

# LHC: Present Status and Prospects for the Future.

APS DPF Conference,  
Providence, Rhode Island,  
USA

Saturday 13<sup>th</sup> August 2011

Steve Myers **(for the LHC team and collaborators from around the world)**

# Topics

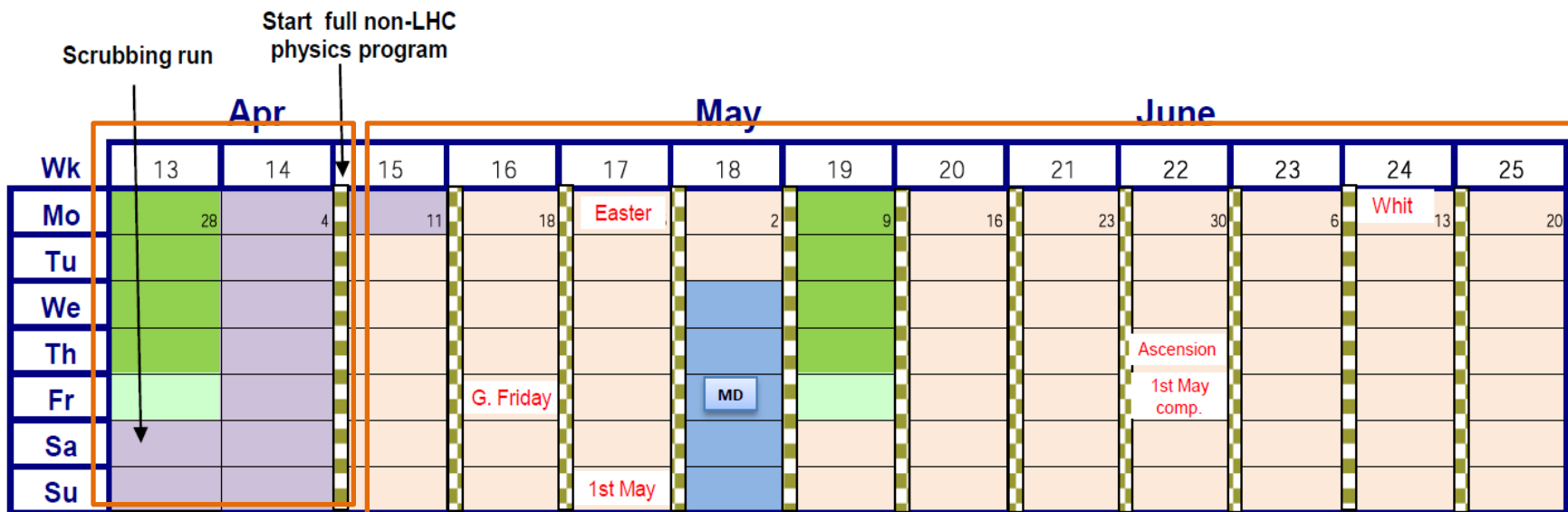
- LHC progress in 2011
- Prospects in the Short term (2011—2012)
- Mid Term Prospects (2014-2021)
- Long Term Prospects (2022--....)

# Topics

- LHC progress in first half of 2011
- Prospects in the Short term (2011—2012)
- Mid Term Prospects (2014-2021)
- Long Term Prospects (2022--....)

# The 3 periods

1. Physics re-established with 75ns and increasing the number of bunches,
2. Intermediate energy run at 1.38 TeV/beam + Scrubbing Run
3. Start of going by steps towards 900b + TS + (MD)



# Estimated Peak and Integrated Luminosity

March CERN Council

- Baseline is 2E32 Peak and 1fb-1 (integrated)
- But following 2010, we are confident we will do better

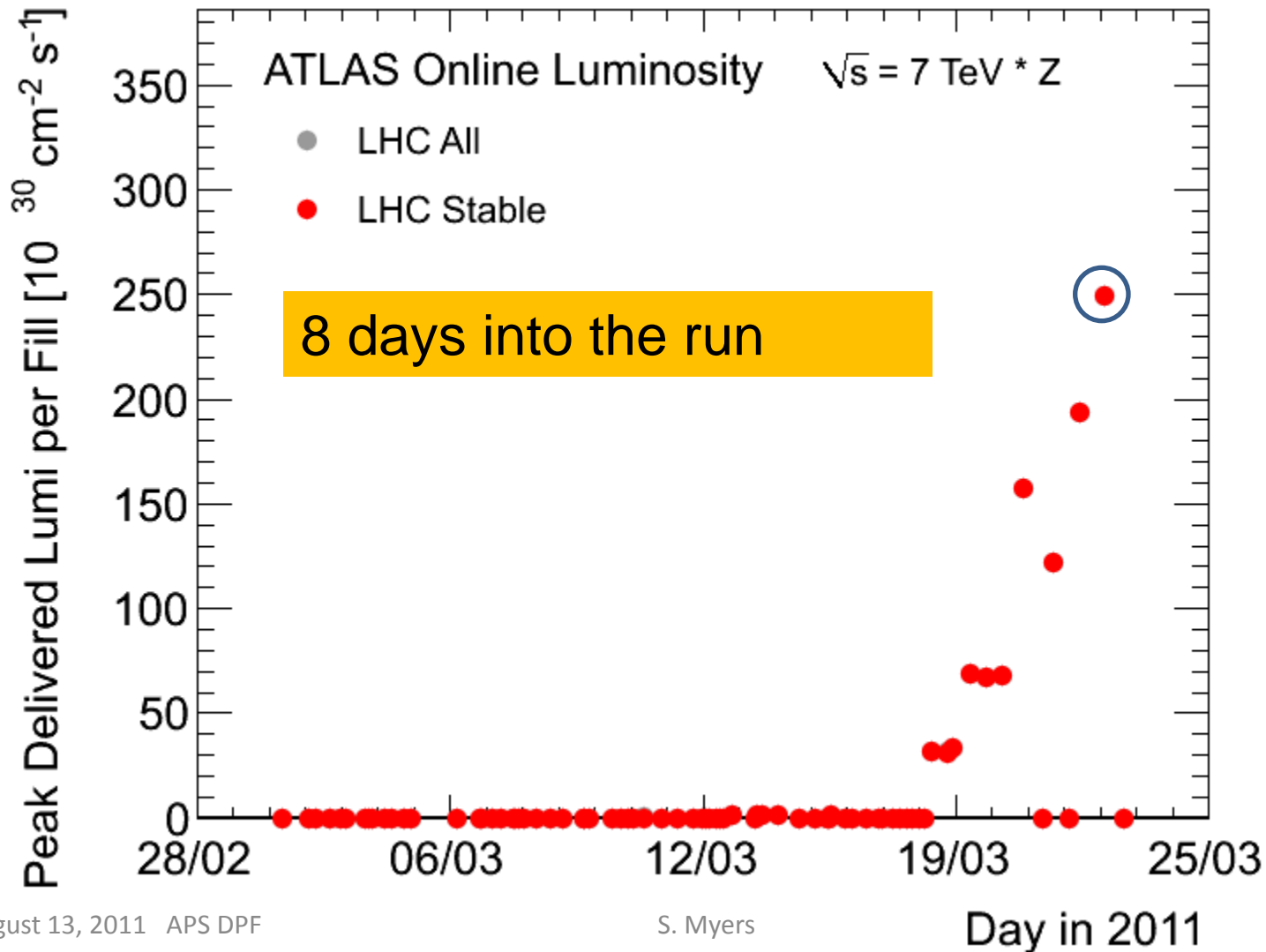
$$\beta^* = 1.5\text{m}$$

days	H.F	Comm with	Fills with	kb	Nb e11	$\epsilon$ $\mu\text{m}$	$\xi/\text{IP}$	L Hz/cm <sup>2</sup>	Stored energy MJ	L Int fb <sup>-1</sup> 4 TeV	L Int fb <sup>-1</sup> 3.5 TeV
160	0.3	150 ns	150 ns	368	1.2	2.5	0.006	~5.2e32	~30	~2.1	~1.9
135	0.2	75 ns	75 ns	936	1.2	2.5	0.006	~1.3e33	~75	~3	~2.7
						2	0.007	~1.6e33		~3.8	~3.3
						1.8	0.008	~1.8e33		~4.2	~3.7
125	0.15	50 ns	50 ns	1404	1.2	2.5	0.006	~2e33	~110	~3.2	~2.8

Possible integrated Luminosity of 2-3 fb-1

# First Record Fill of 2011 (on March 23)

Physics re-established with 75ns and increasing the number of bunches,



# Summary of week 14 & part of 15

372 372 Bubbling run  
hoven, J. Wenninger,

588 588 ni  
er, R. Assmann

Decision: Continue  
physics with 50ns

516 516

660 660

948 948

1020

1020



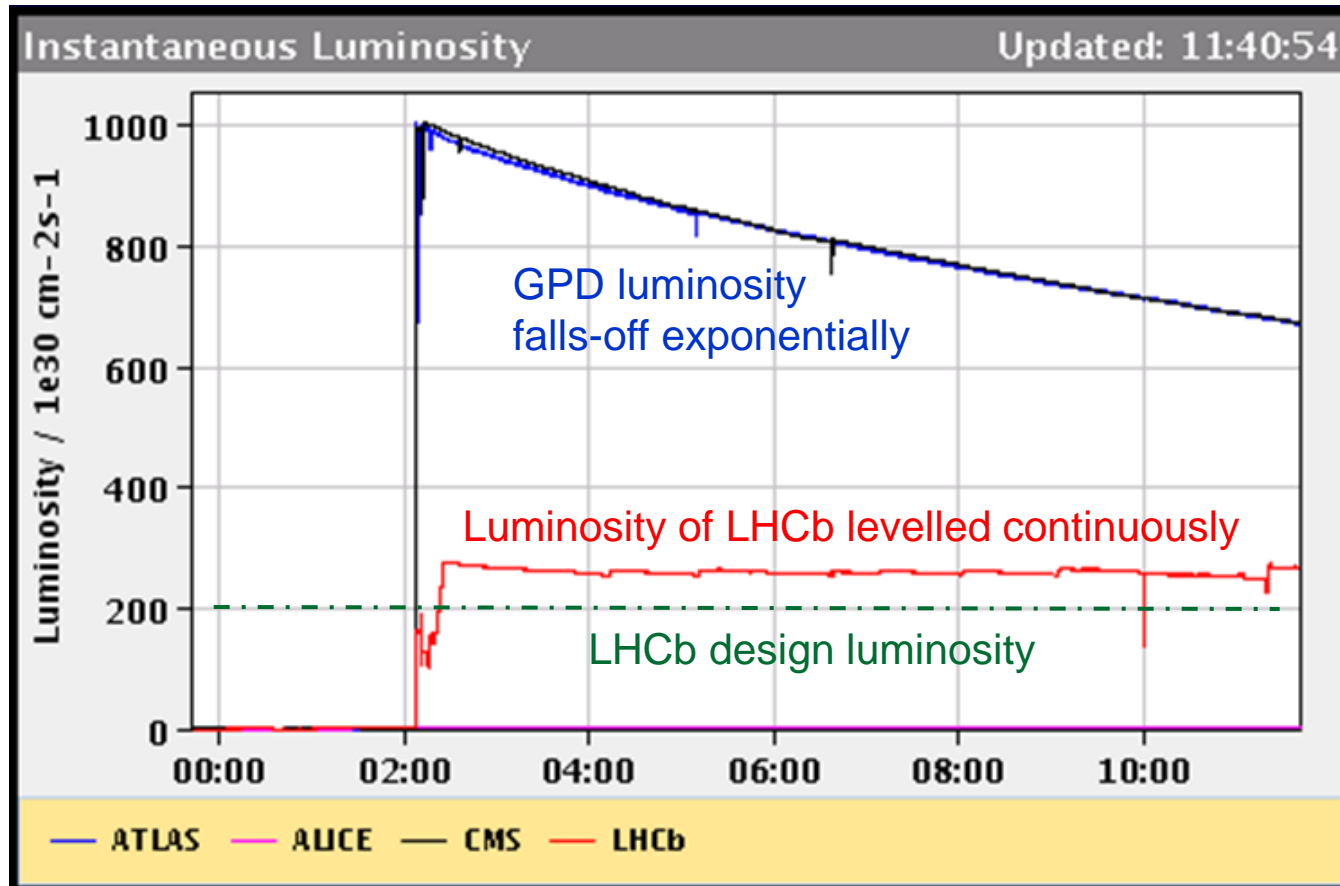
## Issues encountered with Higher Intensities

- Requires much finer control of the beam parameters
  - Chromaticity, gain of feedback and use of Landau octupoles
  - Injection quality
- Many more UFOs: not yet serious



# Expected integrated luminosity for LHCb in 2011

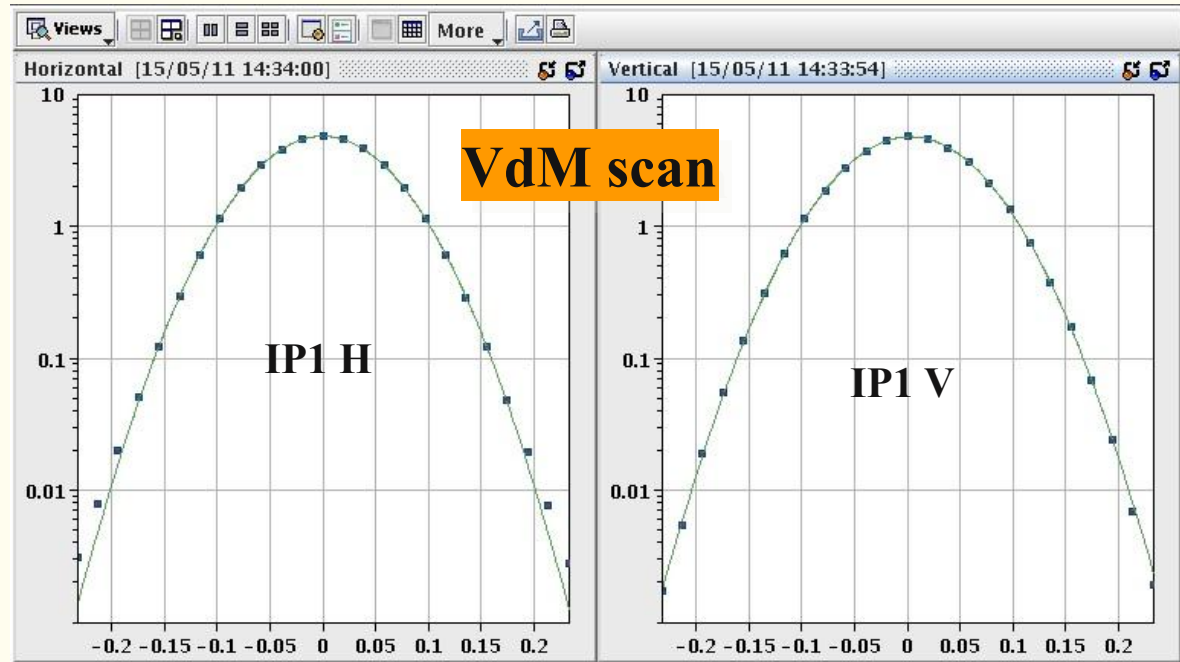
Introduced luminosity leveling for LHCb → can run at optimal  $\mu$  and  $L_{\max}$



→ Since end of May running at constant  $L \sim 3 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$  with  $\mu \sim 1.5$

# LHC precision front

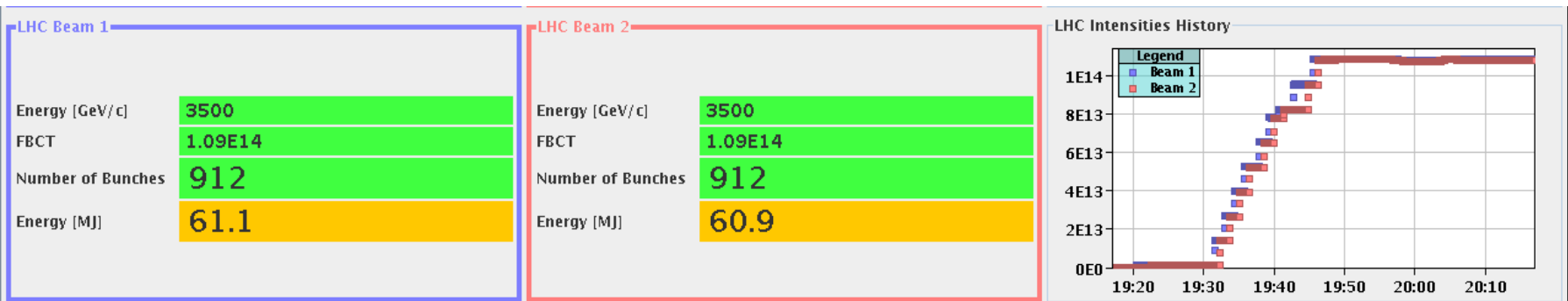
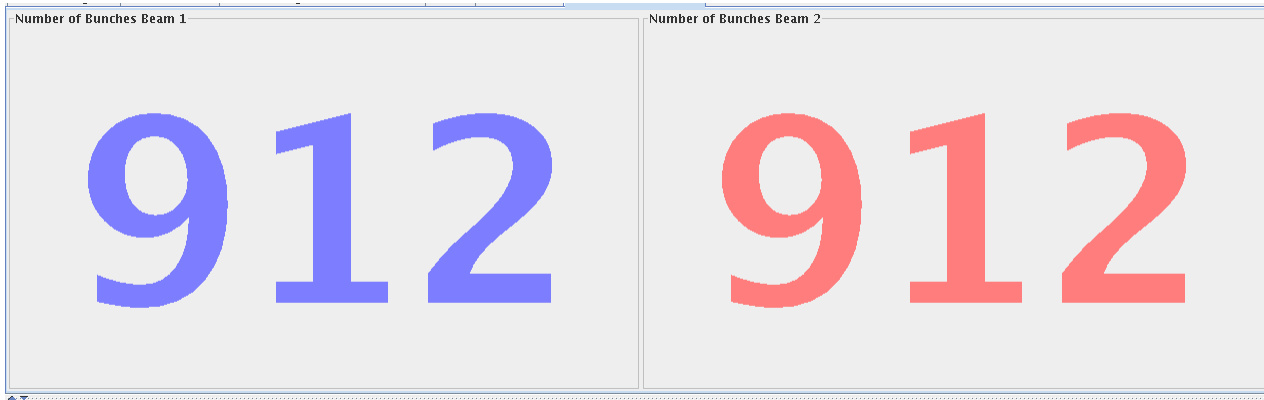
- absolute luminosity normalization
- low, well understood backgrounds
- precision optics for ATLAS-ALFA and TOTEM



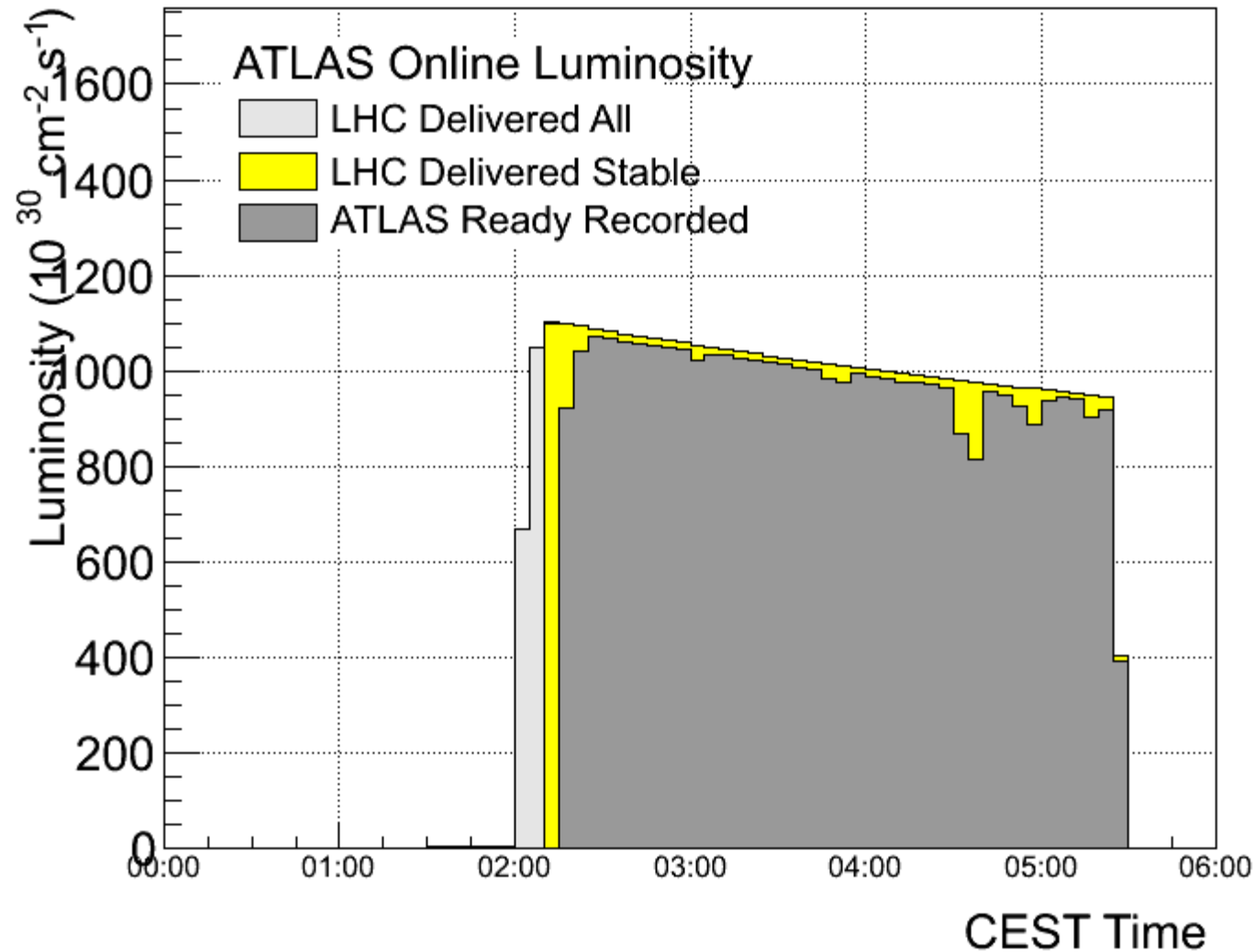
precise measurement of the luminous region +  
beam intensity --> absolute luminosity and  
cross section calibration

currently ~ 3.2 % level

# 21 May: 912 bunches at 3.5TeV

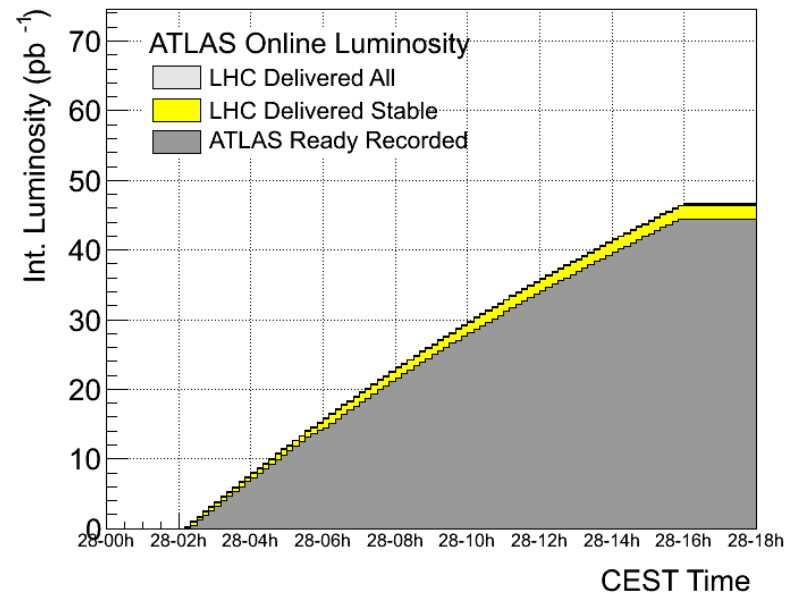
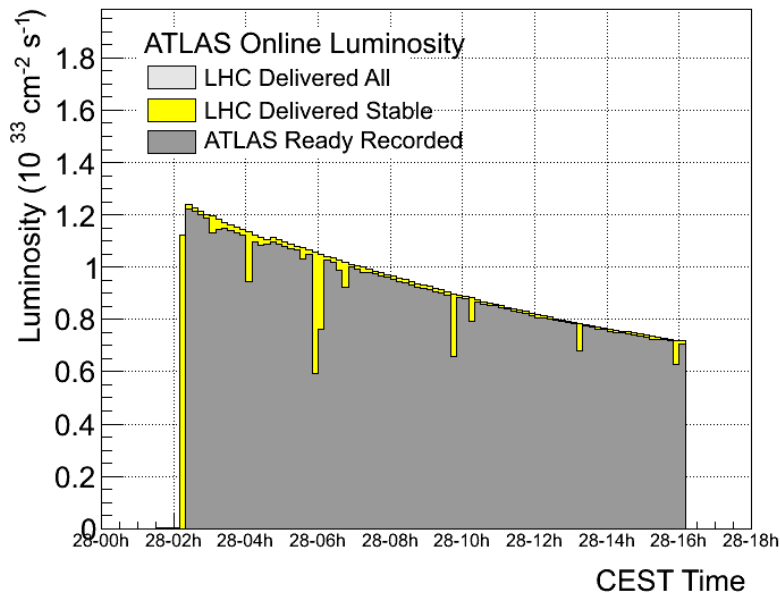


# Sunday morning May 22: $1.1 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$



# Continue to 1380 Bunches

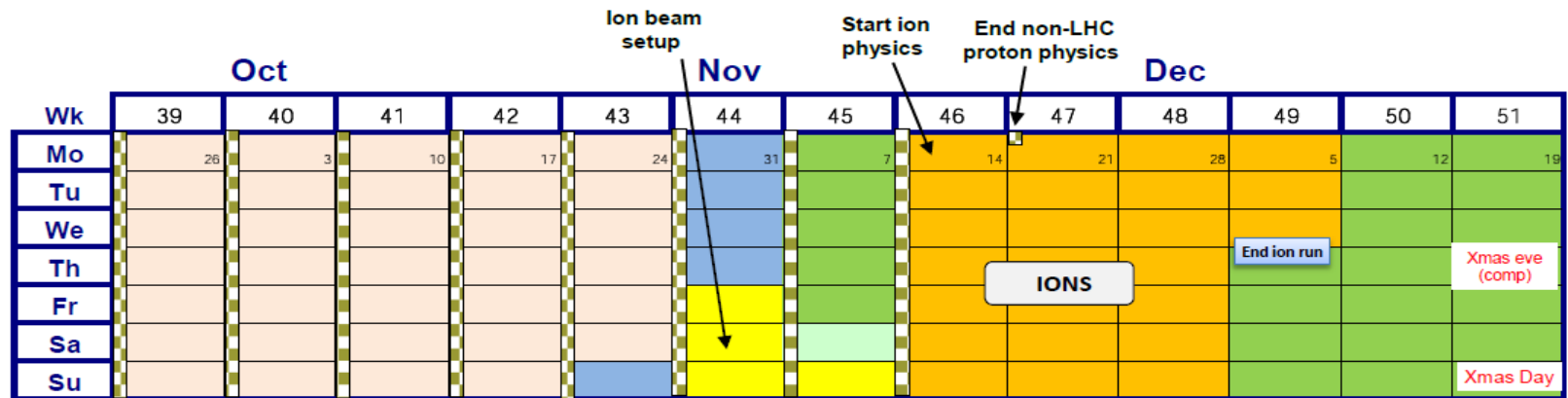
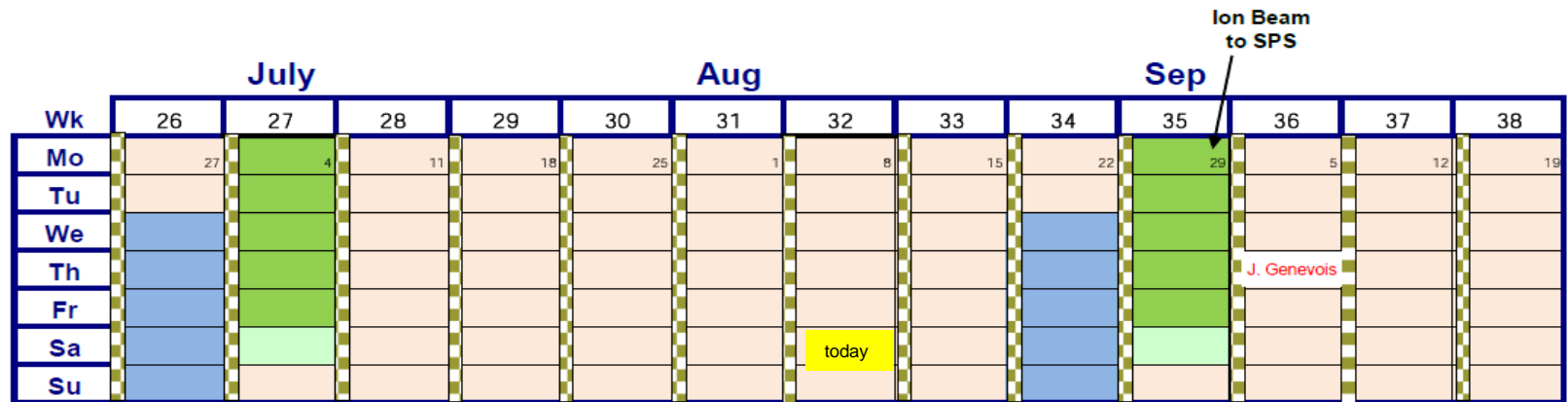
- Reached 1380 (max possible with 50ns) on 28 June fill 1901



# Topics

- LHC progress in 2011
- **Prospects in the Short term (2<sup>nd</sup> half 2011)**
- Mid Term Prospects (2014-2021)
- Long Term Prospects (2022--....)

# Schedule: 2<sup>nd</sup> Half 2011



- Technical Stop
- Recommissioning with beam
- Machine development
- Ion run
- Ion setup

Injectors - proton physics

Special runs (TOTEM etc.) to be scheduled

# Mid Year performance Review

## “mini-Chamonix”

(July 15)

The workshop will examine the possible performance improvement options available during the rest of the LHC's 2011 proton run. It will also consider the experiments' requirements and potential limitations from hardware and beam related phenomena. **The principle aim to arrive at a strategy for maximizing the delivered luminosity by the end of the year.** The results from, and plans for, machine development will be considered where the knowledge gained might impact the above goal.



# Discussion

Luminosity comparisons are wrt 1380 bunch operation with  
1.1E11ppb, emittance 2.7um, beta\* = 1.5, Lumi = 1.2E33

Parameter and Criteria	adiabatic?	Estimated Max Lumi Improvement Factor	Lost Time for physics (days)	Risk/ Reversibility	Pile-up	Cumulative Improvement factor (50ns)	Cumulative Improvement factor (25ns)
ppb	yes	2	0	0	higher	Yes	No
emittance	yes	1.35	0	0	higher	Yes	No
beta*	No	1.5	3	>0	higher	Yes	Yes
25ns	No	1.9	10	>0	same	No	Yes
				Luminosity Factor		4.1	2.9
				Pile Up		28	10
				Estimated <b>Relative</b> Integrated Luminosity		307	185
				<b>Relative</b> Integrated Luminosity if we do nothing		90	

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

# Conclusion

- Continue with 50ns
  - Operate with minimum emittance (2 $\mu$ m)
  - Adiabatically increase the bunch intensity (max  $1.55 \times 10^{11}$ )
  - ? Reduce  $\beta^*$  to 1m (LATER after next Technical Stop)

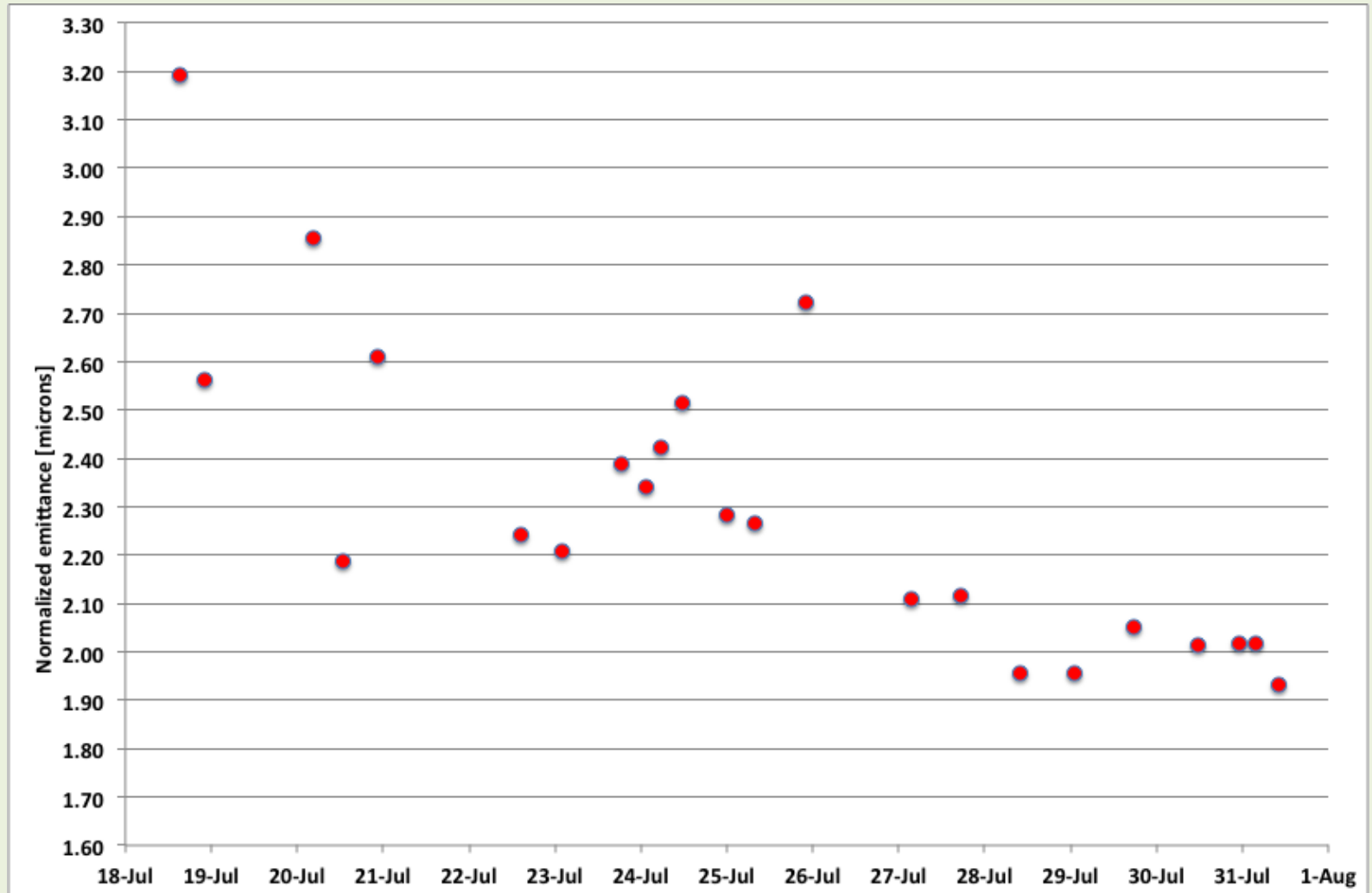
# Discussion

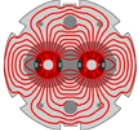
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Parameter and Criteria	adiabatic?	Estimated Max Lumi Improvement Factor	Lost Time for physics (days)	Risk/ Reversibility	Pile-up	Available Improvement factor (50ns)	Available Improvement factor (25ns)
ppb	yes	2	0	0	higher	Yes	No
emittance	yes	1.35	0	0	higher	Yes	No
beta*	No	1	3	>0	higher	Yes	Yes
25ns	No	1.9	10	>0	same	No	Yes
				Luminosity Factor		2.7	1.9
				Pile Up		19	7
				Estimated <b>Relative</b> Integrated Luminosity		209	124
				<b>Relative</b> Integrated Luminosity if we do nothing		90	

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

# Emittances – start of fill – from luminosity





# Beam-beam tune shift

Design report

$$DQ_{tot} @ 0.015$$

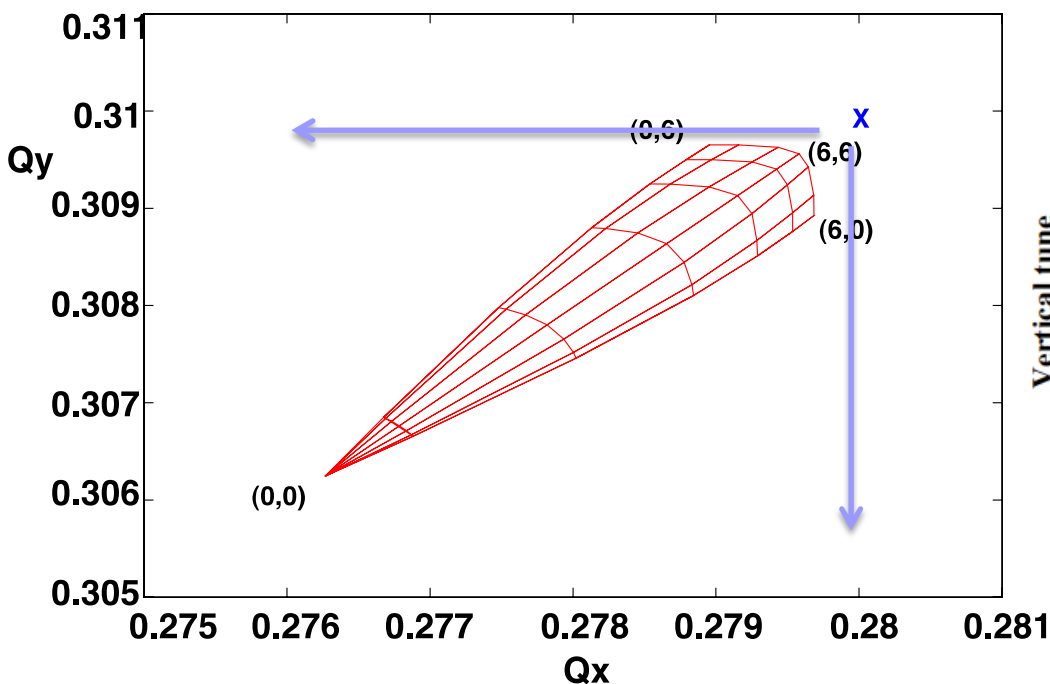
$$\chi_{bb} @ 0.005$$

Now

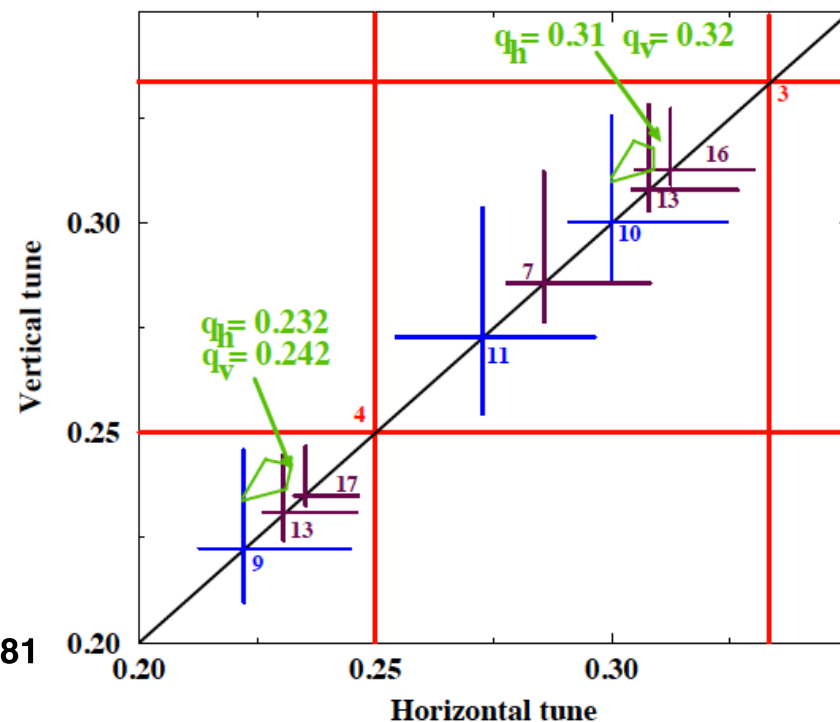
$$DQ_{tot} @ 0.02$$

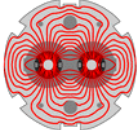
$$\chi_{bb} @ 0.007$$

Tune footprint for head-on collision



Tatiana Pieloni



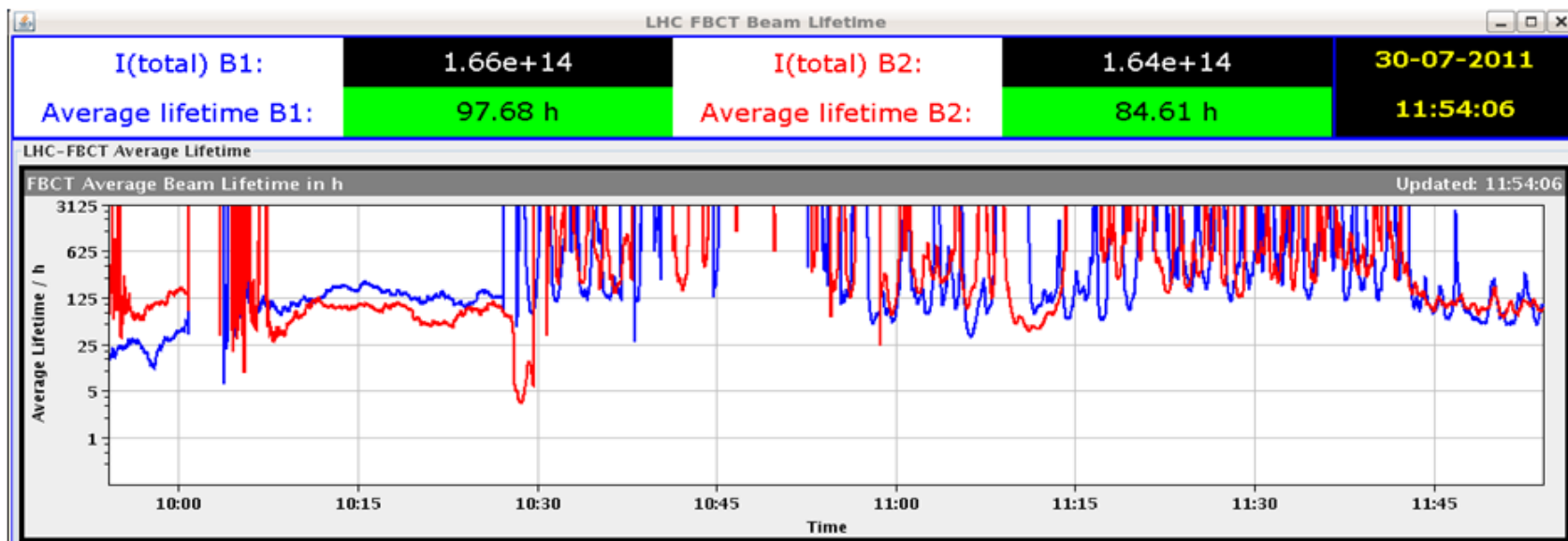


# Working point optimization

Slight shift of the horizontal and vertical tune before collisions

Positive effect on beam lifetime either by moving some of the tune footprint away a resonance, or perhaps, a 50 Hz harmonic

**Fill 1992 –  $Q_h = 0.312$   $Q_v = 0.322$**



Coupled with the removal of transverse blow-up,  
removal of lifetime dip on going into collisions

# Up-to-Date Performance Plots

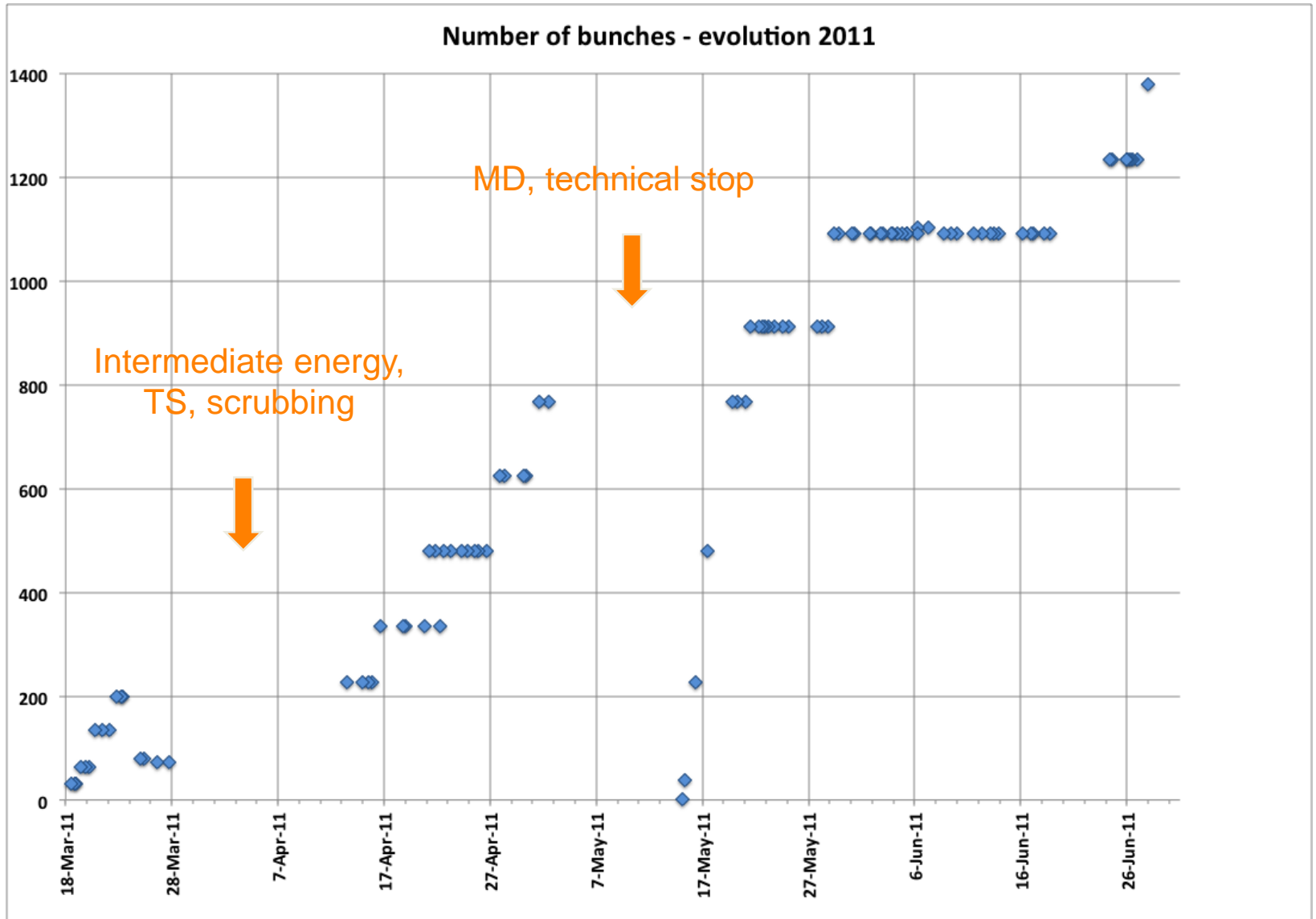
# Evolution of Peak Performances to date

8<sup>th</sup> August 2011

Peak Performances					
Fill Number	Date	Bunch Spacing	Number of Bunches	Peak Luminosity ( $10^{33}\text{cm}^{-2}\text{s}^{-1}$ )	Total Number of protons per beam ( $10^{14}$ )
1635	18 March 2011	75	32	0.03	0.04
1637	19 March 2011	75	64	0.06	0.07
1644	22 March 2011	75	136	0.17	0.16
1645	22 March 2011	75	200	0.25	0.24
1712	15 April 2011	50	228	0.24	0.29
1716	16 April 2011	50	336	0.35	0.42
1739	26 April 2011	50	480	0.51	0.58
1749	30 April 2011	50	624	0.72	0.76
1755	02 May 2011	50	768	0.83	0.93
1809	27 May 2011	50	912	1.10	1.15
1815	29 May 2011	50	1092	1.27	1.33
1901	27 June 2011	50	1236	1.25	1.64
2009	07 August 2011	50	1380	2.11	1.65



# Ramp-up of number of bunches

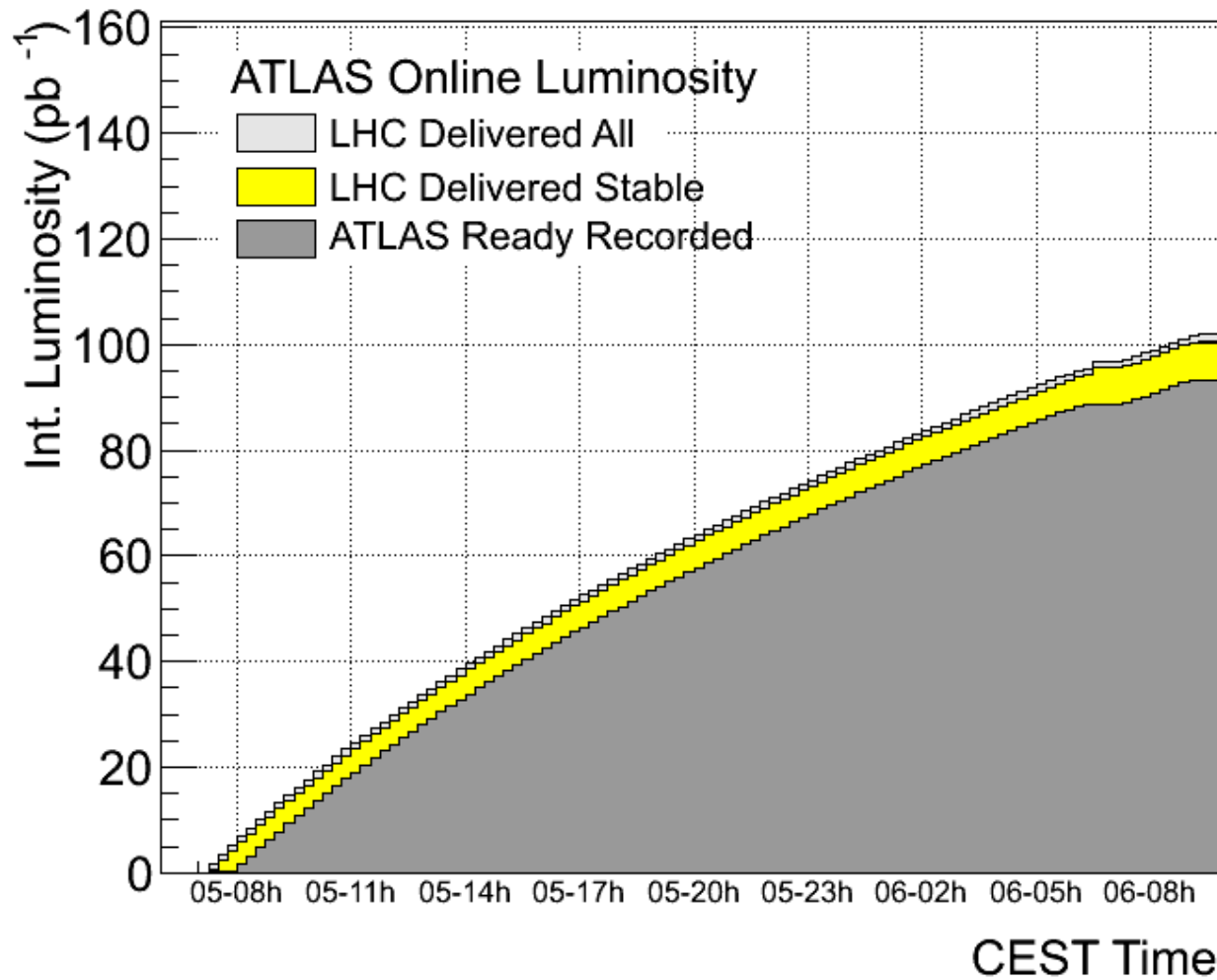


S. Myers

15 weeks

August 13, 2011 APS DPF

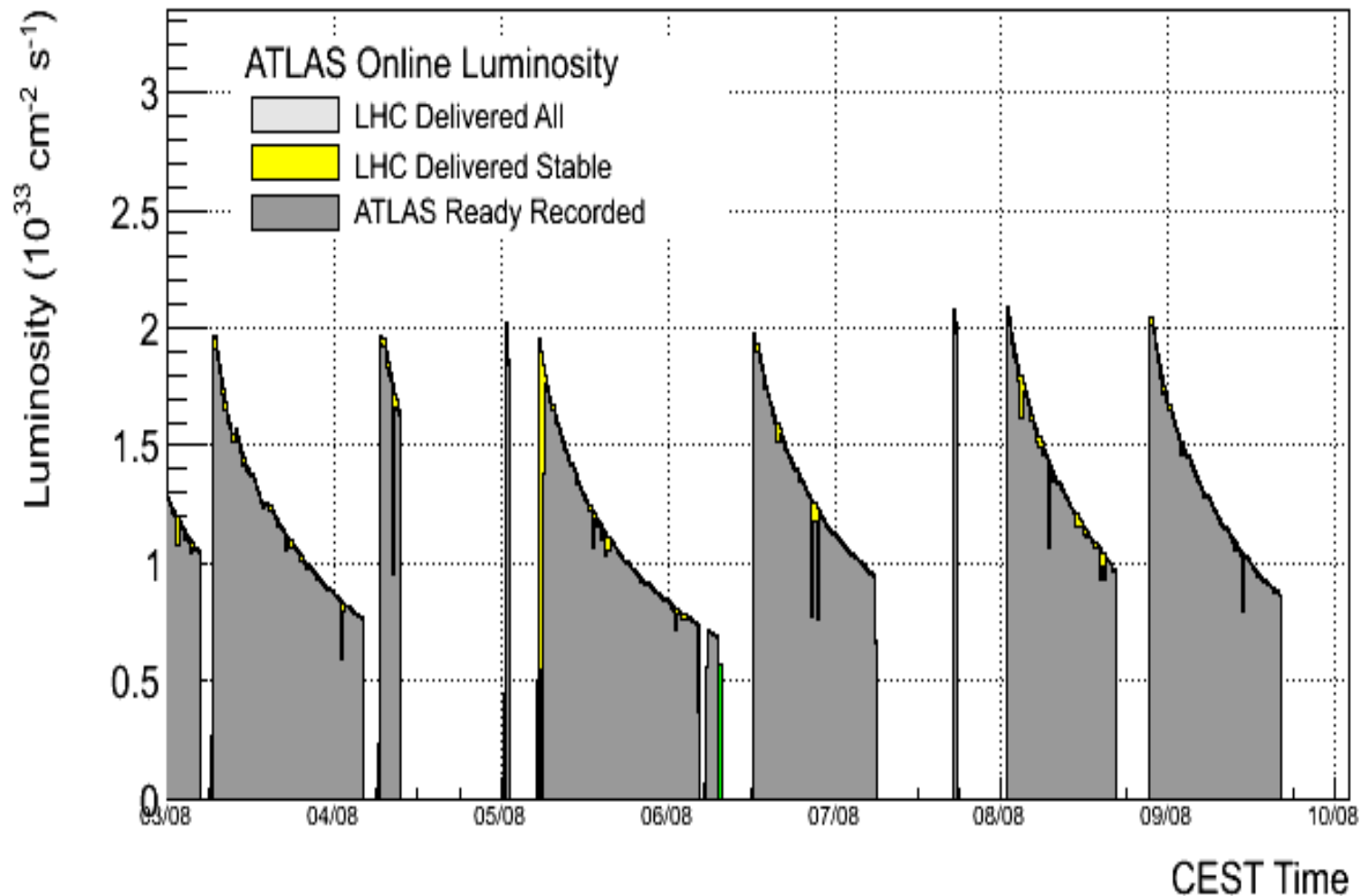
# Best Fill (8<sup>th</sup> Aug 2011)



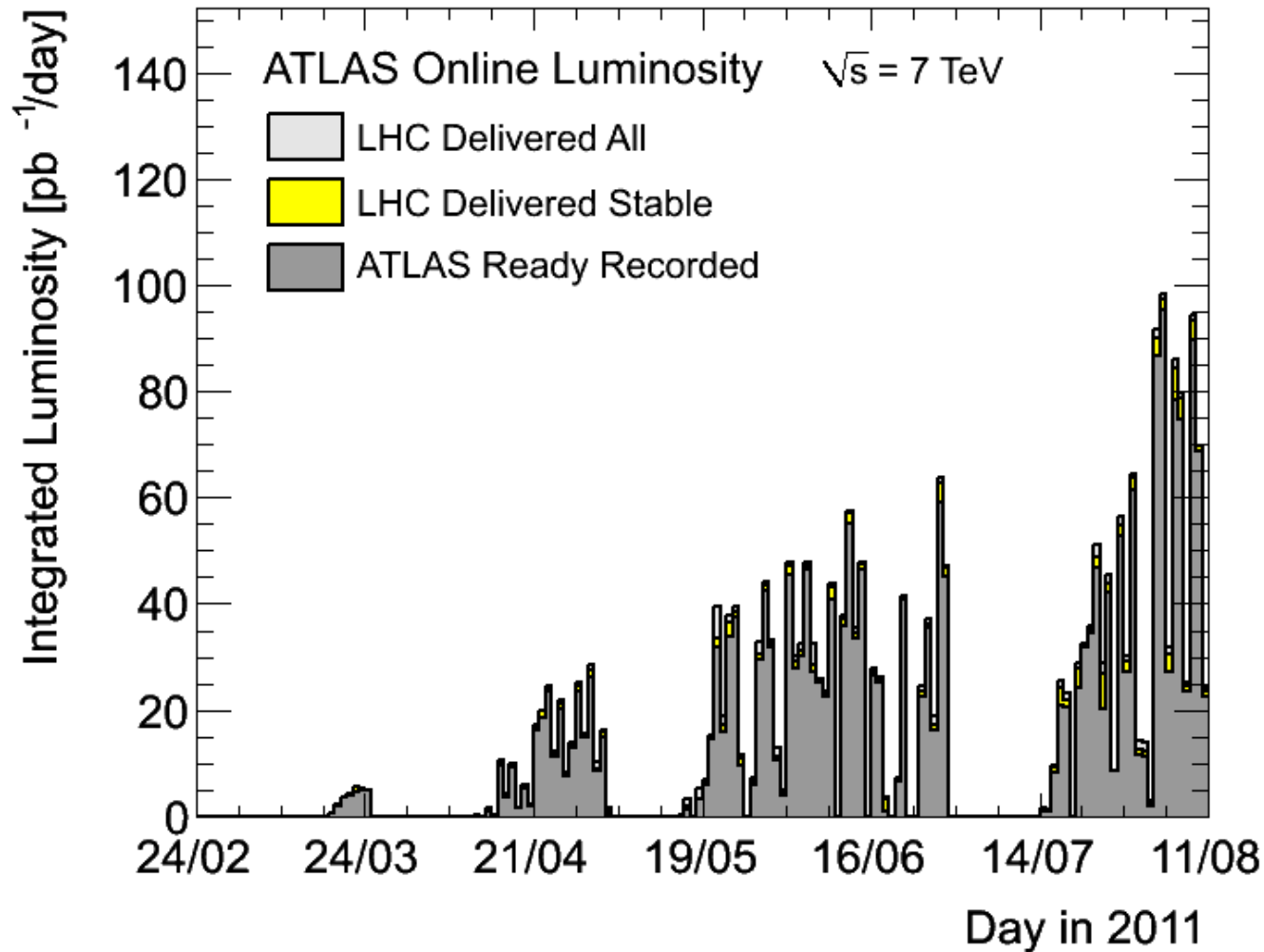
# Records (8<sup>th</sup> Aug 2011)

Peak Stable Luminosity Delivered	$2.11 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$	Fill 2009	11/08/07, 17:48
Maximum Luminosity Delivered in one fill	100.71 pb <sup>-1</sup>	Fill 2006	11/08/05, 01:20
Maximum Luminosity Delivered in one day	97.4 pb <sup>-1</sup>	Wednesday 03 August, 2011	
Maximum Luminosity Delivered in 7 days	440.99 pb <sup>-1</sup>	Tuesday 02 August, 2011 - Monday 08 August, 2011	
Maximum Colliding Bunches	1331	Fill 1956	11/07/18, 08:00
Maximum Peak Events per Bunch Crossing	14.01	Fill 1732	11/04/23, 05:47
Maximum Average Events per Bunch Crossing	10.18	Fill 2009	11/08/07, 17:48
Longest Time in Stable Beams for one fill	26.0 hours	Fill 2006	11/08/05, 05:24
Longest Time in Stable Beams for one day	21.9 hours (91.2%)	Wednesday 03 August, 2011	
Longest Time in Stable Beams for 7 days	94.6 hours (56.3%)	Tuesday 02 August, 2011 - Monday 08 August, 2011	
Fastest Turnaround to Stable Beams	2.12 hours	Fill 2000	11/08/03, 04:37

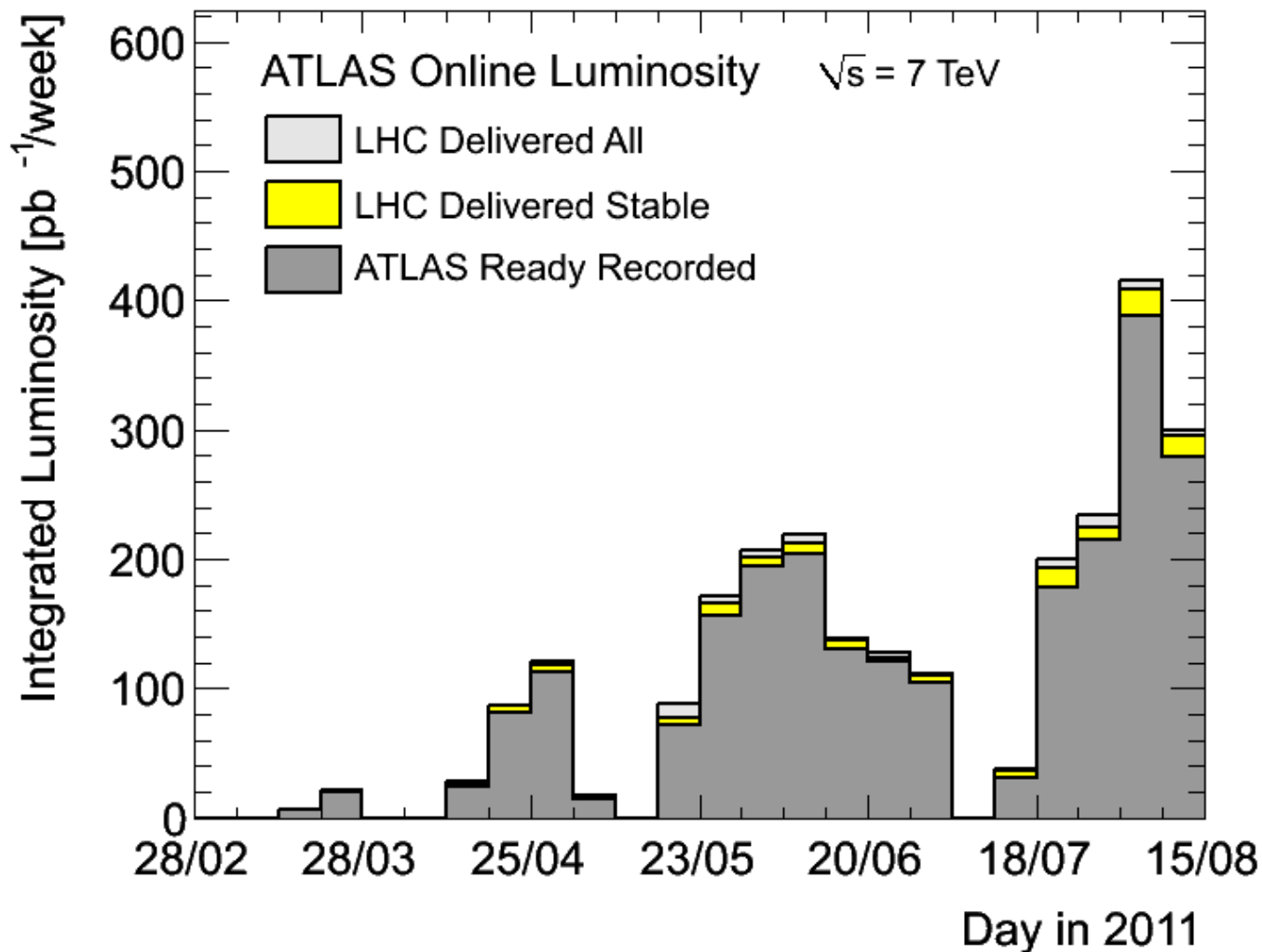
# Last Week (10<sup>th</sup> Aug 2011)



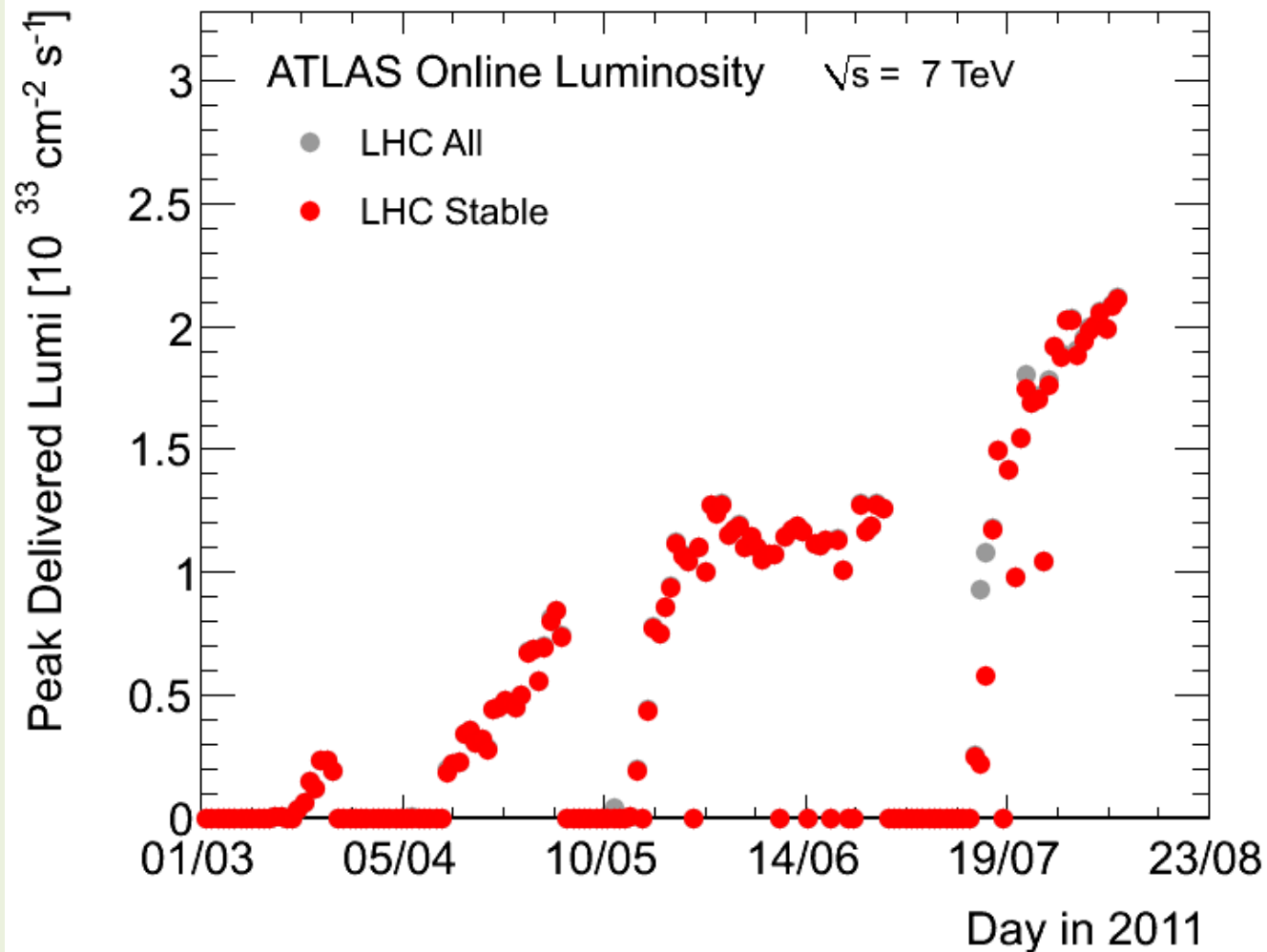
# Daily Integrated Luminosity (10<sup>th</sup> August 2011)



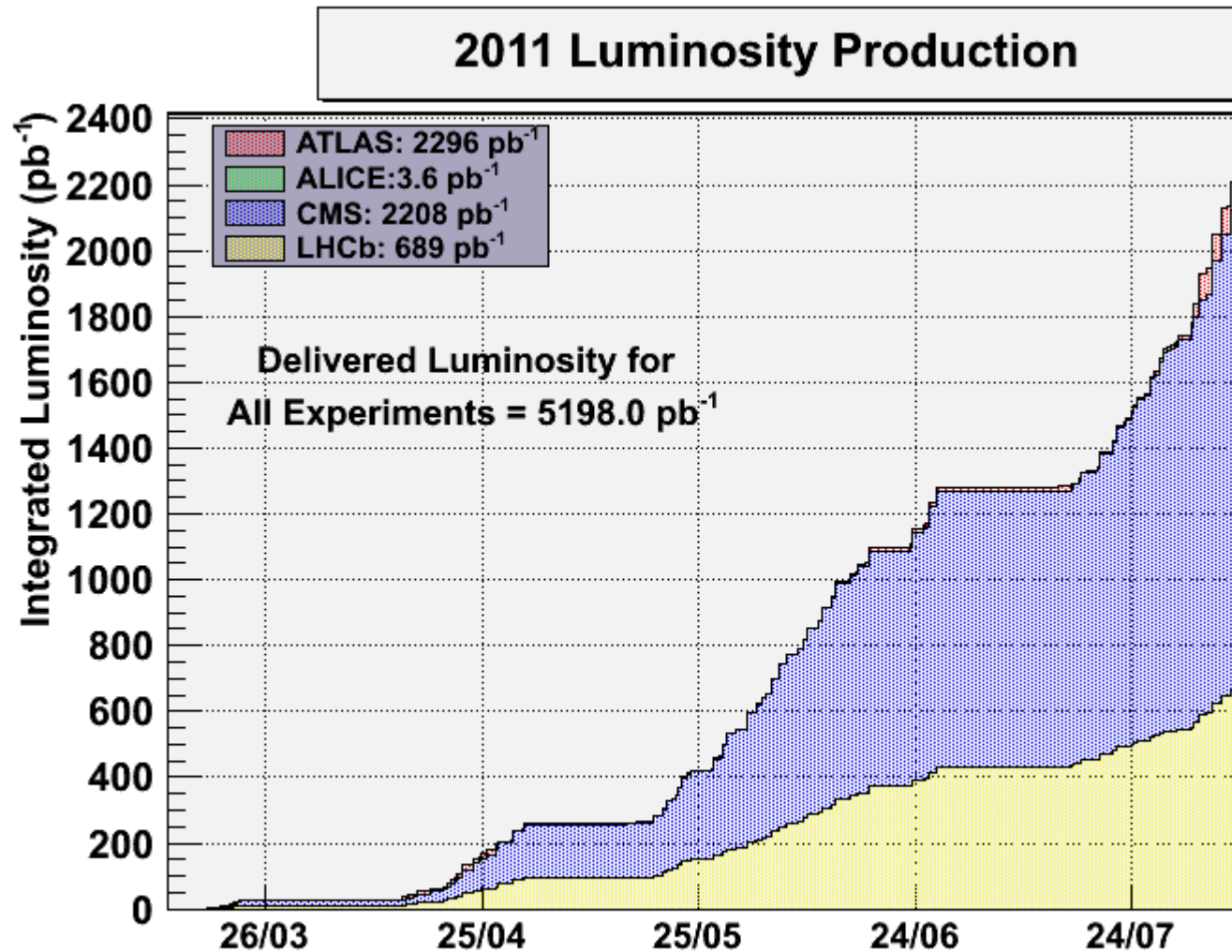
# Weekly Integrated Luminosity (12<sup>th</sup> Aug 2011)



# Peak Luminosity (8<sup>th</sup> Aug 2011)



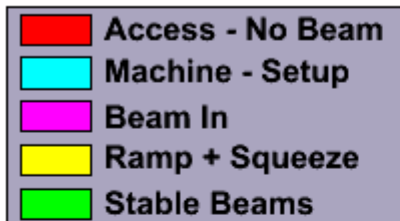
# 10<sup>th</sup> August 2011





# 8<sup>th</sup> August 2011

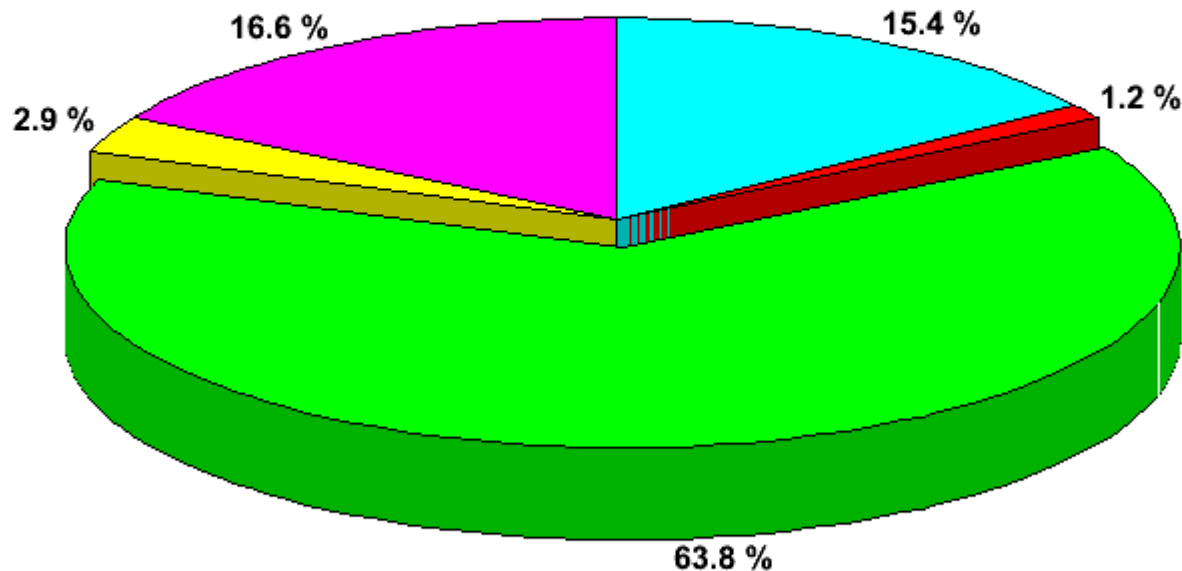
## LHC Efficiency: Last 10 fills



Statistics for fills 1999 [02.08.11] to 2008 [07.08.11]

Total Time Duration [hh:mm:ss]: 124:46:12

Time in Stable Beams [hh:mm:ss]: 79:39:15



# Concerns with High Intensity

- Machine Protection (100MJ per beam)
- Radiation (SEUs)
- UFOs
- Beam Instabilities
- Technical Problems: Vacuum, beam transfer, etc...
- 4 experiments, 2 high luminosity, 1 medium and 1 very low

# Present “Issues”

- SEUs (dependent on total intensity and **luminosity**)
- UFOs (not intensity dependent)
  - Not serious for the moment (at **3.5TeV/beam** but...)
- HOM heating of Injection kickers, cryo, collimators..  
(total intensity and bunch length dependence)
- Vacuum instabilities at very high bunch intensities  
(adiabatic) ? Proton losses causing heating and desorption

These are “slowing” our progress

# Topics

- LHC progress in 2011
- Prospects in the Short term (2012)
  - Protons and ions
- Mid Term Prospects (2014-2021)
- Long Term Prospects (2022--....)

# Short term (protons)

## Physics data-taking until end of 2012

- 50ns or 25 ns
  - For peak luminosity, 50ns is still higher due to the better performance beams from the injectors. But...event pile-up?
  - Very high intensity operation at 50ns may need beam scrubbing with 25ns
- beam energy
  - Following measurements of the copper stabilizers resistances during the Christmas stop, we will re-evaluate the maximum energy for 2012 (Chamonix 2012)

# Short term (ions)

Lead-lead for 4-5 weeks at end of 2011 with increased number of bunches and luminosity

Feasibility Test end 2011 for protons-lead (possibly 2012)

If feasible protons-lead in 2012 otherwise continue with lead-lead. Can profit from any energy increase for the protons

# Topics

- LHC progress in 2011
- Prospects in the Short term (2011—2012)
- **Mid Term Prospects (2014-2021)**
- Long Term Prospects (2022--....)

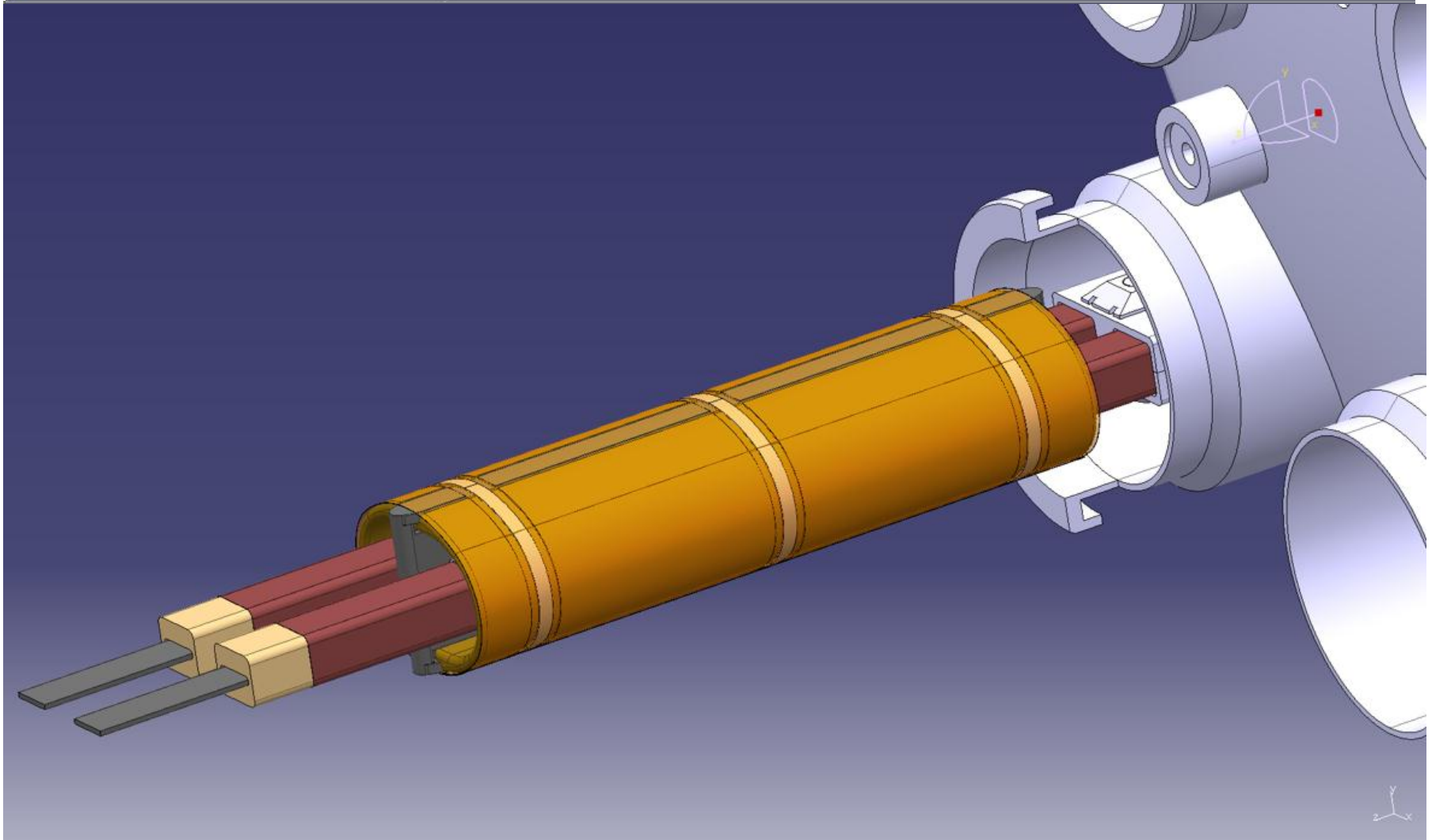
# LS1 then operation around 7TeV/beam

## LS1

- 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
- Not necessary to install the DS collimators in IR3
- Experiments consolidation/upgrades



# LHC MB circuit splice consolidation proposal



Phase III

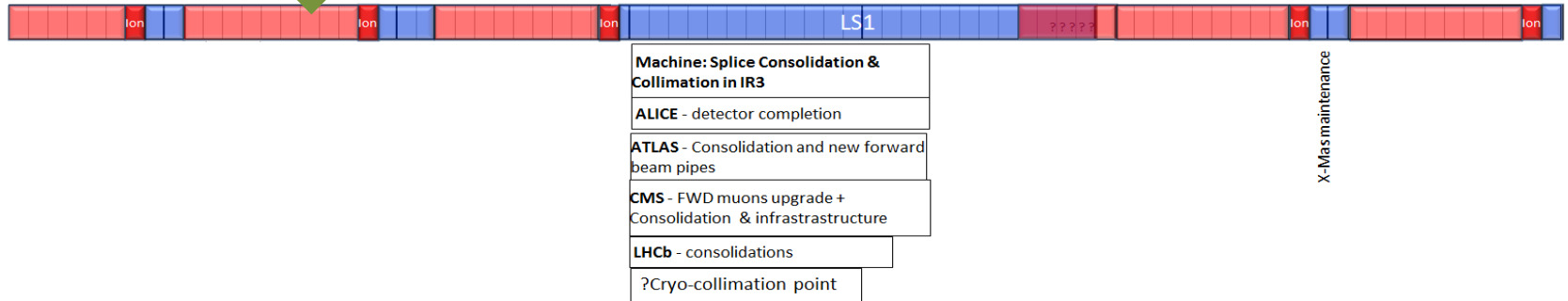
Insulation between bus bar and to ground, Lorentz force clamping

# New rough draft 10 year plan

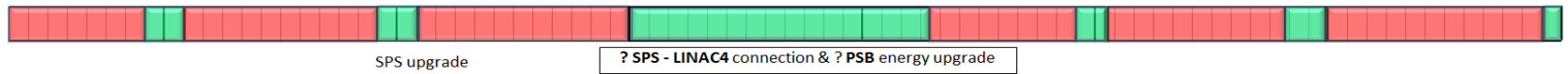
Not yet approved!

2010	2011	2012	2013	2014	2015	2016
M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D	M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D	M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D	M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D	M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D	M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D	M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D

LHC

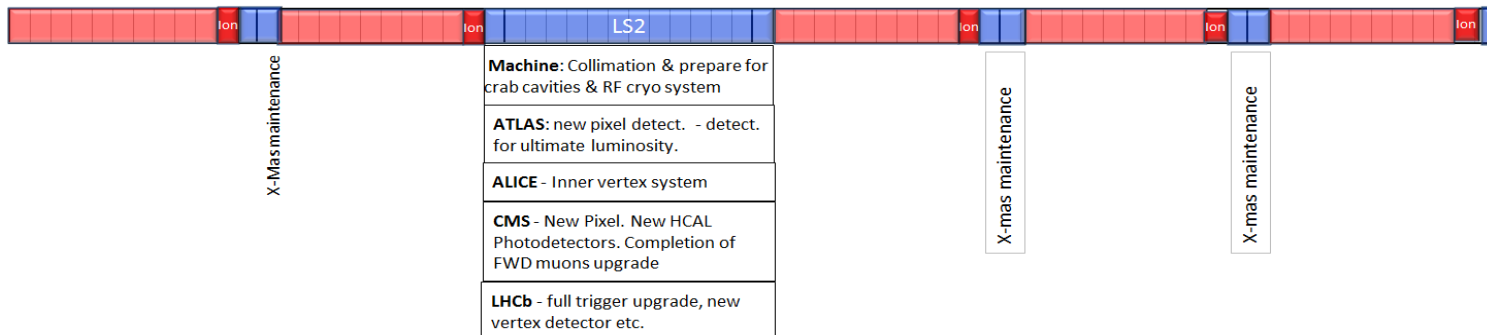


Injectors



2016	2017	2018	2019	2020	2021
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D	J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D	J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D	J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D	J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D	J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D

LHC



Injectors



2022

LS3

Installation of the HL-LHC hardware.  
Installation of LHeC  
Preparation for HE-LHC

# Topics

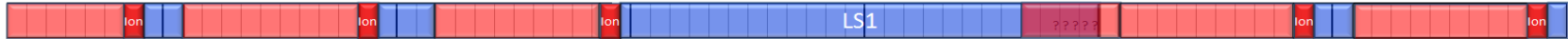
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- Prospects in the Short term (2011—2012)
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# New rough draft 10 year plan

Not yet approved!

2010				2011				2012				2013				2014				2015				2016																			
M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D

LHC



- Machine:** Splice Consolidation & Collimation in IR3
- ALICE** - detector completion
- ATLAS** - Consolidation and new forward beam pipes
- CMS** - FWD muons upgrade + Consolidation & infrastructure
- LHCb** - consolidations
- ?Cryo-collimation point

X-Mas maintenance

Injectors



SPS upgrade

? SPS - LINAC4 connection & ? PSB energy upgrade

2016												2017												2018												2019												2020												2021											
J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D												

LHC



X-Mas maintenance

- Machine:** Collimation & prepare for crab cavities & RF cryo system
- ATLAS:** new pixel detect. - detect. for ultimate luminosity.
- ALICE** - Inner vertex system
- CMS** - New Pixel. New HCAL Photodetectors. Completion of FWD muons upgrade
- LHCb** - full trigger upgrade, new vertex detector etc.

X-mas maintenance

X-mas maintenance

Injectors



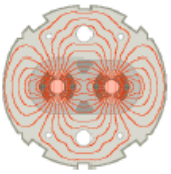
2022

LS3

Installation of the HL-LHC hardware.  
Installation of LHeC  
Preparation for HE-LHC



# Longer Term

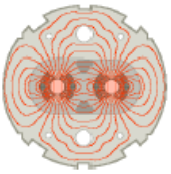


**HL-LHC**

**LHeC**

**HE-LHC**

# HL-LHC

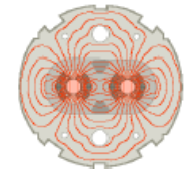


# Luminosity Upgrade Scenario

- For LHC high luminosities, the luminosity lifetime becomes comparable with the turn round time  $\Rightarrow$  Low efficiency
- Preliminary estimates show that the **useful integrated** luminosity is greater with
  - a peak luminosity of  $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  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
  - ??? Off steering
- Goal  $200\text{-}300 \text{ fb}^{-1}$  per year



# Hardware for the Upgrade



- New high field insertion **quadrupoles**
- Upgraded **cryo system** for IP1 and IP5
- Upgrade of the intensity in the **Injector Chain**
- **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



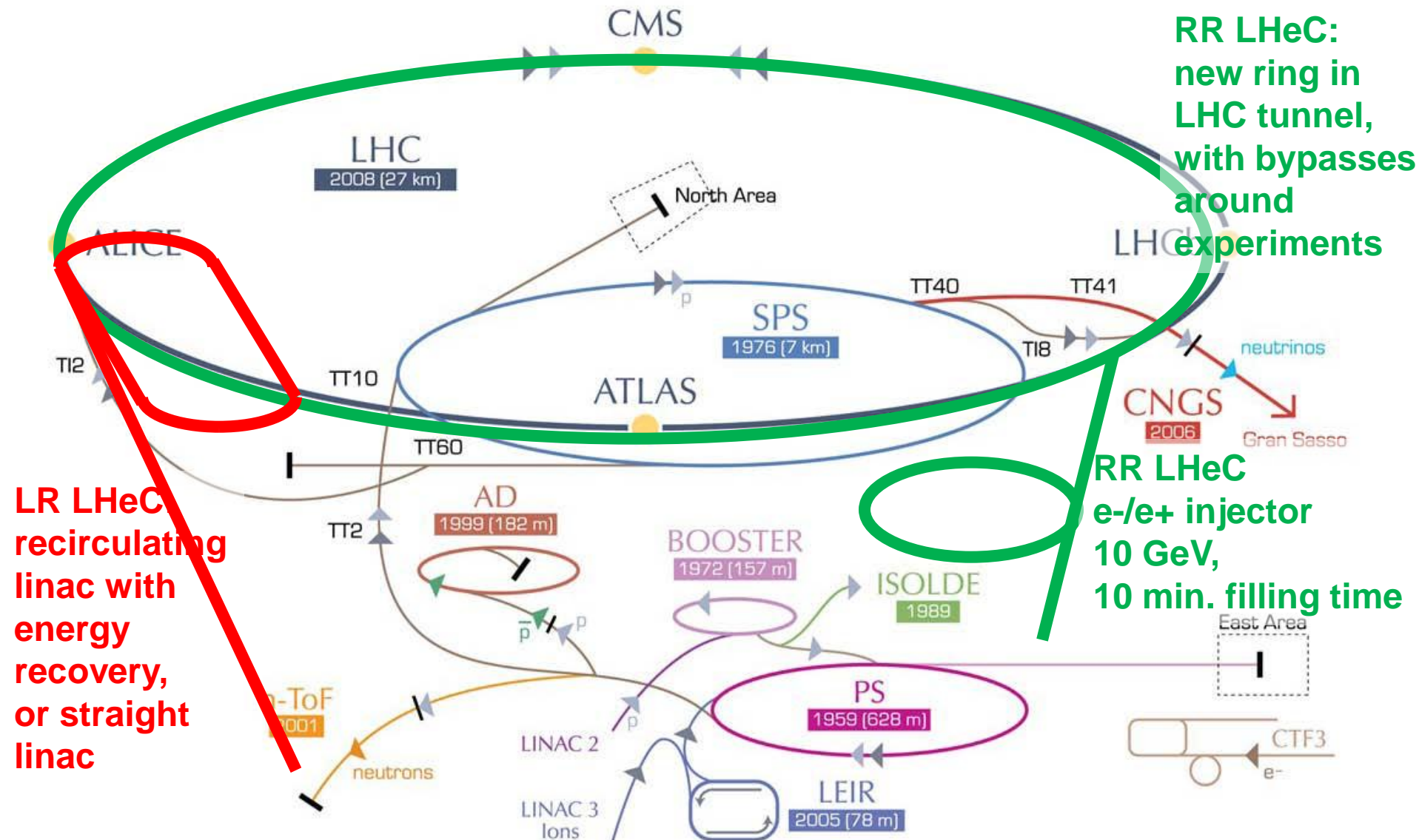
# Draft Parameters HL-LHC

Parameter	nominal	25ns	50ns		
N	1.15E+11	<b>2.0E+11</b>	<b>3.75E+11</b>	<b>5.6 <math>10^{14}</math> and 4.6 <math>10^{14}</math> p/beam</b>	
$n_b$	2808	2808	2808		
beam current [A]	0.58	<b>1.02</b>	<b>1.02</b>		
x-ing angle [ $\mu$ rad]	300	475	580		
beam separation [ $\sigma$ ]	10	10	10		
$\beta^*$ [m]	0.55	<b>0.15</b>	<b>0.15</b>		
$\varepsilon_n$ [ $\mu$ m]	3.75	<b>2</b>	<b>3.75</b>		
$\varepsilon_L$ [eVs]	2.51		2.5		
energy spread	1.00E-04	1.00E-04	1.00E-04		
bunch length [m]	7.50E-02	7.50E-02	7.50E-02		
IBS horizontal [h]	80 -> 106	<b>37</b>	<b>37</b>		
IBS longitudinal [h]	61 -> 60	<b>21</b>	<b>21</b>		
Piwinski parameter	0.68	<b>2.5</b>	<b>2.5</b>		
geom. reduction	0.83	<b>0.37</b>	<b>0.37</b>		
beam-beam / IP	3.10E-03	<b>3.9E-03</b>	<b>3.9E-03</b>		
Peak Luminosity	1 $10^{34}$	<b>7.4 <math>10^{34}</math></b>	<b>6.8 <math>10^{34}</math></b>	(Leveled to 5 $10^{34}$ $\text{cm}^{-2} \text{s}^{-1}$ )	
Events / crossing	19	<b>141</b>	<b>257</b>	<b>95</b>	<b>190</b>

OK for HL goals, if CRAB cavities are a viable option

# LHeC

# LHeC options: RR and LR



# Design Parameters

electron beam	RR	LR	LR*
e- energy at IP[GeV]	60	60	140
luminosity [ $10^{32} \text{ cm}^{-2}\text{s}^{-1}$ ]	17	10	0.44
polarization [%]	40	90	90
bunch population [ $10^9$ ]	26	2.0	1.6
e- bunch length [mm]	10	0.3	0.3
bunch interval [ns]	25	50	50
transv. emit. $\gamma\epsilon_{x,y}$ [mm]	0.58, 0.29	0.05	0.1
rms IP beam size $\sigma_{x,y}$ [ $\mu\text{m}$ ]	30, 16	7	7
e- IP beta funct. $\beta_{x,y}^*$ [m]	0.18, 0.10	0.12	0.14
full crossing angle [mrad]	0.93	0	0
geometric reduction $H_{\text{hg}}$	0.77	0.91	0.94
repetition rate [Hz]	N/A	N/A	10
beam pulse length [ms]	N/A	N/A	5
ER efficiency	N/A	94%	N/A
average current [mA]	131	6.6	5.4
tot. wall plug power[MW]	100	100	100

proton beam	RR	LR
bunch pop. [ $10^{11}$ ]	1.7	1.7
tr.emit. $\gamma\epsilon_{x,y}$ [ $\mu\text{m}$ ]	3.75	3.75
spot size $\sigma_{x,y}$ [ $\mu\text{m}$ ]	30, 16	7
$\beta_{x,y}^*$ [m]	1.8, 0.5	0.1
bunch spacing [ns]	25	25

“ultimate p beam”  
1.7 probably conservative

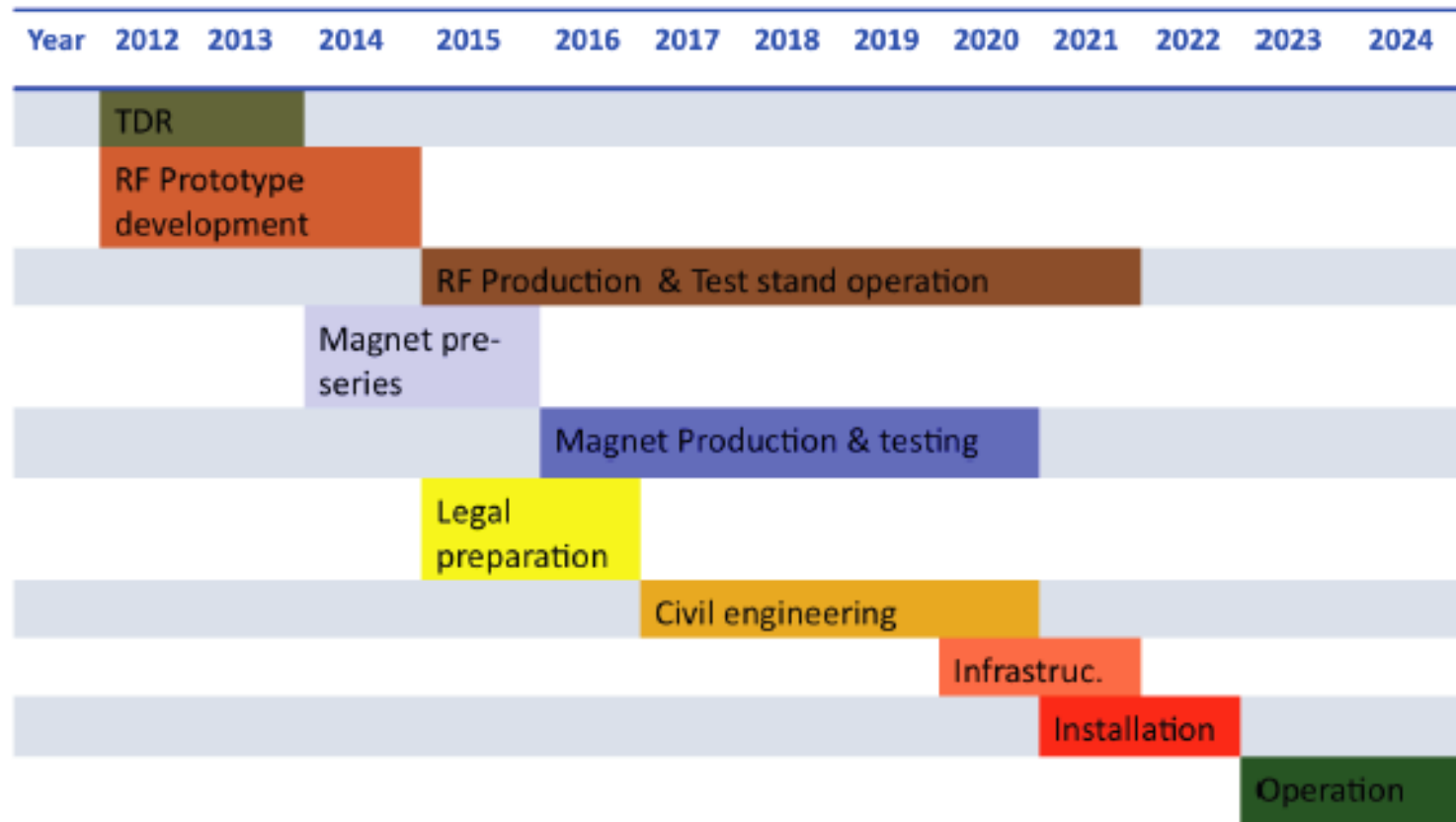
Design also for deuterons  
(new) and lead (exists)

RR= Ring – Ring  
LR =Linac –Ring

Ring uses 1° as baseline : L/2  
Linac: clearing gap: L\*2/3

\*) pulsed, but high energy ERL not impossible

# LHeC Tentative Time Schedule



LS3 --- HL LHC

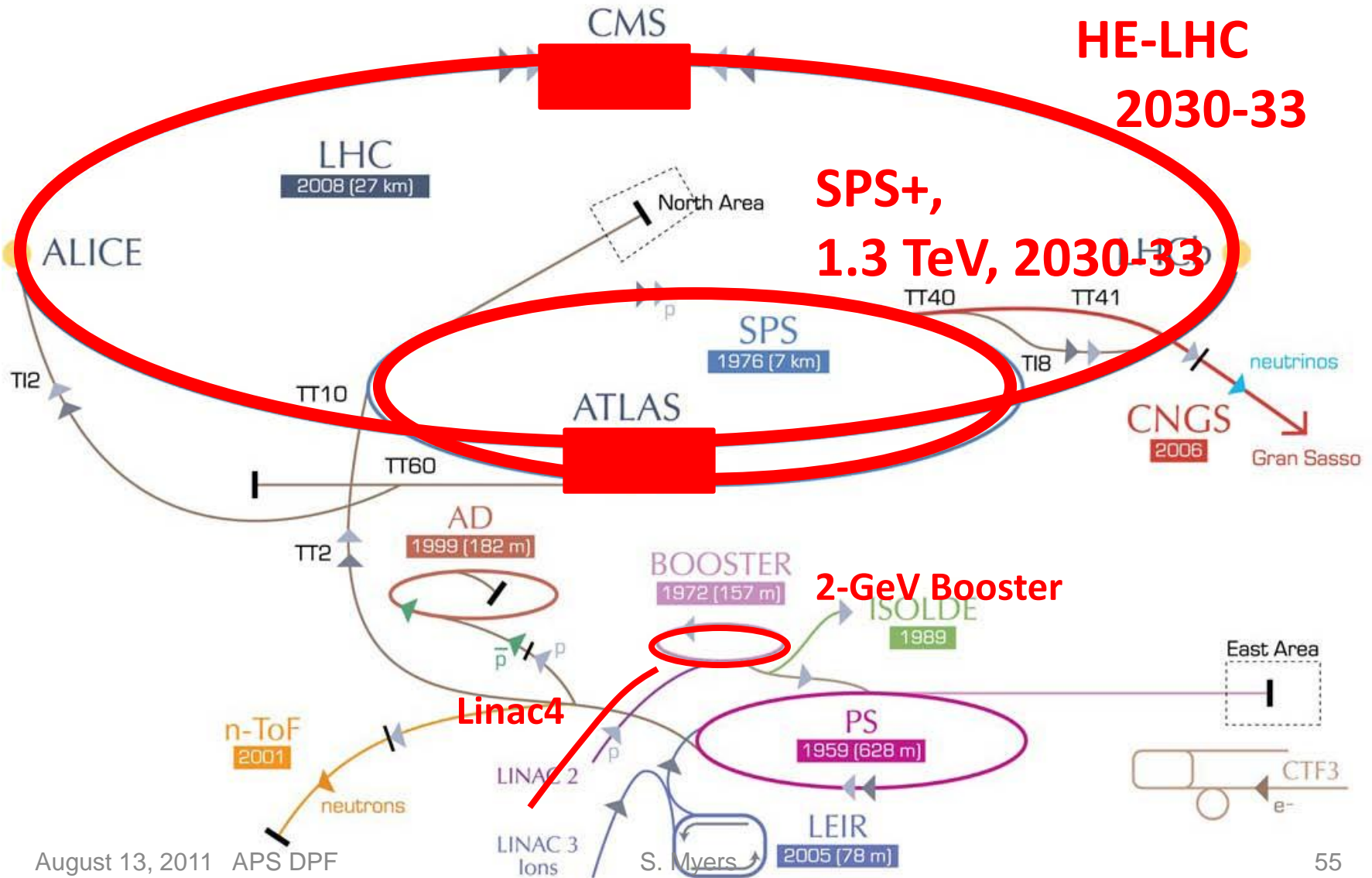


We base our estimates for the project time line on the experience of other projects, such as (LEP, LHC and LINAC4 at CERN and the European XFEL at DESY and the PSI XFEL)

# HE-LHC

## First Thoughts on an Energy Upgrade

# HE-LHC – LHC modifications



# Very Long Term Objectives: Higher Energy LHC



## Preliminary HE-LHC - parameters

	nominal LHC	HE-LHC
beam energy [TeV]	7	<b>16.5</b>
dipole field [T]	8.33	<b>20</b>
dipole coil aperture [mm]	56	40-45
#bunches / beam	1100	<b>1404</b>
bunch population [ $10^{11}$ ]	1.15	1.29
initial transverse normalized emittance [ $\mu\text{m}$ ]	3.75 (x), 1.84 (y)	3.75 (x), 1.84 (y)
number of IPs contributing	3	2
maximum total beam size [mm]	0.01	0.01
IP beta function [m]	0.55	1.0 (x), 0.43 (y)
full crossing angle [mrad]	285 ( $9.5 \sigma_{x,y}$ )	175 ( $12 \sigma_{x0}$ )
stored beam current [mA]	362	<b>479</b>
SR power [MW]	3.6	<b>62.3</b>
longitudinal damping time [h]	12.9	<b>0.98</b>
events per bunch crossing	19	76
peak luminosity [ $\text{cm}^{-2}\text{s}^{-1}$ ]	1.0	2.0
beam life time [h]	46	<b>13</b>
integrated luminosity over 10 y [ $\text{fb}^{-1}$ ]	0.3	<b>0.5</b>

Very preliminary with large error bars



# HE-LHC – main issues and R&D

- ***high-field 20-T dipole** magnets based on  $Nb_3Sn$ ,  $Nb_3Al$ , and HTS*
- ***high-gradient quadrupole magnets** for arc and IR*
  - ***fast cycling SC magnets** for 1-TeV injector*
- ***emittance control** in regime of strong SR damping and IBS*
- *cryogenic handling of **SR heat load** (first analysis; looks manageable)*
  - *dynamic **vacuum***

# Summary



- Beam Intensity, peak and Integrated luminosity still going very **(quite)** rapidly
- Successfully implemented luminosity leveling for LHC luminosity calibration (vdM scans)
- We reached our 2011 target integrated luminosity, with ~16 weeks still to go, and will certainly produce more barrier accidents
- However, progress from here on will be slower due to many simultaneous issues limiting the total intensity
- Conclusions. We are way ahead of the game, and the future is bright. But Euphoria is dangerous
- **We must remain extremely vigilant with protection of the machine (100MJ of stored energy) and hope that there are no more old unexploded bombs in the hardware!!**





Thanks to the dedication of the CERN staff and the many excellent collaborators from around the world who pulled together to make this fast performance increase possible.

# Performance optimization for the LHC

## Luminosity (round beams):

$$L = \frac{n_b \cdot N_{bunch,1} \cdot N_{bunch,2} \cdot f_{rev}}{4\pi \cdot \beta^* \cdot \varepsilon_n} \cdot R(\phi, \beta^*, \varepsilon_n, \sigma_s)$$

Event pileup & e-cloud

- 
- 1) maximize bunch brightness [ $N_{bunch}/\varepsilon_n$ ]  
beam-beam limit and injector complex performance
  - 2) minimize beam size [ $\beta^*$ ] (constant beam power)
  - 3) maximize number of bunches (beam power limit)
  - 4) compensate for 'R'
- 

# LHC Challenges: R

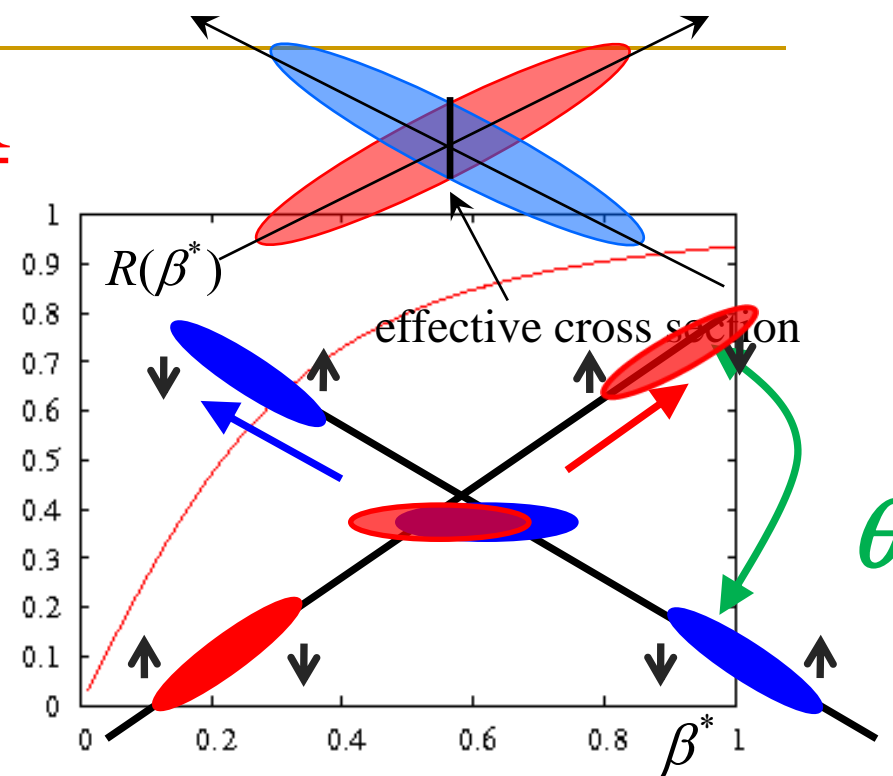
geometric luminosity  
reduction factor:

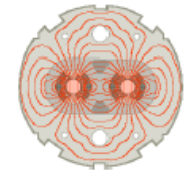
$$R_{\theta} = \frac{1}{\sqrt{1 + \Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$

Piwinski angle

large crossing angle:

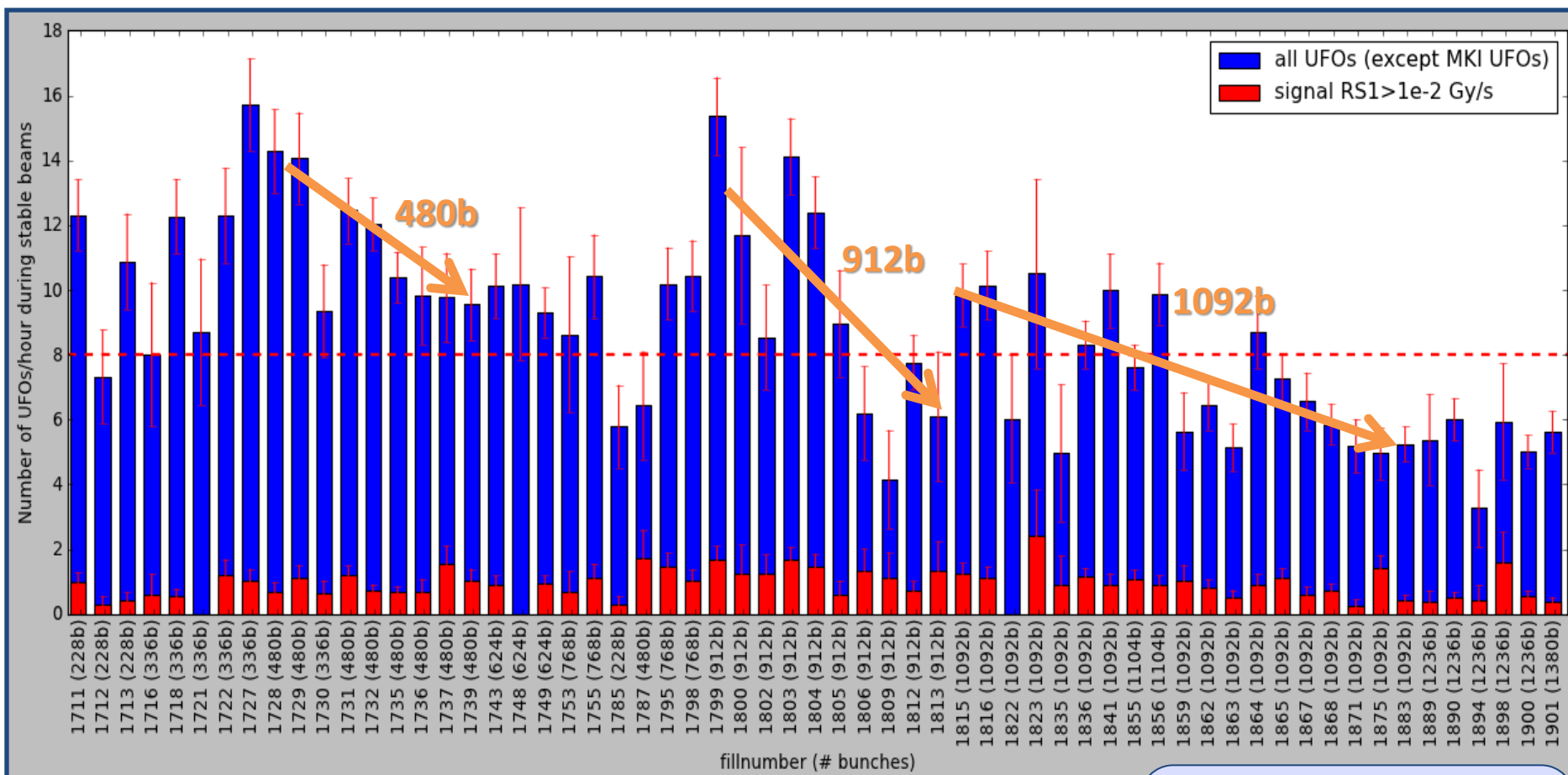
- ➔ reduction of long range beam-beam interactions
- ➔ reduction of head-on beam-beam parameter
- ➔ reduction of the mechanical aperture
- ➔ synchro-betatron resonances
- ➔ reduction of instantaneous luminosity
  - ➔ inefficient use of beam current
  - ➔ option for L leveling!





# UFOs

# UFO rate



On average 8 UFOs/hour.  
Is there a conditioning effect?

2301 candidate UFOs (excluding MKI UFOs) during stable beams in fills with at least 1 hour stable beams.  
all UFOs: Signal RS05 >  $2 \cdot 10^{-4}$  Gy/s.  
Data scaled with 1.85 (detection efficiency from reference data)

# Energy Dependency

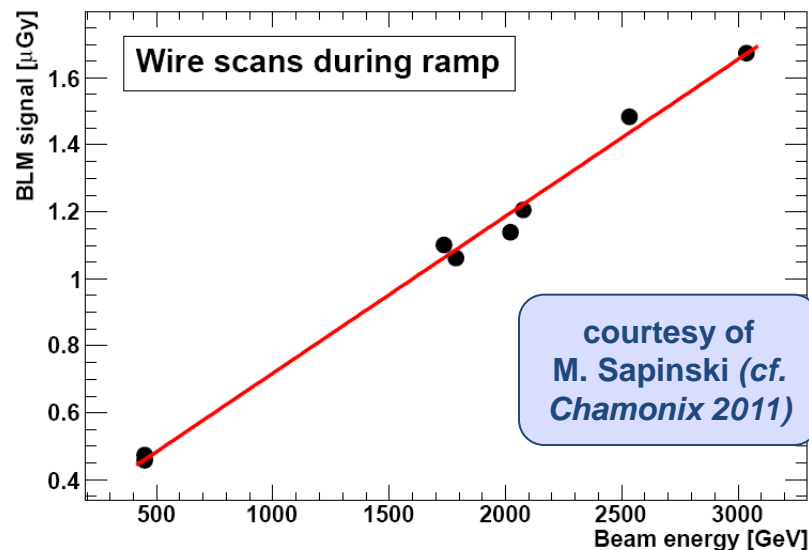
- **Ufo amplitude:** **Linear dependency** of BLM signal on beam energy observed (from wire scans).

*(cf. M. Sapinski at Chamonix 2011)*

- **BLM Thresholds:** Arc Thresholds at 7 TeV are about a **factor 5 smaller** than at 3.5 TeV.

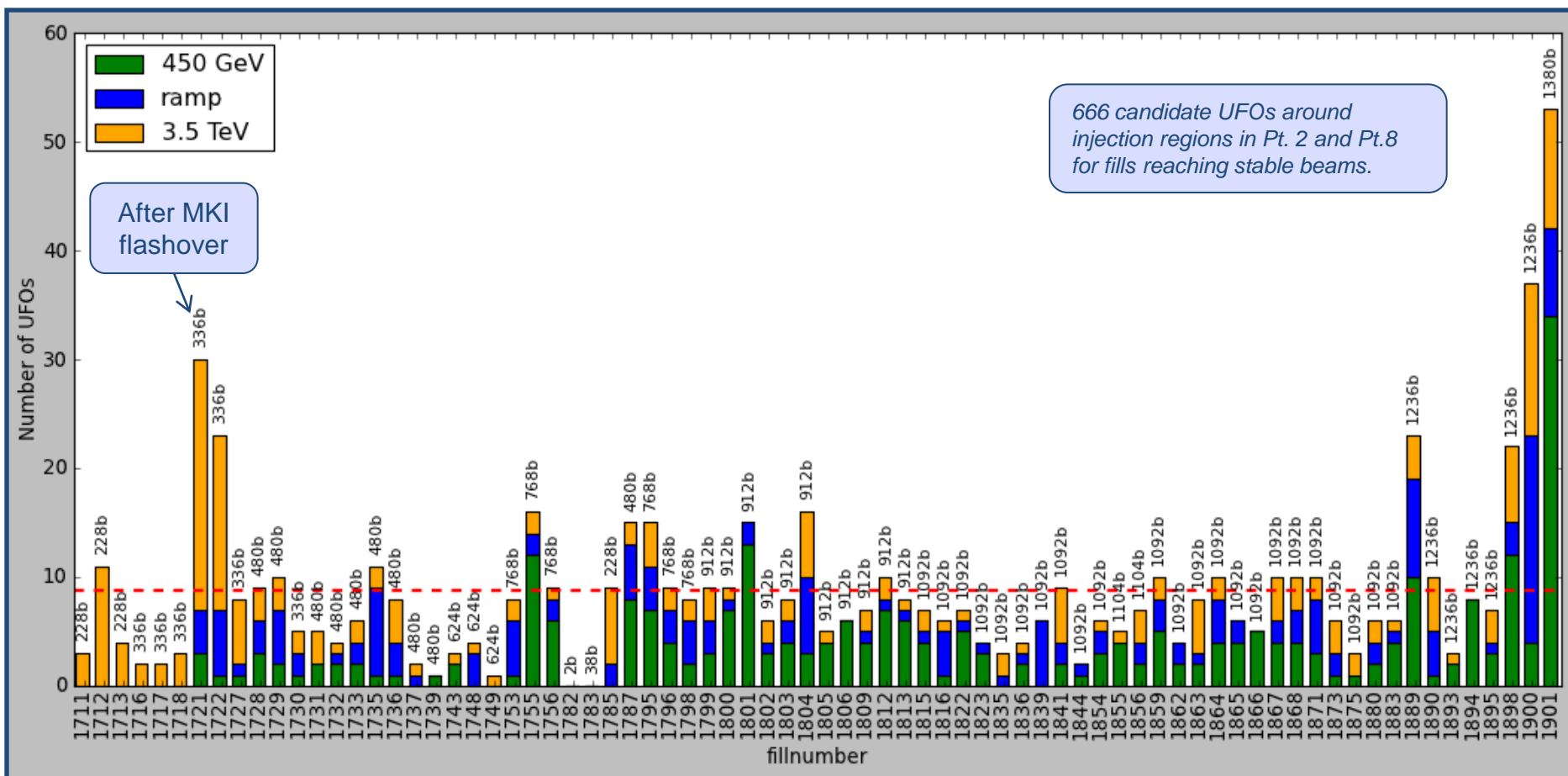
- **UFO rate:**

- At 450 GeV: extremely rare.
- During 1.38 TeV run: 3 UFOs in 36.5 h.
- At 3.5 TeV: 8 UFOs/h.



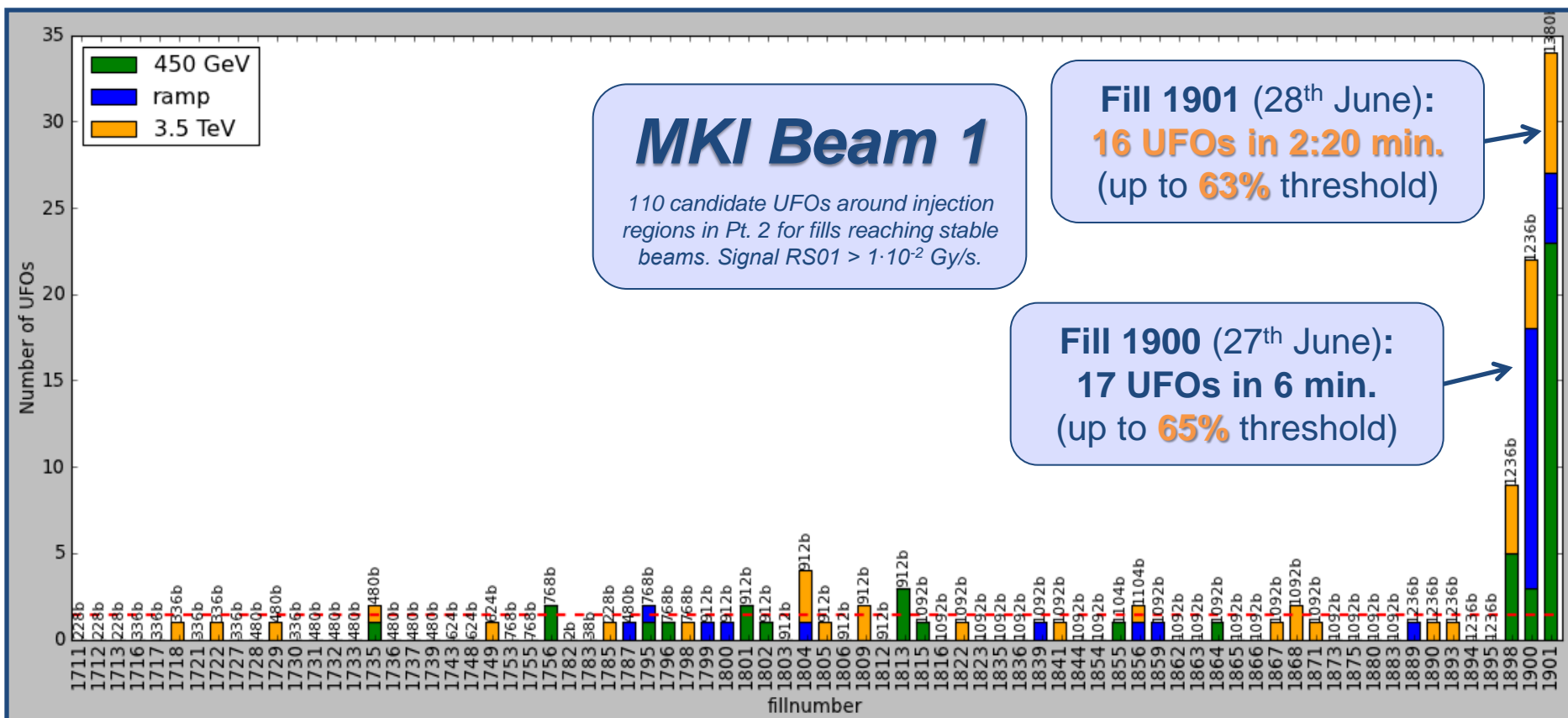


# Number of MKI UFOs



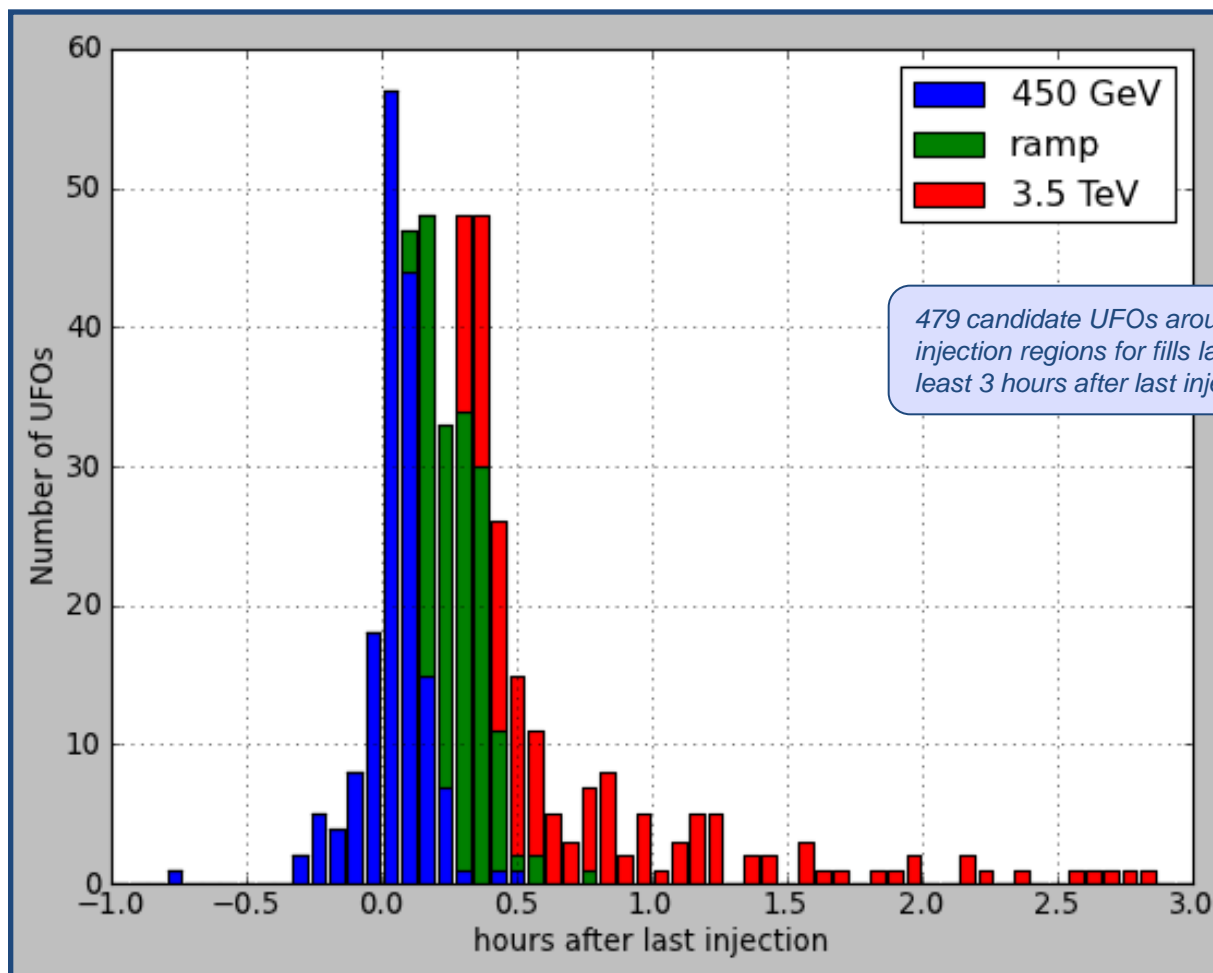
The number of MKI UFOs is much higher in Pt. 2 for the last few fills.

# Number of Large MKI UFOs B1



In the last physics fills **many MKI UFOs** with **large amplitudes** occurred with a **high rate**. No obvious change found to explain this.

# Time of MKI UFOs



Most MKI UFOs occur shortly after the last injections.

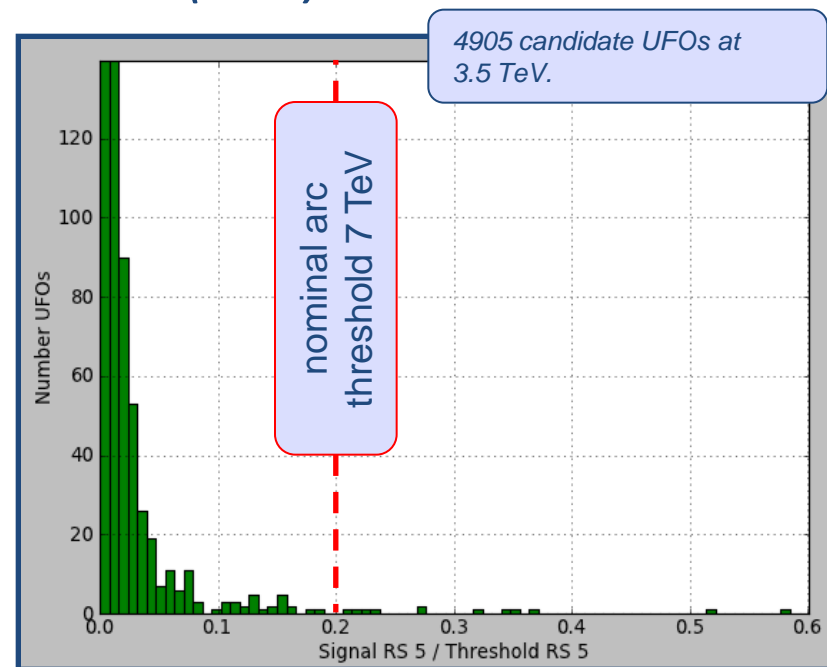
# UFO Detection

- For 2010: 113 UFOs below threshold found in logging database.  
(E. Nebot)
- For 2011: Online UFO detection by **UFO Buster**.

*Detects UFOs in BLM concentrator data (1Hz).*

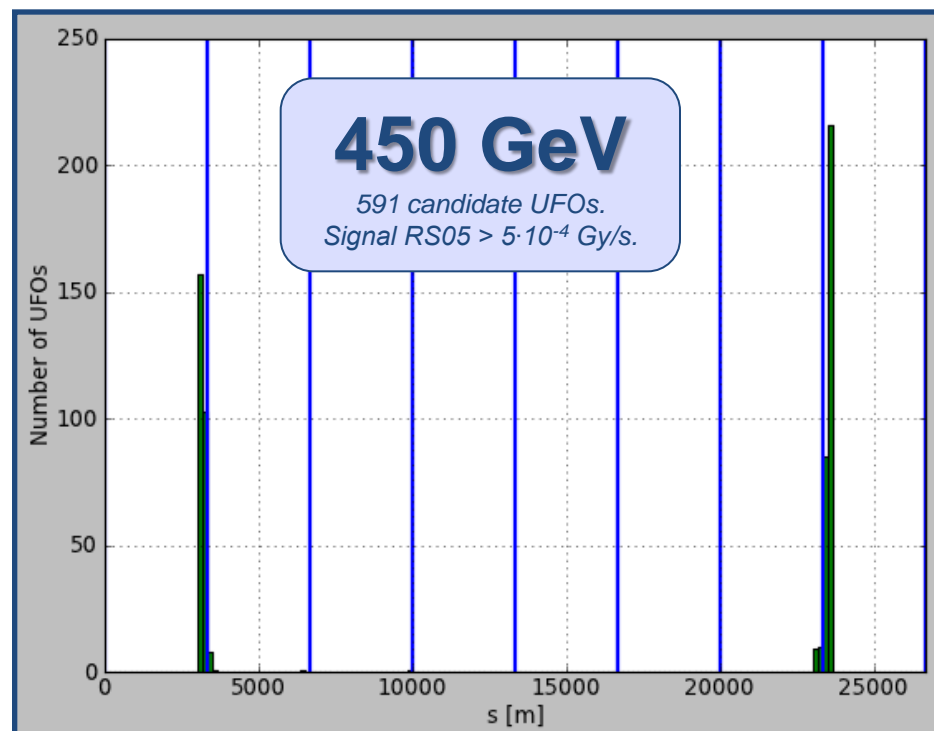
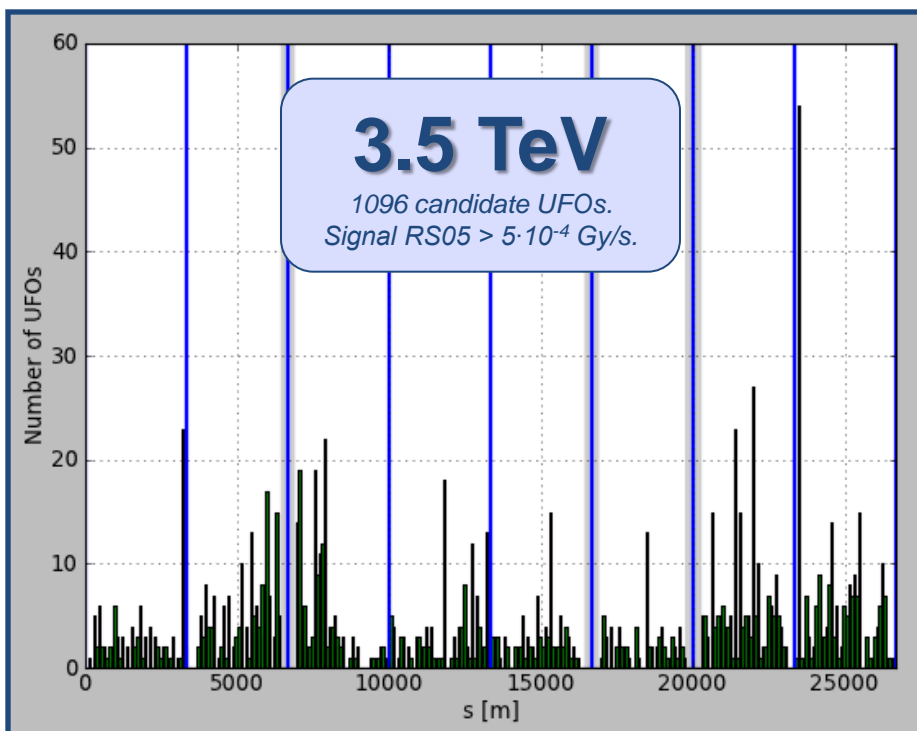
- **5000 UFOs** below threshold found so far.

*Most events are much below threshold.*



*“threshold” = lowest threshold in standard arc cell.*

# Spatial UFO Distribution



The UFOs are distributed all around the machine. About 7% of all UFOs are around the MKIs.

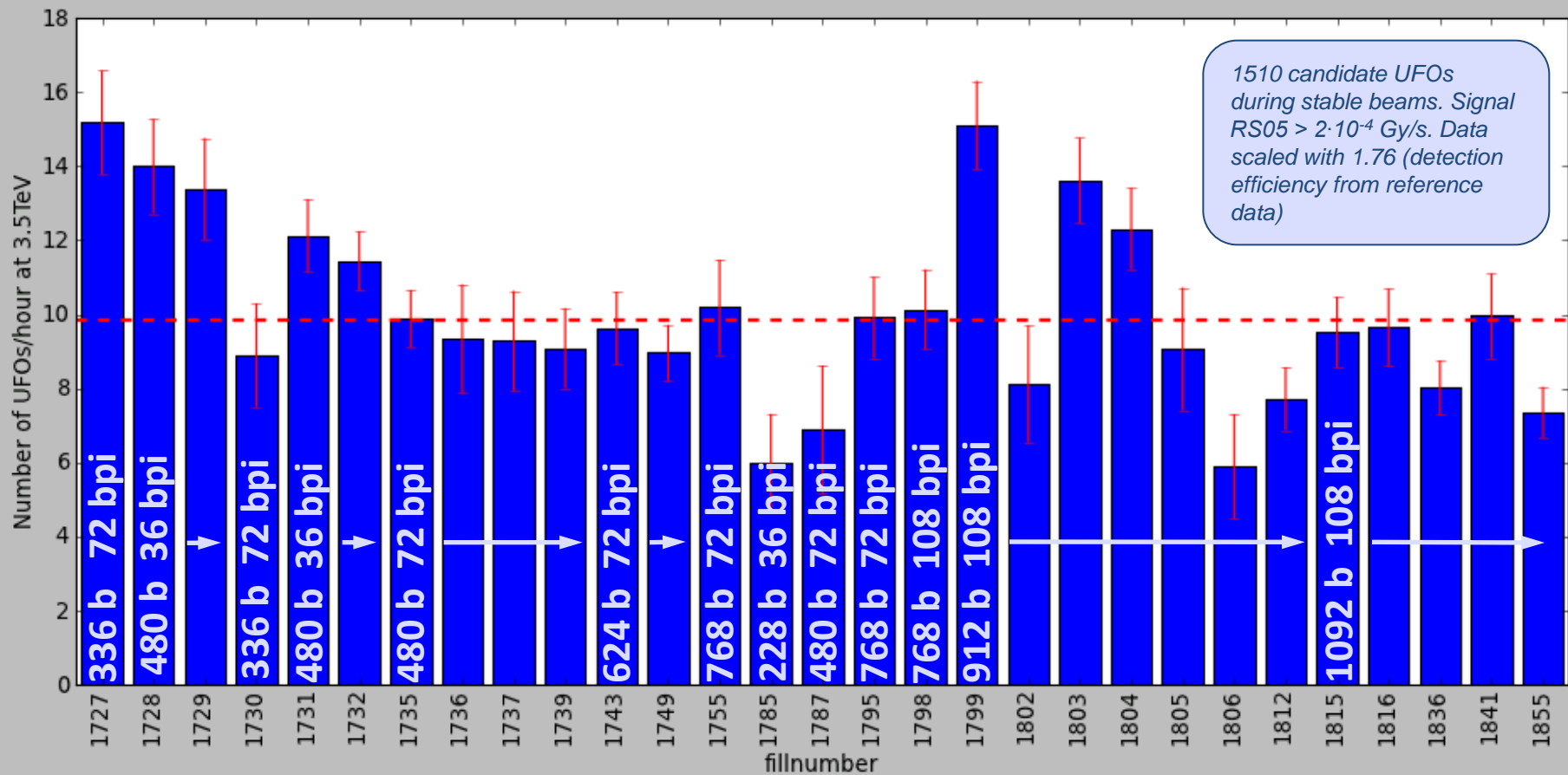
**53 candidate UFOs at MKI for Beam 2.**

*gray areas around IRs are excluded from UFO detection.*

Mainly UFOs around MKIs



# UFO Rate in 2011

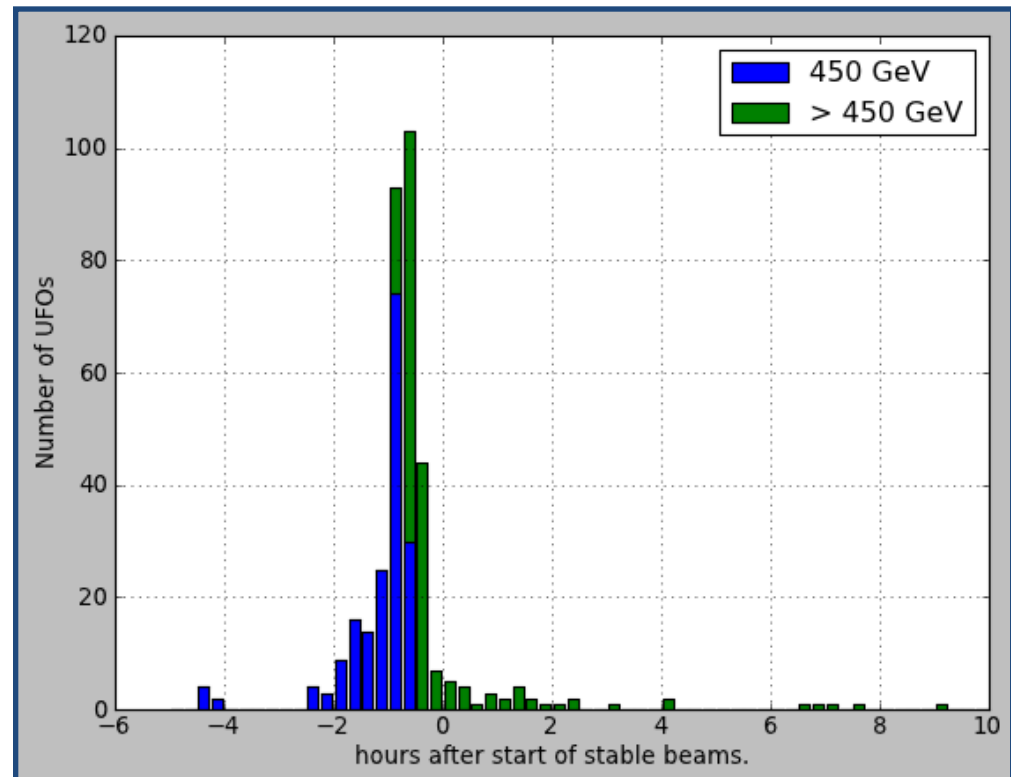


On average: **10 UFOs/hour**

# UFOs around Injection Region

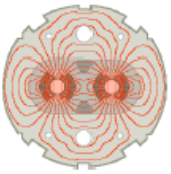
- **679 UFOs** around the MKIs caused **9 beam dumps**.

*Most of the UFOs around the MKIs occur before going to stable beams.*





# Event of 7<sup>th</sup> April

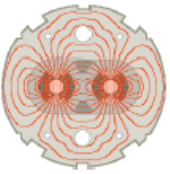


- Thursday afternoon (7<sup>th</sup> April) all **powering was stopped** in the LHC following the discovery of a worrying cabling problem affecting the QPS system protecting the HTS current leads.
- Followed by an extensive verification campaign.
- Lost about 2 days.

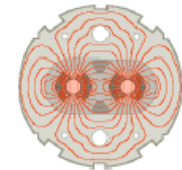




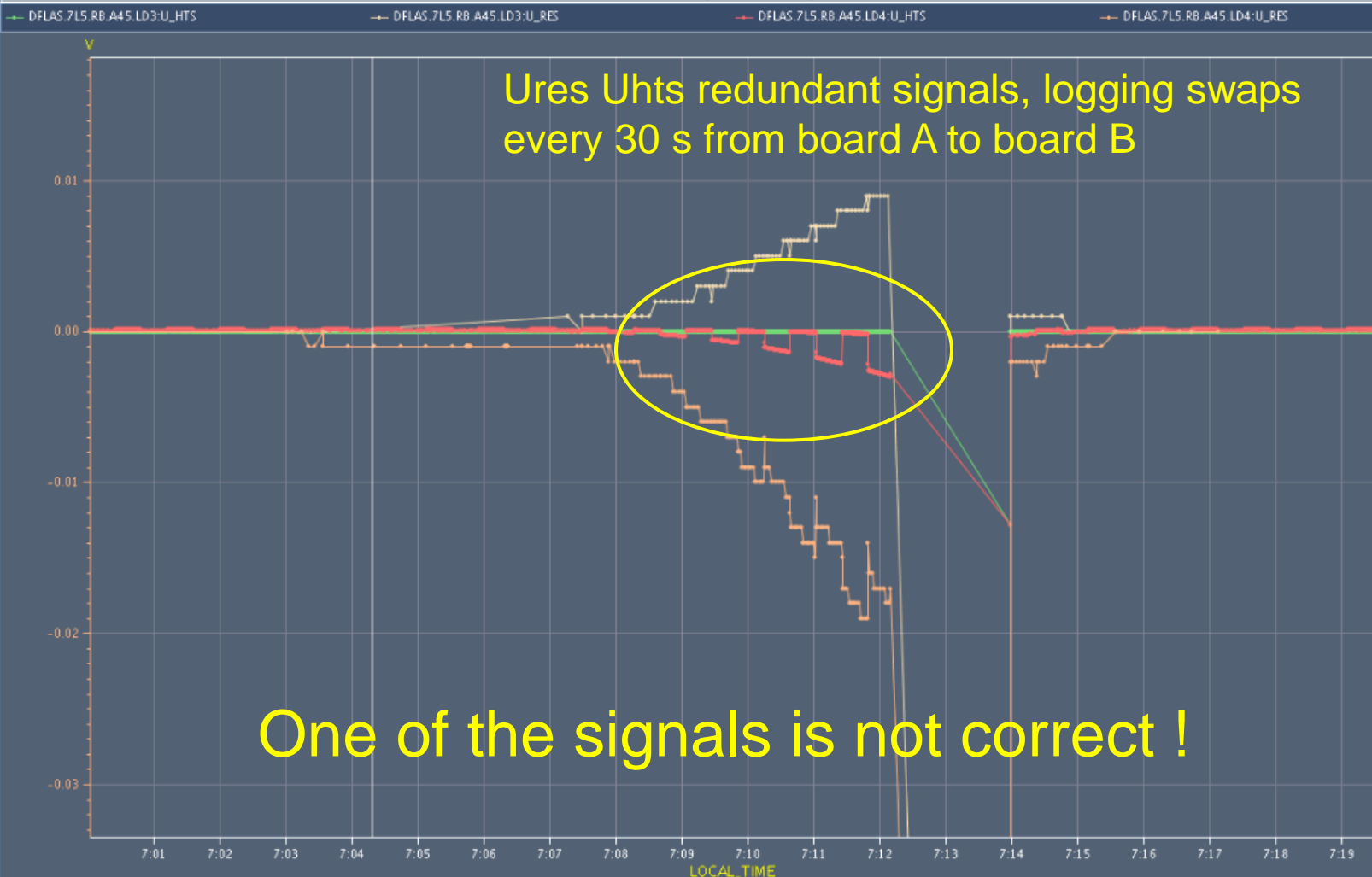
# HTS quench (sc link)- what happened

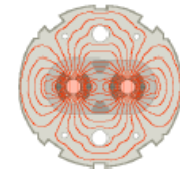


- QPS tripped the RB circuit in sector 45 on Thursday around 07:00.  
*First time ever quench of HTS current lead*
- The HTS quenched due to a lack of cooling in the DFB
  - Faulty electronics board corrupted the temperature feedback loop
- Protection by the QPS monitoring the current leads.
  - Logging of the two HTS signals showed that only one of the two measurements was correct, the other was measuring a short circuit
- *An identical fault on the redundant signal would have left the system unprotected and could lead to beyond repair damage to the DFB. No spares*
- *Decided to stop powering magnets*
  - To validate other circuits



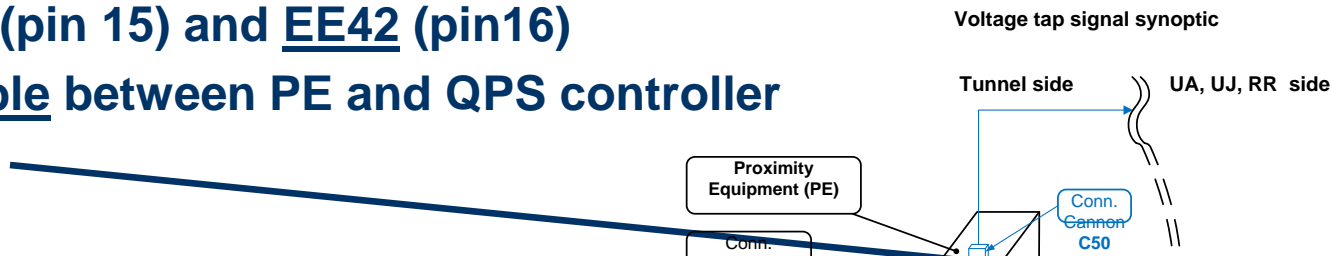
Timeseries Chart between 2011-04-06 06:00:00.000 and 2011-04-07 08:00:00.000 (LOCAL\_TIME)





# What was swapped...?

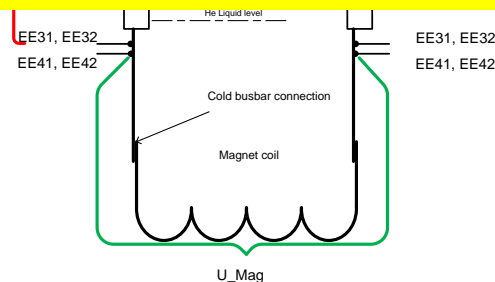
- What was found swapped in RB.A45, Lead#2 on DFBAI (L5)?  
EE22 (pin 15) and EE42 (pin16)  
of cable between PE and QPS controller



This connection had been like this since 2005

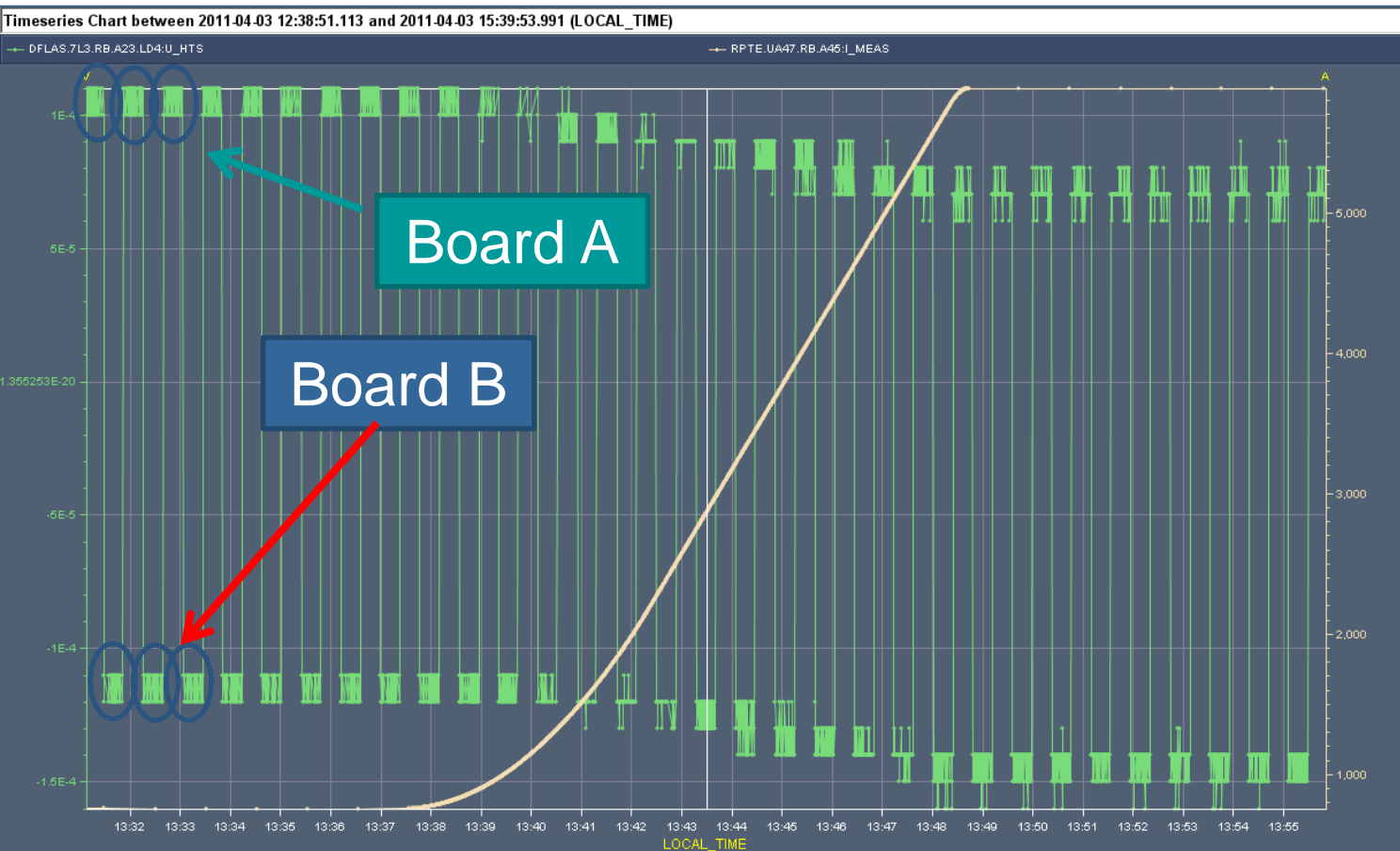
Are all connections like this?

Stop operation until all connections are verified



# From the logging

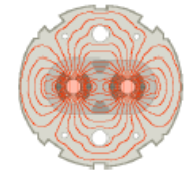
- Analysis of the logging data from old ramps allowed the QPS team to verify the correctness of the signals for other 13 kA circuits
- Verification of U\_RES & U-HTS on all IPQs, IPDs, ITs using dedicated powering cycles by the QPS team
  - **Verification of boards A & B**



Example of a healthy channel: both boards move in unison during a ramp



# Verification - Friday 8<sup>th</sup> April

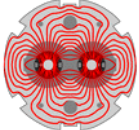


- In the late afternoon all high current circuits except the 600 A circuits had been checked.
  - Acceptable risk for 600 A circuits.
- All tests showed the presence of the expected signals.
- Green light for powering from TE/MPE in the evening.

Among all the high current circuits we happen to quench exactly the one circuit with a cabling problem !!

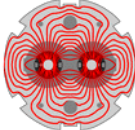
# Event of 18th April

- Flashover (high voltage breakdown) on B2 MKI magnet D (first one seen by the beam) while injecting 72b
- Extensive beam losses through P8 and arc 78: result
  - Kicker interlocked off
  - Quench heaters fired on 11 magnets
  - Vacuum valves closed
  - **Several very anxious hours....**



# Beam Dumps at > 450 GeV – I

Date	Time	State	Reason
30/05	11h08	Stable beams	<b>QPS trigger circuit detector of RCBXH2.L1. SEU?</b>
	15h43	Adjust	<b>New RF interlock not masked</b>
	20h20	Adjust	<b>FMCM. Electrical glitch</b>
31/05	06h22	Stable beams	<b>UFO IR2L</b>
	10h38	Stable beams	<b>Communication with DFBAJ. SEU?</b>
	22h20	Squeeze	<b>UFO IR2L</b>
01/06	02h10	Squeeze	<b>QPS trigger (Quench of Q9R5 ?)</b>
	06h53	Adjust	<b>RF trip (radiation-induced arc detector signal?)</b>
	09h17	Ramp	<b>Collimator temperature</b>
	20h37	Stable beams	<b>Collimation crate IR5R failure (PRS)</b>
02/06	16h58	Beam dump	<b>EIC</b>
	21h50	Stable beams	<b>UFO IR8</b>
03/06	00h28	Squeeze	<b>Trip of RQTF.A23B2</b>
	13h30	Stable beams	<b>Loss of I_meas reading</b>
	18h24	Squeeze	<b>UFO in IR8R</b>
	21h17	Stable beams	<b>Trip undulator IR4.</b>



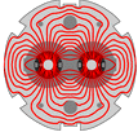
# Beam Dumps at $> 450$ GeV – II

Date	Time	State	Reason
04/06	07:56	Stable beams	<b>QPS FIP communication lost, close to IR1.</b> S12 tripped.
	16:19	Stable beams	<b>Power converter fault.</b>
	20:20	Flat top	<b>UFO IR2L</b>
05/06	00:15	Stable beams	<b>RF trip</b>
	03:48	Adjust	<b>LHCb magnet trip</b>
	06:56	Stable beams	<b>UFO IR2L</b>
06/06	00:31	Stable beams	QPS trigger on RQTL11.R7B1.
	07:39	Stable beams	<b>PC failure of RQ6L2.</b>
07/06	07:28	Stable beams	<b>Bad current reading on RTQX2.R1</b>
08/06	09:22	Stable beams	<b>Alice dipole trip</b>

26 beam dumps at  $> 450$  GeV, only one dumped by OP.

Increase of BLM dump threshold  
for Q4 (MQY) at MKI's by factor 2

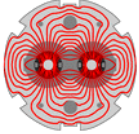




# Bunch length

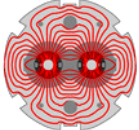
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- Important parameter for
  - ☐ Cryogenics stability
  - ☐ Collimator heating
  - ☐ Injection kicker heating
  - ☐ ...
- Work ongoing to improve blow-up control during the ramp by the RF-team
  - ☐ Better reproducible results -> test operation with longer bunches
  - ☐ Disadvantage is possibly more debunched beam when a cavity trips, but not an issue at the moment



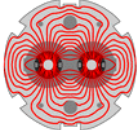
# Fills above 450 GeV 1/4

Date	Mode	Fill	SB	pb <sup>-1</sup>	Cause of dump
MON 18	STABLE BEAMS	1955	6h8m	18.3	<b>QPS</b> trigger, trip of RQTL7.L7B1
MON 18	STABLE BEAMS	1956	17m	.4	Cryo lost S56, <b>SEU</b> on a thermometer at a current lead
MON 18	ADJUST	1957	0	0	Dumped by SW interlock on BLM HV channel (1.3e11/bunch)
MON 18	STABLE BEAMS	1958	21m	1.1	Loss of cryogenic conditions in Sector 34 – PLC crash
WEDS 20	STABLE BEAMS	1960	1h9m	5.2	Problem on valve on DFB in arc 8.1 <b>Possible SEU</b>
WEDS 20	STABLE BEAMS	1961	2h7m	8.2	QPS - blown fuse in WorldFIP repeater
THURS 21	STABLE BEAMS	1962	15h26	46.3	CMS BCM2
FRI 22	SQUEEZE	1963	0	0	QTF trip: QFB versus QPS
FRI 22	RAMP	1964	0	0	RCBXH.R1 tripped, PC changed
FRI 22	STABLE BEAMS	1966	8.56	34.6	CMS BCM2
SAT 23	STABLE BEAMS	1967	11.4	41.7	Valve controller IT.R1 – <b>possible SEU</b>



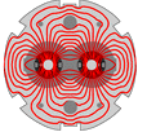
# Fills above 450 GeV 2/4

Date	Mode	Fill	SB	pb <sup>-1</sup>	Cause of dump
Sat 23	STABLE BEAMS	1968	46m	4.0	Electrical network glitch
Sat 23	ADJUST	1969	0	1.8e33!	Vacuum spike 4L8
Sun 24	STABLE BEAMS	1970	1h37m	9.5	Vacuum spike 4L8
Sun 24	STABLE BEAMS	1971	1h8m	6.2	Controller IT5 Possible SEU
Sun 24	STABLE BEAMS	1972	46m	4.4	Cryo – R1 24V supply Possible SEU
Sun 24	FLAT TOP	1973	-	-	QPS communication problem
Sun 24	STABLE BEAMS	1974	5h15	25.5	Electrical network glitch



# Last week: fills above 450 GeV 3/4

	Fill	Mode	Stable [h]	Int. L (pb <sup>-1</sup> )	Dump cause
Mon 25	1975	STABLE	2.5	13	Cryo valve PROFIBUS (UJ76) (SEU?)
Mon 25	1976	ADJUST	-	-	Losses 83s RS on TCSG.A6L7.B1
Mon 25	1977	SQUEEZE	-	-	RF Module trip
Mon 25	1979	STABLE	6	23	QPS RCO/RCD/RCS cross-talk S56
Tue 26	1980	RAMP	-	-	False trip of 600A QPS RQTL7.R7B1.
Wed 27	1982	STABLE	2.5	13	Electrical network perturbation
Wed 27	1984	SQUEEZE	-	-	Vacuum spike R2
Wed 27	1985	STABLE	11h22m	50.4	Electrical network perturbation

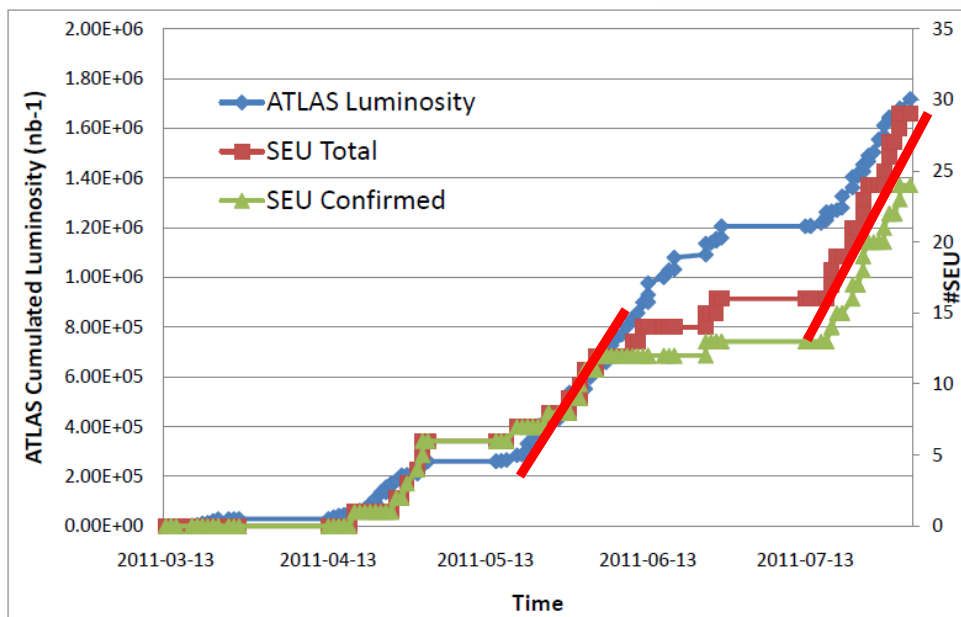
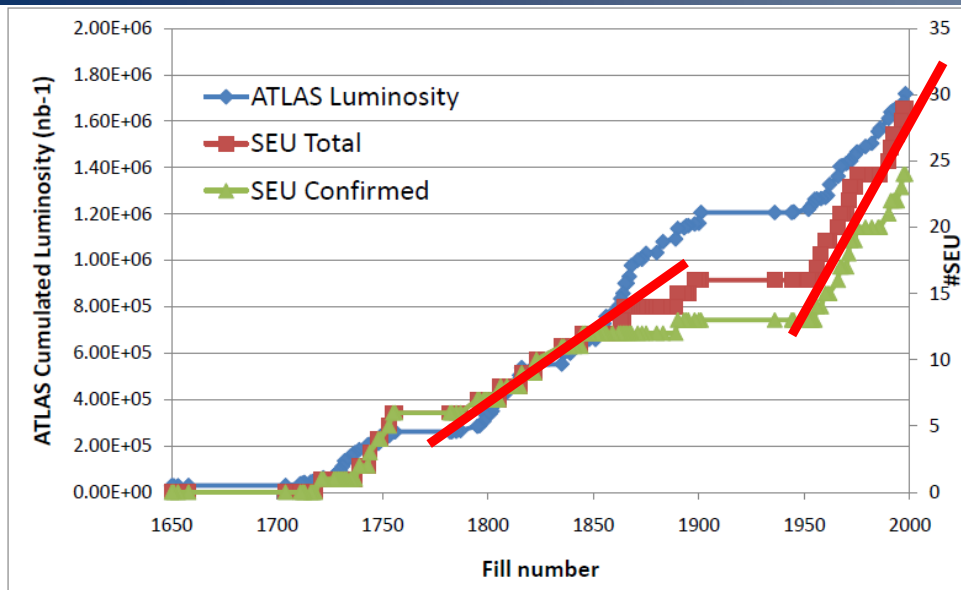


# SEUs

2011 Operation up to Week 30 (2010 excluded):  $\rightarrow \sim 1,8 \text{ fb}^{-1}$  (nominal: x30 for lumi scaling)

RRs	shielded areas		tunnel		
	HEH (cm-2/w30)	HEH (cm-2/2011)	HEH (cm-2/w30)	HEH (cm-2/2011)	BLM dose (mGy/week)
13	<1.0E+6	2.9E+06	1.2E+07	1.1E+08	<10
17	<1.0E+6	3.1E+06	8.6E+06	9.7E+07	<10
53	<1.0E+6	3.7E+06	1.2E+07	1.3E+08	<10
57	<1.0E+6	3.3E+06	5.2E+06	1.0E+08	<10
73	<1.0E+6	3.8E+06	6.0E+07	1.9E+08	<10
77	<1.0E+6	5.8E+06	1.7E+07	1.8E+08	<10
			Luminosity Dominant		
			Intensity Dominant		
UJs	shielded areas		tunnel		
	HEH (cm-2/w30)	HEH (cm-2/2011)	HEH (cm-2/w30)	HEH (cm-2/2011)	BLM dose (mGy/week)
14 (13, tun)	9.4E+06	7.7E+07	6.1E+08	5.1E+10	<10
16 (17, tun)	6.0E+06	5.4E+07	2.0E+09	7.3E+10	<10
22	N/A	N/A	4.7E+07	1.3E+09	<10
23	<1.0E+6	<1.0E+6	6.9E+06	1.8E+08	<10
32	N/A	N/A	<1.0E+6	<1.0E+6	1762
33	<1.0E+6	<1.0E+6	<1.0E+6	<1.0E+6	N/A
56	1.3E+06	1.2E+07	2.7E+09	2.2E+10	<10
76	<1.0E+6	2.4E+06	2.2E+09	1.6E+10	<10
87	<1.0E+6	1.4E+06	2.2E+09	2.9E+09	<10
88	N/A	N/A	6.2E+07	1.1E+09	<10
			Luminosity Dominant		
			Intensity Dominant		
US85/UX85	cavern US85		cavern UX85		
	HEH (cm-2/w30)	HEH (cm-2/2011)	HEH (cm-2/w30)	HEH (cm-2/2011)	
	1.2E+06	2.0E+07		1.0E+08	
			Luminosity Dominant		

Ⓢ Scaling might be non-linear for areas being dominated by direct losses (& distributions) and/or vacuum contributions!



## !!! Only Physics Fills !!!

- Shorter fills with higher luminosity
- > 'more' likely to have SEEs ending the fill since some other failure modes depend rather on time?
- In terms of behavior with time the failures reflect the cumulative luminosity (see slide before)

!!! All Fills !!!

	# of Failures			Dump	Transparent
	Conf	Likely	Grand Total		
<b>Total:</b>	29	21	50		
<b>Shielded Area.:</b>	27	20	47	47	
<b>Tunnel:</b>	2		2	12	28 + ???

Cryogenics WorldFip

Ti2, RR53

2

Dump

Software Update

[Details](#)

Area		Failures			Mitigation Measures		
		Confirmed	Likely	Total	Applied	XmasBreak	LS1
Point 1	UJ14/16	17	5	22		shielding + patches	relocation
	RR13/17	1		1			shielding
Point 4	US45		1	1		some relocation + patches possible	some relocation + patches possible
Point 5	UJ56	1	4	5	some relocations	some relocations possible + patches	relocation
	RR53/57	4	1	5			shielding
Point 7	UJ76		2	2	shielding + some relocations	some relocations possible + patches	relocation
	RR73/77			0	shielding		
Point 8	US85	5	4	9	some relocations & shielding + patches	some relocations possible	

						<a href="#">(H4IRRAD)</a>
Valve Controllers	US85	?			Replacement	under investigation



Solve & Gain Time

RELOCATION

Improve & Gain Time

SHIELDING

## Mitigation Options

Solve & Remain Flexible

RAD-TOL  
DESIGN

No Major CE

~~CIVIL  
ENGINEERING~~

1<sup>st</sup> Safety  
Critical



Immediate Relocation



2<sup>nd</sup> Shielding



"Fast" & Global Improvement



3<sup>rd</sup> Most  
Sensitive



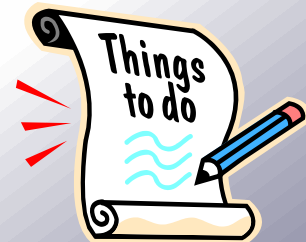
Highest Impact on Operation:  
(1)Relocation  
(2)Shielding



4<sup>th</sup> Remaining



(1)Relocation  
(2)Shielding  
(3)New Design



## ☉ Shielding:

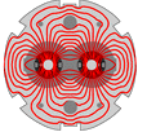
- ☉ P6 (RA63/UA63 and RA67/UA67) (**gain ~factor 5-10**)
- ☉ UJ22/23/76/88/87 (**gain ~factor 10**)
- ☉ RR77/73 (**gain ~factor 10**)
- ☉ US85 Safe-Room (**gain ~factor 10**)

## ☉ Relocations:

- ☉ Fire-Control Racks UJ56/76, US85 (**safe**)
- ☉ RTU relocated from safe room in UJ56/76 (**safe**)
- ☉ Cryo-relocations/valve replacement in UX85 (**safe**)
- ☉ UPS from UJ76 (**safe**)
- ☉ Fire-Detectors: US85, other points prepared (**safe**)
- ☉ PLCs from US85 (**safe**)

## ☉ Replacements & Upgrades:

- ☉ QPS Firmware Upgrade (ISO150 failures) (**transparent**)
- ☉ US85 24V Power Supply -> replaced by old model (**more robust**)

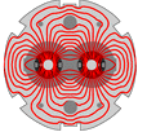


# Instabilities



# Summary

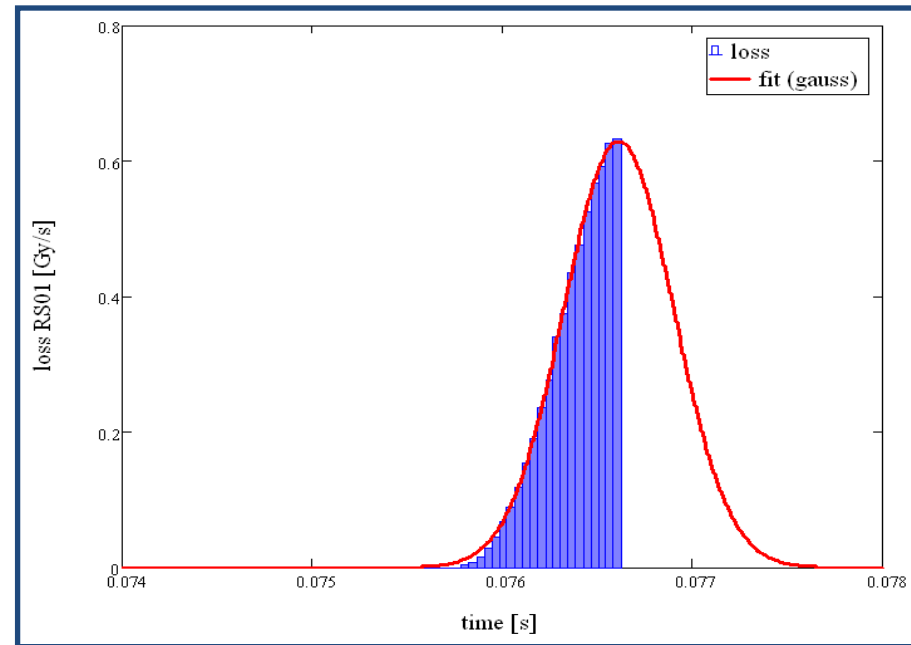
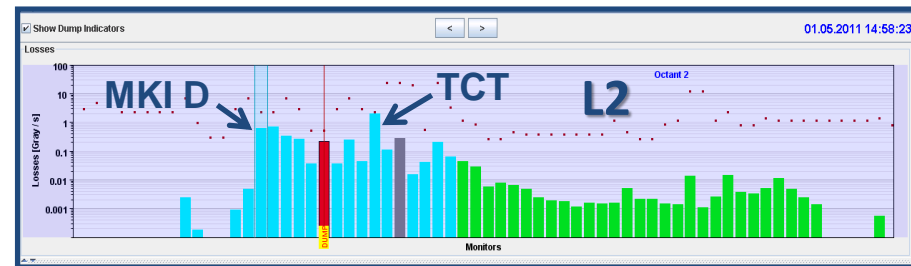
	50ns with higher $N_b$ and lower $\epsilon_{x,y}$	25ns nominal
<b>Single bunch headtail instabilities</b>	More Landau damping required	Present Landau damping settings sufficient
<b>TMCI</b>	Both safely below threshold, multi-bunch effect?	
<b>Coupled bunch instabilities (m=0)</b>	Transverse feedback	
<b>Coupled bunch instabilities (headtail modes)</b>	More Landau damping required	Present Landau damping settings marginally sufficient
<b>Electron cloud build up</b>	Larger than now, maybe more scrubbing needed	Significantly larger than now, efficiency of scrubbing?
<b>Single bunch ECI</b>	Higher chromaticity setting to suppress it during scrubbing	Higher chromaticity setting to suppress it, if e-cloud level tolerable



# UFOs

# UFO related Beam Dumps

- **29 beam dumps** due to UFOs in 2010 (18) and 2011 (11).  
*10 dumps around MKIs.*  
*1 dump at 450 GeV.*
- Temporal width of a few turns.  
*Dump often on running sum with 640 $\mu$ s or 2.5ms integration time.*
- Max Loss amplitude (extrapolated): 7.7 Gy/s



*Beam dump on 01.05.2011*

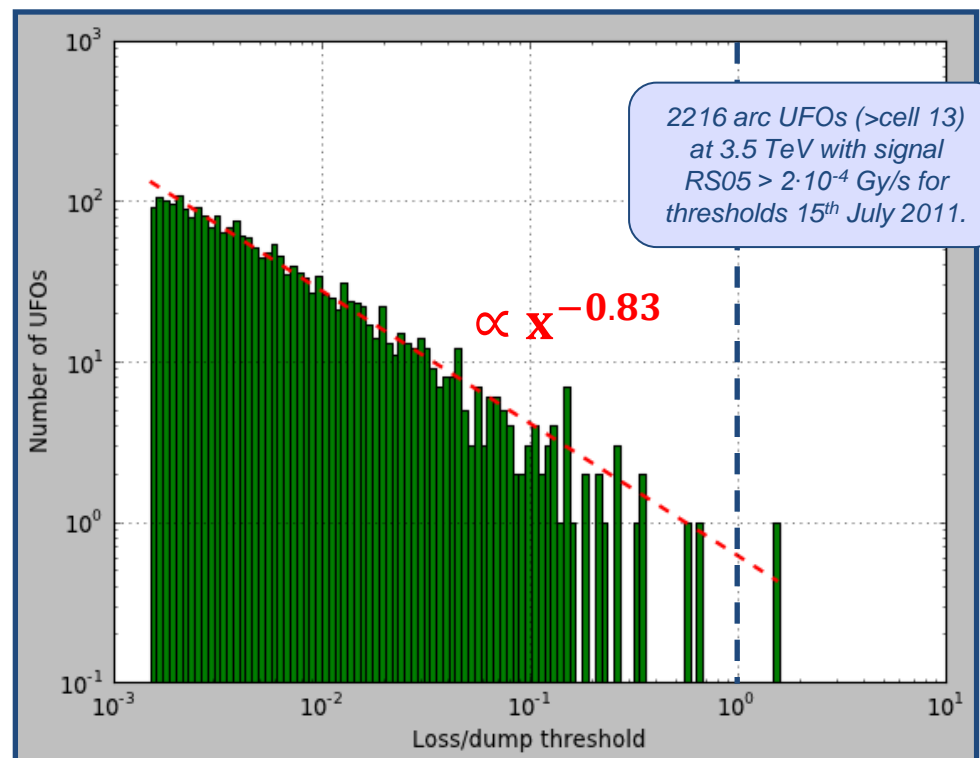
# UFOs Below Dump Threshold

- For 2011: Online UFO detection by **UFO Buster**.

*Detects UFOs in BLM concentrator data (1Hz).*

- Over **5000 UFOs** below threshold found so far.

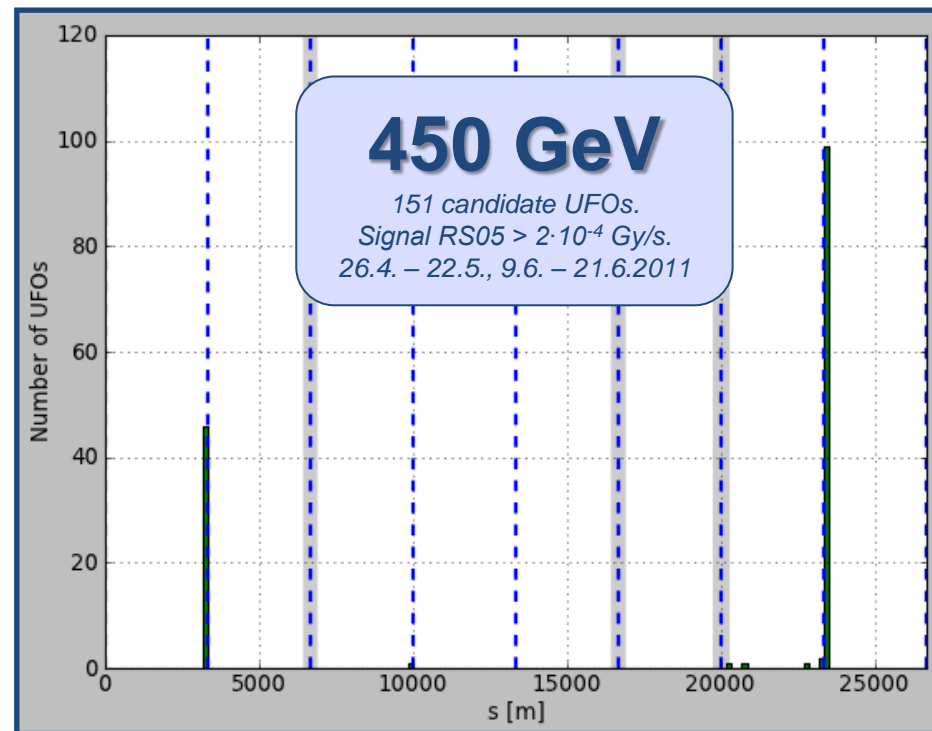
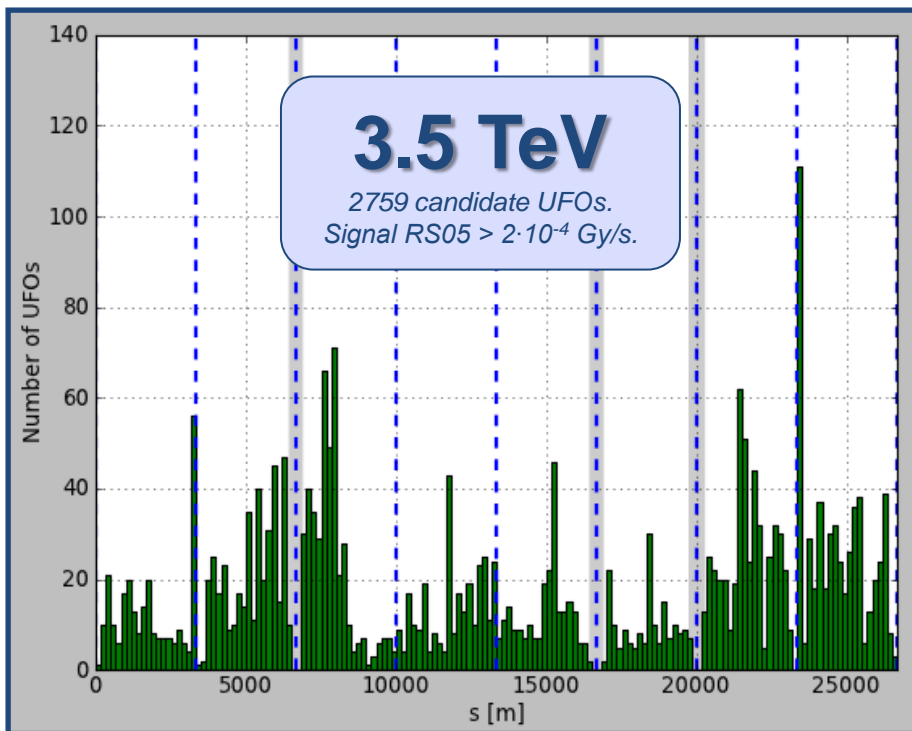
*Most events are much below threshold.*



*Amplitude of arc UFOs.*



# Spatial UFO Distribution



- Many UFOs around **MKIs**.
- Arc locations with many UFOs:

Mainly UFOs around MKIs

**BLMQI.19R3.B1I10\_MQ: 50 UFOs.**

**BLMQI.25R3.B2E10\_MQ: 53 UFOs.**

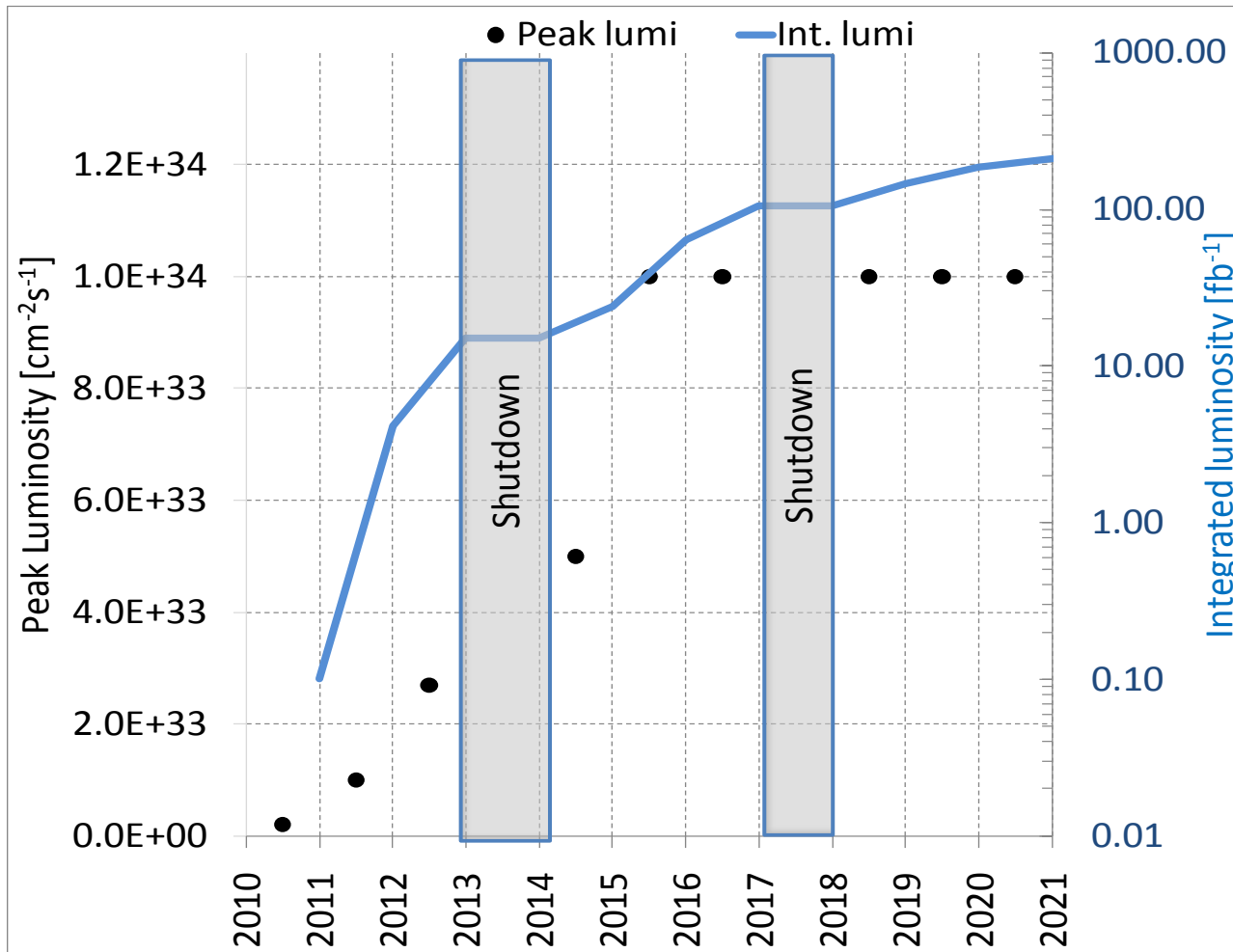
**BLMQI.28R7.B2I10\_MQ: 47 UFOs.**

*gray areas around IRs are excluded from UFO detection.*

# Conclusion

- **For 2011:**
  - **Arc UFOs: No sign that the situation will become worse.** Few dumps are expected.
  - MKI UFOs: **MKI UFO Storms might be critical.**  
*Large effort underway to understand mechanism, in lab and in LHC.*
- **Beyond 2011:**
  - Observations show an **aggressive scaling with beam energy!**  
Situation could be significantly worse above 3.5TeV.  
*Intermediate energy step would be very helpful for extrapolations to nominal energy.*

# Possible Luminosity Evolution: optimistic to 2012, then prudent



Shown by Lucio  
Rossi last  
Saturday  
Not yet validated  
by LMC or  
Directorate