LHC long range plan

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Talk for HEPAP

Friday 19th November 2010
- LHC machine recap and main challenges
- Proton and ion runs in 2010
- Plan in 2011
- 2011-20 plan
- High Luminosity LHC
- High Energy LHC
- Conclusion
LHC Timeline

1982 : First studies for the LHC project
1987 : First 1 m long 1 bore 9 T magnet
1994 : First 10 m long, 9T, dipole prototypes
      Approval of the LHC by the CERN Council) with missing magnet scheme!
1996 : Final approval to start the complete LHC construction
2001 : Main Magnets and QRL bid
2004 : Start of the LHC installation (QRL)
2005 : First 15 m dipole installed
2006 : Start of hardware commissioning
2008 : End of hardware commissioning and 1st commissioning with beam.
      Incident.
2009: Recommissioning and first record: 2x1.18 TeV
2010: 2x3.5 TeV operation, start of Physics
... 
2021: High Luminosity LHC
2035: High Energy LHC
What is special with LHC?

- The highest field accelerator magnets: 8.3 T (ultimate: 9 T)
- Proton-Proton machine: Twin-aperture main magnets
- The largest superconducting magnet system (~8000 magnets)
- The largest 1.9 K cryogenics installation (superfluid helium)
- The highest currents (up to 13 kA) controlled with high precision, few ppm
- A sophisticated and ultra-reliable magnet quench protection system
- 350 MJ beams to steer, collimate, squeeze and dump
Final assembly of cryomagnets at CERN

One main dipole magnet:
- 35 tons, 15m,
- 8.3 T – 7 MJ

1232 main dipoles
400 main quadrupoles
The Sector 3-4 incident

19th September 2008 at 11:18.36
last test of the last circuit of the last sector: 7kA (4TeV) towards 9.3 kA (5TeV)

Electrical arc between two magnets at 8.7 kA
The start ...

From L. Rossi, CERN Courier September 2010
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

½ machine done
All the work done since November 2008 makes certain that a repeat of September 19\textsuperscript{th} 2008 can NEVER happen.

The offending connector in this incident had an estimated resistance of 220nΩ. We have measured all 10,000 inter-magnet connectors and the maximum resistance we have seen is 2.7nΩ for dipole busbars and 3.3nΩ for dipole busbars.
LHC main splices today: busbars SC

Main Dipoles&Quads Bus, sorted by position, 2048 segments
All HWC pyramids and plus ~150 ramps to 3.5TeV analyzed

Dipole Buses

Quad Buses

Top 10 Splice Resistances

(**) number of splices in the quads segments corrected, 1.3 added

From Z. Charifoulline
LHC main splices today: inside magnets

Main Dipoles

3.1±1.2nΩ
8 splices
(but not all the same type)

Main Quads

1.4±1.3nΩ
3 + 2* splices
(* partially)

From Z. Charifoulline
All the work done since November 2008 makes certain that a repeat of September 19\textsuperscript{th} 2008 can NEVER happen. The offending connector in this incident had an estimated resistance of 220n\(\Omega\). We have measured all 10,000 inter-magnet connectors and the maximum resistance we have seen is 2.7n\(\Omega\) for dipole busbars and 3.3n\(\Omega\) for dipole busbars.

BUT in April 2009, we have uncovered a different possible failure scenario which could under certain circumstances produce an electric arc in the “copper stabilizers” of the magnet interconnects: LACK of stabilization at the bus bar-splice interface.
Following the technical discussions in Chamonix (Jan 2010) the CERN management and the LHC experiments decided

- Run at 3.5 TeV/beam with a goal of an integrated luminosity of around $1\text{fb}^{-1}$ by end 2011
  - Implies reaching a peak luminosity of $10^{32}$ in 2010

- Then consolidate the whole machine for 7TeV/beam (during a shutdown in 2012)

- From 2013 onwards LHC will be capable of maximum energies and luminosities

Primary Goal for 2010

Steve Myers
30th March 2010: first collisions at 7 TeV (2 x 3.5 TeV)
First Running Period (low bunch intensity)

<table>
<thead>
<tr>
<th>Event</th>
<th>TeV</th>
<th>OEF</th>
<th>(\beta^*)</th>
<th>Nb</th>
<th>(I_b)</th>
<th>(I_{tot})</th>
<th>MJ</th>
<th>Nc</th>
<th>Peak luminosity</th>
<th>Date</th>
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</table>

> Seven Orders of magnitude below design
Second Running Period (High bunch Intensity)

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<tr>
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<th>TeV</th>
<th>OEF</th>
<th>$\beta^*$</th>
<th>Nb</th>
<th>$I_b$</th>
<th>$I_{tot}$</th>
<th>MJ</th>
<th>Nc</th>
<th>Peak luminosity</th>
<th>Date</th>
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</table>

Maximum reached is $10.7 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$
Approaching 4pb-1 (move to bunch trains)
Plan for getting to $10^{32}$ before ion run

LMC 18\textsuperscript{th} August.

- **Parameters and Conditions**
  - Nominal bunch intensity $1.1 \times 10^{11}$
  - Stick to $\beta^* = 3.5$ m in all IPs
  - Commission bunch trains
    - Complete re-do of the whole machine protection set-up
  - Go to 150 ns bunch spacing

- Commission faster ramp (10 A/s) – magnet were all tested for 20 A/s
• Completely new set up of all phases of LHC under the new conditions needed for safe operation with high intensity bunch trains
  – Beam transfer (collimation)
  – Emittance control in injectors and during ramp in LHC
  – Transverse damper set up with lower noise
  – Injection with crossing angles (collimators and unsafe beam),
  – Accumulation with crossing angle; long discussions about magnitude of crossing angle
  – Ramp with 10A/s
  – Squeeze (changing crossing angles to collision values)
  – Collisions with crossing angles (collimation)
  – (Aperture measurement)
Collisions with bunch trains; 24th September 7x8 bunches; Luminosity = 2x10^{31}
Running with Bunch Trains (Parameters)

<table>
<thead>
<tr>
<th>Nb</th>
<th>lb</th>
<th>MJ</th>
<th>Nc</th>
<th>Peak luminosity (design parameters)</th>
<th>Maximum luminosity (measured)</th>
<th>Pile up (from measured Lumi)</th>
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24MJ stored beam energy and $2.05 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$
Luminosity evolution 2010 (proton)

5 orders of magnitude in ~200 days

~50 pb\(^{-1}\) delivered, half of it in the last week!

LHC 2010 RUN (3.5 TeV/beam)

Luminosity (Hz/μb)

day of year 2010

* ALICE: low pile-up limited since 01.07.2010
Status LHC Stored Energy

80 kg TNT
Did we reach the intensity limit for 150ns?

4.35e13 p (?) \(\rightarrow\) to be followed...

Stored energy reached at 3.5 TeV: 28.0 MJ

Stored energy at 3.5 TeV in stable beams: 25.2 MJ
Vacuum - Bunch trains and vacuum around IR1

Gradual degradation seen with the benefit of hindsight from Friday September 29th
Initially

- Pressure rise seen in common beam pipe regions
- Particularly unbaked warm-cold transitions. All backed area are NEG coated (e-could suppressor)
- Curiously not around CMS. We understood later that CMS solenoid suppress e-cloud.

![Graph showing vacuum behavior over time](image)
Initially

• Pressure rise seen in common beam pipe regions
• Particularly unbaked warm-cold transitions
• Two effects:
  – electron cloud driven by closely space passage of b1 and b2 bunches
  – synchrotron radiation induced desorption
Not everything is perfect. The LHC has reached a stage where interesting things are beginning to pop up …
- The smaller bunch spacing with trains can provoke electron clouds
- In warm regions of the machine this can lead to a vacuum pressure rise
- In cold regions of the machine this would create an additional heat load on the cryogenic system.
- In addition all the electrons in the beam pipe can feed back to affect the beam stability
- Can be eliminated by conditioning the surface - scrubbing

Schematic of electron cloud build up in LHC arc beam pipe, due to photoemission and secondary emission
Initially

- Pressure rise seen in common beam pipe regions.
- Particularly unbaked warm-cold transitions.
- Two effects:
  - electron cloud driven by closely spaced passage of b1 and b2 bunches.
  - synchrotron radiation induced desorption.
- Region +/- 58 m of IP1 equipped with solenoids worked well.
  - classic cure for electron cloud.
- Cleaning observed.

Initially

![Vacuum](image)

Solenoid A4L1 - with solenoids...
Scrubbing in the LSS (50 ns)

Cleaning / Scrubbing with time
(normalised to 1)

Can hope to gain 2 orders of magnitude in ~16h

Valid for a given bunch intensity and filling pattern
Cleaning/Scrubbing ONLY if running with electron cloud!

w/o electron cloud, NO cleaning/scrubbing except by photons (>2 TeV) BUT no pressure rise…

Memory effect will stay (partly/totally) for other schemes
• Sudden local losses
• No quench, but preventive beam dump
• Rise time on the ms scale
• Working explanation: dust particles falling into beam creating scatter losses and showers propagating downstream
UFO - Worrying trend through the summer

Mike Lamont
Lead ion injector chain

• ECR ion source (2005)
  - Provide highest possible intensity of Pb$^{29+}$

• RFQ + Linac 3
  - Adapt to LEIR injection energy
  - Strip to Pb$^{54+}$

• LEIR (2005)
  - Accumulate and cool Linac 3 beam
  - Prepare bunch structure for PS

• PS (2006)
  - Define LHC bunch structure
  - Strip to Pb$^{82+}$

• SPS (2007)
  - Define filling scheme
### Ion Commissioning: First 24h from Nov 4th!


<table>
<thead>
<tr>
<th>Experiment Status</th>
<th>ATLAS</th>
<th>ALICE</th>
<th>CMS</th>
<th>LHCb</th>
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<td>0.000</td>
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<table>
<thead>
<tr>
<th>LHCb VELO Position</th>
<th>OUT</th>
<th>Gap: 58.0 mm</th>
<th>SQUEEZE</th>
<th>TOTEM:</th>
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</table>

### Performance over the last 24 Hrs

Updated: 21:48:16

- Beam 1 Inj., Circ. & Capture
- Beam 2 Inj., Circ. & Capture
- Optics Checks
- BI Checks
- Collimation Checks
- First Ramp
- Collimation Checks Squeeze
Friday 5th Nov. afternoon: first ramp – no losses

**World first:** observation of synchrotron light from nuclei
Appears around 0.55 Z TeV (later if filtered)

Bunch length increasing at injection (IBS), down during the ramp, increasing again at 3.5 TeV (IBS)
First stable beams (2 bunches per beam)
Injectors are giving us 70% beyond design single-bunch intensity of $7 \times 10^7$ ions/bunch, which is wonderful, but has consequences...

- Significant IBS growth and debunching at injection, seems to be in reasonable agreement with theory

- Emittances at injection around 1-2 μm (with Pb gamma!).
- Emittances on flat top 1.5-3 μm
- Emittance blow-up in physics is not too bad, but mostly not IBS

<table>
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<th>Date</th>
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<th>Colliding IR2</th>
<th>Luminosity</th>
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<td>November 9</td>
<td>5</td>
<td>4</td>
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<td>November 9</td>
<td>17</td>
<td>16</td>
<td>$3.5 \times 10^{24}$</td>
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<tr>
<td>November 13</td>
<td>69</td>
<td>66</td>
<td>$9 \times 10^{24}$</td>
</tr>
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<td>November 14</td>
<td>121</td>
<td>114</td>
<td>$2 \times 10^{25}$</td>
</tr>
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<td>November 15</td>
<td>121</td>
<td>114</td>
<td>$2.8 \times 10^{25}$</td>
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Luminosity evolution (not quite up to date)
• Primary ion beam losses are intercepted at the collimators
• Several features contribute to more severe ion loss problems
  – Nuclear physics: Ion dissociation and fragmentation reduce cleaning efficiency by factor ~100 when compared to protons (predicted since years, now confirmed).
    • Collimation upgrade (DS collimators) will solve this.
  – Ion beam lifetimes factor ~3-6 lower than for proton beams
    • Not yet understood

• Effects are clearly seen in Radmon monitors
• And in the equipment!
  – “QPS OK” lost on Q9.L7, communication to quench detector → Single Event Upset (“SEU”). Upgraded firmware in dispersion suppressors of LSS7 on Saturday
  – “QPS OK” lost on Q9.R7 and Q9.L7, FIP communication → SEU? No work-around available at the moment
• Bunch train operation with 150ns was a big success
  – Bunch intensity ~ nominal
  – Normalised emittance $\varepsilon_n$ in collision ~ 2.5 $\mu$m
  – Maximum bunches/colliding 1 & 5 368/348
  – Peak luminosity ~ $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
  – Delivered luminosity ~ 50 pb$^{-1}$
  – Stable beam operation with 25MJ per beam
  – A few interesting (intensity-related) effects for 2011:
    • Beam-beam effects with crossing angles
    • Behaviour of the vacuum system
    • UFOs

• 50ns run
  – Very useful few days
  – Should allow definition of strategy for 2011 (together with ongoing studies)

• Ion run
  – Very fast switch from p to Pb
  – Quickly up to nominal performance for 2010
Summary: What did we learn in 2010

- LHC is magnetically very reproducible on a month to month time scale
- Head on beam-beam limit higher than foreseen
- Aperture better than foreseen
- Not a single magnet quench due to beam
- Careful increase of the number of bunches OK
- Electron cloud and vacuum
- Machine protection
  - Set up is long
  - Quench levels for fast and slow losses needs optimized
  - UFOs
New record of intensity injected in the LHC
8 + 24/24 + 24/24 + … + 24/24 = 680 bunches
at 1.1 \times 10^{11} \text{ p/b}, 75 \text{ ns bunch spacing} \at 450 \text{ GeV}

25\% \text{ of the nominal LHC intensity!}

Beam optimisation ongoing
Beam intensity

$P_{\text{cold/warm}}$ transitions of cryomagnets

$P_{\text{sector @ RT}}$

with synchrotron radiations

w/o synchrotron radiations

$P_{\text{beam}}$ (mbar)

$10^{-7}$

$10^{-8}$

$10^{-9}$

$10^{-11}$

$680 \text{ b, 75 ns spacing, } 1.1 \times 10^{11} \text{ p/b at } 450 \text{ GeV}$

No electron cloud on NEG coated beampipes

No pressure rise/heating observed in arcs

Higher pressure in beampipes with two circulating beams

TODAY are at $850 \text{ bunch @ } 1.3 \times 10^{11} !!!$

in a beam alone, $0.5 I_{\text{nom}}$
2011

- Beam back around 21\textsuperscript{st} February
- 2 weeks re-commissioning with beam (at least)
- 4 day technical stop every 6 weeks
- Count 1 day to recover from TS (optimistic)
- 2 days machine development every 2 weeks or so
- 4 days ions set-up
- 4 weeks ion run
- End of run – 12\textsuperscript{th} December

\(\sim\)200 days proton physics
• Running Conditions in 2011 (Chamonix January 2011)
  – Maximum beam energy
  – Bunch spacing 50ns (max bunches 1404)
  – Integrated luminosity evaluation

=> goal set is $1 fb^{-1}$
2011: “reasonable” numbers

- 4 TeV (to be discussed at Chamonix: but higher beam energy would imply some hardware change: dipole dumping time from 50 to 65 s
- 936 bunches (75 ns)
- 3 micron emittance
- $1.2 \times 10^{11}$ protons/bunch
- $\beta^* = 2.5$ m, nominal crossing
- Hubner factor 0.2

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Peak luminosity</td>
<td>$6.4 \times 10^{32}$</td>
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<tr>
<td>Integrated per day</td>
<td>11 pb$^{-1}$</td>
</tr>
<tr>
<td>200 days</td>
<td>2.2 fb$^{-1}$</td>
</tr>
<tr>
<td>Stored energy</td>
<td>72 MJ</td>
</tr>
</tbody>
</table>

*Usual warnings apply – see problems, problems above*
1.6 x 10^{11} ppb and emittance of 2 microns at 3.5 TeV respects the robustness limits of the collimation system (equivalent to ultimate intensity) Ralph Assmann

- 4 TeV
- 1400 bunches (50 ns)
- 2.5 micron emittance
- 1.5 x 10^{11} protons/bunch
- \beta^* = 2.0 m, nominal crossing angle
- Hubner factor 0.2

<table>
<thead>
<tr>
<th>Peak luminosity</th>
<th>2.2 x 10^{33}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated per day</td>
<td>38 pb^{-1}</td>
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<tr>
<td>200 days</td>
<td>7.6 fb^{-1}</td>
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<tr>
<td>Stored energy</td>
<td>134 MJ</td>
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</table>

Usual warnings particularly apply – see problems, problems above
## 2012 – 2013 long shutdown

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011</th>
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</table>

**Maj maintenance**

**X**

- **Machines:** Splice Consolidation & Collimation in IR3
  - ALICE - detector completion
  - ATLAS - Consolidation and new forward beam pipes
  - CMS - FWD muons upgrade + Consolidation
  - LHCb - consolidations

**SPS upgrade**

---

**Superconducting cable**

- **Busbar (insulated)**
- **Copper shunts (2 per side of each splice)**
- **Interconnection box for ground insulation and for mechanical restraint of the splice**

**Cross profile for bus-to-bus insulation**

**splice length**
Run the LHC between 6.5 TeV and 7 TeV according to magnet training.

We need to insert new 4 collimators in cold zone DS: displacing 24 magnets + 6 cold modules.
Lumi forecast

- Peak luminosity
- Integrated luminosity

Year ending:
- 2010
- 2011
- 2012
- 2013
- 2014
- 2015
- 2016
- 2017
- 2018
- 2019
- 2020

Peak Luminosity [cm⁻²s⁻¹]
- 0.0E+00
- 2.0E+33
- 4.0E+33
- 6.0E+33
- 8.0E+33
- 1.0E+34
- 1.2E+34
- 1.4E+34
- 1.6E+34
- 1.8E+34
- 2.0E+34

Integrated luminosity [fb⁻¹]
- 0.01
- 0.10
- 1.00
- 10.00
- 100.00
- 1000.00
Lumi and halving time
New Studies were launched more than one year ago

- **Performance Aim**
  - To maximize the *useful integrated* luminosity over the lifetime of the LHC

- **Targets set by the detectors are:**
  - $3000\text{fb}^{-1}$ (on tape) by the end of the life of the LHC
  - $250 \text{fb}^{-1}$ per year in the second decade of running the LHC

**Goals**

- Check the *coherence* of the presently considered upgrades wrt
  - accelerator *performance limitations*,
  - Detector needs,
  - manpower resources and,
  - shutdown planning including detectors
For LHC high luminosities, the luminosity lifetime becomes comparable with the turn round time ⇒ Low efficiency

Preliminary estimates show that the useful integrated luminosity is greater with
- a peak luminosity of $5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ and a longer luminosity lifetime (by luminosity levelling)
- than with $10^{35}$ and a luminosity lifetime of a few hours

Luminosity Levelling by
- Beta*, crossing angle, crab cavities, and bunch length

Detector physicists have indicated that their detector upgrades are significantly influenced by the choice between peak luminosities of $5 \times 10^{34}$ and $10^{35}$.
- Pile up events
- Radiation effects
Hardware for the Upgrade

- Upgrade of the intensity in the **Injector Chain**
- New high field insertion **quadrupoles**
- Upgraded **cryo system** for IP1 and IP5
- **Crab Cavities** to take advantage of the small beta*
- Single Event Upsets
  - **SC links** to allow power converters to be moved to surface (and easy integration in crowdy IR zone)

**Misc**

- Upgrade some correctors
- Re-commissioning DS quads at higher gradient
- Change of New Q5/Q4 (larger aperture), with new stronger corrector orbit, displacements of few magnets
- Larger aperture D1/D2
# The 10 year technical Plan

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</tbody>
</table>

**2010**
- Machine: Splice Consolidation & Collimation in IR3
- ALICE - detector completion
- ATLAS - Consolidation and new forward beam pipes
- CMS - FWD muons upgrade + Consolidation
- LHCb - consolidations

**2011**
- SPS upgrade

**2012**
- SPS upgrade

**2013**
- SPS - LINAC4 connection & PSB energy upgrade

**2014**
- Machine: Collimation & prepare for crab cavities & RF cryo system
- ATLAS: nw pixel detect. - detect. for ultimate luminosity.
- ALICE - Inner vertex system upgrade
- CMS - New Pixel. New HCAL Photodetectors. Completion of FWD muons upgrade
- LHCb - full trigger upgrade, new vertex detector etc.

**2015**
- X-Mas maintenance

**2016**
- X-Mas maintenance

**2017**
- X-Mas maintenance

**2018**
- X-Mas maintenance

**2019**
- X-Mas maintenance

**2020**
- X-Mas maintenance

**2021**
- Machine - maintenance & Triplet upgrade
- ATLAS - New inner detector
- ALICE - Second vertex detector upgrade
- CMS - New Tracker

**2020**
- SPS - LINAC4 connection & PSB energy upgrade
Timeline
energy and luminosity 2011-2021

New 3.3.5 m shorter Nb3Sn Dipoles (2 per DS)
HL-LHC Design Study is being launched. Application for grant to EU, with strong participation by USA-JP

Total (€ 21,184,800)

Not final, figures may change
HL-LHC 40 new HF magnets... paving the way to the next jump?
Very Long Term Objectives:
Higher Energy LHC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal HE-LHC</th>
<th>HE-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy [TeV]</td>
<td></td>
<td>16.5</td>
</tr>
<tr>
<td>dipole field [T]</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>dipole coil aperture [mm]</td>
<td></td>
<td>40-45</td>
</tr>
<tr>
<td># bunches / beam</td>
<td></td>
<td>1404</td>
</tr>
<tr>
<td>bunch population ([10^{11}])</td>
<td></td>
<td>1.29</td>
</tr>
<tr>
<td>initial transverse normalized emittance ([\mu m])</td>
<td></td>
<td>3.75 (x), 1.84 (y)</td>
</tr>
<tr>
<td>number of IPs contributing</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>maximum total beam</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>IP beta function</td>
<td>0.55</td>
<td>1.0 (x), 0.43 (y)</td>
</tr>
<tr>
<td>full crossing</td>
<td>285 (9.5 (\sigma_{x,y}))</td>
<td>175 (12 (\sigma_{x_0}))</td>
</tr>
<tr>
<td>stored beam</td>
<td>362</td>
<td>479</td>
</tr>
<tr>
<td>SR power</td>
<td>3.6</td>
<td>62.3</td>
</tr>
<tr>
<td>longitudinal damping time [h]</td>
<td>12.9</td>
<td>0.98</td>
</tr>
<tr>
<td>events per bunch</td>
<td>19</td>
<td>76</td>
</tr>
<tr>
<td>peak luminosity ([cm^{-2}s^{-1}])</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>beam lifetime ([\mu s])</td>
<td>46</td>
<td>13</td>
</tr>
<tr>
<td>integrated luminosity over 10 h ([fb^{-1}])</td>
<td>0.3</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Very preliminary with large error bars
HE-LHC – main issues and R&D

- **high-field 20-T dipole magnets** based on $\text{Nb}_3\text{Sn}$, $\text{Nb}_3\text{Al}$, and HTS
- **high-gradient quadrupole magnets** for arc and IR
- **fast cycling SC magnets** for 1-TeV injector
- **emittance control** in regime of strong SR damping and IBS
- **cryogenic handling of SR heat load** (first analysis; looks manageable)
- **dynamic vacuum**
Reserve slides
The number of Events per second generated by the LHC is given by:

\[ \text{Number of events} = L \times \sigma_{\text{event}} \]

…for rare processes \( L \) must be large in order to generate a significant number of events.

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

Units are per cm\(^2\) per second

"Thus, to achieve high luminosity, all one has to do is make (lots of) high population bunches with low emittance collide at high frequency at locations where the beam optics provides as low values of the beam size as possible."

Nearly all the parameters are variable (and not independent)

- Number of bunches per beam \( k_b \)
- Number of particles per bunch \( N \)
- Normalised emittance \( \varepsilon_n \)
- Relativistic factor \( \gamma = \frac{E}{m_0} \)
- Beta function at the IP \( \beta^* \)
- Crossing angle factor \( F \)
We can put up to 156 equidistant bunches around the LHC without parasitic crossing in the interaction regions occurring.

- But injecting 156 times per ring is a little time consuming …
- Any further increase requires injecting trains of bunches with a smaller spacing.

The nominal LHC injection scheme calls for 25ns (7.5m) spacing in the LHC

So far we have used larger spacing: 150ns (physics in 2010) and 50ns (for physics in 2011)

- With 150ns we can fit ~440 bunches per ring
- With 50ns we can fit around 1400 bunches per ring

We can inject many bunches at once … eventually several hundred in one go

But we get unwanted collisions in the regions around the experiments …
• Beam-beam
  – A lot easier than expected
  – Can collide nominal bunch intensity collisions without problems
  – Even with much lower than nominal beam sizes
  – Resolving expected problems with predicted cures (octupoles, transverse feedback)

  – Still surprising…
Preliminary conclusions

• At 50-ns spacing strong evidence for large electron cloud build up in warm and cold sections

• Cold sections are of bigger concern

• In the arcs significant heat load due to electron cloud has been observed. Its reduction at high energy after scrubbing is not striking.

• Both heat load & instability in 3rd and 4th train indicate SEY $\Delta_{\text{max}} \sim 2.5$ in the arcs (larger than expected) at R=0.5

• Av. e-cloud density $\sim 6 \times 10^{11}$ m$^{-3}$ (from Q’ effect)

• The evaluation of the behaviour with 75 ns beams at 450 GeV and comparison with the 50 ns beam in terms of pressure-rise heat load and beam stability is necessary

Next week: 2 to 3 days

Frank Zimmerman, Gianluigi Arduini, Miguel Jimenez, Laurent Tavian et al
- vacuum pressure rise
- single-bunch instability
  - interplay w. impedance & beam-beam
- multi-bunch instability
- incoherent emittance growth
- heat load in cold arcs (quench)
- perturbation of beam diagnostics
LHC strategy against electron cloud

1) warm sections (20% of circumference) coated by TiZrV getter developed at CERN; low secondary emission; if cloud occurs, ionization by electrons (high cross section ~400 Mbarn) aids in pumping & pressure will even improve

2) outer wall of beam screen (at 4-20 K, inside 1.9-K cold bore) will have a sawtooth surface (30 μm over 500 μm) to reduce photon reflectivity to ~2% so that photoelectrons are only emitted from outer wall & confined by dipole field

3) pumping slots in beam screen are shielded to prevent electron impact on cold magnet bore

4) rely on surface conditioning (‘scrubbing’); commissioning strategy; as a last resort doubling or tripling bunch spacing suppresses e-cloud heat load
50ns run (29/10 to 04/11)

• Motivation (in view of effects seen during 150ns operation)
  – Exploration of physics conditions with 50ns spacing
  – Injection and capture efficiency
  – Behaviour of Beam Instrumentation and RF and damper systems
  – Behaviour of vacuum system

• Planning adapted as observations were made
  – Injection and capture of trains of 12
  – Physics fill with 9x12 bunches + end of fill beam-beam studies
  – Large increase in vacuum pressure when injecting trains of 24 bunches
  – Beam stability at injection
  – Systematic measurements of pressure rise in the straight sections and heat load in the arcs for different filling patterns to provide input for simulations and guide predictions:
    • Dependence on bunch intensity
    • Dependence on bunch train length
    • Dependence on bunch train spacing
  – Measurements for the characterization of the scrubbing
# Heavy Ion Run Parameters

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<tr>
<th>Parameter</th>
<th>Early (2010/11)</th>
<th>Nominal</th>
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<tbody>
<tr>
<td>√s per nucleon</td>
<td>TeV</td>
<td>2.76</td>
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<tr>
<td>Initial Luminosity (L₀)</td>
<td>cm⁻²s⁻¹</td>
<td>~10⁵²⁵</td>
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<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>β*</td>
<td>m</td>
<td>3.5</td>
</tr>
<tr>
<td>Pb ions/bunch</td>
<td></td>
<td>7x10⁷</td>
</tr>
<tr>
<td>Transverse norm. emittance</td>
<td>µm</td>
<td>1.5</td>
</tr>
<tr>
<td>Luminosity half life (1,2,3 expts.)</td>
<td>h</td>
<td>τ_{IBS}=7-30</td>
</tr>
</tbody>
</table>

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

~10⁸ interaction/10⁶s (~1 month)
Ions - conclusions

• Very swift commissioning period leveraging proton set-up to the maximum.
  – pushing though 2 – 17 – 69 toward 120 bunches per beam
  – Peak luminosity around $6 \times 10^{24}$ cm$^{-2}$s$^{-1}$ with 69 bunches

• Injectors are giving us 70% beyond design single-bunch intensity, some consequences...
  – Significant IBS growth and de-bunching at injection, seems to be in reasonable agreement with theory

• Emittance blow-up in physics is not too bad, but mostly not IBS

• Collimation of heavy ions is complicated
  – Simulations roughly right but do not show all details – need considerable effort for refinement ... and counter-measures in future

*John Jowett*
## LHC: Some Technical Challenges: Recap

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<th>Value</th>
<th>Notes</th>
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<td>Circumference (km)</td>
<td>26.7</td>
<td>100-150m underground</td>
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<td>Number of superconducting twin-bore Dipoles</td>
<td>1232</td>
<td>Cable Nb-Ti, cold mass 37million kg</td>
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<td>Length of Dipole (m)</td>
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<td>Dipole Field Strength (Tesla)</td>
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<td>Results from the high beam energy needed</td>
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<tr>
<td>Operating Temperature (K) (cryogenics system)</td>
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<td>Superconducting magnets needed for the high magnetic field</td>
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<td>Super-fluid helium</td>
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<td>Current in dipole sc coils (A)</td>
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<td>Results from the high magnetic field</td>
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<tr>
<td></td>
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<td>1ppm resolution</td>
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<tr>
<td>Beam Intensity (A)</td>
<td>0.5</td>
<td>2.2.10^{-6} loss causes quench</td>
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<tr>
<td>Beam Stored Energy (MJoules)</td>
<td>362</td>
<td>Results from high beam energy and high beam current: 1MJ melts 1.5kg Cu</td>
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<td>Magnet Stored Energy (MJoules)/octant</td>
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<td>Results from the high magnetic field</td>
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<td>Sector Powering Circuit</td>
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<td>1612 different electrical circuits</td>
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