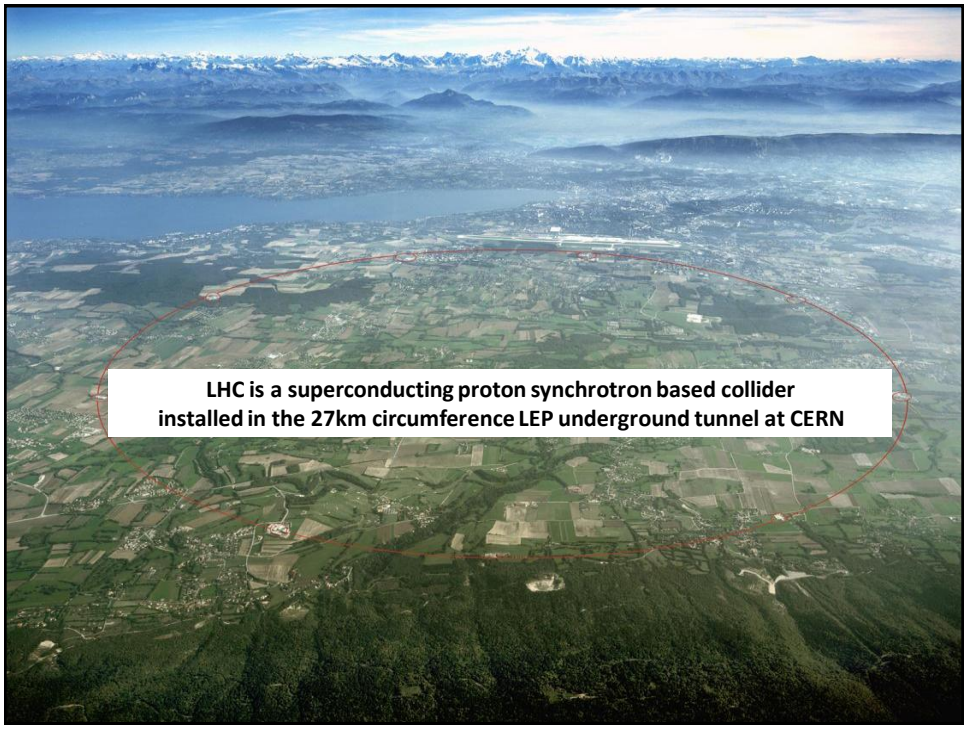
LHC

Overview – what is LHC ?

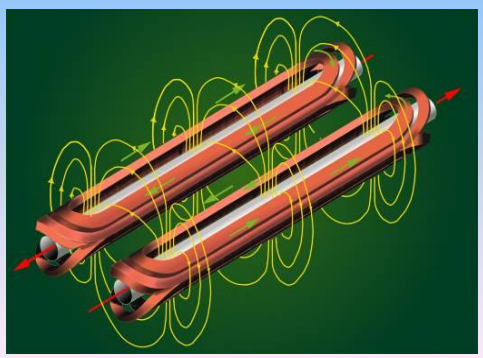
Construction and first commissioning

Beam commissioning



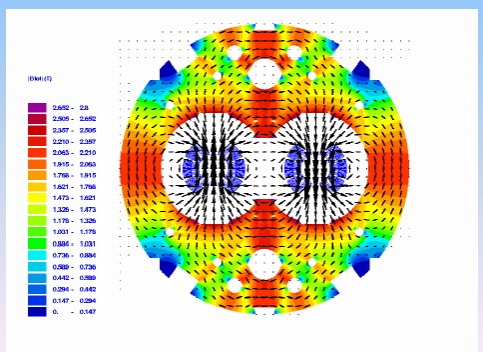
LHC basic design parameters

- Luminosity (defines rate of doing physics) 10^{34} cm^{-2} s^{-1}
  - Need lots of particles to achieve this rate
  - Hence proton – proton machine (unlike Tevatron or SppbarS)
  - Separate bending fields and vacuum chambers in the arcs



LHC basic design parameters

- Energy 7TeV per beam ⇔ Dipole field 8.33Tesla
  - Superconducting technology needed to get such high fields
  - Tunnel cross section (4m) excludes 2 separate rings (unlike RHIC)
  - Hence twin aperture magnets in the arcs



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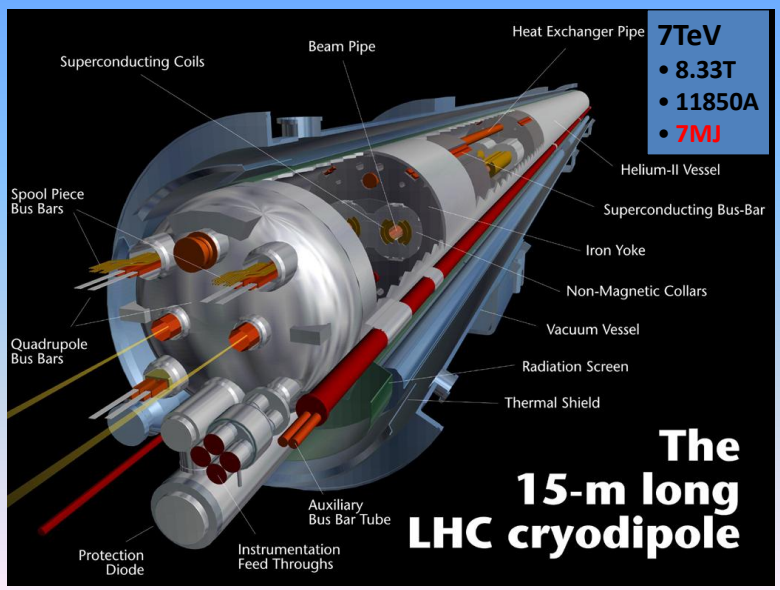
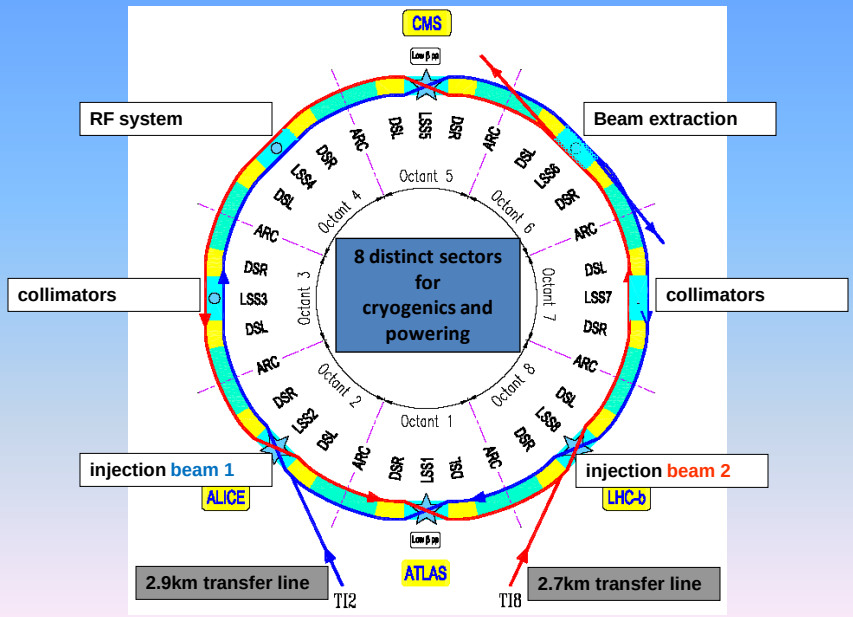
LHC dipoles (1232 of them) operating at 1.9K

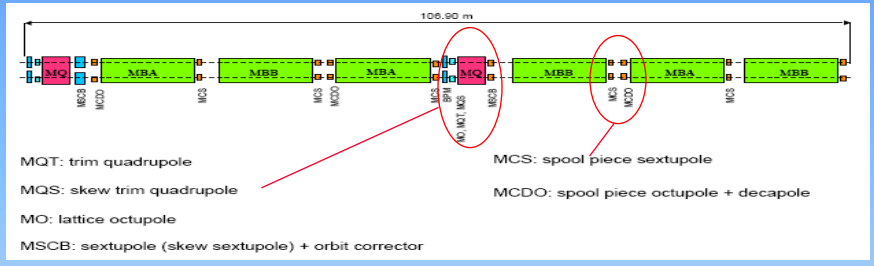


Cooled by liquid helium, distributed around 27km

Schematic of the LHC

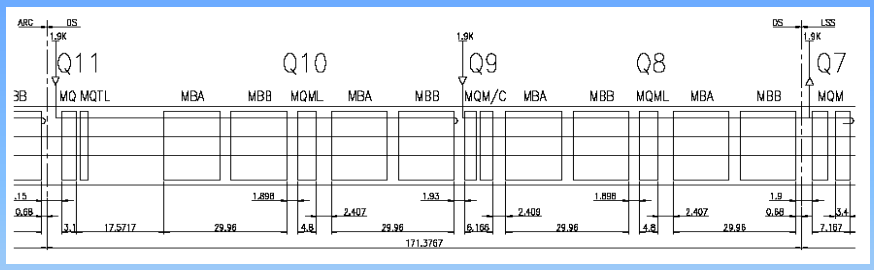


The arcs



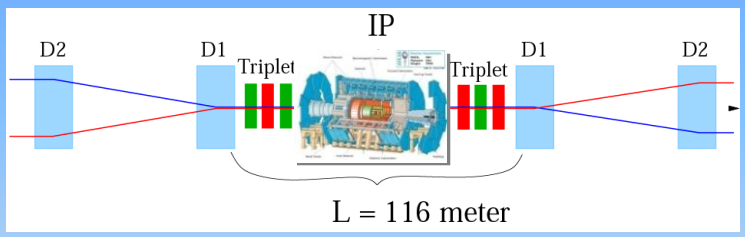
- 23 regular FODO cells in each arc
- 106.9m long, made from two 53.45m long half-cells
- Half cell
  - 3 15m cryodipole magnets, each with spool-piece correctors
  - 1 Short Straight Section (~6m long)
    - Quadrupole and lattice corrector magnets

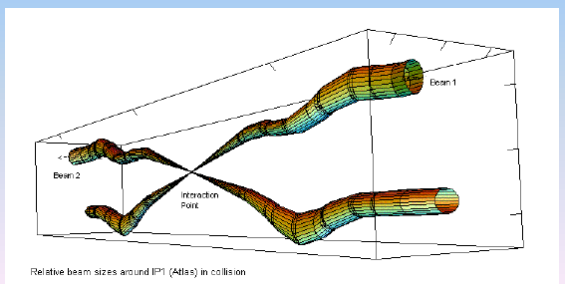
Dispersion suppressors



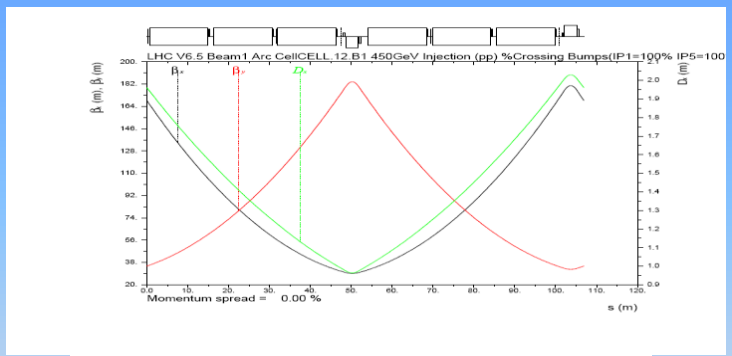
- Standard arc cells with missing dipole magnet and individually powered quadrupoles
- Threefold function
  - adapt the LHC reference orbit to the geometry of the LEP tunnel
  - cancel the horizontal dispersion arising in the arc and generated by the separation / recombination dipole magnets and the crossing angle bumps
  - help in matching the insertion optics to the periodic solution of the arc

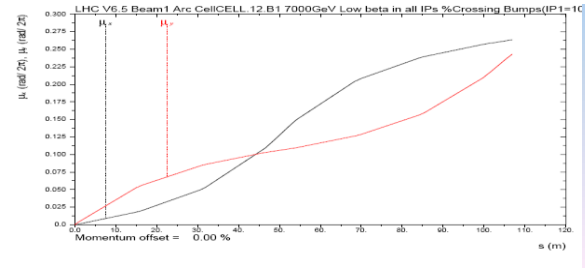
Insertion regions (points 1, 2, 5, 8)



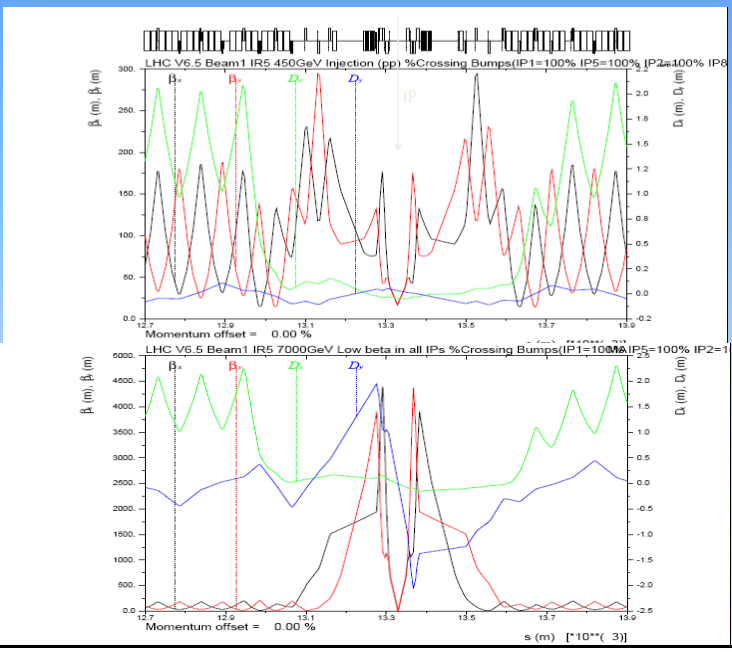


Optics in the arc cell



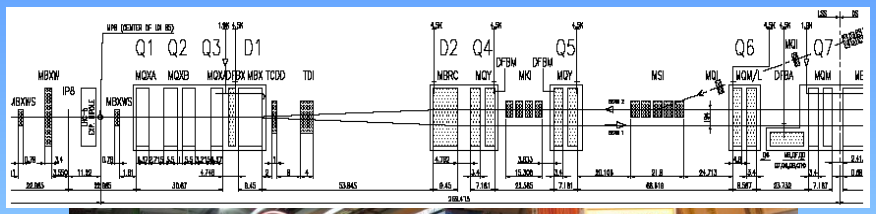


Optics in the high luminosity insertions

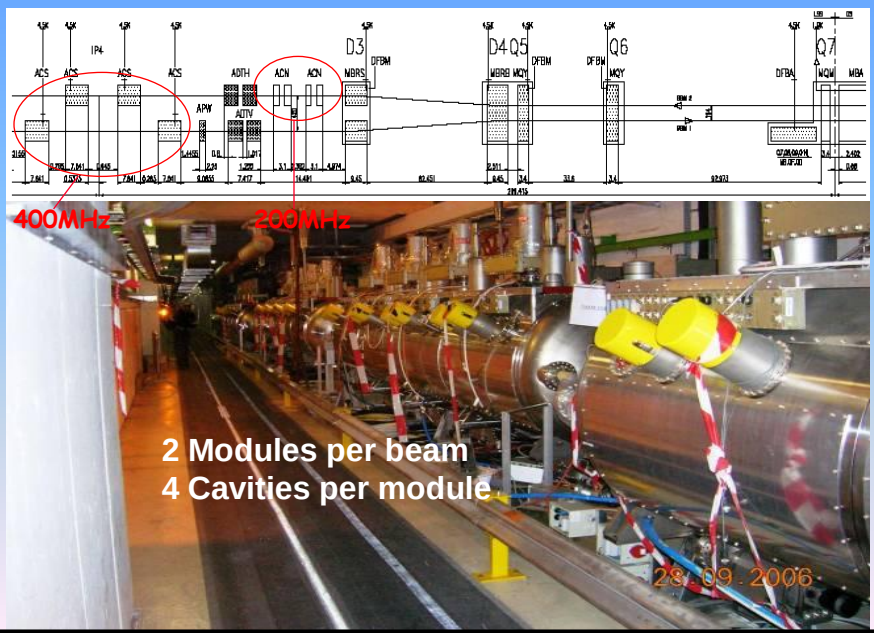


LHC arc

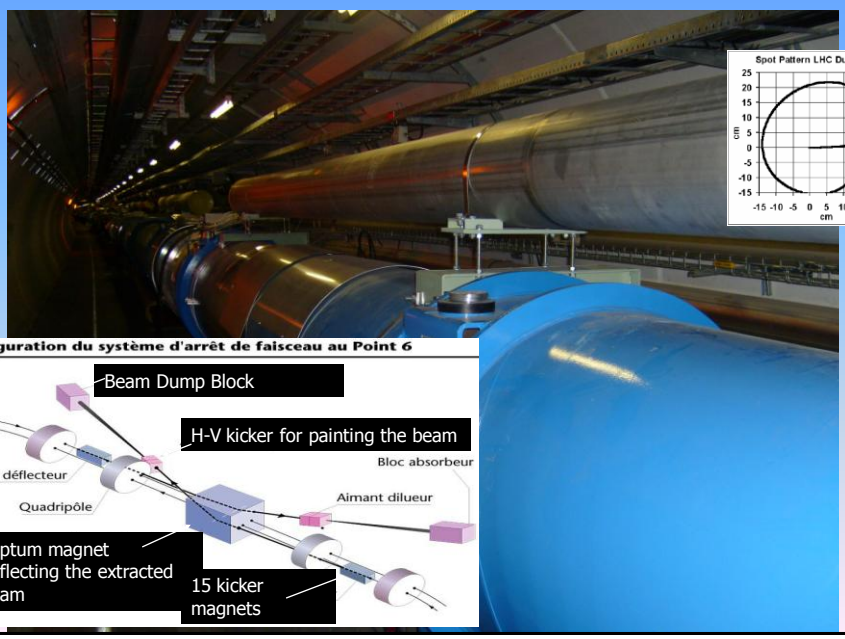
Injection systems (points 2 and 8)



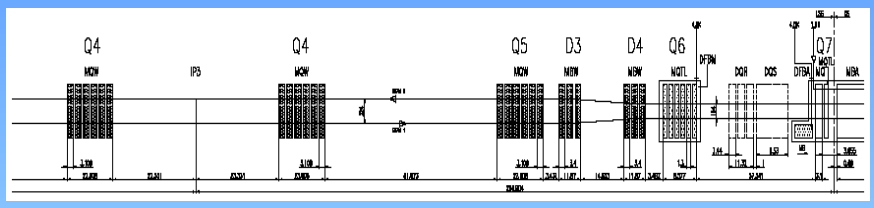
RF systems (point 4)

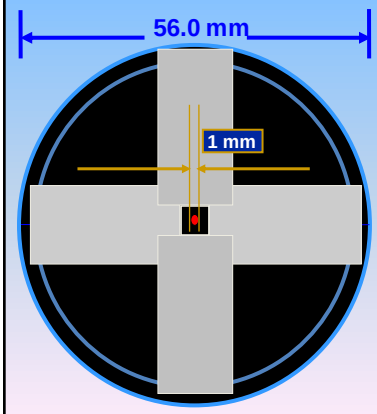


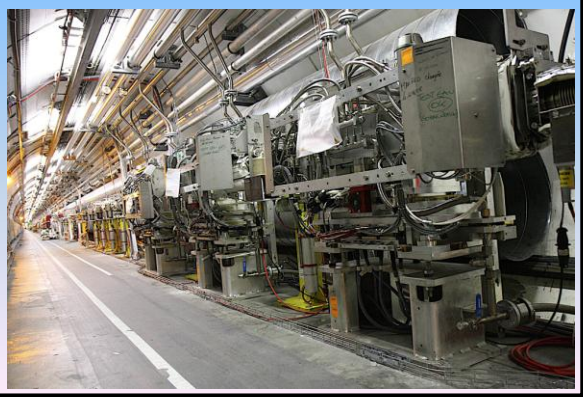
Beam extraction (point 6)



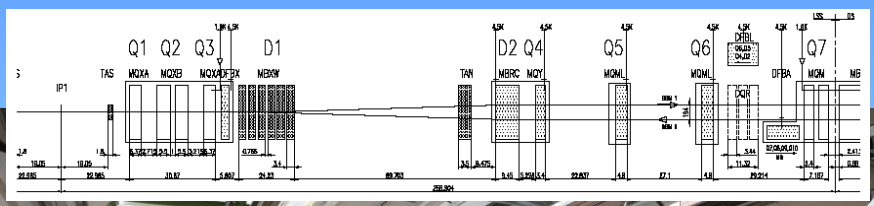
Collimators (points 3 and 7)



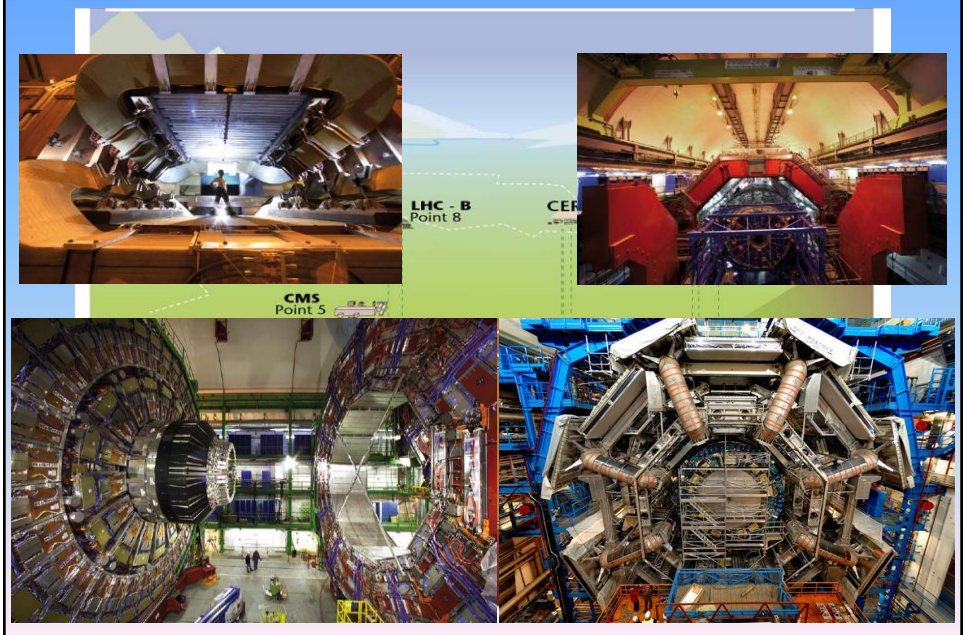




Triplets (points 1, 2, 5, 8)



Experiments (points 1, 2, 5, 8)



Luminosity

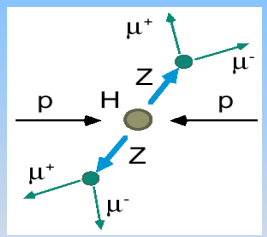
$$L = \frac{N^2 k_b f}{4\pi\sigma_x\sigma_y} F = \frac{N^2 k_b f\gamma}{4\pi\varepsilon_n\beta^*} F$$

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

$$\varepsilon_n = \varepsilon\gamma$$

"Thus, to achieve high luminosity, all one has to do is make (lots of) high population bunches of low emittance to collide at high frequency at locations where the beam optics provides as low values of the amplitude functions as possible." PDG 2005, chapter 25

- Nearly all the parameters are variable
  - Number of particles per bunch N
  - Number of bunches per beam k_b
  - Relativistic factor (E/m_0) γ
  - Normalised emittance ε_n
  - Beta function at the IP β^*
  - Crossing angle factor F
    - Full crossing angle θ_c
    - Bunch length σ_z
    - Transverse beam size at the IP σ^*



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

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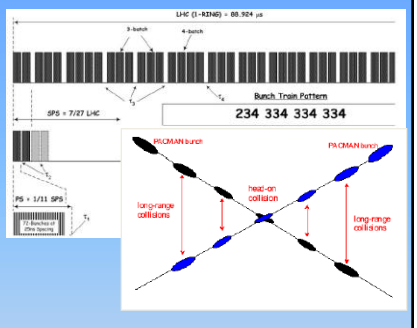
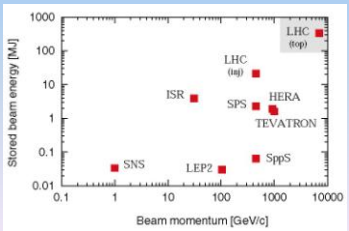
LHC nominal performance

Nominal settings	
Beam energy (TeV)	7.0
Number of particles per bunch	1.15 10^{11}
Number of bunches per beam	2808
Crossing angle (μrad)	285
Norm transverse emittance (μm rad)	3.75
Bunch length (cm)	7.55
Beta function at IP 1, 2, 5, 8 (m)	0.55,10,0.55,10

Derived parameters	
Luminosity in IP 1 & 5 (cm^{-2} s^{-1})	10^{34}
Luminosity in IP 2 & 8 (cm^{-2} s^{-1})*	~5 10^{32}
Transverse beam size at IP 1 & 5 (μm)	16.7
Transverse beam size at IP 2 & 8 (μm)	70.9
Stored energy per beam (MJ)	362

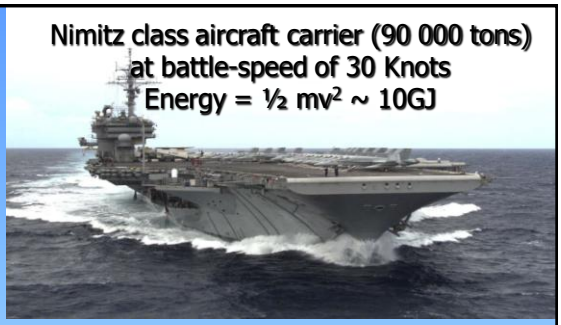
* Luminosity in IP 2 and 8 optimized as needed





So what is LHC ?

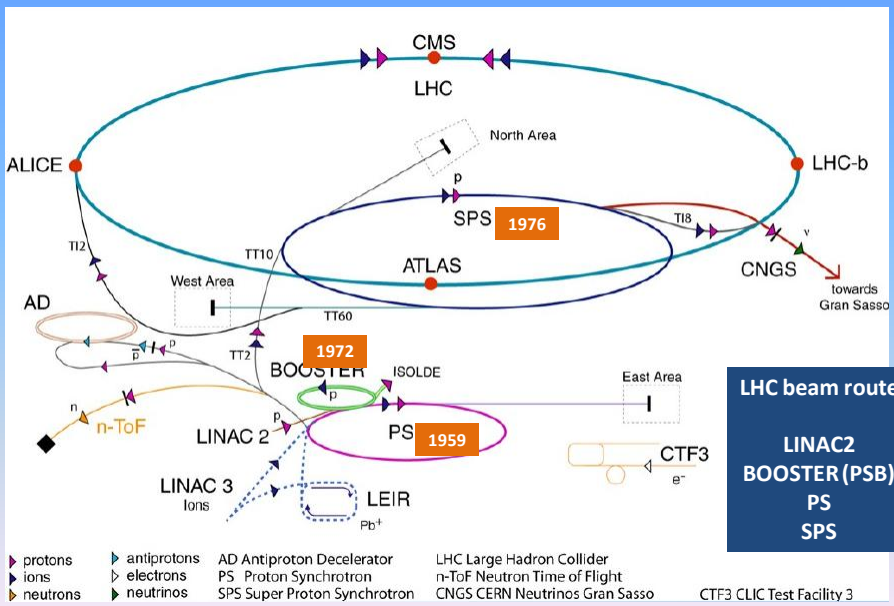
- Big
- Cold
- Complex
- Very powerful
  - Nominal performance
    - Energy stored in the magnets 10 GJ
    - Energy stored in each beam 362 MJ



Copper
Melting point 1356 K
Specific heat capacity 386 J kg^{-1} K^{-1}
Latent heat of fusion 205000 J kg^{-1}

So to heat and melt 1kg takes (1354*386+205000) J
--- or ---
362MJ would heat and melt half a tonne of copper

CERN accelerator complex



LHC beam route

LINAC2
BOOSTER (PSB)
PS
SPS

Injector chain

- The present accelerators are getting old (PS is 50 years old…) and they operate far beyond their initial design parameters
- Luminosity depends directly upon beam brightness N/ε^*

$$L \propto \frac{1}{\beta^*}\frac{N_b}{\varepsilon_{X,Y}} \cdot N_b \cdot k_b$$

N_b : number of protons/bunch
$\varepsilon_{X,Y}$: normalized transverse emittances
k_b : number of bunches per ring

- Brightness is limited by space charge at low energy in the injectors

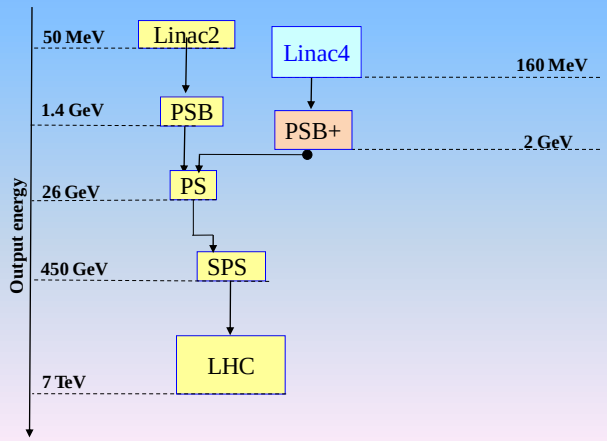
$$\Delta Q_{SC} \propto \frac{N_b}{\varepsilon_{X,Y}} \cdot \frac{R}{\beta\gamma^2}$$

N_b : number of protons/bunch
$\varepsilon_{X,Y}$: normalized transverse emittances
R : mean radius of the accelerator
$\beta\gamma$: classical relativistic parameters

⇒ Need to increase the injection energy in the injection synchrotrons

Strategy for injector chain upgrade

- Replace Linac 2 with Linac 4
- Consolidate all machines
- Upgrade PSB energy to 2 GeV (PSB+)



LHC

Overview – what is LHC ?

Construction and first commissioning

Beam commissioning

LHC and LEP timeline

Same tunnel !

1982 : First studies for the LHC project

← 1984 : Start of LEP construction

← 1989 : Start of LEP operation

1994 : Approval of the LHC by the CERN Council

← 1995 : Start of LHC experiment civil engineering

1996 : Final decision to start the LHC construction *(7TeV machine)*

← 2000 : End of LEP operation

2002 : Start of the LHC construction

2006 : Start of hardware commissioning

2007 : End of installation and start of cool-down

2008 : First beam commissioning

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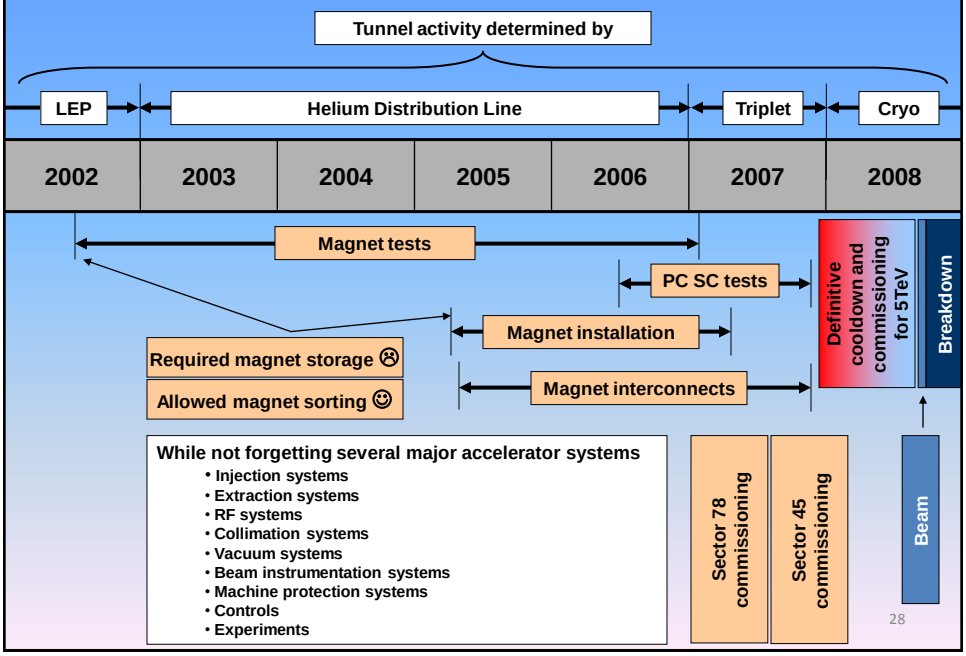
Construction and commissioning 2002-2008



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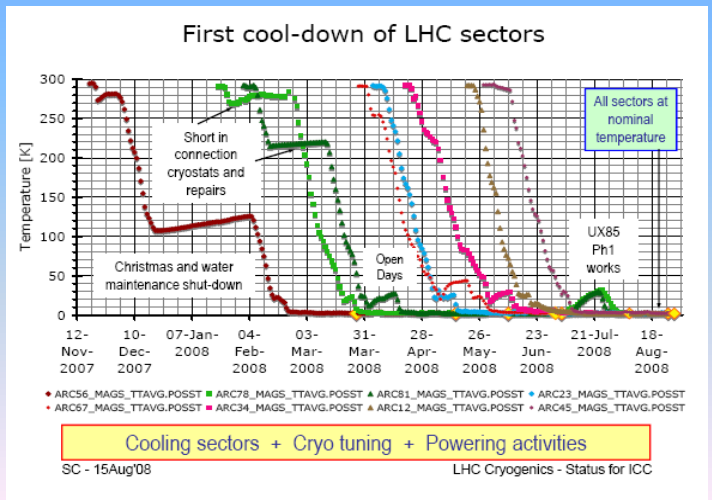
Definitive cool down 2008

- Sector by sector
- Quickest took 6 weeks



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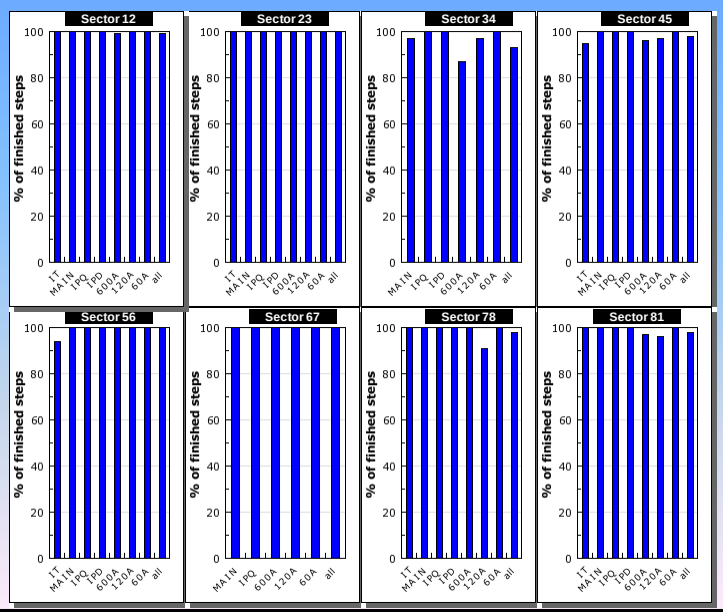
Commissioning of the electrical circuits for 5TeV



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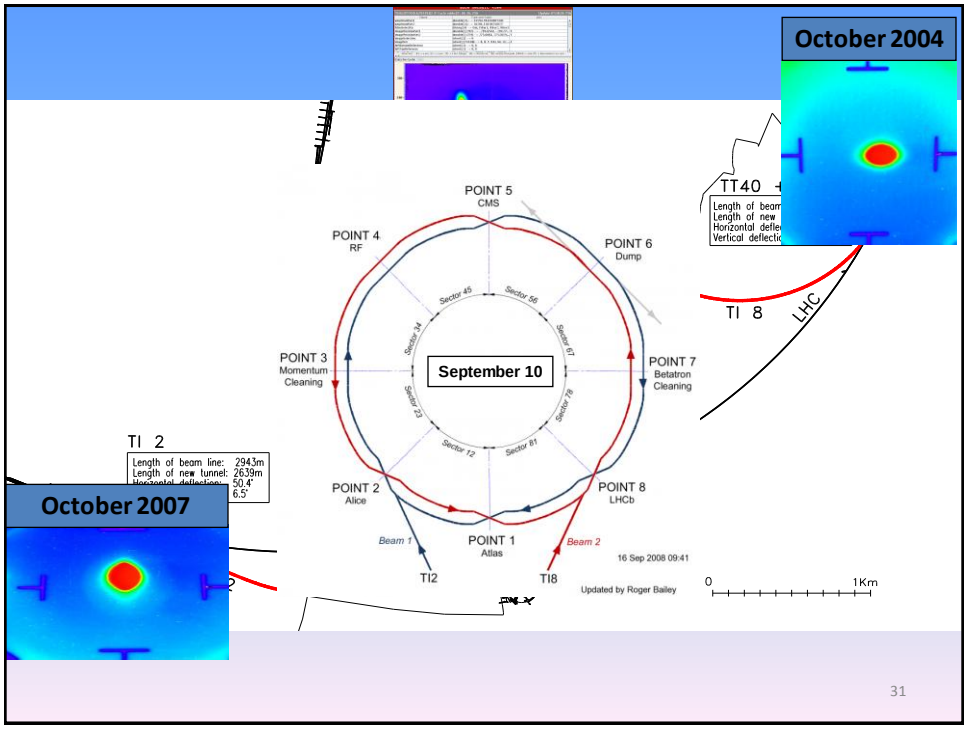

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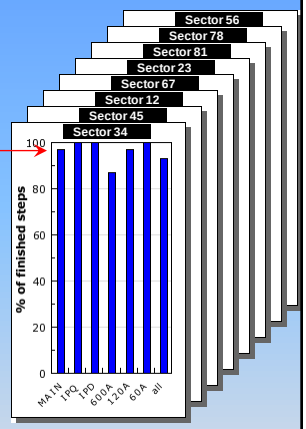
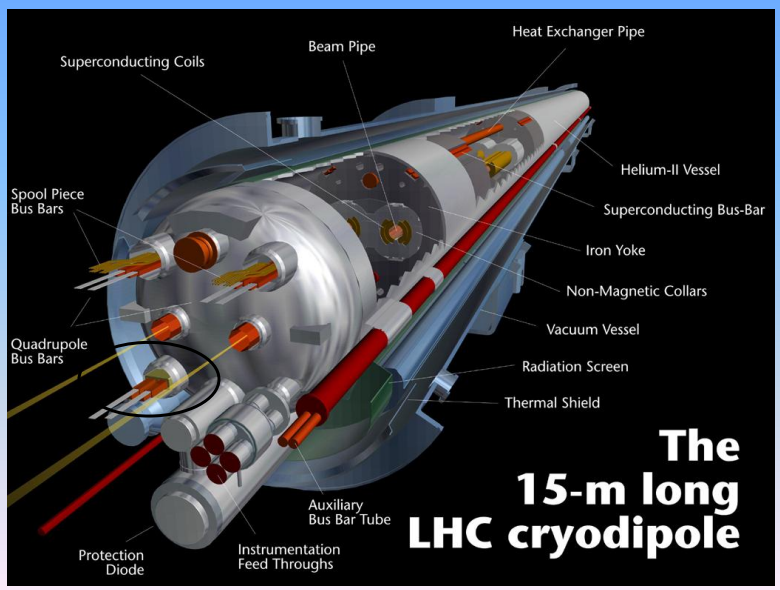
Incident of September 19th 2008

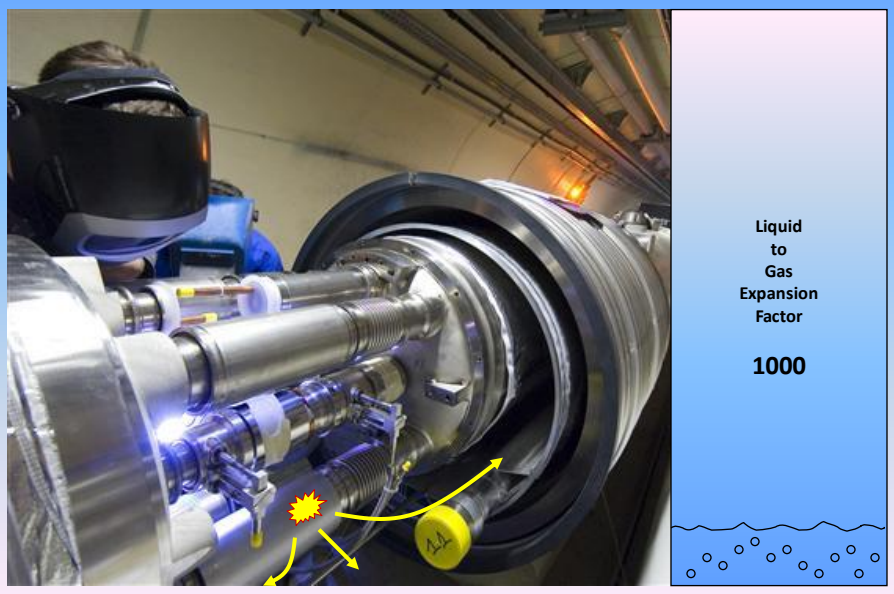
- During a few days period without beam while recovering from transformer failure
- Making the last step of the dipole circuit in sector 34, to 9.3kA
- At 8.7kA, development of resistive zone in the dipole bus bar splice between Q24 R3 and the neighbouring dipole
  - Later estimated (from cryogenic data on heat deposition) to be 220nΩ
- Electrical arc developed which punctured the helium enclosure, allowing helium release into the insulating vacuum
- Large pressure wave travelled along the accelerator in both directions



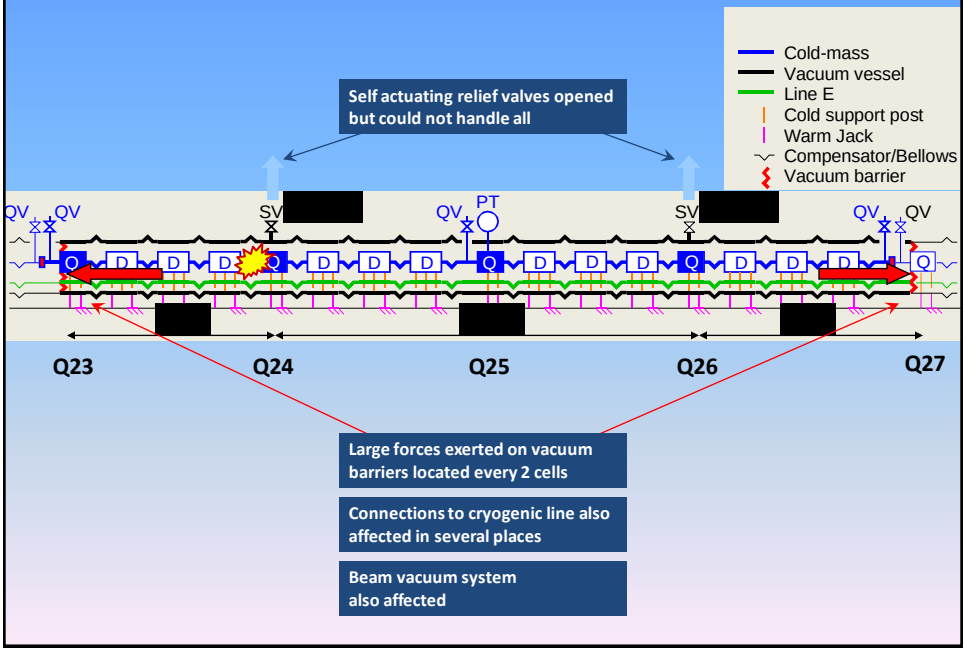
Development of resistive zone in dipole bus bar splice



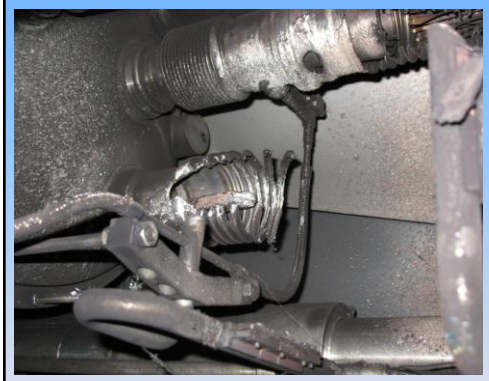
Arc and helium released into the insulating vacuum



Large pressure wave travelled along the accelerator



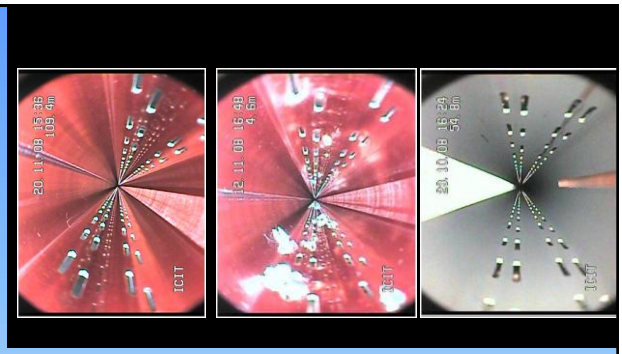
Multi kA electrical arc



Consequences – Magnets displaced

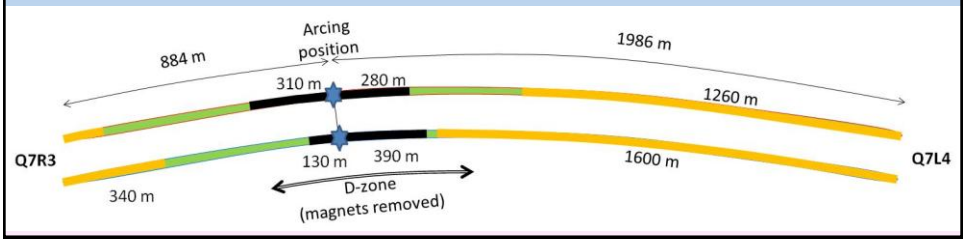
Consequences – Magnets displaced

Beam vacuum

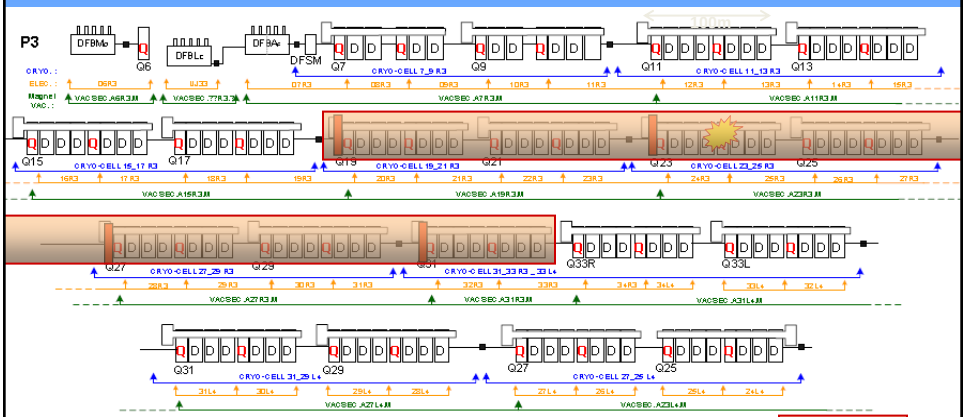


Ok
Debris
MLI
Soot

LSS3 LSS4



Repair



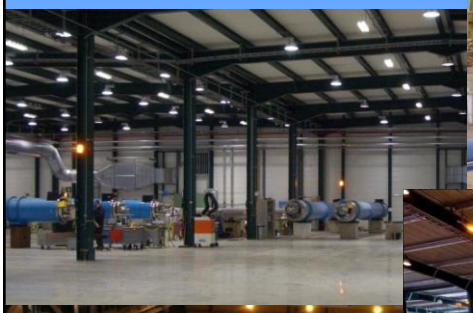
- Had to treat to lesser or greater degree all magnets Q19 to Q33 as shown
- 53 had to be brought to the surface (39 dipoles and 14 quads)
- Replaced with spare or refitted, then retested and reinstalled
- Huge enterprise; last magnet back in mid April 2009
- Not forgetting cleaning the beam pipes
- Then have to align, make all interconnections, cool down, power test

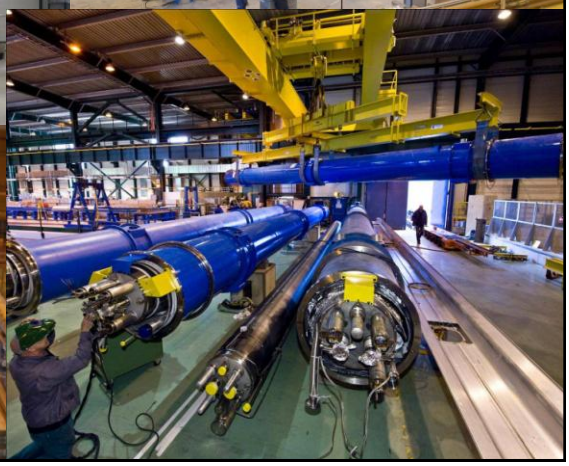
Magnet removal

Special tooling needed for safe transport of damaged magnets

Underground logistics tricky at best

Surface activities





Preventing recurrence

Sector 34 repair | Restart

Q4 2008	Q1 2009	Q2 2009	Q3 2009	Q4 2009

- Electrical measurements everywhere at cold (measuring nΩ)
  - Had to warm up sectors 12 56 67

Superconducting splices limit operation to 5 TeV

- Electrical measurements everywhere at warm or at 80K (measuring μΩ)
  - Had to warm up sector 45

Copper stabilizers limit operation to 3.5 TeV

- Major new protection system based on electrical measurements
- Pressure relief valves installed everywhere
- Reinforcement of floor anchors everywhere

	Q4 2008	Q1 2009	Q2 2009	Q3 2009	Q4 2009
12	Cold	Cold → Warm	Warm	Warm → Cold	Cold
23	< 100K	< 100K	< 100K → Cold	Cold → 80K → Cold	Cold
34	Warm	Warm	Warm	Warm → Cold	Cold
45	< 100K	< 100K	< 100K → Warm	Warm → Cold	Cold
56	Cold	Cold → Warm	Warm	Warm → Cold	Cold
67	Cold	Cold → Warm	Warm	Warm → Cold	Cold
78	Cold	< 100K	< 100K → 80K	80K → Cold	Cold
81	Cold	< 100K	< 100K → 80K	80K → Cold	Cold

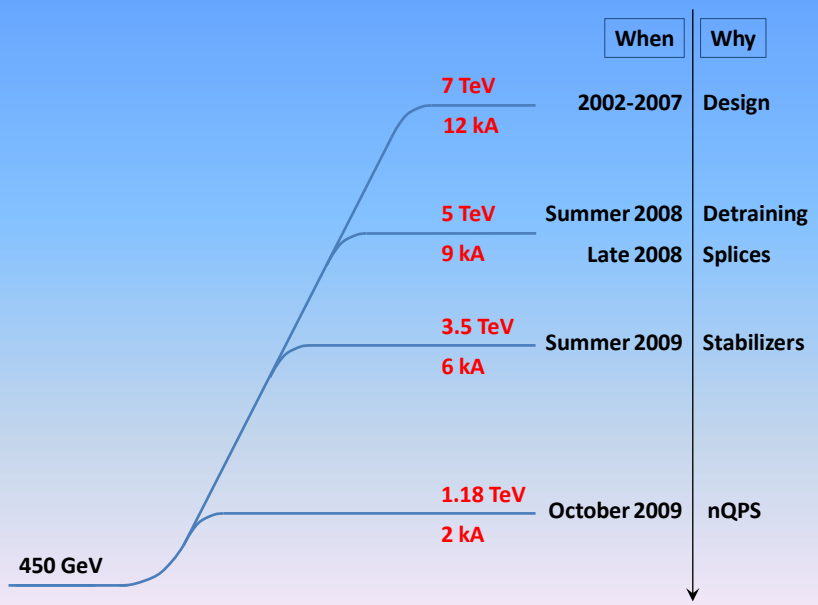
LHC

Overview – what is LHC ?

Construction and first commissioning

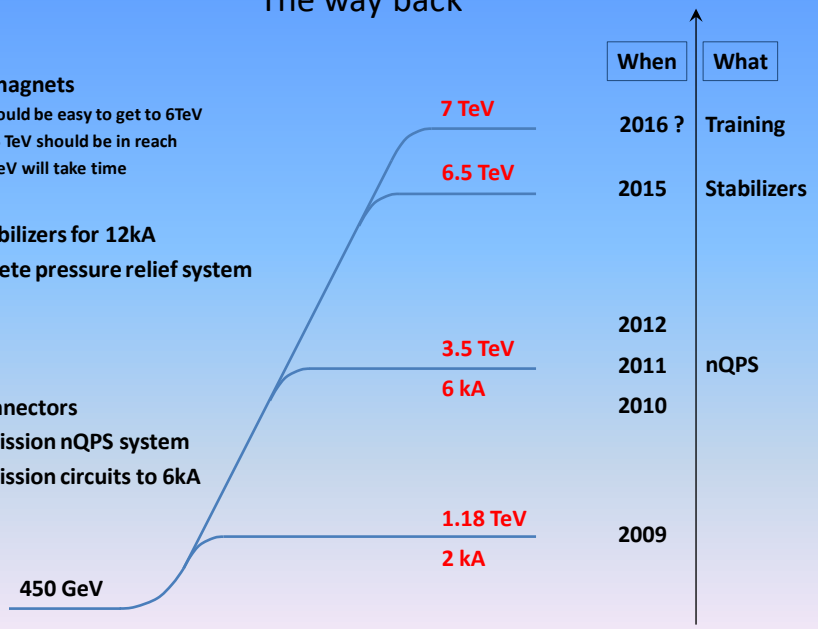
Beam commissioning

Evolution of target energy



The way back

- Train magnets
  - Should be easy to get to 6TeV
  - 6.5 TeV should be in reach
  - 7 TeV will take time
- Fix stabilizers for 12kA
- Complete pressure relief system
- Fix connectors
- Commission nQPS system
- Commission circuits to 6kA

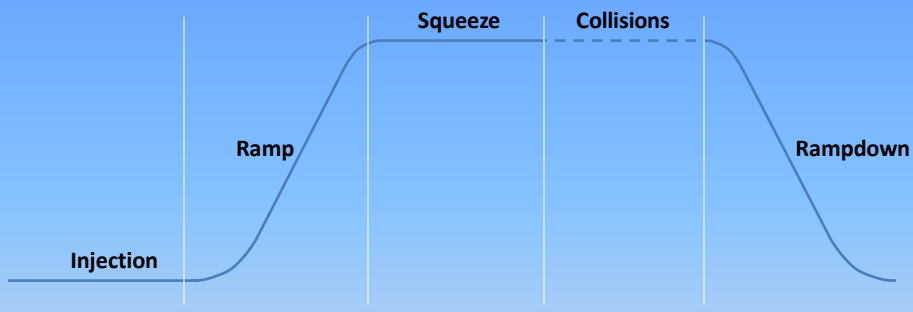


Commissioning strategy

- At whatever energy
  - Correct everything we can with safe beams
  - Then establish references
  - Then set up protection devices (injection, collimators, beam dump)
  - Then increase intensity incrementally
    - Low bunch currents, increase k_b
    - Increase bunch current
    - Higher bunch current, low k_b, same total current
    - Higher bunch currents, increase k_b
    - Once k_b > 50 or so, need bunch trains
  - **At each stage, re-qualify machine protection systems**

Some numbers			
What	**Limit**		**Comment**
Pilot	**Single bunch of 5 10^9 protons**		**Quench limit**
Safe beam	**10^{12} protons at 450 GeV**		**Damage limit**
	Energy	**Safe beam**	**Scales with $1/E^{1.7}$**
	0.45	**1.00E+12**	
	1.18	**1.94E+11**	
	3.5	**3.06E+10**	
	7	**9.41E+09**	

The operational cycle



Injection	Ramp	Squeeze	Collisions	Rampdown
Many schemes Injection channel	Dynamic effects Feedbacks	Optics Collimators	Beam steering Beam-beam	Ramp rates Reproducibility

All through the cycle

Beam dump
Collimations system
Protection devices

Early beam operation

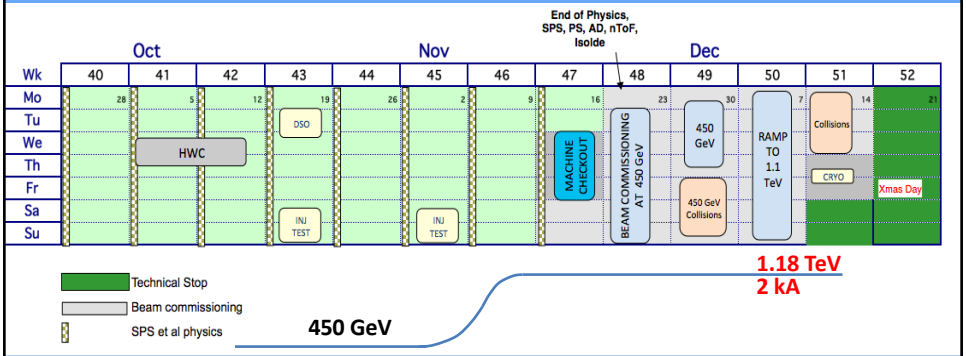
2009			2010			2011			2012
Repair of Sector 34	1.18 TeV	nQPS 6kA	3.5 TeV $I_{safe} < I < 0.2\ I_{nom}$ $\beta^* > 2$ m	Ions		3.5 TeV $< 0.5\ I_{nom}$ β^* 1.5 m	Ions		3.5 TeV $< I_{nom}$ β^* 1.5 m
No Beam	B		Beam			Beam			Beam

- 2009
  - Energy limited to 1.18 TeV
- 2010
  - Energy limited to 3.5 TeV
  - Intensity carefully increased to collimation limit
  - β^* not too low to provide margins
  - Target luminosity 10^{32} cm^{-2}s^{-1}
- 2011
  - Energy limited to 3.5 TeV
  - Push the intensity to 50% nominal
  - β^* pushed as low as possible
  - Target luminosity 10^{33} cm^{-2}s^{-1}
  - Target integrated luminosity > 1 fb^{-1}

40% efficiency for physics → 10^6 seconds collisions per month

10^6 seconds @ <L> of 10^{33} cm^{-2} s^{-1} → 1 fb^{-1}

2009



AIMS

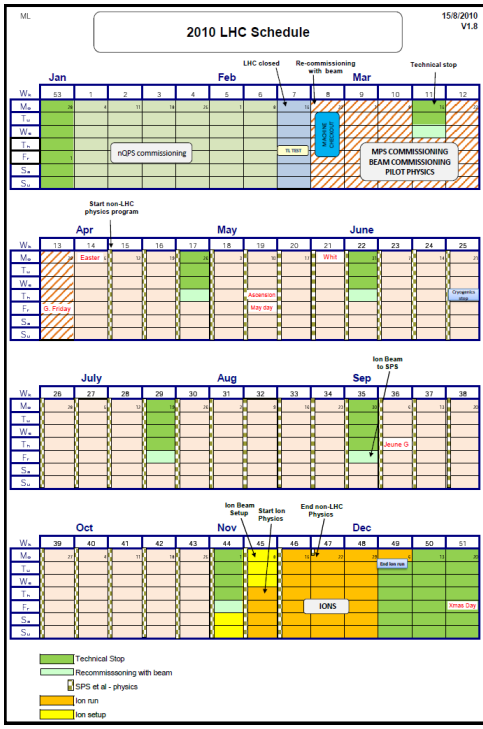
450 GeV collisions
10^6 events

Ramp to 1.18 TeV
Collisions at 1.18 TeV

Do this with SAFE BEAMS

10^{12} at 450 GeV → 2 10^{11} at 1.18 TeV

LIMITS
2 on 2 with 5 10^{10} per bunch at 1.18 TeV
4 on 4 with 2 10^{10} per bunch at 1.18 TeV



2010

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

Bunch trains on crossing angles, 150 ns
Increase k_b
Machine protection systems qualified
368 on 368 high intensity bunches at 3.5m
20 MJ stored energy per beam

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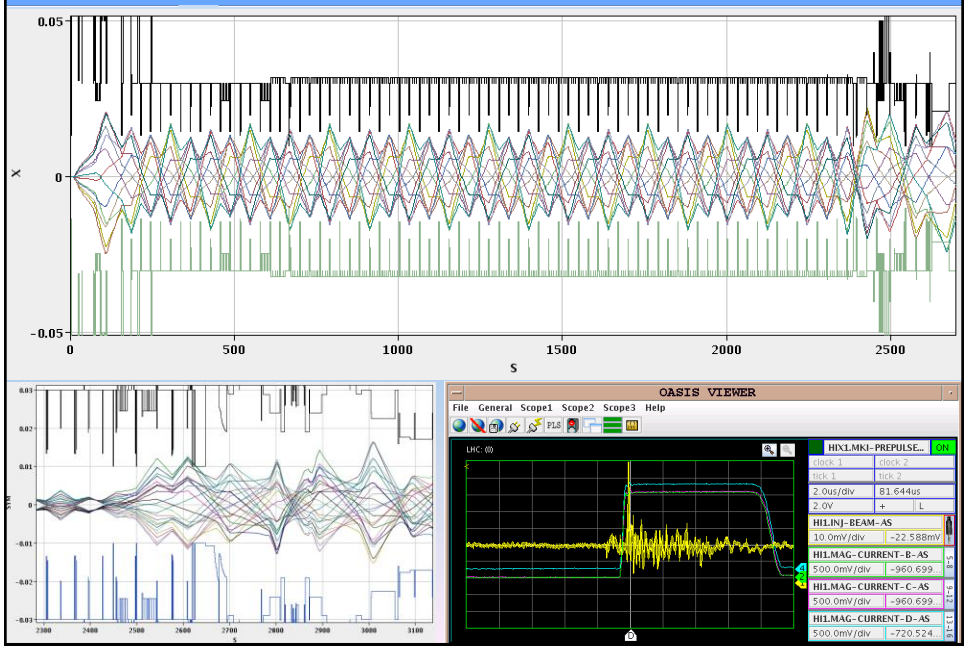
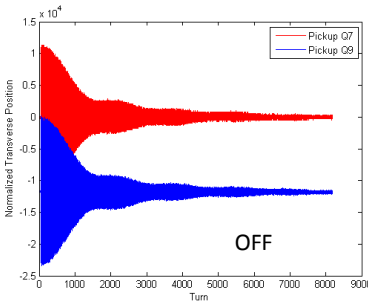
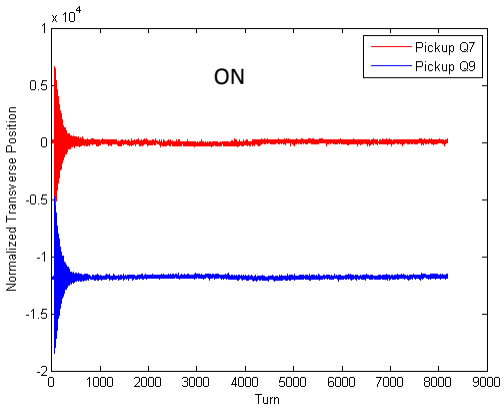
2010 - Beam transfer and Injection



2010 - Injection oscillations

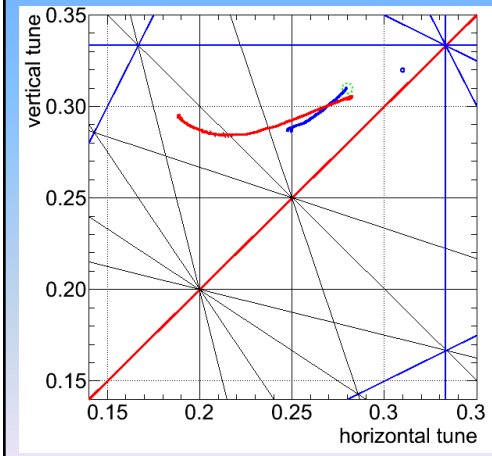


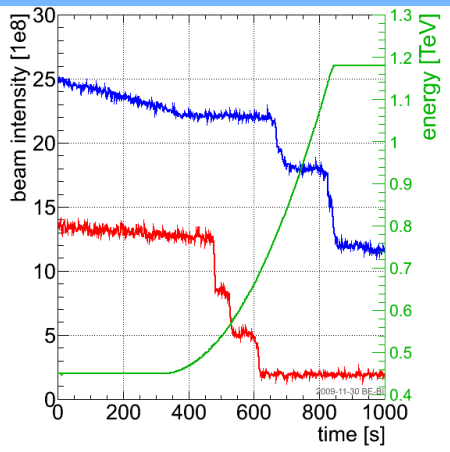


Transverse damper - Crucial device to keep emittance growth under control!

2010 - Ramp - Tunes

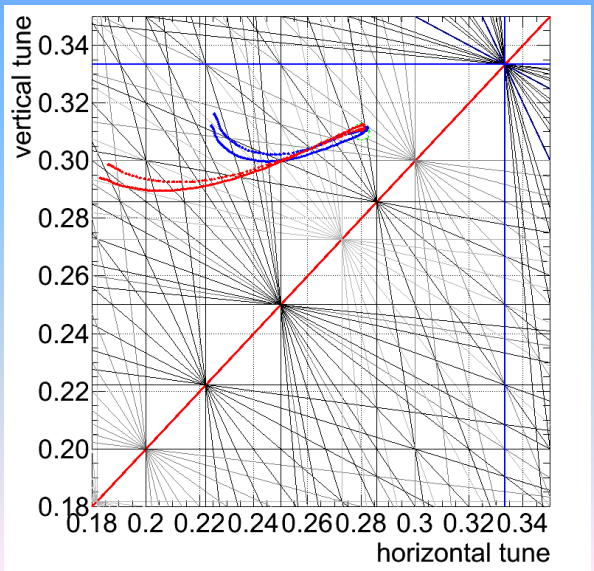
Tune excursions during the ramp → Losses on resonances



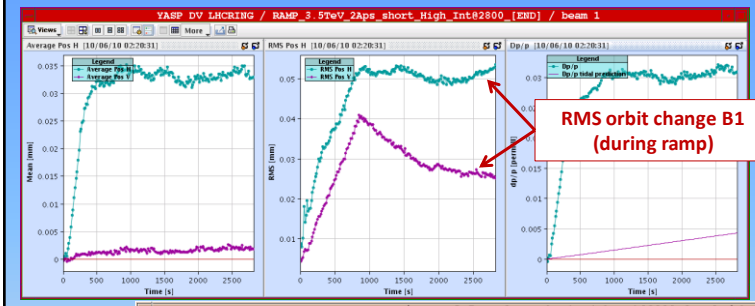


2010 - Ramp – Tune feedback

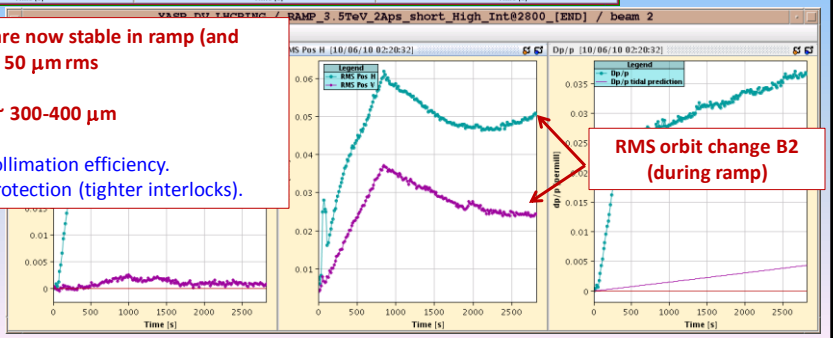
Feedback employed early. Reconstructed tune excursions



2010 - Ramp - Orbit feedback



RMS orbit change B1 (during ramp)



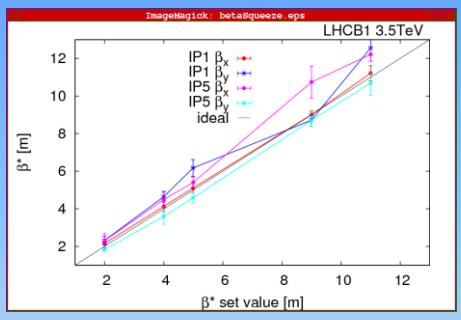
RMS orbit change B2 (during ramp)

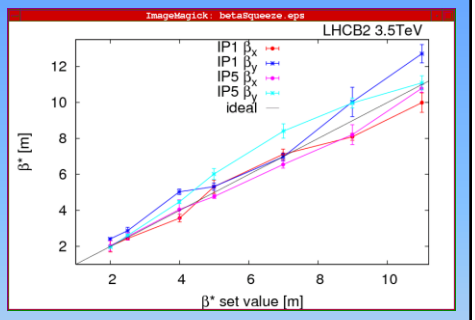
The orbits are now stable in ramp (and squeeze) to 50 µm rms

Previously ~ 300-400 µm

>> Better collimation efficiency.
>> Better protection (tighter interlocks).

2010 - Squeeze in points 1 and 5



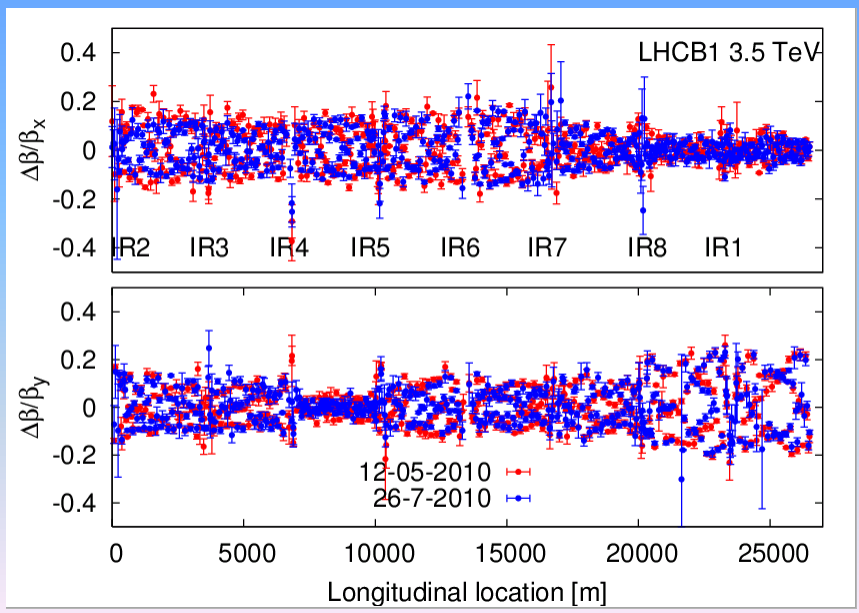


Measured β^*s at 3.5m

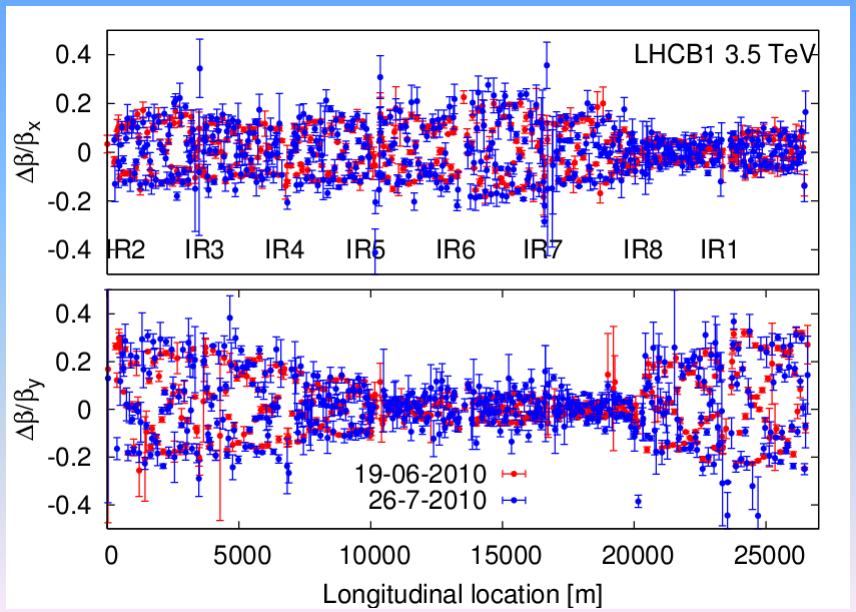
	Beam 1		Beam 2	
IP	β_x^*	β_y^*	β_x^*	β_y^*
IP1	3.27±0.01	3.8±0.3	3.5±0.2	3.8±0.4
IP2	3.45±0.09	2.6±0.2	3.3±0.3	4.2±0.1
IP5	3.70±2	3.4±0.3	3.7±0.4	3.9±0.4
IP8	3.42±0.14	3.9±0.7	3.6±0.2	3.1±0.5

Important mismatch in IP2 β_y

2010 - Beta-beat B1 on flat top (10/11 m) - reproducible



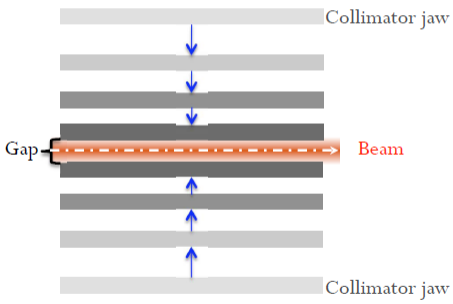
2010 - Beta-beat B1 at 3.5 m - reproducible



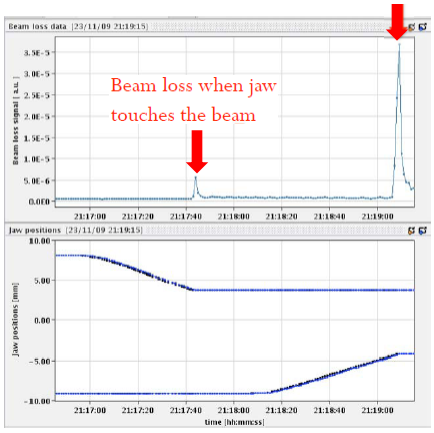
2010 - Collimation system commissioning

Collimation system is for beam cleaning and passive protection
Each collimator has to be positioned using beam based alignment

Beam based alignment:

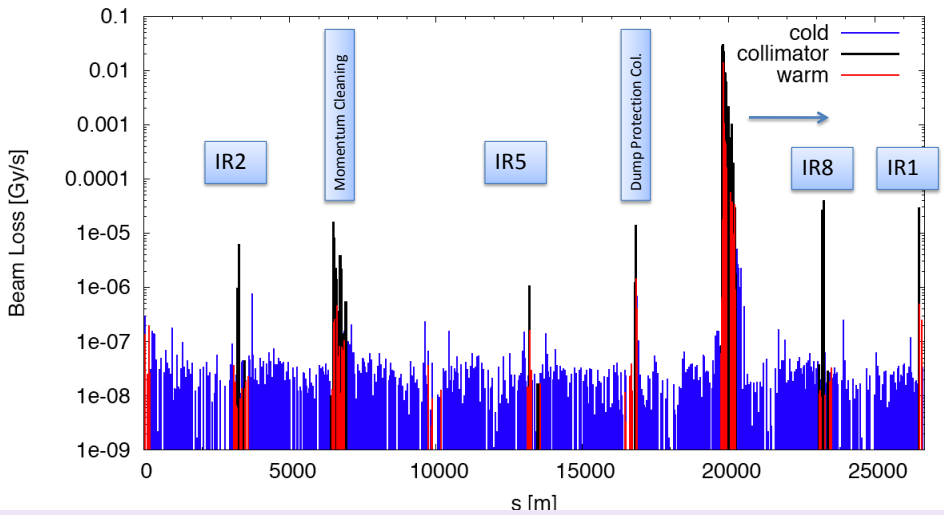


Gap => Beam centre
Beam size => Nominal settings

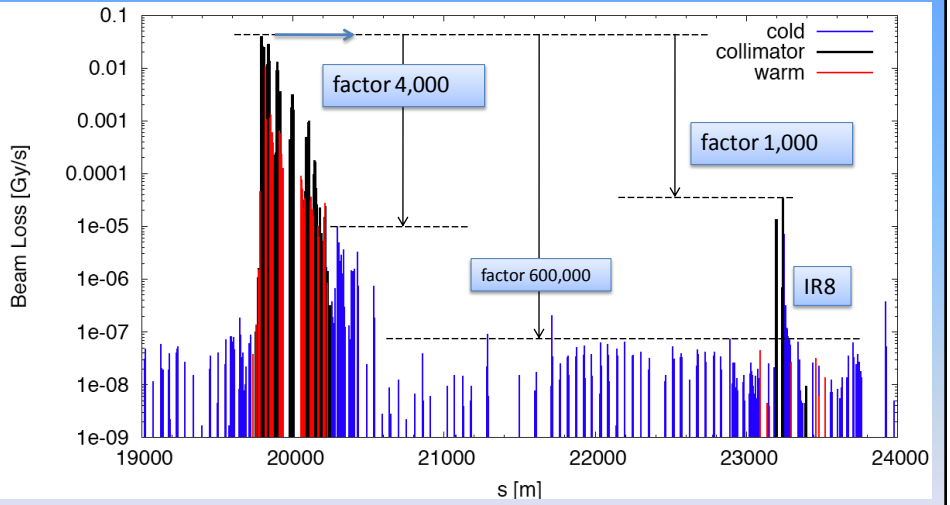


2010 - Collimation system efficiency

Provoked vertical beam loss on beam 1, 2m optics

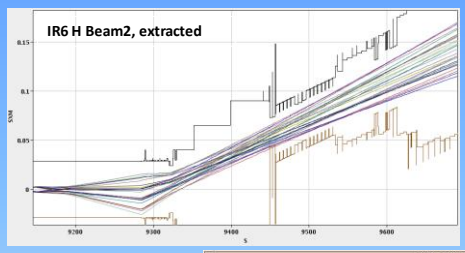


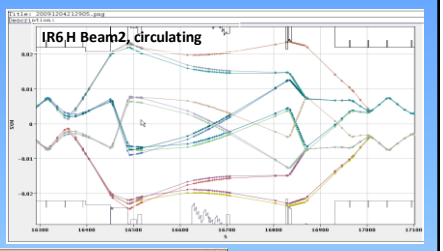
2010 - Zoom around betatron cleaning

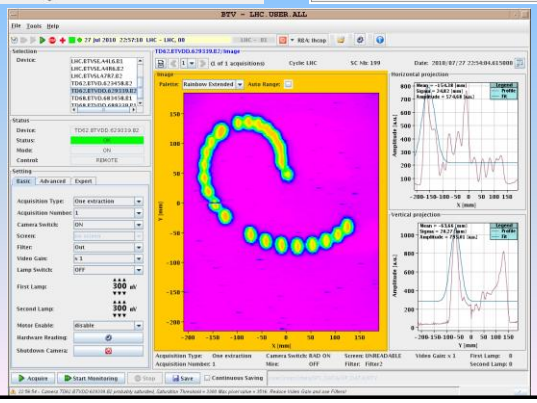


➔ **OK for stable beams from collimation**

2010 - Beam dump

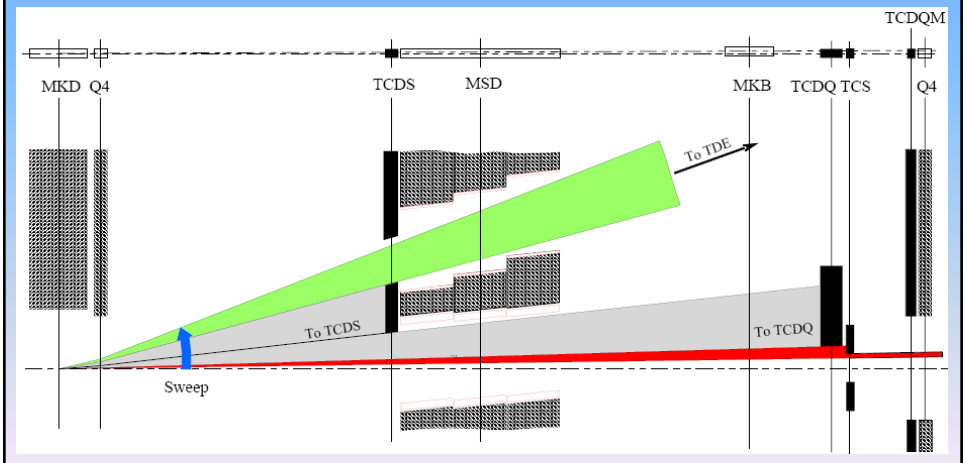






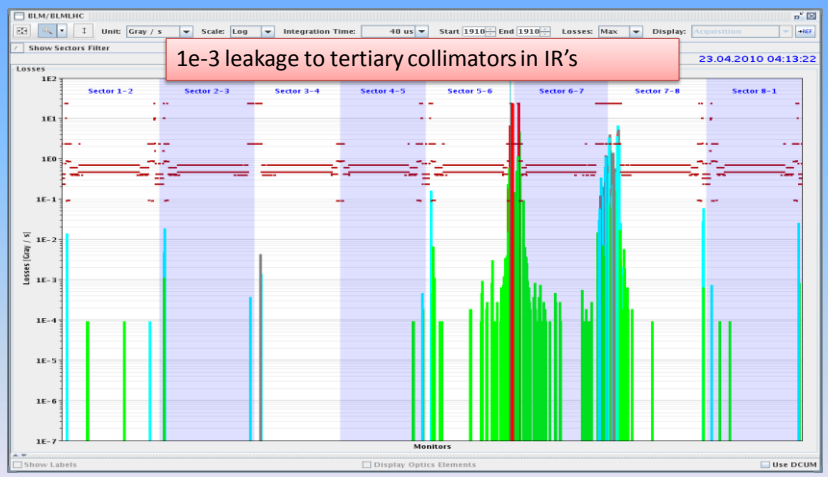
2010 - Beam dump protection systems

Protection devices to catch beam in abort gap



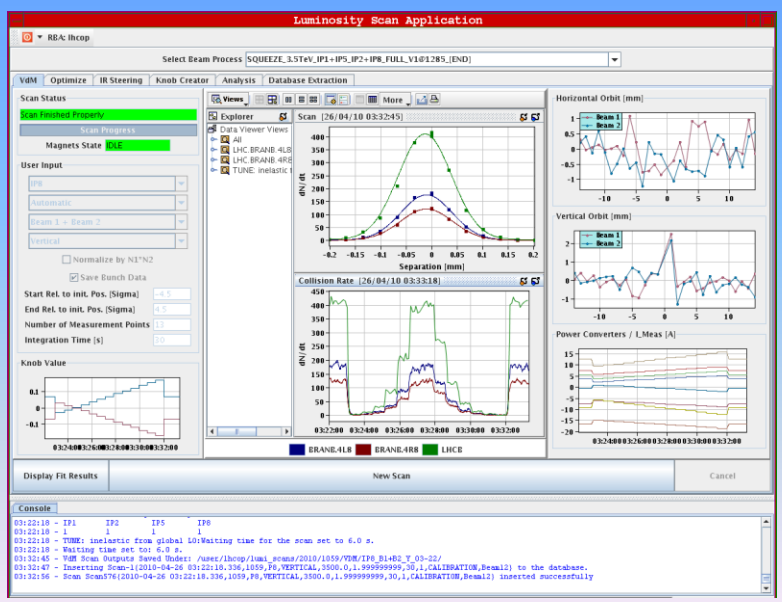
2010 - Beam dump protection systems efficiency

Provoked asynchronous beam dump



➔ **OK for stable beams from beam dump**

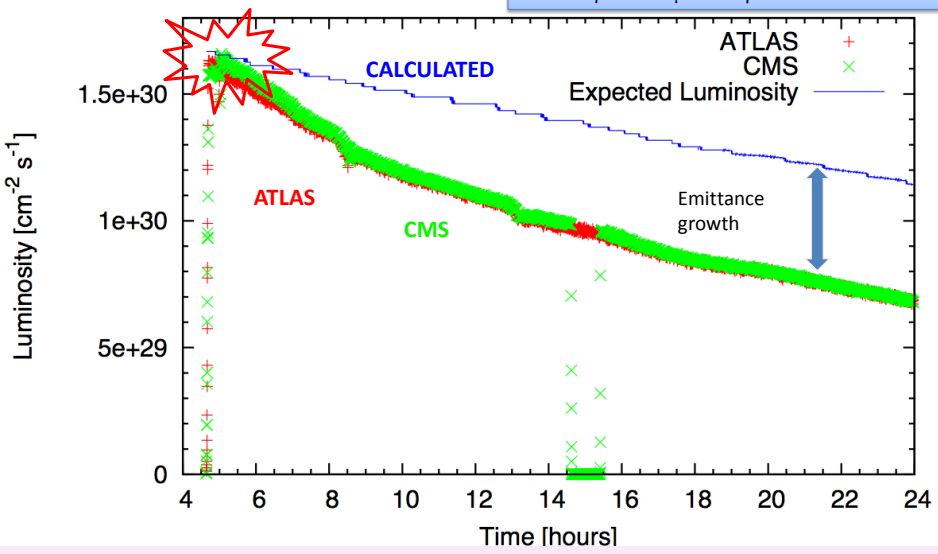
2010 - Collisions



2010 - Collisions – emittance blow up

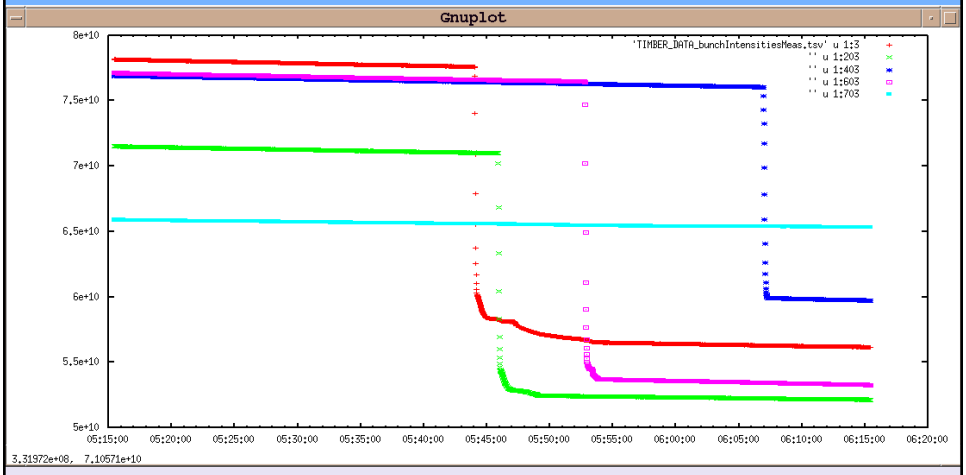
Machine parameters very well controlled!

calculated with measured bunch intensity, nominal $\gamma\varepsilon$ = 3.75 μm and β^*=3.5m

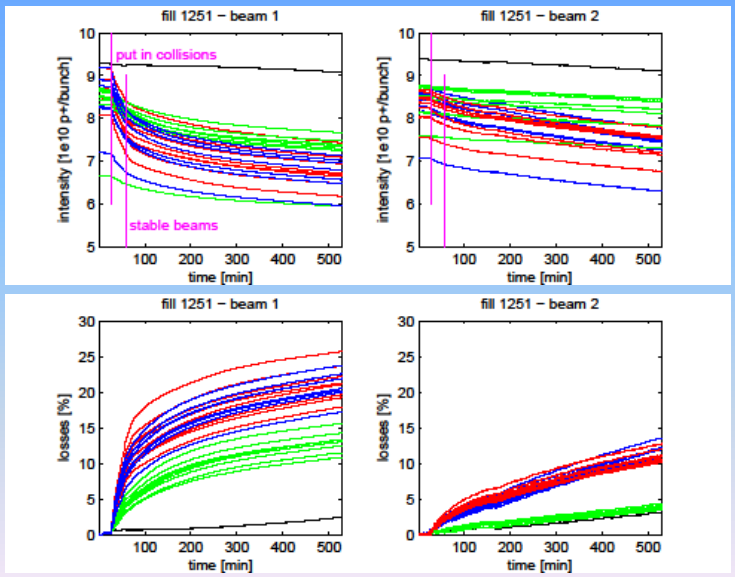


2010 - Collisions – beam-beam effects

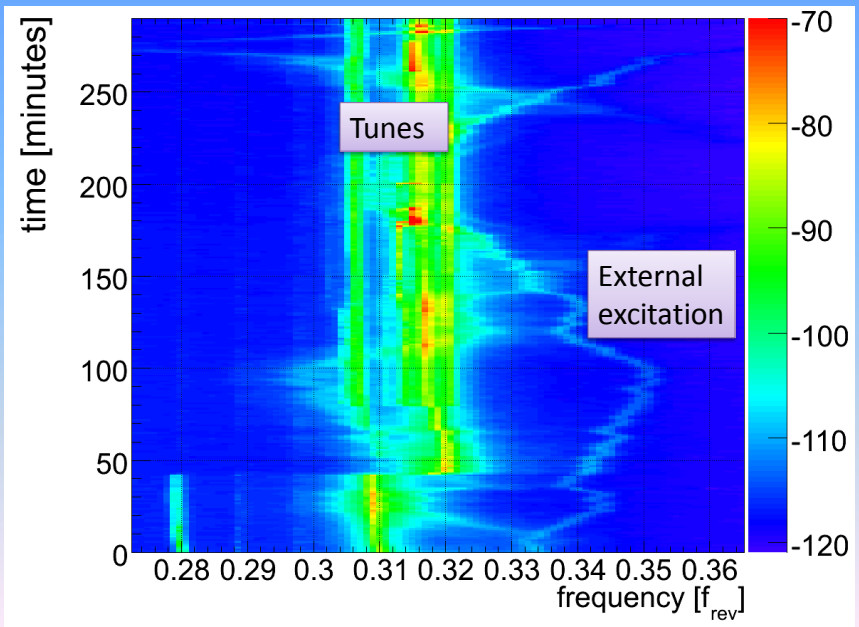
Losses only in first 4 bunches, from bucket 1 onwards



2010 - Collisions – behaviour of different beams / bunches



2010 - Unwanted excitation - source still unknown



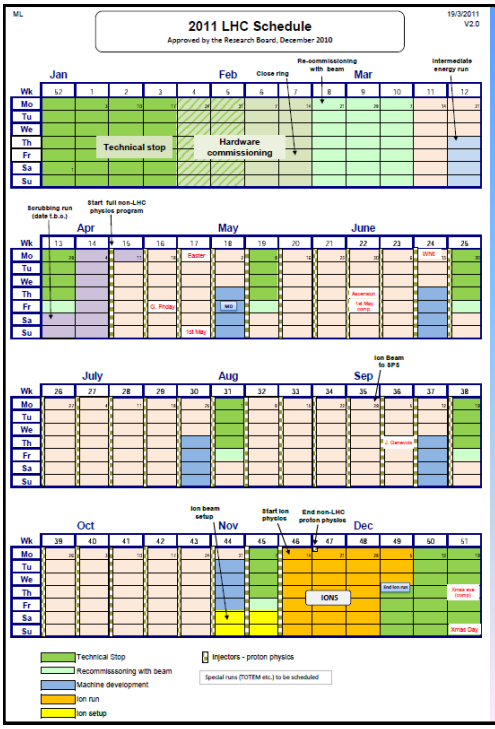
Progress in 2010 with nominal intensity bunches

Date	Bunches/beam	Colliding bunches	Luminosity $cm^{-2}s^{-1}$
15th November	121	113	2.88e25
9th November	17	16	3.5e24
4th November	LHC switched to heavy ions (fully stripped lead)		
25th October	368	348	2.07e32
16th October	312	295	1.35e32
14th October	248	233	1e32
8th October	248	233	8.8e31
4th October	204	186	7e31
29th September	152	140	5e31
25th September	104	93	3.5e31
23rd September	56	47	2e31
22nd September	24	16	4.6e30
1st - 22nd September	Bunch train commissioning, 150 ns bunch spacing		
29th August	50	35	1e31

20 MJ

Comments on 2010

- Machine commissioned with beam under strict conditions
- Machine parameters under control
- Machine protection paramount and dictated intensity
  - Low bunch currents, increase k_b
  - Increase bunch current
  - Higher bunch current, low k_b, same total current
  - Higher bunch currents, increase k_b
- Big surprise that we could 'easily' get to nominal *N*
- Nominal bunch intensities thereafter, 'just' increasing k_b
- Intensity related effects starting to show up
  - UFOs
  - Electron cloud
  - SEUs



2011

Re-commission machine for 3.5TeV
Squeeze to 1.5m at 3.5 TeV
Get back to 2010 performance levels
200 on 200 high intensity bunches, 75 ns

Prepare machine for high intensity (scrub)
Increase number of bunches
Operate machine with higher intensity
1000 on 1000 high intensity bunches, 50 ns

Increase number of bunches to 1400
Operate machine with higher intensity
Try not to break anything!
1400 on 1400 high intensity bunches, 50 ns
100 MJ stored energy per beam

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Progress in 2011 (to end May)

Date	Bunches/beam	Colliding bunches (Atlas & CMS)	Luminosity $cm^{-2}s^{-1}$
29th May	1092	1042	1.2e33
22nd May	912	873	1.1e33
1st May	768	700	8.4e32
27th April	624	598	6.7e32
21st April	480	424	4.67e32
16th April	336	322	3.57e32
14th April	220	214	2.28e32
24-27th March	1.38 TeV run (followed by technical stop and scrubbing)		
22nd March	200	194	2.5e32

75 MJ

6/8/2011

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Observation

- No battle plan ever survives contact with the enemy
  - Original plan was
    - Equidistant bunches, moderate bunch intensity
    - 75 ns, moderate bunch intensity
    - 25ns, moderate bunch intensity
    - 25ns, nominal bunch intensity
  - What actually happened was
    - Equidistant bunches, moderate bunch intensity
    - Equidistant bunches, nominal bunch intensity
    - 150 ns, nominal bunch intensity
    - 75 ns, nominal bunch intensity
    - 50 ns, nominal bunch intensity
    - 25ns, nominal bunch intensity (still to do)

Summary

- After a long and painful birth, LHC came online in 2008
- Major incident of September 2008 took a year to fix
- Lessons learned from this impacted on the commissioning
- At start-up II (2009/10), fantastic set of tools at our disposal
  - Allowed fast commissioning with beam
- Machine protection (hardware and beam) paramount
  - Necessarily slowed down the progress
- Fantastic progress through 2010
  - 5 orders of magnitude increase in instantaneous luminosity to 2 10^{32}
  - 50 pb^{-1} delivered at com 7 TeV
- Similarly impressive progress so far through 2011
  - At 1.2 10^{33} already, and integrated luminosity looking good (> 0.5 fb^{-1})
  - Expect to deliver 1-3 fb^{-1} before we switch to ions in November
  - Let's hope that there is something there to find!

Future schools

Year	Special topic (May, June)	Accelerator physics (September)
2011	High Power Hadron Machines, Bilbao, ES	Level II, Chios, GR
2012	Ions Sources, Senec, SK	Level I, Granada, ES
2013	Applications of Superconductivity, Erice, IT	Level II, Norway, Finland
2014	Power Convertors, CH	Level I, Hungary, Portugal
2015	Vacuum	
2016	Medical applications (or do as a JAS in Russia?)	