LHC Upgrade (accelerator)

- Time scale of LHC luminosity upgrade
- Machine performance limitations
- Scenarios for the LHC upgrade
  - Phase 0: no hardware modifications
  - Phase 1: Interaction Region upgrade
  - Phase 2: major hardware modifications
- Expected beam physics issues
- Effective luminosity

http://care-hhh.web.cern.ch/CARE-HHH/
The life expectancy of LHC IR quadrupole magnets is estimated to be <10 years owing to high radiation doses. The statistical error halving time will exceed 5 years by 2011-2012. Therefore, it is reasonable to plan a machine luminosity upgrade based on new low-β IR magnets before ~2015.
Chronology of LHC Upgrade studies

- **Summer 2001**: two CERN task forces investigate physics potential (CERN-TH-2002-078) and accelerator aspects (LHC Project Report 626) of an LHC upgrade by a factor 10 in luminosity and 2-3 in energy.
- **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”
- **2003**: US LHC Accelerator Research Program (LARP)
- **2004**: CARE-HHH European Network on *High Energy High Intensity Hadron Beams*
## Nominal LHC parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>2x7</th>
<th>TeV</th>
</tr>
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<tbody>
<tr>
<td><strong>Nominal LHC parameters</strong></td>
<td></td>
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<tr>
<td>Collision energy</td>
<td>TeV</td>
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<td>Dipole peak field</td>
<td>T</td>
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<td>Injection energy</td>
<td>GeV</td>
<td></td>
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<tr>
<td>Protons per bunch</td>
<td>1.15</td>
<td>10^{11}</td>
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<tr>
<td>Bunch spacing</td>
<td>25</td>
<td>ns</td>
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<td>Average beam current</td>
<td>0.58</td>
<td>A</td>
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<td>Stored energy per beam</td>
<td>MJ</td>
<td></td>
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<td>Radiated power per beam</td>
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<td>Normalized emittance</td>
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<td>RMS bunch length</td>
<td>7.55</td>
<td>μm</td>
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<tr>
<td>Beam size at IP1&amp;IP5</td>
<td>16.6</td>
<td>μm</td>
<td></td>
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<td>Beta function at IP1&amp;IP5</td>
<td>0.55</td>
<td>m</td>
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<tr>
<td>Full crossing angle</td>
<td>285</td>
<td>μrad</td>
<td></td>
</tr>
<tr>
<td>Luminosity lifetime</td>
<td>15.5</td>
<td>h</td>
<td></td>
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<tr>
<td>Peak luminosity</td>
<td>10^{34}</td>
<td>cm^{-2}s^{-1}</td>
<td></td>
</tr>
<tr>
<td>Events per bunch crossing</td>
<td>19.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>66.2</td>
<td>fb^{-1}/year</td>
<td></td>
</tr>
</tbody>
</table>

**F. Ruggiero**

CERN

LHC upgrade scenarios
F. Ruggiero LHC upgrade scenarios

Peak luminosity at the beam-beam limit \( L \sim \frac{I}{\beta^*} \)

Total beam intensity \( I \) limited by electron cloud, collimation, injectors

Minimum crossing angle depends on beam intensity: limited by triplet aperture

Longer bunches allow higher bb-limit for \( \frac{N_b}{\varepsilon_n} \): limited by the injectors

Less ecloud and RF heating for longer bunches: \(~50\%\) luminosity gain for flat bunches longer than \( \beta^* \)

Event pile-up in the physics detectors increases with \( N_b \)

Luminosity lifetime at the bb limit depends only on \( \beta^* \)
The peak LHC luminosity can be multiplied by:

- **factor 2.3** from nominal to ultimate beam intensity (0.58 $\Rightarrow$ 0.86 A)
- **factor 2** (or more?) from new low-beta insertions with $\beta^* = 0.25$ m

$$T_{\text{turnaround}} \approx 10 \text{ h} \Rightarrow \int Ldt \approx 3 \times \text{nominal} \approx 200/(\text{fb*year})$$

Major hardware upgrades (LHC main ring and injectors) are needed to exceed ultimate beam intensity. The **peak luminosity** can be increased by:

- **factor 2** if we can double the number of bunches (maybe impossible due to electron cloud effects) or increase bunch intensity and bunch length

$$T_{\text{turnaround}} \approx 10 \text{ h} \Rightarrow \int Ldt \approx 6 \times \text{nominal} \approx 400/(\text{fb*year})$$

Increasing the LHC injection energy to 1 TeV would potentially yield:

- **factor $\sim 2$** in peak luminosity (2 x bunch intensity and 2 x emittance)
- **factor 1.4** in integrated luminosity from shorter $T_{\text{turnaround}} \approx 5$ h

thus ensuring $L \sim 10^{35}$ cm$^{-2}$ s$^{-1}$ and $\int Ldt \sim 9 \times \text{nominal} \sim 600/(\text{fb*year})$
F. Ruggiero LHC upgrade scenarios

LHC Cleaning System

- Single-stage cleaning
- No collimation
- Two-stage cleaning (phase 1)
- Two-stage cleaning (phase 2)
- LHC (inj)
- LHC (top)
- ISR
- SPS
- HERA
- TEVATRON
- SNS
- LEP2
- SppS
- Pilot
**Luminosity optimization**

Transverse beam size at IP:
\[ \sigma^* = \sqrt{\varepsilon \beta^*} \]

Normalized emittance:
\[ \varepsilon_n = \gamma \varepsilon = \gamma \frac{\sigma^2}{\beta} \]

Peak luminosity for head-on collisions:
\[ L = \frac{n_b f_{\text{rev}} N_b^2}{4\pi \sigma^*^2} = \frac{\gamma}{4\pi \beta^*} \frac{N_b}{\varepsilon_n} I \]

Beam brightness:
\[ \frac{N_b}{\varepsilon_n} \]
- head-on beam-beam
- space-charge in the injectors
- transfer dilution

Collisions with full crossing angle \( \theta_c \)
reduce luminosity by a geometric factor \( F \)
maximum luminosity below beam-beam limit
⇒ short bunches and minimum crossing angle (baseline scheme)
H-V crossings in two IP’s ⇒ no linear tune shift due to long range
total linear bb tune shift also reduced by \( F \)
\[ F \cong \frac{1}{\sqrt{1 + \left( \frac{\theta_c \sigma z}{2\sigma^*} \right)^2}} \]

\[ \Delta Q_{\text{bb}} = \xi_x + \xi_y \cong \frac{N_b r_p}{2\pi \varepsilon_n} F \]
If bunch intensity and brightness are not limited by the injectors or by other effects in the LHC (e.g. electron cloud) ⇒ luminosity can be increased without exceeding beam-beam limit \( \Delta Q_{bb} \approx 0.01 \) 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

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

At high beam intensities or for large emittances, the performance will be limited by the angular triplet aperture

\[
L \approx \frac{\gamma}{2r_p} \Delta Q_{bb} I \min \left\{ \frac{1}{\beta^*}, \frac{1}{\varepsilon} \left( \frac{A_{\text{tripl}} / \ell^*}{20 + \theta_c / \sigma_\theta} \right)^2 \right\}
\]
Minimum crossing angle

Beam-Beam Long-Range collisions:
• perturb motion at large betatron amplitudes, where particles come close to opposing beam
• cause ‘diffusive’ (or dynamic) aperture, high background, poor beam lifetime
• increasing problem for SPS, Tevatron, LHC, i.e., for operation with larger # of bunches

**Dynamic aperture caused by** $n_{\text{par}}$ **parasitic collisions around two IP’s**

$$\frac{d_{\text{da}}}{\sigma} \approx \frac{\theta_c}{\sigma_\theta} - 3 \sqrt{\frac{n_{\text{par}} N_b}{32 \times 10^{11}}} \frac{3.75 \mu \text{m}}{\varepsilon_n}$$

$$\Rightarrow \frac{\theta_c}{\sigma_\theta} \approx 6 + 3 \sqrt{\frac{I}{0.5 \text{A}}} \frac{3.75 \mu \text{m}}{\varepsilon_n}$$

$$\sigma_\theta = \sqrt{\frac{\varepsilon}{\beta^*}}$$

angular beam divergence at IP

higher beam intensities or smaller $\beta^*$ require larger crossing angles to preserve dynamic aperture and shorter bunches to avoid geometric luminosity loss

$\Rightarrow$ **baseline scaling**: $\theta_c \sim 1/\sqrt{\beta^*}$, $\sigma_\theta \sim \beta^*$
2nd prototype BBLR in the CERN SPS has demonstrated benefit of compensation

Crab cavities combine advantages of head-on collisions and large crossing angles. They require lower voltages compared to bunch shortening RF systems but tighten on phase jitter to avoid emittance growth.

<table>
<thead>
<tr>
<th></th>
<th>KEKB</th>
<th>Super-KEKB</th>
<th>ILC</th>
<th>Super-LHC</th>
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<tr>
<td>$\sigma_x^*$</td>
<td>100 $\mu$m</td>
<td>70 $\mu$m</td>
<td>0.24 $\mu$m</td>
<td>11 $\mu$m</td>
</tr>
<tr>
<td>$\theta_c$</td>
<td>+/- 11 mrad</td>
<td>+/-15 mrad</td>
<td>+/-5 mrad</td>
<td>+/- 0.5 mrad</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>6 ps</td>
<td>3 ps</td>
<td><strong>0.03 ps</strong></td>
<td><strong>0.08 ps</strong></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.
Scaling of electron cloud effects

experience at several storage rings suggests that the e-cloud threshold scales as $N_b \sim \Delta t_{sep}$

possible LHC upgrades consider either smaller $\Delta t_{sep}$ with constant $N_b$, or they increase $\Delta t_{sep}$ in proportion to $N_b$
Schematic of reduced electron cloud build up for a long bunch. Most electrons do not gain any energy when traversing the chamber in the quasi-static beam potential, resulting in a negligible heat load. [after V. Danilov]
Scenarios for the luminosity upgrade

- ultimate performance without hardware changes (phase 0)
- maximum performance with only IR changes (phase 1)
- maximum performance with “major” hardware changes (phase 2)

Nominal LHC performance

- beam-beam tune spread of 0.01
- $L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in ATLAS and CMS
- Halo collisions in ALICE
- Low-luminosity in LHCb

Phase 0: steps to reach ultimate performance without hardware changes:

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 9T (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/machine protection considerations.
# Scenarios for the luminosity upgrade

**Phase 1:** steps to reach maximum performance with only IR changes

1. Modify the insertion quadrupoles and/or layout ⇒ $\beta^* = 0.25 \text{ m}$
2. Increase crossing angle $\theta_c$ by $\sqrt{2}$ ⇒ $\theta_c = 445 \text{ µrad}$
3. Increase $N_b$ up to ultimate intensity ⇒ $L = 3.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
4. Halve $\sigma_z$ with high harmonic RF system ⇒ $L = 4.6 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
5. Double the no. of bunches $n_b$ (and increase $\theta_c$) ⇒ $L = 9.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

Excluded by electron cloud? **Step 5 belongs to Phase 2**

😊 Step 4) requires a new RF system providing
- an accelerating voltage of 43 MV at 1.2 GHz
- a power of about 11 MW/beam
- longitudinal beam emittance reduced to 1.8 eVs
- horizontal Intra-Beam Scattering (IBS) growth time decreases by $\sim \sqrt{2}$

رياضياتية Operational consequences of step 5) ⇒ exceeding ultimate beam intensity
- upgrade LHC cryogenics, collimation, RF and beam dump systems
- the electronics of all LHC beam position monitors should be upgraded
- possibly upgrade SPS RF system and other equipment in the injectors
# Various LHC upgrade options

<table>
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<tr>
<th>parameter</th>
<th>symbol</th>
<th>nominal</th>
<th>ultimate</th>
<th>shorter bunch</th>
<th>longer bunch</th>
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<tr>
<td>no of bunches</td>
<td>$n_b$</td>
<td>2808</td>
<td>2808</td>
<td>5616</td>
<td>936</td>
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<td>proton per bunch</td>
<td>$N_b \cdot 10^{11}$</td>
<td>1.15</td>
<td>1.7</td>
<td>1.7</td>
<td>6.0</td>
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<tr>
<td>bunch spacing</td>
<td>$\Delta t_{\text{sep}} [\text{ns}]$</td>
<td>25</td>
<td>25</td>
<td>12.5</td>
<td>75</td>
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<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>
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<td>normalized emittance</td>
<td>$\epsilon_n \ [\mu\text{m}]$</td>
<td>3.75</td>
<td>3.75</td>
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<td>longit. profile</td>
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<td>Gaussian</td>
<td>Gaussian</td>
<td>Gaussian</td>
<td>flat</td>
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<td>rms bunch length</td>
<td>$\sigma_z \ [\text{cm}]$</td>
<td>7.55</td>
<td>7.55</td>
<td>3.78</td>
<td>14.4</td>
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<td>$\beta^*$ at IP1&amp;IP5</td>
<td>$\beta^* \ [\text{m}]$</td>
<td>0.55</td>
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<td>0.25</td>
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<td>full crossing angle</td>
<td>$\theta_c \ [\mu\text{rad}]$</td>
<td>285</td>
<td>315</td>
<td>445</td>
<td>430</td>
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<td>Piwinski parameter</td>
<td>$\theta_c \sigma_z/(2\sigma^*)$</td>
<td>0.64</td>
<td>0.75</td>
<td>0.75</td>
<td>2.8</td>
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<tr>
<td>peak luminosity</td>
<td>$L \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$</td>
<td>1.0</td>
<td>2.3</td>
<td>9.2</td>
<td>8.9</td>
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<td>events per crossing</td>
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<td>19</td>
<td>44</td>
<td>88</td>
<td>510</td>
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<tr>
<td>luminous region length</td>
<td>$\sigma_{\text{lum}} \ [\text{mm}]$</td>
<td>44.9</td>
<td>42.8</td>
<td>21.8</td>
<td>36.2</td>
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</table>
Interaction Region upgrade

**goal:** reduce $\beta^*$ by at least a factor 2

**options:** NbTi ‘cheap’ upgrade, NbTi(Ta), Nb$_3$Sn
- new quadrupoles
- new separation dipoles

**factors driving IR design:**
- minimize $\beta^*$
- minimize effect of LR collisions
- large radiation power directed towards the IRs
- accommodate crab cavities and/or beam-beam compensators. Local $Q'$ compensation scheme?
- compatibility with upgrade path

**maximize magnet aperture, minimize distance to IR**
IR ‘baseline’ schemes

- Short bunches & minimum crossing angle & BBLR
- Crab cavities & large crossing angle
alternative IR schemes

- Dipole magnets
- Triplet magnets

Dipole first & small crossing angle:
- Reduced # LR collisions
- Collision debris hit D1

Dipole first & large crossing angle & long bunches or crab cavities
Several **LHC IR upgrade options** are being explored and will be further discussed in a LARP workshop at FNAL:

- quadrupole-first and dipole-first solutions based on conventional NbTi technology and on high-field Ni$_3$Sn magnets, possibly with structured SC cable
- energy deposition, absorbers, and quench limits
- schemes with **Crab cavities** as an alternative to the baseline bunch shortening RF system at 1.2 GHz to avoid luminosity loss with large crossing angles
- early beam separation by a “D0” dipole located a few metres away from the IP (or by tilted experimental solenoids?) may allow operation with a reduced crossing angle. Open issues: compatibility with detector layout, reduced separation at first parasitic encounters, energy deposition by the collision debris
- **local chromaticity correction schemes**
- **flat beams**, i.e. a final doublet instead of a triplet. Open issues: compensation of long range beam-beam effects with alternating crossing planes
Tentative milestones for future machine studies

- **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, complementary to Tevatron results
- **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 (RHIC?) to validate low RF noise and emittance preservation
Injector chain for 1 TeV proton beams

injecting at 1 TeV into the LHC reduces dynamic effects of persistent currents, i.e.:
- persistent current decay during the injection flat bottom
- snap-back at the beginning of the acceleration ⇒ easier beam control
⇒ decreases turn-around time and hence increases integrated luminosity

\[ T_{\text{run}} \text{ (optimum)} \Rightarrow \left\{ \begin{array}{c}
\int_0^{T_{\text{run}}} L \, dt = \frac{L_0}{\tau_L} \times \frac{T_{\text{run}} + T_{\text{turnaround}}}{T_{\text{run}} + T_{\text{turnaround}} + \tau_L} \\
1 + \frac{T_{\text{run}} + T_{\text{turnaround}}}{\tau_L} = e^{\frac{T_{\text{run}}}{\tau_L}}
\end{array} \right\}

with \( \tau_{\text{gas}} = 85 \text{ h} \) and \( \tau_{\text{IBS}} = 106 \text{ h (nom)} \Rightarrow 40 \text{ h (high-L)} \)

<table>
<thead>
<tr>
<th>( L_0 ) [cm(^{-2})s(^{-1})]</th>
<th>( \tau_L ) [h]</th>
<th>( T_{\text{turnaround}} ) [h]</th>
<th>( T_{\text{run}} ) [h]</th>
<th>( \int_{200 \text{ days}} L , dt ) [fb(^{-1})]</th>
<th>( L , dt ) gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 10^{34} )</td>
<td>15</td>
<td>10</td>
<td>14.6</td>
<td>66</td>
<td>x1.0</td>
</tr>
<tr>
<td>( 10^{34} )</td>
<td>15</td>
<td>5</td>
<td>10.8</td>
<td>85</td>
<td>x1.3</td>
</tr>
<tr>
<td>( 10^{35} )</td>
<td>6.1</td>
<td>10</td>
<td>8.5</td>
<td>434</td>
<td>x6.6</td>
</tr>
<tr>
<td>( 10^{35} )</td>
<td>6.1</td>
<td>5</td>
<td>6.5</td>
<td>608</td>
<td>x9.2</td>
</tr>
</tbody>
</table>
LHC injector complex upgrade

- CERN is preparing a road map for an upgrade of its accelerator complex to optimize the overall proton availability in view of the LHC luminosity upgrade and of all other physics users.

- Scenarios under consideration include a new proton linac (Linac 4, 160 MeV) to overcome space charge limitations at injection in the PS Booster and a new Superconducting PS reaching an energy of 50-60 GeV.

- This would open the possibility of a more reliable production of higher-brightness beams for the LHC, with lower transmission losses in the SPS thanks to the increased injection energy.

- It would also offer the opportunity to develop new fast pulsing SC magnets in view of a Super-SPS, injecting at 1 TeV into the LHC.
Additional Slides
luminosity upgrade: baseline scheme

- Increase $N_b$
- $F \approx \left(1 + \left(\frac{\theta_c \sigma_z}{2 \sigma^*}\right)^2\right)^{-1/2}$
- $\theta_c > \theta_{\text{min}}$ due to LR-bb compensation
- Use large $\theta_c$ and pass each beam through separate magnetic channel
- Simplified IR design with large $\theta_c$
- Reduce $\sigma_z$ by factor $\sim 2$
- Reduce $\theta_c$ (squeeze $\beta^*$)
- If e-cloud, dump & impedance ok
- Increase $n_b$ by factor $\sim 2$
- Peak luminosity gain
- Beam current $1.72 \text{ A}$
luminosity upgrade: Piwinski scheme

- Reduce $\beta^*$ by factor ~2
- New IR magnets
- Decrease $F$
  \[ F \approx \left( 1 + \left( \frac{\theta \sigma_z}{2\sigma} \right)^2 \right)^{-1/2} \]
- Increase $\sigma_z \theta_c$
- Superbunches?
- Flatten profile?
- Increase $N_b$

\[ N_b = \frac{2\pi \varphi_n}{r_p F} \Delta q_{bb} \]

- Yes
- No

- Reduce #bunches to limit total current?
- Beam current
  - 0.58 A
  - 0.86 A
  - 1.72 A
- Luminosity gain
  - 7.7
  - 15.5
### beam-beam: tune shift

#### tune shift from head-on collision (primary IPs)

\[
\xi_{HO} = \frac{N_b r_p}{4\pi\gamma\epsilon_{x,y}} 
\]

**limit on** \(\xi_{HO}\) **limits** \(N_b/(\gamma\epsilon)\)

#### tune shift from long-range collisions

\[
\xi_{LR} = 2n_{par} \frac{\xi_{HO}}{d^2}
\]

**increases with** reduced bunch spacing or crossing angle

\(d\): normalized separation, \(d \propto \theta_c\)

### Table

<table>
<thead>
<tr>
<th></th>
<th>(\xi_{HO}/\text{IP})</th>
<th>no. of IPs</th>
<th>(\Delta Q_{bb} \text{ total})</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS</td>
<td>0.005</td>
<td>3</td>
<td>0.015</td>
</tr>
<tr>
<td>Tevatron (pbar)</td>
<td>0.01-0.02</td>
<td>2</td>
<td>0.02-0.04</td>
</tr>
<tr>
<td>RHIC</td>
<td>0.002</td>
<td>4</td>
<td>~0.008</td>
</tr>
<tr>
<td>LHC (nominal)</td>
<td>0.0034</td>
<td>2 (4)</td>
<td>~0.01</td>
</tr>
</tbody>
</table>

**Conservative value for total tune spread based on SPS collider experience**
Schematic of a **super-bunch collision**, consisting of ‘head-on’ and ‘long-range’ components. The luminosity for long bunches having flat longitudinal distribution is \(~1.4\) times higher than for conventional Gaussian bunches with the same beam-beam tune shift and identical bunch population (see LHC Project Report 627)
arc heat load vs. intensity, 25 ns spacing, ‘best’ model

heat load

R=0.5

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

$R=0.5$

cooling capacity

Frank Zimmermann, LTC 06.04.05
Events per bunch crossing and beam lifetime due to nuclear p-p collisions

\[
\frac{\text{events}}{X\text{-ing}} = \frac{L}{n_b f_{\text{rev}}} \sigma_{bb}
\]

\[
\tau_N = \frac{n_b N_b / L}{2\sigma_{\text{TOT}}}
\]

\[
\frac{L}{n_b N_b} \approx \frac{\gamma f_{\text{rev}} \Delta Q_{bb}}{2r_p \beta^*}
\]

\[
\tau_L = \frac{1}{2 \tau_{\text{IBS}}^x + \frac{2}{\tau_{\text{gas}}} + \frac{1.54}{\tau_N}}
\]

\[
(\sqrt{e} - 1) \tau_N \approx \frac{\tau_N}{1.54}
\]

\(\sigma_{bb} = 60 \text{ mb} \) total inelastic cross section

Beam intensity halving time due to nuclear p-p collisions at two IP’s with total cross section \(\sigma_{\text{TOT}} = 110 \text{ mb}\)

Nuclear scattering lifetime at the beam-beam limit depends only on \(\beta^*\)!

Luminosity lifetime: assumes radiation damping compensates diffusion

Exponential luminosity lifetime due to nuclear p-p interactions
Optimum run time and effective luminosity

\[ \frac{\tau_L + \frac{T_{\text{run}}}{\tau_L} + \frac{T_{\text{turnaround}}}{\tau_L}}{\tau_L} = \frac{T_{\text{run}}}{\tau_L} \]

The optimum run time and the effective luminosity are universal functions of \( T_{\text{turnaround}}/\tau_L \)

\[ \frac{T_{\text{run}}}{\tau_L} = -1 - \frac{T_{\text{turnaround}}}{\tau_L} - \text{ProductLog}\left[-1, -e^{-\frac{T_{\text{turnaround}}}{\tau_L}}\right] \]

\[ \frac{L_{\text{eff}}}{L} = \frac{\tau_L}{\tau_L + \frac{T_{\text{run}}}{\tau_L} + \frac{T_{\text{turnaround}}}{\tau_L}} = -\frac{1}{\text{ProductLog}\left[-1, -e^{-\frac{T_{\text{turnaround}}}{\tau_L}}\right]} \]

where \( w = \text{ProductLog}[z] \Leftrightarrow z = we^w \)

When the beam lifetime is dominated by nuclear proton-proton collisions, then \( \tau_L = \frac{\tau_N}{1.54} \) and the effective luminosity is a universal function of \( T_{\text{turnaround}}/\beta^* \)
### Effective luminosity for various upgrade options

<table>
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<tr>
<th>parameter</th>
<th>symbol</th>
<th>nominal</th>
<th>ultimate</th>
<th>shorter bunch</th>
<th>longer bunch</th>
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<tr>
<td>protons per bunch</td>
<td>$N_b \times 10^{11}$</td>
<td>1.15</td>
<td>1.7</td>
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<td>bunch spacing</td>
<td>$\Delta t_{\text{sep}} \text{[ns]}$</td>
<td>25</td>
<td>25</td>
<td>12.5</td>
<td>75</td>
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<td>average current</td>
<td>$I \text{[A]}$</td>
<td>0.58</td>
<td>0.86</td>
<td>1.72</td>
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<td>longitudinal profile</td>
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<td>Gaussian</td>
<td>Gaussian</td>
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<td>rms bunch length</td>
<td>$\sigma_z \text{[cm]}$</td>
<td>7.55</td>
<td>7.55</td>
<td>3.78</td>
<td>14.4</td>
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<td>$\beta^*$ at IP1&amp;IP5</td>
<td>$\beta^* \text{[m]}$</td>
<td>0.55</td>
<td>0.50</td>
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<td>full crossing angle</td>
<td>$\theta_c \text{[\mu rad]}$</td>
<td>285</td>
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<tr>
<td>Piwinski parameter</td>
<td>$\theta_c \sigma_z/(2\sigma^*)$</td>
<td>0.64</td>
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<tr>
<td>peak 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>
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<td>events per crossing</td>
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<td>19</td>
<td>44</td>
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<td>IBS growth time</td>
<td>$\tau_{\text{IBS}} \text{[h]}$</td>
<td>106</td>
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<td>75</td>
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<td>nuclear scatt. lumi lifetime</td>
<td>$\tau_N/1.54 \text{[h]}$</td>
<td>26.5</td>
<td>17</td>
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<td>luminosity lifetime ($\tau_{\text{gas}} = 85 \text{h}$)</td>
<td>$\tau_{\text{l}} \text{[h]}$</td>
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<td>effective luminosity</td>
<td>$L_{\text{eff}} \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$</td>
<td>0.4</td>
<td>0.8</td>
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<td>($T_{\text{turnaround}} = 10 \text{h}$)</td>
<td>$T_{\text{run}} \text{[h]}$ optimum</td>
<td>14.6</td>
<td>12.3</td>
<td>8.9</td>
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<td>effective luminosity</td>
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<td>1.0</td>
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<tr>
<td>($T_{\text{turnaround}} = 5 \text{h}$)</td>
<td>$T_{\text{run}} \text{[h]}$ optimum</td>
<td>10.8</td>
<td>9.1</td>
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F. Ruggiero

CERN: the World’s Most Complete Accelerator Complex (not to scale)
Injector chain for 1 TeV proton beams

injecting in LHC more intense proton beams with constant brightness, within the same physical aperture

⇒ will increase the peak luminosity proportionally to the proton intensity

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

\[ \frac{d_{\text{sep}}}{\sigma} \approx \theta_c \sqrt{\frac{\gamma \beta^*}{\varepsilon_n}} \]

• at the beam-beam limit, peak luminosity \( L \) is proportional to normalized emittance \( \varepsilon_n = \gamma \varepsilon \), unless limited by the triplet aperture
• an increased injection energy (Super-SPS) allows a larger normalized emittance \( \varepsilon_n \) in the same physical aperture, thus more intensity and more luminosity at the beam-beam limit.
• the transverse beam size at 7 TeV would be larger and the relative beam-beam separation correspondingly lower: long range beam-beam effects have to be compensated.
‘cheap’ IR upgrade

in case we need to double LHC luminosity earlier than foreseen

triplet magnets

short bunches & minimum crossing angle & BBLR

each quadrupole individually optimized (length & aperture) reduced IP-quad distance from 23 to 22 m conventional NbTi technology: $\beta^* = 0.25 \text{ m}$ is possible
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
Baseline LHC Luminosity Upgrade: workpackages and tentative milestones

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<td>Beam-beam compensation test at RHIC</td>
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<td>Install new SPS kickers</td>
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<td><strong>Other Tentative Milestones</strong></td>
<td>Crab cavity test at KEKB</td>
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<td>Low-noise crab cavity test at RHIC</td>
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<td>Nominal LHC luminosity 10^34</td>
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<td>Ultimate LHC luminosity 2.3x10^34</td>
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<td>Double ultimate LHC luminosity 4.6x10^34</td>
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Baseline LHC Upgrade scenario: peak luminosity 4.6x10^34/(cm^2 sec)
Integrated luminosity 3 x nominal ~ 200/(fb*year) assuming 10 h turnaround time

new superconducting IR magnets for beta*=0.25 m
phase 2 collimation and new SPS kickers needed to attain ultimate LHC beam intensity of 0.86 A
beam-beam compensation may be necessary to attain or exceed ultimate performance
new superconducting RF system: for bunch shortening or Crab cavities
hardware for nominal LHC performance (cryogenics, dilution kickers, etc) not considered as LHC upgrade
R&D for further luminosity upgrade (intensity beyond ultimate) is recommended: see Injectors Upgrade

R&D - scenarios & models
specifications & prototypes
construction & testing
installation & commissioning