text{da}})/\sigma\) is independent of \(\beta\) and beam energy; it is again a function of the brilliance \(N_b/\varepsilon_n\). From particle tracking

\[
d_{\text{da}}/\sigma \simeq \theta_c \sqrt{\beta^*/\varepsilon} - 3 \sqrt{\frac{k_{\text{par}}}{2 \times 32} \frac{N_b}{10^{11}} \frac{3.75 \mu \text{m}}{\varepsilon_n}}
\]

nominal LHC parameters \(\theta_c = 300 \mu\text{rad}\) and \(\sigma_\theta = 31.7 \mu\text{rad}\) \(\implies\)
\(d_{\text{sep}} \simeq 9.5\sigma\) and \(d_{\text{da}} \simeq 6 \div 6.5\sigma\). Preserving a comparable dynamic aperture with higher bunch intensities, shorter bunch spacings, and/or smaller \(\beta^*\) requires larger crossing angles.
2nd prototype BBLR in the CERN SPS has demonstrated benefit of compensation

Summary Beam-Beam Compensation

- active beam-beam compensation programme in progress for Tevatron & LHC

- TEL promising, but conditions difficult to control

- wire compensation of LR collisions at LHC will allow smaller crossing angles and/or higher bunch charges;

  - experimental demonstration in the SPS;

  - pulsed wire desirable for selective correction of PACMAN bunches

- crab cavities alternative option for large crossing angle
Crab Cavity


combines all advantages of head-on collisions and large crossing angles

<table>
<thead>
<tr>
<th>variable</th>
<th>symbol</th>
<th>KEKB</th>
<th>SuperLHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy</td>
<td>$E_b$</td>
<td>8 GeV</td>
<td>7 TeV</td>
</tr>
<tr>
<td>rf frequency</td>
<td>$f_{crab}$</td>
<td>508 MHz</td>
<td>0.35</td>
</tr>
<tr>
<td>crossing angle</td>
<td>$\Theta_c$</td>
<td>11 mrad</td>
<td>8 mrad</td>
</tr>
<tr>
<td>IP $\beta$</td>
<td>$\beta^*$</td>
<td>0.33 m</td>
<td>0.25 m</td>
</tr>
<tr>
<td>cavity $\beta$</td>
<td>$\beta_{cav}$</td>
<td>100 m</td>
<td>2 km</td>
</tr>
<tr>
<td>kick voltage</td>
<td>$V_{crab}$</td>
<td>1.44 MV</td>
<td>171</td>
</tr>
<tr>
<td>phase tolerance</td>
<td>$\Delta\phi$</td>
<td>0.02</td>
<td>0.06 mrad</td>
</tr>
</tbody>
</table>
In the LHC, photoelectrons created at the vacuum pipe wall are accelerated by proton bunches up to 200 eV and cross the pipe in about 5 ns. Slow or reflected secondary electrons survive until the next bunch. Depending on vacuum pipe surface conditions (SEY) and bunch spacing, this may lead to an electron cloud build-up with implications for beam stability, emittance growth, and heat load on the cold LHC beam screen.
arc heat load vs. intensity, 25 ns spacing, ‘best’ model

heat load

R=0.5

delta_max=1.1

delta_max=1.3

delta_max=1.5

delta_max=1.7

cooling capacity

heat load for quadrupoles higher in 2nd batch; still to be clarified
arc heat load vs. spacing, $N_b=1.15 \times 10^{11}$, ‘best’ model

heat load

$bunch$ spacing [ns]

Frank Zimmermann, LTC 06.04.05
Schematic of reduced electron cloud build-up for a super-bunch. (Courtesy F. Zimmermann)
LHC Upgrade Scenarios

- LHC Phase 0: maximum performance without hardware changes
- LHC Phase 1: maximum performance with the LHC arcs unchanged
- LHC Phase 2: maximum performance with ‘major’ hardware changes

The nominal LHC performance at 7 TeV corresponds to a total beam-beam tune spread of 0.01, with a luminosity of $10^{34} \text{ cm}^{-2} \text{s}^{-1}$ in IP1 and IP5 (ATLAS and CMS), halo collisions in IP2 (ALICE) and low-luminosity in IP8 (LHC-b). The steps to reach ultimate performance without hardware changes (LHC Phase 0) are:

1. collide beams only in IP1 and IP5 with alternating H-V crossing
2. increase $N_b$ up to the beam-beam limit $\rightarrow L = 2.3 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$
3. increase the dipole field to 9 T (ultimate field) $\rightarrow E_{\text{max}} = 7.54 \text{ TeV}$

The ultimate dipole field of 9 T corresponds to a beam current limited by cryogenics and/or by beam dump considerations.
<table>
<thead>
<tr>
<th>parameter</th>
<th>symbol</th>
<th>units</th>
<th>nominal</th>
<th>ultimate</th>
<th>Piwinski</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of bunches</td>
<td>$n_b$</td>
<td></td>
<td>2808</td>
<td>2808</td>
<td>2808</td>
</tr>
<tr>
<td>bunch spacing</td>
<td>$\Delta t_{\text{sep}}$</td>
<td>ns</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>protons per bunch</td>
<td>$N_b$</td>
<td>$10^{11}$</td>
<td>1.1</td>
<td>1.7</td>
<td>2.6</td>
</tr>
<tr>
<td>aver. beam current</td>
<td>$I_{\text{av}}$</td>
<td>A</td>
<td>0.56</td>
<td>0.86</td>
<td>1.32</td>
</tr>
<tr>
<td>norm. tr. emittance</td>
<td>$\varepsilon_n$</td>
<td>$\mu$m</td>
<td>3.75</td>
<td>3.75</td>
<td>3.75</td>
</tr>
<tr>
<td>long. emittance</td>
<td>$\varepsilon_L$</td>
<td>eV s</td>
<td>2.5</td>
<td>2.5</td>
<td>4.0</td>
</tr>
<tr>
<td>peak RF voltage</td>
<td>$V_{\text{RF}}$</td>
<td>MV</td>
<td>16</td>
<td>16</td>
<td>3/1</td>
</tr>
<tr>
<td>RF frequency</td>
<td>$f_{\text{RF}}$</td>
<td>MHz</td>
<td>400.8</td>
<td>400.8</td>
<td>200.4/400.8</td>
</tr>
<tr>
<td>r.m.s. bunch length</td>
<td>$\sigma_z$</td>
<td>cm</td>
<td>7.55</td>
<td>7.55</td>
<td>15.2</td>
</tr>
<tr>
<td>r.m.s. energy spread</td>
<td>$\sigma_E$</td>
<td>$10^{-4}$</td>
<td>1.13</td>
<td>1.13</td>
<td>0.9</td>
</tr>
<tr>
<td>IBS growth time</td>
<td>$\tau_{x,\text{IBS}}$</td>
<td>h</td>
<td>111</td>
<td>72</td>
<td>87</td>
</tr>
<tr>
<td>beta at IP1-IP5</td>
<td>$\beta^*$</td>
<td>m</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>full crossing angle</td>
<td>$\theta_c$</td>
<td>$\mu$rad</td>
<td>300</td>
<td>315</td>
<td>345</td>
</tr>
<tr>
<td>lumi at IP1-IP5</td>
<td>$L$</td>
<td>$10^{34}/\text{cm}^2\text{s}$</td>
<td>1.0</td>
<td>2.3</td>
<td>3.6</td>
</tr>
</tbody>
</table>
Comparison of tune footprints, corresponding to betatron amplitudes extending from 0 to 6 $\sigma$, for LHC nominal (red-dotted), ultimate (green-dashed), and large Piwinski parameter configuration (blue-solid) with alternating H-V crossing only in IP1 and IP5. (Courtesy H. Grote)
LHC Phase 1: Luminosity Upgrade

Possible steps to increase the LHC luminosity with hardware changes only in the LHC insertions and/or in the injector complex include the following baseline scheme:

1. modify insertion quadrupoles and/or layout $\rightarrow \beta^* = 0.25$ m
2. increase crossing angle by $\sqrt{2} \rightarrow \theta_c = 445$ $\mu$rad
3. increase $N_b$ up to ultimate intensity $\rightarrow L = 3.3 \times 10^{34}$ cm$^{-2}$ s$^{-1}$
4. halve $\sigma_z$ with high harmonic RF system $\rightarrow L = 4.6 \times 10^{34}$ cm$^{-2}$ s$^{-1}$
5. double number of bunches (and increase $\theta_c$!) $\rightarrow L = 9.2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

excluded by electron cloud?

Step 4 is not cheap since it requires a new RF system with 43 MV at 1.2 GHz and a power of about 11 MW/beam (estimated cost 56 MCHF). The changeover from 400 to 1200 MHz is assumed at 7 TeV, or possibly at an intermediate flat top, where stability problems may arise in view of the reduced longitudinal emittance of 1.78 eVs. The horizontal Intra-Beam Scattering growth time decreases by about $\sqrt{2}$.
luminosity upgrade: baseline scheme

1.0

增加 $N_b$

增加 $F$

$F \approx \left(1 + \left(\frac{\theta_c \sigma_z}{2\sigma^2}\right)^2\right)^{-1/2}$

$\theta_c > \theta_{\text{min}}$ 由于 LR-bb 补偿

BBLR 补偿

crab cavities

- 降低 $\sigma_z$ 由因子 ~2 使用更高 $f_{\text{rf}}$ 及更低 $\varepsilon_{||}$
- (larger $\theta_c$ ?)

2.3

- 降低 $\theta_c$ (压缩 $\beta^*$)

4.6

- 如果 e-cloud，丢弃 & 阻抗 ok

- 降低 $\beta^*$ 由因子 ~2 新 IR 磁铁

- 增加 $n_b$ 由因子 ~2

- 简化 IR 设计带大 $\theta_c$

- 使用大 $\theta_c$ 及通过分离的磁性通道

- 带大 $\theta_c$ 的简化 IR 设计

- 1.72 A 包含电流

- 0.86 A 包含电流

- 0.58 A 包含电流
luminosity upgrade: Piwinski scheme

- Reduce $\beta^*$ by factor $\sim 2$
- New IR magnets
- Increase $\sigma_z \theta_c$
- Decrease $F$

\[ F \approx \left(1 + \left(\frac{\theta \sigma_z}{2\sigma^2}\right)^2\right)^{-1/2} \]

- Increase $N_b$
- Superbunches?
- Flatten profile?
- Reduce #bunches to limit total current?

\[ N_b = \frac{2\pi}{r_p F} (\gamma \varepsilon) \Delta Q_{bb} \]

- Yes
- No

Luminosity gain: 7.7
Beam current: 0.86 A
Beam current: 1.72 A

Options:
- 1.0
- 0.58 A
## example parameter sets

<table>
<thead>
<tr>
<th>parameter</th>
<th>symbol</th>
<th>nominal</th>
<th>ultimate</th>
<th>shorter bunches</th>
<th>longer bunches</th>
<th>superbunch</th>
</tr>
</thead>
<tbody>
<tr>
<td>#bunches</td>
<td>$n_b$</td>
<td>2808</td>
<td>2808</td>
<td>5616</td>
<td>936</td>
<td>1</td>
</tr>
<tr>
<td>protons/bunch</td>
<td>$N_b \times 10^{11}$</td>
<td>1.15</td>
<td>1.7</td>
<td>1.7</td>
<td>6.0</td>
<td>5600</td>
</tr>
<tr>
<td>bunch spacing</td>
<td>$\Delta t_{sep} \ [\text{ns}]$</td>
<td>25</td>
<td>25</td>
<td>12.5</td>
<td>75</td>
<td>89000</td>
</tr>
<tr>
<td>average current</td>
<td>$I \ [\text{A}]$</td>
<td>0.58</td>
<td>0.86</td>
<td>1.72</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>norm. transv. emittance</td>
<td>$\varepsilon_n \ [\mu \text{m}]$</td>
<td>3.75</td>
<td>3.75</td>
<td>3.75</td>
<td>3.75</td>
<td>3.75</td>
</tr>
<tr>
<td>longit. profile</td>
<td></td>
<td>Gaussian</td>
<td>Gaussian</td>
<td>Gaussian</td>
<td>uniform</td>
<td>uniform</td>
</tr>
<tr>
<td>rms b. length</td>
<td>$\sigma_z \ [\text{cm}]$</td>
<td>7.55</td>
<td>7.55</td>
<td>3.78</td>
<td>14.4</td>
<td>6000</td>
</tr>
<tr>
<td>beta at IP1&amp;IP5</td>
<td>$\beta^* \ [\text{m}]$</td>
<td>0.55</td>
<td>0.5</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>crossing angle</td>
<td>$\theta_c \ [\mu \text{rad}]$</td>
<td>285</td>
<td>315</td>
<td>445</td>
<td>430</td>
<td>1000</td>
</tr>
<tr>
<td>Piwinski parameter</td>
<td>$\theta_c\sigma_z/(\sigma^*)^2$</td>
<td>0.64</td>
<td>0.75</td>
<td>0.75</td>
<td>2.8</td>
<td>2700</td>
</tr>
<tr>
<td>luminosity</td>
<td>$L \times 10^{34} \ [\text{cm}^{-2} \text{s}^{-1}]$</td>
<td>1.0</td>
<td>2.3</td>
<td>9.2</td>
<td>8.9</td>
<td>9.0</td>
</tr>
<tr>
<td>events/ crossing</td>
<td></td>
<td>19</td>
<td>44</td>
<td>88</td>
<td>510</td>
<td>5x10^5</td>
</tr>
<tr>
<td>length luminous region (rms)</td>
<td>$\sigma_{lum} \ [\text{mm}]$</td>
<td>44.9</td>
<td>42.8</td>
<td>21.8</td>
<td>36.3</td>
<td>16.7</td>
</tr>
</tbody>
</table>

baseline  'Piwinski'  super-bunch
statement from experiments on super-bunches: [S. Tapprogge, modified]

“based on the physics motivation for an upgrade of the LHC luminosity by an order of magnitude it is not seen how in case of the super-bunch scenario, this increase in luminosity could be exploited by an upgraded ATLAS or CMS detector”

the above assumes that detector upgrade does not mean building a completely new detector

pile up for super-bunches would be problematic in any case

integrated luminosity in stable running mode is what counts most

preference from experiments: shorter but finite bunch spacing, e.g., 12.5 ns; present detector read-out electronics at 80 MHz! (but actually, for the accelerators it is much easier to provide 10 ns or 15 ns spacing!); eases especially pattern recognition
Experimental conditions at $10^{35}$ cm$^{-2}$ s$^{-1}$ (12.5ns)

~ 100 pile-up events per bunch crossing - if 12.5 nsec bunch spacing - compared to ~ 20 for operation at $10^{34}$cm$^{-2}$s$^{-1}$ and 25 nsec (nominal LHC regime),

\[ \frac{dN_{ch}}{d\eta}/\text{crossing} \approx 600 \text{ and } \approx 3000 \text{ tracks in tracker acceptance} \]

$H \rightarrow ZZ \rightarrow ee\mu\mu$, $m_H = 300$ GeV, in CMS

Generated tracks, $p_t > 1$ GeV/c cut, i.e. all soft tracks removed!

If same granularity and integration time as now: tracker occupancy and radiation dose in central detectors increases by factor ~10, pile-up noise in calorimeters by ~ 3 relative to $10^{34}$
Consequences of running at $\sim 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$

if 12.5 nsec bunch spacing $(dn^\text{ch}/d\eta/crossing \approx 600)$ - which is the least demanding option in terms of changes to CMS and ATLAS - relative to nominal LHC running, assuming same detector performances as for present ones:

$\Rightarrow$ reduced efficiency for selection of isolated objects ($\mu$, $e$, $\gamma$, $\tau$), trigger and off-line

$\Rightarrow$ degraded energy resolution due to pile-up for $e$, $\gamma$, jets, missing $E_t$,
  effect decreases with increasing $E_t$, small beyond $\sim 50 \ (e,\gamma) - 200 \ (jets)$ GeV

$\Rightarrow$ reduced selectivity of missing $E_t$ cuts (below $\sim 100$ GeV)

$\Rightarrow$ reduced efficiency and purity of forward jet tagging and central jet vetoing techniques used to improve S/B

$\Rightarrow$ somewhat reduced muon acceptance, to $|\eta| < \sim 2.0$, due to need for increased forward shielding, not essential as heavy objects are centrally produced, but potentially damaging for ew studies....
Foreseeable changes to detectors for $10^{35}$ cm$^{-2}$s$^{-1}$

changes to CMS and ATLAS:

- **Trackers**, to be replaced due to increased occupancy to maintain performance, need improved radiation hardness for sensors and electronics
  - present Si-strip technology is OK at $R > 60$ cm
  - present pixel technology is OK for the region $\sim 20 < R < 60$ cm
  - at smaller radii new techniques required
- **Calorimeters**: ~ OK
  - endcap HCAL scintillators in CMS to be changed
  - endcap ECAL VPT's and electronics may not be enough radiation hard
  - desirable to improve granularity of very forward calorimeters - for jet tagging
- **Muon systems**: ~ OK
  - acceptance reduced to $|\eta| \ll 2.0$ to reinforce forward shielding
- **Trigger(L1)**, largely to be replaced, L1(trig.elec. and processor) for 80 MHz data sampling

VF calorimeter for “jet tagging”
IR based on High Fields Magnets with reduced $\beta^*$

New Interaction Regions: beam dynamics versus magnet technology and design

See PAC03 pp 42-44
The ‘poor man’ way: LHC-IR upgrade with new NbTi quadrupoles -> $\beta^*=0.25$ m

The quadrupole aperture is matched to the real beam size

<table>
<thead>
<tr>
<th>quad</th>
<th>length (m)</th>
<th>gradient at 7 TeV (T/m)</th>
<th>coil aperture (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>6.0</td>
<td>275</td>
<td>53</td>
</tr>
<tr>
<td>Q2</td>
<td>7.4</td>
<td>197</td>
<td>85</td>
</tr>
<tr>
<td>Q3</td>
<td>7.8</td>
<td>196</td>
<td>82</td>
</tr>
</tbody>
</table>

See EPAC 04 pp 608-10

Comparison between NbTi, NbTiTa and Nb$_3$Sn conductors
FY04 Dipole Development (LARP)

- Based on “Dipole-first” IR design
  - Large aperture, asymmetric
  - Non-cos-theta
  - Split coil geometry

High field (~15T), long (~10m), large radiation heat load (~9 kW) into 70 K

Calculations from Mokhov show that the concept may work

FY04 Quadrupole Development (LARP)

- Design Studies
  - Dual-bore
  - Aperture
  - Geometries

- Support Structure
  - Key-bladder-shell
  - Coil-yoke-skin
LHC Phase 2: Luminosity and Energy Upgrade

- Modify the injectors to significantly increase the beam intensity and brilliance beyond its ultimate value (possibly in conjunction with beam-beam compensation schemes).

- Equip the SPS with superconducting magnets, upgrade transfer lines, and inject into the LHC at 1 TeV. For given mechanic and dynamic apertures at injection, this option can increase the LHC luminosity by nearly a factor two, at constant beam-beam parameter $N_b/\varepsilon_n$, in conjunction with long range b-b compensation schemes. This would also be the natural first step in view of an LHC energy upgrade $\Rightarrow$ energy swing reduced by a factor 2. Interesting alternative $\Rightarrow$ cheap, compact low-field booster rings in the LHC tunnel.

- Install new dipoles with a field of 15 T and a safety margin of about 2 T, which are considered a reasonable target for 2015 and could be operated by 2020 $\Rightarrow$ beam energy around 12.5 TeV.
Possible upgrade of the injector chain

Poor-man way:
- RF upgrade for batch compression in the PS

Rich-man way:
- Up to 160 MeV: LINAC 4
- Up to 2.2 GeV: the SPL (or a super-BPS)

The superconducting way:
- Up to 60 GeV a SC super-PS
- Up to 1 TeV a super SPS
- SC transfer lines to LHC

The normal conducting way:
- Up to 30 GeV a refurbished PS
- Up to 450 GeV a refurbished SPS

A 1 TeV booster ring in the LHC tunnel may also be considered
- Easy magnets (super-ferric technology?)
- Difficult to cross the experimental area (a bypass needed?)

See CARE-HIPPI
See CARE-HHH and CARE-NED
Sketch of the Common Coil design for a double aperture dipole magnet. The coils couple the two apertures and can be flat (no difficult ends). One of the most difficult challenges will be to make it at reasonable cost, less than 5 kEuro/(double)T.m say, including cryogenics, to be compared with about 4.5 kEuro/(double)T.m for the present LHC.
Tentative milestones for future machine studies:

- **2005/2006**: installation and test of a beam-beam long range compensation system at RHIC to be validated with colliding beams.
- **2006/2007**: new SPS experiment for crystal collimation.
- **2006**: installation and test of Crab cavities at KEKB to validate higher beam-beam limit and luminosity with large crossing angles.
- **2007**: if KEKB test successful, test of Crab cavities in a hadron machine to validate low RF noise and emittance preservation.
Additional Slides
# LHC, LC, SLHC, CLIC (3, 5TeV) reaches

<table>
<thead>
<tr>
<th>Process</th>
<th>LHC</th>
<th>LC</th>
<th>SLHC</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Squarks</td>
<td>2.5</td>
<td>0.4</td>
<td>3</td>
<td>1.5</td>
</tr>
<tr>
<td>Sleptons</td>
<td>0.34</td>
<td>0.4</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>New gauge boson Z'</td>
<td>5</td>
<td>8</td>
<td>6</td>
<td>22</td>
</tr>
<tr>
<td>Excited quark q*</td>
<td>6.5</td>
<td>0.8</td>
<td>7.5</td>
<td>3</td>
</tr>
<tr>
<td>Excited lepton l*</td>
<td>3.4</td>
<td>0.8</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Two extra space dimensions</td>
<td>9</td>
<td>5–8.5</td>
<td>12</td>
<td>20–35</td>
</tr>
<tr>
<td>Strong WlWl scattering</td>
<td>2σ</td>
<td>-</td>
<td>4σ</td>
<td>70σ</td>
</tr>
<tr>
<td>Triple-gauge Coupling(TGC) (95%)</td>
<td>.0014</td>
<td>0.0004</td>
<td>0.0006</td>
<td>0.00013</td>
</tr>
</tbody>
</table>

Integrated luminosities used are 100 fb–1 for the LHC, 500 fb–1 for the 800 GeV LC, and 1000 fb–1 for the SLHC and CLIC. Most numbers given are TeV, but for strong WLWL scattering the numbers of standard deviations, and pure numbers for the triple gauge coupling (TGC).
e- density vs. intensity, 25 ns spacing, ‘best’ model

R=0.5

calculation for 1 batch

typical instability threshold

delta_max=1.1

delta_max=1.3

delta_max=1.5

delta_max=1.7

Frank Zimmermann, LTC 06.04.05
heat load for higher intensity

nominal LHC

$N_b = 1.15 \times 10^{11}$, 25 ns spacing

ultimate LHC

$N_b = 1.7 \times 10^{11}$, 25 ns spacing

upgrade with 12.5 ns spacing

$N_b = 1.7 \times 10^{11}$, 12.5 ns spacing, $\sigma_z = 3.78$ cm (1/2 nominal)

upgrade with 75 ns spacing

$N_b = 6 \times 10^{11}$, 75 ns spacing, $\sigma_z = 14.4$ cm flat profile

HHH-2004 proceedings

Frank Zimmermann, LTC 06.04.05
W. Scandale  Technological Challenges

in upgrading the injectors

Losses are a major concern -> Vigorous R&D program needed

- Study and evaluate different scenarios of beam losses in PS and SPS
- Study and evaluate a maximum allowed cryogenic budget
- Optimize the dipoles not only for good quench performance in condition of cable/iron losses, but also for cryogenic budget

Tentative SPS cycle

- A SC dipole for the SPS may produce 70 W/m peak ($35 \text{ W/m effective} \Rightarrow 140 \text{ kW}$ for the SPS, equivalent to the cryogenic power of the LHC !)
- A rather arbitrary 'guess' for beam loss is of about $10^{12} \text{px100GeV/10s} = 15 \text{ kW}$
- By dedicated R&D magnet losses should be lowered to 10 W/m peak ($5 \text{ W/m effective} \Rightarrow 20 \text{ kW}$ ), comparable to expected beam loss power
**Triplet aperture requirements: baseline scheme**

rough estimate of triplet quadrupole aperture $D_{\text{trip}}$ for $\ell^* = 23\,\text{m}$:

- $9\sigma$ beam envelope
- $7.5\sigma$ beam separation
- 20% $\beta$-beating
- 4 mm spurious dispersion
- 3 mm peak orbit excursion
- 1.6 mm mechanical tolerances
- beam screen and cold bore

$$D_{\text{trip}} > 1.1 \times (7.5 + 2 \times 9) \cdot \sigma + 2 \times 8.6\,\text{mm}$$

$\beta^* = 0.5\,\text{m} \rightarrow \sigma_{\text{max}} \simeq 1.5\,\text{mm} \quad \implies \quad D_{\text{trip}} > 60\,\text{mm} \rightarrow 70\,\text{mm ID coil}$

$\beta^* = 0.25\,\text{m} \rightarrow \sigma_{\text{max}} \simeq 2.2\,\text{mm} \quad \implies \quad D_{\text{trip}} > 80\,\text{mm} \rightarrow 90\,\text{mm ID coil}$
Sketch of a possible IR layout for an LHC luminosity upgrade with separation dipoles close to the IP and separated magnet bores inside the triplet magnets. (Courtesy O. Brüning)

Main advantages:

- reduce number of long range beam-beam interactions
- no crossing-angle bump inside the triplet magnets $\implies$ no feed-down errors
# Magnet requirements for alternative IR layout with $\beta^* = 0.25$ m

<table>
<thead>
<tr>
<th>magnet</th>
<th>type</th>
<th>length</th>
<th>diameter range</th>
<th>beam separation</th>
<th>strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>1 aperture</td>
<td>11.4 m</td>
<td>34 mm ↔ 131 mm</td>
<td>0 ↔ 84 mm</td>
<td>15 T</td>
</tr>
<tr>
<td>D2</td>
<td>2-in-1</td>
<td>11.4 m</td>
<td>50 mm ↔ 60 mm</td>
<td>110 mm ↔ 194 mm</td>
<td>15 T</td>
</tr>
<tr>
<td>Q1</td>
<td>2-in-1</td>
<td>4.5 m</td>
<td>60 mm ↔ 70 mm</td>
<td>194 mm</td>
<td>230 T/m</td>
</tr>
<tr>
<td>Q2</td>
<td>2-in-1</td>
<td>2 × 4.5 m</td>
<td>70 mm ↔ 78 mm</td>
<td>194 mm</td>
<td>257 T/m</td>
</tr>
<tr>
<td>Q3</td>
<td>2-in-1</td>
<td>5.0 m</td>
<td>70 mm ↔ 78 mm</td>
<td>194 mm</td>
<td>280 T/m</td>
</tr>
</tbody>
</table>

Tentative magnet parameters for a triplet layout with separated beams inside the triplet magnets. The beam separation does not include the additional separation from the crossing angle bump. We assume that the beam separation can be done via two 11.4 m long 15 T dipole magnets (possibly with high temperature superconducting coils).
Recommendations for future studies and R&D

nominal LHC performance is challenging (not to mention ultimate) ⇒ learn how to overcome electron cloud effects, inject, ramp, and collide almost 3000 high intensity bunches, protect superconducting magnets, safely dump the beams, etc. Upgrades in beam intensity are a viable option, require R&D for cryogenics, vacuum, RF, beam dump, and injectors, and operation with large crossing angles

radiation damage limit for IR quads (∼ 700 fb$^{-1}$) reached by 2013? ⇒ new triplet quadrupoles with high gradient and larger aperture (or alternative IR layouts) are needed for a luminosity upgrade. Opening the quads has the advantage of letting radiation through

further studies are needed to specify field quality of IR magnets, required upgrades of beam instrumentation, collimation and machine protection. To reduce collimator impedance during β-squeeze and physics conditions, triplet aperture should be i) LARGE and ii) possibly protected by local tertiary collimators
experimental studies on electron cloud (e.g. beam scrubbing in cold conditions), long range, and strong-strong beam-beam effects are important, as well as MDs in existing hadron colliders with large Piwinski parameter and many (flat) bunches \(\Rightarrow\) international collaboration (e.g. US-LHC, ESGARD) is welcome/needed for LHC machine studies/commissioning

beam-beam compensation schemes with pulsed wires would reduce tune footprints and loss of dynamic aperture due to long range collisions \(\Rightarrow\) need experimental validation

Interesting possibilities currently under study to pass each beam through separate final quadrupoles include: alternative beam separation schemes with separation dipoles in front of the triplet quadrupoles and collision of long super-bunches with very large \(\theta_c\). With a crossing angle of a few mrad, a 300 m long super-bunch with intensity \(I_{\text{beam}} = 1\,\text{A}\) in each LHC ring would be compatible with the beam-beam limit. The corresponding luminosity in ATLAS and CMS (with alternating H-V crossings) would be \(9 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}\).
The super-bunch option is interesting for large crossing angles, can potentially avoid electron cloud effects and minimize the cryogenic heat load. One could inject a bunched beam, accelerate it to 7 TeV, and then use barrier buckets to form about 100 long super-bunches to reduce pile-up noise in the experiments.

A major and sustained R&D effort on new SC materials and magnet design is needed for any LHC performance upgrade → foster and extend collaboration with other labs: new low-β quadrupoles with high gradient and larger aperture based on Nb$_3$Sn superconductor require 9-10 years for short model R&D and component development, prototyping, and final production.

An increased 1 TeV injection energy into the LHC in conjunction with beam-beam compensation schemes would yield a luminosity gain → a pulsed Super-SPS (and new SC transfer lines) or cheap low-field booster rings in the LHC tunnel could be the first step for an LHC energy upgrade.