LHC machine – status and plans

R. Bailey
CERN, Geneva, Switzerland
LHC machine – status and plans

- Progress in 2005/2006
  - Cryogenic distribution line (QRL)
  - Magnet procurement
  - Installation
  - Electrical power tests

- Plans for beam commissioning
Cryogenic system

Point 8

Storage

QSCC QSCA QSCB QSCC

QSRA QSRB

QURA QUIC

QURC QURC

Sector 7-8 Sector 8-1

Surface Shaft Cavern Tunnel

R. Bailey, HERA-LHC, June 2006
The huge number of stored dipoles allowed matching each individual slot to a specific dipole and opened the opportunity to minimize the effect of field quality differences between individual magnets.
Magnet transport

- Power tests
- Stripping
- Fiducialization

Pt18

Storage → SMI2
Final preparation
Final checks

SMI2 → Storage → SMI2

PMI2 & Final position

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Magnet installation

- First magnet lowered down PMI2 on March 7th 2005

- Needed to install a magnet
  - Slot available in the tunnel
  - Magnet available
  - Logistics and associated infrastructure operational

![Dipoles Installation Rate](image)

Last Update Wed, 31 May 2006 16:37:35
24h short circuit heat run (October 2005)

Short-circuit tests are not only power converter tests: energy extraction tests, DC cables tests, AC network conditions, cooling and ventilation, interlocks, control,…
Installation & testing targets

- Complete full installation and tests of QRL in 06
- Complete the cold tests of the 1232 dipoles in 06
- Cool down of sectors 7-8 and 8-1 in 06
- Start hardware commissioning in 06

Target potential bottlenecks
- Optimize magnet transport logistics still further
- Rate of magnet interconnections
- Procurement of electrical feedboxes (DFBs)

- Last magnet lowered March 2007
- Last interconnect (ring closed) June 2007

Then
- Cool down of last sectors
- Hardware commissioning of last sectors
- Machine checkout
- Beam commissioning

Revised schedule in preparation based on these targets (for approval at the TCC of June 16th)

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Beam test 8-7-6 in 2007?

Aim to send beam:

- Out of SPS TT40 ✓
- Down TI8 ✓
- Inject into LHC R8
- Through insertion R8
- Through LHCb
- Through IP8
- Through insertion L8
- Through arc 8-7
- Through point 7
- Through arc 7-6 ?
- To beam dump at L6 ?

Injection
25% of the ring
Extraction
End of installation in 2007 - then what?

Don’t believe what you read

“When it is finished, this is what will happen: someone will push a button, and then small bundles ... will be accelerated by powerful magnetic fields ... up to almost the speed of light” UK Daily Mail, May 2006

More seriously

“Thus, to achieve high luminosity, all one has to do is make (lots of) high population bunches of low emittance to collide at high frequency at locations where the beam optics provides as low values of the amplitude functions as possible.” PDG 2005, chapter 25

Nearly all the parameters are variable

- Number of particles per bunch \( N \)
- Number of bunches per beam \( k_b \)
- Relativistic factor \( \gamma \)
- Normalised emittance \( \varepsilon_n \)
- Beta function at the IP \( \beta^* \)
- Crossing angle factor \( F \)
  - Full crossing angle \( \theta_c \)
  - Bunch length \( \sigma_z \)
  - Transverse beam size at the IP \( \sigma \)

\[
L = \frac{N^2 k_b f \gamma}{4 \pi \varepsilon_n \beta^*} F
\]
Global requirements

ATLAS and CMS
- Proton collisions @ highest energy
  - Nominal luminosity $10^{34}$ cm$^{-2}$ s$^{-1}$ in points 1 and 5
  - Minimize event pileup early on (to 2 or 3 cf 20 nominal)
  - Go to 25ns as soon as possible
  - Will make use of any beam for detector commissioning

LHCb
- Proton collisions @ highest energy
  - Nominal luminosity ~ $5 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ in point 8
  - Tune IP8 to optimize luminosity ($1 m < \beta^* > 50 m$)
  - Go to 25ns as soon as possible (optimized for ~ 1 events/crossing)
  - Frequent dipole polarity changes (~every fill !)

ALICE
- Proton collisions @ various energies
  - Will use proton beams (intrinsic interest and reference data)
  - Nominal luminosity ~ $10^{30}$ cm$^{-2}$ s$^{-1}$ in point 2
  - Tune IP2 to optimize luminosity ($0.5 m < \beta^* > 50 m$)
  - Magnet polarities change (+/- 0) a few times per year

IONS
- Collisions @ various energies for ALICE
  - Nominal luminosity ~ $10^{27}$ cm$^{-2}$ s$^{-1}$ in point 2
  - ATLAS and CMS will also take data

TOTEM
- Proton collisions @ various energies
  - Special machine conditions (low emittance, high $\beta^*$)
    - $10^6$ seconds @ $<L>$ of $10^{33}$ cm$^{-2}$ s$^{-1} \rightarrow 1$ fb$^{-1}$
## Machine considerations

<table>
<thead>
<tr>
<th>Nominal settings</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Beam energy (TeV)</td>
<td>7.0</td>
</tr>
<tr>
<td>Number of particles per bunch</td>
<td>$1.15 \times 10^{11}$</td>
</tr>
<tr>
<td>Number of bunches per beam</td>
<td>2808</td>
</tr>
<tr>
<td>Crossing angle ($\mu$rad)</td>
<td>288</td>
</tr>
<tr>
<td>Norm transverse emittance ($\mu$m rad)</td>
<td>3.75</td>
</tr>
<tr>
<td>Bunch length (cm)</td>
<td>7.55</td>
</tr>
<tr>
<td>Beta function at IP 1, 2, 5, 8 (m)</td>
<td>0.55, 10, 0.55, 10</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Related parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity in IP 1 &amp; 5 (cm$^{-2}$ s$^{-1}$)</td>
<td>$10^{34}$</td>
</tr>
<tr>
<td>Luminosity in IP 2 &amp; 8 (cm$^{-2}$ s$^{-1}$)</td>
<td>$\sim 5 \times 10^{32}$</td>
</tr>
<tr>
<td>Transverse beam size at IP 1 &amp; 5 ($\mu$m)</td>
<td>16.7</td>
</tr>
<tr>
<td>Transverse beam size at IP 2 &amp; 8 ($\mu$m)</td>
<td>70.9</td>
</tr>
<tr>
<td>Stored energy per beam (MJ)</td>
<td>362</td>
</tr>
</tbody>
</table>
So how to get there?

- Find a balance between robust operation and satisfying the experiments
  - Maximize integrated luminosity
  - Minimize event pile-up (to event + 2)

- Avoid quenches (and damage)
  - Higher $\beta^*$ to avoid problems in the (later part of) the squeeze
  - Reduce total current to reduce stored beam energy
    - Lower $i_b$
    - Fewer bunches
  - Reduce energy to get more margin?
    - Against transient beam losses
    - Against magnet operating close to training limit
    - Hardware commissioning will tell us more

- With lower currents in mind, two machine systems will be staged
  - Only 8 of 20 beam dump dilution kickers initially installed
    - Total beam intensity < 50% nominal
    - Install the rest when needed

- Collimators (robustness, impedance and other issues)
  - Phased approach
  - Run at the impedance limit during phase I
    - Lower currents
    - Higher $\beta^*$

Eventrate / Cross = $\frac{L_\sigma_{TOT}}{k_b f}$
I. **Pilot physics run**
   - First collisions
   - 43 bunches, no crossing angle, no squeeze, moderate intensities
   - Push performance (156 bunches, partial squeeze in 1 and 5, push intensity)
   - Performance limit $10^{32}$ cm$^{-2}$ s$^{-1}$ (event pileup)

II. **75ns operation**
   - Establish multi-bunch operation, moderate intensities
   - Relaxed machine parameters (squeeze and crossing angle)
   - Push squeeze and crossing angle
   - Performance limit $10^{33}$ cm$^{-2}$ s$^{-1}$ (event pileup)

III. **25ns operation I**
   - Nominal crossing angle
   - Push squeeze
   - Increase intensity to 50% nominal
   - Performance limit $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$

IV. **25ns operation II**
   - Push towards nominal performance

R.Bailey, HERA-LHC, June 2006
Stage I

- **Start as simple as possible**
  - No squeeze
    - $\beta^* = 18\text{m} \text{ in 1 & 5}$
    - $\beta^* = 10\text{m} \text{ in 2 & 8}$
  - Avoid parasitic beam-beam
    - No crossing angle
    - D1L to D1R $\sim 116\text{m}$
    - Minimum bunch spacing 232m, $\sim 0.8\mu$s
    - 43 bunches per beam convenient for the injectors, spacing 2.025$\mu$s
  - Switch off all unused equipment

- **Under these relatively clean, safe conditions**
  - Injection of beam from SPS is always safe
  - Stored beam energy comparable to other facilities
  - Commission the nominal cycle
  - Establish reproducible operation
  - Commission machine protection systems
  - Beam measurement campaign
  - Make a few single beam runs at top energy
  - First high energy collisions
  - Increase performance

- **Bring on crossing angle**
  - Luminosity may well go down (remember SPS collider and LEP)
  - Recover as much as possible without parasitic beam-beam

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Stage I physics run

- Start as simple as possible
- Change 1 parameter \((k_b, N, \beta^*_1, s)\) at a time
- All values for
  - nominal emittance
  - 7TeV
  - 10m \(\beta^*_s\) in point 2 (luminosity looks fine)

\[
L = \frac{N^2 k_b f \gamma}{4\pi \varepsilon \beta^*} F
\]

Eventrate / Cross = \(\frac{L \sigma_{TOT}}{k_b f}\)

Protons/beam \(\leq 10^{13}\)
(LEP beam currents)

Stored energy/beam \(\leq 10\text{MJ}\)
(SPS fixed target beam)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Beam levels</th>
<th>Rates in 1 and 5</th>
<th>Rates in 2</th>
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<tbody>
<tr>
<td>(k_b)</td>
<td>(N)</td>
<td>(\beta^*)</td>
<td>(I_{beam})</td>
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<tr>
<td></td>
<td></td>
<td>((m))</td>
<td>proton</td>
</tr>
<tr>
<td>1</td>
<td>10^{10}</td>
<td>18</td>
<td>1.10^{10}</td>
</tr>
<tr>
<td>43</td>
<td>10^{10}</td>
<td>18</td>
<td>4.3 10^{11}</td>
</tr>
<tr>
<td>43</td>
<td>4 10^{10}</td>
<td>18</td>
<td>1.7 10^{12}</td>
</tr>
<tr>
<td>43</td>
<td>4 10^{10}</td>
<td>2</td>
<td>1.7 10^{12}</td>
</tr>
<tr>
<td>156</td>
<td>4 10^{10}</td>
<td>2</td>
<td>6.2 10^{12}</td>
</tr>
<tr>
<td>156</td>
<td>9 10^{10}</td>
<td>2</td>
<td>1.4 10^{13}</td>
</tr>
</tbody>
</table>

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LHCb during Stage I

- Displace bunches in one ring (n on m)
  - 4 per SPS cycle in 43 bunch, 16 per SPS cycle in 156 bunch mode
- Dedicated runs for LHCb (n on n)?
- Squeeze in point 8 (2m limit for ‘bad’ LHC dipole polarity)
- All values for
  - nominal emittance
  - 7TeV

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Rates in 8</th>
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<tr>
<td></td>
<td>Luminosity (cm⁻²s⁻¹)</td>
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<tr>
<td>k_b</td>
<td>N</td>
</tr>
<tr>
<td>1 on 1</td>
<td>10⁻¹⁰</td>
</tr>
<tr>
<td>4 on 43</td>
<td>10⁻¹⁰</td>
</tr>
<tr>
<td>4 on 43</td>
<td>4 10⁻¹⁰</td>
</tr>
<tr>
<td>4 on 43</td>
<td>4 10⁻¹⁰</td>
</tr>
<tr>
<td>16 on 156</td>
<td>4 10⁻¹⁰</td>
</tr>
<tr>
<td>156 on 156</td>
<td>4 10⁻¹⁰</td>
</tr>
<tr>
<td>156 on 156</td>
<td>9 10⁻¹⁰</td>
</tr>
</tbody>
</table>

Eventrate / Cross = \( \frac{L\sigma_{TOT}}{k_b f} \)
Stage II physics run

- Relaxed crossing angle (250 μrad)
- Start un-squeezed
- Then go to where we were in stage I
- All values for
  - nominal emittance
  - 7TeV
  - 10m $\beta^*$ in points 2 and 8

![Equation with formula](image)

Protons/beam ≈ few $10^{13}$

Stored energy/beam ≤ 100MJ

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Beam levels</th>
<th>Rates in 1 and 5</th>
<th>Rates in 2 and 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_b$</td>
<td>$N$</td>
<td>$\beta^* 1.5$ (m)</td>
<td>$I_{beam}$ proton</td>
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<td>936</td>
<td>$4 \times 10^{10}$</td>
<td>18</td>
<td>$3.7 \times 10^{13}$</td>
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<tr>
<td>936</td>
<td>$4 \times 10^{10}$</td>
<td>2</td>
<td>$3.7 \times 10^{13}$</td>
</tr>
<tr>
<td>936</td>
<td>$6 \times 10^{10}$</td>
<td>2</td>
<td>$5.6 \times 10^{13}$</td>
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<tr>
<td>936</td>
<td>$9 \times 10^{10}$</td>
<td>1</td>
<td>$8.4 \times 10^{13}$</td>
</tr>
</tbody>
</table>

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Stage III physics run

- Nominal crossing angle (285 μrad)
- Start un-squeezed
- Then go to where we were in stage II
- All values for
  - nominal emittance
  - 7TeV
  - 10m β* in points 2 and 8

Protons/beam ≈ 10^{14}

Stored energy/beam ≥ 100MJ

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Beam levels</th>
<th>Rates in 1 and 5</th>
<th>Rates in 2 and 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>k_b</td>
<td>N</td>
<td>( \beta^* ) 1.5 (m)</td>
<td>( I_{beam} ) proton</td>
</tr>
<tr>
<td>2806</td>
<td>4 (10^{10})</td>
<td>18</td>
<td>1.1 (10^{14})</td>
</tr>
<tr>
<td>2808</td>
<td>4 (10^{10})</td>
<td>2</td>
<td>1.1 (10^{14})</td>
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<tr>
<td>2808</td>
<td>5 (10^{10})</td>
<td>2</td>
<td>1.4 (10^{14})</td>
</tr>
<tr>
<td>2808</td>
<td>5 (10^{10})</td>
<td>1</td>
<td>1.4 (10^{14})</td>
</tr>
<tr>
<td>2808</td>
<td>5 (10^{10})</td>
<td>0.55</td>
<td>1.4 (10^{14})</td>
</tr>
<tr>
<td>Nominal</td>
<td>3.2 (10^{14})</td>
<td>362</td>
<td>10^{34}</td>
</tr>
</tbody>
</table>
Evolution of beam levels and luminosity

Stage I
- 18m, 43 bunch, 4\times10^{10}
- 2m, 156 bunch, 4\times10^{10}
- ~5% of nominal I

Stage II
- 18m, 75ns, 4\times10^{10}
- 2m, 75ns, 6\times10^{10}
- 1m, 75ns, 9\times10^{10}
- ~25% of nominal I

Stage III
- 18m, 25ns, 4\times10^{10}
- 2m, 25ns, 4\times10^{10}
- 1m, 25ns, 5\times10^{10}
- 0.55m, 25ns, 5\times10^{10}
- ~45% of nominal I
Ions

Experiment side
- ALICE, ATLAS and CMS will all take Pb-Pb data
- Detectors and machine will be already commissioned with pp
- ALICE requests
  - 4 week ion runs at the end of each year
  - first short run as early as possible

Machine side
- Start with early ion scheme (62 bunches instead of 592, $7 \times 10^7$ ions per bunch)
- Will have to
  - Set up RF capture
  - Commission essential instrumentation
  - Commission squeeze in IR2
  - Establish collisions
- Could do (some of) this early on if injectors are ready (same optics as for p)
- Ion runs could provide cool down of PS SPS LHC after proton operation
- After early ion scheme run, increase number of bunches
- Move to nominal when possible

Estimate $\geq$ 1 week for first setup
Followed by physics run

R.Bailey, HERA-LHC, June 2006
A standard TOTEM year would be

- $\sigma_{\text{tot}}$ measurement high priority
- Nominal emittance OK for $\sigma_{\text{tot}}$, 1 $\mu$m needed for elastic scattering
- 3 * 1 day runs at $\beta^*$ of 1540m (90m ?) with 43 or 156 bunches per beam
- 2 * 1 day runs at $\beta^*$ of 18m with 2808 bunches per beam (25ns)

**ATLAS requests a period of a few weeks after first years of running**

Machine side

- Special machine conditions, similar to polarisation runs at LEP
- Very demanding on beam and optics quality, and for collimation
- Initial setup will take several days (maybe better dispersed)
- Subsequent setups should take a shift or two
- Longer runs may be more efficient if machine reproducibility is an issue
Scheduling

Every year we will need a long shutdown (3-4 months)

At the end of every shutdown
- Close the machine personnel access system
- Get all equipment ready for beam (machine checkout, ~ 3-4 weeks)
- Get machine ready for operation (setup with beam, 2-3 weeks)

During periods of operation
- Need regular technical stops (3 days every month)
  - Interventions need careful but flexible planning
- Get machine ready for operation (1 day)
- Machine development (around 15% during first years)
- Operations for physics
- Access as required for unscheduled stops

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Breakdown of a normal year

~ 140-160 days for physics per year
Not forgetting ion and TOTEM operation
Leaves ~ 100-120 days for proton luminosity running
? Efficiency for physics 50% ?
~ 1200 h or ~ 4 \times 10^6 s of proton luminosity running / year