The First Years of LHC Operation

Steve Myers

For the LHC team and

All our international collaborators and contributors

Main Topics

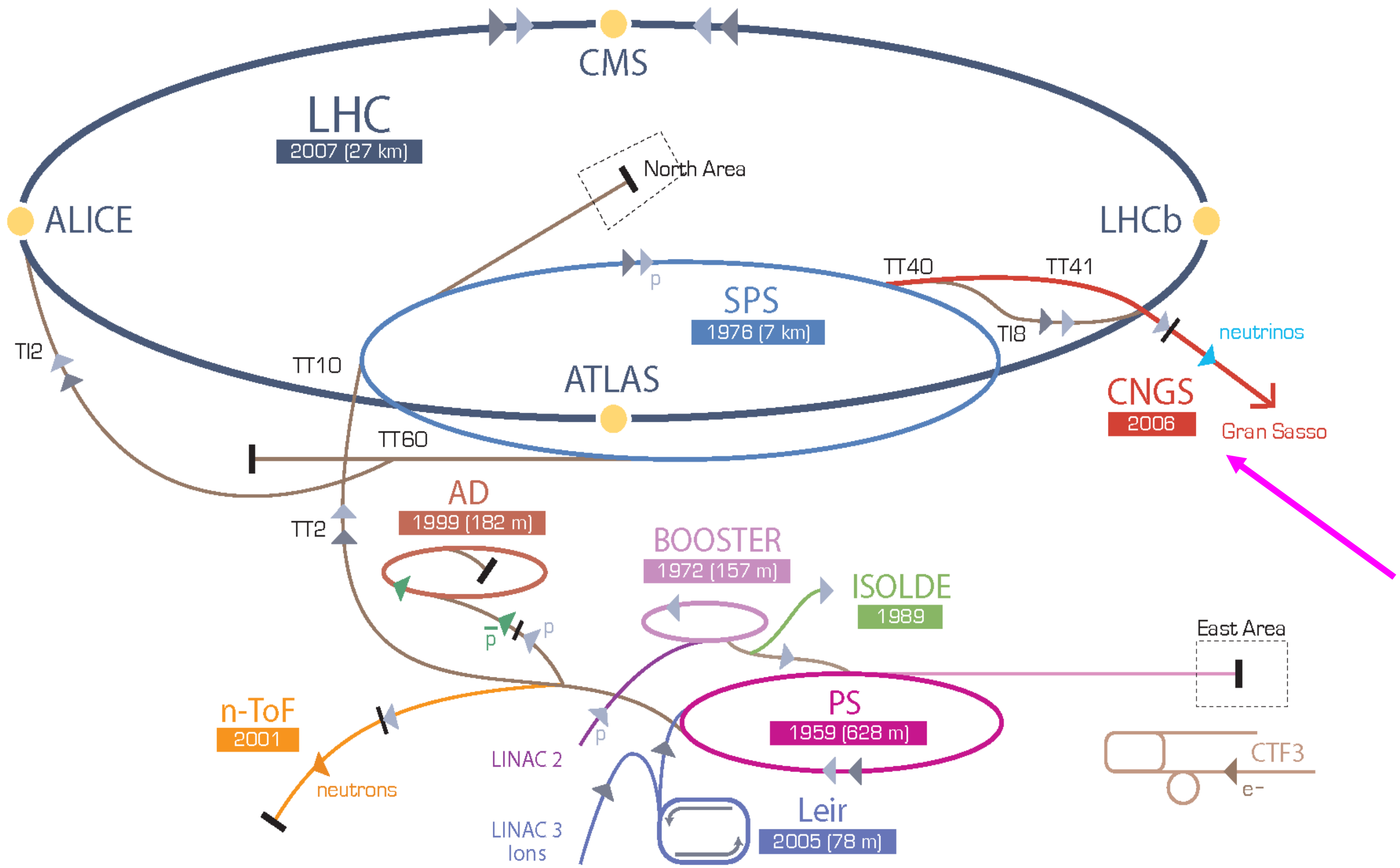
- LHC in 2008
- Repair

Introduction

- LHC Performance in 2010/2011/2012
- Estimates of Performance in 2012
- Future
  - Long Shutdown 1 (LS1) 2013-2014
  - Estimated performance in 2015
- Upgrades
  - Luminosity Upgrade (HL-LHC)
  - Energy Upgrade (HE-LHC)
  - LHeC
  - LEP3

Lack of time

CERN Accelerator Complex



p (proton) ion neutrons p̄ (antiproton) proton/antiproton conversion neutrinos electron

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice

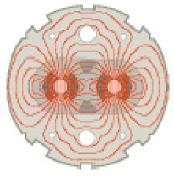
LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

The LHC

Superconducting Proton Accelerator and Collider installed in a 27km circumference underground tunnel (tunnel cross-section diameter 4m) at CERN

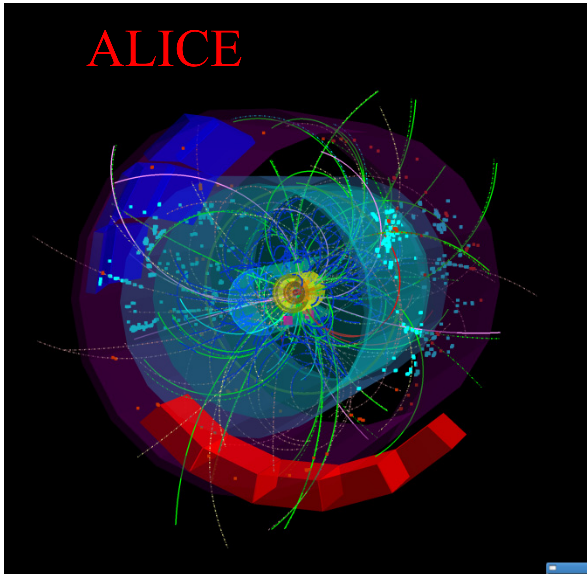
Tunnel was built for LEP collider in 1985

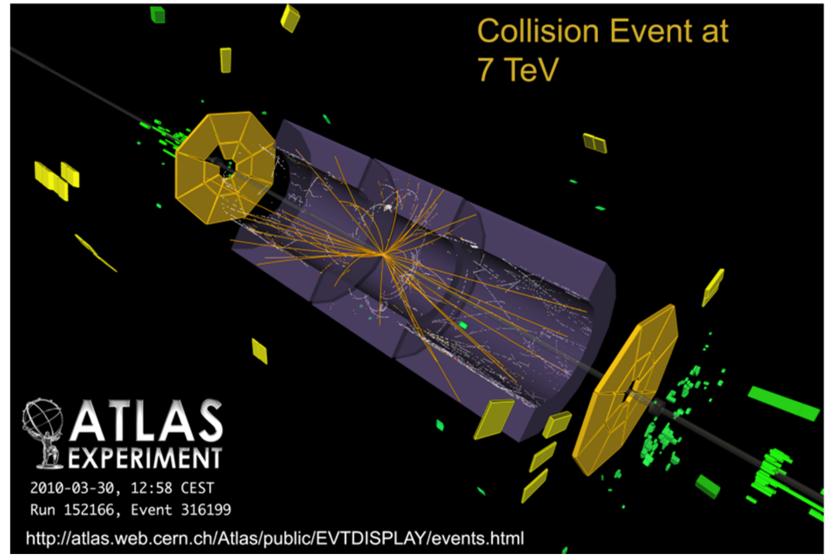
LHC: Some of the Technical Challenges



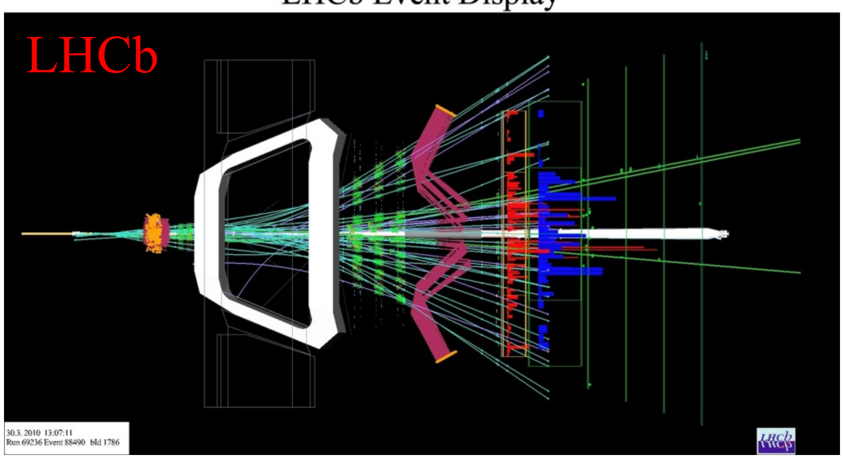
Circumference (km)	26.7	100-150m underground
Number of Dipoles	1232	Cable Nb-Ti, cold mass 37million kg
Length of Dipole (m)	14.3	
Dipole Field Strength (Tesla)	8.4	Results from the high beam energy needed
Operating Temperature (K)	1.9	Superconducting magnets needed for the high magnetic field Super-fluid 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

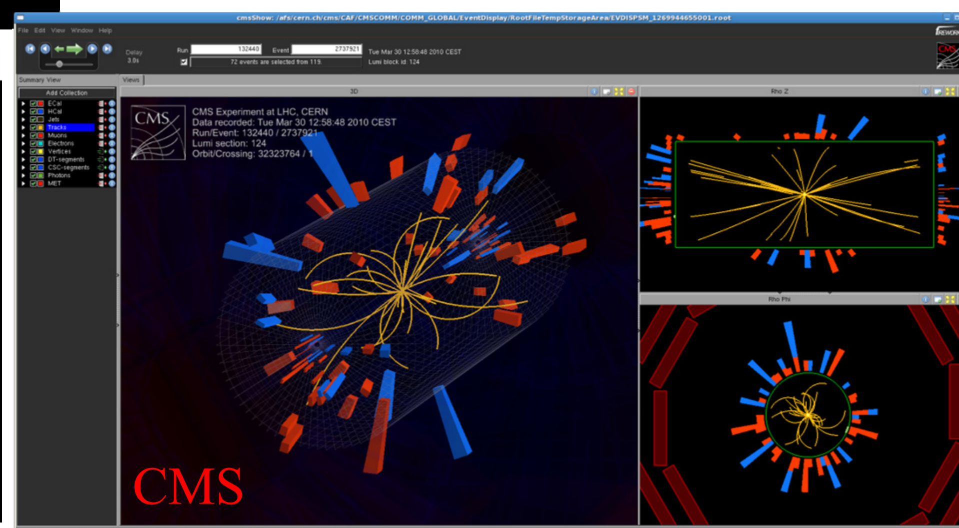
LHC: First collisions at 7 TeV on 30 March 2010





LHCb Event Display





Peak Luminosity for First Run 10^{27} cm^{-2} s^{-1}

Maximizing the Luminosity

Luminosity (round beams):

$$L = \frac{n_b \cdot N_{bunch1} \cdot N_{bunch2} \cdot f_{rev}}{4\pi \cdot \beta^* \cdot \varepsilon_n} \cdot R(\phi, \beta^*, \varepsilon_n, \sigma_s)$$

➔1) maximize bunch brightness [N_{bunch}/ε_n]
beam-beam limit and injector complex performance

➔2) minimize beam size [β^*] (constant beam power)

➔3) maximize number of bunches (beam power limit)

➔4) compensate for ‘R’

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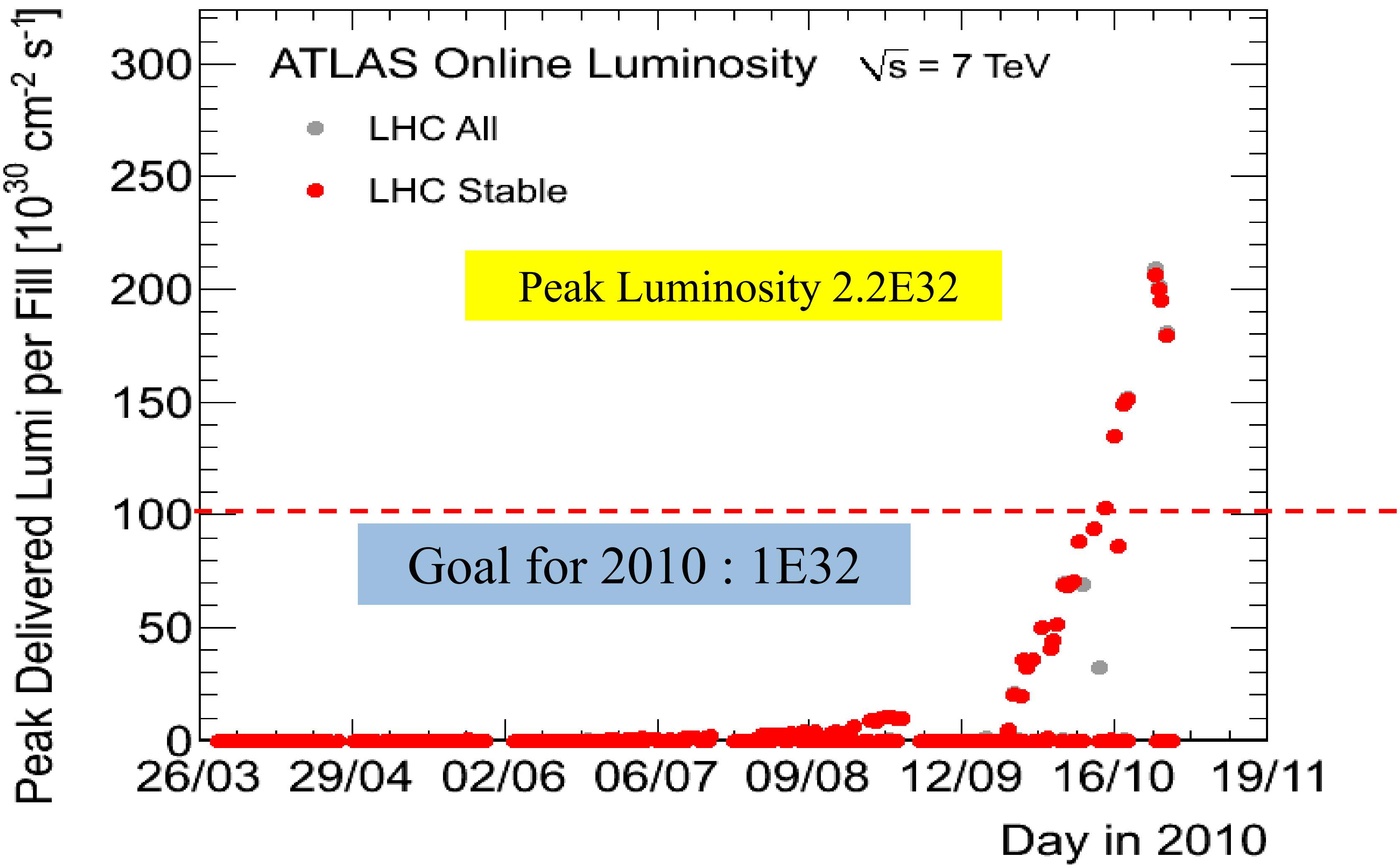
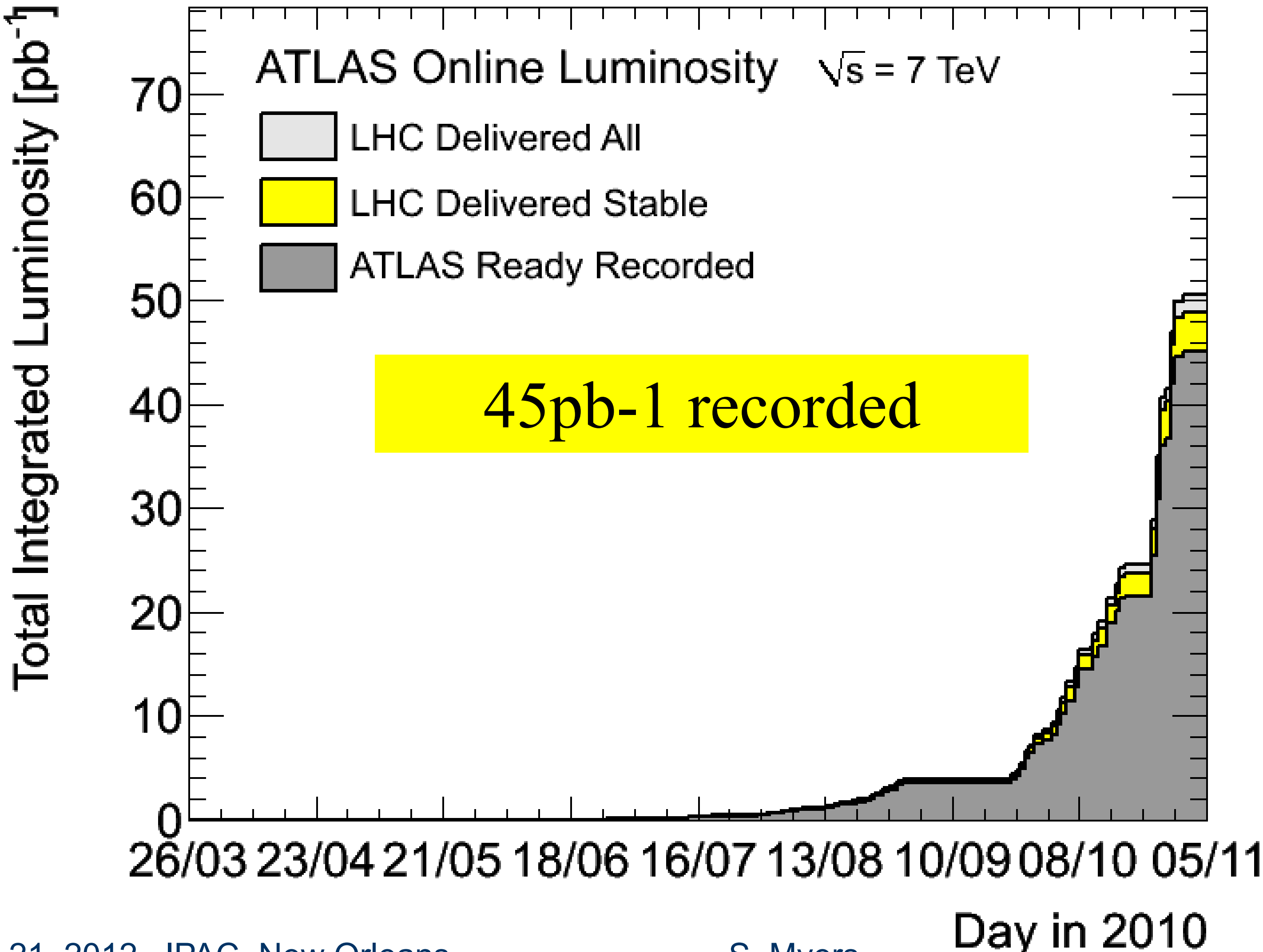
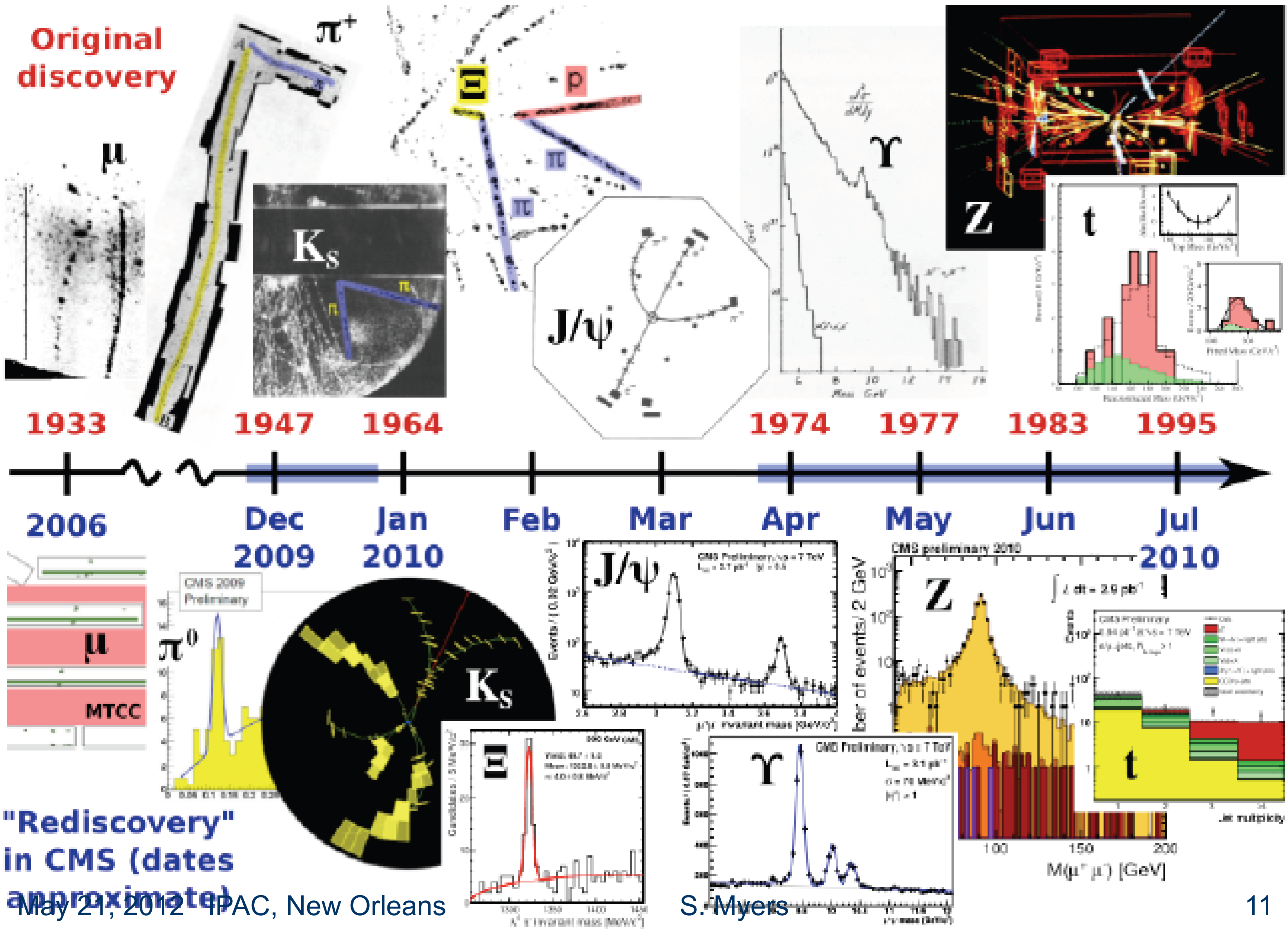
Peak Luminosity 2010



Integrated Luminosity in 2010



Brief History of the Standard Model

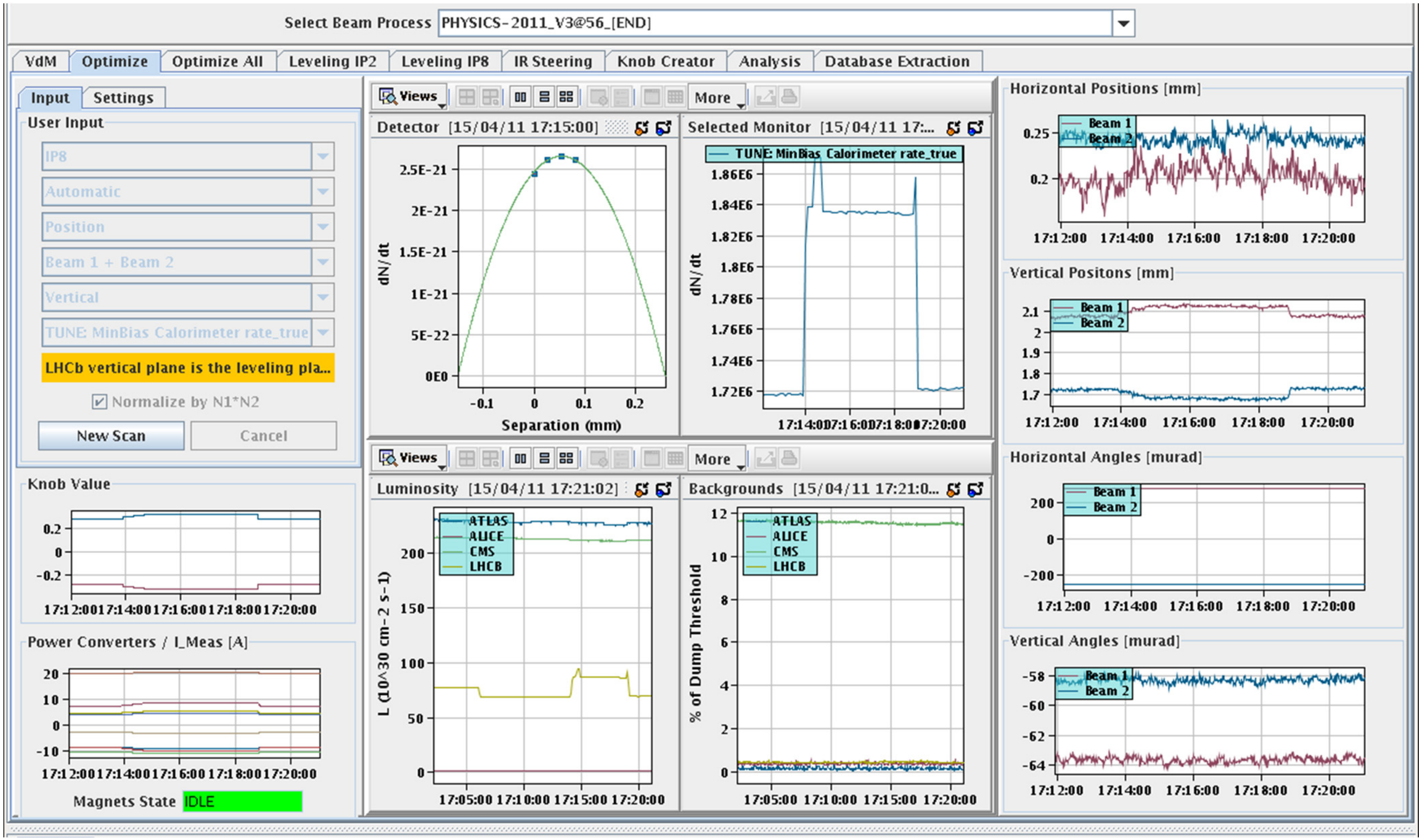


2011 Operation

(Goal for the year was 1000pb-1
i.e 22 times more than 2010)

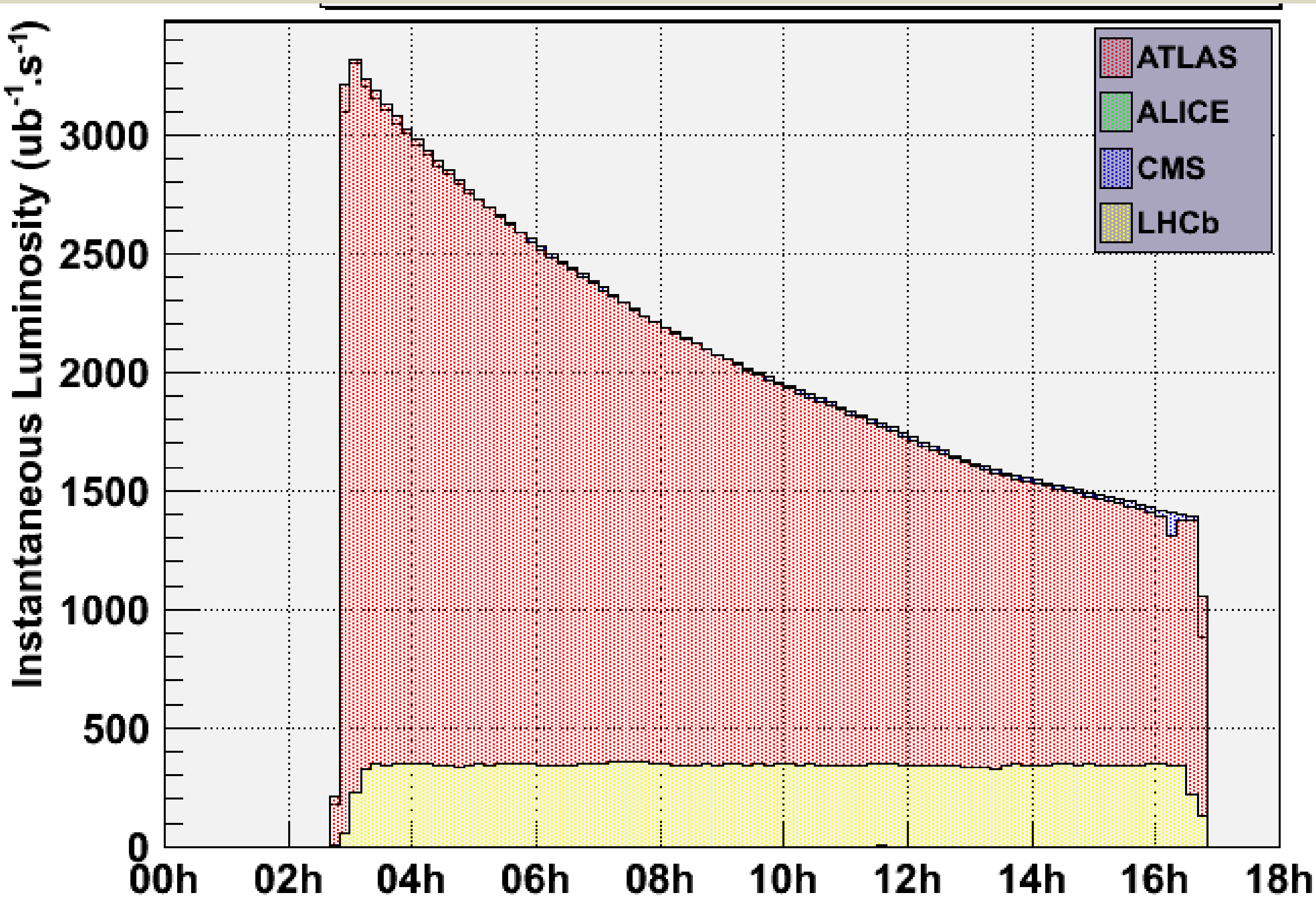
*** THPPP018, J. Wenninger: for the LHC operations group

"Lumi leveling" first tested 15th April 2011



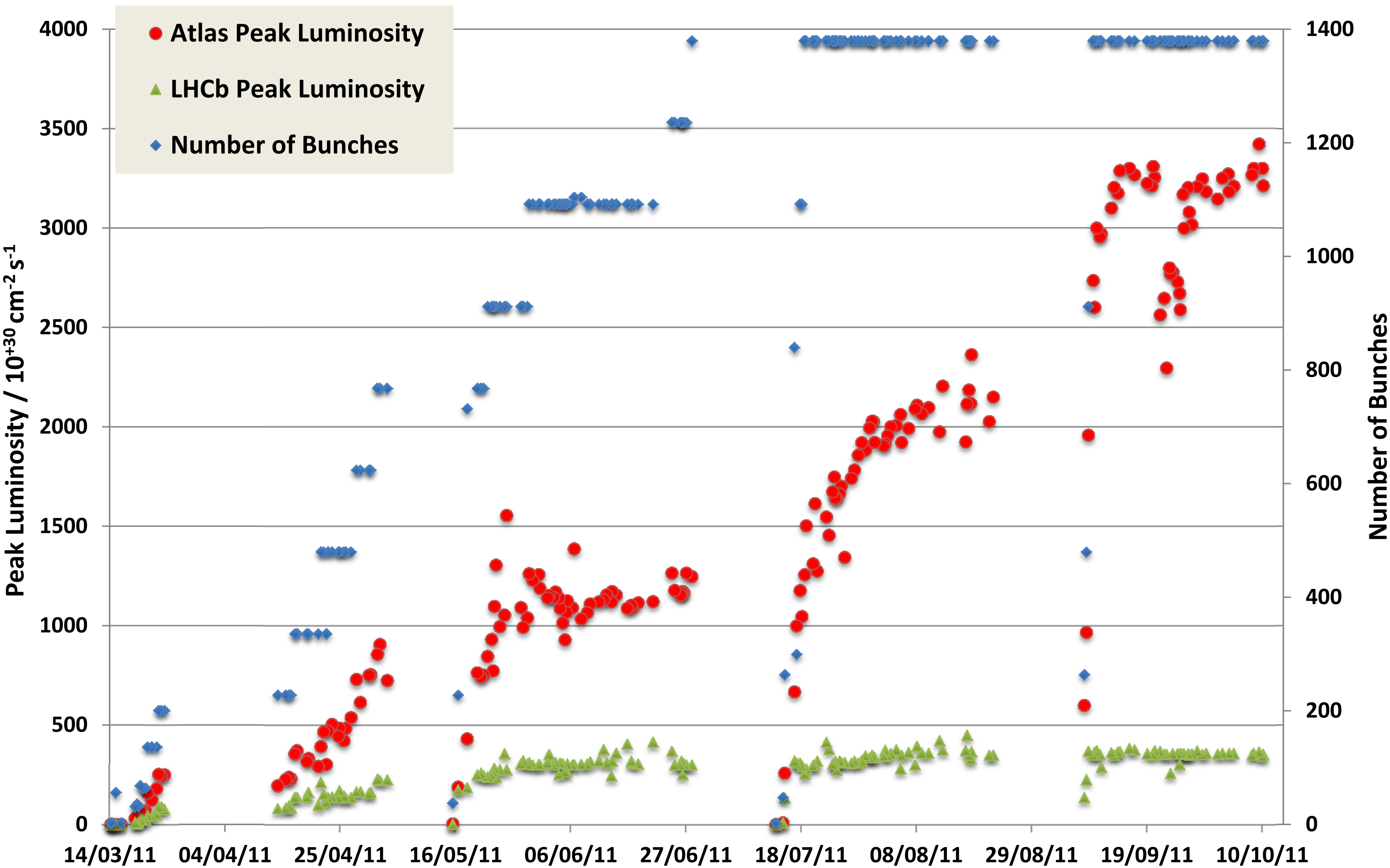
Luminosity Leveling via beam Separation

Introduced luminosity leveling for LHCb → can run at optimal μ and L_{max}



→ Since end of May running at constant $L \sim 3\text{-}3.5\cdot10^{32}$ cm^{-2}s^{-1} with $\mu \sim 1.5$
→ LHCb want maximum time in physics and not an increase in peak performance

History of 2011 Peak Luminosity



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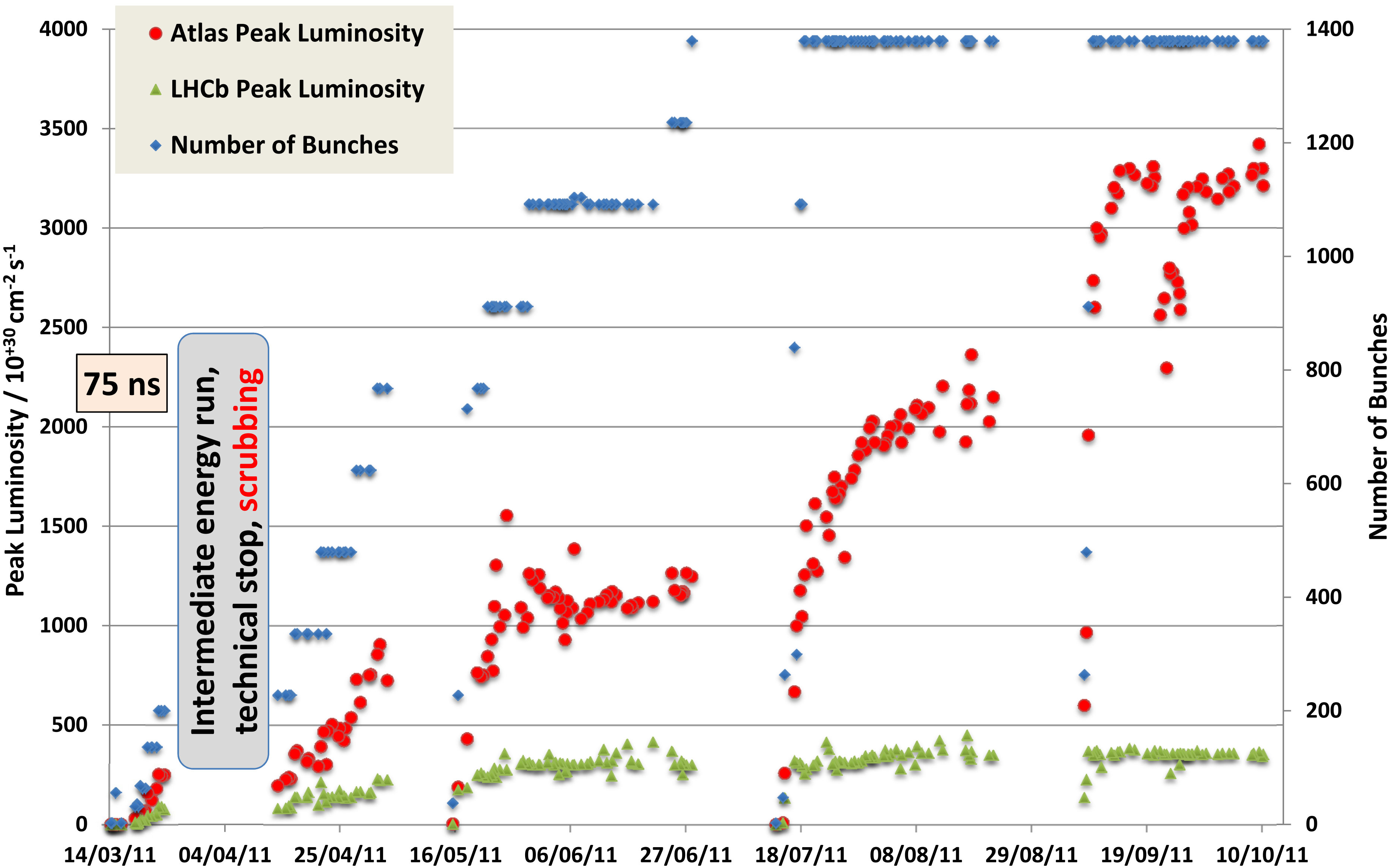

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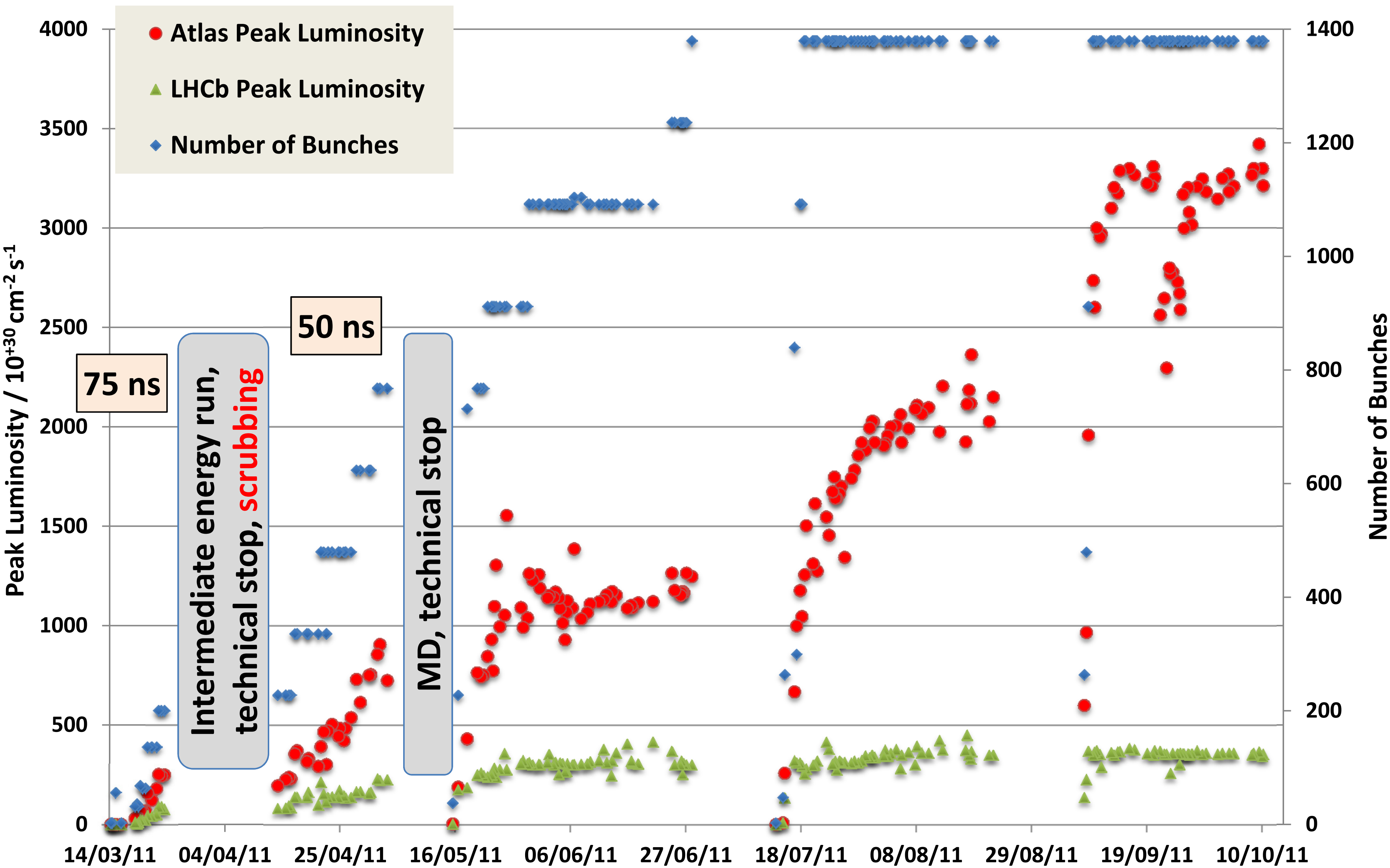

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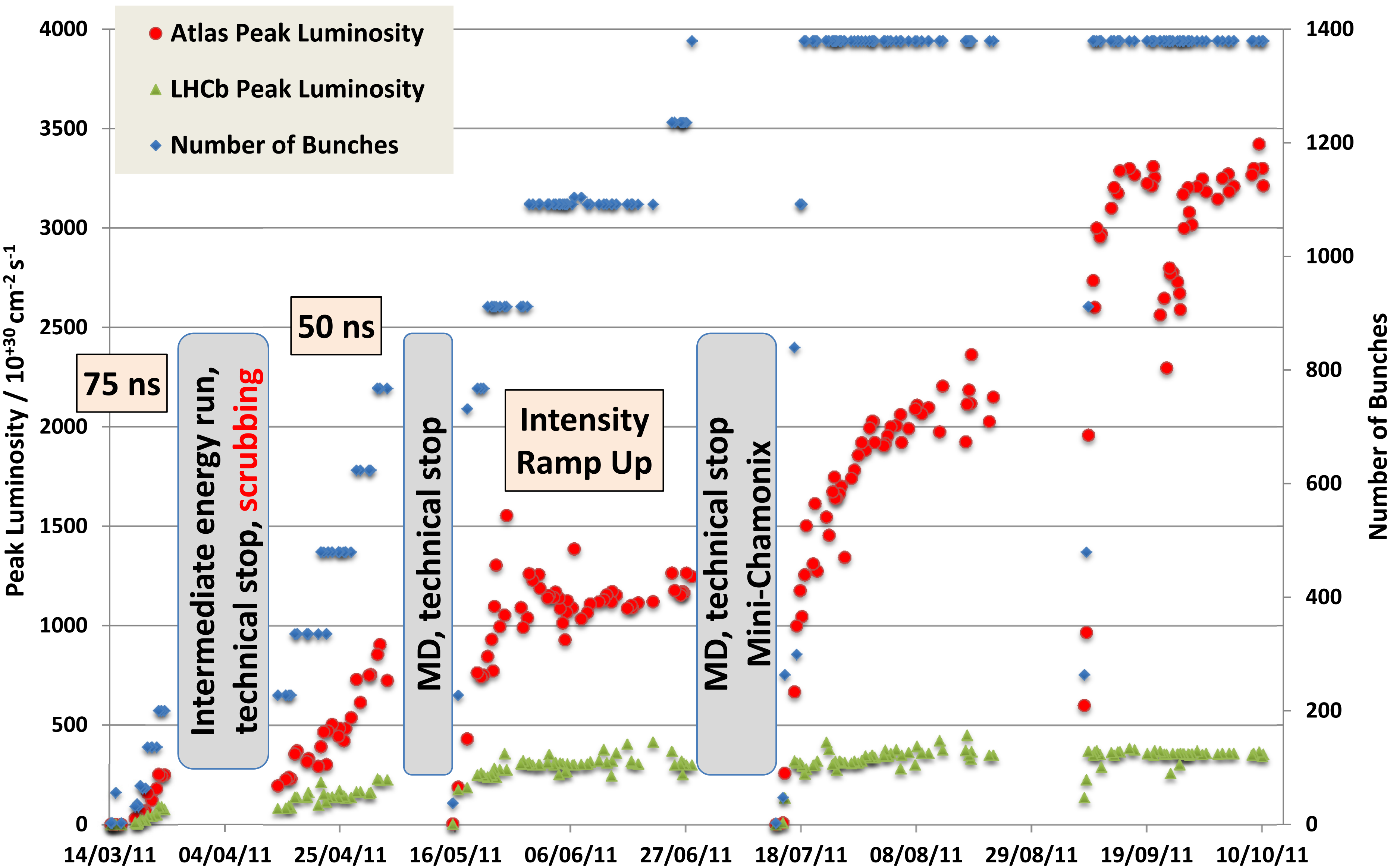

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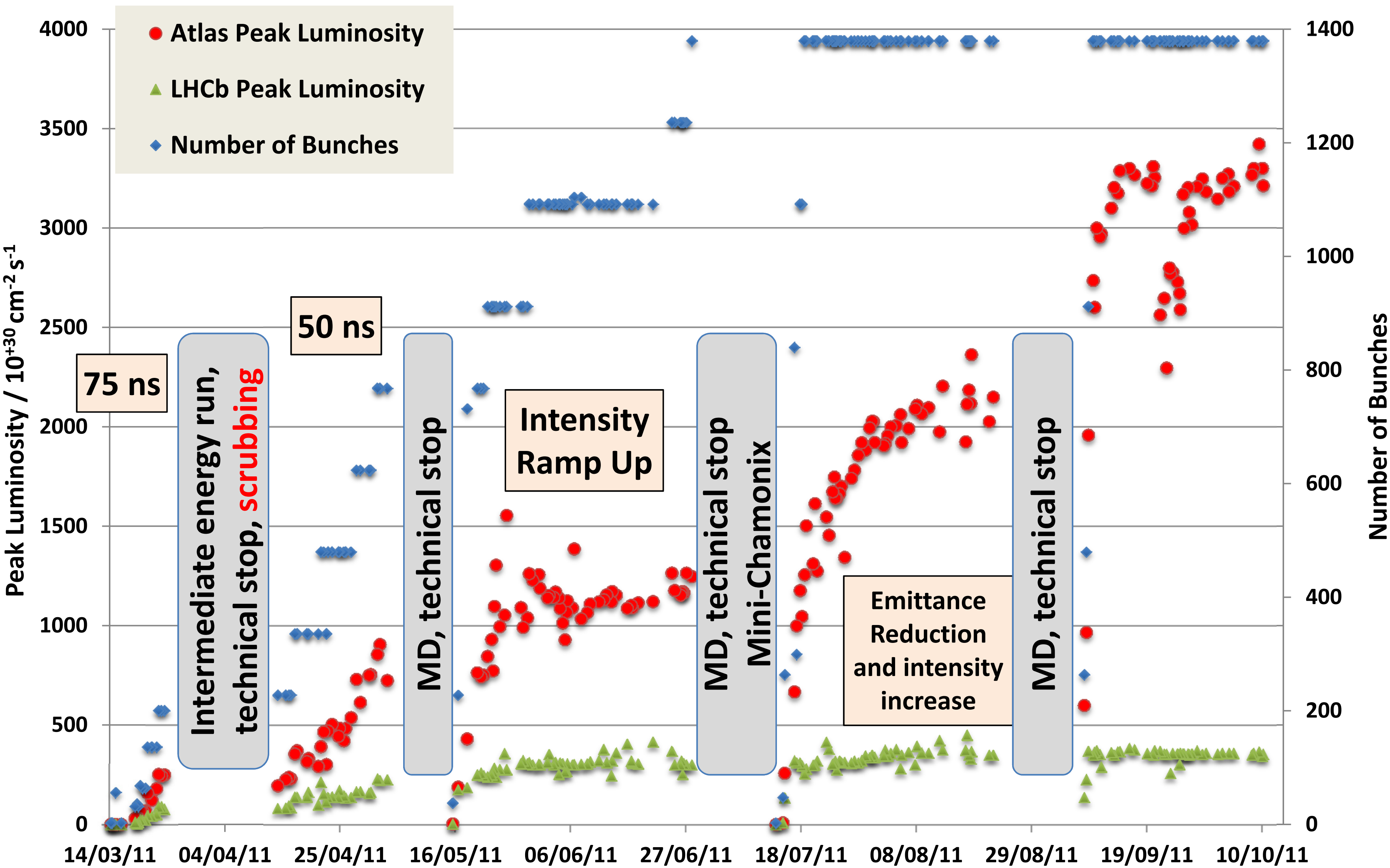

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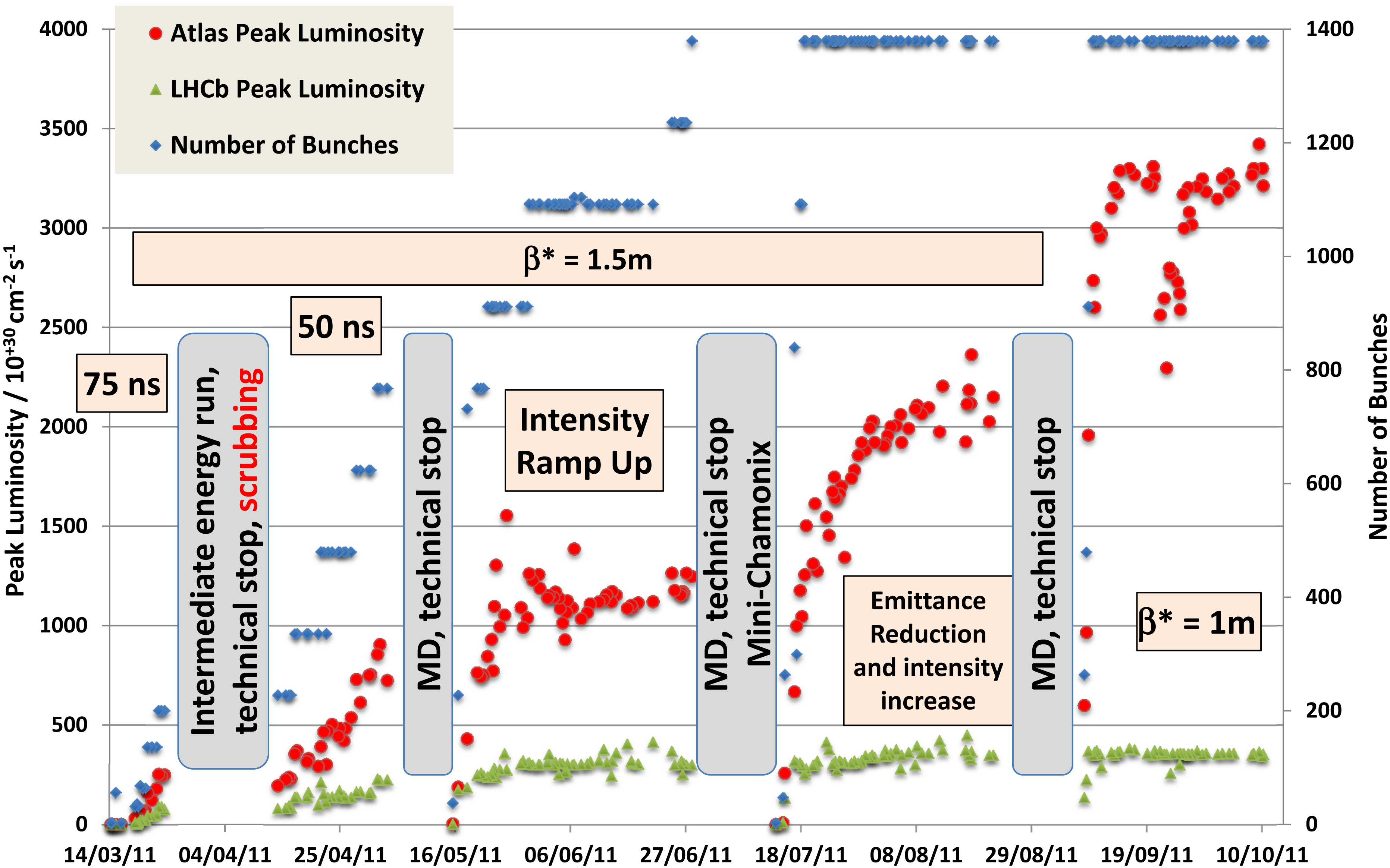
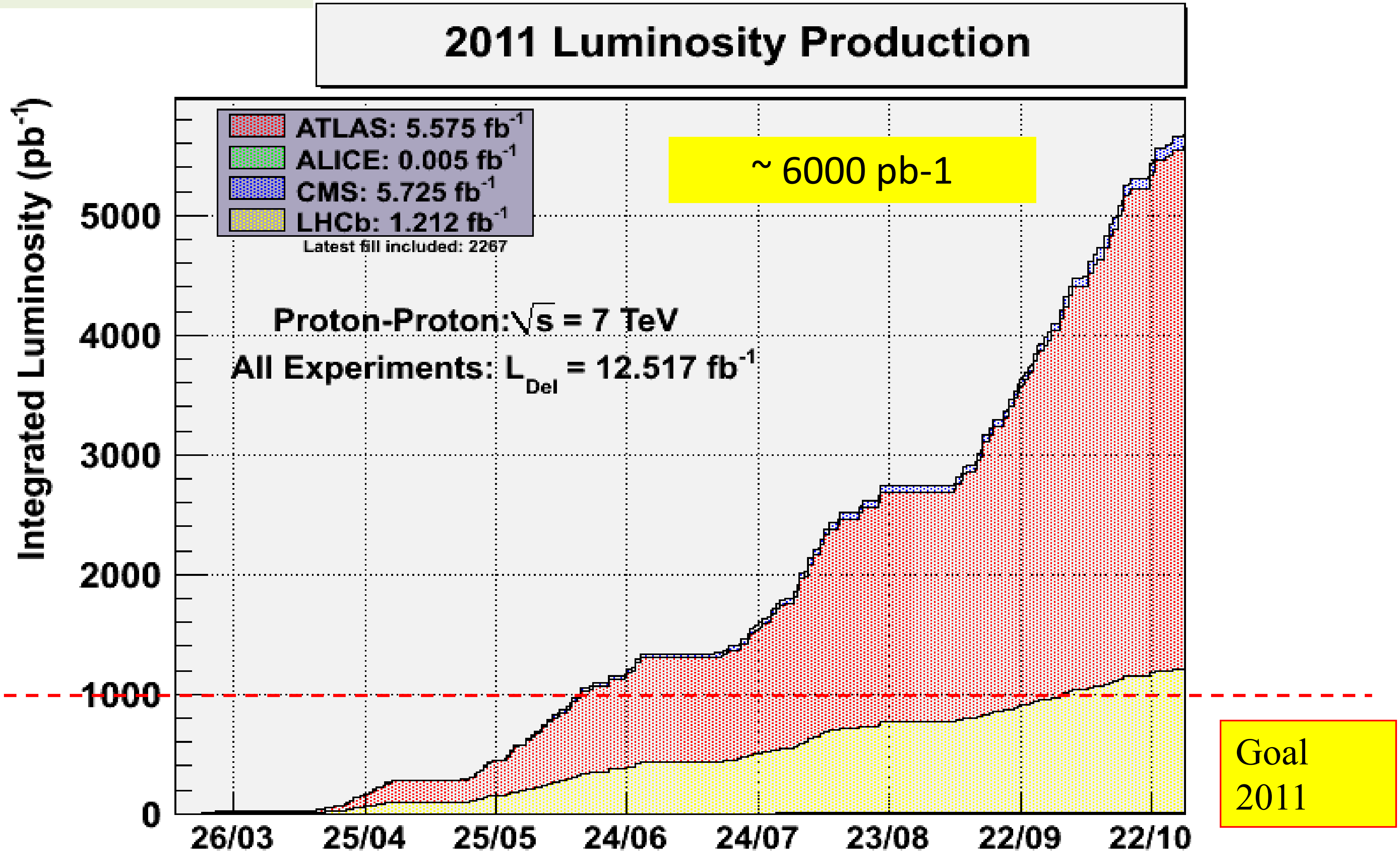


Protons

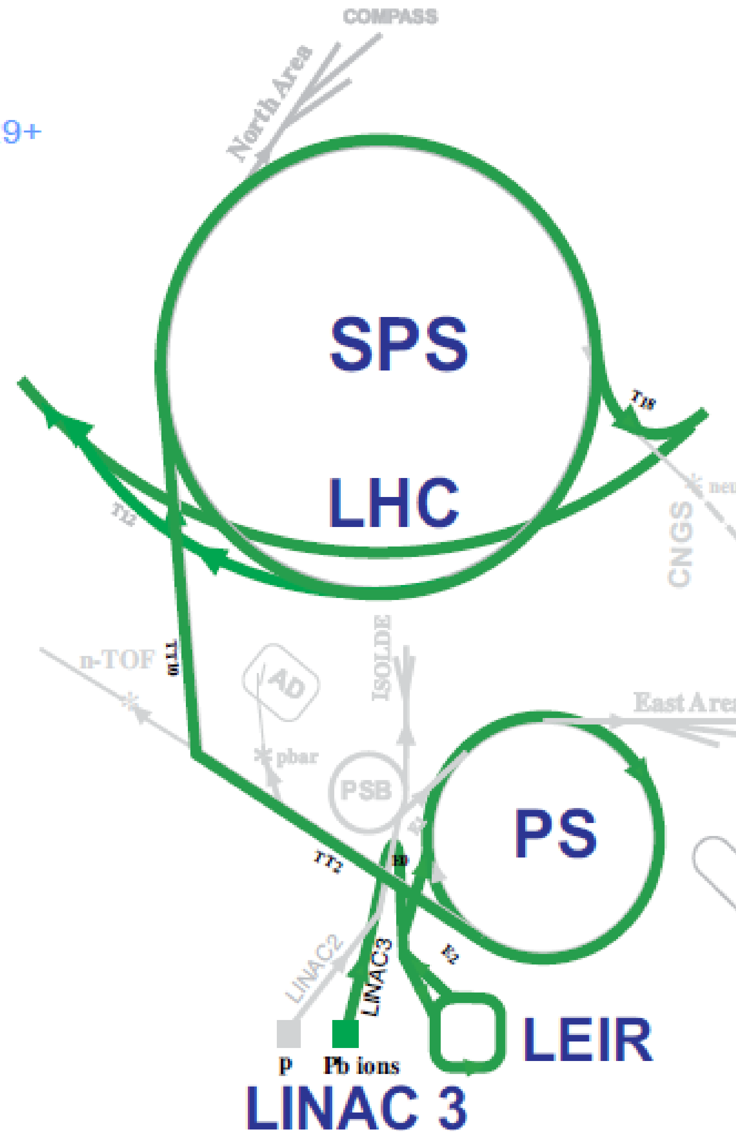

2011 Luminosity Production
ATLAS: 5.575 fb-1
ALICE: 0.005 fb-1
CMS: 5.725 fb-1
LHCb: 1.212 fb-1
Latest fill included: 2267
~ 6000 pb-1
Proton-Proton: √s = 7 TeV
All Experiments: L_Del = 12.517 fb-1
Integrated Luminosity (pb-1)
5000
4000
3000
2000
1000
0
26/03
25/04
25/05
24/06
24/07
23/08
22/09
22/10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

Heavy Ion Operation

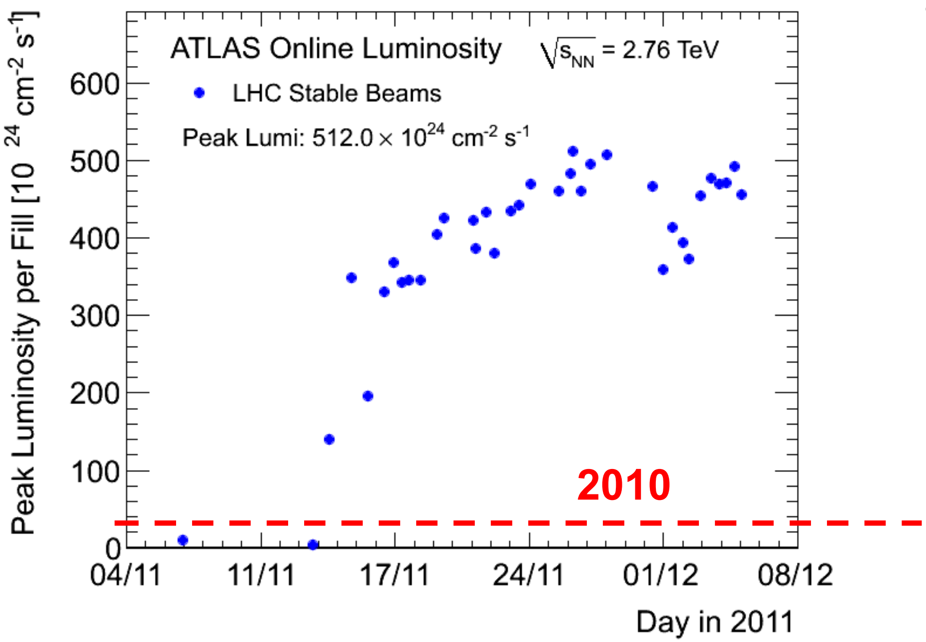
THPPP012, D. Manglunki, THPPP013, Y. Papaphilippou:

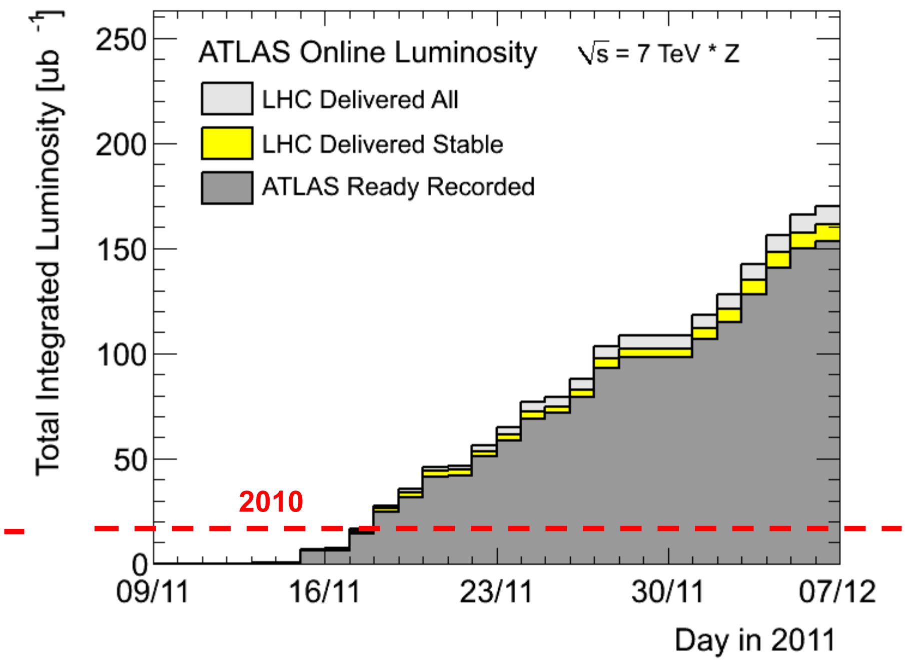
Lead ion injector chain

- 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



Peak and Integrated luminosity





356 bunches

<u>In 2010:</u>

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

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Reminder of 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.

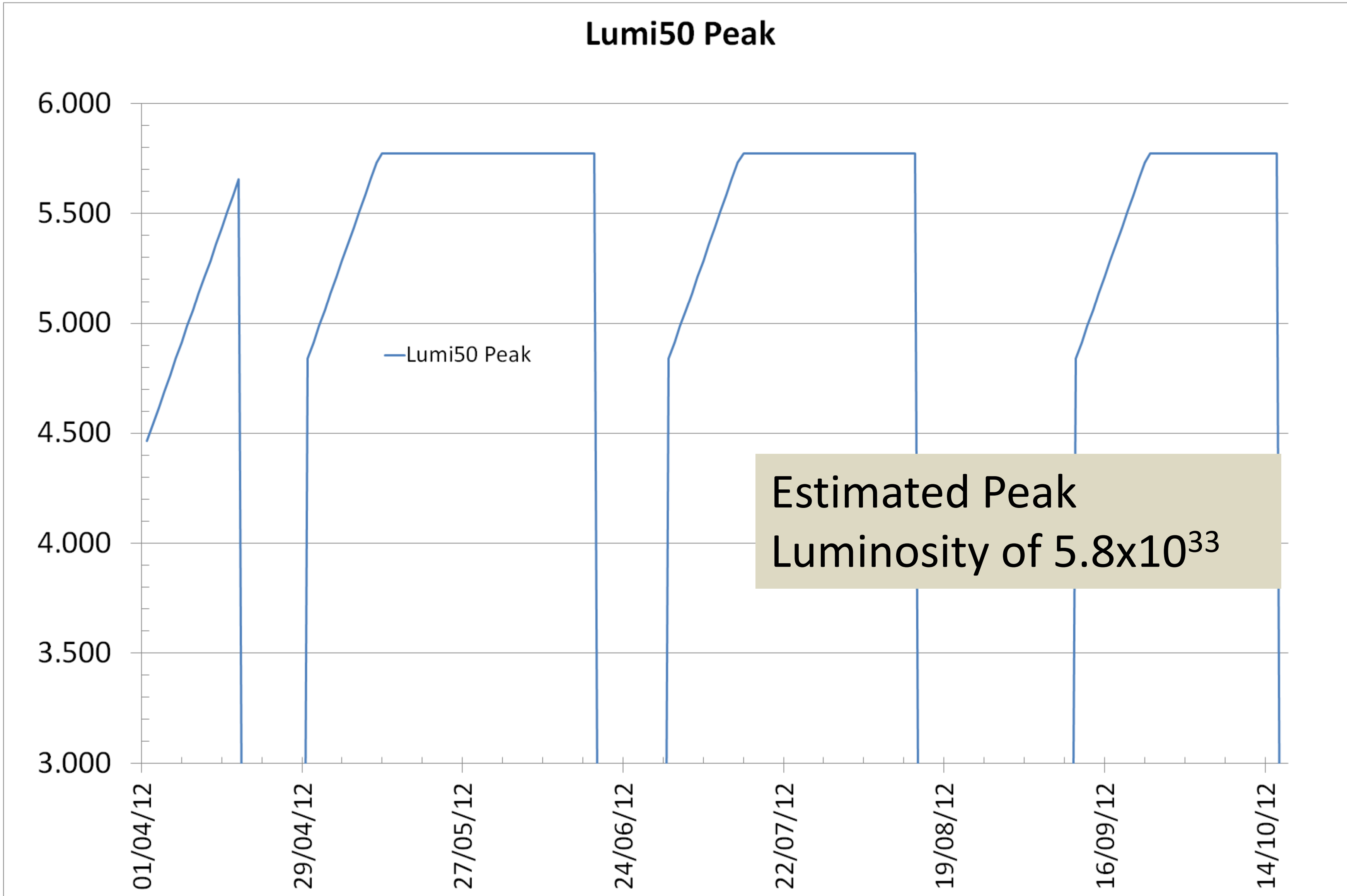
3. We must (in 2012) do the necessary machine experiments to allow high energy, useful high luminosity running after LS1.

Pile up and 25ns

Integrated luminosity needed for Discovery of Higgs

Year	fb-1	signal (in σ)	Beam Energy	
2011	5	2.5	3.5	
2012	15	5	3.5	Needed
2012	11.5	5	4.0	Needed
2012	13.3	5	4.0	addditional 15% for pile up and margin

Estimated Peak Luminosity with 50ns (2012)



Estimated Peak Luminosity of 5.8×10^{33}

Reminder 2012 run configuration

- Energy – 4 TeV
- Bunch spacing - 50 ns
- Collimator settings – tight
- Atlas and CMS beta* - 60 cm
- Alice and LHCb beta* - 3 m
  - – Natural satellites versus main bunches in Alice

Reminder 2012 run configuration

- Energy – 4 TeV
- Bunch spacing - 50 ns
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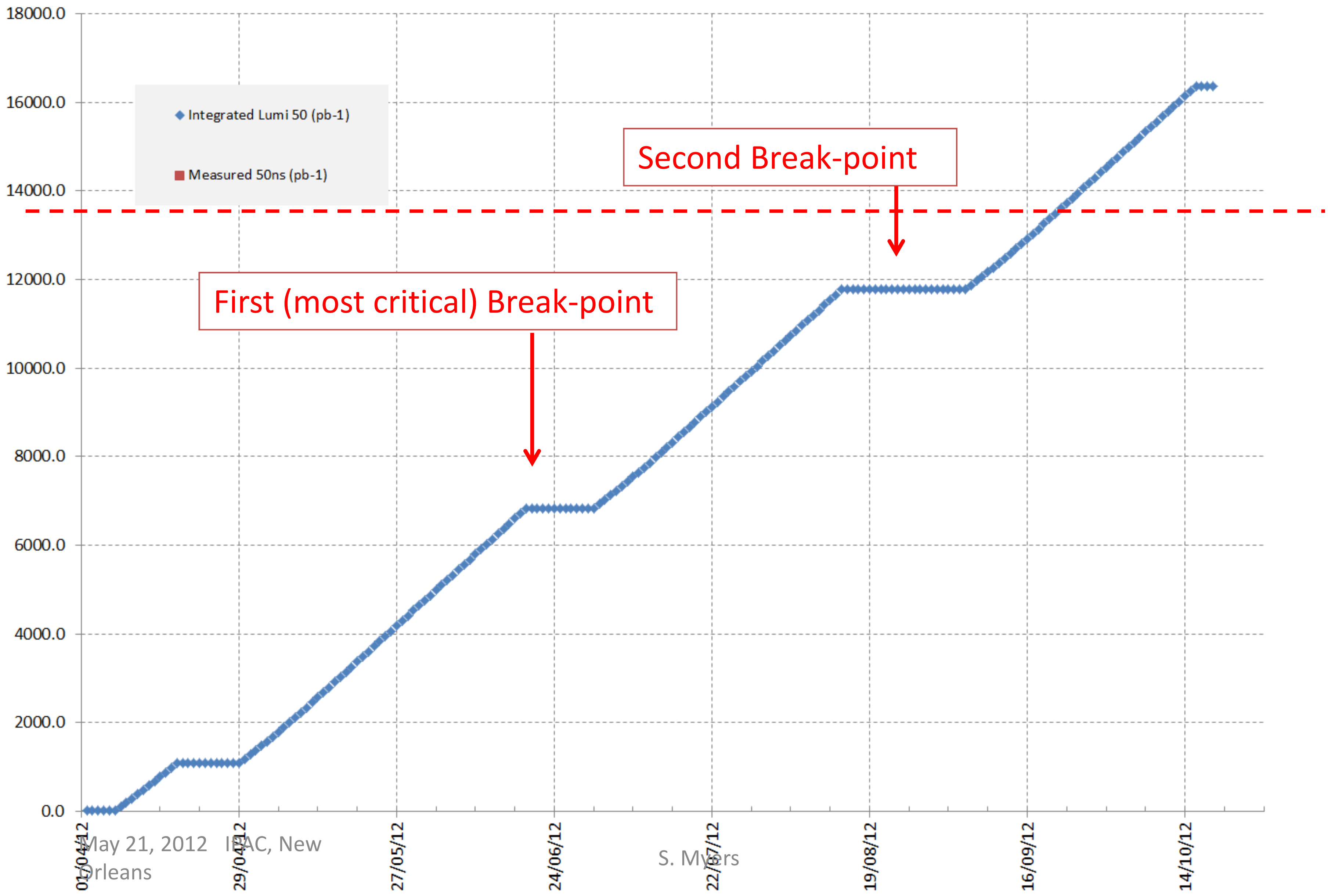
Reminder 2012 run configuration

- Energy – 4
- Bunch spa
- Collimator settings – tight
- Atlas and CMS beta* - 60 cm
- Alice and LHCb beta* - 3 m
  - Natural satellites versus main bunches in Alice

Real Challenge
2 high luminosity experiments(ATLAS, CMS)
1 mid-luminosity (LHCb) x20 lower
1 low-luminosity (ALICE) x10,000
Also TOTEM and ALFA

Draft 10 year plan (27/10/2011)

2012 Measured vs Predicted Integrated Luminosity



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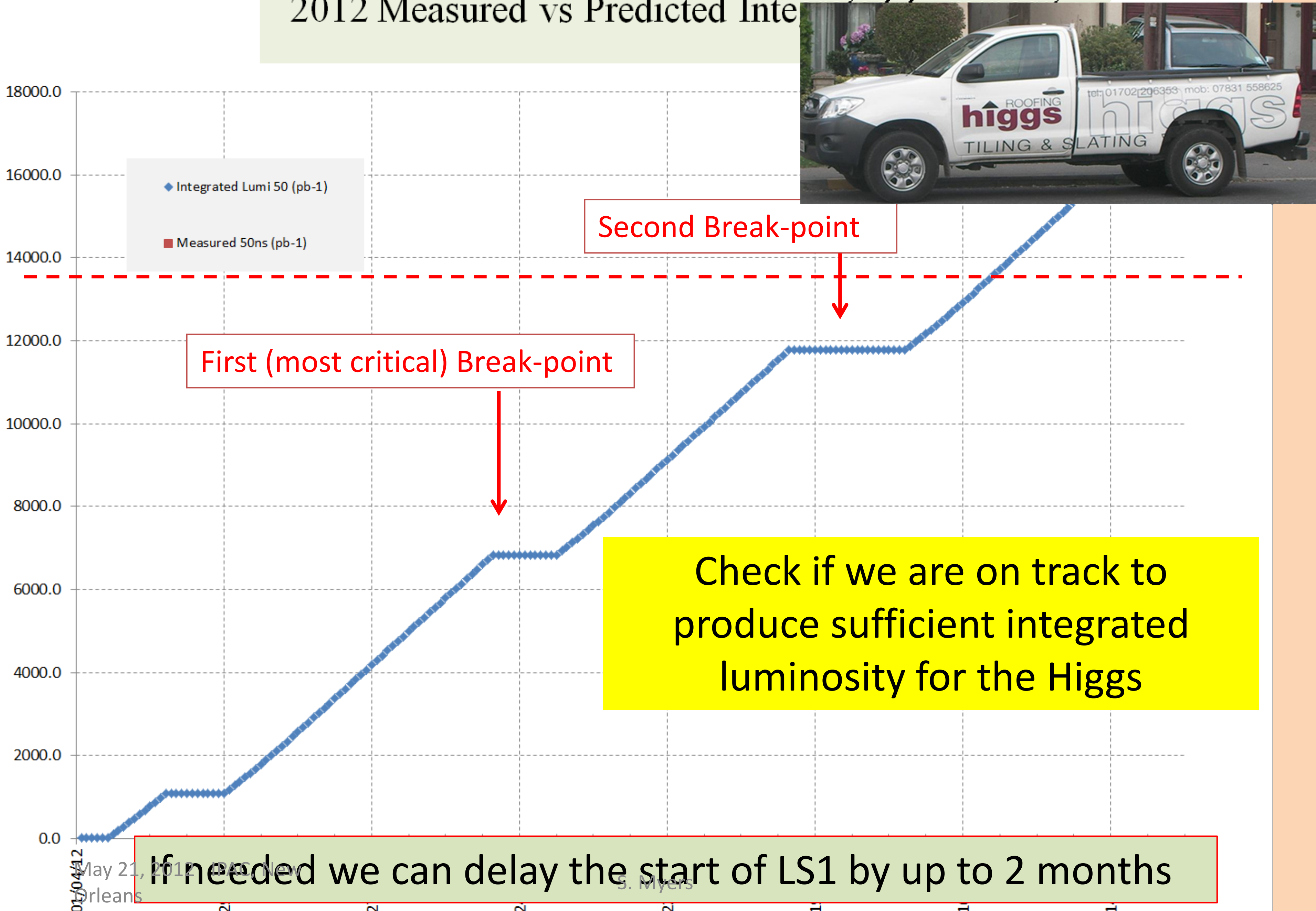

Check if we are on track to produce sufficient integrated luminosity for the Higgs

If needed we can delay the start of LS1 by up to 2 months

Target p-Pb performance in 2012 (ATLAS/CMS)

Main choice:	**Units**	**200 ns**	**200ns**	**100 ns**	**100**
Beam energy/(Z TeV)	Z TeV	3.5	4	3.5	4
Colliding bunches		356	356	550	550
β^*	m	0.7	0.6	0.7	0.6
Emittance protons	µm	3.75	3.75	3.75	3.75
Emittance Pb	µm	1.5	1.5	1.5	1.5
Pb/bunch	10^8	1.2	1.2	0.8	0.8
p/bunch	10^{10}	1.15	1.15	1.15	1.15
Initial Luminosity L_0	10^{28} cm^{-2} s^{-1}	**6.2**	**8.3**	**6.4**	**8.5**
Operating days		**22**	**24**	**22**	**24**
Difficulty (subjective)		**0.9**	**1**	**0.9**	**1**
Integrated luminosity	µb^{-1}	**15.4**	**22.4**	**15.9**	**23.1**

Integrate luminosity by scaling from 2011.
Average Pb bunch intensities from best 2011 experience.
Proton bunch intensities conservative, another factor 10 ????
Proton emittance conservative, another factor 1.37 ??
Untested moving encounter effects, possible reduction factor 0.1 ??

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Draft 10 year plan (27/10/2011)

LS1 then operation around 7TeV/beam

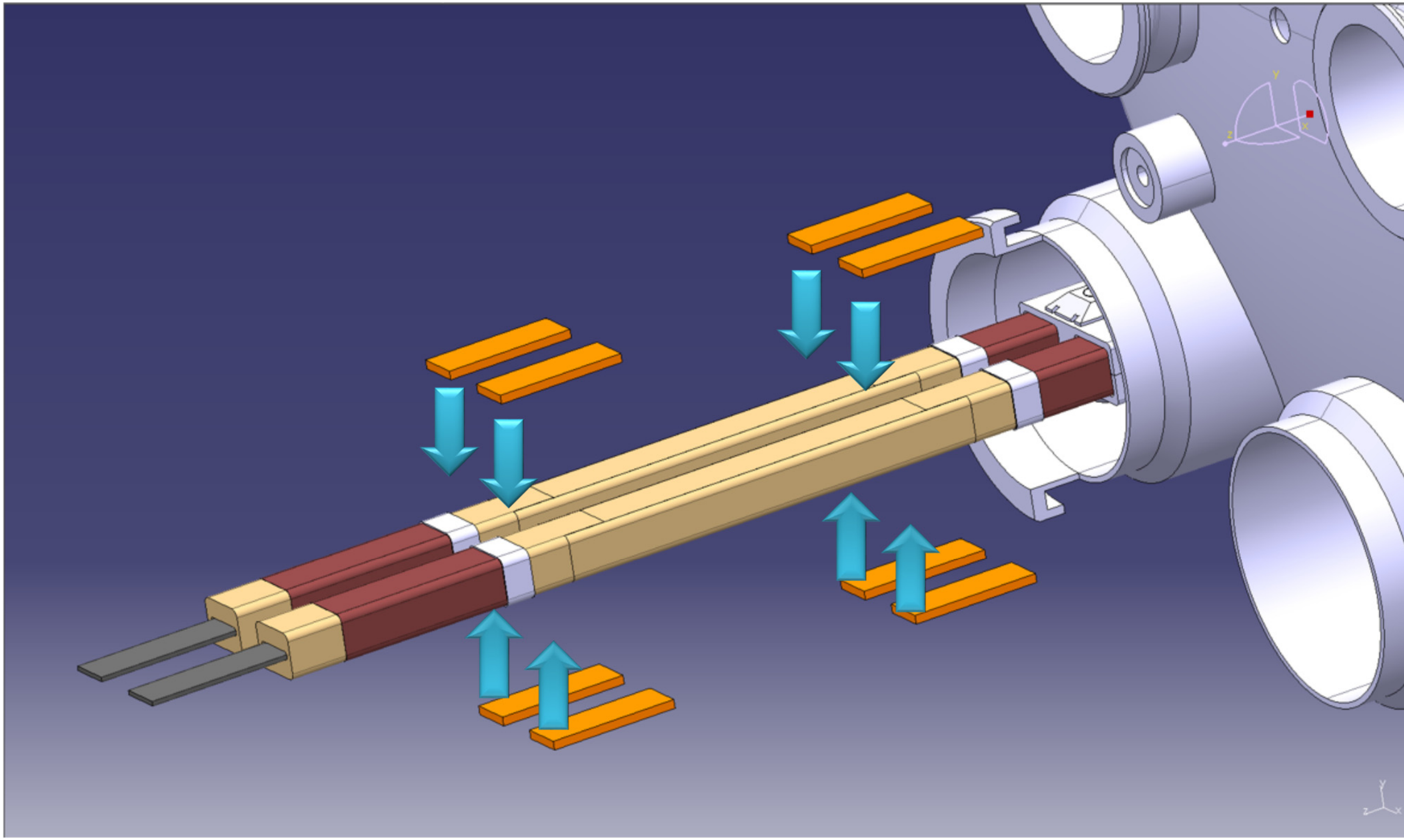
LS1 Work

- Repair defectuous interconnects

THPPD026, Z Charifoulline:

- Consolidate all interconnects with new design THPPD032 J-Ph. Tock
- Finish off pressure release valves (DN200)
- Bring all necessary equipment up to the level needed for 7TeV/beam

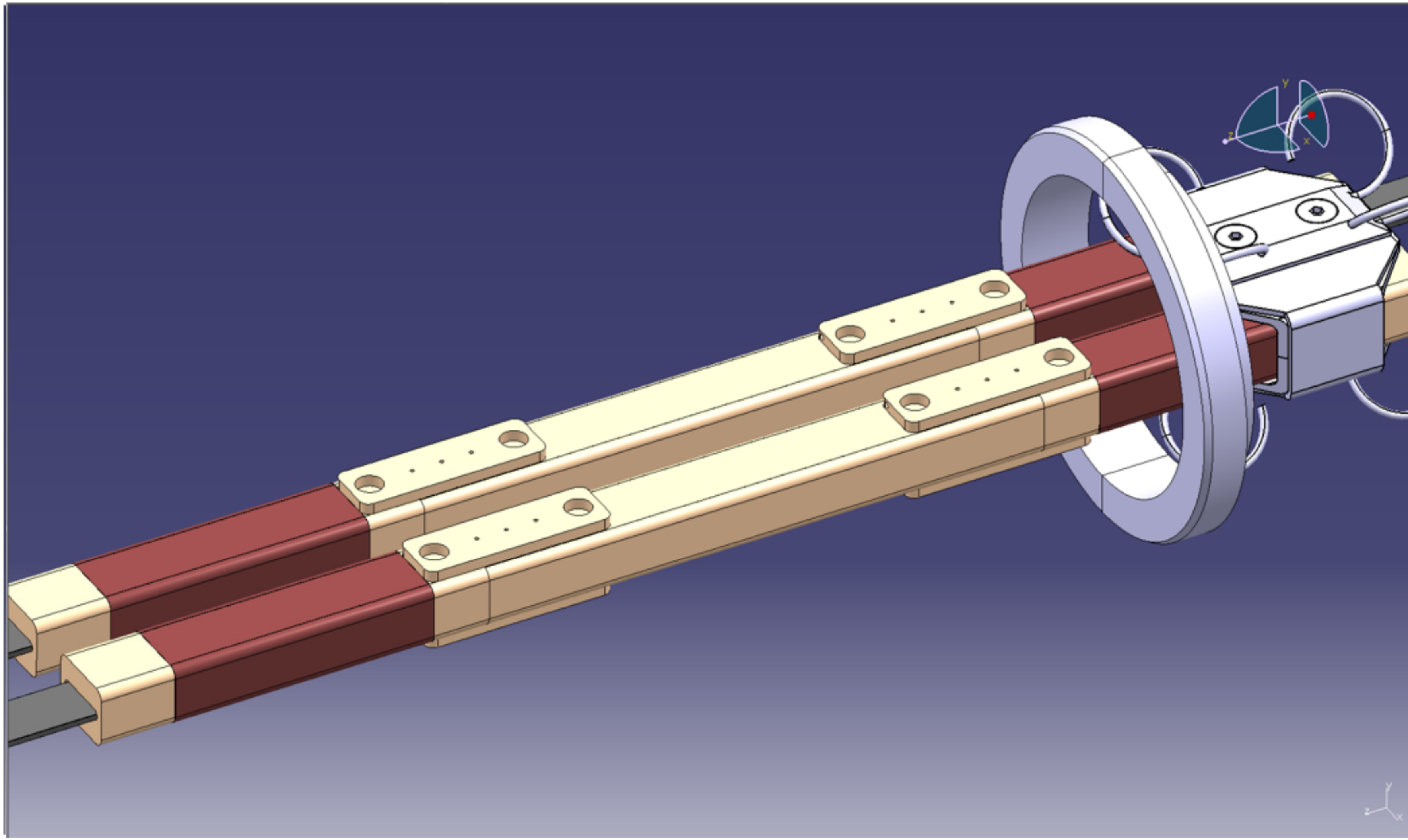
LHC MB circuit splice consolidation proposal



Phase I

Surfacing of bus bar and installation of redundant shunts by soldering

LHC MB circuit splice consolidation proposal



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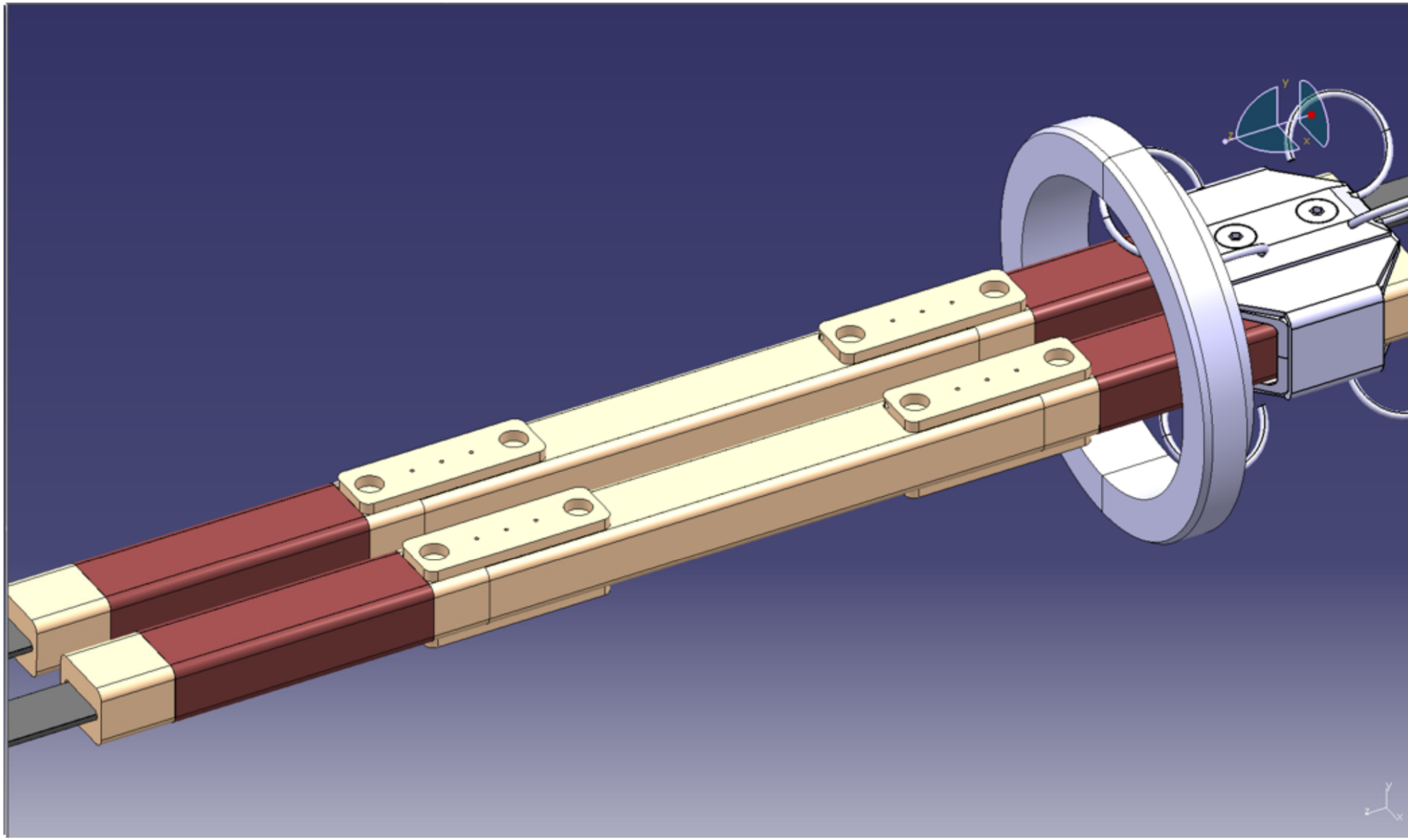

Phase II

Application of clamp and reinforcement of nearby bus bar insulation

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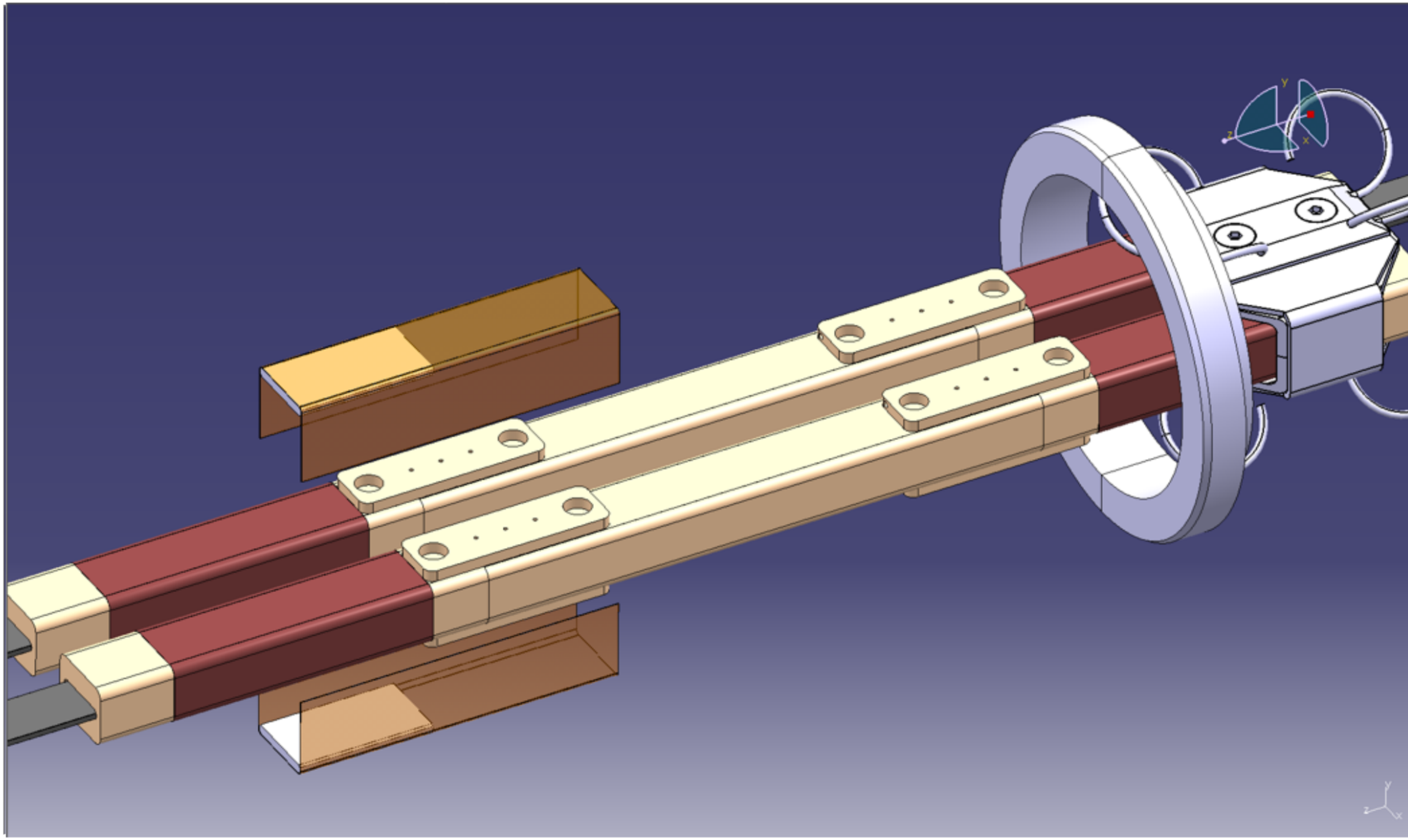

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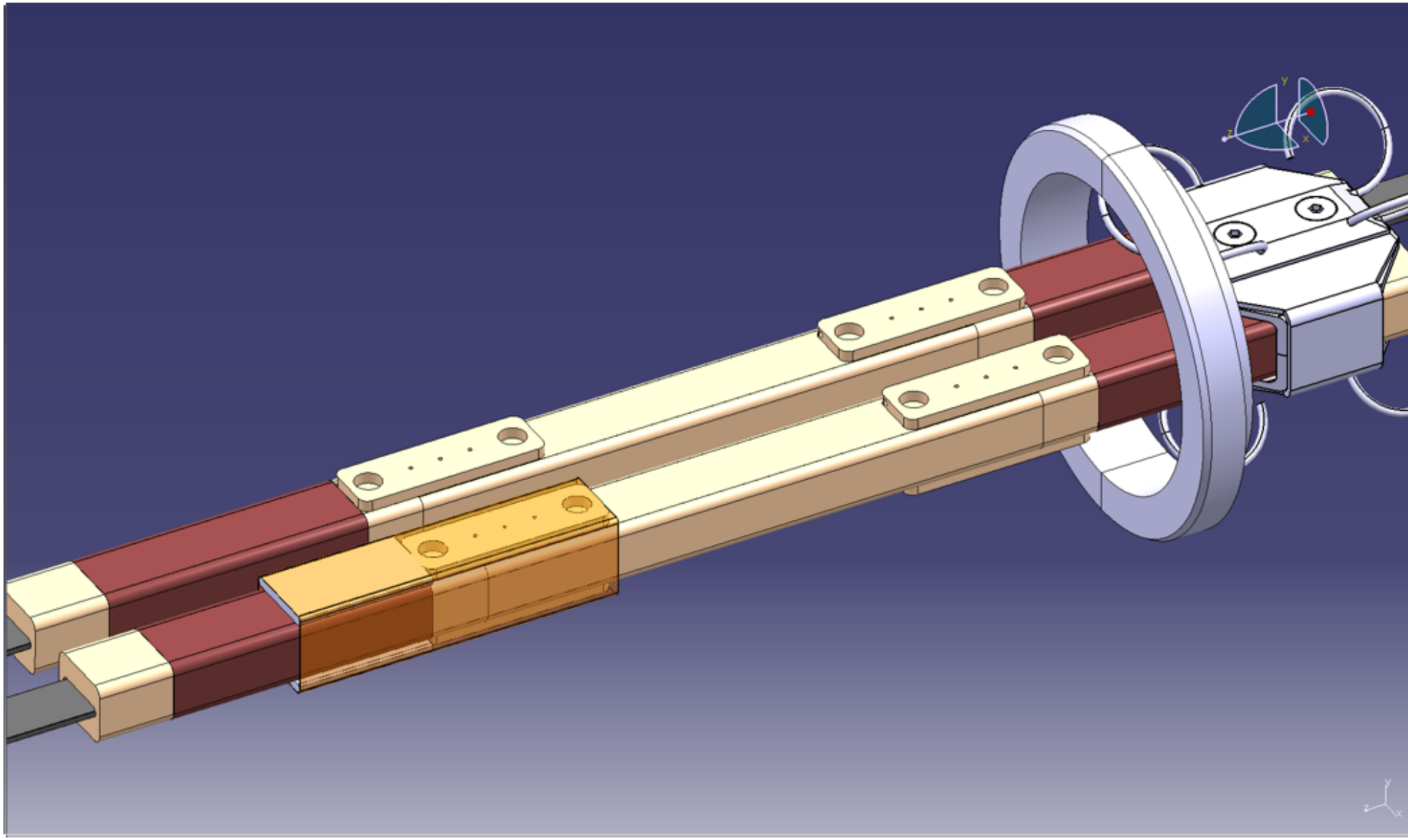

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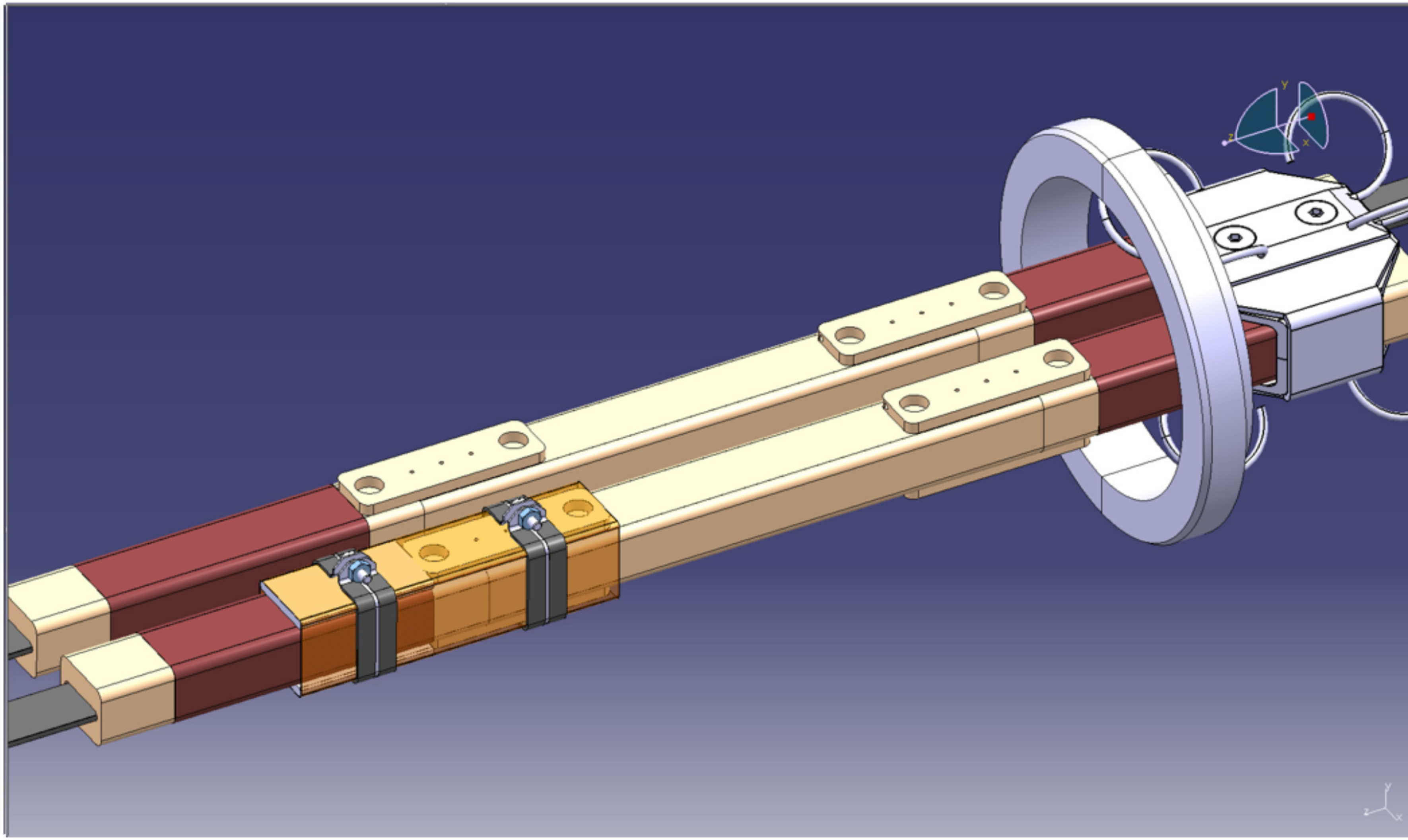

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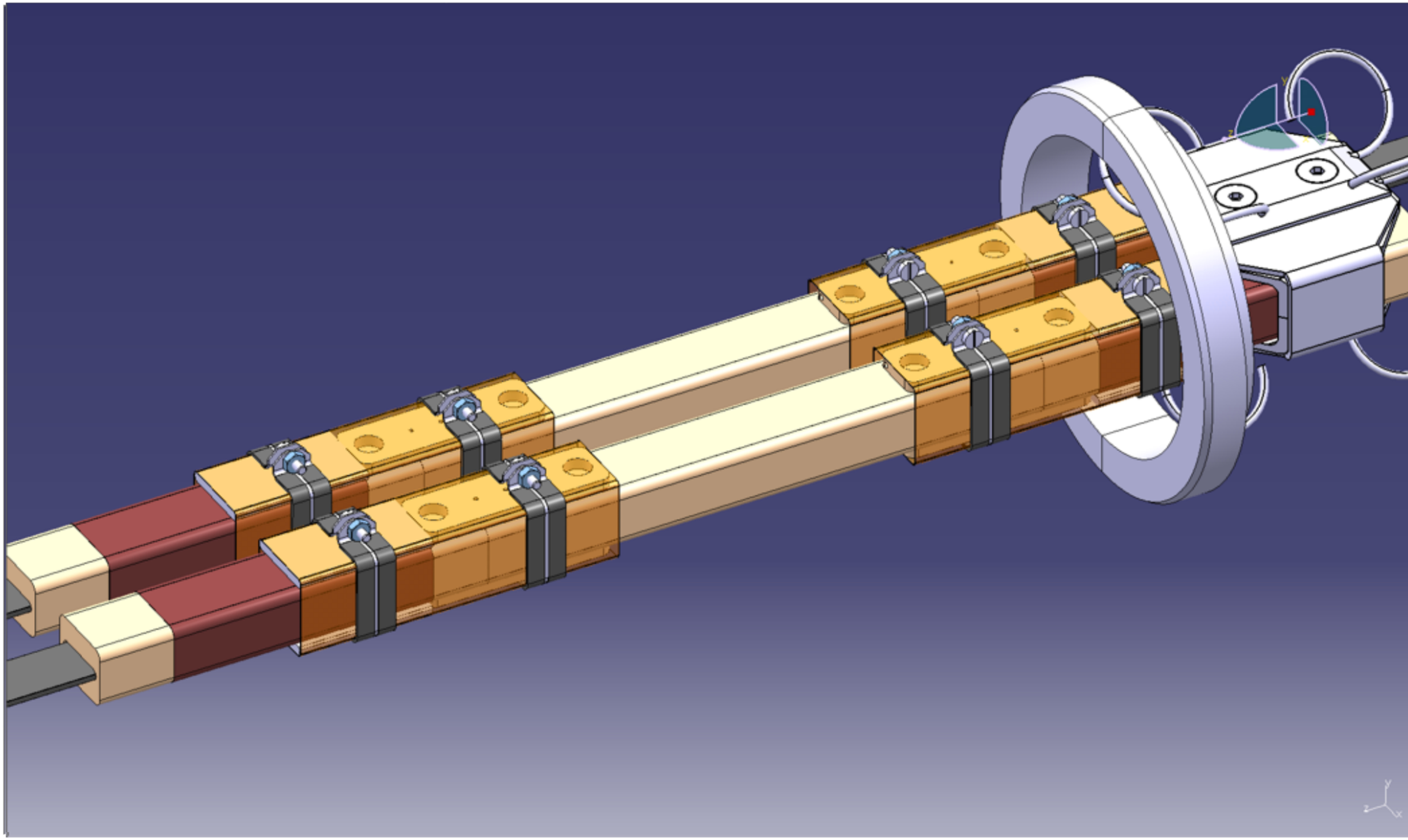

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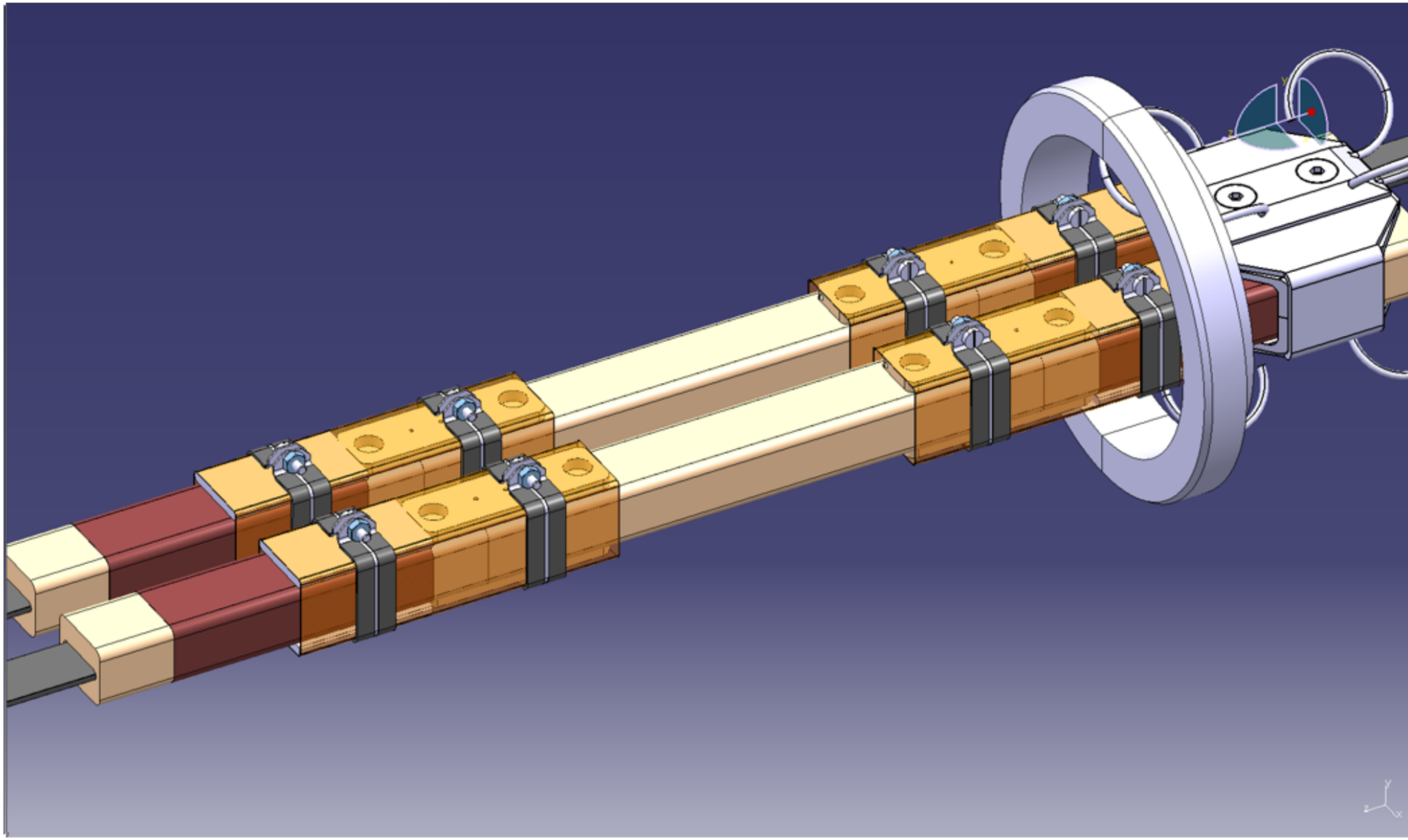
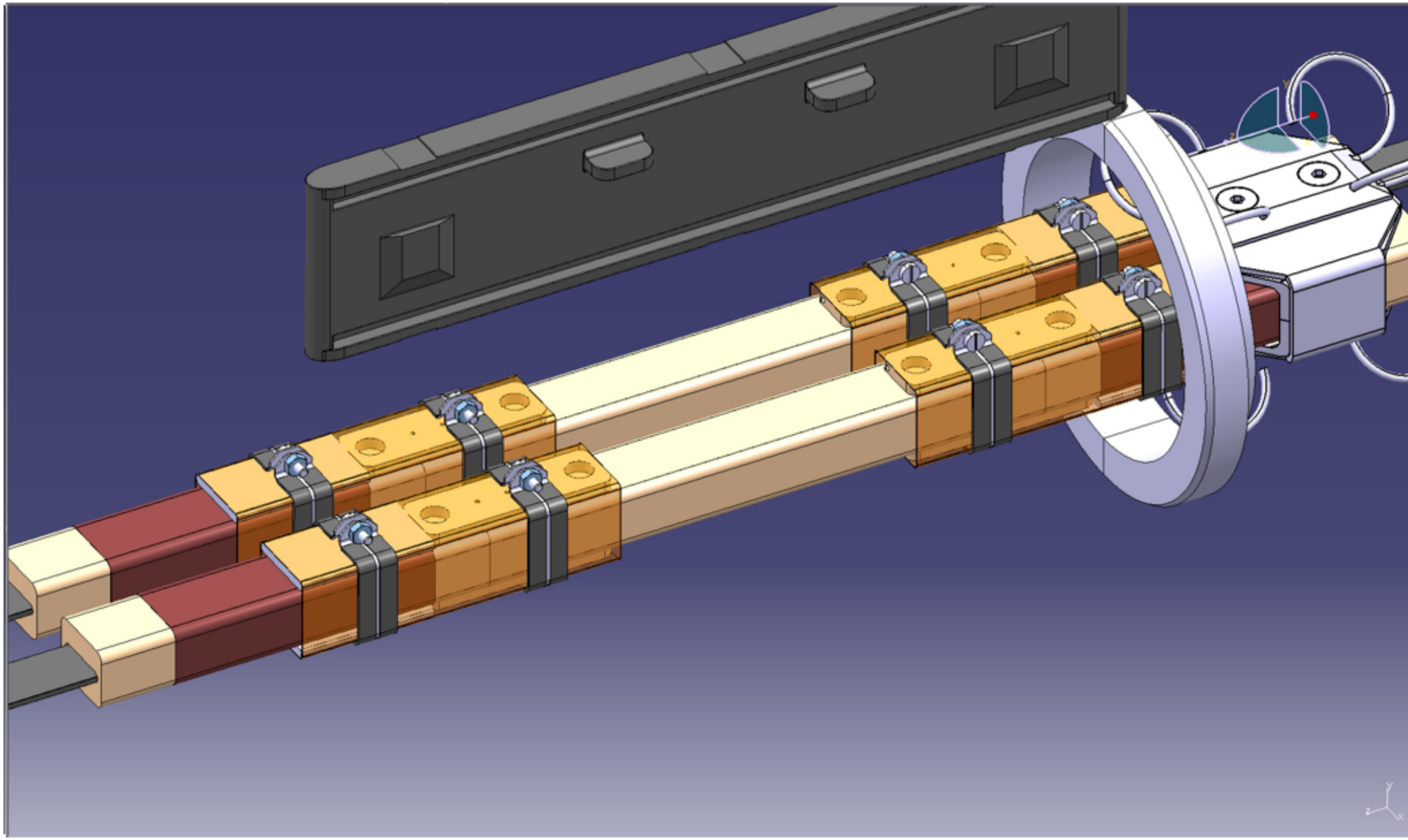


Phase III

Insulation between bus bar and to ground, Lorentz force clamping

LHC MB circuit splice consolidation proposal



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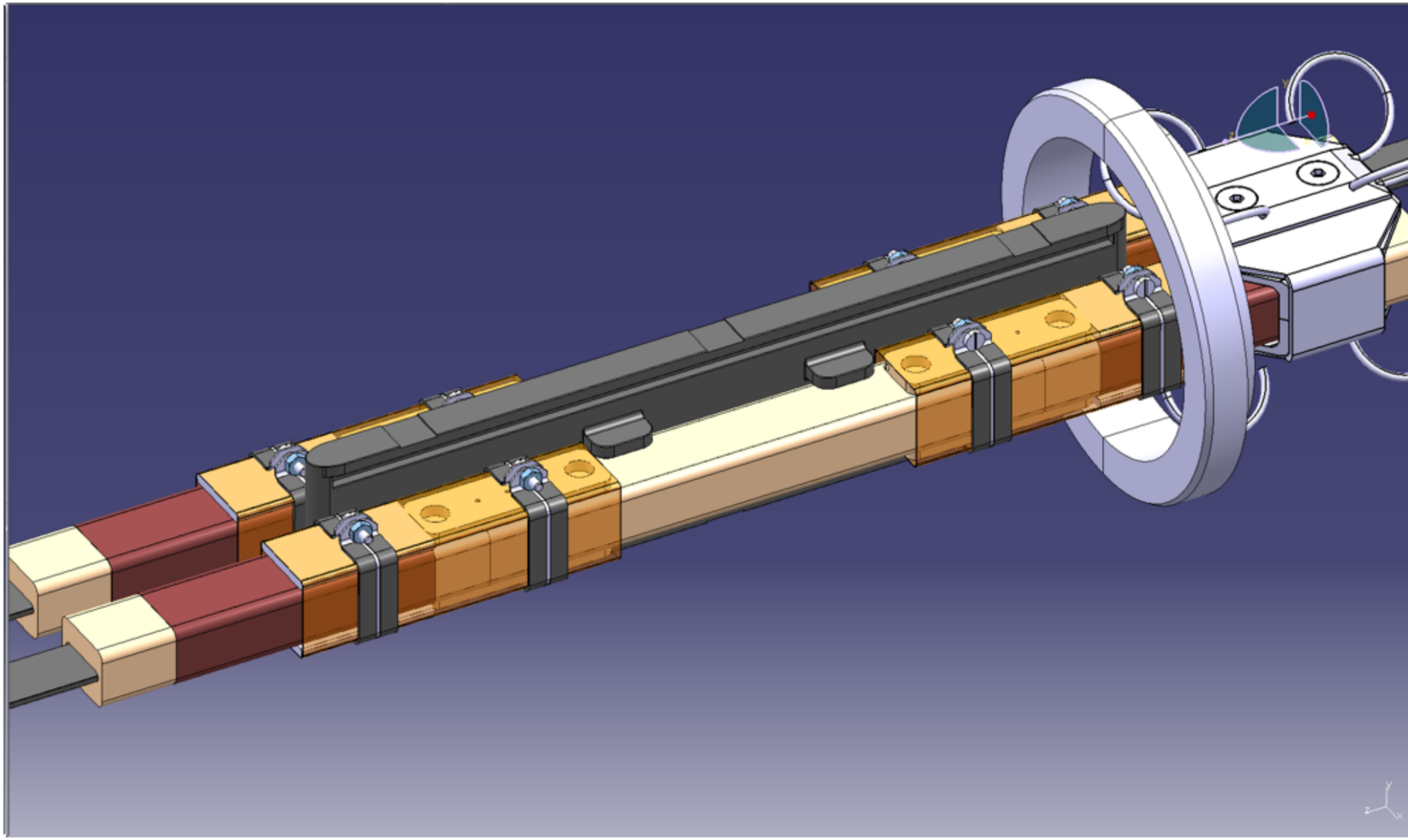

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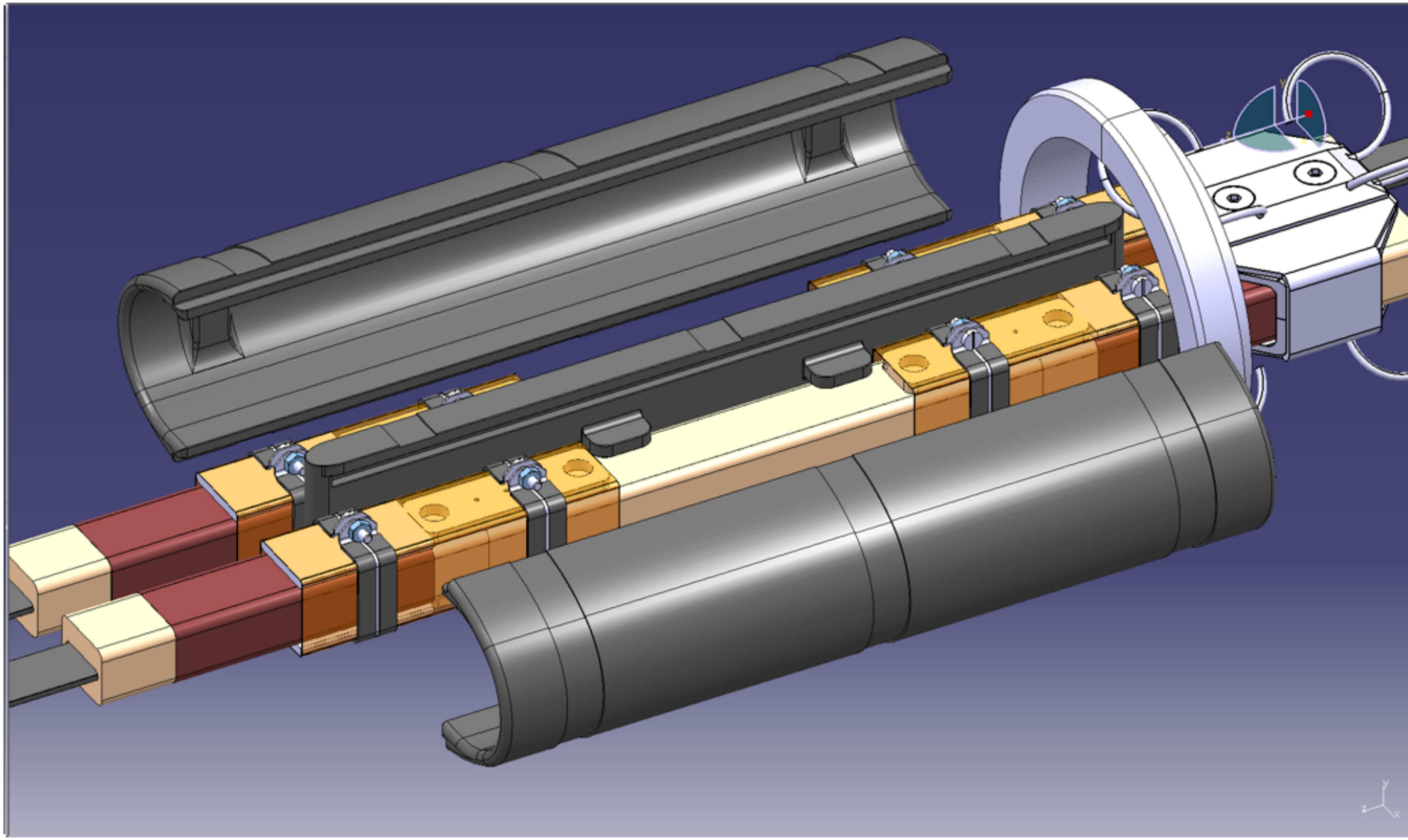

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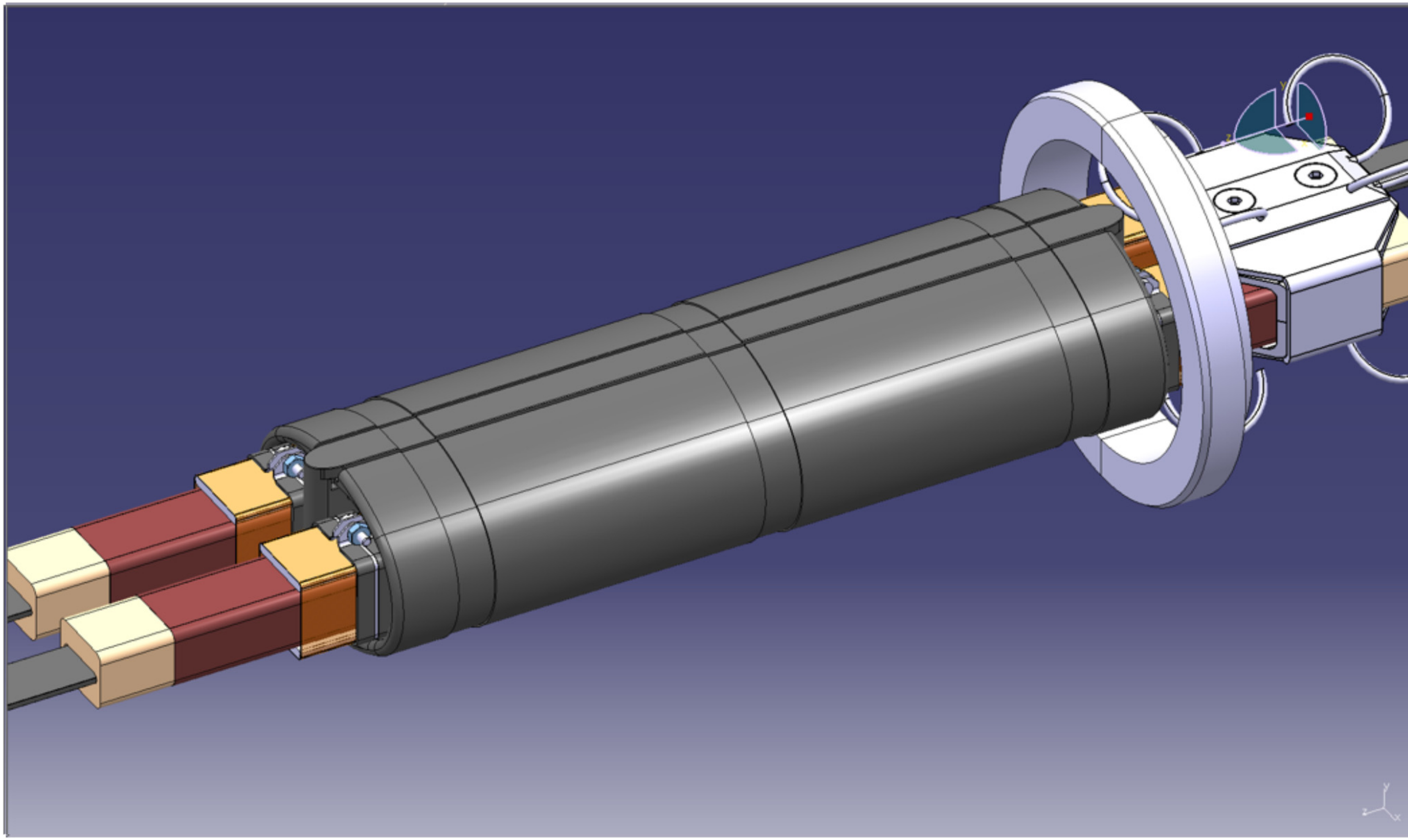

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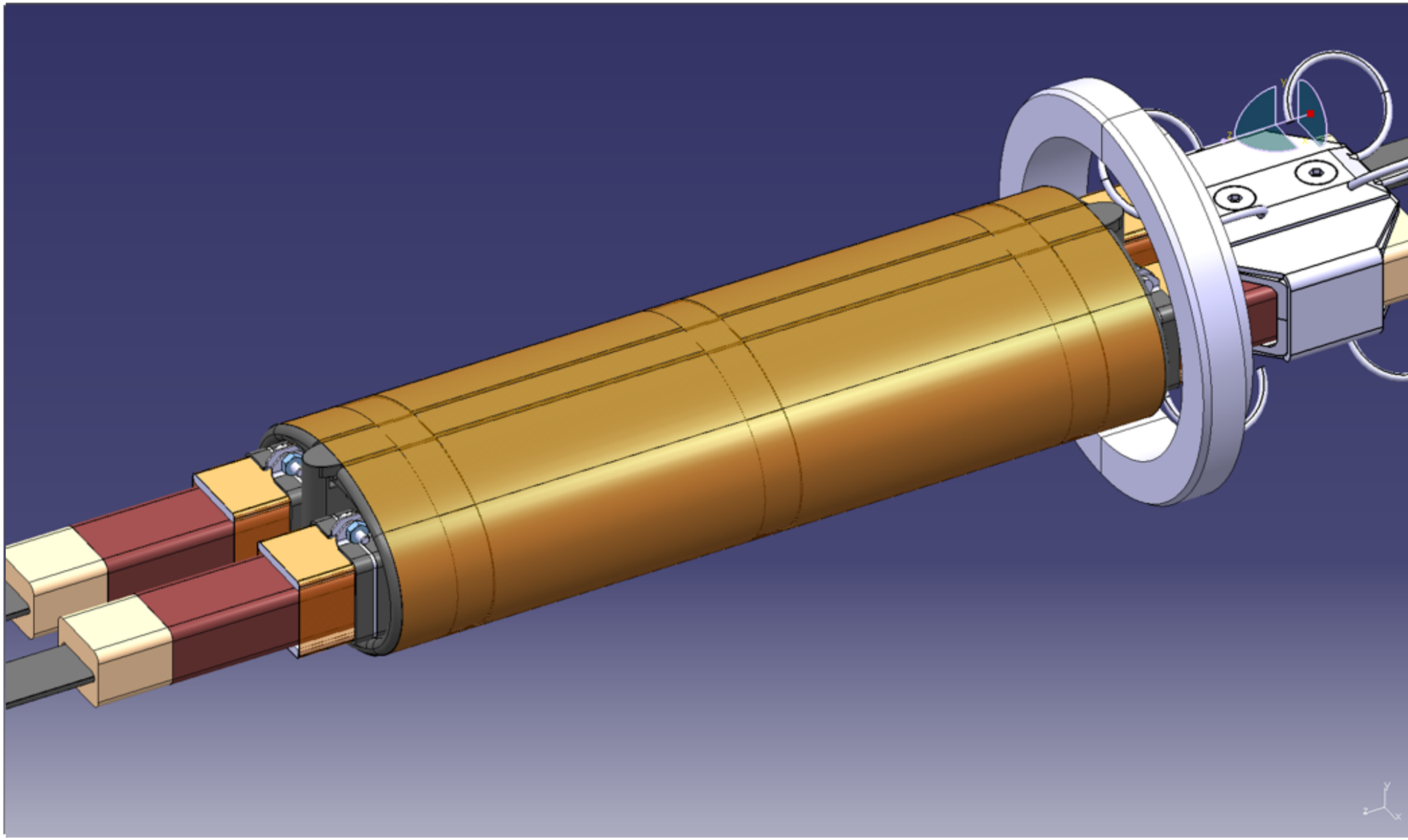

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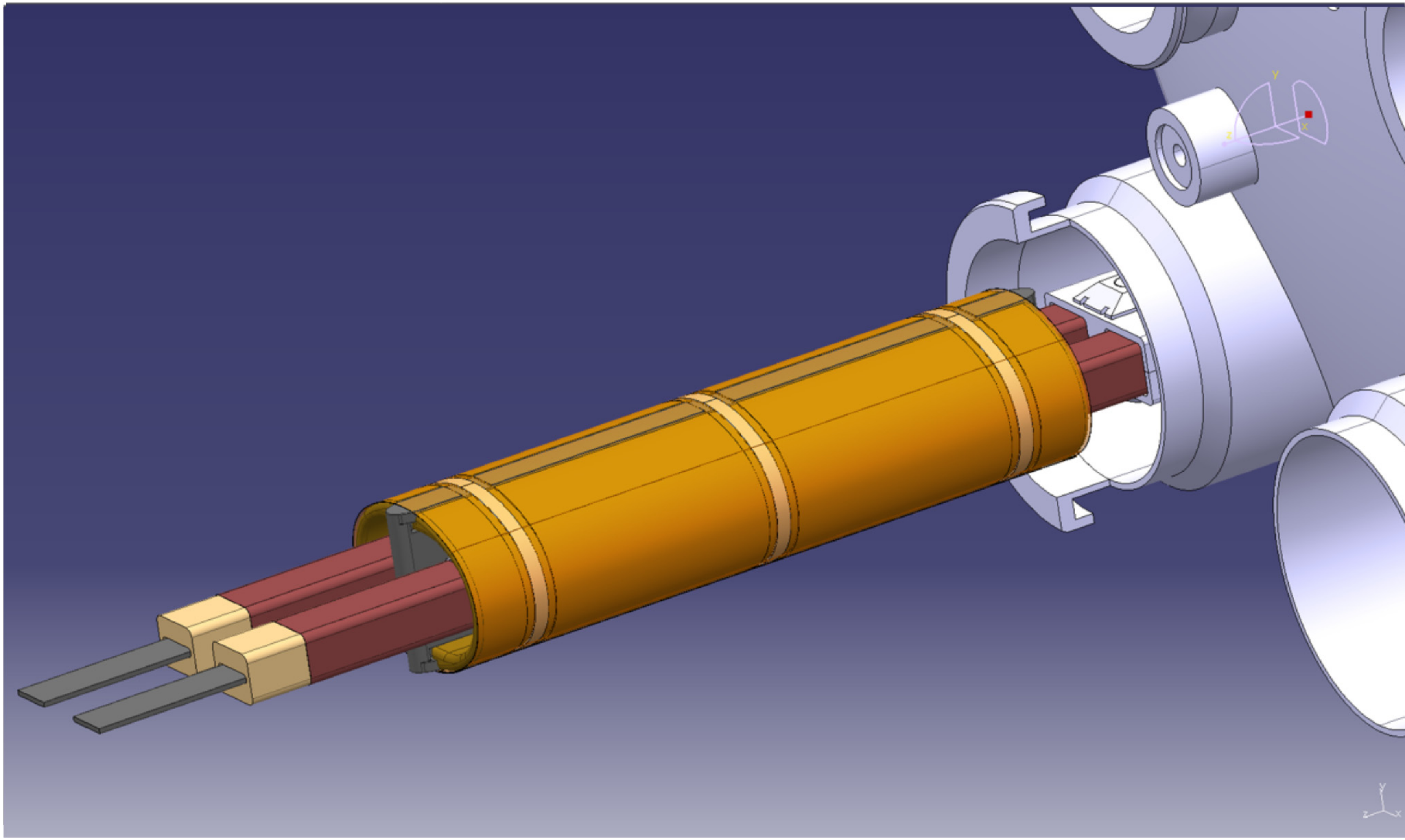


Phase III

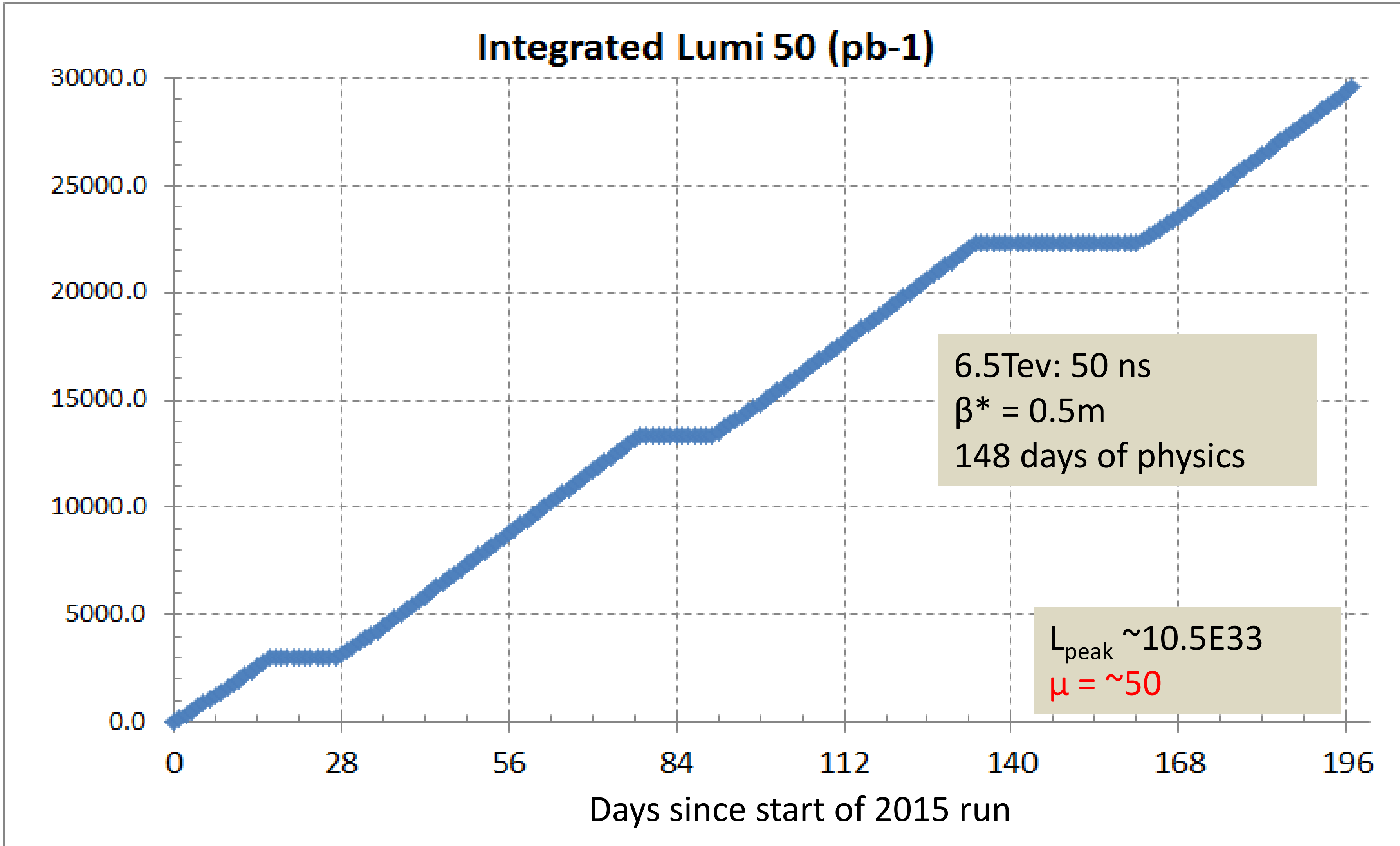
Insulation between bus bar and to ground, Lorentz force clamping

Then operation at 6.5TeV per beam

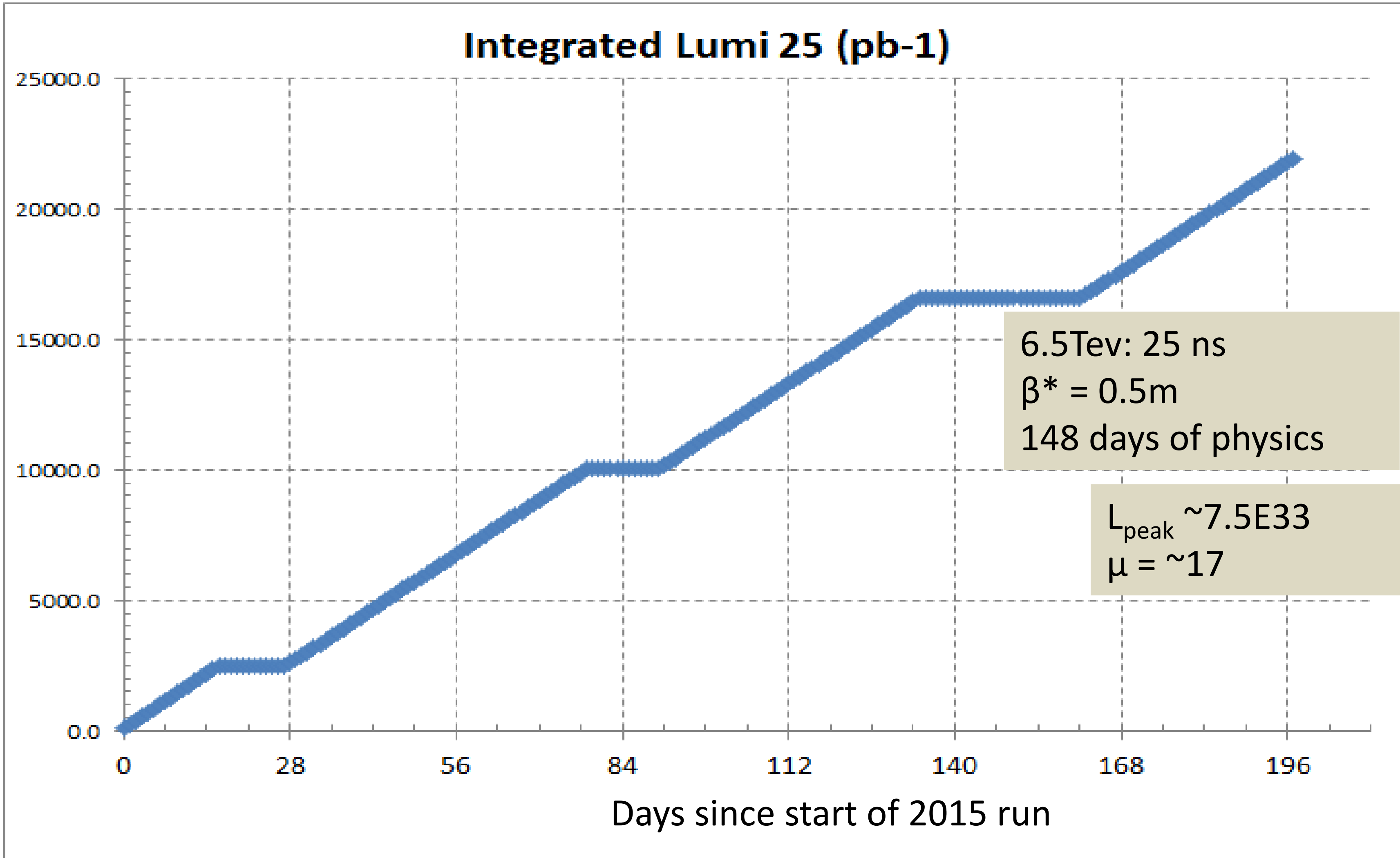
Assumptions

- E=6.5TeV
- β^* = 0.5m
- All other conditions as in 2012 i.e. no improvement (yet) in injector brightness, LHC availability same etc

6.5TeV per beam with 50ns



6.5TeV: 25ns



Integrated Lumi 25 (pb-1)
25000.0
20000.0
15000.0
10000.0
5000.0
0.0
0
28
56
84
112
140
168
196
Days since start of 2015 run
6.5Tev: 25 ns
β* = 0.5m
148 days of physics
L peak ~7.5E33
μ = ~17

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  - LHC Injectors Upgrade (LIU) see TUXA02 R. Garoby
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Draft 10 year plan (27/10/2011)

LS2 : 2018, LHC Injector Upgrades

see TUXA02 R. Garoby

Connect Linac4 to PS Booster, (if not already achieved)

TUPPR091, W. Weterings:

- New PS Booster injection channel

Upgrade PS Booster from 1.4 to 2.0 GeV

- New Power Supplies, RF system etc.
- Upgrade transfer lines, instrumentation etc.

MOPPD057, W. Bartmann:
THPPP016, A. Sarrio Martinez:

Upgrades to the PS

- New Injection region for 2.0 GeV Injection
- New/Upgraded RF systems
- Upgrades to Feedbacks/Instrumentation etc.

Upgrades to the SPS

WEPPP079, C. Rivetta: WEPPP074 S.De Santis:

- Electron Cloud mitigation – strong feedback system, or coating of the vacuum system
- Impedance reduction, improved feedbacks
- Large-scale modification to the main RF system

MOPPD056, W. Bartmann:
WEPR072 H. Bartosik:

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HL- LHC Upgrade

Aim to produce ~3000fb^{-1} delivered to the experiments over 10 years.

With a luminosity ~$5x10^{34}$ and leveling to limit pile-up

- Increased bunch charge, low emittance from the injectors
- Very Low β* (10-20 cm) in Atlas and CMS: new insertions TUPPR068, S. Fartoukh:
- (Crab-cavities to perform leveling)
- (Enhanced Collimation system)

Presently in the R&D Phase (magnets, RF, beam studies)

- Major R&D Effort for High-Field Magnets

THPPD030, S. Russenschuck: THPPD039, B. Auchmann:

- Studies of Crab-Cavity designs underway
- Collimators in the cold arcs + robust jaw material studies

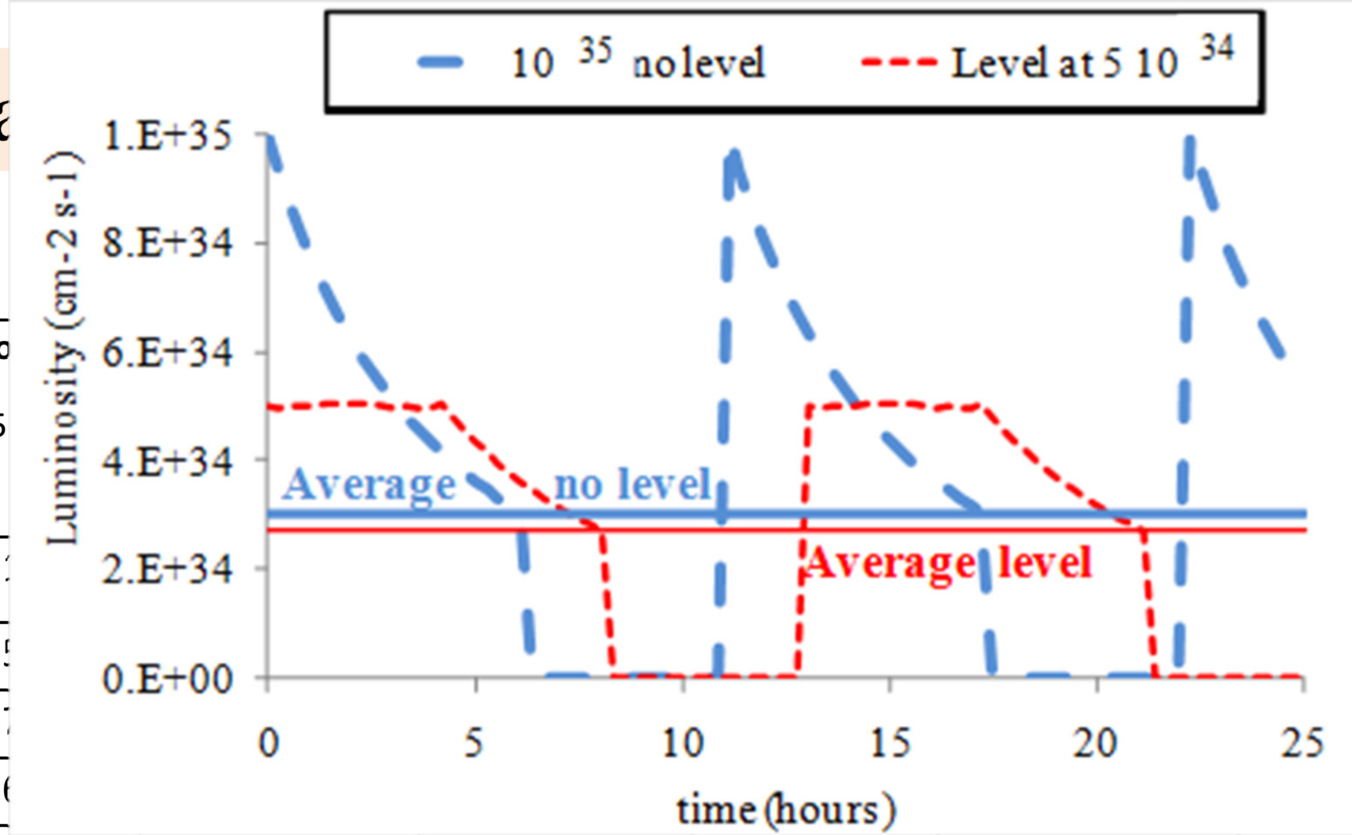
Construction of technical equipment is likely to start around 2016-17
For installation during Long shutdown 3 (2022)

TUOAC03, A.V. Zoblin: MOPPC005, F. Zimmermann: MOPPC010 R.DE Maria: MOPPC011 S. Fartoukh: WEPPC085, D. Gorelov:

Preliminary HL-LHC Performance Estimates

Parameter	Nom. 25 ns	Stretched 25 ns	Stretched 50 ns	Baseline 25 ns	Baseline 50 ns
N_b [10^{11}]	1.15	**2.2**	**3.5**	1.7	2.5
β^* [m]	0.55	**0.15**	**0.15**	**0.15**	**0.15**
ε_n [μm]	3.75	**2.5**	**3.0**	**2.5**	**2.0**
Piwinski	0.68	2.54	2.66	2.56	2.56
b-b/IP[10^{-3}]	3.1	3.9	5	3	**5.6**
L_{peak} (no crab)	1	9.0	9.0	5.3	**7.2**
Crabbing	no	**yes**	**yes**	**yes**	**yes**
$L_{peak\ virtual}$	1	25	25	14.3	19.5
Lumi level	=	5	2.5	5	2.5
Pileup L_{lev}=5L_0	19	95	95	95	95

Prelimina



Parameter	**No** 25				
N_b [10^{11}]	1.				
β^* [m]	0.				
ε_n [μm]	3.				
Piwinski	0.				
b-b/IP[10^{-3}]	3.1	3.9	5	3	**5.6**
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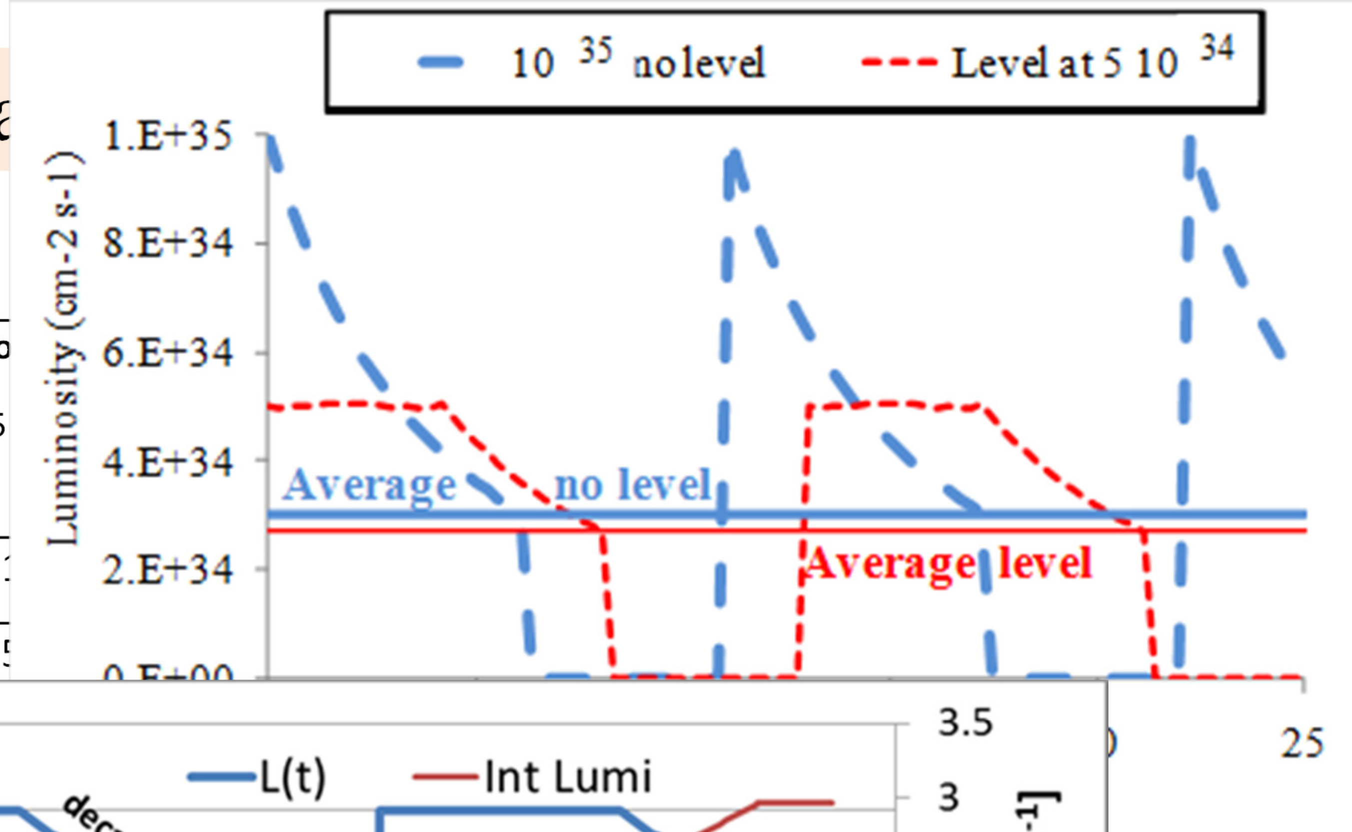
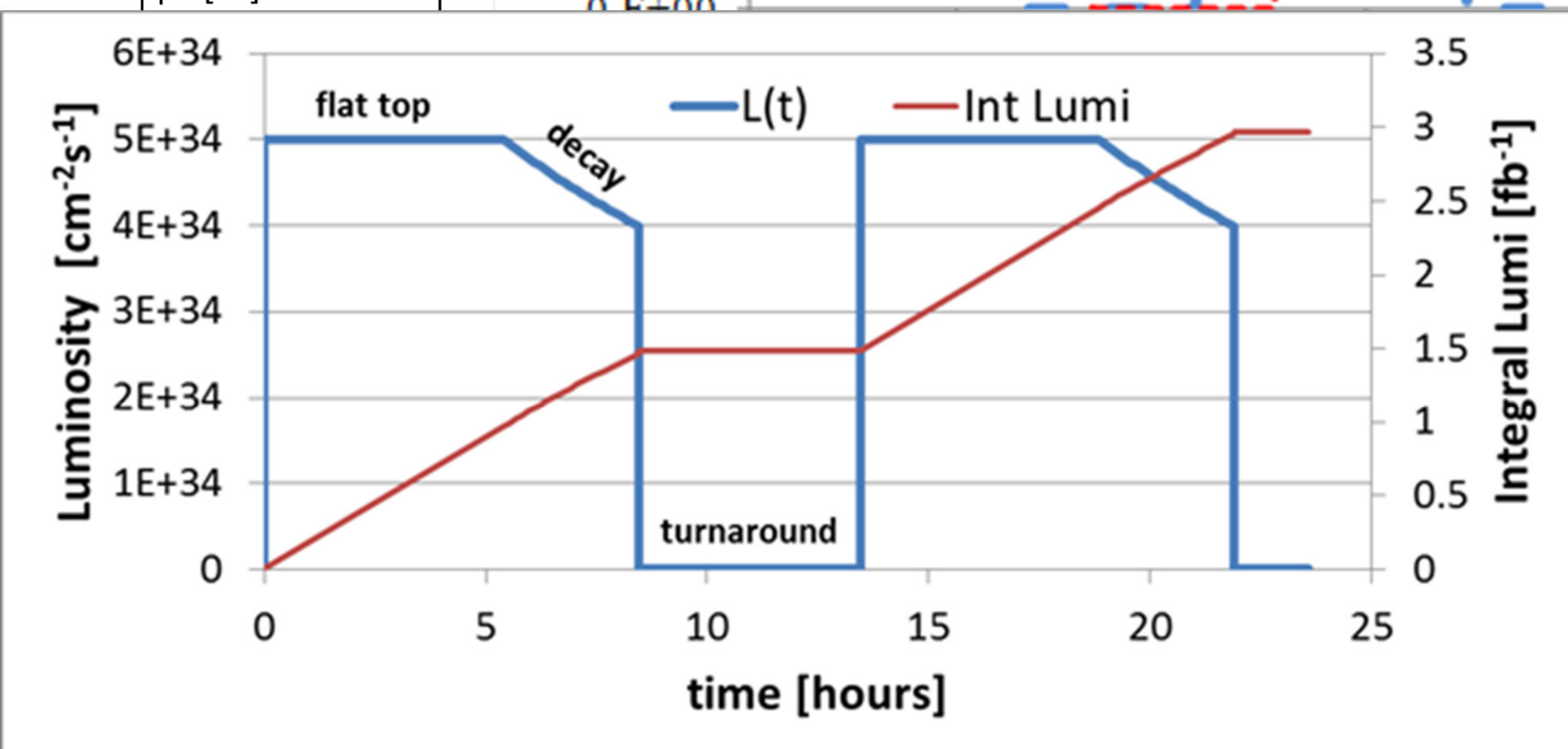
Prelimina

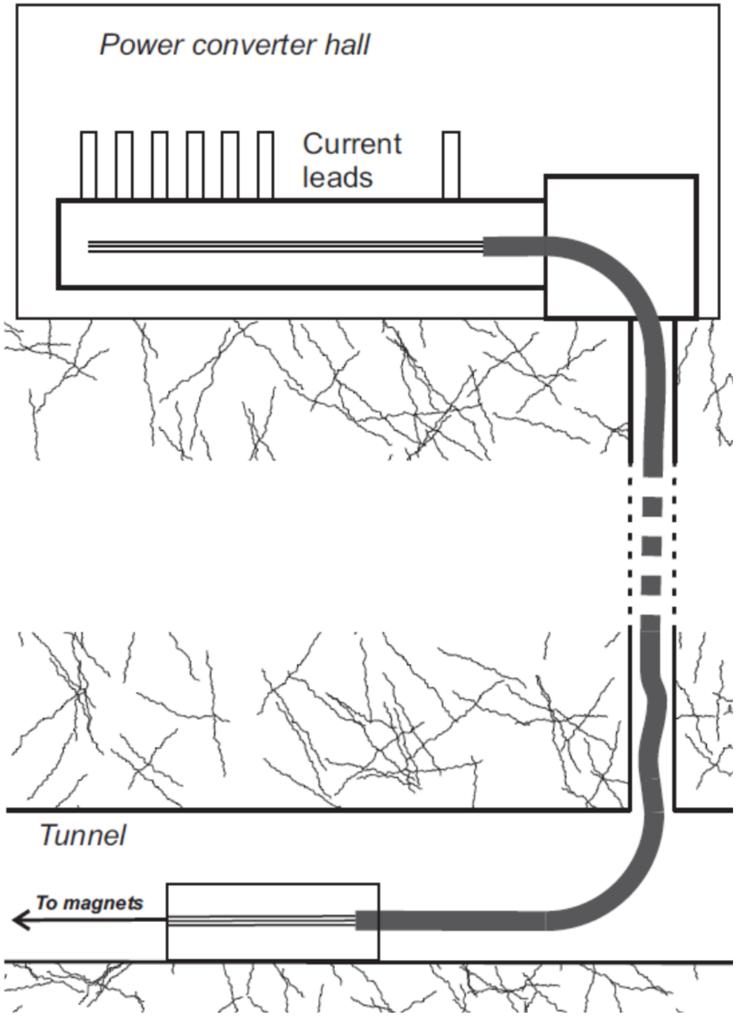
Parameter	No 25
N_b [10^{11}]	1.1
β* [m]	0.5

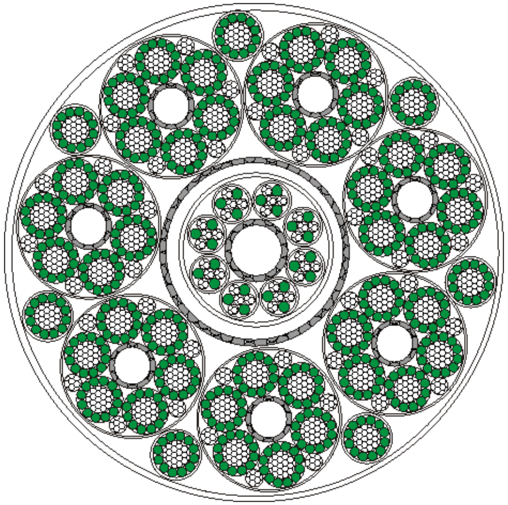


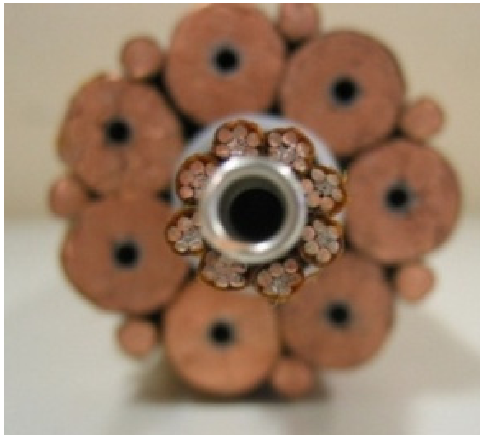


R&D Superconducting Links

Motivated by the need to remove the power converters out of the tunnel, avoiding radiation effects







Φ = 62 mm

MgB2
(or other HTS)

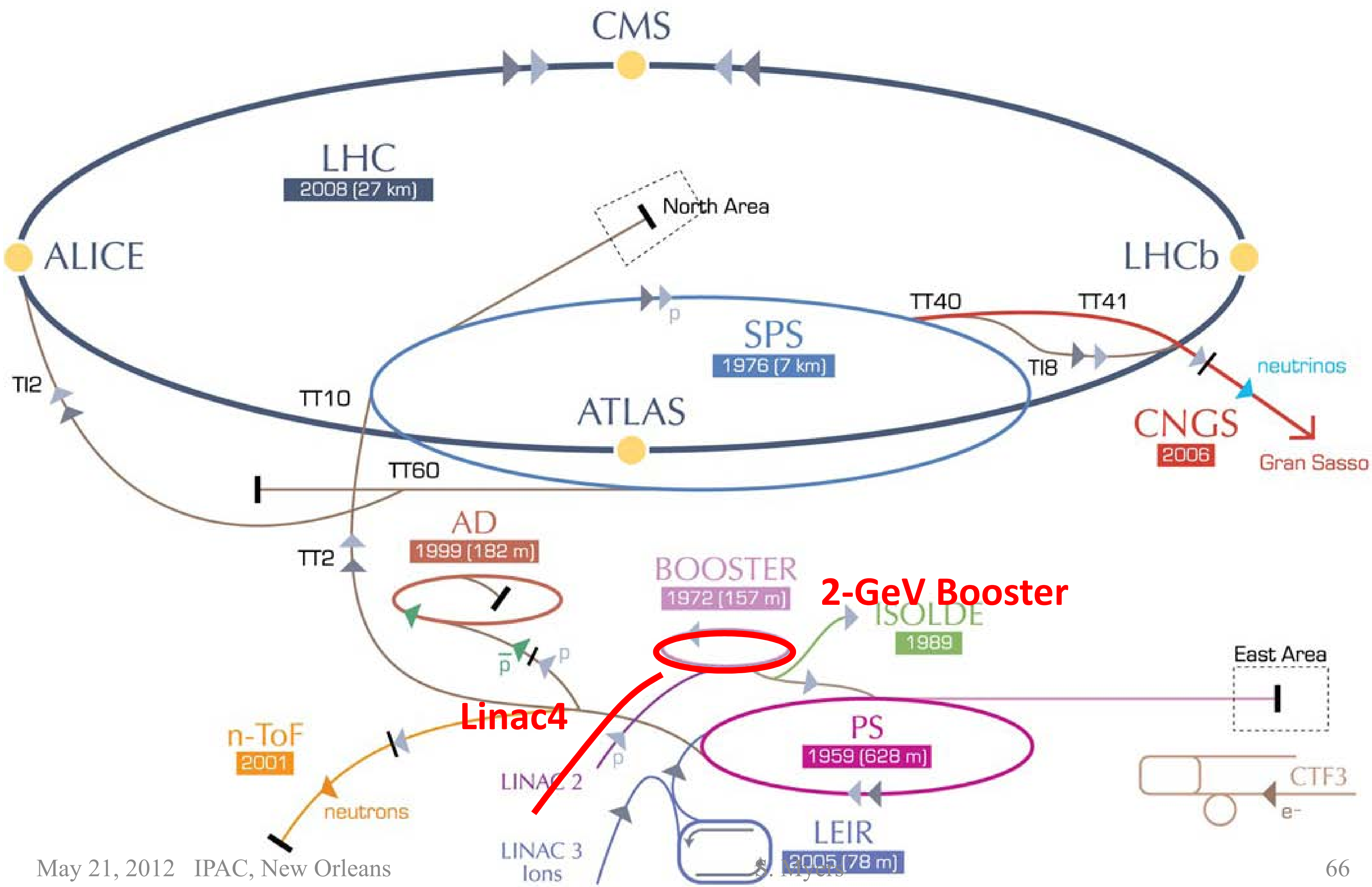
7 × 14 kA, 7 × 3 kA and 8 × 0.6 kA cables – Itot~120 kA @ 30 K

Also DFs with current leads removed to surface
Definitive solution to R2E problem
Make room for shielding unmovable electronics
Make much easier maintnance and application ALARA

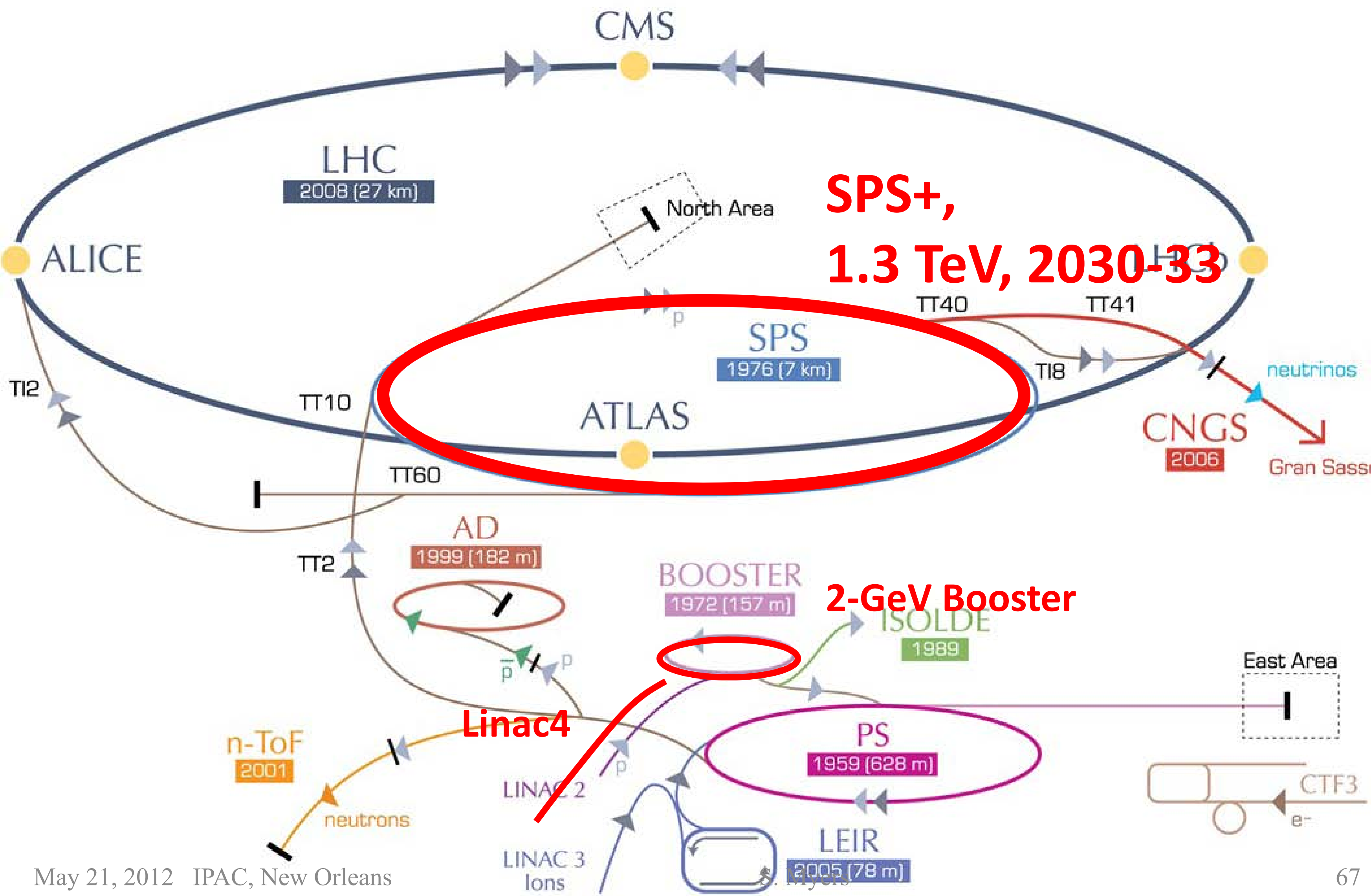
Main Topics

- General Description of LHC
- LHC in 2008
- Repair
- LHC Performance in 2010/2011
- Future
  - Estimated performance in 2012
  - Long Shutdown 1 (LS1) 2013-2014
  - Estimated performance in 2015
- Upgrades
  - Luminosity Upgrade (HL-LHC)
  - Energy Upgrade (HE-LHC)

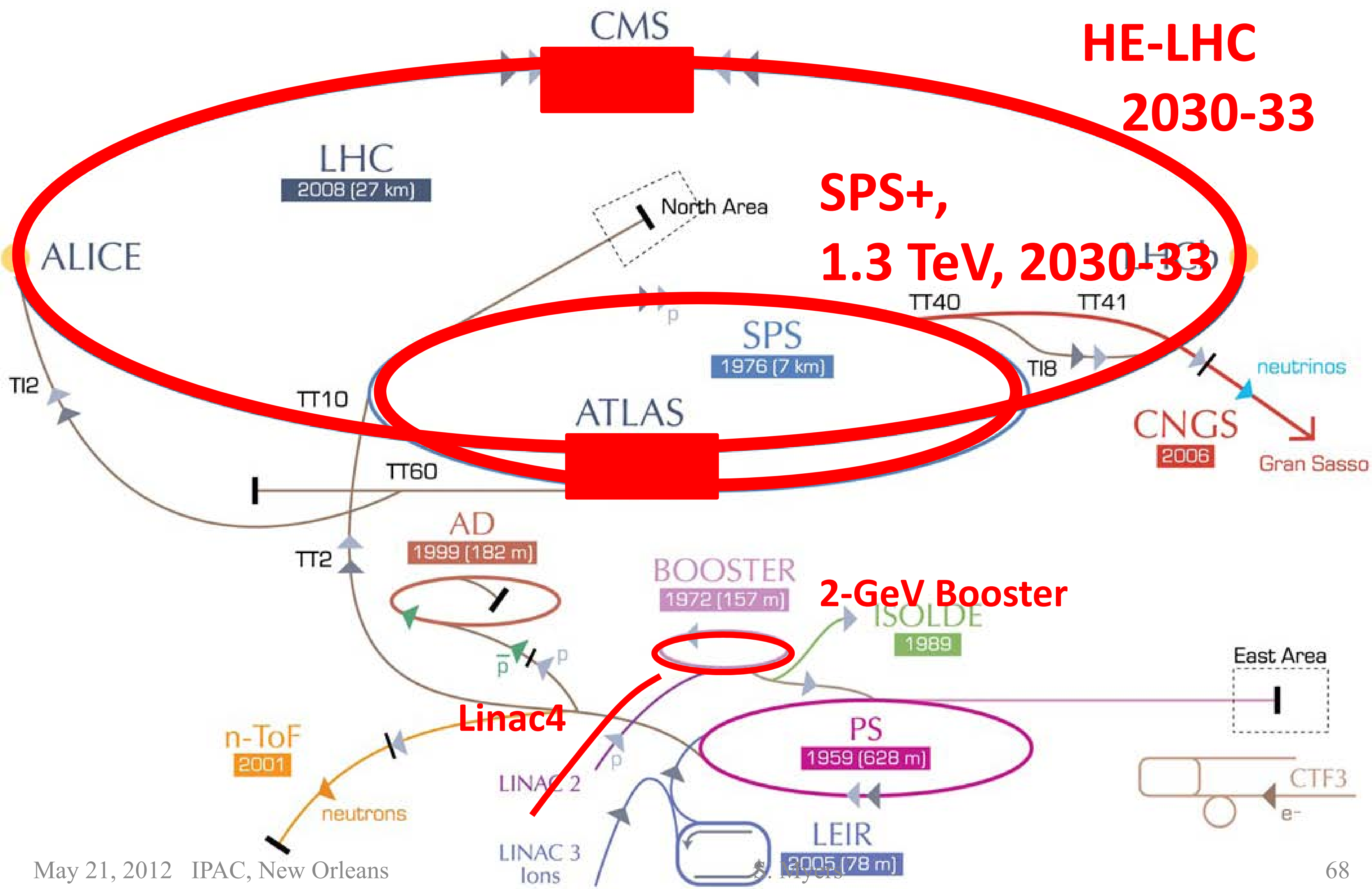
HE-LHC – LHC modifications



HE-LHC – LHC modifications



HE-LHC – LHC modifications



Very Long Term Objectives: Higher Energy LHC

Preliminary HE-LHC - parameters

	nominal LHC	HE-LHC
beam energy [TeV]	7	16.5
dipole field [T]	8.33	20
dipole coil aperture [mm]	56	40-45
#bunches / beam	2808	1404
bunch population [10^{11}]	1.15	1.29
initial transverse normalized emittance [μm]	3.75	3.75 (x), 1.84 (y)
number of IPs contributing to tune shift	3	2
maximum total beam-beam tune shift	0.01	0.01
IP beta function [m]	0.55	1.0 (x), 0.43 (y)
full crossing angle [μrad]	285 (9.5 $\sigma_{x,y}$)	175 (12 σ_{x0})
stored beam energy [MJ]	362	479
SR power per ring [kW]	3.6	62.3
longitudinal SR emittance damping time [h]	12.9	0.98
events per crossing	19	76
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	2.0
beam lifetime [h]	46	13
integrated luminosity over 10 h [fb^{-1}]	0.3	0.5

Very Long Term Objectives: Higher Energy LHC

Preliminary HE-LHC - parameters

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)
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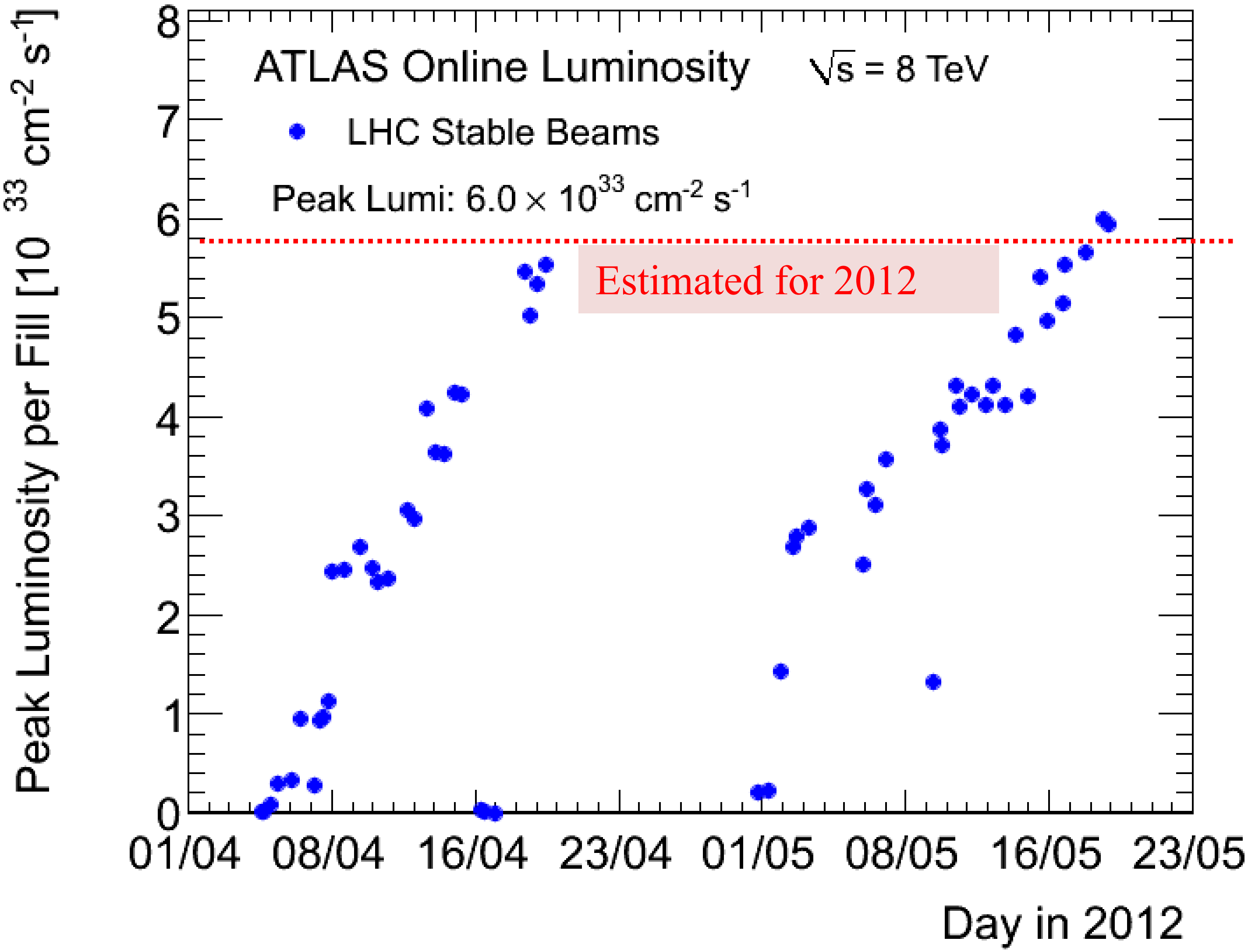
peak lumin[illegible] $cm^{-2}s^{-1}$]	1.0	2.0
beam lifetime [illegible]]	46	13
integrated luminosity over 10 h [fb^{-1}]	0.3	0.5

HE-LHC – main issues and R&D

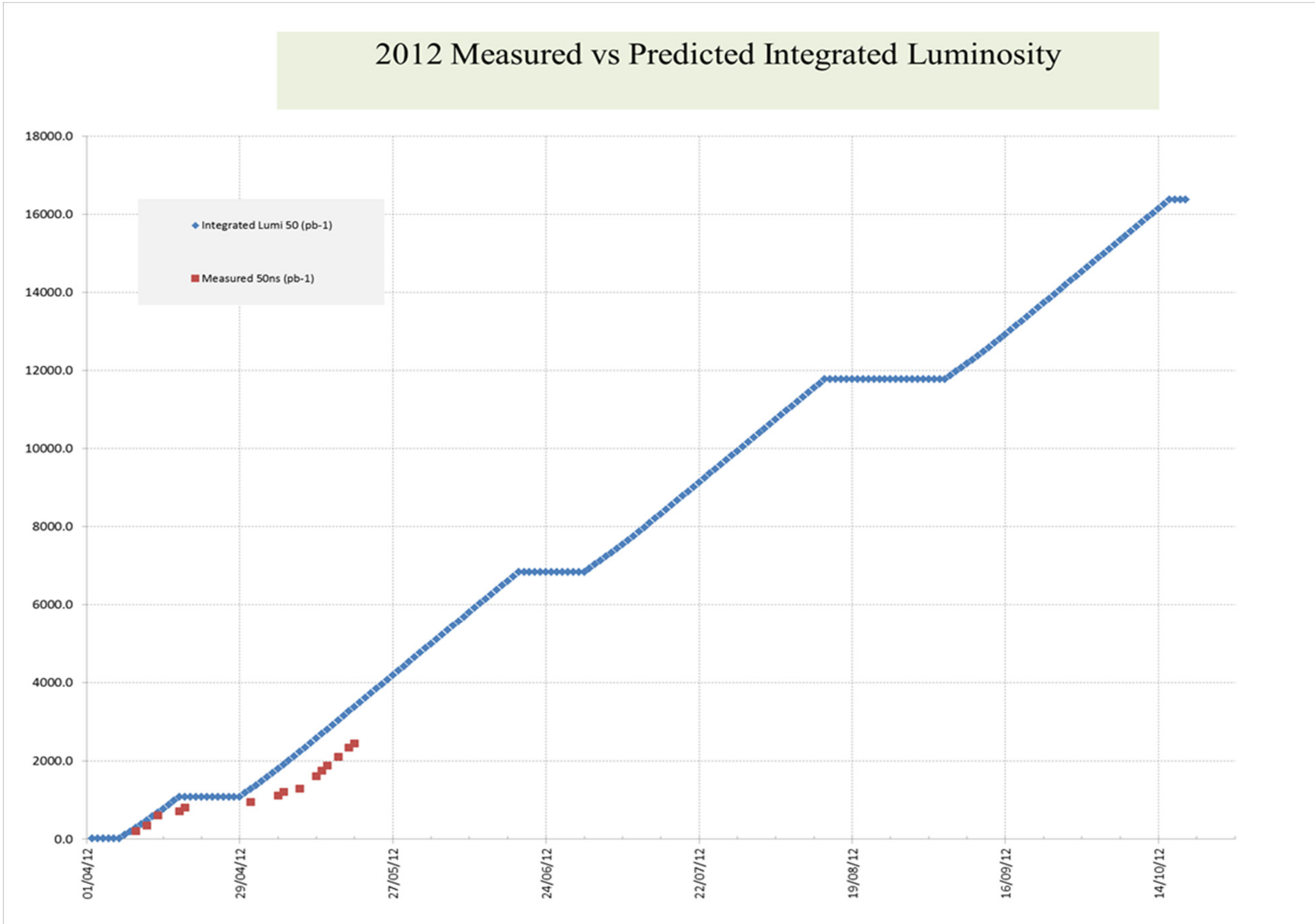
- High-field 20T dipole magnets based on Nb_3Sn, Nb_3Al, and HTS
- High-gradient quadrupole magnets for arc and IR
- Fast cycling SC magnets for ~1.3TeV injector
- Emittance control in regime of strong SR damping and IBS
- Cryogenic handling of SR heat load (first analysis; looks manageable)
- Dynamic vacuum

Stop Press: Present Performance

Peak Luminosity (as of today)

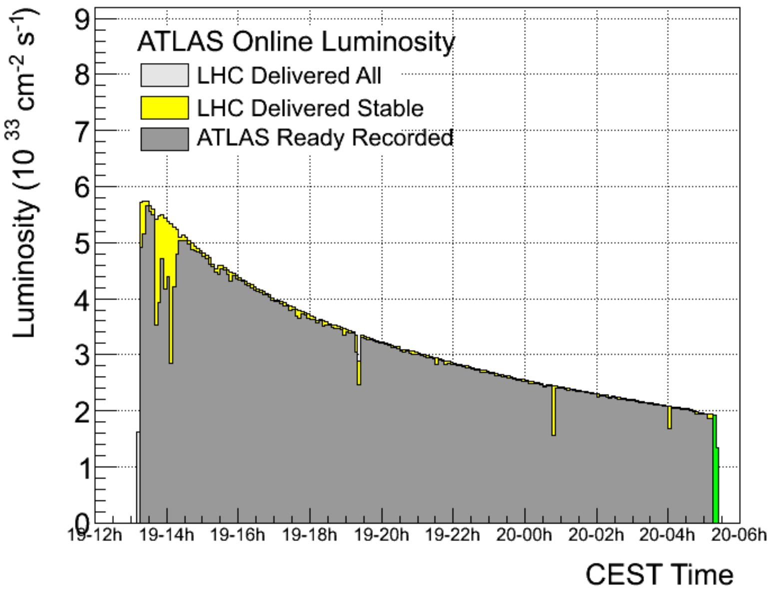


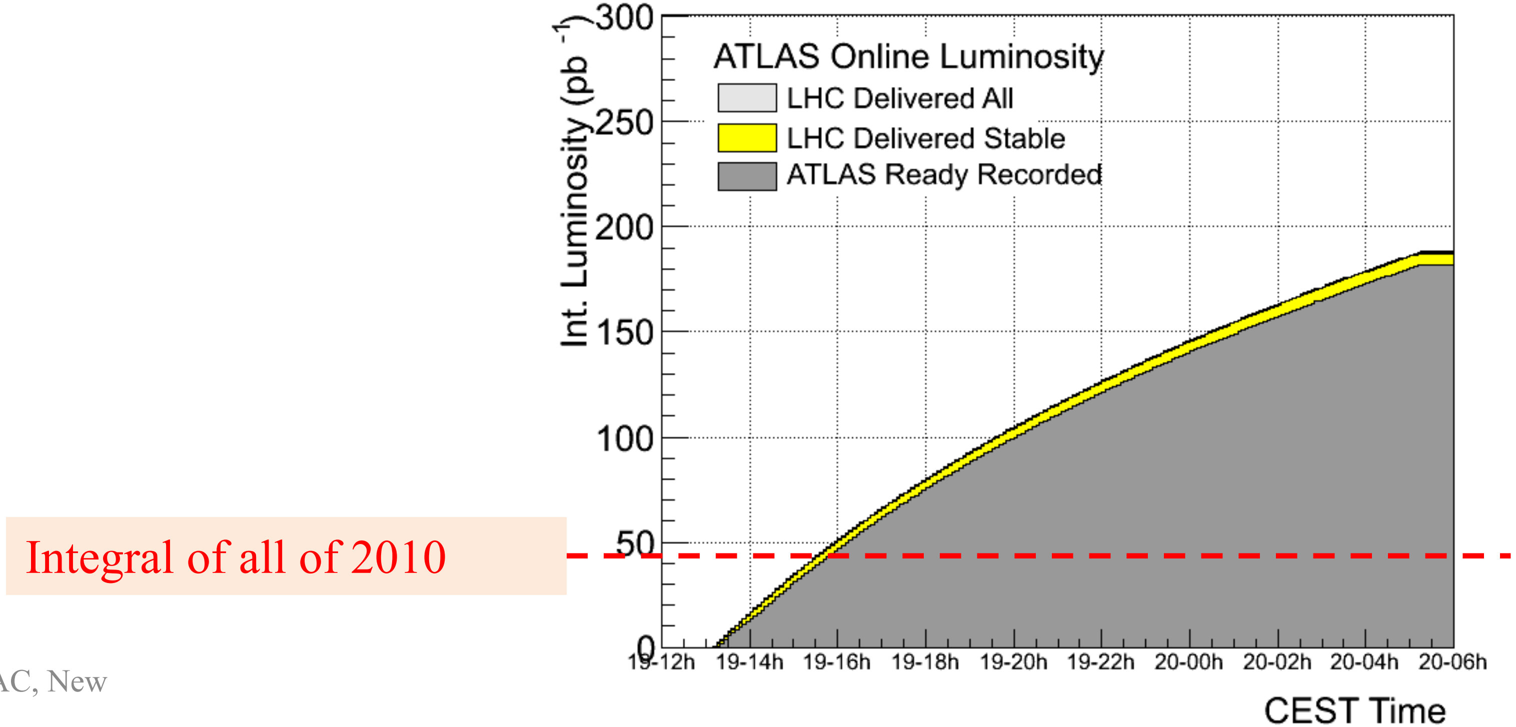
Luminosity Evolution (as of today)



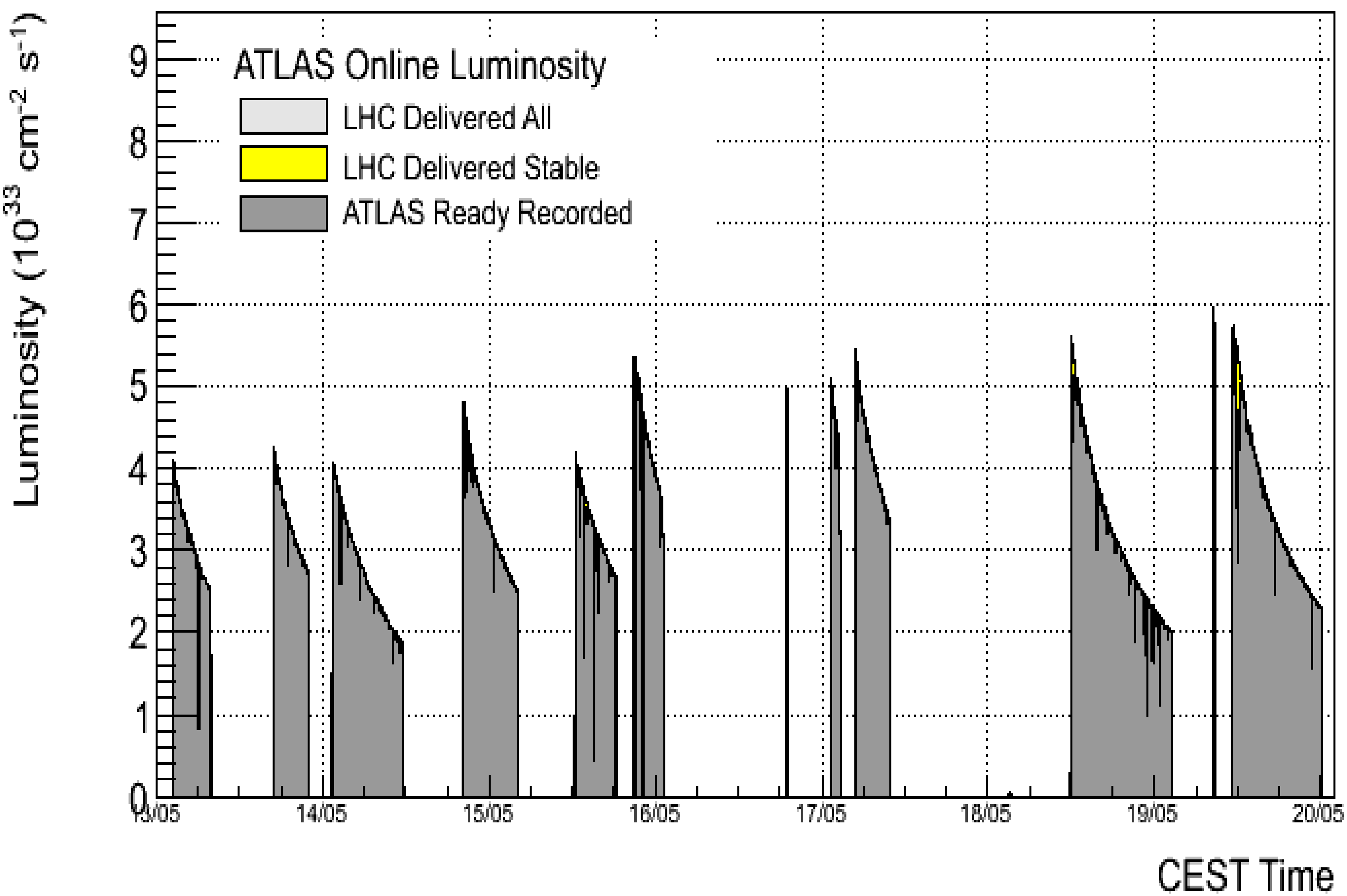
Saturday 19th May

Fill 2646 (16 hours)





Last 7 Days



Orleans

Not properly addressed (1)

MOPPC014, A. Macpherson:

- Beam-beam TUPPR076, T. Rijoff:
  - luminosity levelling by transverse separation,
  - crossing angle and separation schemes
  - bunches with a range of betatron tunes,
- Instabilities (TMCI, Head-tail, coherent instabilities, electron cloud)

  THYB03, E. Metral: MOEPPB10, A.Jeff: MOPPC004, C. Bracco: WEPPR068 K. Li:WEPPR069, N. Mounet:
  - Transverse Damping
  - Landau damping octupoles,
  - Beam-beam stabilization
  - Solenoidal fields in warm regions
- Beam Induced Heating WEPPR065, B. Salvant

Not properly addressed (2)

- Magnet System WEEPPB14, E. Todesco
- Machine protection THPPR040, M. Zerlauth: THPPP010, K. Fuchsberger:
  - Injection (protection devices, BLMS, injection interlocks..) THPPR037, M. Sapinski: TUPPR093/094, L. Drosdal:
  - Ramp and squeeze (collimators, BLMS, orbit control…)
  - Collisions (idem, FCMM, UFOs…) MOPPC017 M. Kuhn
- Emittance Control
- Aperture Measurements

MOPPD062, S. Redaelli: THPPR039, W. Hofle

Not properly addressed (3)

- UFOs… dust particles THPPP086, T. Baer: TUPPR092, B. Goddard:
- R2E and Single Event Upsets(SEUs)

THPPP006, M. Brugger

- Abort gap cleaning and Beam dump

MOPPD058, E. Gianfelica-Wendt: MOPPD078, L. Lari:

- Beam feedback; orbit, tune, chromaticity

THPPR039, W. Hofle

- Vacuum and electron cloud

MOPPR063, R. Veraci: WEPPD015 G. Brezliozzi: WEPPD018, G. Lanza: WEPPR075, C. Dominguez:

Not properly addressed (4)

- Collimation system

  MOPPD079, M. Cauchi: MOPPD080, L.Lari:
  MOPPD081, W. Weterings:TUPPR097, G. Valentino

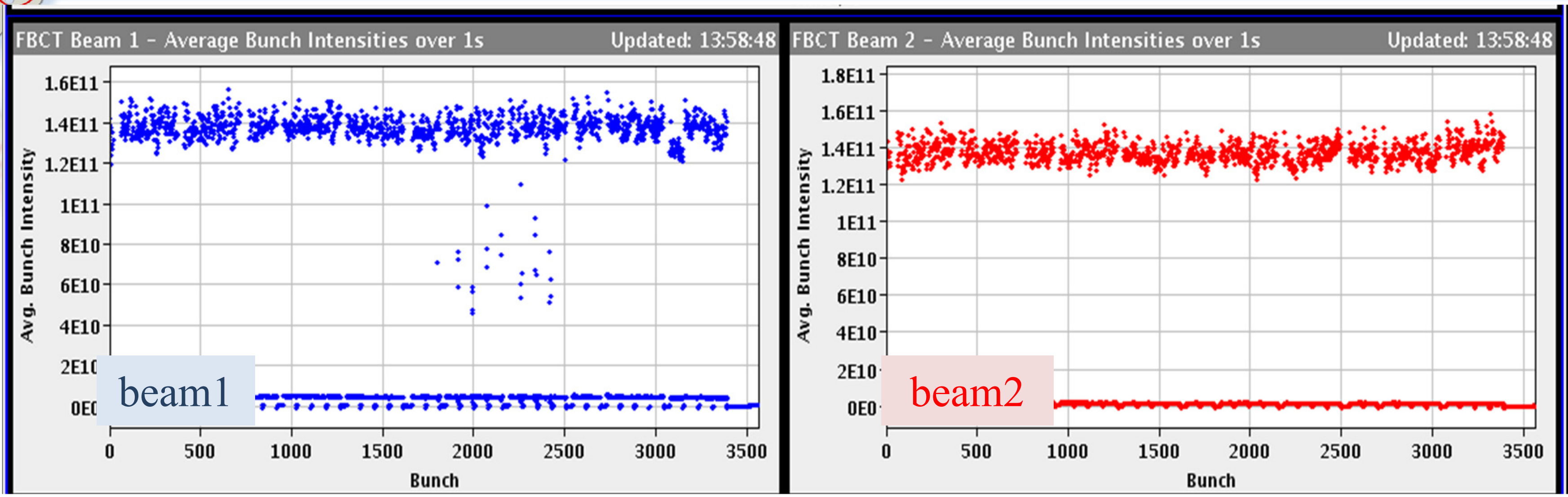
- LHeC

  TUPPR076, F. Zimmermann: TUPPR075, S. Russenschuck:TUPPC037, M. Kitterer: TUPPC038/039, L. Thompson: WEPPR076, F. Zimmermann:

- LEP3

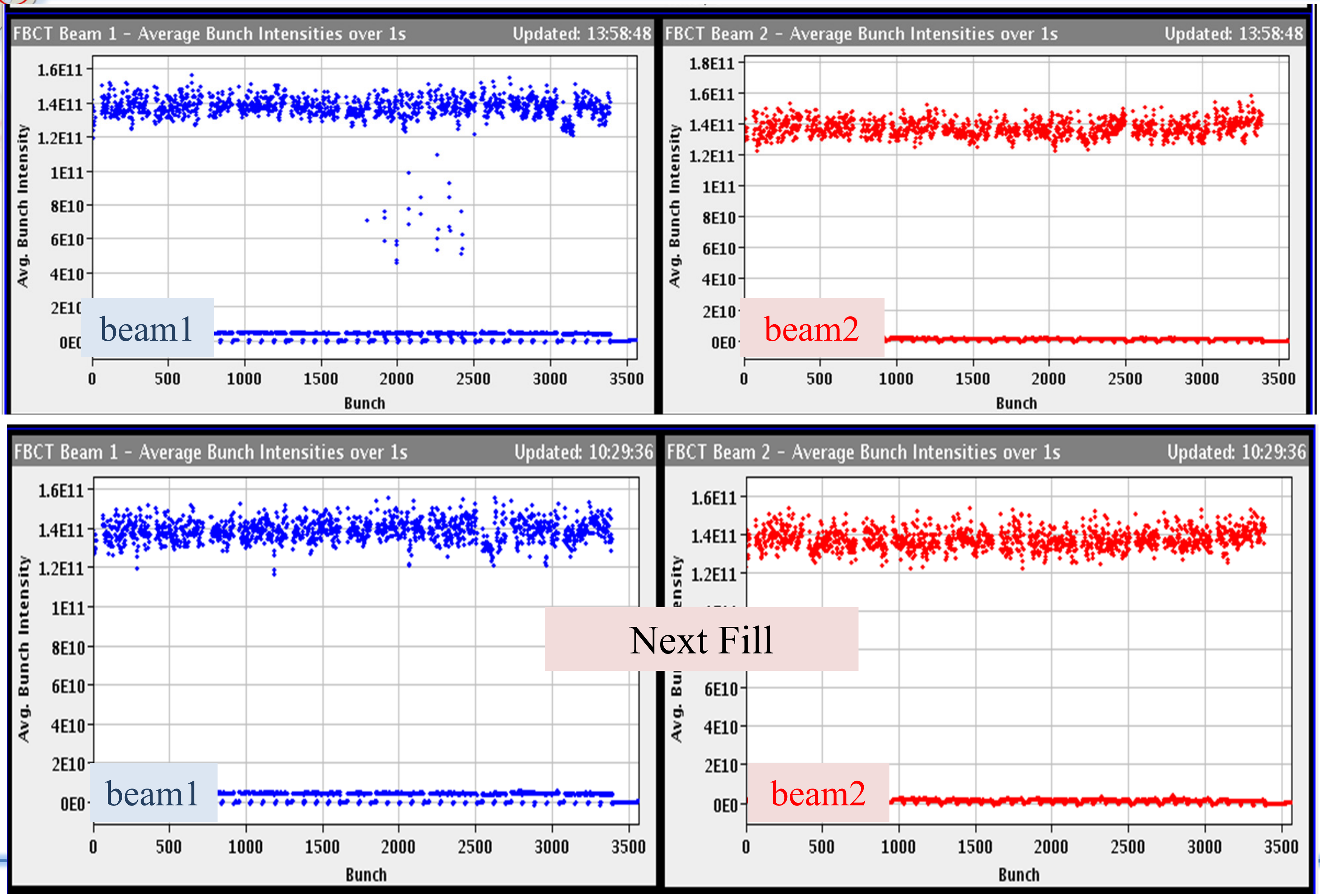
  TUPPR078, F. Zimmermann

Recent Example (2 days ago)



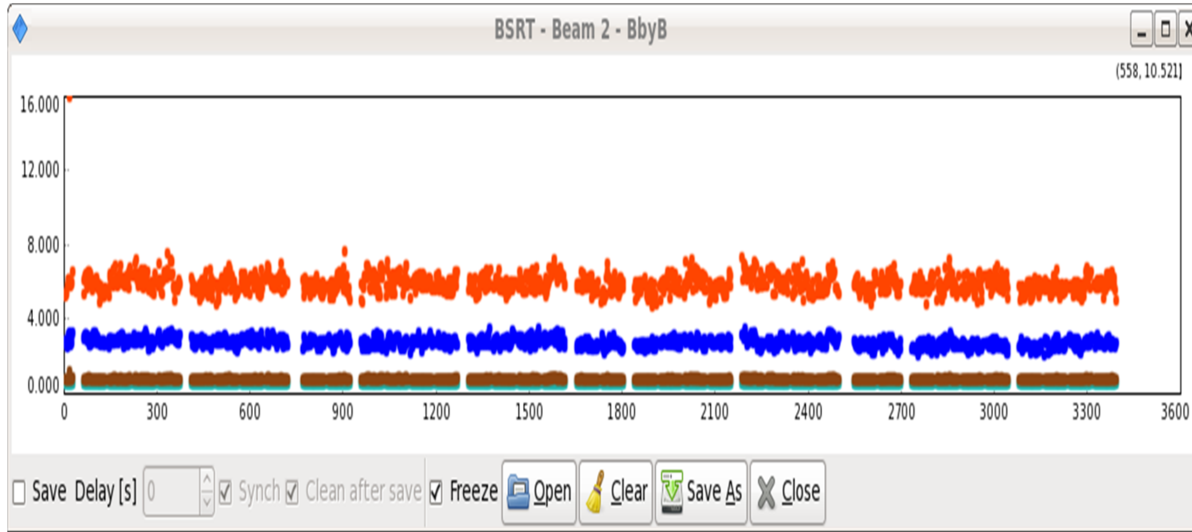
Plot shows the intensity of each bunch in each beam sometime after the start of collisions:
Several tens of bunches in beam 1 have decayed in intensity close to the limit to dump the beam
No effect on beam 2 bunches
The decaying bunches are the ones which only «collide» (separated collisions) in LHCb
For the next fill we decide to use a different bunch distribution where much fewer bunches «collide» only in LHCb

Recent Example (2 days ago)



Emittance Measurements (BSRT)

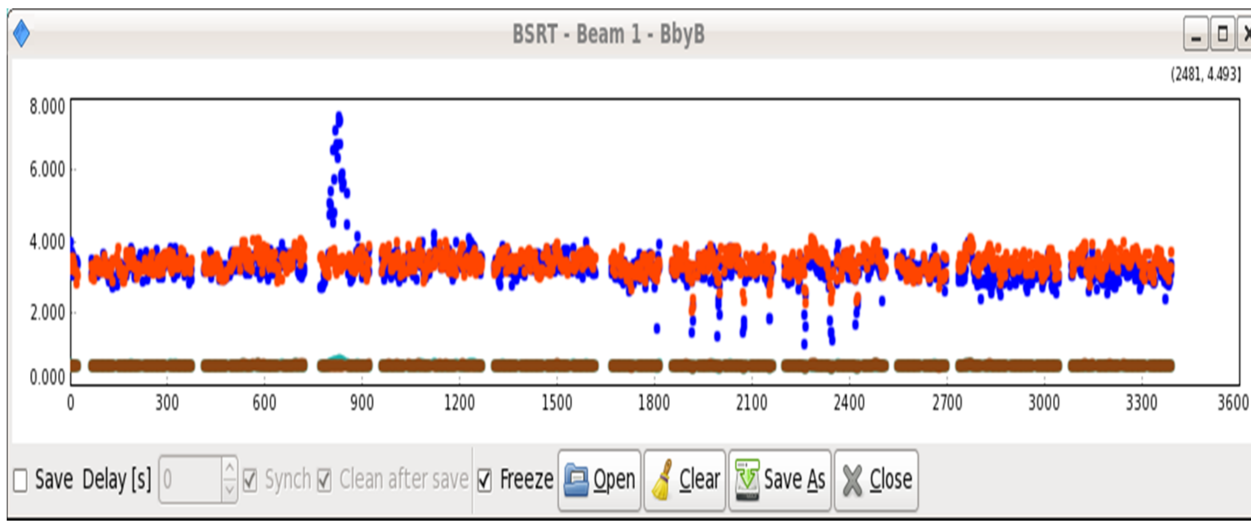
emittances of beam 2 bunches: the healthy one
Red/blue are Horiz and vert



emittances of beam 1 bunches:

preliminary observation:

- the bunches that lose intensity have much lower emittances



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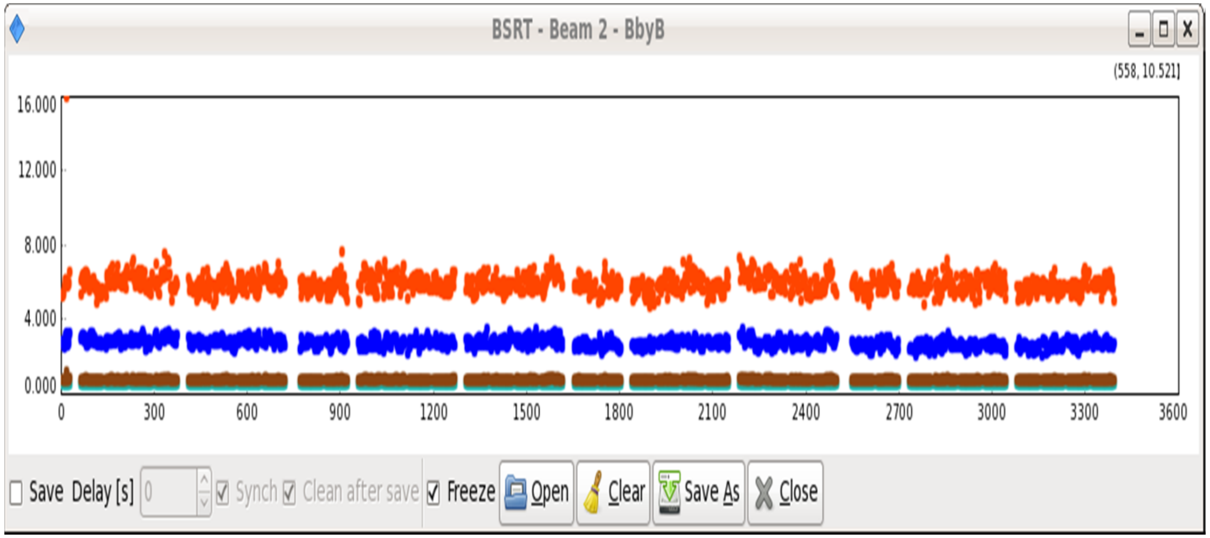

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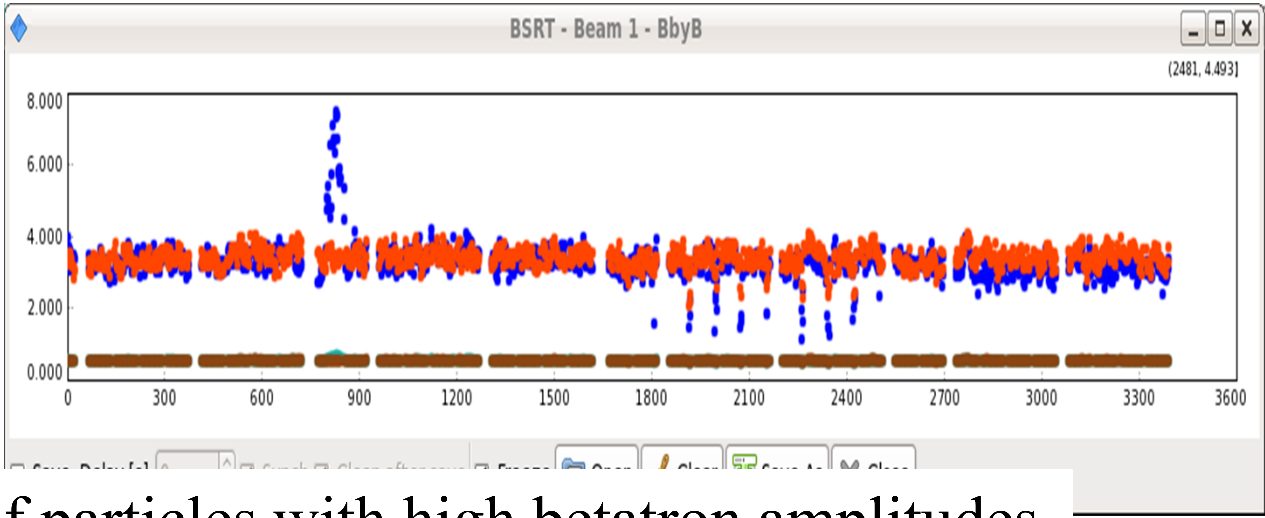
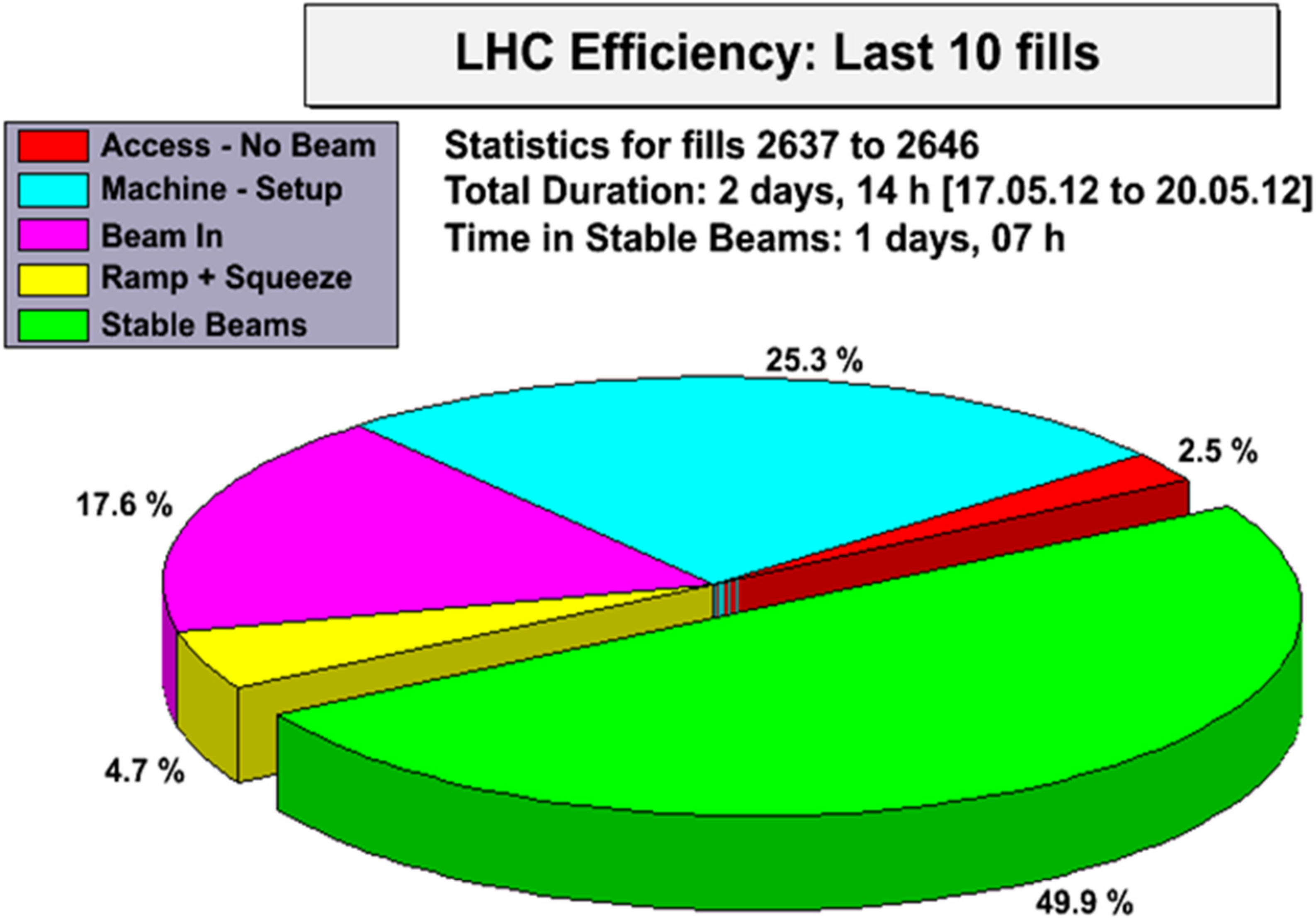


?Preferential losses of particles with high betatron amplitudes
?? Sort of resonant extraction on 3rd order resonance


LHC Efficiency: Last 10 fills
Access - No Beam
Machine - Setup
Beam In
Ramp + Squeeze
Stable Beams
Statistics for fills 2637 to 2646
Total Duration: 2 days, 14 h [17.05.12 to 20.05.12]
Time in Stable Beams: 1 days, 07 h
25.3 %
2.5 %
17.6 %
4.7 %
49.9 %

LHC Efficiency: Last 10 fills

Statistics for fills 2637 to 2646
Total Duration: 2 days, 14 h [17.05.12 to 20.05.12]
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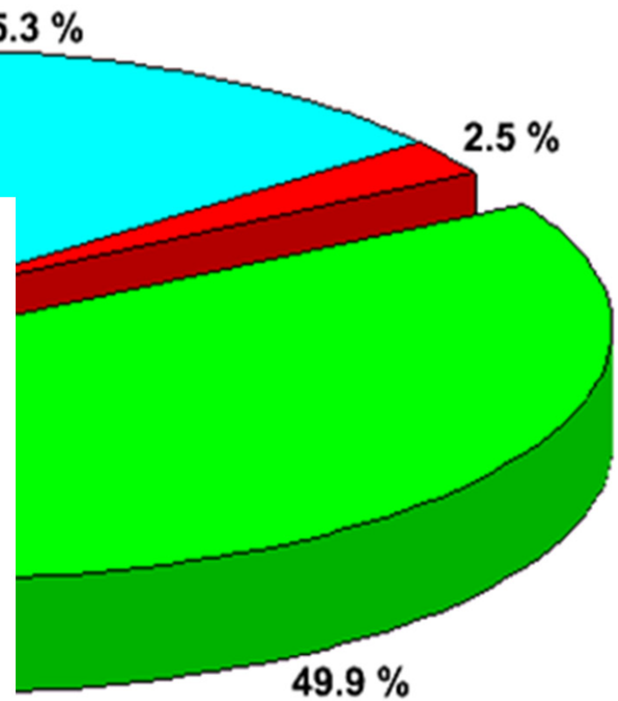

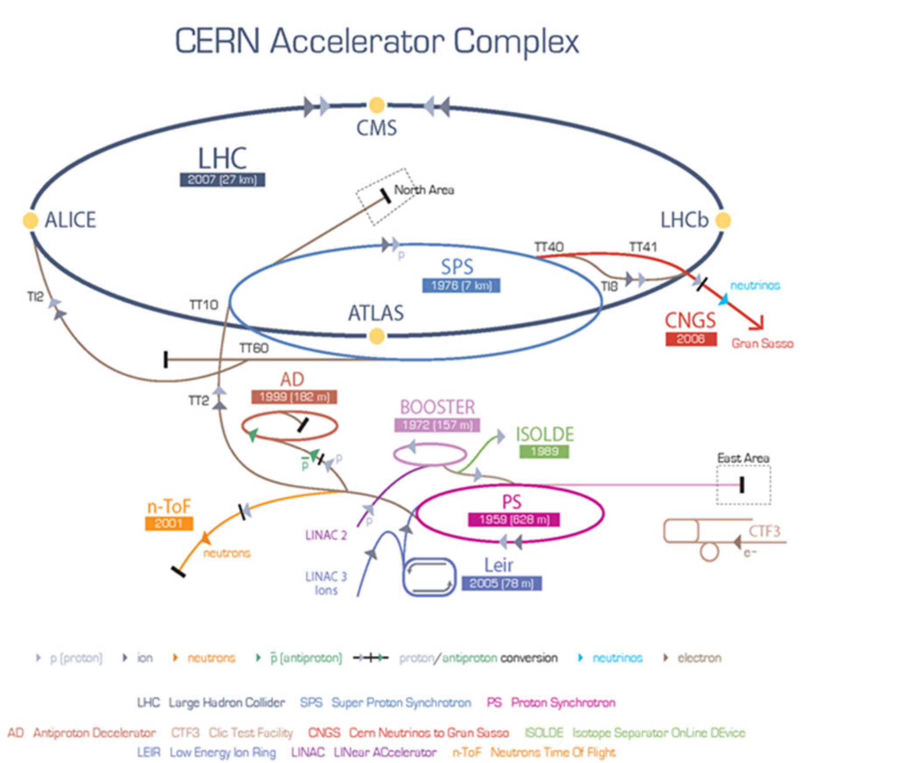

Acknowledgements

- The performance of the LHC is due to many hundreds of engineers and physicists working at CERN and our collaborating institutes
- The operation from the control room is carried out by
  - Machine coordinators (week to week)
  - Engineers-in-Charge and operators (shift to shift)
  - All under the capable leadership of the Operations group leader Mike Lamont

*** THPPP018, J. Wenninger: for the LHC operations group

Summary

- The First two years of LHC operation have produced sensational performance: well beyond our wildest expectations
- The combination of the performance of the LHC machine, the detectors and the Grid have proven to be a terrific success story in particle physics.
- However, we must remain extremely vigilant with respect to the protection of the machine (120MJ of stored energy) and hope that there are no old “unexploded bombs” in the hardware!!
- In the absence of any major technical failure, the LHC machine WILL produce enough integrated luminosity in 2012 to allow the detectors to discover or exclude the Higgs Boson. EITHER DISCOVERY OR EXCLUSION WILL BE A MAJOR DISCOVERY!
- The high energy operation after the Long Shutdown will be another exciting era in discovery physics

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Thank you for your attention