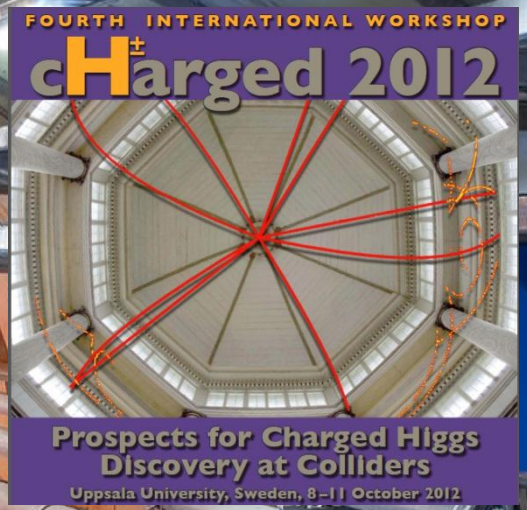
Review of the Status of the LHC



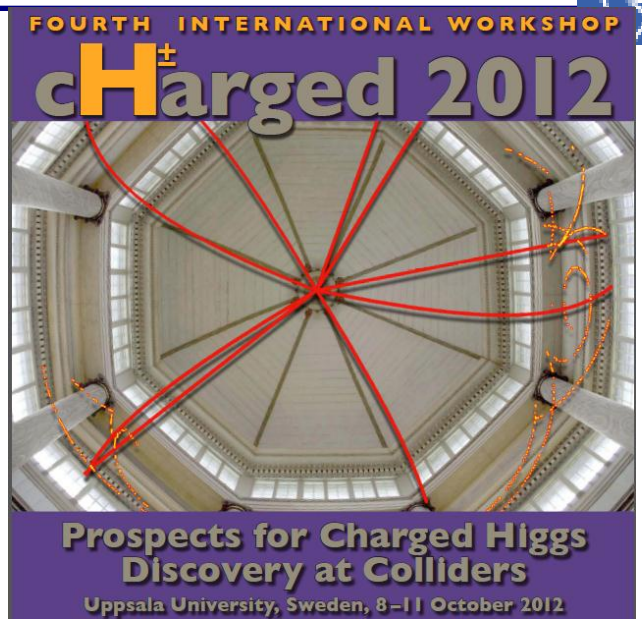
Jan Uythoven - CERN
for the LHC team

Charged Higgs 2012
Uppsala, 8 – 11 October 2012

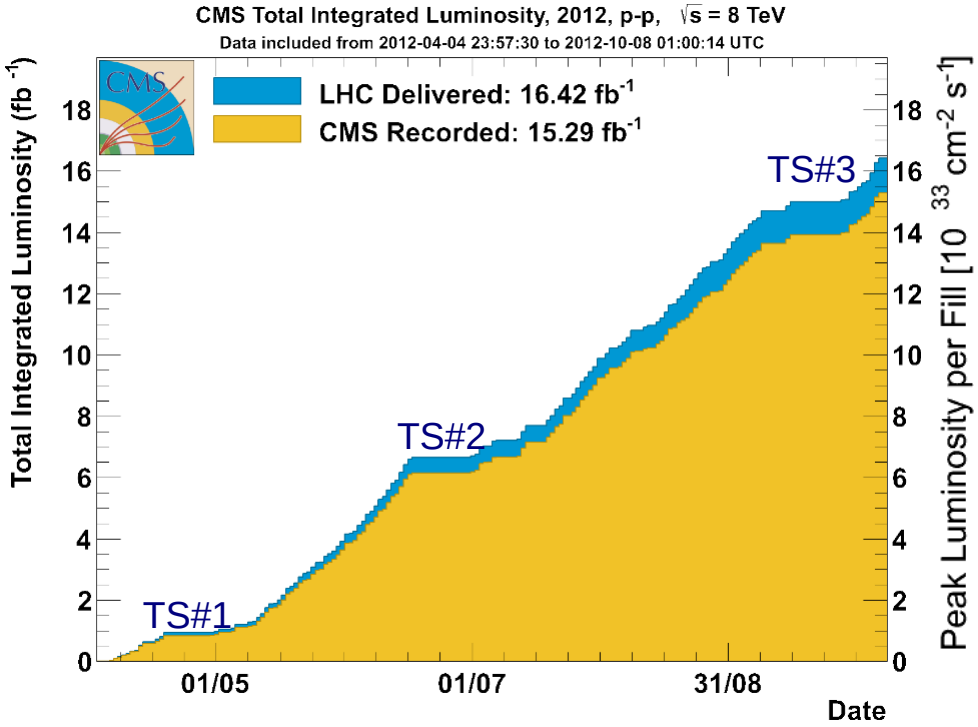
Overview

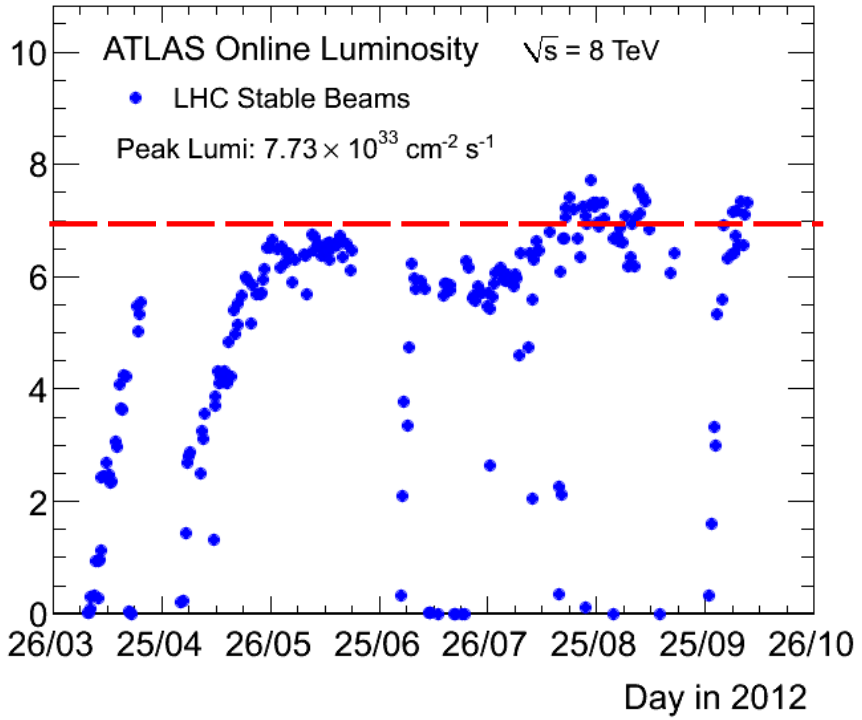
- Status of LHC
  - Performance so far in 2012
  - Solutions and problems
- Plan for the rest of the year
  - Physics & exploration
- Plan for after Long Shutdown 1
  - No answers but some parameters are known which allow for simulations and discussion

Not treating proton – ion operation



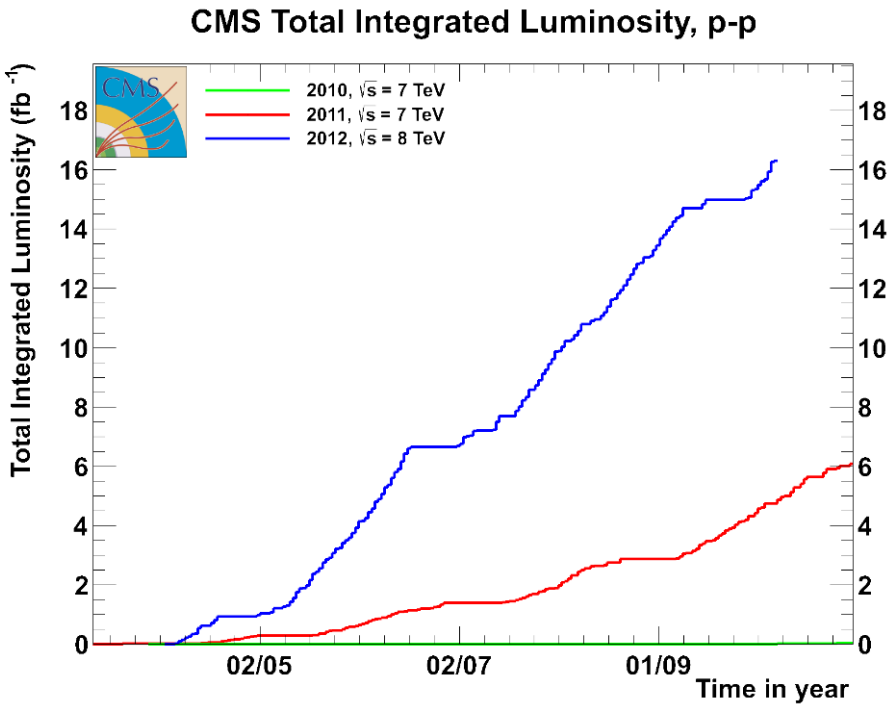
Luminosity 2012, so far





- Integrated luminosity 16.4 fb^{-1}, as of 08/10/2012 (last night)
- Peak lumi at start of fill reached up to 7.7×10^{33} Hz $cm^{-2}s^{-1}$
  - Octupole polarity change
- A good week is delivering about 1 fb^{-1} , the best week 1.3 fb^{-1}
- Maximum lumi per day ~~262 pb^{-1}~~, 2 days ago: 286 pb^{-1}

Comparison 2010 – 2011 - 2012



- 2010: 0.04 fb^{-1}
  - Machine commissioning
- 2011: 6.1 fb^{-1}
  - Production
- 2012: 16.4 fb^{-1} so far
  - Higher energy
  - Smaller beta*
  - Increased bunch current

24-Aug-2012 08:32:07 Fill #: 2998 Energy: 4000 GeV I(B1): 2.13e+14 I(B2): 2.16e+14

	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	STANDBY	STANDBY	PHYSICS
Instantaneous Lumi [(ub.s)^-1]	7728.0	0.000	7537.3	28.4
BRAN Luminosity [(ub.s)^-1]	7707.1	2.030	7399.0	27.0
Fill Luminosity (nb)^-1	0.0	0.0	514.0	2.1
BKGD 1	0.550	0.736	2.065	0.272
BKGD 2	158.291	0.000	6.755	9.490
BKGD 3	2.522	7.467	19.376	0.167

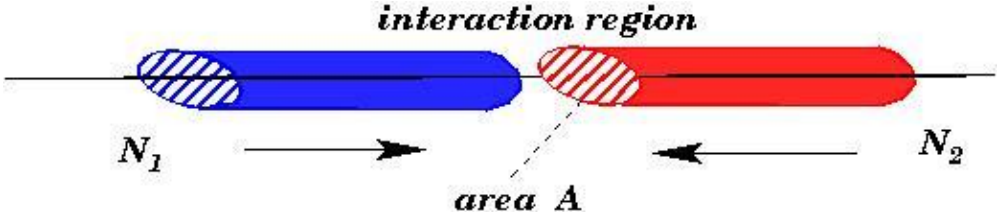
LHCb VELO Position OUT Gap: 58.0 mm | STABLE BEAMS | TOTEM: STANDBY

Luminosity

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

$$N_{events} = L\sigma$$

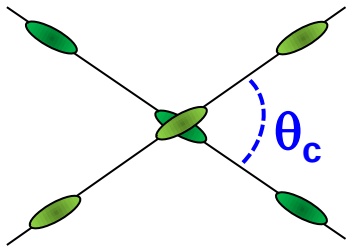
$\sigma_{x,y} = (\beta^* \varepsilon)^{1/2}$
presently $\approx$ ***18*** μm



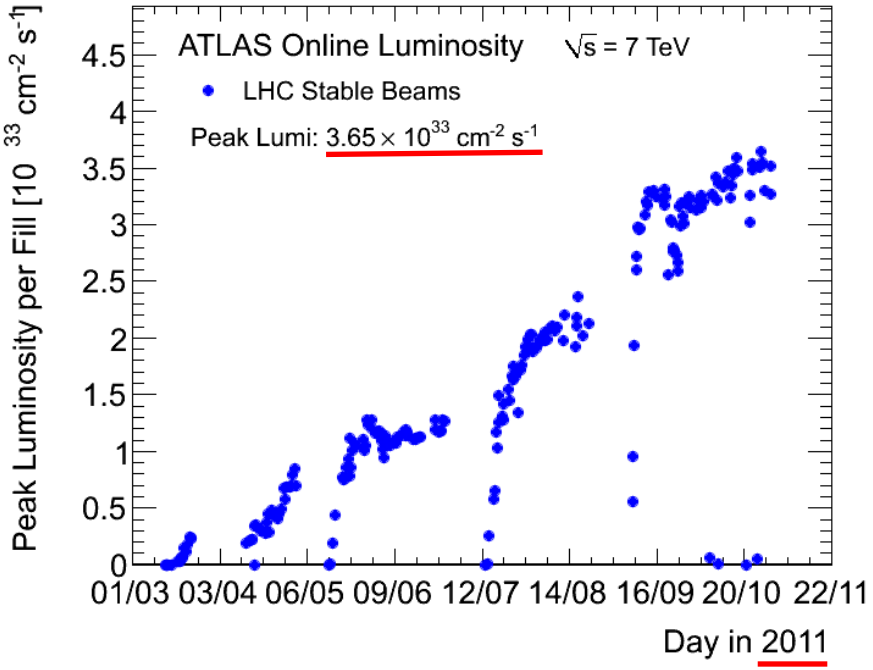
- Nearly all the parameters are variable (and not independent)
  - **Number of bunches per beam** k_b — Total Intensity
  - Number of particles per bunch N
  - Normalised emittance ε_n
    — Beam Brightness
  - Relativistic factor (E/m_0) γ — Energy
  - **Beta function at the IP** β^*
  - Crossing angle factor F
    — Interaction Region
    - Full crossing angle θ_c
    - Bunch length σ_z
    - Transverse beam size at the IP σ^*

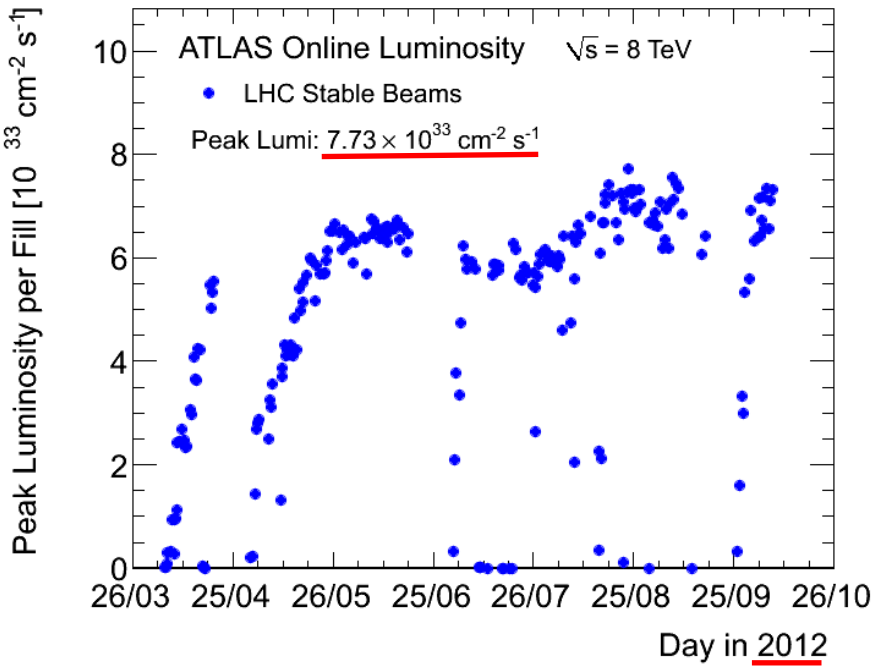
$$F = 1/\sqrt{1+\left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$$

Presently $F \approx 0.8$



Comparing 2012 with 2011 peak Lumi





- Compare 2012 with 2011
  - Energy γ factor 4.0 / 3.5 = 1.14
  - Beta* 1.0 / 0.6 = 1.67
  - Bunch intensity N factor (1.6/1.5)^2 = 1.14
- **3.6** * 1.14 * 1.67 * 1.14 = **7.8** Hz/nb
  - Assuming about the same emittance and crossing angle

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

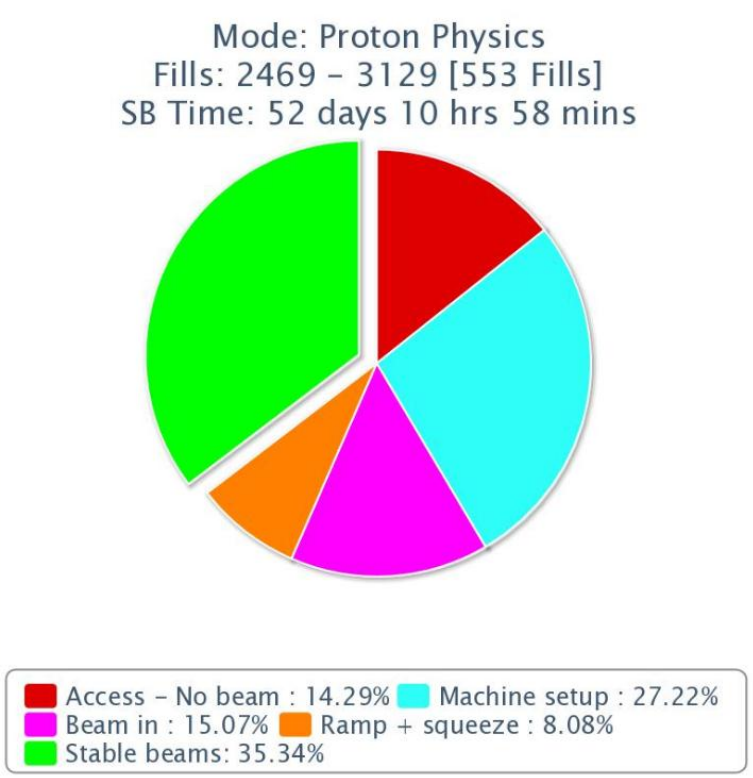
Comparison with nominal & pile-up

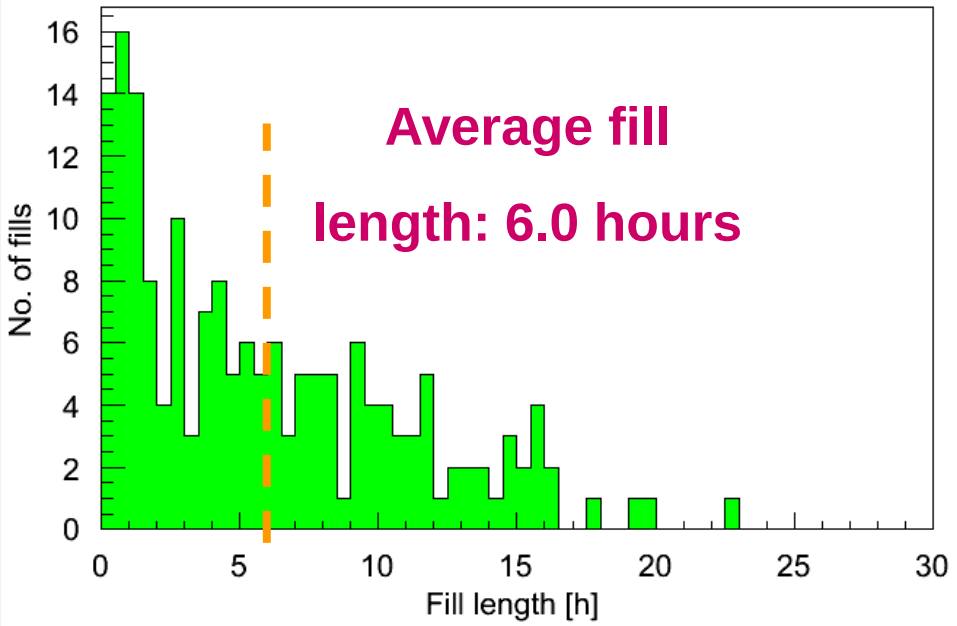
- Add to this equation the **pile-up** in the experiments number of events per bunch crossing

$$\text{Pile-up: } \mu = \sigma_{inel} \frac{L}{k_b \, frev}, \; \sigma_{inel} \approx 72 \text{ mbarn}$$

Parameter	2010	2011	2012	Nominal
N (10^{11} p/bunch)	1.2	1.5	1.6	1.15
k (no. bunches)	368	1380	1368 1374 1380	2808
Bunch spacing	150	75 / 50	50	25
e_n (mm rad)	2.4-4	1.9-2.4	2.2-2.5	3.75
β^* (m)	3.5	1.5 → 1	0.6	0.55
L ($cm^{-2}s^{-1}$)	2×10^{32}	4.0×10^{33}	7.6×10^{33}	10^{34}
μ	3	19	35	23

Efficiency: more important than 10 % peak lumi





35 % of scheduled time was with stable beams

(32 % in 2011)

Only few fills are dumped by the operators

Most fills are very short

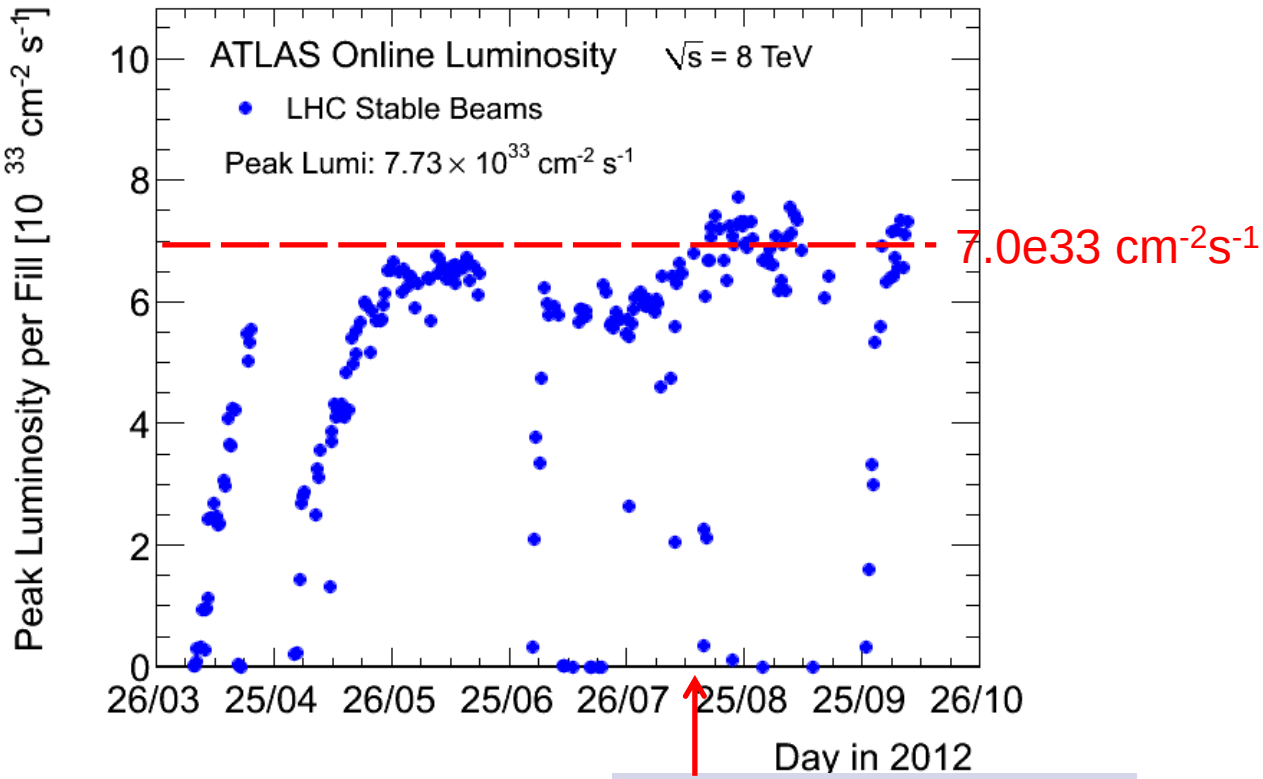
Length of fill not determined by operator

- Table of fills in week 34, 5 weeks ago
- Very good week with almost record integrated lumi of 1.3 fb^{-1}
- Only one physics fill dumped by the operator!

Fill #	Length [h]	L0 [Hz/nb]	int L [pb-1]	Dump
3009	0:16	7.3	6.8	UFO 5L4 (BSRT)
3007	2:47	7.0	57	cryo Pt 4
3006	0:21	6.9	8.5	Vacuum – RF finger
3005	8:15	7.6	132	SEU (BLM)
3003	0:42	7.3	16	Vacuum – RF finger
3002	**12:39**	**7.3**	**177**	QPS
3000	2:23	7.4	52	BLM (hardware)
2998	7:29	7.7	135	FMCM (D1 IR1)
2997	5:08	7.3	100	QPS
2996	3:38	6.9	71	FMCM (D1 IR1)
2995	0:23	7.1	88	SIS (OFB)
2994	0:27		14	Operation (H9)
2993	**12:04**	**7.3**	**179**	matching-section L1, power conv.
2992	6:41	6.5	105	EDF
2991	**13:45**	**6.7**	**171**	**Operation**

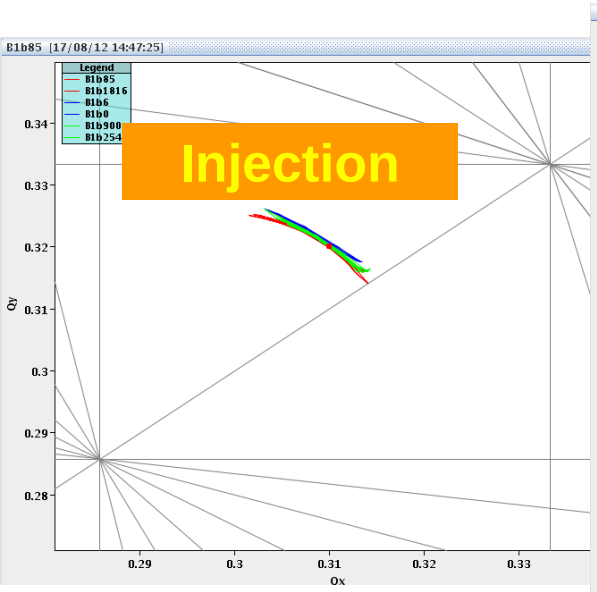
Octupole polarity changed

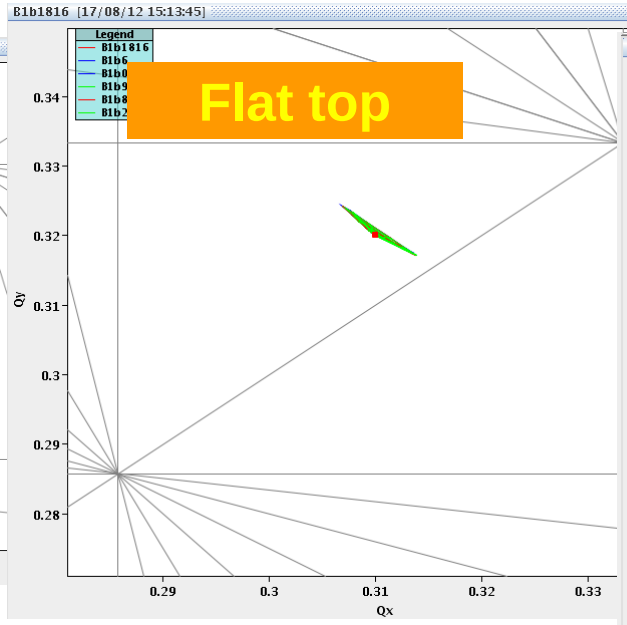
- Beam was going unstable when going into collision
  - Beam losses above thresholds dumped the beams
- Could not further increase the bunch current

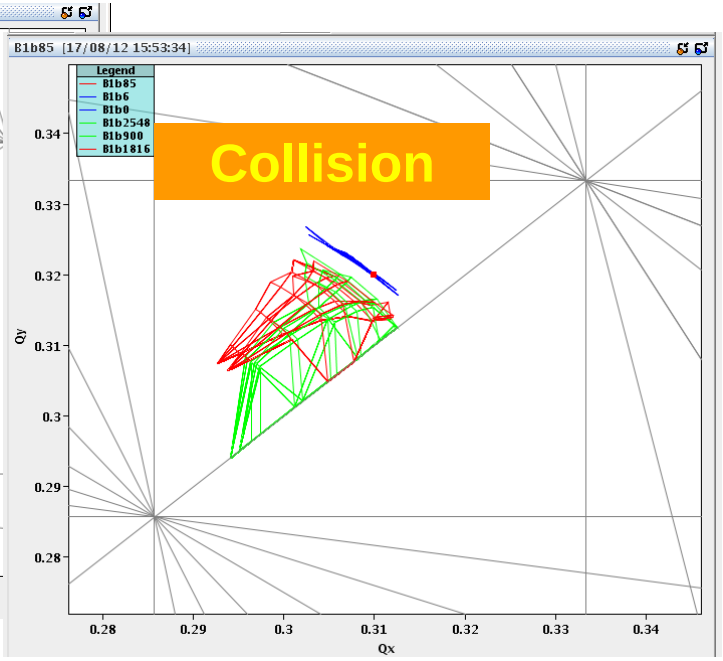


Octupole polarity & Beam Stability

- Changed octupole polarity so the tune shift created by the octupoles doesn't counteract the beam-beam tune shift
- Need to take care during squeeze and going into collision. To keep the beam stable
  - Octupole 'reversed polarity' **at almost max** (510 A, max is 600 A)
  - Chromaticites very high (13 / 15)
  - Damper at max normalised gain (0.04 -> 50 turns damping time)
- In physics reduce chroma to 11 to improve lifetime
- Getting close to a solution, this allowed to increase the **bunch intensities to 1.6e11** and reach record peak lumi of **7.7e33 cm-2s-1**

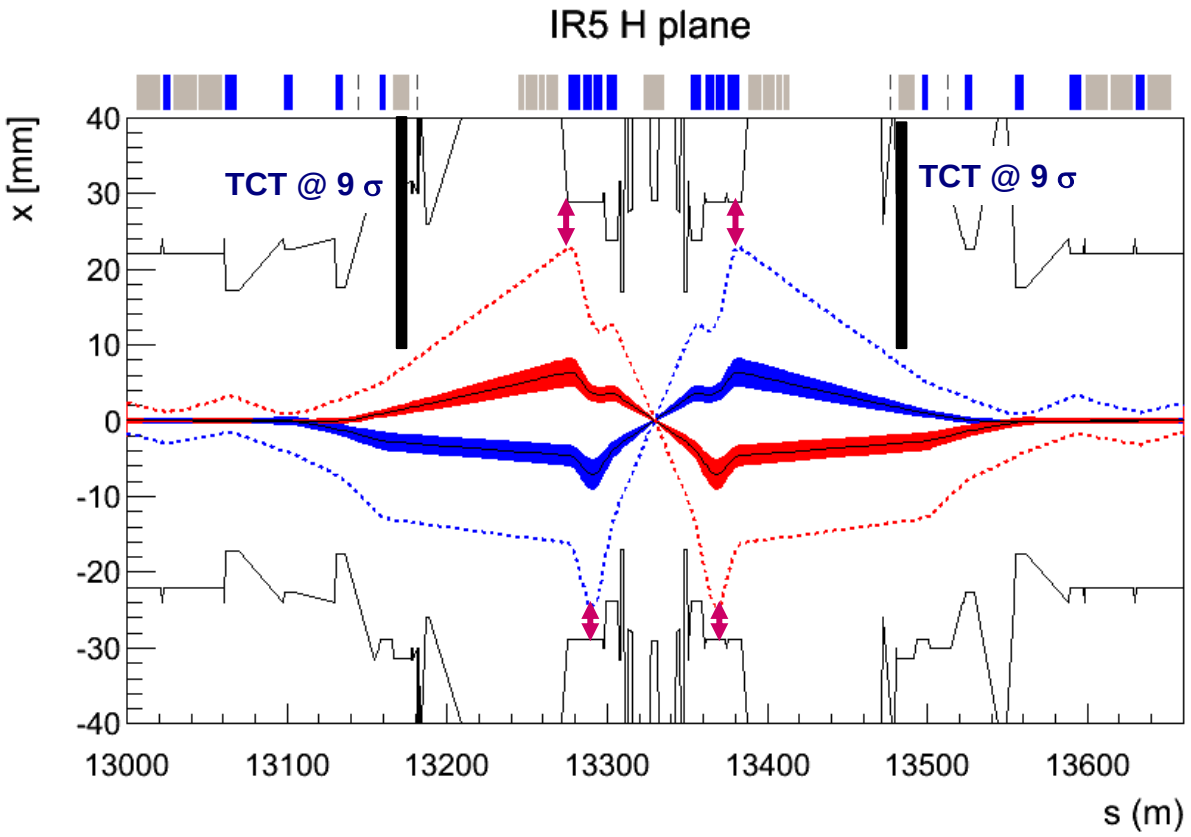






Collimation

- Routine collimation of 125 MJ LHC beams without a single quench from stored beams



1σ beam envelopes

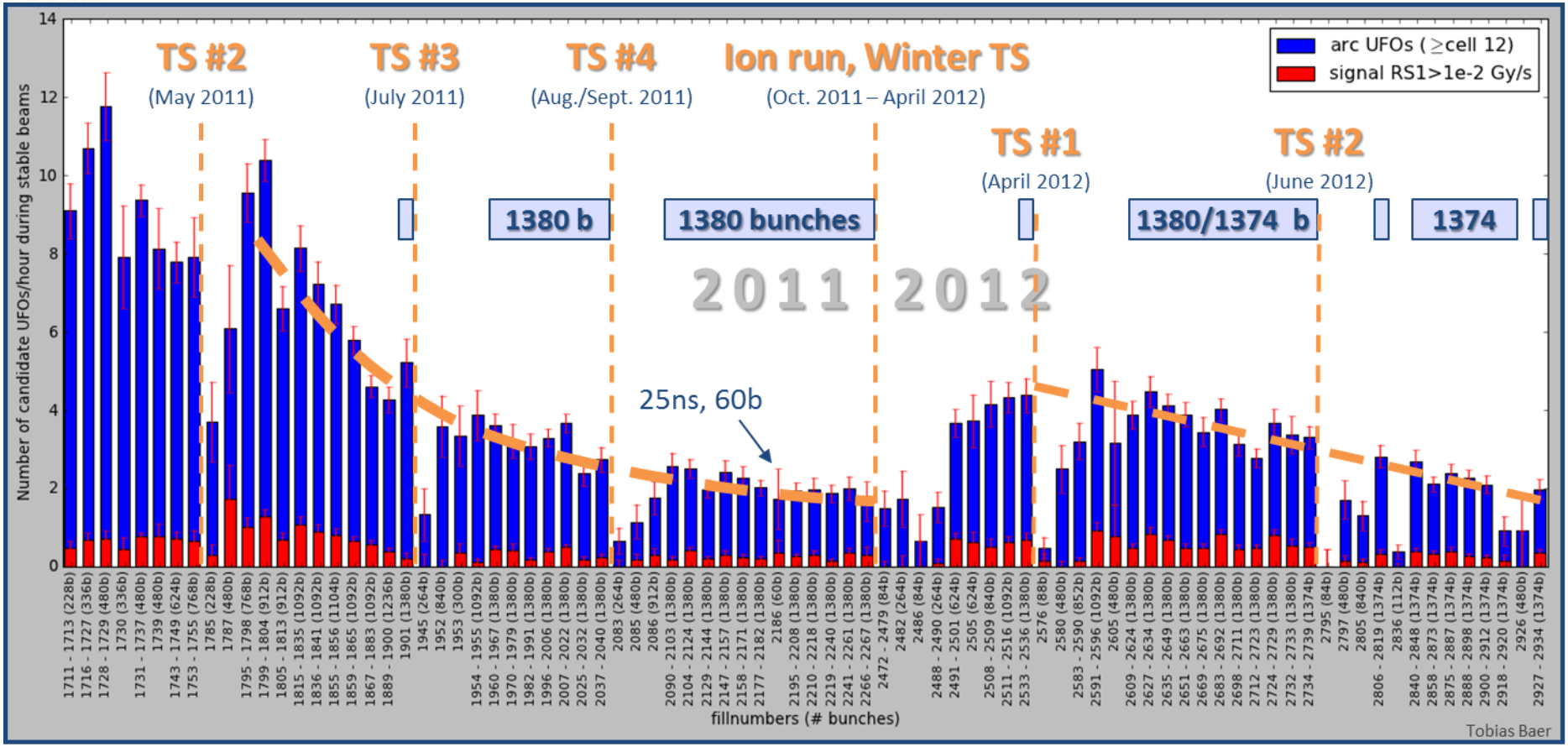
9σ extreme beam envelopes

1.5σ margin to triplet

emittance = 3.5 μm,

β* =0.6m

Unidentified Falling Objects (UFOs)



2011: Decrease from **≈10 UFOs/hour** to **≈2 UFOs/hour.**

2012: Initially, about **2.5 times higher** UFO rate compared to October 2011. **UFO rate decreases** since then.

7982 candidate arc UFOs during stable beams between 14.04.2011 and 14.08.2012. Fills with at least 1 hour stable beams are considered. Up to 5 consecutive physics fills with the same number of bunches are grouped. Signal RS04 > $2 \cdot 10^{-4}$ Gy/s.

Large beam currents limiting performance

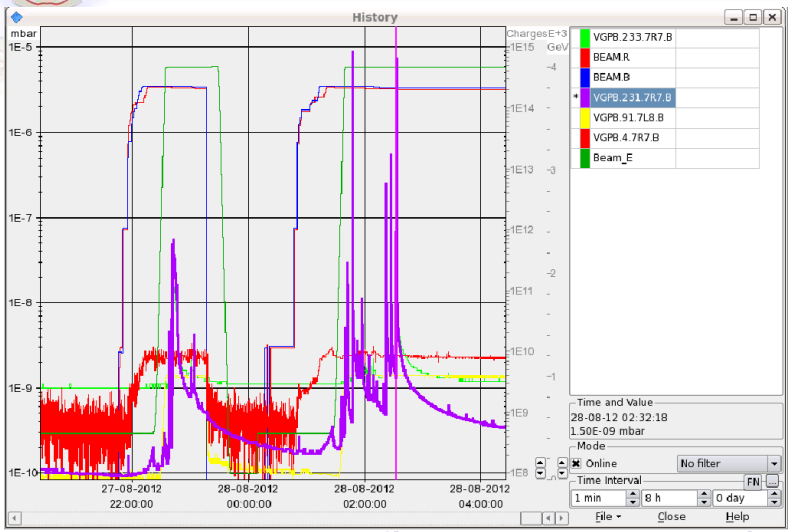
- "RF Heating"
  - Beam induces em fields in various equipment
  - The injection kicker magnets have yokes made out of ferrites, above the Curie temperature, ≈120 °C, the ferrite becomes none magnetic
  - Resonances can cause Higher Order Modes and significantly heat the equipment, causing mechanical damage
- Single Event Upsets
  - Radiation affecting the electronics
  - Equipment 'trips' and dumps the beam

Single Event Upsets (SEU)

- Electronics 'hit' by radiation
- Cause of many dumps
- Would be a lot worse without the huge effort ongoing

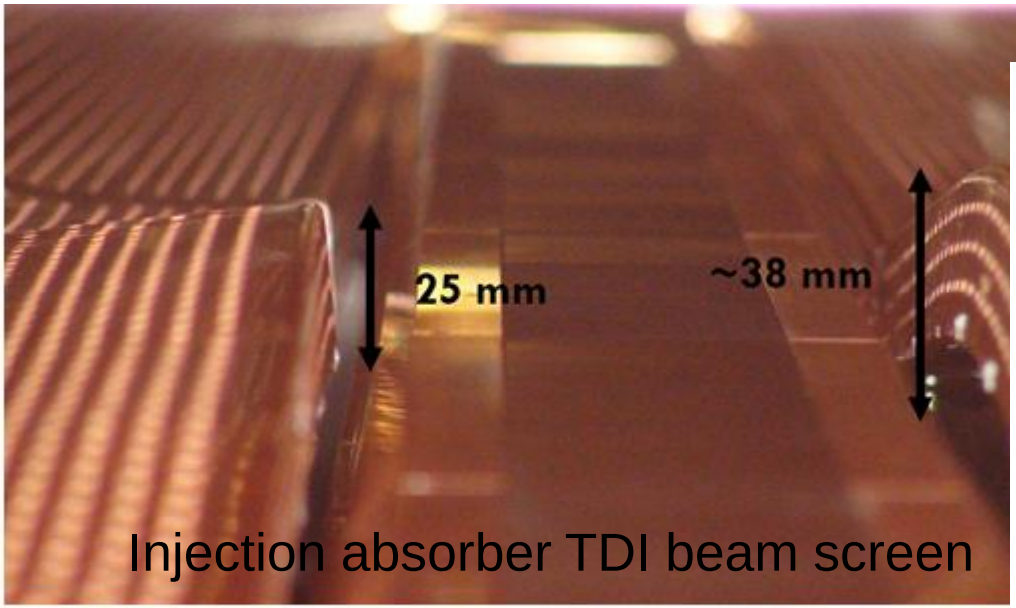
Affected Equipment Group	LHC Critical Areas	2011 #ofDumps	2011 #ofFailures	Estimated Downtime (partl. in shadow)	2011 Avoided SEE Dumps	2012 Expected Dumps	No Additional Mitigation	2012 Estimated Dumps	With Mitigation
QPS	Tunnel, UJs/RRs	23	140	~60 hours	150	69		~20	
Cryogenics	UJs	25	48	~250 hours	~25	75		1-2	
Power-Converters	Tunnel, UJs/RRs, UAs	13	15	~30 hours	few (FGC)	39		10-20	
Collimation Control	UJs (P1/5)	6	8	~20 hours	-	18		7	
B/P/WIC	UJs, US85	3	4	~15 hours	1-2	9		0	
Access	UJs	-	~4-8	~10 hours	-	-			
EN/EL	UJ56, US85	2	3	~15 hours	-	6		~1	
	Totals	**72**	**~220**	**~400h**	**~180**	**216**		**~30-50**	

RF heating

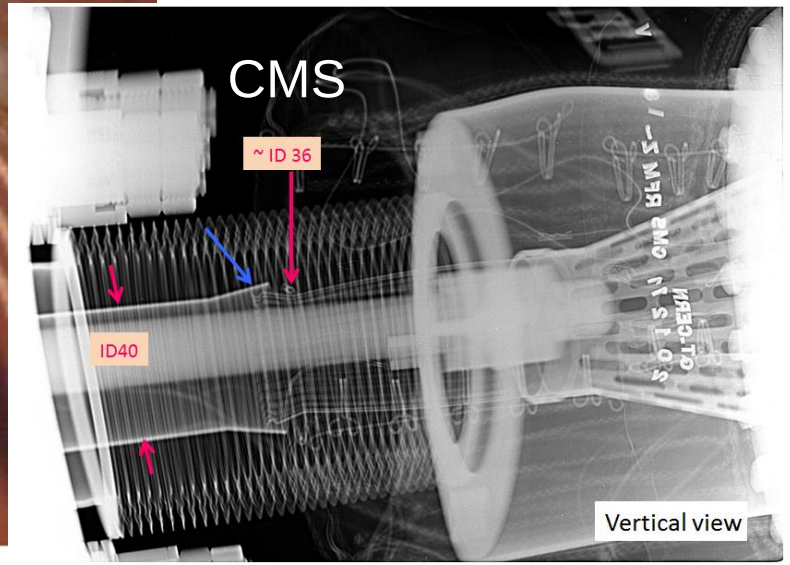


Vacuum, RF fingers 7R7, 27/8/2012

Synchrotron light monitor, removed 29/8/2012

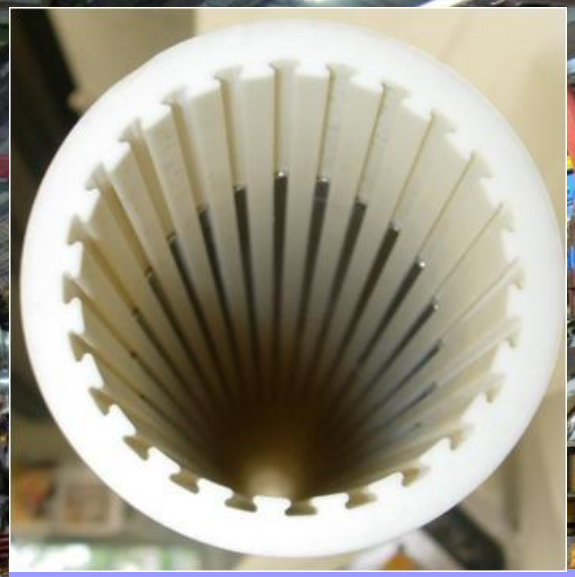


Injection absorber TDI beam screen

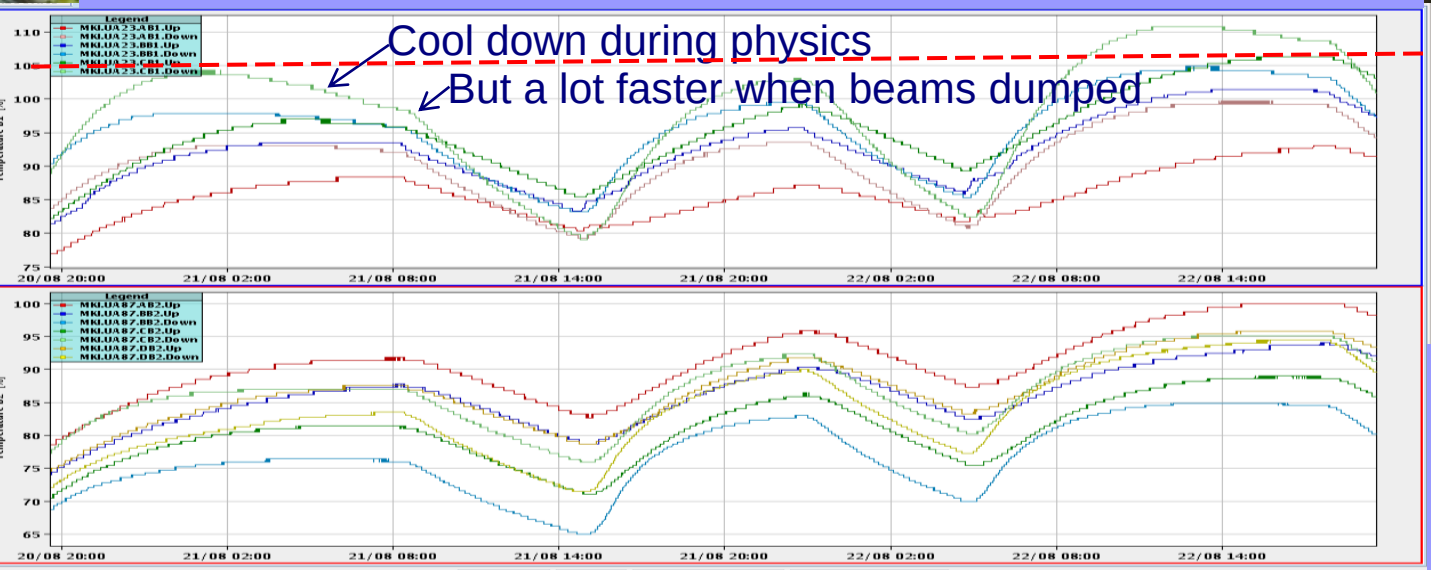


X-mas stop 2011/2012

Ferrite heating of injection kickers



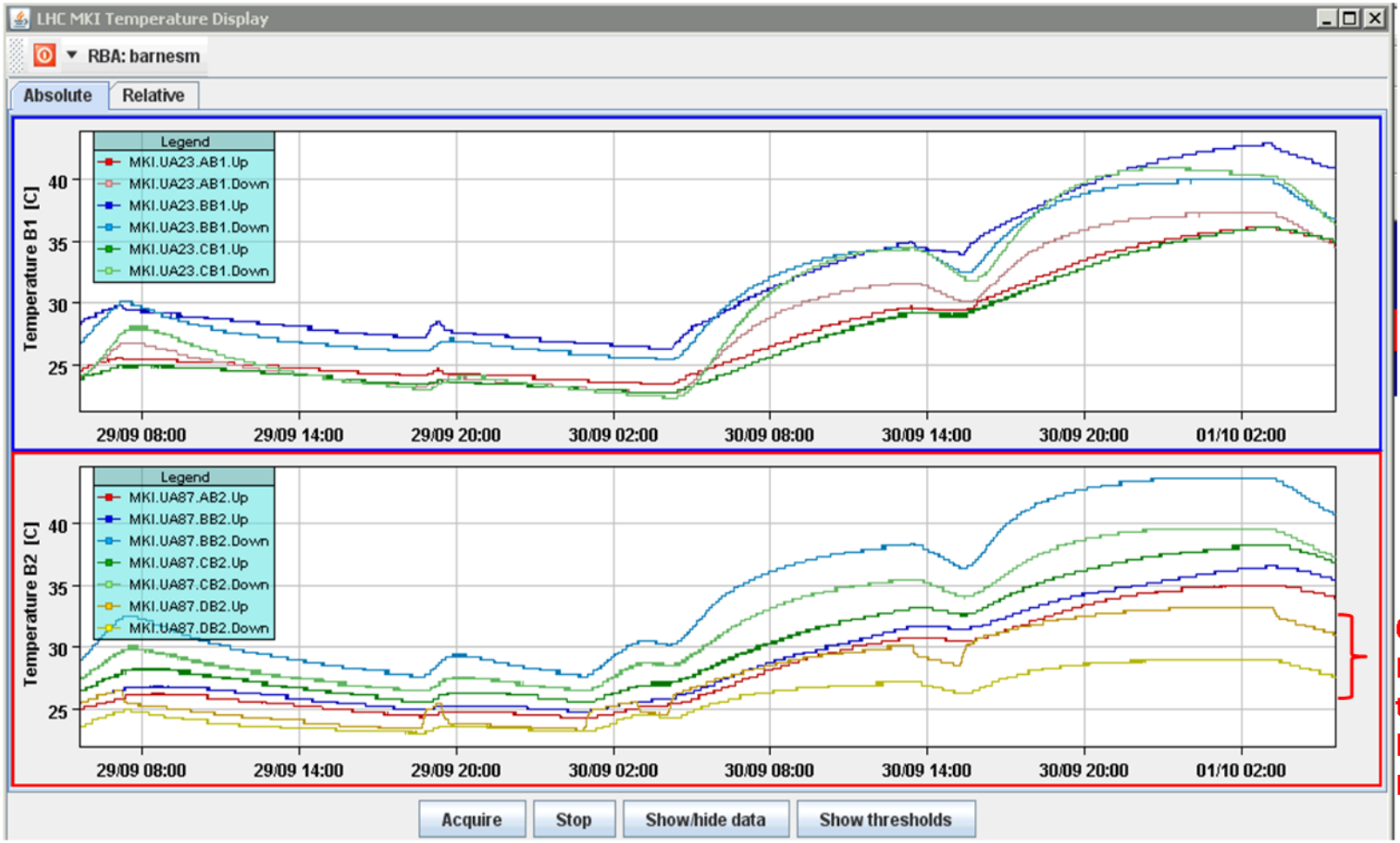
Injection kicker MKI ferrite temperatures



MKI-8D
Replaced 2 wks ago, more ‘stripes’. Full system exchange LS1

Temperatures of replaced kicker magnet

The "old" MKI8D had the highest measured temperature of all the MKIs, prior to TS3. Since TS3, the "new" MKI8D has the lowest measured temperature (it is estimated that the "old" MKI8D would have been at ~60°C, at 02:00hrs on 01/10/2012).
Note: measurements are not absolute, because of thermal contacts, etc.



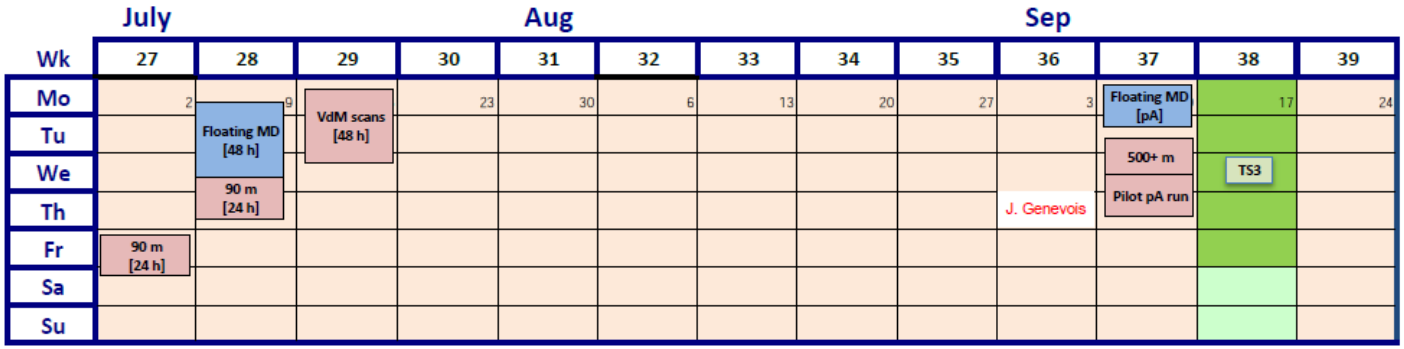
01/10/2012: MKI8D measur temperatures lowest of all MKI8s!

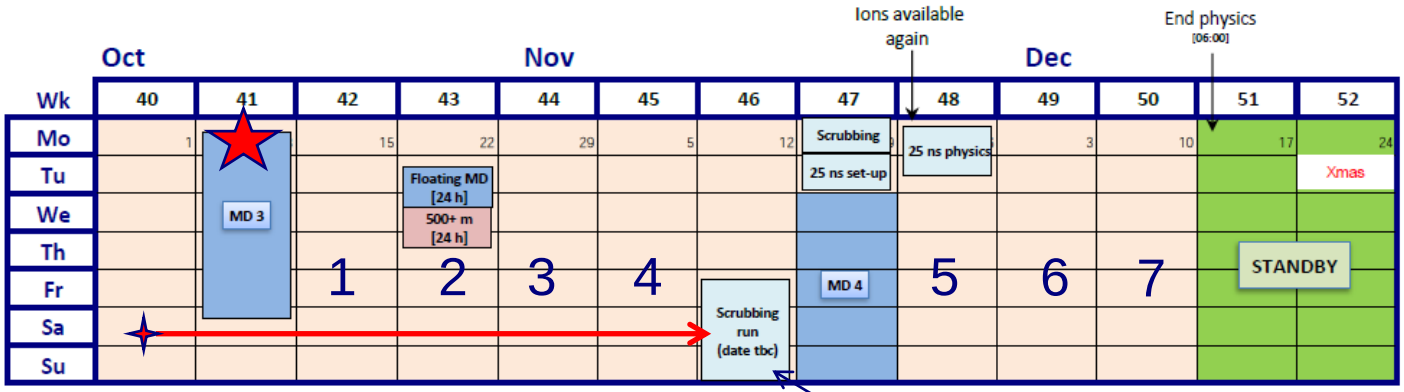
New after the Technical Stop #3

- Presently ramping up stable operation after third Technical Stop
  - Series of unlucky events following the TS but not related to TS
  - Performance over the last weekend beating records (L/24 h)
- New after the third Technical Stop
  - Injector SPS running with Q20 optics
    - Allows for more bunch intensity and smaller beams
    - Need to develop longitudinal blow-up at injection
    - Should profit in the weeks to come
  - Split beam process for going into collision
    - First collide head-on in ATLAS and CMS to stabelise the beam
    - Only then collide ‘off-set’ in LHCb
  - Replaced the mentioned injection kicker magnet
    - Additional ‘wires’ on ceramic chamber to reduce beam induced heating of the ferrites forming the yoke
    - New ceramic chamber needs to be vacuum conditioned with beam
    - Scrubbing test with 25 ns bunch spacing postponed by 6 weeks

Plan for 2012, remaining weeks

- Another 11 weeks of proton physics runs: 16 + 7 ≈ 23 fb^{-1}
  - 25 fb^{-1} if things go really well
- Mainly with 50 ns spacing, all parameters similar to present one
  - Don't expect peak lumi much above 8e33 cm-2s-1
- Some tests with 25 ns to explore this option for future operation





2012:
50 ns operation with some 25 ns tests

Scrubbing with 25 ns beam

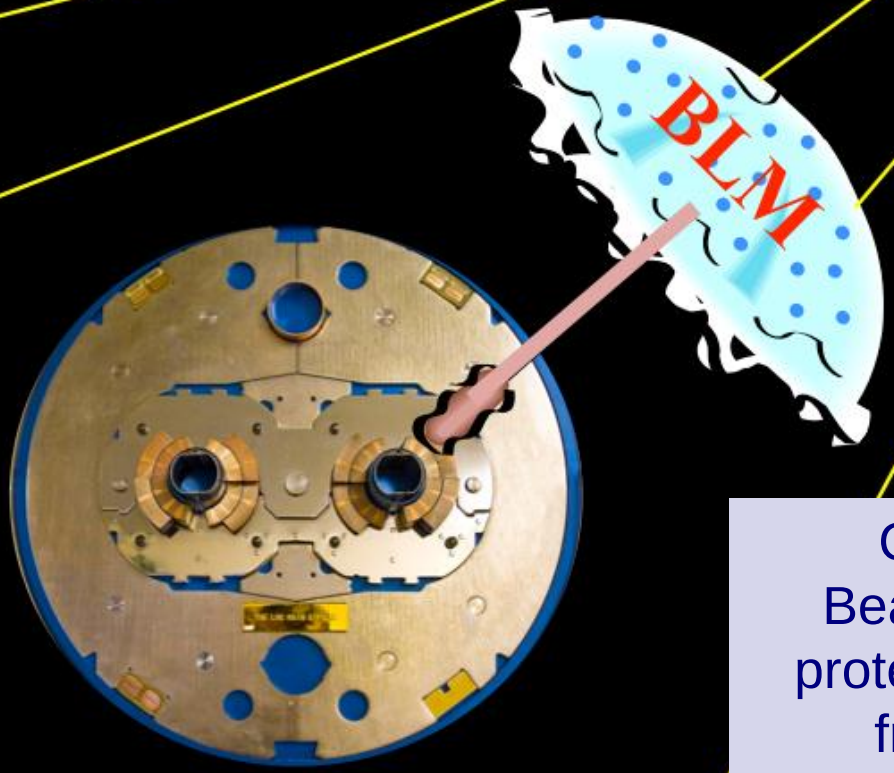
Long Shutdown 1

- End March 2013 – November 2014
- Consolidation for 6.5 – 7.0 TeV operation
  - Measure all splices and repair defective ones
  - Repair of magnet interconnects after 2008 event with new design (clamp, shunt)
  - Finish installation of pressure release valves
  - Exchange of weak cryo-magnets and DFBAs
  - Relocation of equipment to reduce radiation effects on electronics
  - Installation of collimators with integrated beam position measurement, injection absorbers refurbishment
  - Injection kickers reduction of heating
  - Experiments consolidation and upgrades
- Plus a lot of other work ongoing
  - Cryogenics, Quench Protection, electrical infrastructure, cooling & ventilation, Radio Frequency, beam dump absorber & magnet, change of dump switches (radiation), electron cloud mitigations …

Energy ≈ 6.5 TeV

- Magnets coming from sector 3 – 4 (2008) do not show degradation of performance
- Our best estimates to train the LHC (with large errors)
  - ~ 30 quenches to reach 6.25 TeV
  - ~ 100 quenches to reach 6.5 TeV
- Two quenches/day → 2 to 5 days of training per sector
  - With 100 quenches one expects 400 quench heater firings
- The plan
  - Try to reach 6.5 TeV in **four** sectors in March 2014
  - Based on that experience, we decide if to go at 6.5 TeV or step back to 6.25 TeV in March 2014

The future looks bright



Collimation with
Beam Loss Monitors
protecting the magnets
from quenching,
also at 7 TeV

Expected UFO's in 2015

Extrapolation to 7 TeV:

*BLM Signal/BLM Threshold is for arc UFOs about **20 times larger** than at 3.5 TeV.*

Arc UFOs resulting in dump:

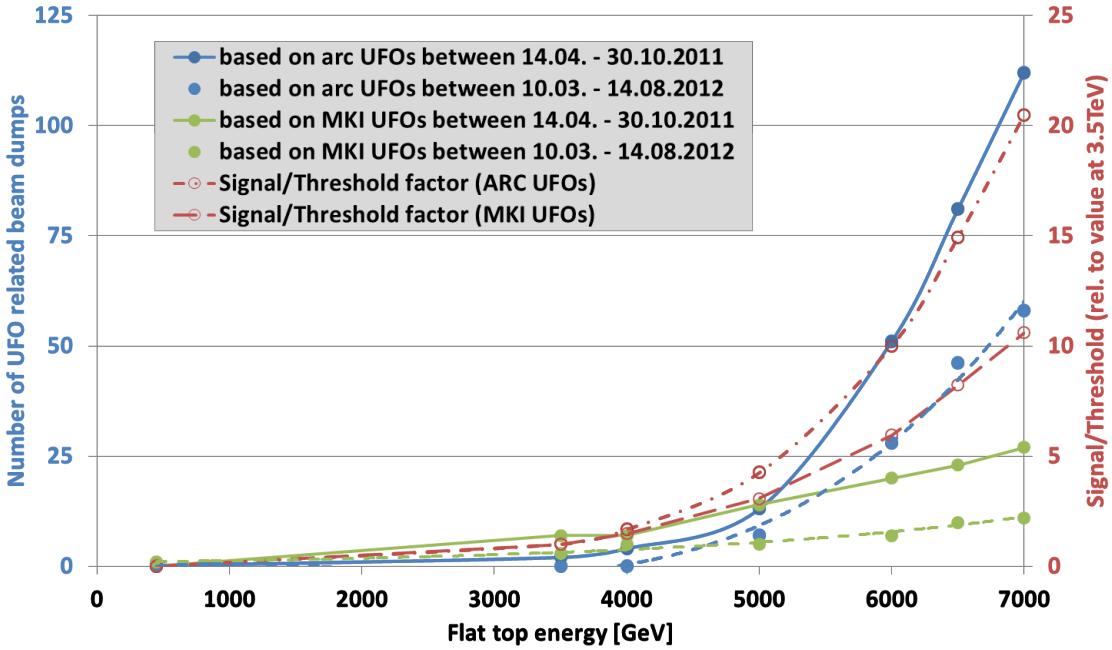
112 UFOs (2011 data)

58 UFOs (2012 data)

Additionally MKI UFOs:

27 beam dumps (2011 data)

11 beam dumps (2012 data)



Based on the applied threshold table from 01.01.2012 (for 2011 data) and 19.07.2012 (for 2012 data). 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. Several unknowns are not included: margin between BLM thresholds and actual quench limit, 25ns bunch spacing, intensity increase, beam size, scrubbing for arc UFOs, deconditioning after long technical stops.

UFOs seem to be worse with 25 ns (worse vacuum), but very limited statistics

Injector plans for small emittances

- Situation at end of **Long Shutdown 1**
  - LINAC4 being commissioned, proton operation possible
  - PS Booster for H- not yet available
- Possible improvements after LS1
  - SPS improvements: optics (Q20), RF, impedance
- Major upgrades within LIU project, including the increase of the PS Booster – PS transfer energy from 1.4 TeV to 2.0 TeV **only in Long Shutdown 2**
- Low emittance option after LS1, to be confirmed
  - Risk due to strongly increased energy density
  - Beam dynamic effects: blow-up do to IBS
  - Noise induced emittance growth can become important

Potential Performance after LS1

- Determined by the performance of the injector chain
- Different collimator scenarios, not detailed here
- LHC Injector Upgrade (LIU) fruits after LS2
- Straight gain in Peak Lumi due smaller beams (energy, β*)

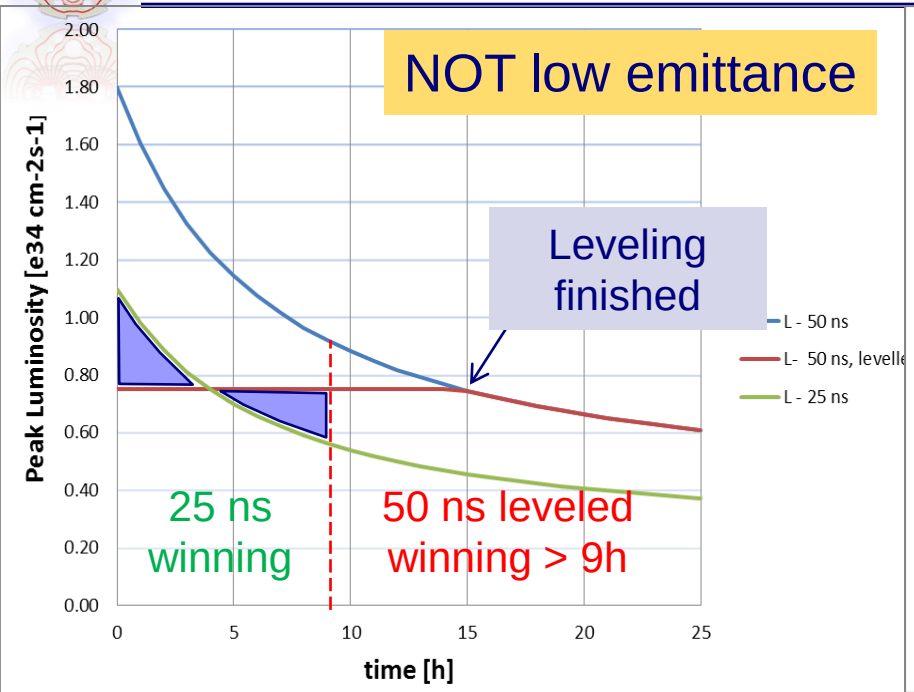
	Number of bunches	β* [m]	Half X-angle [μrad]	Ib SPS	Emit SPS [um]	Peak Lumi [cm^{-2}s^{-1}]	~Pile-up	Int. Lumi [fb^{-1}]
25 ns	2800	0.50	190	1.2e11	2.8	1.1e34	23	~30
50 ns	1380	0.40	140	1.7e11	2.1	1.8e34 β* level	81 β* level	?
25 ns low emit	2600	0.40	150	1.15e11	1.4	2.0e34	48	52
50 ns low emit	1200	0.40	120	1.71e11	1.5	2.2e34	113 β* level	?

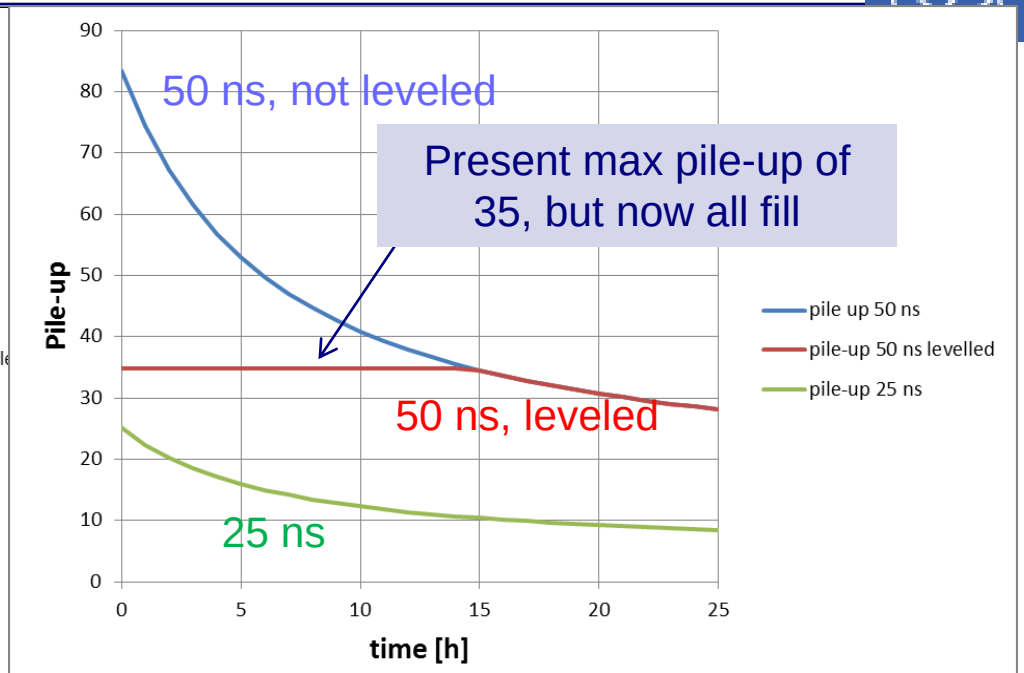
Presently at 4 TeV, β = 0.6 m, half X-angle 145 μrad*

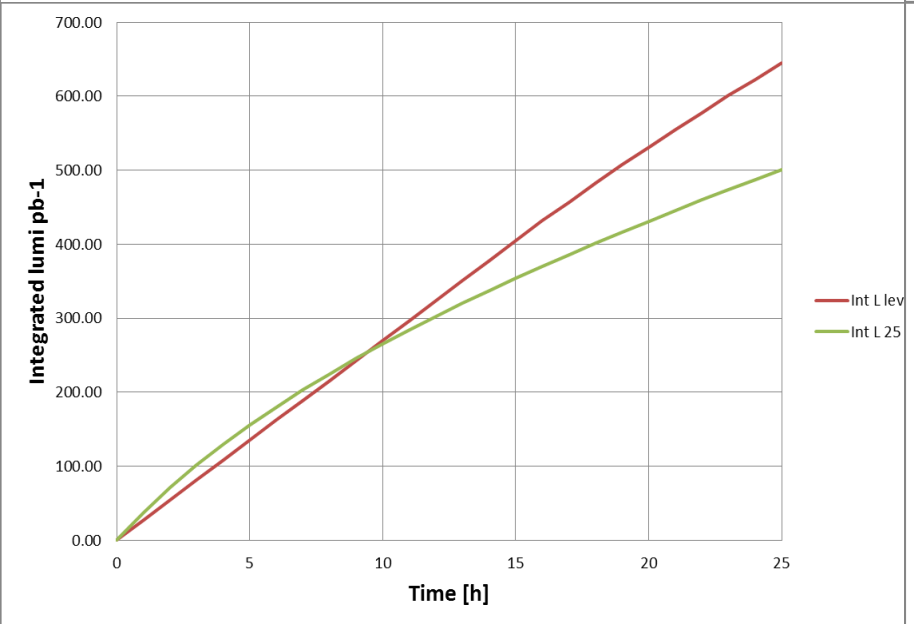
50 ns vs. 25 ns (not low emittance)

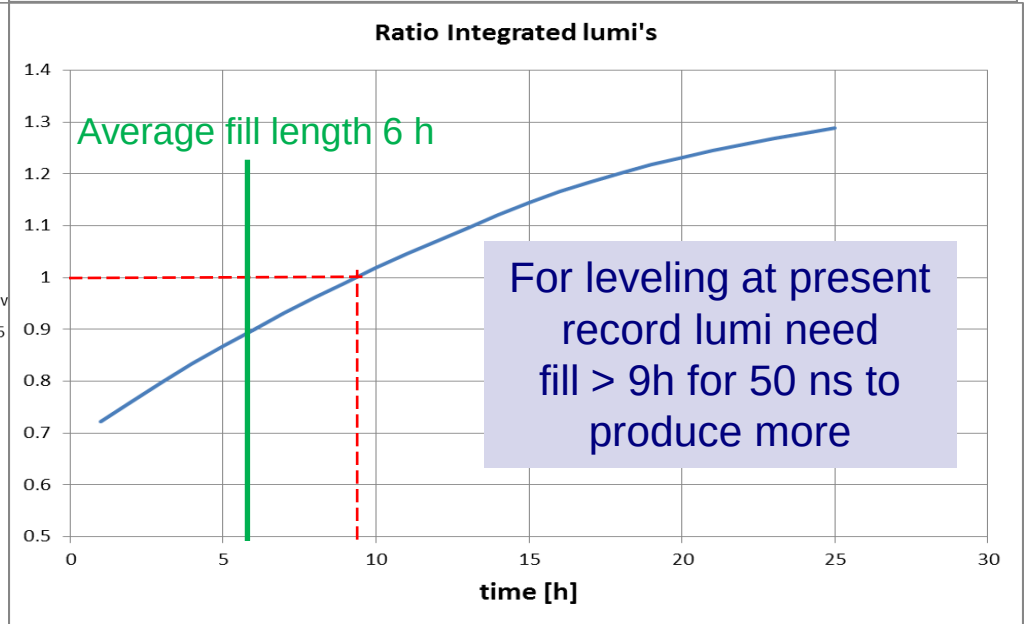
- 50 ns operation, 1380 bunches
  - Best known. Small emittances from the injectors, high lumi
  - Need to vary the beta* during the fill to limit the pile-up in the beginning of the fill (or most of the fill, depending on leveling)
    - First tests of beta* leveling look promising
- 25 ns operation, 2800 bunches
  - Naturally low pile-up without leveling. Obligatory for after LS2
  - Also obligatory to profit from low emittances from injectors
  - Possible problems
    - Electron cloud: stability, emittance growth, vacuum, cryogenics load
    - RF heating: larger total beam current and higher frequencies
    - More long range collisions, long range beam-beam effect
    - UFO rate seems to increase with 25 ns bunches
  - Will need more operational experience
    - Start tests after (delayed) scrubbing run 5 weeks

Beta* leveling at 7.5e33 cm-2s-1









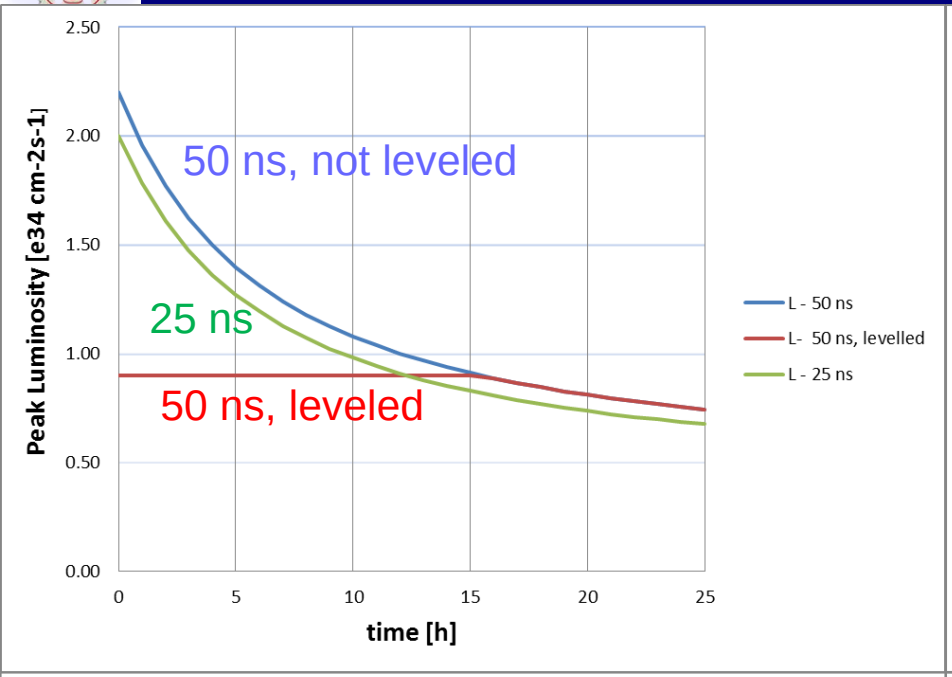
Beta* Leveling (no low emittance)

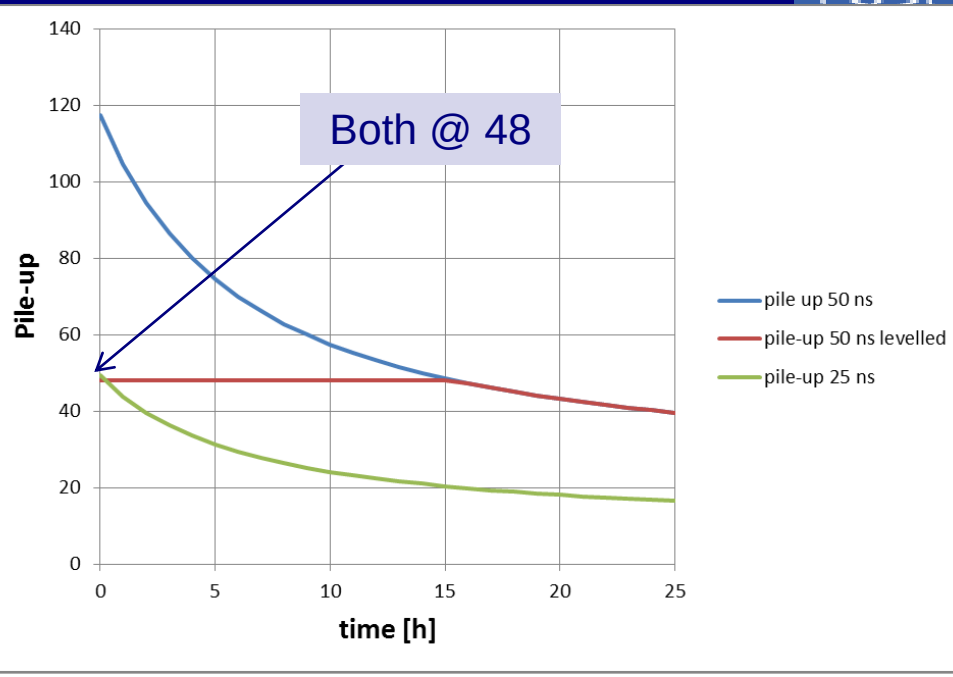
- The theoretical 'break-even' time depends strongly on the allowed pile-up (=peak lumi)
- Of course, results also depend strongly on assumed lumi life time, initial lumi's etc. Numbers are approximate.
- The usefulness of such calculations depends first and for all on the length of the fill, how easy it is to work with 25 ns or 50 ns beams at 6.5 TeV

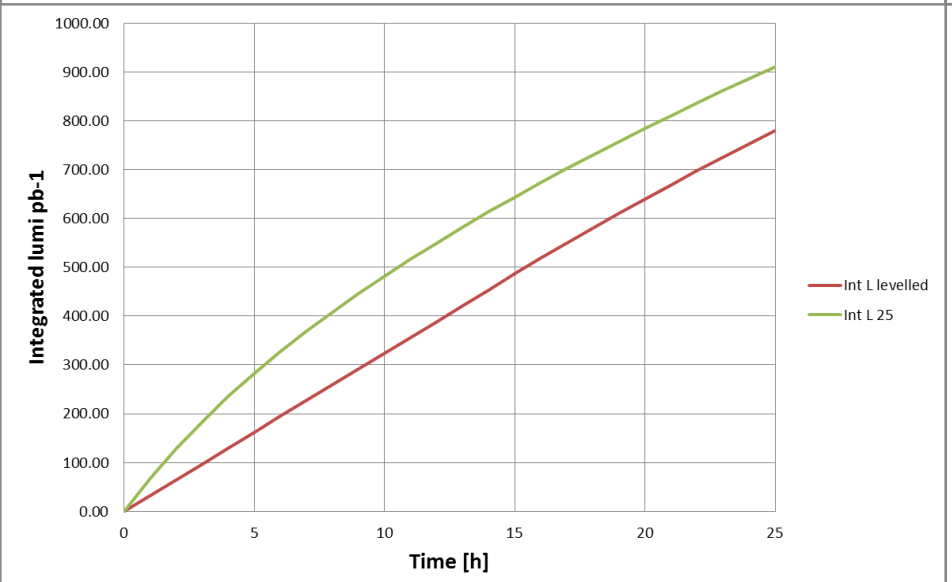
Peak lumi for β* leveling	Max pile-up	Break-even 50 ns vs. 25 ns
1e34	46	2 h
7.5e33	35	9 h
6.5e33	30	15 h

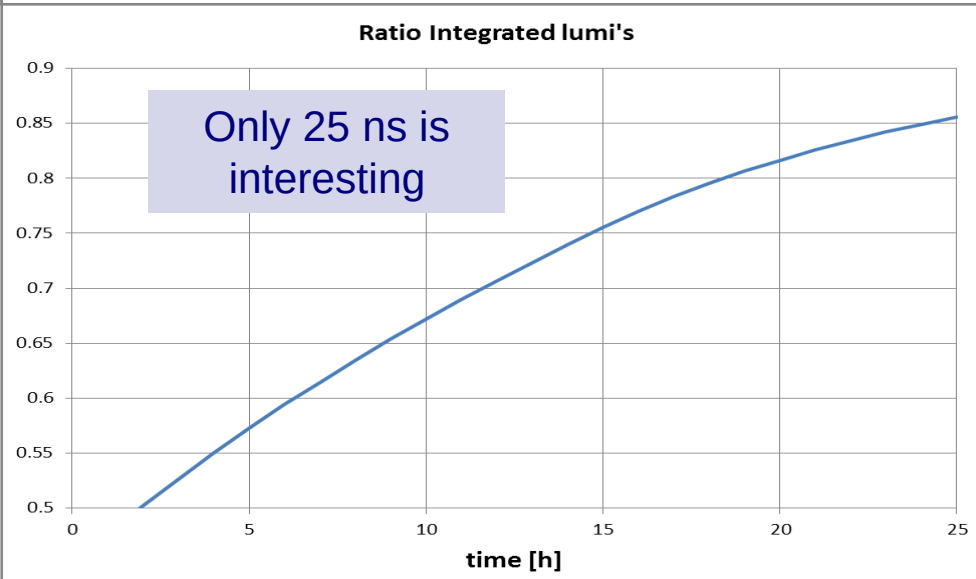
Remember that the present average fill length is 6 hours!

Low emittance option from injectors









Conclusions

- 2012 is well on the way to be a good production year
  - Reached the official target of 15 fb^{-1} for the year
  - Presently 16 fb^{-1}, personal forecast 23 fb^{-1} for the year
- High luminosity limits are showing up
  - Beam stability with high bunch currents
  - RF-heating, damaging equipment or limiting operation
  - Radiation affecting electronics resulting in beam dumps
- In a few weeks: scrubbing and first tests with 25 ns operation
- Post LS1, 2015, physics
  - Beam energy around 6.5 TeV
  - Operation with both 25 ns and 50 ns are valid options
  - 50 ns will need beta* leveling to reduce pile-up
    - Experiments will need to define the tolerable pile-up
    - First operational tests of β^* leveling are encouraging
  - 25 ns has many unknowns in its operation but needs to be explored, also to prepare for post LS2
    - Only way to profit from small emittances from the injectors, also in 2015