The LHC accelerator: challenges, achievements and the future

3rd June, Zurich (45mins in total)

Steve Myers

Director of Accelerators and Technology,

CERN

LEP/LIBRARY

ps

LEP Note 440
11.4.1983

PRELIMINARY PERFORMANCE ESTIMATES FOR A LEP PROTON COLLIDER

S. Myers and W. Schnell

The Start:
First documented proposal

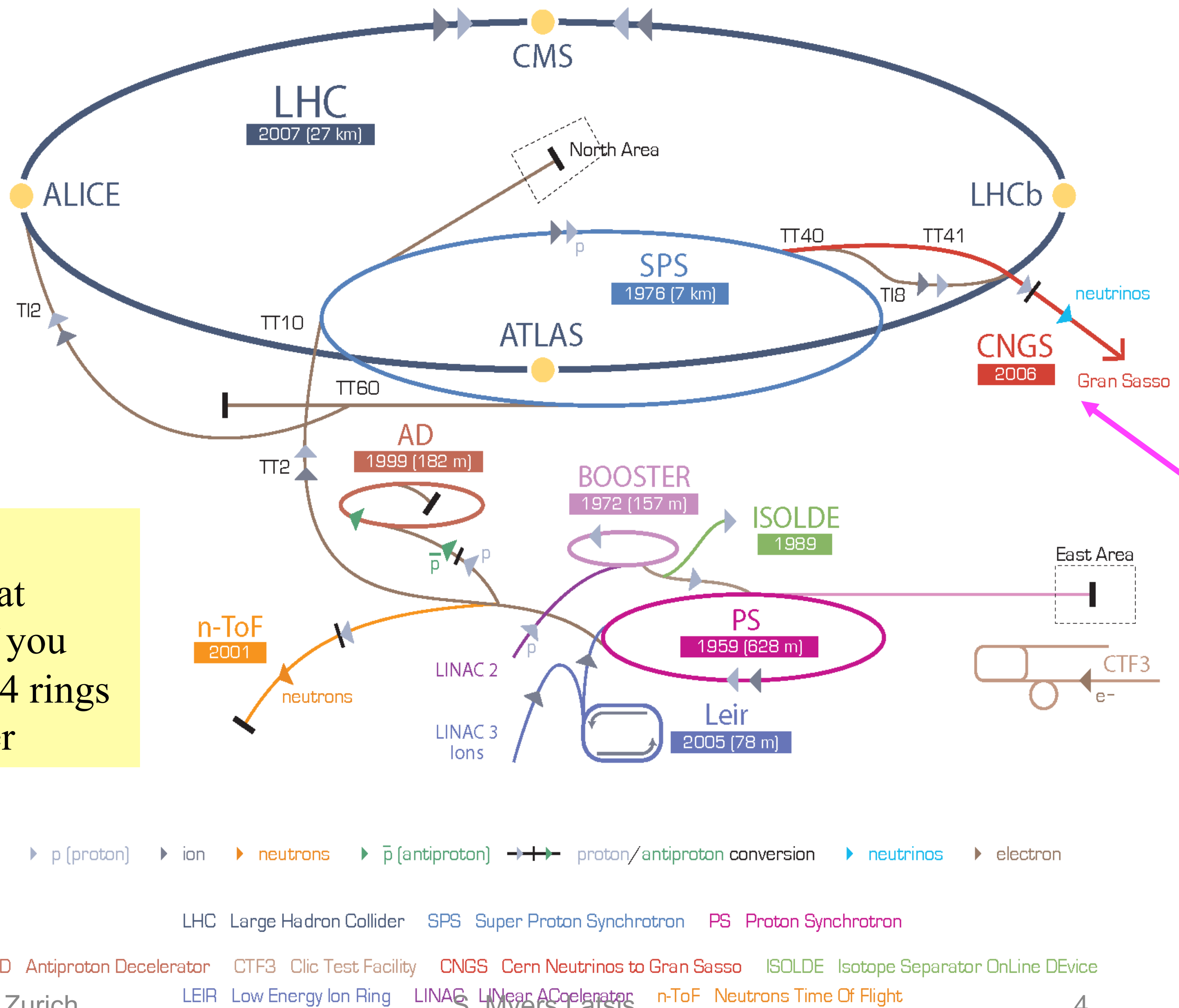
1. Introduction

This analysis was stimulated by news from the United States where very large $p\bar{p}$ and pp colliders are actively being studied at the moment. Indeed, a first look at the basic performance limitations of possible $p\bar{p}$ or pp rings in the LEP tunnel seems overdue, however far off in the future a possible start of such a p-LEP project may yet be in time. What we shall discuss is, in fact, rather obvious, but such a discussion has, to the best of our knowledge, not been presented so far.

We shall not address any detailed design questions but shall give basic equations and make a few plausible assumptions for the purpose of illustration. Thus, we shall assume throughout that the maximum energy per beam is 8 TeV (corresponding to a little over 9 T bending field in very advanced superconducting magnets) and that injection is at 0.4 TeV. The ring circumference is, of course that of LEP, namely 26,659 m. It should be clear from this requirement of "Ten Tesla Magnets" alone that such a project is not for the near future and that it should not be attempted before the technology is ready.

Superconducting Proton Accelerator and Collider
installed in a 27km circumference underground tunnel (tunnel cross-section diameter 4m) at CERN
Tunnel was built for LEP collider in 1985

CERN Accelerator Complex



Total of 9 accelerators at CERN, 12 if you consider the 4 rings of the booster

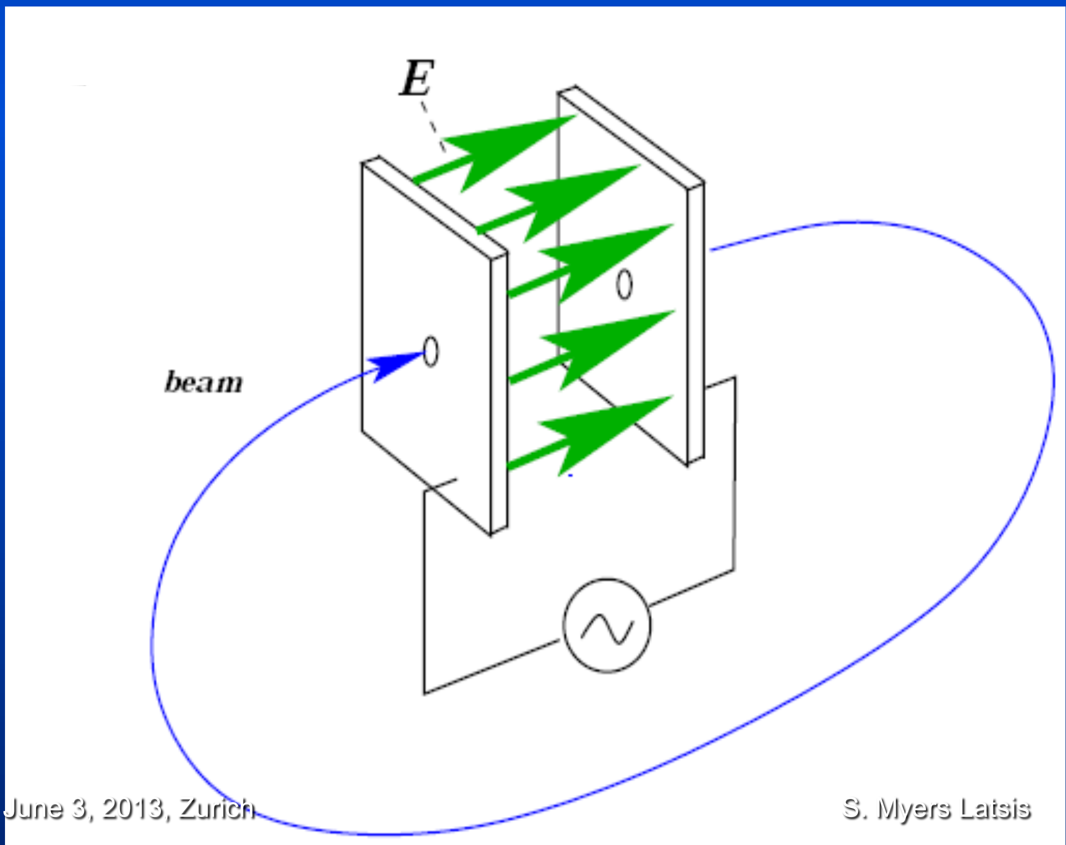
Technologies needed for Accelerators and Detectors (some examples)

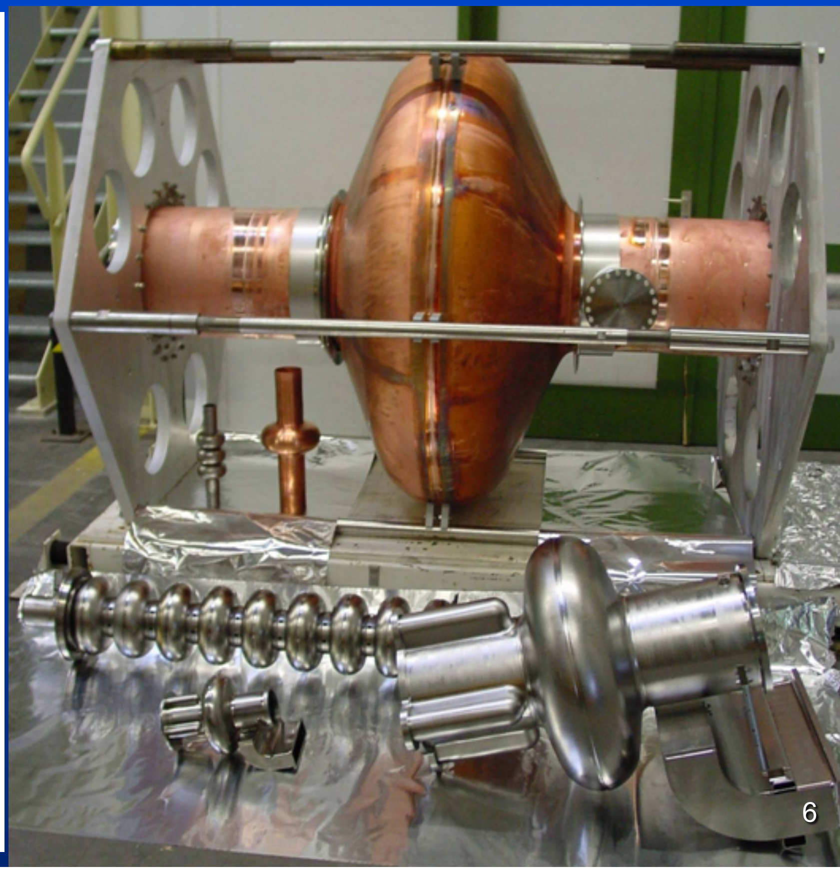
- Civil engineering (underground caverns and tunnelling...)
- Geodesy (align all components to accuracies not needed in any other domain.)
- Electrical distribution (fast switching and power sharing between Swiss and French networks, network protection, active compensators, susceptibility to electrical storms...)
- Cryogenics (1.9K, superfluid helium, 37Mkg of cold mass, 100 tonnes He. 1260tonnes nitrogen)
- Magnets (9T, twin bore, NbTi sc cable, ~3000 sc magnets + “normal” magnets...)
- Power converters (13kA DC conversion from AC, with 1ppm ripple, resolution,..)
- Ultra High Vacuum (10^{-9} to 10^{-11} mbar (Torr) in the presence of beam, 27km)
- Acceleration System (sc RF 400MHz, 1MW klystrons, control of cavities wrt beam)
- Beam Instrumentation (all types of particle detection and control)
- Beam feedback (EM instabilities, detect and stabilize)
- Injection, extraction(high rise time magnetic pulses, PFN, ferrite loaded magnets, UHV)
- Machine protection (10GJ EM stored energy, 720MJ beams energy)
- Targets, dumps and collimators (materials research for particle beams)

Acceleration (RF) system

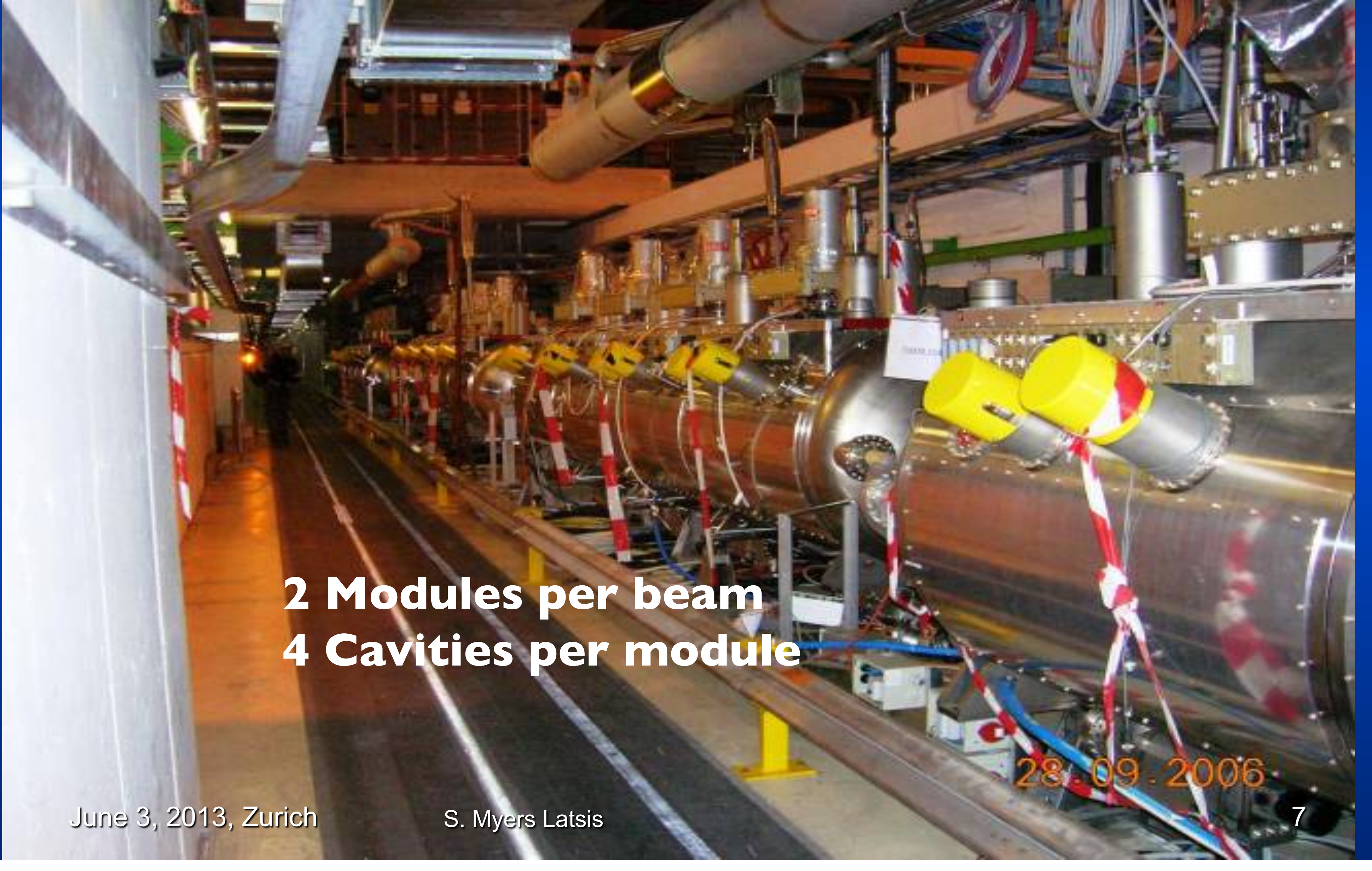
Radiofrequency (RF) electric fields

- RF cavities are located intermittently along the beam pipe. Each time a beam passes the electric field in an RF cavity, some of the energy from the radio wave is transferred to the particles.

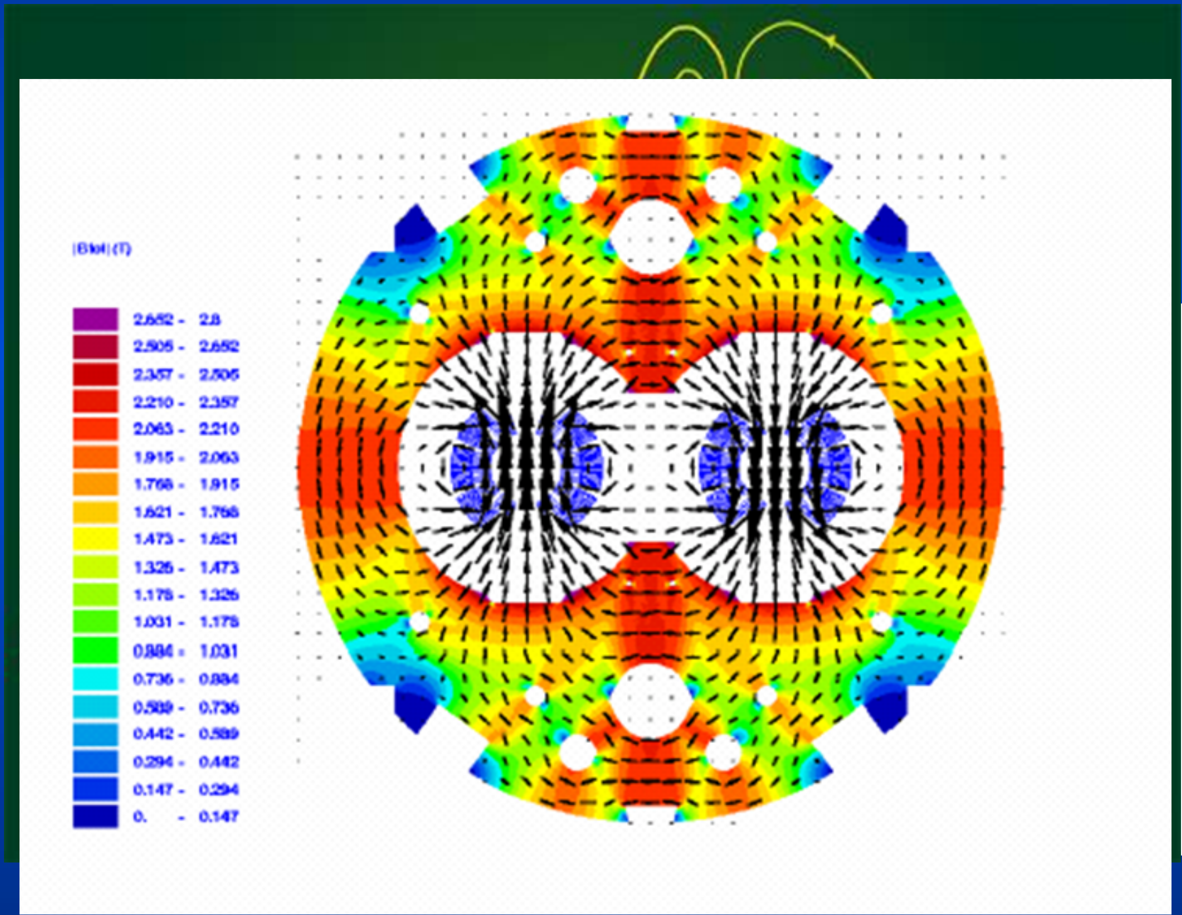




In Reality (point 4)



Dipole or Bending Magnets



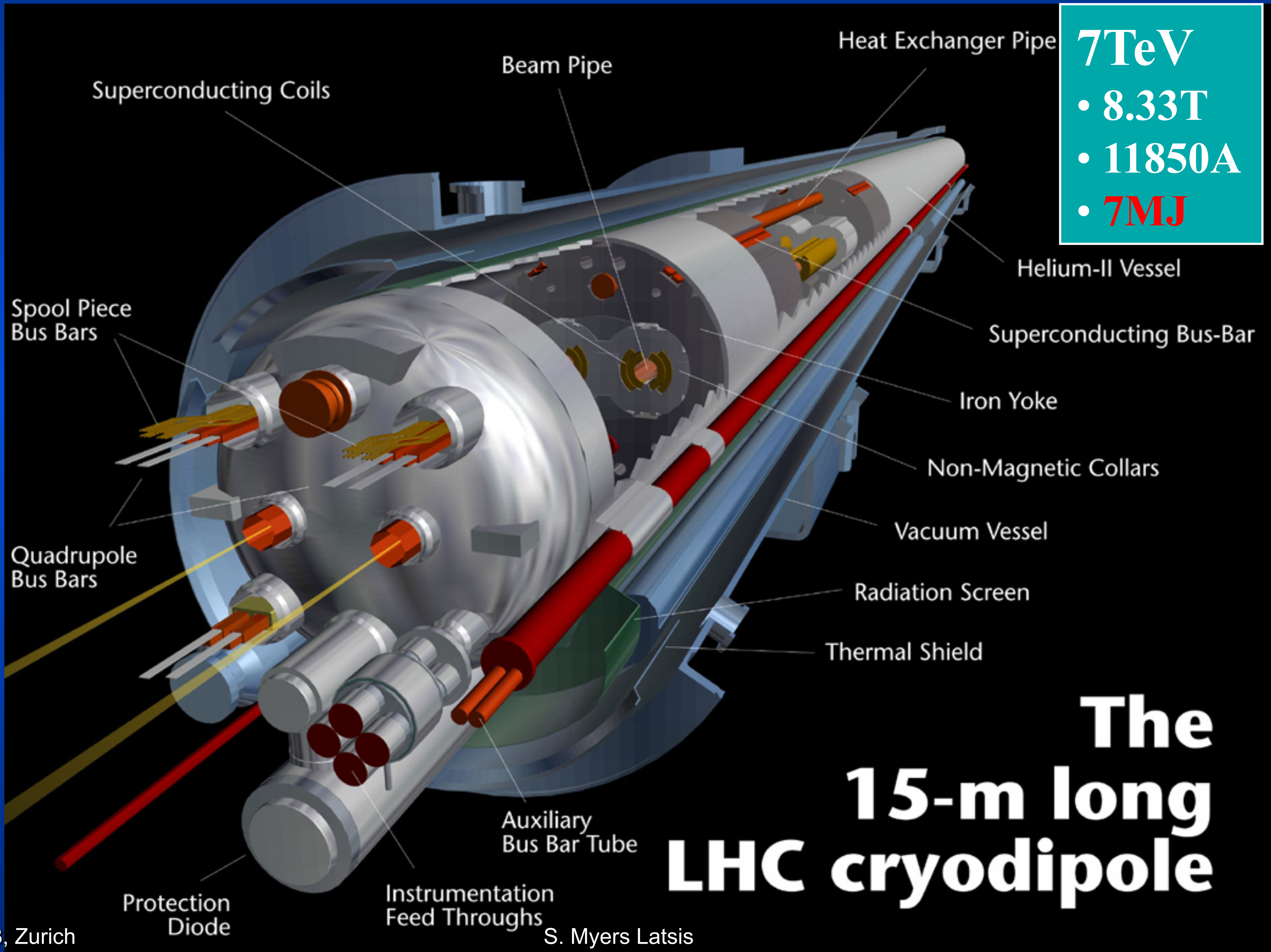
If the LHC did not use superconductivity

The LHC has a circumference of 26.7 km, with 20km filled with superconducting magnets operating at 8.3 T. The refrigerators producing the liquid helium to cool the magnets consume 40 MW of power.

An equivalent machine with classical electromagnets would have a circumference of 100 km and would consume 1000 MW of power.

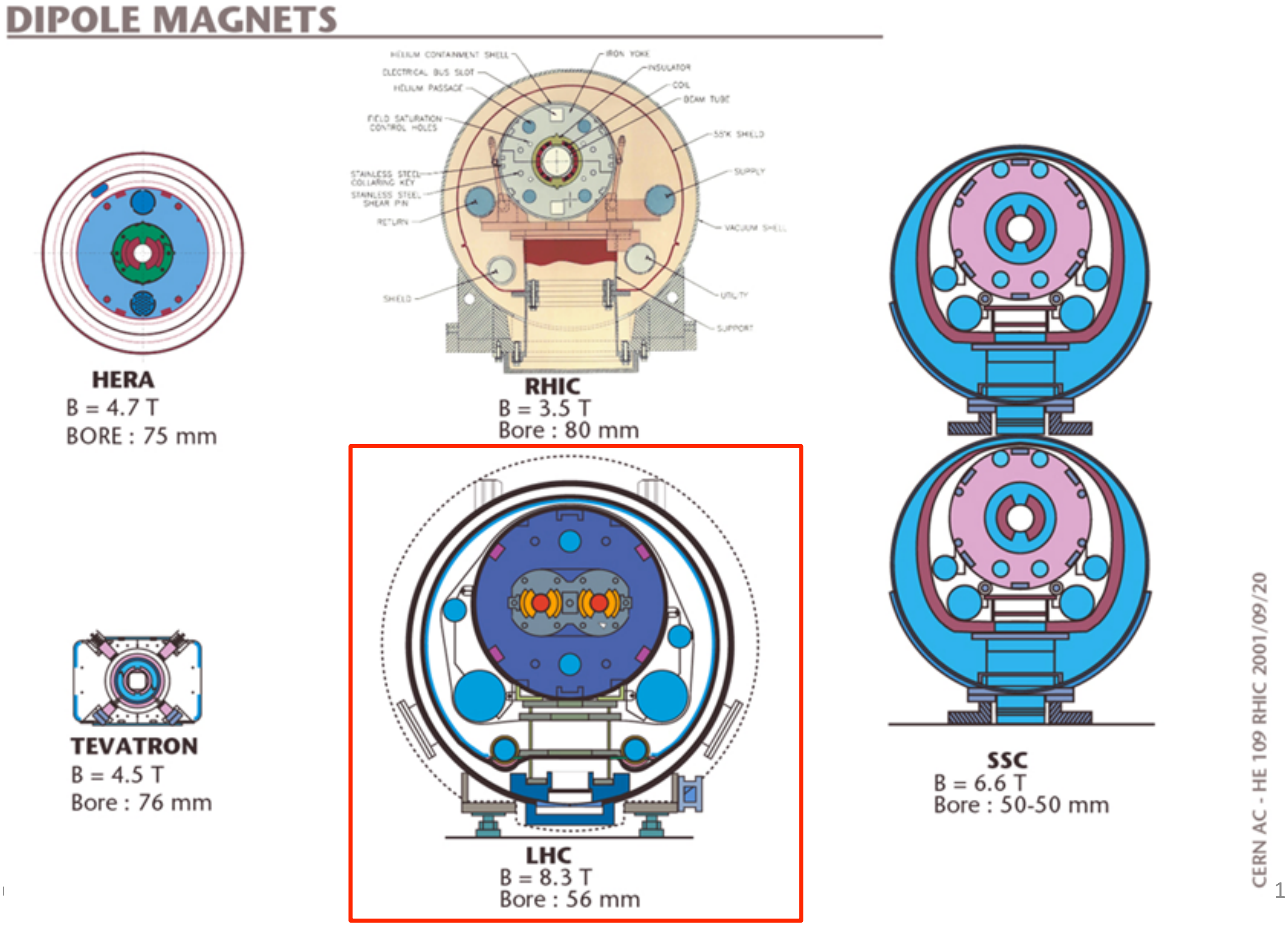
LHC dipoles (1232 of them) operating at 1.9K

Contracts by 4.7cm during cool-down

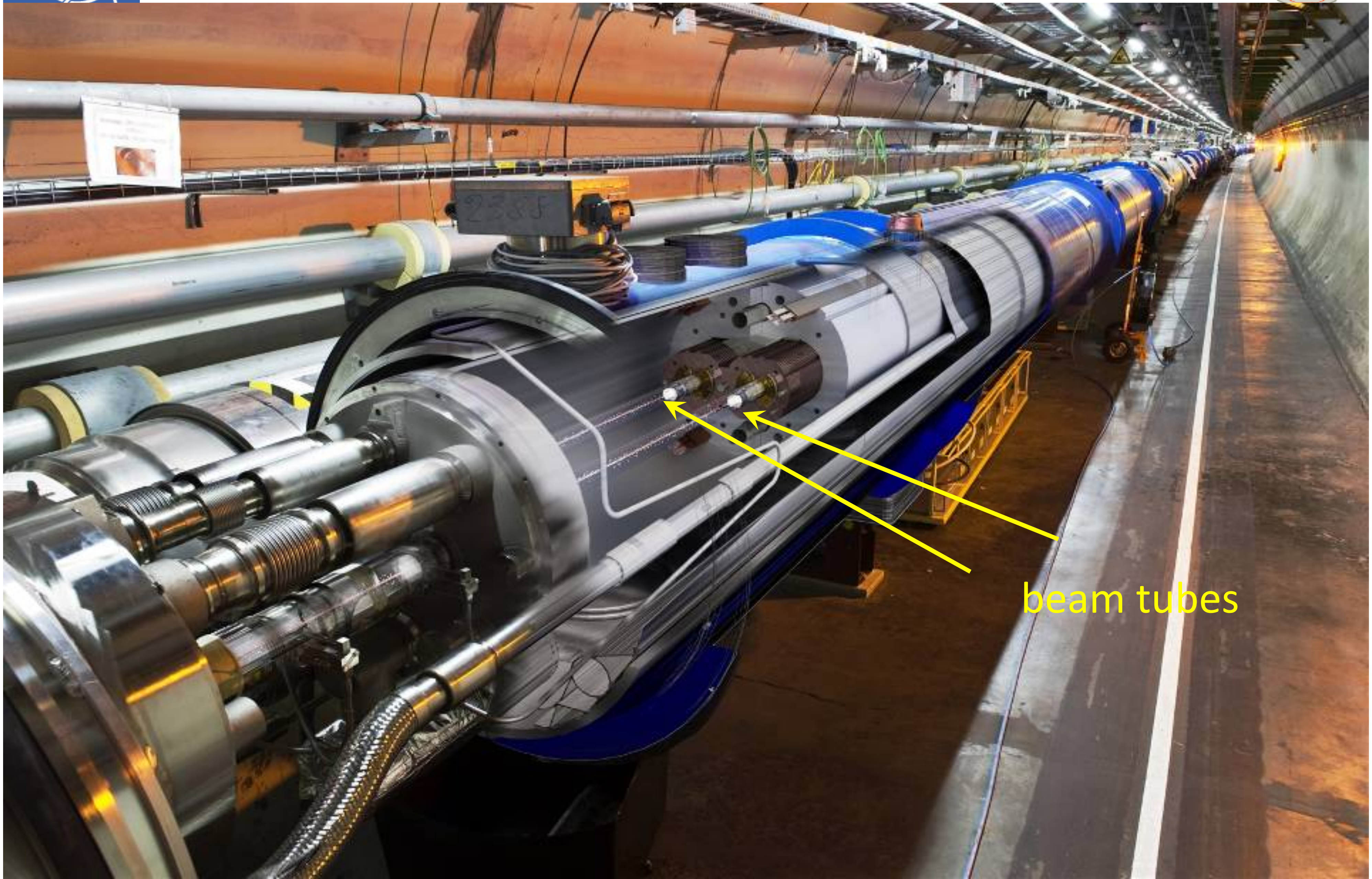


7TeV
- 8.33T
- 11850A
- 7MJ

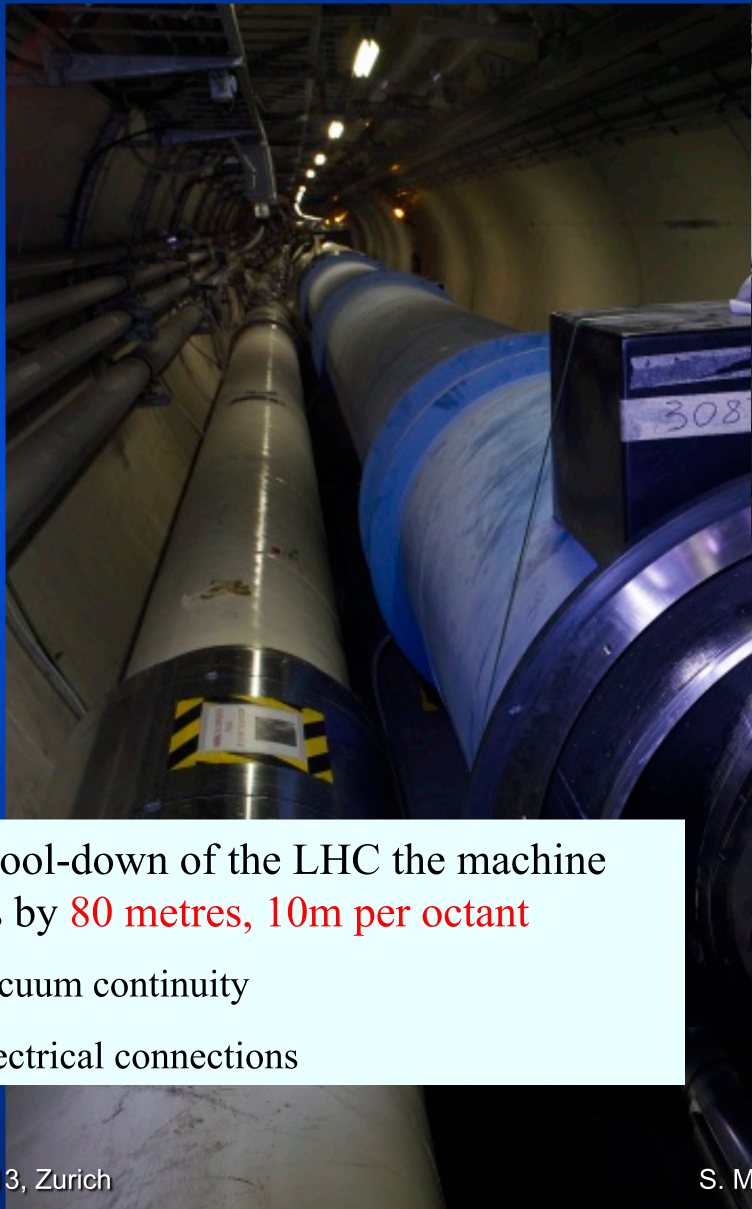
Superconducting Dipoles from Recent Colliders

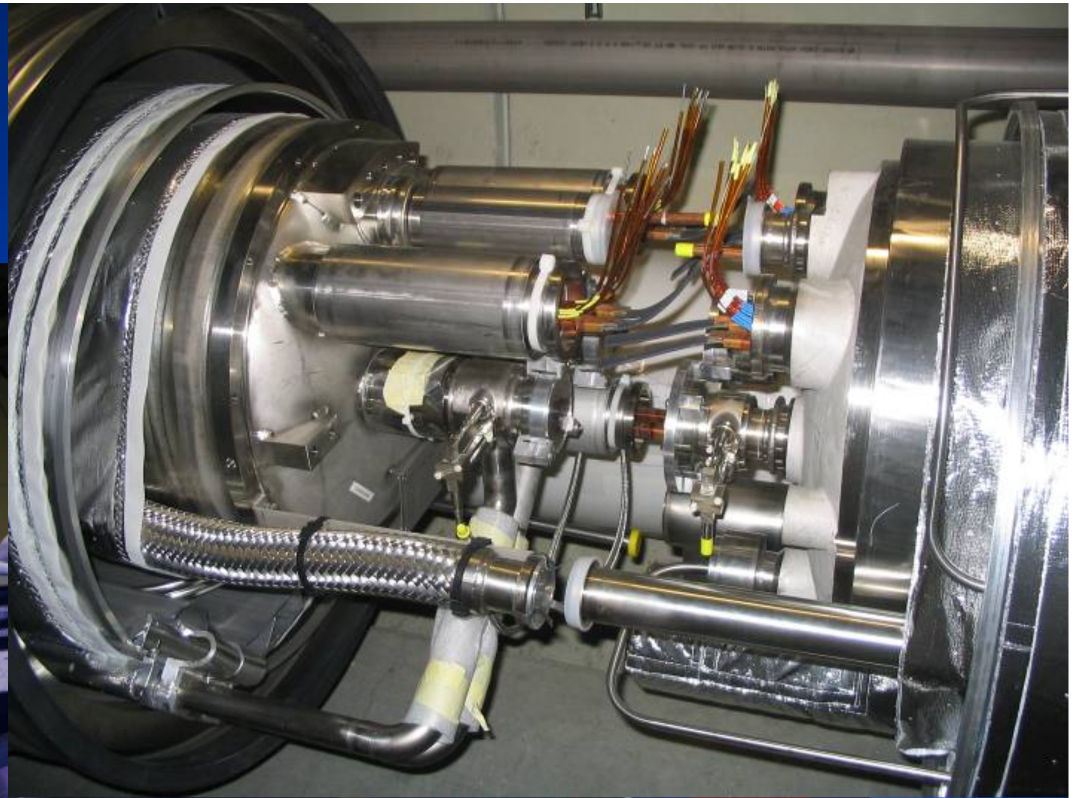


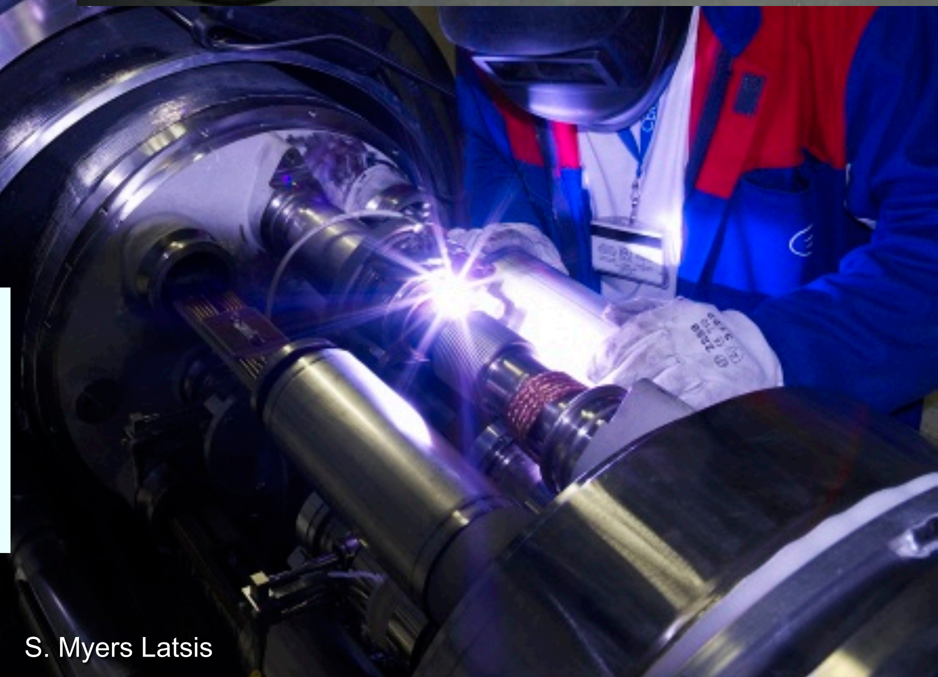
The LHC tunnel with dipole magnets



Interconnections







During cool-down of the LHC the machine contracts by 80 metres, 10m per octant

- Vacuum continuity
- Electrical connections

LHC: Some of the Technical Challenges

Circumference (km)	26.7	100-150m underground
Number of 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)	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 2kg Cu
Magnet Stored Energy (MJoules)/ octant	1100	Results from the high magnetic field
Sector Powering Circuit	8	1612 different electrical circuits

How Much Energy is this?

Nimitz class aircraft carrier (90 000 tons) at battle-speed of 30 Knots; Energy = ½ mv^2 ~ 10GJ

- **Energy stored in the magnets 10 GJ (1100 MJ/octant)**
- **In LHC we must dump the magnetic energy in around 40 seconds i.e. stop the aircraft carrier in 40 seconds**

- **Energy stored in each beam 362 MJ (in 89us) 4TW (power)**

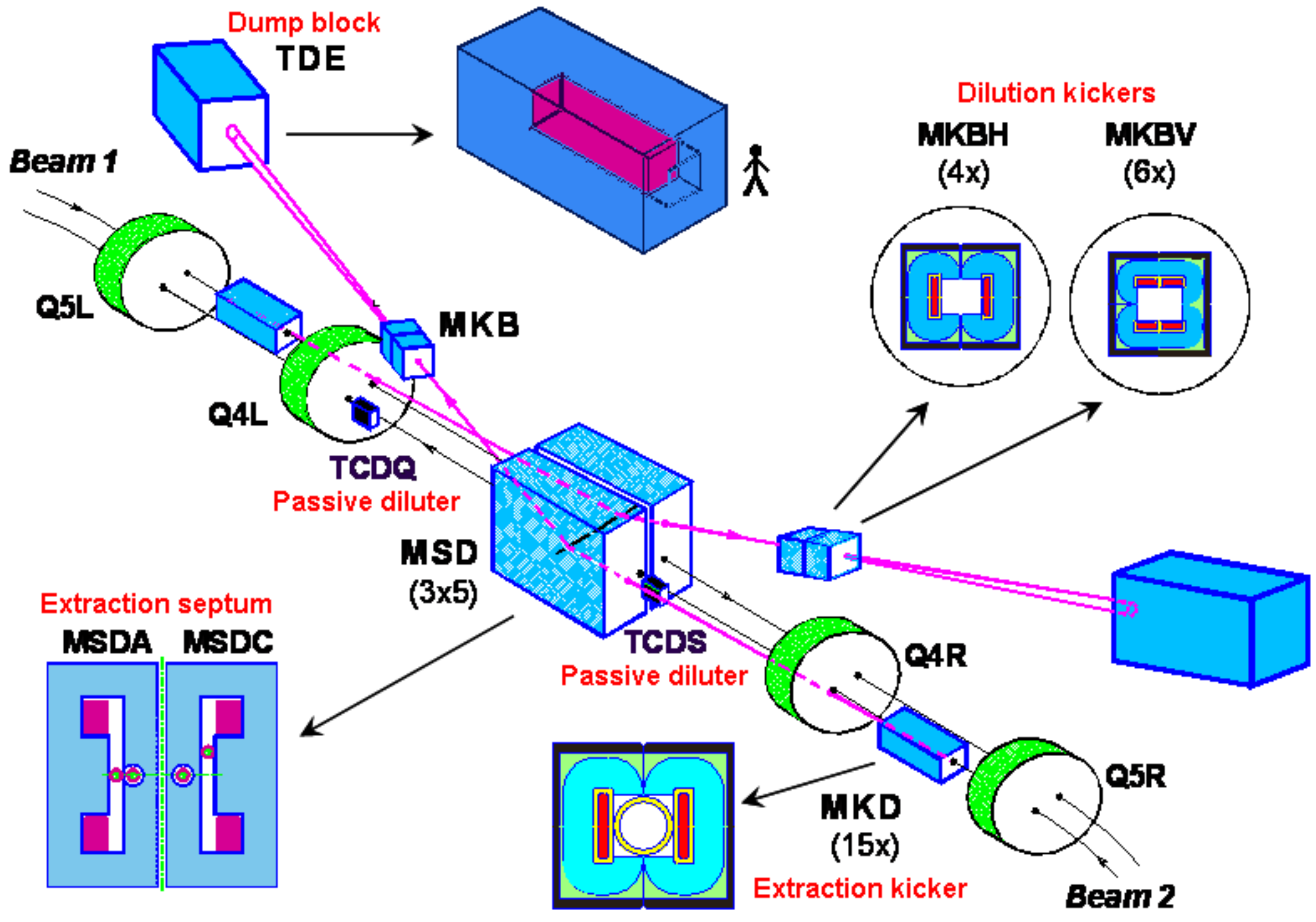
Copper
Melting point 1356 K
Specific heat ... K^{-1}
Latent ...000 J kg^{-1}
...elt 1kg takes (1354*386+205000) J =0.73MJ
...uld heat and melt half a tonne (500kg) of copper

A very thin long hole

How to Deal with the LHC self Destructive Power

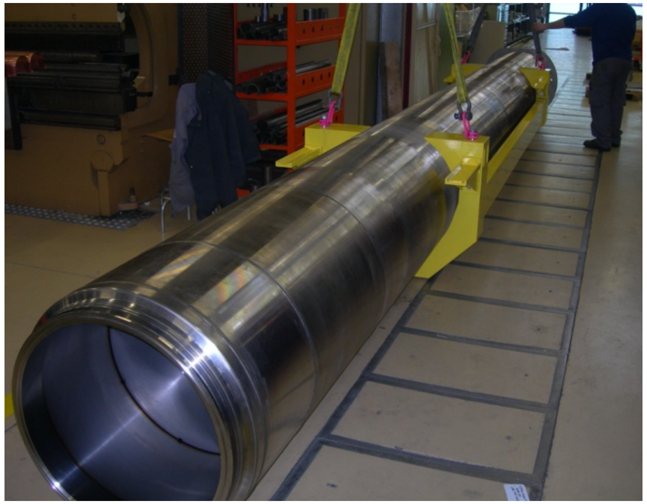
- In case of a problem the stored energy in the magnets and in the beam must be transferred to and dissipated in a safe, clearly defined place
- Magnet Protection system
  - "Quench" Protection (measures resistance)
  - Energy dump triggered and energy dissipated as heat in resistors (after of course aborting the beams)
- Machine Protection System
  - All critical elements which could provoke a beam loss are equipped with an emergency beam abort signal which triggers the beam dump system. There is also a beam loss monitoring system all around the circumference which will abort the beam if anomalous losses occur
  - The beam dump system is the last safety net

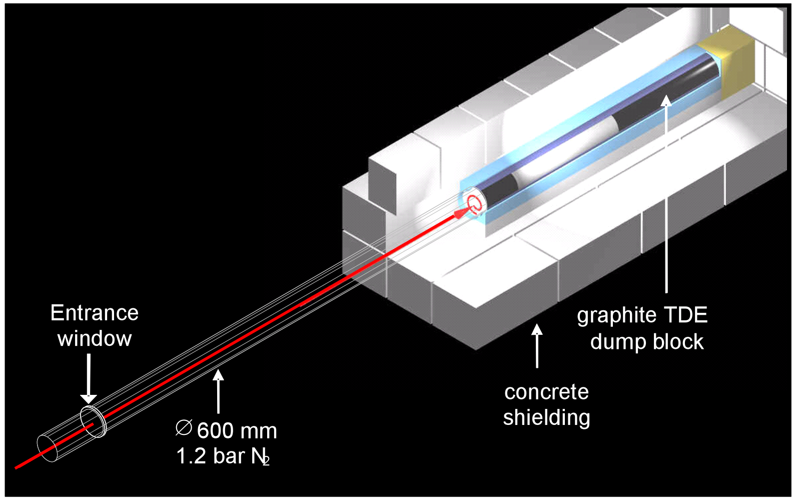
LHC beam dump principle (and acronyms)



Beam dump core (TDE)

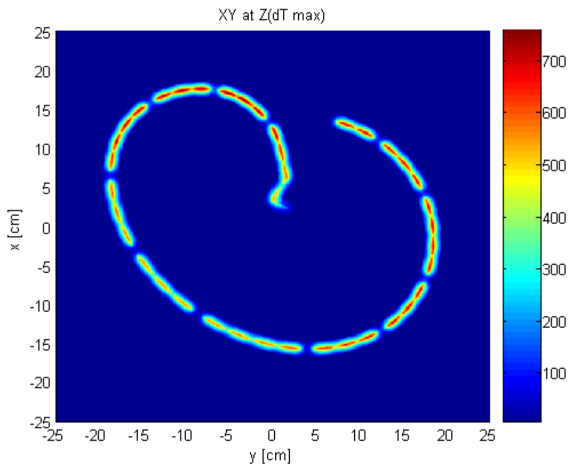
- 7.7m long, 700 mm ∅ graphite core
- Graded density of 1.1 g/cm^3 and 1.7 g/cm^3
- 12 mm wall, stainless-steel welded pressure vessel, filled with 1.2 bar of N_2
- Surrounded by ~1000 tonnes of concrete/steel radiation shielding blocks



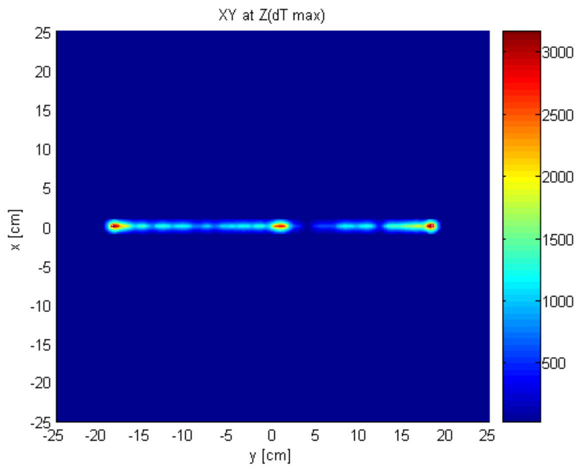


Beam dump core with dilution failures

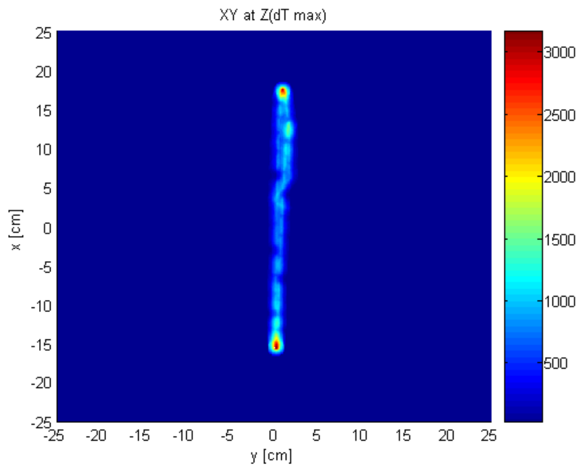
Nominal



0/6 vertical diluters



0/4 horizontal diluters



Nominal beam intensity (3.2×10^{14} p+)

Maximum energy density in dump block

		number active MKBV						
	kJ/g	6	5	4	3	2	1	0
number active MKBH	4	**1.09**	1.17	1.28	1.65	2.44	4.25	7.96
	3	1.33	1.38	1.45	1.67	2.43	4.32	**8.98**
	2	1.74	1.75	1.85	2.01	2.50	4.50	**11.30**
	1	2.74	2.89	2.87	2.99	3.36	4.74	**16.03**
	0	6.67	7.56	**8.41**	**9.90**	**12.70**	**17.44**	**53.29**

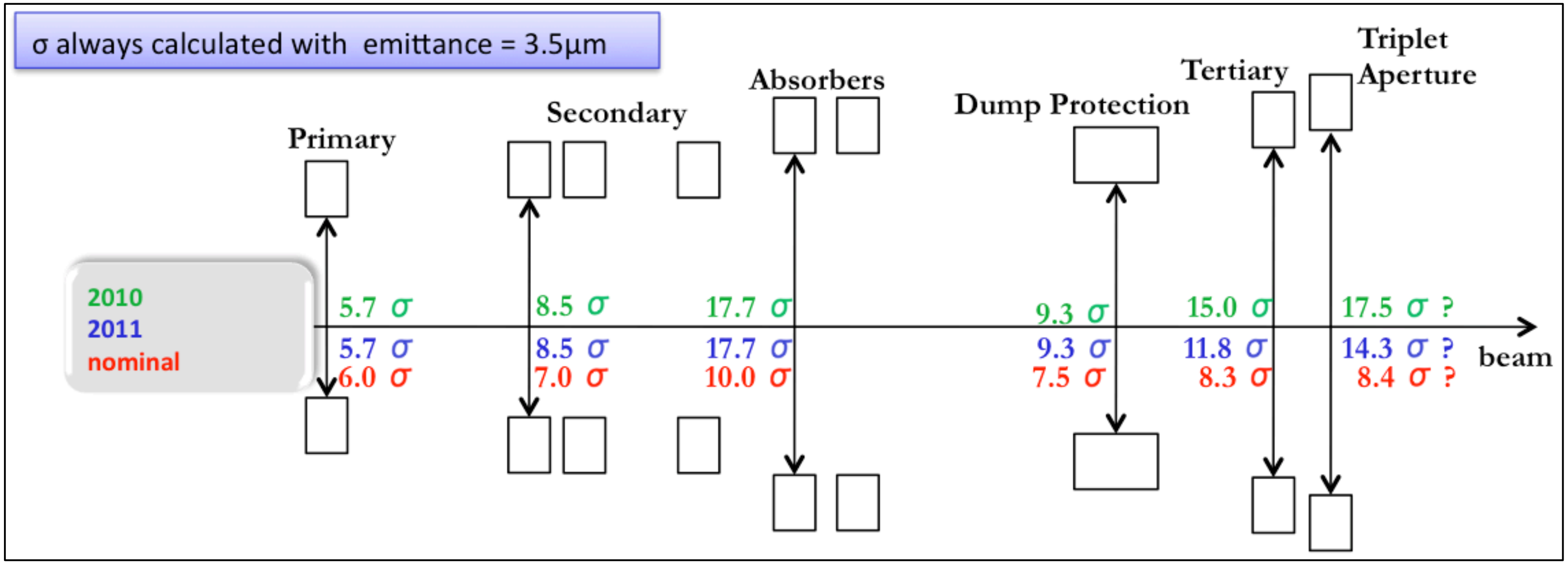
Maximum temperature rise in dump block

		number active MKBV						
	K	6	5	4	3	2	1	0
number active MKBH	4	**761**	804	867	1060	1455	2308	**3727**
	3	894	919	954	1069	1451	2340	**3727**
	2	1105	1110	1164	1244	1482	2425	**3727**
	1	1603	1670	1661	1720	1895	2534	**3727**
	0	3397	**3727**	**3727**	**3727**	**3727**	**3727**	**Vapour**

31 kJ/g for onset of sublimation, 60 kJ/g for complete vaporization

Collimation

Collimator settings 2012



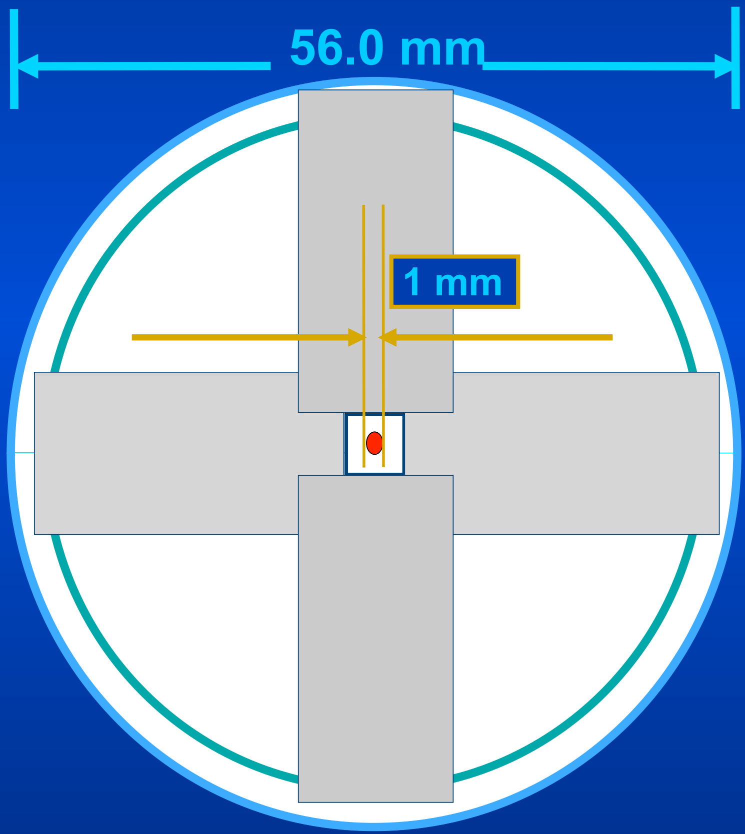
Collimation hierarchy has to be respected in order to achieve satisfactory protection and cleaning

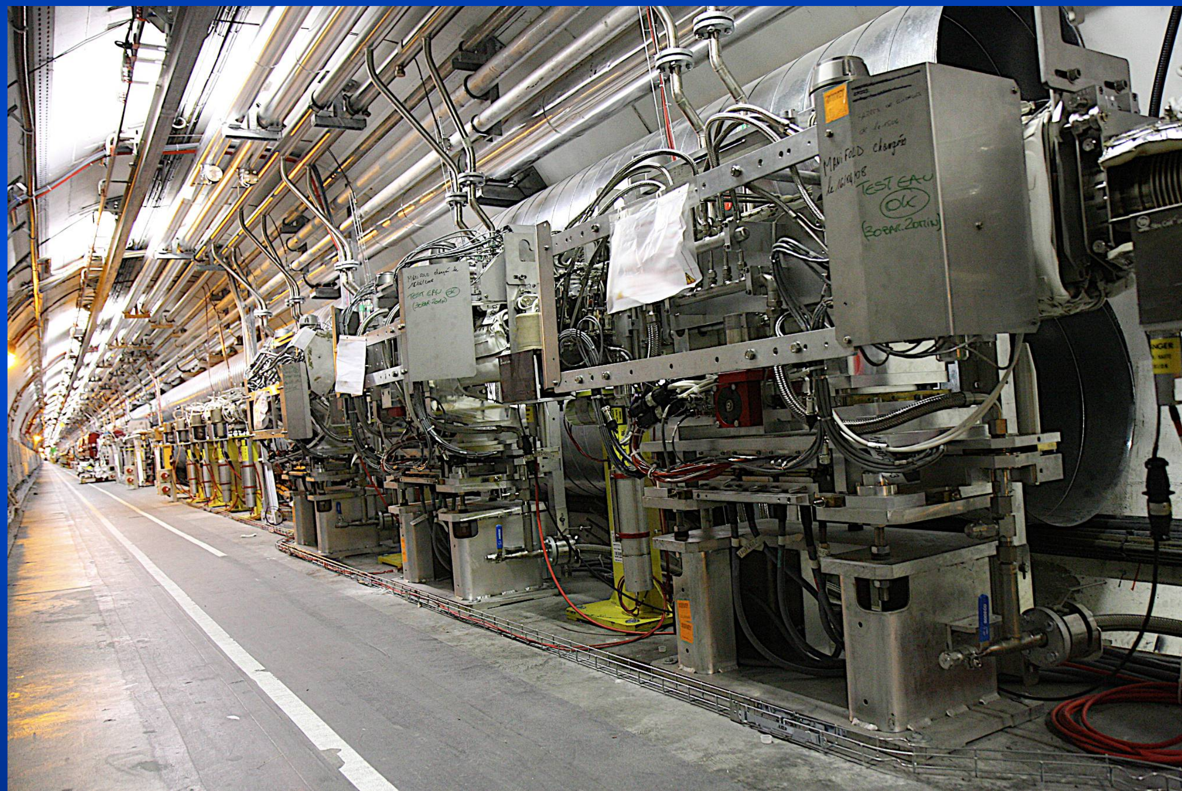
2012: tight settings

	σ
TCP 7	4.3
TCSG 7	6.3
TCLA 7	8.3
TCSG 6	7.1
TCDQ 6	7.6
TCT	9.0
Aperture	10.5

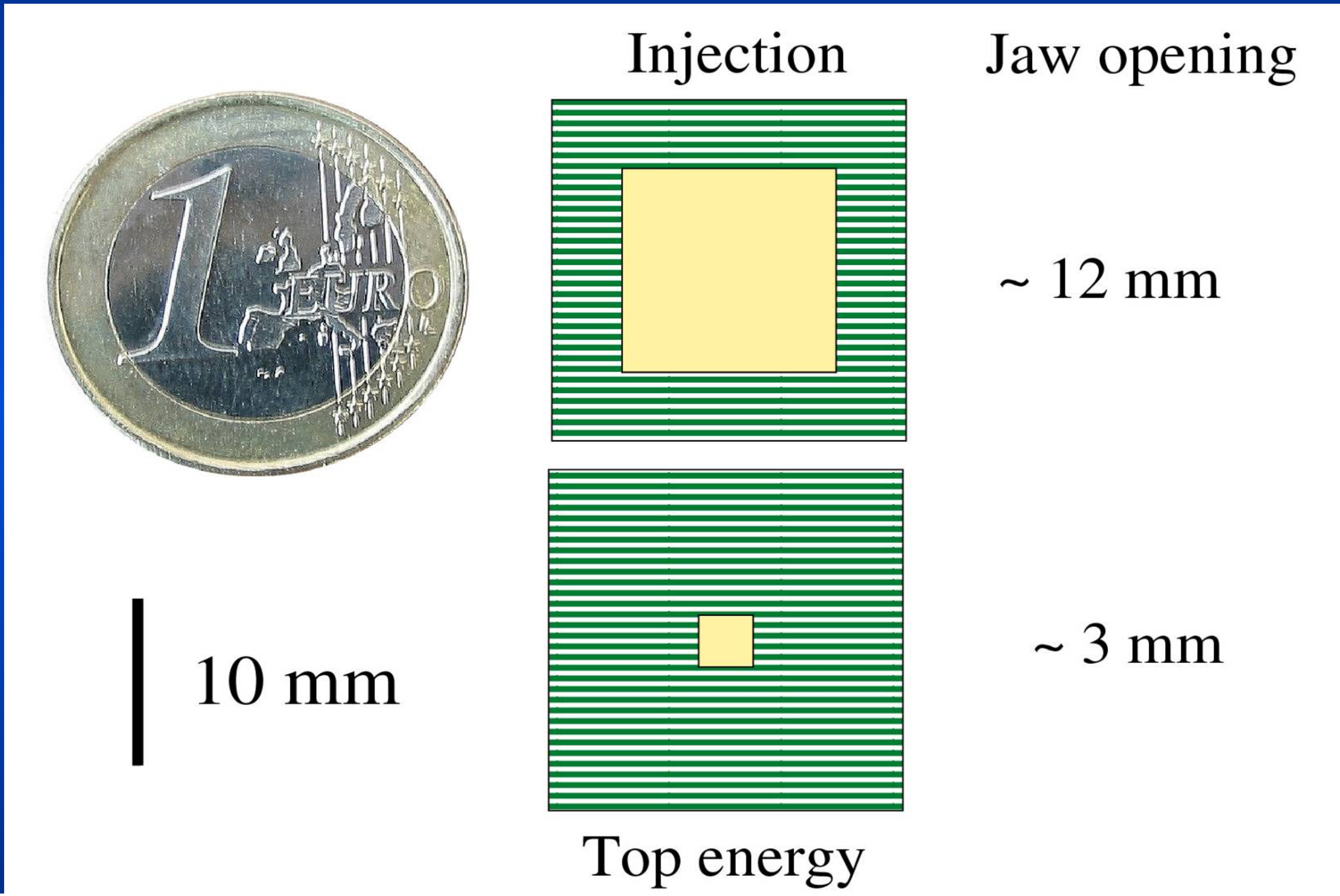
Collimators (points 3 and 7)

- **Intercept particles that have strayed outside acceptable limits**





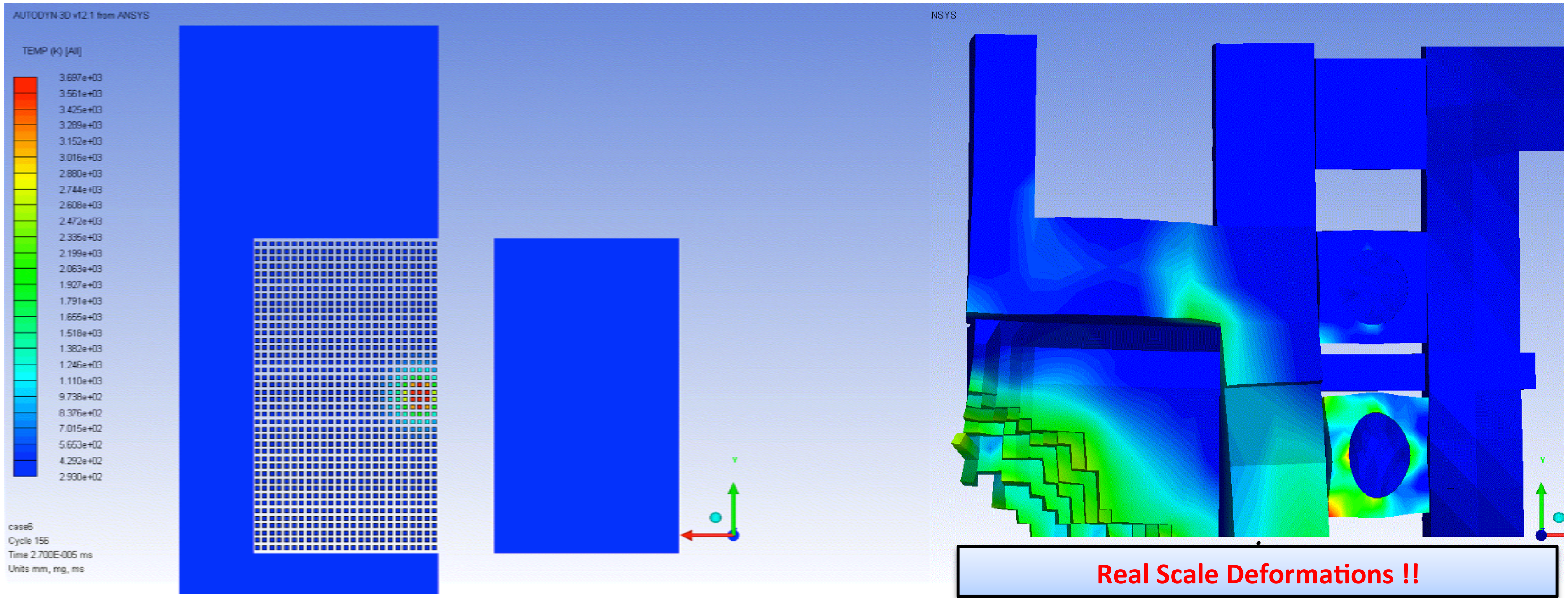
Collimating with small gaps



LHC beam will be physically quite close to collimator material and collimators are long (up to 1.2 m)!

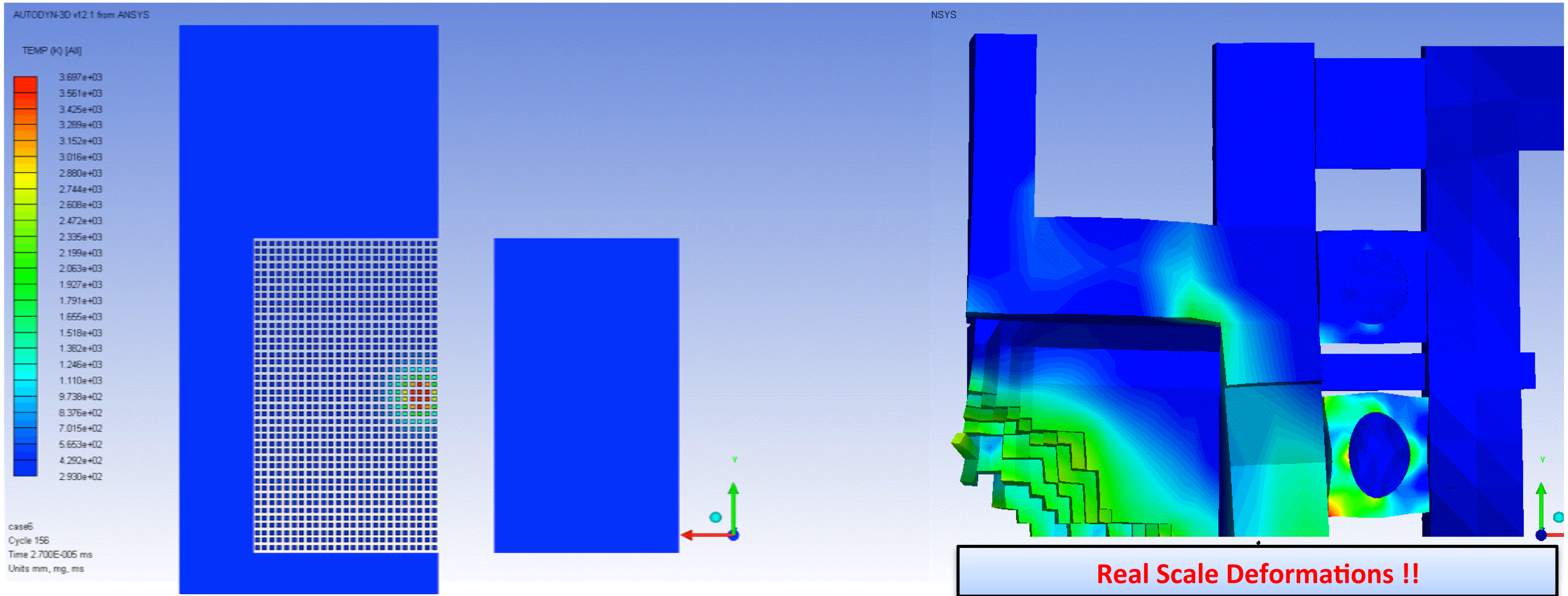
Accident Simulations for TCT

- **Case 7** (**8 bunches at 5 TeV**) is the only studied case falling in Damage Level 3.
- High probability of **water leakage** due to very severe plastic deformations on pipes.
- Impressive **jaw damage** :
  - Extended eroded and deformed zone.
  - **Projections of hot and fast solid tungsten bullets (T≈2000K, V_{max} ≈ 1 km/s) towards opposite jaw.** Slower particles hit tank covers (at velocities just below ballistic limit).
  - Risk of "bonding" the two jaws due to the projected resolidified material.



Accident Simulations for TCT

- **Case 7** (**8 bunches at 5 TeV**) is the only studied case falling in Damage Level 3.
- High probability of **water leakage** due to very severe plastic deformations on pipes.
- Impressive **jaw damage** :
  - Extended eroded and deformed zone.
  - **Projections of hot and fast solid tungsten bullets ($T \approx 2000K$, $V_{max} \approx 1$ km/s) towards opposite jaw.** Slower particles hit tank covers (at velocities just below ballistic limit).
  - Risk of “bonding” the two jaws due to the projected resolidified material.



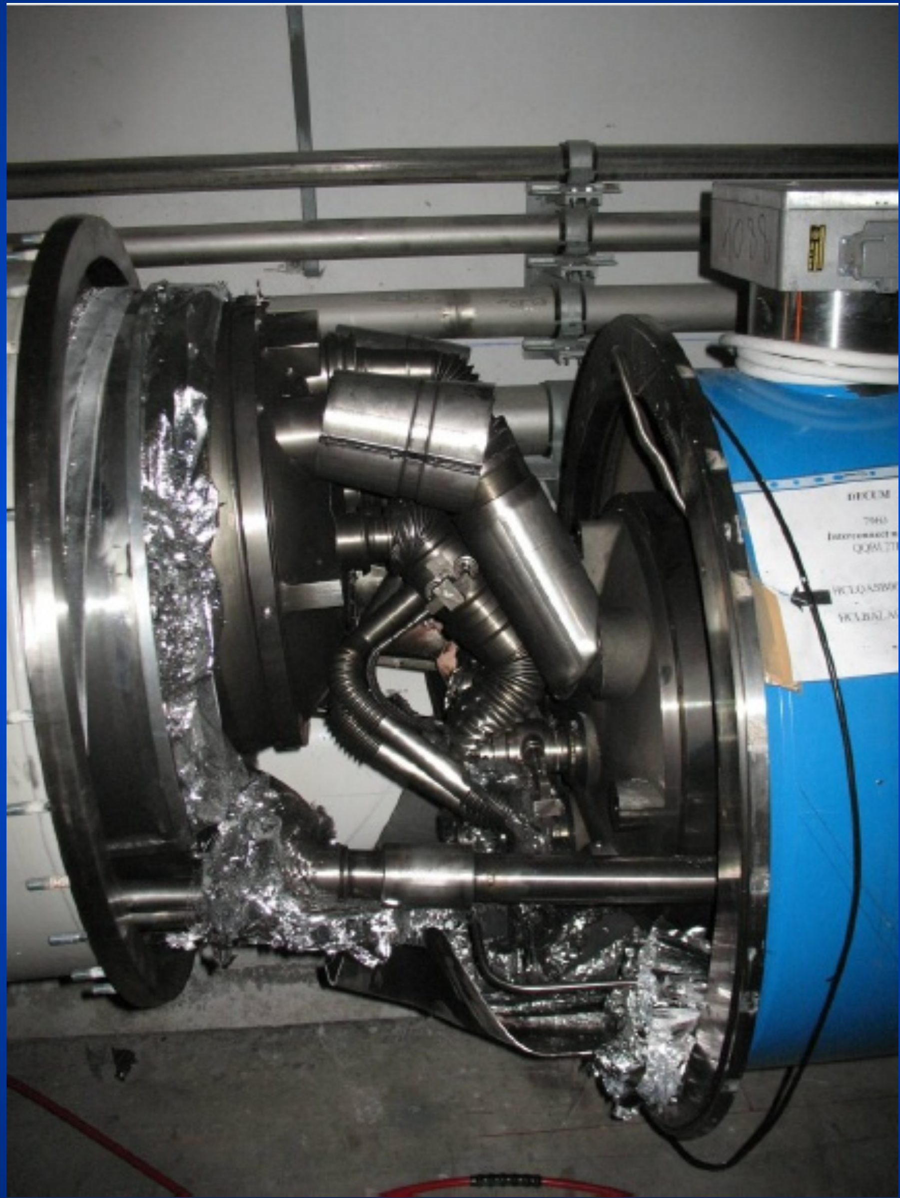
September 10, 2008; It worked!

And 9 days later

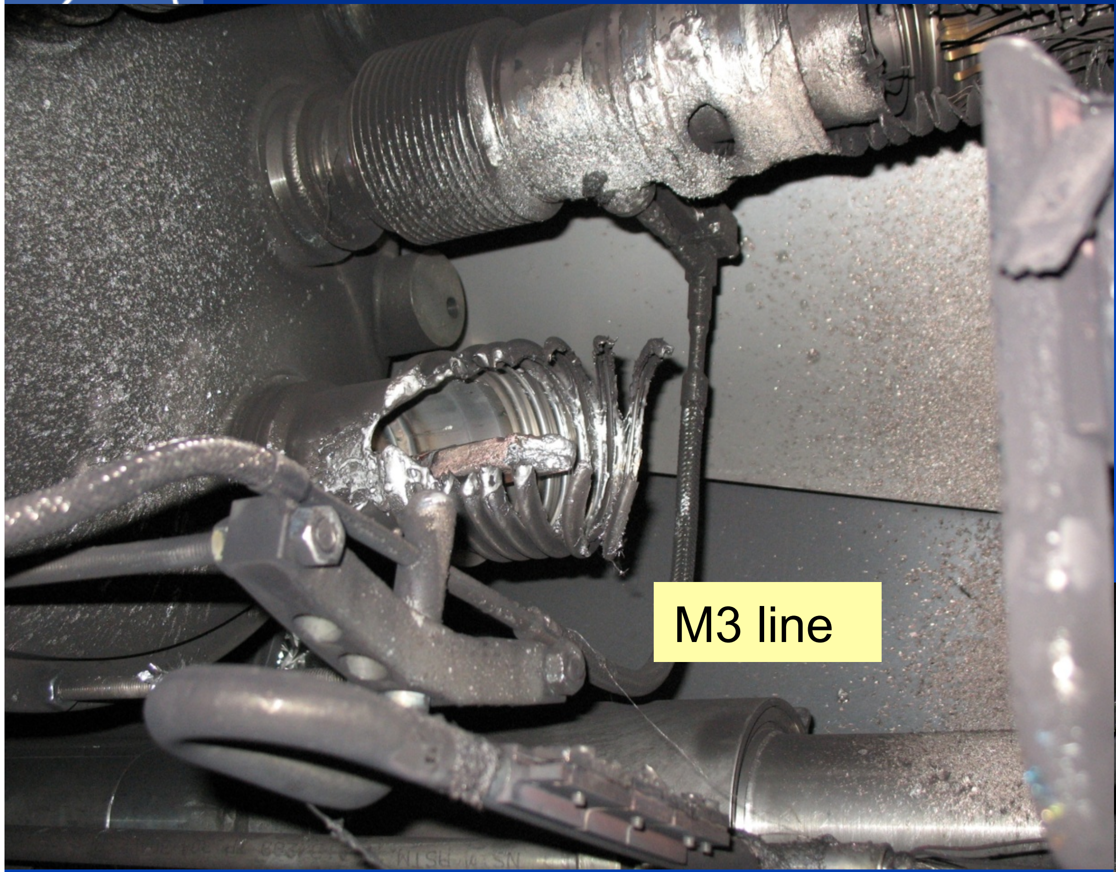
- Making the last step of dipole circuit in sector 34, to 9.3kA
- At 8.7kA, development of resistive zone in the dipole bus bar splice between Q24 R3 and the neighbouring dipole
- Electrical arc developed which punctured the helium enclosure

One inter-magnet connector (out of 100,000) was badly soldered and…
The magnet protection system did not protect

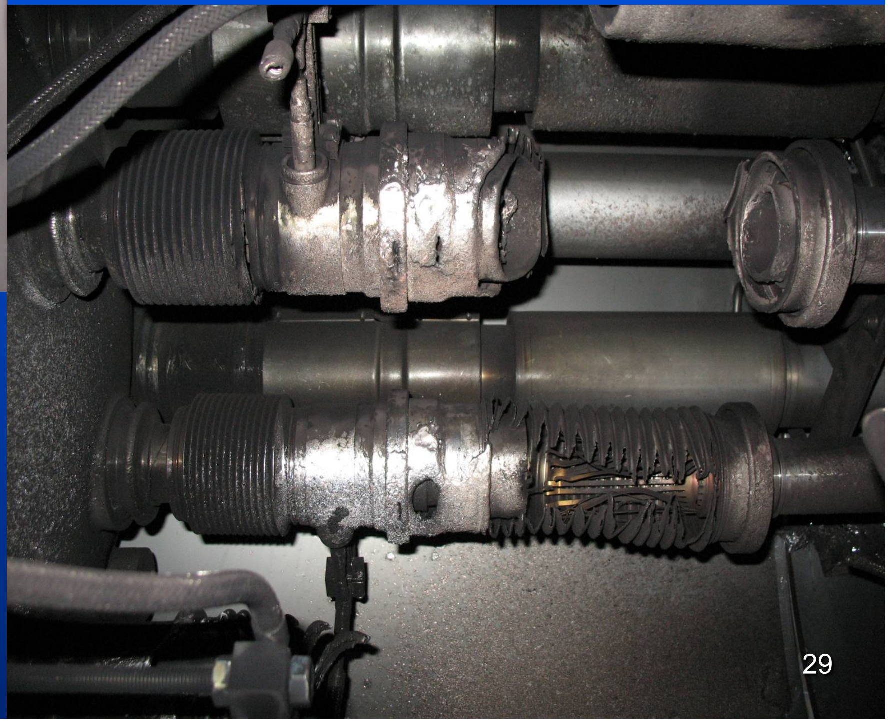
Consequences



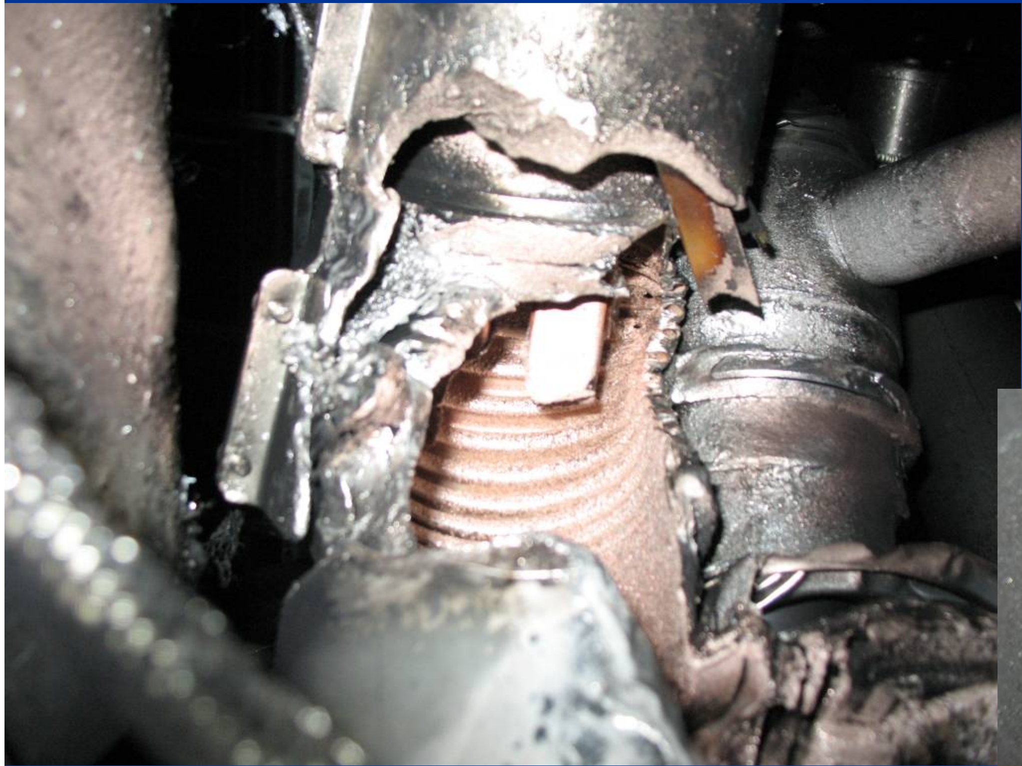
Electrical arc between C24 and Q24



V lines



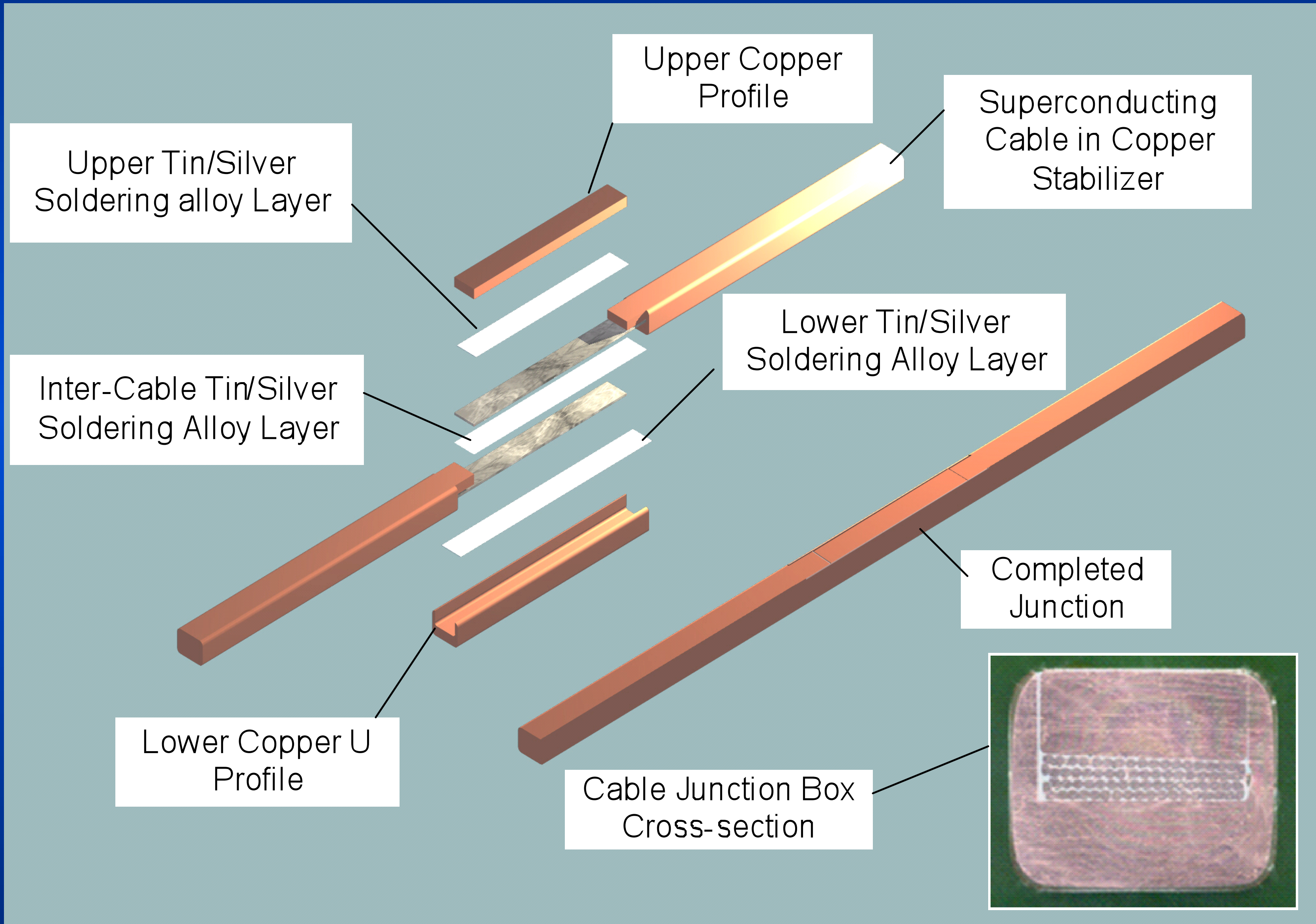
Collateral damage: secondary arcs



QQBI.27R3 M3 line

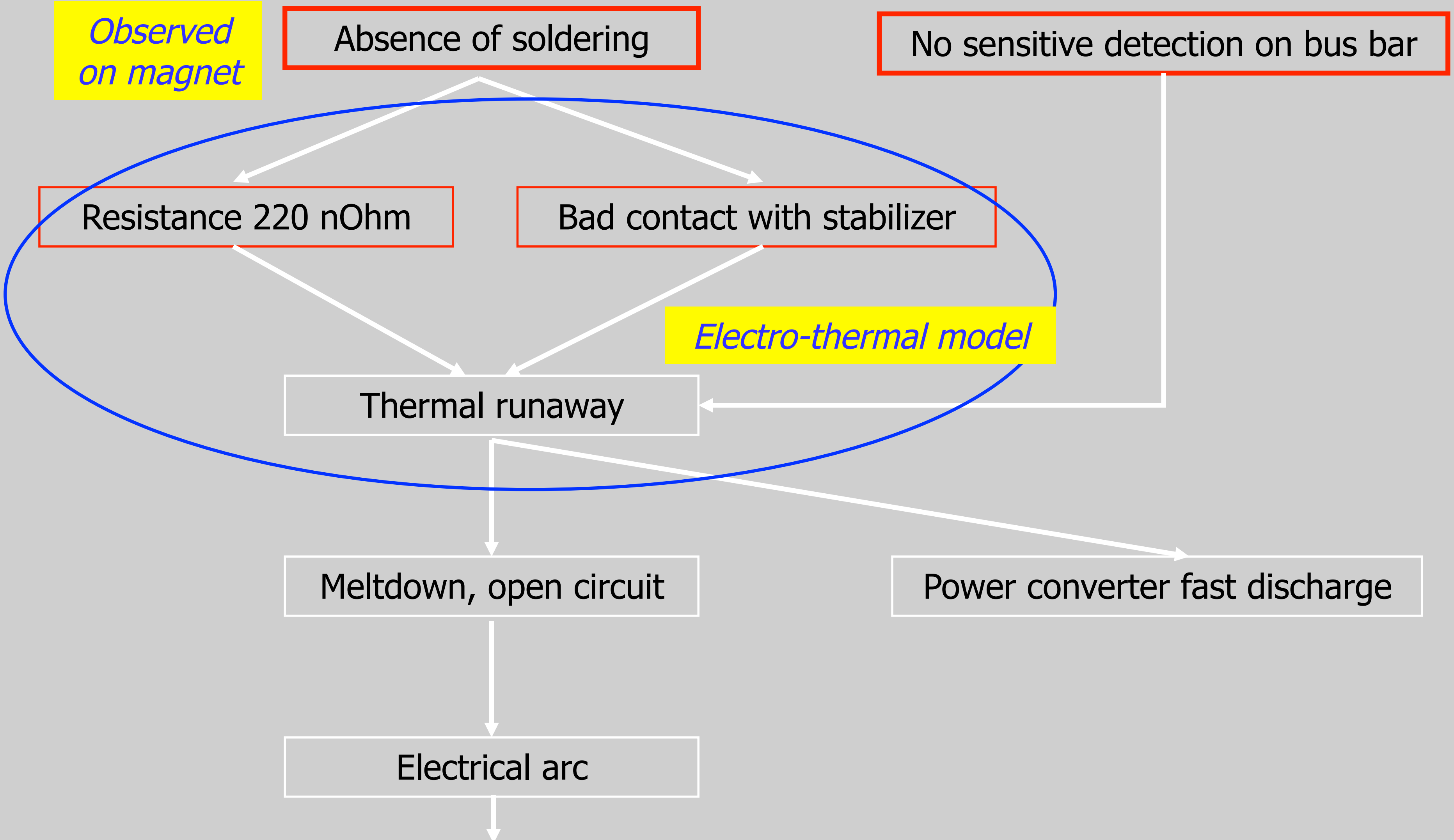
QBBI.B31R3 M3 line

Bus bar splice

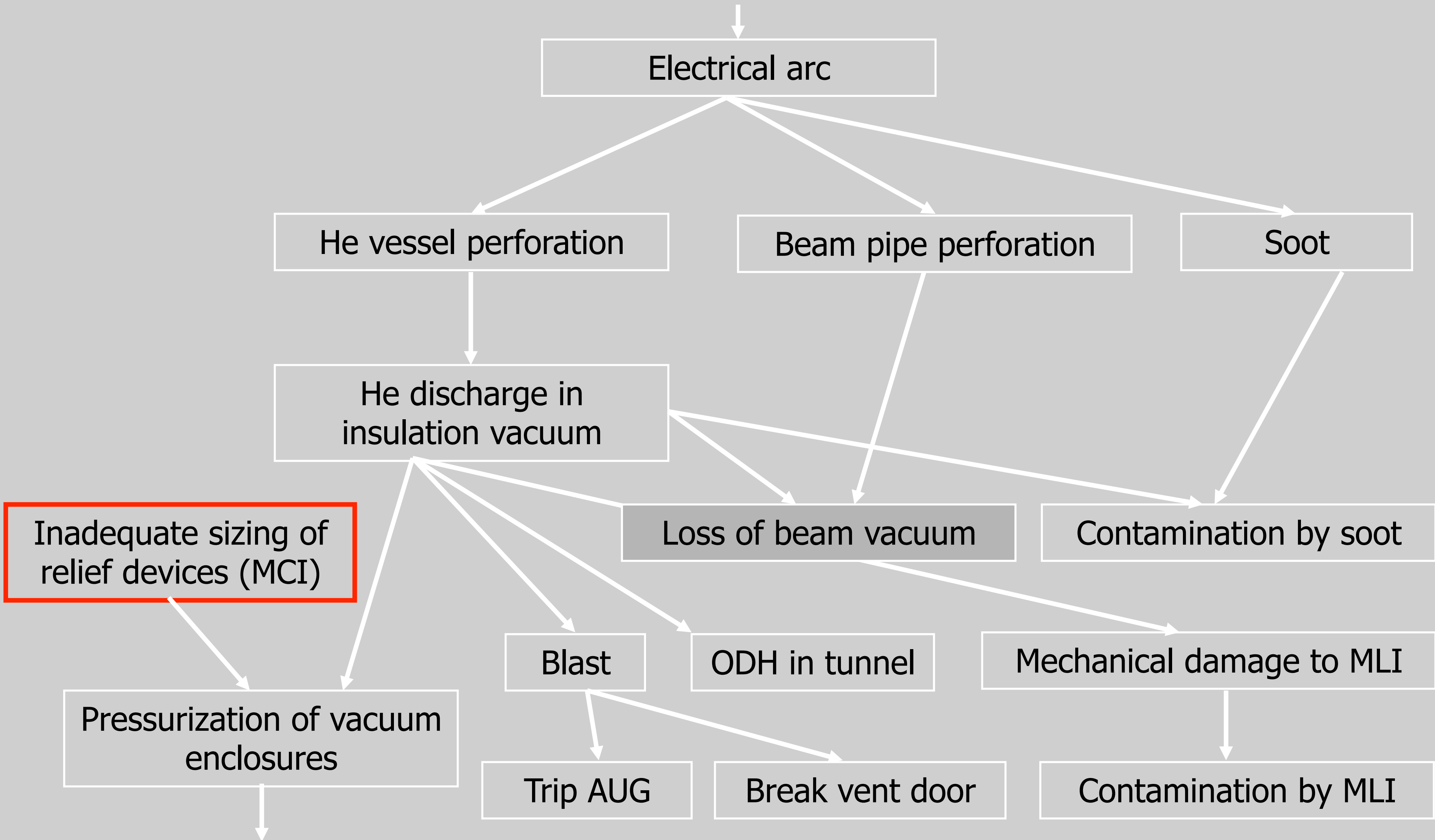


What went wrong?

Fault tree [1/3]



Fault tree [2/3]



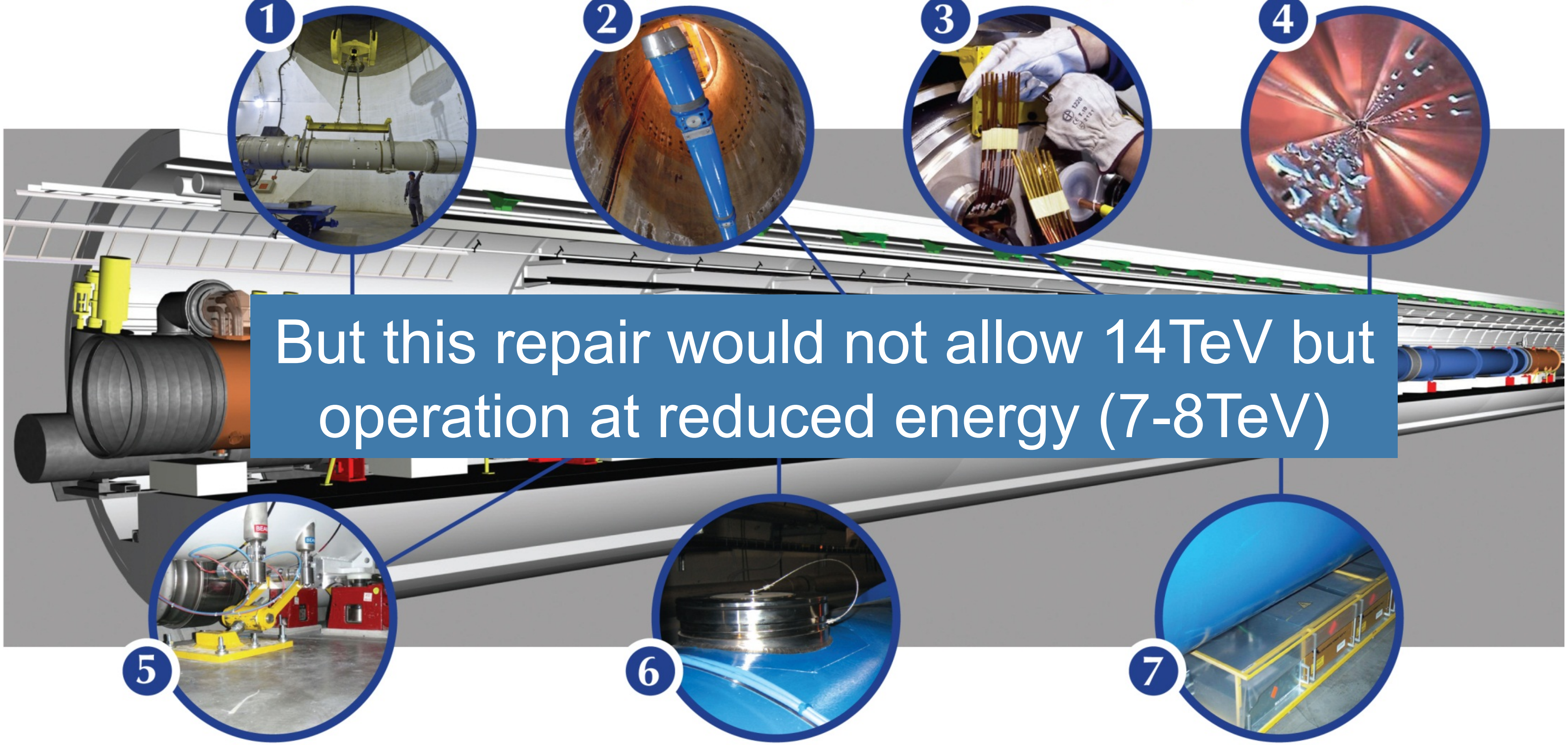
The LHC repairs in detail

14 quadrupole magnets replaced

39 dipole magnets replaced

54 electrical interconnections fully repaired. 150 more needing only partial repairs

Over 4 km of vacuum beam tube cleaned



But this repair would not allow 14TeV but operation at reduced energy (7-8TeV)

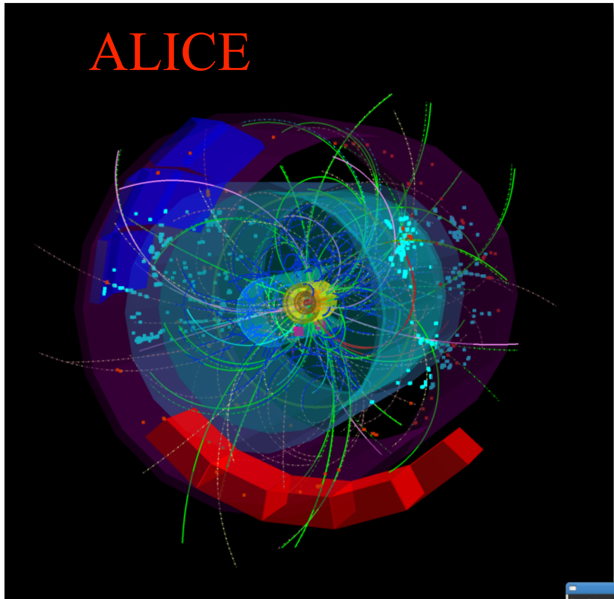
A new longitudinal restraining system is being fitted to 50 quadrupole magnets

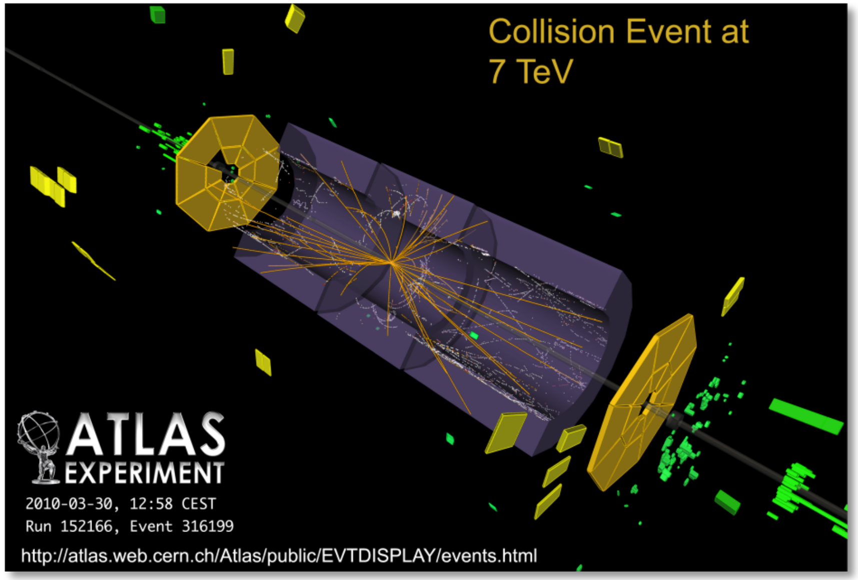
Nearly 900 new helium pressure release ports are being installed around the machine

6500 new detectors are being added to the magnet protection system, requiring 250 km of cables to be laid

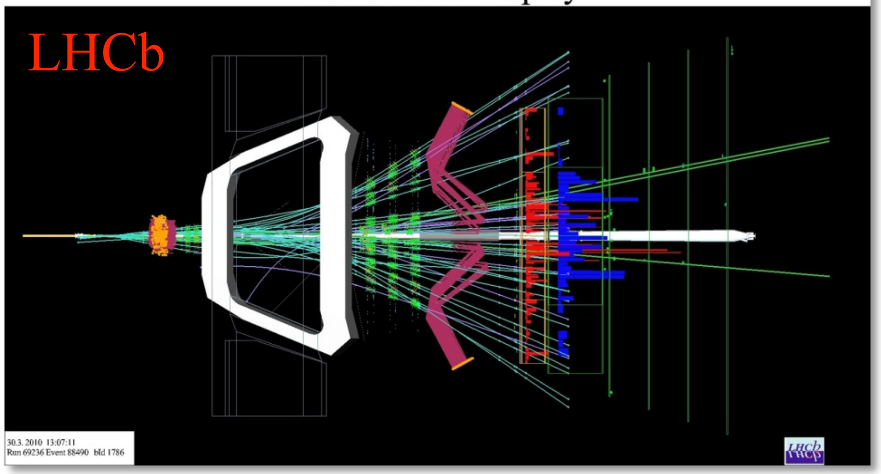
+ 8 cryogenics!

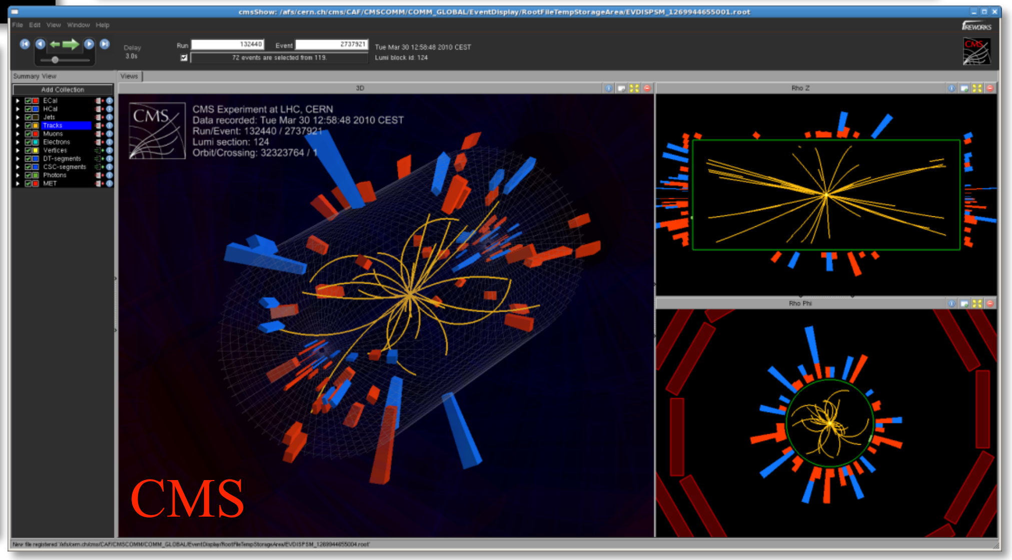
LHC: First collisions at 7 TeV on 30 March 2010





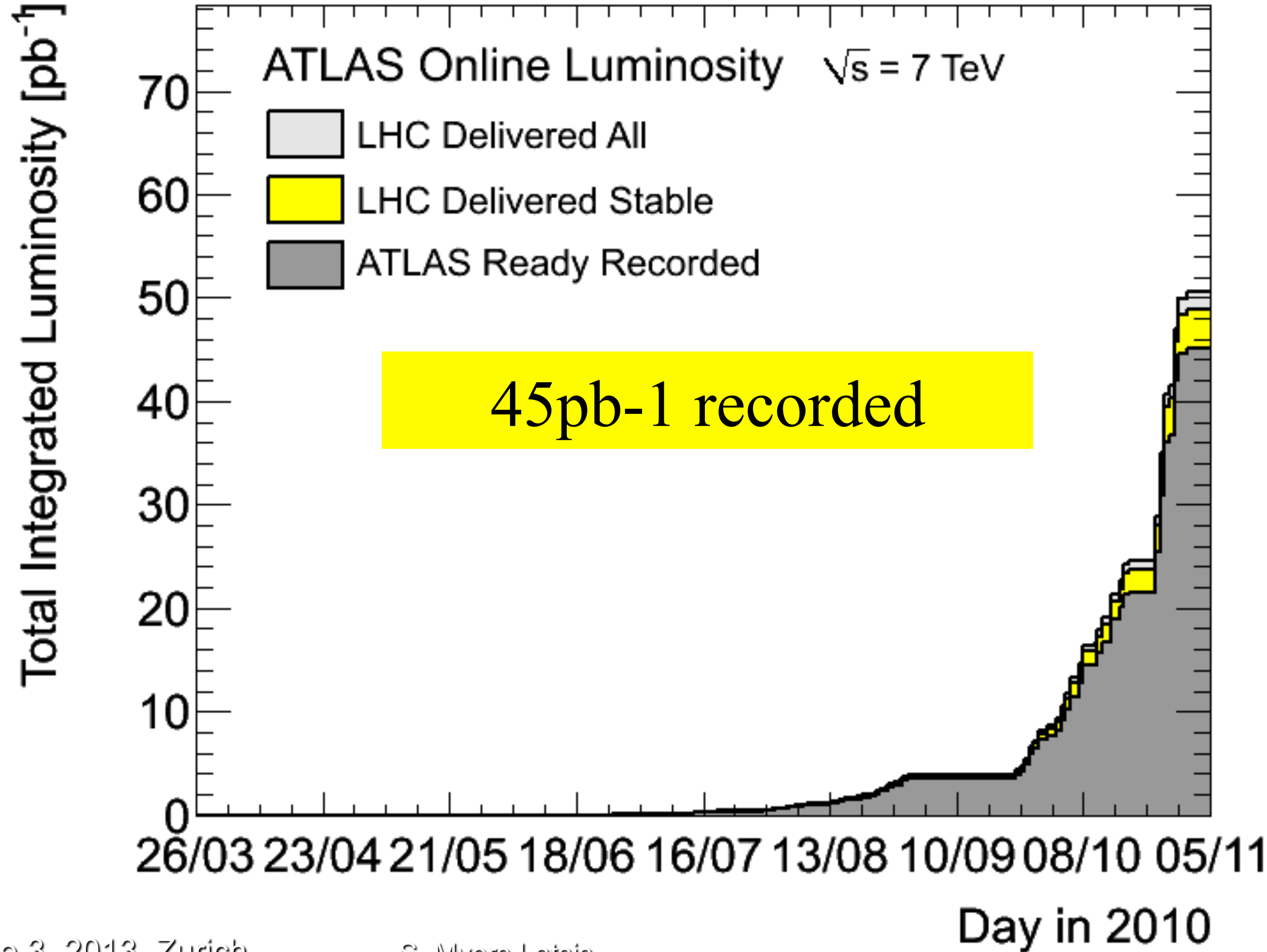
LHCb Event Display





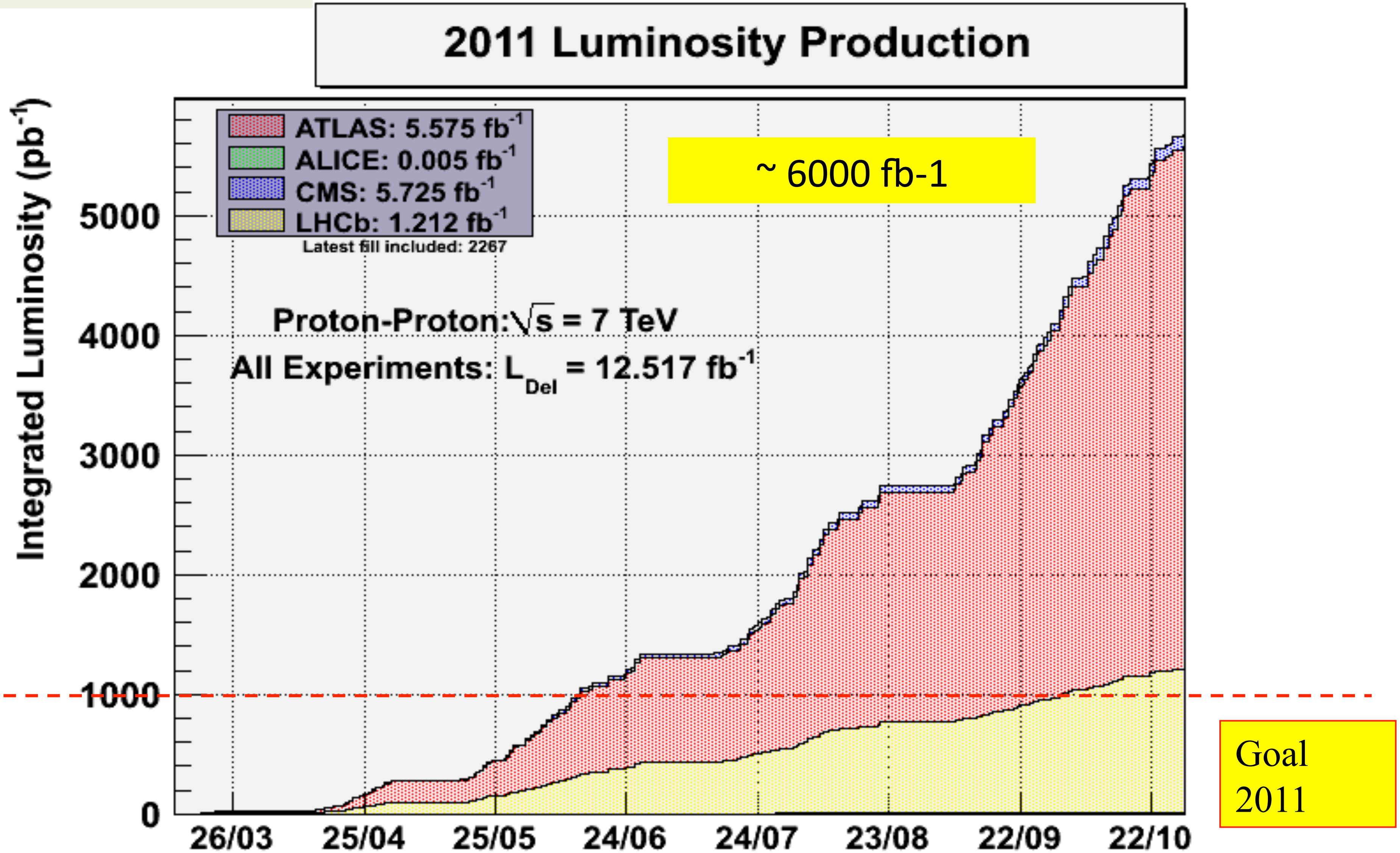
Performance in 2010

Integrated Luminosity in 2010



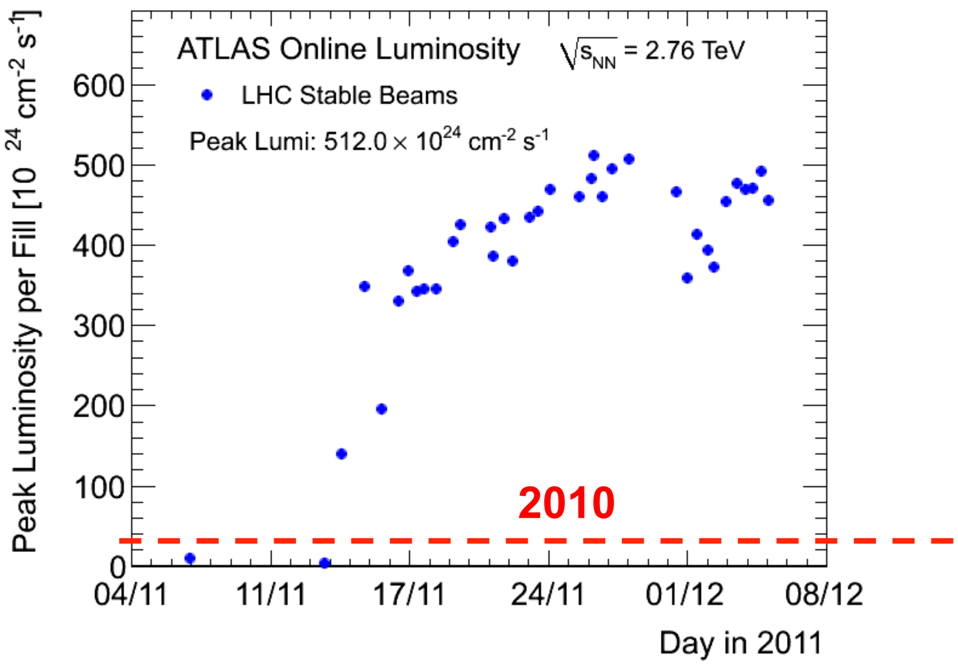
Performance in 2011

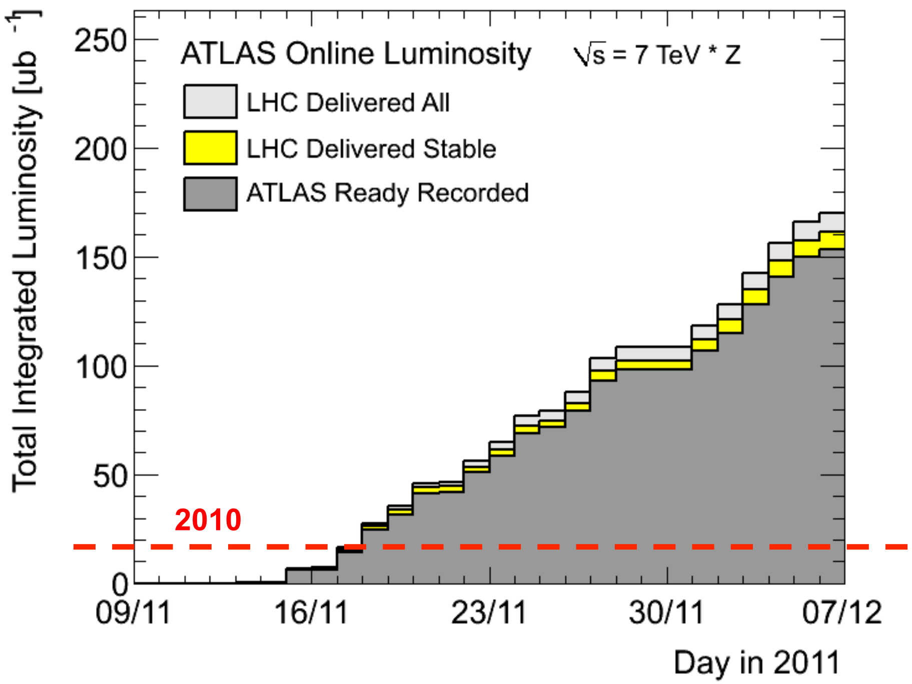
Protons


2011 Luminosity Production
ATLAS: 5.575 fb-1
ALICE: 0.005 fb-1
CMS: 5.725 fb-1
LHCb: 1.212 fb-1
Latest fill included: 2267
~ 6000 fb-1
Proton-Proton: √s = 7 TeV
All Experiments: L_Del = 12.517 fb-1
Integrated Luminosity (pb-1)
0
1000
2000
3000
4000
5000
26/03
25/04
25/05
24/06
24/07
23/08
22/09
22/10
Goal 2011

Ions

Peak and Integrated luminosity



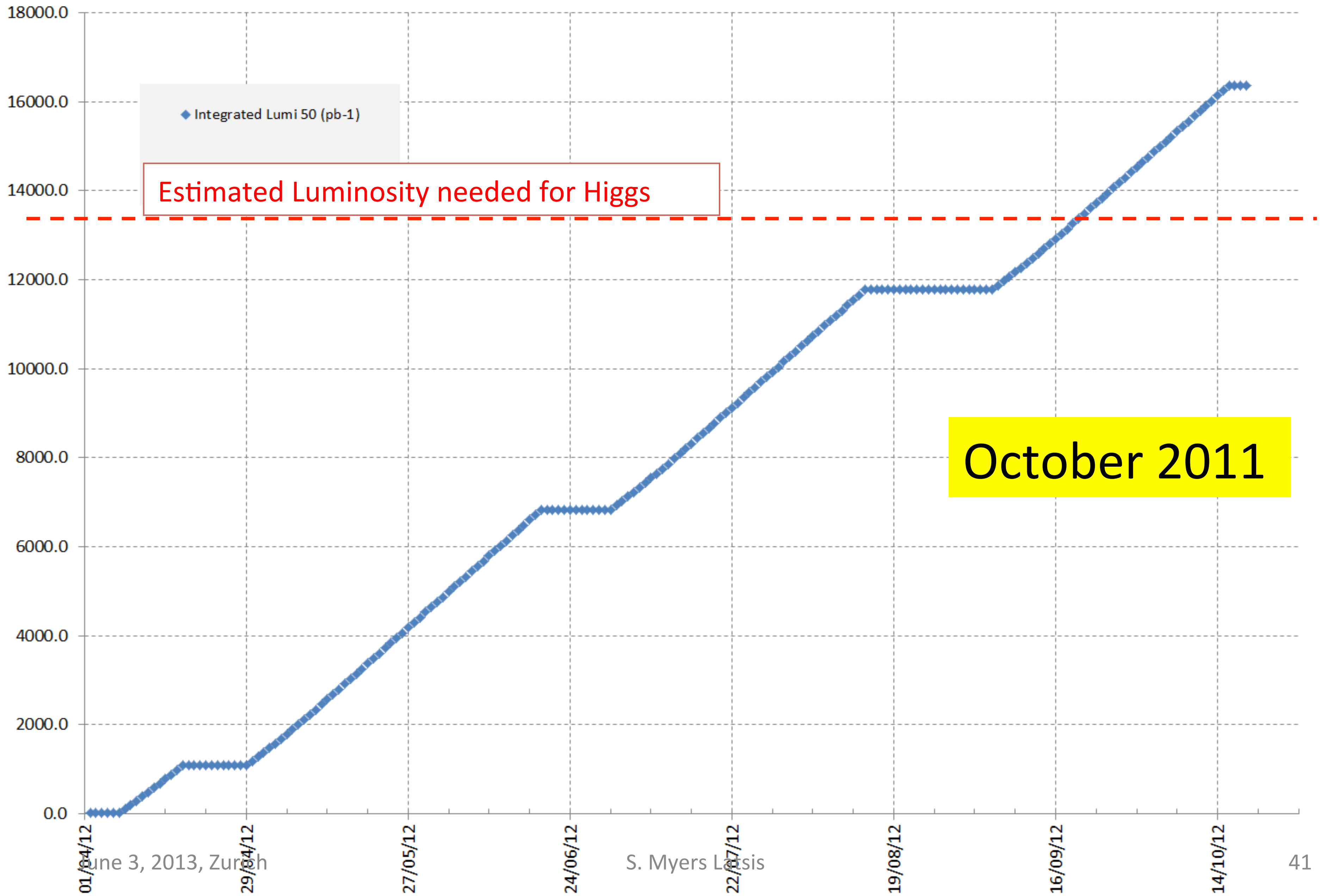


356 bunches

<u>In 2010:</u>

Peak ~18E24; Integrated ~18ub-1
Max 137 bunches, larger β*, smaller bunch intensities

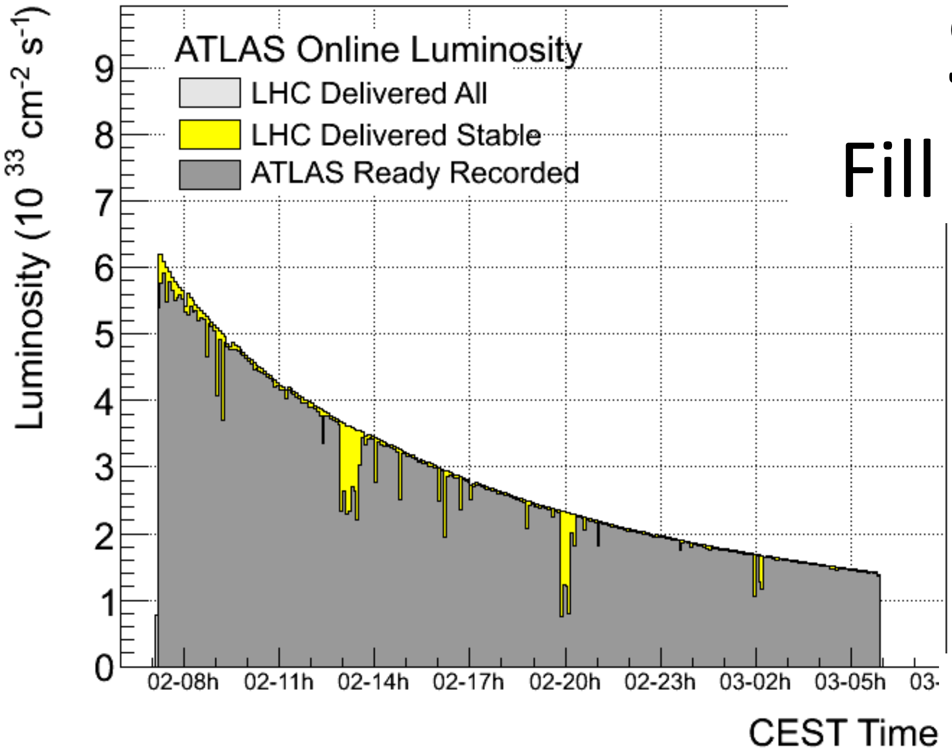
2012 Measured vs Predicted Integrated Luminosity



2012 Priorities

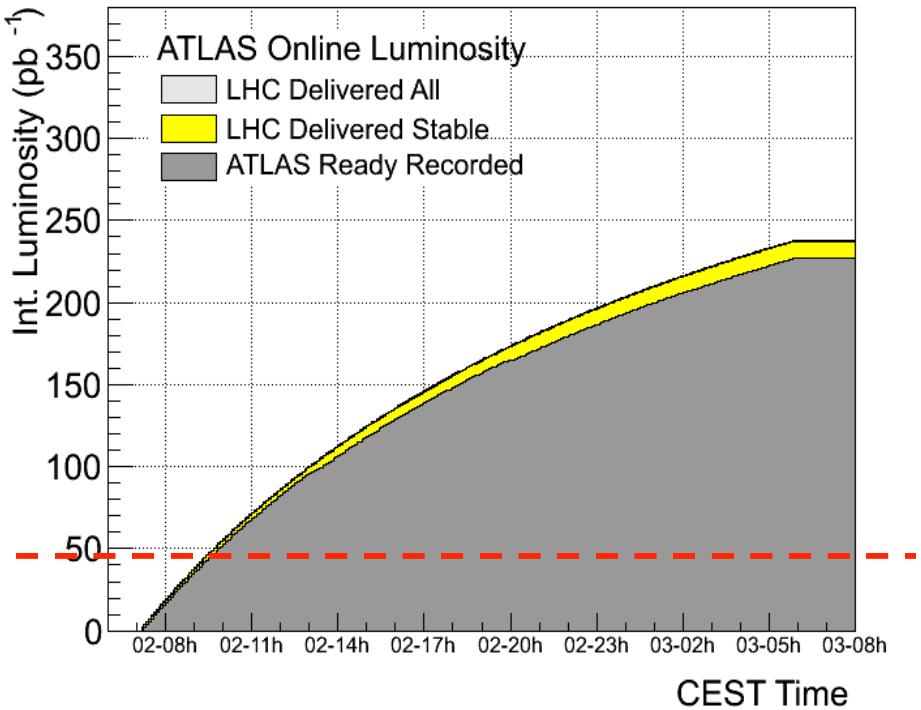
1. The LHC machine must produce enough integrated luminosity to allow ATLAS and CMS to independently discover the Higgs before the start of LS1.
2. We must also prepare for the proton-lead ion run at the end of the year.
3. We must (in 2012) do the necessary machine experiments to allow high energy, useful high luminosity running after LS1.

Performance in 2012



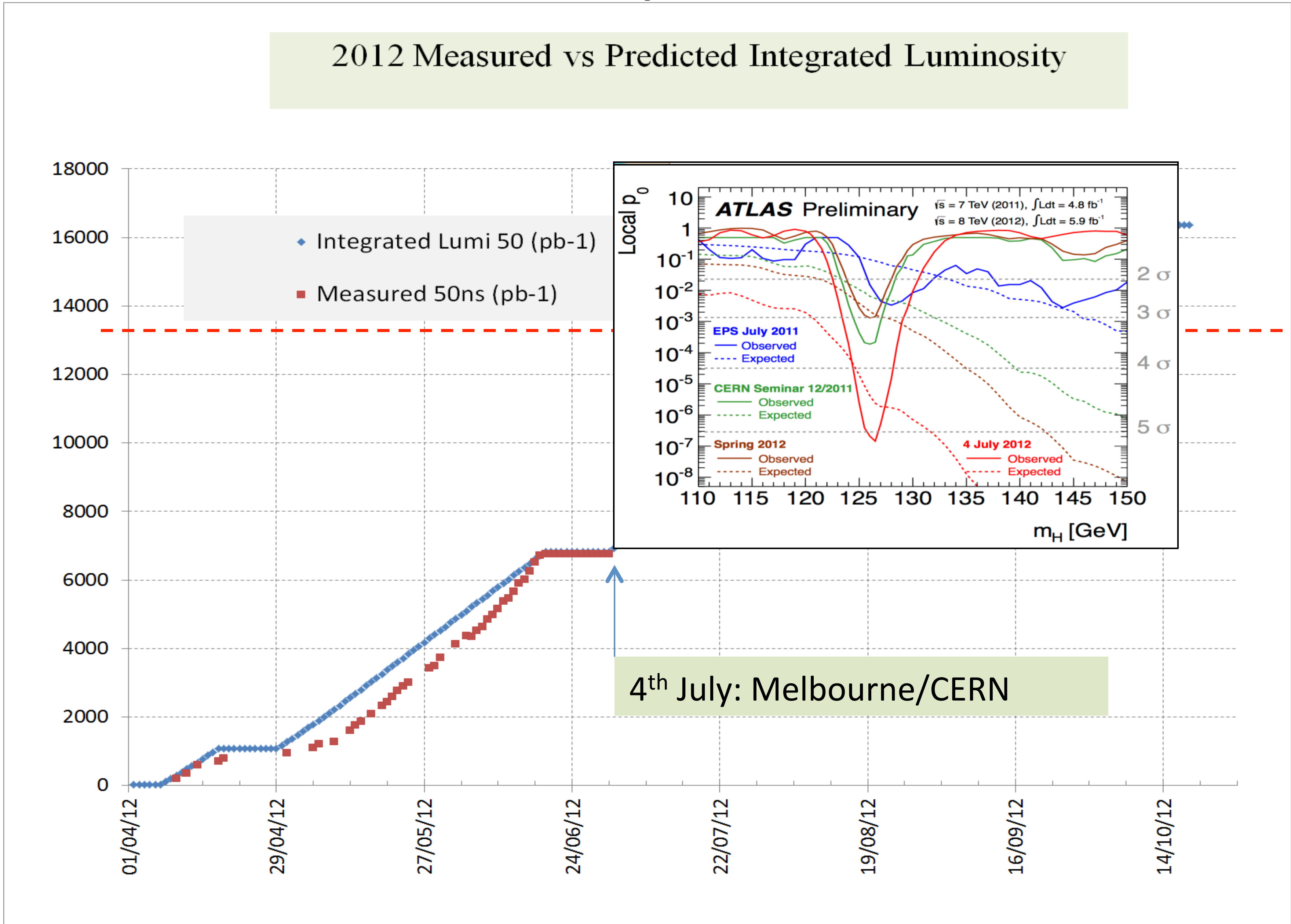
Saturday 2nd June

Fill 2692 (238pb-1 in 23 hours)

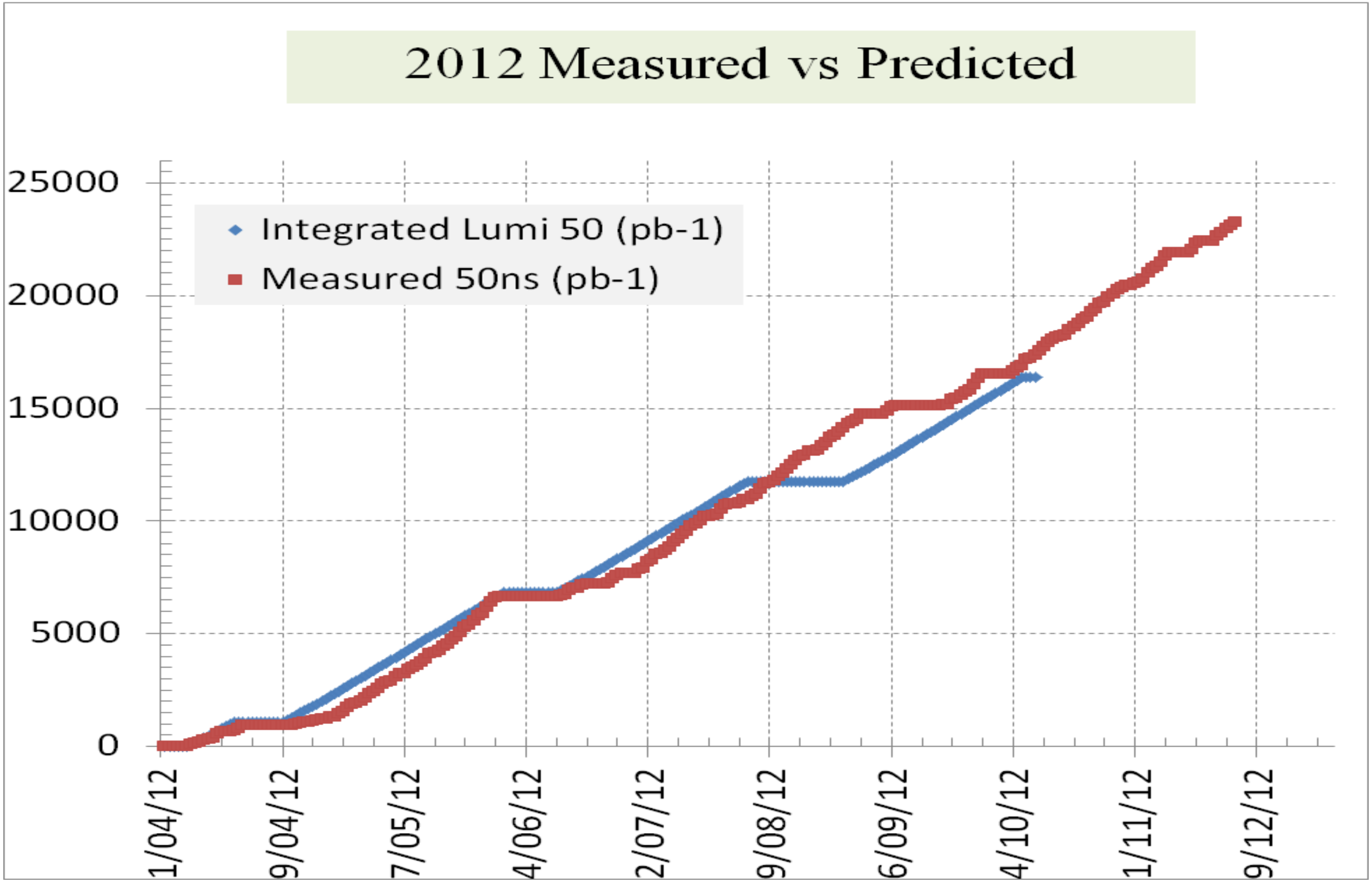


Integral of all of 2010
now in 2.5 hours

Mid 2012: With Respect to estimates

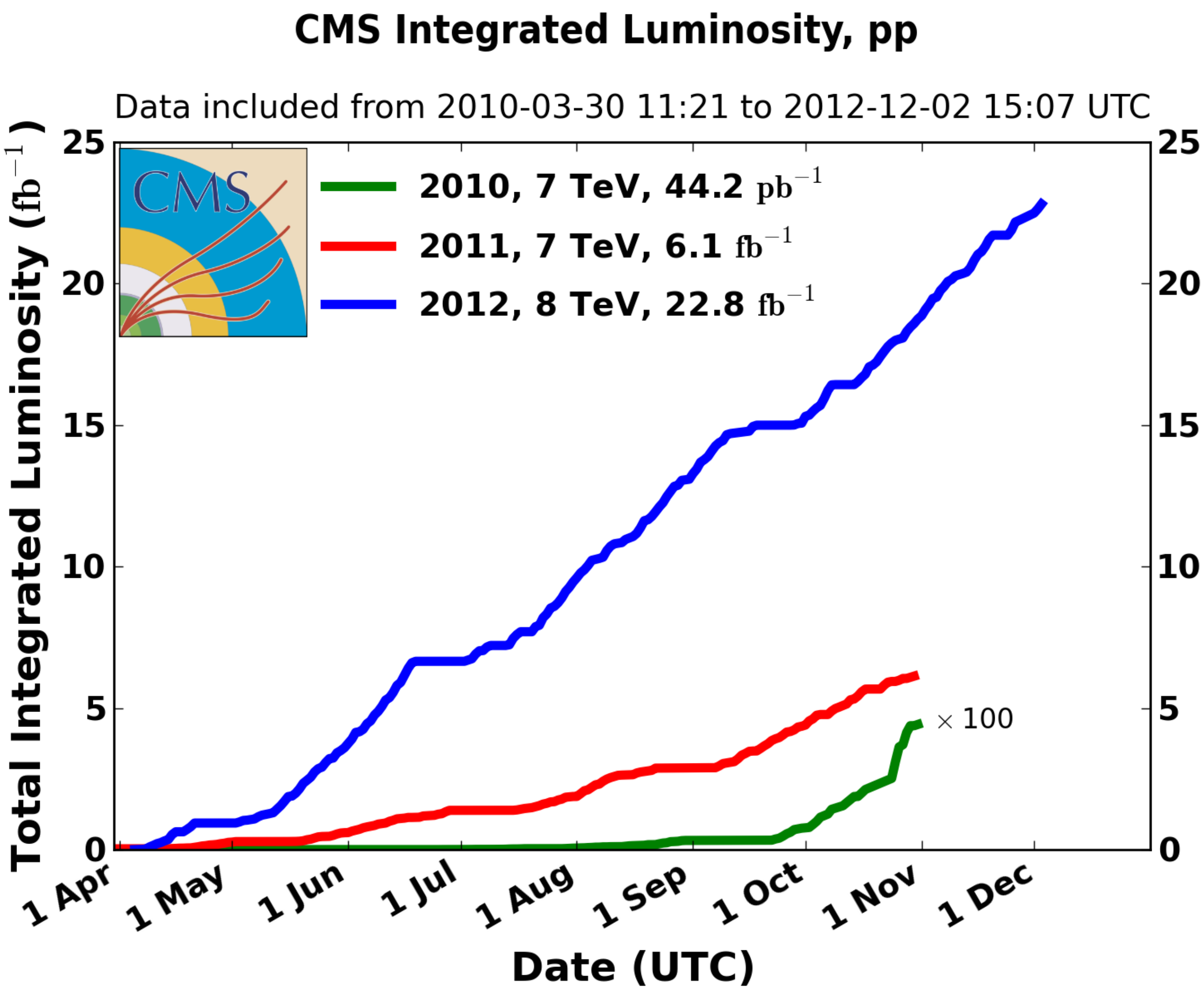


2012



2012 Measured vs Predicted
25000
20000
15000
10000
5000
0
Integrated Lumi 50 (pb-1)
Measured 50ns (pb-1)
1/04/12
9/04/12
7/05/12
4/06/12
2/07/12
9/08/12
6/09/12
4/10/12
1/11/12
9/12/12

Last 3 years


CMS Integrated Luminosity, pp
Data included from 2010-03-30 11:21 to 2012-12-02 15:07 UTC
CMS
2010, 7 TeV, 44.2 pb^{-1}
2011, 7 TeV, 6.1 fb^{-1}
2012, 8 TeV, 22.8 fb^{-1}
$\times$ 100
Total Integrated Luminosity (fb^{-1})
0
5
10
15
20
25
1 Apr
1 May
1 Jun
1 Jul
1 Aug
1 Sep
1 Oct
1 Nov
1 Dec
Date (UTC)

Tests towards the end of 2012

- 25 ns tests
  - Electron cloud and vacuum (scrubbing)
  - Crossing angle, aperture, beam-beam, min β^*
  - UFOs
  - HOM heating
  - Short Physics run with Maximum pile up?
- Comparison 25 vs 50 ns
  - β^* levelling testing (already tested in Machine studies)

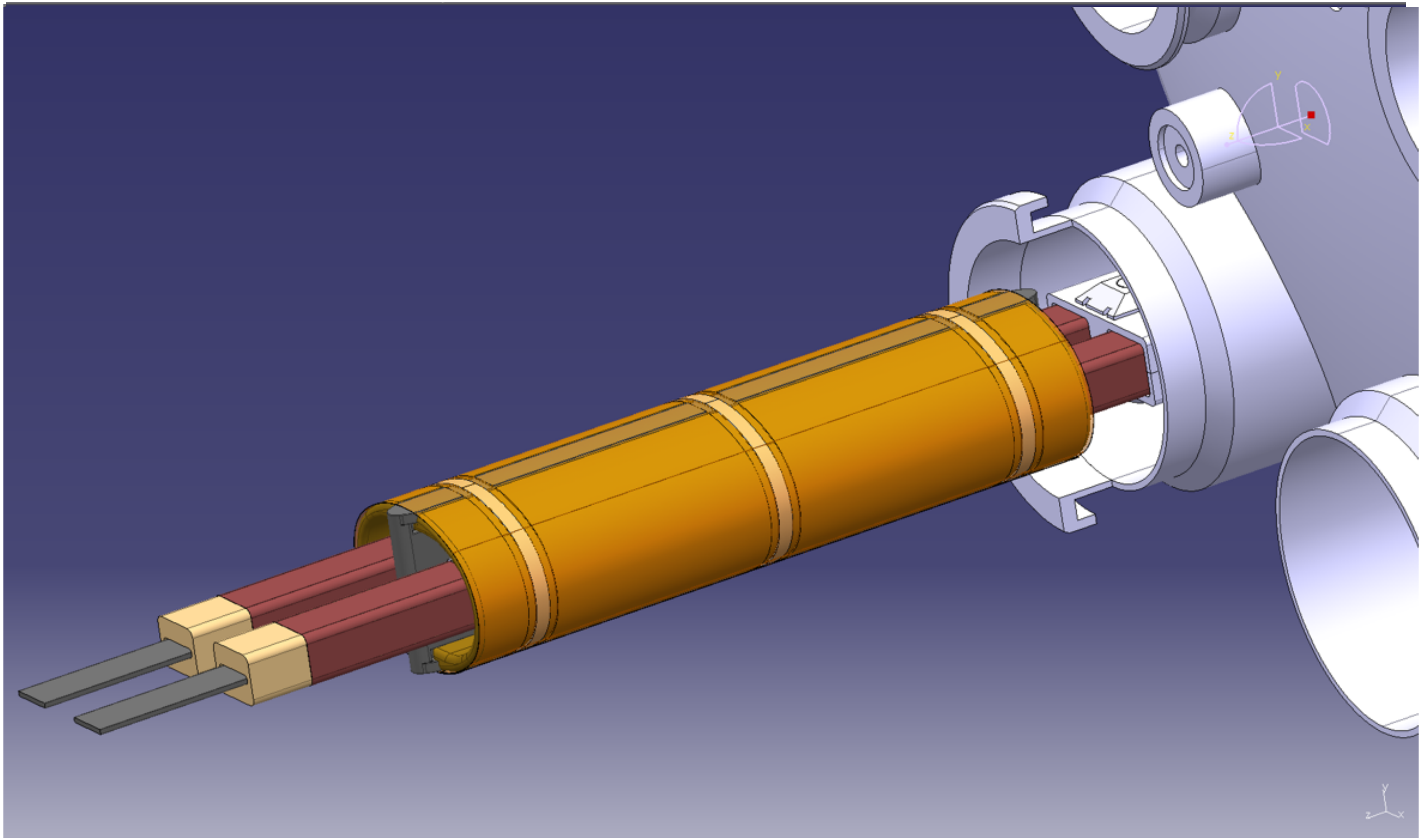
FUTURE

LS1 then operation around 7TeV/beam

LS1 Work

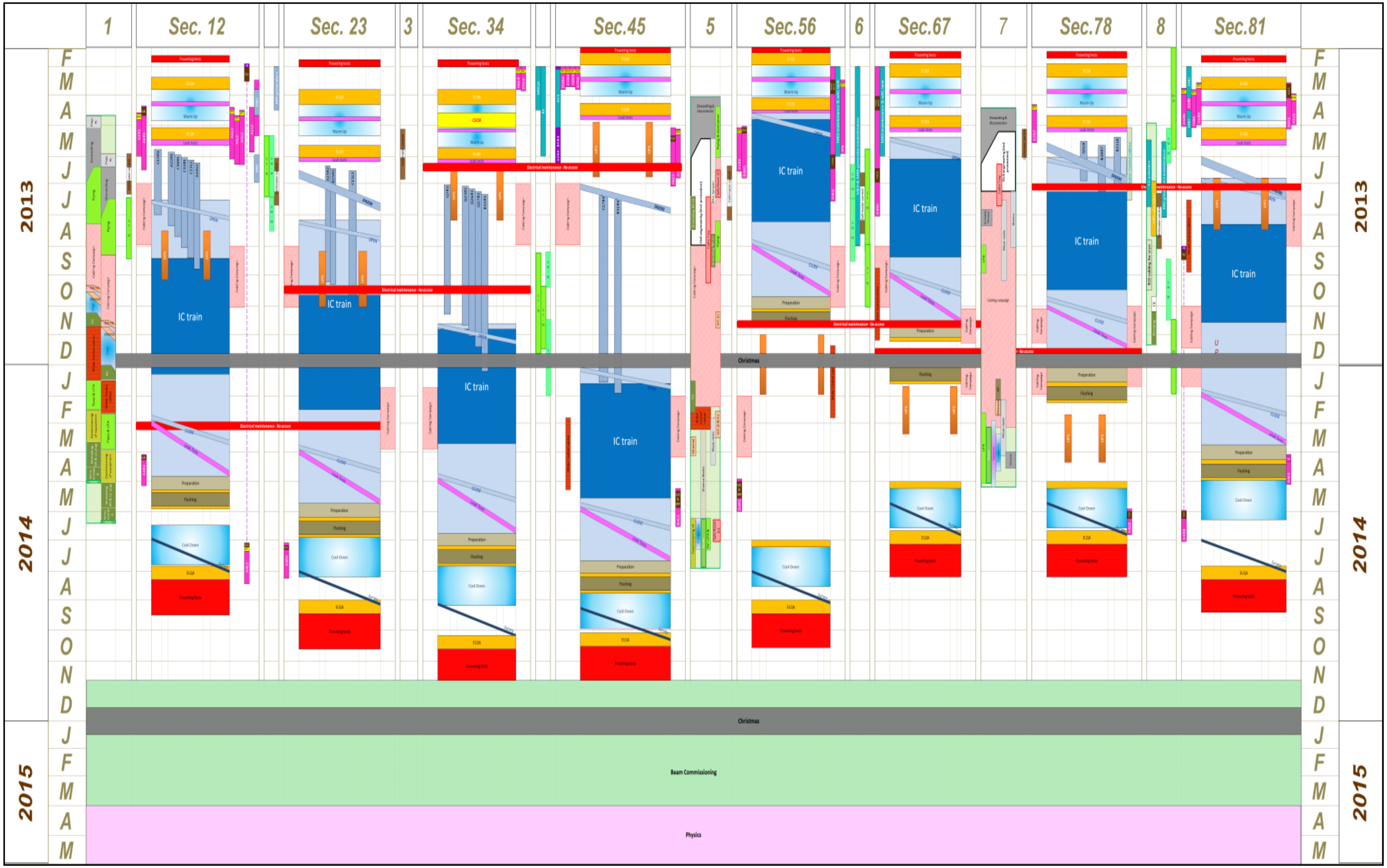
- Repair defectuous interconnects
- Consolidate all interconnects with new design
- Finish off pressure release valves (DN200)
- Bring all necessary equipment up to the level needed for 7TeV/beam

LHC MB circuit splice consolidation proposal



Phase III
Insulation between bus bar and to ground, Lorentz force clamping

Linear schedule



EDMS 1227656 (rev1.0, July 26th, 2012)
No contingency

Then operation at 6.5TeV per beam

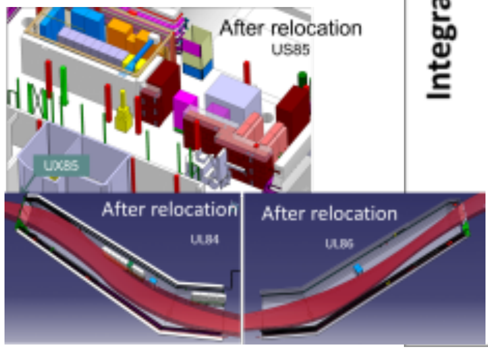
Assumptions

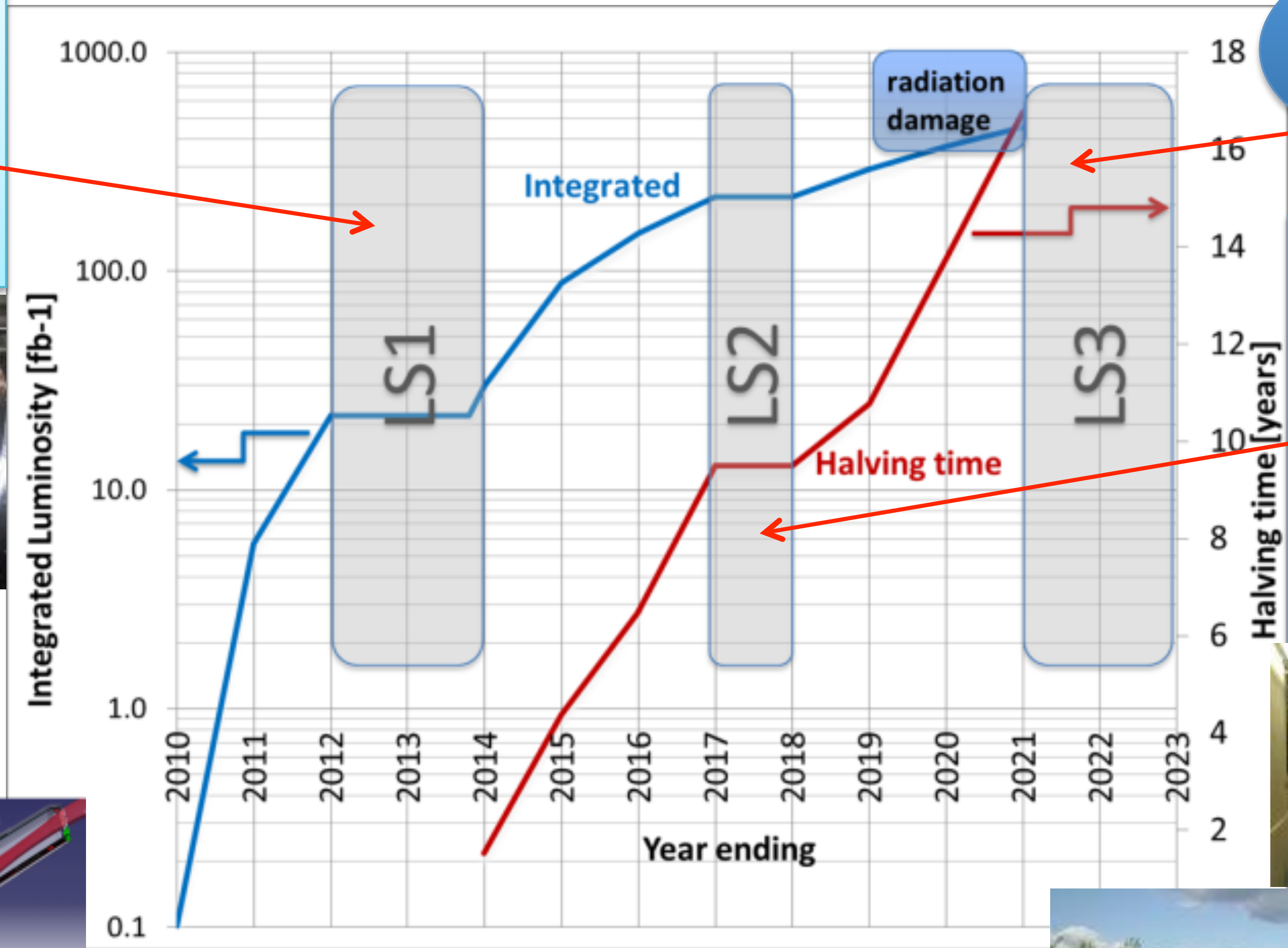
- E=6.5TeV
- β* = 0.5m (maybe 0.4)
- All other conditions as in 2012 i.e. LHC availability same etc

Mid-Term Future
HL-LHC

Two Reasons for upgrade: Performance & Technical (Consolidation)

Shut down to fix interconnects and overcome energy limitation (LHC incident of Sept 2008) and R2E

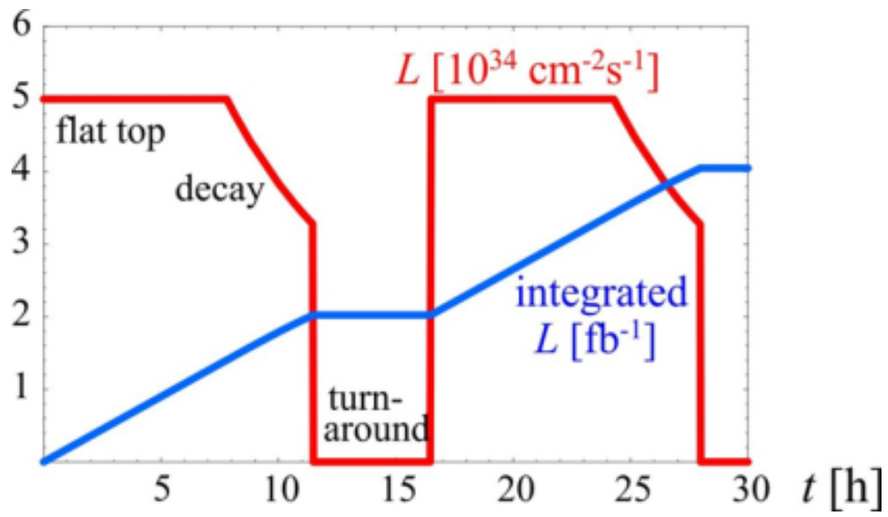




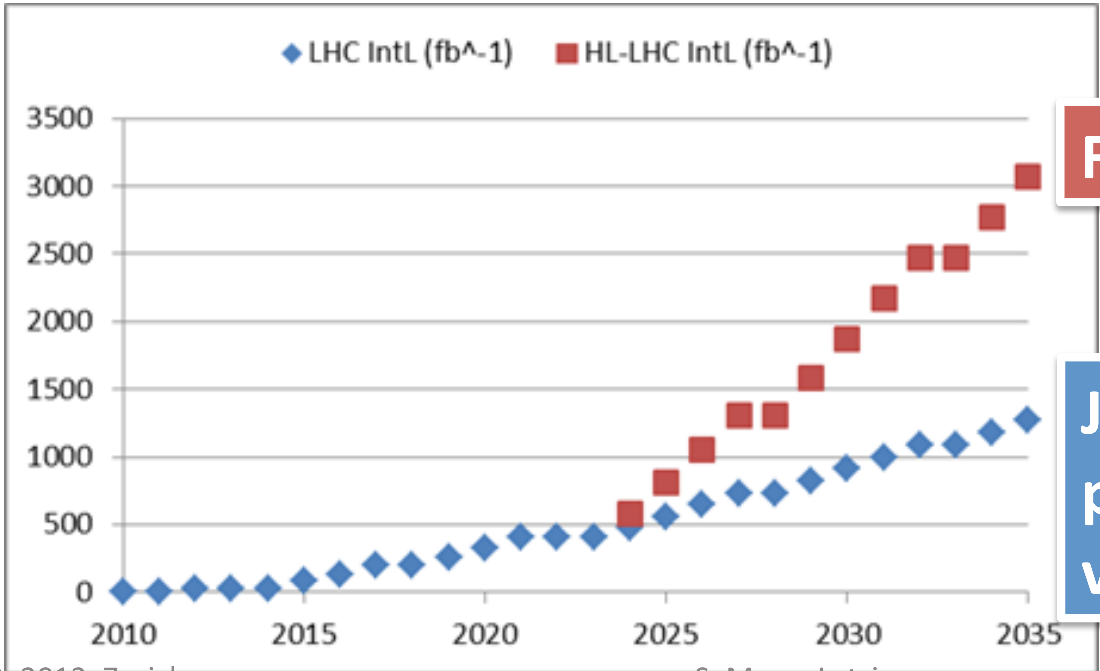
Full upgrade

Shut down to overcome beam intensity limitation (Injectors, collimation and more…)

Final goal : 3000 fb^{-1} by 2030's...



5 10^{34} levelled lumi
(25 10^{34} virtual peak lumi)
140 pile up (average)
3 fb-1 per day
60% of efficiency
250 fb-1 /year
300 fb-1/year as «ultimate»



Full project

Just continue improving performance through vigorous consolidation

Official Beam Parameters

(see PLC by O.Bruning)

Parameter	nominal	25ns	50ns		
N	1.15E+11	**2.2E+11**	**3.5E+11**		
n_b	2808	2808	1404		
beam current [A]	0.58	**1.12**	**0.89**		
x-ing angle [μrad]	300	590	590		
beam separation [σ]	10	12.5	11.4		
β^* [m]	0.55	**0.15**	**0.15**		
ε_n [μm]	3.75	2.5	3.0		
ε_L [eVs]	2.51	2.5	2.5		
energy spread	1.20E-04	1.20E-04	1.20E-04		
bunch length [m]	7.50E-02	7.50E-02	7.50E-02		
IBS horizontal [h]	80 -> 106	**20.0**	**20.7**		
IBS longitudinal [h]	61 -> 60	**15.8**	**13.2**		
Piwinski parameter	0.68	**3.1**	**2.9**		
geom. reduction	0.83	**0.35**	**0.33**		
beam-beam / IP	3.10E-03	**3.9E-03**	**5.0E-03**		
Peak Luminosity	$1\ 10^{34}$	**$7.4\ 10^{34}$**	**$8.5\ 10^{34}$**		
Virtual Luminosity	$1.2\ 10^{34}$	**$21\ 10^{34}$**	**$26\ 10^{34}$**		
Events / crossing (peak & leveled L	28	**210**	**475**	**140**	**140**

$6.2\ 10^{14}$ and $4.9\ 10^{14}$ p/beam

➔ sufficient room for leveling (with Crab Cavities)

Virtual luminosity (25ns) of $L = 7.4 / 0.35\ 10^{34}\ cm^{-2}\ s^{-1}$

$= 21\ 10^{34}\ cm^{-2}\ s^{-1}$ ('k' = 5)

Virtual luminosity (50ns) of $L = 8.5 / 0.33\ 10^{34}\ cm^{-2}\ s^{-1}$

$= 26\ 10^{34}\ cm^{-2}\ s^{-1}$ ('k' = 10)

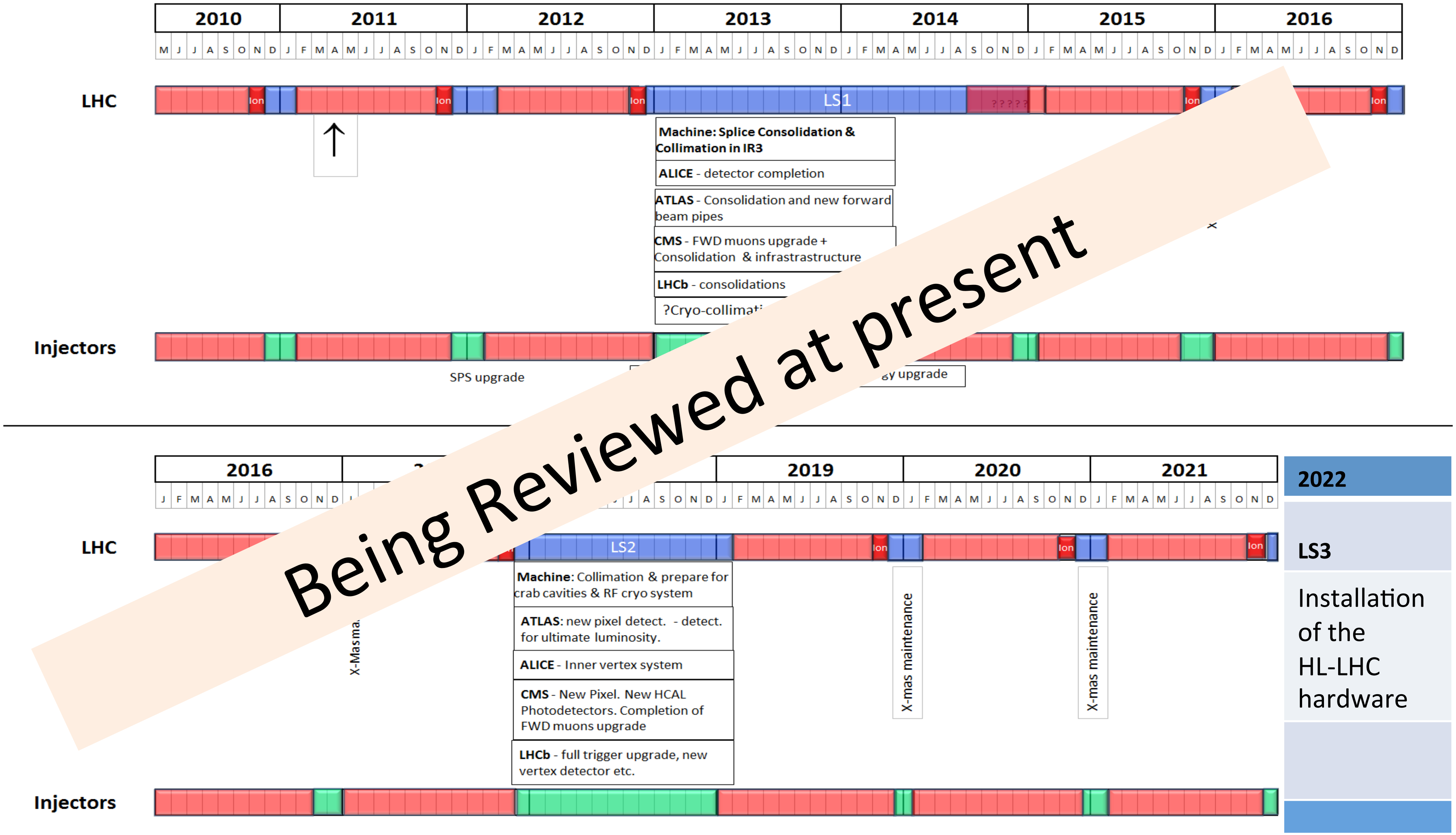
(Leveled to $5\ 10^{34}\ cm^{-2}\ s^{-1}$ and $2.5\ 10^{34}\ cm^{-2}\ s^{-1}$)

HiLumi: Two branches (with overlap)

- **PIC - Performance Improving Consolidation upgrade (~1000 fb^{-1})**
  - IR quad change (rad. Damage, enhanced cooling)
  - Cryogenics (P4, IP4,IP5) separation Arc -RF and IR(?)
  - Enhanced Collimation (11T?)
  - SC links (in part) and rad. Mitigation (ALARA)
  - QPS and Machine Prot.
    - Kickers
    - Interlock system

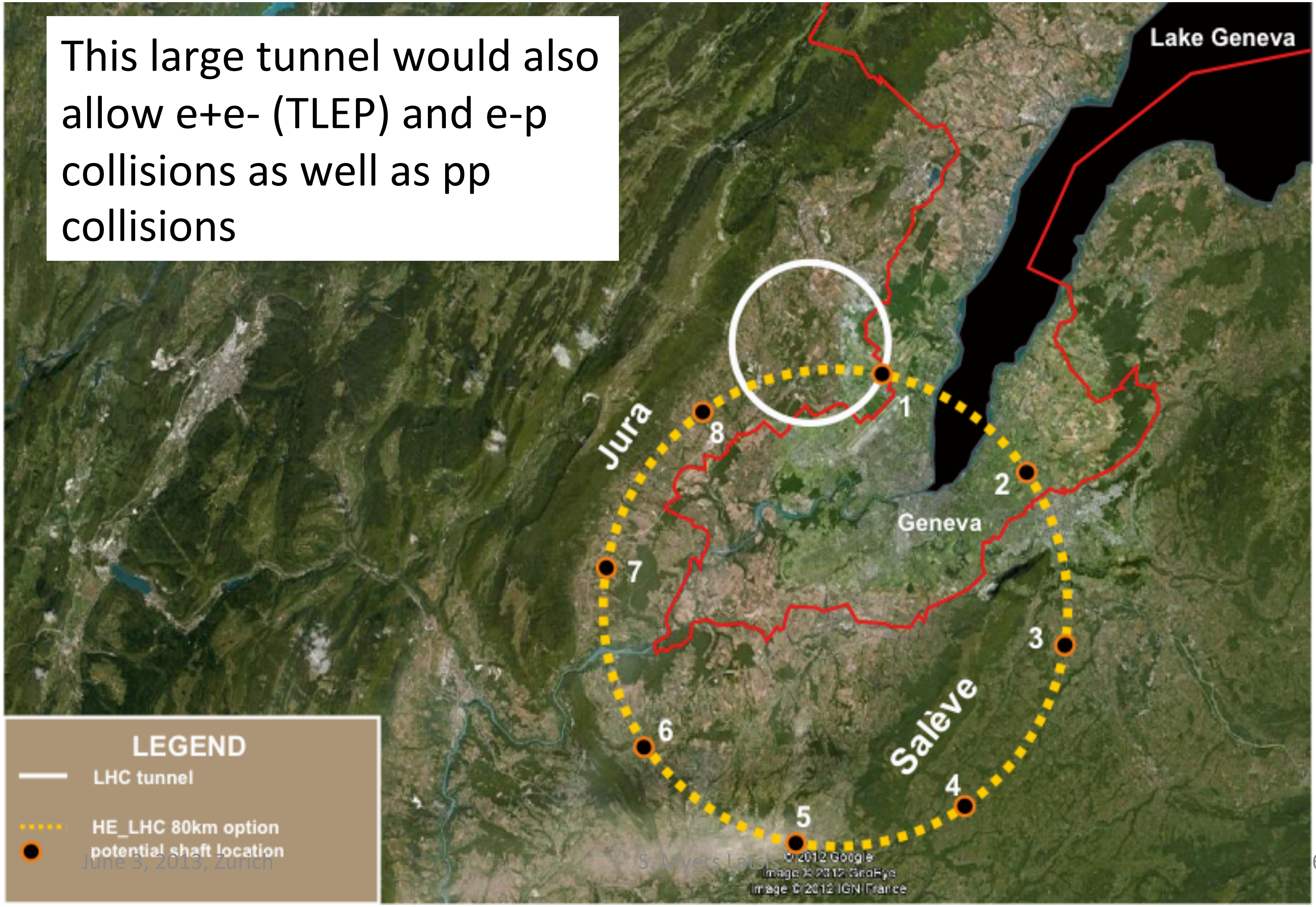
- **FP- Full Performance upgrade (3000 fb^{-1})**
  - Crab Cavities
  - HB feedback system (SPS)
  - Advanced collimation systems
  - E-lens (?)
  - SC links (all)
  - R2E and remote handling for 3000 fb^{-1}

New rough draft 10 year plan



Long-Term Future: VHE-LHC, e+e-, and ep options

HE-LHC and VHE-LHC



Parameters list of LHC upgrades
(O. Dominguez and F. Zimmermann)

Table 1.1 Parameters of LHC, HL-LHC, HE-LHC, and VHE-LHC

parameter	LHC	HL-LHC	HE-LHC	VHE-LHC
c.m. energy [TeV]	14	14	33	100
circumference C [km]	26.7	26.7	26.7	80
dipole field [T]	8.33	8.33	20	20
dipole coil aperture [mm]	56	56	40	40
beam half aperture [cm]	2.2 (x), 1.8 (y)	2.2 (x), 1.8 (y)	1.3	1.3
injection energy [TeV]	0.45	0.45	>1.0	7.0
no. of bunches	2808	2808	1404	4210
bunch population [10^{11}]	1.125	2.2	1.62	1.34
init. transv. norm. emit. [μm]	3.73,	2.5	2.10	1.53
initial longitudinal emit. [eVs]	2.5	2.5	5.67	17.2
no. IPs contributing to tune shift	3	2	2	2
max. total beam-beam tune shift	0.01	0.015	0.01	0.01
beam circulating current [A]	0.584	1.12	0.412	0.338
rms bunch length [cm]	7.55	7.55	7.7	7.7
IP beta function [m]	0.55	0.15	0.3	1.5

High Luminosity LHC

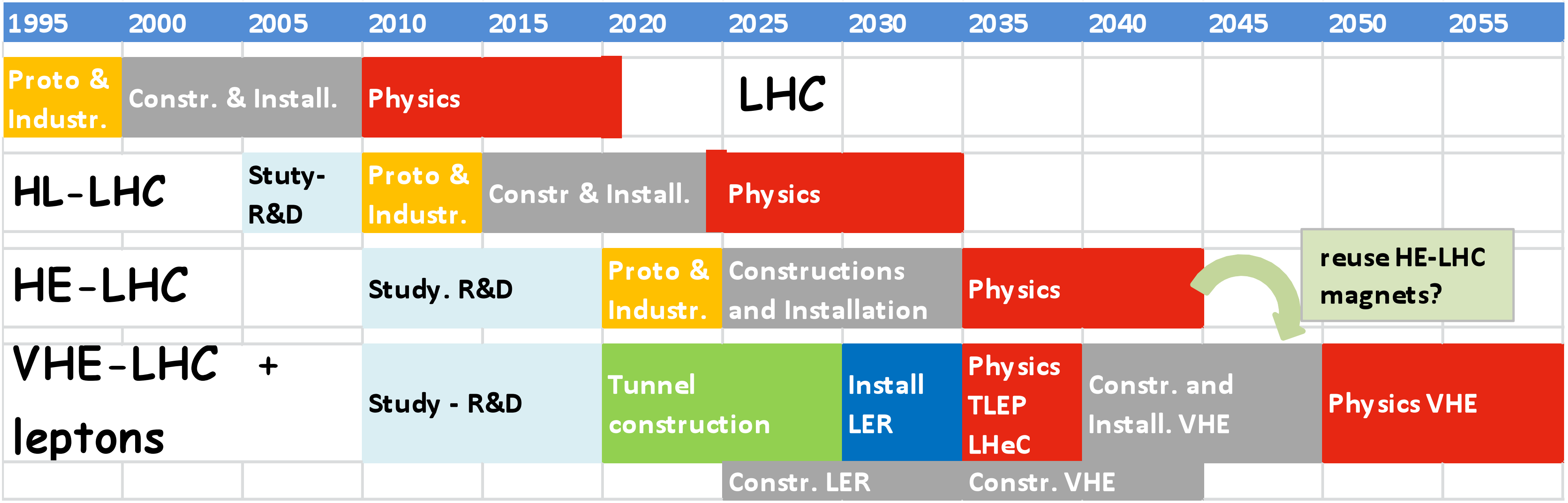
Table 1.1 Parameters of LHC, HL-LHC, HE-LHC, and VHE-LHC

parameter	LHC	HL-LHC	HE-LHC	VHE-LHC
c.m. energy [TeV]	14	14	33	100
circumference C [km]	26.7	26.7	26.7	80
dipole field [T]	8.33	8.33	20	20
dipole coil aperture [mm]	56	56	40	40
beam half aperture [cm]	2.2 (x), 1.8 (y)	2.2 (x), 1.8 (y)	1.3	1.3
injection energy [TeV]	0.45	0.45	>1.0	7.0
no. of bunches	2808	2808	1404	4210
bunch population [10^{11}]	1.125	2.2	1.62	1.34
init. transv. norm. emit. [μm]	3.73,	2.5	2.10	1.53
initial longitudinal emit. [eVs]	2.5	2.5	5.67	17.2
no. IPs contributing to tune shift	3	2	2	2
max. total beam-beam tune shift	0.01	0.015	0.01	0.01
beam circulating current [A]	0.584	1.12	0.412	0.338
rms bunch length [cm]	7.55	7.55	7.7	7.7
IP beta function [m]	0.55	0.15	0.3	1.5
init. rms IP spot size [μm]	16.7	7.1	6.0	6.5
full crossing angle [μrad]	285	590	240	52.3
stored beam energy [MJ]	362	694	601	4573
SR power per ring [kW]	3.6	6.9	82.5	1991
arc SR heat load dW/ds	0.21	0.40	3.5	84
energy loss per turn [keV]	6.7	6.7	201.3	5857
critical photon energy [eV]	44	44	575	5474
photon flux [10^{17}/m/s]	1.0	1.9	1.6	1.3
longit. SR emit. damping time [h]	12.9	12.9	1.0	0.32
horiz. SR emit. damping time [h]	25.8	25.8	2.0	0.64
init. longit. IBS emit. rise time [h]	57	21.0	78	305
d init. transv. IBS emit. rise time [h]	103	15.4	41	72.2
peak events per crossing	19	140 (lev.)	190	193
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	7.4	5.0	5.0
beam lifetime due to burn off [h]	45	11.6	6.3	15.5
optimum run time [h]	15.2	8.9	7.0	11.8
opt. av. int. luminosity / day [fb^{-1}]	0.47	3.7	1.5	2.1

Need to be addressed

High Luminosity LHC

In principle a plan for all (?) is possible (for LHC exploitation): **2018-2020 is critical time**

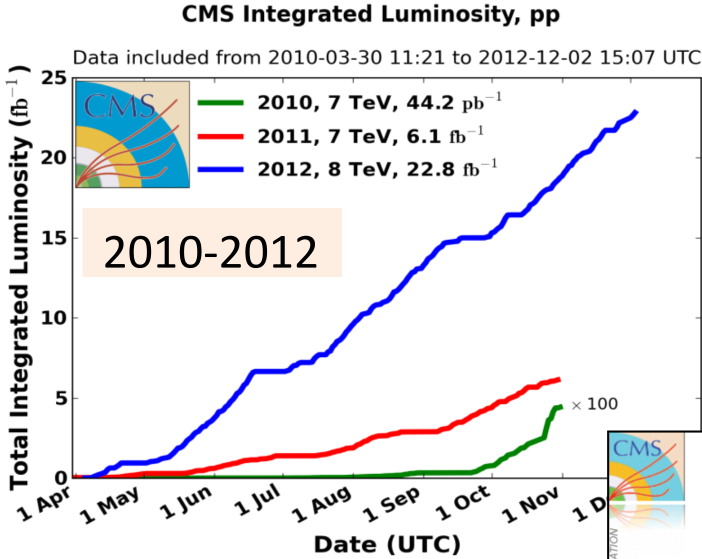


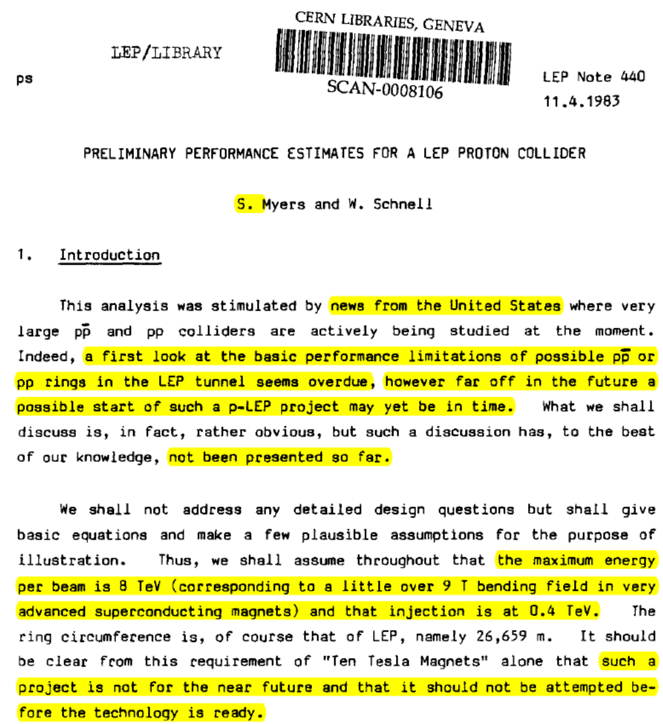
- **According to Physics needs, the 80-100 km tunnel can:**
  - **Be alternative to HE-LHC**
  - **Or complementary to HE-LHC**
  - **Accomodating at negligible extra-cost TLEP and VLHeC (this last at 50GeV/5TeV and 350 GeV/50-100 TeV)**
  - **Skipping TLEP/VLHeC may shorten 5-10 years VHE-LHC**

Summary

- Integrated luminosity goal for 2012 exceeded
- "Higgs" discovered
- Proton-lead run a big success
- LS1 progress is good
- Operation after LS1 at 6.5TeV/beam
  - 25ns much preferred by detectors
- Many (ideas) plans for the future!

Thank you for your attention





CERN LIBRARIES, GENEVA

LEP/LIBRARY

ps

SCAN-0008106

LEP Note 440

11.4.1983

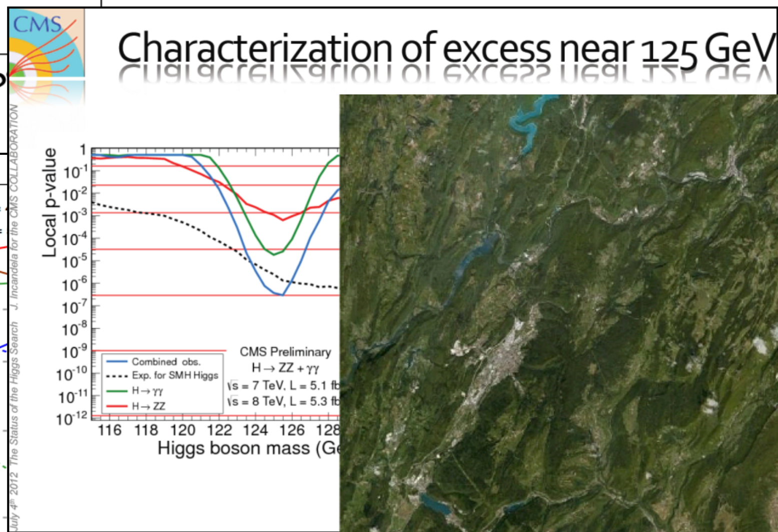
PRELIMINARY PERFORMANCE ESTIMATES FOR A LEP PROTON COLLIDER

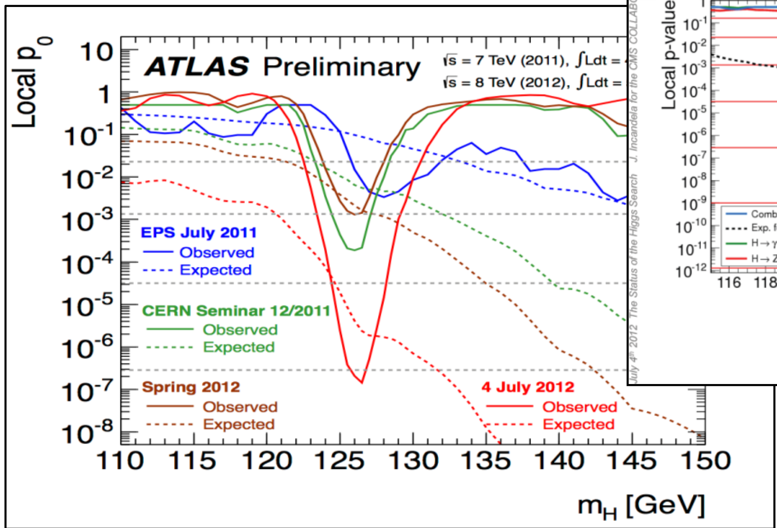
S. Myers and W. Schnell

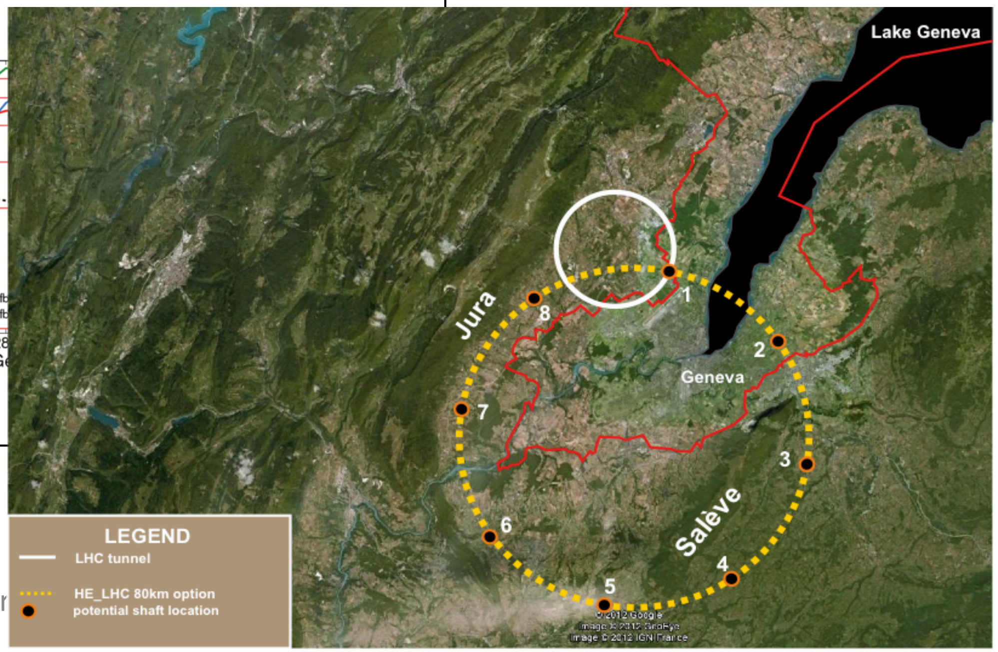
1. Introduction

This analysis was stimulated by news from the United States where very large $p\bar{p}$ and pp colliders are actively being studied at the moment. Indeed, a first look at the basic performance limitations of possible $p\bar{p}$ or pp rings in the LEP tunnel seems overdue, however far off in the future a possible start of such a p-LEP project may yet be in time. What we shall discuss is, in fact, rather obvious, but such a discussion has, to the best of our knowledge, not been presented so far.

We shall not address any detailed design questions but shall give basic equations and make a few plausible assumptions for the purpose of illustration. Thus, we shall assume throughout that the maximum energy per beam is 8 TeV (corresponding to a little over 9 T bending field in very advanced superconducting magnets) and that injection is at 0.4 TeV. The ring circumference is, of course that of LEP, namely 26,659 m. It should be clear from this requirement of "Ten Tesla Magnets" alone that such a project is not for the near future and that it should not be attempted before the technology is ready.

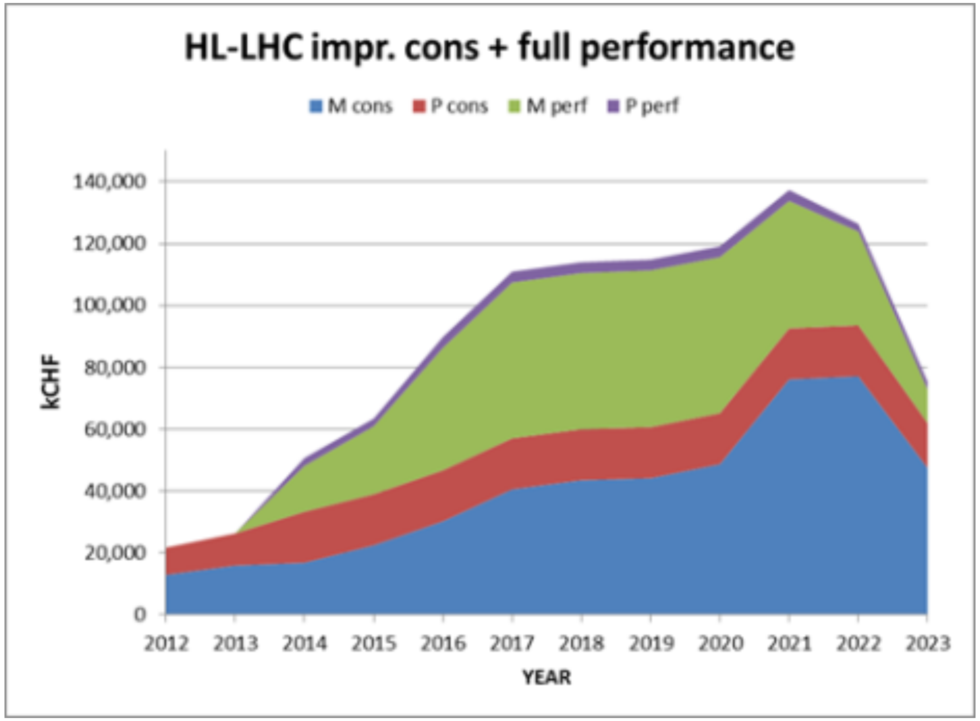






This Ends the Presentation

Preliminary budget estimate



	Improving Consolidation	Full performance	Total HL-LHC
Mat. (MCHF)	476	360	836
Pers. (MCHF)	182	31	213
Pers. (FTE-y)	910	160	1070
TOT (MCHF)	658	391	1,049

High Luminosity LHC

HE-LHC cost:
rough evalution based on LHC

- LHC (machine): about 3.4 BCHF, **1.7 BCHF** for the magnet system,
- HE-LHC: The non-magnet is ~ same 1.5 BCHF
  - Magnet System Nb_3Sn (**26 TeV c.o.m.**) : ~ **3.5 BCHF** (for a total of **5 BCHF** for the whole machine)
  - Magnet System HTS (**33 TeV c.o.m**) : ~ **5 BCHF** (for a total of **6.5 BCHF** for the whole machine)
  - The above cost are for a new machine, like LHC. Economy could be made because Cryo and other systems need only renovation;
  - however one should consider the cost of LHC removal)

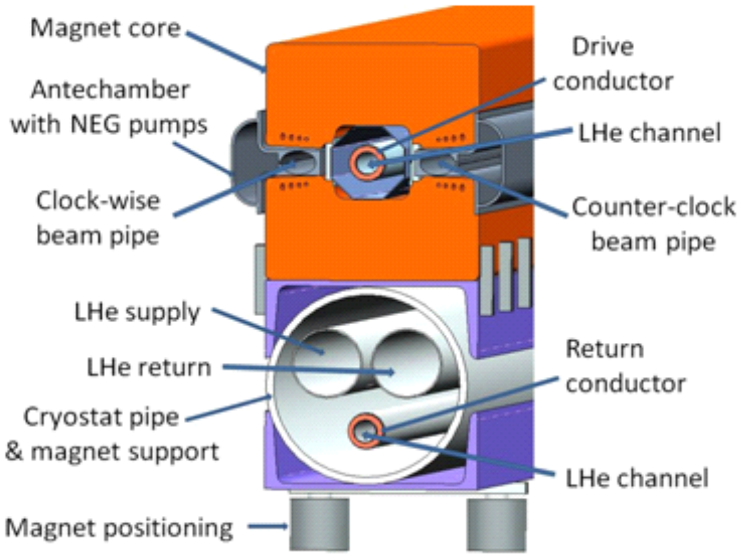
Other important issues (among many …)

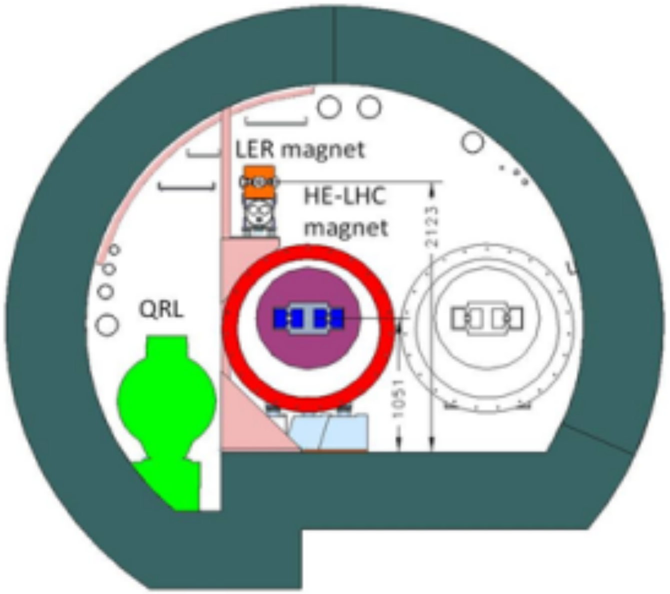
- **Synchrotron radiation**
- 15 to 30 times!
- The best is to use a window given by vacuum stability at around 50-60 K (gain a factor 15 in cryopower removal!)
- First study on beam impedance seems positive but to be verified carefully
- Use of HTS coating on beam screen?

- **Beam in & out**
- Both injection and beam dump region are constraints.
- Ideally one would need twice stronger kickers
- Beam dumps seems feasable by increasing rise time from 3 to 5μs
- Injection would strongly benefit form stronger kickers otherwise a new lay-out is needed (different with or wihtout experiments)

Alternate scenarios for Injectors

- Keeping SPS (and its transfer lines: 6 km!): Low Energy Ring in LHC tunnel with superferric Pipetron magnets (W. Foster).
- Work done by Fermilab (**H. Piekarz**), see Malta workshop proc.
  - cost of LER is lower than SC-SPS option.
  - Integration is difficult but no show-stoppers





S. Myers Latsis

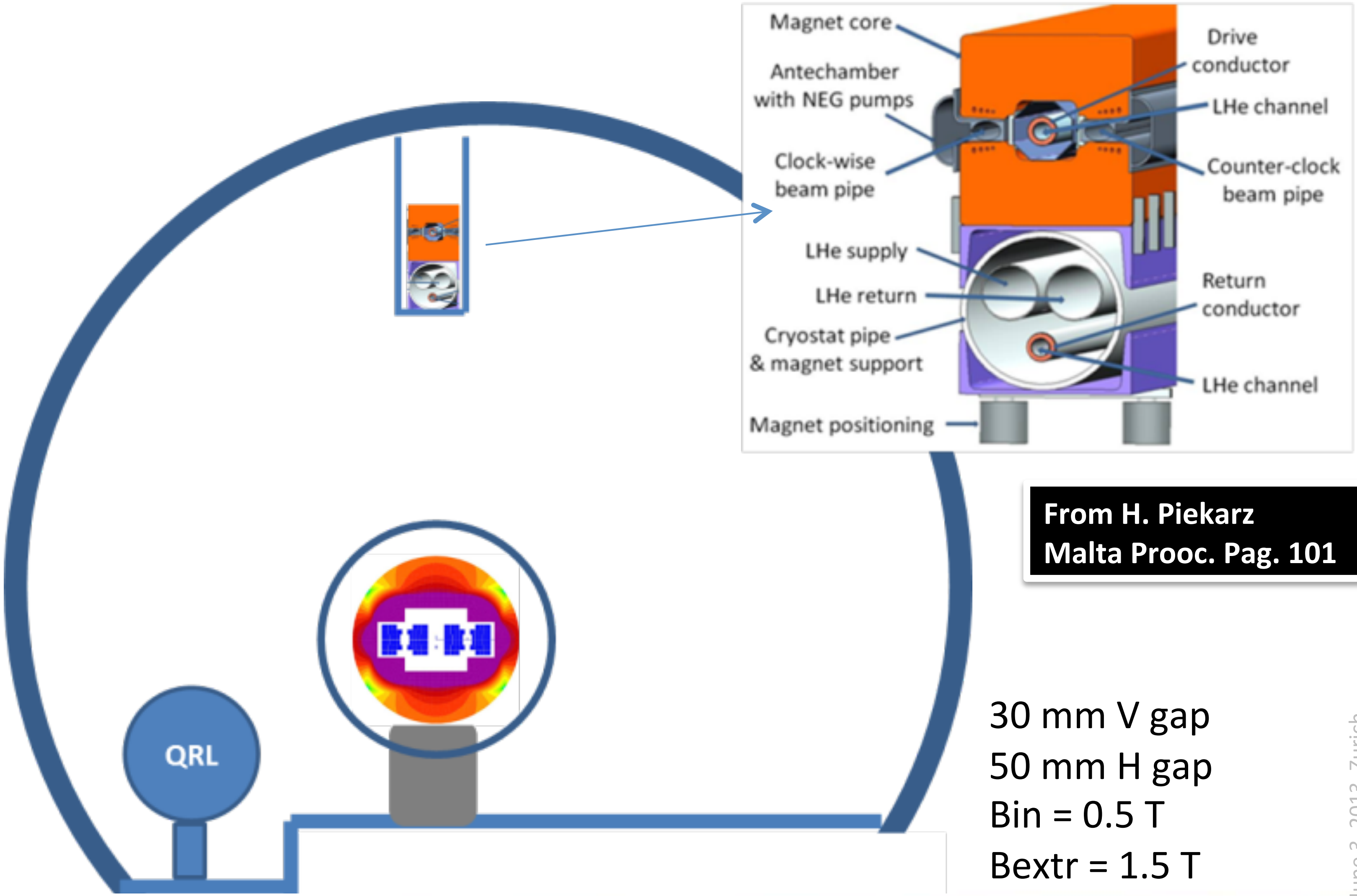
Steps for Potential Large Projects beyond the LHC infrastructure: the 47-80 km long ring tunnel

- Several proposals exist for major projects at CERN to complement / succeed the LHC
  - CLIC, HE-LHC, TLEP, LHeC etc…

J. Osborne

- Steps to undertake before starting construction planning
  - Determine requirements for the project
  - Create basic civil engineering drawings
  - Perform siting studies
  - Perform feasibility studies to determine optimal location
    - Optimal is most feasible from civil engineering point of view
  - Select optimal location
  - Optimize civil engineering drawings according to identified optimal location

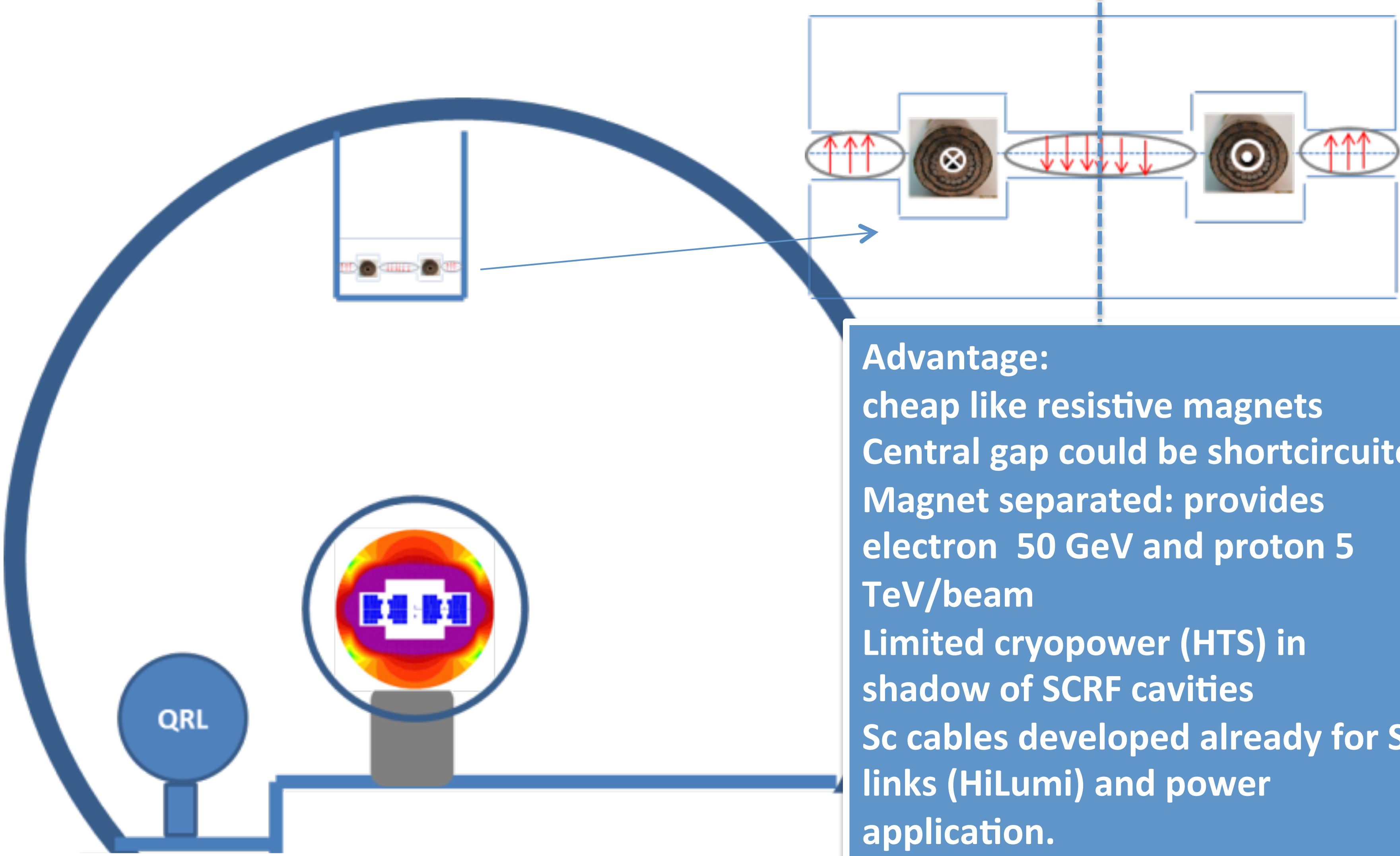
Possible arrangement in VHE-LHC tunnel



From H. Piekarz Malta Prooc. Pag. 101

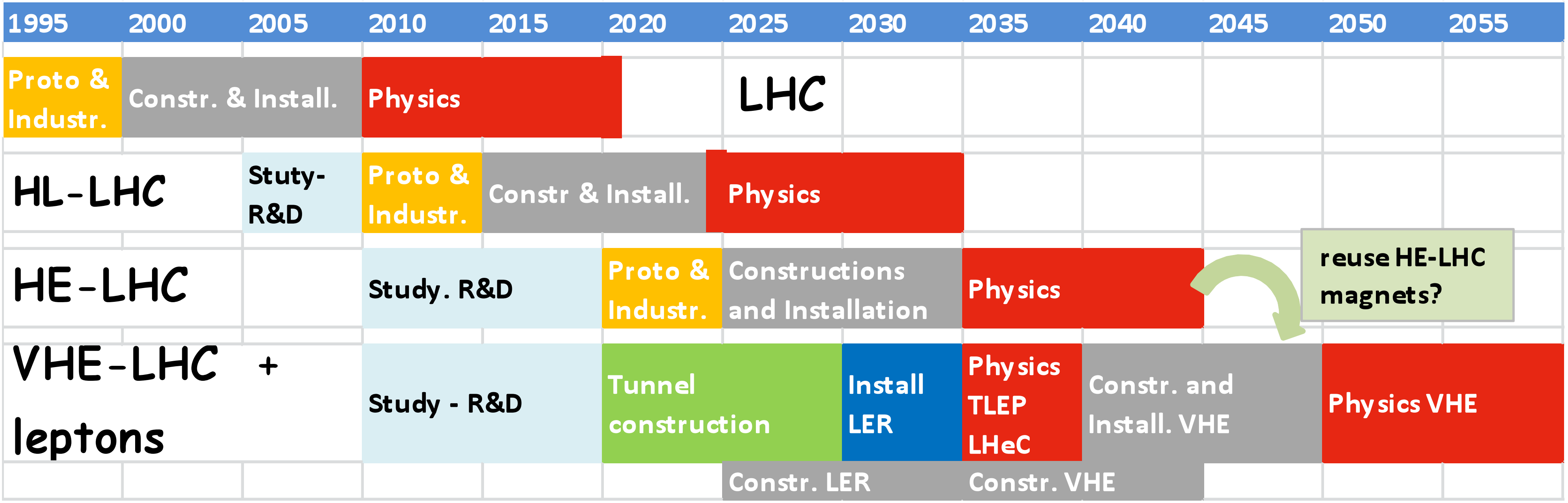
30 mm V gap
50 mm H gap
Bin = 0.5 T
Bextr = 1.5 T

Possible VHE-LHC with a LER **suitable also for e^+-e^- collision (and VLHeC) – 100 MW sr**



Advantage:
cheap like resistive magnets
Central gap could be shortcircuited
Magnet separated: provides electron 50 GeV and proton 5 TeV/beam
Limited cryopower (HTS) in shadow of SCRF cavities
Sc cables developed already for SC links (HiLumi) and power application.
SR taken at 300 K: is possible???

In principle a plan for all (?) is possible (for LHC exploitation): **2018-2020 is critical time**



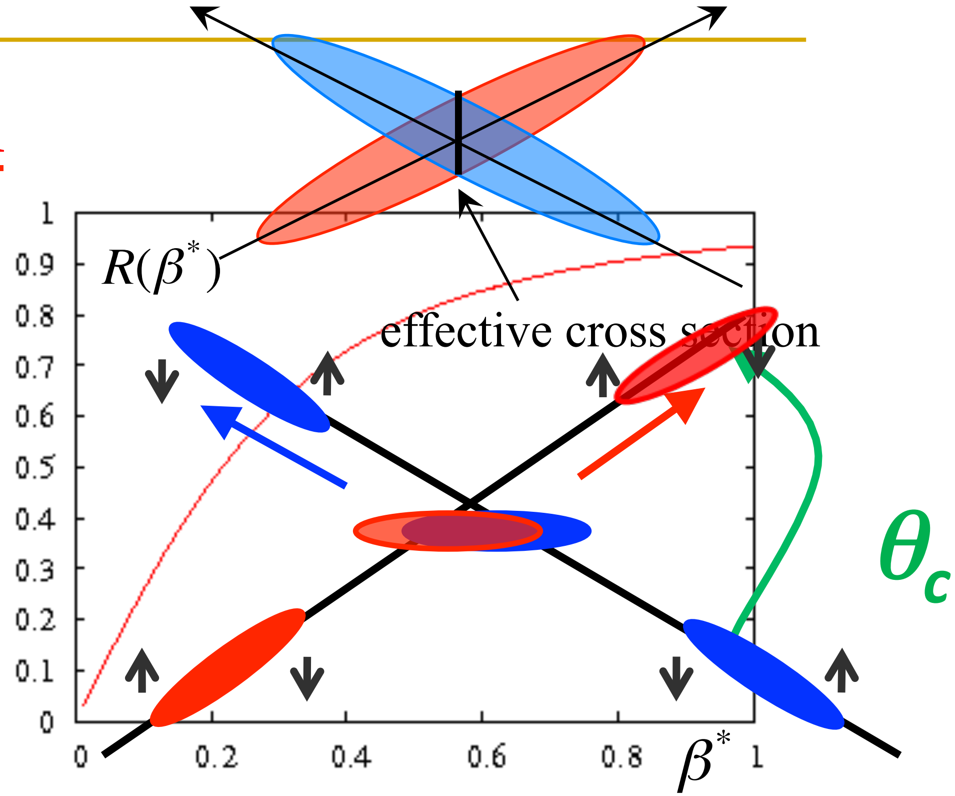
- **According to Physics needs, the 80 km tunnel can:**
  - **Be alternative to HE-LHC**
  - **Or complementary to HE-LHC**
  - **Accomodating at negligible extra-cost TLEP and VLHeC (this last at 50GeV/5TeV and 350 GeV/50-100 TeV)**
  - **Skipping TLEP/VLHeC may shorten 5-10 years VHE-LHC**

LHC Challenges: R

- geometric luminosity reduction factor:

Piwinski angle

$$R_\theta = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$



large crossing angle:

- ➔ reduction of long range beam-beam interactions
- ➔ reduction of head-on beam-beam parameter
- ➔ reduction of the mechanical aperture
- ➔ synchro-betatron resonances
- ➔ reduction of instantaneous luminosity
  - ➔ inefficient use of beam current
  - ➔ option for L leveling!

HL-LHC Performance Goals

- Operation at performance limit
  ➔ choose parameters that allow higher than design performance
  ➔ leveling mechanisms for controlling performance during run

- Preferred leveling mechanism: Crab Cavities

Reservations: technology & field quality

➔ Supplementary tools for leveling:
  # crossing angle and long-range and beam-beam wire compensators
  # transverse offsets at IP
  # dynamic β^* squeeze

The LHC Life cycle

- 1983: Preliminary Performance Estimates for the LHC (S.Myers and W. Schnell, 11th April 1983)
- 1984: Kick off meeting to discuss ideas for an accelerator to co[...]s at very high energy
- 1996: Final decision for the LHC, the most compl[...] instrument ever constructed
- 10 September 2008: Start of commi[...]ith beam
- 19 September 2008: Serio[...] and damage
- 19 November 200[...] beam operation
- Decemb[...] collisions at 2.38 TeV

Today[...]ssful operation, providing millions of particle collisions for the LHC experiments

- About 2035: The LHC physics programme to be finished ?

A >50 Years Adventure

ps

LEP Note 440
11.4.1983

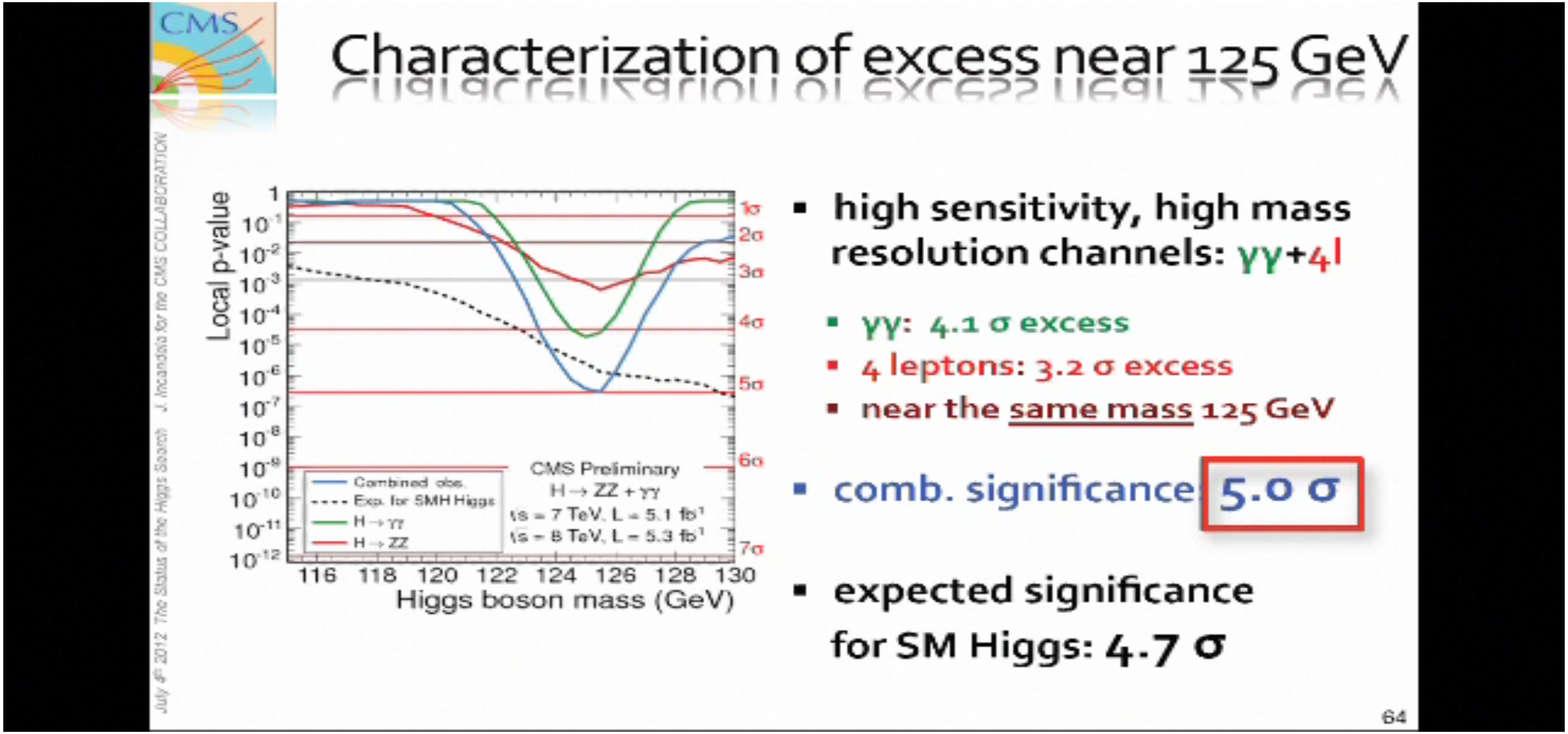
PRELIMINARY PERFORMANCE ESTIMATES FOR A LEP PROTON COLLIDER

S. Myers and W. Schnell

1. Introduction

This analysis was stimulated by news from the United States where very large $p\bar{p}$ and pp colliders are actively being studied at the moment. Indeed, a first look at the basic performance limitations of possible $p\bar{p}$ or pp rings in the LEP tunnel seems overdue, however far off in the future a possible start of such a p-LEP project may yet be in time. What we shall discuss is, in fact, rather obvious, but such a discussion has, to the best of our knowledge, not been presented so far.

We shall not address any detailed design questions but shall give basic equations and make a few plausible assumptions for the purpose of illustration. Thus, we shall assume throughout that the maximum energy per beam is 8 TeV (corresponding to a little over 9 T bending field in very advanced superconducting magnets) and that injection is at 0.4 TeV. The ring circumference is, of course that of LEP, namely 26,659 m. It should be clear from this requirement of "Ten Tesla Magnets" alone that such a project is not for the near future and that it should not be attempted be-



120903 Joe_Steve-H.264 pour podcasts vidéo.m4v

LHC Status Report

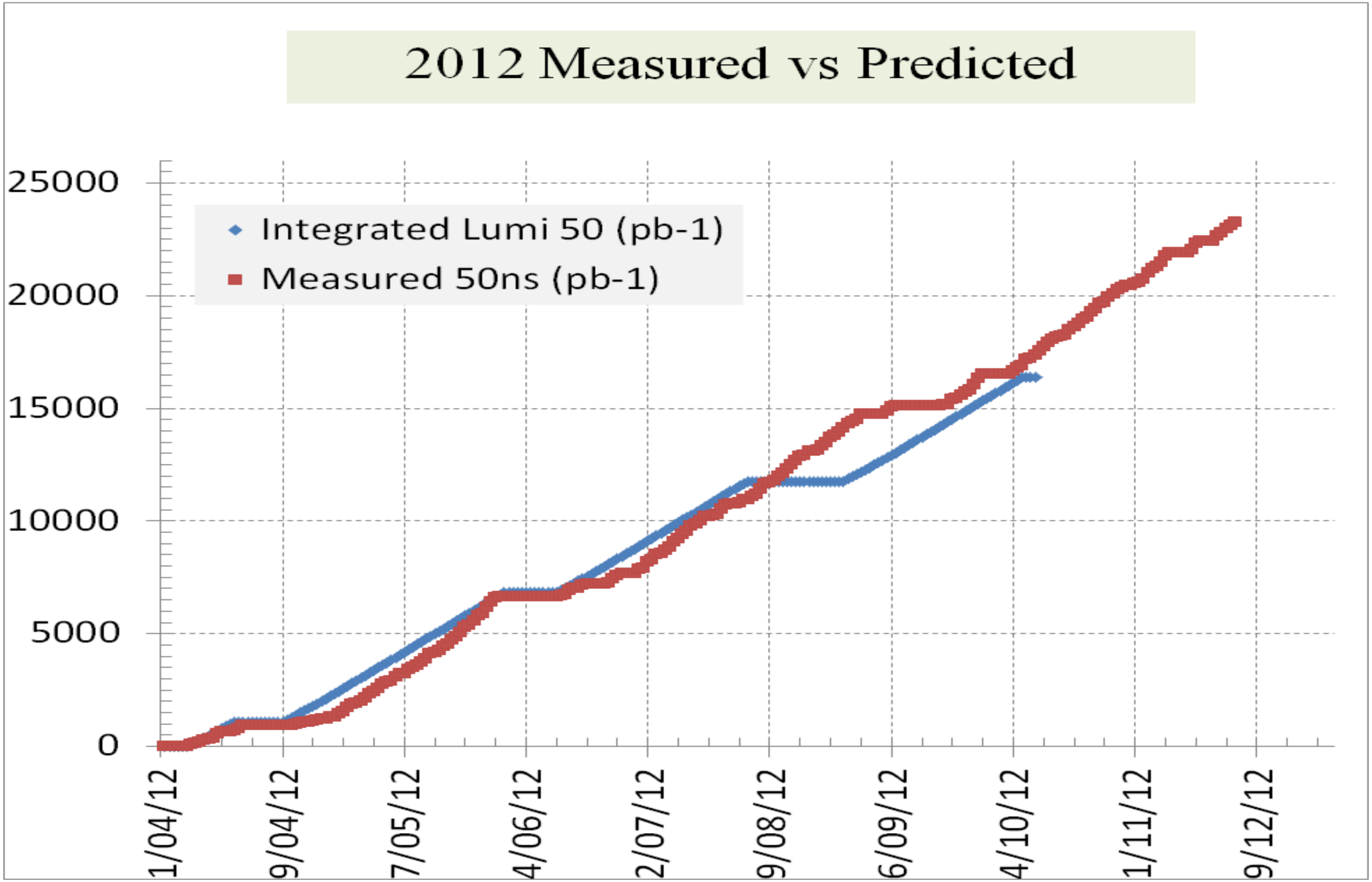
Steve Myers
On behalf of all LHC teams

Last Weeks/Months of Run 1 (2009-2013)

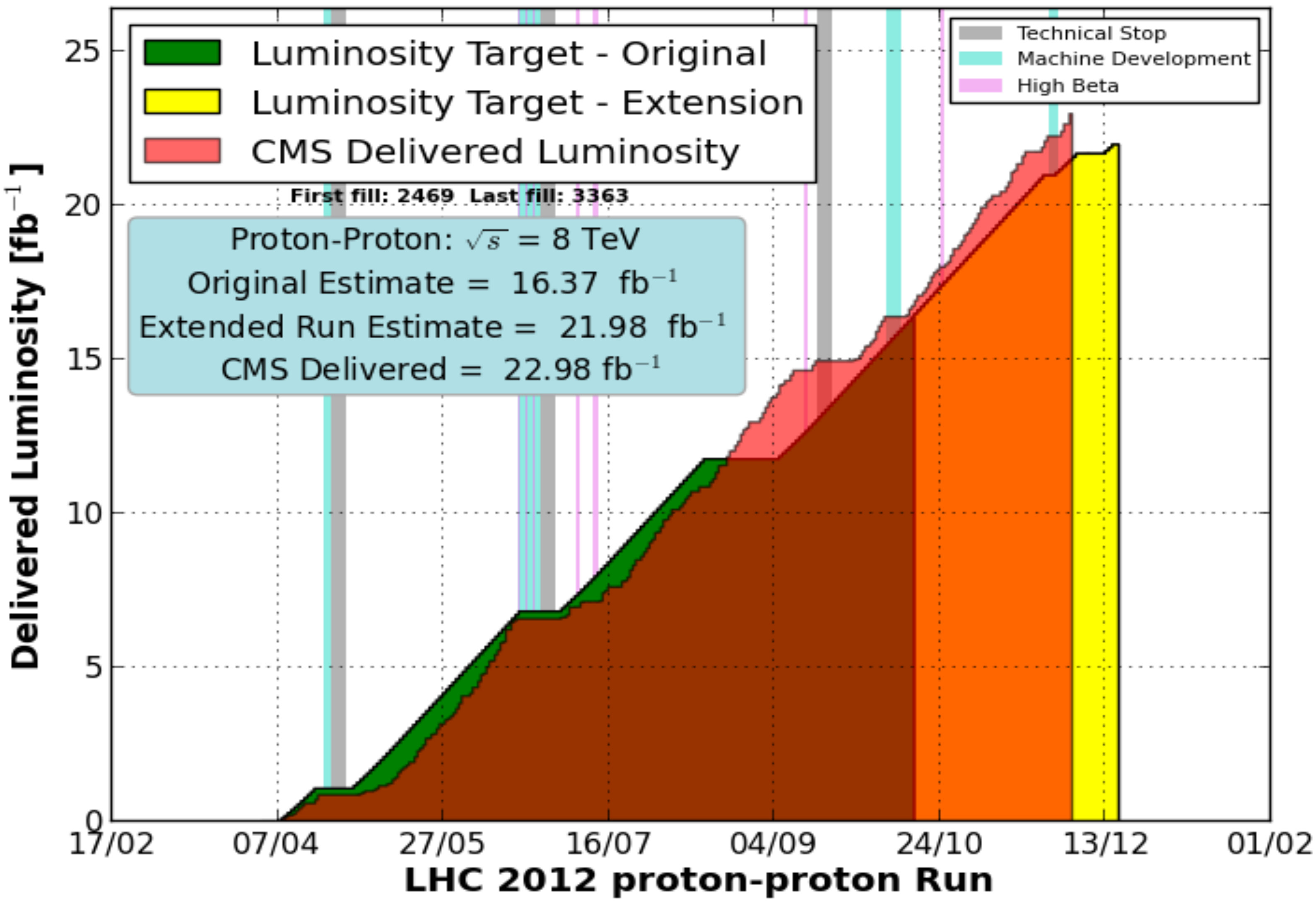
Topics

- Last days of p-p
- End of year tests
  - 25ns and scrubbing
  - Quench tests
    - Collimation test
    - UFOs
    - magnets
- Lead-proton run + 1.38TeV/beam run, +VDM scans (F
- CERN Machine Advisory Ctte (15-16 March)
- 'mini-Chamonix (at CERN)' performance of LIU and HL-LHC

2012

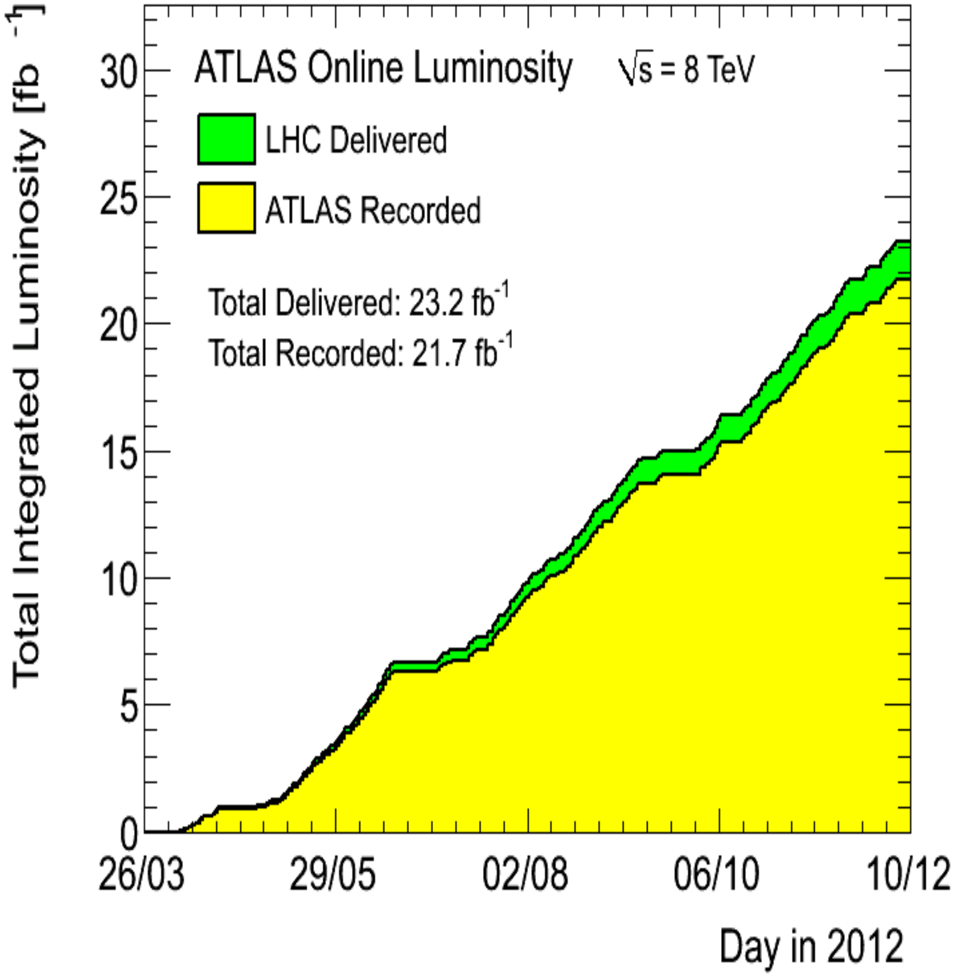

2012 Measured vs Predicted
Integrated Lumi 50 (pb-1)
Measured 50ns (pb-1)
25000
20000
15000
10000
5000
0
1/04/12
9/04/12
7/05/12
4/06/12
2/07/12
9/08/12
6/09/12
4/10/12
1/11/12
9/12/12

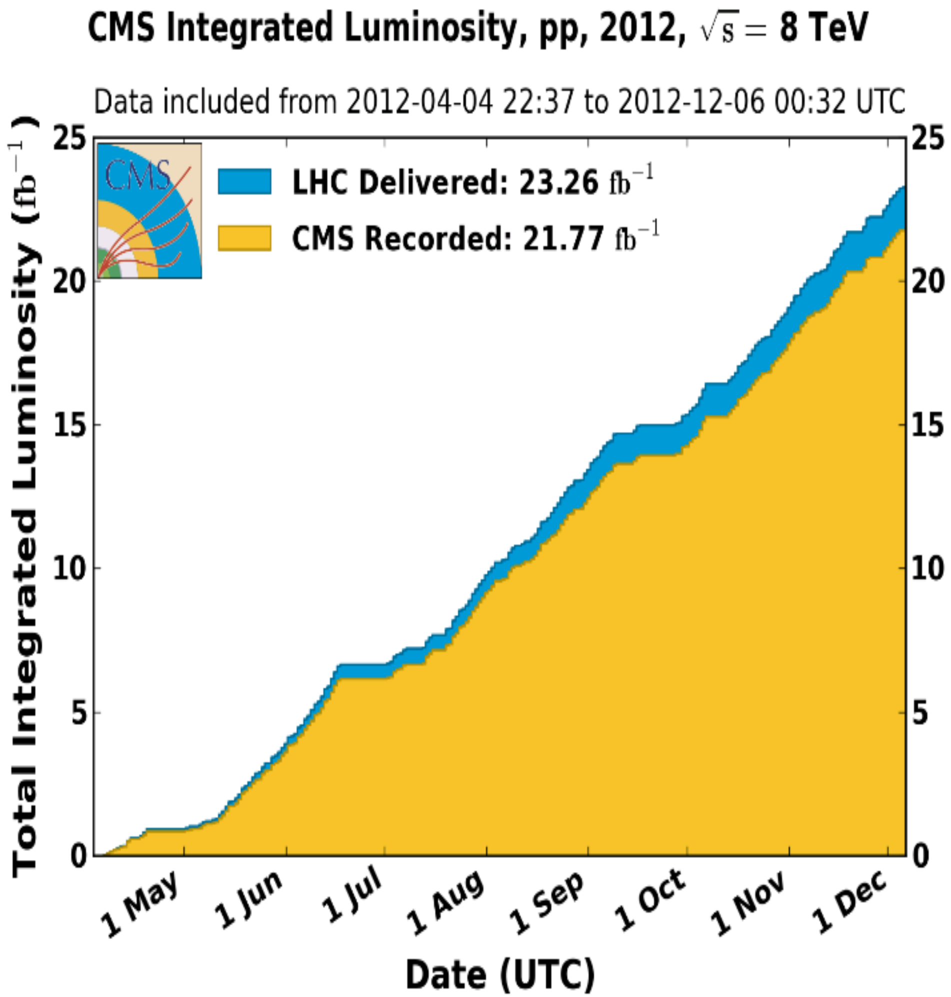
With the modified schedule



Total Luminosities 2012

ALICE: 9.81 pb^{-1} ATLAS: 23.25 fb^{-1} CMS: 23.26 fb^{-1} LHCb: 2.19 fb^{-1}

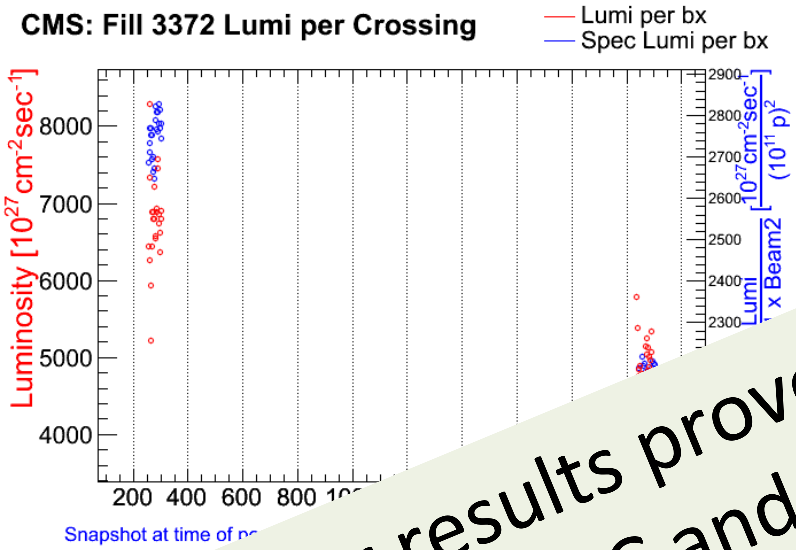




End of Run Tests

- High Injector Brightness
- End of year tests @ 25ns
  - electron cloud and scrubbing
  - Quench tests
    - Collimation test
    - UFOs
    - Magnet quench test
    - HOM heating

Injector High Brightness Beams



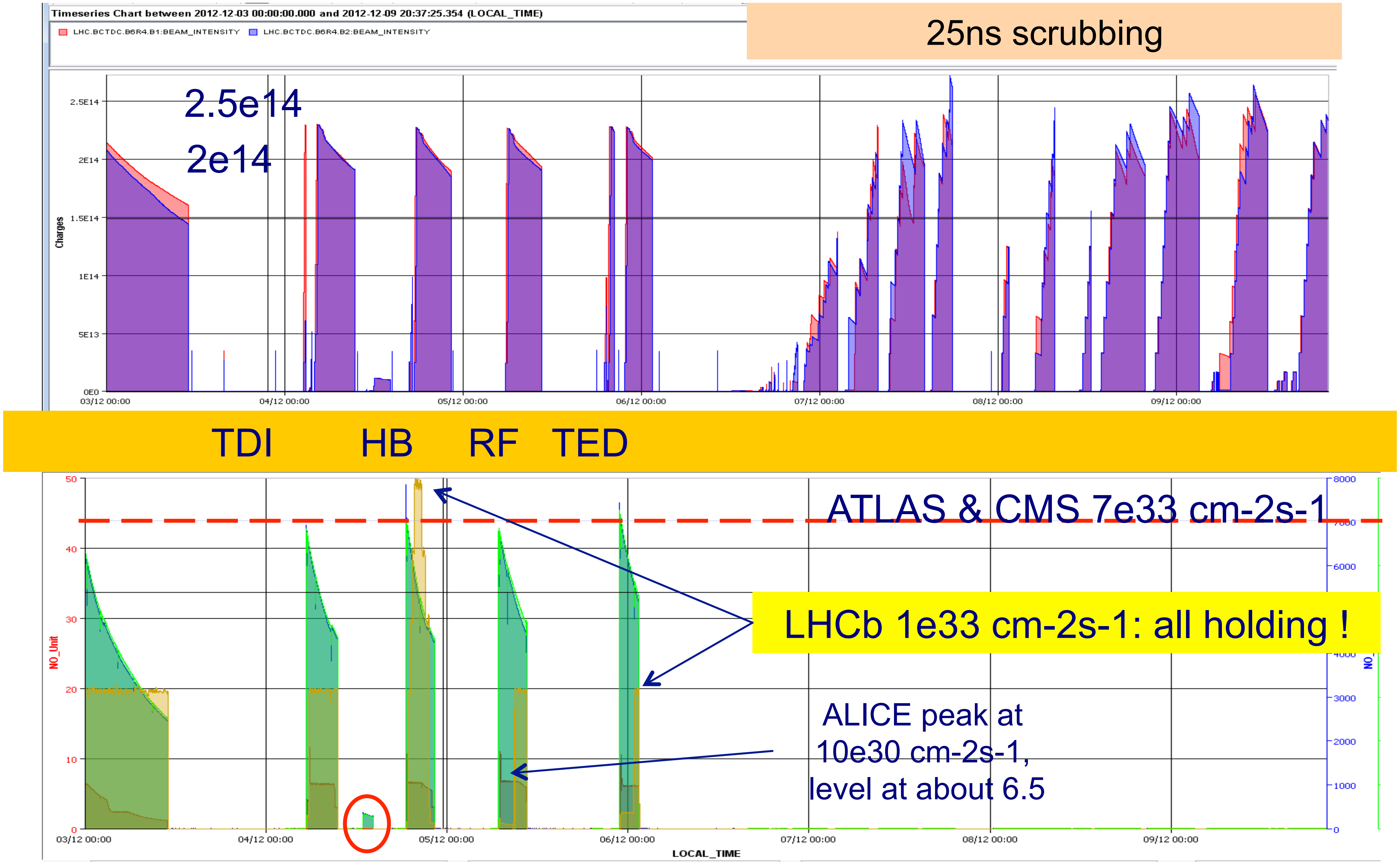
About 30 % ... specifi...

...on, now ...ssible 1.15E11 with ...ittance of 1.4µm at LHC inj.

These and other results provoked the review of the performance of HL-LHC and the needs from LIU

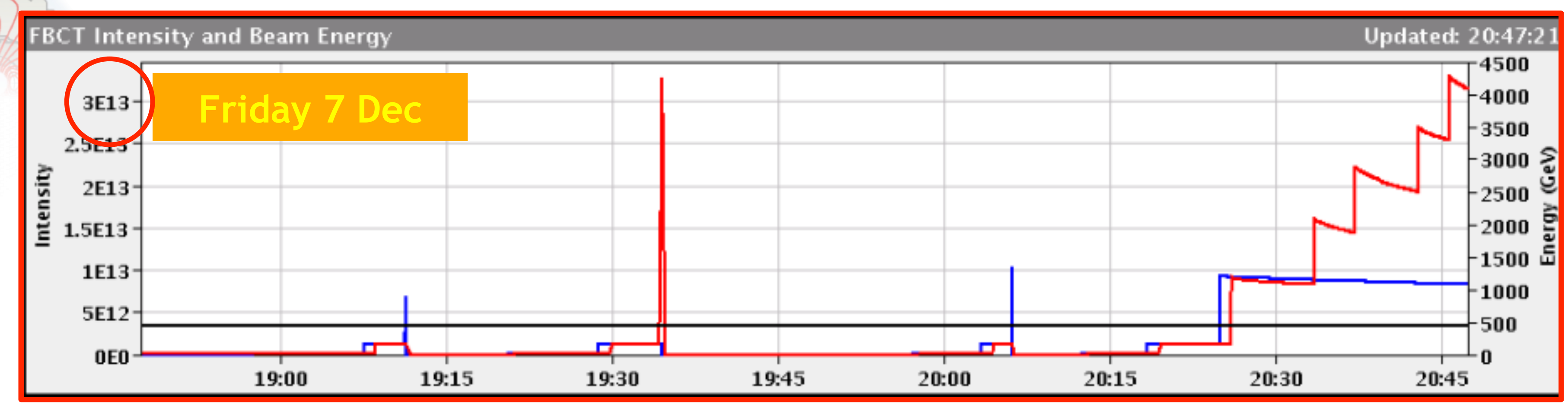
- Hi... ...s from the injector chain
  - ...ing option for 2015 operation, both 50 ns and ...beam spacing
- ...ill with one batch HB and 1 batch 'standard' 50 ns
  - Emittance for HB beam ~ 1-1.2 um, standard 1.4-1.6 um.

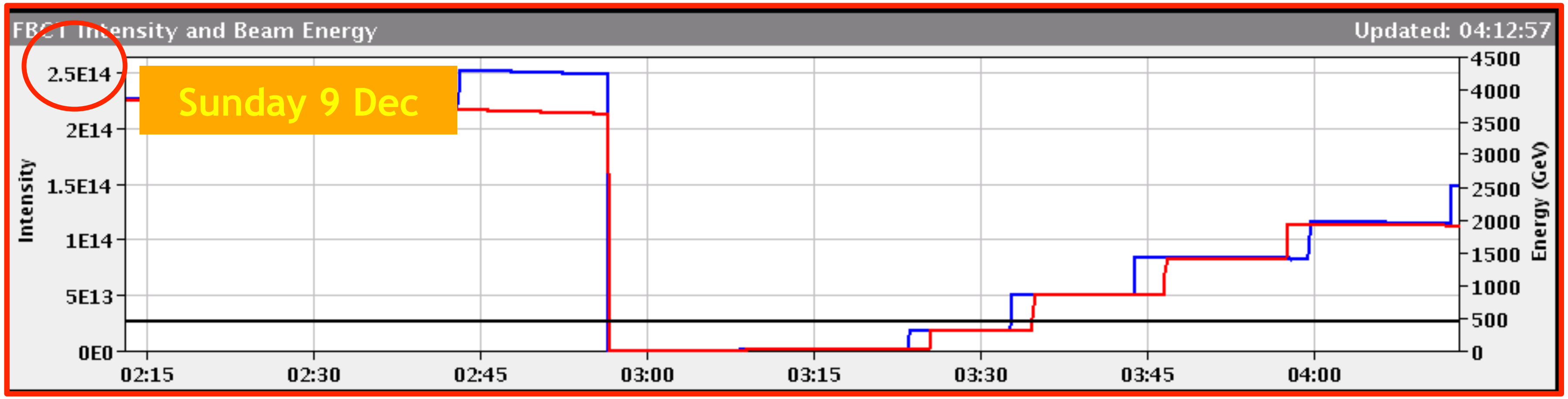
Beam currents and luminosity



Beam quality evolution

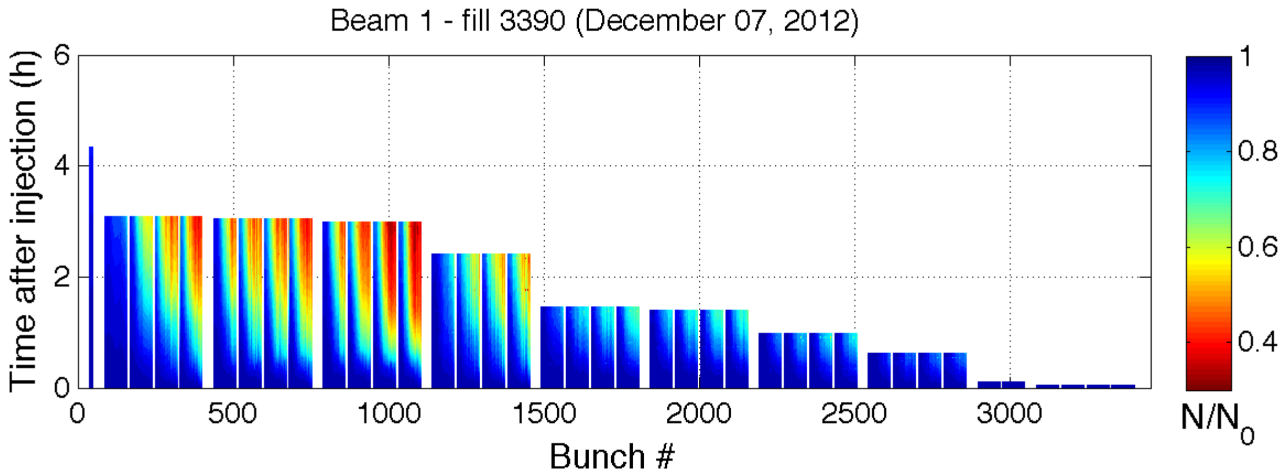
Beam lifetime

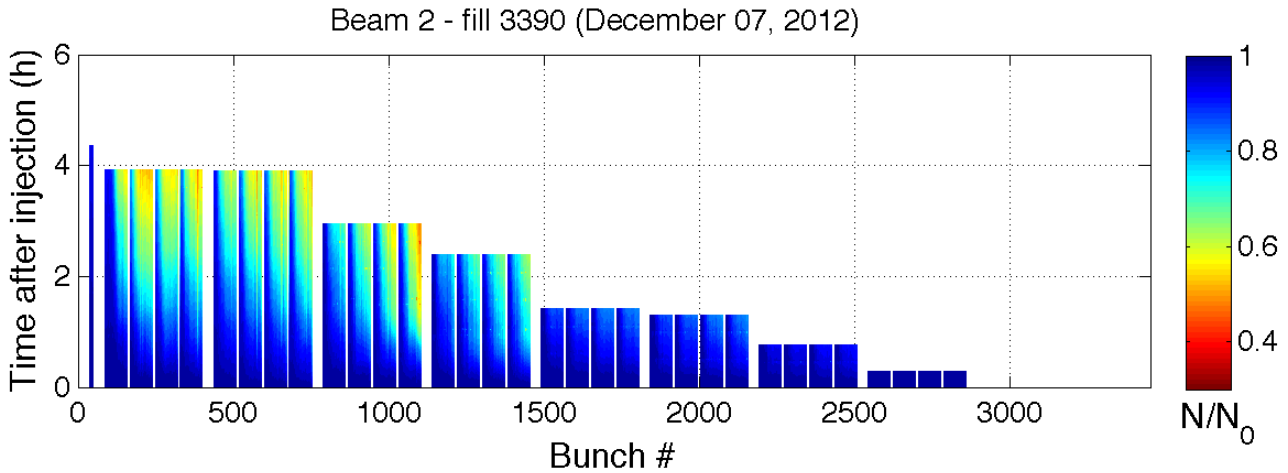




Beam quality evolution (preliminary)

Beam lifetime - Friday Dec. 7th

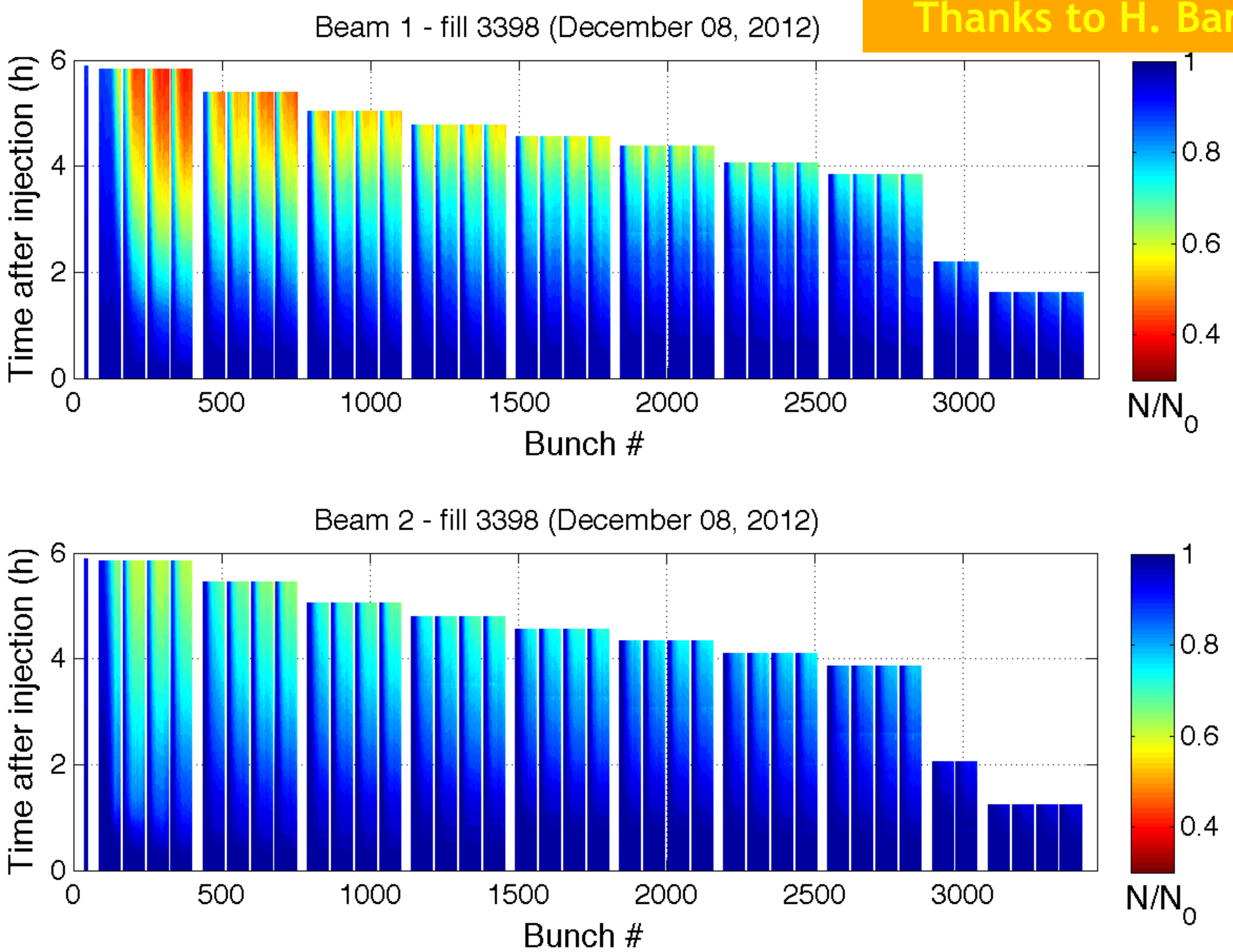




Beam quality evolution (preliminary)

Beam lifetime - Saturday Dec. 8th

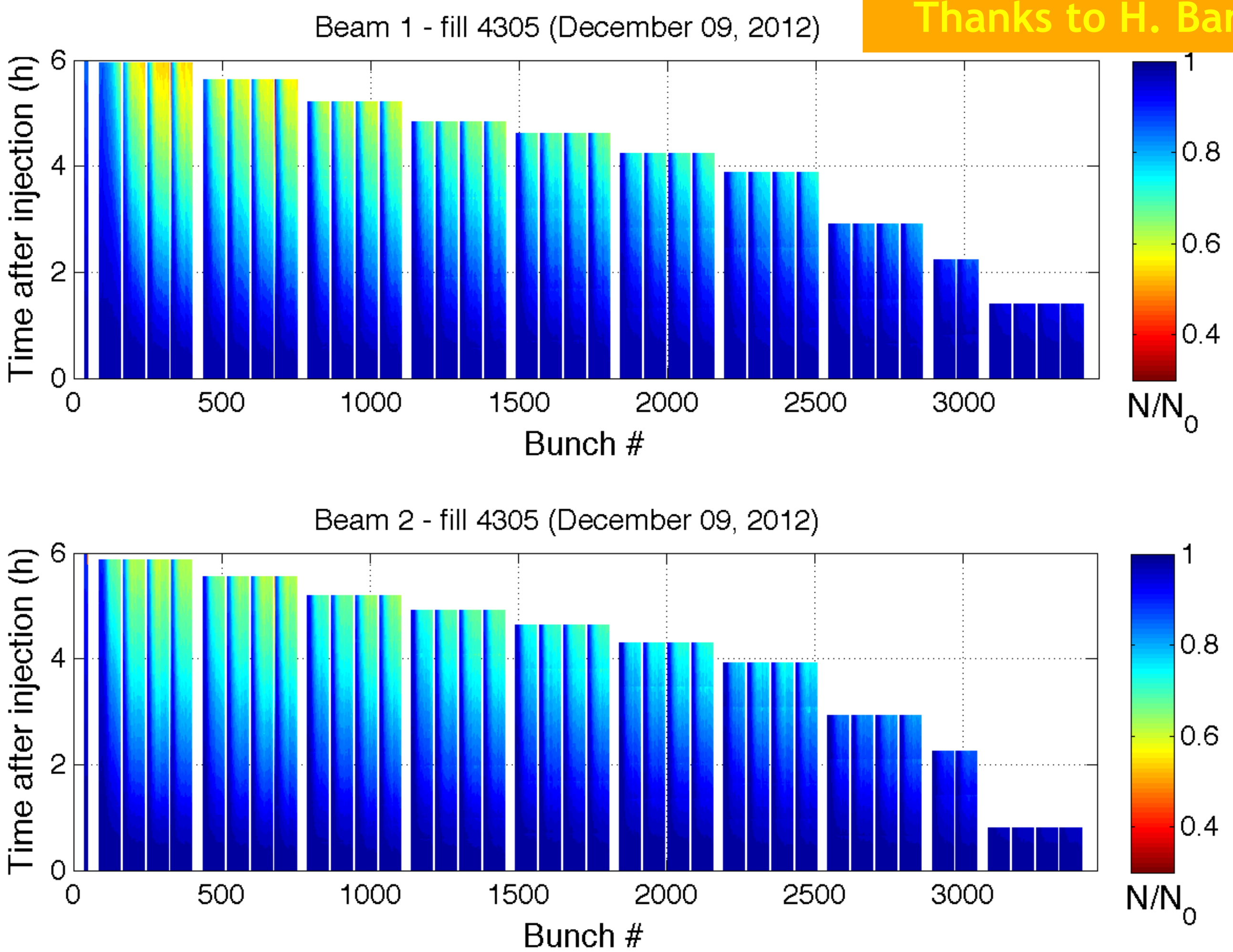
Thanks to H. Bartosik



Beam quality evolution (preliminary)

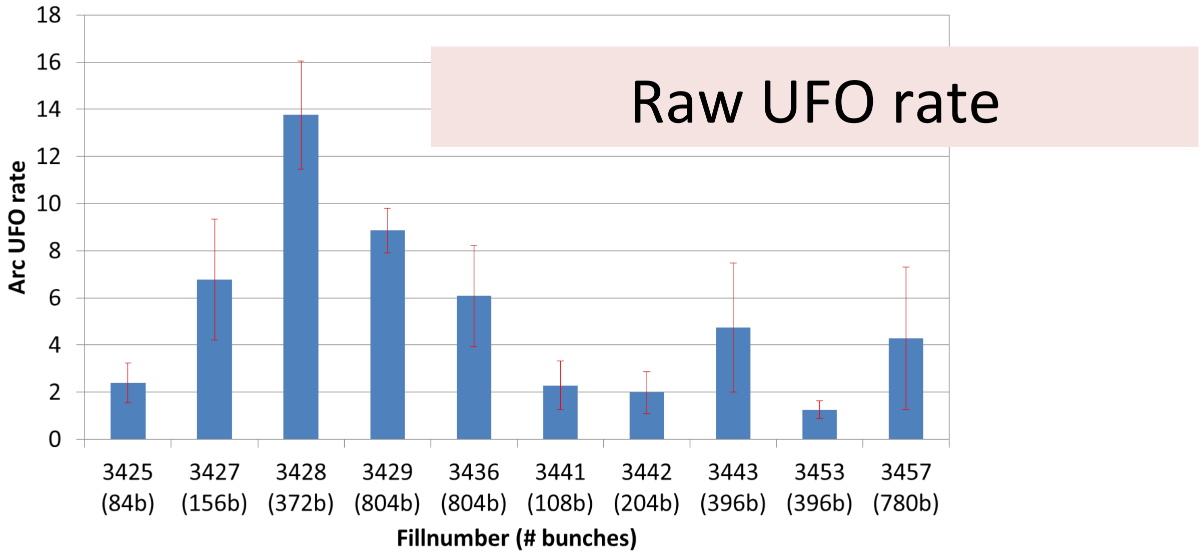
Beam lifetime - Sunday Dec. 9th

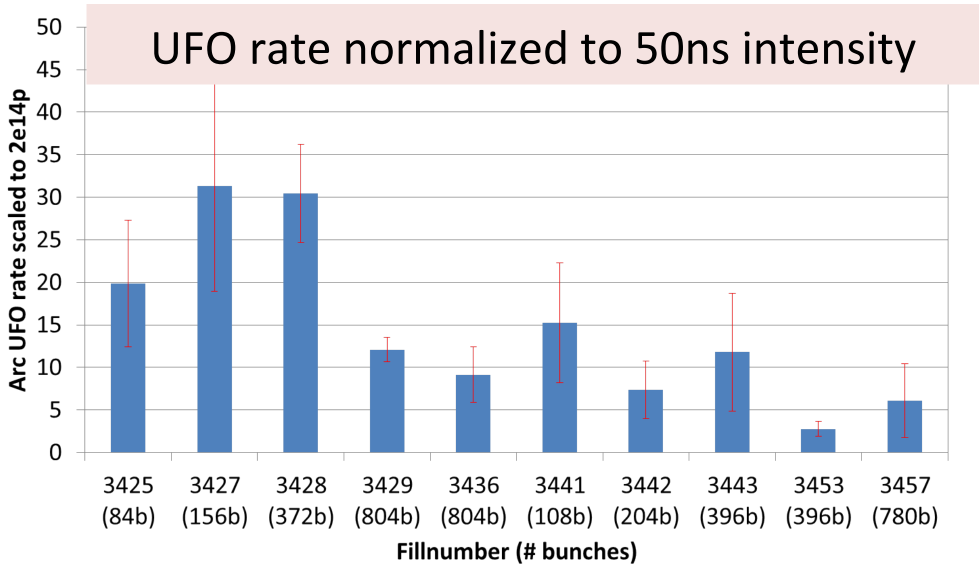
Thanks to H. Bartosik



UFOs

25ns Fills





- Initially > factor 10 increase in UFO activity with 25ns.
- Tendency for conditioning in only 10 fills.

Quench Margin at 7 TeV

Simulations by A. Lechner and the FLUKA team

Peak energy density in MB coils from FLUKA for largest arc UFO in 2012:

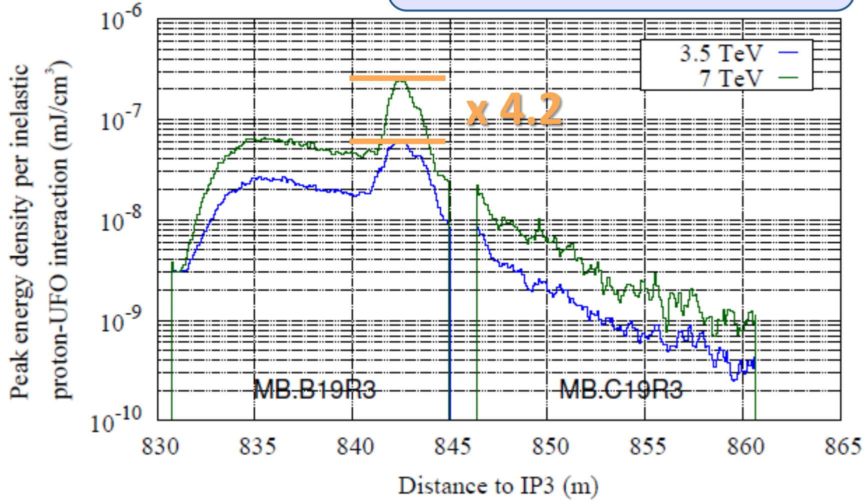
at 3.5TeV: ≈7.8 mJ/cm³

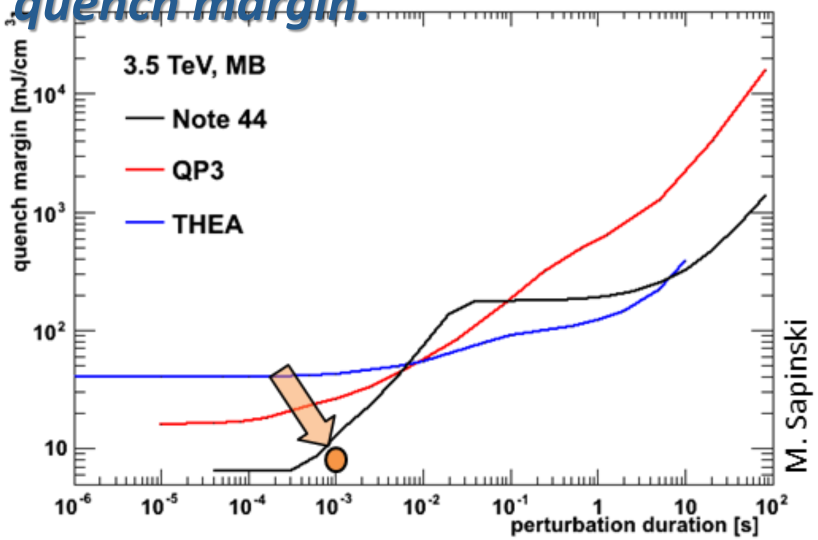
≈ factor 3 below QP3 quench margin.

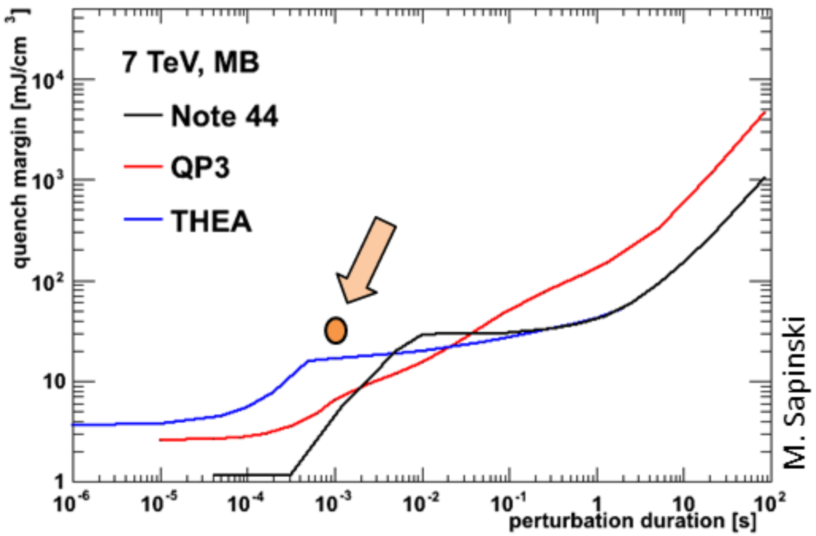
(T. Baer et al., Evian Workshop 2012)

at 7.0TeV: ≈32.5 mJ/cm³

≈ factor 5 – 10 (QP3/Note44) above quench margin.







Energy Extrapolation

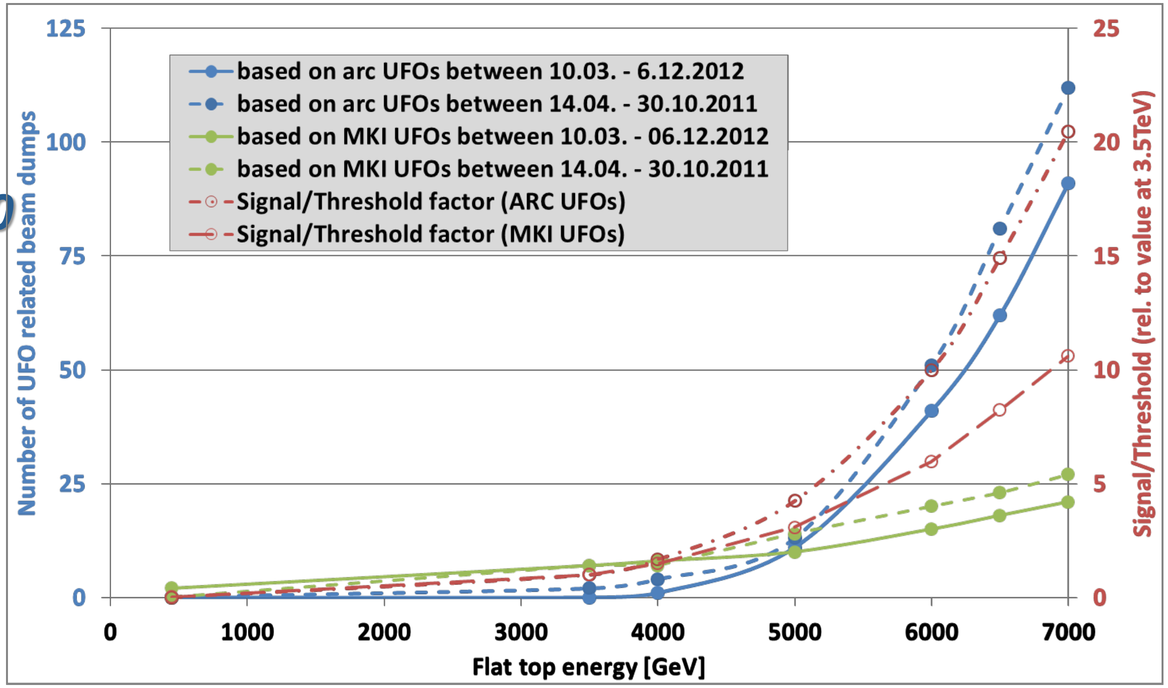
Extrapolation to 7 TeV:

*BLM signal/threshold (based on Note44) is for arc UFOs about **20 times larger** than at 3.5 TeV.*

Based on 2012 arc UFOs:
91 UFO related beam dumps.
(based on 2011: 112 dumps)

*Additionally, **21 beam dumps by MKI UFOs** (2012 data, full cycle).*
(based on 2011: 27 dumps)

For 50ns!



Based on the applied threshold table from 10.12.2012. For MKI UFOs, only the BLMs at Q4 and D2 are considered. The energy scaling applies only to events at flat top, but (for MKI UFOs) the full cycle is taken into account for the extrapolation. Apart from the beam energy, identical running conditions as in 2011/2012 are assumed. In particular not included are: margin between BLM thresholds and actual quench limit, 25ns bunch spacing, intensity increase, beam size, scrubbing for arc UFOs, deconditioning after LS1.

UFO Quench Test

On 15.02.2013 UFO quench test to verify quench level:

1. Large orbit bump in arc (MQ.12L6.B2).

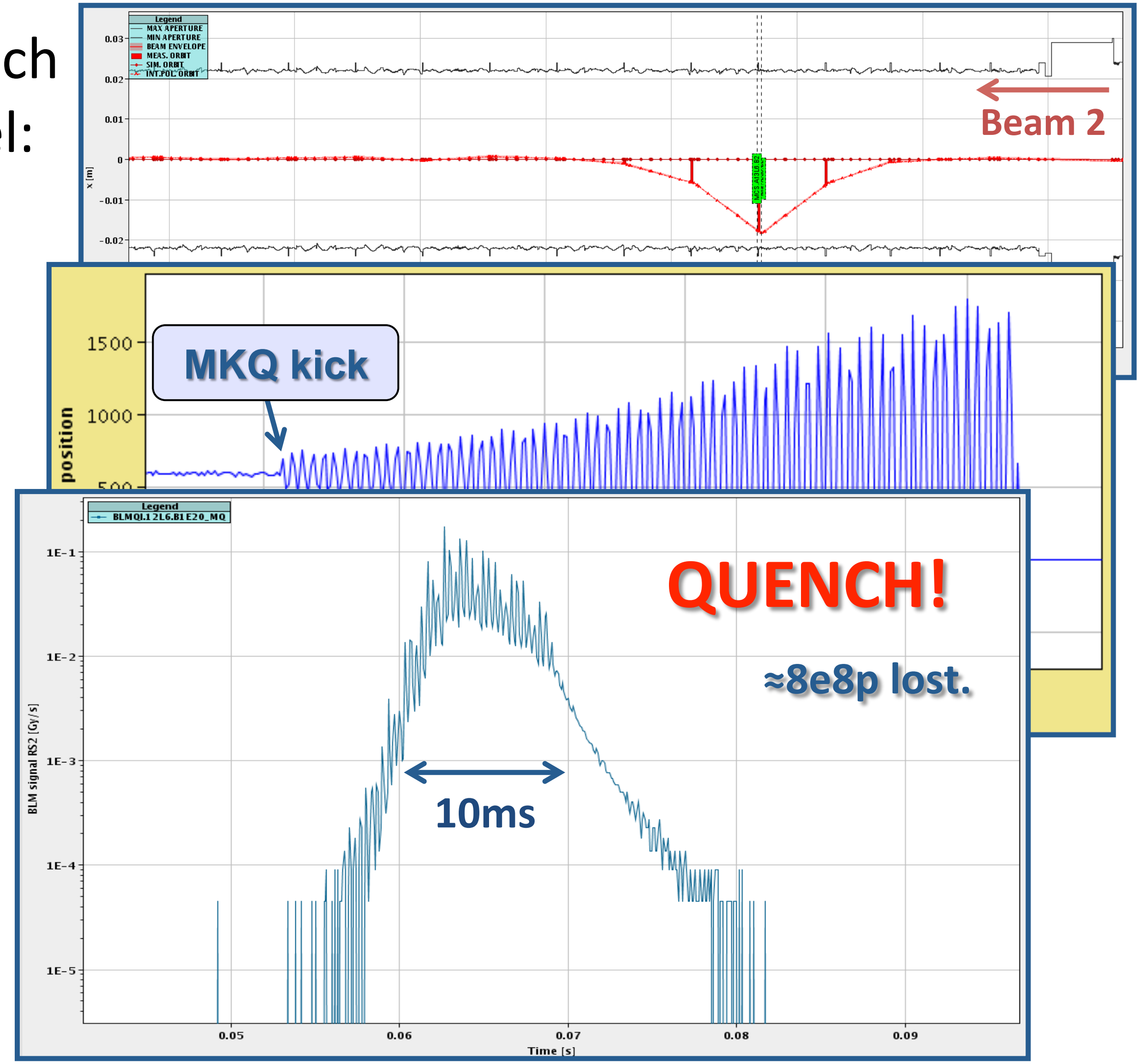
2. Fast beam excitation with tune kicker and transverse damper (inverse sign).

***3.Post analysis ongoing**: Geant4, MadX and FLUKA simulations to determine energy density in magnet.*

Preliminary estimate:

Quench level about a factor 6-13 higher than expected.

(not included in analysis on previous slides)



Summary

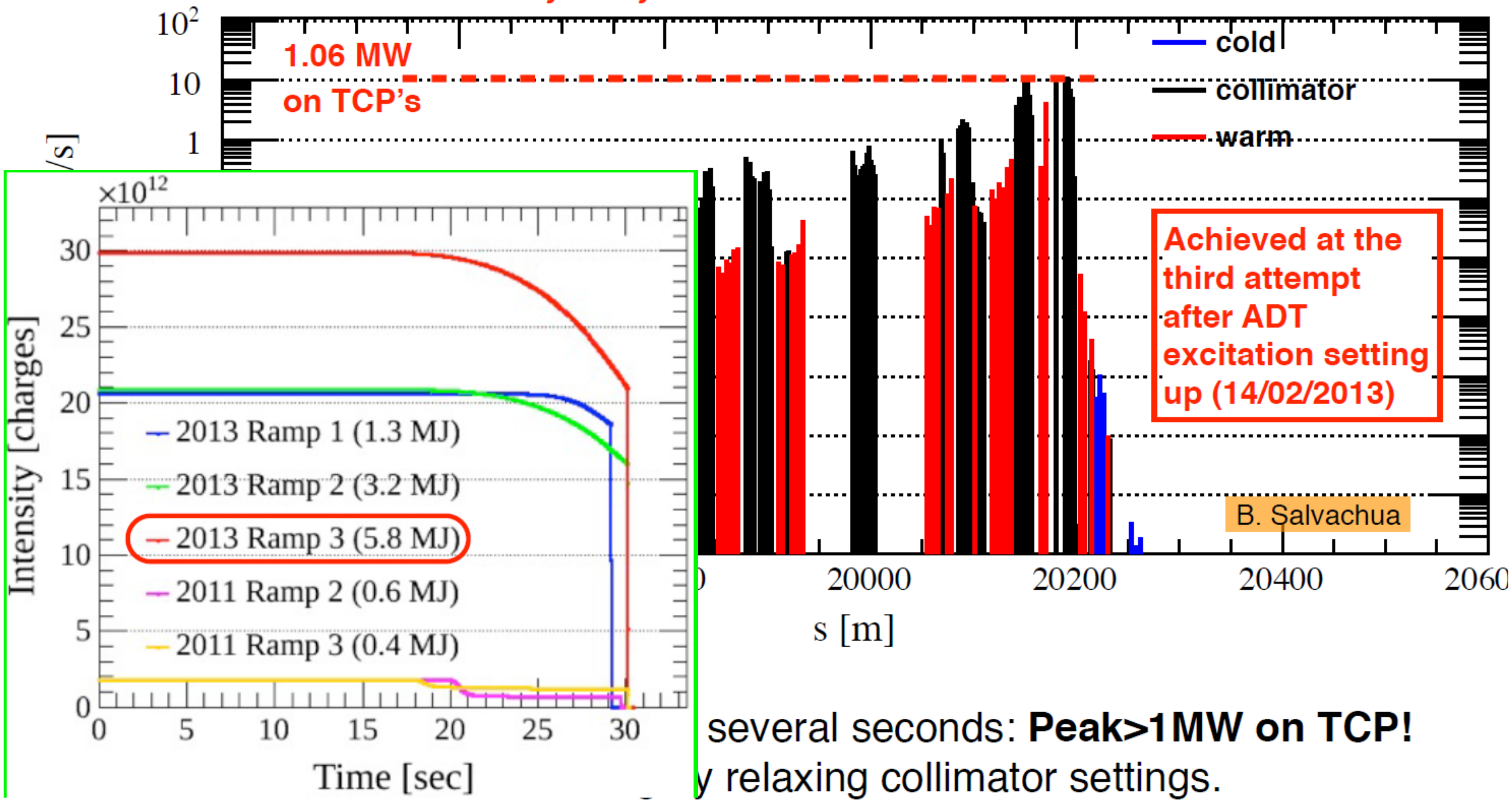
- **21 beam dumps** due to UFOs in 2012 (58 dumps since 2010).
- Temporal width often **< 1 turn (89μs).**
  *At higher energy, some events may be **too fast for active protection.***
- Clear **conditioning effect** of arc UFO rate (≈ factor 5) in 2011/12.
- Extrapolation to after LS1:
  ***25ns**: initially **>10 times higher arc UFO rate** observed, conditioning expected.*
  ***Energy extrapolation** to 7TeV:*
    2012** arc and MKI UFOs would have caused **112 beam dumps (2011: 139).
    *First estimates from **UFO quench test** indicate that **quench level estimates may be too pessimistic.** (factor of 6-13). Detailed analysis is ongoing.*
- Mitigations: *For Arc UFOs, optimized BLM distribution to allow better UFO protection.*

$$N_{dumps} \approx 100 \cdot \underbrace{F_{25ns}}_{10 \rightarrow 2} \cdot \underbrace{F_{quench}}_{0.17 \rightarrow 0.08} \approx 170 \rightarrow 16 \quad \text{(cf 21 in 2012)}$$

Collimators

Collimator quench tests

Preliminary analysis of beam tests done on 14/02/2013



several seconds: **Peak>1MW on TCP!**

y relaxing collimator settings.

Achieved 3.4 times the assumed quench limit at 4.0 TeV **without quenching**!

(2011: only achieved ~65% of 3.5 TeV limit.)

Ongoing work for review

Minimum (assumed) beam lifetime

Quench limit of SC magnets

LHC total intensity reach from collimation
(estimates for Cham. 2012)

$$\boxed{N_{\mathrm{tot}} = \frac{\tau R_q}{\tilde{\eta}_c}}$$

Collimation cleaning at limiting cold location

Preliminary 7 TeV performance estimate
based on ACHIEVED loss rates at 3.5 TeV
(500 kW for protons, 27 kW for ions, τ=1h)

→

Protons: > 1.5 x nominal
Ions: 5-25 x nominal
***Ions (L debris)** closer to limit!*

Some items being addressed:

- **Tracking + energy deposition** simulations of quench test conditions
  - *Estimates are independent of simulations at 4 TeV, but we want to understand the deposited energy in SC coils.*
- Refined beam lifetime analysis and dump statistics
- **Ion cleaning**: effect of cryo collimator of DS in IR2 (no more details here)
  - *Efficiency of DS collimator in IR2 and parametric study (length, material).*
  - *Review IR7 performance reach in light of new quench tests.*
- **LHC impedance limitations**: trade off between settings, instabilities and beta*.

Lead ion Run

Physics requests for the end of the run

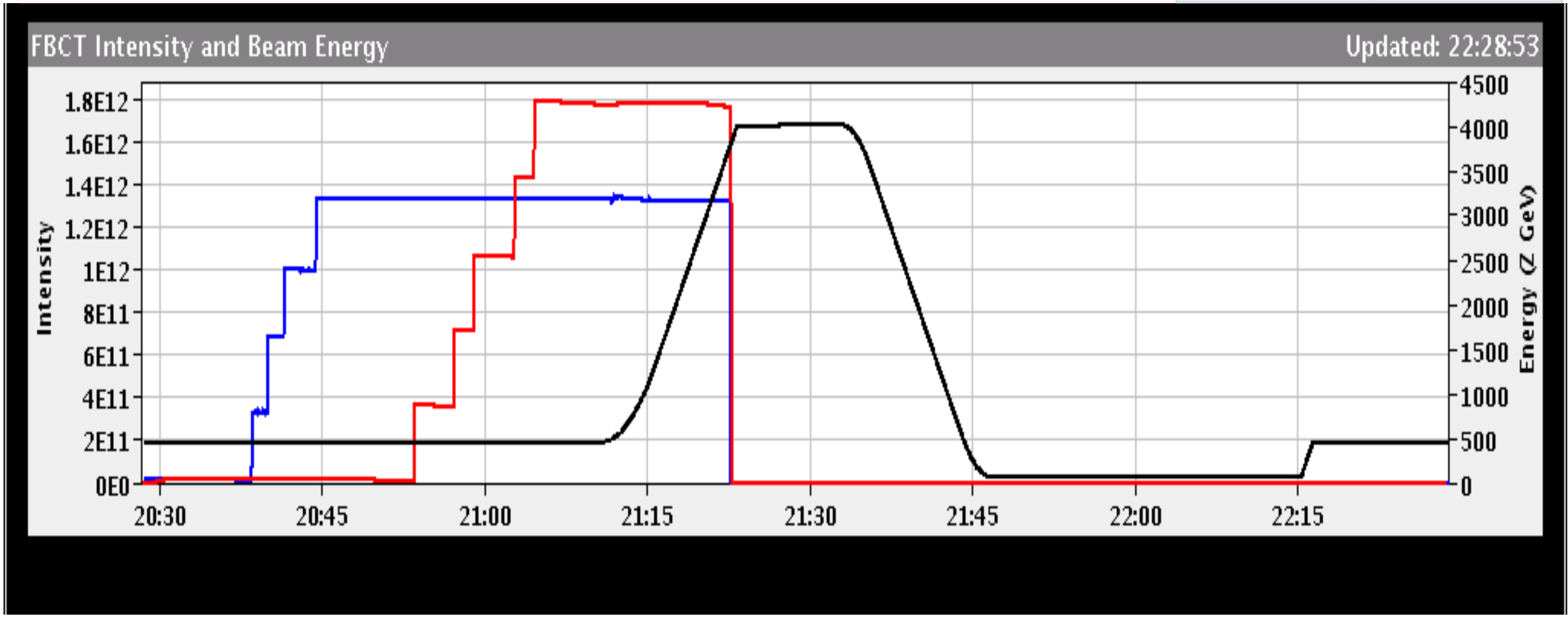
- Initial minimum bias p-Pb for ALICE
  - $L < .05 \times 10^{29}$ cm^{-1} s^{-1}, pile up < .003, 4TeV/beam
- Integrate 30 nb^{-1} in ALICE :
  - L < 1.0 x 10^{29} cm^{-1} s^{-1}; pile up < .05, 4TeV/beam
- High luminosity in ATLAS and CMS
- Beam reversal p-Pb to Pb-p for ALICE, LHCb
- 2 ALICE polarity reversals (also LHCb)
- Few nb^{-1} in LHCb (new to heavy-ion operation)
- 2^{nd} priority: intermediate energy p-p operation; 1.38 TeV/ beam
  - Integrate 5 nb^{-1} in ATLAS, CMS

LHC new features

- Unequal revolution frequency injection and ramp
  - Potential problems of moving long-range beam-beam kicks (killed this mode of operation of RHIC, was a killer in the ISR)
- Frequency-locking, off-momentum operation at top energy, cogging of IPs back to proper positions
- New squeeze including ALICE to 0.8 m and LHCb to 2 m
- Off-momentum correction of squeeze
- Usual, many collimation setups, loss maps in various conditions
- Small crossing angle in ALICE (for ZDC)
- New filling scheme with collisions of 2 trains in LHCb
  - Very close encounters near ALICE

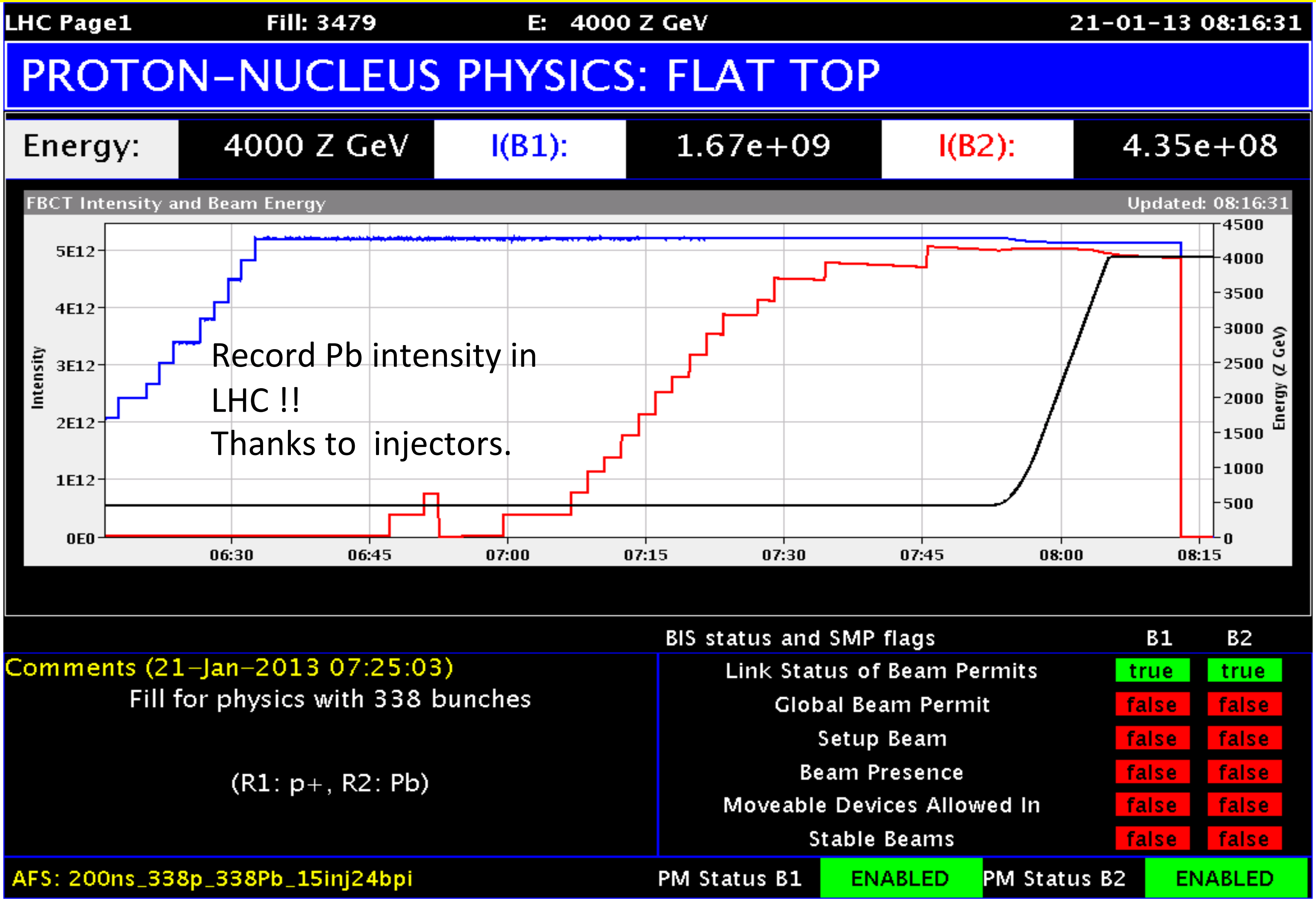
The Acid Test, 20/1/2013

Fill 3474
First injection and ramp of Pb trains against proton trains
(the MD the team had been trying to do since November 2011).



Conclusion: The moving long-range beam-beam encounters did not cause significant beam losses or emittance blow-up

Full filling scheme 21st Jan.



Run overview

Monday	7	January
Tuesday	8	January
Wednesday	9	January
Thursday	10	January
Friday	11	January
Saturday	12	January
Sunday	13	January
Monday	14	January
Tuesday	15	January
Wednesday	16	January
Thursday	17	January
Friday	18	January
Saturday	19	January
Sunday	20	January
Monday	21	January
Tuesday	22	January
Wednesday	23	January
Thursday	24	January
Friday	25	January
Saturday	26	January
Sunday	27	January
Monday	28	January
Tuesday	29	January
Wednesday	30	January
Thursday	31	January
Friday	1	February
Saturday	2	February
Sunday	3	February
Monday	4	February
Tuesday	5	February
Wednesday	6	February
Thursday	7	February
Friday	8	February
Saturday	9	February
Sunday	10	February

→ Restart (7–10 January)

→ First injection in the LHC (11 January)

→ Injection checks and Squeeze commissioning (12–15 January)

>4 days lost to cryo, power failures

→ Collimation set up, IR2 aperture measurements, first collisions (16–19 January)

→ First Stable beams, first injection of trains of p and Pb (20 January)

p-Pb (21–31 January):

→ End of ALICE minimum bias data taking (25 January)

→ ALICE polarity change (27 January)

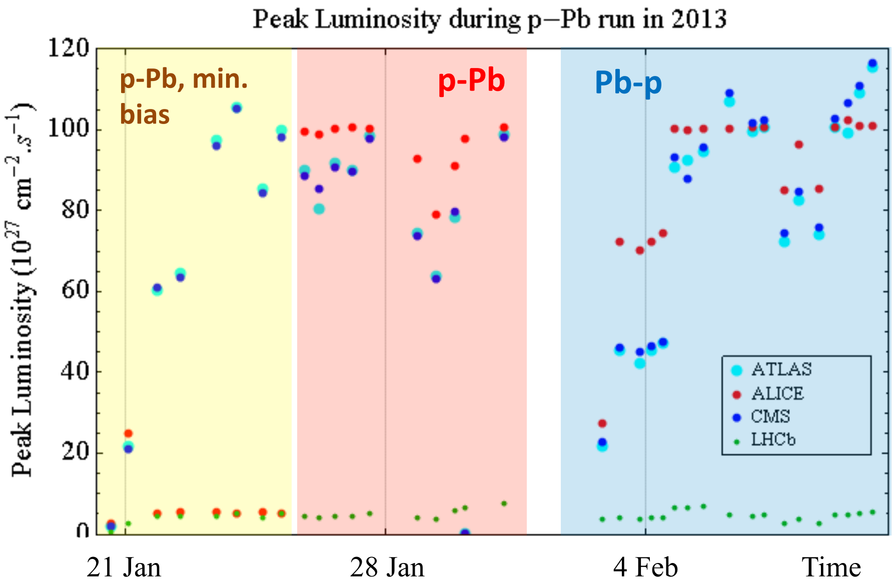
→ Van der Meer scans (28–29 January)

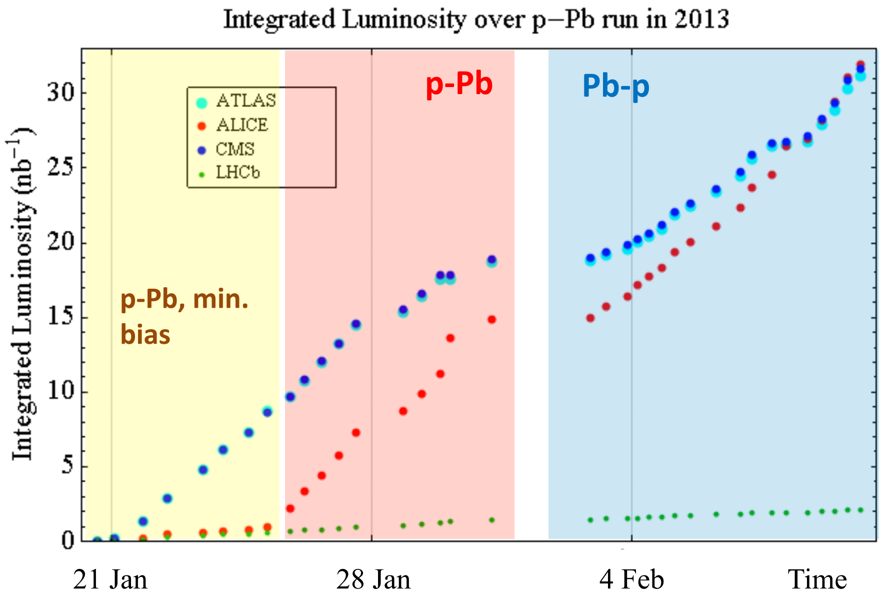
→ Pb source refill (30 January)

→ Beams reversal (1–2 February)

Pb-p (3–10 February):

→ Van der Meer scans (8–10 February)





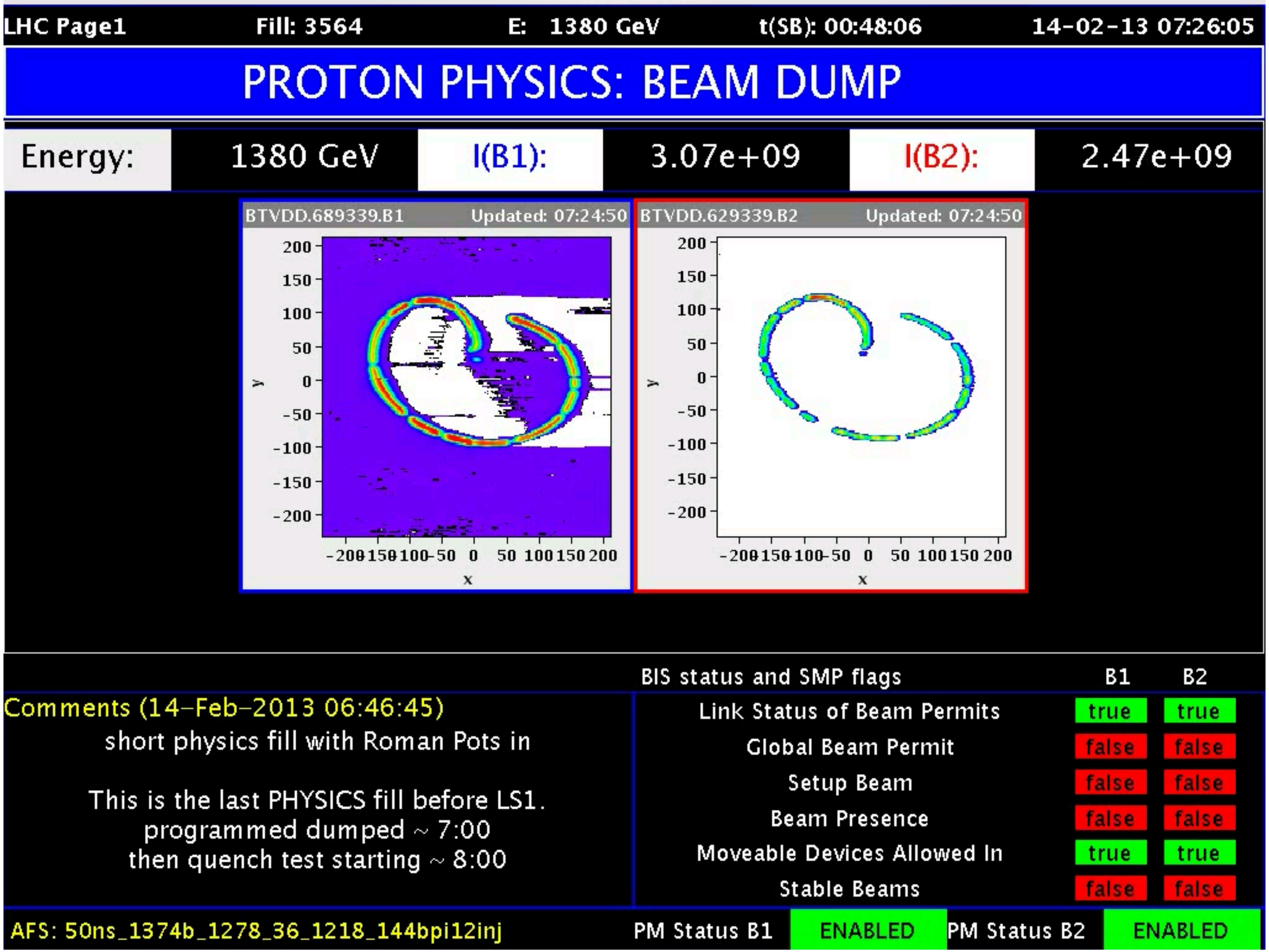
- Full instantaneous luminosity 1×10^{29} cm^{-2}.s^{-1} already reached with the first fill with full filling scheme
- Levelling in ALICE at 1×10^{29} cm^{-2}.s^{-1} in almost all standard fills
- Two fills were done with IP1 and 5 separated, allowing ALICE to catch up after initial minimum-bias
- Van der Meer scans done in both configurations
- Final integrated luminosity above experiments' request of 30 nb^{-1}
- The run ended with record peak luminosity of 1.15×10^{29} cm^{-2}.s^{-1}, record turn around of 2.37 h

ALICE: 31.94 nb^{-1} ATLAS: 31.2 nb^{-1} CMS: 31.69 nb^{-1} LHCb: 2.12 nb^{-1}

Summary LHC p-Pb run

- A new mode of operation, unforeseen in the baseline design of the LHC, was commissioned in 10 days (including >4 days' down time).
- The physics requirements were fulfilled in both configurations p-Pb and Pb-p in three weeks of physics,
- ALICE, ATLAS, CMS, LHCb, ALFA, TOTEM, LHCf all took data.
- Fills were routinely dumped by the BPMS false reading
- The run gave important data to prepare future high luminosity Pb-Pb and p-Pb runs.

THE LAST PHYSICS BEAM OF LHC RUN 1 (2009 - 2013)



Thank you

HL-LHC LIU Performance Review (8-10 October, CERN)

- Review 'Present' Performance with 25ns
- Review present assumptions (radiation damage) on needed shutdowns
- Review present limitations and 'staged' upgrades to the injectors and the LHC
- For each staged upgrade estimate
  - Resources needed (M+P)
  - Increase in yearly Integrated luminosity
  - Shutdown time needed
- Propose optinized machine plan for integrated luminosity and shutdowns till mid 2030s

Outlook for LHC heavy-ion programme, post-LS1

- Prospects of higher performance in **p-Pb**:

$$L \sim \text{several} \times 10^{29}\ \text{cm}^{-2}\text{s}^{-1}\ \ \text{at}\ \sqrt{s_{NN}} = 8.16\ \text{TeV}\ (6.5Z\ \text{TeV/beam})$$

  – Usual scalings of geometrical emittance, β* with energy
  – Higher p intensity (solve BPM problems, …)

- Prospects of higher performance in **Pb-Pb**:

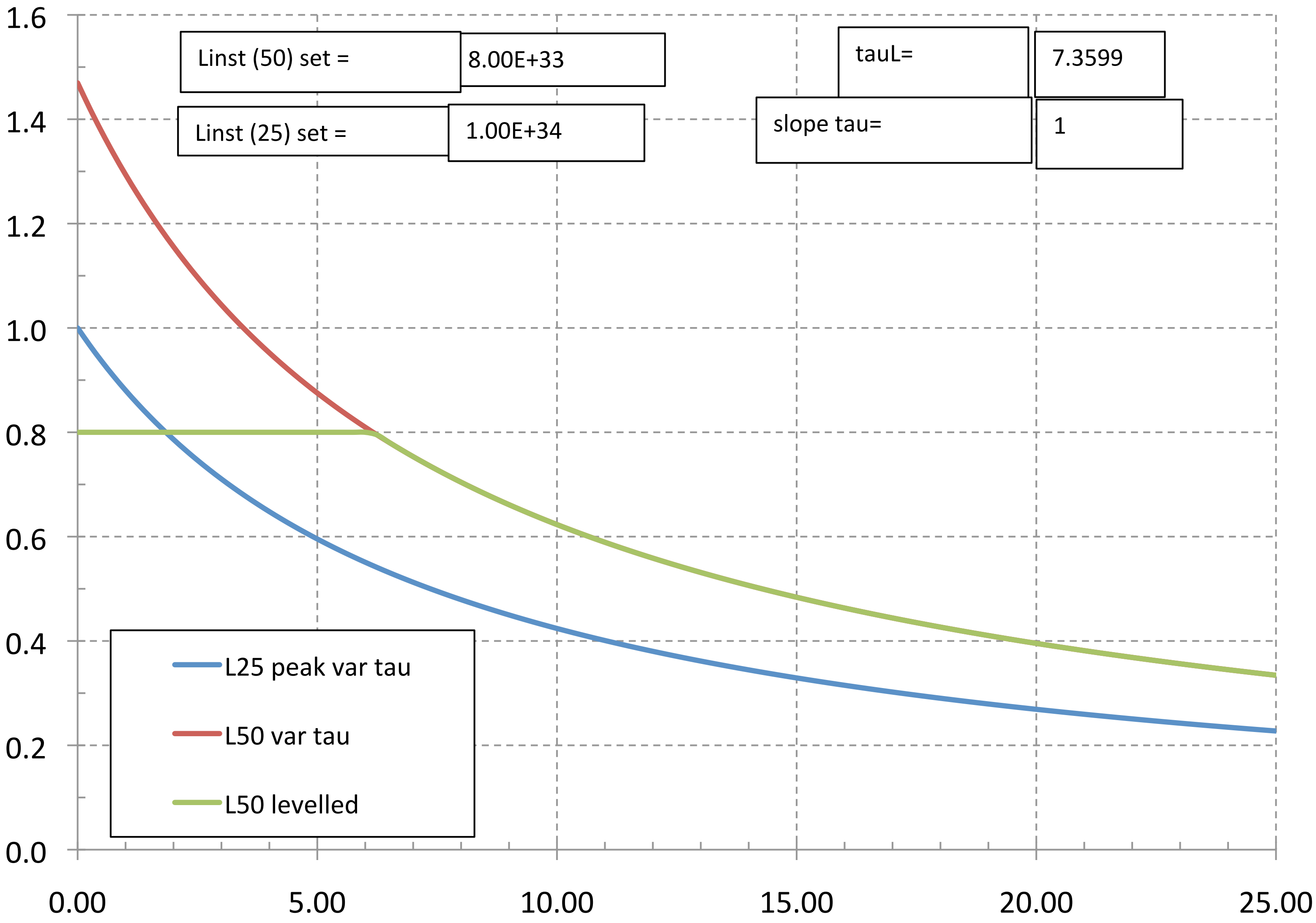
$$L \sim \text{few} \times 10^{27}\ \text{cm}^{-2}\text{s}^{-1}\ \ \text{at}\ \sqrt{s_{NN}} = 5.125\ \text{TeV}\ (6.5Z\ \text{TeV/beam})$$

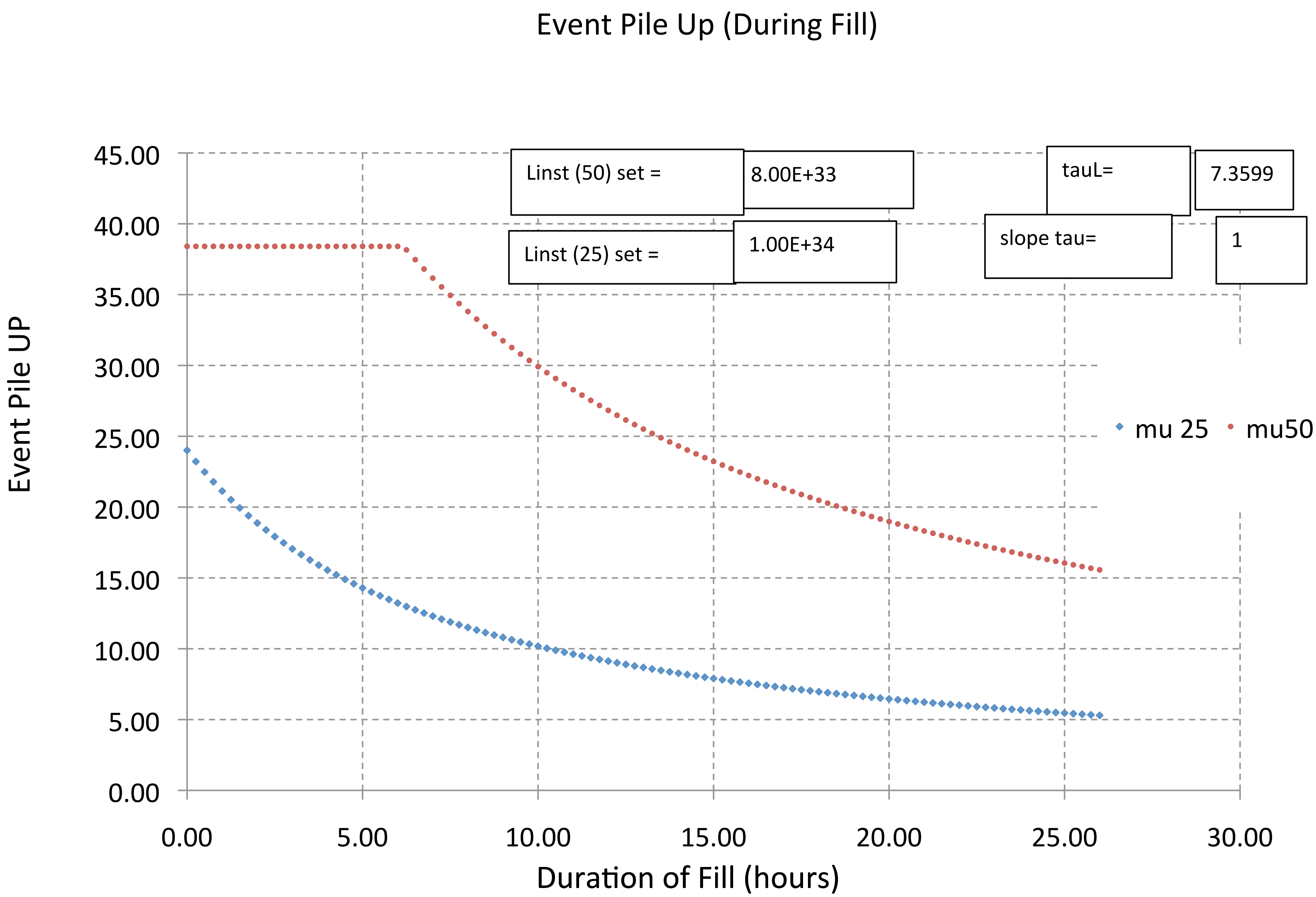
  – Pb injector performance in p-Pb
  – Quench limits ?
  – Mitigation strategies for DS quenches by BFPP beams from IPs demonstrated in 2011

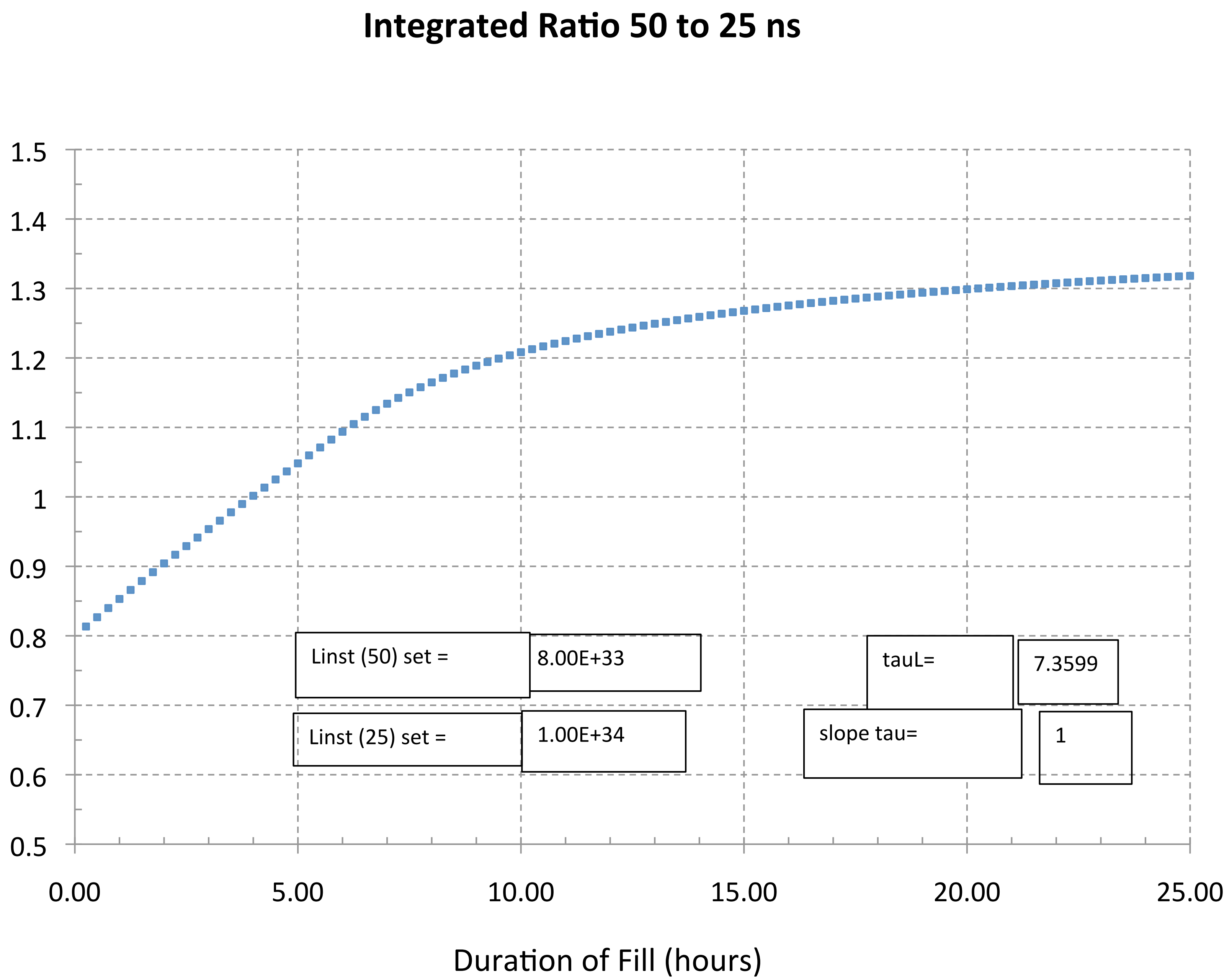
- It will be crucial to define physics priorities and luminosity-levelling strategies !
  – Luminosity decay from burn-off will dominate

Comparison 25ns and 50ns

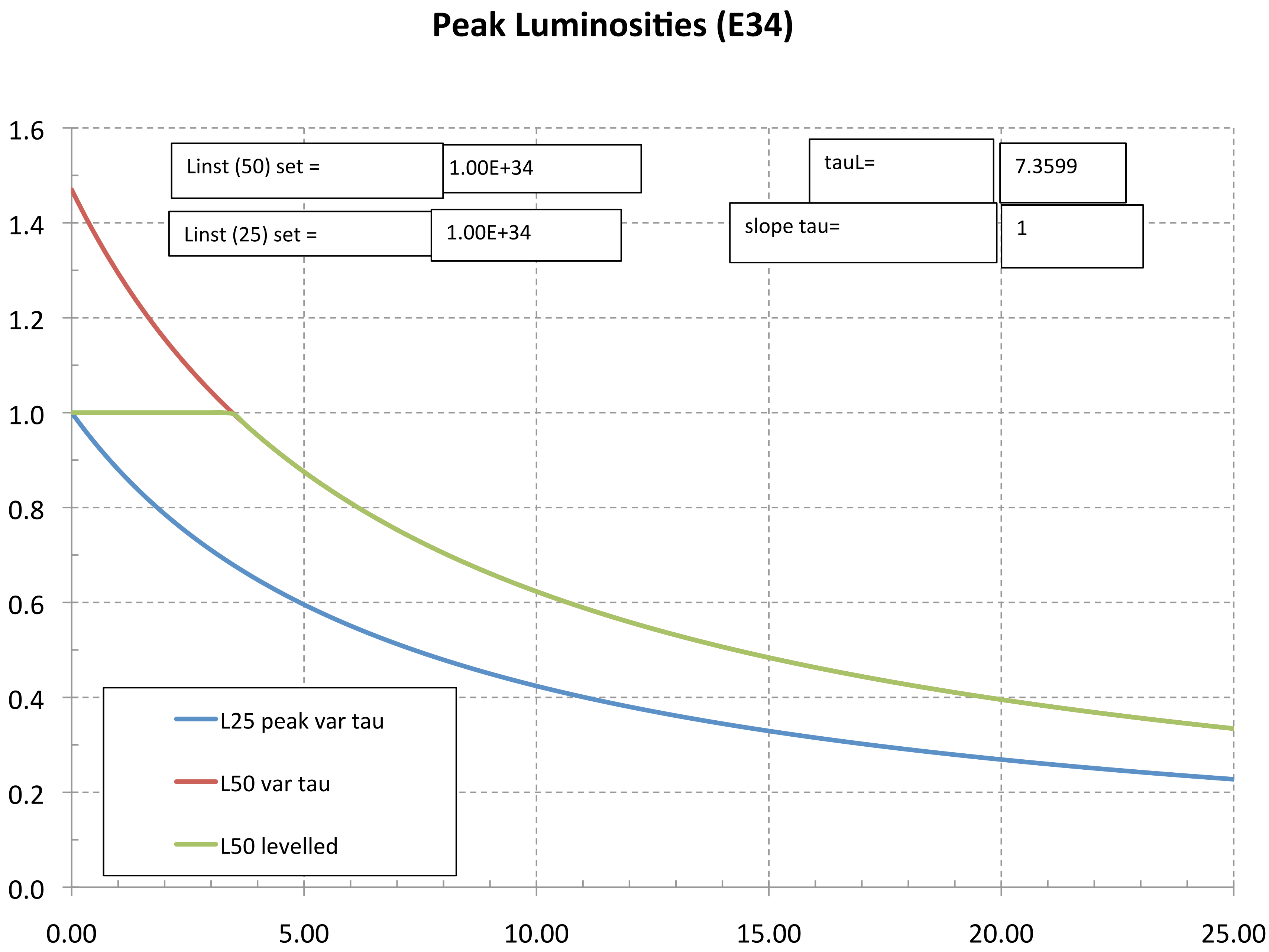
Peak Luminosities (E34)

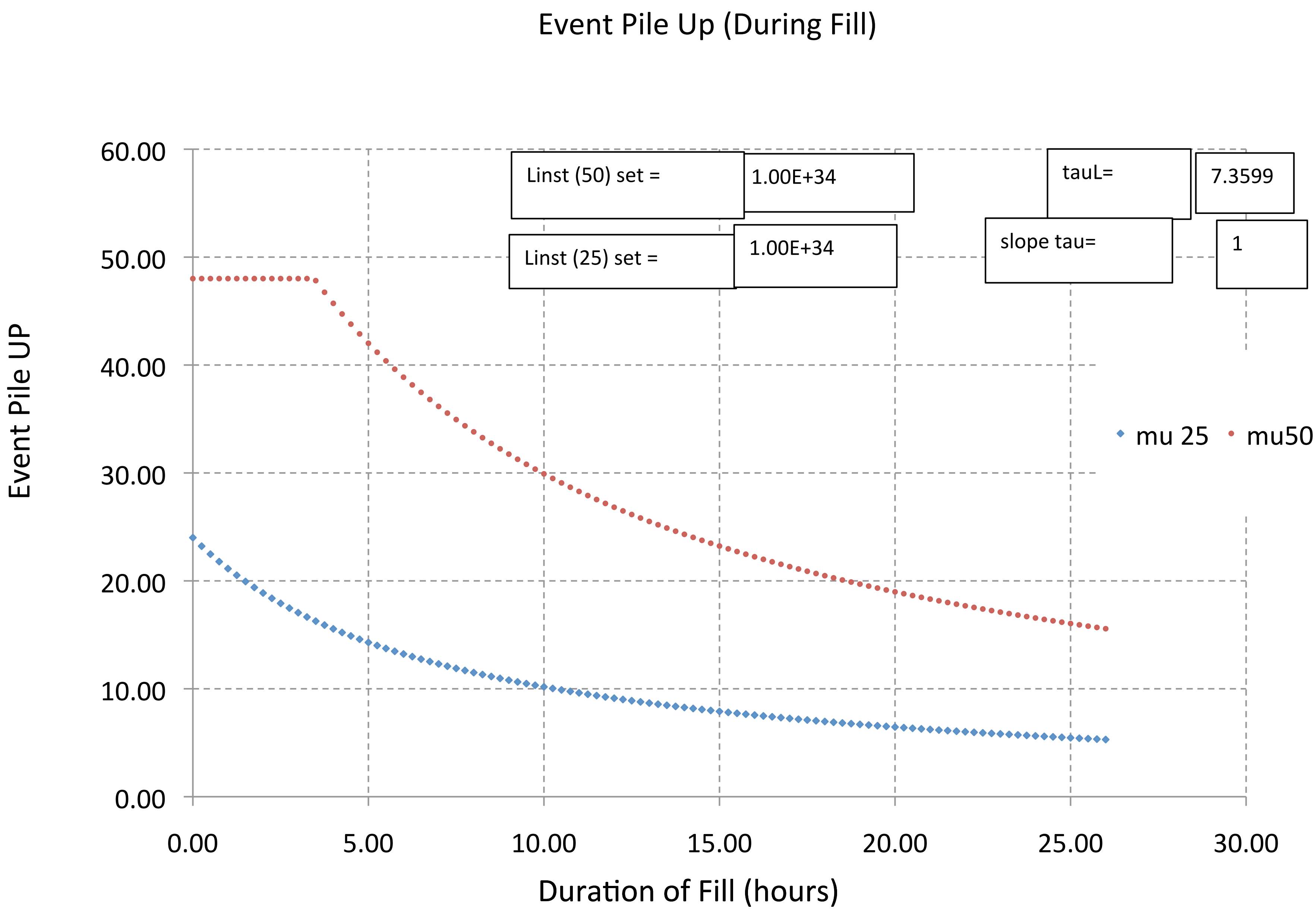



Event Pile Up (During Fill)
Linst (50) set =
8.00E+33
Linst (25) set =
1.00E+34
tauL=
7.3599
slope tau=
1
Event Pile UP
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
Duration of Fill (hours)
mu 25
mu50

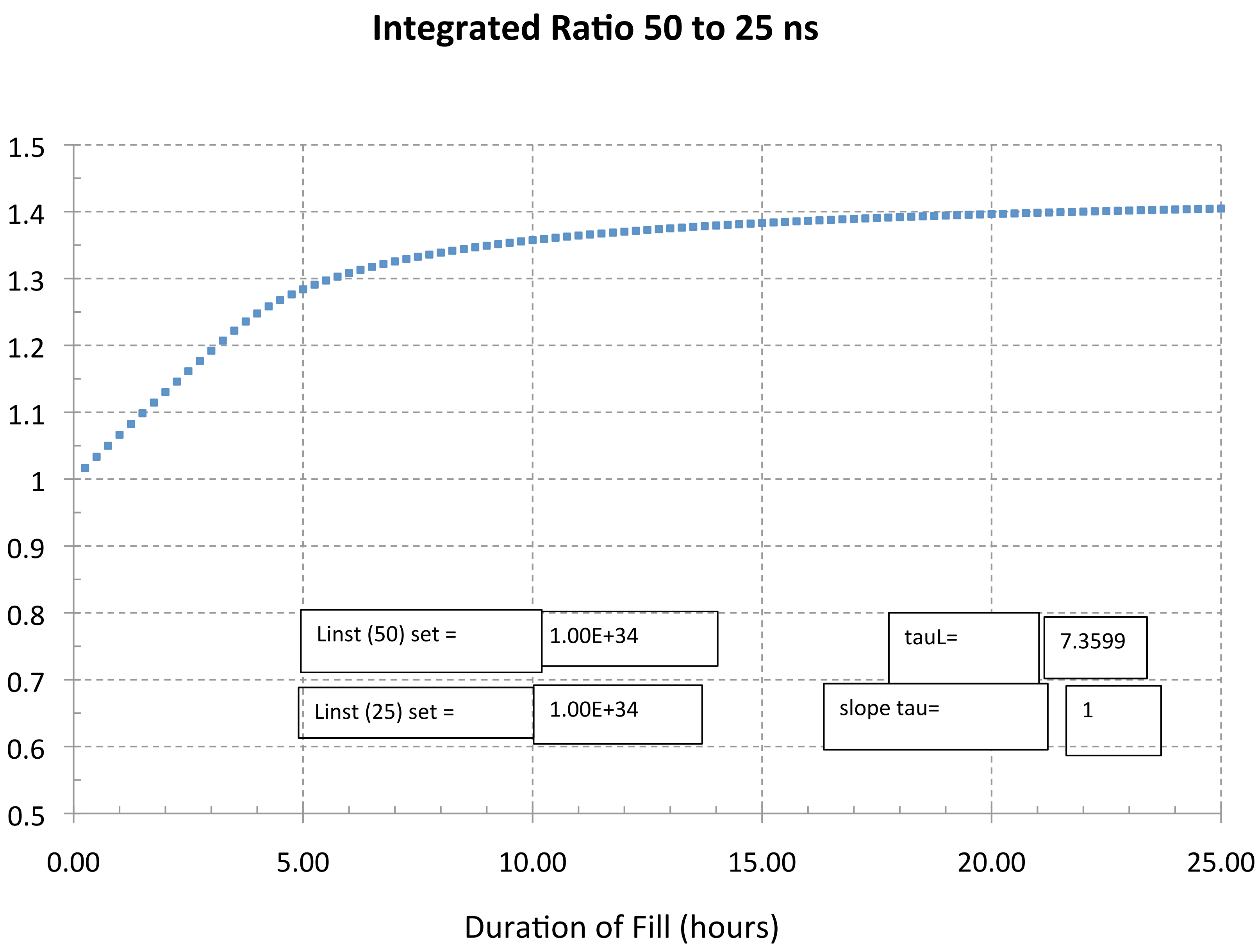


Integrated Ratio 50 to 25 ns
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.00
5.00
10.00
15.00
20.00
25.00
Duration of Fill (hours)
Linst (50) set =
8.00E+33
Linst (25) set =
1.00E+34
tauL=
7.3599
slope tau=
1


Peak Luminosities (E34)
Linst (50) set =
1.00E+34
Linst (25) set =
1.00E+34
tauL=
7.3599
slope tau=
1
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.00
5.00
10.00
15.00
20.00
25.00
L25 peak var tau
L50 var tau
L50 levelled



Event Pile Up (During Fill)
Linst (50) set =
1.00E+34
Linst (25) set =
1.00E+34
tauL=
7.3599
slope tau=
1
mu 25
mu50
Event Pile UP
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
Duration of Fill (hours)


Integrated Ratio 50 to 25 ns
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.00
5.00
10.00
15.00
20.00
25.00
Duration of Fill (hours)
Linst (50) set =
1.00E+34
Linst (25) set =
1.00E+34
tauL=
7.3599
slope tau=
1