Possible Uses of Rapid Switching Devices and Induction RF for an LHC Upgrade

Frank Zimmermann, CERN

Thanks to Ulrich Dorda, Wolfram Fischer, Jean-Pierre Koutchouk, Peter McIntyre, Kazuhito Ohmi, Francesco Ruggiero, Walter Scandale, Daniel Schulte, Tanaji Sen, Ken Takayama, Kota Torikai
Large Hadron Collider (LHC)

- proton-proton collider
- next energy-frontier discovery machine
- c.m. energy 14 TeV (7x Tevatron)
- design luminosity $10^{34}$ cm$^{-2}$s$^{-1}$ (~100x Tevatron)
- sector beam test end of 2006; start full ring commissioning in fall 2007; physics run 2008
LHC upgrade
higher-energy injectors ← RPIA’06
stronger dipoles
interaction-region choices
long-range beam-beam compensation by pulsed electro-magnetic wires ← RPIA’06
rf crab cavities ← RPIA’06
superbunches & QCD Explorer ← RPIA’06
LHC upgrade
European Accelerator Network on

High Energy
High Intensity
Hadron Beams

http://care-hhh.web.cern.ch/care-hhh/

- road map for upgrade of European accelerator infrastructure (LHC & GSI complex)
- technical realization & scientific exploitation
- accelerator R&D and experimental studies


September 2005: 2\textsuperscript{nd} CARE-HHH-APD Workshop (LHC-LUMI-05) on ‘Scenarios for the LHC Luminosity Upgrade’
http://care-hhh.web.cern.ch/CARE-HHH/LUMI-05/
stages

- **push LHC performance w/o new hardware**
  luminosity $\rightarrow 2.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, $E_b = 7 \rightarrow 7.54 \text{ TeV}$

- **LHC IR upgrade**
  replace low-$\beta$ quadrupoles after $\sim 7$ years
  luminosity $\rightarrow 4.6 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

- **LHC injector upgrade**
  luminosity $\rightarrow 9.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

- **LHC energy upgrade**
  $E_b \rightarrow 13 - 21 \text{ TeV}$ (15 $\rightarrow$ 24 T dipole magnets)
peak luminosity at beam-beam limit $L \sim I/\beta^*$
total beam intensity limited by electron cloud, collimation, injectors
minimum crossing angle depends on intensity, limited by triplet aperture
longer bunches allow higher beam-beam limit for $N_b/\varepsilon_n$, limited by Injectors
less e- cloud and rf heating for longer bunches; ~50% luminosity gain for flat bunches longer than $\beta^*$
event pile up in physics detectors increases with $N_b^2$
luminosity lifetime at beam-beam limit depends only on $\beta^*$
## Effective luminosity for various upgrade options

<table>
<thead>
<tr>
<th>parameter</th>
<th>symbol</th>
<th>nominal</th>
<th>ultimate</th>
<th>shorter bunch</th>
<th>longer bunch</th>
</tr>
</thead>
<tbody>
<tr>
<td>protons per bunch</td>
<td>$N_b [10^{11}]$</td>
<td>1.15</td>
<td>1.7</td>
<td>1.7</td>
<td>6.0</td>
</tr>
<tr>
<td>bunch spacing</td>
<td>$\Delta t_{sep}[ns]$</td>
<td>25</td>
<td>25</td>
<td>12.5</td>
<td>75</td>
</tr>
<tr>
<td>average current</td>
<td>$I[A]$</td>
<td>0.58</td>
<td>0.86</td>
<td>1.72</td>
<td>1.0</td>
</tr>
<tr>
<td>longitudinal profile</td>
<td>Gaussian</td>
<td>Gaussian</td>
<td>Gaussian</td>
<td>flat</td>
<td></td>
</tr>
<tr>
<td>rms bunch length</td>
<td>$\sigma_z [cm]$</td>
<td>7.55</td>
<td>7.55</td>
<td>3.78</td>
<td>14.4</td>
</tr>
<tr>
<td>$\beta^*$ at IP1&amp;IP5</td>
<td>$\beta^*[m]$</td>
<td>0.55</td>
<td>0.50</td>
<td>0.25</td>
<td>0.25</td>
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<tr>
<td>full crossing angle</td>
<td>$\theta_c [\mu rad]$</td>
<td>285</td>
<td>315</td>
<td>445</td>
<td>430</td>
</tr>
<tr>
<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>
</tr>
<tr>
<td>peak luminosity</td>
<td>$L [10^{34} cm^{-2} s^{-1}]$</td>
<td>1.0</td>
<td>2.3</td>
<td>9.2</td>
<td>8.9</td>
</tr>
<tr>
<td>events per crossing</td>
<td></td>
<td>19</td>
<td>44</td>
<td>88</td>
<td>510</td>
</tr>
<tr>
<td>IBS growth time</td>
<td>$\tau_{x,IBS}[h]$</td>
<td>106</td>
<td>72</td>
<td>42</td>
<td>75</td>
</tr>
<tr>
<td>nuclear scatt. lumi lifetime</td>
<td>$\tau_N/1.54 [h]$</td>
<td>26.5</td>
<td>17</td>
<td>8.5</td>
<td>5.2</td>
</tr>
<tr>
<td>lumi lifetime ($\tau_{gas}=85 h$)</td>
<td>$\tau_L [h]$</td>
<td>15.5</td>
<td>11.2</td>
<td>6.5</td>
<td>4.5</td>
</tr>
<tr>
<td>effective luminosity</td>
<td>$L_{eff} [10^{34} cm^{-2} s^{-1}]$</td>
<td>0.4</td>
<td>0.8</td>
<td>2.4</td>
<td>1.9</td>
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<tr>
<td>$(T_{\text{turnaround}}=10 h)$</td>
<td>$T_{\text{run}} [h]$ optimum</td>
<td>14.6</td>
<td>12.3</td>
<td>8.9</td>
<td>7.0</td>
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<tr>
<td>effective luminosity</td>
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<td>2.7</td>
</tr>
<tr>
<td>$(T_{\text{turn}}=5 h)$</td>
<td>$T_{\text{run}} [h]$ optimum</td>
<td>10.8</td>
<td>9.1</td>
<td>6.7</td>
<td>5.4</td>
</tr>
</tbody>
</table>
# Heat loads per beam aperture for various LHC upgrade options

<table>
<thead>
<tr>
<th>parameter</th>
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<th>nominal (10^{11})</th>
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<td>7.55</td>
<td>3.78</td>
<td>14.4</td>
</tr>
<tr>
<td>Average electron-cloud heat load at 4.6–20 K in the arc for R=50% and $\delta_{max} = 1.4$ (in parentheses for $\delta_{max} = 1.3$)</td>
<td>$P_{ecloud}$ [W/m]</td>
<td>1.07 (0.44)</td>
<td>1.04 (0.59)</td>
<td>13.34 (7.85)</td>
<td>0.26 (0.26)</td>
</tr>
<tr>
<td>Synchrotron radiation heat load at 4.6–20 K</td>
<td>$P_\gamma$ [W/m]</td>
<td>0.17</td>
<td>0.25</td>
<td>0.50</td>
<td>0.29</td>
</tr>
<tr>
<td>Image currents power at 4.6–20 K</td>
<td>$P_\Omega$ [W/m]</td>
<td>0.15</td>
<td>0.33</td>
<td>1.87</td>
<td>0.96</td>
</tr>
<tr>
<td>Beam-gas scattering heat load at 1.9 K for 100-h beam lifetime (in parentheses for a 10-h lifetime). It is assumed that elastic scattering (\sim 40% of the total cross section) leads to local loss.</td>
<td>$P_{gas}$ [W/m]</td>
<td>0.038 (0.38)</td>
<td>0.056 (0.56)</td>
<td>0.113 (1.13)</td>
<td>0.066 (0.66)</td>
</tr>
</tbody>
</table>
electron cloud in the LHC

schematic of e- cloud build up in the arc beam pipe, due to **photoemission** and **secondary emission**

[Courtesy F. Ruggiero]
blue: e-cloud effect observed
red: planned accelerators
schematic of electron motion during passage of long proton bunch; most electrons do not gain any energy when traversing the chamber in the quasi-static beam potential.

negligible heat load
upgrade issues

**IR upgrade for lower \( \beta^* \) & higher current**
- optics: quadrupole first or dipole first
- heat load due to collision debris
- magnet technology & apertures & field quality

**crossing angle & long-range collision**
- geometric luminosity loss
- dynamic-aperture reduction

**electron cloud**
- heat load, vacuum pressure, beam lifetime, instabilities

…
upgrade roadmap → complex interdependence

- IR magnet technology
- IR optics & layout
- crab cavities
- aperture
- current
- injector upgrade
- dynamic aperture
- electron cloud
- energy deposition
- long-range beam-beam
- long-range compensation
- crossing angle
- beam structure
- higher harm. rf
- luminosity
- \( \beta^* \)
higher-energy injectors
injector upgrade - motivations

raising beam intensity (higher bunch charge, shorter spacing etc.), for limited geometric aperture, $L \sim \varepsilon_N$

reduction of dynamic effects (persistent currents, snapback, etc.)

$\rightarrow$ improvement of turn-around time by factor $\sim 2$, effective luminosity by $\sim 50\%$

benefit to other CERN programmes (ν physics, β beams,...)
LHC injector upgrade

**Super SPS**
- extraction energy $450 \text{ GeV} \rightarrow 1 \text{ TeV}$

**Super PS**
- extraction energy $26 \text{ GeV} \rightarrow 50 \text{ GeV}$

**Super LHC**
- injection energy $450 \text{ GeV} \rightarrow 1 \text{ TeV}$

[**Super ISR** is alternative to **Super PS**]

Space constraints in existing tunnels $\rightarrow$ **incentive to develop more efficient kickers**, i.e., by improving their technology reaching higher deflecting strength per unit! – opportunity for RPIA technology
# present kicker parameters

<table>
<thead>
<tr>
<th></th>
<th>PS extr.</th>
<th>SPS extr.</th>
<th>LHC inj.</th>
</tr>
</thead>
<tbody>
<tr>
<td>magnet length (mechanical)</td>
<td>0.22 m</td>
<td>1.674 m</td>
<td>3.4 m</td>
</tr>
<tr>
<td>aperture (diameter)</td>
<td>158x53 mm</td>
<td></td>
<td>38 mm</td>
</tr>
<tr>
<td># units</td>
<td>4</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>average field</td>
<td>0.07 T</td>
<td>0.0866 T</td>
<td>0.096 T</td>
</tr>
<tr>
<td>flat top length</td>
<td>5-12 μs</td>
<td>8-10 μs</td>
<td>8 μs</td>
</tr>
<tr>
<td>flat top ripple</td>
<td>&lt;1%</td>
<td>&lt;0.5%</td>
<td></td>
</tr>
</tbody>
</table>

*can we double the kicker strengths?*
stronger dipoles
energy upgrade - motivations

predicting the energy for discovery is perilous

for a decade, after the discovery of the $b$ quark we knew there should be a companion $t$ quark; predictions of its mass over that decade grew $20 \rightarrow 40 \rightarrow 80 \rightarrow 120$ GeV

4 colliders were built with top discovery as a goal

finally top was discovered by Fermilab at 175 GeV

Ellis et al, McIntyre PAC05

mass of lightest two sparticles in MSSM constrained by astrophysics & cosmology

production of W-like boson, at $M > 3.5$ TeV, higher energy is preferred
proposed design of 24-T block-coil dipole for “LHC energy tripler”

P. McIntyre, Texas A&M, PAC’05

Bi-2212 in inner (high field) windings, Nb₃Sn in outer (low field) windings

- Dual dipole (ala LHC)
- Bore field: 24 Tesla
- Max stress in superconductor: 130 MPa
- Superconductor x-section:
  - Nb₃Sn: 26 cm²
  - Bi-2212: 47 cm²
- Cable current: 25 kA
- Beam tube dia.: 50 mm
- Beam separation: 194 mm

magnets are getting more efficient!
IR choices
higher-luminosity IR optics


Candidate solutions:
Combined function NbTi magnets with large l* (O. Bruning)
Dipole first options with Nb$_3$Sn (CERN & FNAL)
Quad 1st Nb$_3$Sn (T. Sen)
Quad 1st with detector-integrated dipole (J.-P. Koutchouk)
Quad 1first flat beam (S. Fartoukh)
Quad 1st plus crab cavities (in preparation)

Criteria: aperture, energy deposition, technology, chromatic correction, beam-beam compensation, …
maximum crossing angle

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

Piwinski angle

luminosity reduction factor

![Graph showing the relationship between R_\theta and \Theta with a red arrow indicating nominal LHC](image-url)
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 collider, Tevatron, LHC, i.e., for operation with larger # bunches (9 → 70 → 120)

\[ \theta_c \approx \sqrt{\frac{\varepsilon}{\beta^*}} \left( \frac{d_{da}}{\sigma} + 3 \sqrt{\frac{k_{par} N_b}{2 \times 32 \times 10^{11}} \frac{3.75 \mu m}{\gamma \varepsilon}} \right) \]

- \( d \): dynamic aperture
- \( k_{par} \): # parasitic collisions
- \( N_b \): bunch population
various approaches to boost LHC performance:

1) **increase crossing angle AND reduce bunch length**
   (higher-frequency rf & reduced longitudinal emittance)
   [J. Gareyte ~2000; J. Tuckmantel, HHH-20004]

2) **reduce crossing angle & apply “wire” compensation**
   [J.-P. Koutchouk]

3) **reduce crossing angle & early separation dipole ‘D0’ inside detector** [J.-P. Koutchouk, 2005]

4) **crab cavities** → large crossing angles w/o luminosity loss
   [R. Palmer for LC, 1988;
    K. Oide, K. Yokoya for e+e- factories, 1989;
    1st demonstration KEKB 2006;
    F. Zimmermann for LHC upgrade ~2000]

5) **collide long super-bunches with large crossing angle**
   [Ken Takayama et al, ~2000;
    F. Ruggiero, F. Zimmermann for LHC, ~2002
    W. Fischer for RHIC, ~2003?]

RPIA technology?
IR ‘baseline’ schemes

short bunches & minimum crossing angle & BBLR

crab cavities & large crossing angle (what is minimum crossing angle for separate channels?)
long-range beam-beam compensation by wire
wire compensation “BBLR”

- SPS studies
- simulations
- LHC situation
- RHIC experiments
- US LARP
- pulsed wire
**merits of wire compensation**
- long-range compensation was demonstrated in SPS using 2 wires (lifetime recovery)
- simulations predict $1-2\sigma$ gain in dynamic aperture for nominal LHC
- allows keeping the same – or smaller – crossing angle for higher beam current → no geometric luminosity loss

**challenges & plans**
- further SPS experiments ($3^{rd}$ wire in 2007)
- demonstrate effectiveness of compensation with real colliding beams (at RHIC)
- study options for a pulsed wire
not to degrade lifetime for the PACMAN bunches, the **wire should be pulsed train by train**

LHC bunch filling pattern

example excitation patterns (zoom)
### Parameters of Pulsed Beam-Beam Compensator for LHC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revolution Period $T_{\text{rev}}$</td>
<td>$88.9 \mu s \pm 0.0002 \mu s$ (variation with beam energy)</td>
</tr>
<tr>
<td>Maximum Strength</td>
<td>120 Am</td>
</tr>
<tr>
<td>Maximum Current</td>
<td>120 A (1m)</td>
</tr>
<tr>
<td>(smaller currents will also be needed)</td>
<td>60 A (2m)</td>
</tr>
<tr>
<td>0→max ramp up/down time</td>
<td>374.25 ns</td>
</tr>
<tr>
<td>Length of max. excitation</td>
<td>1422.15 ns</td>
</tr>
<tr>
<td>Lengths of min. excitation</td>
<td>573.85 ns &amp; 598.8 ns</td>
</tr>
<tr>
<td>(larger min. times may be needed too)</td>
<td></td>
</tr>
<tr>
<td>Length of abort gap (could vary)</td>
<td>2594.75 ns</td>
</tr>
<tr>
<td>Number of pulses per cycle</td>
<td>39</td>
</tr>
<tr>
<td>Average pulse rate</td>
<td>439 kHz</td>
</tr>
<tr>
<td>Pulse accuracy with respect to ideal</td>
<td>5%</td>
</tr>
<tr>
<td>Turn-to-turn amplitude stability (relative to peak)</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Turn-to-turn timing stability</td>
<td>0.04 ns</td>
</tr>
</tbody>
</table>

**Issues:** High repetition rate, jitter & turn-to-turn stability tolerance
emittance growth from noise → jitter tolerance
including decoherence & feedback (Y. Alexahin):

\[
\frac{1}{\varepsilon} \frac{d\varepsilon}{dt} \approx f_{rev} \frac{1 - s_0}{4} \frac{(\Delta x)^2}{\sigma_x^2} \left(1 + \frac{g}{2\pi|\xi|}\right)^2
\]

\( g \sim 0.2 \) feedback gain, \( \xi \sim 0.01 \) total beam-beam parameter, \( s_0 \sim 0.645 \) related to the fact that only a small fraction of the energy received from a kick is imparted on the continuum eigenmode spectrum

1% emittance growth per hour ↔ \( \Delta x = 1.5 \) nm with feedback ↔ \( \Delta x = 0.6 \) nm w/o feedback (\( \sigma_x^* = 11 \ \mu m \))

beam jitter from wire jitter:

\[
\left(\frac{\Delta x}{\sigma}\right)_{rms} = \frac{2r_p I_w I_w}{n_{IP} e c n \varepsilon_N} \left(\frac{\Delta I_w}{I_w}\right)_{rms}
\]

for \( I_w I_w = 120 \) Am, jitter tolerance for 1% emittance growth w/o FB per hour becomes \( \Delta I_w/I_w \sim 1 \times 10^{-4} \)
crab cavities
Crab Cavities

KEKB s.c. crab cavity production
Super-KEKB crab cavity scheme

RF Deflector
(Crab Cavity)

Head-on Collision

Crossing Angle
(11 x 2 m rad.)

Electrons

Positrons

2 crab cavities / beam / IP

1.44 MV

1.41 MV

1.44 MV

1.41 MV

Palmer for LC, 1988
Oide & Yokoya for storage rings, 1989

first crab cavities will be installed at KEKB in early 2006
crab cavities

- combine advantages of head-on collisions and large crossing angles
- require lower voltages than bunch shortening rf systems
- but tight tolerances on phase jitter to avoid emittance growth
crab voltage compared with bunch-shortening rf

\[ V_{rf} \text{ [MV]} \]

\[ \sigma^* = 11.7 \mu m, R_{12} = 30 \text{ m} \]

bunch shortening rf

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

crab cavity

- 200 MHz
- 400 MHz
- 800 MHz

\[ \theta_c \text{ [rad]} \]

crab voltage compared with bunch-shortening rf
\( V_{rf} \text{ [MV]} \)

\[\sigma^* = 11.7 \mu m, R_{12} = 30 \text{ m}\]

bunch shortening rf

200 MHz

400 MHz

800 MHz

crab cavity

zoom

\( \theta_c \text{ [rad]} \)

crab voltage required for Super-LHC
crab cavity voltage for different crossing angles & crab rf frequencies

\[ V_{\text{crab}} = \frac{cE_0 \tan(\theta_c / 2)}{e2\pi f_{rf} R_{12}} \approx \frac{cE_0}{e4\pi f_{rf} R_{12}} \theta_c \]

<table>
<thead>
<tr>
<th>crossing angle</th>
<th>0.3 mrad</th>
<th>1 mrad</th>
<th>8 mrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>800 MHz</td>
<td>2.1 MV</td>
<td>7.0 MV</td>
<td>56 MV</td>
</tr>
<tr>
<td>400 MHz</td>
<td>4.2 MV</td>
<td>13.9 MV</td>
<td>111 MV</td>
</tr>
<tr>
<td>200 MHz</td>
<td>8.4 MV</td>
<td>27.9 MV</td>
<td>223 MV</td>
</tr>
</tbody>
</table>

*R₁₂ = 30 m

*800 MHz would be too high for nominal LHC bunch length
comparison of timing tolerance with others

<table>
<thead>
<tr>
<th></th>
<th>KEKB</th>
<th>Super-KEKB</th>
<th>ILC</th>
<th>Super-LHC</th>
</tr>
</thead>
<tbody>
<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>22 mrad</td>
<td>30 mrad</td>
<td>10 mrad</td>
<td>1 mrad</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>6 ps</td>
<td>3 ps</td>
<td>0.03 ps</td>
<td>0.002 ps</td>
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</table>

$\Delta x_{\text{max}} = 0.6 \text{ nm}$ from Y. Alexahin’s formula
$\Delta x_{\text{max}} = 0.5 \text{ nm}$ scaled from strong-strong beam-beam simulation by K. Ohmi (HHH-2004), for 1% $\varepsilon$ growth per hour

IP offset of 0.2 $\sigma_{x^*}$

IP offset of 0.6 nm, $\sim 5 \times 10^{-5} \sigma^*$

$\Delta t \leq \frac{2\Delta x_{\text{max}}}{n_{\text{IPc}} \theta_c}$
Gupta: Quad Pairs for (not so) Large Crossing Angle, 4 mrad, why not 8 mrad?

Consider the two counter-rotating beams with the first going through a quad. How close can the second beam be?

Displaced quads with the first beam in the quad and counter rotating beam just outside the coil in a field free region.

Minimum X-ing angle is determined by how close the other beamline can come.

50 m free space !, 45 cm lateral

[H. Padamsee, US LARP IR meeting October 2005]
KEKB crab cavity, ~1.5 MV@500 MHz
TM2-1-0 (x-y-z) rect. mode (=TM110 cyl.)
radial size 43 cm

Courtesy K. Akai
Solutions

• plane of separation need not be the plane of crossing
• new fundamental mode 2-beam crab cavity [H. Padamsee]
• compact induction rf crab cavity?
Can This Work (Maybe 2 Cavities if necessary)

[Forward beam]

RF Cavity
$TM_{010}$ (cyl)

$TM_{1-1-0}$ (rect)

[Return Beam]

[Dampers]

[H. Padamsee, US LARP IR meeting October 2005]
superbunch hadron collider

K. Takayama et al.,
PRL 88, 14480-1 (2002)

x-y crossing or 45/135 degree crossing

V-crossing

H-crossing
superbunches for LHC

+ negligible electron-cloud heat load
+ no PACMAN bunches
+ reduced IBS
+ higher luminosity for same tune shift
  & smaller beam current

- huge event pile up
# example parameter sets (HHH-2004)

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<th>superbunch</th>
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<td>norm. transv. emittance</td>
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<td>$\sigma_z [\text{cm}]$</td>
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<td>beta at IP1&amp;IP5</td>
<td>$\beta^* [\text{m}]$</td>
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<td>$\theta_c \sigma_z / (\sigma^* / 2)$</td>
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<td>luminosity</td>
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<td>$\sigma_{lum} [\text{mm}]$</td>
<td>44.9</td>
<td>42.8</td>
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baseline 'Piwinski' super-bunch
joint statement by LHC ATLAS & CMS experiments on super-bunches at CARE-HHHH-2004 workshop

“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 the luminosity could be exploited by an upgraded ATLAS or CMS detector”
QCD Explorer based on LHC and CLIC-1
QCD Explorer based on LHC and CLIC-1

some key points

- extends reach of HERA by 2 orders of magnitude
- as fundamental for QCD as the Higgs for electro-weak interaction
- highest-energy linac-ring collider
- optimum luminosity $L > 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ is achieved with proton superbunch
- e- beam emittances relaxed from CLIC goal
luminosity maximized by concentrating p’s over length of e- train

2808 p bunches spaced by 25 ns

filling patterns with nominal LHC proton beam

220 e- bunches spaced by 0.267 ns

1 p superbunch, 18 m long

filling patterns with LHC proton superbunch

220 e- bunches spaced by 0.267 ns
schematic IR layout

vertical bend  protons  horizontal bend

electrons

interaction length l

vertical and horizontal dipoles combine and separate the two beams
## QCDE parameters

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<th>parameter</th>
<th>e-</th>
<th>P</th>
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<td>beam energy</td>
<td>$E_b$ 75 GeV (or higher)</td>
<td>7 TeV</td>
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<td>bunch population</td>
<td>$N_b$ 2.56x10^9</td>
<td>6.5x10^{13}</td>
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<td>bunch length</td>
<td>$\sigma_z$ 31 $\mu$m (rms)</td>
<td>18 m (full)</td>
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<td>Spacing</td>
<td>$L_{sep}$ 0.267 ns</td>
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<td># bunches</td>
<td>$n_b$ 220</td>
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<td>effective line density</td>
<td>$\lambda_b$ 3.2x10^{10} m^{-1}</td>
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<td>IP beta</td>
<td>$\beta^*$ 0.25 m</td>
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<td>interaction length</td>
<td>$l_{IR}$ 2 m</td>
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<td>collision frequency</td>
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<td>luminosity</td>
<td>$L$ 1.3x10^{31} cm^{-2} s^{-1}</td>
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<td>beam-beam tune shift</td>
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<td>$\gamma\varepsilon_{x,y}$ 73 $\mu$m</td>
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<td>IP spot size</td>
<td>$\sigma_{x,y}$ 11 $\mu$m</td>
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conclusions
RPIA’06 issues @ LHC upgrade:

- pulser for long-range beam-beam compensation
- crab-cavity optimization
- stronger kickers at Super-PS/SPS/LHC
- superbunches for QCD Explorer
tentative milestones for future machine studies

- **2006**: installation of *crab cavities in KEKB*, validation of KEKB beam-beam performance with crabbing; installation of a long-range compensator in RHIC
- **2007**: experiments with *three dc beam-beam compensators at SPS; dc compensation experiments with colliding beams in RHIC*; also at RHIC installation of a pulsed compensator (LARP)
- **2008**: experiment with *pulsed beam-beam compensation in RHIC*; installation of *crab cavity in hadron machine* (also RHIC?) to validate low rf noise and emittance preservation; studies of *electron lenses* in RHIC?
Reference LHC Luminosity Upgrade: workpackages and tentative milestones

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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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Reference LHC Upgrade scenario: peak luminosity 4.6x10⁻²⁹/(cm²2 see)
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
thank you for your attention!