A short summary to:

Review
The large hadron collider

O.Brüning, H.Burkhardt, S.Myers

Progress in Particle and Nuclear Physics 67 (2012) 705-734

M. Isacson, M. J. Kareem

HASCO 2013

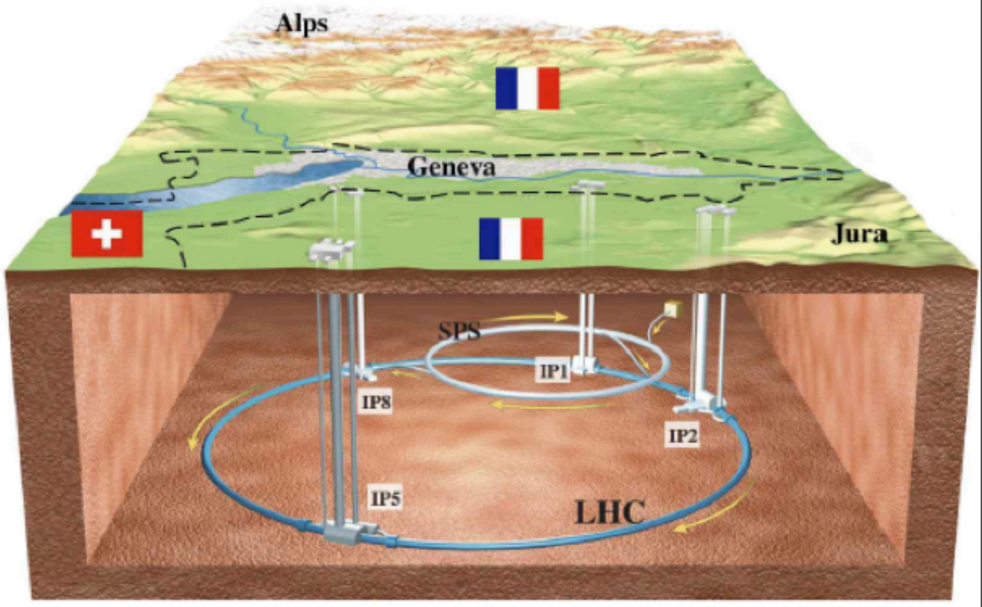
Outline

Part I :

- Basic Design Considerations
- Injection
- Machine protection
- Interaction regions

Part II :

- Experience from early operation
- Upgrade Considerations



LHC by the numbers

✦Underground tunnel of 27.6k m circumference.

✦Two beam-pipes which cross at four interaction regions.

✦Nominal LHC design aims at proton beam energies of 7 Tev.

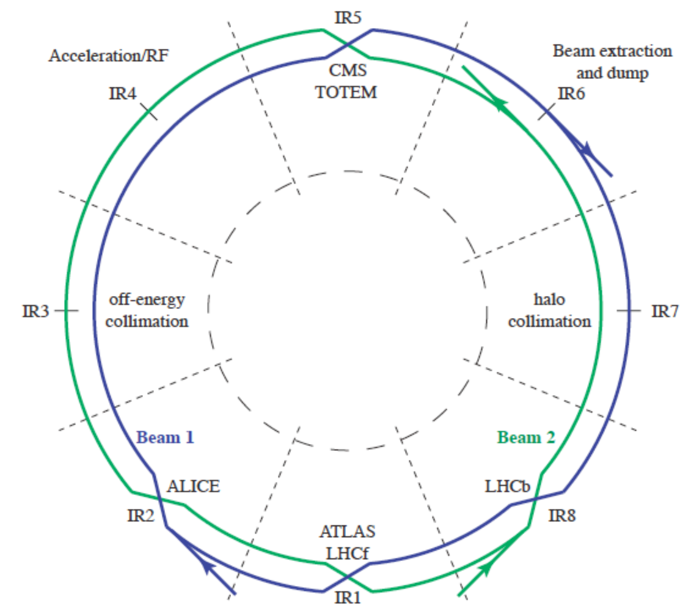
✦High rate of event production --> High luminosity:

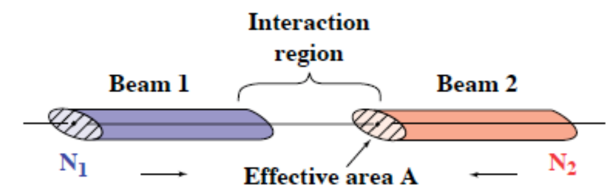
1) Increasing the bunches in the beam

2) Reducing the transverse beam size at IP by the magnetic focusing system with strong quadrupole magnets.

✦Built with superconducting Niobium-titanium (NbTi) magnets, operating at superfluid Helium temperature of 1.9K.

✦ Magnetic field B = 8.33 T





Project Goals:

✦Discussions of the Large Hadron Collider (LHC) started as early as 1983.

✦The key objective of the LHC is the exploration of the **Standard Model in the TeV** energy range, the search for the **Higgs Boson** and potential **new physics** signatures.

✦**Why not colliding Leptons?** ---> lepton colliders allow for a well defined collision energy BUT limited in luminosity and maximum beam energy at comparable size and cost.

Muon colliders --> ?

Project Goals:

✦Discussions of the Large Hadron Collider (LHC) started as early as 1983.

✦The key objective of the LHC is the exploration of the **Standard Model in the TeV** energy range, the search for the **Higgs Boson** and potential **new physics** signatures.

✦**Why not colliding Leptons?** ---> lepton colliders allow for a well defined collision energy **BUT** limited in luminosity and maximum beam energy at comparable size and cost.

Muon colliders --> ?

✦**Colliding hadrons is like colliding two garbage cans and watching carrots come out !**

BUT the advantages are :

1) the collisions naturally cover a wide energy range --> ideal instruments for the exploration of unknown territory.

2) A hadron collider offers the highest energy reach.

Project Goals:

Two distinct design options for a circular collider:

1) Collisions between particles and anti-particles:

advantages: efficient accelerator design, beams share the same vacuum chamber and magnetic elements

disadvantages: are intrinsically limited by the rate at which anti-particles can be generated.

2) Collisions between a wider range of particles

advantages: achieves higher luminosity.

disadvantages: require a two ring design with separate magnet and vacuum systems.

Basic Design Considerations

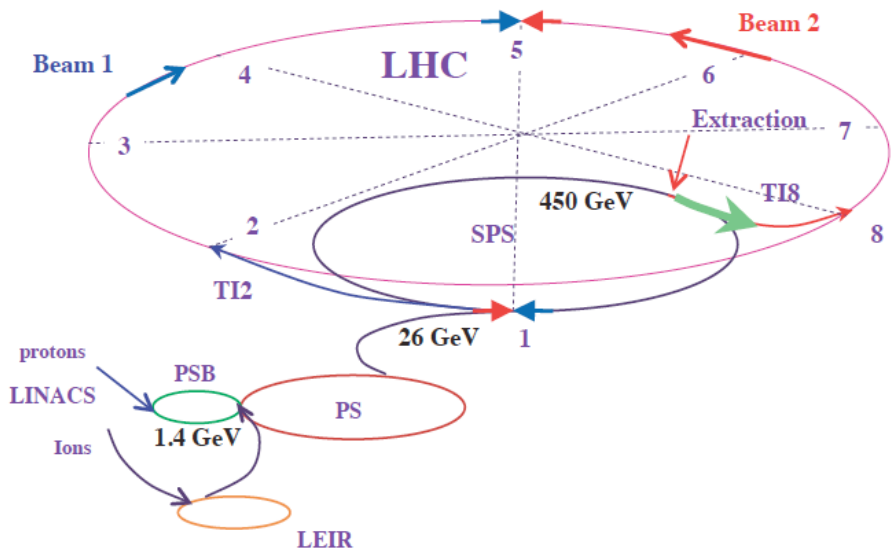
Project Goals:

✦ Four experimental insertions:

- ATLAS and CMS --> **high luminosity** experiments $L \geq 10^{34} cm^{-2} s^{-1}$
- LHCb requiring **medium luminosities** $L \propto 10^{32} cm^{-2} s^{-1}$
- ALICE experiment for ion collisions --> requiring **low luminosities** $L \propto 10^{29} cm^{-2} s^{-1}$

How to Maximize the instantaneous luminosity?

- Optimizing the overlap of the two beams at the IP.
- Minimizing the beam size at the IP.
- Maximizing the number of particles per bunch.
- Maximizing the number of bunches in the collider.



Pre-accelerators:

Source and linear accelerator “LINAC” followed by the Booster (PSB), PS and SPS rings.

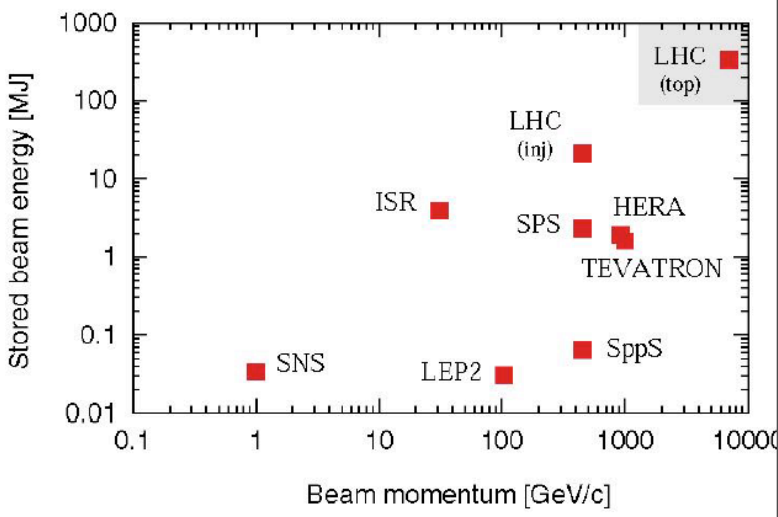
machine	L [m]	relative	ρ [m]	beam momentum [GeV/c]	bunches
LINAC	30		–	10^{-4}	4×2
PSB	157		8.3	0.05	4×2
PS	628.318	1	70.676	1.4	72
SPS	6911.56	11×PS	741.257	26	4×72
LHC	26658.883	27/7×SPS	2803.98	450	2×2808

Large amount of energy stored in:

✦Superconducting magnet system (10 GJ at the design energy).

$$E = \frac{1}{2} I^2 L$$

✦Circulating beams (362 MJ / beam).



Quench protection

✦Transition from super to normal conduction state.

✦Detected as a resistance increase causing a voltage rise over a magnet.

==> safely **discharge** the quenched magnet and **bypass** the current of the other magnets

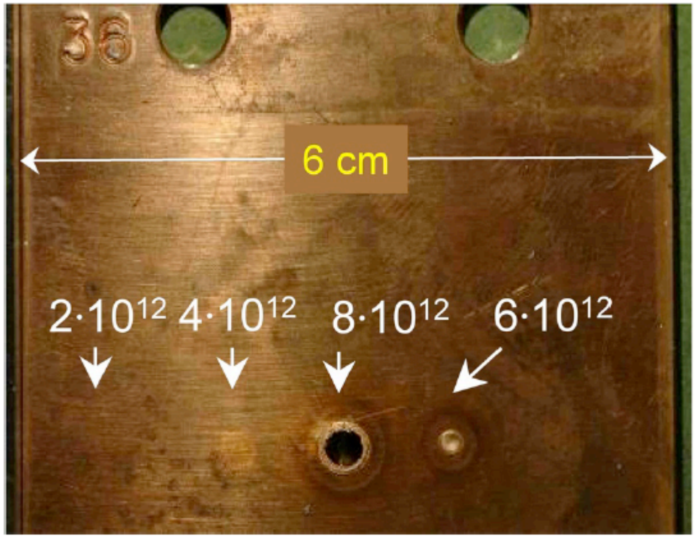
Beam loss protection

✦ Fast beam loss and protection system.

✦**Beam dump system** installed around LHC point 6:

✦beams can be cleanly removed from the LHC using kicker magnets within a single turn.

✦The particles leave the LHC ==> beam dump channels on either side of point 6, ==> stopped in the ~8m long graphite core ==> surrounded by concrete and iron located at 700m downstream from point 6.



Machine protection

Large amount of energy stored in:

✦Superconducting magnet system (10 GJ at the design energy).

✦Circulatin

Quench

✦Transitior

✦Detected

==> safely

other magn

Beam lo

✦ Fast bea

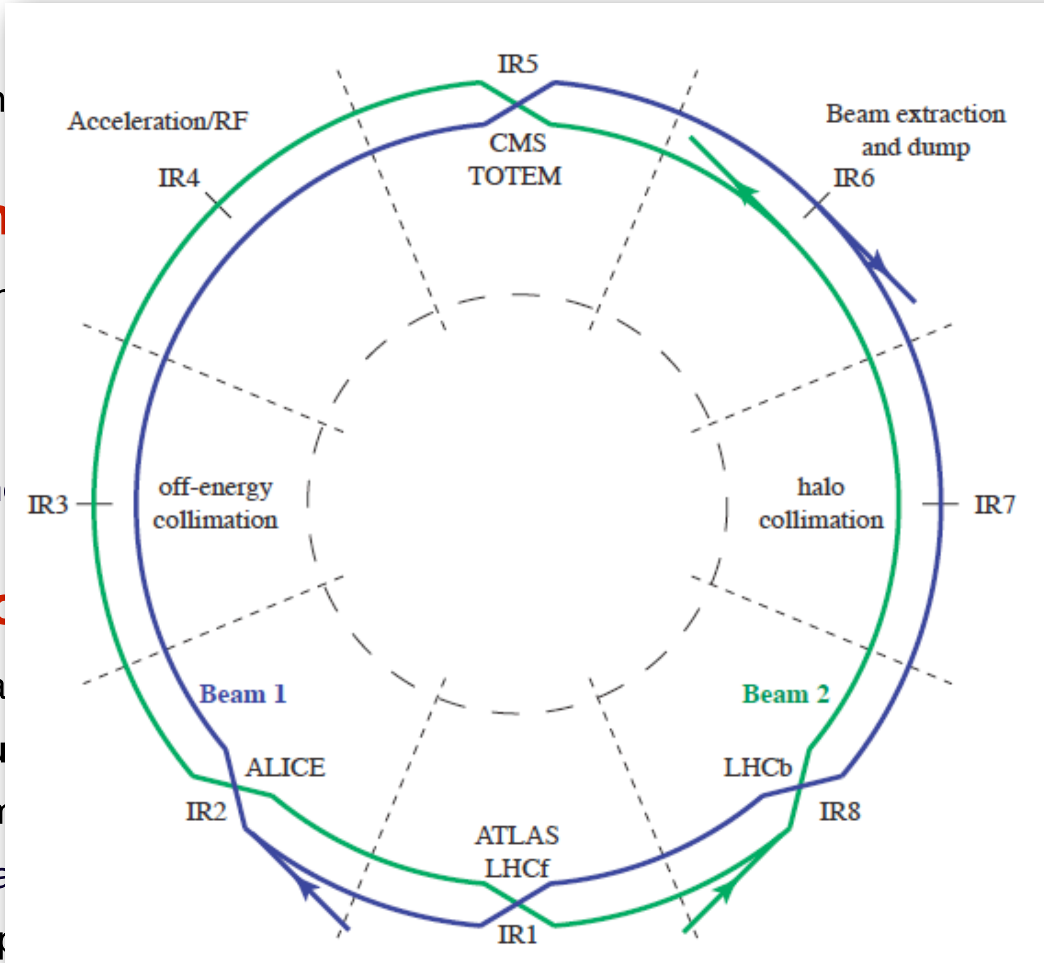
✦**Beam du**

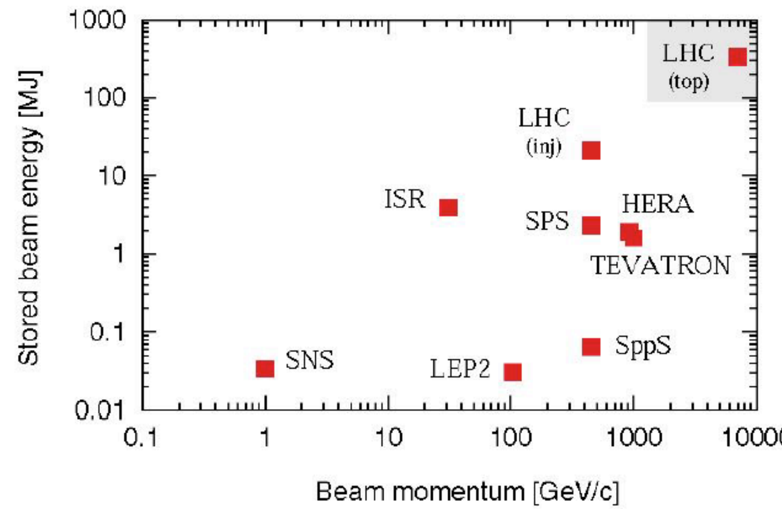
✦beam

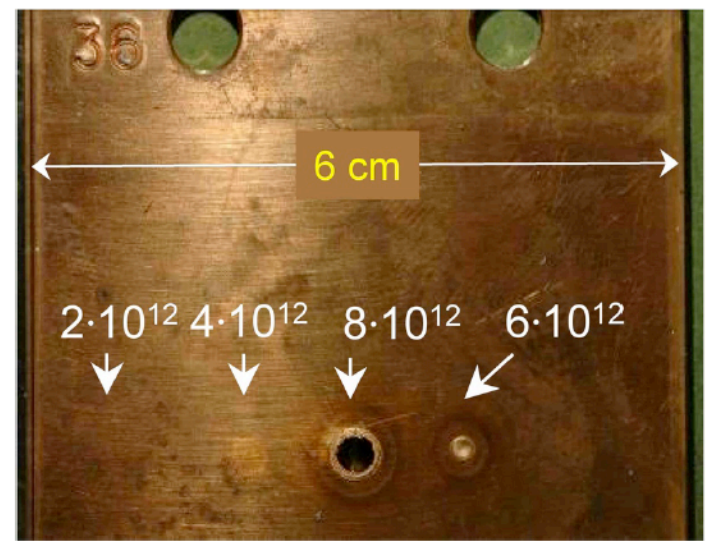
within a

✦The p

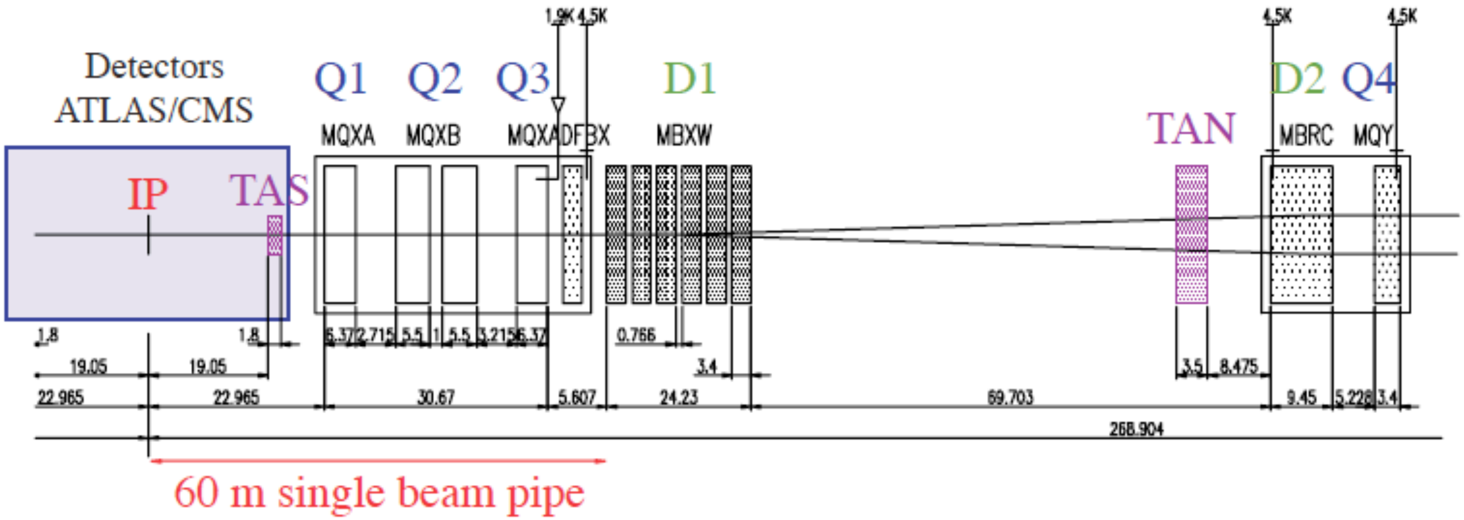
of point 6, ==> stopped in the ~8m long graphite core ==> surrounded by concrete and iron located at 700m downstream from point 6.







Interaction regions



✤ The two LHC beams share the same beam pipe over the first **+/-** 60 m from the interaction point**.**

✤ From the recombination magnet D2 on, the two beams travel in parallel, separated horizontally by 194 mm.

✤The strong superconducting quadrupoles Q1-Q3 focus the beams transversely to small beam sizes at the interaction points.

✤ The TAS (Target Absorber Secondaries) VS The TAN (Target Absorber Neutrals)

The final step after all these preparations, is to make the two beams colliding!

✤ Information from the collision rate that are being sent to the LHC control room are used to center the collisions for maximum luminosity.

Part II: Overview of the Operation of LHC during 2010 and 2011

On september 10, 2008 the LHC was started. The start-up was successful at first, with both beams making a full machine turn. Later however, commissioning was put on hold for a few days.

During this time it was decided to perform tests with a current of up to 9.3 kA through the dipole magnets in the last octant. At 8.7 kA an resistive zone developed in the dipole bus bar magnet interconnects. This resulted in a chain of events where the release of helium caused damage to magnets, interconnects and pollution of the ultra-high vacuum system.

Causes of damage:

- Abscence of solder
- Poor electrical contact
- Fault detection too insensitive
- Pressure relief ports under-dimensioned
- Anchorage of the magnets inadequate

Repairs:

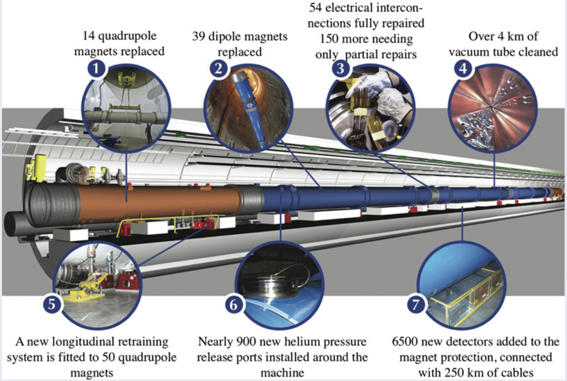


Fig. 17. Schematic of the main elements of the repair.

In 2009 measurements of the inter magnet splices where performed. However the measurement method had a precision of $\sim$3 times the resistance of a perfect slice. Consequently only splices with a significantly higher resistance could be identified and repaired.

Due to this it was suspected that several of the inter magnet splices had a higher resistance than required to run the LHC at maximum beam energy and it was decided to operate the LHC at a safe energy of 3.5 TeV per beam until 2013.

The first collision at $\sqrt{s} = 7$ TeV was made, on the third attempt, on March 30, 2010.

Table 4
Evolution of beam performance in 2010 (n_c is the number of bunches colliding). The main changes are highlighted with bold characters.

Event	E_b (TeV)	β* (m)	n_b	$N_{1,2}$	E_{tot} (MJ)	n_c	$L(cm^{-2}s^{-1})$	Date
1	3.5	10	2	1×10^{10}	0.01	1	8.9×10^{26}	30/03/2010
2	3.5	10	2	$\mathbf{2 \times 10^{10}}$	0.02	1	3.6×10^{27}	02/03/2010
3	3.5	**2**	2	2×10^{10}	0.02	1	1.8×10^{28}	10/04/2010
4	3.5	2	**4**	2×10^{10}	0.05	2	3.6×10^{28}	19/04/2010
5	3.5	2	**6**	2×10^{10}	0.07	4	7.1×10^{28}	15/05/2010
6	3.5	2	**13**	2.6×10^{10}	0.19	8	2.4×10^{29}	22/05/2010
7	3.5	**3.5**	**3**	$\mathbf{1.1 \times 10^{11}}$	0.19	2	6.1×10^{29}	26/06/2010
8	3.5	3.5	**6**	1.0×10^{11}	0.34	4	1.0×10^{30}	02/07/2010
9	3.5	3.5	**8**	9.0×10^{10}	0.41	6	1.2×10^{30}	12/07/2010
10	3.5	3.5	**13**	9.0×10^{10}	0.66	8	1.6×10^{30}	15/07/2010
11	3.5	3.5	**25**	1.0×10^{11}	1.41	16	4.1×10^{30}	30/07/2010
12	3.5	3.5	**48**	1.0×10^{11}	2.71	36	9.1×10^{30}	14/08/2010

Table 5
Performance evolution with bunch trains.

n_b	$N_{1,2}$	E_{tot} (MJ)	n_c	L (cm^{-2} s^{-1})	Pile up	Date
56	1.10×10^{11}	3.5	47	2.0×10^{31}	1.91	30/03/2010
104	1.10×10^{11}	6.5	93	3.5×10^{31}	1.80	25/09/2010
152	1.10×10^{11}	9.4	140	5.0×10^{31}	1.76	29/09/2010
204	1.10×10^{11}	12.7	186	7.0×10^{31}	1.83	04/10/2010
248	1.10×10^{11}	15.4	233	1.03×10^{32}	2.22	14/10/2010
312	1.10×10^{11}	19.4	295	1.50×10^{32}	2.57	16/10/2010
368	1.15×10^{11}	23.9	348	2.05×10^{32}	2.97	25/10/2010

$$L = \frac{N_1 N_2 n_b f_{rev}}{4\pi \sigma_x \sigma_y} \qquad \sigma(s) = \sqrt{\epsilon \beta(s)}$$

Table 6
Evolution of peak performance in 2011.

Fill number	Date	Bunch spacing	Number of bunches	Peak luminosity (10^{33} cm^{-2} s^{-1})	Total number of protons per beam (10^{14})
1635	18 March 2011	75	32	0.03	0.04
1637	19 March 2011	75	64	0.06	0.07
1644	22 March 2011	75	136	0.17	0.16
1645	22 March 20l1	75	200	0.25	0.24
1712	15 April 2011	50	228	0.24	0.29
1716	16 April 2011	50	336	0.35	0.42
1739	26 April 2011	50	480	0.51	0.58
1749	30 April 2011	50	624	0.72	0.76
1755	02 May2011	50	768	0.83	0.93
1809	27 May2011	50	912	1.10	1.15
1815	29 May2011	50	1092	1.27	1.33
1901	27 June 2011	50	1236	1.25	1.64
2032	18 August 2011	50	1380	2.40	1.68

$$L = \frac{N_1 N_2 n_b f_{rev}}{4\pi\sigma_x\sigma_y} \qquad \sigma(s) = \sqrt{\epsilon\beta(s)}$$

Planned shutdowns

- LS1 (2013): Consolidation of the inter-magnet splice connections to operate at 7 TeV beam energy and increase the peak luminosity four fold.
- LS2 (2018): Connection of the LINAC4 accelerator to the CERN PSB and consolidation of the LHC and its injector chain. This will double the peak luminosity further after the LS1 upgrade.

Further upgrades

- The LHC Injector Upgrade Project (LIU) to increase beam brightness
- The High Luminosity upgrade project (HL-LHC) to increase luminosity production (200-300 fb^{-1} per year)

Conclusions

In conclusion the LHC is a marvelous piece of machinery and even with some "minor" hiccups it has performed better than expected. Surely there is more exciting physics to follow after the 2013 and 2018 upgrade.