LHC upgrade based on a high intensity high energy injector chain

Walter Scandale CERN AT department

LHC-LUMI 2005
Arcidosso, 31 August 2005

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

♦ nominal parameters and timescale for their upgrade

♦ path for the performance upgrade
  ◆ phase 0: the ultimate luminosity
  ◆ phase 1: the IR upgrade
  ◆ phase 3: the injector complex upgrade

♦ concluding remarks
### nominal parameters of LHC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision energy (TeV)</td>
<td>2x7.0</td>
</tr>
<tr>
<td>Dipole peak field (T)</td>
<td>8.3</td>
</tr>
<tr>
<td>Luminosity (cm(^{-2}) s(^{-1}))</td>
<td>10(^{34})</td>
</tr>
<tr>
<td>Injection energy (TeV)</td>
<td>0.45</td>
</tr>
<tr>
<td>Circulating current per beam (A)</td>
<td>0.56</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2808</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>1.15x10(^{11})</td>
</tr>
<tr>
<td>Stored beam energy per beam (MJ)</td>
<td>350</td>
</tr>
<tr>
<td>Beam size at IP ((\mu)m)</td>
<td>15.9</td>
</tr>
<tr>
<td>Beta values at IP (m)</td>
<td>0.55</td>
</tr>
<tr>
<td>Normalised emittance ((\mu)m)</td>
<td>3.75</td>
</tr>
<tr>
<td>Crossing angle ((\mu)rad)</td>
<td>300</td>
</tr>
<tr>
<td>Beam lifetime (h)</td>
<td>22</td>
</tr>
<tr>
<td>Luminosity lifetime (h)</td>
<td>10</td>
</tr>
<tr>
<td>Radiated power per beam (kW)</td>
<td>3.7</td>
</tr>
</tbody>
</table>
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 → $L = 2.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
3) increase the dipole field from 8.33 to 9 T → $E_{\text{max}} = 7.54 \text{ TeV}$

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 $\rightarrow \beta^* = 0.25$ m
2) increase crossing angle $\theta_c$ by $\sqrt{2} \rightarrow \theta_c = 445$ $\mu$rad
3) increase $N_b$ up to ultimate luminosity $\rightarrow L = 3.3 \times 10^{34}$ 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 the no. of bunches $n_b$ (increasing $\theta_c$) $\rightarrow L = 9.2 \times 10^{34}$ cm$^{-2}$s$^{-1}$

⚠️ step 4) is not cheap: it requires a new RF system in LHC providing

- an accelerating voltage of 43MV at 1.2GHz
- a power of about 11MW/beam $\rightarrow$ estimated cost 56 MCHF
- a longitudinal beam emittance reduced to 1.78 eVs
- horizontal Intra-Beam Scattering (IBS) growth time will decrease by about $\sqrt{2}$

⚠️ operational consequences of step 5) ($\rightarrow$ exceeding ultimate beam intensity)

- upgrade LHC cryogenics, collimation and beam dump systems
- upgrade the electronics of beam position monitors
- possibly upgrade the SPS RF system and other equipments in the injector chain
## phase 0 & phase 1 upgrade options

<table>
<thead>
<tr>
<th>parameter</th>
<th>symbol</th>
<th>nominal luminosity</th>
<th>ultimate luminosity</th>
<th>shorter bunch</th>
<th>longer bunch</th>
<th>Super bunch</th>
</tr>
</thead>
<tbody>
<tr>
<td>no of bunches</td>
<td>$n_b$</td>
<td>2808</td>
<td>2808</td>
<td>5616</td>
<td>936</td>
<td>1</td>
</tr>
<tr>
<td>proton per 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>$89 \times 10^3$</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>normalized emittance</td>
<td>$\varepsilon_n \text{[\mu m]}$</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>Gaussian</td>
<td>Gaussian</td>
<td>Gauss.</td>
<td>flat</td>
<td>flat</td>
<td></td>
</tr>
<tr>
<td>rms bunch length</td>
<td>$\sigma_s \text{[cm]}$</td>
<td>7.55</td>
<td>7.55</td>
<td>3.78</td>
<td>14.4</td>
<td>$6 \times 10^3$</td>
</tr>
<tr>
<td>$\beta^*$ at IP1&amp;IP5</td>
<td>$\beta^* \text{[m]}$</td>
<td>0.55</td>
<td>0.50</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>full crossing angle</td>
<td>$\theta_c \text{[\mu rad]}$</td>
<td>285</td>
<td>315</td>
<td>445</td>
<td>430</td>
<td>$1 \times 10^3$</td>
</tr>
<tr>
<td>Piwinsky parameter</td>
<td>$\theta_c \sigma_s/(2\sigma^*)$</td>
<td>0.64</td>
<td>0.75</td>
<td>0.75</td>
<td>2.8</td>
<td>$2.7 \times 10^3$</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>event par crossing</td>
<td>19</td>
<td>44</td>
<td>88</td>
<td>510</td>
<td>$5 \times 10^5$</td>
<td></td>
</tr>
<tr>
<td>$l_{\text{rms of luminous region}}$</td>
<td>$\sigma_{\text{lum}} \text{[mm]}$</td>
<td>44.9</td>
<td>42.8</td>
<td>21.8</td>
<td>36.2</td>
<td>16.7</td>
</tr>
</tbody>
</table>
phase 0 & phase 1 tentative conclusion

statement from experiments on super-bunch scenario:

“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”

◆ detector upgrade does not mean building a completely new detector
◆ pile up for super-bunches would be problematic in any case

preference from experiments:

◆ integrated luminosity in stable running mode is what counts most
◆ use shorter but finite bunch spacing, e.g., 12.5 ns;
◆ present detector read-out electronics already at 80 MHz!

(for the accelerator it is much easier to provide 10 ns or 15 ns spacing!)

final choice of bunch spacing should be based on cost effectiveness
luminosity and energy upgrade

**Phase 2: steps to reach maximum performance with major hardware changes:**

- Equip the SPS with SC magnets, upgrade transfer lines to LHC and the injector chain, to inject into the LHC at 1 TeV (→ super-SPS option)
  - Beam luminosity should increase
  - First step in view of an LHC energy upgrade

  - For a given mechanic and dynamic apertures at injection, this option can double the beam intensity (at constant beam-beam parameter $\Delta Q_{bb} \propto \frac{N_b}{\epsilon_n}$) increasing the LHC peak luminosity by nearly a factor two, in conjunction with long range beam-beam compensation schemes

  - LHC energy swing is reduced by a factor 2, hence the SC transient phenomena should be smaller and the turnaround time to fill LHC should decrease

  - Interesting alternative → cheap, compact low-field booster rings in the LHC tunnel

- Install in LHC new dipoles with a operational field of 15 T considered a reasonable target for 2015 ÷ 2020 → beam energy around 12.5 TeV
  - Luminosity should increase with beam energy
  - Major upgrade in several LHC hardware components
scenarios for upgrading the injector chain

- up to 160 MeV: LINAC 4
- up to 2.2 GeV: the SPL (or a super-BPS)

- up to 25 GeV: a fully refurbished PS

The superconducting way:
- up to 150 GeV: a refurbished SPS
- up to 1 TeV: a SC super SPS
- SC transfer lines to LHC

The normal conducting way:
- 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
reusing the ISR tunnel

- up to 160 MeV: LINAC 4
- up to 2.2 GeV: the SPL (or a super-BPS)

- up to 25 GeV: a fully refurbished PS

the superconducting way:
- transfer line to ISR-tunnel
- up to 100 GeV: a SC super-PS in the ISR tunnel
- up to 1 TeV: a SC super SPS
- SC transfer lines to LHC

See CARE-HIPPI
basic assumptions

◆ PS extraction energy ≥ 25 GeV
◆ PS bunch population $2 \times 10^{11}$ within $3.5 \, \mu m$ emittance, and $4 \times 10^{11}$ within $7 \, \mu m$,
◆ PS bunch separation 12.5 ns (or 10 ns, if the impact on RF system should be minimised)
◆ To evenly spread the energy swing from 25 to 1000 GeV, we need two rings: the first ring should reach 150 GeV and the second 1 TeV
◆ As an alternative the first ring can reach 100 GeV and the second 1000 GeV

luminosity upgrade should mostly come from:
  ■ shorter turnaround time in filling the LHC
  ■ increased circulating intensity and bunch population
shortening the turnaround time

- injecting in LHC 1 TeV protons reduces the dynamic effects of persistent currents i.e.:
  - persistent current decay during the injection flat bottom
  - snap-back at the beginning of the ramp
→ decrease the turn-around time and hence increases the integrated luminosity

\[ T_{\text{run}} (\text{optimum}) \Rightarrow \left\{ \begin{array}{l}
1 + \frac{T_{\text{run}} + T_{\text{turnaround}}}{\tau_L} = e^{\frac{T_{\text{run}}}{\tau_L}} \\
\int_0^{T_{\text{run}}} L \, dt \approx \frac{T_0 \tau_L}{T_{\text{run}} + T_{\text{turnaround}} + \tau_L} \end{array} \]

\[ L(t) = L_0 e^{-\frac{t}{\tau_L}} \]

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

| \( L_0 \) [cm\(^{-2}\)s\(^{-1}\)] | \( \tau_L \) [h] | \( T_{\text{turnaround}} \) [h] | \( T_{\text{run}} \) [h] | \( \int_{200 \, \text{runs}} \) L dt [fb\(^{-1}\)] | gain |
|---|---|---|---|---|
| \( 10^{34} \) | 15 | 10 | 14.6 | 66 | \( \times 1.0 \) |
| \( 10^{34} \) | 15 | 5 | 10.8 | 85 | \( \times 1.3 \) |
| \( 10^{35} \) | 6.1 | 10 | 8.5 | 434 | \( \times 6.6 \) |
| \( 10^{35} \) | 6.1 | 5 | 6.5 | 608 | \( \times 9.2 \) |
increasing the circulating intensity

- 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

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

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

- at the beam-beam limit, peak luminosity \( L \) is proportional normalized emittance = \( \gamma \varepsilon \) (we propose doubling \( N \) and \( \varepsilon_n \), keeping constant \( \varepsilon_n/N \)).
- 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 b-b effects have to be compensated.
why not a 1 TeV ring in the LHC tunnel?

😊 positive aspects:
1) no need to upgrade the injection lines TI2 and TI8
2) more relaxed magnets in the injector ring
3) higher injection energy (if needed)

😊 drawbacks
1) unchanged aperture limitation in the transfer lines
2) by-pass needed for ATLAS and CMS (especially to avoid loss of test beams)
3) difficult optics for injection extraction with limited space in a dedicated long straight section of LHC tunnel
pulsed SC magnets for the super-SPS

- with the present SPS dipole packing factor, at 1 TeV we need SC dipole with $B_{\text{peak}} \approx 4.5$ T
- to reduce dynamic effects of persistent current, the energy swing should not exceed $\times 10$
- the optimal injection energy is of about $100\div150$ GeV
- a repetition rate of 10 s should halve the LHC filling time

**SPS beam size:**
- normalized emittance: $\varepsilon^* = 2 \times 3.5$ µm (2 factor is related to the higher bunch intensity)
- peak-beta: $\beta_{\text{max}} \approx 100$ m (assuming the same focusing structure of the present SPS)
- rms beam size at injection: $\sigma_{150\text{GeV}} \approx 2.2$ mm $\sigma_{1000\text{GeV}} \approx 0.8$ mm

**SPS aperture**
- peak closed orbit: $\text{CO}_{\text{max}} = 5$ mm
- dispersive beam size $D \times \delta = 12$ mm (assuming $D = 4$ m, $\delta_{\text{bucket}} = 3 \times 10^{-3}$)
- betatron beam size $6 \times \sigma_{150\text{GeV}} = 12$ mm and $6 \times \sigma_{1000\text{GeV}} = 5$ mm
- separatrix size for slow extraction 20 mm
- clearance of 6 mm

adding in quadrature the betatron and the dispersive beam size and linearly the closed orbit, the separatrix size, and the clearance one will need a radial aperture of at least 29 mm at injection and 44 mm at top energy.
pulsed SC magnets for the super-SPS

- a SC dipole for the SPS may produce 70 W/m peak (35 W/m effective ⇒ 140 kW for the SPS, equivalent to the cryogenic power of the LHC!)

- a rather arbitrary 'guess' for tolerable beam loss is of about $10^{12} \times 1000 \text{GeV}/10s = 15 \text{kW}$

- by dedicated R&D magnet losses should be lowered to 10 W/m peak (5 W/m effective ⇒ 20 kW), comparable to 'tolerable' beam loss power
present SPS supercycle for filling LHC

PS cycle duration: 3.6 s

SPS ramp rate: 78 GeV/s

LHC

SPS

PS

= 88.924 μS

= 7/27 LHC

= 1/11 SPS
interleaved SPS & super-SPS cycles

<table>
<thead>
<tr>
<th></th>
<th>SPS</th>
<th>Super-SPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSB</td>
<td>$E_{\text{inj}} = 26 \text{ GeV}$</td>
<td>$E_{\text{inj}} = 150 \text{ GeV} \rightarrow B = 0.675 \text{ T}$</td>
</tr>
<tr>
<td></td>
<td>$E_{\text{ext}} = 150 \text{ GeV}$</td>
<td>$E_{\text{ext}} = 1000 \text{ GeV} \rightarrow B = 4.5 \text{ T}$</td>
</tr>
<tr>
<td></td>
<td>10.8 s rep-rate</td>
<td>10.8 s rep-rate</td>
</tr>
<tr>
<td>PS</td>
<td>51.67 GeV/s ramp-rate</td>
<td>166.67 GeV/s ramp-rate</td>
</tr>
<tr>
<td></td>
<td>3 PS-batches/cycle</td>
<td>dB/dt = 0.75 T/s</td>
</tr>
<tr>
<td></td>
<td>2.7 s rep-rate</td>
<td>3 PS-batches/cycle</td>
</tr>
</tbody>
</table>
test beam cycle for the super-SPS

Super-SPS

- \( E_{\text{inj}} = 150 \text{ GeV} \rightarrow B = 0.675 \text{ T} \)
- \( E_{\text{ext}} = 1000 \text{ GeV} \rightarrow B = 4.5 \text{ T} \)
- 10.8 s rep-rate
- 200 GeV/s ramp-rate
- \( \frac{dB}{dt} = 0.9 \text{ T/s} \)
- 3 PS-batches/cycle
- flat-top 2 s
the super-ISR

- the PS can provide 30 GeV proton beams with \( N_b = 4 \times 10^{11} \) (assuming the high intensity option upgrade based on LINAC4 and either on the SPL or on a RCS as preinjectors up to about 2 GeV)
- to inject in the SPS we need another ring providing an energy swing of about \( \times 3 \)
- this can be a SC ring located in the ISR tunnel providing 100 GeV protons

**ISR beam size:**
- normalized emittance: \( \varepsilon^* = 2 \times 3.0 \ \mu m \) (2 factor is related to the higher bunch intensity)
- peak-beta: \( \beta_{\text{max}} \approx 100 \ \text{m} \) (assuming the same focussing structure of the present SPS)
- rms beam size at injection: \( \sigma_{30\text{GeV}} \approx 4.8 \ \text{mm} \)
- radial aperture = (assuming \( CO_{\text{max}} = 5 \ \text{mm}, D = 4 \ \text{m}, \delta_{\text{bucket}} = 3 \times 10^{-3} \) and a clearance of \( \approx 9 \ \text{mm} \))

**Tentative ISR/SPS cycles**

- **fast cycling option**
  - Single ring
  - 1/3 time occupancy for LHC
  - 6 Ts-1 ramp
  - heavy R&D requested

- **slow cycling option**
  - triple ring (or three rings)
  - full time occupancy for LHC
  - 1+2 Ts-1 ramp
  - light R&D requested

---

31 August 2005 - LHC-LUMI 05  
W.Scandale, LHC upgrade based on high intensity high energy injector chain
recent activity on fast cycling dipoles

SIS 200 (abandoned)
- 4 T central field, 1 T/sec ramp
- Design based on RHIC dipoles
- Costeta, Rutherford cable
- One phase He cooling

BNL model: optimize to higher ramp-rate
- Wire twist pitch 4 mm instead of 13 mm
- Stabrite coating instead of no coating
- Stainless steel core (2x25 microns)
- G-11 wedges instead of copper wedges
- Thinner yoke laminations (0.5 mm instead of 6.35 mm), 3.5 % silicon, glued with epoxy.

Cable inner edge

31 August 2005 - LHC-LUMI 05  W.Scandale, LHC upgrade based on high intensity high energy injector chain
the BNL fast cycling dipole model

cross section of GSI-001 prototype magnet

Cable with core

RHIC coil with G11 wedges

SS collars

G11 collar keys

0.5 mm Si-steel yoke lamination

GSI COLDMASS CROSS SECTION

G10 COIL SHIM

G10 COLLAR PACK STACKING RODDS

G11 SLEEVES FOR RODDS

SST YOKE TIE RODDS

G11 COLLARING KEYS

G10 YOKE ALIGNMENT KEY

WELD BACKING STRIP

COLDMASS SHELL

SST COLLARS

G11 COIL WEDGES

HELIUM VENT SLOT

.020" THICK YOKE LAMINATIONS

Courtesy A.Ghosh
**the SIS 300 fast cycling dipole model**

**SIS 300**
- 6 T, 1 T/sec ramp, 100 mm bore
- Design based on UNK dipoles, bore from 80 mm to 100 mm
- 2-layers Cosθ, Rutherford cable
- One phase He cooling

**Challenges:**
*high operational field for 4.2 K, pulsed, high losses*

**Activity on cable development:**
- Reduction of conductor AC loss adjusting filament hysteresis, strand matrix coupling current, cable crossover resistance Rc, and adjacent resistance Ra.
- A 3.5 micrometer filament diameter was chosen because it appears to be the minimum value that can be reached in a standard copper matrix strand without the onset of proximity coupling.
- The use of a Cu-0.5% Mn as an interfilamentary matrix material is also under consideration, to reduce both matrix coupling current losses (due to the high resistivity of CuMn) and hysteresis losses.
Motivation: 60 - 70% of the coil AC losses caused by wire magnetization

- filament size reduction
- but limit due to 'proximity coupling'

\[ d_{\text{fil}} \geq 3.5 \mu m \text{ for Copper matrix} \]

\[ d_{\text{eff}} = 3.5 \mu m, \text{ but problems with stacking of 12000 monocores (1.5 mm wide)} \]

\[ d_{\text{eff}} = 4.8 \mu m \text{ due to filament distortion (near the copper)} \]
open items

1. evaluate all consequences of higher intensity operation
2. installation staging in the SPS tunnel, minimising the duration of the shutdown
3. lattice design also considering the partial use the present SPS ring
4. refined estimate of the magnet aperture
5. slow extraction design at 1 TeV within the space available
6. optimal extraction & injection channels (kickers and septa operating on more energetic particles within serious space occupancy constraints)
7. estimate of the expected loss
8. design of SC transfer lines to the LHC
9. optimal design for the SC magnets for the super-SPS: nominal parameters should be proposed and a road map for the requested R & D presented.
10. cryogenic system: solution should be investigated for the needs and the installation of cryogenics in the SPS tunnel.
11. RF systems: the optimal choice of the RF parameter is not yet available.

foreseeing other uses of the super-SPS

1. scenario to fill the whole super-SPS ring
2. upper value of the circulating intensity
3. optimal cycle duration
4. optimal bunch distance
concluding remarks

the expected factors for the LHC luminosity upgrade are

- factor 2 from new low-beta insertions with $\beta^*=0.25\ m$
- factor 2.3 from nominal to ultimate bunch intensity ($1.7\times10^{11}\ p$)

with an upgraded injector we expect a farther increase in luminosity of

- factor 2 if we can double the number of bunches
- factor 2 from a twice larger bunch intensity
- factor 1.4 from a shorter LHC turnaround time

ensuring $L=10^{35}\ cm^{-2}\ s^{-1}$ and a gain of about 9 in $\int Ldt$

R & D is required on
- optics, beam control, machine protection
- high gradient high aperture SC quadrupoles and RF
- SC fast ramping magnets