LHC performance and prospects

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Linear Collider Workshop of the Americas

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Outline

Introduction

Proton operation

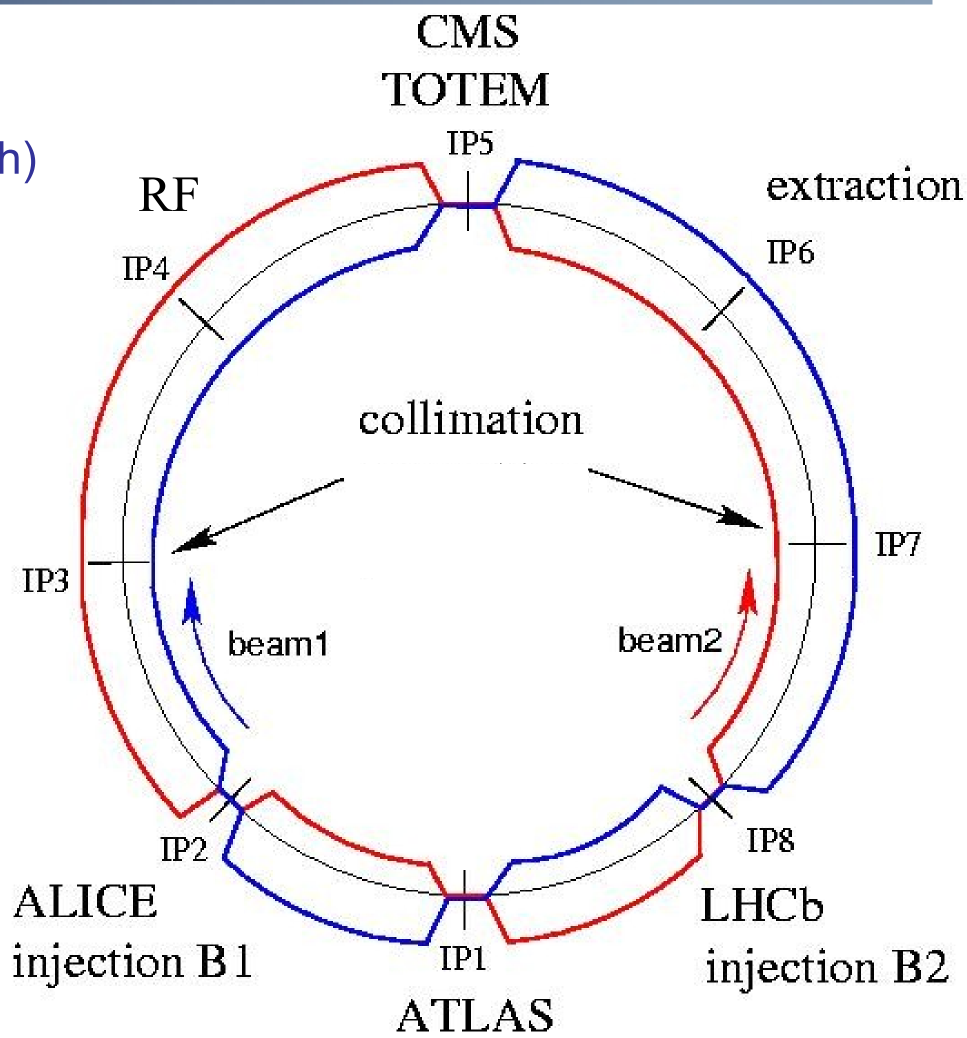
High intensity issues

Ion operation

Outlook

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



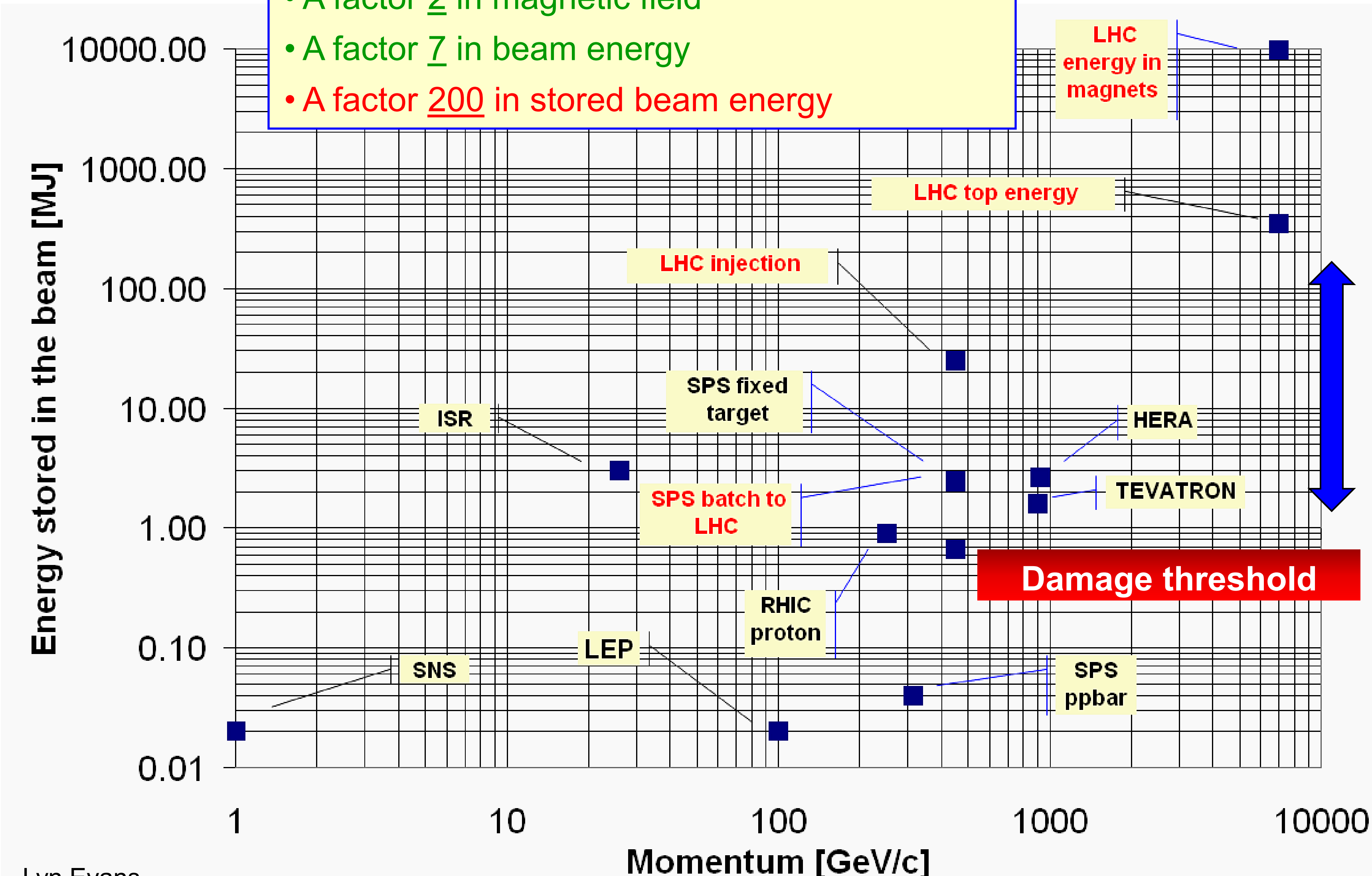
Nominal LHC parameters	
Beam energy (TeV)	7.0
No. of particles per bunch	1.15×10^{11}
No. of bunches per beam	2808
Stored beam energy (MJ)	362
Transverse emittance (μm)	3.75
Bunch length (cm)	7.6

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

Stored energy

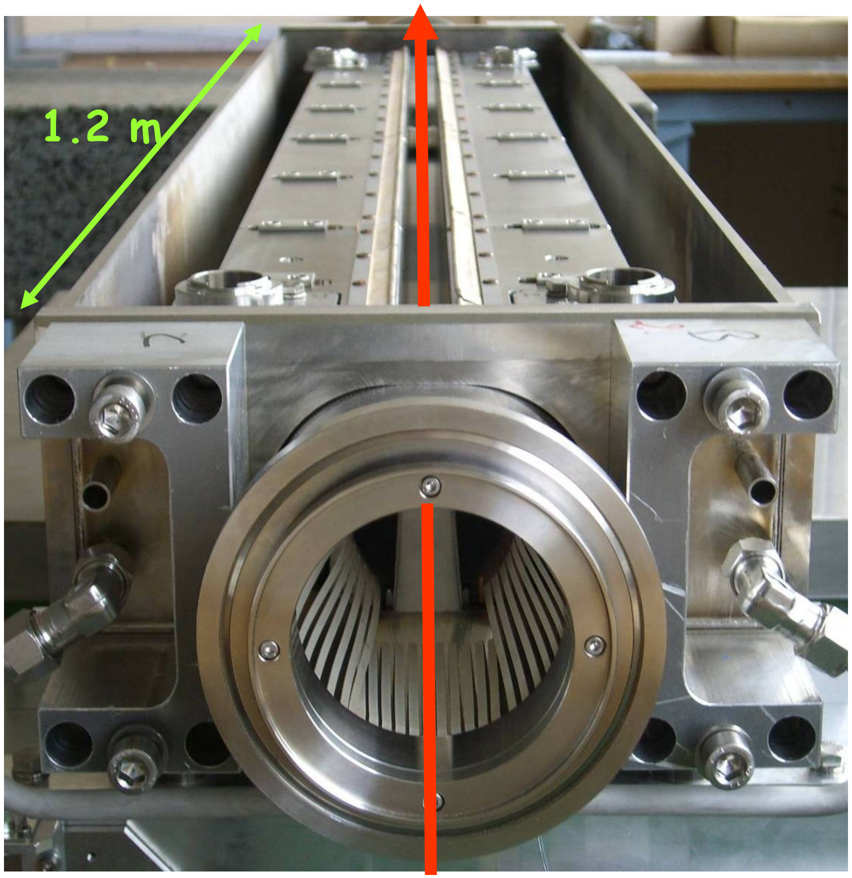
Increase with respect to existing accelerators :

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



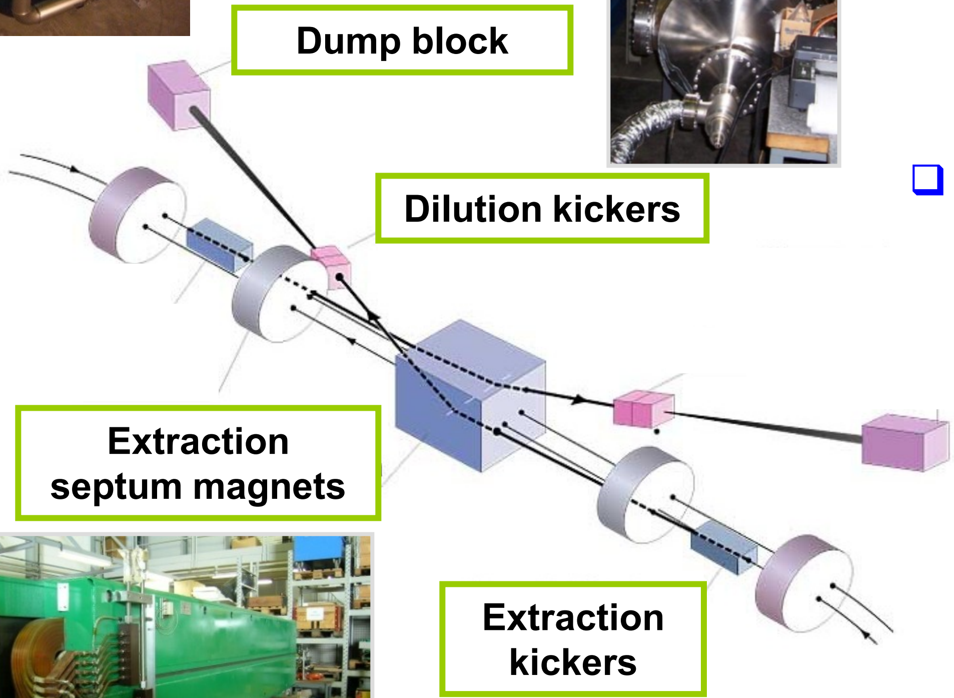
Collimation

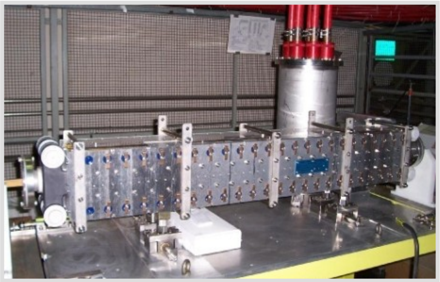
- To operate at nominal performance the LHC requires a large and complex collimation system
  - *Previous colliders used collimators mostly for experimental background conditions - the LHC can only run with collimators.*



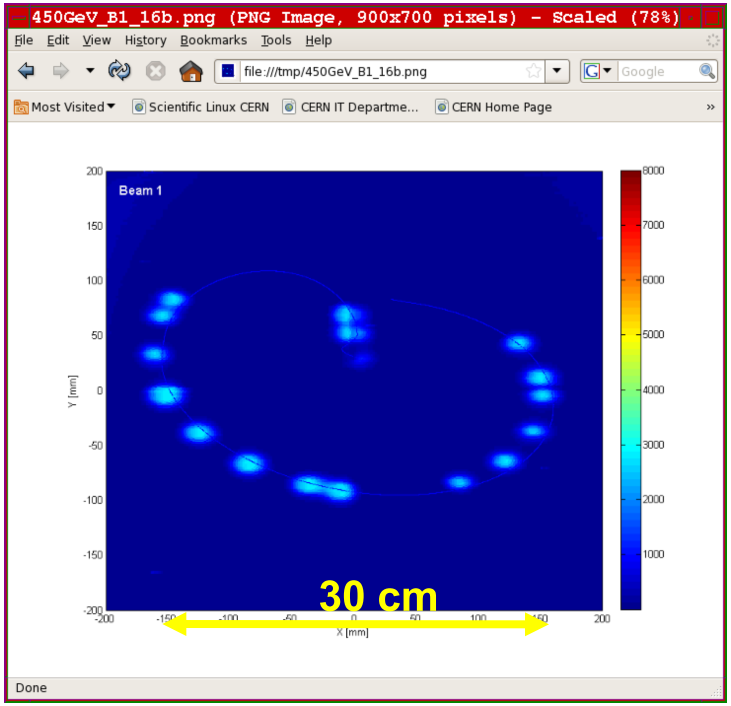
- Ensure 'cohabitation' of:
  - 360 MJ of stored beam energy,
  - super-conducting magnets with quench limits of few mJ/cm^3
- Almost 100 collimators and absorbers.
- Alignment tolerances <0.1 mm to ensure that over 99.99% of the protons are intercepted.
- Primary and secondary collimators are made of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



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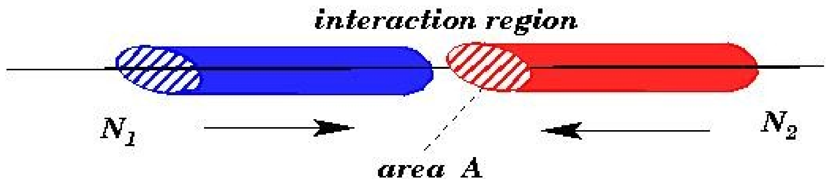
Luminosity : collider figure-of-merit

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) — **Optics property**

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

High beam "brillance" N/ε (particles per phase space volume)

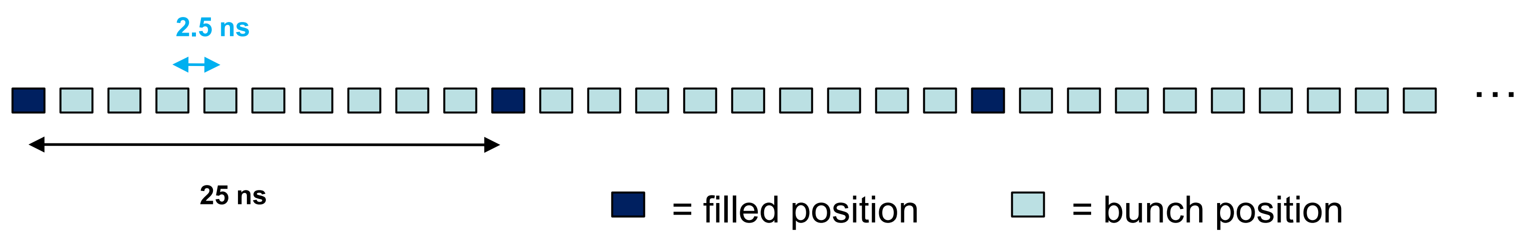
→ **Injector chain performance !**

Small envelope

→ **Strong focusing !**

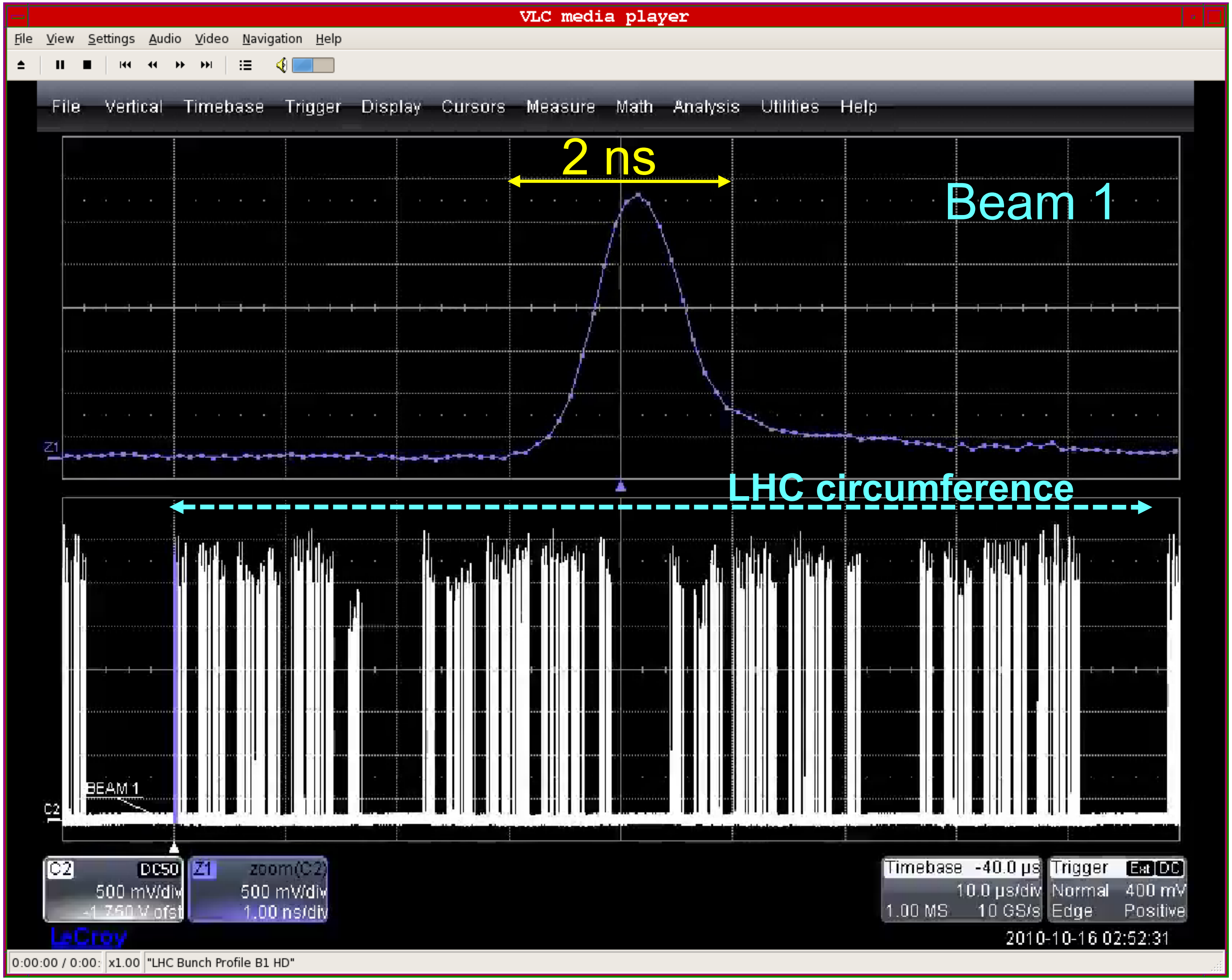
Bunch filling schemes

- 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 3564*** (- 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.*

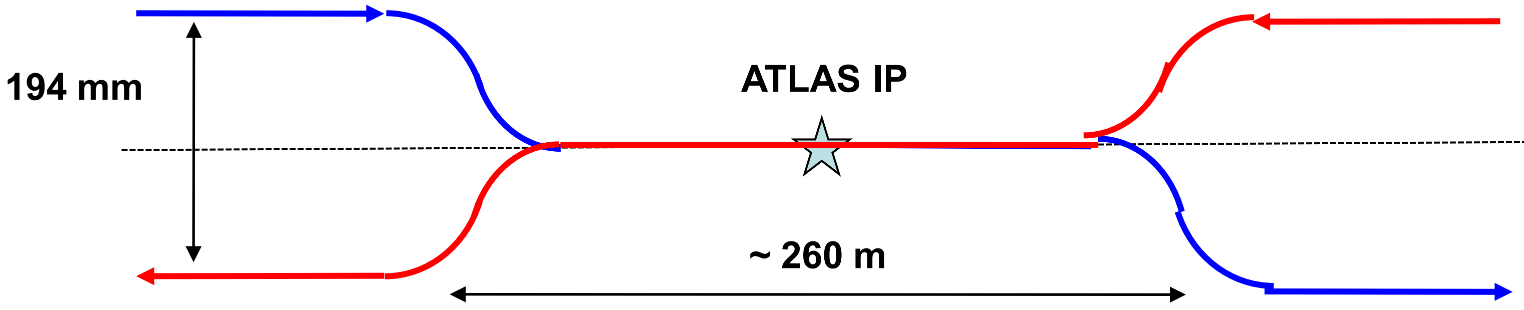
312 bunches



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 -1.760 V ofst
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 Ext DC Normal 400 mV Edge Positive
LeCroy
2010-10-16 02:52:31
0:00:00 / 0:00: x1.00 "LHC Bunch Profile B1 HD"

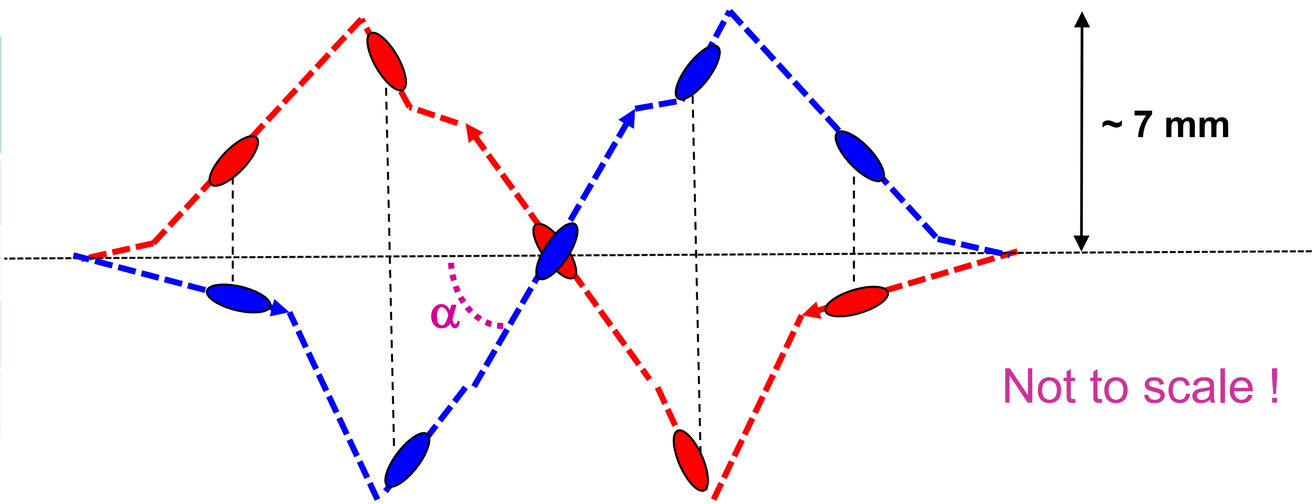
Separation and crossing: example of ATLAS

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**

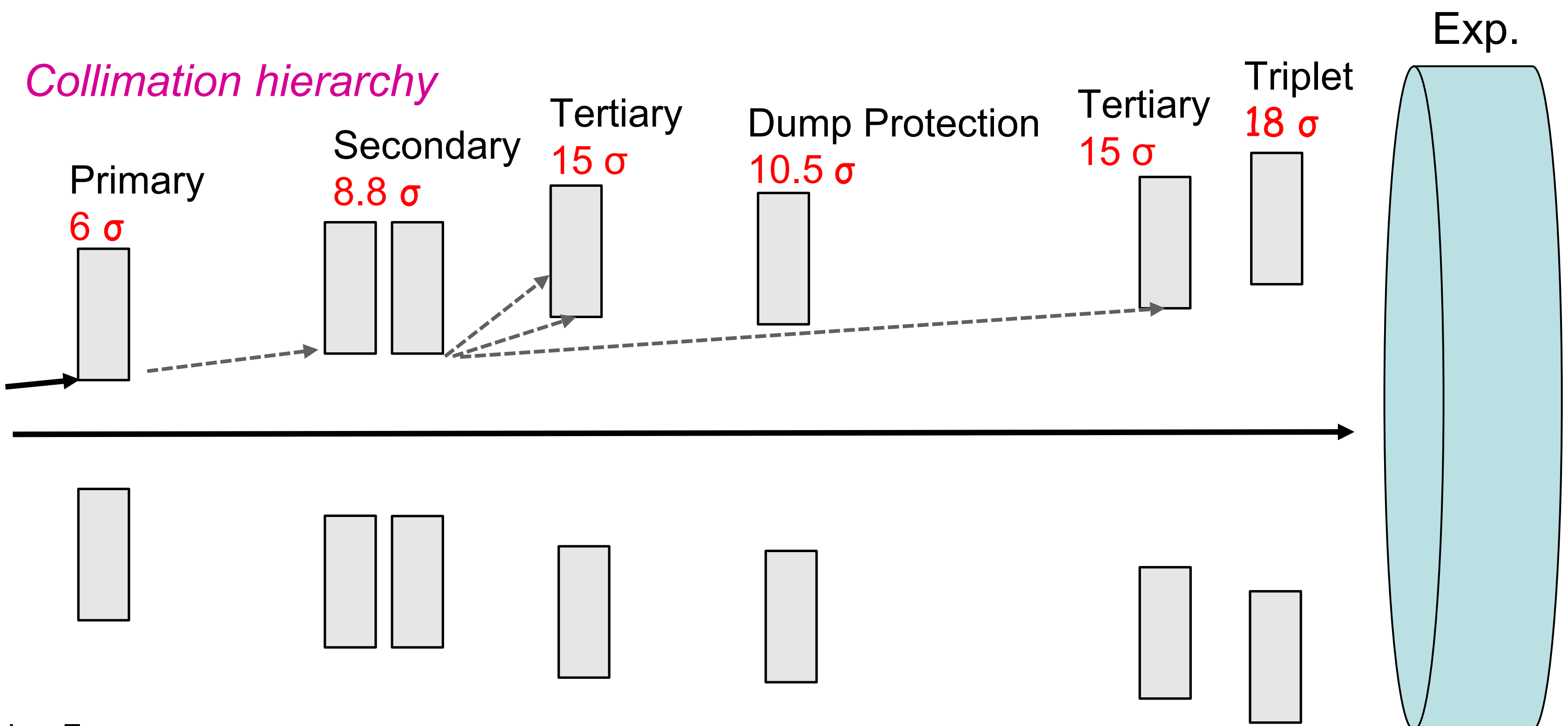


Aperture and collimation

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

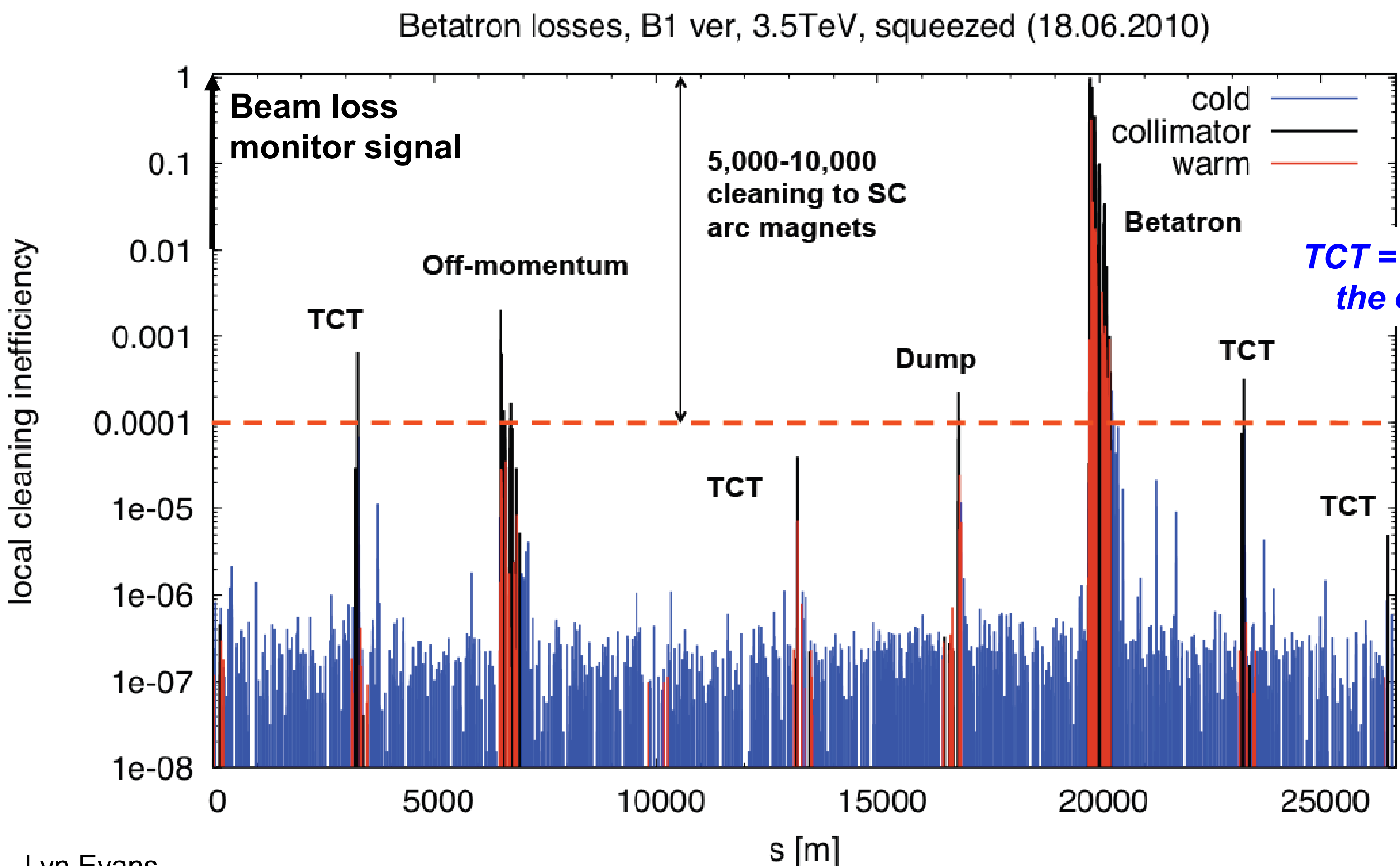
- *Hierarchy of collimators is essential to avoid quenching super-conducting magnets and for damage protection.*
- ***So far we never quenched a magnet with beam !***

⇔ excellent machine and collimation system stability !!!



Collimation

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



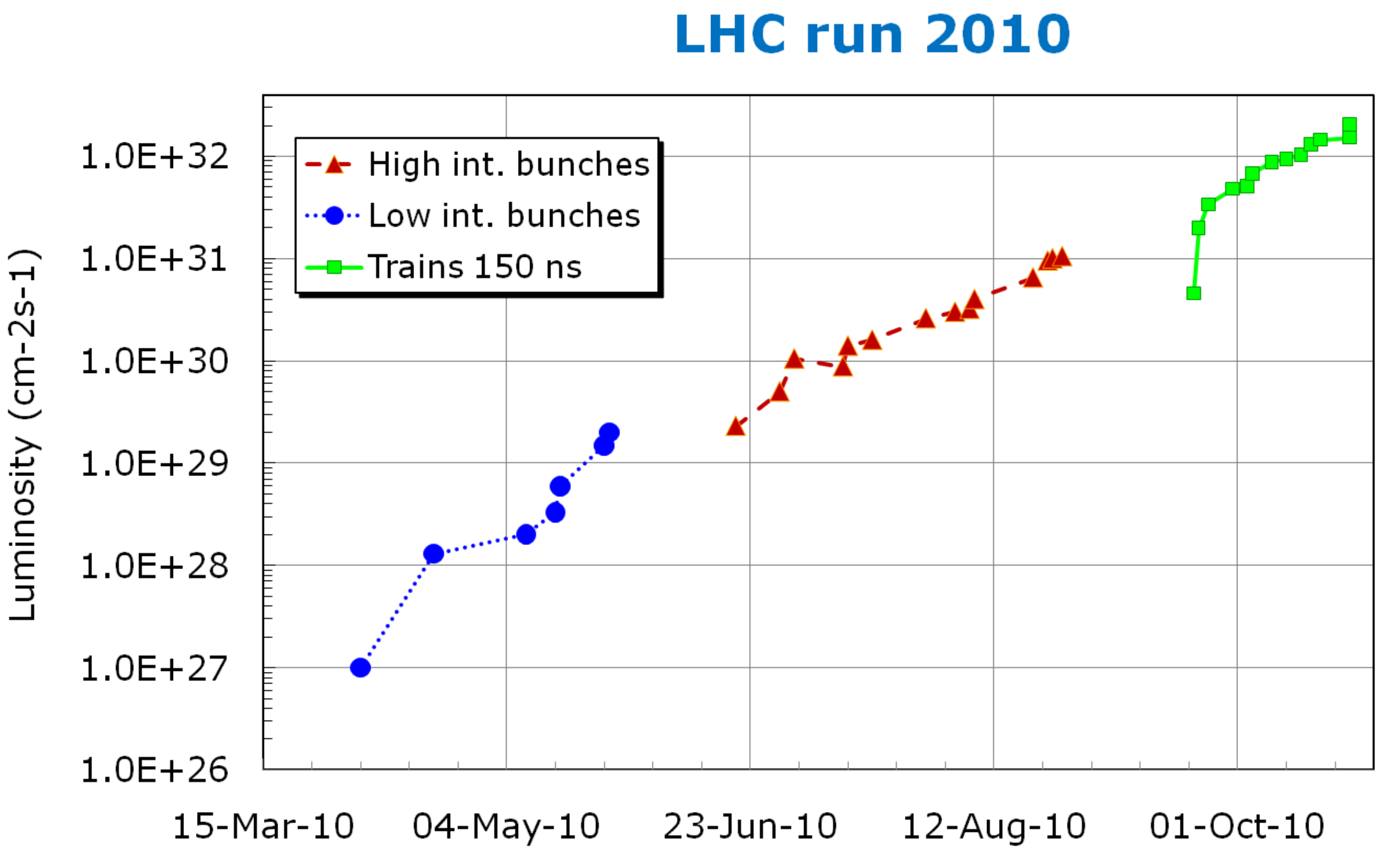
TCT = tertiary coll. at the experiments.

Lyn Evans

Peak luminosity performance

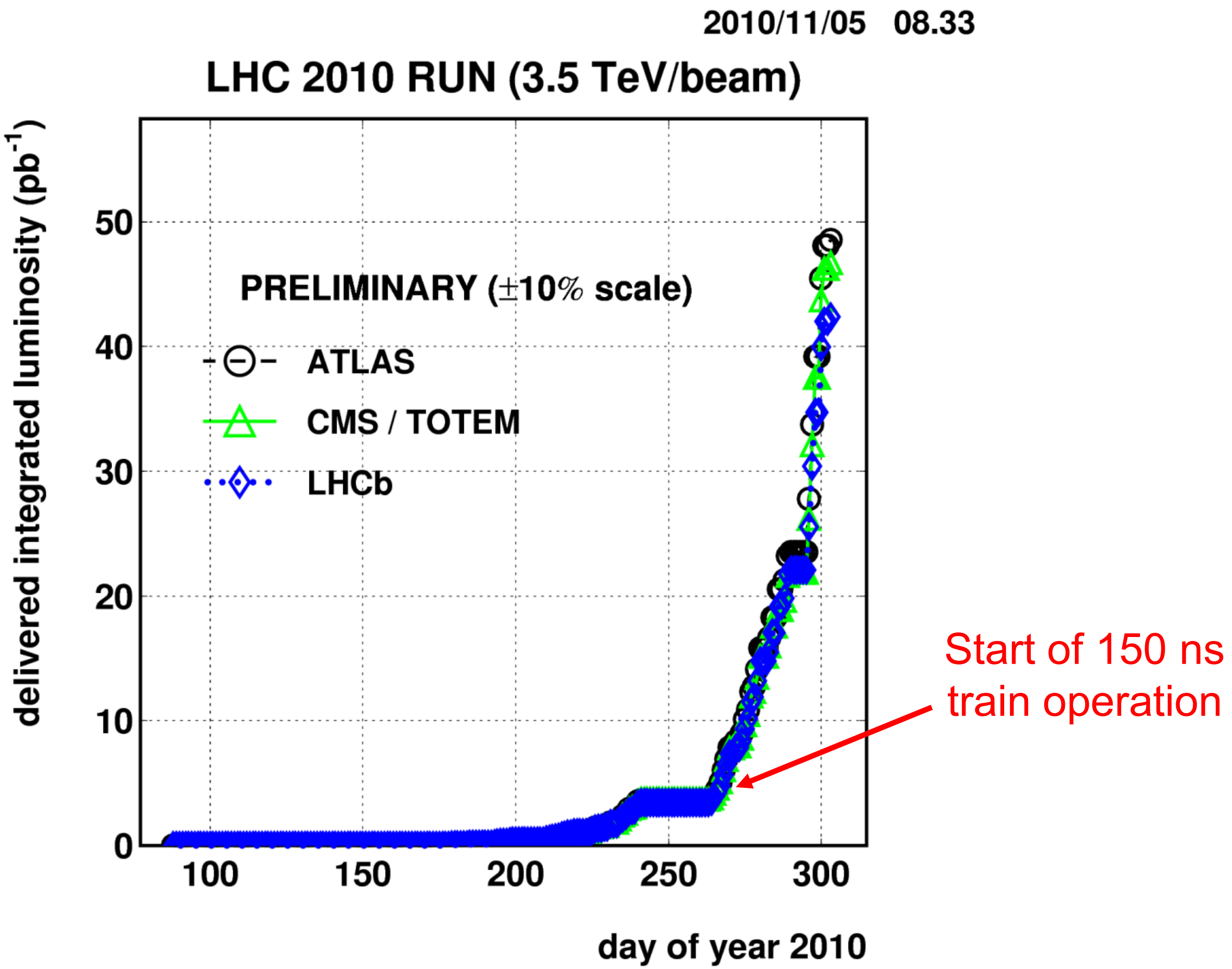
Peak luminosity = 2×10^{32} cm^{-2}s^{-1}

(368 bunches/beam, 348 colliding bunches)



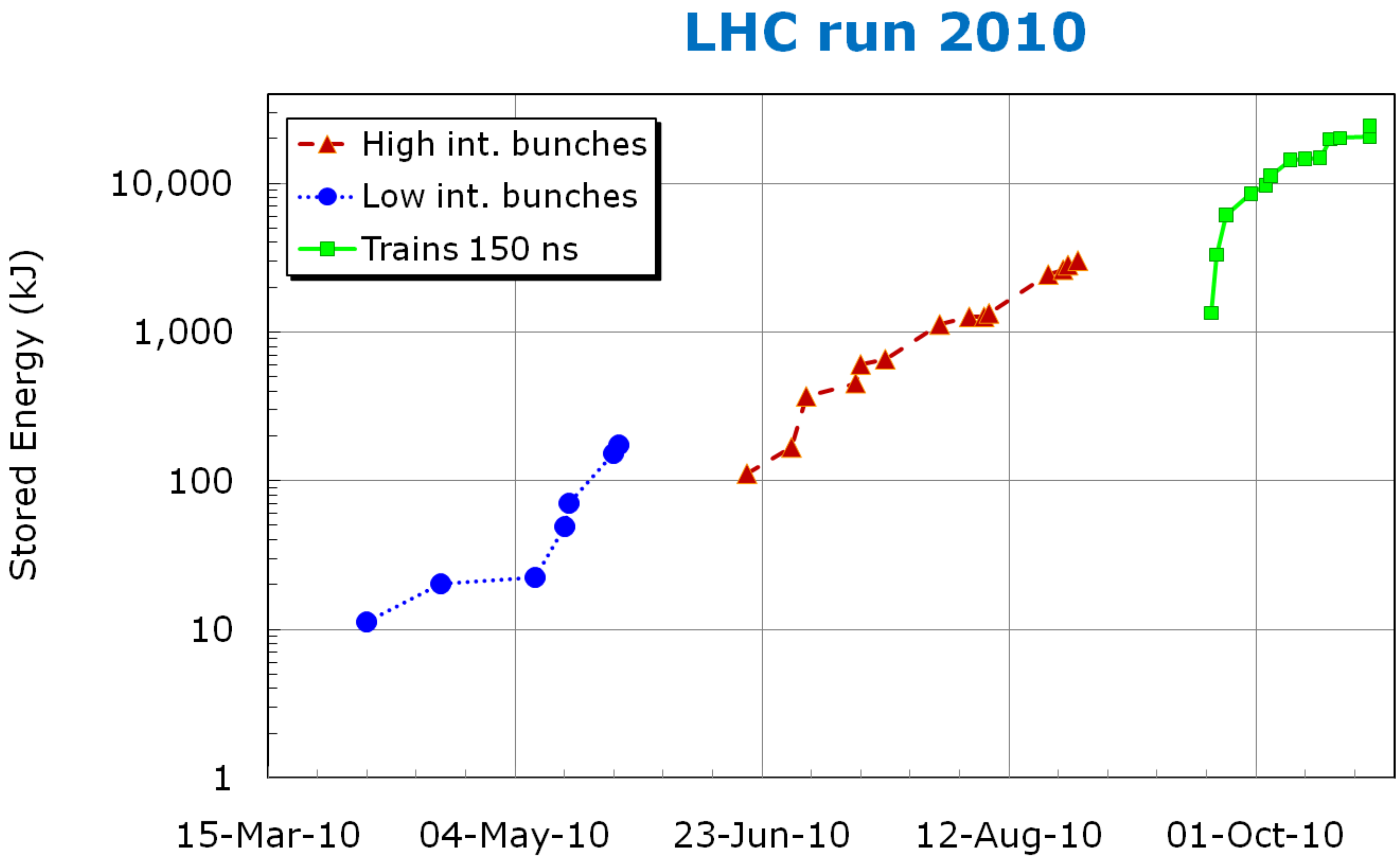
Integrated luminosity

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



Stored energy

Stored energy ~24 MJ (TEVATRON ~2 MJ)



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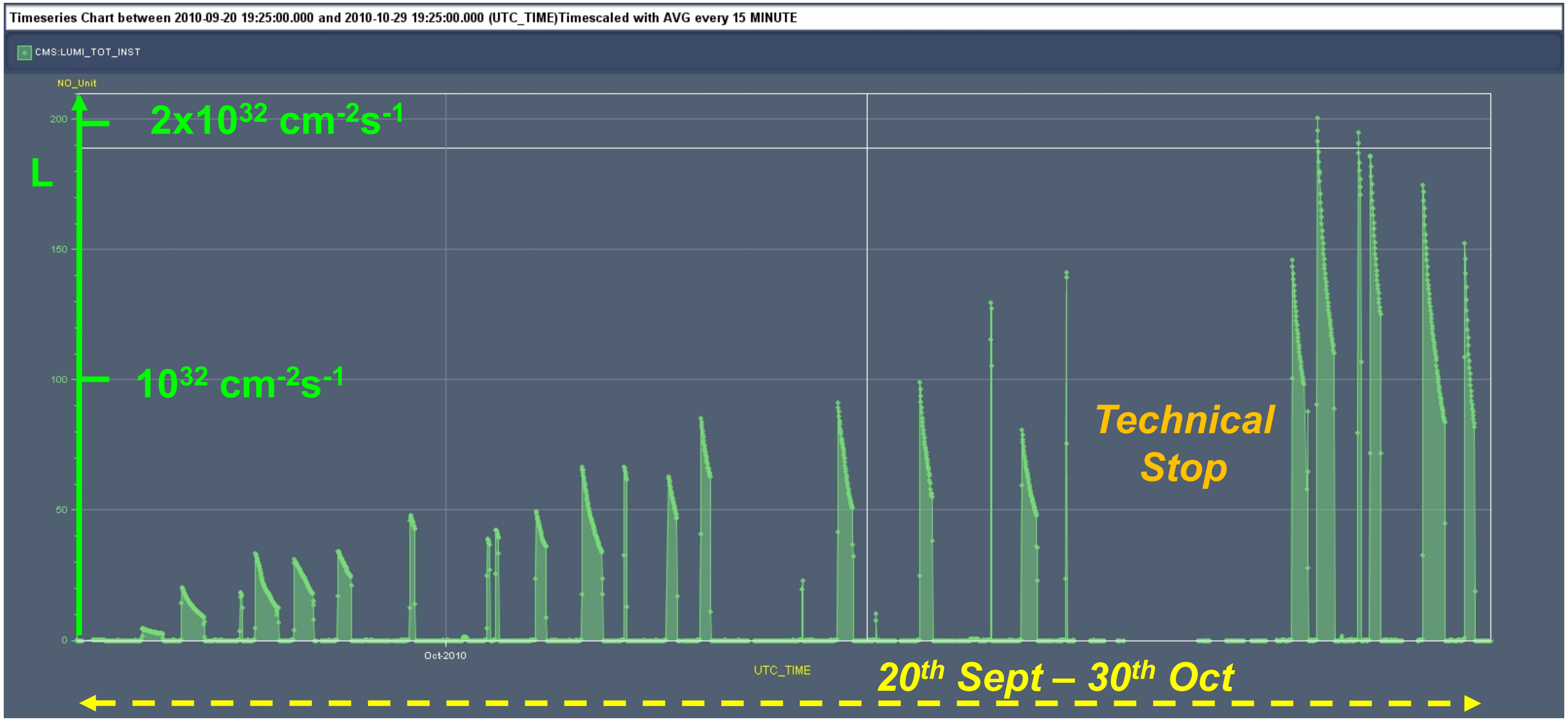
Operation with 150 ns

- 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).

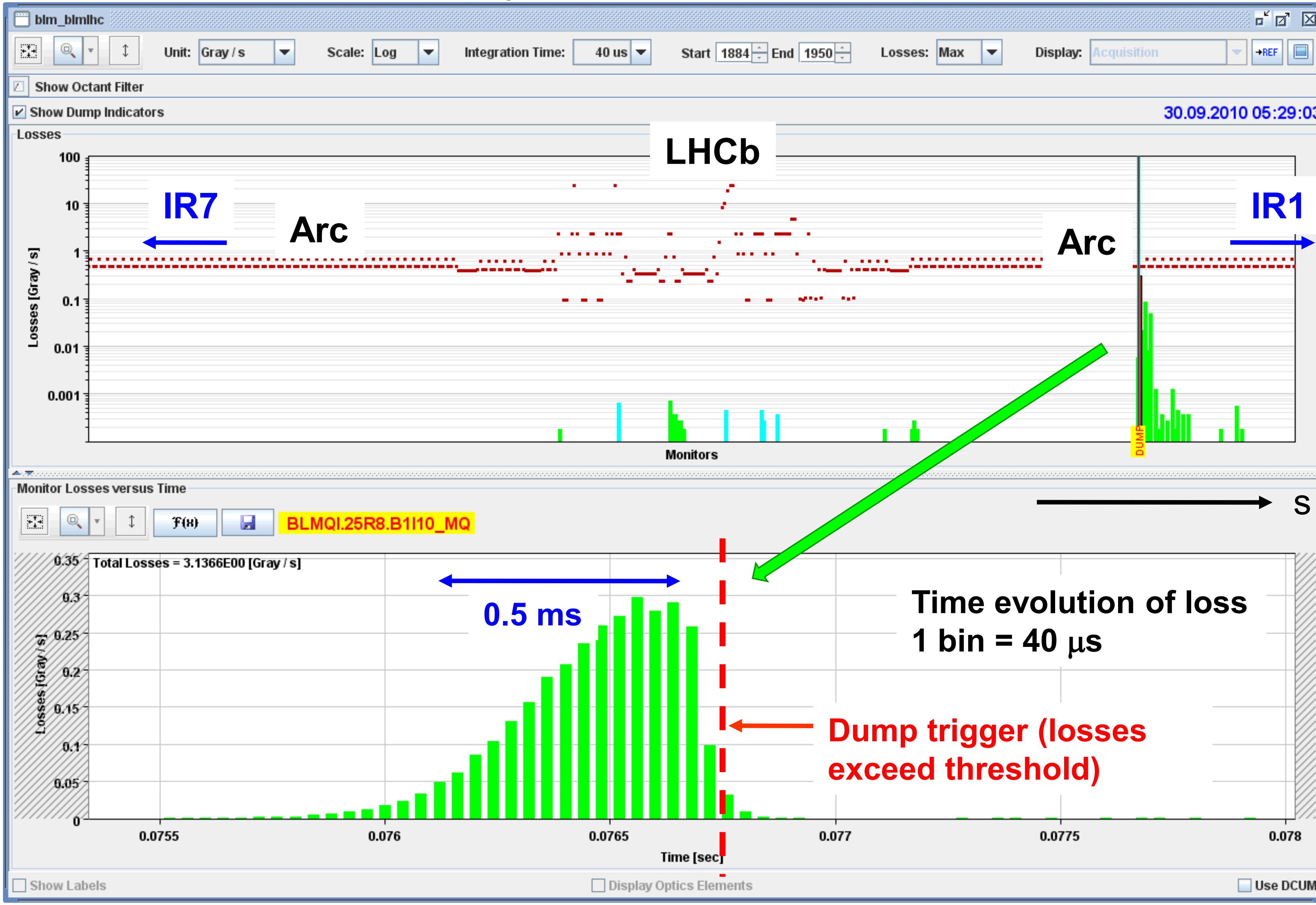


Unidentified Flying Objects - UFOs

- 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



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 4x10^{-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.

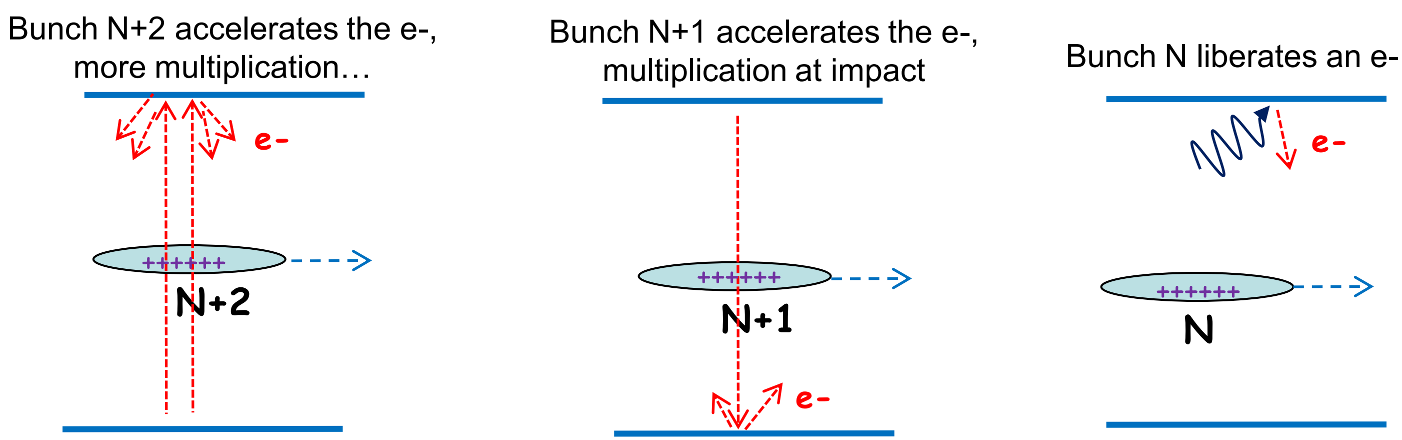
  *Consistent with the signature of **electron clouds**.*

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 !

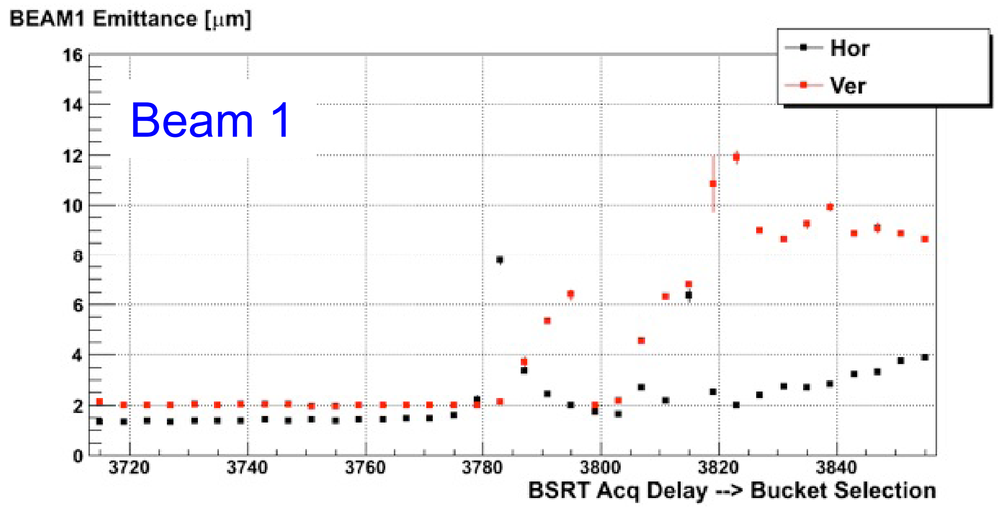
→ The cloud can 'cure itself': the impact of the electrons cleans the surface (Carbon migration), reduces the electron emission probability and eventually the cloud disappears – ***'beam scrubbing'***

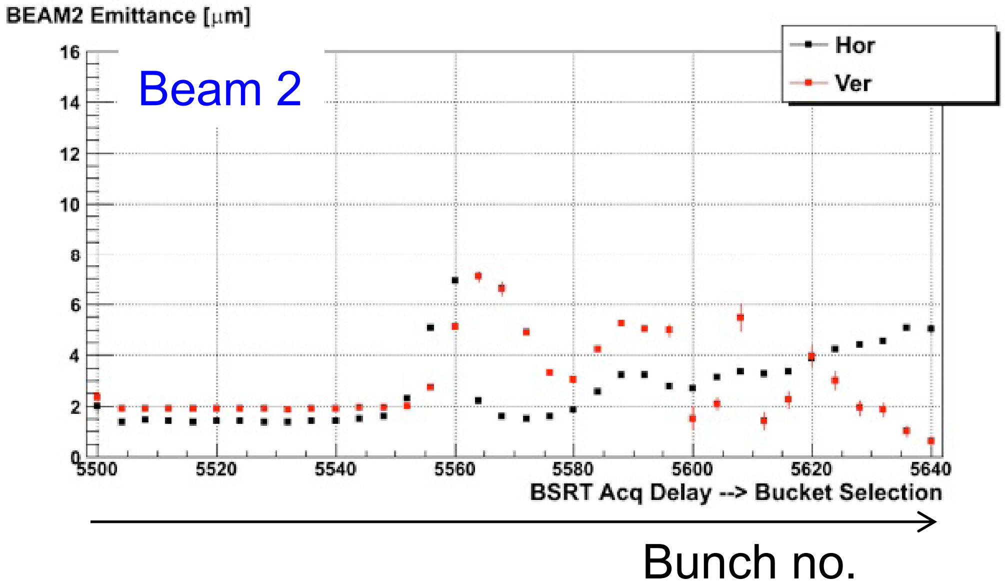


Electron clouds at LHC

- 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 everywhere:
  - *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.

Beam (in)stability with e-clouds

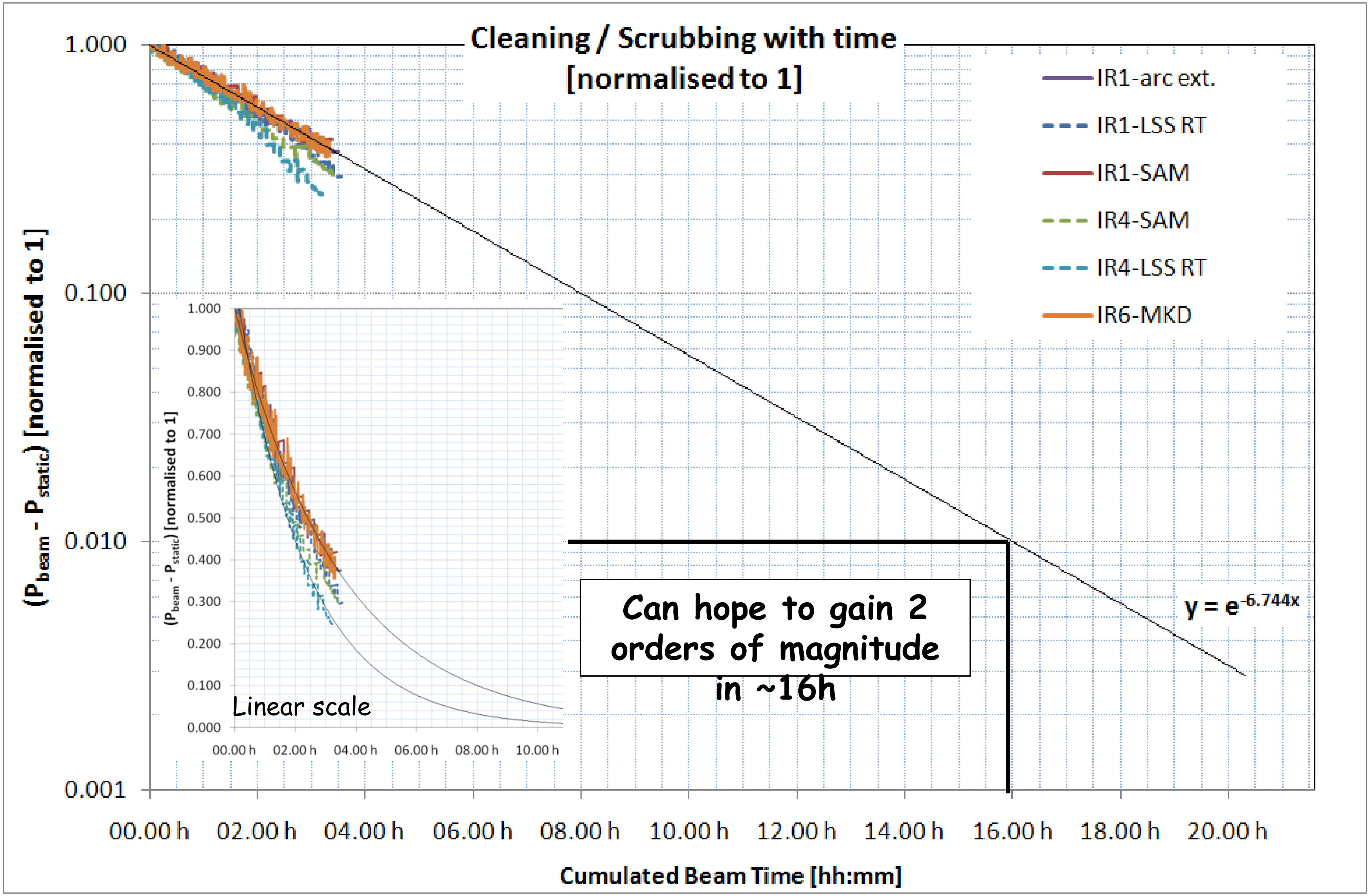




Example of beam emittance (size) growth along a train of 50 ns bunches.

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

Scrubbing in the LSS



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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 followed proton running.
- 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.

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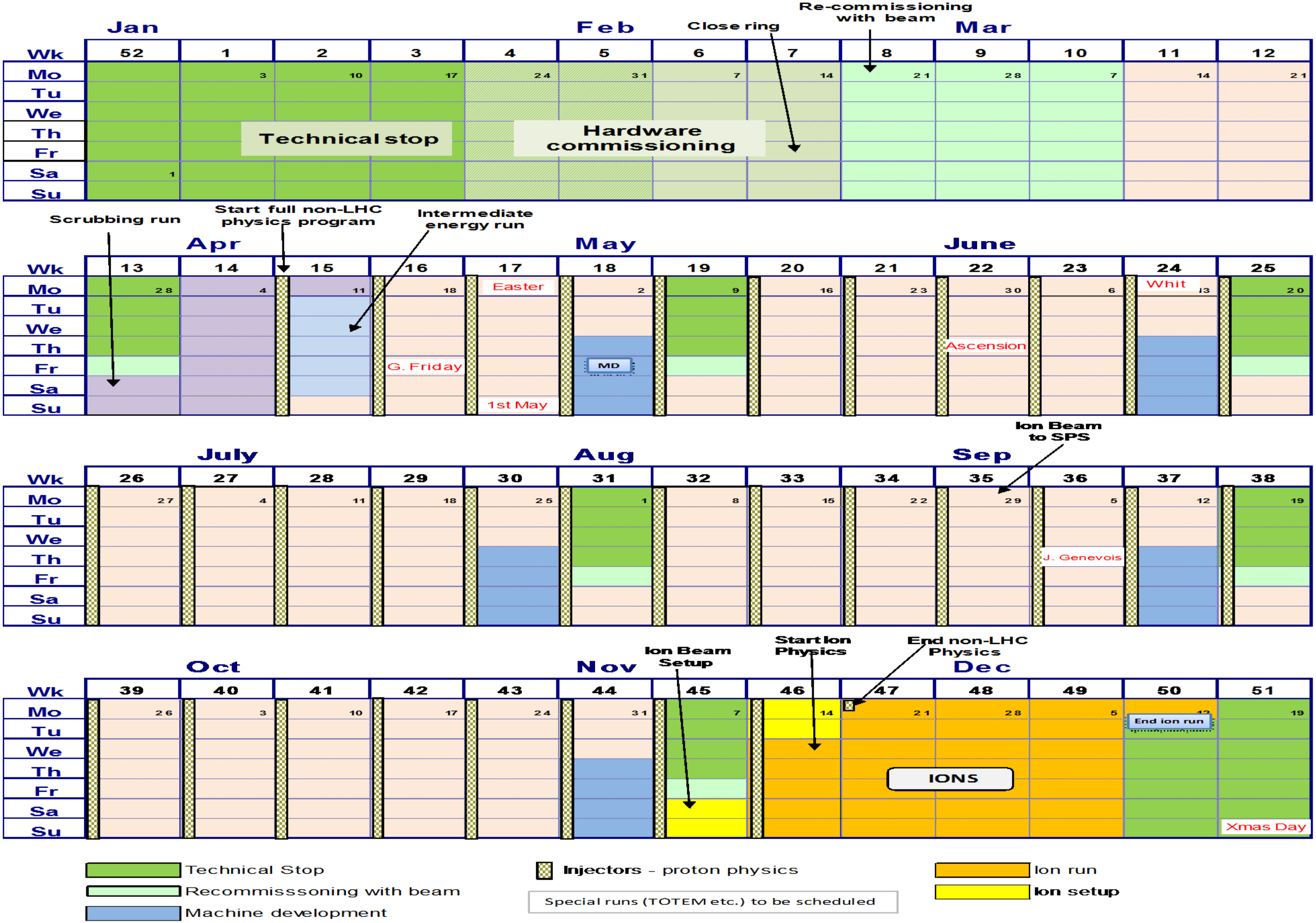
2011 LHC Schedule



Predicted machine performance in 2011

	Nominal	Probable 2011
Energy (GeV)	7000	3500
Bunches per beam	2800	900
Bunches intensity (10^{11})	1.1	1.2
Normalised emittance (10^{-6}m)	3.75	2.4
β^* (m)	0.55	1.5

Peak Luminosity 10^{33} cm^{-2} s^{-1}

Assume 160 days operation with 40 % efficiency and average luminosity 7 x 10^{32} cm^{-2} s^{-1}

Integrated luminosity in 2011   4 fb^{-1}

Conclusions

- Luminosity target of 10^{32} $cm^{-2}s^{-1}$ for 2010 has been reached.
- The 2011 run will start mid March.
  - *In 2011 peak luminosities up to 10^{33} $cm^{-2}s^{-1}$ can be expected.*
  - *Peak luminosity and bunch configuration will depend on e-cloud effects.*
  - *3-4 fb-1 is within reach.*
- The Pb ion proceeded smoothly.
  - *Transition was fast.*
  - *A similar run will take place end of 2011.*
- The LHC will run in 2012
  - *A reasonable target is 10 fb-1 by the end of 2012*