Status of the LHC

Mike Lamont
for the LHC team
COMMISSIONING PROGRESS
Hardware commissioning for 3.5 TeV
Ramp beams to 3.5 TeV
Machine protection systems qualified
Colliding safe stable beams (2 on 2 pilots)

Squeeze to 2m
Low bunch currents, increase $k_b$
Machine protection systems qualified
13 on 13 low intensity bunches at 2m

High bunch currents, low $k_b$
Increase $k_b$
Machine protection systems qualified
50 on 50 high intensity bunches at 3.5m (Aug)
Crossing angles on, bunch trains, Increase $k_b$

Ions (early scheme, max 62 bunches per beam)
Same magnetic machine as for protons
1 week to switch
4 weeks ion run
<table>
<thead>
<tr>
<th>Date</th>
<th>Achieved</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb 28</td>
<td>Restart with beam.</td>
<td></td>
</tr>
<tr>
<td>Mar 30</td>
<td><strong>First collisions at 7 TeV centre of mass.</strong></td>
<td><strong>Luminosity ~ 2 (10^{27}) cm(^{-2}) s(^{-1})</strong></td>
</tr>
<tr>
<td>Apr 01</td>
<td>Start squeeze commissioning.</td>
<td></td>
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<tr>
<td>Apr 07</td>
<td>Squeeze to 2 m in points 1 and 5.</td>
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<tr>
<td>Apr 09</td>
<td>Single nominal bunch of 1.1 (10^{11}) stable at 450GeV.</td>
<td><strong>Regular physics runs 2 on 2 bunches of (10^{10})</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Un-squeezed 1 colliding pairs per experiment</strong></td>
</tr>
<tr>
<td>Apr 13</td>
<td>Squeeze to 2 m in point 8.</td>
<td></td>
</tr>
<tr>
<td>Apr 16</td>
<td>Squeeze to 2m in point 2.</td>
<td></td>
</tr>
<tr>
<td>April 24</td>
<td><strong>First stable beams at 7 TeV, 3 on 3, squeeze to 2m.</strong></td>
<td><strong>Luminosity ~ 2 (10^{28}) cm(^{-2}) s(^{-1})</strong></td>
</tr>
</tbody>
</table>
## Milestones reached 2010 (to August)

<table>
<thead>
<tr>
<th>Date</th>
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<th>Achieved Details</th>
<th>Status</th>
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<tbody>
<tr>
<td>May</td>
<td>Increase bunch intensity to $2 \times 10^{10}$, Increase $k_b$.</td>
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<td>Regular physics runs</td>
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<td>May 24</td>
<td>13 on 13, 8 colliding pairs per experiment.</td>
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<td>Luminosity ~ $3 \times 10^{29}$ cm$^{-2}$ s$^{-1}$</td>
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<td>June</td>
<td>Increase bunch intensity to nominal, squeeze to 3.5m.</td>
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<td>Machine development</td>
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<td>June 25</td>
<td>First stable beams at 7 TeV, 3 on 3 nominal bunch.</td>
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<td>Luminosity ~ $5 \times 10^{29}$ cm$^{-2}$ s$^{-1}$</td>
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<td>July 15</td>
<td>13 on 13, 8 colliding pairs, $9 \times 10^{10}$/b</td>
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<td>Luminosity ~ $1.5 \times 10^{30}$ cm$^{-2}$ s$^{-1}$</td>
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<tr>
<td>July 30</td>
<td>25 on 25, 16 colliding pairs, $9 \times 10^{10}$/b</td>
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<td>Luminosity ~ $3 \times 10^{30}$ cm$^{-2}$ s$^{-1}$</td>
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<tr>
<td>Aug 19</td>
<td>48 on 48, 36 colliding pairs $15$ and $8, 9 \times 10^{10}$/b</td>
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<td>Luminosity ~ $6 \times 10^{30}$ cm$^{-2}$ s$^{-1}$</td>
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<tr>
<td>Aug</td>
<td>Stable running period to consolidate operation and MP 50x50, $11 \times 10^{10}$/b</td>
<td></td>
<td>~2-3 MJ per beam, Luminosity ~ $1 \times 10^{31}$ cm$^{-2}$ s$^{-1}$</td>
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</table>
Commissioning recap

- Magnetically and optically well understood
  - Excellent agreement with model and machine

- Magnetically reproducible
  - Important because it means optics and thus set-up remains valid from fill to fill

- Aperture clear and as expected

- Excellent performance from instrumentation and controls
  - Still ironing out features

- Key systems performing well
  - Injection
  - Beam dump
  - Collimation
  - Machine protection
Routinely over-inject **nominal bunch intensities**
- Up to September 4 bunches per injection
- September – switch to 150 ns bunch trains

Ramp to 3.5 TeV, squeeze, bring them into collisions and deliver stable beams.

Keep them there

And do it again

A remarkably successful initial commissioning period

which is still ongoing… [NB]
Optics

- Stunningly stable

LHCB1 3.5TeV $\beta^*=3.5\text{m}$

- $\Delta \beta/\beta_x$
  - R2, R3, R4, R5, R6, R7, R8, R1
  - 5-9-2010 (10 A/s)
  - 19-6-2010 (2 A/s)

- $\Delta \beta/\beta_y$

Longitudinal location [m]
FBs in action: ramp

Fill 1309
29.08.2010

OFB trims (µrad)

QFB trims

Energy (TeV)
OFB performance: ramp

Orbit stability in the ramp: $\leq 80 \, \mu\text{m rms}$

R. Steinhagen
The performance of the FBs is good

The LHC only operates reliably with both orbit and tune FBs (ramp and squeeze).

- Ramp and squeeze essentially without losses !!!!

Timeseries Chart between 2010-06-28 17:11:44.172 and 2010-06-28 20:42:34.398 (UTC TIME)

- B2
- Ramp
- Squeeze
- B1
- Bunch length artifact
- Collide

Fill 1308
28.08.2010
Transverse dampers

Crucial to keep emittance growth under control

Already operational through the cycle – including stable beams
Briefly, 5 important machine things
or why we can’t deliver 1e32 cm$^{-2}$s$^{-1}$ immediately

**BEAM SAFETY**

This might seem academic but it is what dominates commissioning and operations at present
Beam Interlock System

**TASK:** trigger beam dump within 3 turns

User inputs include:
- Experiments
- Beam Loss Monitors
- Powering
- Fast magnets
- Vacuum
- Beam dump
- OP

8.9.2010 LHC status
The beam dump

Dump block
TDE

Dilution kickers
MKBH (4x)
MKBV (6x)

Extraction septum

Passive diluter

MSD (3x5)

Passive diluter

Extraction kicker

Beam 1
Q5L
Q4L

MKB

TCDQ

Beam 2
Q4R
Q5R

MSDA
MSDC

MKD (15x)
Abort Gap

LHC (1-RING) = 88.924 µs

3-batch

4-batch

dump trigger

Extraction kicker MKD deflection

3.0 µs particle-free abort gap

LHC Beam

MKD kick [mrad]

0 0.05 0.1 0.15 0.2 0.25 0.3

-10 -8 -6 -4 -2 0 2 4 6 8 10

time [us]
Asynchronous Beam Dump

Estimated occurrence: at least once per year,
0 events up to now!

TCDQ = 6 m long CFC* one-sided collimator
TCSG = 1 m long CFC* two-sided collimator

*CFC = carbon fibre compound

TCDQ + TCSG to protect downstream superconducting magnets (Q4)

8.9.2010 LHC status
Collimation is set up with multi-stage logic for cleaning and protection

Let’s look in normalized phase space, talking in nominal sigmas:

"The hierarchy"

"The jaws of power are always open to devour…"
Collimation is set up with multi-stage logic for cleaning and protection.

Let’s look in normalized phase space, talking in nominal sigmas:
Pedagogical collimation III

- Collimation is set up with multi-stage logic for cleaning and protection
- Let’s look in normalized phase space, talking in nominal sigmas:

![Diagram of collimation stages](Diagram.png)

Primary | Secondary | Dump Protection | Tertiary + Triplet | Tertiary + Triplet

Beam dump envelope
Collimation is set up with multi-stage logic for cleaning and protection.

Let’s look in normalized phase space, talking in nominal sigmas:

- **Primary**
- **Secondary**
- **Dump Protection**
- **Tertiary**
  - +Triplet
- **Not robust**

---

**ROBUST**

- **Beam dump envelope**
- **Not robust**

---

**Dump Kicker**

---

**… but efficient …**

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8.9.2010

LHC status
Pedagogical collimation V

- Collimation is set up with multi-stage logic for cleaning and protection
- Let’s look in normalized phase space, talking in nominal sigmas:

**Diagram:**

- Primary
- Secondary
- Dump Protection
- Tertiary + Triplet
- Not robust
- Beam dump envelope
- MARGIN
- Not robust
- Dump Kicker
- Tertiary + Triplet
- … but efficient …
Conclusions from the pedagogical break

- The collimators and protection devices must be in position at all times
- The hierarchy must be respected
- The collimators and protection devices are positioned with respect to the closed orbit
- Therefore the closed orbit must be in tolerance at all times. This includes the ramp and squeeze.
  - Orbit feedback becomes mandatory
  - Interlocks on orbit position become mandatory
- If these rules are not respected something will get broken.
- Frequent validation to make sure that the rules are respected…
Measured Cleaning at 3.5 TeV

(beam1, vertical beam loss, intermediate settings)

Beam Loss [Gy/s]

s [m]

8.9.2010

LHC status
Qualification: Off-momentum collimation

Loss map for off-momentum error. All OK. See expected low leakage to experimental IR's. OK for stable beams from coll.
LUMINOSITY PRODUCTION
We were never meant to run at 3.5 TeV
- 7 TeV studied in exquisite detail
- 3.5 TeV - bigger beams, less aperture, less attention

Very good single beam lifetime
- Vacuum, non-linearities, lifetimes
- Inject nominal bunch intensities, ramp, squeeze…

Beam-beam
- A lot easier than expected
- Nominal bunch intensity collisions – resolving expected problems with predicted cures. Still surprising.

Transverse emittance (read beam size)
- Too small emittance from injectors!
- Ditto longitudinal plane

Beta* = 3.5 m
Beam current during fill 25/08/2010

Quite frankly: we’re dreaming...

“The price of freedom is eternal vigilance.”

LHC operations 6.9.2010
Two weeks in August

8.9.2010  LHC status
<table>
<thead>
<tr>
<th>August</th>
<th>Fill</th>
<th>Bunches</th>
<th>Stable</th>
<th>nb⁻¹</th>
<th>EOF</th>
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<tr>
<td>18</td>
<td>1293</td>
<td>25x25</td>
<td>12h01</td>
<td>93</td>
<td>Programmed dump</td>
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<tr>
<td>19/20</td>
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<td>48x48</td>
<td>14h43</td>
<td>238</td>
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<td>13h07</td>
<td>280</td>
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<td>24</td>
<td>1299</td>
<td>48x48</td>
<td>3h18</td>
<td>87</td>
<td>RD1.R2 trip.</td>
</tr>
<tr>
<td>24/25</td>
<td>1301</td>
<td>50x50</td>
<td>14h17</td>
<td>345</td>
<td>EOF studies</td>
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<td>26</td>
<td>1303</td>
<td>50x50</td>
<td>13h07</td>
<td>369</td>
<td>fast beam loss event Q25.R5.</td>
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<td>27</td>
<td>1305</td>
<td>50x50</td>
<td>3h30</td>
<td>118</td>
<td>EOF studies</td>
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<td>28/29</td>
<td>1308</td>
<td>50x50</td>
<td>13h42</td>
<td>335</td>
<td>Programmed dump</td>
</tr>
<tr>
<td>29/30</td>
<td>1309</td>
<td>50x50</td>
<td>11h18</td>
<td>312</td>
<td>Programmed dump</td>
</tr>
</tbody>
</table>

& Totem
Including some dedicated bunch train commissioning

<table>
<thead>
<tr>
<th>Availability</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>W33</td>
<td>47.3%</td>
</tr>
<tr>
<td>W34</td>
<td>~85%</td>
</tr>
</tbody>
</table>

**Remarkable machine availability**: impressive performance of cryogenics, QPS, converters, RF, instrumentation, collimators, injectors…

**Very effective** use of available time
# New Record Lumi

**26-Aug-2010 04:24:46**  
**Fill #: 1303**  
**Energy: 3500 GeV**  
**I(B1): 5.51e+12**  
**I(B2): 5.23e+12**

## Experiment Status

<table>
<thead>
<tr>
<th>Experiment</th>
<th>ATLAS</th>
<th>ALICE</th>
<th>CMS</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instantaneous Lumi (ub.s)^-1</td>
<td>10.456</td>
<td>0.138</td>
<td>10.719</td>
<td>8.882</td>
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<tr>
<td>BRAN Luminosity (ub.s)^-1</td>
<td>9.573</td>
<td>0.137</td>
<td>7.914</td>
<td>7.327</td>
</tr>
<tr>
<td>Fill Luminosity (nb)^-1</td>
<td>2.0</td>
<td>0.0</td>
<td>2.0</td>
<td>1.7</td>
</tr>
<tr>
<td>BKGD 1</td>
<td>0.018</td>
<td>0.019</td>
<td>20.644</td>
<td>0.197</td>
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<tr>
<td>BKGD 2</td>
<td>16.000</td>
<td>0.290</td>
<td>0.002</td>
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<tr>
<td>BKGD 3</td>
<td>5.000</td>
<td>0.008</td>
<td>0.003</td>
<td>0.106</td>
</tr>
</tbody>
</table>

## LHCb VELO Position

- **001**  
- Gap: 58.0 mm  
- STABLE BEAMS  
- TOTEM: STANDBY

## FBCT History Beam Lifetime in h

[Graph showing FBCT history beam lifetime in h]

**Updated: 04:31:17**
Emittance evolution during a fill

Guilia Papotti

Color code:
- grey for bunches colliding in 1258;
- green for bunches colliding in 158;
- red for bunches colliding in 15.

Average emittances derived from scan IP1:
X: 4.4um
Y: 4.9um

Average growth of 10-20% over the fill

8.9.2010
Tevatron Luminosity model on the LHC

- The major (preliminary) conclusions for the LHC fill 1303
- Luminosity lifetime – 20 hour
- Intensity loss times
  - Total 94 & 72 hour (Beam 1 & Beam 2)
    - 267 & 253 hour (Beam 1 & Beam 2) due to luminous loss (For $\sigma$ =90 mbarn - need a more accurate number)
    - 170 & 112 hour (Beam 1 & Beam 2) due to longitudinal heating and clipping
- Beam loss is dominated by the longitudinal loss
  - Beam-beam loss is important for some bunches but does not dominate the average
- The transverse emittance growth is dominated by transverse noise at betatron sidebands: feedback and hump

Valeri Lebedev
2010 INCOMING
2010 – main aims

- Clear priority to lay the foundations for 2011 and delivery of 1 fb$^{-1}$
- Have performed a safe, phased increase in intensity with validation and a running period at each step so far
- Gained solid operational experience of [not faultlessly] injecting, ramping, squeezing and establishing stable beams
- Aimed for steady running at or around 1 MJ over the summer – around 3 weeks in the end
- Followed by commissioning of bunch trains and a comparatively fast ramp up in beam intensity
Next up - bunch trains

Step 1: bring on the crossing angles

through the full cycle and then validate with loss maps etc

8.9.2010

LHC status
on_x8 := 1;
on_sep8 := 1;
on_lhcb := 0;

Implications for machine protection

450 GeV Crossing angle at IP8 -170 microrad
High intensity bunch trains

- Bunch spacing 150 ns
- Push through 4, 12, 24 bunches per beam
- Monitor & adjust
  - ADT
  - Longitudinal blow-up
  - RF
  - Feedbacks
- First stable beams: 3x4

<table>
<thead>
<tr>
<th>STEPS</th>
<th># bunches/beam</th>
<th># SPS bunch trains</th>
<th># SPS bunches/train</th>
<th># bunches/injection</th>
<th># injections</th>
<th>E/inj [MJ]</th>
<th>I/inj (e12)</th>
<th>E/total (MJ @ 3.5 TeV)</th>
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<tbody>
<tr>
<td>A</td>
<td>46</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>12</td>
<td>0.03</td>
<td>0.4</td>
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<td>0.26</td>
<td>3.6</td>
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</tr>
</tbody>
</table>

Brennan Goddard, Malika Meddahi

8.9.2010 LHC status
Nominal bunch intensity $1.1 \times 10^{11}$ 
Nominal emittance 
200 microrad crossing angle 
$\beta^* = 3.5 \text{ m}$ 
150 ns bunch spacing

<table>
<thead>
<tr>
<th>Number of bunches</th>
<th>Peak Luminosity [cm$^{-2}$s$^{-1}$]</th>
<th>5day@0.2 [pb$^{-1}$]</th>
<th>MJ</th>
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<tbody>
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<td>$1.5 \times 10^{31}$</td>
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<td>$1.0 \times 10^{32}$</td>
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# Schedule – rest of 2010

Aggressive schedule, assuming excellent machine availability

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<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
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<table>
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</tr>
</tbody>
</table>

- Ion Beam to SPS
- Bunch Trains
- Jeune G
- 96x96
- 48 x 48
- Ion Beam Setup
- Start Ion Physics
- End non-LHC Physics
- End Ion run
- Xmas Day
## Early Heavy Ion Run Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Early (2010/11)</th>
<th>Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ per nucleon</td>
<td>TeV</td>
<td>2.76</td>
</tr>
<tr>
<td>Initial Luminosity ($L_0$)</td>
<td>cm$^{-2}$s$^{-1}$</td>
<td>$\sim 10^{25}$</td>
</tr>
<tr>
<td>Number of bunches</td>
<td></td>
<td>62</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>ns</td>
<td>1350</td>
</tr>
<tr>
<td>$\beta^*$</td>
<td>m</td>
<td>3.5</td>
</tr>
<tr>
<td>Pb ions/bunch</td>
<td></td>
<td>$7 \times 10^7$</td>
</tr>
<tr>
<td>Transverse norm. emittance</td>
<td>$\mu$m</td>
<td>1.5</td>
</tr>
<tr>
<td>Luminosity half life (1,2,3 expts.)</td>
<td>h</td>
<td>$\tau_{\text{IBS}}=7-30$</td>
</tr>
</tbody>
</table>

Initial interaction rate: 100 Hz (10 Hz central collisions $b = 0 – 5$ fm)

$\sim 10^8$ interaction/10$^6$s ($\sim 1$ month)
## 2011 Q1&2

### LHC status

<table>
<thead>
<tr>
<th>Week</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo</td>
<td>3</td>
<td>LHC closed</td>
<td>Re-commissioning</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td></td>
<td>with beam</td>
</tr>
<tr>
<td>Tu</td>
<td>17</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>We</td>
<td>24</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>Th</td>
<td>31</td>
<td>Technical stop</td>
<td>10</td>
</tr>
<tr>
<td>Fr</td>
<td>7</td>
<td>MACHINE CHECKOUT</td>
<td>11</td>
</tr>
<tr>
<td>Sa</td>
<td>14</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>Su</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>28</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>14</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Start non-LHC physics program

<table>
<thead>
<tr>
<th>Week</th>
<th>Apr</th>
<th>May</th>
<th>June</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo</td>
<td>16</td>
<td>18 Easter</td>
<td>24 Whit</td>
</tr>
<tr>
<td>Tu</td>
<td>11</td>
<td>19</td>
<td>21</td>
</tr>
<tr>
<td>We</td>
<td>18</td>
<td>20</td>
<td>22 Ascension</td>
</tr>
<tr>
<td>Th</td>
<td>28</td>
<td>G. Friday</td>
<td>23</td>
</tr>
<tr>
<td>Fr</td>
<td>1</td>
<td>May day</td>
<td>24</td>
</tr>
<tr>
<td>Sa</td>
<td></td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>Su</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2011 – 3.5 TeV

- Restart 4th February
- 9 months protons, 4 weeks ions
- Integrated luminosity target driven – 1 fb⁻¹
- Need to run flat out above 1e32 cm⁻²s⁻¹

Table 4: Possible 2011 ball-park scenarios with 1.1 × 10¹¹ protons per bunch.

<table>
<thead>
<tr>
<th>Nₜ</th>
<th>β*</th>
<th>Energy per beam [MJ]</th>
<th>Peak Luminosity [cm⁻²s⁻¹]</th>
<th>Int. Lumi per month [pb⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>432</td>
<td>3.5</td>
<td>27</td>
<td>1.3 × 10³²</td>
<td>61</td>
</tr>
<tr>
<td>432</td>
<td>2.5</td>
<td>27</td>
<td>1.8 × 10³²</td>
<td>85</td>
</tr>
<tr>
<td>796</td>
<td>3.5</td>
<td>49</td>
<td>2.4 × 10³²</td>
<td>113</td>
</tr>
<tr>
<td>796</td>
<td>2.5</td>
<td>49</td>
<td>3.4 × 10³²</td>
<td>157</td>
</tr>
</tbody>
</table>
Conclusions

- Very successful period of initial commissioning
  - 5 months since first collisions at 3.5 TeV
  - Commissioning is still ongoing...

- All key systems performing remarkably well – some hugely complex systems out there.
  - Some commissioning still required, issues still to address

- Performance with beam (losses, lifetimes, luminosity, emittance growth etc.) is very encouraging.

- Have bedded in the nominal cycle but it remains a complex procedure with a number of critical manual actions required – mistakes still possible

- Moving towards a MJ culture.

- Aggressive planning for the rest of 2010

- Smooth running with 10s MJ in 2011 foreseen
Collimation system conceived as a staged system

- First stage to allow 40% of nominal intensity at 7TeV
  - Under certain assumptions
    - LHC lifetimes and loss rates
    - 0.1%/s assumed (0.2h lifetime)
    - Ideal cleaning
  - Imperfections bring this down
    - Deformed jaws
    - Tilt & offset & gap errors
    - Machine alignment
  - Machine stability
    - Tight settings a challenge early
    - Intermediate settings make use of aperture to relax tolerances

Fix $I_{\text{max}}$ to $6 \times 10^{13}$ protons per beam at 3.5TeV
(about 20% nominal intensity)

30MJ stored beam energy

0.2%/s assumed