LHC status, commissioning plans and a brief overview of upgrade issues

Mike Lamont
## Installation

<table>
<thead>
<tr>
<th>Sector</th>
<th>In progress</th>
<th>Next</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>QRL installation</td>
<td>Finish October 2006</td>
</tr>
<tr>
<td>2-3</td>
<td>QRL consolidation</td>
<td>Magnet installation</td>
</tr>
<tr>
<td>3-4</td>
<td>Magnets in place, quench protection/cryo instrumentation</td>
<td>Interconnects</td>
</tr>
<tr>
<td>4-5</td>
<td>Most magnets in place</td>
<td>Finish interconnects</td>
</tr>
<tr>
<td>5-6</td>
<td>Most magnets in place</td>
<td>Interconnects</td>
</tr>
<tr>
<td>6-7</td>
<td>Magnet installation</td>
<td>All magnets in Feb. 07</td>
</tr>
<tr>
<td>7-8</td>
<td>Most magnets in place, interconnects</td>
<td>Cool-down November 06</td>
</tr>
<tr>
<td>8-1</td>
<td>All magnets in place, interconnects</td>
<td>Finish interconnects Cool-down - start 07</td>
</tr>
</tbody>
</table>

**Note:** Cryogenic supply lines (QRL) – solved problem
Dipoles

Cryodipole overview

Updated 31 Aug 2006
Data provided by D. Tommasini AT-MAS, L. Bottura AT-MTM
Magnets

5 September, the 1000th cryo-magnet was installed in the LHC tunnel in the arc between point 3 and point 4.

1000 out of 1746 (1232 dipoles)

Last one due in March 2007
Interconnects

Joining everything up – 1700 times

- Vacuum, bellows, RF contacts plus leak checks
- Cryogenics, thermal shield, heat exchanger
- Bus bars
  - superconducting splices x 10,000 (induction welding)
- Corrector circuit
  - splices x 50,000 (ultrasonic welding)

Huge, painstaking & industrialised
Clearly on the critical path
DFBs

Responsible for feeding the room temperature cables into the cold mass.

DFBA - arcs
DFBM - quads
DFBL - links
DFBX – triplets

52 total
DFBs

Have to be in position before cool-down
DFBs

DFB Electrical Feed Boxes

Close to the critical path

Units

01-Jan-01 01-Jan-02 01-Jan-03 01-Jan-04 01-Jan-05 01-Jan-06 01-Jan-07

Nominal component delivery  Components delivered  DFB ready for installation  Just-in-time

Updated 31 Aug 2006  Data provided by A. Perin AT-ACR
Potential aperture restrictions
Bits and bobs
LSSs

Cryo, Powering

MBX

“D1”

BNL
Installation - remarks

It is a huge job

- QRL problem solved
- Magnet installation proceeding well
- Interconnects – work in progress
- DFBs – just in time (plus some other stuff…)
- A lot still to do, plus the challenges of hardware commissioning:
  - First sector to start cool-down in November
  - Powering test to still to come
    - Quench protection, quenches, energy extraction, cold leaks, DFB commissioning at cold, interlocks etc. etc.
And that’s before we even mention beam.

Challenges will include:

• High beam energy – demands on machine protection system
• Very low tolerance to beam loss (quenches)
• Which implies tight constraints on key beam parameters
• Dynamic characteristics of the magnets (persistent currents etc.)
Installation activities in a sector

- QRL installation
- QRL consolidation after pressure test
- Cryo-magnet transport
- Interconnection phase 1
- LSS installation
- End of 1st interconnect activity
- Cryostat closure – Interconnect consolidation
- Insulation // Interconnect phase 1
- Beam pipes & bake-out
- ELQA at warm
- Power tests
- Cool-down
- Machine check-out
- Beam at 450 GeV/C
End 2007

Hardware Commissioning qualification of circuits to 7 TeV – not trivial
### End 2007

<table>
<thead>
<tr>
<th>Oct</th>
<th>ACCESS TESTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Operations testing</td>
</tr>
<tr>
<td></td>
<td>Machine Checkout (Access, Vacuum, Equipment Tests, Controls, Cycle (partial), Beam dump, Interlocks and INB)</td>
</tr>
</tbody>
</table>

**Nov**

- Beam Commissioning at 450 GeV
- 16 days beam time estimated

**Dec**

- Calibration run (Collisions at 450GeV + ramp commissioning etc.)

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**Sectors 5-6, 6-7, 1-2 & 2-3:**

- baseline commissioning of main circuits to 1.1 TeV
- minimal circuit set
450 GeV – Calibration Run

- Operations’ aims:
  - Commission essential safety systems
  - Commission essential beam instrumentation
  - Commission essential hardware systems
  - Perform beam based measurements to check:
    - Polarities
    - Aperture
    - Field characteristics
  - Establish collisions
  - Provide stable two beam operation at 450 GeV
  - Interleave collisions with further machine development, in particular, the ramp.

Should provide a firm platform for eventual commissioning to 7 TeV and provide adequate lead time for problem resolution.
Machine Configuration

- **Optics:**
  - $\beta^*= 11 \text{ m in IR 1 & 5} \text{ (no squeeze)}$
  - $\beta^*= 10 \text{ m in IR 2 & 8}$
  - Limited by triplet aperture

- **Crossing angles off**
  - 1, 12, 43, 156 bunches per beam

- **Separation bumps - two beam operation**

- **Shift bunches for LHCb**
  - 4 out of 43 bunches, or 24 bunches out of 156

- **Solenoids & Exp. Dipoles etc.**
  - off (to start with)
## 450 GeV Beam Commissioning: Phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>Main Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 First turn</td>
<td>End T12, T18, injection region, BPMs, BLMs, thread first turn, polarity checks</td>
</tr>
<tr>
<td>2 Establish circulating beam</td>
<td>Closed orbit, chromaticity, energy matching, tune, RF capture</td>
</tr>
<tr>
<td>3 Initial commissioning</td>
<td>RF, control &amp; correction, transverse diagnostics, linear optics checks, BLMs, beam dump, machine protection</td>
</tr>
<tr>
<td>4a Measurements</td>
<td>Beta beating, aperture, field quality checks, transfer functions</td>
</tr>
<tr>
<td>4b System commissioning</td>
<td>RF, transverse feedback, BLMs to MPS, tune PLL, collimators and absorbers</td>
</tr>
<tr>
<td>5a Two beam operations</td>
<td>Parallel injection, separation bumps, instrumentation and control</td>
</tr>
<tr>
<td>5b Collisions</td>
<td>Establish collisions, luminosity monitors, collimation, solenoids</td>
</tr>
<tr>
<td>6 Increase intensity</td>
<td>Collimators, LFB, multi-batch injection</td>
</tr>
</tbody>
</table>
Beam

- **Pilot Beam**
  - Single bunch, 5 - 10 x 10^9 protons, reduced emittance
- **Pilot++**
  - Single bunch 3 to 4 x 10^{10} protons
- **4, 12 bunches etc. pushing towards…**
- **43,156 bunches**
  - 3 to 4 x 10^{10} ppb

<table>
<thead>
<tr>
<th>Bunches</th>
<th>Bunch Intensity [10^{10} p]</th>
<th>Total intensity [10^{14} p]</th>
<th>Fraction of nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>One pilot</td>
<td>1</td>
<td>0.5</td>
<td>0.00005</td>
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<tr>
<td>12 Nominal</td>
<td>12</td>
<td>10.0</td>
<td>0.01</td>
</tr>
<tr>
<td>43</td>
<td>43</td>
<td>4.0</td>
<td>0.017</td>
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<tr>
<td>156 - I</td>
<td>156</td>
<td>4.0</td>
<td>0.062</td>
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<tr>
<td>156 - II</td>
<td>156</td>
<td>10.0</td>
<td>0.156</td>
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<tr>
<td>75 ns</td>
<td>936</td>
<td>4.0</td>
<td>0.37</td>
</tr>
<tr>
<td>25 ns - 1</td>
<td>2808</td>
<td>4.0</td>
<td>1.1</td>
</tr>
<tr>
<td>Nominal</td>
<td>2808</td>
<td>11.5</td>
<td>3.2</td>
</tr>
<tr>
<td>Phase</td>
<td>Beam time [days]</td>
<td>Beam</td>
<td></td>
</tr>
<tr>
<td>------------------------------</td>
<td>------------------</td>
<td>--------------</td>
<td></td>
</tr>
<tr>
<td>1 First turn</td>
<td>4</td>
<td>1 x Pilot</td>
<td></td>
</tr>
<tr>
<td>2 Establish circulating beam</td>
<td>3</td>
<td>1 x Pilot</td>
<td></td>
</tr>
<tr>
<td>3 450 GeV – initial</td>
<td>3</td>
<td>1 x Pilot++</td>
<td></td>
</tr>
<tr>
<td>4a 450 GeV - consolidation</td>
<td>1-2</td>
<td>1 x Pilot++</td>
<td></td>
</tr>
<tr>
<td>4b 450 GeV – system</td>
<td>2-3</td>
<td>1 x Pilot++</td>
<td></td>
</tr>
<tr>
<td>commissioning</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5a 2 beam operations</td>
<td>1</td>
<td>2 x Pilot++</td>
<td></td>
</tr>
<tr>
<td>5b Collisions</td>
<td>1-2</td>
<td>2 x 1 x 10^{11}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>16 days</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Given an operational efficiency of 60%, this gives an elapsed time of about 26 days. **CAVAET: MACHINE AVAILABILITY**

Some opportunities for parallel development and parasitic studies…
### 450 GeV - Performance

<table>
<thead>
<tr>
<th></th>
<th>Reasonable</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_b$</td>
<td>43</td>
<td>156</td>
</tr>
<tr>
<td>$i_b \times 10^{10}$</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>$\beta^* \text{ (m)}$</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Intensity per beam</td>
<td>$8.6 \times 10^{11}$</td>
<td>$1.7 \times 10^{12}$</td>
</tr>
<tr>
<td>Beam energy (MJ)</td>
<td>.06</td>
<td>.12</td>
</tr>
<tr>
<td>Luminosity (cm^{-2}s^{-1})</td>
<td>$2 \times 10^{28}$</td>
<td>$7.2 \times 10^{28}$</td>
</tr>
<tr>
<td>Event rate $^1$(kHz)</td>
<td>0.4</td>
<td>2.8</td>
</tr>
<tr>
<td>W rate $^2$ (per 24h)</td>
<td>0.5</td>
<td>3</td>
</tr>
<tr>
<td>Z rate $^3$ (per 24h)</td>
<td>0.05</td>
<td>0.3</td>
</tr>
</tbody>
</table>

**Several days**

1. Assuming 450GeV inelastic cross section  40 mb
2. Assuming 450GeV cross section $W \rightarrow l\nu$  1 nb
3. Assuming 450GeV cross section $Z \rightarrow ll$  100 pb
Calibration Run 2007

• 6 weeks beam time

• 3 weeks beam commissioning
  - Essentially single beam, low intensity for the most part

• 3 weeks collisions
  - Single bunch initially, with staged increase to 156 x 4 x 10^{10} (+)
  - Luminosities: 1.3 \times 10^{28} to 2.6 \times 10^{29} cm^{-2}s^{-1} (+)
  - Interleafed with low intensity single beam MD
    • Initial ramping tests to 1.1 TeV etc.
Beam spot – transverse

• **Bigger beams at 450 GeV**
  - 290 µm at $\beta^* = 11$ m.
  - 277 µm at $\beta^* = 10$ m.

• **2 challenges:**
  - **Colliding the beams**: should be able to get them within 150 µm using BPMs
  - **Orbit stability**: feedback to be commissioned

• **Vertex position**
  - Transverse: 1 mm run-to-run, 3 mm long term
  - Absolute position: approx. ±400 µm from BPMs

---

**Transverse beam size from one of:**
Synchrotron Light Monitor, Rest Gas Monitor or Wire Scanner
*plus optics measurements*
Relative Luminosity Measurement

- Low luminosity will be straining bounds of machine luminosity monitors (LBL ionization chambers - BRAN)
  - Low event rates of high energy neutrons in BRAN
  - Background, Signal/Noise

- Initial collisions with single bunch $1.1 \times 10^{11}$ to give BRAN something to see.

- Other ideas:
  - Beam-beam coupling signal from high sensitivity BPM
  - Schottky
  - Scintillators [machine]
Background

Beam gas interactions and beam halo muon/hadron rates

- Residual gas within experiments
  - Baked out – low rates
- Residual gas in LSSs
- Gas pressure in adjacent cold sectors
  - Relative high pressures, elastic scattering
- Inefficiency of cleaning in IR7 & IR3

See: M Huhtinen, V. Talanov, G. Corti et al

Nikolai Mokhov
The 450 GeV run will be stage 0.
No conditioning, minimal pump-down time in some sectors. Static vacuum.

Potentially some LSSs un-baked - no NEG activation. Experiments should be baked.

Vacuum life time shall be greater than 35 h and 50 h for 2007 and 2008 respectively cf 100 h nominal
Halo

• Scrape in the SPS, collimate in the transfer lines
• Expect halo generation from
  ■ RF noise
  ■ Intra Beam Scattering
  ■ Optics mismatch
  ■ Beam-gas
  ■ Poor parameter control (tune, chromaticity), poor lifetime, stream particles to aperture limit

• Nominally this is cleaned by the collimation system with the resulting tertiary halo potentially finding its way to the experiments insertion – and the tertiary collimators

Vadim Talanov & team plan detailed studies, given scenario of collimator operation at the 450 GeV start-up (loss maps etc.)
450 GeV: Collimation I

- Lower intensity
- Lower energy
- Bigger beams
- Un-squeezed
- Aperture limitation is the arcs & DS

With low beam intensity:

- Primary collimators: 6σ
- Secondary collimators: out
- Tertiary collimators: out
- Absorbers: out
- TCDQ: 10σ
- TDI: out
450 GeV: Collimation II

- With an optimistic beam intensity we might see:
  - Primary collimators: 5.7σ
  - Secondary collimators at 6.7σ
  - Tertiary collimators: out
  - Absorbers: out
  - TCDQ: 9σ
  - TDI: 6.8σ

Un-squeezed – tertiary collimators out – aperture limit in the arcs – would expect low halo losses in IRs
**Who knows...**

--- **STABLE BEAMS** ---

<table>
<thead>
<tr>
<th>E = 0.450 TeV/c</th>
<th>Beam</th>
<th>In Coast</th>
<th>0.5 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beams</td>
<td>Beam 1</td>
<td>Beam 2</td>
<td></td>
</tr>
<tr>
<td>#bun</td>
<td>43</td>
<td>43</td>
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<tr>
<td>Nprot(t)</td>
<td>1.71e12</td>
<td>1.73e12</td>
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<tr>
<td>tau(t) h</td>
<td>121</td>
<td>140</td>
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</table>

<table>
<thead>
<tr>
<th>Luminosities</th>
<th>ATLAS</th>
<th>ALICE</th>
<th>CMS</th>
<th>LHC-B</th>
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</thead>
<tbody>
<tr>
<td>L(t) 1e28 cm-2s-1</td>
<td>5.23</td>
<td>6.23</td>
<td>7.13</td>
<td>5.21</td>
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<td>/L(t) nb-1</td>
<td>0.78</td>
<td>0.68</td>
<td>0.78</td>
<td>0.52</td>
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<tr>
<td>BKG 1</td>
<td>1.20</td>
<td>0.52</td>
<td>0.90</td>
<td>0.43</td>
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<tr>
<td>BKG 2</td>
<td>0.85</td>
<td>0.82</td>
<td>0.50</td>
<td>0.80</td>
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</tbody>
</table>

Comments: 31-11-07 11:40:26
COLLIMATORS in coarse settings
Separation Scan in IR1/Atlas

Helmut Burkhardt
2008 (briefly)
# Staged commissioning plan for protons@7TeV

## 2008

<table>
<thead>
<tr>
<th>Year</th>
<th>Stage I</th>
<th>II</th>
<th>III</th>
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</thead>
<tbody>
<tr>
<td>Hardware commissioning 7TeV</td>
<td>No beam</td>
<td>Beam</td>
<td>Machine checkout 7TeV</td>
</tr>
<tr>
<td>Machine checkout 7TeV</td>
<td></td>
<td></td>
<td>43 bunch operation</td>
</tr>
<tr>
<td>Beam commissioning 7TeV</td>
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<td>75ns ops</td>
</tr>
<tr>
<td>7TeV Machine checkout</td>
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<td></td>
<td>25ns ops I</td>
</tr>
<tr>
<td>Machine checkout 7TeV</td>
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<td>Shutdown</td>
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</tbody>
</table>

## 2009

<table>
<thead>
<tr>
<th>Year</th>
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<th>II</th>
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</thead>
<tbody>
<tr>
<td>Shutdown</td>
<td>No beam</td>
<td>Beam</td>
</tr>
<tr>
<td>Machine checkout 7TeV</td>
<td></td>
<td>Install Phase II and MKB</td>
</tr>
<tr>
<td>Beam setup</td>
<td></td>
<td>25ns ops I</td>
</tr>
</tbody>
</table>

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25.09.06 LHC Machine - LECC 06
2008

Should look something like…

<table>
<thead>
<tr>
<th>Month</th>
<th>1-2</th>
<th>2-3</th>
<th>3-4</th>
<th>4-5</th>
<th>5-6</th>
<th>6-7</th>
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<td></td>
<td>Powering tests</td>
<td>Magnet stepping</td>
<td>Magnet stepping</td>
<td>Magnet stepping</td>
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<td>Magnets</td>
<td>Magnets</td>
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<td>Feb</td>
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<tr>
<td></td>
<td>Shutdown cooling</td>
<td>Cold standby</td>
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<td>Cold standby</td>
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<td></td>
<td>Machine checkout</td>
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<td>Setting up of beam</td>
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</tbody>
</table>

Provisional

- **Hardware commissioning to 7 TeV**
  - Machine Checkout \( \approx 1 \text{ month} \)
  - Commissioning with beam \( \approx 2 \text{ months} \)
  - Pilot Physics \( \approx 1 \text{ month} \)
Beam Commissioning: usual stuff..

First turn
- Commission injection region
- Instrumentation
- Threading

Establish circulating beam
- Circulating low intensity beam

450 GeV Initial
- Polarities and aperture checked.
- Basic optics checks performed.
- First pass commissioning of BI performed.
- Phase 1 of machine protection system commissioning performed.
- Beam Dump commissioned with beam

450 GeV Detailed
- Well-adjusted beam parameters, detailed optics checks
- Fully functioning beam instrumentation.
- Machine protection as required for ramp
- RF - beam control loops operational and adjusted

Switch to nominal
- 2 beams, well-adjusted beam parameters,
  beam instrumentation, cross talk etc.

Snapback
- Single beam, good transmission through snapback
- Requisite measurements (orbit, tune, chromaticity)

Ramp Single Beam
- Single beam, good transmission to top energy
- Commission beam dump in ramp
- Stops in ramp - measurements
- RF

Two beams to top energy
- Two beams, good transmission to top energy
- Measurements

Squeeze
- Single beam - step through squeeze
- Parameter control, measurements

25.09.06 LHC Machine - LECC 06
# Full commissioning to 7 TeV

<table>
<thead>
<tr>
<th>Step</th>
<th>Rings</th>
<th>Total [days] both rings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection and first turn</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Circulating beam</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>450 GeV - initial</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>450 GeV - detailed</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>450 GeV - two beams</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Snapback - single beam</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Ramp - single beam</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Ramp - both beams</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>7 TeV - setup for physics</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Physics un-squeezed</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td><strong>TOTAL to first collisions</strong></td>
<td></td>
<td><strong>45</strong></td>
</tr>
<tr>
<td>Commission squeeze</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Increase Intensity</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Set-up physics - partially squeezed.</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Pilot physics run</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Should benefit from 450 GeV run

### Given 450 GeV run and reasonable machine availability might expect first 7 TeV collisions in around 2 months

**RHIC 2000:**
- First beam April 3rd
- First successful ramp: June 1st
- First collisions June 12th
7 TeV commissioning

• Around 2 months elapsed time to establish first collisions
  ▪ Mostly pilot++, low intensity, single beam, alternate rings
  ▪ No crossing angle
  ▪ No squeeze: $\beta^* = 17 – 10 – 17 – 10$ m.

• Stage 1 vacuum conditions
  ▪ Experiments & LSSs should be baked out
  ▪ Other LSSs potentially not
  ▪ Full details: LHC project note 783

• Collimation during initial commissioning
  ▪ Minimal collimation scheme under discussion, probably primary & secondary with no tertiary/absorbers
  ▪ Again, un-squeezed, expect low halo loss in experiments

• First collisions
  ▪ Single bunch
  ▪ Un-squeezed

• Pilot physics


### Pilot physics

<table>
<thead>
<tr>
<th>Sub-phase</th>
<th>Bunches</th>
<th>Bun. Int.</th>
<th>beta*</th>
<th>Luminosity</th>
<th>Time</th>
<th>Int lumi</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Collisions</td>
<td>1 x 1</td>
<td>4 x 10¹⁰</td>
<td>17 m</td>
<td>1.6 x 10²⁸</td>
<td>12 hours</td>
<td>0.6 nb⁻¹</td>
</tr>
<tr>
<td>Repeat ramp - same conditions</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2 days @ 50%</td>
<td>1.2 nb⁻¹</td>
</tr>
<tr>
<td>Multi-bunch at injection &amp; through ramp - collimation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2 days</td>
<td>-</td>
</tr>
<tr>
<td>Physics</td>
<td>12 x 12</td>
<td>3 x 10¹⁰</td>
<td>17 m</td>
<td>1.1 x 10²⁹</td>
<td>2 days @ 50% in physics</td>
<td>6 nb⁻¹</td>
</tr>
<tr>
<td>Physics</td>
<td>43 x 43</td>
<td>3 x 10¹⁰</td>
<td>17 m</td>
<td>4.0 x 10²⁹</td>
<td>2 days @ 50% in physics</td>
<td>30 nb⁻¹</td>
</tr>
<tr>
<td>Commission squeeze – single beam then two beams, IR1, IR5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2 days</td>
<td>-</td>
</tr>
<tr>
<td>Measurements squeezed</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1 day</td>
<td>-</td>
</tr>
<tr>
<td>Physics</td>
<td>43 x 43</td>
<td>3 x 10¹⁰</td>
<td>10 m</td>
<td>7 x 10²⁹</td>
<td>3 days - 6 hr t.a. - 70% eff.</td>
<td>75 nb⁻¹</td>
</tr>
<tr>
<td>Commission squeeze to 2m collimation etc.</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3 days</td>
<td>-</td>
</tr>
<tr>
<td>Physics</td>
<td>43 x 43</td>
<td>3 x 10¹⁰</td>
<td>2 m</td>
<td>3.4 x 10³⁰</td>
<td>3 days - 6 hr t.a. - 70% eff.</td>
<td>0.36 pb⁻¹</td>
</tr>
<tr>
<td>Commission 156 x 156</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1 day</td>
<td>-</td>
</tr>
<tr>
<td>Physics</td>
<td>156 x 156</td>
<td>2 x 10¹⁰</td>
<td>2 m</td>
<td>5.5 x 10³⁰</td>
<td>2 days - 6 hr t.a. - 70% eff.</td>
<td>0.39 pb⁻¹</td>
</tr>
<tr>
<td>Physics</td>
<td>156 x 156</td>
<td>3 x 10¹⁰</td>
<td>2 m</td>
<td>1.2 x 10³¹</td>
<td>5 days - 5 hr t.a. - 70% eff.</td>
<td>2.3 pb⁻¹</td>
</tr>
</tbody>
</table>

28 days total

Leading into 75 ns running
Conclusions

• **450 GeV calibration run**
  - 3 weeks single beam machine commissioning
  - Low beam current but potentially interesting vacuum conditions
  - Minimal collimation scheme
  - 3 weeks collisions with the hope to push over $10^{29}$ cm$^{-2}$s$^{-1}$
  - Detailed BG studies planned

• **7 TeV**
  - 6-8 weeks single/two beam machine commissioning
  - Low beam current but potentially interesting vacuum conditions
  - Un-squeezed initially, with minimal collimation
  - Still work to do after first collisions – pilot physics
  - Detailed BG studies already performed and on-going

http://cern.ch/lhc-commissioning/
(1) *Life expectancy of LHC IR quadrupole magnets* is estimated to be <10 years due to high radiation doses

(2) the *statistical error halving time* will exceed 5 years by 2011-2012

(3) therefore, it is reasonable to plan a *machine luminosity upgrade based on new low-\(\beta\) IR magnets* before \(~2014\)
Basic Issues

- Head-on beam-beam
- Long-range beam-beam
- Crossing angle
  - Larger – reduces luminosity
  - Larger – eats aperture
- $\beta^*$ - beam size at IP
  - Smaller the $\beta^*$ - larger the beam size in the triplets - aperture

$$\sigma^* = \sqrt{\beta^* \varepsilon}$$

$$F = \frac{1}{\sqrt{1 + \left(\frac{\sigma^2 \theta_c}{2\sigma^*}\right)^2}}$$
Some Options

• **More beam**
  - Increase bunch intensity (⇒ upgrade injectors)
  - Increase number of bunches - reduce bunch spacing to 12.5 ns (or 10 ns or...) - see Andy Butterworth later this week
  - Super bunches

• **Increase F**
  - Redesign insertions
  - Crab cavities

• **Fight the long range beam-beam**
  - Wires

• **Squeeze harder**
  - New magnets
luminosity upgrade: baseline scheme

1.0

0.58 A

increase \(N_b\)

bb limit?

yes

no

0.86 A

\[ F = \left( 1 + \left( \frac{\theta_c \sigma_z}{2\sigma^2} \right)^{1/2} \right) \]

\(\theta_c > \theta_{\text{min}}\) due to LR-bb

BBLR compensation

crab cavities

reduce \(\sigma_z\) by factor \(~2\) using higher \(f_{\text{rf}}\) & lower \(\varepsilon_{||}\) (larger \(\theta_c\) ?)

reduce \(\theta_c\) (squeeze \(\beta^*\))

2.3

use large \(\theta_c\) & pass each beam through separate magnetic channel

new IR magnets

\(\text{reduce } \beta^* \text{ by factor } \sim 2\)

4.6

0.86 A

\(\text{if } e\text{-cloud, dump } \& \text{ impedance ok}\)

increase \(n_b\) by factor \(\sim 2\)

0.86 A

luminosity gain \(9.2\)

beam current \(1.72 \text{ A}\)

simplified IR design with large \(\theta_c\)
**IR 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

---

**alternative IR schemes**

- dipole first &
  - small crossing angle
- reduced # LR collisions
- collision debris hit D1

- dipole first &
  - large crossing angle &
  - long bunches or crab cavities

---

**IR ‘baseline’ schemes**

- short bunches &
  - minimum crossing angle &
  - BBLR
- crab cavities &
  - large crossing angle

---

**‘cheap’ IR upgrade**

*in case we need to double LHC luminosity earlier than foreseen*

- short bunches & minimum crossing angle & BBLR
- each quadrupole individually optimized (length & aperture)
  - $\beta^*$-quad distance reduced from 23 to 22 m
  - NbTi, $\beta^*=0.25$ m possible
Expected factors for the LHC luminosity upgrade

The peak LHC luminosity can be multiplied by:
- factor 2.3 from nominal to ultimate beam intensity (0.58 ⇒ 0.86 A)
- factor 2 (or more?) from new low-beta insertions with $\beta^* = 0.25$ m

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

Increasing the LHC injection energy to 1 TeV would potentially yield:
- factor ~2 in peak luminosity (2 x bunch intensity and 2 x emittance)
- factor 1.4 in integrated luminosity from shorter $T_{\text{turnaround}}$ ~ 5 h thus ensuring $L \sim 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ and $\int L dt \sim 9 \times$ nominal $\sim 600/(\text{fb*year})$
## Various LHC 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>No of bunches</td>
<td>$n_b$</td>
<td>2808</td>
<td>2808</td>
<td>5616</td>
<td>936</td>
</tr>
<tr>
<td>Proton per bunch</td>
<td>$N_b$</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>$I$</td>
<td>0.58</td>
<td>0.86</td>
<td>1.72</td>
<td>1.0</td>
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<tr>
<td>Normalized emittance</td>
<td>$\varepsilon_n$ [\mu m]</td>
<td>3.75</td>
<td>3.75</td>
<td>3.75</td>
<td>3.75</td>
</tr>
<tr>
<td>Longitudinal profile</td>
<td></td>
<td>Gaussian</td>
<td>Gaussian</td>
<td>Gaussian</td>
<td>flat</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>
</tr>
<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>Luminous region length</td>
<td>$\sigma_{lum}$ [mm]</td>
<td>44.9</td>
<td>42.8</td>
<td>21.8</td>
<td>36.2</td>
</tr>
</tbody>
</table>
Upgrades - summary

• **Baseline scenario includes:**
  - a reduction of $\beta^*$ to 0.25 m,
  - an increased crossing angle
  - and a new bunch-shortening RF system.

• **Corresponding peak luminosity with ultimate beam intensity is** $4.6 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ **at two IP’s.**
  - Electron cloud effects and/or cryogenic heat loads may exclude the possibility to double the number of bunches.

• **R&D ongoing**
  - Magnets, crab cavities, LRBB compensation etc. etc.

• **Several LHC IR upgrade options are currently being explored**

• **Major conference here in Valencia in 3 weeks (CARE – HHH)**