LHC: Past, Present and Future

XX GIORNATE DI STUDIO sui RIVELATORI

Torino
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Sergio Bertolucci
CERN, Geneva
LHC: Exploration of a new energy frontier

Proton-proton collisions at $E_{CM} = 14$ TeV
Heavy ions: Lead-lead collisions: Energy/nucleon = 2.76 TeV/u

The LHC will illuminate a new landscape of physics, possibly answering some of the most fundamental questions in modern physics, like e.g.:
- The origin of mass
- Unification of fundamental forces
- New forms of matter
- Extra dimensions of spacetime
Major LHC challenges

High design Centre-of-mass energy of 14 TeV in given (ex LEP) tunnel

• Magnetic field of 8.33 T with superconducting magnets
• Helium cooling at 1.9 K
• Large amount of energy stored in magnets
• “Two accelerators” in one tunnel with opposite magnetic dipole field and ambitious beam parameters pushed for very high of luminosity of \(10^{34} \text{ cm}^{-2} \text{ s}^{-1}\)
• Many bunches with large amount of energy stored in beams

Complexity and Reliability

• Unprecedented complexity with 10000 magnets powered in 1700 electrical circuits, complex active and passive protection systems, ....

- Emittance conservation \(\Sigma_N = \mathcal{O} \mathcal{C} \Sigma\), related to phase space density conservation, Liouville constant “intrinsic” normalized emittance \(\Sigma_N\), real space emittance \(\Sigma\) decreases with energy
- in absence of major energy exchange in synchrotron radiation / rf damping
- clean, perfectly matched injection, ramp, squeeze, minimize any blow up from: rf,
- kicking beam, frequent orbit changes, vibration, feedback, noise,..
- dynamic effects - persistent current decay and snapback
- non-linear fields (resonances, diffusion, dynamic aperture, non-linear dynamics)
Beam parameters, LHC compared to LEP

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHC</th>
<th>LEP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum at collision, TeV/c</td>
<td>7.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Nominal design Luminosity, cm⁻²s⁻¹</td>
<td>1.0E+34</td>
<td>1.0E+32</td>
</tr>
<tr>
<td>Dipole field at top energy, T</td>
<td>8.33</td>
<td>0.11</td>
</tr>
<tr>
<td>Number of bunches, each beam</td>
<td>2808</td>
<td>4</td>
</tr>
<tr>
<td>Particles / bunch</td>
<td>1.15E+11</td>
<td>4.20E+11</td>
</tr>
<tr>
<td>Typical beam size in ring, μm</td>
<td>200 – 300</td>
<td>1800/140 (H/V)</td>
</tr>
<tr>
<td>Beam size at IP, μm</td>
<td>16</td>
<td>200/3 (H/V)</td>
</tr>
</tbody>
</table>

- **Energy stored in the magnet system:** 10 GJoule  
  Airbus A380, 560 t at 700 km/h
- **Energy stored in one (of 8) dipole circuits:** 1.1 GJ
- **Energy stored in one beam:** 362 MJ
  20 t plane
- **Energy to heat and melt one kg of copper:** 0.7 MJ

the LEP2 total stored beam energy was about 0.03 MJ
The total stored energy of the LHC beams

Nominal LHC design: $3.2 \times 10^{14}$ protons accelerated to 7 TeV circulating at 11 kHz in a SC ring

LHC: $> 100 \times$ higher stored energy and small beam size: ~3 orders of magnitude in energy density and damage potential. Active protection (beam loss monitors, interlocks) and collimation for machine and experiments essential. Only the specially designed beam dump can safely absorb this energy.
Damage potential: confirmed in controlled SPS experiment

Controlled experiment with beam extracted from SPS at 450 GeV in a single turn, with perpendicular impact on Cu + stainless steel target

\[ \text{450 GeV protons} \]

r.m.s. beam sizes \( \sigma_{x/y} \approx 1 \text{ mm} \)

Cu and stainless steel sandwich 108 plates

25 cm

SPS results confirmed:

\[ 8 \times 10^{12} \text{ clear damage} \quad 2 \times 10^{12} \text{ below damage limit} \]

For details see V. Kain et al., PAC 2005 RPPE018

For comparison, the LHC nominal at 7 TeV:

\[ 2808 \times 1.15 \times 10^{11} = 3.2 \times 10^{14} \text{ p/beam} \]

at \( < \sigma_{x/y} > \approx 0.2 \text{ mm} \)

over 3 orders of magnitude above damage level for perpendicular impact
Beam size of protons decreases with energy: area $\sigma^2 \propto 1 / E$

Beam size largest at injection, using the full aperture
Critical Issues

Past
• QRL cryo-line (He supply)
• DFB power connections, warm to cold transition
• Triplet quadrupoles - differential pressure

More recent
• PIM plug in module with bellow, systematically checked / repaired after warm up using “ping-pong” ball with RF-emitter: polycarbonate shell, Ø 34 mm, 15 g, 2h battery powered, 40 MHz emitter, signals recorded by LHC BPM
• Vacuum leaks, condensation - humidity sector 3/4
• Magnet powering check / correct: min/max, cabling - polarity
• Single event upset, radiation to electronics, shielding etc
• Magnet re-training magnets quenching below what was reached in SM18
10:30 beam 1 3 turns
15:00 beam 2 3 turns
22:00 beam 2 several 100 turns
few days later…
September 19, 2008: incident in sector 3-4

The incident was traced to a faulty electrical connection between segments of the LHC’s superconducting cable (busbars)

High impact was caused by collateral damage

53 Magnets (along a zone of about 700 m) to be removed from tunnel and repaired/exchanged (a few % of entire LHC)

2 most severely damaged interconnects
Busbar Splice

**JOINT**
- Joint length: 120 mm
- Cu U-profile: 155 mm x 20 mm x 16 mm
- Cu wedge: 120 mm x 15 mm x 6 mm
- Insulation:
  - 2 U-shaped layers of kapton (240 mm x 0.125 mm thick)
  - 2 U-shaped layers of G10 (190 mm x 1 mm)

**BUS**
- Cross-section Cu: 282 mm²
- Cross section NbTi: 6.5 mm²
- Kapton+isopreg insulation
- RRR specification: >120
- RRR experimental (D. Richter)
  - RB bus: 223-276 (4 data)
  - RQ bus: 237-299 (4 data)
Electrical arc between C24 and Q24
Bringing back the LHC: how was it done?

Five Phases:

1. Repair of sector 34
2. Consolidation and Avoidance of collateral damage
3. Hardware Commissioning
4. Preparations for Beams (long term)
5. Operation with Beams
Phase 1 and 2
Repair and Consolidation
The LHC repairs in detail

1. 14 quadrupole magnets replaced
2. 39 dipole magnets replaced
3. 54 electrical interconnections fully repaired. 150 more needing only partial repairs
4. Over 4 km of vacuum beam tube cleaned
5. A new longitudinal restraining system is being fitted to 50 quadrupole magnets
6. Nearly 900 new helium pressure release ports are being installed around the machine
7. 6500 new detectors are being added to the magnet protection system, requiring 250 km of cables to be laid

+ cryogenics!
sector 3-4: Magnet repair in SMI2
Last Repaired Magnet (SSS) going down (30/4/2009)
Magnet protection and anchoring

- DN200 on dipoles 732/1344 installed
- DN200 on ITs 24/24 installed
- DN160 on SAM 92/96 installed
- SSS anchoring 104/104 installed
normal conducting, soldered electrical connection between SC cables
1684 units × 6 ≈ 10 000 splices at magnet interconnects; 1/3 dipole, 2/3 quads

possible problems in soldering:
overheating - SnAg loss
too cold - SnAg unmelted, poor connection

Now possible to diagnose: X-ray, ultrasound, resistance measurement.
Most reliable: resistance measured at room temperature
good: 10 μΩ dipole (RB), 17 μΩ quadrupole (RQ).
Measured in 5 sectors which were warmed up. Fixed all above ~ 40 μΩ. Other sectors measured at 80 K
Enhanced QPS
Role of the Enhanced QPS System

• To protect against the new ‘problems’ discovered in 2008
  • The Aperture-Symmetric Quench feature in the Main Dipoles and
  • Defective Joints in the Main Bus-bars, inside or in-between the magnets.

QPS Upgrade also allows

• precision measurements of the joint resistances at cold (sub-nΩ range) of every Busbar segment. This will allow complete mapping of the splice resistances (the bonding between the s.c. cables).

• To be used as the basic monitoring system for future determination of busbar resistances at warm (min. 80 K), to measure regularly the continuity of the copper stabilizers.
The nQPS project

DQQTE board for ground voltage detection
(total 1308 boards, 3 units/crate)

DQLPUS Power Packs
2 units / rack (total 872 units)

DQLPU-type S crate
total 436 units

DQAMG-type S controller board
1 unit / crate, total 436 units

DQQBS board for busbar splice detection
5 such boards / crate, total 2180 units

DQQDS board for SymQ detection
4 boards / crate, total 1744

'D internal' and 'external' cables for sensing, trigger, interlock, UPS power, uFIP (10'400 + 4'400)

Original racks

2 UPS Patch Panels / rack & 1 Trigger Patch Panel / rack total 3456 panel boxes
Decision; Beam Energy at Start-up (August 2009)

- **Avoidance of thermal runaway** (during a quench)
  - Maximum safe current flowing in joint (beam energy)
    - Electro-magnetic, thermo-dynamic simulations
    - Probability of simultaneous quench in magnet and joint (?beam losses FLUKA)
    - Quench propagation time from the magnet to the joint
  - Resistance of the copper stabilizers (measurements)
  - Quality of the copper in the sc cable and the Cu stabiliser (RRR)
  - Energy extraction time (modification of dump resistors quads and dipoles)
  - Gaseous cooling of the joint?

**Choices**
- Stick to 5TeV/beam and repair all necessary Cu stabilizer joints => warm up of several sectors and delay start of physics till 2010
- Aim for **maximum safe energy** with no additional repairs on CU stabilizers => allows us to gain experience up to this maximum energy (accelerator and detectors)
Sc cable Splices
missing electrical contact on at least one side of the connection

lack of solder within the joint
## Number of splices in RB, RQ circuits

<table>
<thead>
<tr>
<th>circuit</th>
<th>splice type</th>
<th>splices per magnet</th>
<th>number of units</th>
<th>total splices</th>
</tr>
</thead>
<tbody>
<tr>
<td>RB</td>
<td>inter pole</td>
<td>2</td>
<td>1232</td>
<td>2464</td>
</tr>
<tr>
<td>RB</td>
<td>inter aperture</td>
<td>1</td>
<td>1232</td>
<td>1232</td>
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<tr>
<td>RB</td>
<td>interlayer</td>
<td>4</td>
<td>1232</td>
<td>4928</td>
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<tr>
<td>RB</td>
<td>internal bus</td>
<td>1</td>
<td>1232</td>
<td>1232</td>
</tr>
<tr>
<td>RB</td>
<td>interconnect</td>
<td>2</td>
<td>1686</td>
<td>3372</td>
</tr>
<tr>
<td>RQ</td>
<td>Inter pole</td>
<td>6</td>
<td>394</td>
<td>2364</td>
</tr>
<tr>
<td>RQ</td>
<td>internal bus</td>
<td>4</td>
<td>394</td>
<td>1576</td>
</tr>
<tr>
<td>RQ</td>
<td>interconnect</td>
<td>4</td>
<td>1686</td>
<td>6744</td>
</tr>
</tbody>
</table>

**total**

23912

Mike Koratzinos - Splices update
Methods for testing splices

The methods we have at our disposal to measure spice resistances (either directly or indirectly) are four:

- The ‘Keithley’ method
- The ‘QPS snapshot’ method
- The calorimetric method
- The ultrasound method
Simultaneous busbar and magnet quench?

**FLUKA Simulations**

- Combined busbar and magnet quench can not be excluded but is highly unlikely
- Magnet will quench at a significantly lower level of beam loss than adjacent bus bars (in inter-connects or the empty cryostat)
  - $10^6$ protons sufficient to quench the magnets
  - $10^9$-$10^{10}$ protons required to quench the busbars
- According to the present studies it is **very unlikely to quench the busbar only** (not observed in these studies)
New RQ dump resistors; preparation was launched immediately
RB: case 1 (instantaneous quench in busbar/magnet)

Quench of RB joint due to beam loss
QPS delay=0 s, RRR_cable=80, RRR_bus=100, with self-field, cable without bonding at one bus extremity, no contact between bus stabiliser and joint stabiliser.

- tau=68 s, adiab.
- tau=68 s, bus cooling to 1.9 K
- tau=50 s, adiab.
- tau=50 s, bus cooling to 1.9 K

Max. safe current [A]

R_additional [microOhm]

Arjan Verweij, TE-MPE, 23 July 2009

A. Verweij, TE-MPE, 5 Aug 2009, LMC meeting
Thermal propagation time (for case 2)

Experience from HWC for RB quenches at 7-11 kA.

Assume that the joint quenches after half the MB-MB thermal propagation time,

\[ t_{JQ} = 0.5 \times (70 - I_Q / 300) \]

Maybe possible to get more accurate value from thermal analysis.....
**RB: case 2 (quench propagation from magnet to busbar)**

Quench of RB joint due to warm He
QPS delay=0 s, RRR_cable=80, RRR_bus=100, with self-field, cable without bonding at one bus extremity, no contact between bus stabiliser and joint stabiliser.
\[ t_{JQ}=35-I_Q/600. \]

Arjan Verweij, TE-MPE, 23 July 2009

A. Verweij, TE-MPE. 5 Aug 2009, LMC meeting
Phase 3
Hardware Commissioning

“Hardware commissioning” is essentially the electrical qualification (ELQA) and commissioning of the electrical circuits (magnets, power converters, current leads, protection systems, …)

• About 10000 magnets
• More than 50 different types of magnets
• Magnets can be powered in series or individually
• 1618 electrical circuits grouped into nine “Electrical Circuit Types” (eight for circuits with superconducting magnets, one for circuits with normal conducting magnets)
• There are more than a thousand current leads installed in the DFBs (to bring the current from the warm into the cold)
Powering Tests overview

**2009**
86 days - 10398 tests done

**2008**
162 days – 11637 tests done
First Dipole Busbar Resistances from first scan to 2 kA

QPS team

Splice Mapping of Dipoles

1nΩ!!
Splice Mapping of Quadrupoles

Measured Segment Resistances

Normalized to Number of Splices

1nΩ

Splice Resistance statistics

- Gaussian Center: 324pOhm
- Gaussian StdDev: 52pOhm

Histogram count
- Sum: 843
- Mean: 322pOhm
- Standard deviation: 311pOhm
Every single sc splice has now been measured.
Decision on Initial Beam Operating Energy  
(August 2009)

- Highest measured value of excess resistance ($R_{\text{long}}$) in 5 sectors measured at 300K was $53\mu\Omega$.
- Operating at 7TeV cm with a energy extraction times of 50s, 10s (dipoles and quadrupoles)
  - Simulations show that resistances of $\leq 120\mu\Omega$ are safe from thermal runaway under conservative assumed conditions of worst case conditions for the copper quality (RRR) and no cooling to the copper stabilizer from the gaseous helium.
- Operating at 10TeV cm with a dipole energy extraction time of 68 s
  - Simulations show that resistances of $\leq 67\mu\Omega$ are safe from thermal runaway under conservative assumed conditions of worst case conditions for the copper quality (RRR), and with estimated cooling to the stabilizer from the gaseous helium.

Decision:
- Operation initially at 7TeV cm (energy extraction time of 50s, 10s) with a safety factor or more than 2 for the worst stabilizers. During this time
  - monitor carefully all quenches to gain additional information.
  - Continue simulations and validation of simulations by experimentation (FRESCA)
- Then operate at around 10TeV cm.
- At the end of 2010, perform a ion run
Phase 4
Preparation for Beam

- Started a long time ago in 2001!! (after the closure of LEP and using the ex-LEP staff)
Prep: beam tests through the years

2003: TT40

2004: TI8

CNGS

TI2

2005: FIRST HOLE (SPS)

2008: FIRST BEAM TO LHC

2008: FIRST BEAM TO IR3

2009: FIRST IONS TO LHC

2009: Sectors test

2009!
Prep: dry runs and checkout

Extraction
Transfer lines
Injection
RF, injection sequence
Timing System
Beam Interlock System
Collimators
Vacuum
Interlocks, SIS
BLMs, BPMs
BTV, BCT
Beam dump
PGCs
Magnet model
Sequencer, alarms
Controls, logging, DBs
LSA, optics model, YASP

PSB
Re-phase with beam ~50ms
Re-phase with beam ~20ms
Re-phase with beam: The time difference between the target bucket FREV and the source bucket FREV is measured by a TDC. The TDC value then changes the RF frequency so they come in line. This takes time to complete, and disturbs the orbit.

RF frequency is nearly fixed. Just jump to the next bucket. This can only happen if the SPS is empty.

Filling LHC Ring 1

Re-phasing in the SPS:
Phase 5 Operation with Beam
Friday November 20

18:30 Beam 1

- 19.00 beam through CMS (23, 34, 45)
  - beam1 through to IP6 19.55 Starting again injection of Beam1
  - corrected beam to IP6, 7, 8, 1
- 20.40 Beam 1 makes 2 turns
  - Working on tune measurement, orbit, dump and RF
  - Beam makes several hundred turns (not captured)
    - Integers 64 59, fractional around .3 (Qv trimmed up .1)
- 20.50 Beam 1 on beam dump at point 6
- 21.50 Beam 1 captured

22:15 Beam2

- 23.10 Start threading Beam2
  - Round to 7 6 5 2 1
- 23.40 First Turn Beam2
  - Working on tune measurement, orbit, dump and RF
  - Beam makes several hundred turns (not captured)
    - Integers 64 59, fractional around .3 (Qv trimmed up .05)
- 24.10 Beam 2 captured

2h10 for 27km: 12.5km/h average speed

1h25 for 27km: a bit faster
Beam threading

Threading by sector:

- One beam at the time
- Beam through 1 sector (1/8 ring), correct trajectory, open collimator and move on.

Beam 2 threading
Friday: 8:15pm:    Beam 1 First 2 turns
Beam is circulating and stable

- magnets
- power supplies
- vacuum
- RF
- cryogenics
- all infrastructure
- optics
- injection
BCT – lifetime around 10h
Green dots are measured: blue line calculated
Saturday - Beam 1

- **Splashes** for experiments overnight Friday/Saturday
- Beam 1 again from 16.00
  - RF fine tuning
  - Beam Instrumentation on tune, orbit and more
- Circulate and not dump
  - Lifetime 10h
- From 19.00
  - Dispersion and Chromaticity
- Kick response (with circulating beam) overnight
- Concern about transformer in point 8!
  - 20ms earth leak (800A) – to be watched
Tune measure and trim
Beta-beat
BCT – lifetime around 10h
Dispersion B1

Green dots are measured: blue line calculated
Wire scan

Red is the fit
Blue is measured
Monday Midday

Status both beams at midday Monday
- Lots of successful BI system commissioning
- RF capture and phase loop on
- Orbit, Q, Q’, coupling measured and corrected to first order
- Lifetimes ~10h
- Dispersion remarkably good
- Beta beating measured
- Kick response almost done for beam 1
Monday afternoon

- Both beams circulating in LHC. Hands off by OP for half an hour.
- Transverse Steering into collision using BPMs through 1 and 5.
- Hands off by OP for half an hour

• Recorded collision events in ATLAS and CMS

• From 16:00
  - Two beams in LHC at buckets 1 and 8911
  - Quiet beams for ALICE
  - Then 2 beams in LHC at buckets 1 and 26701
  - Quiet beams for LHCb

• Recorded collision events in ALICE and LHCb

• From 19.00
  - Beam 2 back in bucket 1
  - 2 beams in for collimation set up
  - Quickly steer IR5 (with new knob) and IR1
  - Quiet beams for 15’ for CMS and ATLAS
Candidate Collision Event

ATLAS

2009-11-23, 14:22 CET
Run 140541, Event 171897

LHCb

LHCb Event Display

23.11.2009 17:59:29
Run 62558 Event 278
Monday

- From 19.30 to 22.30 – first collimator set up (20 collimators done)
- Dump debunched beam
  - All losses on TCDS and TCDQ – looks good

- First test ramp just after midnight
  - Beam 1
  - Beam to 560 GeV
    - Some losses at start
    - Then stable
    - Then losses (3rd order resonance)
First Multi-Stage Betatron and Momentum Collimation

21/100 coll. beam-based aligned to nominal settings for trial ramp 24.11.2009 (others coarse).

<table>
<thead>
<tr>
<th>IR7</th>
<th>Primary: 5.7 σ</th>
<th>Secondary: ~10 σ</th>
<th>Tungsten absorber: 10 σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR3</td>
<td>Primary: 8.0 σ</td>
<td>Secondary: ~10 σ</td>
<td>Tungsten absorber: 10 σ</td>
</tr>
<tr>
<td>IR6</td>
<td>TCS: ~7.0 σ</td>
<td>TCDQ: ~8.0 σ</td>
<td></td>
</tr>
</tbody>
</table>

• No unexpected losses in arcs, experimental insertions, …

• Initial cleaning efficiency: > 99 %
Monday November 30

Both beams accelerated at 1.18 TeV!
Beam commissioning strategy

<table>
<thead>
<tr>
<th>Energy</th>
<th>Safe</th>
<th>Very Safe</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>1 e12</td>
<td>1 e11</td>
</tr>
<tr>
<td>1 TeV</td>
<td>2.5 e11</td>
<td>2.5 e10</td>
</tr>
<tr>
<td>3.5 TeV</td>
<td>3.0 e10</td>
<td>probe</td>
</tr>
</tbody>
</table>

Global machine checkout

Essential 450 GeV commissioning

Machine protection commissioning 1

Experiments’ magnets at 450 GeV

450 GeV collisions

Ramp commissioning to 1.2 TeV

All has been accomplished!

System/beam commissioning

Machine protection commissioning 2

2010

3.5 TeV beam & first collisions

Full machine protection qualification

System/beam commissioning

Pilot physics

Trial ramps

Xmas
Next steps

- Technical stop until end February 2010 to:
  - Fix connectors problem to the nQPS cables
  - Insert the nQPS in the Machine protection system
  - Allow CMS to fix a cooling circuit problem
  - Perform the Chamonix retreat

- Ramp to 3.5 TeV
- Commission beams for collisions
- Start Physics run at 7 TeV c.m
- .......
### Plugging in the numbers with a step in energy

<table>
<thead>
<tr>
<th>Month</th>
<th>OP scenario</th>
<th>Max number bunch</th>
<th>Protons per bunch</th>
<th>Min beta*</th>
<th>Peak Lumi</th>
<th>Integrate d</th>
<th>% nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Beam commissioning</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Pilot physics combined with commissioning</td>
<td>43</td>
<td>$3 \times 10^{10}$</td>
<td>4</td>
<td>$8.6 \times 10^{29}$</td>
<td>~200 nb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>43</td>
<td>$5 \times 10^{10}$</td>
<td>4</td>
<td>$2.4 \times 10^{30}$</td>
<td>~1 pb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>156</td>
<td>$5 \times 10^{10}$</td>
<td>2</td>
<td>$1.7 \times 10^{31}$</td>
<td>~9 pb$^{-1}$</td>
<td>2.5</td>
</tr>
<tr>
<td>5a</td>
<td>No crossing angle</td>
<td>156</td>
<td>$7 \times 10^{10}$</td>
<td>2</td>
<td>$3.4 \times 10^{31}$</td>
<td>~18 pb$^{-1}$</td>
<td>3.4</td>
</tr>
<tr>
<td>5b</td>
<td>No crossing angle – pushing bunch intensity</td>
<td>156</td>
<td>$1 \times 10^{11}$</td>
<td>2</td>
<td>$6.9 \times 10^{31}$</td>
<td>~36 pb$^{-1}$</td>
<td>4.8</td>
</tr>
<tr>
<td>6</td>
<td>Shift to higher energy: approx 4 weeks</td>
<td></td>
<td></td>
<td></td>
<td>Would aim for physics without crossing angle in the first instance with a gentle ramp back up in intensity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>4 – 5 TeV (5 TeV luminosity numbers quoted)</td>
<td>156</td>
<td>$7 \times 10^{10}$</td>
<td>2</td>
<td>$4.9 \times 10^{31}$</td>
<td>~26 pb$^{-1}$</td>
<td>3.4</td>
</tr>
<tr>
<td>8</td>
<td>50 ns – nominal Xing angle</td>
<td>144</td>
<td>$7 \times 10^{10}$</td>
<td>2</td>
<td>$4.4 \times 10^{31}$</td>
<td>~23 pb$^{-1}$</td>
<td>3.1</td>
</tr>
<tr>
<td>9</td>
<td>50 ns</td>
<td>288</td>
<td>$7 \times 10^{10}$</td>
<td>2</td>
<td>$8.8 \times 10^{31}$</td>
<td>~46 pb$^{-1}$</td>
<td>6.2</td>
</tr>
<tr>
<td>10</td>
<td>50 ns</td>
<td>432</td>
<td>$7 \times 10^{10}$</td>
<td>2</td>
<td>$1.3 \times 10^{32}$</td>
<td>~69 pb$^{-1}$</td>
<td>9.4</td>
</tr>
<tr>
<td>11</td>
<td>50 ns</td>
<td>432</td>
<td>$9 \times 10^{10}$</td>
<td>2</td>
<td>$2.1 \times 10^{32}$</td>
<td>~110 pb$^{-1}$</td>
<td>12</td>
</tr>
</tbody>
</table>
Very exciting years are ahead of us

LHC ring:
27 km circumference

CMS
ALICE
LHCb
ATLAS