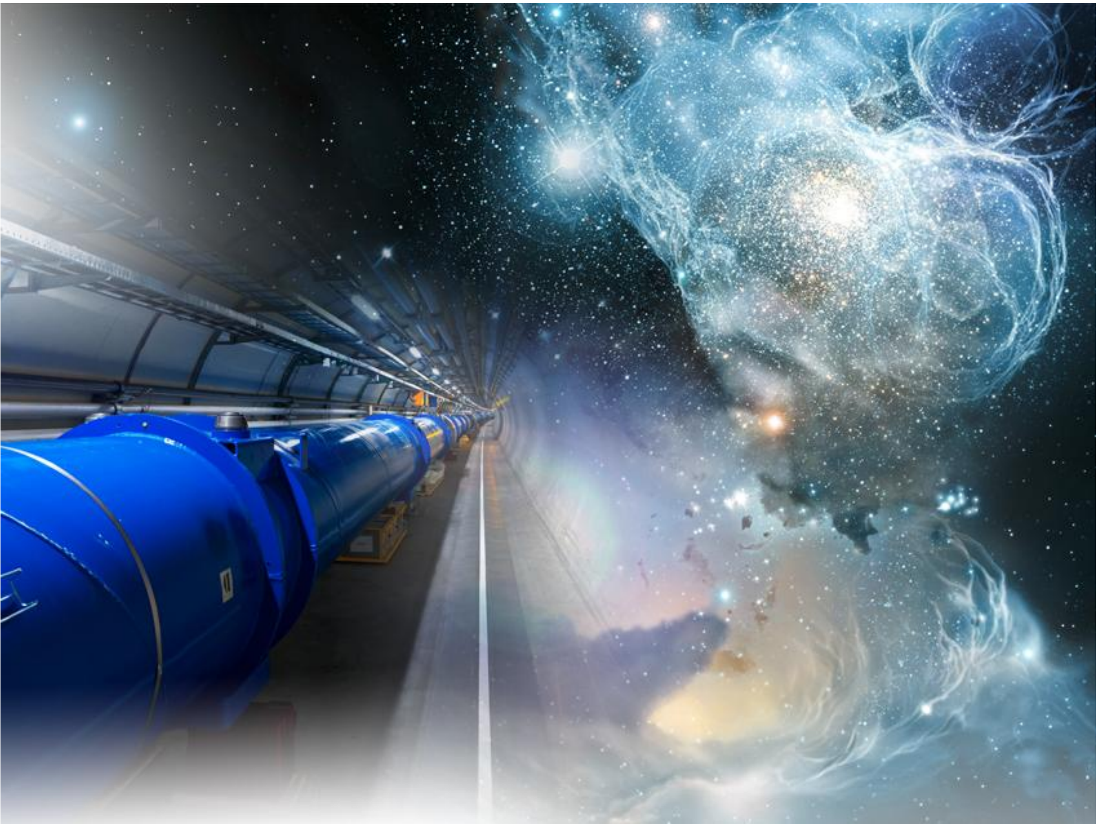
CERN

European Organization for Nuclear Research
Organisation Européenne pour la Recherche Nucléaire

LHC machine
Status and future plans



Dr. Frédérick BORDRY
CERN – Head of Technology Department

Friday 10th December 2010

Menu

- **LHC machine recap and main challenges**
- **LHC repair and restart in 2009**
- **Proton and ion runs in 2010**
- **Plan for 2011**
- **2012- 2030 scenarii**
- **Conclusion**

What is LHC (Large Hadron Collider) ?

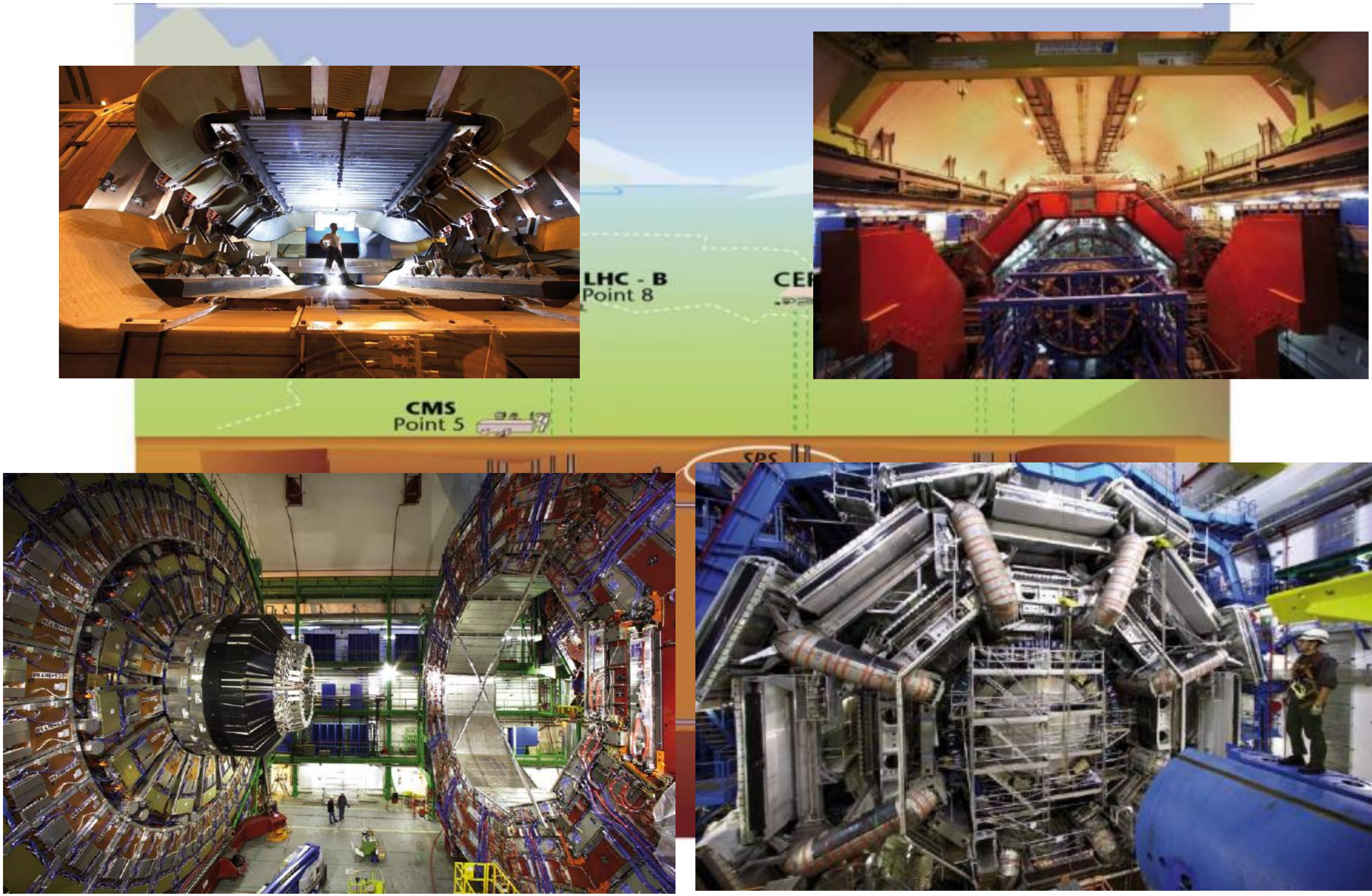
7 TeV
proton-proton
accelerator-collider
built in the LEP
tunnel

Beams of LEAD nuclei will be also accelerated, smashing together with a collision energy of 1150 TeV

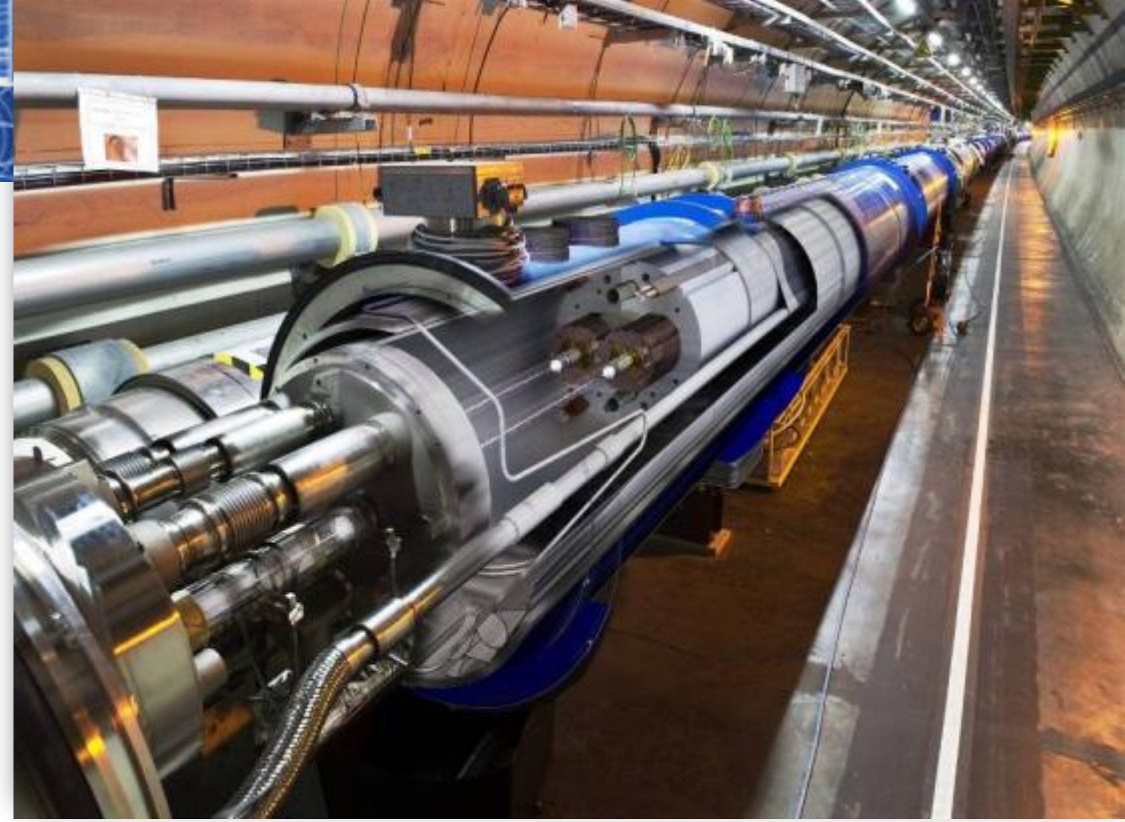
1982 : First studies for the LHC project
1994 : Approval of the LHC by the CERN Council
1996 : Final decision to start the LHC construction
2004 : Start of the LHC installation
2006 : Start of hardware commissioning
2008 : End of hardware commissioning and start of commissioning with beam
2009-2030: physics operation

Four large experiments

Overall layout of LHC



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 controlled with high precision (up to 13 kA)
- The highest precision ever demanded from the power converters, a few ppm
- A sophisticated and ultra-reliable magnet quench protection system

Final assembly of cryomagnets at CERN

1232 main dipoles
400 main quadrupoles

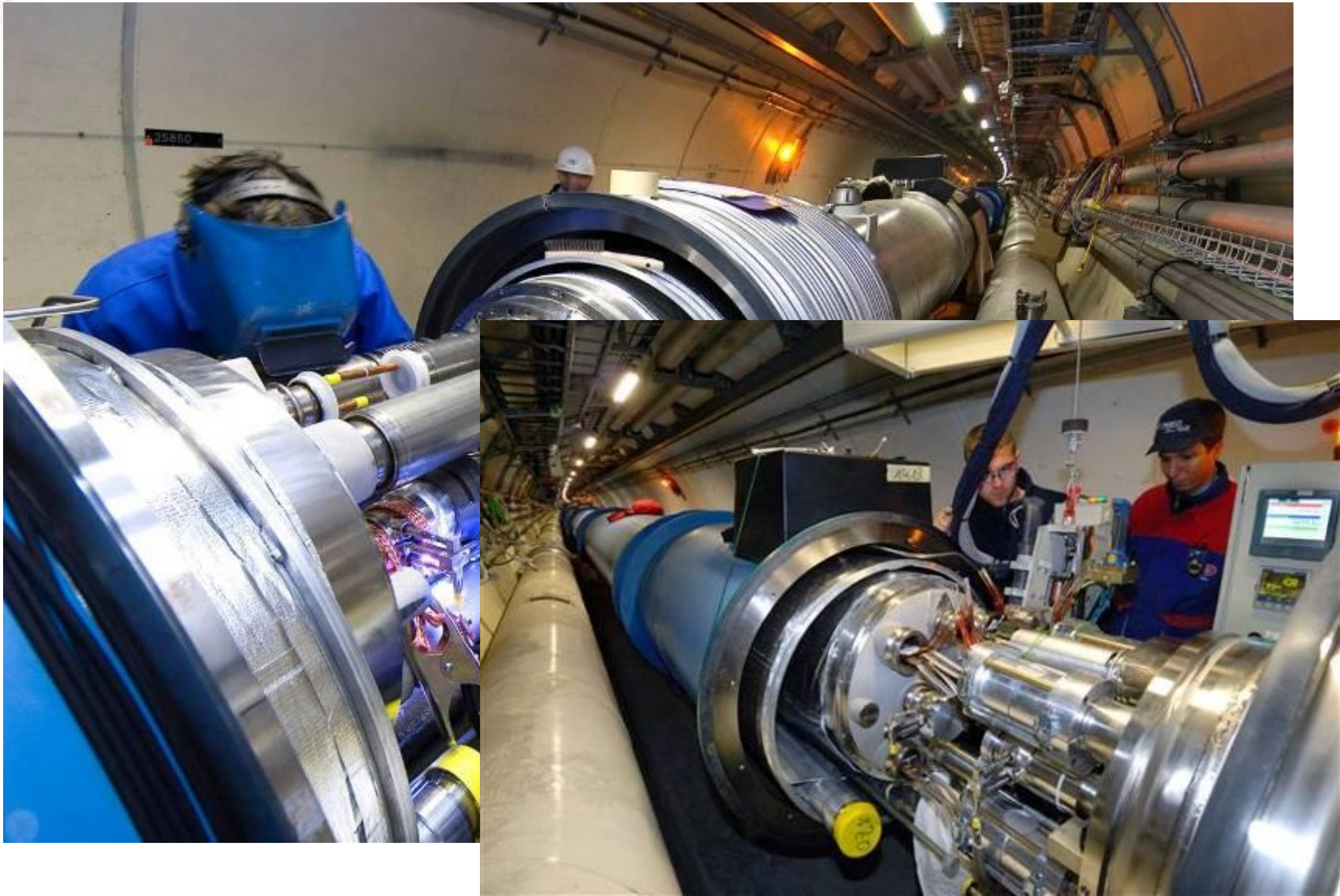
100% cold tests at CERN (up to ultimate field)

1232 dipoles and 400 quadrupoles

Cold magnetic performance measured on 20% of the magnets (correlation between warm and cold measurements)

Cryomagnet interconnects challenge

123 000 helium-tight *in situ* welds



LHC accelerator magnet stored energy

1232 * 108 mH = 133 H ; ½ L . I^2 ~ 10 GJ

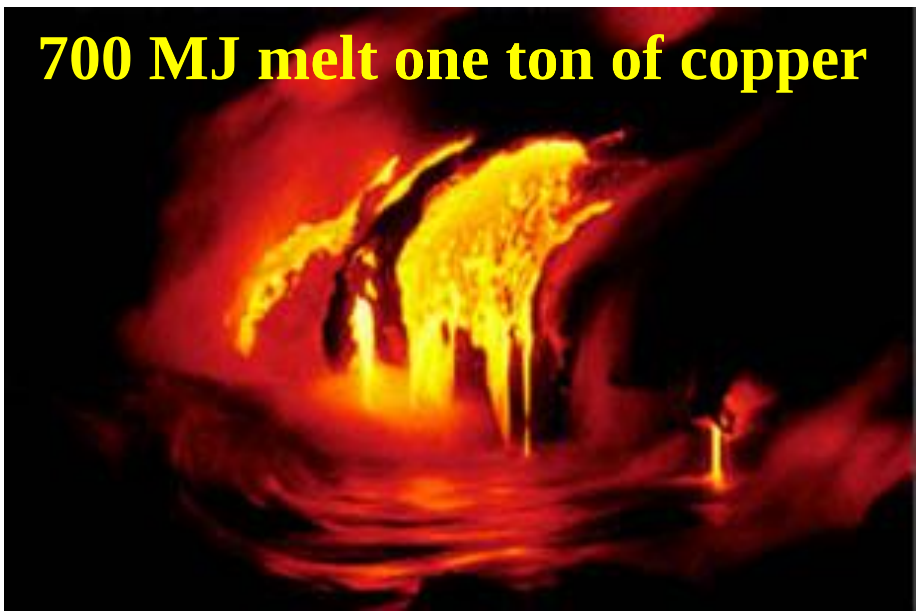
- **Energy stored in the magnet system: 10 GJoule**
- **Energy stored in one (of 8) dipole circuit: 1.3 GJoule**

The energy stored in the LHC magnets corresponds approximately to 8 such trains running at 300 km/h

LHC beam stored energy

Momentum at collision	7 TeV (1 eV = 1,6 × 10^{-19} Joule)
Number of bunches	2808
Protons per bunch	$1.15 \cdot 10^{11}$
Total number of protons (2 beams)	6.5 . 10^{14} (1 ng of H^+)

Energy stored in the two beams:	**724 MJoule**
Energy to heat and melt one ton of copper:	**700 MJoule**



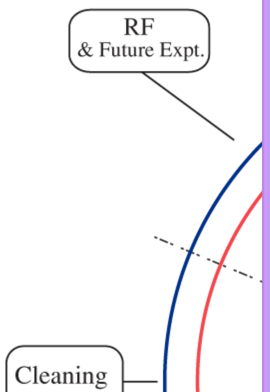
700 MJoule dissipated in 88 μs

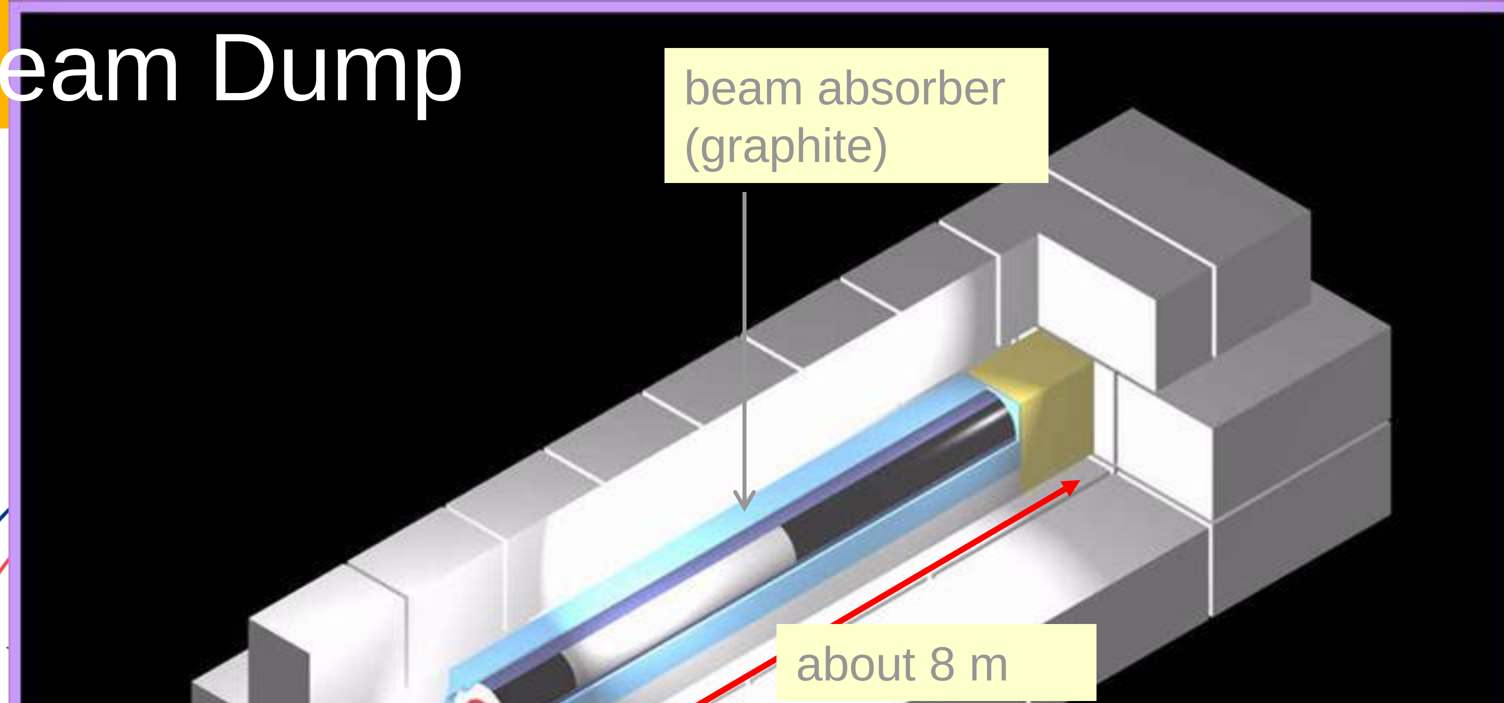
$700.10^6 / 88.10^6 \cong 8$ TW

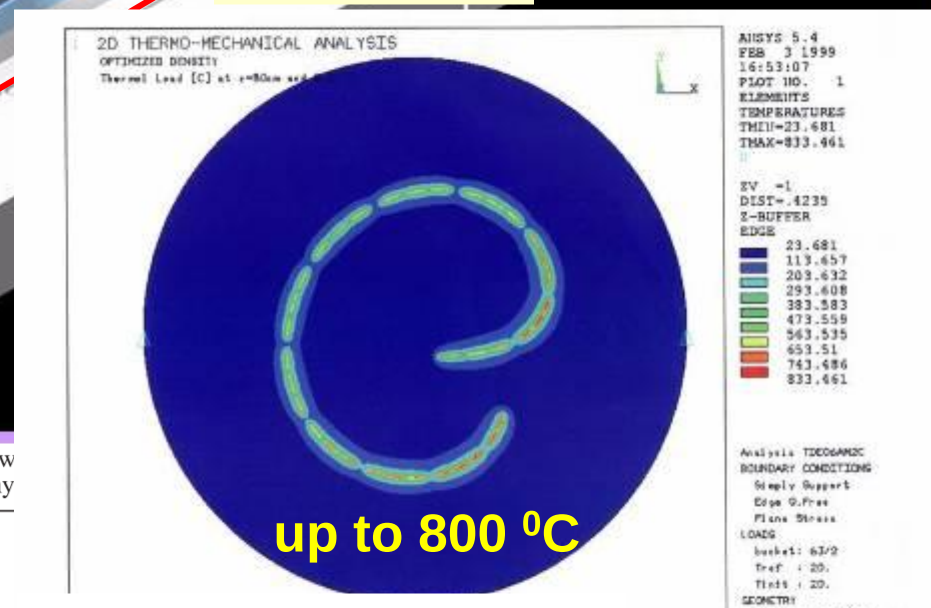
World Electrical Installed Capacity ≅ 3.8 TW

90 kg of TNT per beam

Beam Dump







Temperature of beam dump block at 80 cm inside

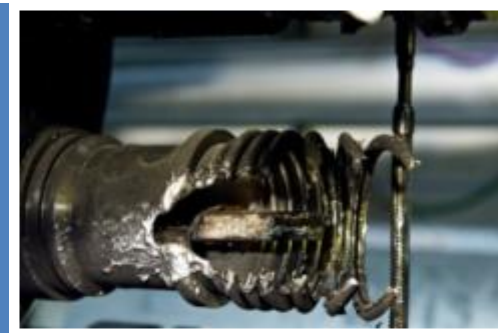
10th September 2008…

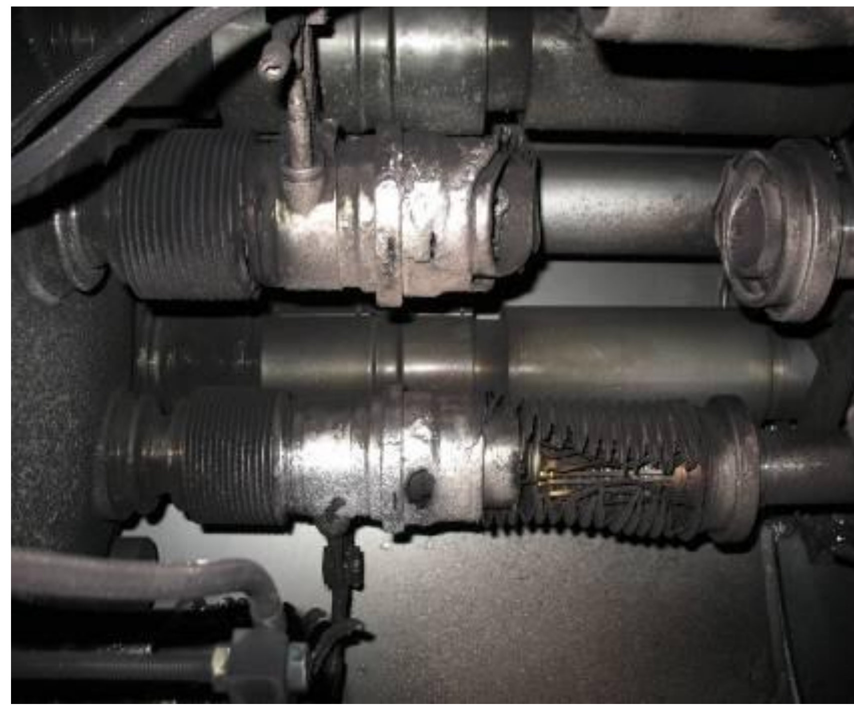
The Sector 3-4 incident (just before the 1st ramp)

19th September 2008 at 11:18.36

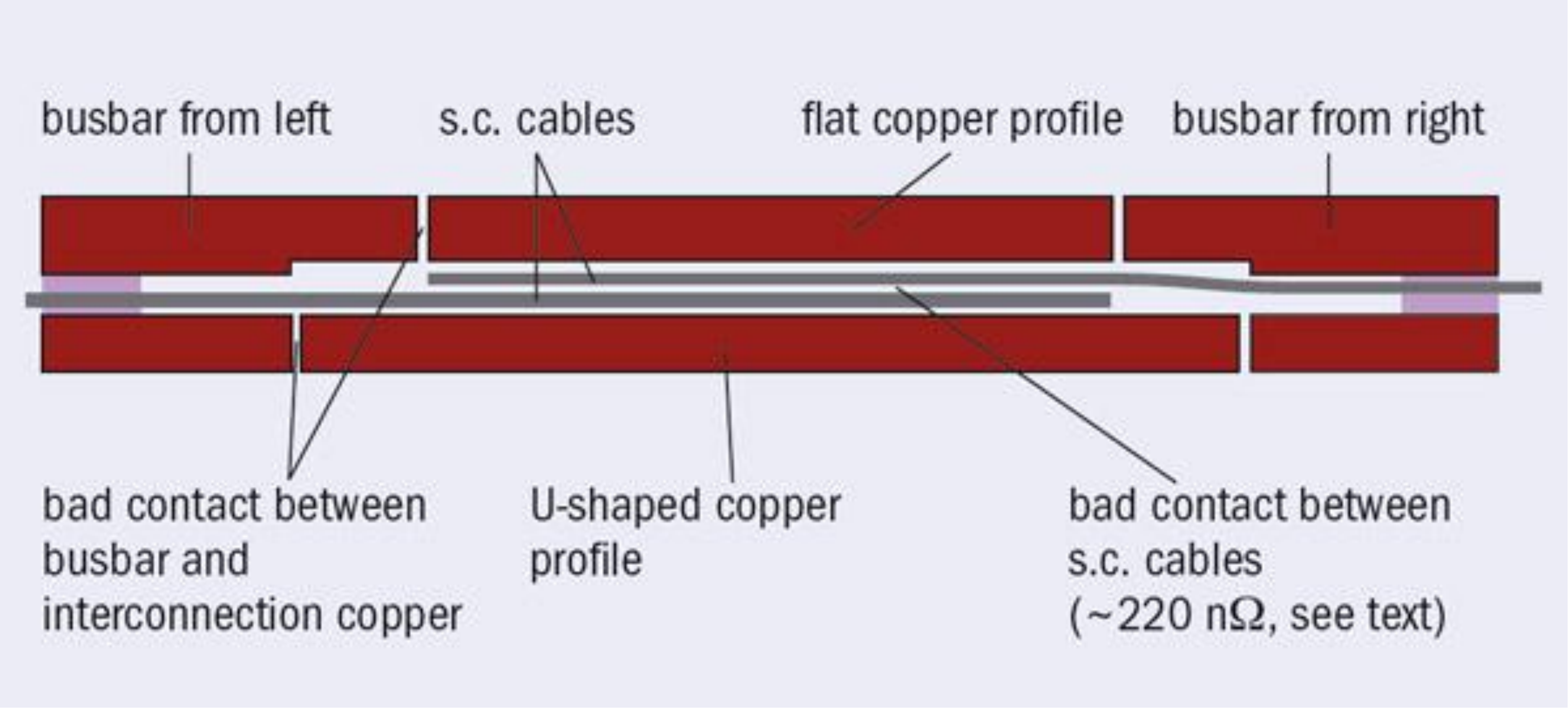
last test of the last circuit of the last sector: 7kA (4TeV) towards 9.3 kA (5TeV)

Electrical arc between two magnets at 8.7 kA



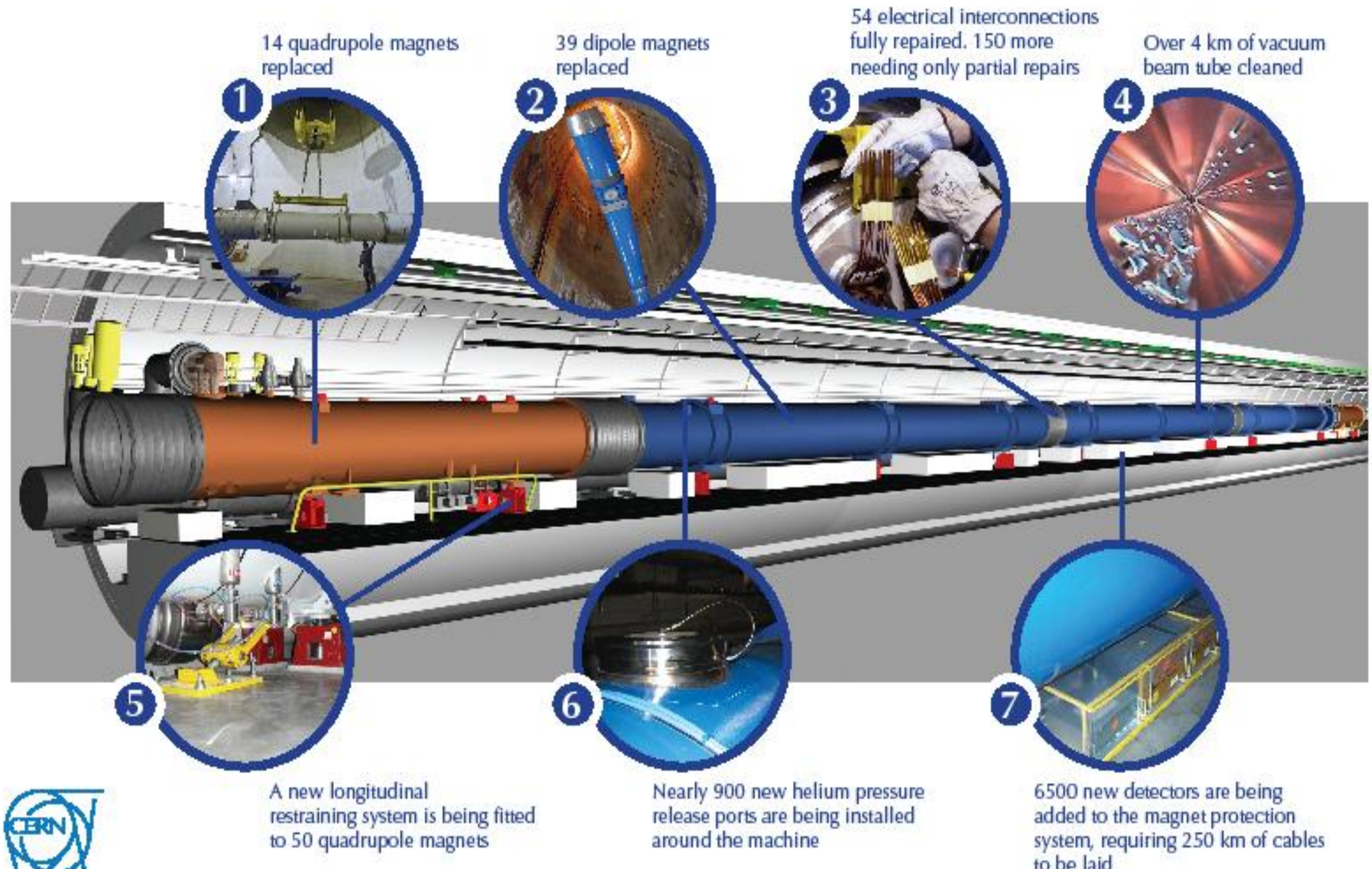


The start …



From L. Rossi, CERN Courier September 2010

The LHC repairs in detail



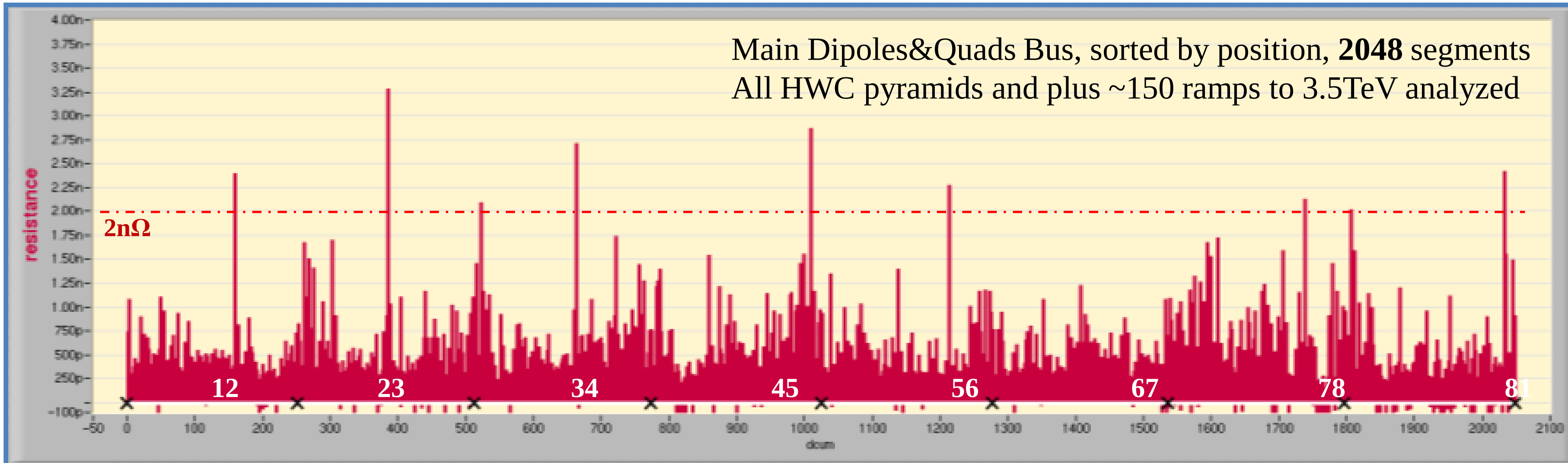
½ machine done

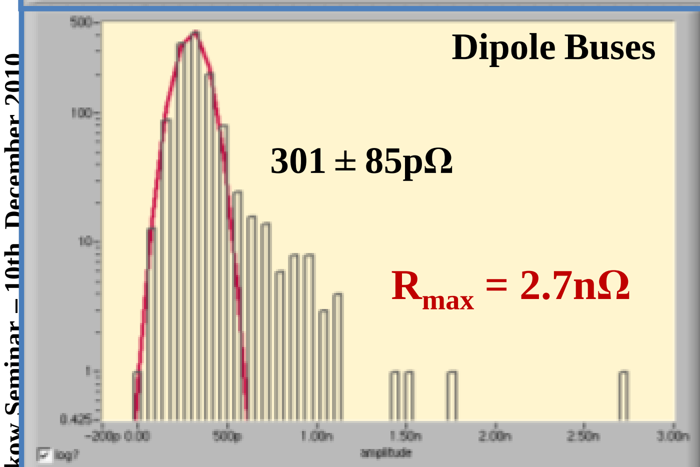
Why do we limit the beam energy to 3.5TeV in 2010-2011?

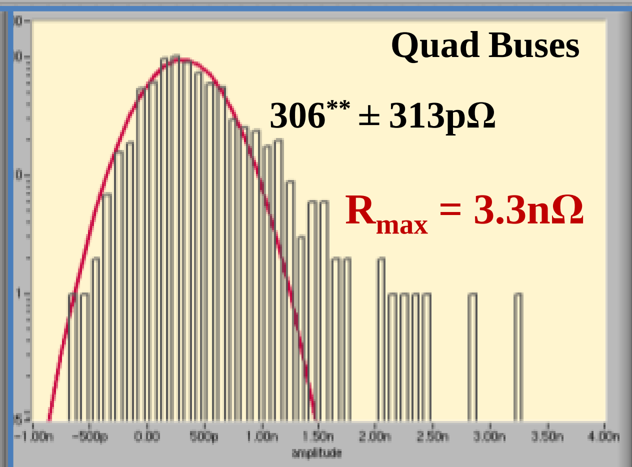
All the work done since November 2008 makes certain that a repeat of September 19th 2008 can NEVER happen.

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







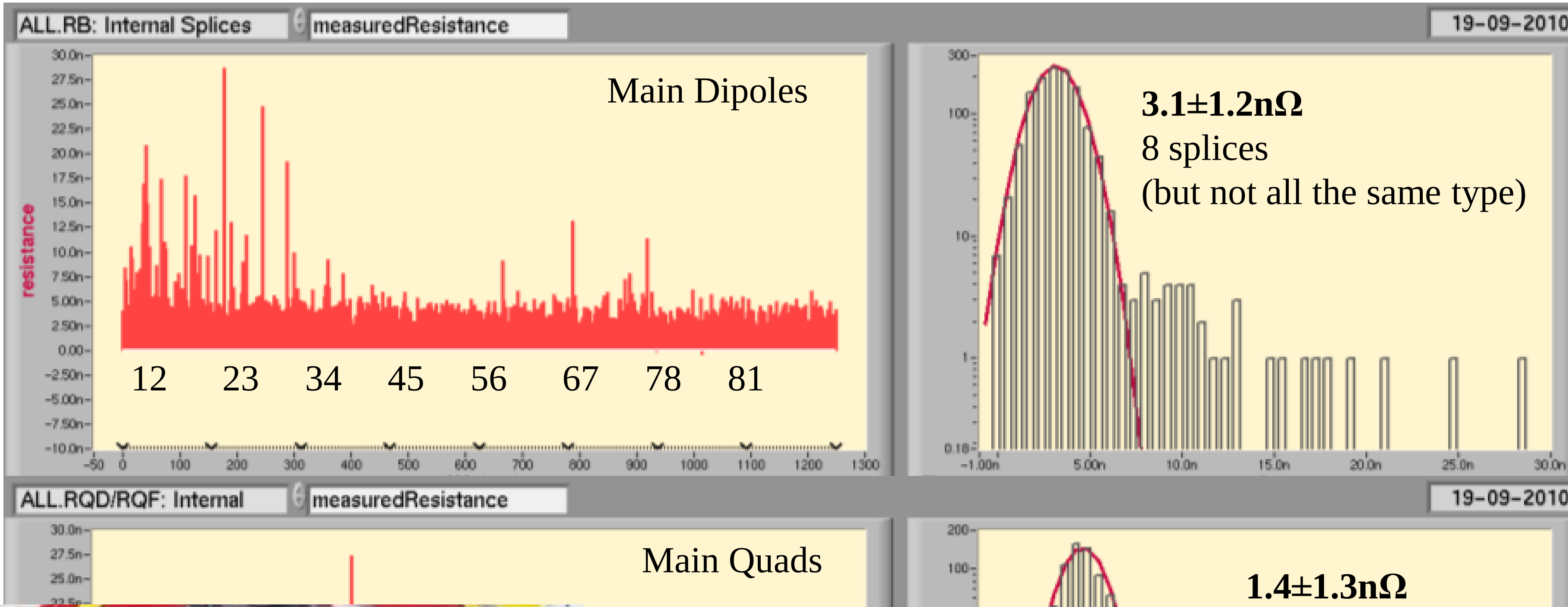
Top 10 Splice Resistances

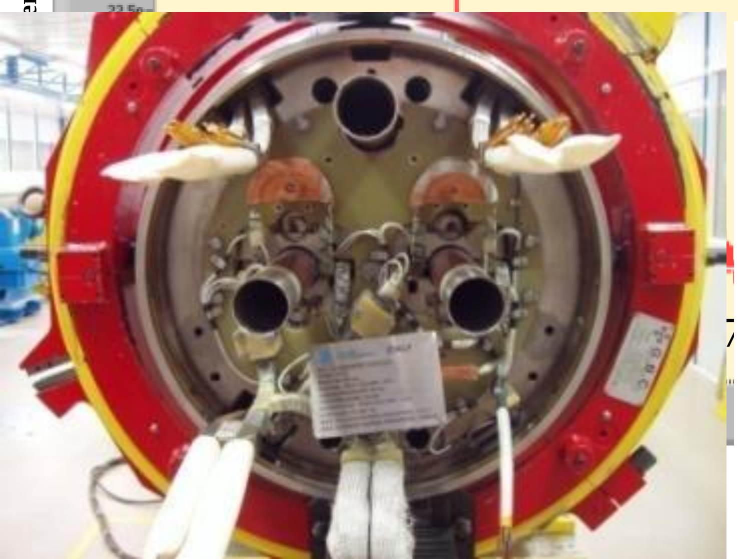
MQ.A23	MQ.33L3.B2	<->	MQ.33R2.B2	3.28E-09
MQ.A45	MQ.12L5.B2	<->	MQ.11L5.B1	2.87E-09
MB.A34	MB.A31L4	<->	MB.C31L4	2.71E-09
MQ.A81	MQ.12L1.B2	<->	MQ.11L1.B1	2.42E-09
MQ.A12	MQ.27L2.B2	<->	MQ.25L2.B2	2.40E-09
MQ.A56	MQ.21L6.B2	<->	MQ.19L6.B2	2.27E-09
MQ.A78	MQ.20L8.B1	<->	MQ.22L8.B1	2.13E-09
MQ.A34	MQ.9R3.B2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

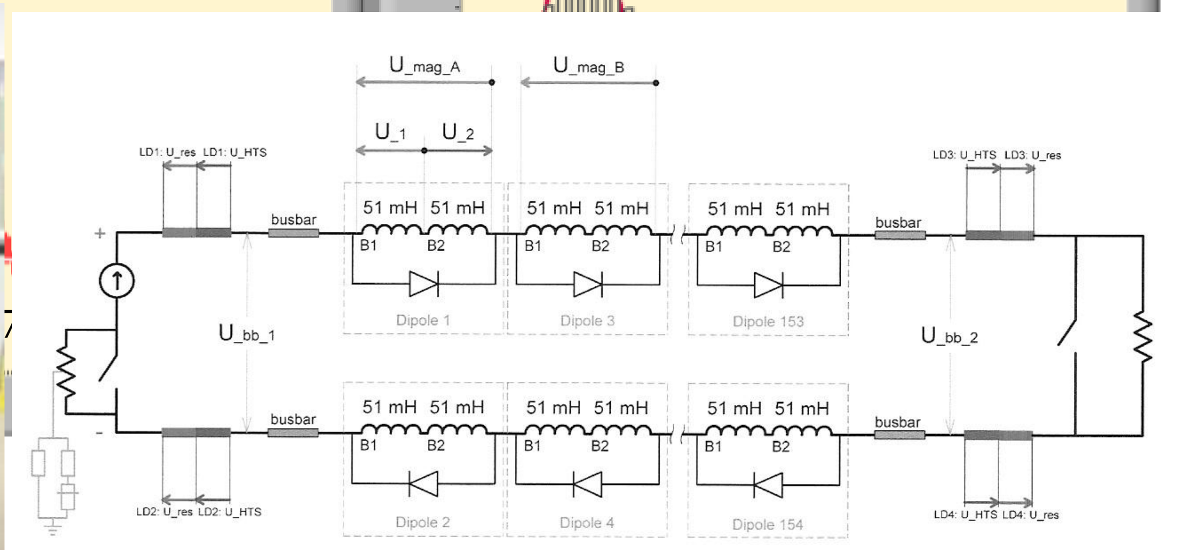
(**) number of splices in the quads segments corrected, 1.3 added

From Z. Charifoulline

LHC main splices today: magnets SC







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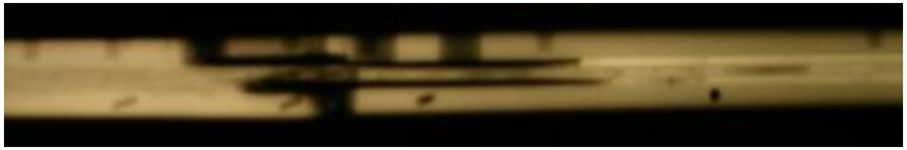
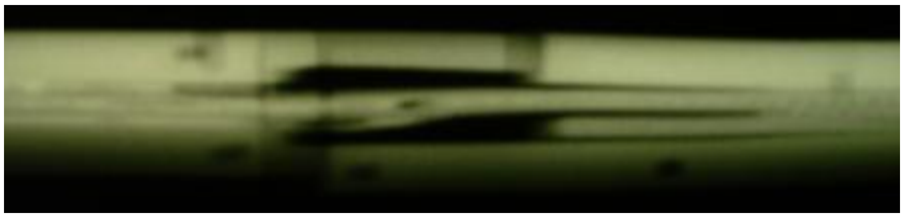
BUT in April 2009, we have uncovered a different possible failure scenario which could under certain circumstances produce an electric arc in the "copper stabilizers" of the magnet interconnects

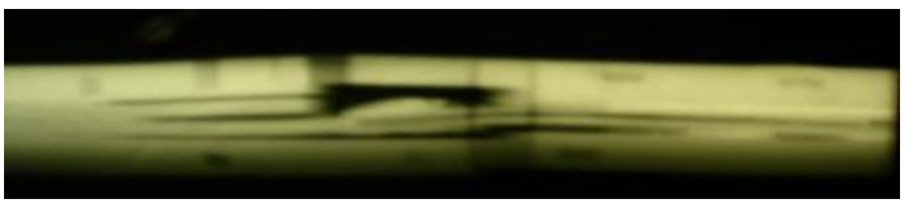
Sample pictures



Sample 1 (61 μΩ)

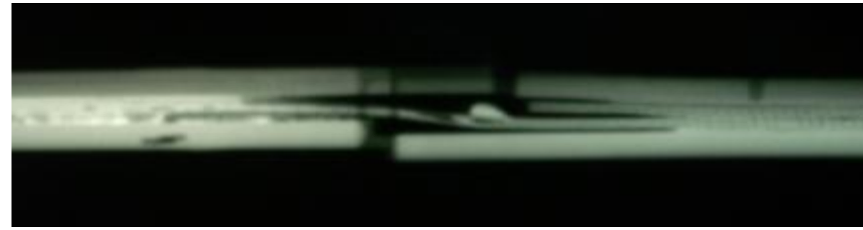


Sample 2A left (32 μΩ)

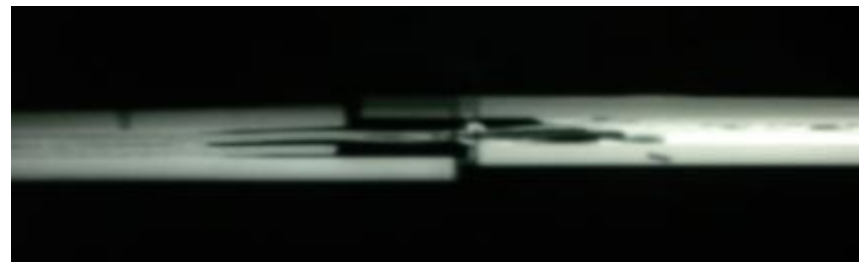


Sample 2A right (43 μΩ)

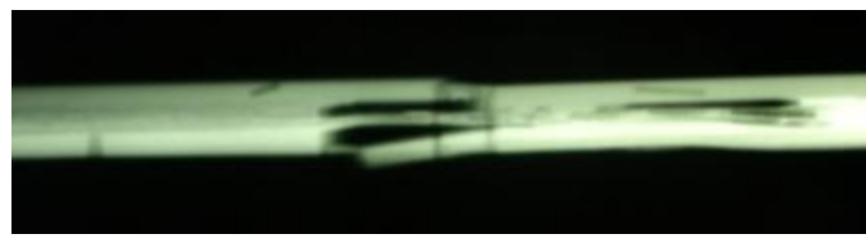
Sample 2B (42 μΩ)



Sample 3A left (26 μΩ)



Sample 3A right (43 μΩ)



Sample 3B (21 μΩ)

Pictures by J.-M. Dalin

Summary of LHC Commissioning in 2009

- November 20th 2009
  - First beams around again
- November 29th 2009
  - Both beams accelerated to 1.18 TeV simultaneously
- December 8th 2009
  - 2x2 accelerated to 1.18 TeV
  - First collisions at 2.36 TeV cm! **LHC - highest energy collider**
- December 14th 2009
  - Stable 2x2 at 1.18 TeV
  - Collisions in all four experiments

Limited to 2 kA in main circuits (1.18 TeV) during deployment and testing of new Quench Protection System

Decided Scenario 2010-2011

Following the technical discussions in Chamonix workshop (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 6.5 – 7 TeV/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

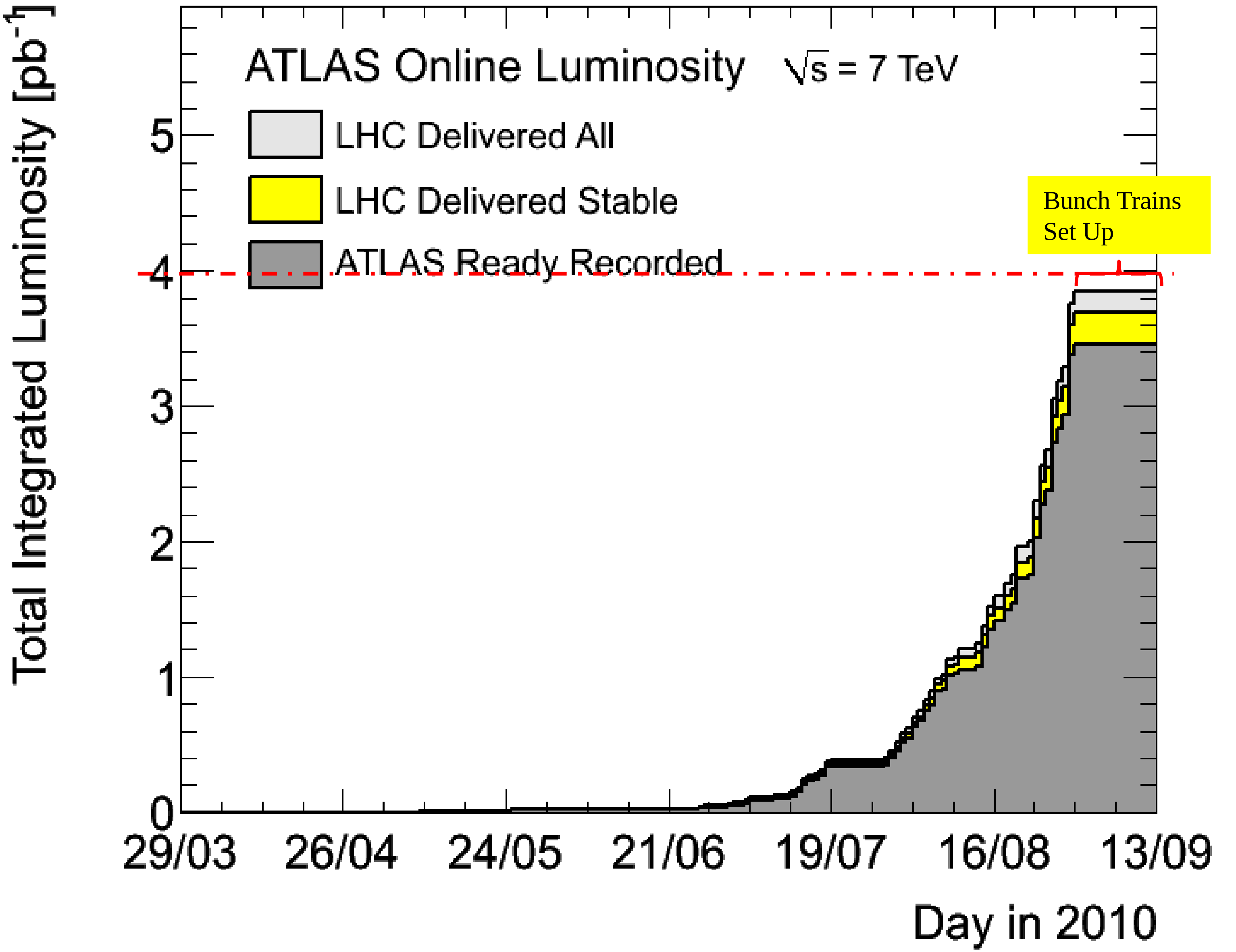
Second Running Period (High bunch Intensity)

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)



Running with Bunch Trains (Parameters)

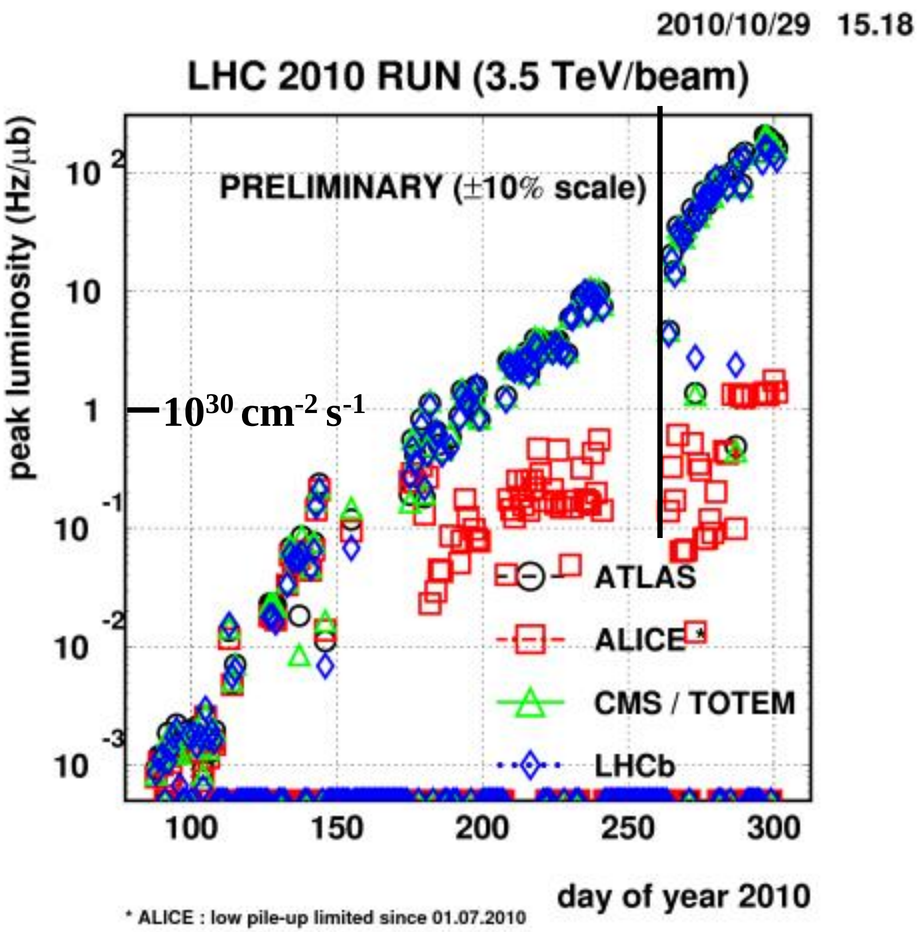
Nb	Ib	MJ	Nc	Peak luminosity (design parameters)	Maximum luminosity (measured)	Pile up (from measured Lumi)	Date
56	1.10E+11	3.5	47	1.203E+31	2.000E+31	1.9054	23/09/2010
104	1.10E+11	6.5	93	2.381E+31	3.500E+31	1.7955	25/09/2010
152	1.10E+11	9.4	140	3.584E+31	5.000E+31	1.7550	29/09/2010
204	1.10E+11	12.7	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

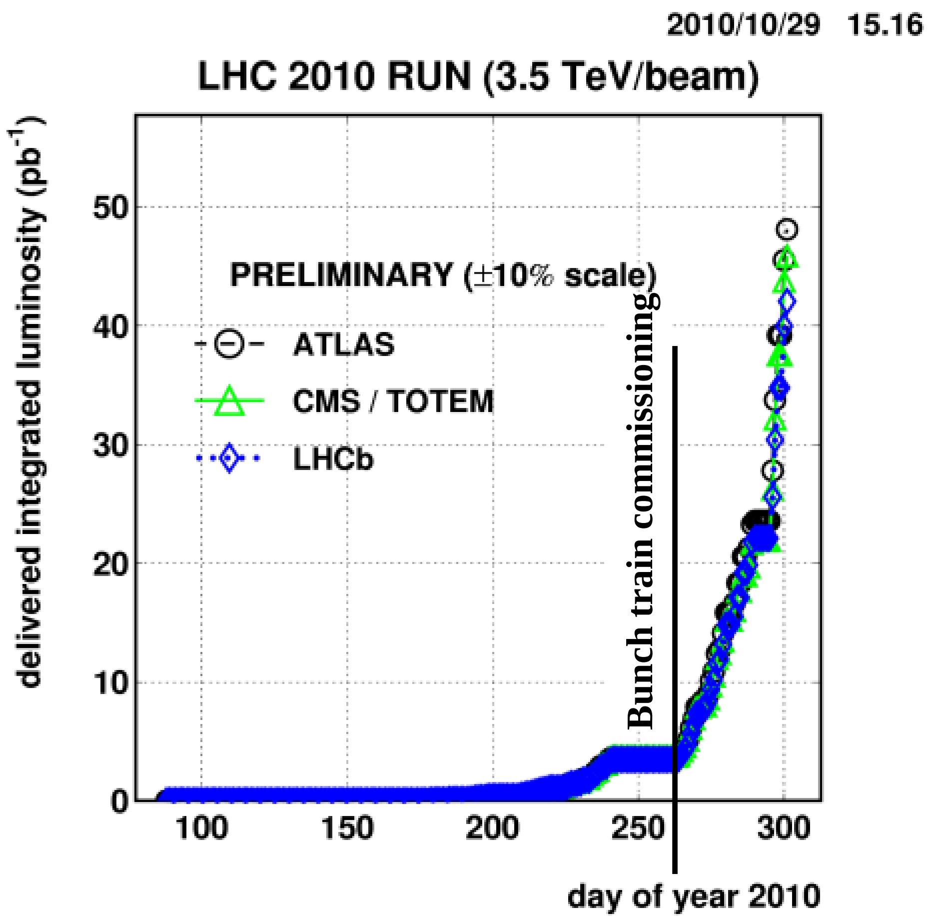
24MJ stored beam energy and $2.05 \times 10^{32} cm^{-2} s^{-1}$

Luminosity evolution 2010 (proton)

5 orders of magnitude in ~200 days

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



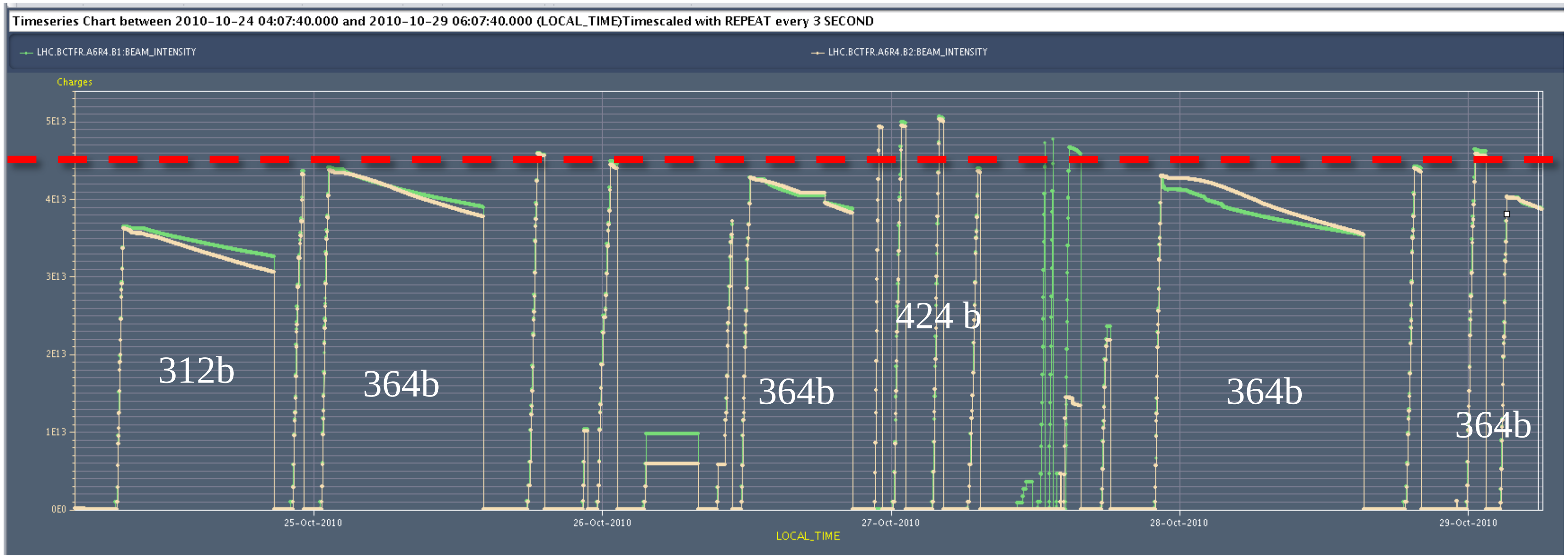


Fk. Bordry , F

Roger Bailey

Did we reach the intensity limit for 150ns ?

4.35e13 p (?) → to be followed…



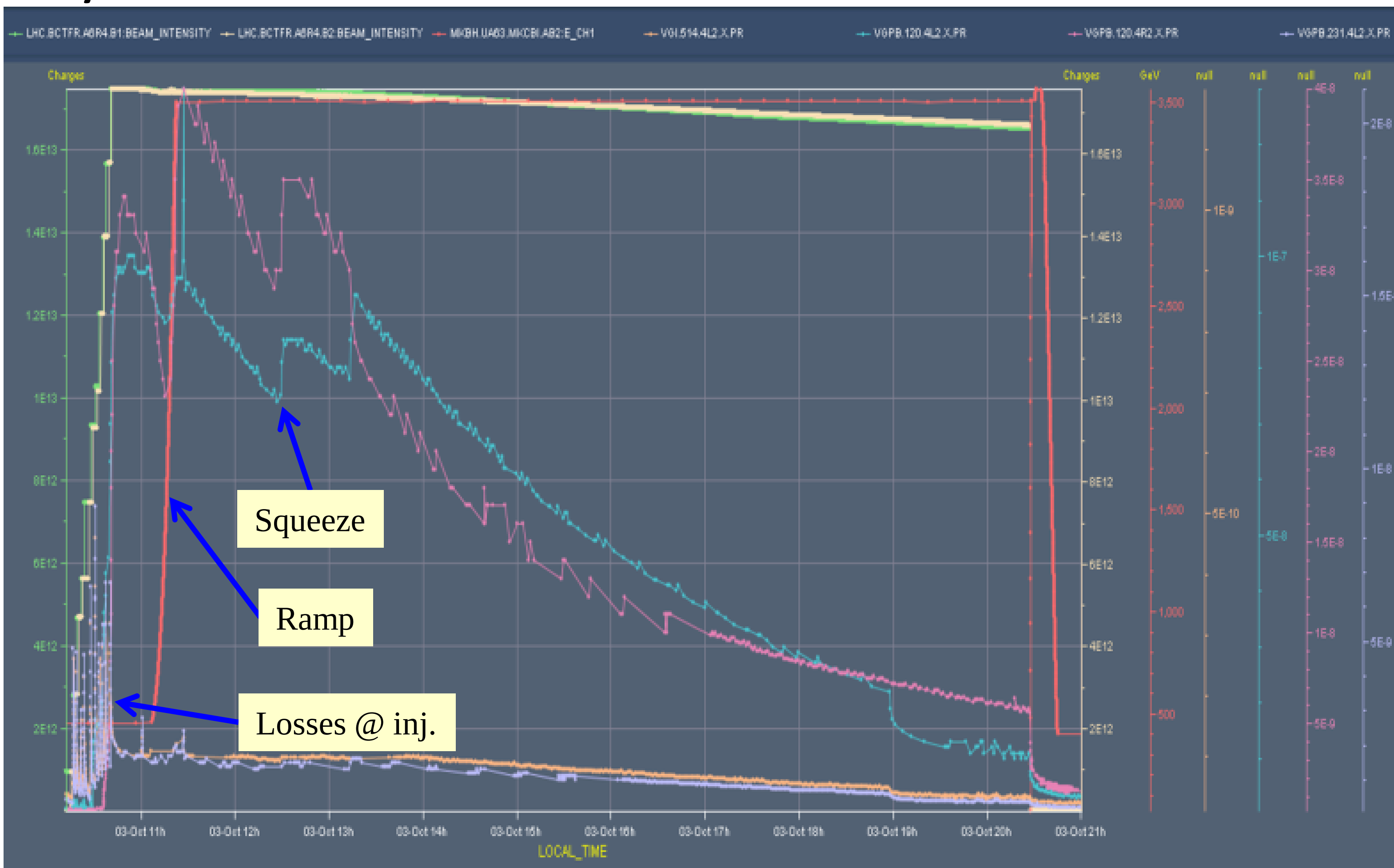
Stored energy reached at 3.5 TeV: **28.0 MJ**

Stored energy at 3.5 TeV in stable beams: **25.2 MJ**

Vacuum – a very brief history

Initially

- Pressure rise seen in common beam pipe regions
- Particularly unbaked warm-cold transitions



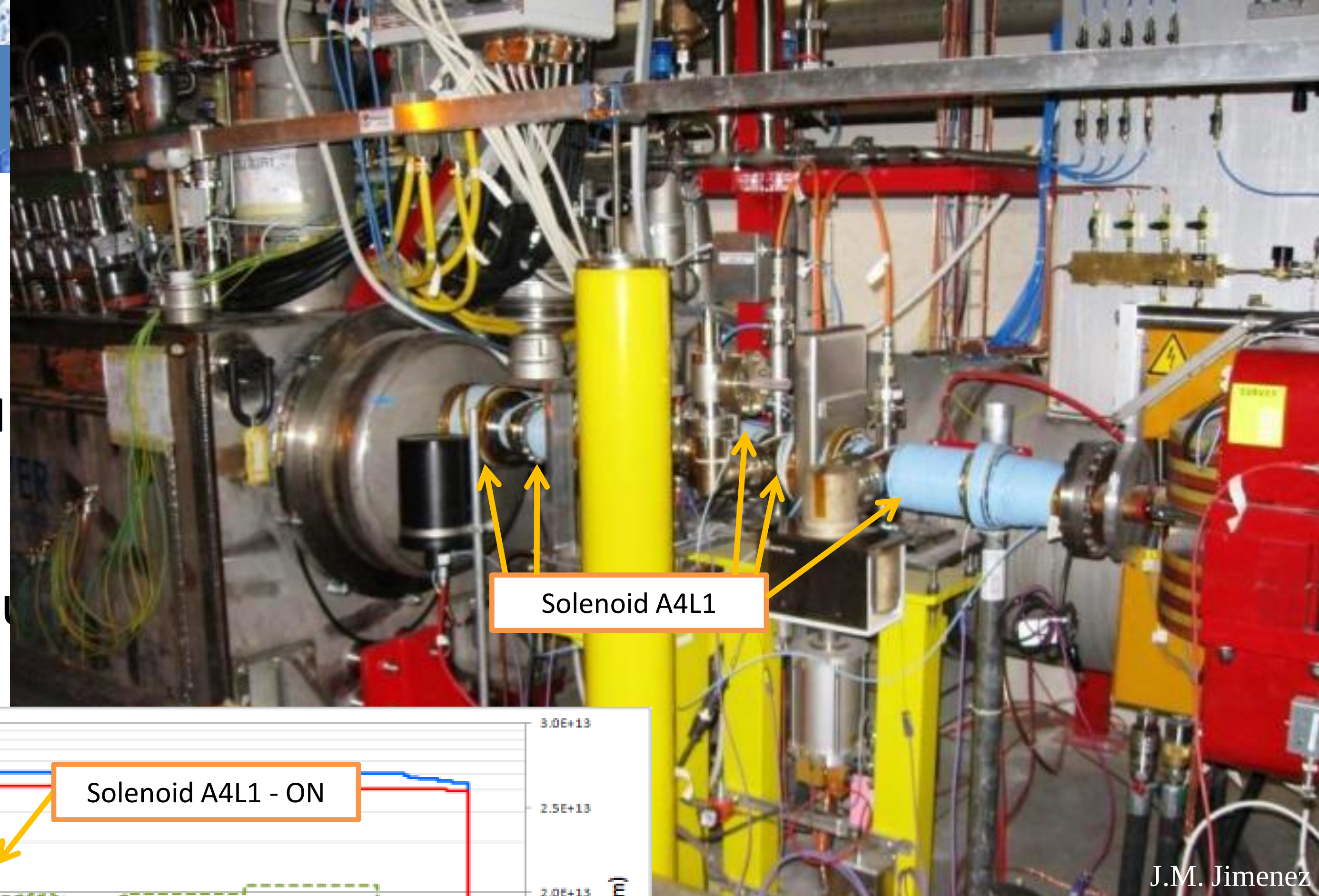
Vacuum – a very brief history

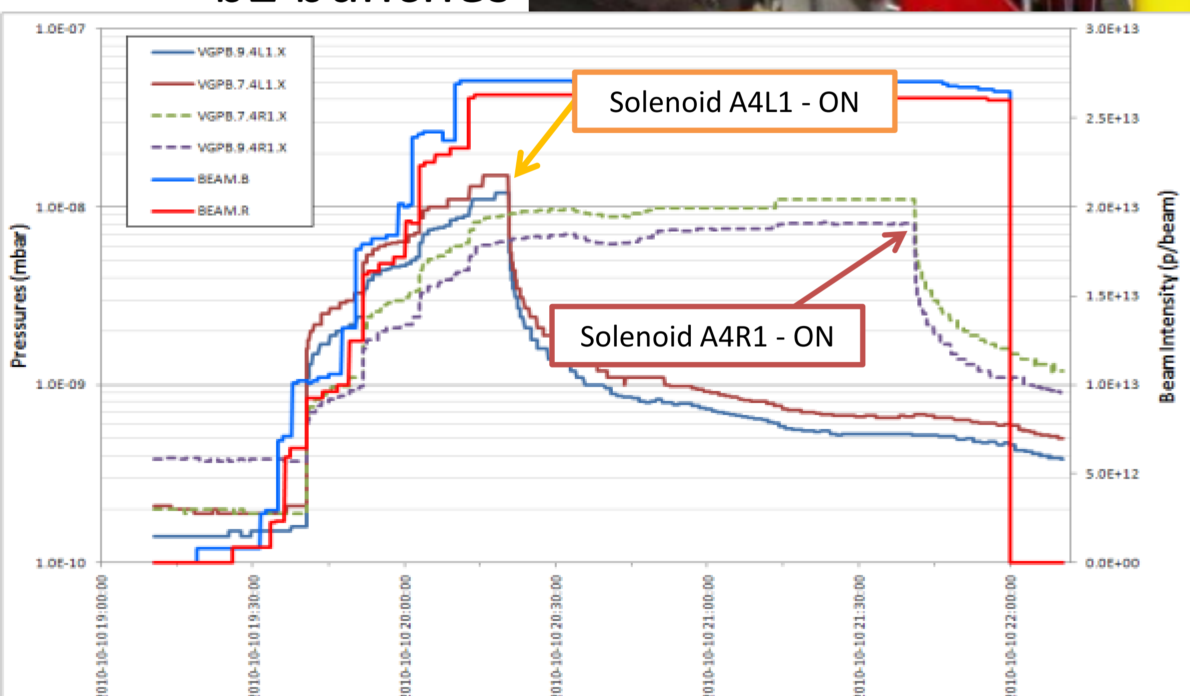
Initially

- 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

Initially

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

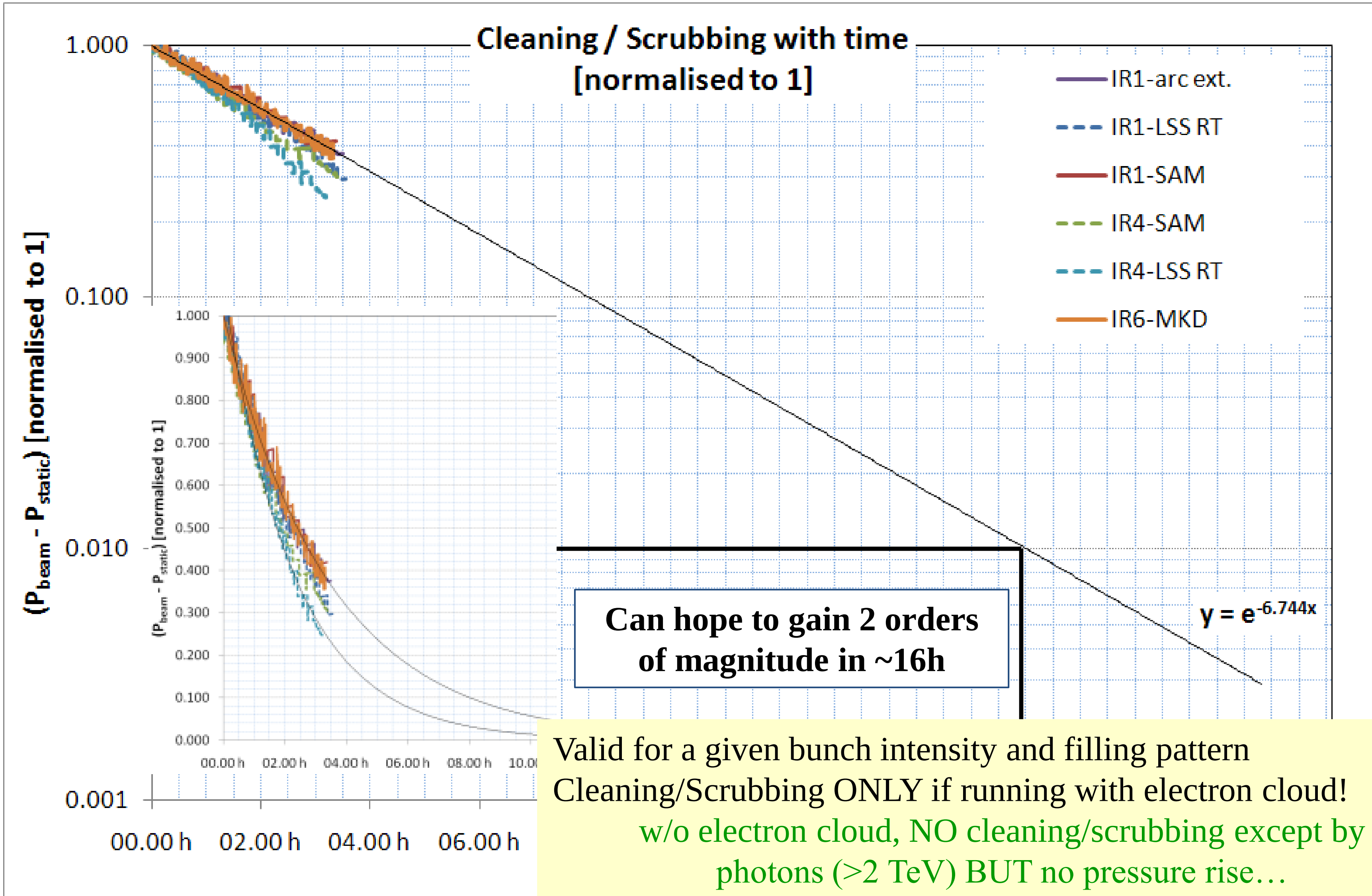




th solenoids

cloud

Scrubbing in the LSS (50 ns)



Valid for a given bunch intensity and filling pattern

Cleaning/Scrubbing ONLY if running with electron cloud!

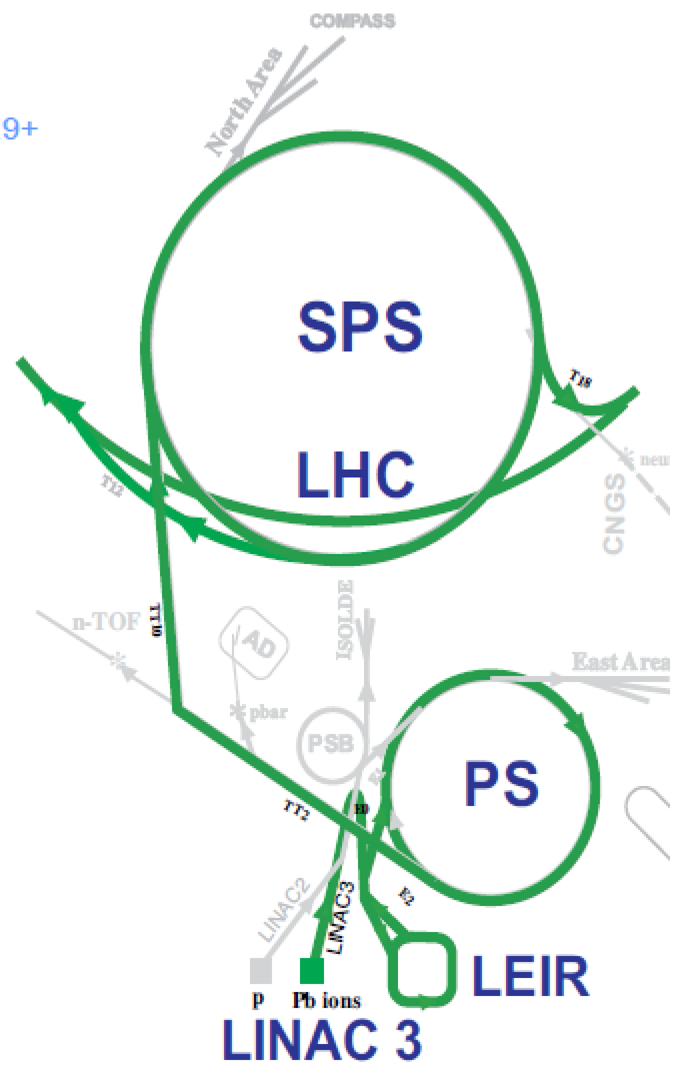
w/o electron cloud, NO cleaning/scrubbing except by photons (>2 TeV) BUT no pressure rise…

Memory effect will stay (partly/totally) for other schemes

Miguel Jimenez

Long preparation from 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



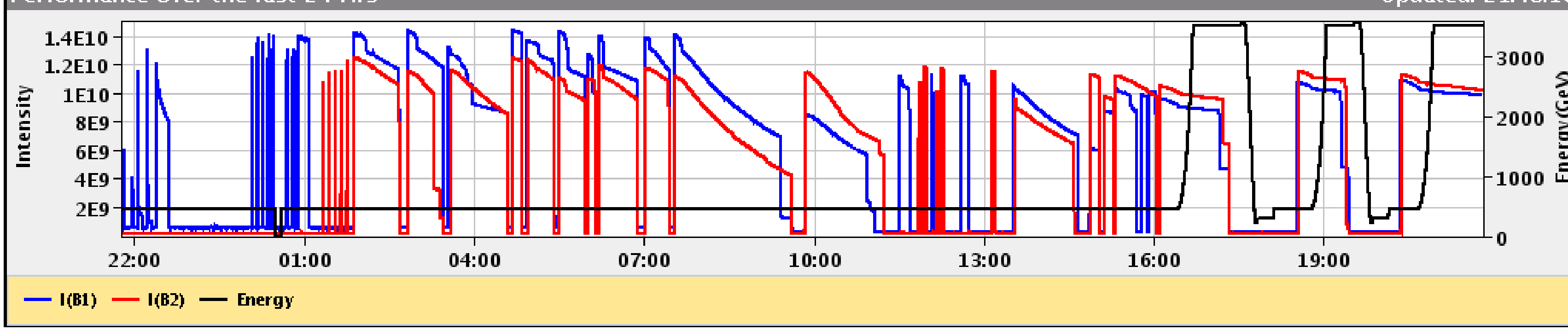
Ion Commissioning: First 24h from Nov 4th !

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

Performance over the last 24 Hrs Updated: 21:48:16

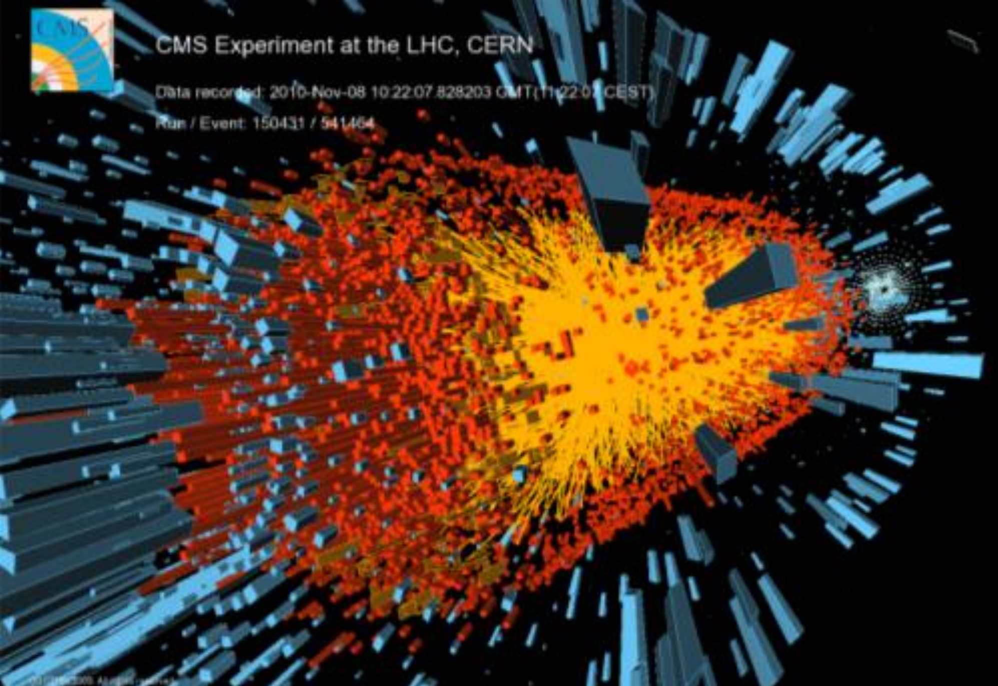


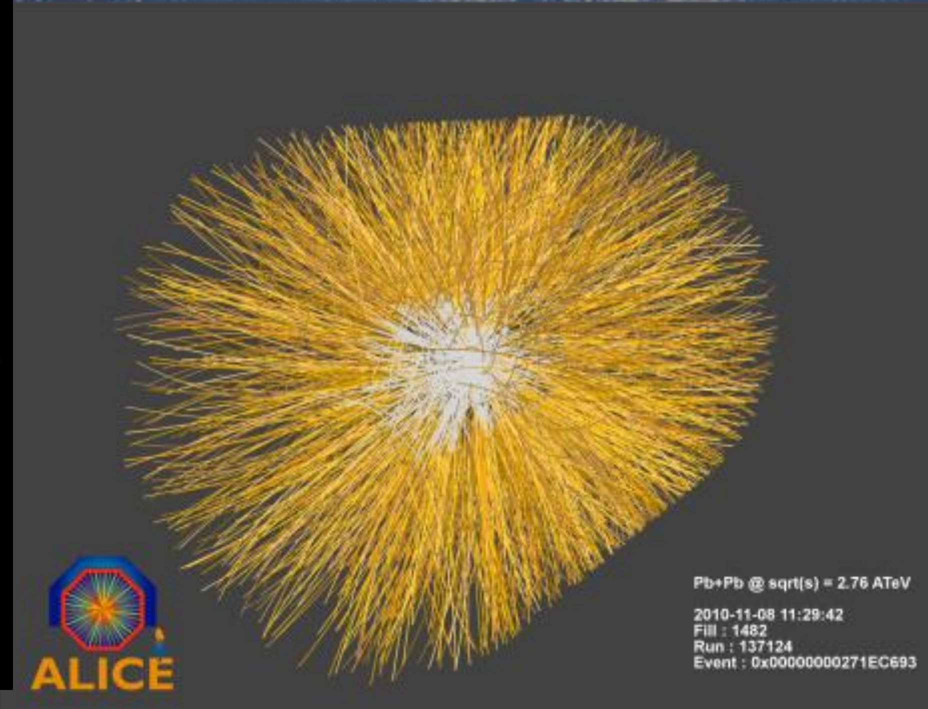
Beam 1 Inj., Circ. & Capture

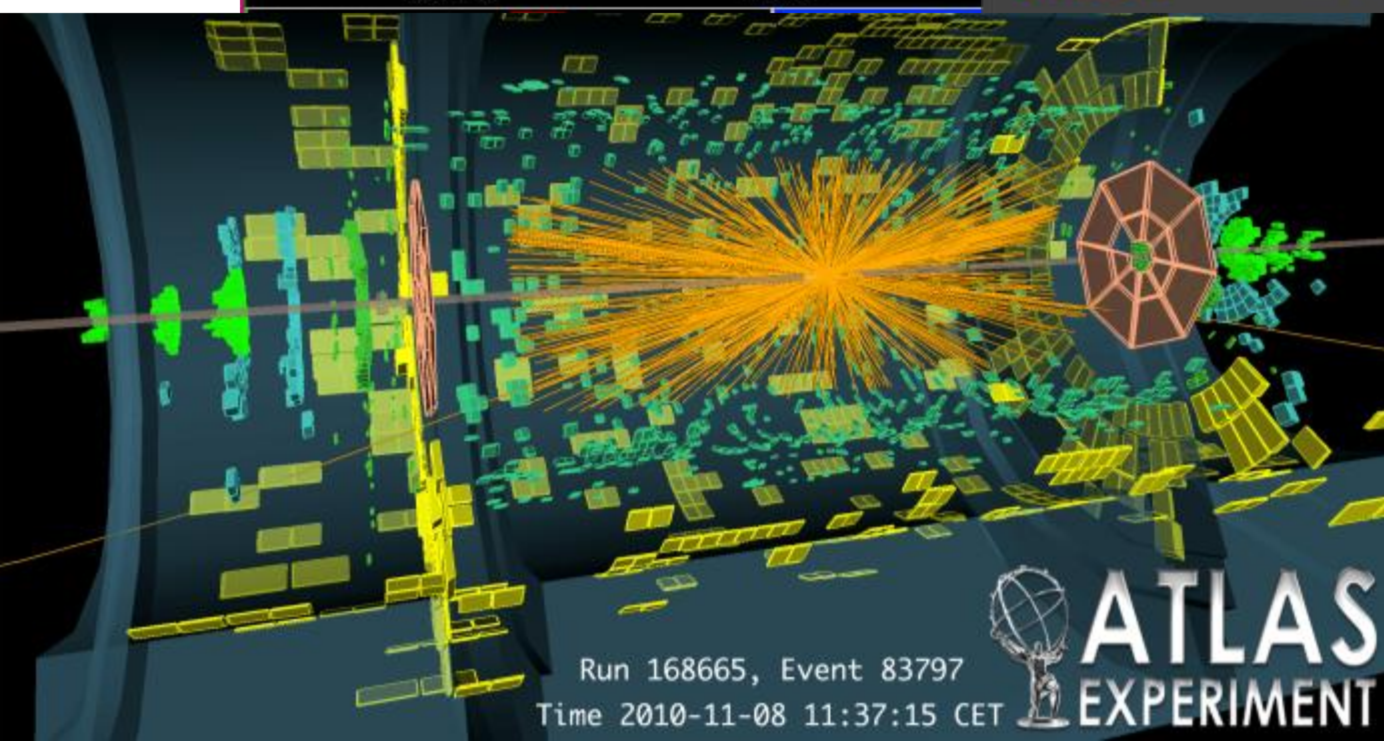
Beam 2 Inj., Circ. & Capture

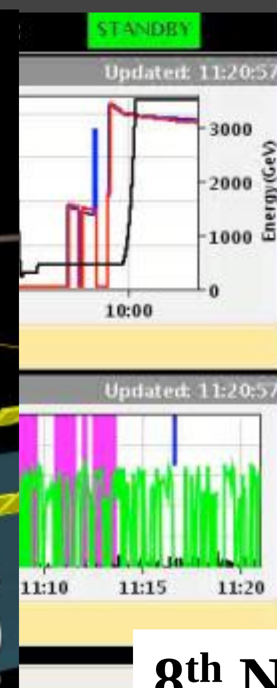
Optics Checks
BI Checks
Collimation Checks

First Ramp
Collimation Checks
Squeeze


CMS Experiment at the LHC, CERN
Data recorded: 2010-Nov-08 10:22:07.828203 GMT(11:22:07 CEST)
Run / Event: 150431 / 541464


ALICE
Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:29:42
Fill : 1482
Run : 137124
Event : 0x00000000271EC693

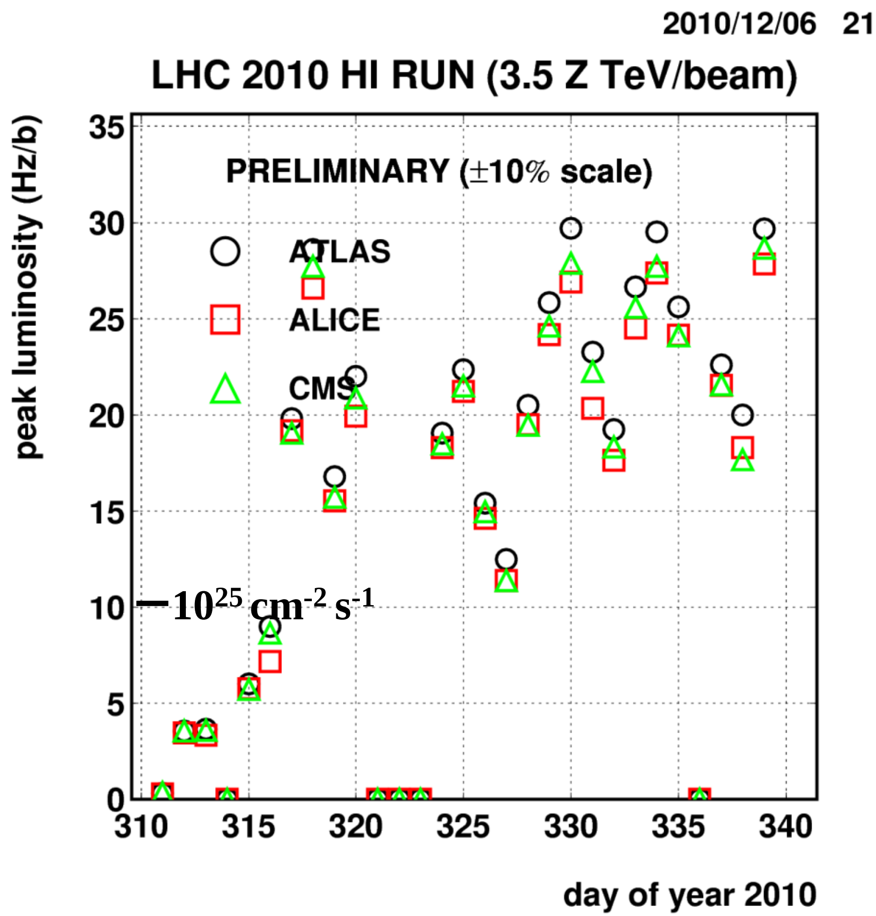

Run 168665, Event 83797
Time 2010-11-08 11:37:15 CET
ATLAS
EXPERIMENT

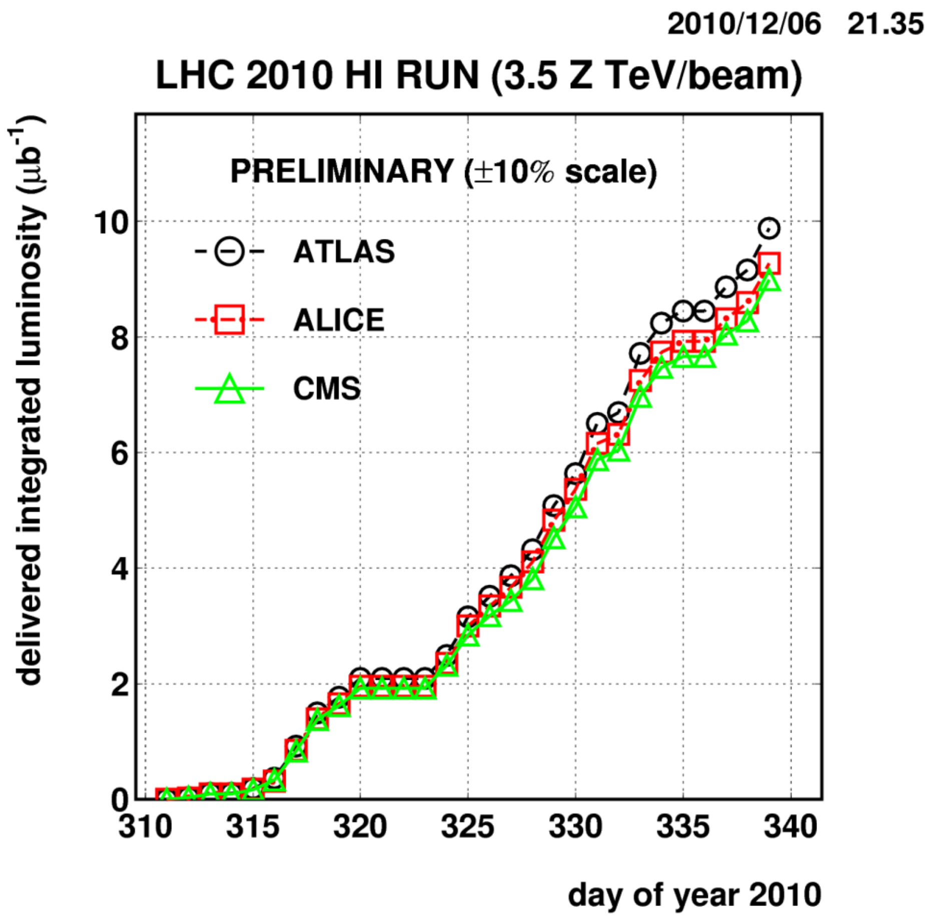

STANDBY
Updated: 11:20:57
3000
2000
1000
0
Energy (GeV)
10:00
Updated: 11:20:57
11:10
11:15
11:20

8th Nov. 2010

Luminosity evolution

- Integrated luminosity ~10 μb^{-1}.





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

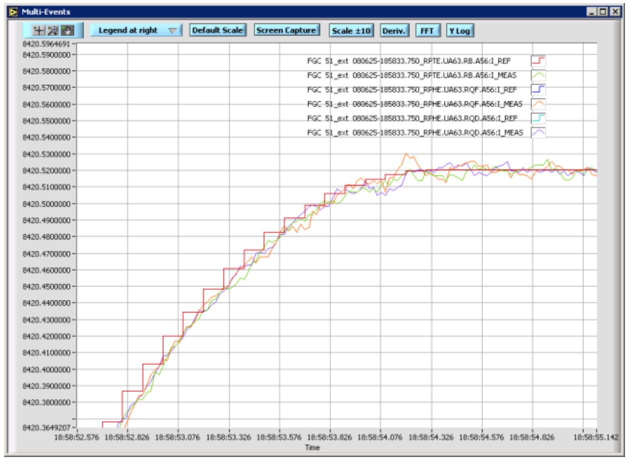
Summary: What did we learn in 2010 ?

- LHC is magnetically very reproducible on a month to month time scale
- High precision of the powering system (8 independent sectors !)
- High availability of the cryogenics and hardware system
- 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 (Unidentified Falling Object: dust ?)
- Radiation to Electronics (R2E)

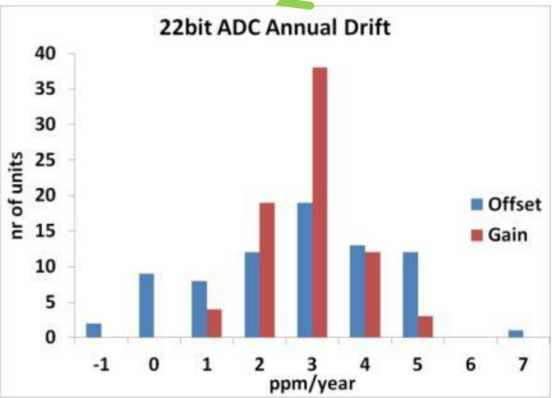
LHC power converter accuracy

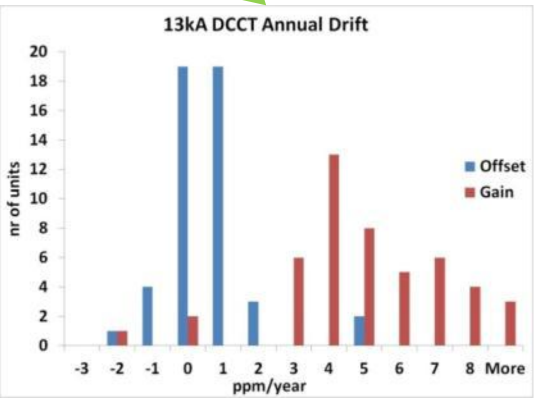
- High accuracy of LHC power converters
  - Drift less than 15ppm/year (50ppm was specified)
  - No tracking issue between the 8 sectors

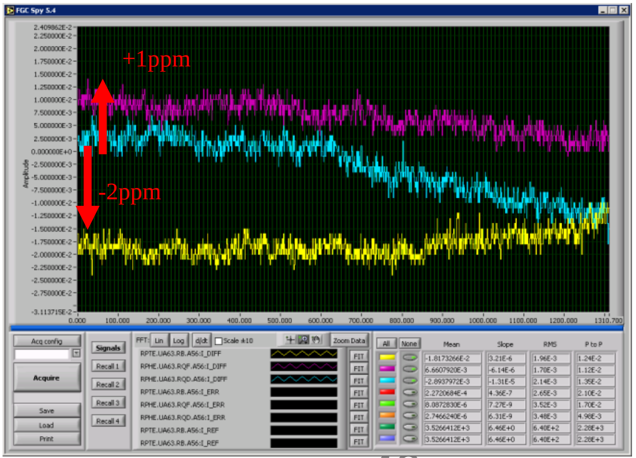


Converter category	Accuracy class	1 year accuracy (ppm)
Main dipoles, quads, inner triplets	Class 1	50
Separation dipoles, insertion quadrupoles	Class 2	70

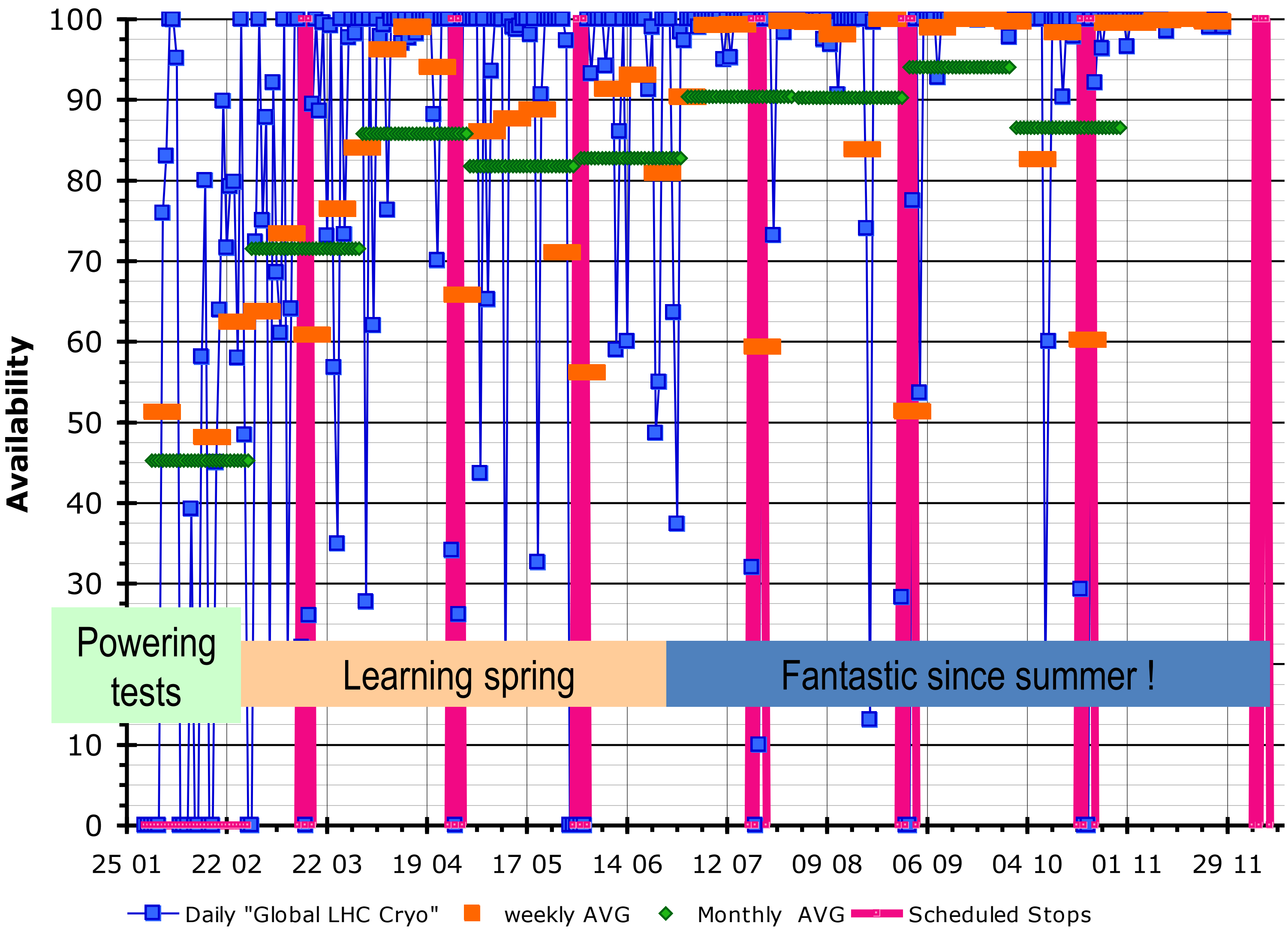
CCC sees the sectors as one!



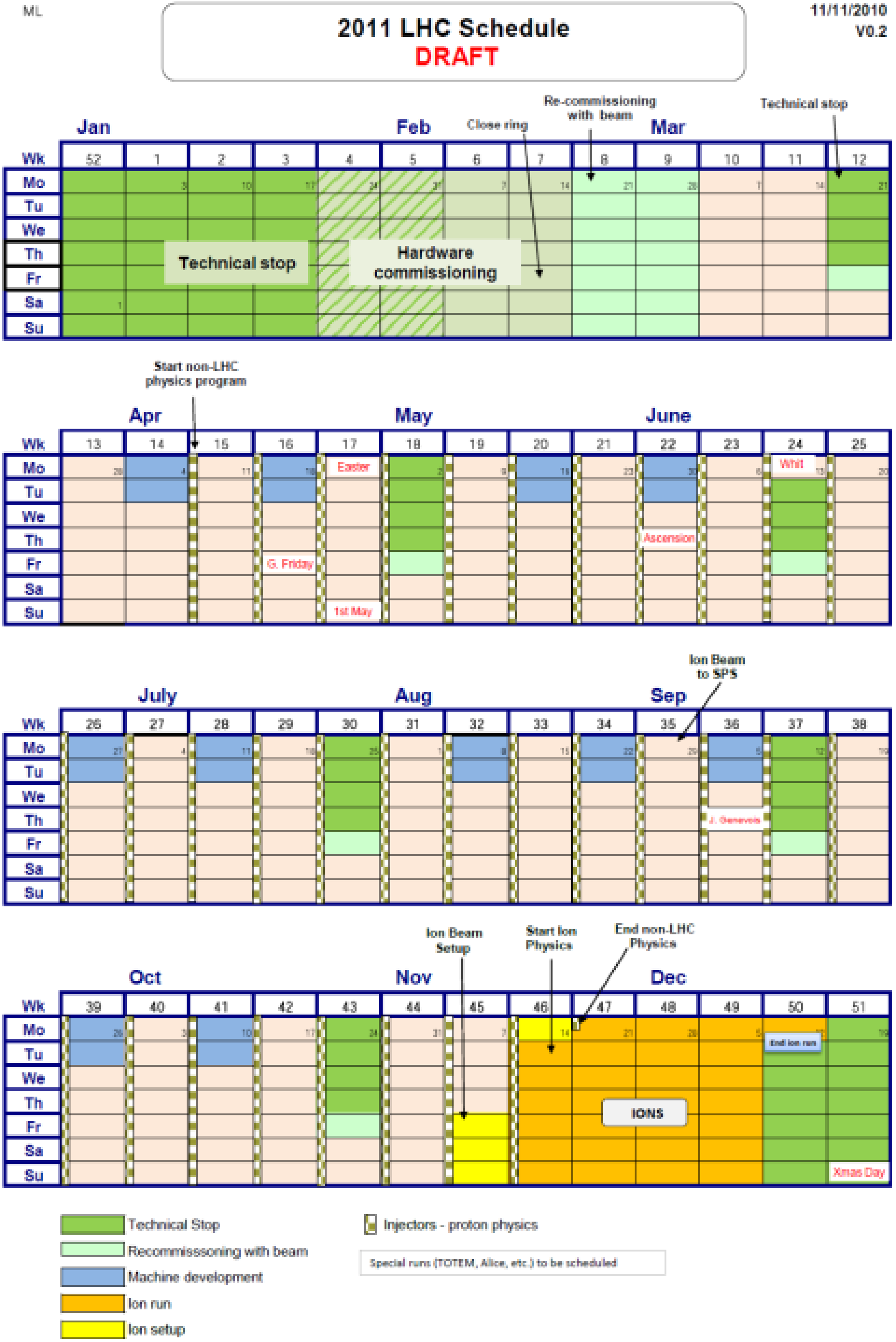




LHC Cryo global availability



Results for 2010 above expectations, thanks as well to periodic technical stops



2011

- Beam back around 21st Feb.
- 2 weeks re-commissioning with beam (at least)
- 4 day Technical Stop (TS) 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

  (will be discussed at Chamonix Workshop 24th-28th January 2011)

  - Maximum beam energy
  - Bunch spacing

    75 ns (max bunches 936)

    50ns (max bunches 1404)

  - Integrated luminosity evaluation

    => goal set is 1fb^{-1}

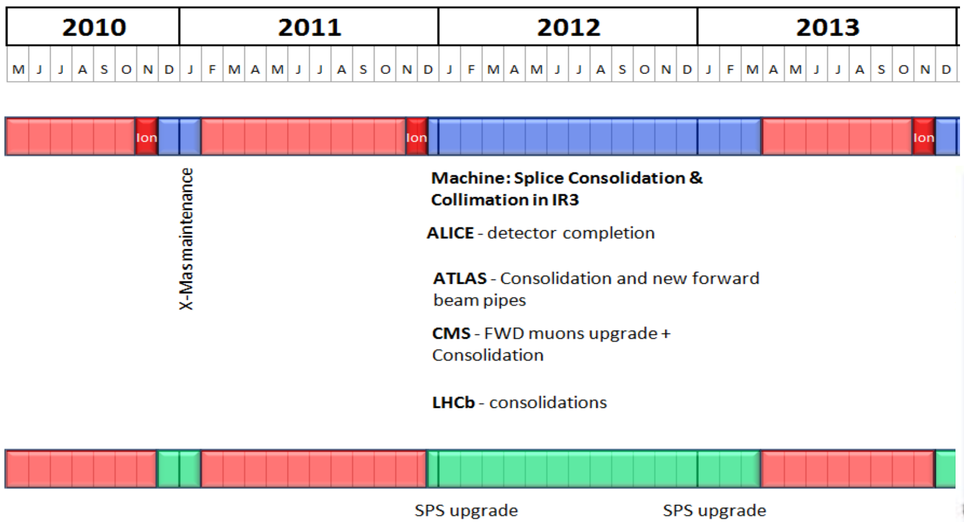
2011: “reasonable” numbers

- 4 TeV (to be discussed at Chamonix)
- 936 bunches (75 ns)
- 3 micron emittance
- 1.2×10^{11} protons/bunch
- beta* = 2.5 m, nominal crossing angle
- Hubner factor 0.2

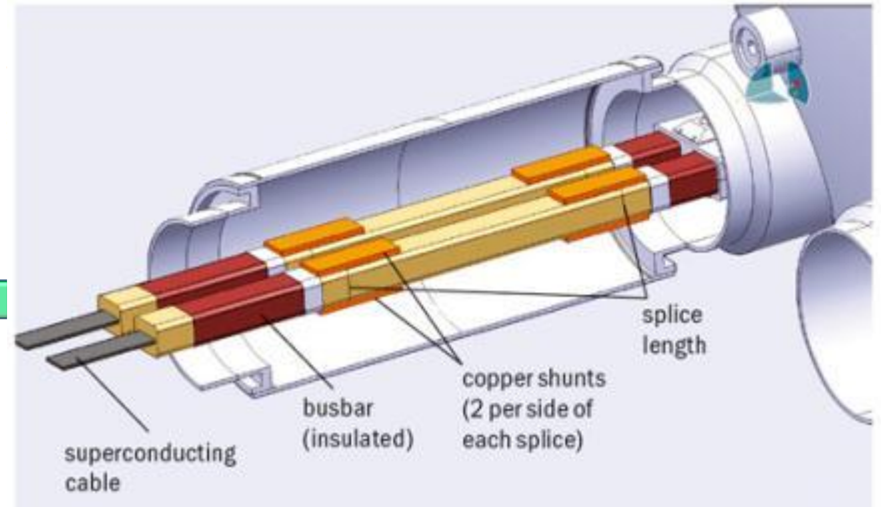
Peak luminosity	6.4×10^{32}
Integrated per day	11 pb^{-1}
200 days	2.2 fb^{-1}
Stored energy	72 MJ

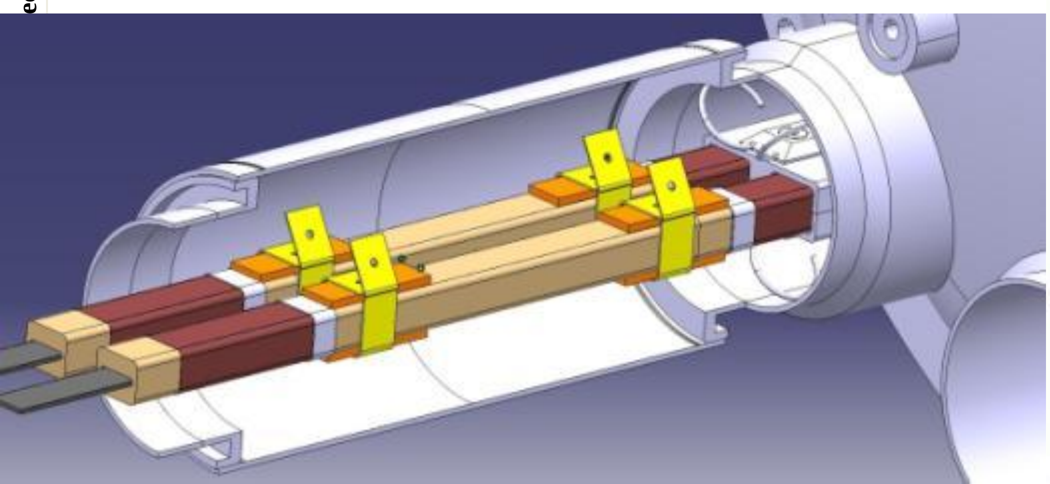
Usual warnings apply – see problems, problems above

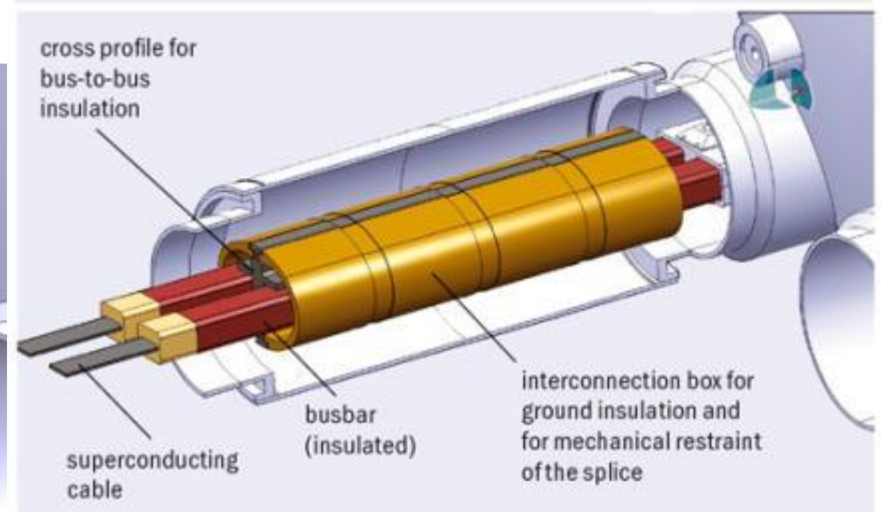
2012 – 2013 long shutdown



10-15 % of interconnections to be opened and to be re-welded
100% (10'000) to be consolidated



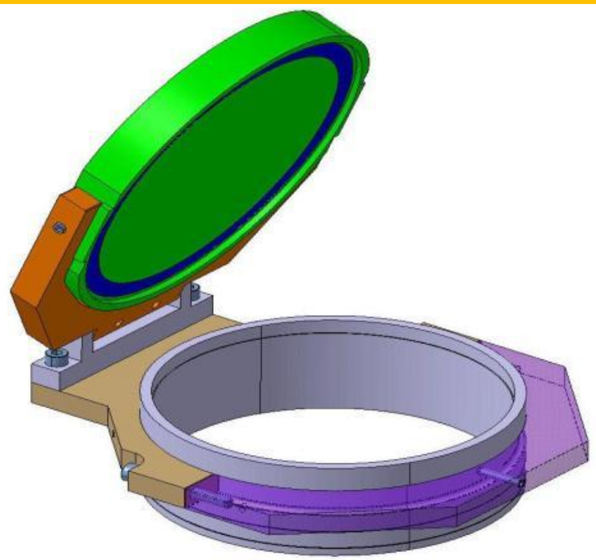


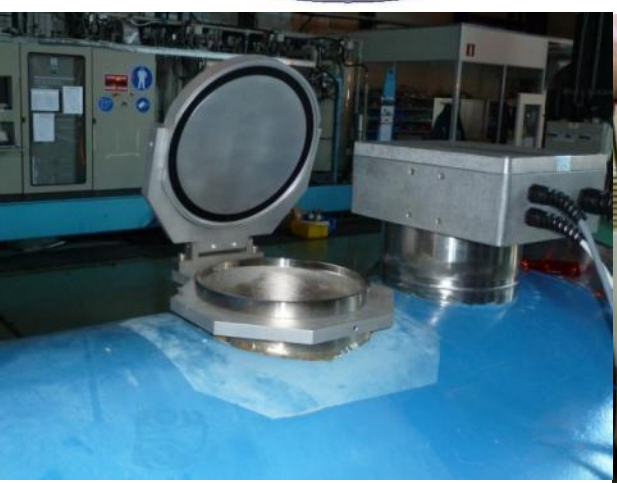


Consolidation of LHC Vacuum systems

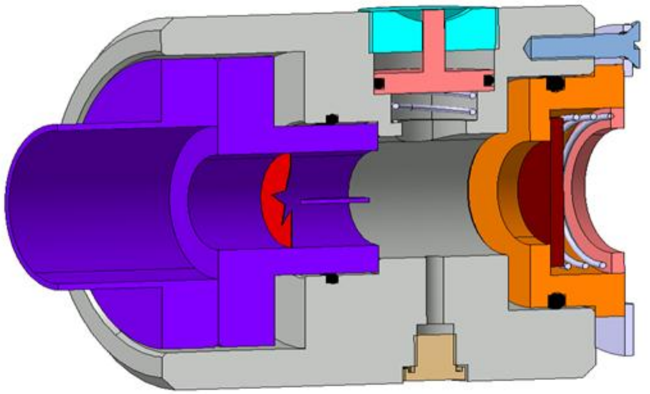
Pressure relief valves, rupture disks and protective shells

New design of DN200/160/100 valves





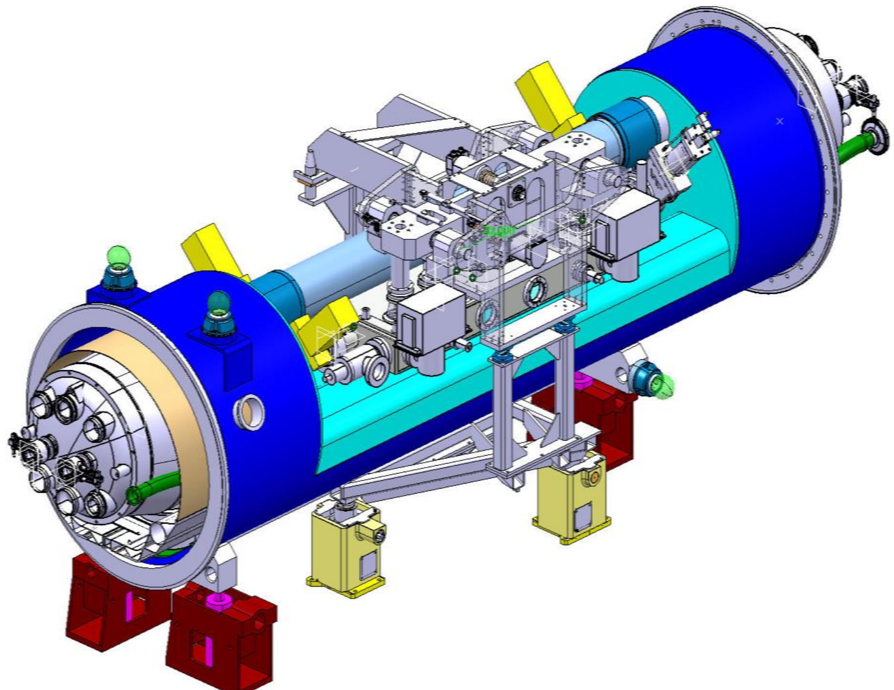
PIMs protection

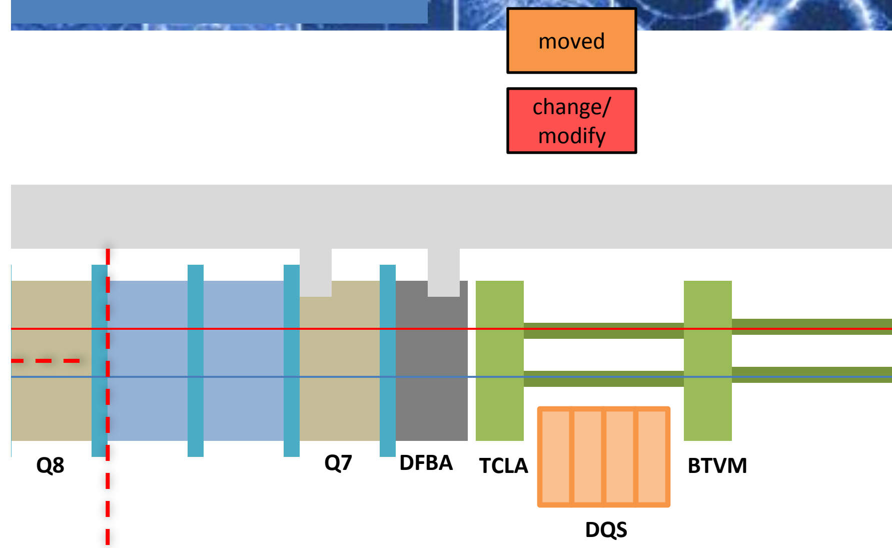


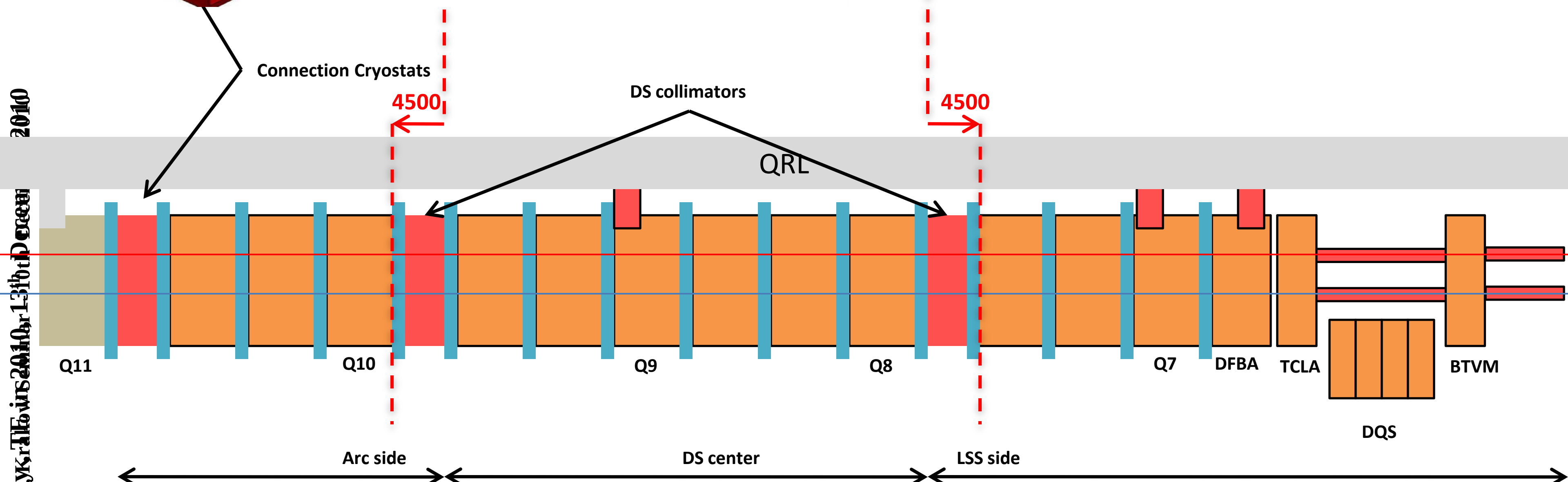
For Beam Vacuum

rk

S collimators

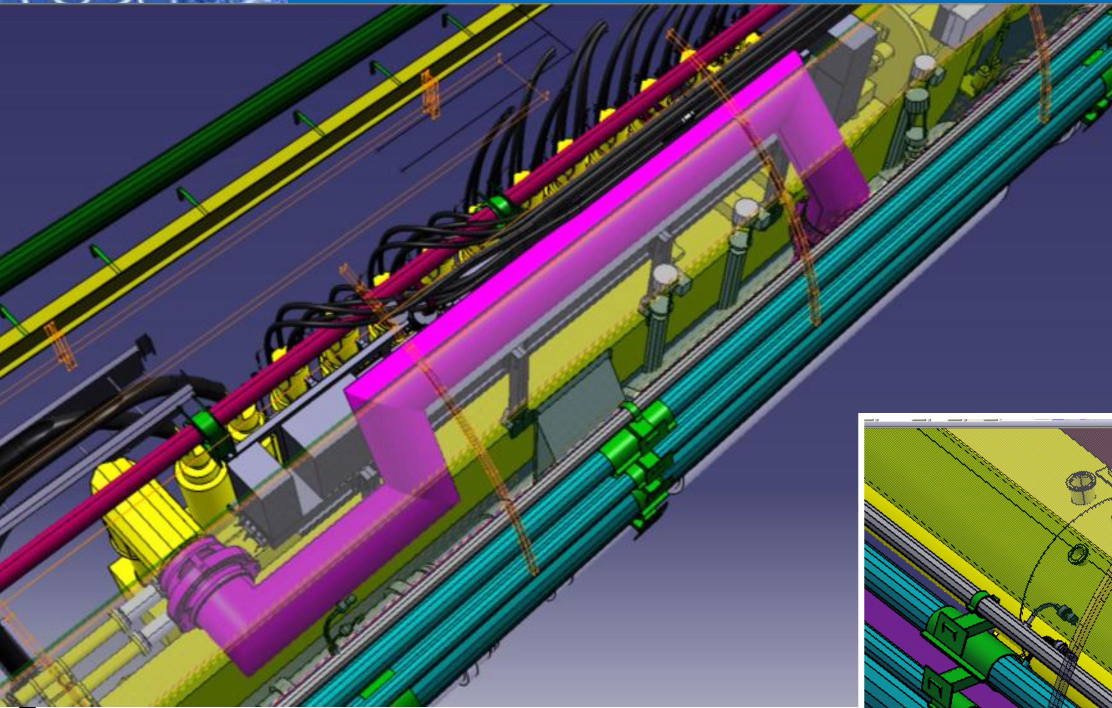




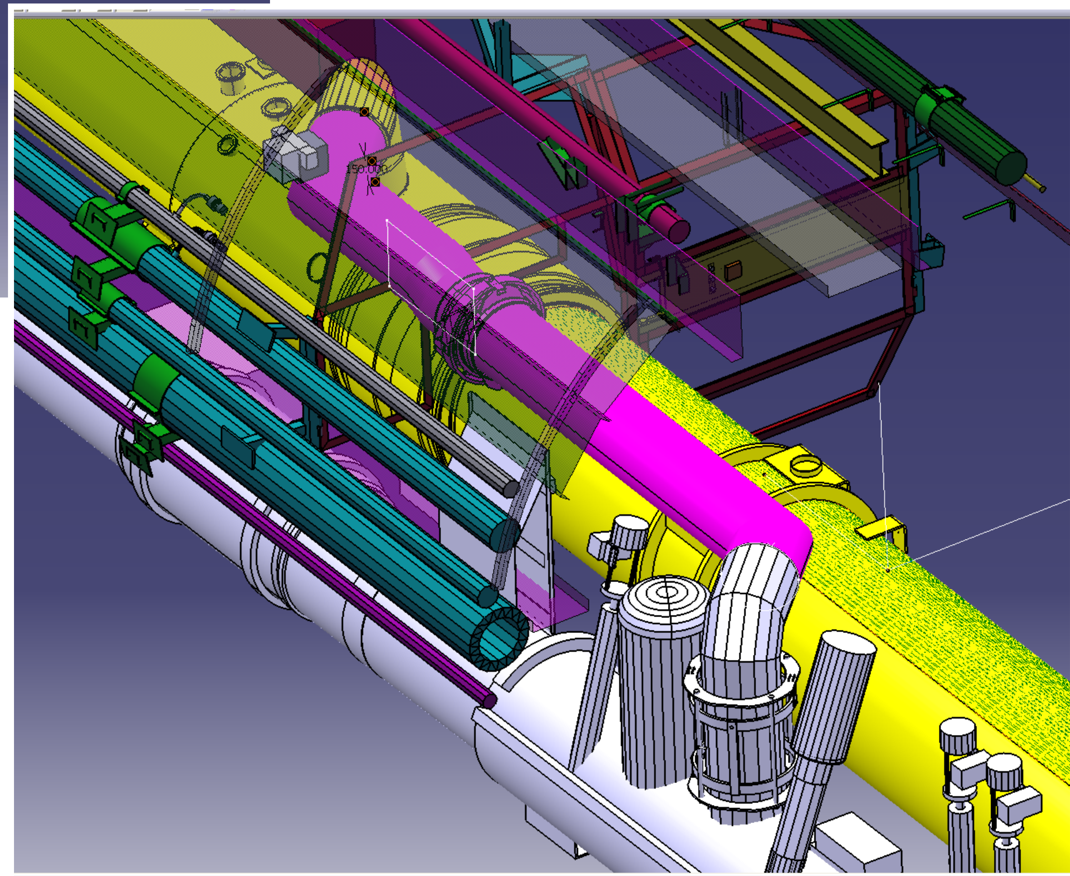


Courtesy: J.Coupard

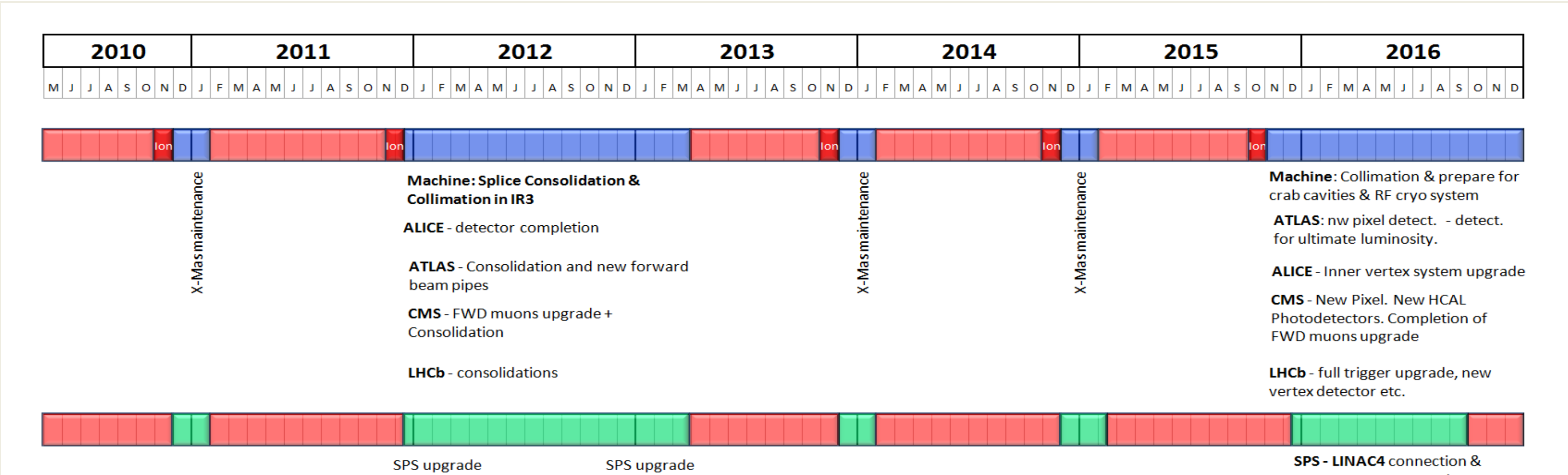
LHC cryo-collimator upgrade



New cryo collimators in P3 : move of DFBAE/F & Q4s : QRL extension studies



2011 - 2016



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

Upgrades: Foreword

New Studies were launched more than one year ago

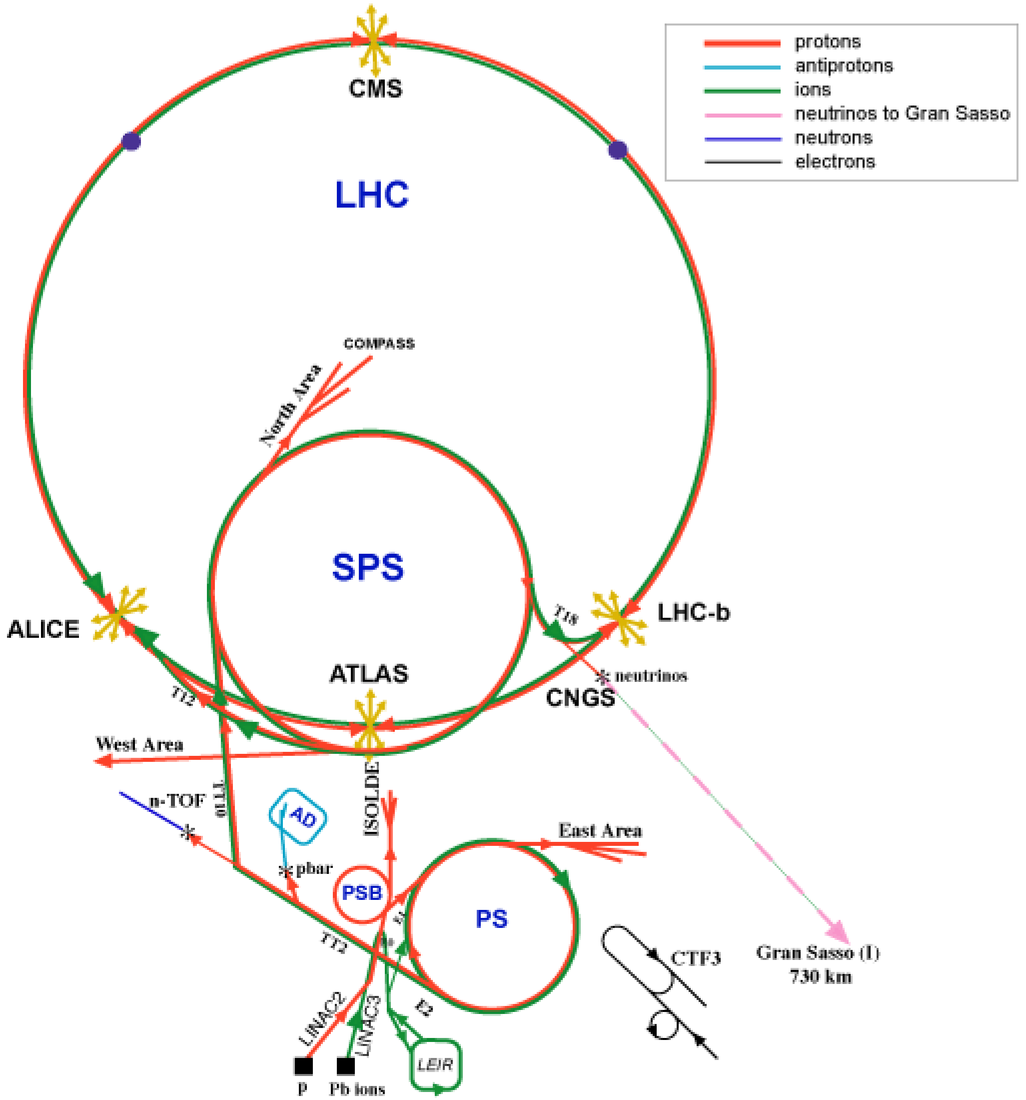
- Performance Aim
  - To maximize the useful integrated luminosity over the lifetime of the LHC

- Targets set by the detectors are:
  3000fb^{-1} (on tape) by the end of the life of the LHC
  → 250-300fb^{-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

The CERN accelerator network



LIU project

LHC Injectors Upgrade

Linac 4 (ready 2014, connection in 2016 or 2017)

PSB (Booster) 2 GeV

SPS upgrade

PS review

Consolidation project

Injectors must operate hit high reliability up to 2030

Luminosity Upgrade Scenario: HL-LHC

– 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 $5x10^{34}$ 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 $5x10^{34}$ and 10^{35}.
- ***Pile up events***
- ***Radiation effects***

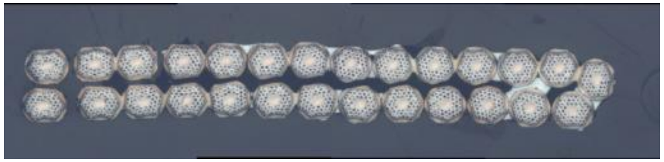
HL-LHC: Hardware for the Upgrade

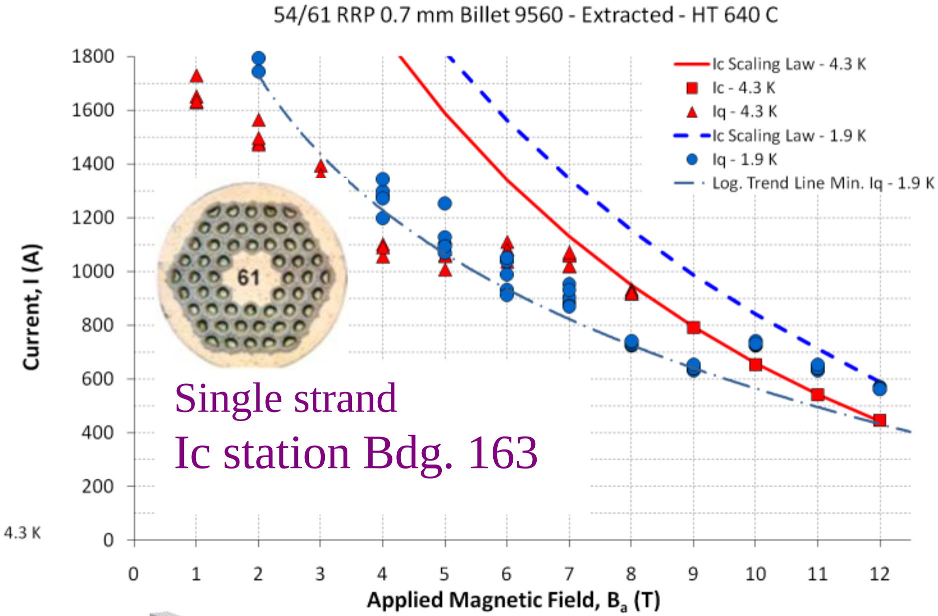
- Upgrade of the intensity in the Injector Chain (LIU)
- New high field insertion quadrupoles
- Upgraded cryo system for IP1 and IP5
- Crab Cavities to take advantage of the small beta*
- Single Event Upsets
  - SC links to allow power converters to be moved to surface

- 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 D2

Nb_3Sn for High-Field Magnets

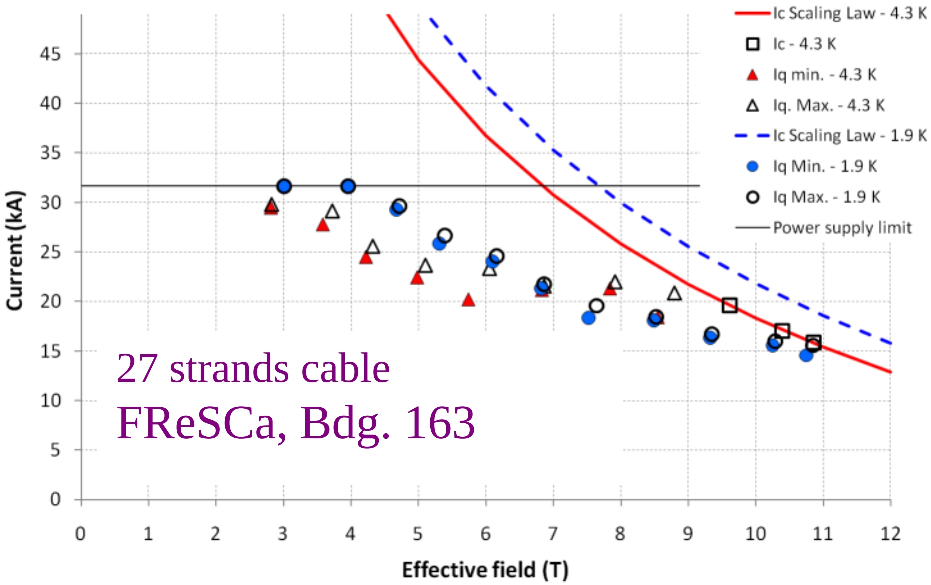
We now have a **good grasp** on the current carrying limits for Nb_3Sn strand and cables



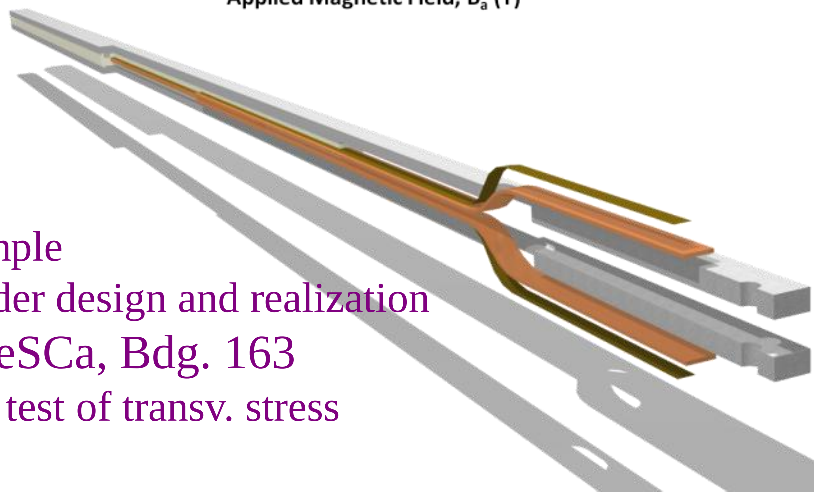


Single strand
Ic station Bdg. 163

LARP CABLE 983 - RRP 0.7 mm Strand Billet 9560 - HT 640 C



27 strands cable
FReSCa, Bdg. 163

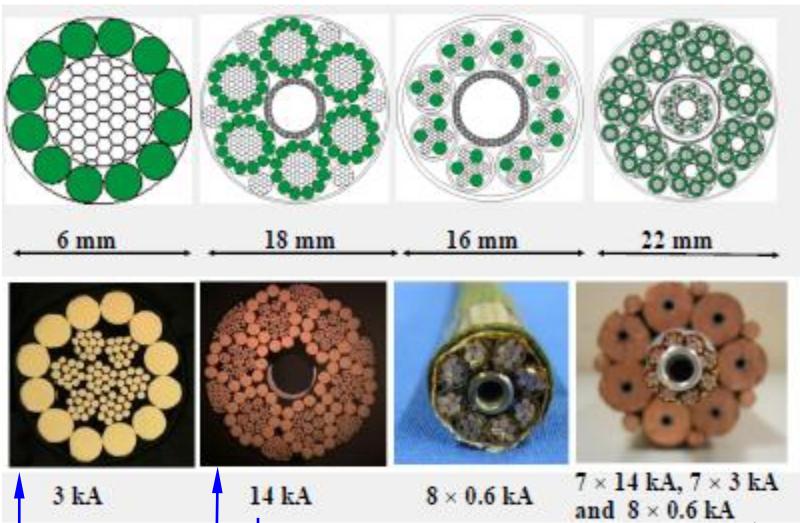


Sample
holder design and realization
FReSCa, Bdg. 163
For test of transv. stress

Links

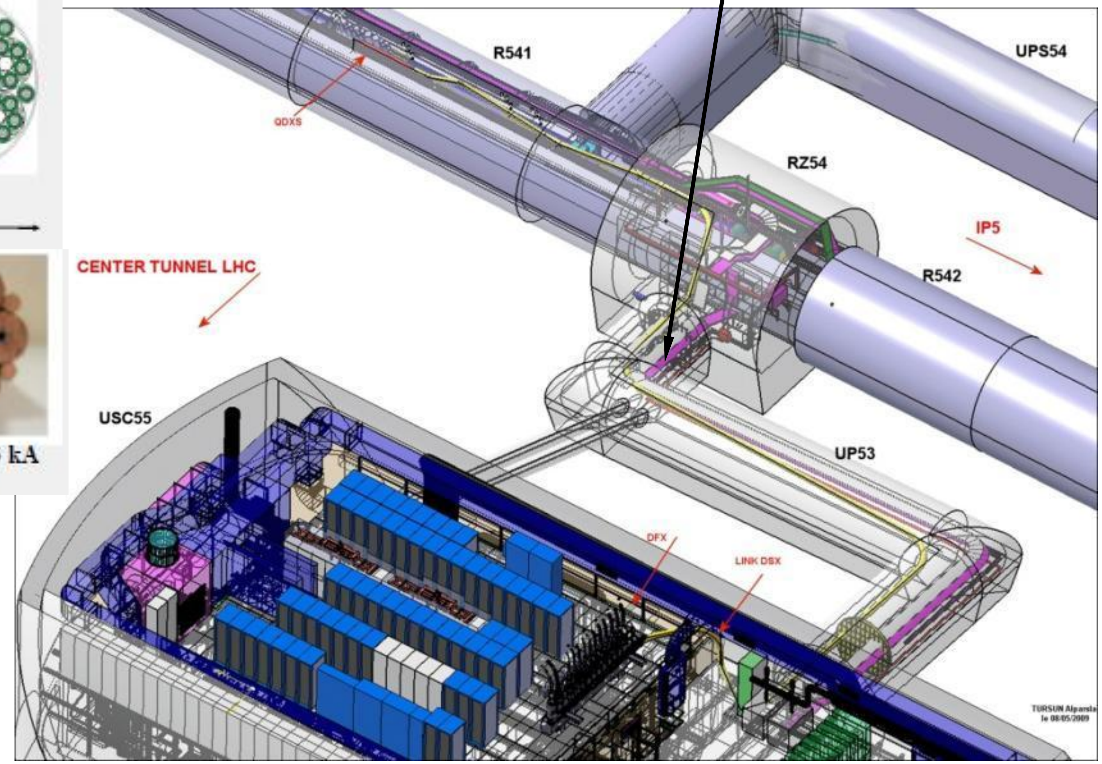
Design and preliminary test of MgB_2 feeder system (□120 kA) that could be used to remove the power converters from the proximity of the tunnel (access, radiation issues)

SC link



Reached 17 kA w/o quench !!!

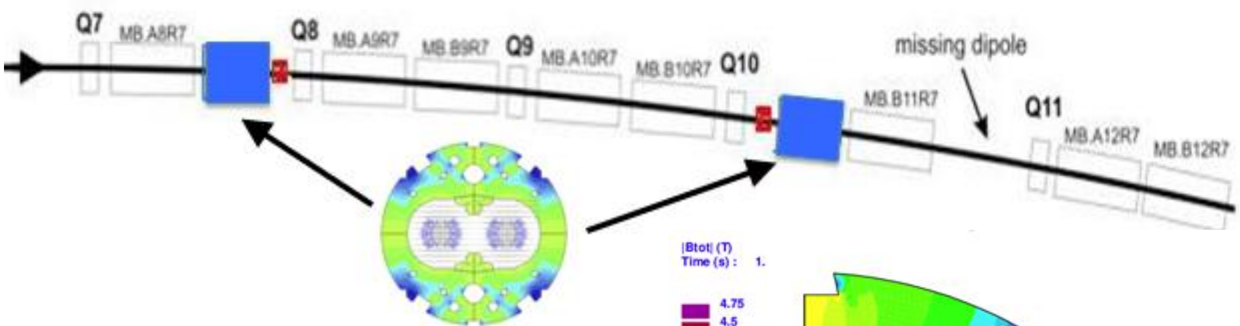
Reached 11 kA w/o quench !!!

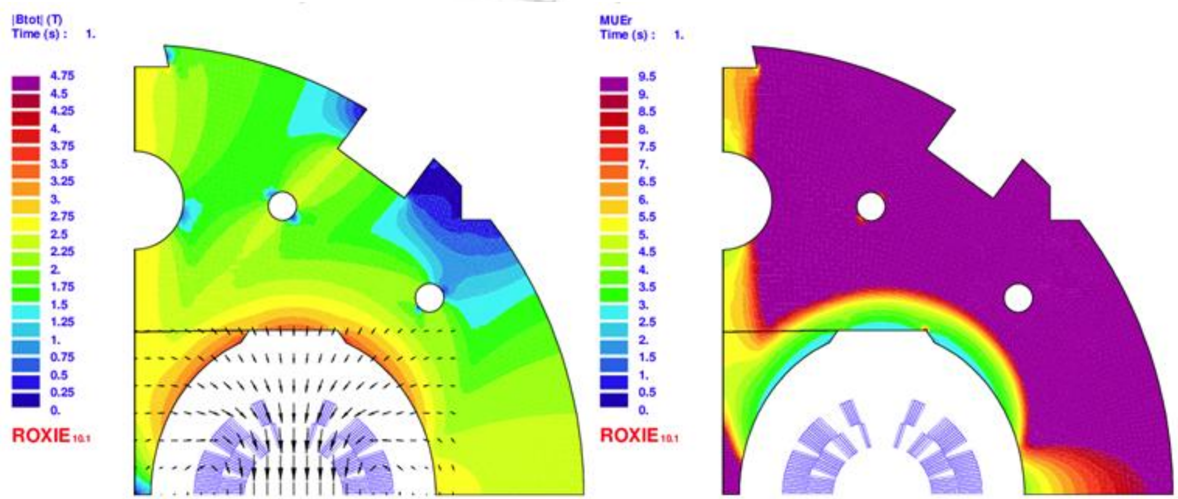


Cold powering system for the LHC IR Upgrade Phase 1

11T DS Dipole

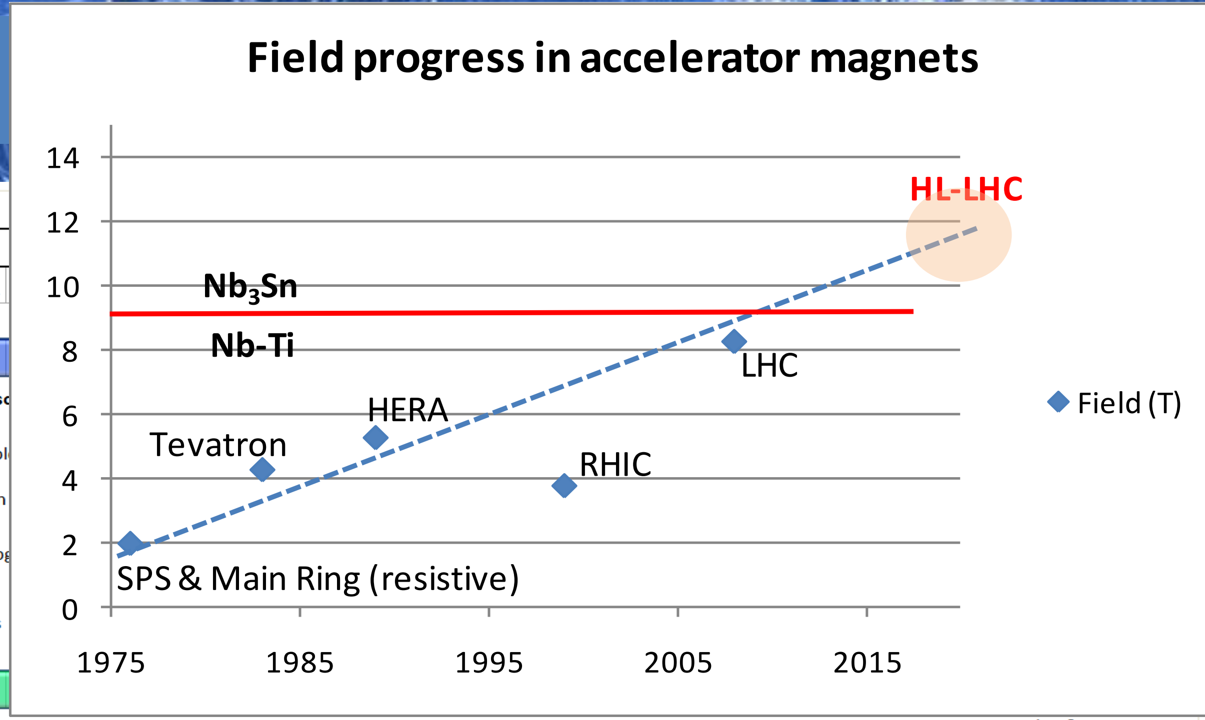
- Goal: liberate space for collimation phase II upgrade in the DS regions of points 2 & 7.
- Scenarios: replacing MBs by shorter twin-aperture dipoles with higher field (same integrated strength)
  - using Cryo-collimators: 2 HF dipoles / DS
  - using Warm collimators: 4 HF dipoles / DS

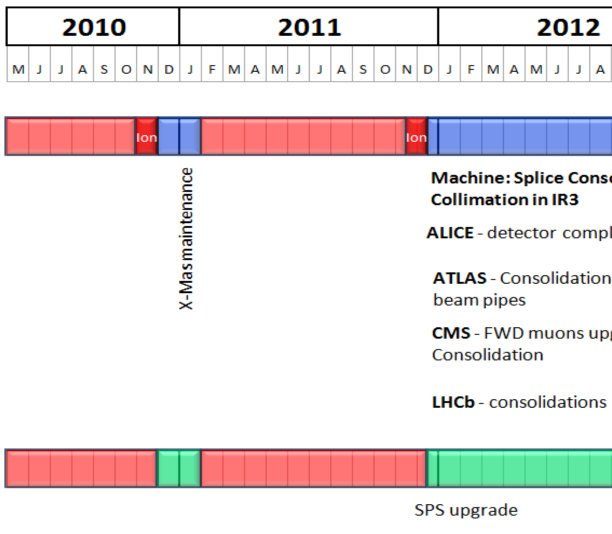


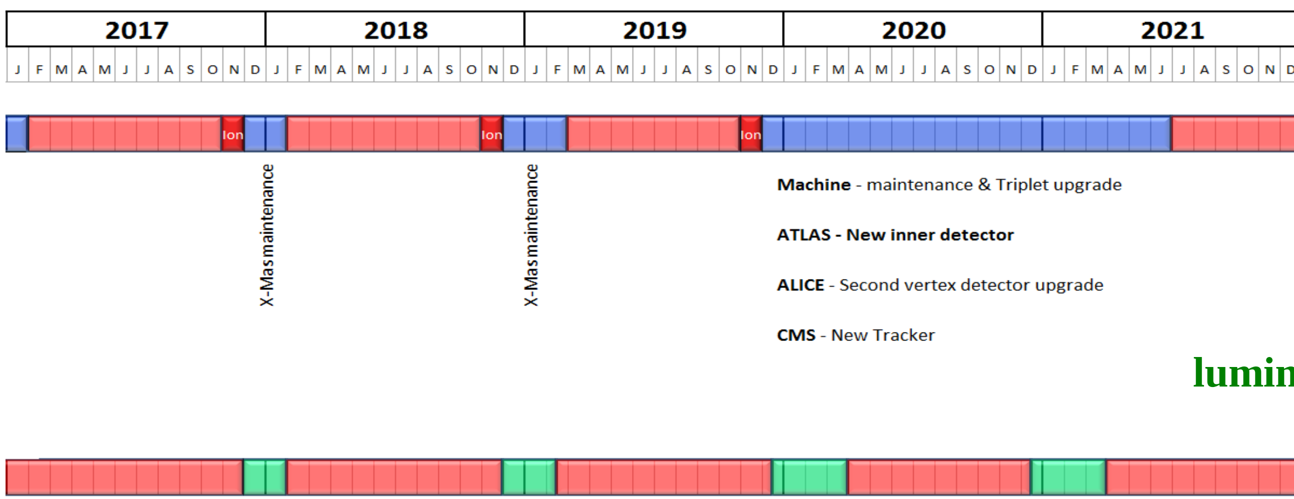


Fermilab puts 400 k$ + 5-8 FTE
1m-1bore model by end 2011 !!!

The 10





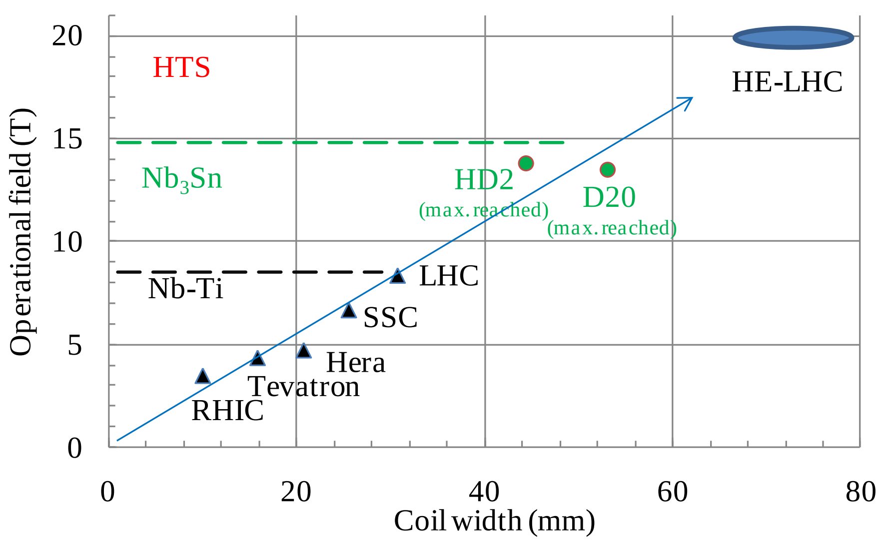


5.10^{34}
and
luminosity levelling

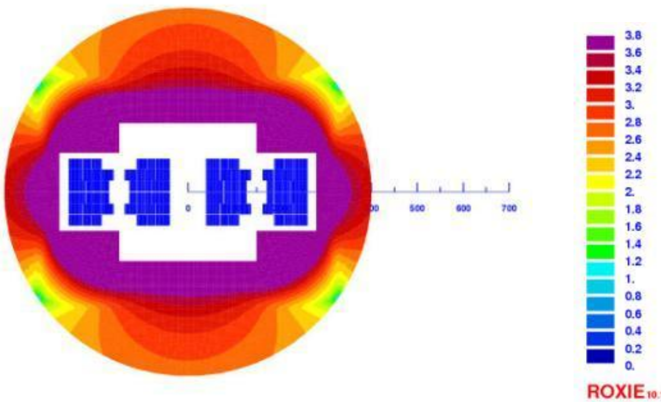
• A 20 T operational field dipole for a HE-LHC

– Preliminary conceptual design [R. Assman, et al., CERN ATS 2010 177]

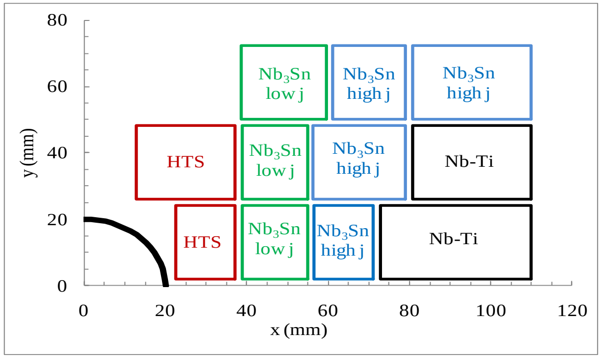
- A 80 mm thick coil with ~400 A/mm² operational *j*
- Grading of the material necessary to reduce cost



Coil thickness versus operational field in accelerator magnets

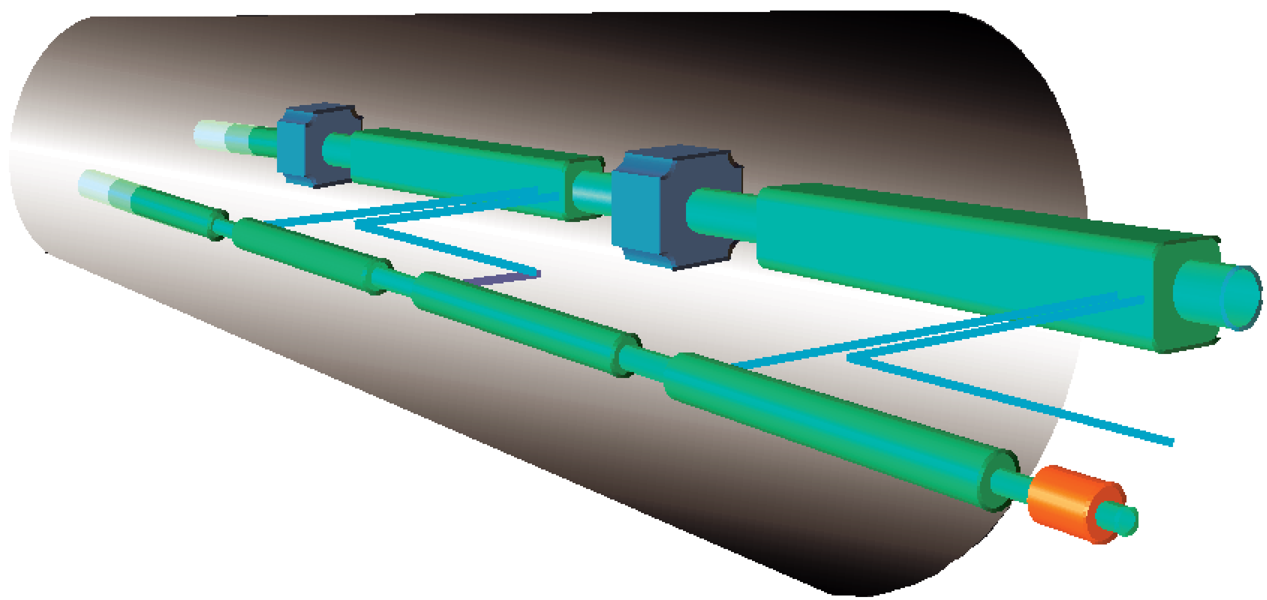


Magnet cross-section [E. Todesco]



Coil lay out

High energy linear colliders: ILC, CLIC



Linear Collider Studies Leader:
Steinar Stapnes as from 1 January 2011.

2010 was an absorbing, captivating and successful year for the LHC

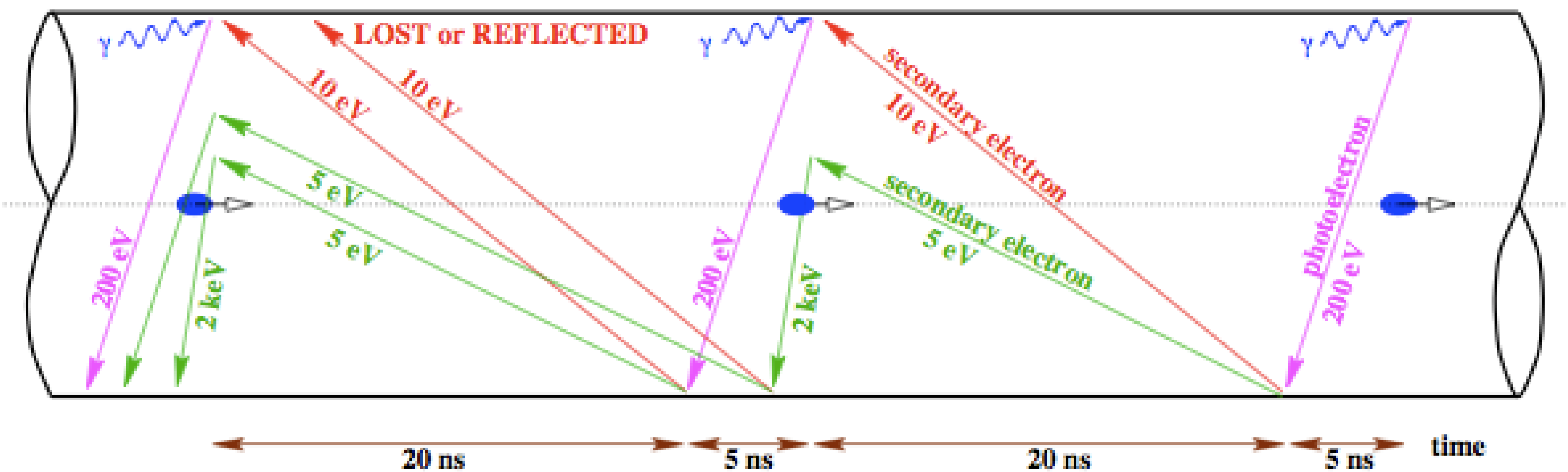
As any large and complex project, LHC was not all plain sailing project but CERN and collaborations have shown an impressive reactive force to overcome the obstacles, continue progressing towards the nominal performance and to prepare the next high energy frontier project

Thanks for your attention and for your kind hospitality

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

Fk. Bordry , Krako