LHC performance in the first run

J. Wenninger
CERN
Beams Department
Operation group

Outline

Introduction

Proton operation

High intensity issues

Ion operation

Outlook

The Large Hadron Collider LHC

Installed in 26.7 km LEP tunnel

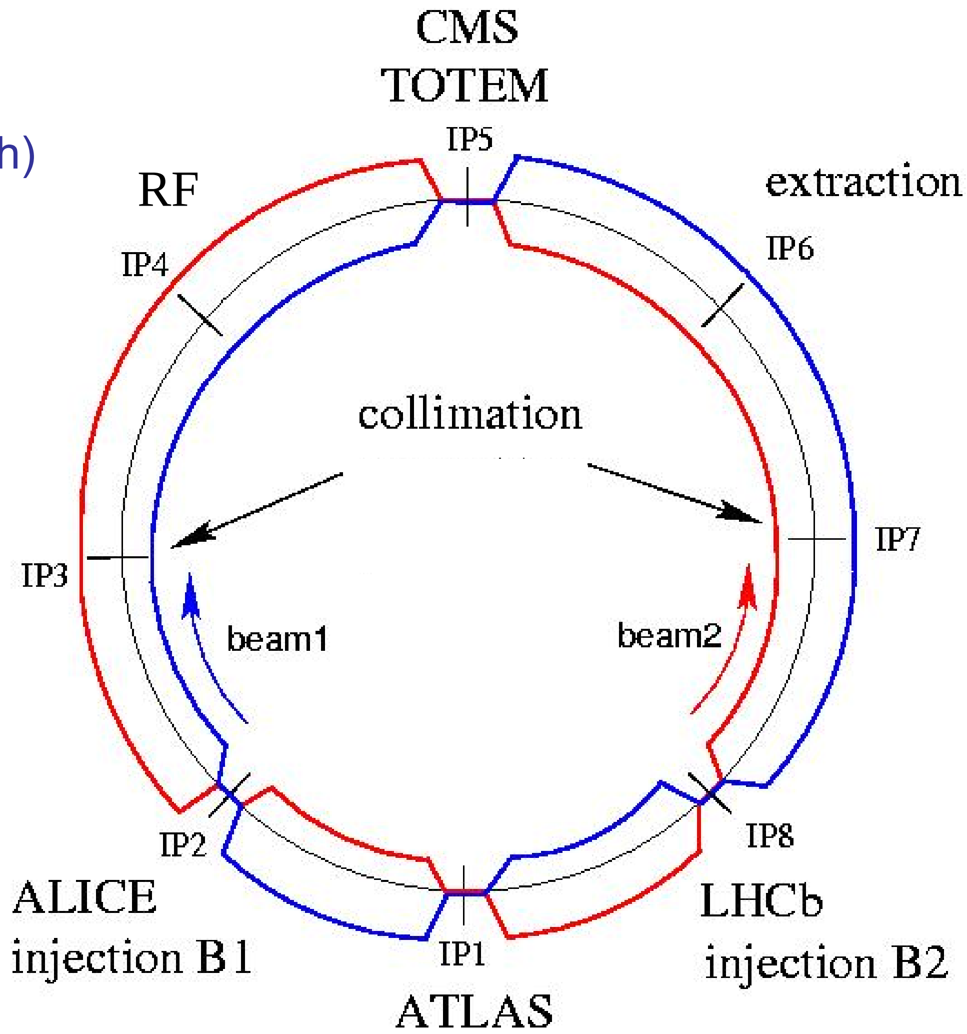
Depth of 70-140 m

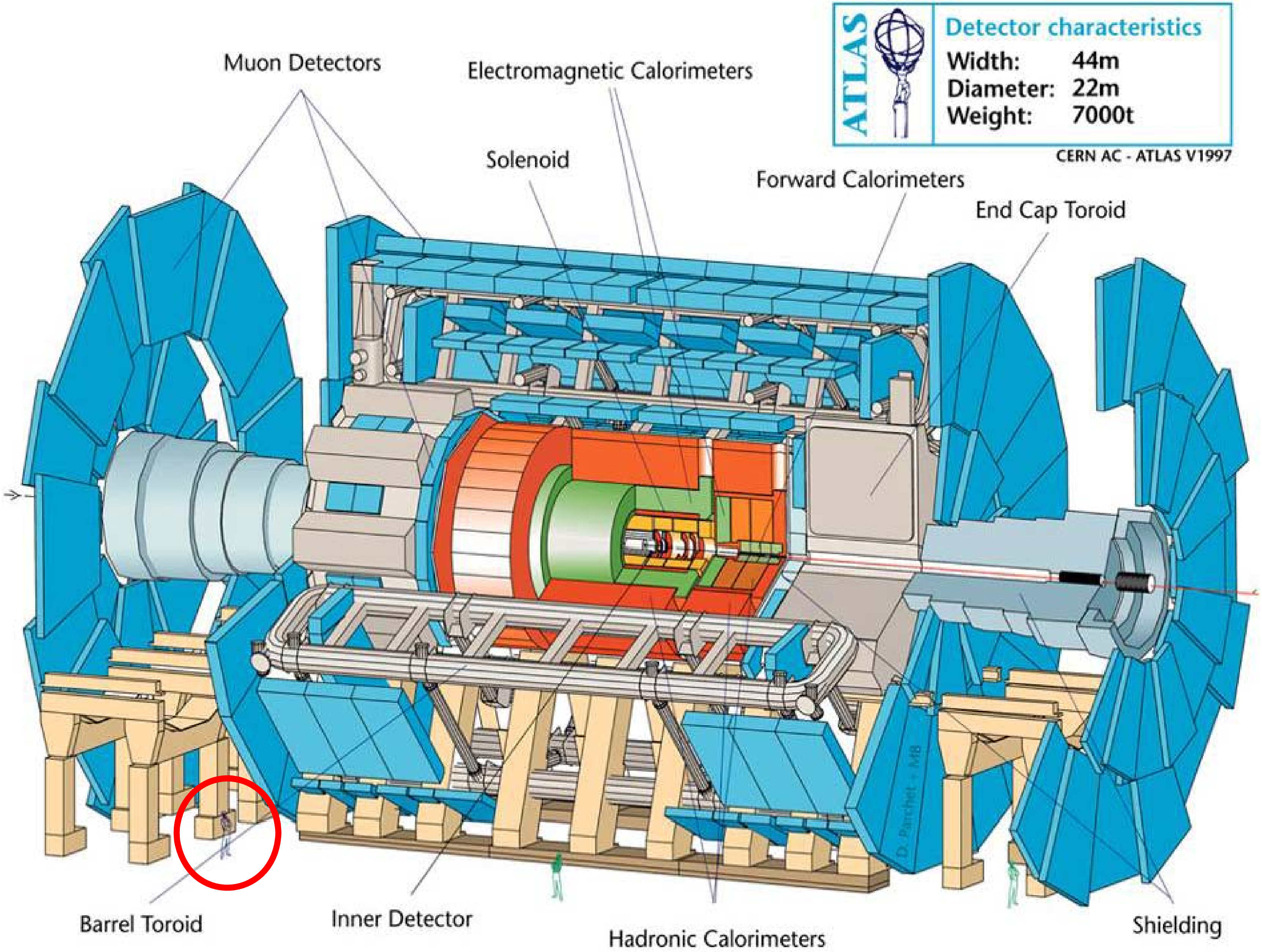
LHC layout and parameters

- 8 arcs (sectors), ~3 km each
- 8 long straight sections (700 m each)
- beams cross in 4 points
- 2-in-1 magnet design with separate vacuum chambers → *p-p* collisions

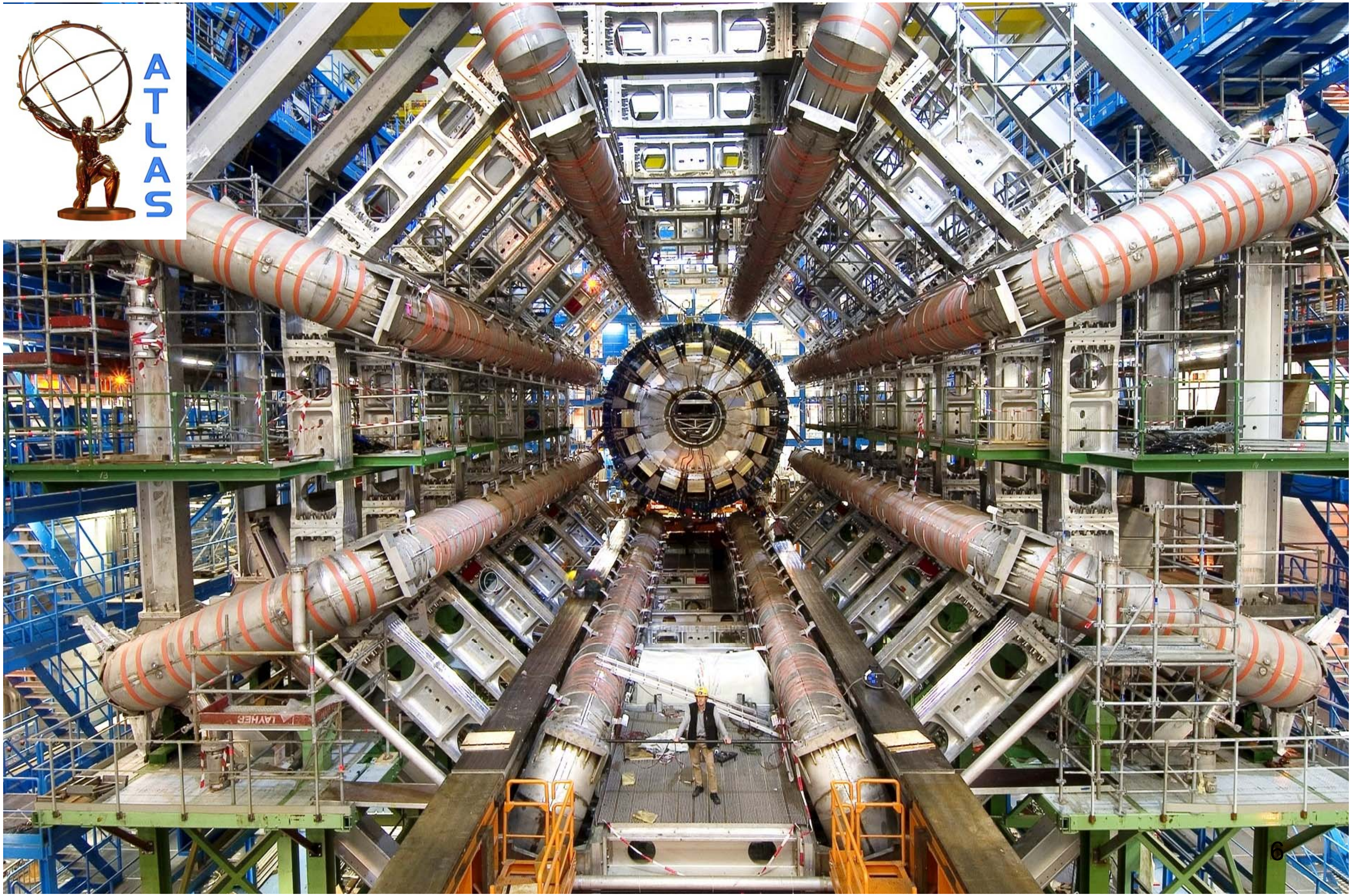
Nominal LHC parameters	
Beam energy (TeV)	7.0
No. of particles per bunch	1.15×10^{11}
No. of bunches per beam	2808
Stored beam energy (MJ)	362
Transverse emittance (µm)	3.75
Bunch length (cm)	7.6

- $\beta^* = 0.55$ m (beam size =17 µm)
- Crossing angle = 285 µrad
- $L = 10^{34}$ cm^{-2} s^{-1}



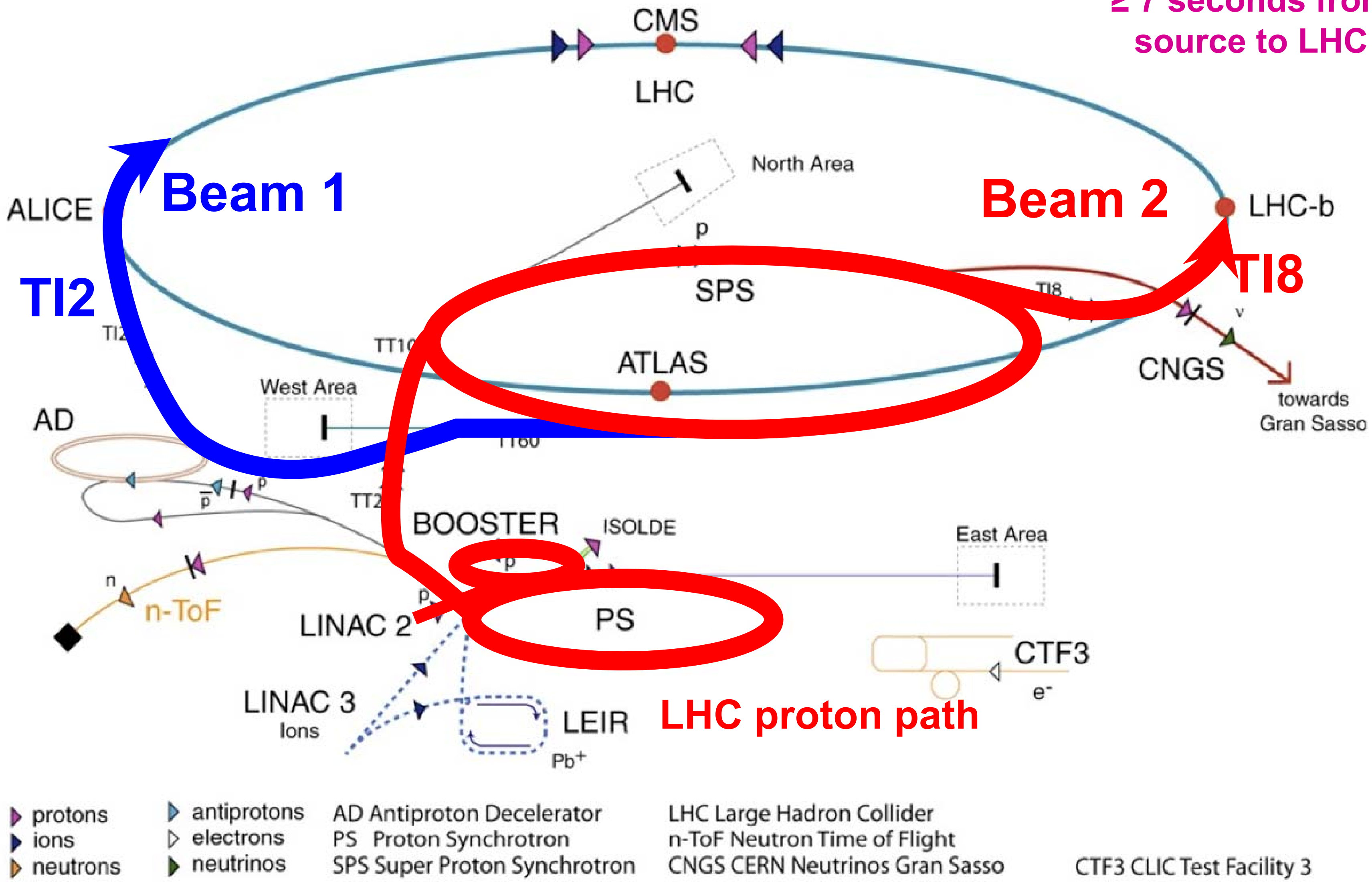

Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
ATLAS
CERN AC - ATLAS V1997
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding

ATLAS



LHC accelerator complex

≥ 7 seconds from source to LHC



The LHC needs most of the CERN accelerators...

LHC challenges

The LHC surpasses existing accelerators/colliders in 2 aspects :

- The energy of the beam of 7 TeV that is achieved within the size constraints of the existing 26.7 km LEP tunnel.

LHC dipole field	8.3 T
HERA/Tevatron	~ 4 T

A factor <u>2</u> in field

A factor <u>4</u> in size

- The luminosity of the collider that will reach unprecedented values for a hadron machine:

LHC	pp	10^{34} cm^{-2} s^{-1}
Tevatron	$p\bar{p}$	$3x10^{32}$ cm^{-2} s^{-1}
Sp$\bar{p}$S	$p\bar{p}$	$6x10^{30}$ cm^{-2} s^{-1}

A factor <u>30</u> in luminosity

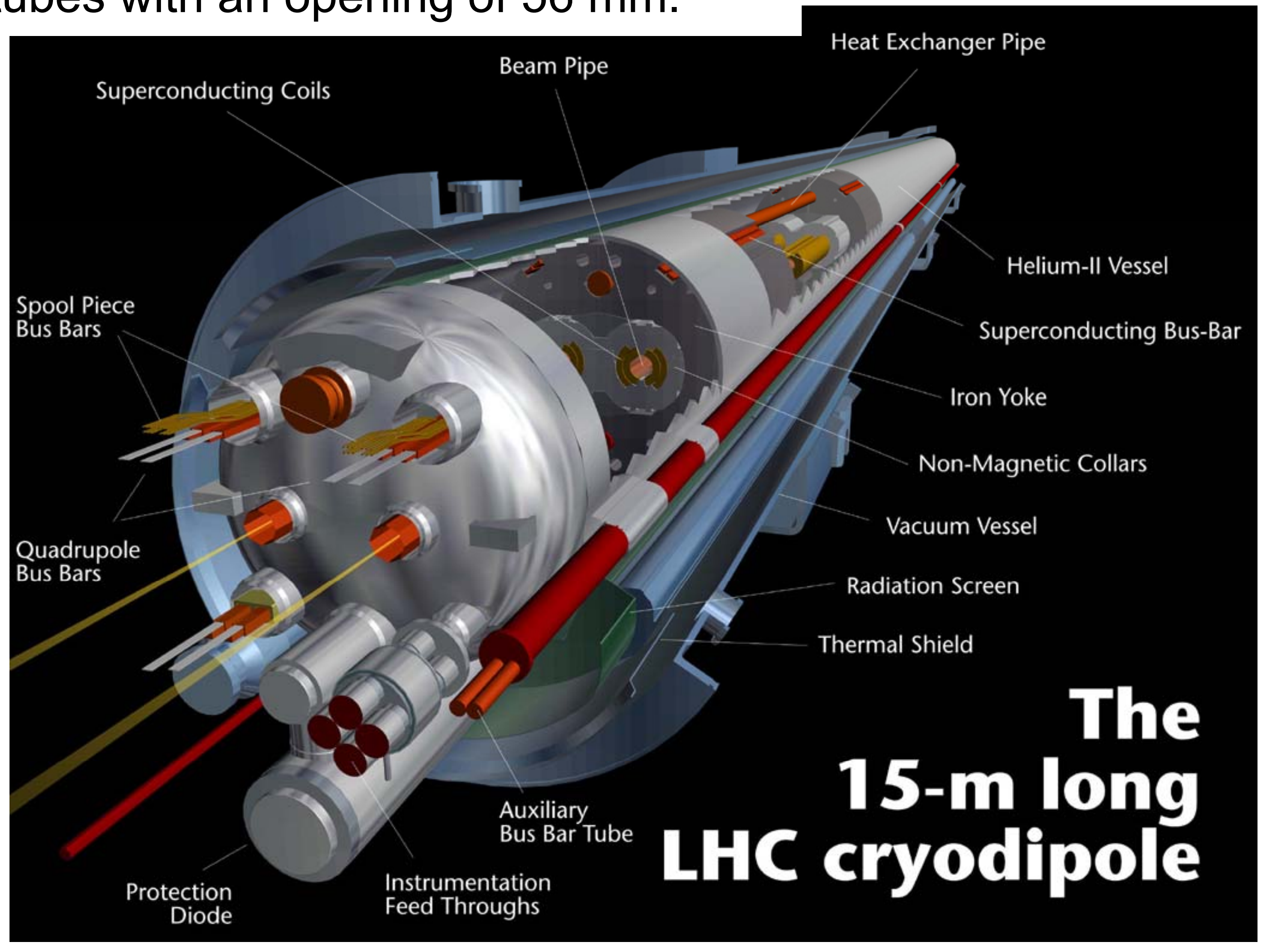
Very high field magnets and very high beam intensities:

- Operating the LHC is a great challenge.
- There is a significant risk to the equipment and experiments.

LHC dipole magnet

- 1232 dipole magnets.
- B field 8.3 T (11.8 kA) @ 1.9 K (super-fluid Helium)
- 2 magnets-in-one design : two beam tubes with an opening of 56 mm.

- Operating challenges:
  - *Dynamic field changes at injection.*
  - *Very low quench levels (~ mJ/cm^3)*



Installation

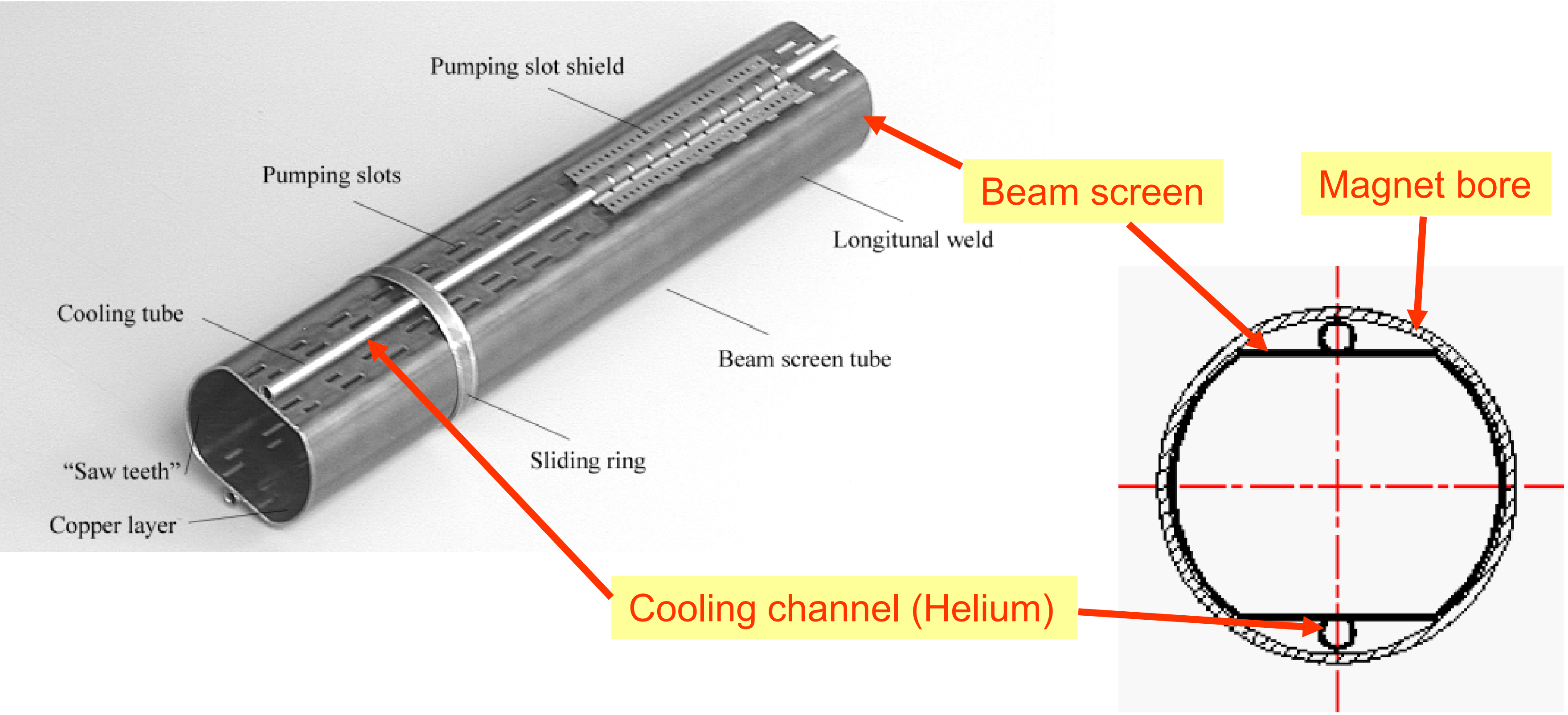
- Magnets were produced by industry.
- First dipole lowered March 2005.
  Magnet installation until spring 2007
  Interconnection work finished end 2007

- Transport in the tunnel with an optically guided vehicle.
- Approximately 1600 magnet assemblies transported over up to 20 km at 3 km/hour.

Tunnel View

Vacuum chamber

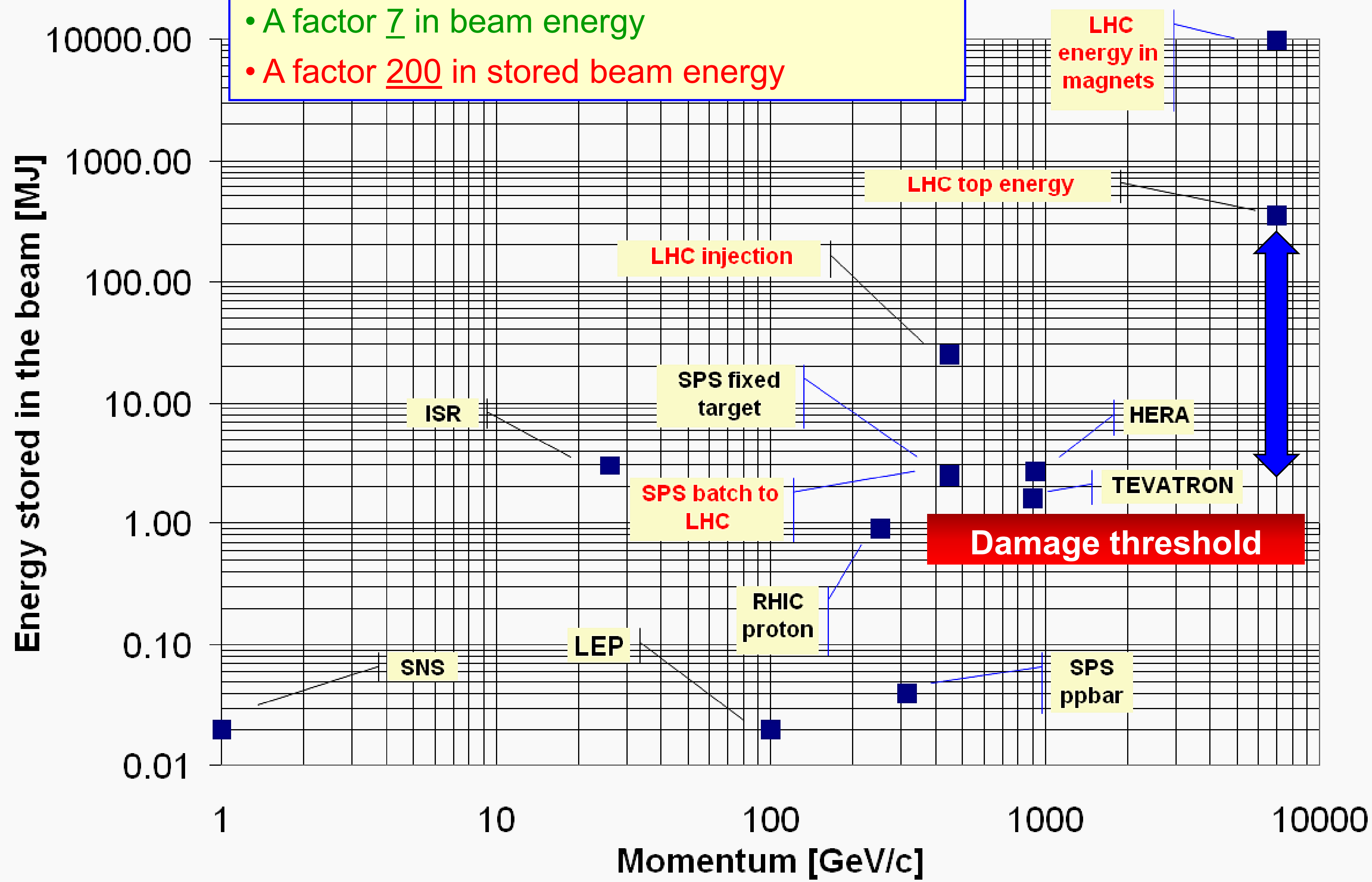
- The beams circulate in two ultra-high vacuum chambers, P ~10^{-10} mbar.
- A Copper beam screen protects the bore of the magnet from heat deposition due to image currents, synchrotron light etc from the beam.
- The beam screen is cooled to T = 4-20 K.



Stored energy

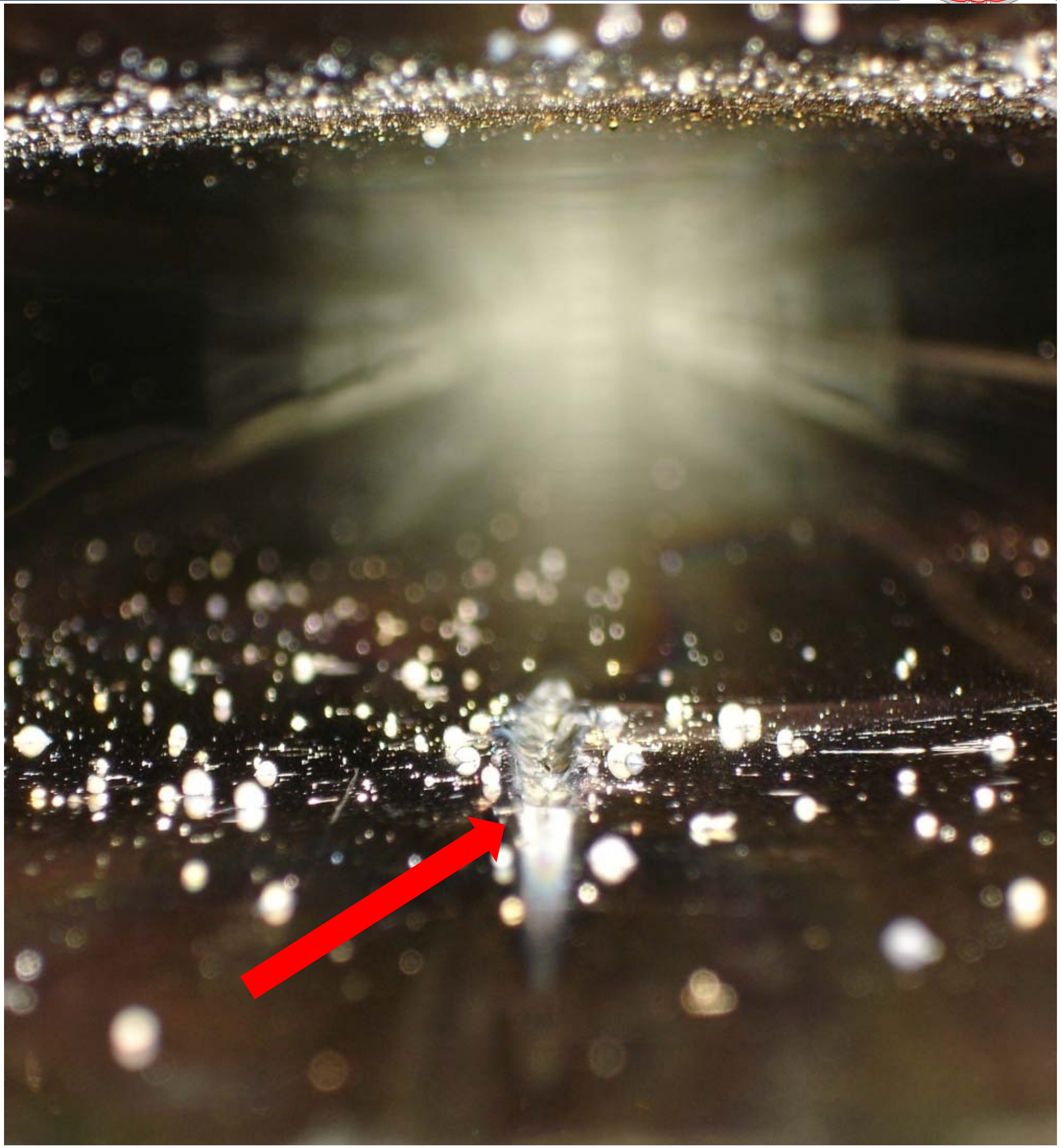
Increase with respect to existing accelerators :

- A factor 2 in magnetic field
- A factor 7 in beam energy
- A factor 200 in stored beam energy



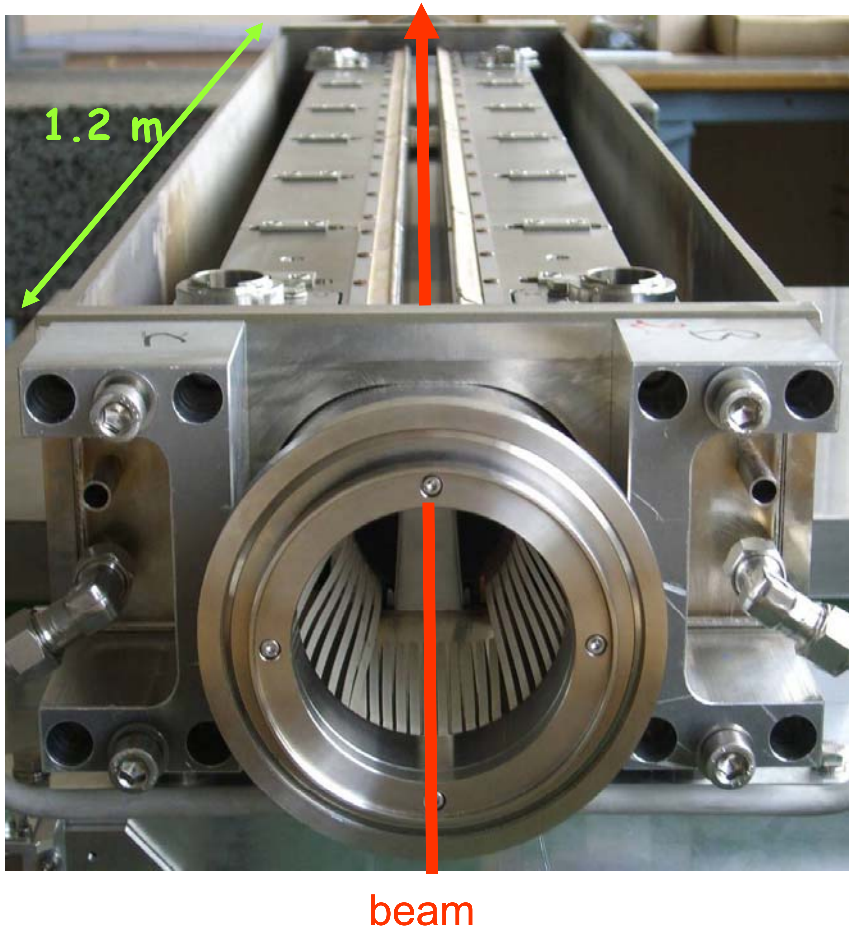
To set the scale…

A few cm long groove in a SPS vacuum chamber after the impact of **~1% of a nominal LHC beam (2 MJ)** during an 'incident'



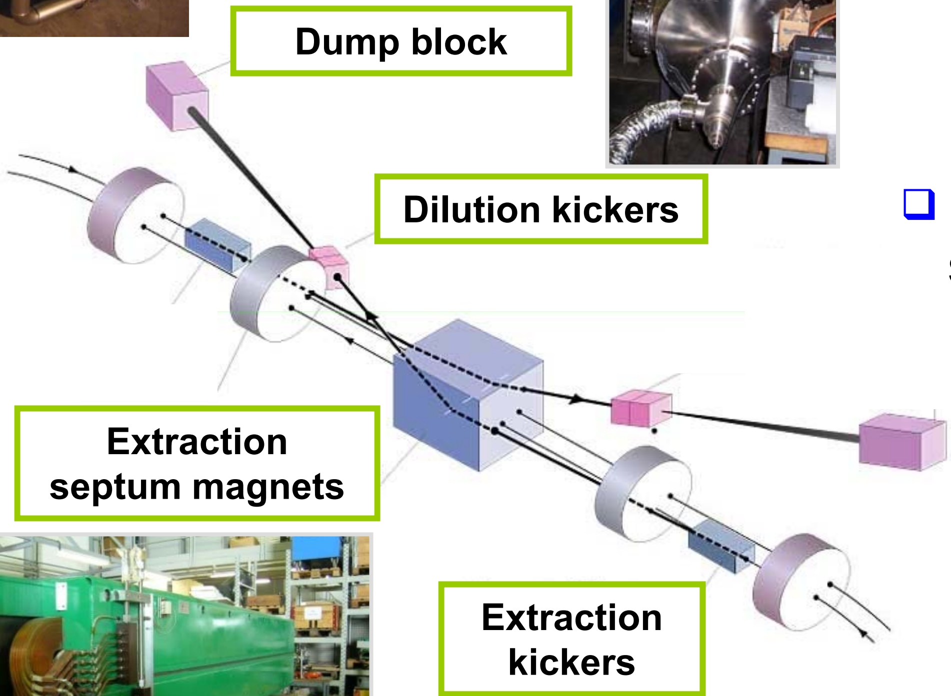
Collimation

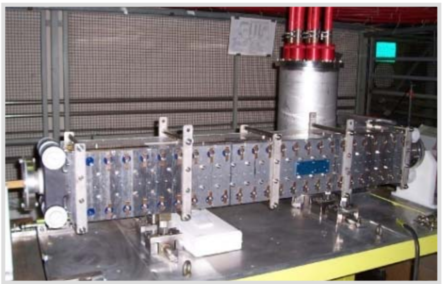
- To operate at nominal performance the LHC requires a large and complex collimation system
  - *Previous colliders used collimators mostly for experimental background conditions - the LHC can only run with collimators.*



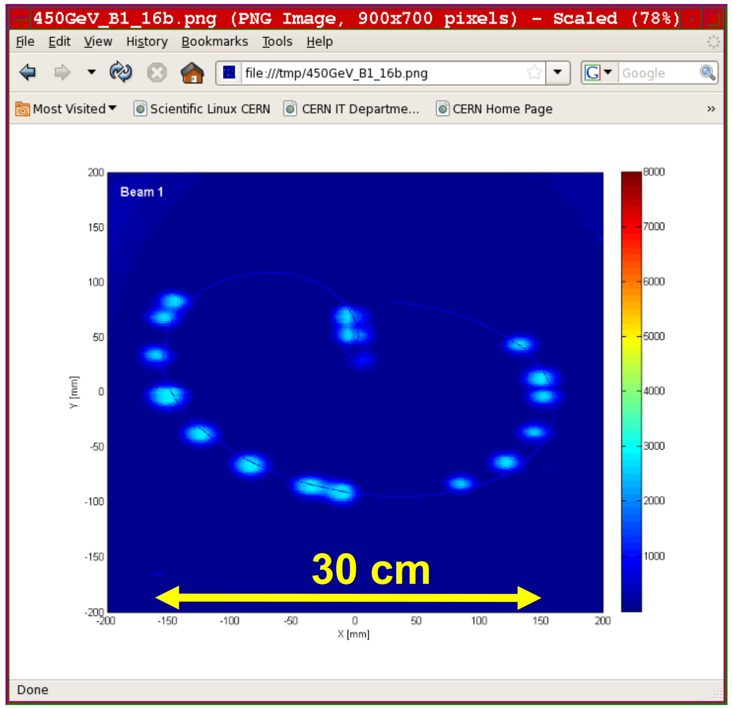
- Ensure ‘cohabitation’ of:
  - 360 MJ of stored beam energy,
  - super-conducting magnets with quench limits of few mJ/cm^3
- Almost 100 collimators and absorbers.
- Alignment tolerances <0.1 mm to ensure that over 99.99% of the protons are intercepted.
- Primary and secondary collimators are made of Carbon to survive large beam loss.

Beam dumping system





- The dump is the only LHC element capable of absorbing the nominal beam.
  - *Beam swept over dump surface (power load).*
- Ultra-high reliability and fail-safe system.



LHC target energy: the way down

- All main magnets commissioned for 7TeV operation before installation
- Detraining found when hardware commissioning sectors in 2008
  - 5 TeV poses no problem
  - Difficult to exceed 6 TeV
- Machine wide investigations following S34 incident showed problem with joints
- Commissioning of new Quench Protection System (nQPS)

Energy / Current	When	Why
7 TeV / 12 kA	2002-2007	Design
5 TeV / 9 kA	Summer 2008	Detraining
3.5 TeV / 6 kA	Late 2008 Spring 2009	Joints
1.18 TeV / 2 kA	Nov. 2009	nQPS

450 GeV

LHC target energy: the way up

- Train magnets
  - 6.5 TeV is in reach
  - 7 TeV will take time
- Repair joints
- Complete pressure relief system
- Commission nQPS system

Energy	When	What
7 TeV	2014 ?	Training
6 TeV	2013	Stabilizers
3.5 TeV	2011 / 2010	nQPS
1.18 TeV	2009	
450 GeV		

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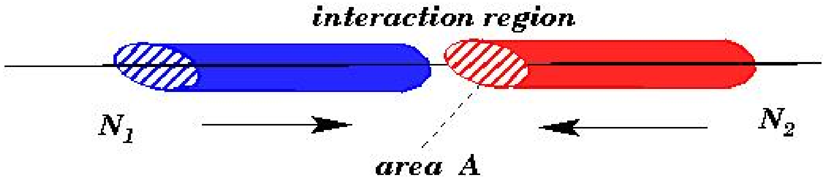
Luminosity : collider figure-of-merit

The event rate N for a physics process with cross-section σ is proprotional to the collider Luminosity L:

$$N = L\sigma$$



$$L = \frac{kN^2 f}{4\pi\sigma_x^* \sigma_y^*} = \frac{kN^2 f \gamma}{4\pi \beta^* \varepsilon}$$

Design

k = number of bunches = 2808
N = no. protons per bunch = 1.15×10¹¹
f = revolution frequency = 11.25 kHz
σ^*_x, σ^*_y = beam sizes at collision point (hor./vert.) = 16 μm

To maximize L:

- **Many bunches (*k*)**
- **Many protons per bunch (*N*)**
- **Small beam sizes $\sigma^*_{x,y} = (\beta^* \varepsilon)^{1/2}$**

β^* : beam envelope (optics)

ε : beam emittance, the phase space volume occupied by the beam (constant along the ring)

Optics property

Beam property

High beam "brillance" N/ε
(particles per phase space volume)
→ **Injector chain performance !**

Small envelope
→ **Strong focusing !**

LHC targets for 2011

- The integrated luminosity target for **2010-2011**:

Deliver > 1 fb^{-1} at 3.5 TeV

…to make the LHC competitive with TEVATRON at FNAL.

- This target requires operation at L > $2x10^{32}$ $cm^{-2}s^{-1}$.

  More or less the present TEVATRON luminosity…

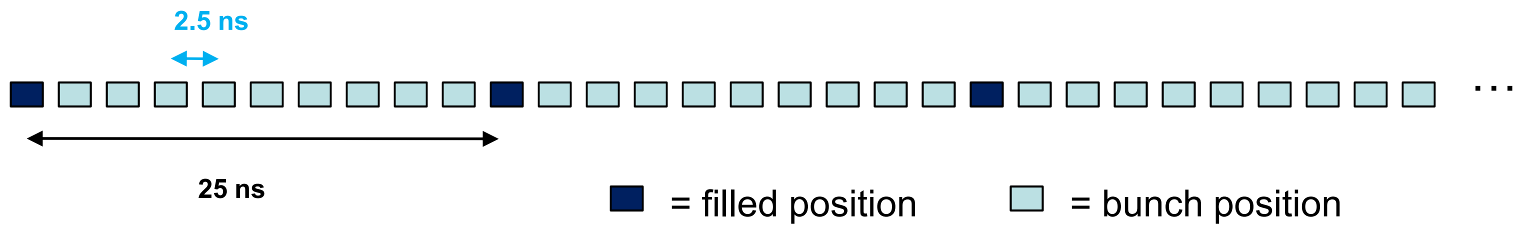
- To prove that this is feasible, the target for the luminosity in **2010** was set to

$L \geq 10^{32}\ cm^{-2}s^{-1}$

This goal is far from trivial, since it requires ~10% of the design intensity at 3.5 TeV.

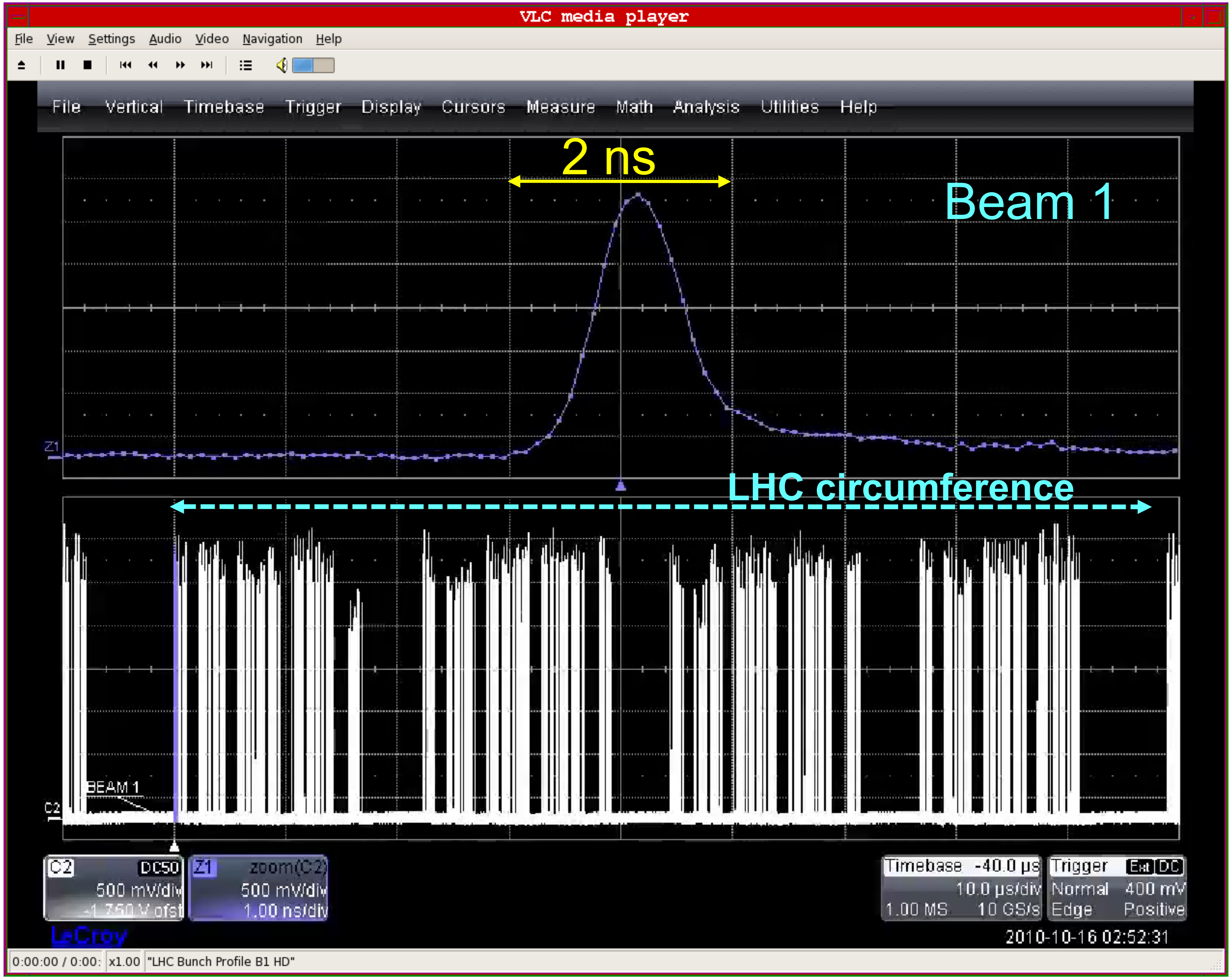
Bunch filling schemes

- The LHC 400 MHz Radio-Frequency system provides **35’640 possible bunch positions** every 2.5 ns (0.75 m) along the LHC circumference.
  - *A priori any of those positions could be filled with a bunch…*
- The smallest bunch-to-bunch distance is fixed to 25 ns: ***max. number of bunches is <u>3564</u>*** (- some space for the dump kicker beam free region).

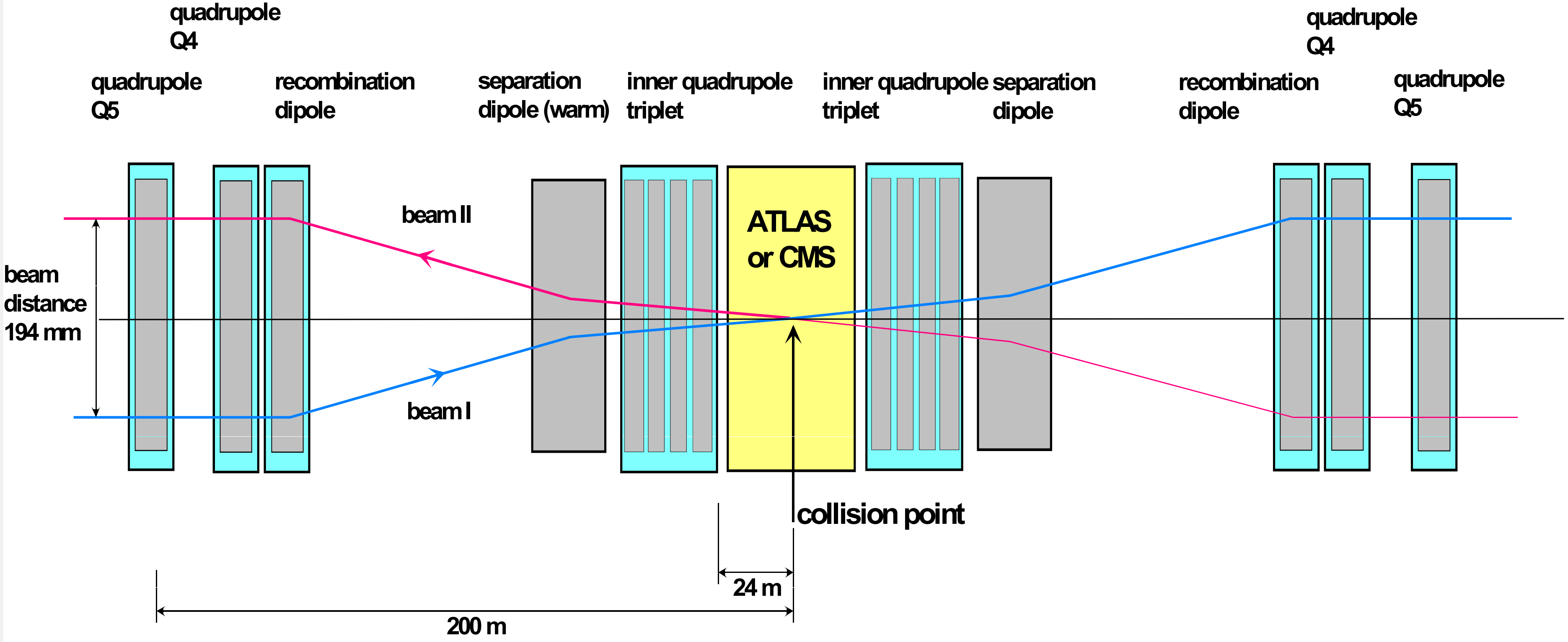


- Because of the injector flexibility, the LHC can operate with ***isolated bunches*** or with ***trains of closely spaced bunches***.
  - *Operation in 2010 began with isolated bunches (separation ≥ 1 μs), up to a maximum of 50 bunches.*
  - *From September 2010 the LHC was operated with trains of bunches separated by 150 ns (45 m), up to 368 bunches.*

312 bunches


VLC media player
File View Settings Audio Video Navigation Help
File Vertical Timebase Trigger Display Cursors Measure Math Analysis Utilities Help
2 ns
Beam 1
LHC circumference
BEAM 1
C2 DC50
500 mV/div
Z1 zoom(C2)
500 mV/div
1.00 ns/div
Timebase -40.0 μs
10.0 μs/div
1.00 MS 10 GS/s
Trigger
Normal 400 mV
Edge Positive
LeCroy
2010-10-16 02:52:31
0:00:00 / 0:00: x1.00 "LHC Bunch Profile B1 HD"

Experimental long straight sections

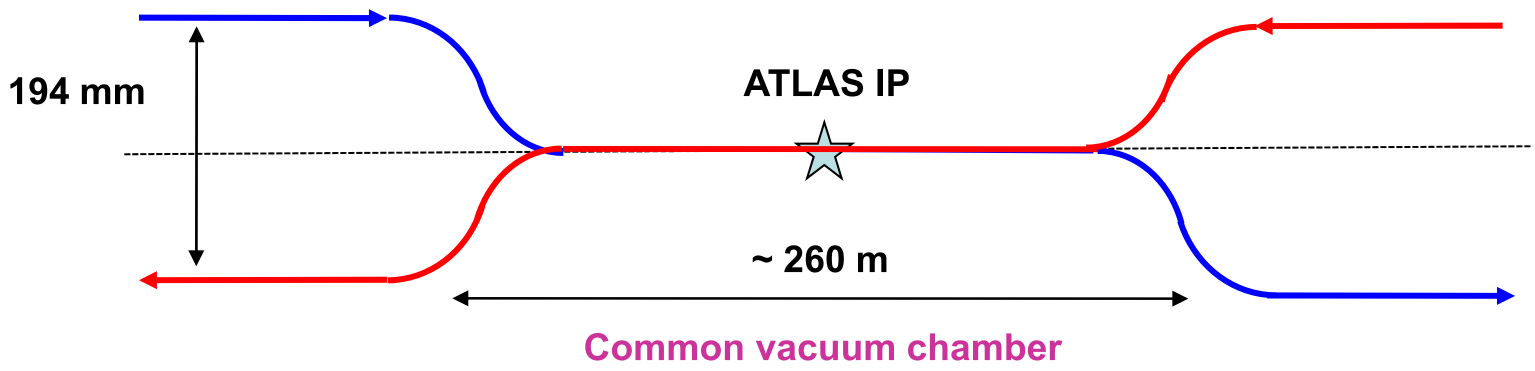


Example for an LHC insertion with ATLAS or CMS

- The 2 LHC beams are brought together to collide in a 'common' region.
- Over ~260 m, the beams circulate in the same vacuum chamber where they can potentially be 'parasitic' encounters (when the spacing is small enough).

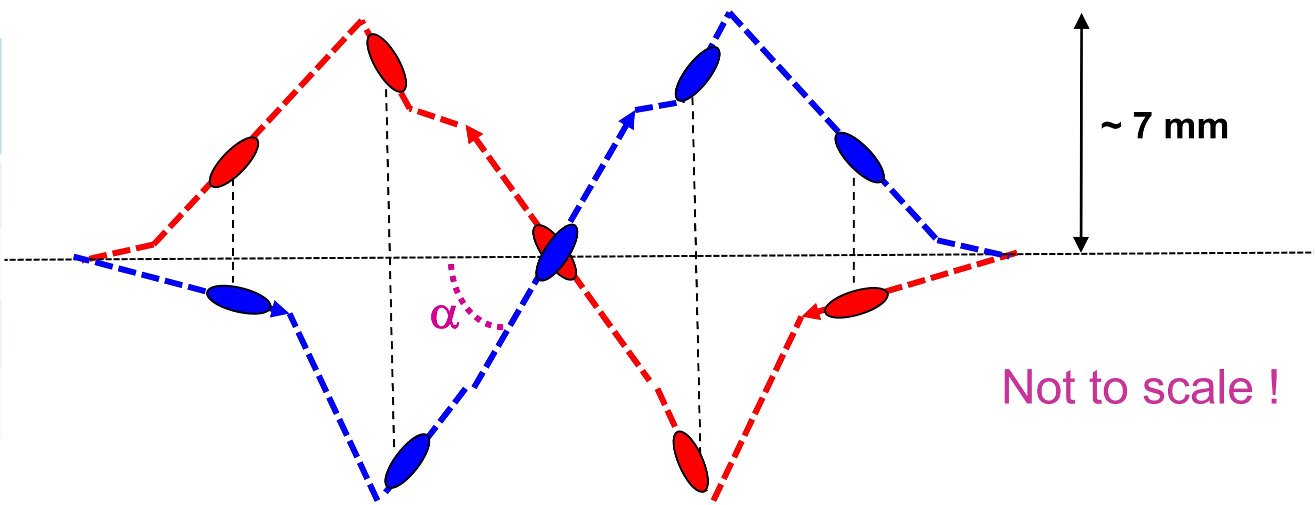
Separation and crossing: example of ATLAS

Horizontal plane: the beams are combined and then separated



Vertical plane: the beams are deflected to produce a crossing angle at the IP to avoid undesired encounters in the region of the common vac. chamber.

	α (μrad) / plane
ATLAS	-100 / ver.
ALICE	110 / ver.
CMS	100 / hor
LHCb	-100 /hor



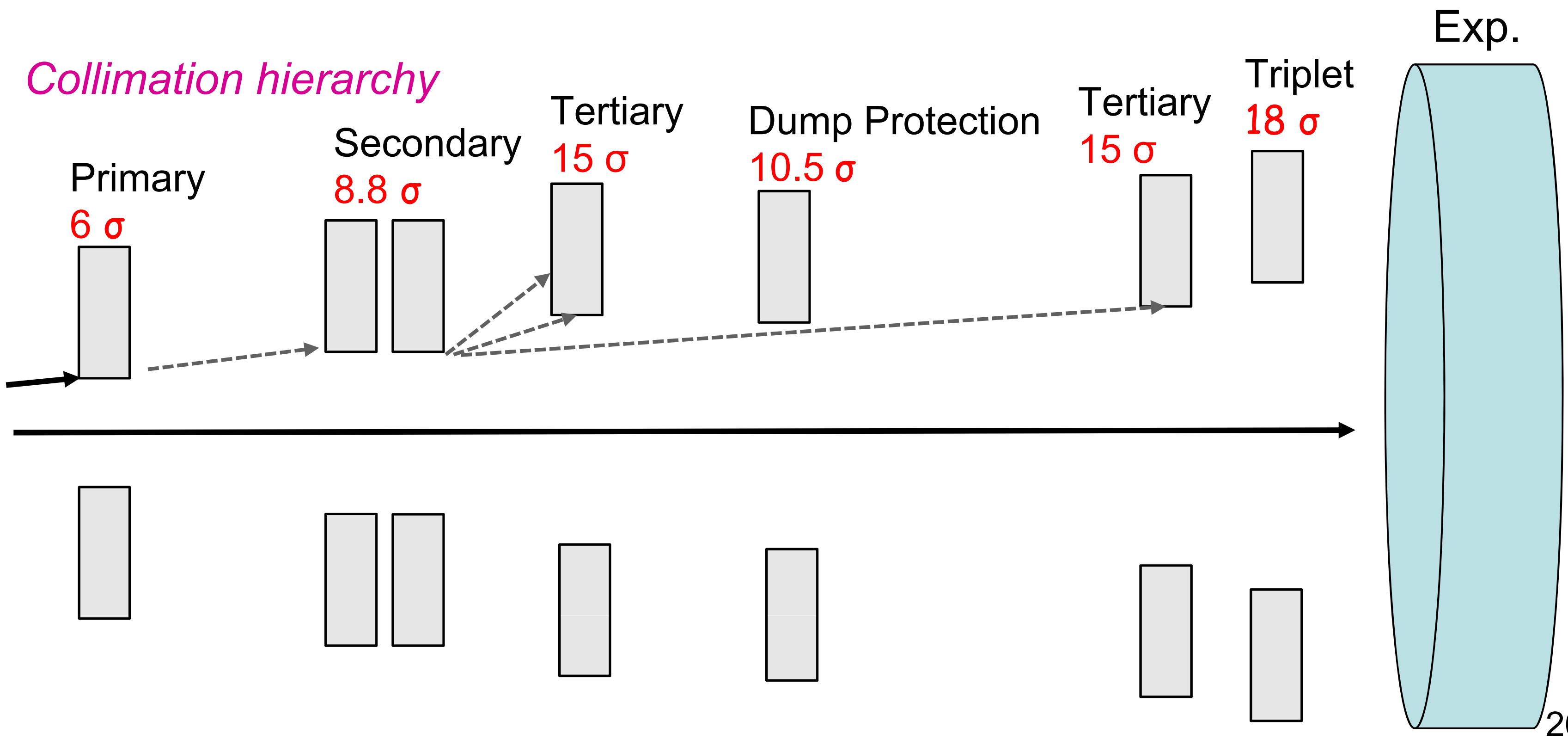
Aperture and collimation

During experiments data taking, the aperture limit of the LHC is in the strong focusing quadrupoles (*triplets*) next to the experiments.

- *Hierarchy of collimators is essential to avoid quenching super-conducting magnets and for damage protection.*
- ***So far we never quenched a magnet with beam !***

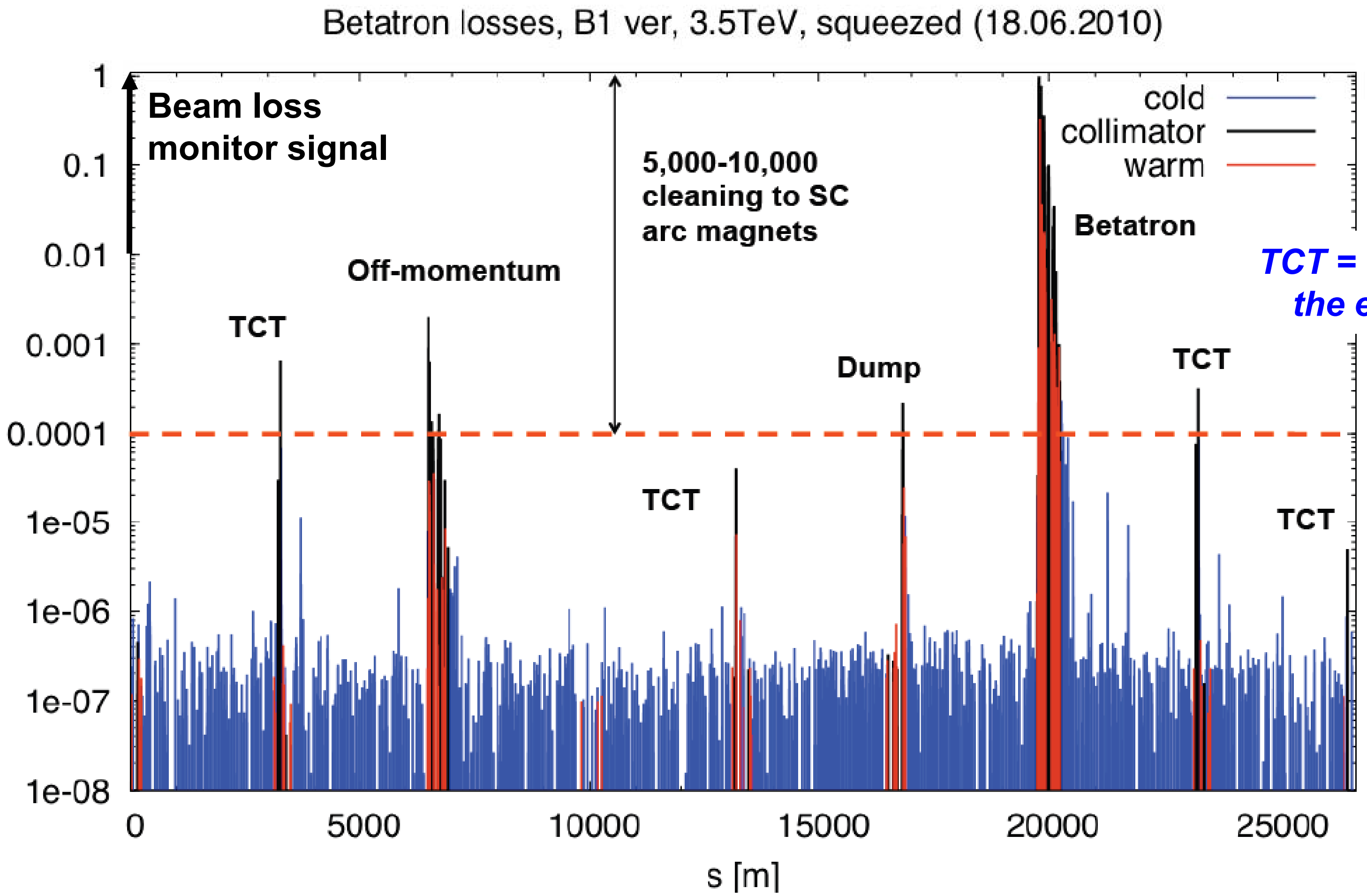
⇔ excellent machine and collimation system stability !!!

Collimation hierarchy



Collimation

- Collimator alignment is made with beam and then monitored from the loss distribution around ring.
- Beam cleaning efficiencies ≥ 99.98% ~ as designed



TCT = tertiary coll. at the experiments.

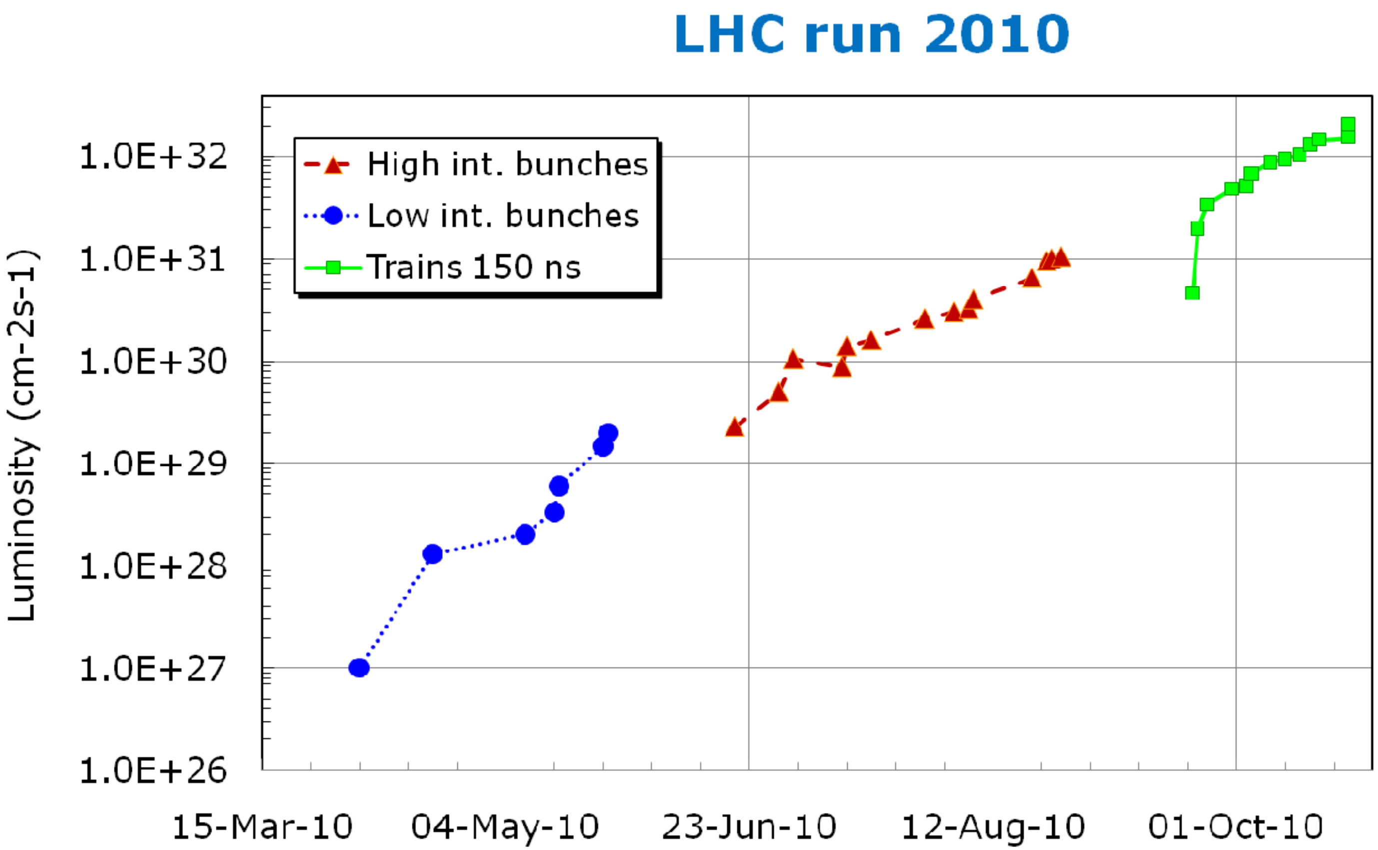
Three main phases of LHC operation in 2010:

- Phase 1: low intensity MP commissioning.
  - *Commissioning of the protection systems.*
  - *Low intensity single bunch commissioning of the systems, including beam tests (manually triggered failures).*
- Phase 2: MP running in with gradual intensity increase.
  - *Intensity increase in steps, factor 2 – 4, up to ~ MJ stored energy.*
  - *Stability run of a few weeks around 1-3 MJ in August 2010.*
- Phase 3: intensity increase to 10's MJ regime – October 2010.
  - *Intensity increase in steps of 2-3 MJ (≈1 TEVATRON beam).*
  - *1-2 steps per week depending on smooth operation (> 20 hours of stable collisions).*

Peak luminosity performance

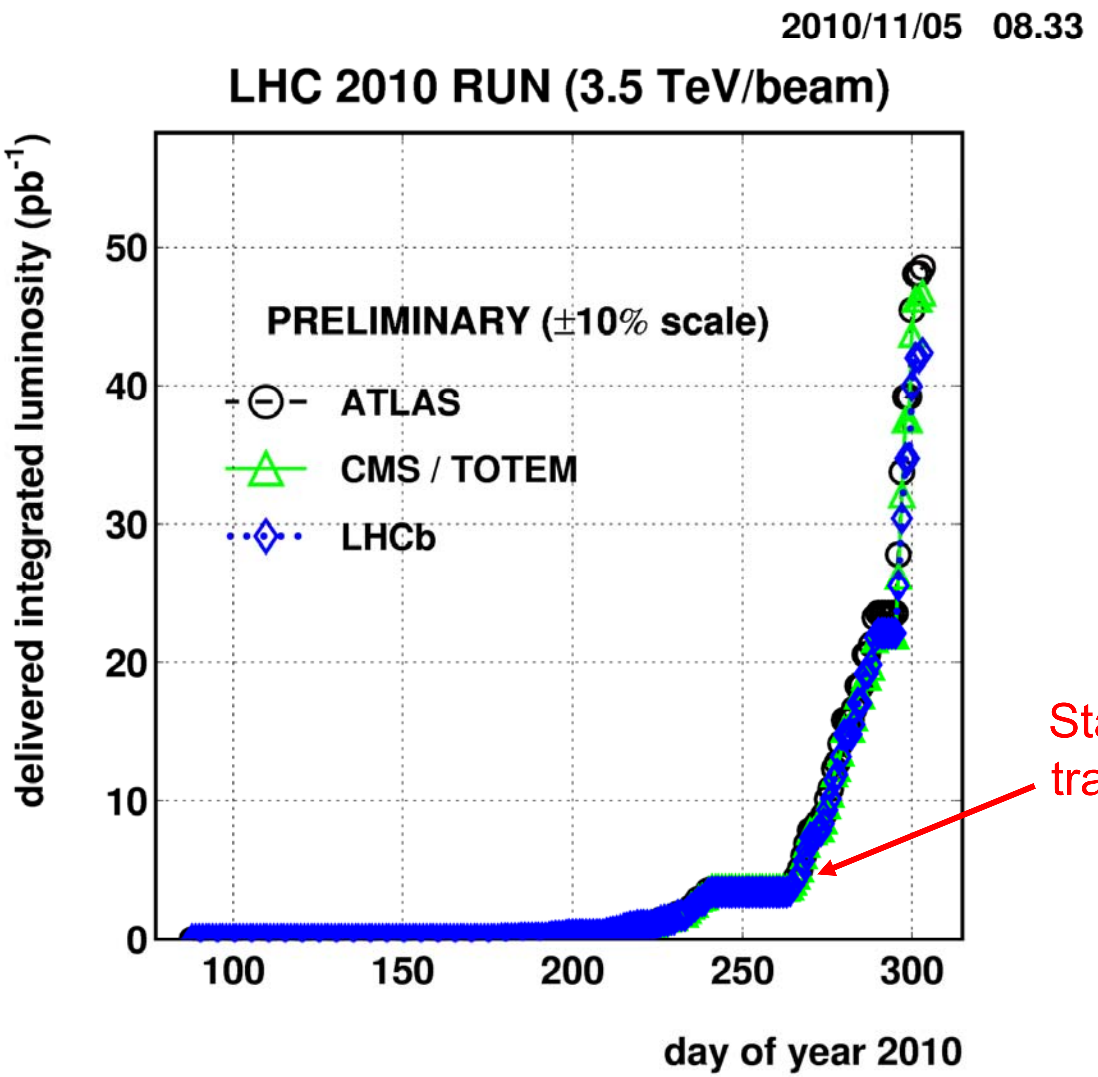
Peak luminosity = 2×10^{32} $cm^{-2}s^{-1}$

(368 bunches/beam, 348 colliding bunches)



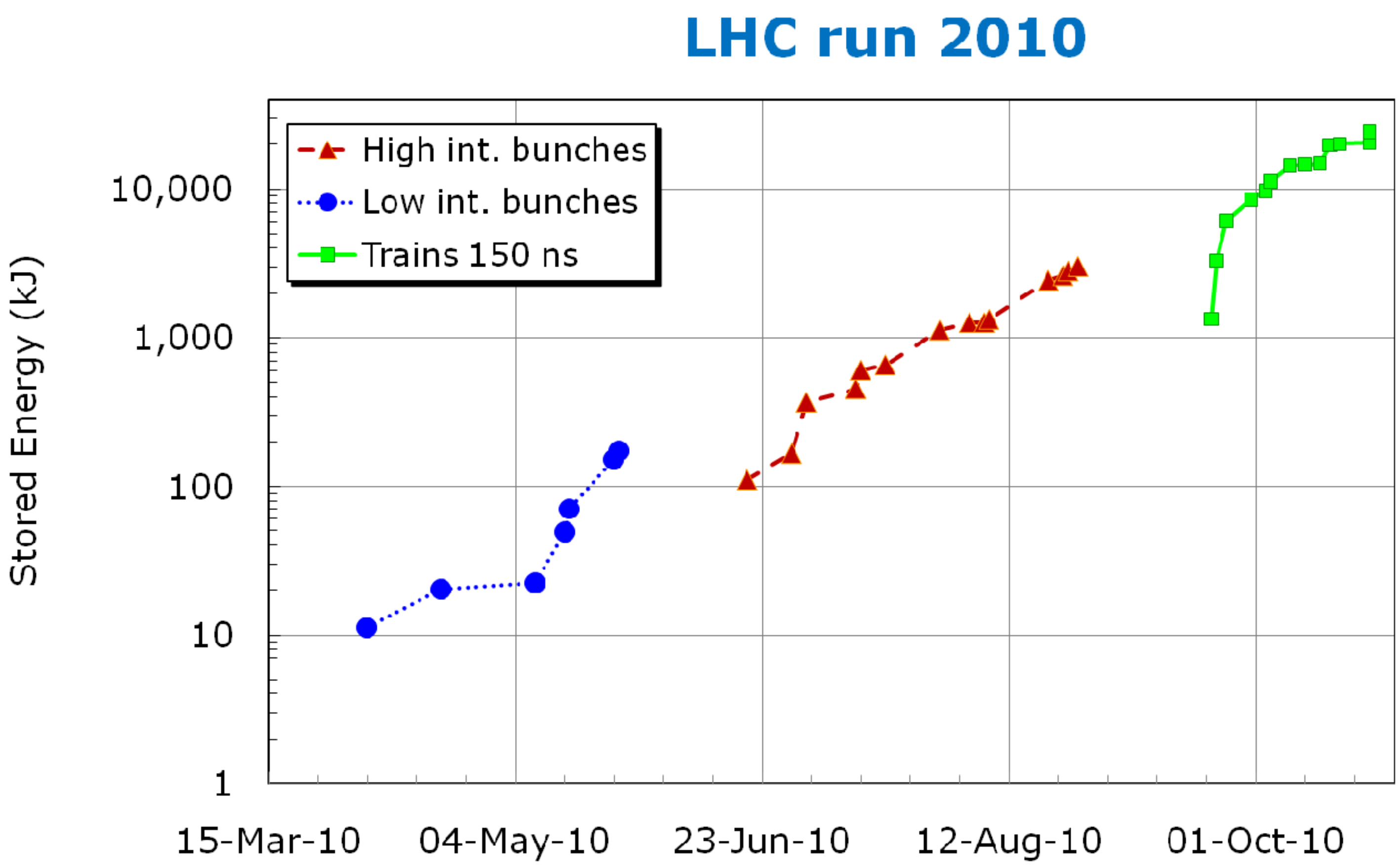
Integrated luminosity

Integrated proton luminosity 2010 ~48 pb^{-1}



Start of 150 ns train operation

Stored energy ~24 MJ (TEVATRON ~2 MJ)



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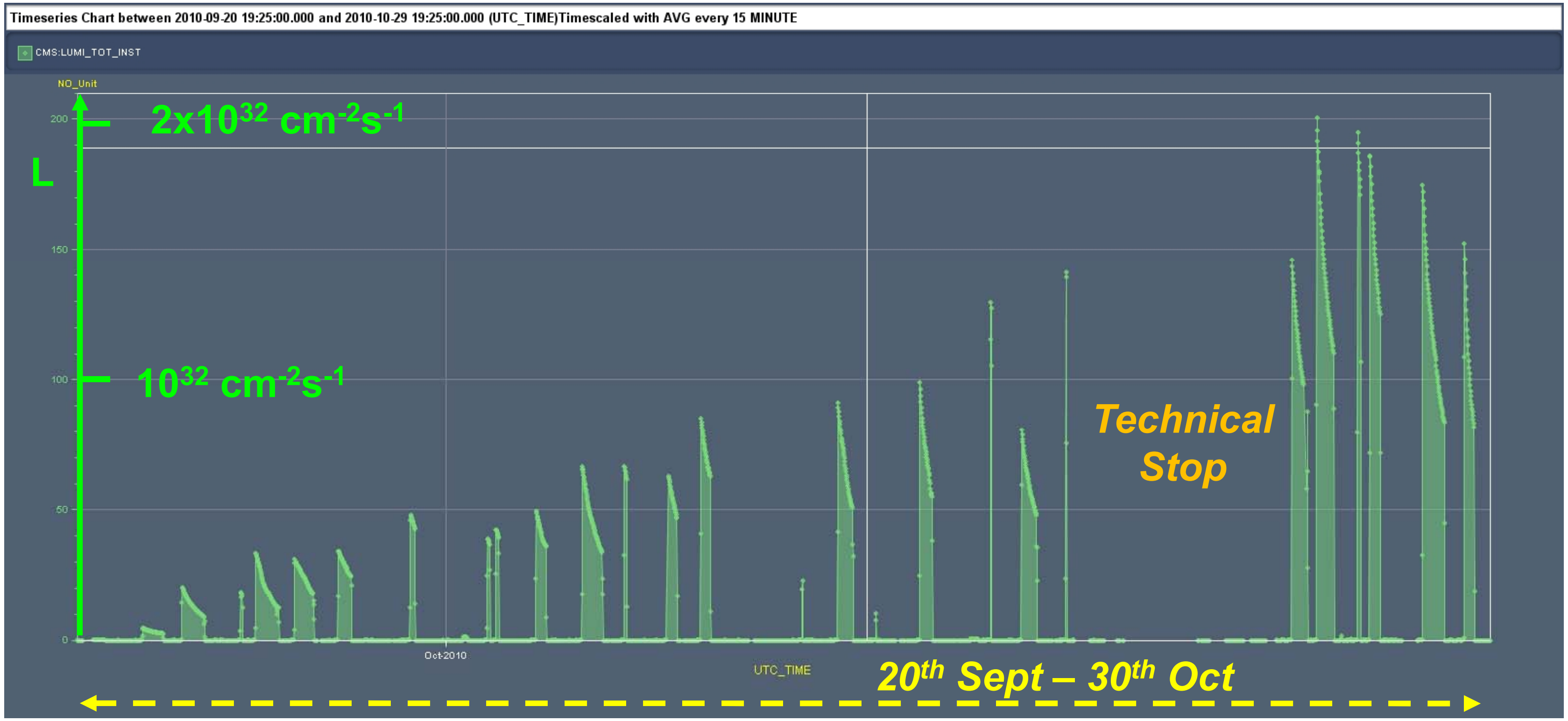
Operation with 150 ns

- Operation with 150 ns was rather smooth - ***some warning signs cfor even higher intensities*** – see next slides.
- Bunch intensities were pushed slightly above design, emittances were 40% smaller than design.
- No problems with beam-beam effects, beam lifetimes typically 25 hours in collisions, luminosity lifetimes ~12-15 hours (due to emittance growth).

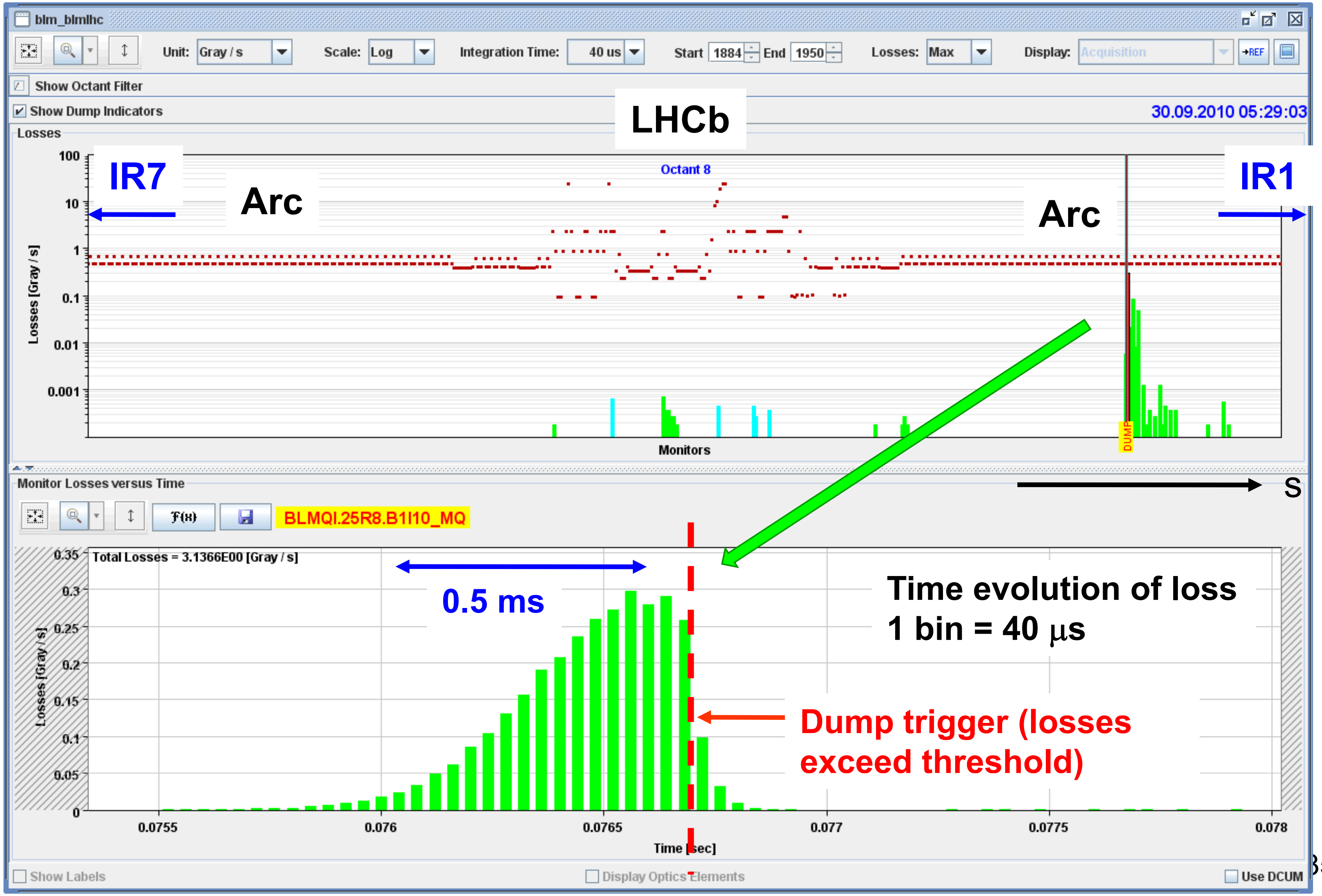


Unidentified Flying Objects - UFOs

- As the beam intensity was increased ***unexpected fast beam loss events*** were observed in the super-conducting regions of the ring:
  - *Fast loss over ~0.5-2 ms, leading to a dump of the beam.*
  - *Most events occurred during 'rock' stable periods.*
  - *Losses in regions of very large aperture.*
- The hypothesis quickly emerged that it is not the beam that moves to the aperture, but rather the opposite !
  - *'Dust' particles 'falling' into the beam, estimated size ~100 μm thick Carbon-equivalent object.*
- We do not understand the mechanism that triggers such events.
  - *It is clearly induced by (presence of) beam – electromagnetic fields at the surface of the vacuum chamber. Sparking ???*

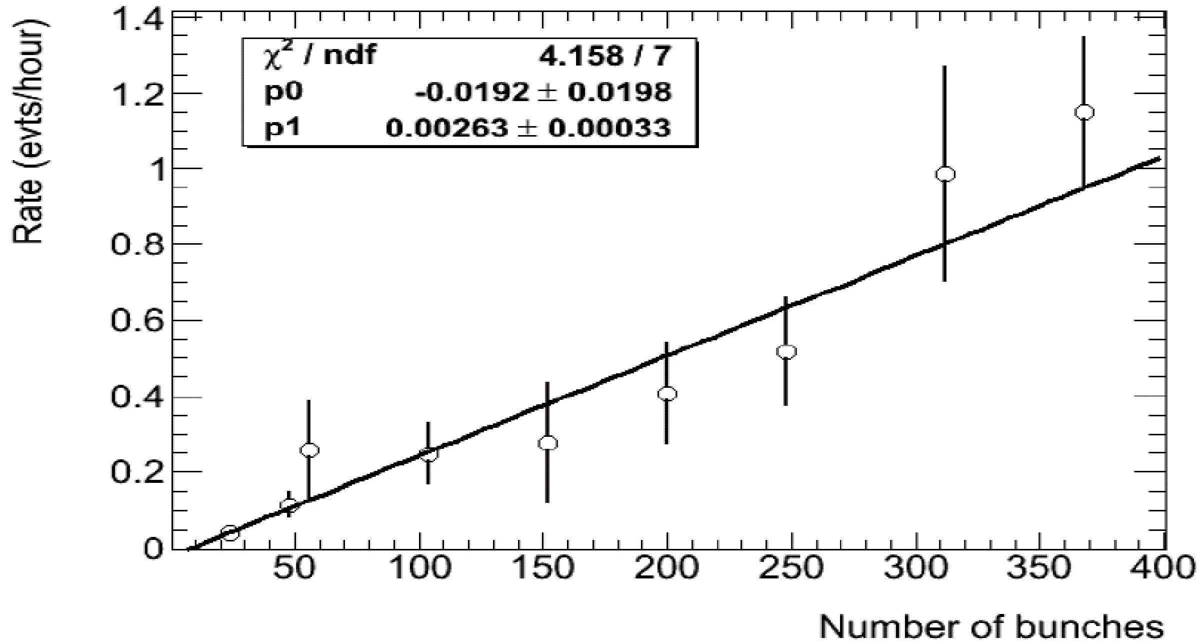
Example of a UFO (152 bunches)

Beam loss monitor post-mortem



A worrying correlation…

E. Nebot



- The UFO rate keeps increasing with intensity, even if only few of them lead to a beam dump (< 10%).
- The beam dump rate was reduced by increasing the thresholds of the beam loss monitors by a factor 3 – we were initially too conservative.

Vacuum effects

- Vacuum pressure increases were observed around the 4 experiments from the moment LHC switched to 150 ns train operation – issue became more critical as the intensity increased.

  Effects can be suppressed by solenoids (CMS, ALICE stray fields…).

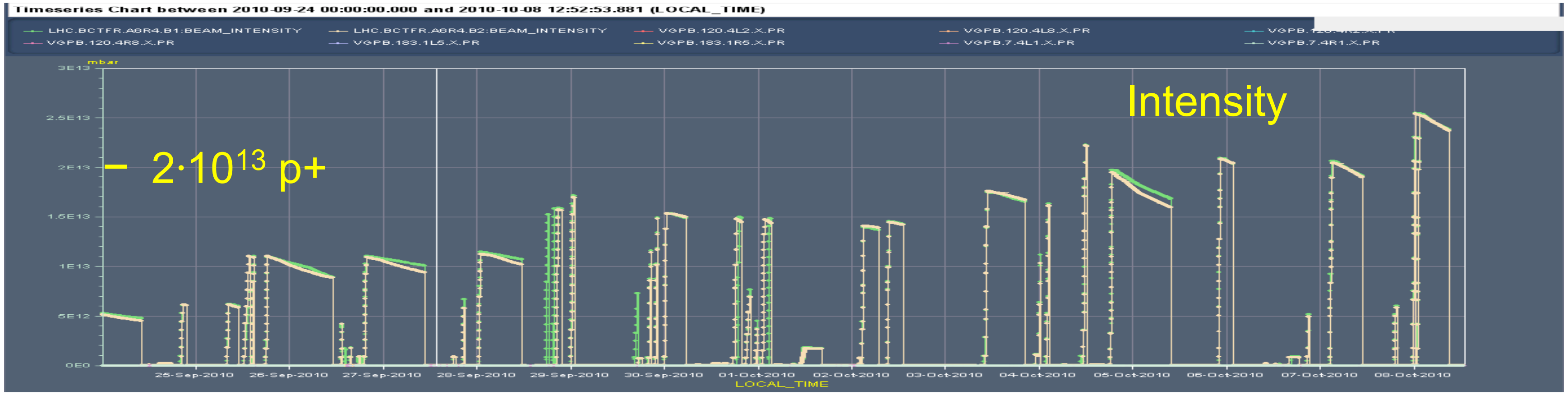
- It was not possible to operate the LHC with bunch spacing of 50 ns for experiments data taking because the vacuum pressure increases were already too large at injection.

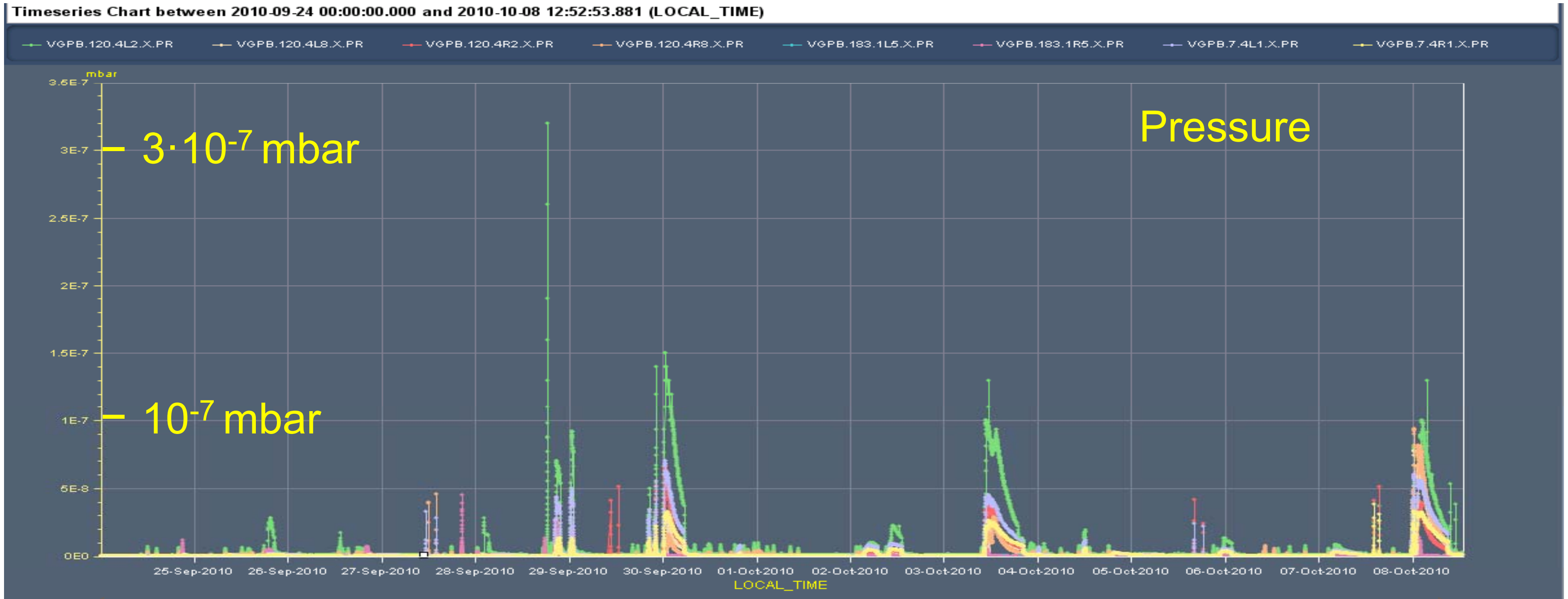
  Pressures easily exceeded 4×10^{-7} mbar (normal is 10^{-9} or less) leading to closure of the vacuum valves.

- Signs of cleaning by beam, with strong dependence on bunch intensity and bunch spacing.

  *Consistent with the signature of **electron clouds**.*

Intensity and vacuum (150 ns)





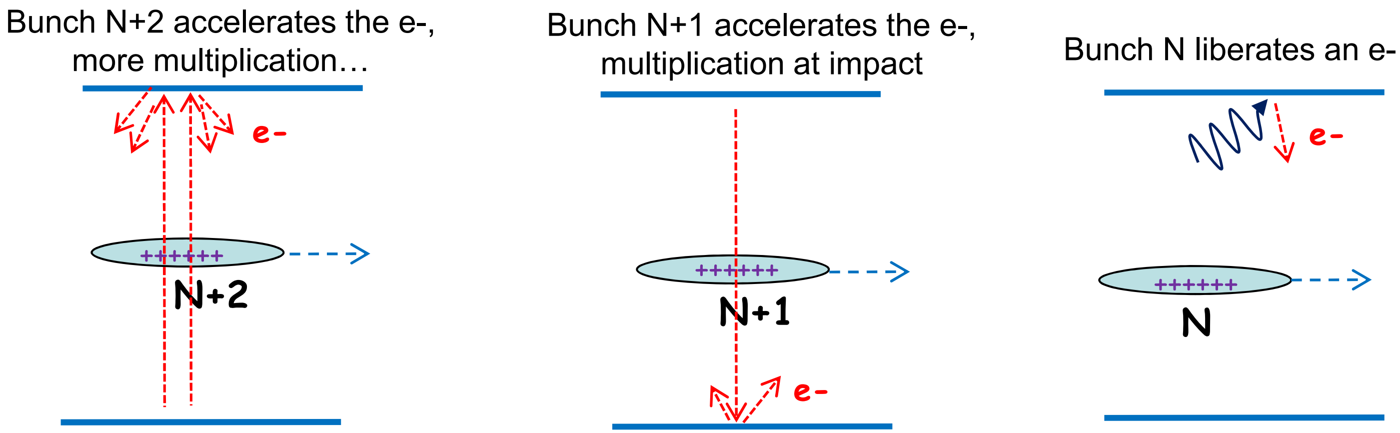
24th Sept – 8th Oct

Electron clouds

… affect high intensity beams with positive charge and closely spaced bunches.

- Electrons are generated at the vacuum chamber surface by beam impact, photons…
- If the probability to emit secondary e- is high (enough), more e- are produced and accelerated by the field of a following bunch(es). Multiplication starts…
  - *Electron energies are in the 10- few 100 eV range.*
- The cloud of e- can drive pressure rise, beam unstabilities and possibly overload the cryogenic system by the heat deposited on the chamber walls !

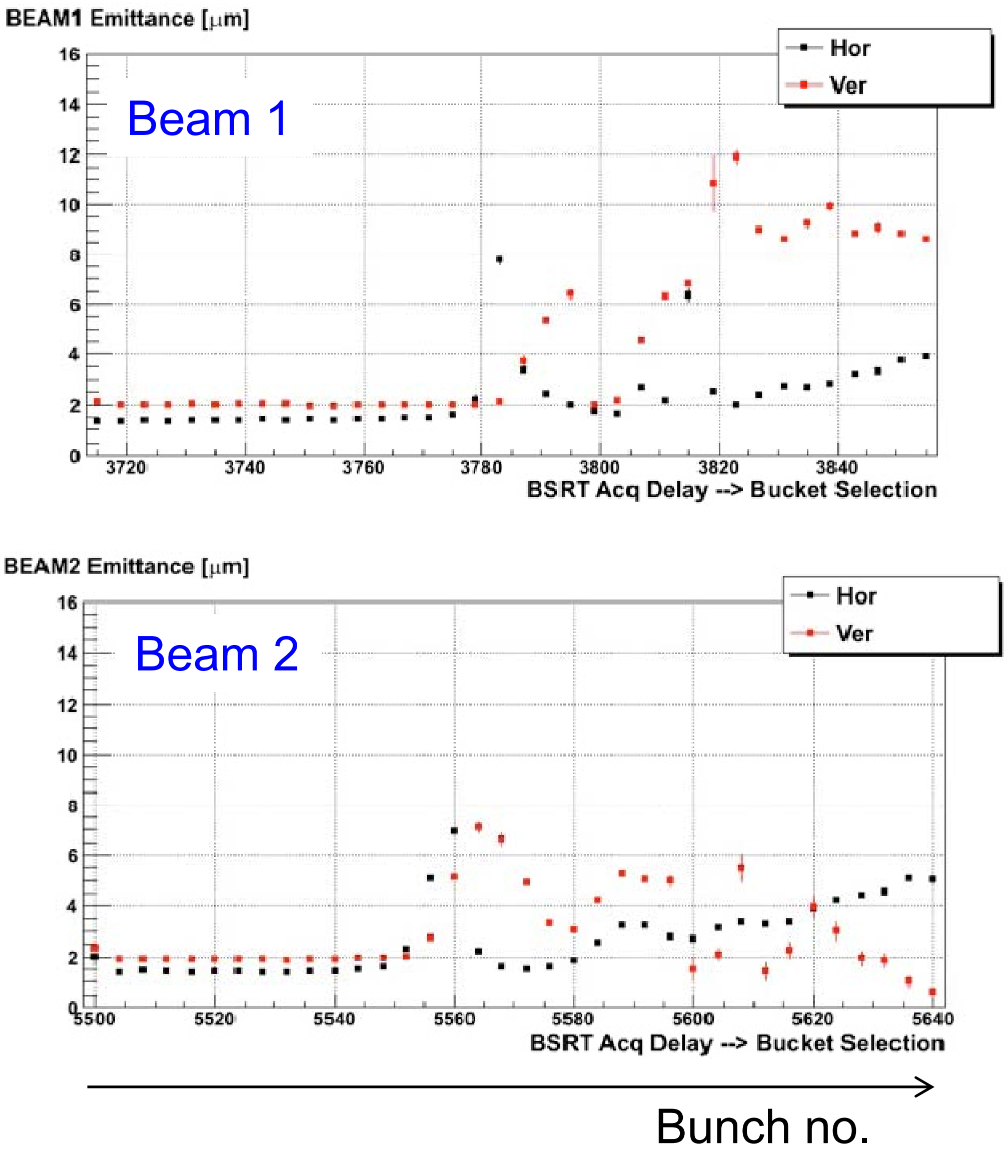
→ The cloud can 'cure itself': the impact of the electrons cleans the surface (Carbon migration), reduces the electron emission probability and eventually the cloud disappears – ***'beam scrubbing'***



Electron clouds at LHC

- In principle no electron cloud was expected with 150 ns beams.
  - *Room temperature vacuum chambers are coated with a NEG that kills/reduces the likelihood of electron clouds.*
  - *But not the few pieces at the transition between cold and warm regions.*
- With smaller bunch spacing of 50 ns, signatures of e-cloud eveywhere:
  - *Steep vacuum pressure dependence on spacing of trains.*
  - *Emittance growth along a train of bunches.*
  - *Instability of bunches at the end of trains.*
  - *Heat load on the vacuum chamber beam screen of some 10 mW/m with 200 bunches at injection → the cloud is present in the arcs !*
- It seems that the secondary emission yield is too high (~2.5 while ~1.5 was expected) and that we will have to cure the e-cloud before starting operation with 50 ns.
  - *Test/comparison with 75 ns spacing taking place at the moment.*

Beam (in)stability with e-clouds



Example of beam emittance (size) growth along a train of 50 ns bunches.

Bunches from the second ½ of the train are affected by the e-cloud that builds up along the train.

How to overcome e-cloud?

- Inject as much beam as you can at injection (run at the limit of the vacuum / beam stability).
  - *Must keep a high intensity and strong cloud activity since more cloud means more cloud cleaning…*

- Operate for some time, then re-inject fresh beam/higher intensity, always staying at the vacuum / stability limit.

- Iterate until conditions are acceptable / good.
  - *This takes many days (weeks…) – experience from the SPS.*

- Ramp the beams. Hope that the cleaning is also good for the conditions at 3.5 TeV, or else one has to (partly) repeat the exercise at 3.5 TeV…

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Ions ≈ protons at the LHC

- The ion program of the LHC is based on **Pb^{82+}** for 2010/2011.
- A 4 week ion run is in progress just now - until the beginning of December.
- At the LHC the difference between Pb ions and protons is very small because of the high energy.
  - *Transition is rather 'easy'.*
  - *Main difference between ions and protons is the RF frequency (small difference in speed) :*
    - *RF frequency swing from injection to 3.5 TeV is 5 kHz for ions and 800 Hz for protons (wrt 400 MHz).*
- To first order, all one has to do is to change the frequency of the RF system !!

Pb collisions were established ~54 hours after the first injections.

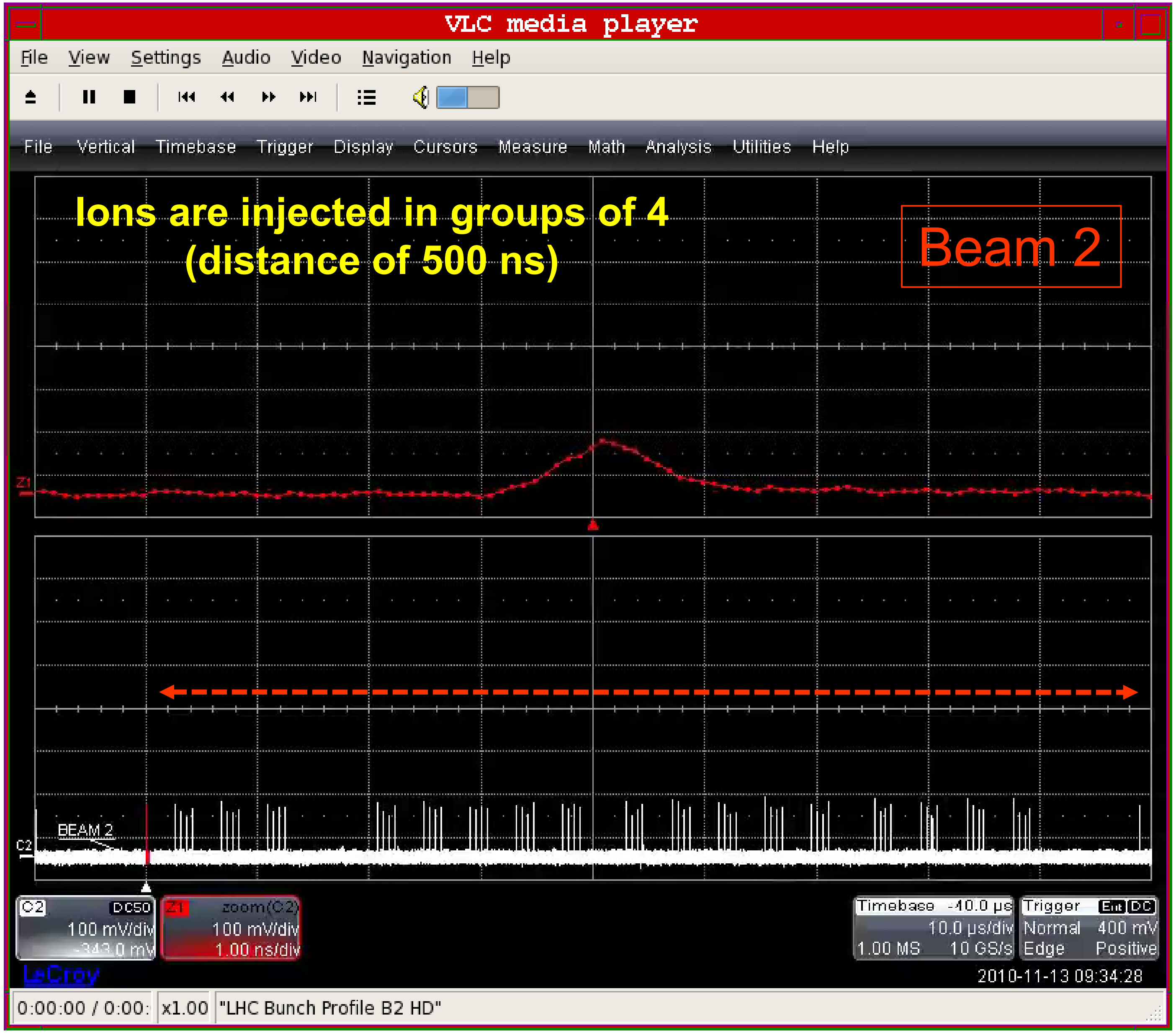
Ions versus protons (2010)

- Pb bunches are more than a factor ~10^3 less intense than protons.
- The bunch structure is different, with a spacing of 500 ns between groups of bunches.

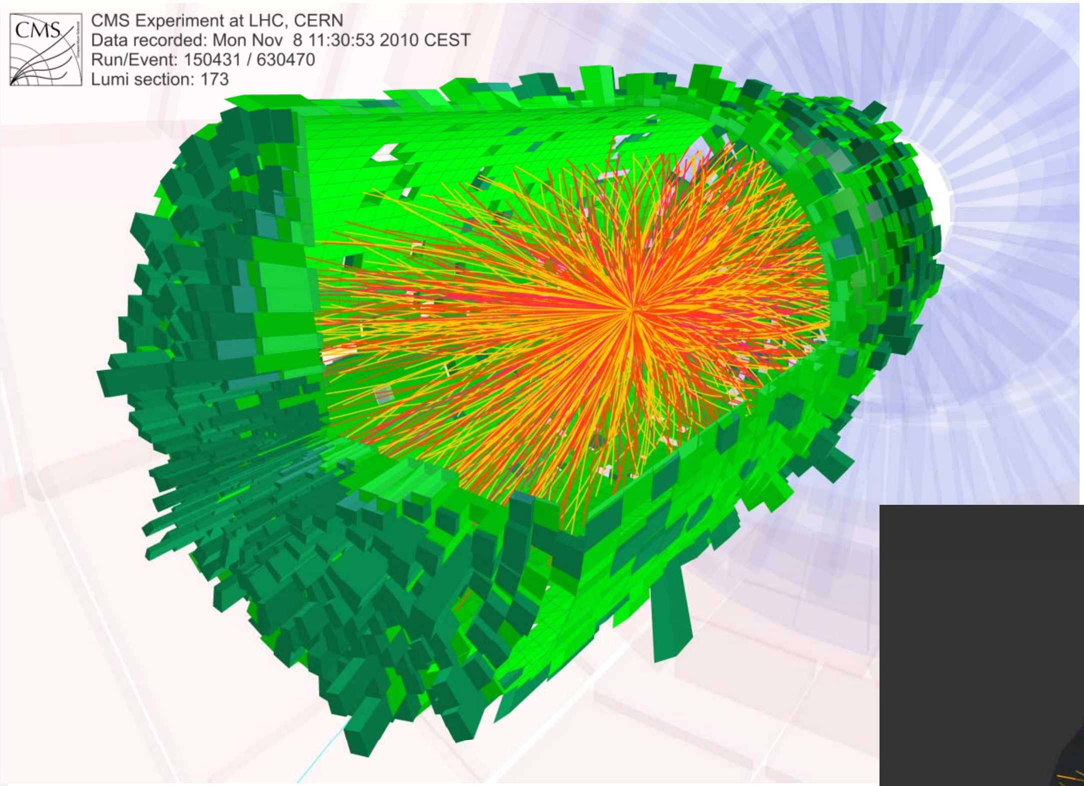
Luminosity for ions is ~ 10^7 times lower than for protons, but the cross-sections are much larger !

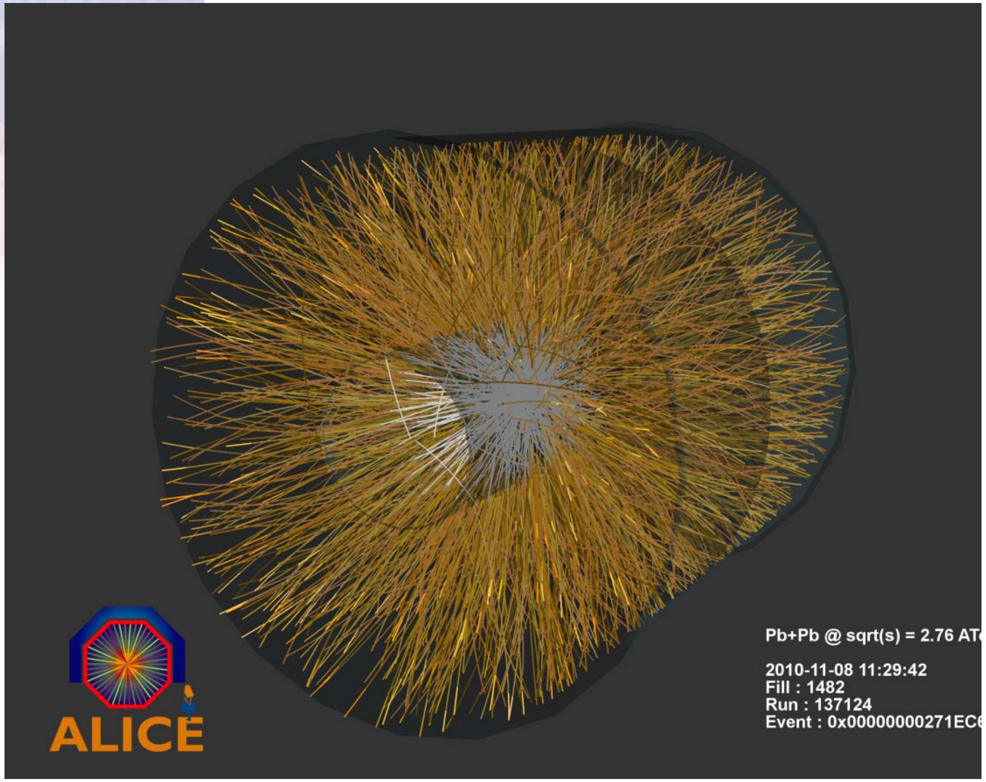
Parameter	Protons	Pb82
N (particles/bunch)	1.2×10^{11}	$(7\text{-}10)\times10^{8}$
k_b (no. bunches)	368	121
CM energy (TeV)	7	574
L ($cm^{-2}s^{-1}$)	**2×10^{32}**	**$(2\text{-}3)\times10^{25}$**

69 bunches ion beam



Spectacular events



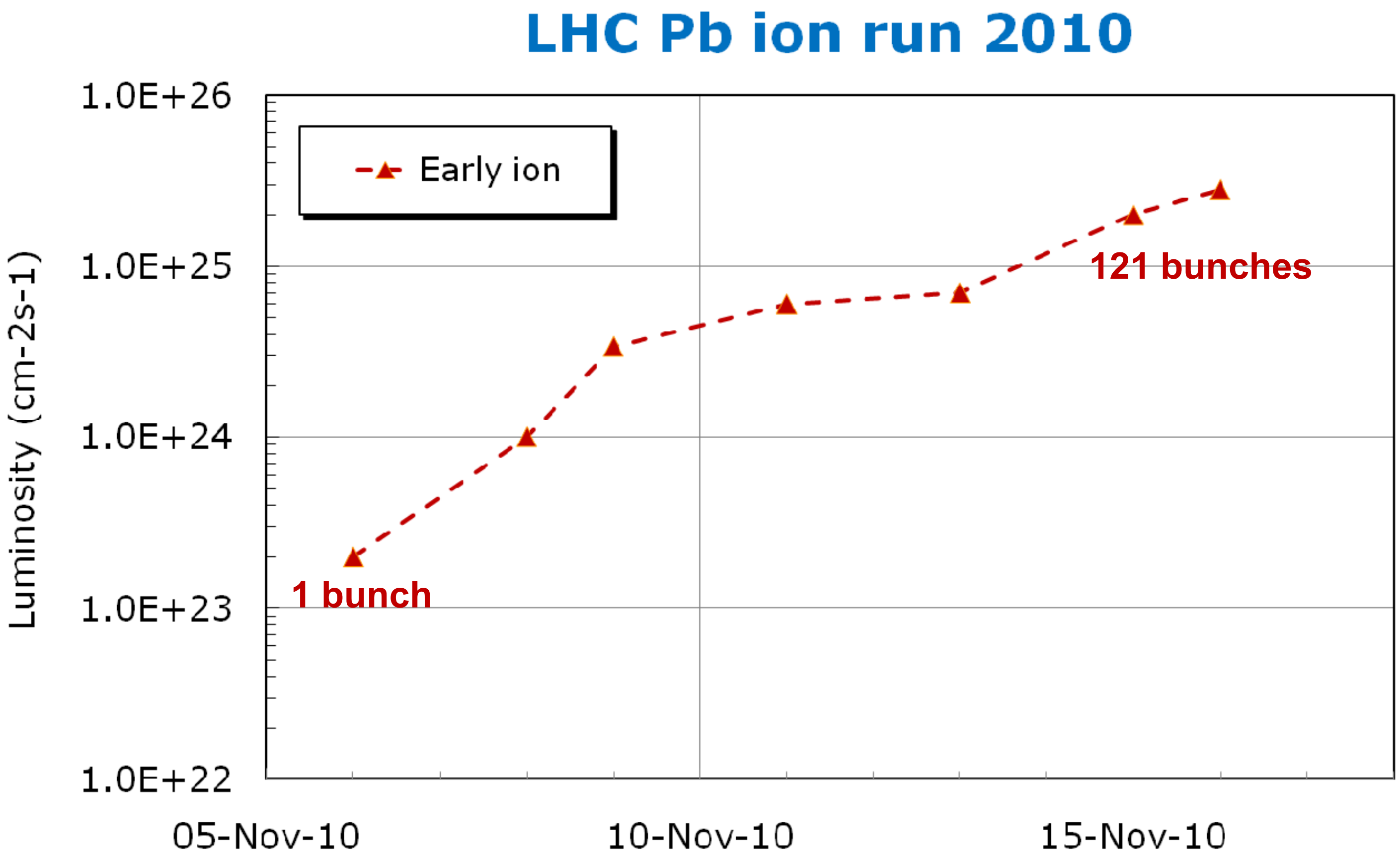


Peak luminosity performance

Peak luminosity = 2.8×10^{25} $cm^{-2}s^{-1}$

(121 bunches/beam, 114 colliding bunches)

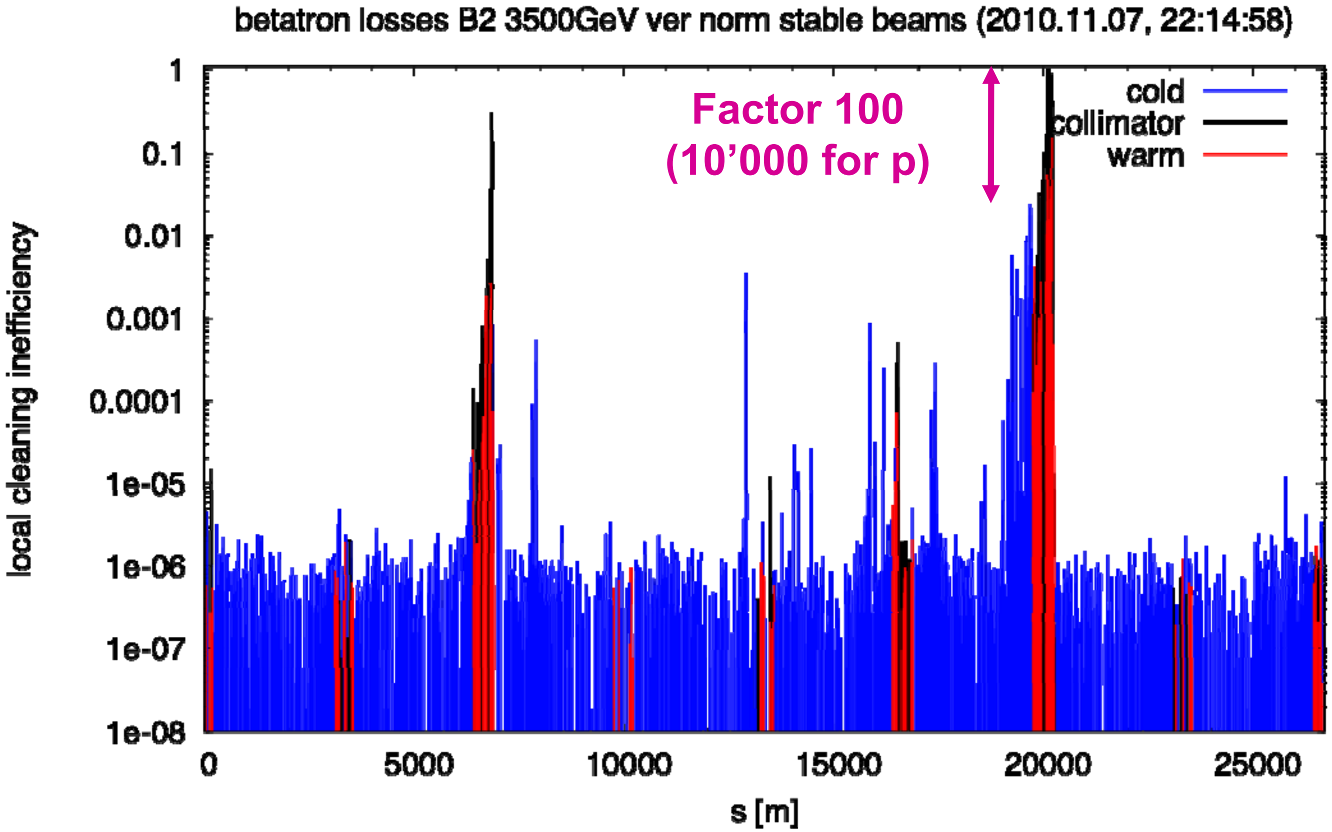
Integrated ion luminosity now ~2 μb^{-1}



Ion collimation

Ions induce **higher losses** due to **fragmentation and dissociation**: fragments lost at the first dipoles downstream of collimation.

- *Efficiency is a factor 100-500 worse than for protons >>* ***intensity limited*** *!*
- *Similar issue near the experiments due to Bound Free Pair Production (BFPP) where one Pb ion captures an e- in a collision and is lost as soon as it reaches the bending sections of the arcs.*



Outline

Introduction

Proton operation

High intensity issues

Ion operation

Outlook

Present LHC proton parameters

Parameter	Present	Nominal
N (p/bunch)	**1.2×10^{11}**	**1.15×10^{11}**
k_b (no. bunches)	368	2808
ε (μm rad)	**2.4-4**	**3.75**
β^* (m)	3.5	0.55
σ^* (μm)	45-60	16
L ($cm^{-2}s^{-1}$)	2×10^{32}	10^{34}

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

Improvements for 2011:

- Reduction of β^* to 2-2.5 m (measured aperture larger than design).
- Increase of N to 1.4×10^{11} or higher if possible.
- Increasing number of bunches using 50 ns or 75 ns spacing.
  - *Must overcome e-clouds effects.*

Outlook 2011

Possible gains in luminosity:

- 50 ns trains x 3
- β^* = 2.5 m x 1.4
- Bunch charge to 1.4×10^{11} p x 1.4

Total x 6

Luminosities in the range $4 \times 10^{32} – 10^{33}$ are within reach

Conclusions

- Luminosity target of 10^{32} $cm^{-2}s^{-1}$ has been reached.
- The 2011 run will start end of February.
  - *In 2011 peak luminosities ≥ 4×10^{32} $cm^{-2}s^{-1}$ can be expected.*
  - *Peak luminosity and bunch configuration will depend on e-cloud effects.*
  - *1 fb-1 in 2011 is within reach.*
- Ongoing discussions to increase the energy in 2011 to 4 (4.5) TeV.
  - *Decisions must come soon, as this requires ~2 weeks of electrical circuit commissioning.*
- The Pb ion is progressing smoothly.
  - *Transition was fast.*
  - *A similar run will take place end of 2011.*

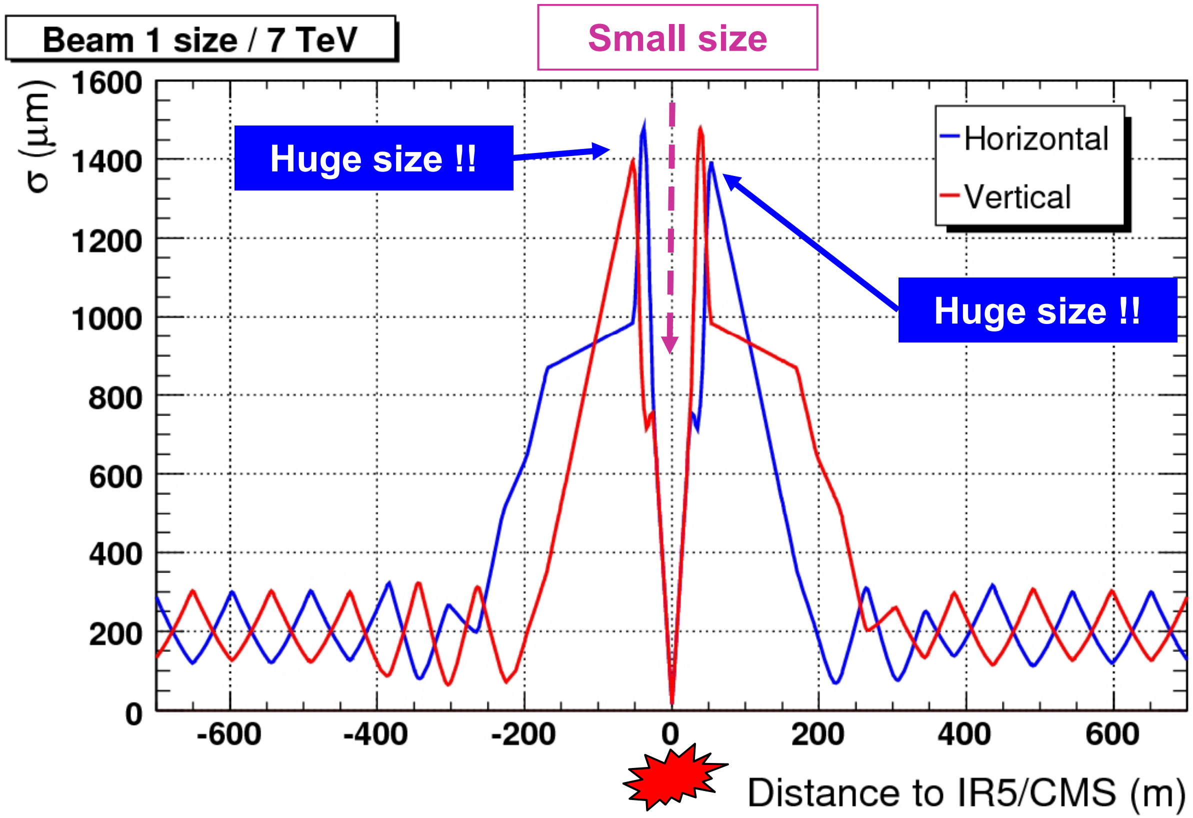
Spares

β* and aperture

- The figure of merit for the focusing at the collision point is given by β* - the beam envelope function. The beam size σ is given by

$$\sigma^2 = \beta^* \varepsilon$$

- β* / s are limited towards small values by the aperture of the focusing magnets (quadrupoles) around the collision point.

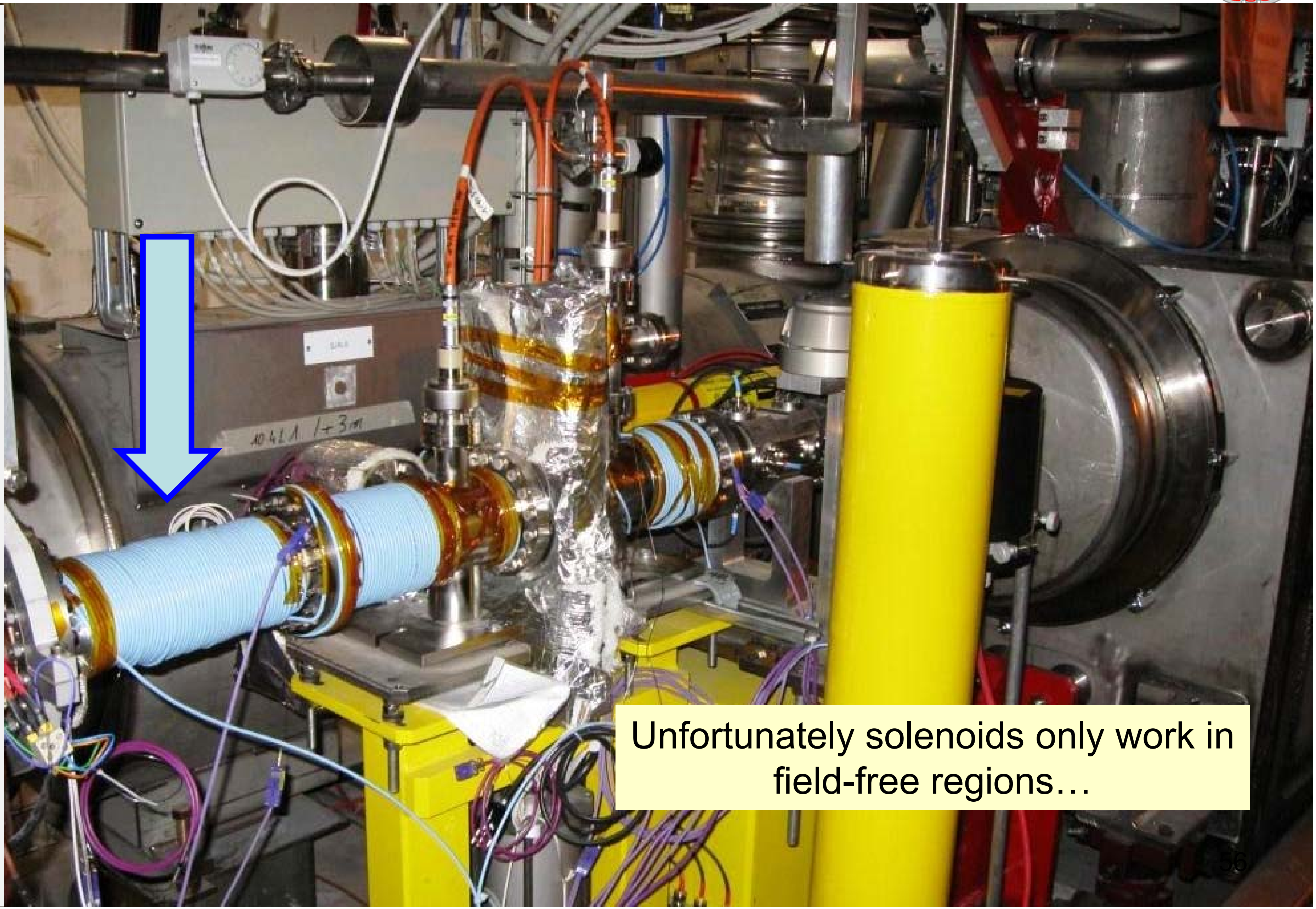


Smaller the size at IP:

→ Larger divergence (phase space conservation !)

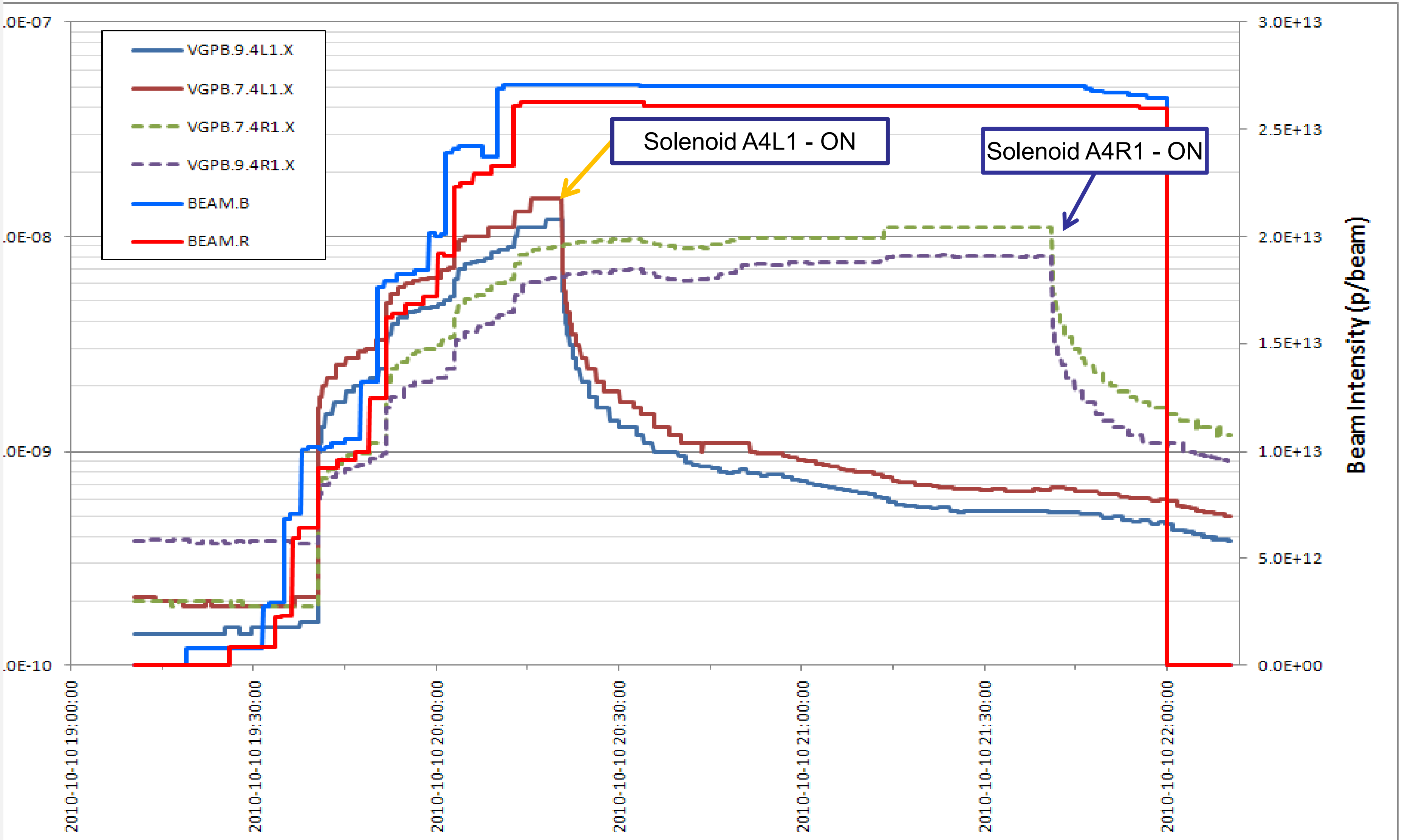
→ Faster beam size growth in the space from IP to first quadrupole !

Solenoids (around ATLAS) as cure for clouds…



Unfortunately solenoids only work in field-free regions…

Effect of solenoids



Incident of Sept. 19th 2008

The final circuit commissioning was performed in the week following the startup with beam.

- During the last commissioning step of the last main dipole circuit an electrical fault developed at ~5.2 TeV (8.7 kA) in the **dipole bus bar (cable)** at the interconnection between a quadrupole and a dipole magnet.

  Later correlated to quench due to a local R ~220 nΩ – nominal 0.35 nΩ.

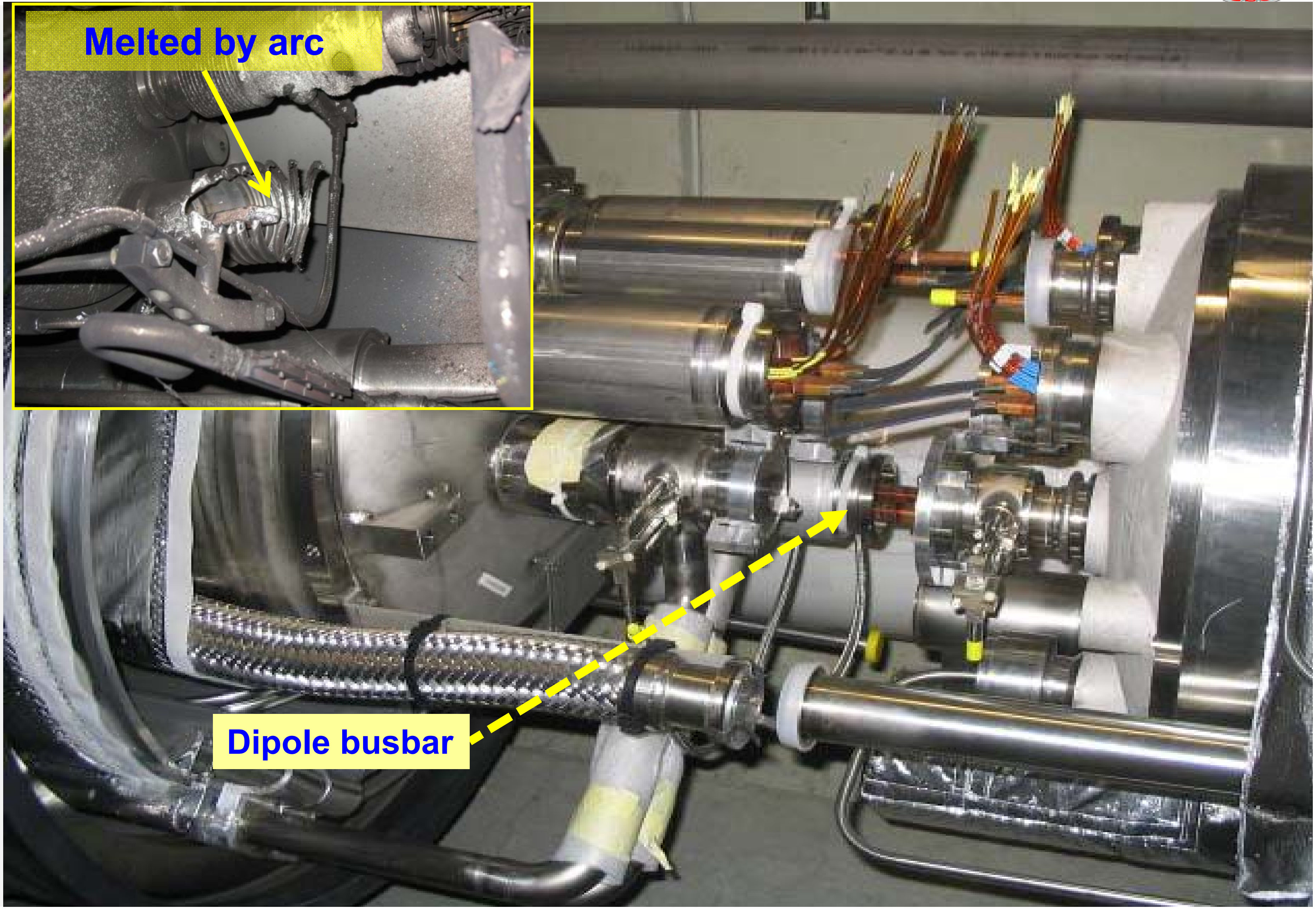
- An electrical arc developed and punctured the helium enclosure.

  Around 400 MJ from a total of 600 MJ stored in the circuit were dissipated in the cold-mass and in electrical arcs.

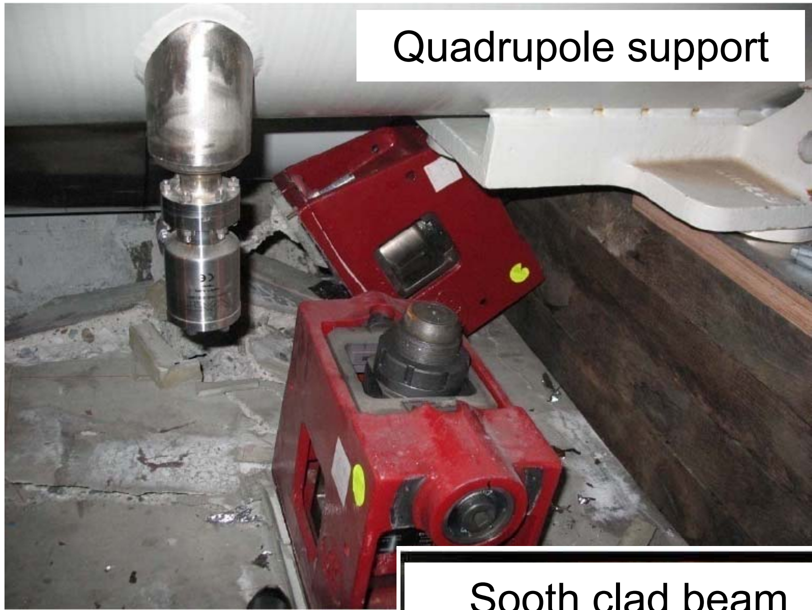
- Large amounts of Helium were released into the insulating vacuum.

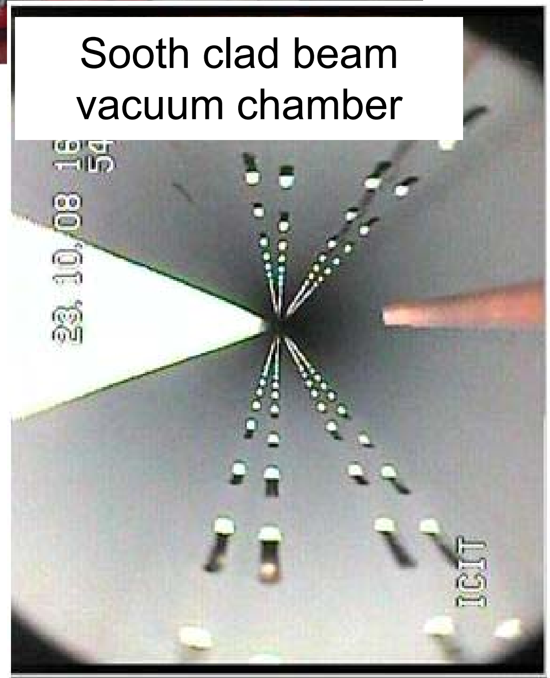
  The pressure wave due to Helium flow was the cause of most of the damage (collateral damage).

Magnet Interconnection



Collateral damage





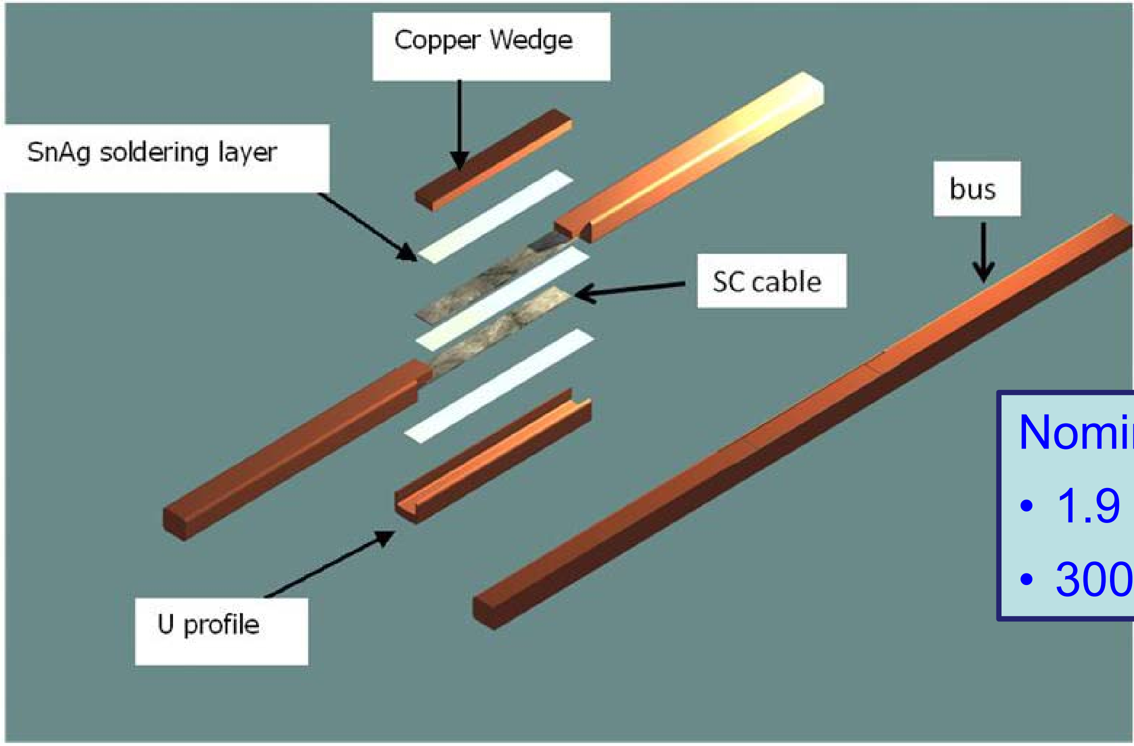
Main damage area covers ~ 700 metres.

- **39** out of 154 main **dipoles**,
- **14** out of 47 main **quadrupoles**

from the sector had to be moved to the surface for repair (16) or replacement (37).

Bus-bar joint

- 24'000 bus-bar joints in the LHC main circuits.
- 10'000 joints are at the interconnection between magnets.
  They are welded in the tunnel.



Nominal joint resistance:
- 1.9 K **0.3 nΩ**
- 300K **~10 μΩ**

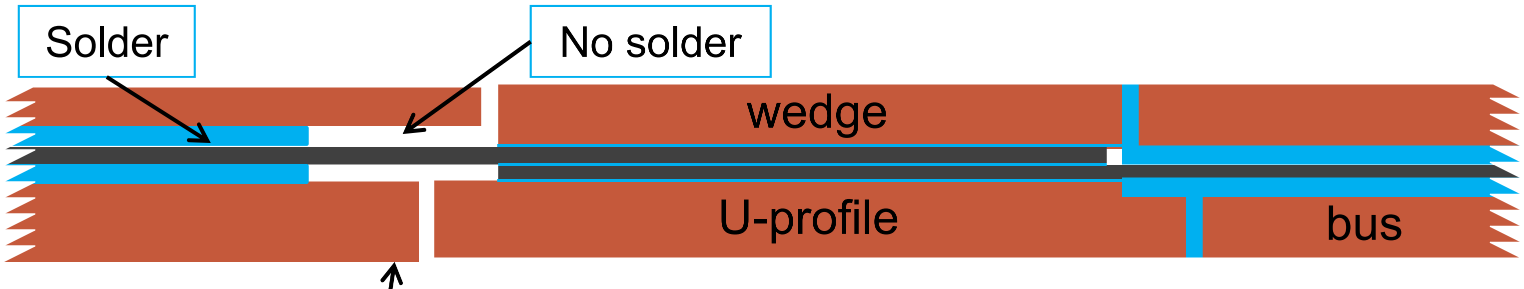
For the LHC to operate safely at a certain energy, there is a limit to maximum value of the joint resistance.

Joint quality

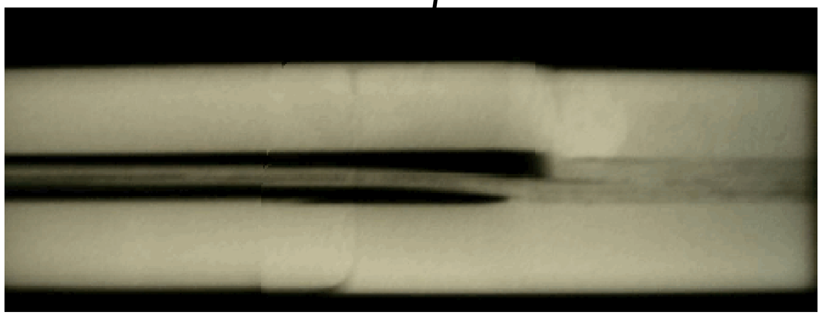
- The copper stabilizes the bus bar in the event of a cable quench (=bypass for the current while the energy is extracted from the circuit).

  Protection system in place in 2008 not sufficiently sensitive.

- A copper bus bar with reduced continuity coupled to a superconducting cable badly soldered to the stabilizer can lead to a serious incident.



X-ray of joint



- During repair work in the damaged sector, inspection of the joints revealed systematic voids caused by the welding procedure.

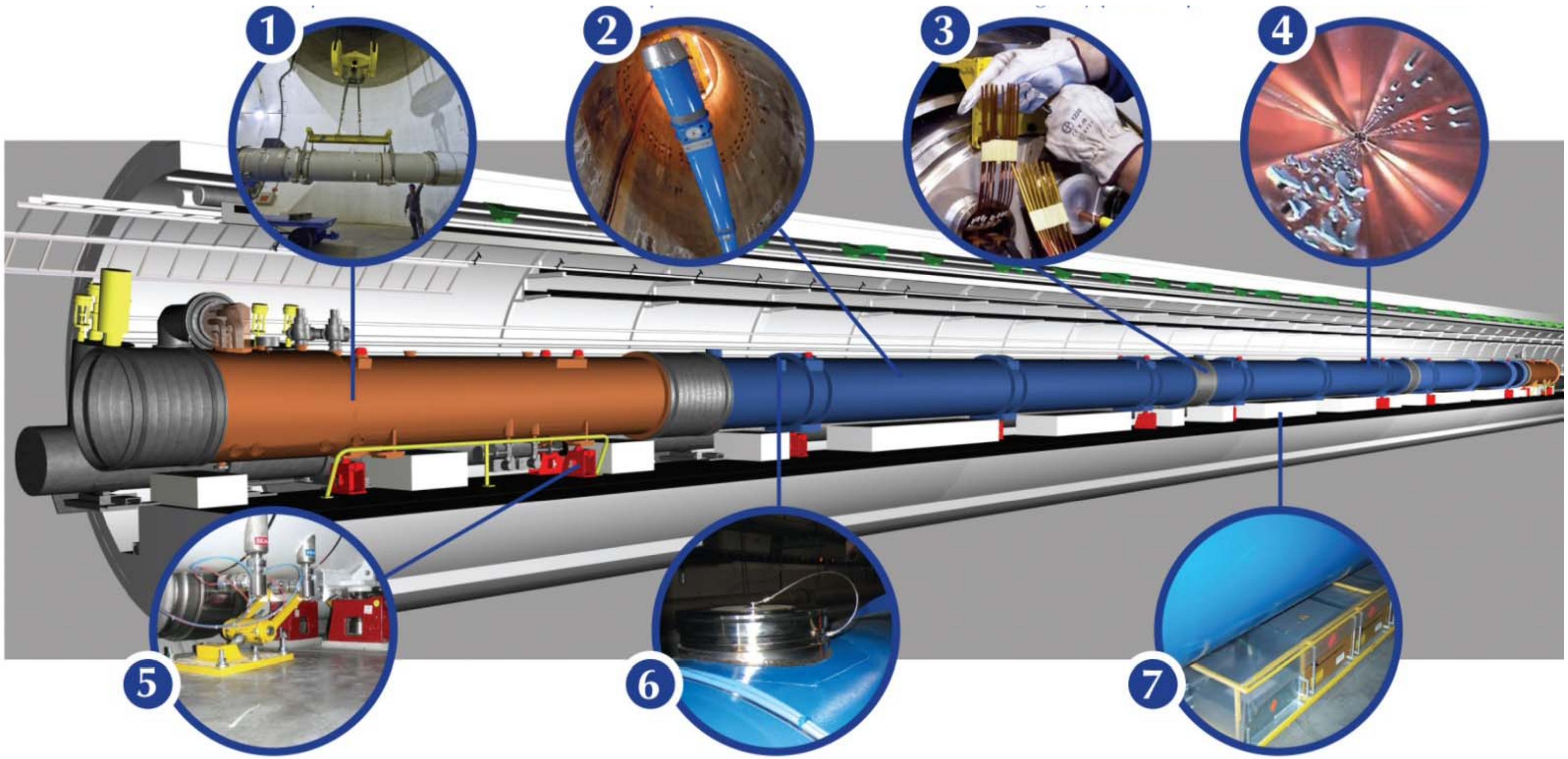
LHC repair and consolidation

14 quadrupole magnets replaced

39 dipole magnets replaced

204 electrical inter-connections repaired

Over 4km of vacuum beam tube cleaned



New longitudinal restraining system for 50 quadrupoles

Almost 900 new helium pressure release ports

6500 new detectors and 250km cables for new Quench Protection System to protect from busbar quenches

Collateral damage mitigation