CERN

European Organization for Nuclear Research

Organisation Européenne pour la Recherche Nucléaire

LHC long range plan

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Talk for HEPAP

Friday 19th November 2010

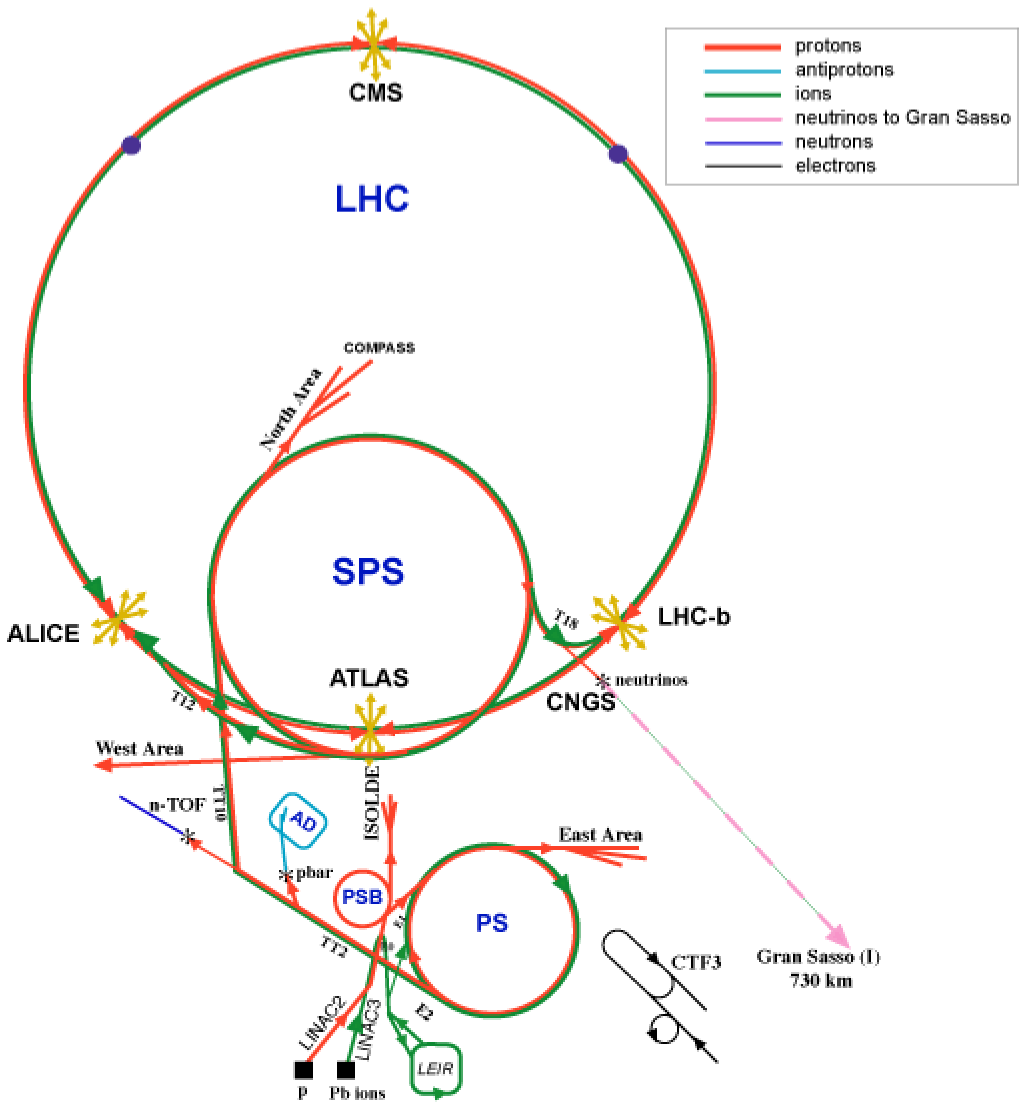
Content

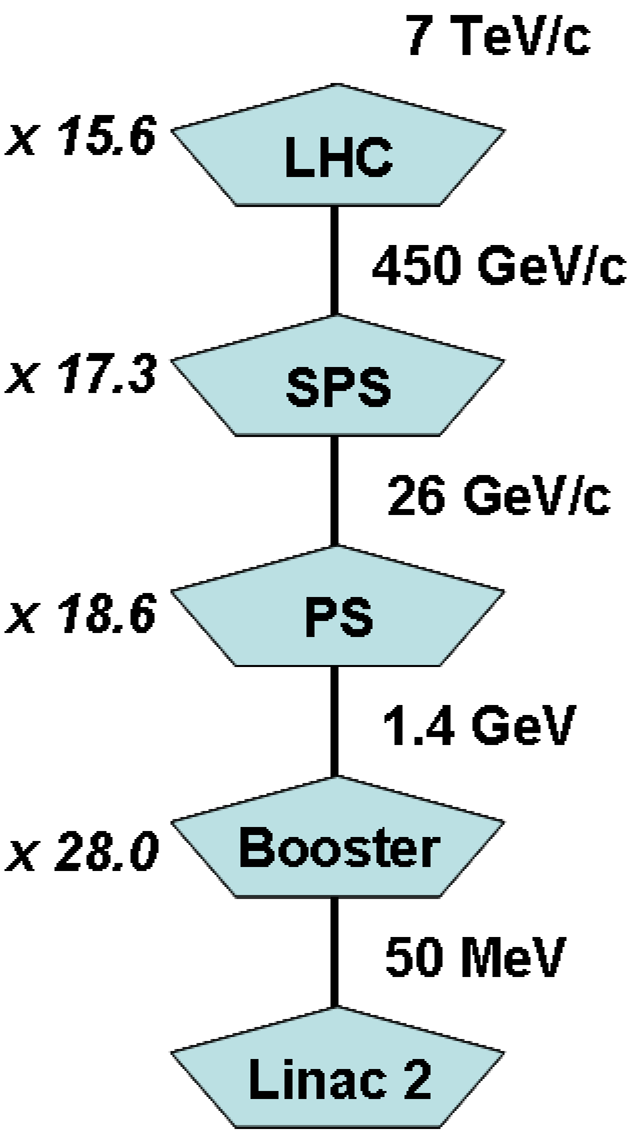
- **LHC machine recap and main challenges**
- **Proton and ion runs in 2010**
- **Plan in 2011**
- **2011-20 plan**
- **High Luminosity LHC**
- **High Energy LHC**
- **Conclusion**

LHC Timeline

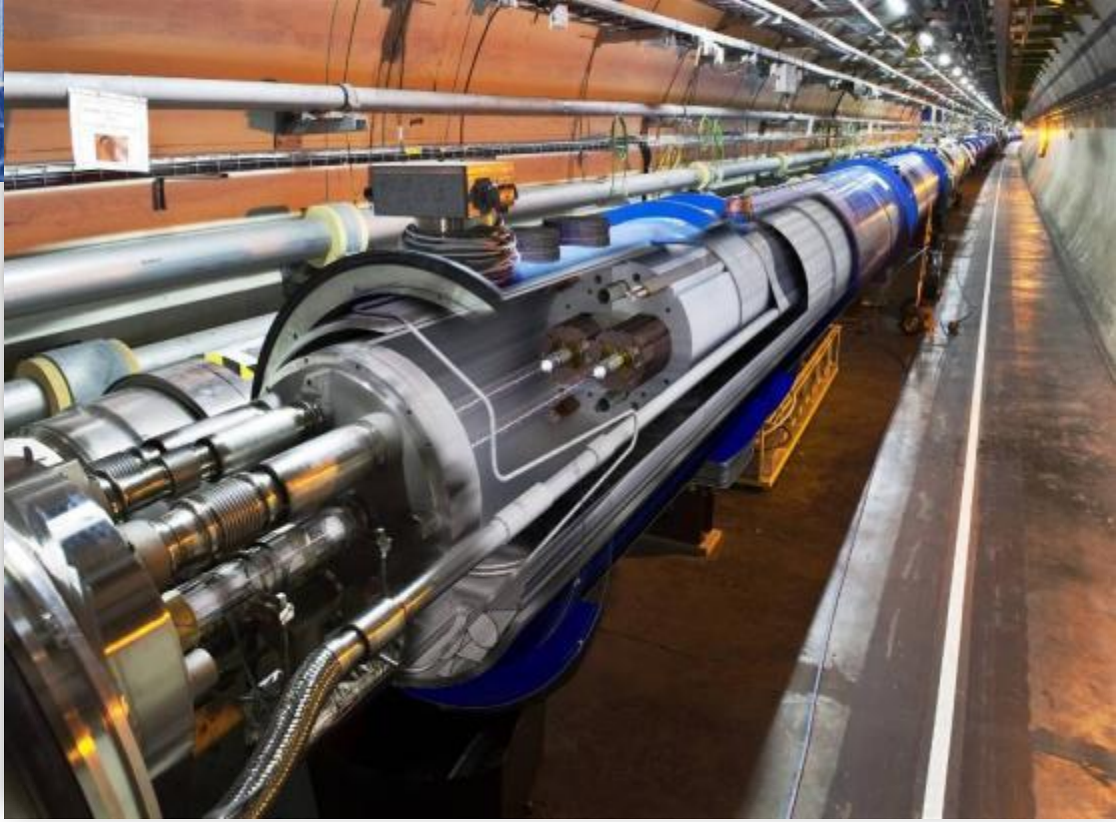
1982 : First studies for the LHC project
1987 : First 1 m long 1 bore 9 T magnet
1994 : First 10 m long, 9T, dipole prototypes
Approval of the LHC by the CERN Council) with missing magnet scheme!
1996 : Final approval to start the complete LHC construction
2001 : Main Magnets and QRL bid
2004 : Start 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

The CERN accelerator network





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

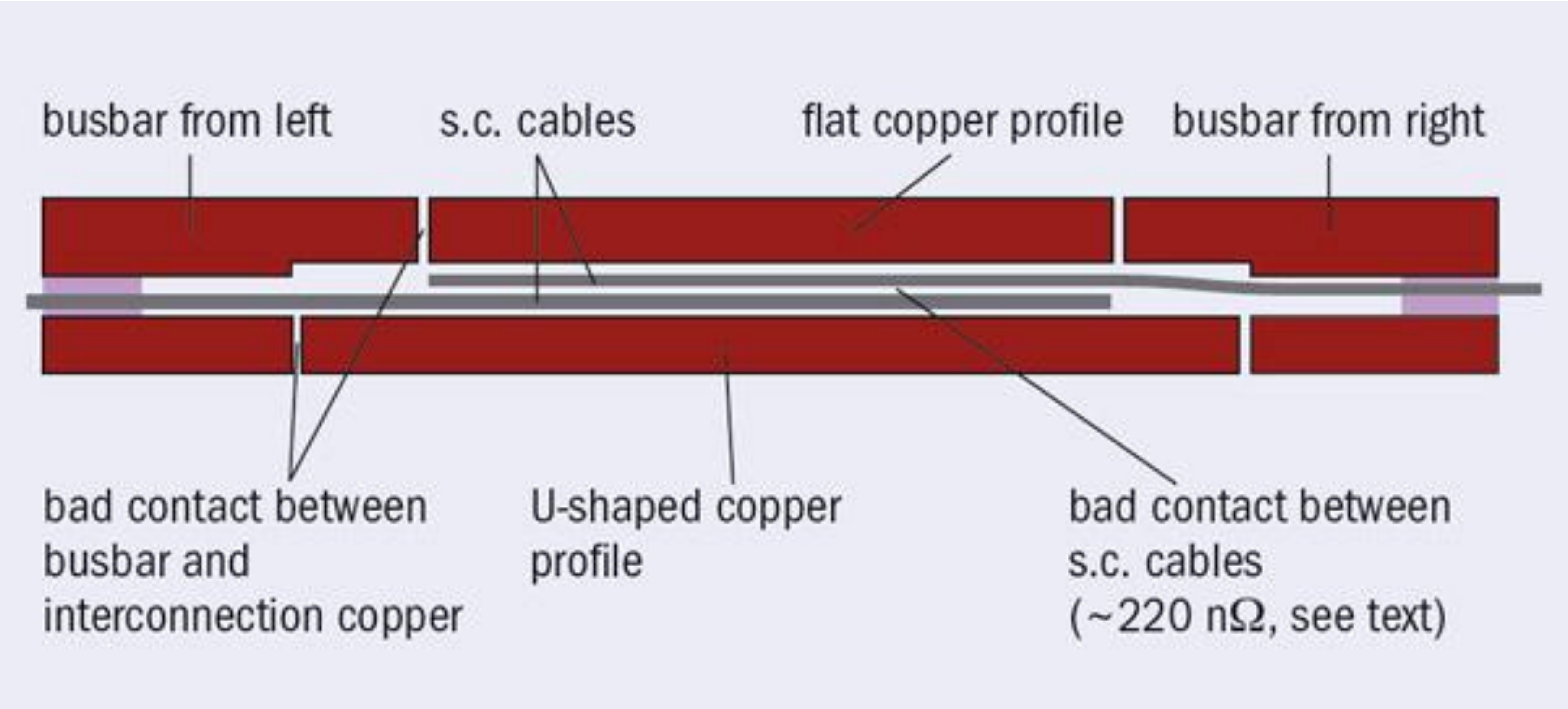
The Sector 3-4 incident

19th September 2008 at 11:18.36

last test of the last circuit of the last sector: 7kA (4TeV) towards 9.3 kA (5TeV)

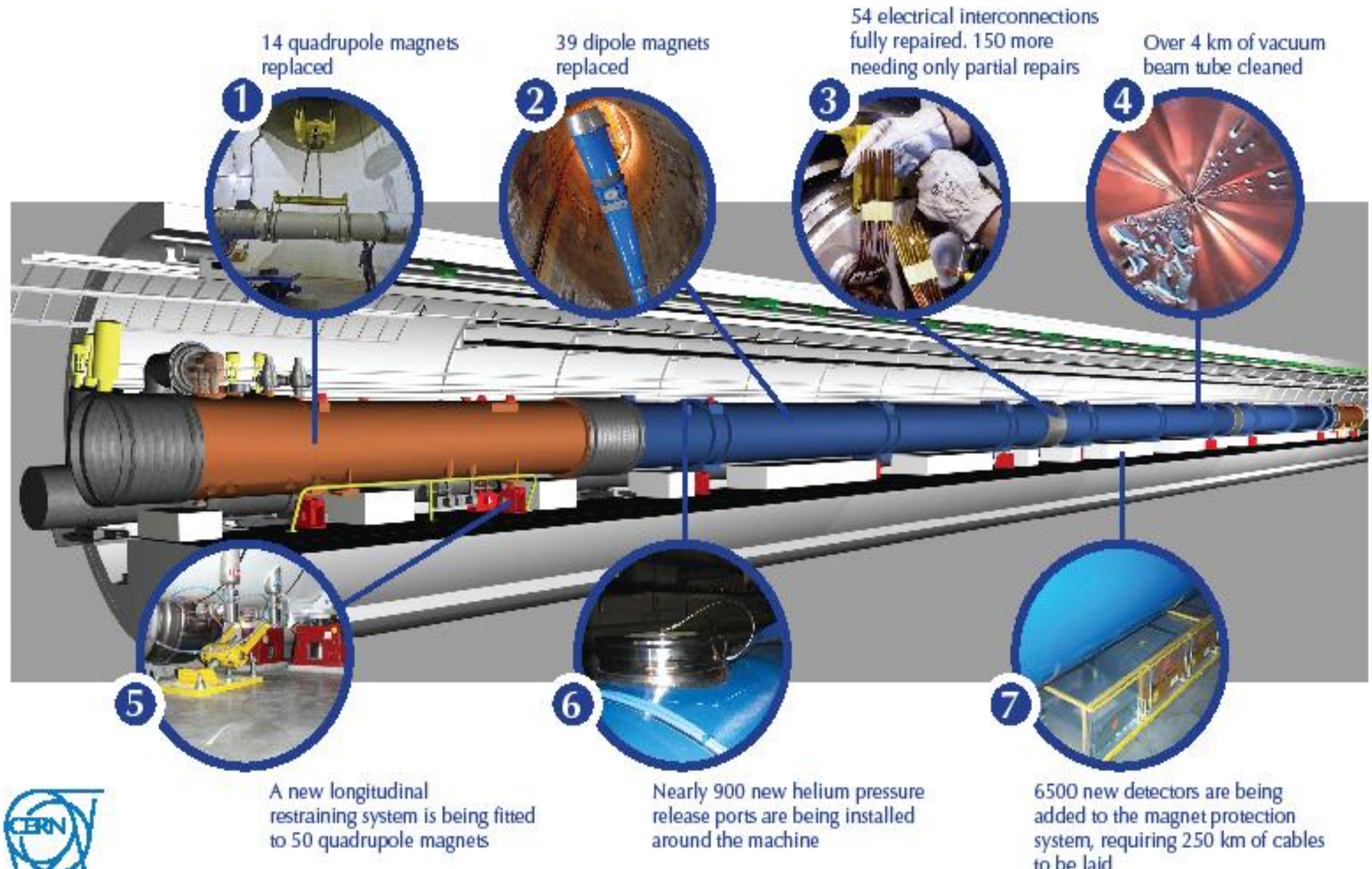
Electrical arc between two magnets at 8.7 kA

The start ...



From L. Rossi, CERN Courier September 2010

The LHC repairs in detail



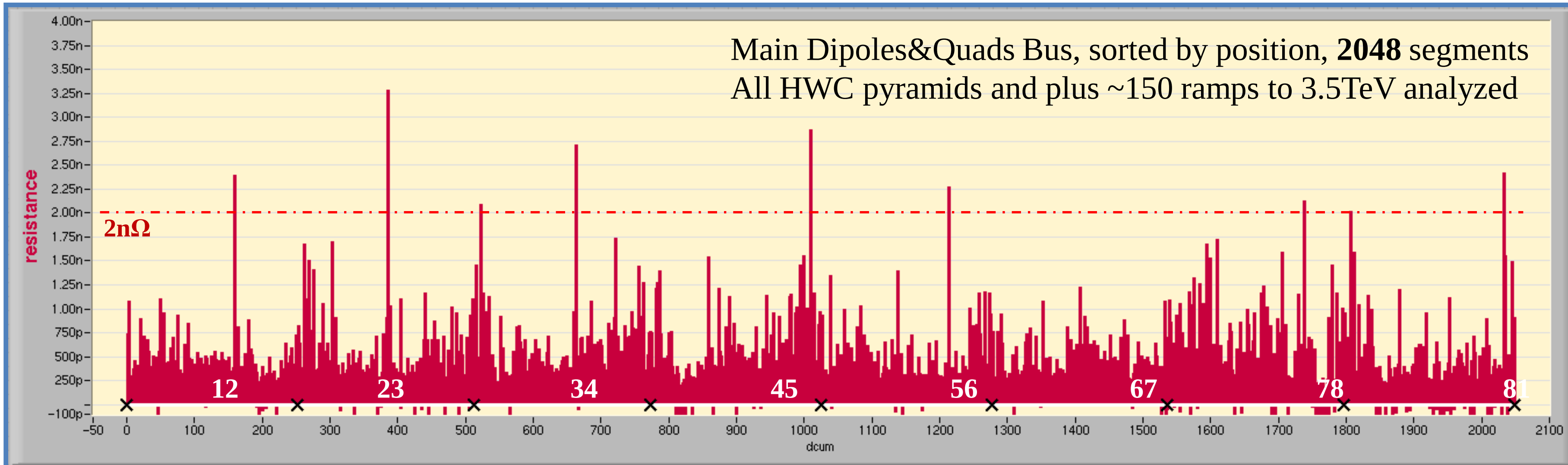
½ machine done

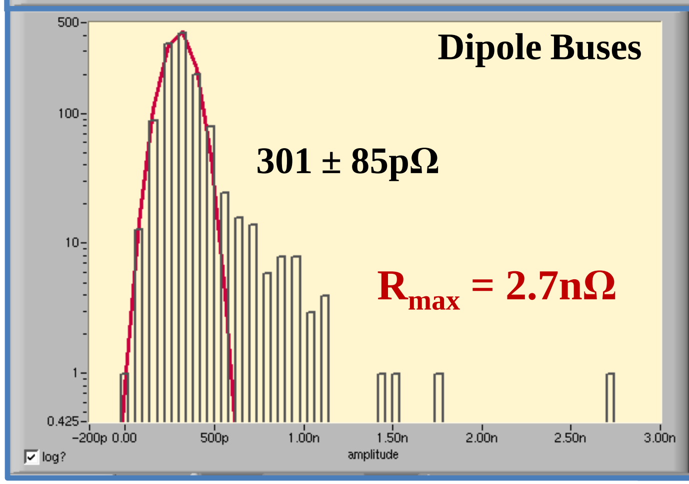
Why do we limit the beam energy to 3.5TeV in 2010-2011?

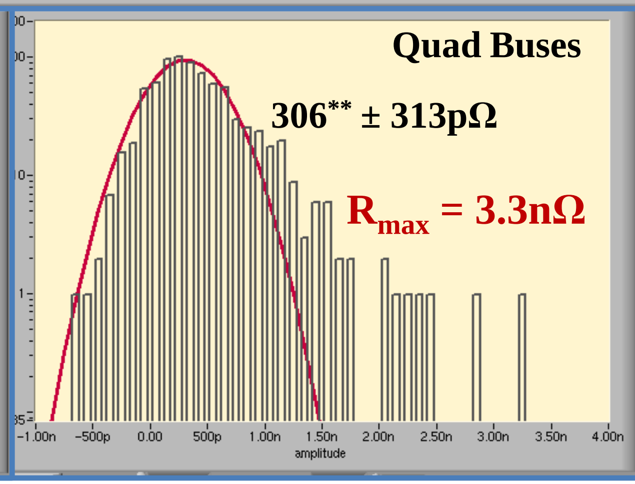
All the work done since November 2008 makes certain that a repeat of September 19th 2008 can NEVER happen.

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







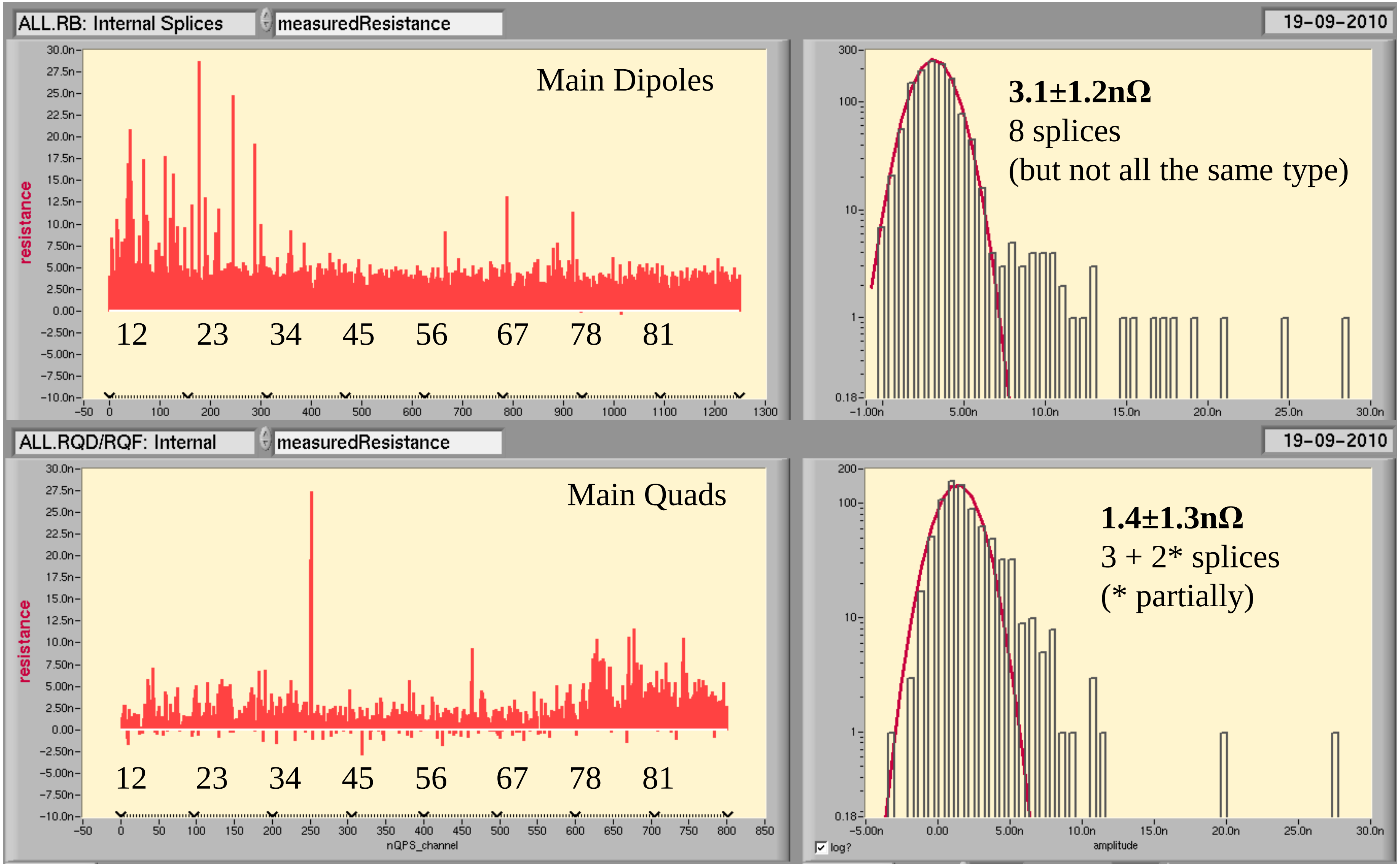
Top 10 Splice Resistances

MQ.A23	MQ.33L3.B2	<->	MQ.33R2.B2	3.28E-09
MQ.A45	MQ.12L5.B2	<->	MQ.11L5.B1	2.87E-09
MB.A34	MB.A31L4	<->	MB.C31L4	2.71E-09
MQ.A81	MQ.12L1.B2	<->	MQ.11L1.B1	2.42E-09
MQ.A12	MQ.27L2.B2	<->	MQ.25L2.B2	2.40E-09
MQ.A56	MQ.21L6.B2	<->	MQ.19L6.B2	2.27E-09
MQ.A78	MQ.20L8.B1	<->	MQ.22L8.B1	2.13E-09
MQ.A34	MQ.9R3.B2	<->	MQ.11R3.B2	2.09E-09
MQ.A81	MQ.11R8.B2	<->	DFLAS.7R8.4	2.02E-09
MB.A34	MB.C19L4	<->	MB.B20L4	1.74E-09

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

From Z. Charifoulline

LHC main splices today: inside magnets



From Z. Charifoulline

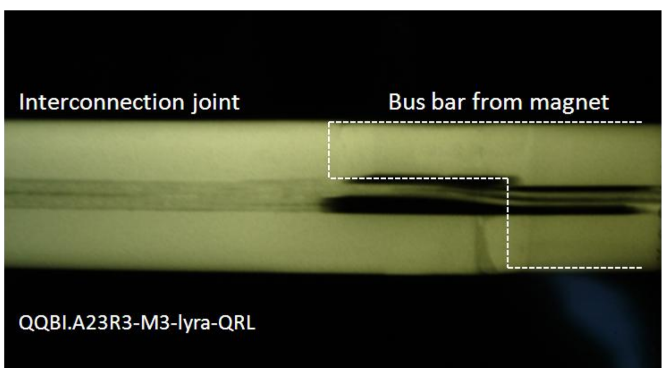
Why do we limit the beam energy to 3.5TeV in 2010-2011?

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

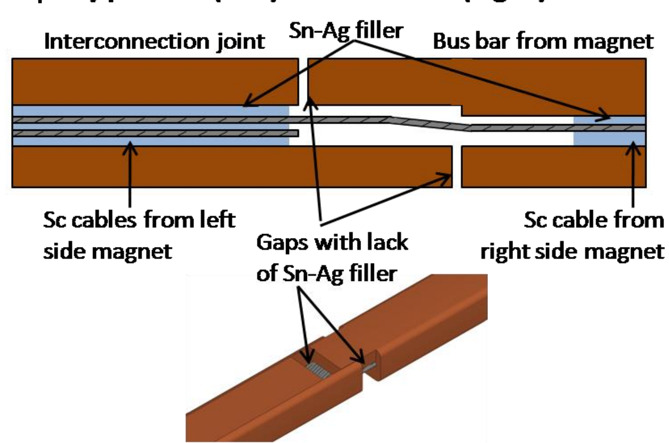
The offending connector in this incident had an estimated resistance of 220nΩ. We have measured all 10,000 inter-magnet connectors and the maximum resistance we have seen is 2.7nΩ for dipole busbars and 3.3nΩ for dipole busbars

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



Defective interconnetion-bus bar transition
γ-ray picture (left) and scheme (right)



Decided Scenario 2010-2011

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 1fb^{-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

30th March 2010: first collisions at 7 TeV (2 x 3.5 TeV)

First Running Period (low bunch intensity)

calculated

Event	TeV	OEF	β*	Nb	Ib	Itot	MJ	Nc	Peak luminosity	Date
1	3.5	0.2	10	2	1.00E+10	2.0E+10	0.0113	1	8.9E+26	30 March 2010
2	3.5	0.2	10	2	2.00E+10	4.0E+10	0.0226	1	3.6E+27	02 April 2010
3	3.5	0.2	2	2	2.00E+10	4.0E+10	0.0226	1	1.8E+28	10 April 2010
4	3.5	0.2	2	4	2.00E+10	8.0E+10	0.0452	2	3.6E+28	19 April 2010
5	3.5	0.2	2	6	2.00E+10	1.2E+11	0.0678	4	7.1E+28	15 May 2010
6	3.5	0.2	2	13	2.60E+10	3.4E+11	0.1910	8	2.4E+29	22 May 2010

> Seven Orders of magnitude below design

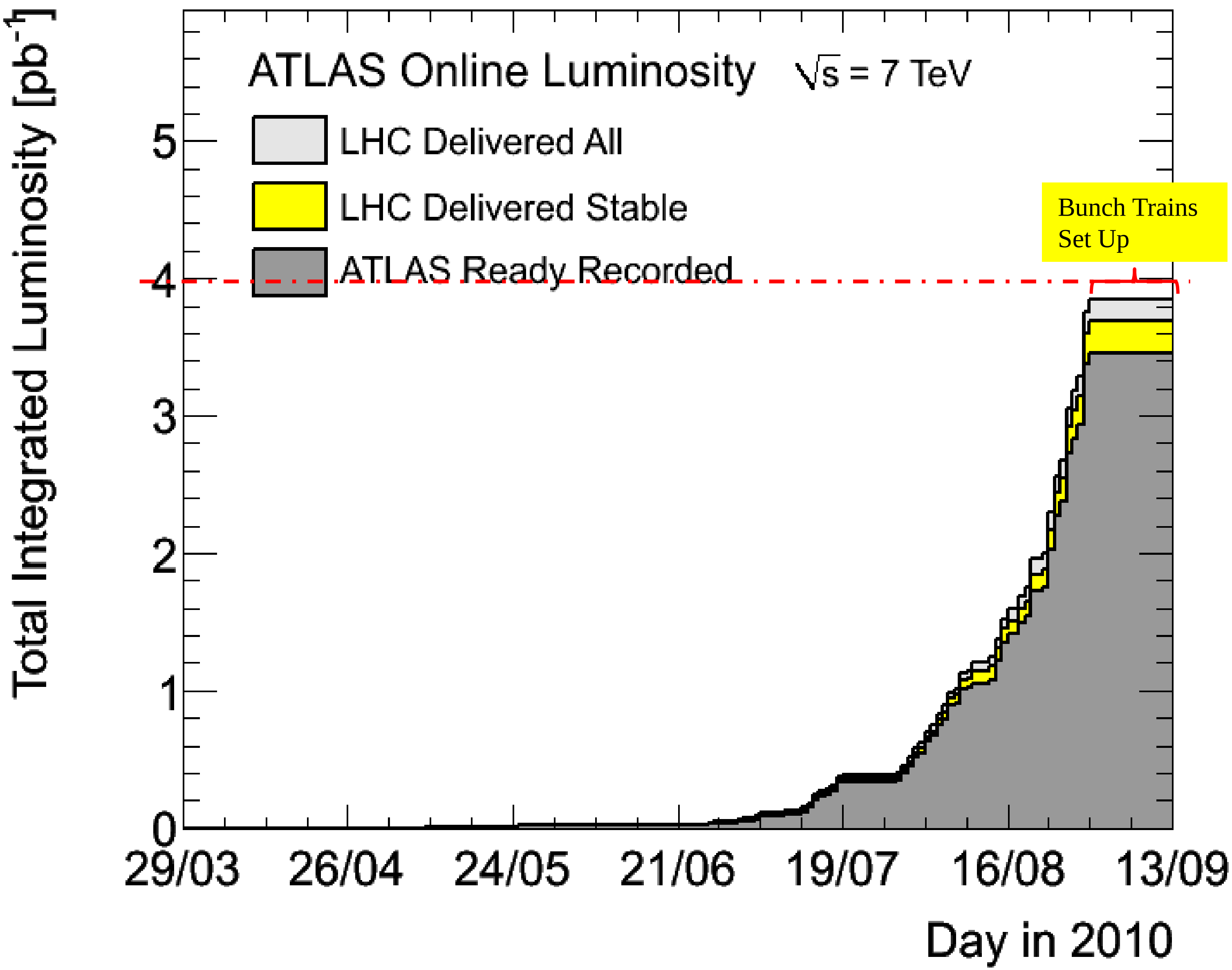
Second Running Period (High bunch Intensity)

calculated

Event	TeV	OEF	β*	Nb	Ib	Itot	MJ	Nc	Peak luminosity	Date
1	3.5	0.2	10	2	1.00E+10	2.0E+10	0.0113	1	8.9E+26	30 March 2010
2	3.5	0.2	10	2	2.00E+10	4.0E+10	0.0226	1	3.6E+27	02 April 2010
3	3.5	0.2	2	2	2.00E+10	4.0E+10	0.0226	1	1.8E+28	10 April 2010
4	3.5	0.2	2	4	2.00E+10	8.0E+10	0.0452	2	3.6E+28	19 April 2010
5	3.5	0.2	2	6	2.00E+10	1.2E+11	0.0678	4	7.1E+28	15 May 2010
6	3.5	0.2	2	13	2.60E+10	3.4E+11	0.1910	8	2.4E+29	22 May 2010
7	3.5	0.2	3.5	3	1.10E+11	3.3E+11	0.1865	2	6.1E+29	26 June 2010
8	3.5	0.2	3.5	6	1.00E+11	6.0E+11	0.3391	4	1.0E+30	02 July 2010
9	3.5	0.2	3.5	8	9.00E+10	7.2E+11	0.4069	6	1.2E+30	12 July 2010
10	3.5	0.2	3.5	13	9.00E+10	1.2E+12	0.6612	8	1.6E+30	15 July 2010
11	3.5	0.2	3.5	25	1.00E+11	2.5E+12	1.4129	16	4.1E+30	30 July 2010
12	3.5	0.2	3.5	48	1.00E+11	4.8E+12	2.7127	36	9.1E+30	19 August 2010

Maximum reached is 10.7×10^{30} $cm^{-2}s^{-1}$

Approaching 4pb-1 (move to bunch trains)



Plan for getting to 10^{32} before ion run

LMC 18th August.

- Parameters and Conditions
  - Nominal bunch intensity 1.1E11
  - Stick to β* = 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**

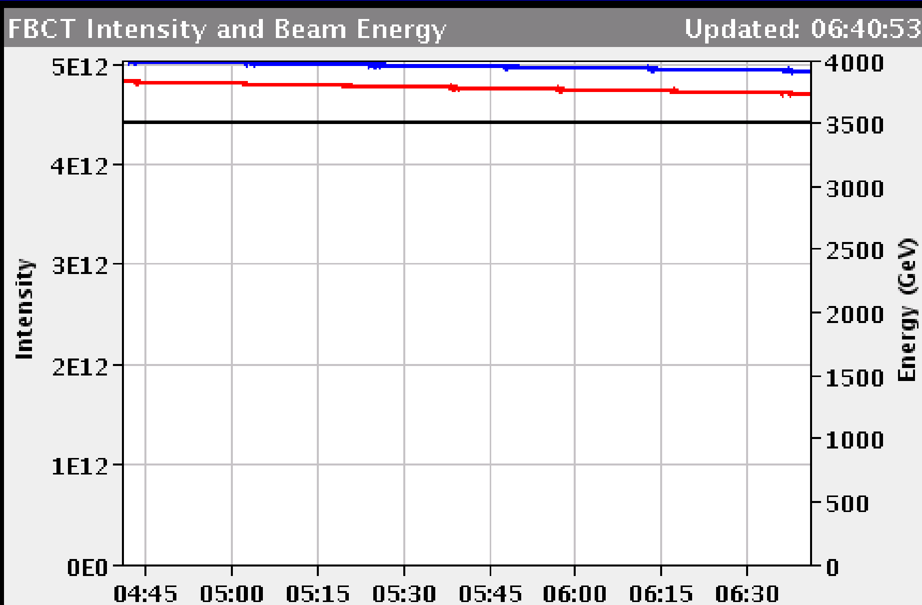
Additional work for bunch trains

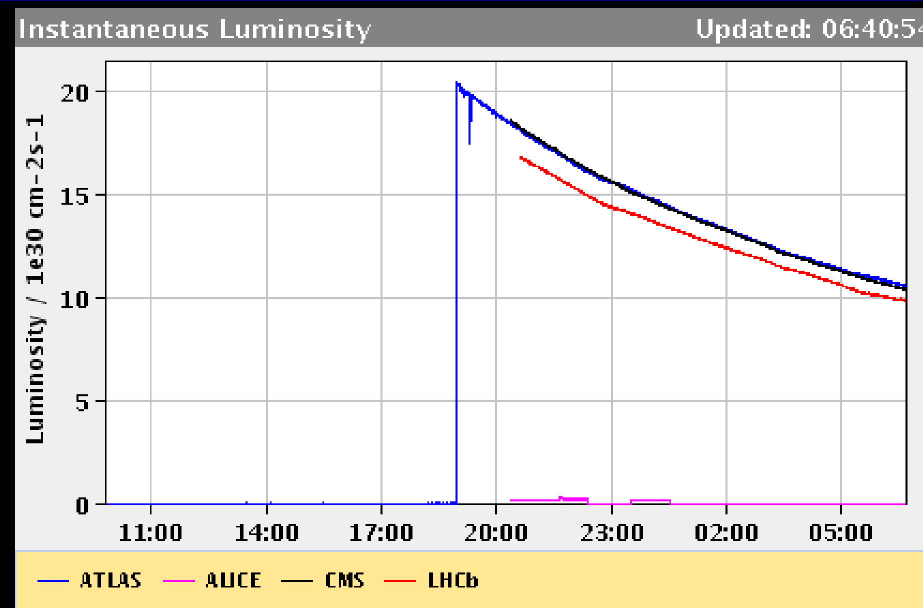
- Completely new set up of all phases of LHC under the new conditions needed for safe operation with high intensity bunch trains
  - Beam transfer (collimation)
  - Emittance control in injectors and during ramp in LHC
  - Transverse damper set up with lower noise
  - Injection with crossing angles (collimators 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)

LHC Page1 Fill: 1366 E: 3500 GeV 24-09-2010 06:40:53

PROTON PHYSICS: STABLE BEAMS

Energy:	3500 GeV	I(B1):	5.01e+12	I(B2):	4.73e+12





Comments 23-09-2010 22:16:30 :

Stable beams

Fill. scheme: 150 ns_56b_47_16_47_8bpi

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

Collisions with bunch trains; 24th September 7x8 bunches; Luminosity = $2x10^{31}$

LHC Operation in CCC : 77600, 70480

PM Status B1 ENABLED PM Status B2 ENABLED

Running with Bunch Trains (Parameters)

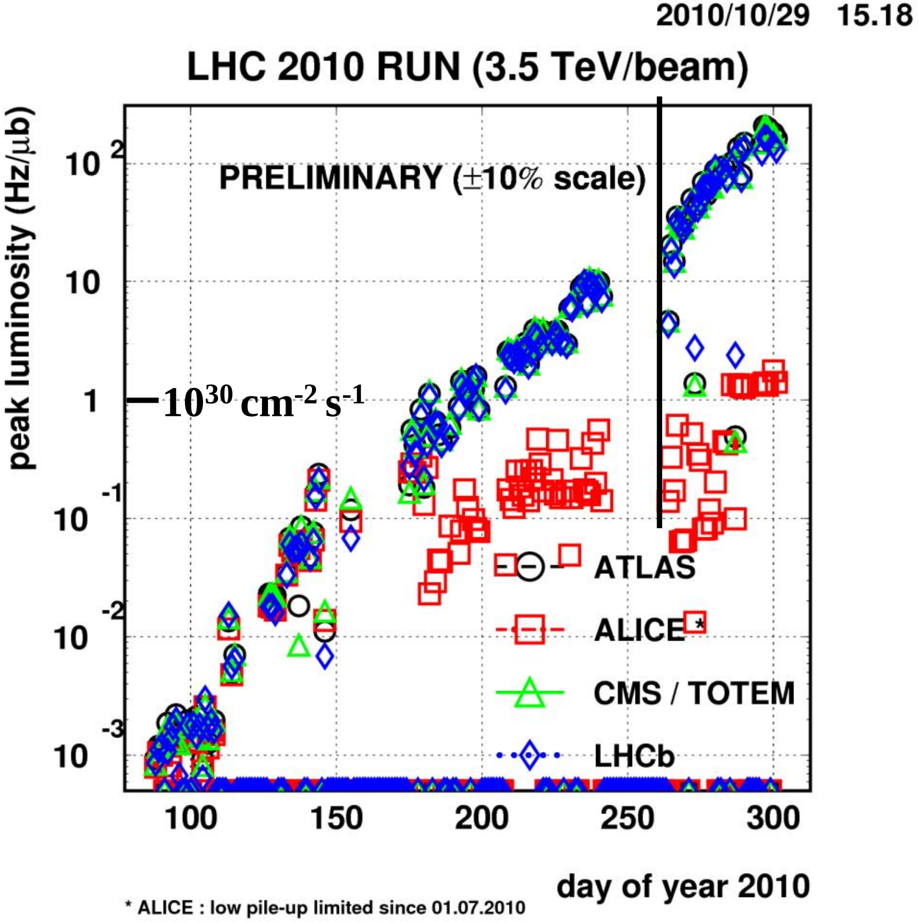
Nb	Ib	MJ	Nc	Peak luminosity (design parameters)	Maximum luminosity (measured)	Pile up (from measured Lumi)	Date
56	1.10E+11	3.5	47	1.203E+31	2.000E+31	1.9054	23/09/2010
104	1.10E+11	6.5	93	2.381E+31	3.500E+31	1.7955	25/09/2010
152	1.10E+11	9.4	140	3.584E+31	5.000E+31	1.7550	29/09/2010
204	1.10E+11	12.7	186	4.762E+31	7.000E+31	1.8307	04/10/2010
248	1.10E+11	15.4	233	5.965E+31	1.030E+32	2.2158	14/10/2010
312	1.10E+11	19.4	295	7.552E+31	1.500E+32	2.5650	16/10/2010
368	1.15E+11	23.9	348	9.737E+31	2.050E+32	2.9721	25/10/2010

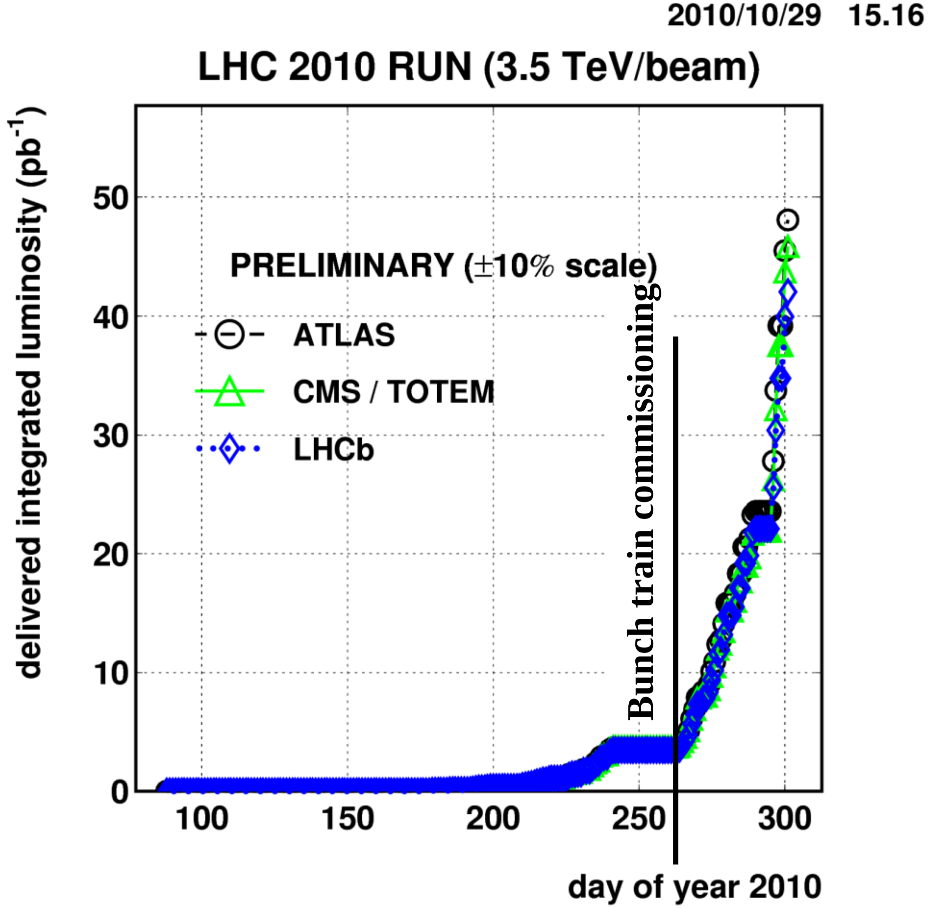
24MJ stored beam energy and $2.05 \times 10^{32} cm^{-2}s^{-1}$

Luminosity evolution 2010 (proton)

5 orders of magnitude in ~200 days

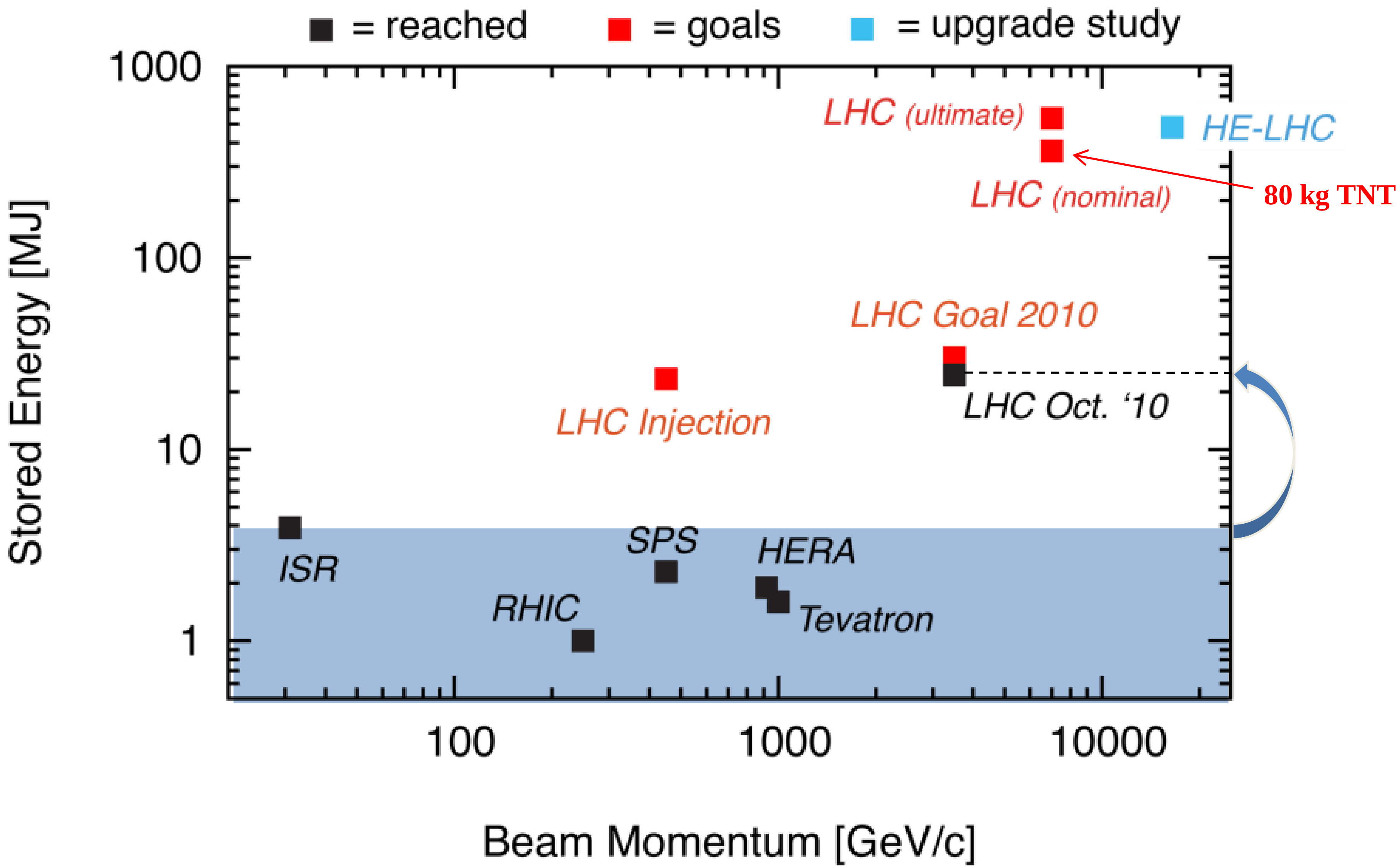
~50 pb^{-1} delivered, half of it in the last week !





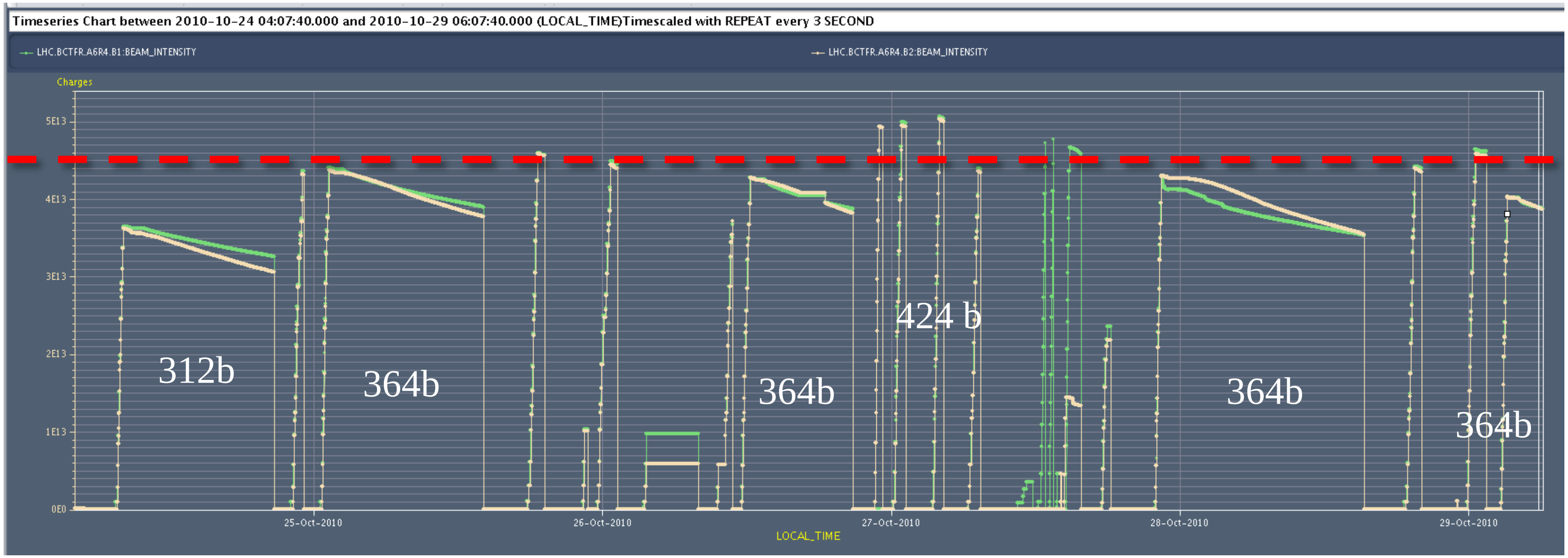
Roger Bailey

Status LHC Stored Energy



Did we reach the intensity limit for 150ns ?

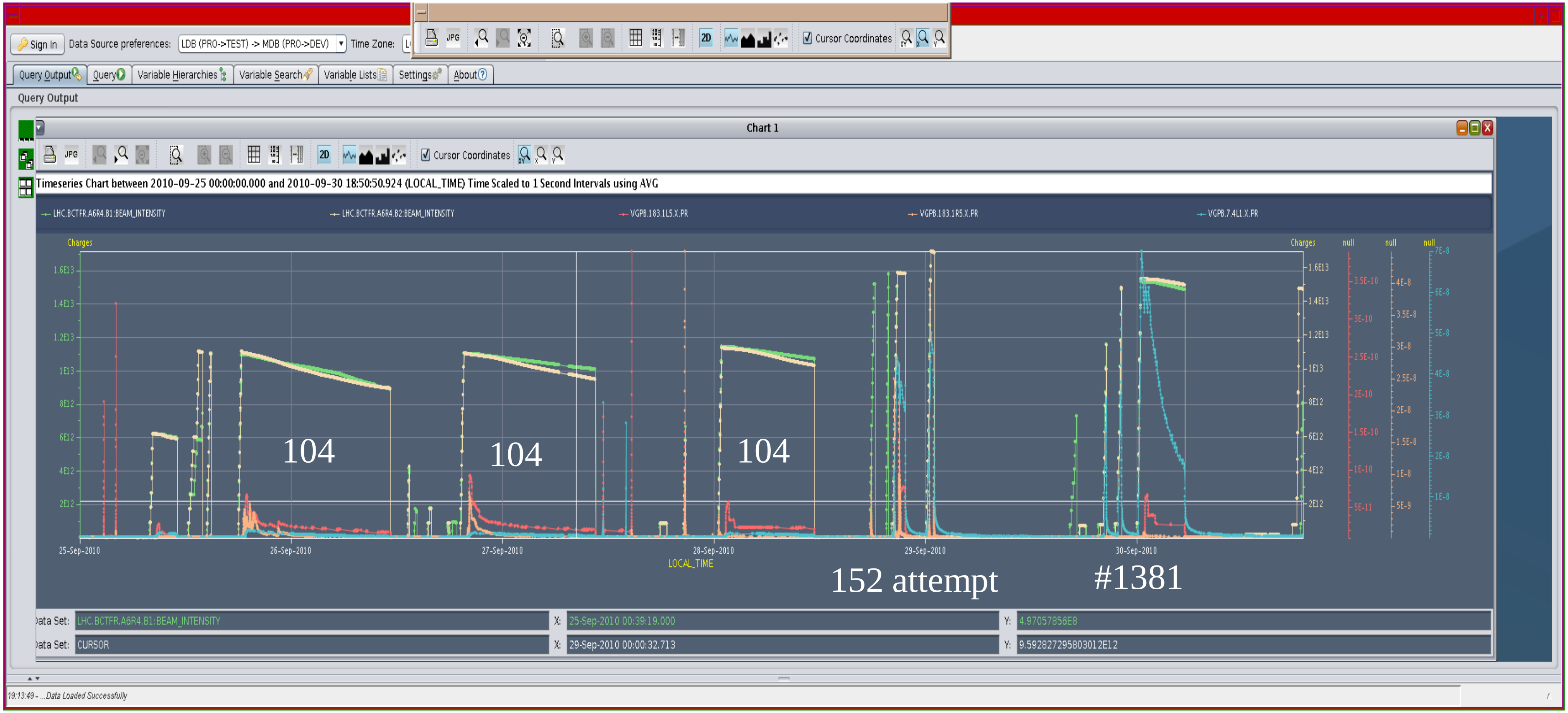
4.35e13 p (?) → to be followed…



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

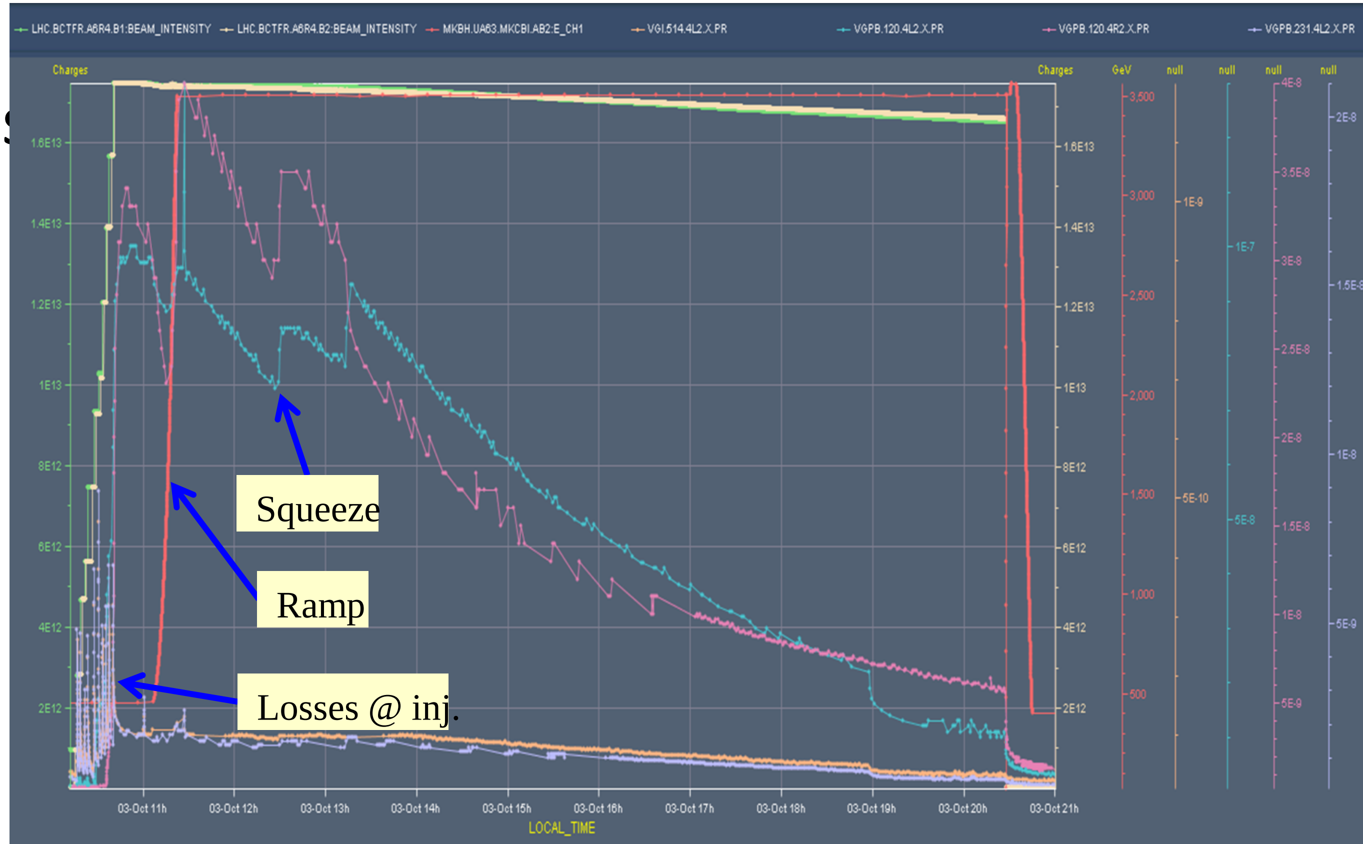


Gradual degradation seen with the benefit of hindsight from Friday September 29th

Vacuum – a very brief history

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
CMS solenoid s



Vacuum – a very brief history

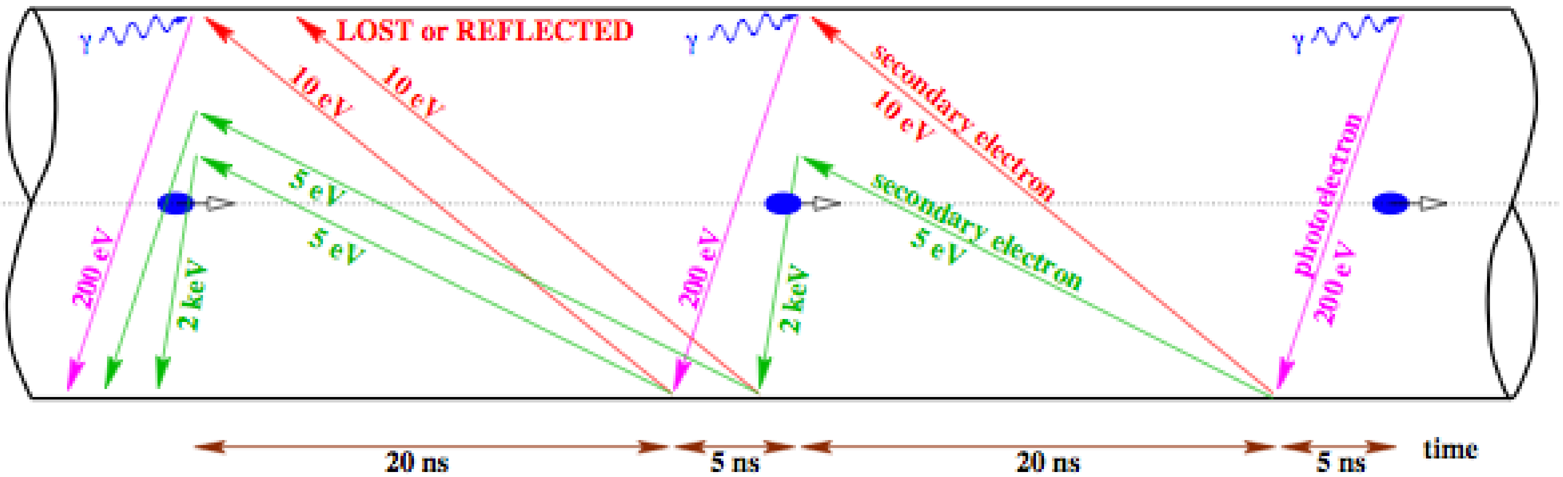
Initially

- 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

Vacuum : electron cloud

Not everything is perfect. The LHC has reached a stage where interesting things are beginning to pop up …

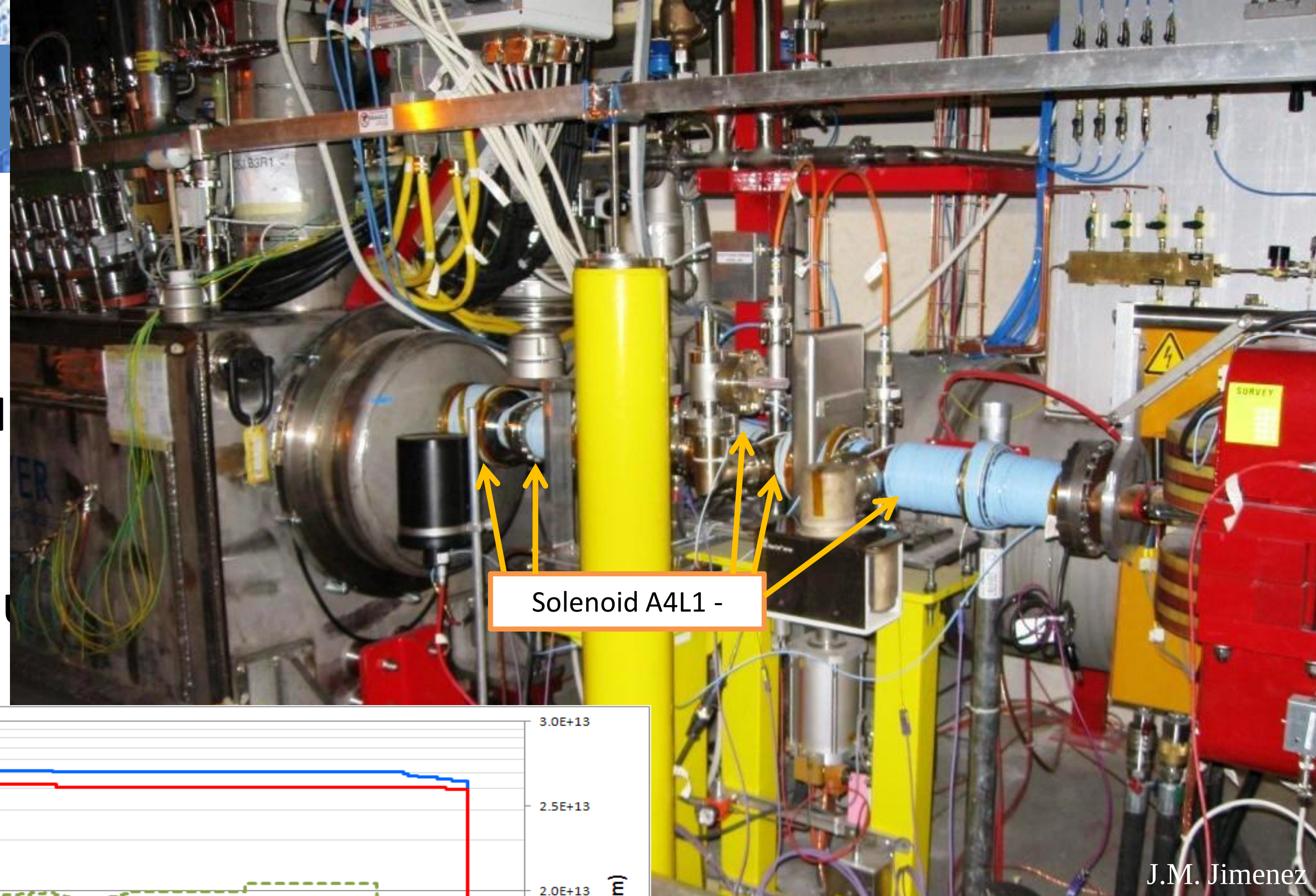
- **The smaller bunch spacing with trains can provoke electron clouds**
- **In warm regions of the machine this can lead to a vacuum pressure rise**
- **In cold regions of the machine this would create an additional heat load on the cryogenic system.**
- **In addition all the electrons in the beam pipe can feed back to affect the beam stability**
- **Can be eliminated by conditioning the surface - scrubbing**

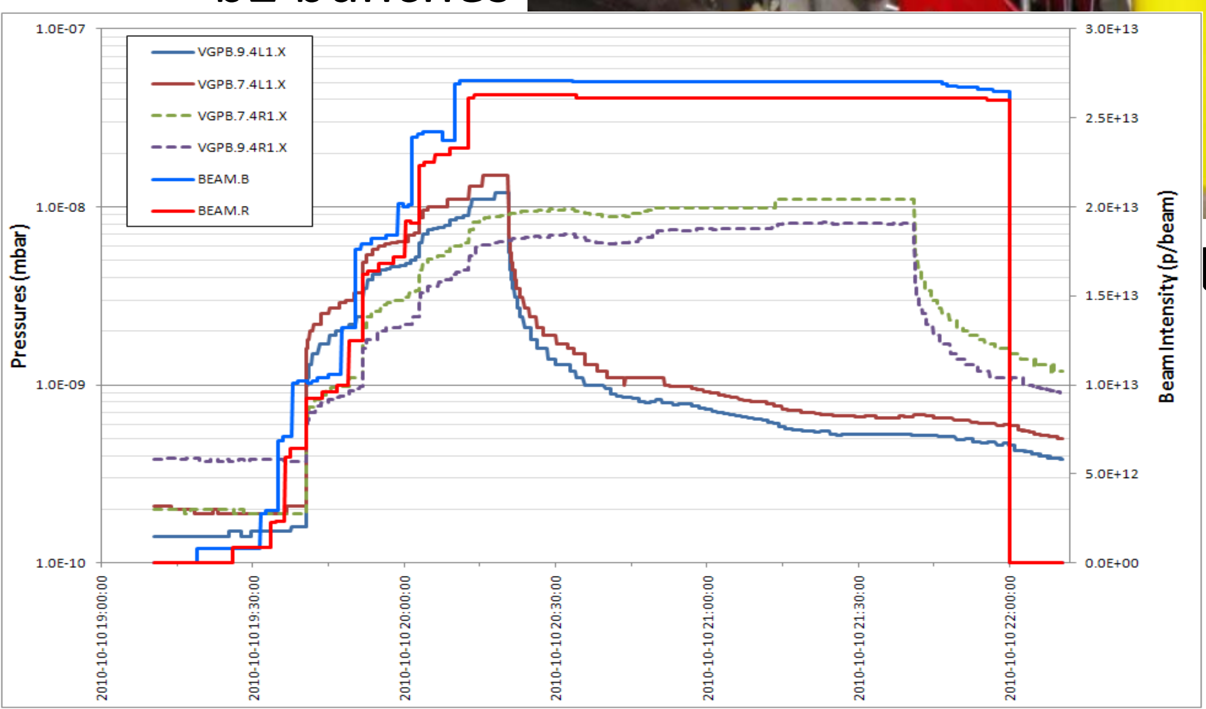


schematic of e- cloud build up in LHC arc beam pipe, due to photoemission and secondary emission

Initially

- Pressure rise
- Particularly u
- Two effects:
  - electron clo
    b2 bunches

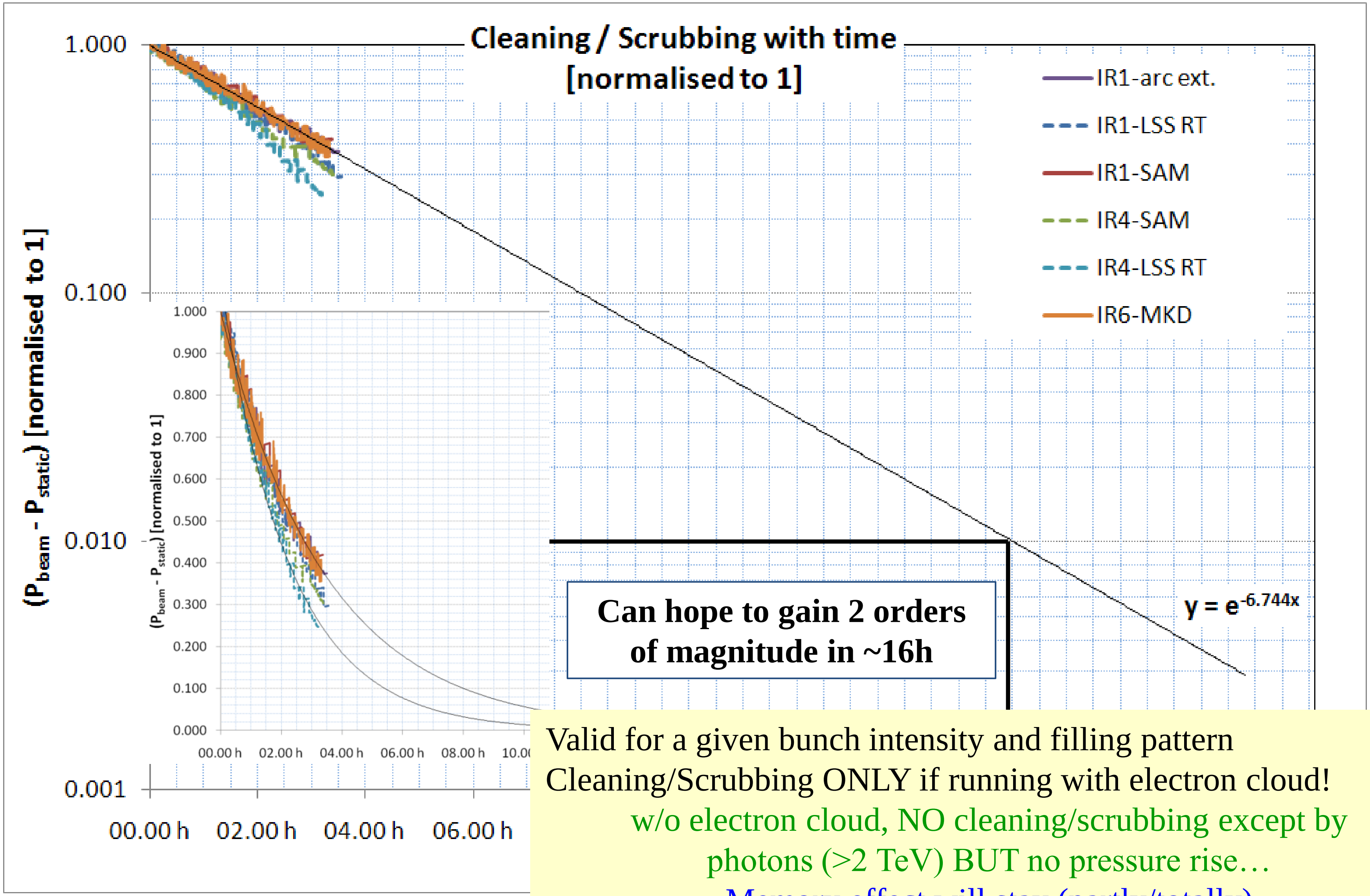




th solenoids

cloud

Scrubbing in the LSS (50 ns)



Valid for a given bunch intensity and filling pattern

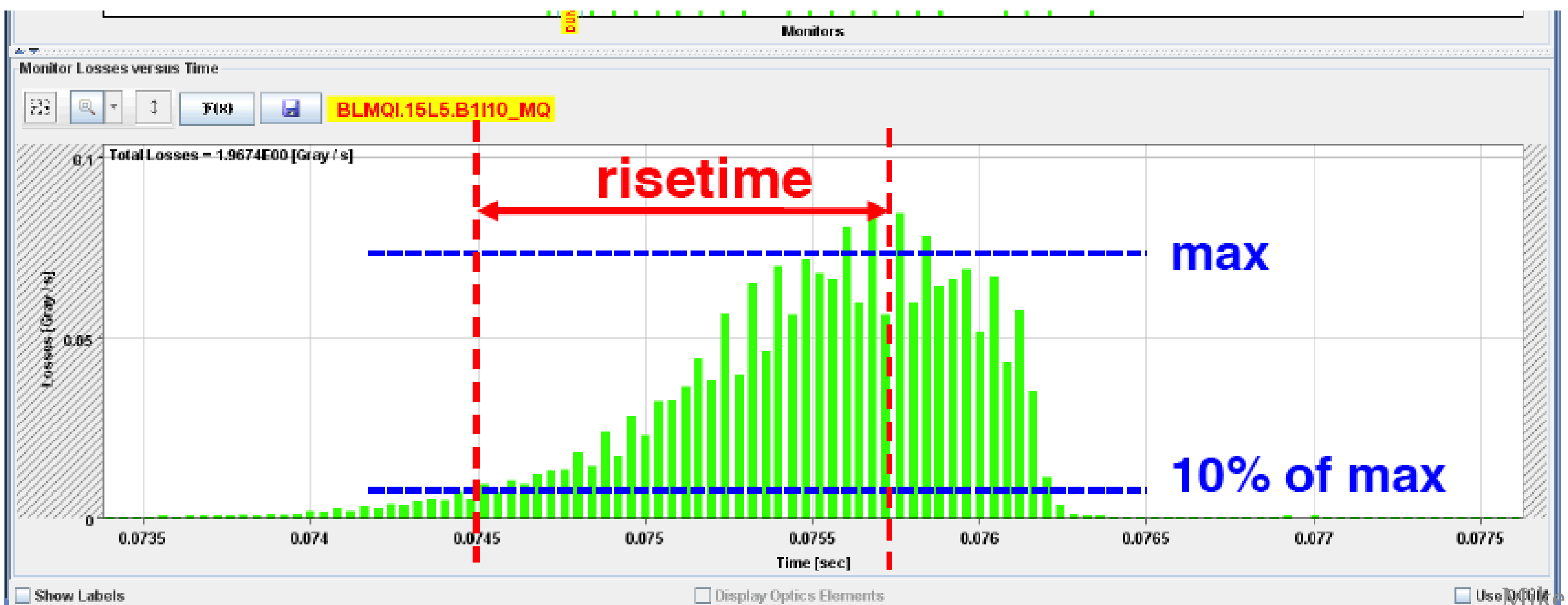
Cleaning/Scrubbing ONLY if running with electron cloud!

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

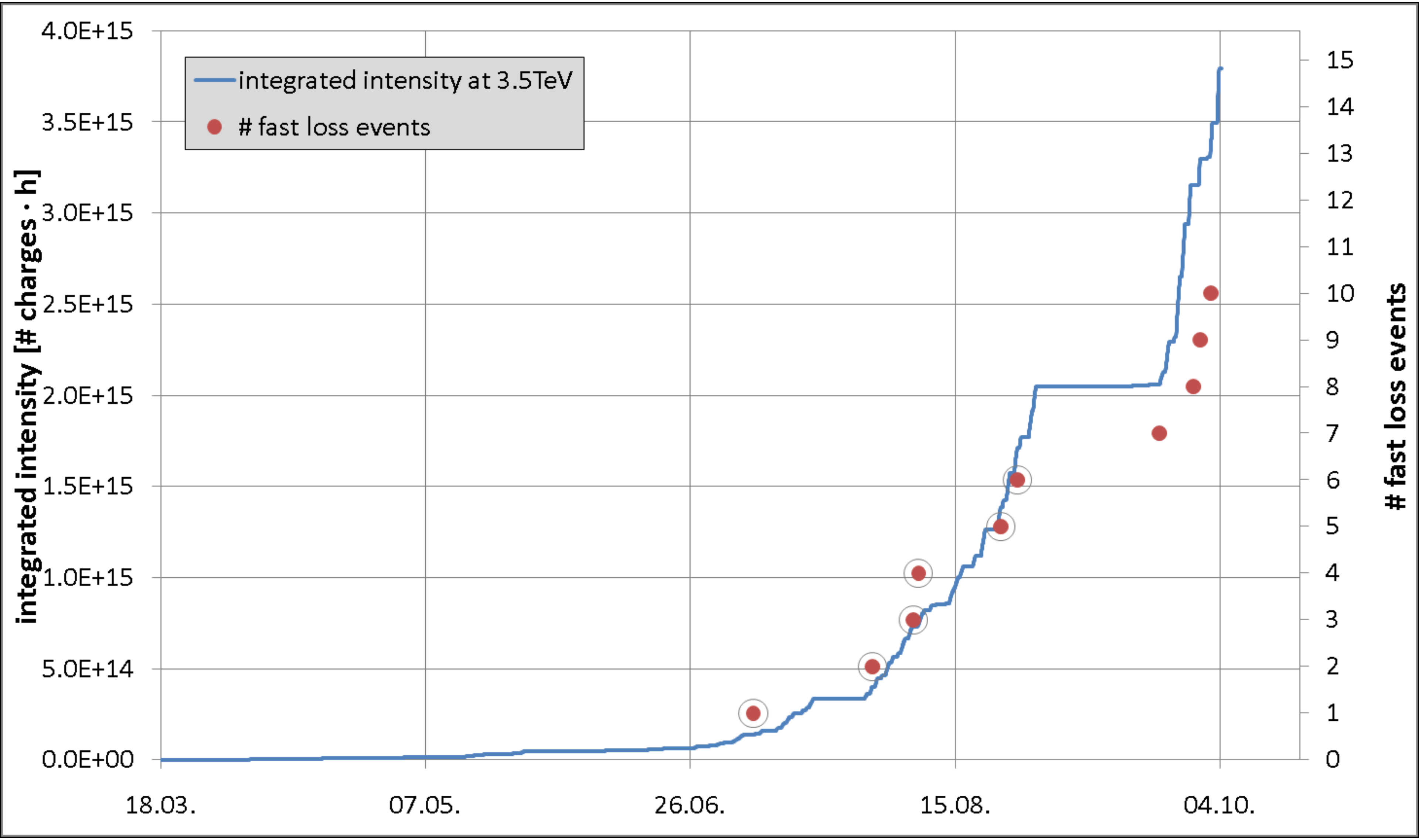
UFO - Unidentified Falling Object
Unforeseen Failure during Operation

- 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



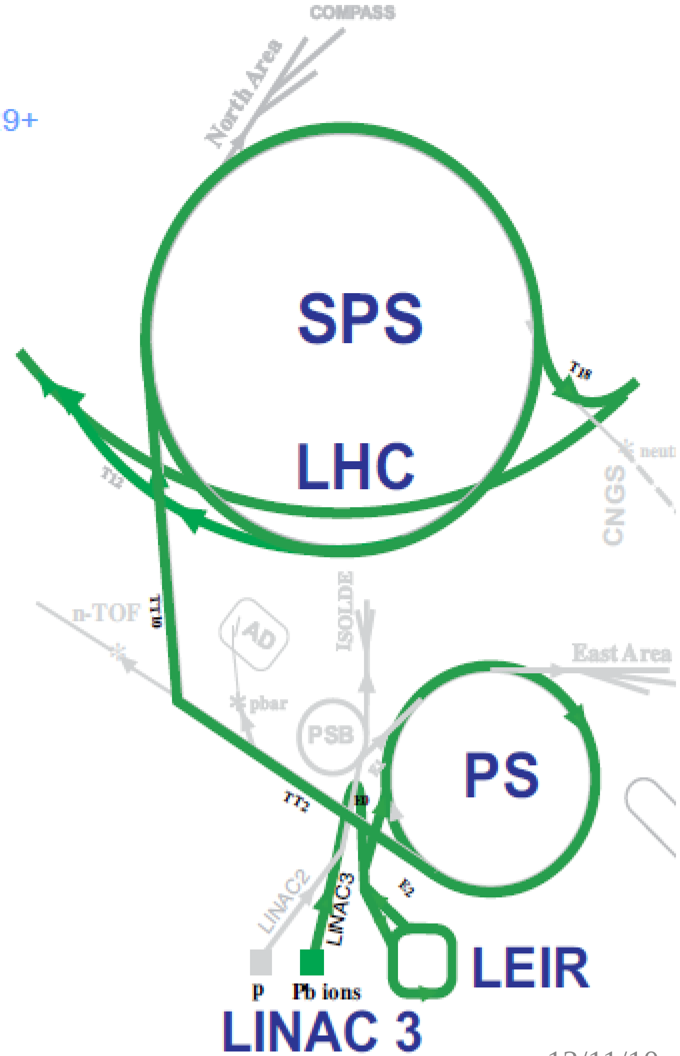
Mike Lamont

UFO - Worrying trend through the summer



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

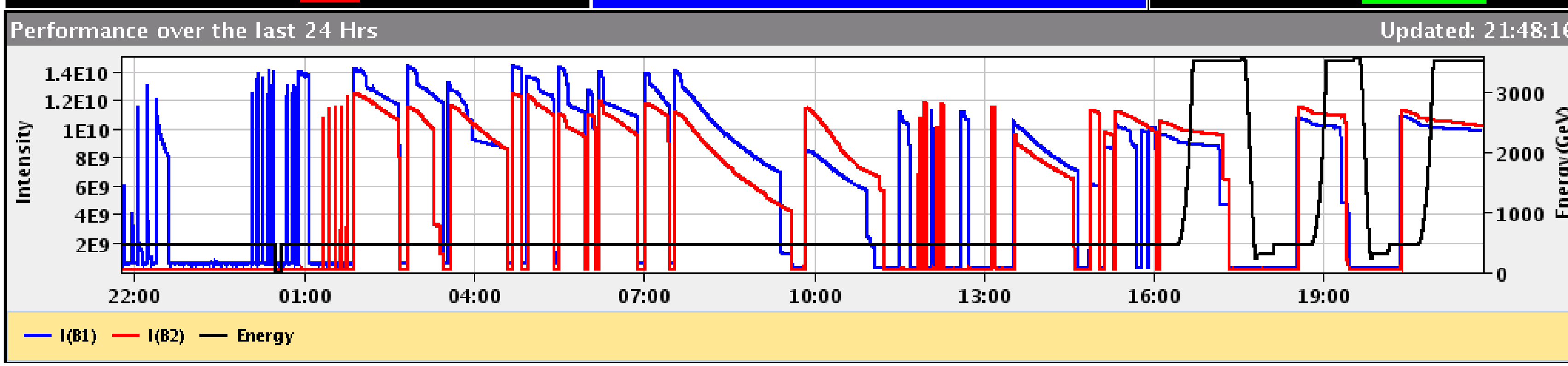


Ion Commissioning: First 24h from Nov 4th !

05-Nov-2010 21:48:18 Fill #: 1473 Energy: 3500 Z GeV I(B1): 9.86e+09 I(B2): 1.02e+10

	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	STANDBY	STANDBY	STANDBY
Instantaneous Lumi (ub.s)^-1	0.000	0.000	0.000	0.000
BRAN Luminosity (ub.s)^-1	0.000	0.000	0.000	0.000
Inst Lumi/CollRate Parameter	1.00e+00		0.00e+00	
BKGD 1	0.002	0.244	0.000	0.122
BKGD 2	0.000	0.000	0.000	0.407
BKGD 3	0.000	1.628	0.098	0.044

LHCb VELO Position	OUT	Gap: 58.0 mm	SQUEEZE	TOTEM:	STANDBY



Beam 1 Inj., Circ. & Capture

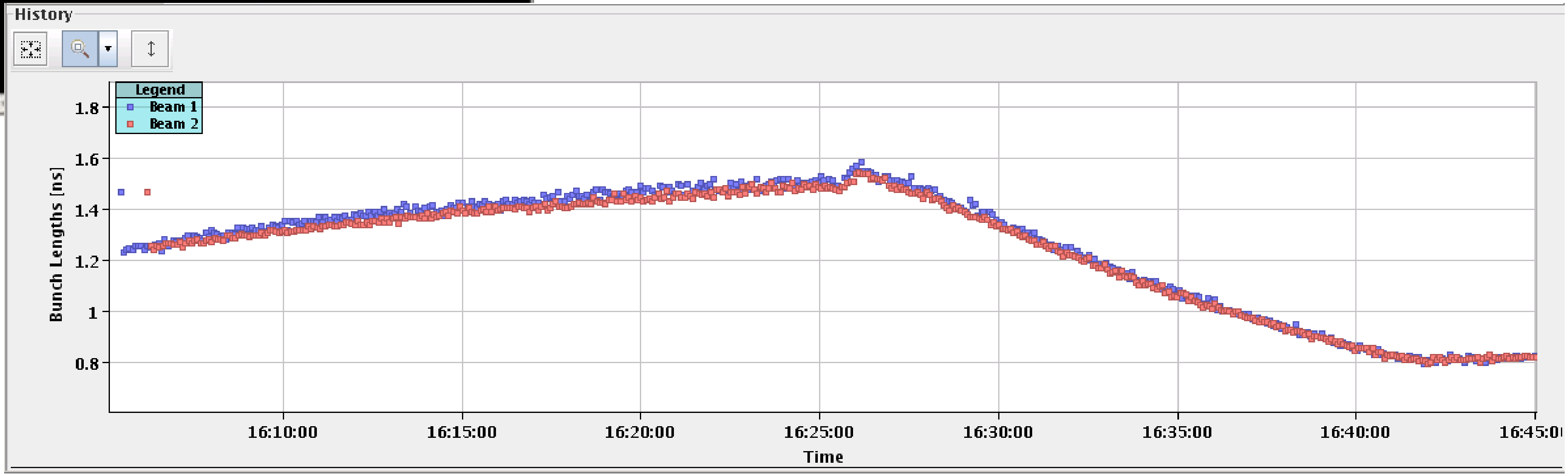
Beam 2 Inj., Circ. & Capture

Optics Checks
BI Checks
Collimation Checks

First Ramp
Collimation Checks
Squeeze

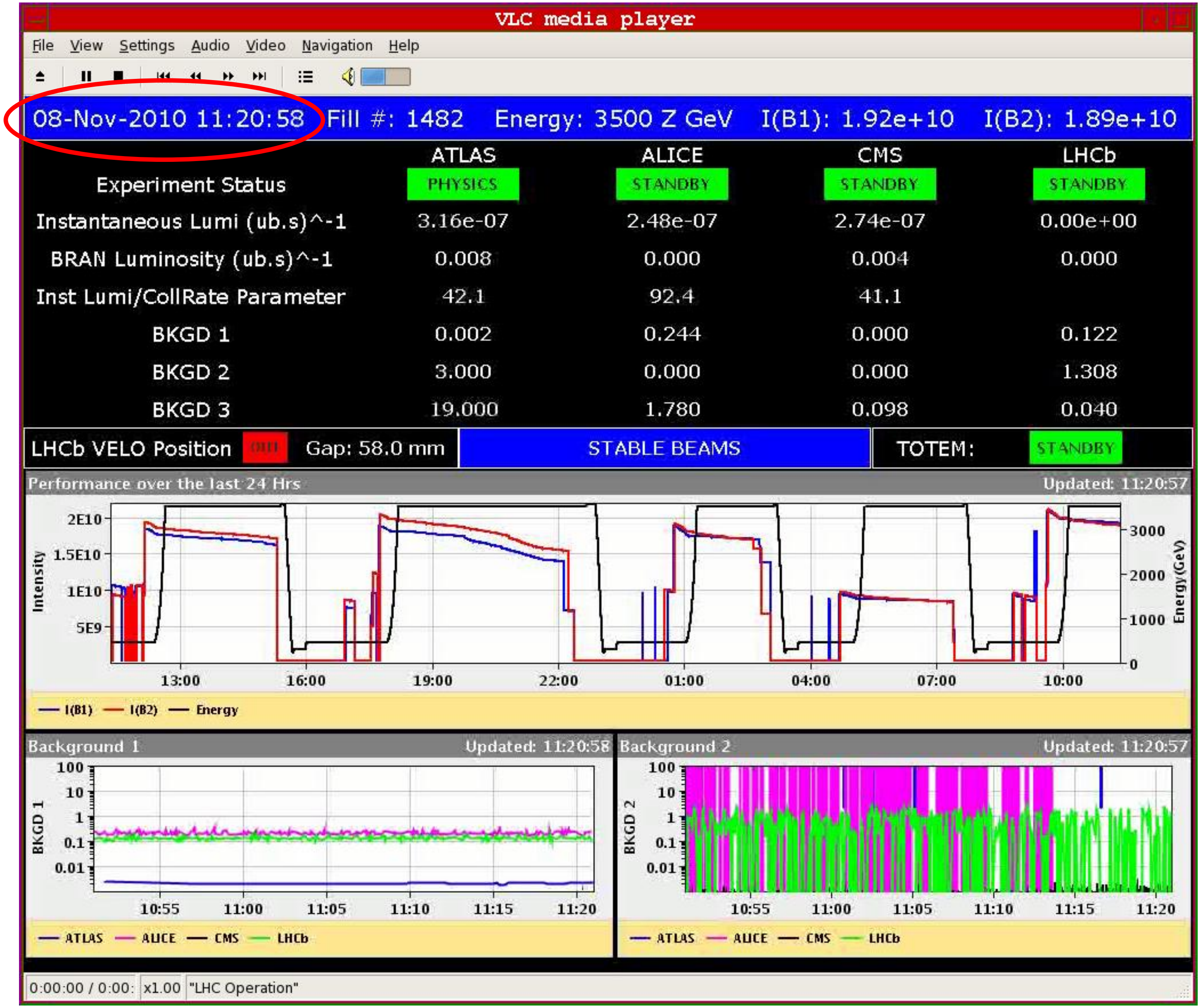
Friday 5th Nov. afternoon: first ramp – no losses

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)

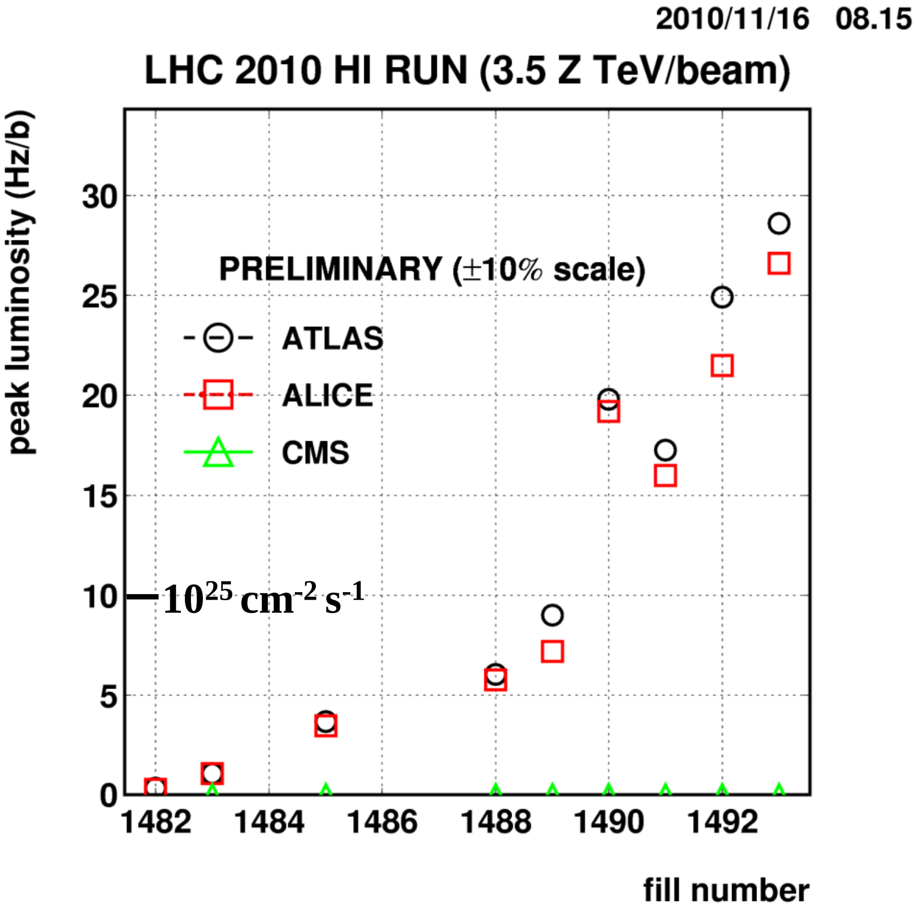


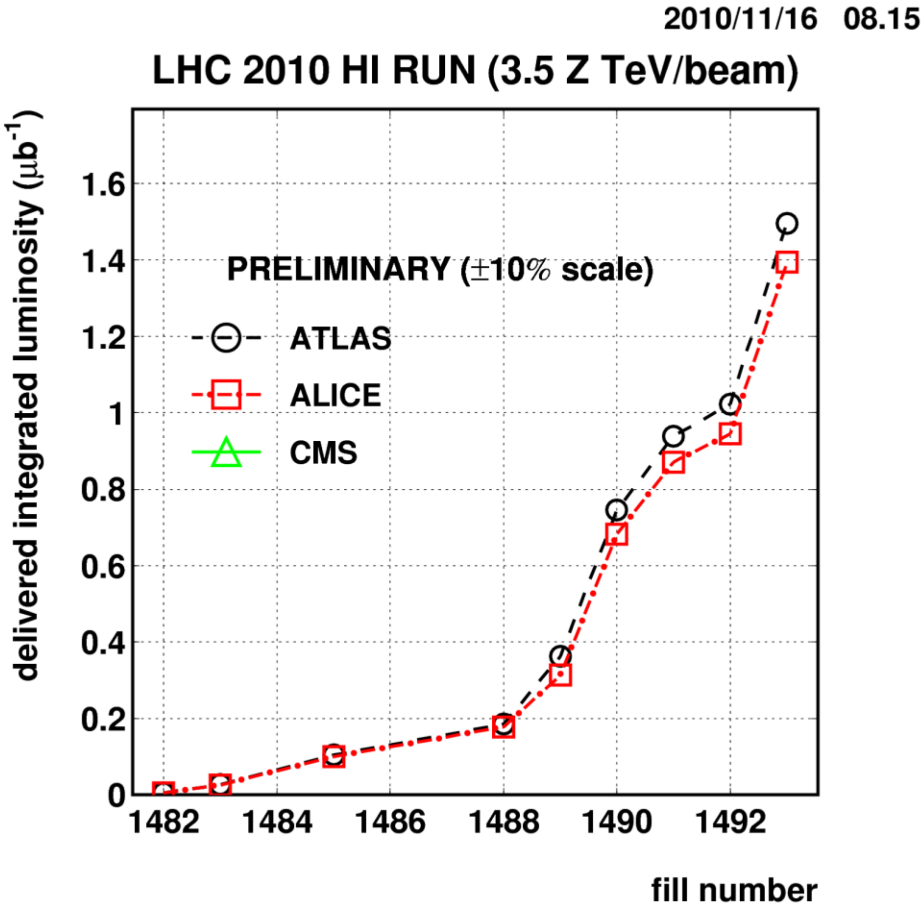
Characteristics and Evolution

- Injectors are giving us 70% beyond design single-bunch intensity of $7\ 10^7$ 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

Date	Bunches	Colliding IR2	Luminosity
November 8	2	1	$3\ 10^{23}$
November 9	5	4	$5\ 10^{23}$
November 9	17	16	$3.5\ 10^{24}$
November 13	69	66	$9\ 10^{24}$
November 14	121	114	$2\ 10^{25}$
November 15	121	114	$2.8\ 10^{25}$

Luminosity evolution (not quite up to date)





Single Event Upset (SEU)

- 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

Summary 2010

- **Bunch train operation with 150ns was a big success**
  - Bunch intensity ~ nominal
  - Normalised emittance ε_n in collision ~ 2.5 µm
  - Maximum bunches/colliding 1 & 5 368/348
  - Peak luminosity ~ 2 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

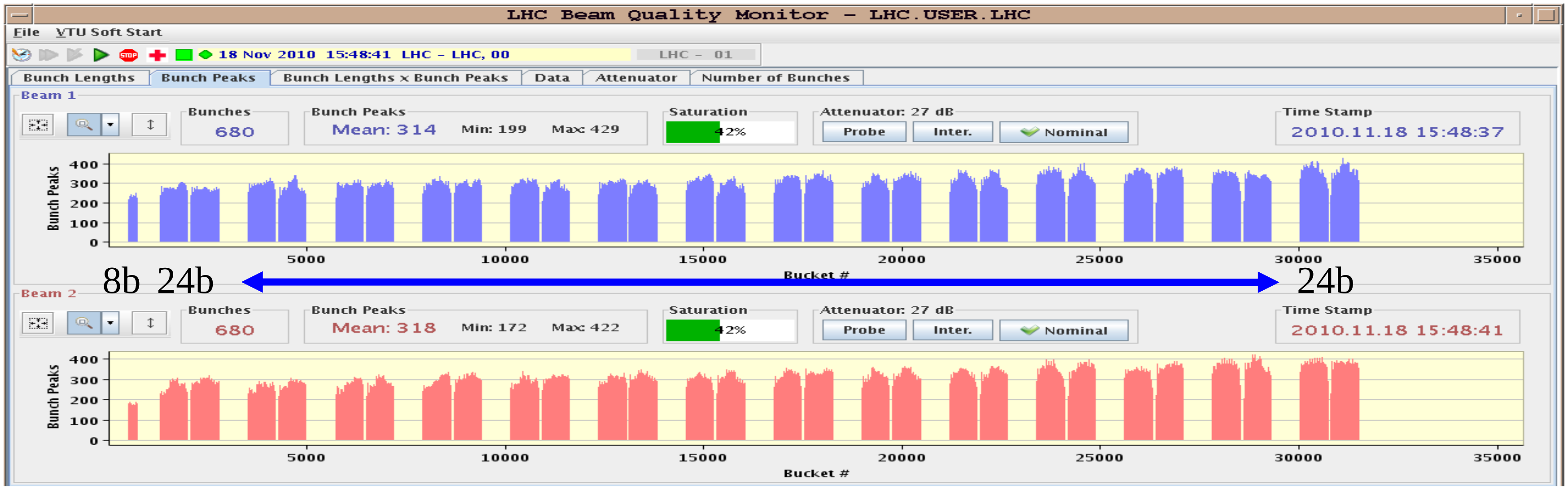
New record of intensity injected in the LHC

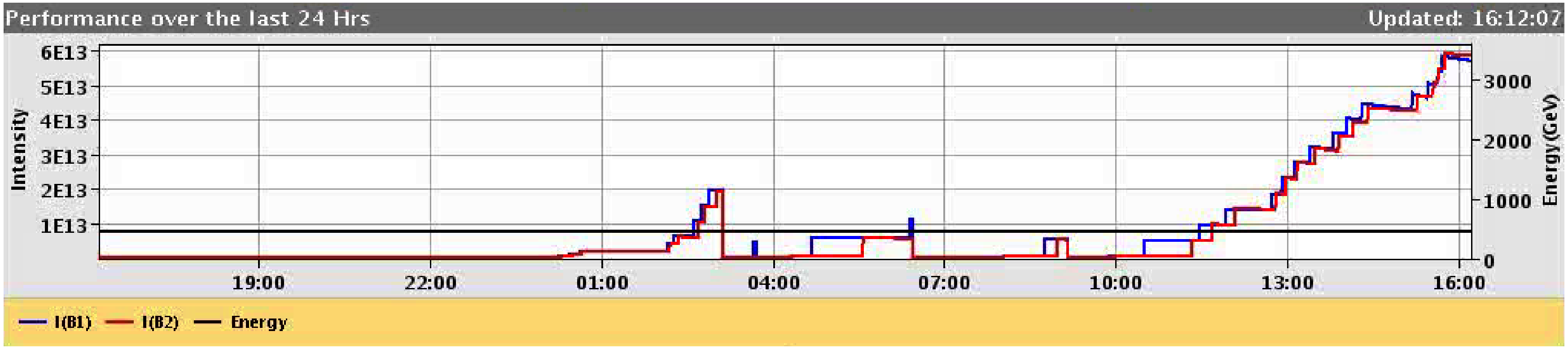
8 + 24/24 + 24/24 +……+ 24/24 = 680 bunches

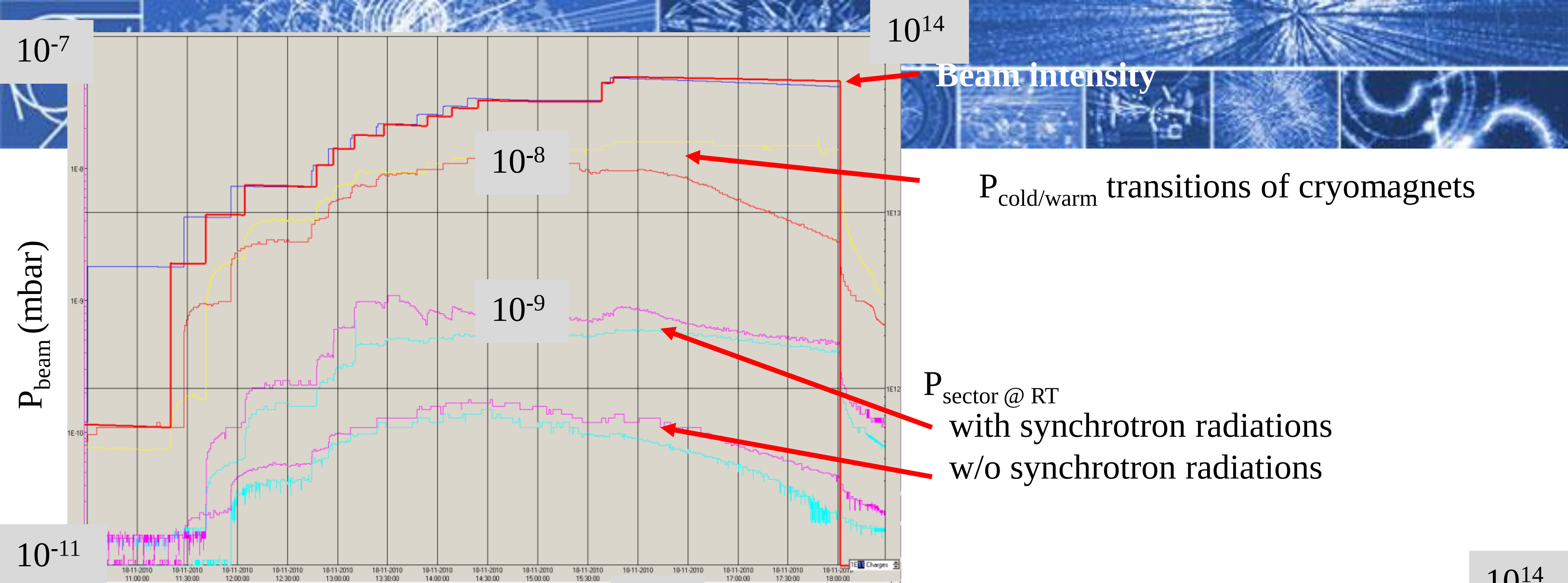
at 1.1 10^{11} p/b, 75 ns bunch spacing@450 GeV

25 % of the nominal LHC intensity!

Beam optimisation ongoing







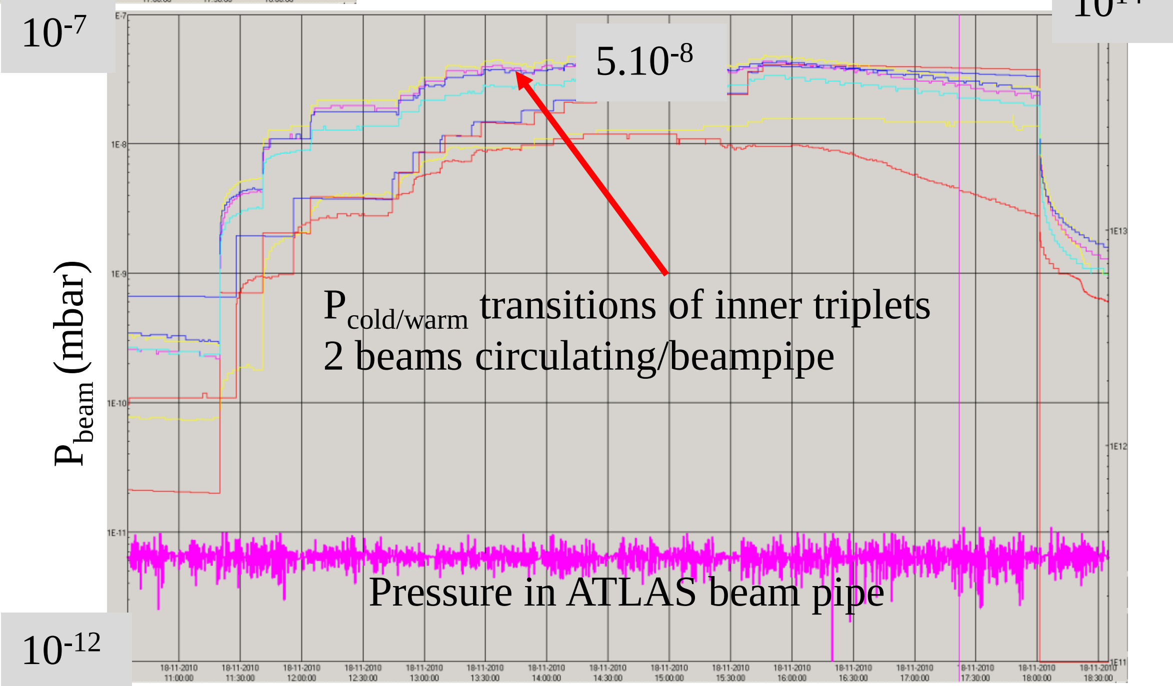
680 b, 75 ns spacing, 1.1 10^{11} p/b @ 450 GeV

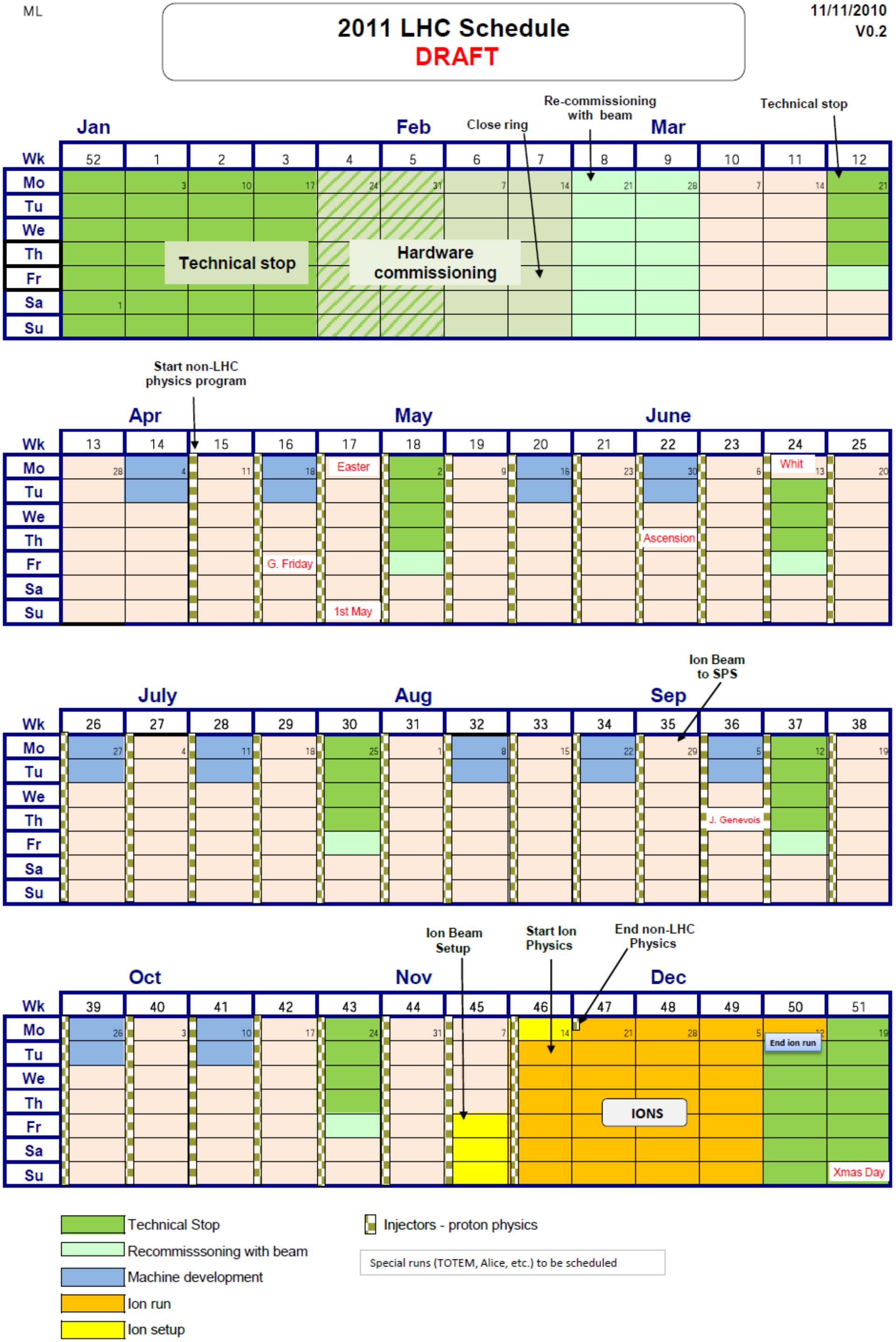
No electron cloud on NEG coated beampipes

No pressure rise/heating observed in arcs

Higher pressure in beampipes with two circulating beams

TODAY are at 850 bunch @ 1.3e11 !!!
in a beam alone, 0.5 I_{nom}





2011

- Beam back around 21st 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 – 12th December

~200 days proton physics

Plans for 2011

- Running Conditions in 2011 (Chamonix January 2011)
  - Maximum beam energy
  - Bunch spacing 50ns (max bunches 1404)
  - Integrated luminosity evaluation

    => goal set is 1fb^{-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 x 10^{11} protons/bunch
- beta* = 2.5 m, nominal crossir
- Hubner factor 0.2

Peak luminosity	6.4 x 10^{32}
Integrated per day	11 pb^{-1}
200 days	2.2 fb^{-1}
Stored energy	72 MJ

Usual warnings apply – see problems, problems above

Ultimate reach

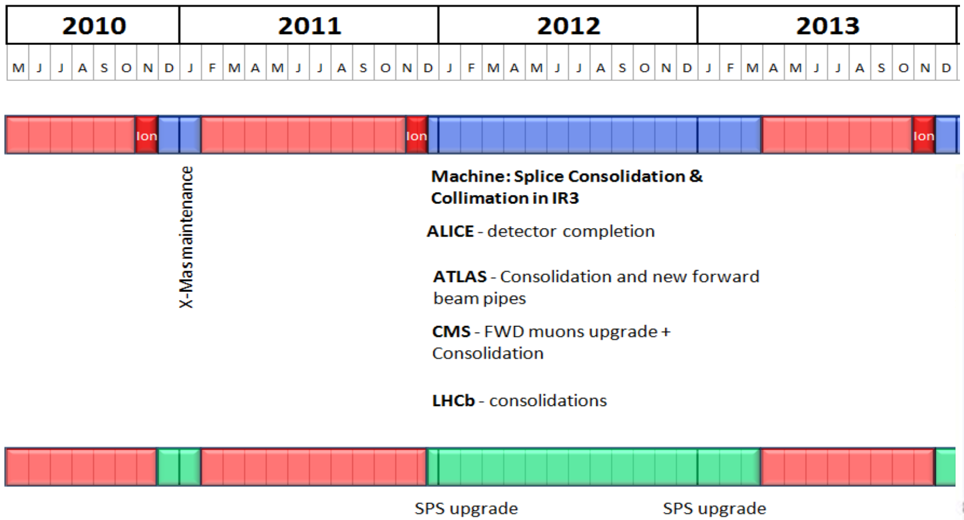
1.6 x10^{11} ppb and emittance of 2 microns at 3.5 TeV respects the robustness limits of the collimation system (equivalent to ultimate intensity) *Ralph Assmann*

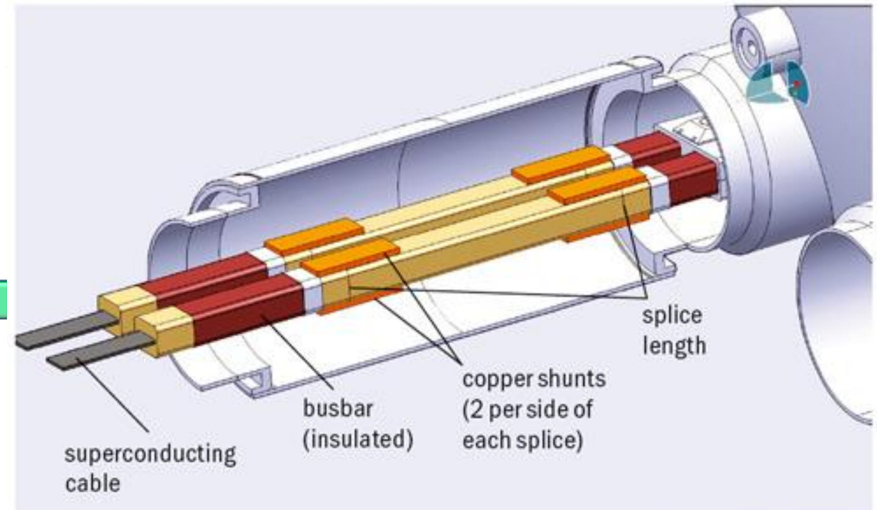
- 4 TeV
- 1400 bunches (50 ns)
- 2.5 micron emittance
- 1.5 x 10^{11} protons/bunch
- beta* = 2.0 m, nominal crossing angle
- Hubner factor 0.2

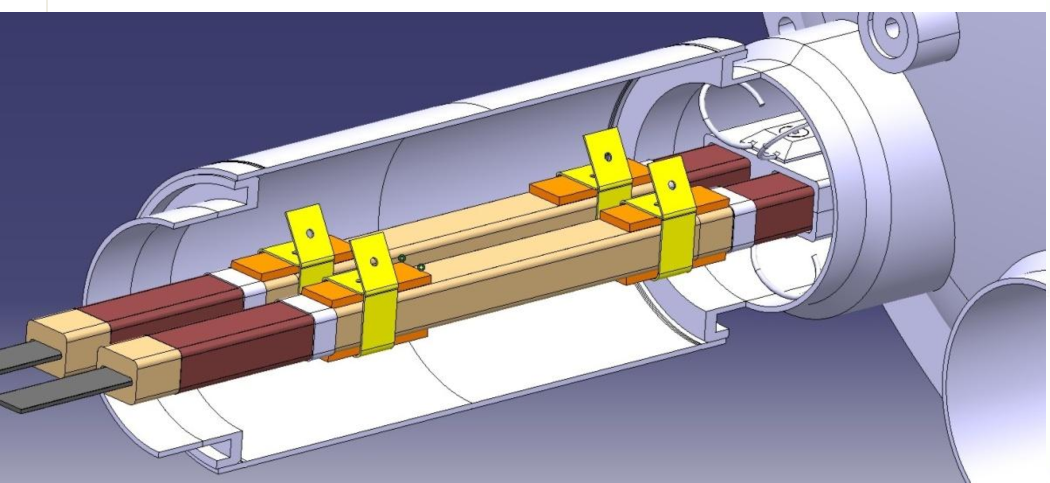
Peak luminosity	2.2 x 10^{33}
Integrated per day	38 pb^{-1}
200 days	7.6 fb^{-1}
Stored energy	134 MJ

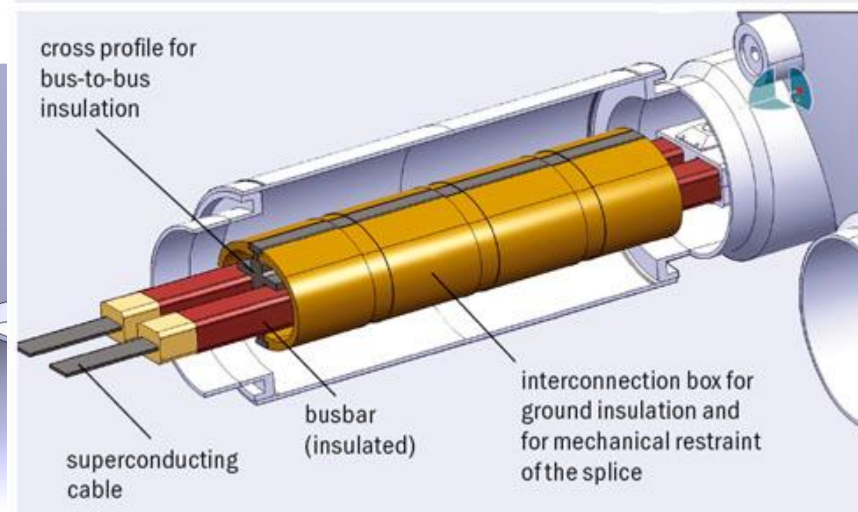
Usual warnings particularly apply – see problems, problems above

2012 – 2013 long shutdown

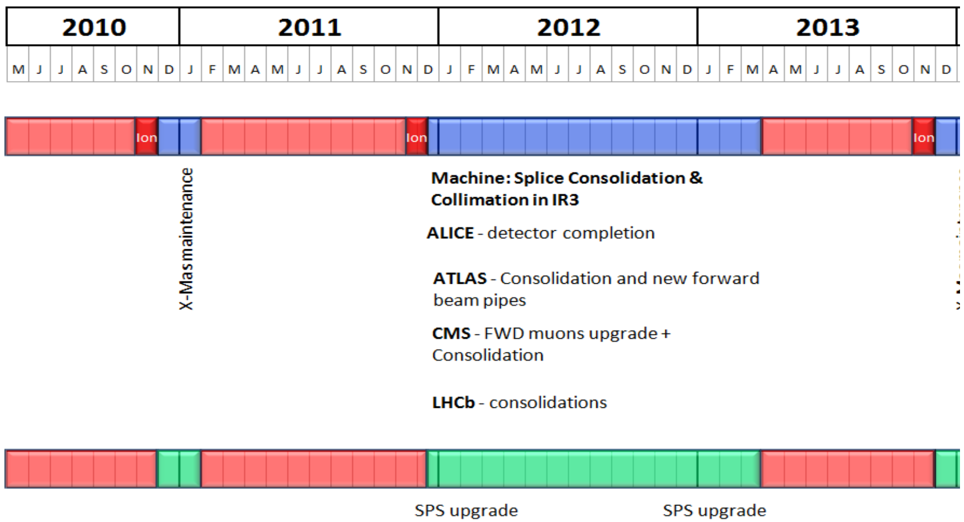




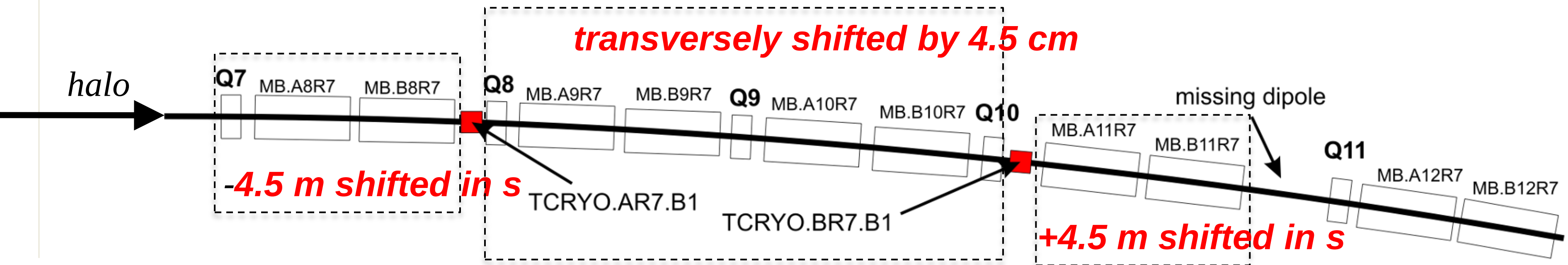


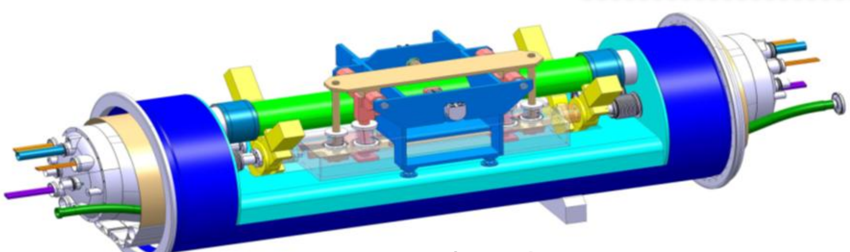


2011 - 2016



Run the LHC between 6.5 TeV and 7 TeV according to magnet training

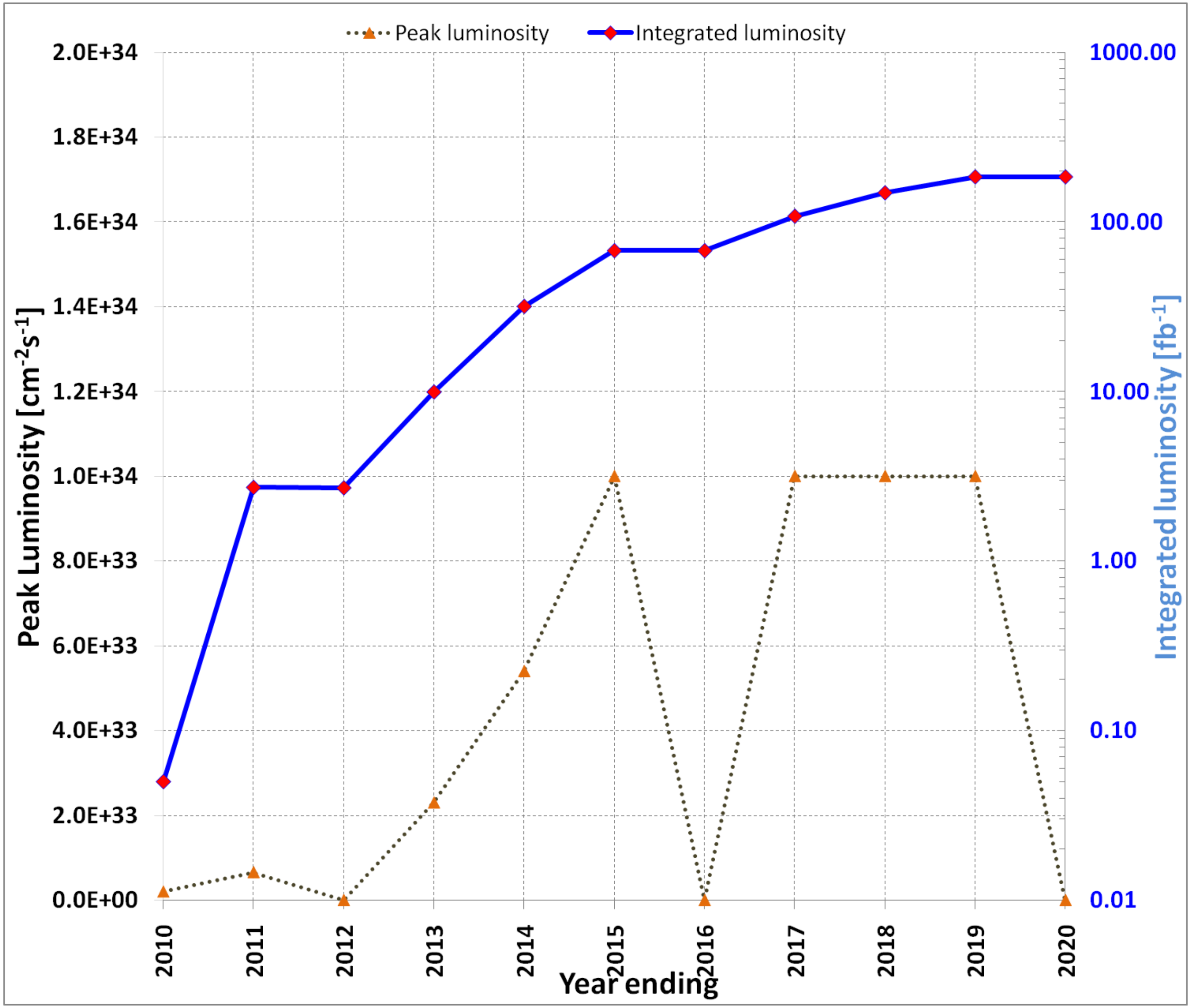




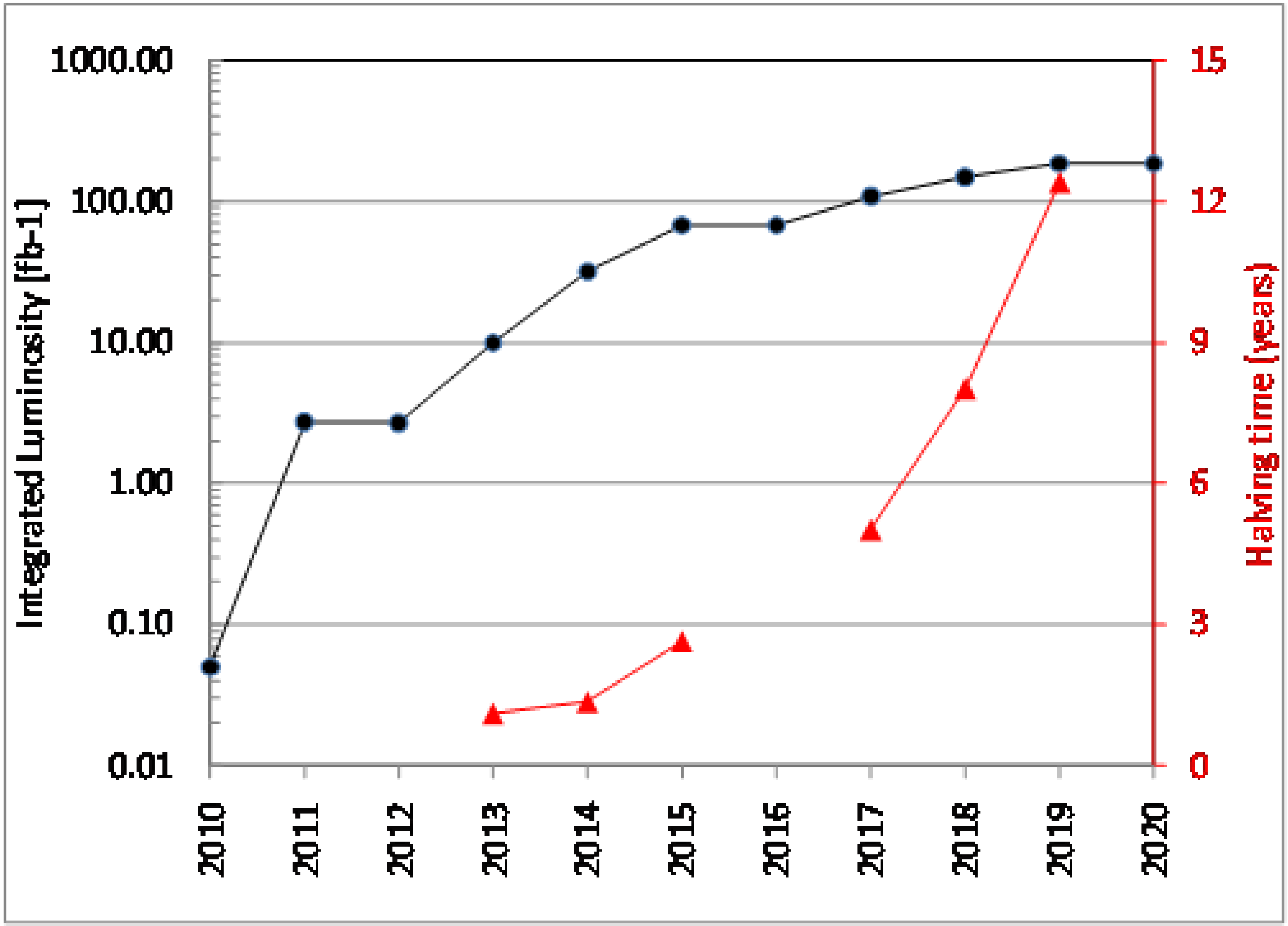
70 MCHF

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

Lumi forecast



Lumi and halving time



Upgrades: Foreword

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:
  3000fb^{-1} (on tape) by the end of the life of the LHC
  → 250 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

Luminosity Upgrade Scenario

– For LHC high luminosities, the luminosity lifetime becomes comparable with the turn round time $\Rightarrow$ Low efficiency

– Preliminary estimates show that the useful integrated luminosity is greater with
  - a peak luminosity of 5×10^{34} cm^{-2} 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 5×10^{34} and 10^{35}.

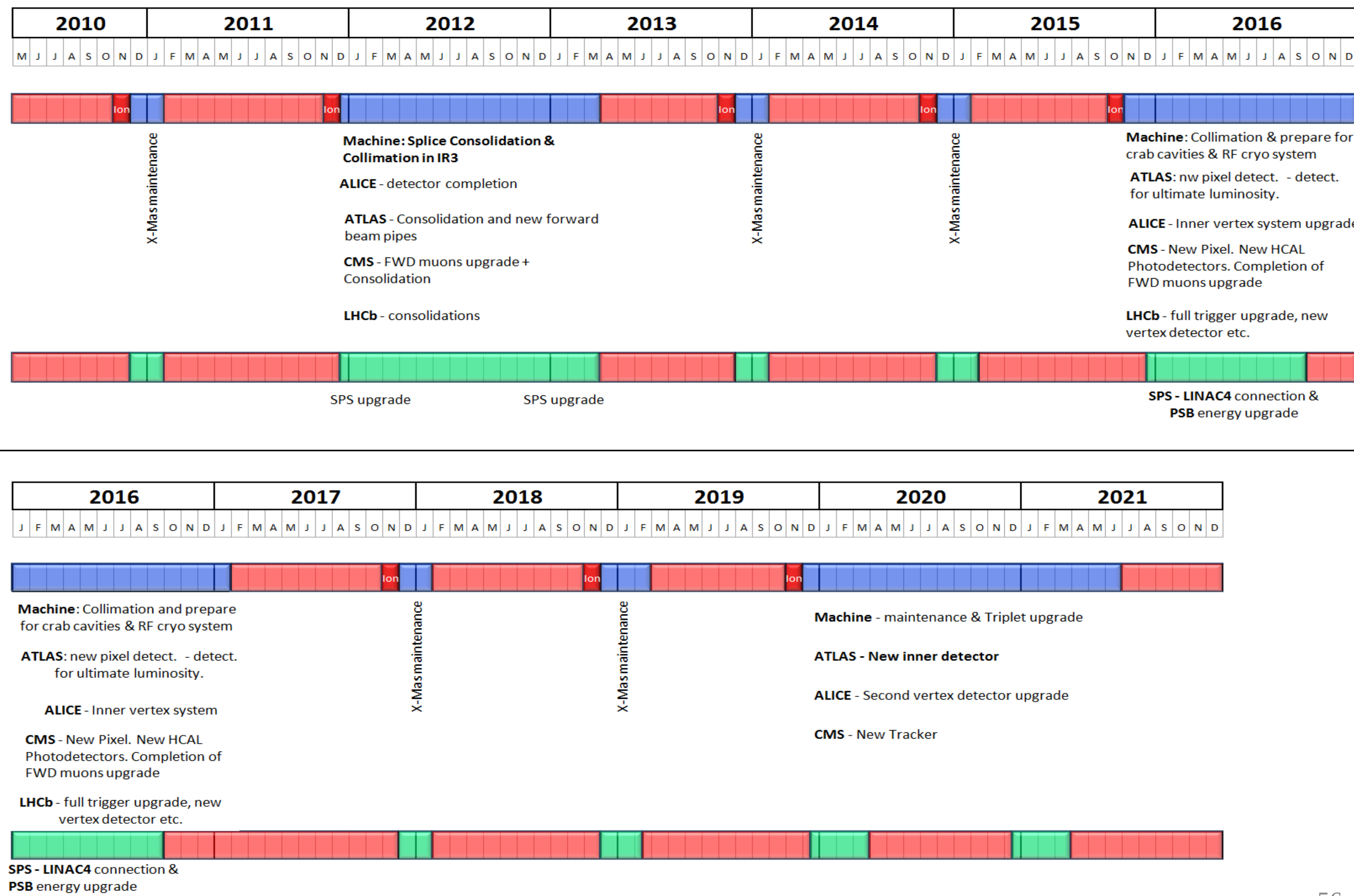
- ***Pile up events***
- ***Radiation effects***

Hardware for the Upgrade

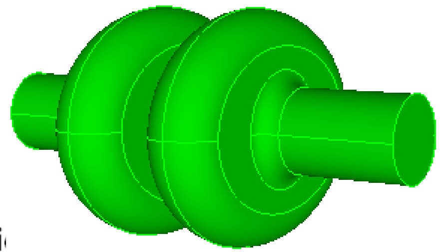
- Upgrade of the intensity in the Injector Chain
- New high field insertion quadrupoles
- Upgraded cryo system for IP1 and IP5
- Crab Cavities to take advantage of the small beta*
- Single Event Upsets
  - SC links to allow power converters to be moved to surface (and easy integration in crowdy IR zone)

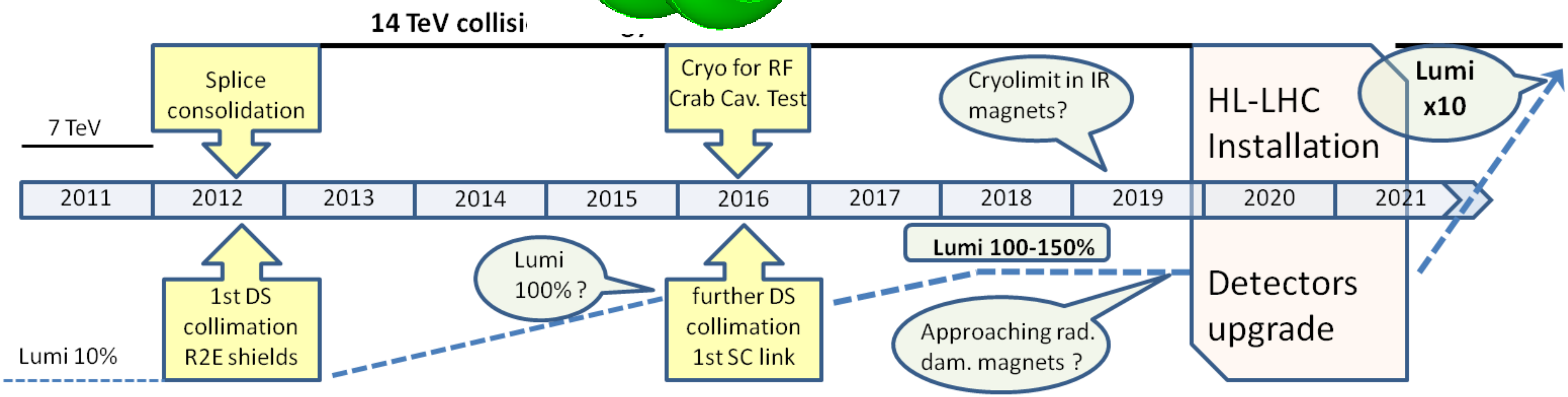
- Misc
  - Upgrade some correctors
  - Re-commissioning DS quads at higher gradient
  - Change of New Q5/Q4 (larger aperture), with new stronger corrector orbit, displacements of few magnets
  - Larger aperture D1/D2

The 10 year technical Plan

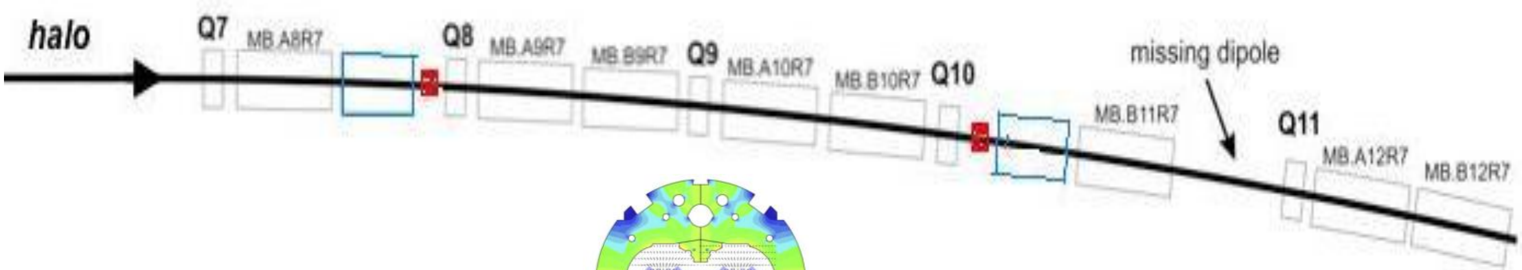


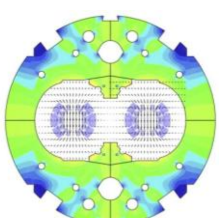
Timeline
energy and luminosity 2011-2021

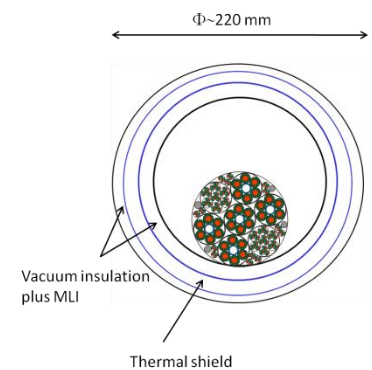




New 3..3.5 m shorter Nb3Sn Dipoles (2 per DS)

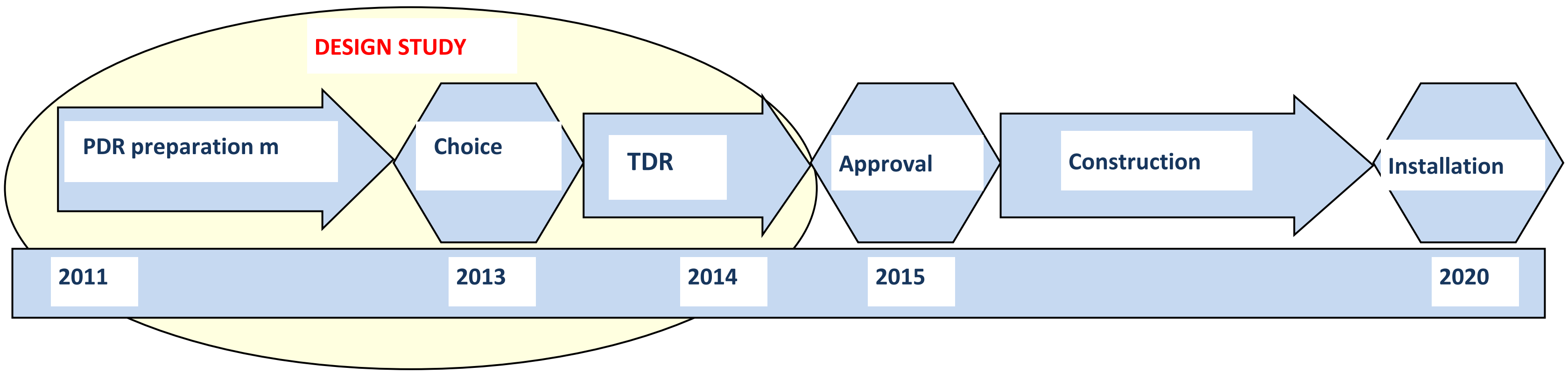




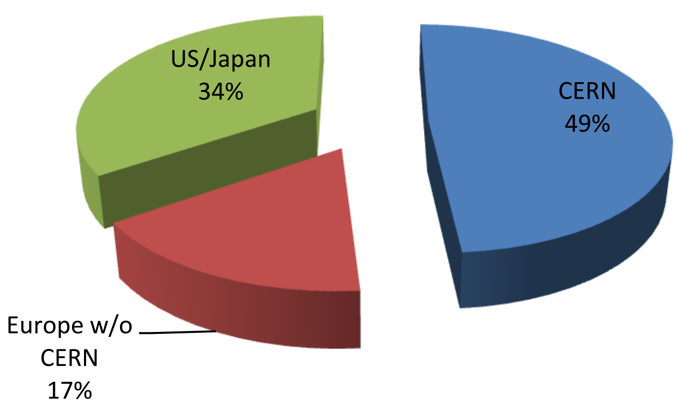


HL-LHC project defined this summer

HL-LHC Design Study is being launched. Application for grant to EU, with strong partecipation by USA-JP

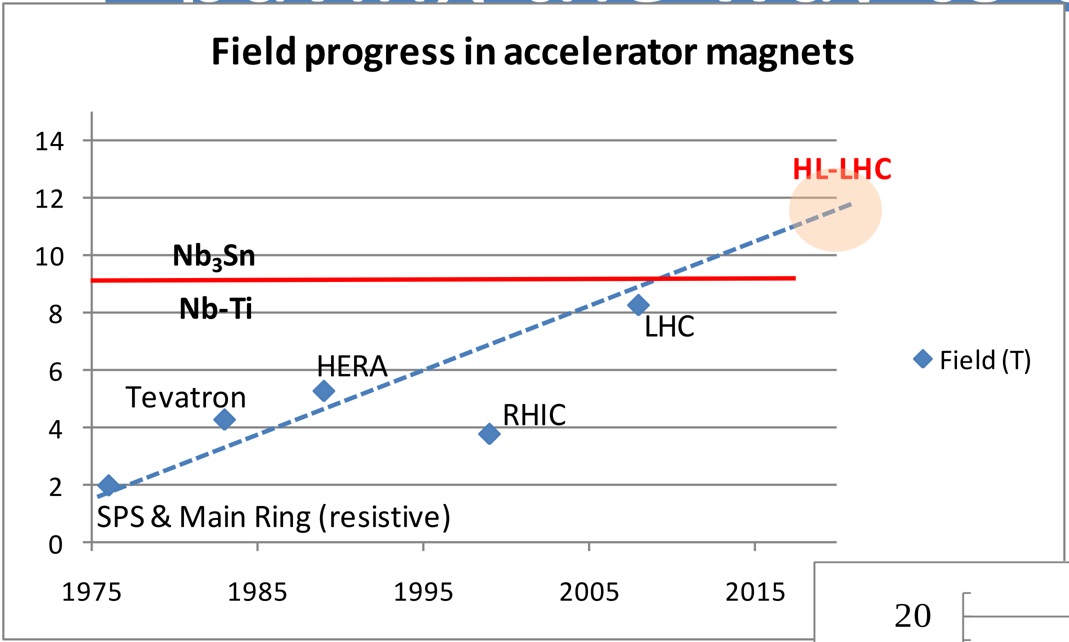


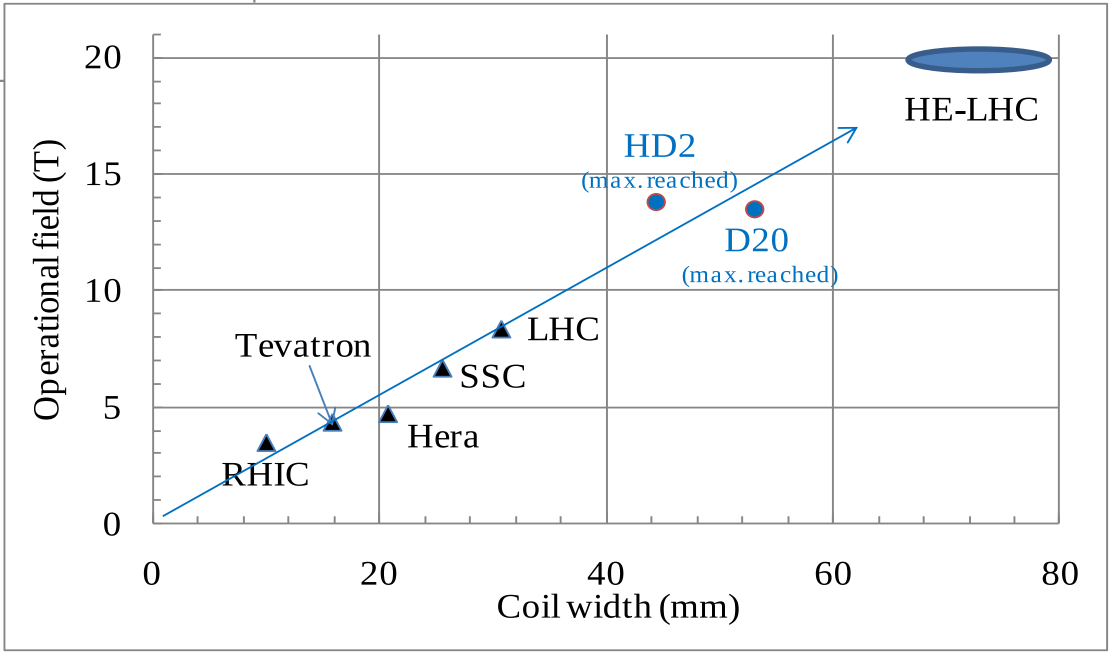
Total (€ 21,184,800)



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

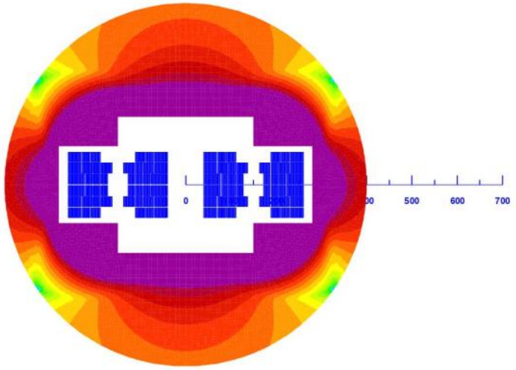
Preliminary HE-LHC - parameter[illegible]

Very preliminary with large error bars

	nom[illegible]	HE-LHC
beam energy [TeV]	[illegible]	16.5
dipole field [T]	[illegible]	20
dipole coil aperture [mm]	[illegible]	40-45
#bunches / beam	[illegible]	1404
bunch population [10^{11}]	[illegible]	1.29
initial transverse normalized em[illegible] [μm]	[illegible]	3.75 (x), 1.84 (y)
number of IPs contributi[illegible]	3	2
maximum total bea[illegible]	0.01	0.01
IP beta function [illegible]	0.55	1.0 (x), 0.43 (y)
full crossing [illegible]	285 (9.5 $\sigma_{x,y}$)	175 (12 σ_{x0})
stored b[illegible]	362	479
SR p[illegible]	3.6	62.3
longitu[illegible] damping time [h]	12.9	0.98
events pe[illegible]	19	76
peak lumin[illegible] $cm^{-2}s^{-1}$]	1.0	2.0
beam lifetime [illegible]]	46	13
integrated luminosity over 10 h [fb^{-1}]	0.3	0.5

HE-LHC – main issues and R&D

- ***high-field 20-T dipole*** *magnets based on Nb_3Sn, Nb_3Al, 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

Instantaneous Luminosity

The number of Events per second generated by the LHC is given by:

$$\textit{Number of events} = L \times \sigma_{event}$$

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

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

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 — Total Intensity
- Number of particles per bunch N — Beam Brightness
- Normalised emittance ε_n — Beam Brightness
- Relativistic factor (E/m_0) γ — Energy
- Beta function at the IP β^* — Interaction Region
- Crossing angle factor F — Interaction Region

Bunch Numbers, Patterns and Spacing (2)

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 …

Some remarks… (cont'd)

- 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…

However…

Crash program of investigations with 50 ns

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 $\square_{max}$~2.5 in the arcs (larger than expected) at R=0.5
- Av. e-cloud density ~6×10^{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

Electron cloud effects

- 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

Frank Zimmermann

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

unique vacuum system!

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

		Early (2010/11)	Nominal
$\sqrt{s}$ per nucleon	TeV	2.76	5.5
Initial Luminosity (L_0)	$cm^{-2}s^{-1}$	$\sim 10^{25}$	10^{27}
Number of bunches		62	592
Bunch spacing	ns	1350	99.8
β^*	m	3.5	0.5
Pb ions/bunch		7×10^7	7×10^7
Transverse norm. emittance	μm	1.5	1.5
Luminosity half life (1,2,3 expts.)	h	τ_{IBS}=7-30	8, 4.5, 3

Initial interaction rate: 100 Hz (10 Hz central collisions *b* = 0 – 5 fm)
$\sim 10^8$ interaction/10^6s (~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 x 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

Circumference (km)	26.7	100-150m underground
Number of superconducting twin-bore Dipoles	1232	Cable Nb-Ti, cold mass 37million kg
Length of Dipole (m)	14.3	
Dipole Field Strength (Tesla)	8.4	Results from the high beam energy needed
Operating Temperature (K) (cryogenics system)	1.9	Superconducting magnets needed for the high magnetic field Super-fluid helium
Current in dipole sc coils (A)	13000	Results from the high magnetic field 1ppm resolution
Beam Intensity (A)	0.5	$2.2.10^{-6}$ loss causes quench
Beam Stored Energy (MJoules)	362	Results from high beam energy and high beam current: 1MJ melts 1.5kg Cu
Magnet Stored Energy (MJoules)/octant	1100	Results from the high magnetic field
Sector Powering Circuit	8	1612 different electrical circuits