How to reach the required availability of LHC to reach the required level?

Squeezing out the ab^{-1}s

Mike Lamont

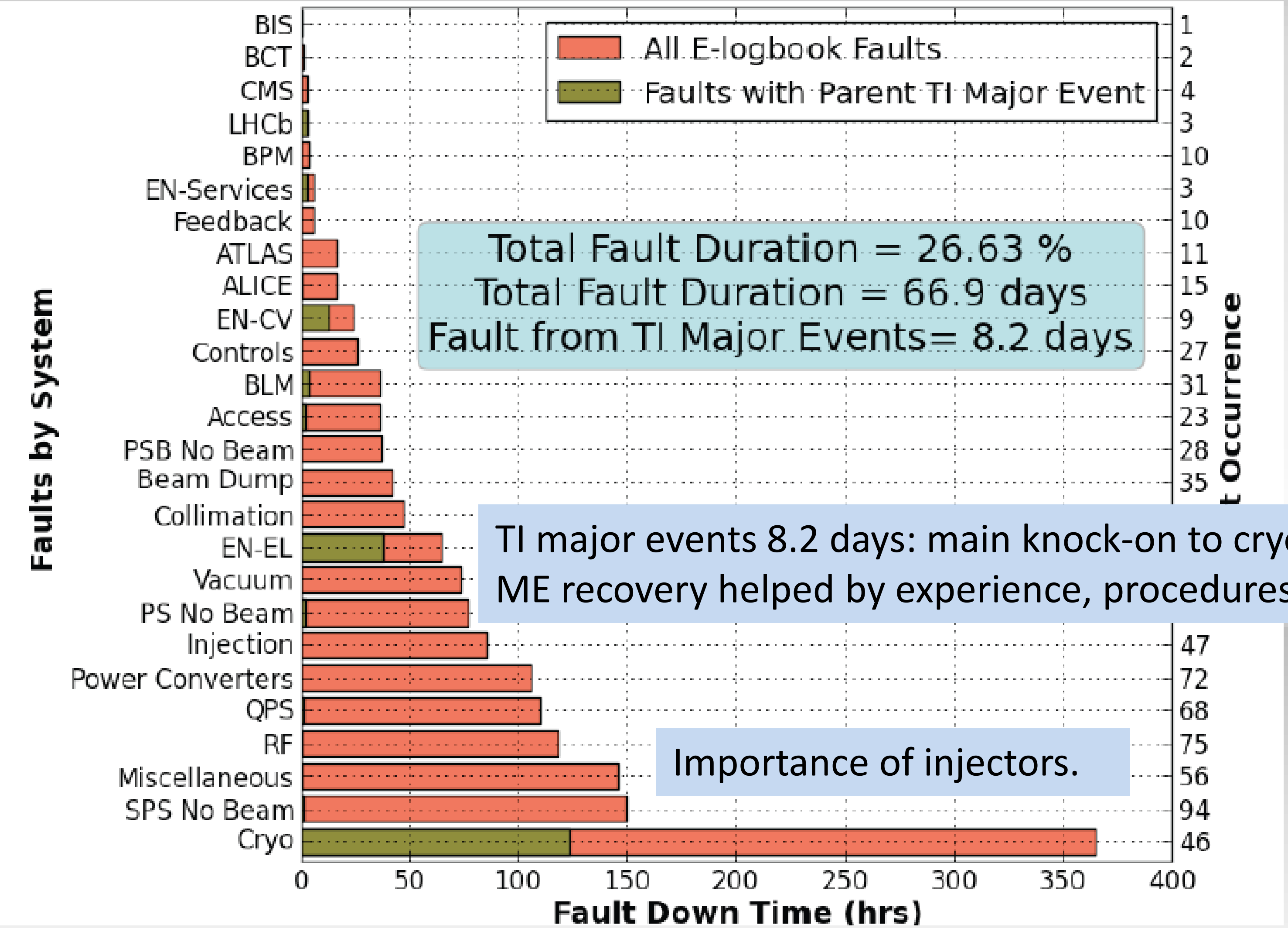
30th October 2013

Thanks for input: Serge Claudet, Markus Brugger, Andrea Apollonio, Benjamin Todd, Jorg Wenninger, Daniel Wollmann, Markus Zerlauth

Availability

- Scheduled proton physics
  - Does not include initial commissioning, special physics runs, ions, MD, technical stops etc.
  - Does include intensity ramp-up
- **Scheduled proton physics time minus fault time**
  - Edge effects (recovery from access, precycle) tend not, at present, to be included in the fault time
- One could include special physics, ions, MD but we single out proton physics because we eventually want to make luminosity predictions

Recorded fault time 2012



TI major events 8.2 days: main knock-on to cryogenics
ME recovery helped by experience, procedures, buy-in..

Importance of injectors.

1411 hours 58.8 days => 71% availability for a 200 day physics run

Anatomy of a random fault

06:01	Beam dump - QPS trigger – trip of RQX.L8 Quench – lost cryo conditions for IT.L8	DIAGNOSIS
06:29	Call MP3 piquet – he will come and have a look	TRAVEL DIAGNOSIS
10:28	Preparing access for QPS – reset on RQX.L8 – switching off sector 78	ACCESS
	Access	INTERVENTION
12:21	Cryogenics conditions back	RECOVERY
12:38	Start pre-cycle	RECOVERY
13:44	Change mode to injection probe beam	

25th May 2012

The overhead of a fault

- Besides the obvious cost to fix fault:
- Faults generally dump the beam - for the big ones this is almost incidental
- But for the rest the cost is
  - Premature dump of fill
  - Diagnosis of the problem
  - Travel/Intervention – switch off, radiation survey, access
  - Recovery – things don't like being switched off (knock-on faults), precycle…

Clear message: fixing the fault is only part of the problem – overheads and the pain of losing a fill (in ramp, in squeeze, in physics)…

Premature dumps 2012

Dump Cause	#	Dump Cause	#
Beam: Losses	58	BPM	8
Quench Protection	56	Operations: Error	6
Power Converter	35	SIS	4
Electrical Supply	26	LBDS	4
RF + Damper	23	TOTEM	4
Feedback	19	CMS	3
BLM	18	BCM	2
Vacuum	17	Water	2
Beam: Losses (UFO)	15	Access System	2
Cryogenics	14	LHCb	2
Collimation	12	ALICE	2
Controls	12	Beam: Orbit	1

External
Beam
Equipment
Operations
Experiment

Worth considering in some detail…
What will still be an issue in the HL era?

Ben Todd et al

Premature dumps

- Our number one cause of lost fills was in fact not fault related, somewhat self-inflicted:
  - Tight collimator settings, bunch intensity…
- Number 2 & 3 (QPS and power converters)
  - Huge distributed systems
  - Significant fraction to Single Event Effects (10% of total dumps)…

7 TeV turnaround

Turn around: time from stable beams to stable beams
Physics efficiency: fraction of schedule physics time in stable beams

Table 3. Breakdown of turn around with estimated minimum times shown

Phase	Time [minutes]
Ramp down/pre-cycle	60
Pre-injection checks and preparation	15
Checks with set-up beam	15
Nominal injection sequence	20
Ramp preparation	5
Ramp	25
Squeeze	30
Adjust/collisions	10
Total	180

Access or lost of magnetic elements results in a full or partial precycle
Will be of the order of an hour – dominated by decay of 1Q quad circuits

Turn around time

2h8m24s and practice (once) and in principle
Average in 2012 5.5 hours   What's going on?

Nominal cycle

Inject, ramp, squeeze,
Ramp-down/precycle

Test ramps & squeezes

Transfer optimization
Injector optimization
Injection wrestling

Unrecorded faults
(fixed on the fly)
Problem resolution

Fault recovery
Precycle after faults

Fills lost in the ramp
and squeeze

A case for a more detailed break-down: "TEST", "LOST"….

Lost fills before stable beams

- Besides the usual mix of equipment faults exposed to some other problems.
- Noticeably in 2012:
  - Orbit feedback – resolution time short
  - Instabilities and beam loss in squeeze and adjust crucified by losses (32 dumps)
  - Also a lot of test ramp, squeeze & adjusts
- Does it matter?
  - 58 fills lost to losses – say 180 hours – 7.5 days – 1.3 fb^{-1} maximum – insignificant on the grand scale of things
  - Probably worth it for the instruction
  - Clearly unacceptable in HL-LHC era – operationally robust solutions required

Fill length etc.

$$PE = A \times SPT - N_f T_{turn}$$

$$N_f = \frac{SPT \times A}{T_{fill} + T_{turn}}$$

$$PE = SPT \times A\left(1 - \frac{T_{turn}}{T_{fill} + T_{turn}}\right)$$

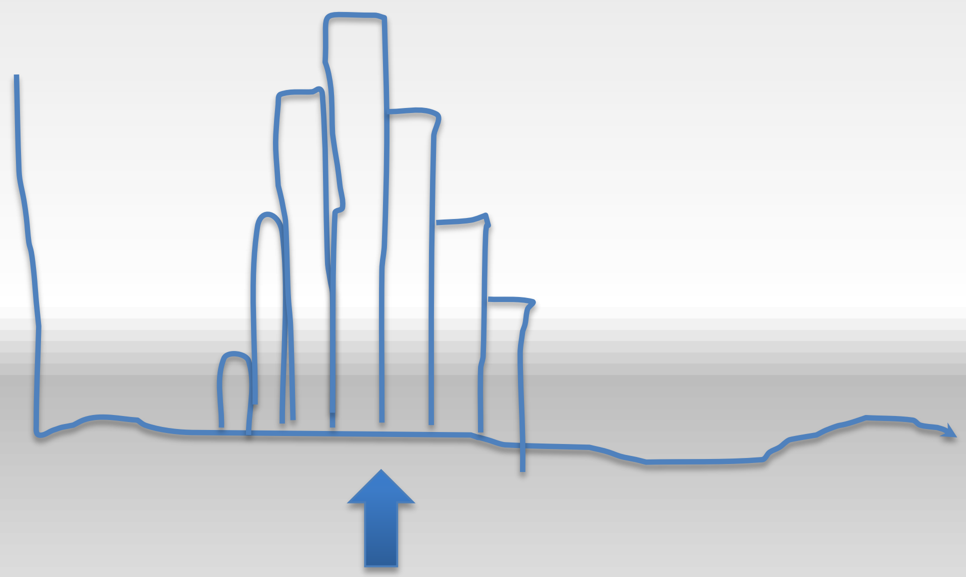
- Knock off availability
- Average turn around, average fill length in the time that's left
- Knock off number of fills times turn around to get time left over for physics
- Call this Physics Efficiency
- How much luminosity can you produce in this time?
  - It is not amount in average fill length*number of fills because…

Table 5. Overall operational performance 2012

Scheduled physics time	201 days
Availability	71%
Average fill length	6.0 hours
Average turn around	5.5 hours
Mean luminosity delivery rate	12.97 pb^{-1}/hour
Peak luminosity delivery rate	≈ 25 pb^{-1}/hour

Average fill length

- 6 hours sounds pretty good but there’s a difference between

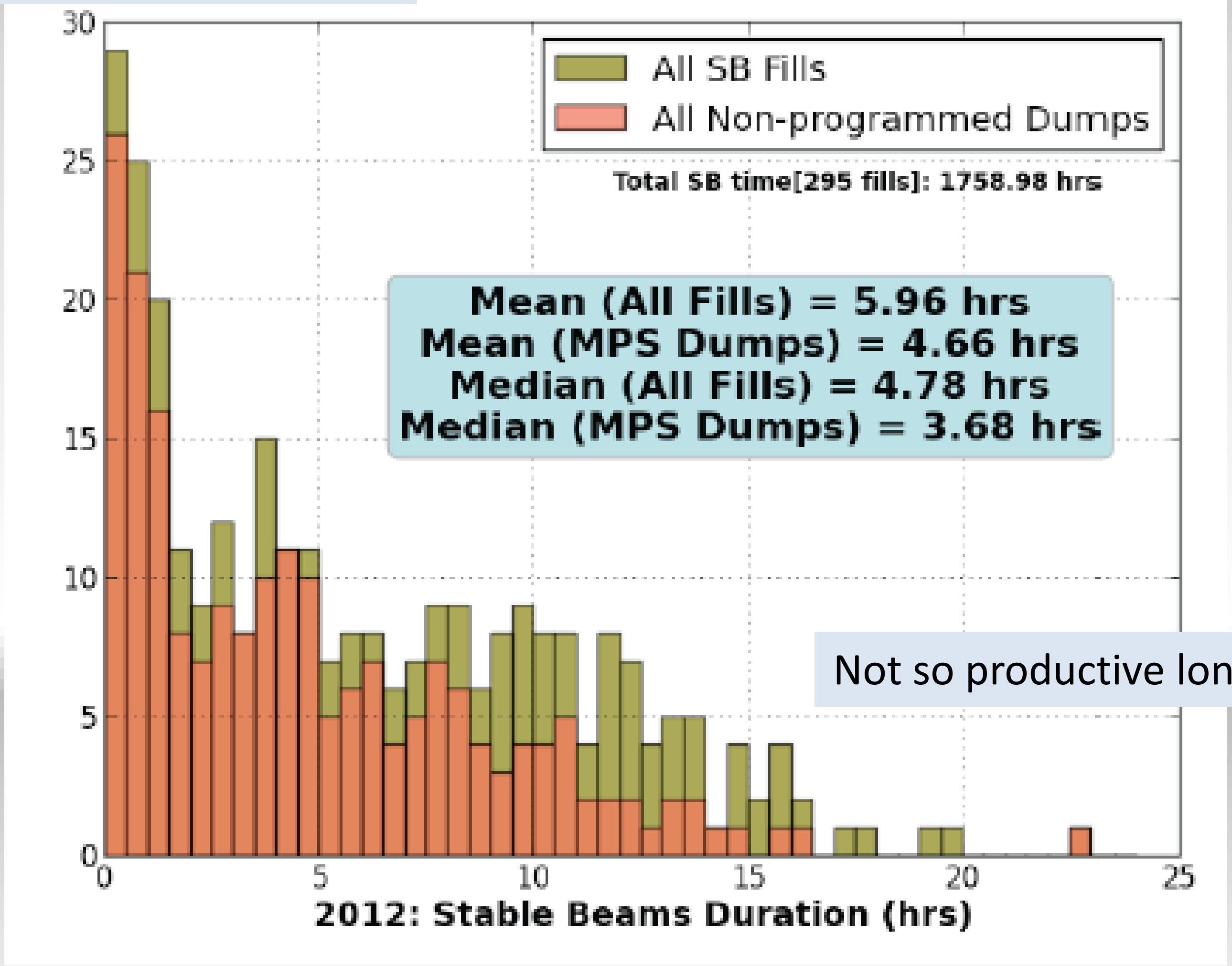


6 hours

and…

Fill length 2012

Lot of short unproductive fills



Not so productive long fills

70% fills terminated by fault

Lost SB first two hours

Peak losses in collimator regions
Peak losses in IRs
Peak beam loading

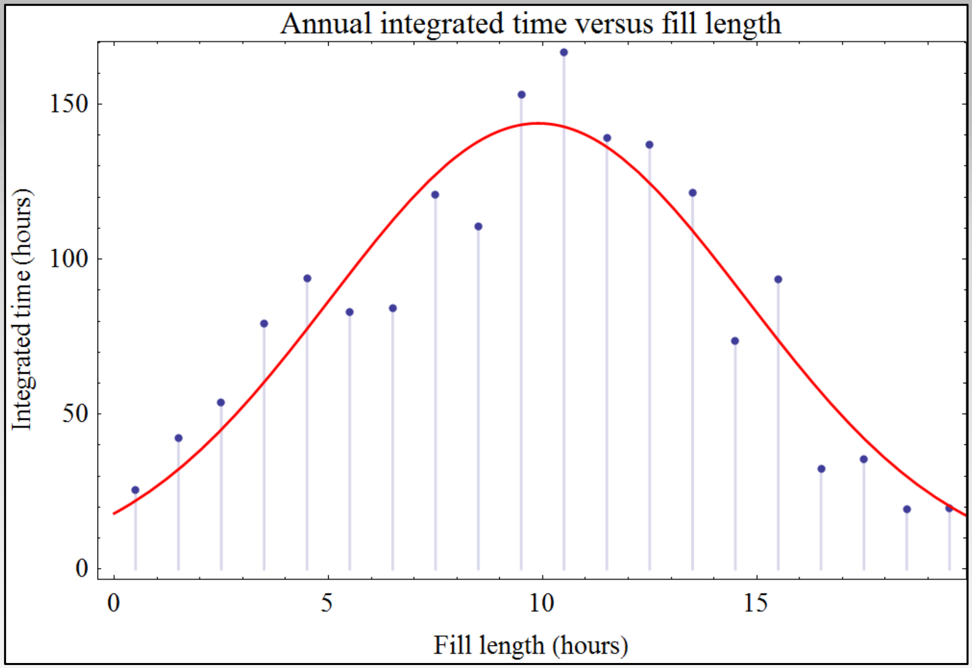
Which with levelling we're planning to maintain for as long as possible

- Lots of short unproductive fills
- Lots of extra turnarounds
- 2012 – reasons:

System	
Power converters*	17
Tests	10
QPS*	8
Vacuum	8
UFO	6

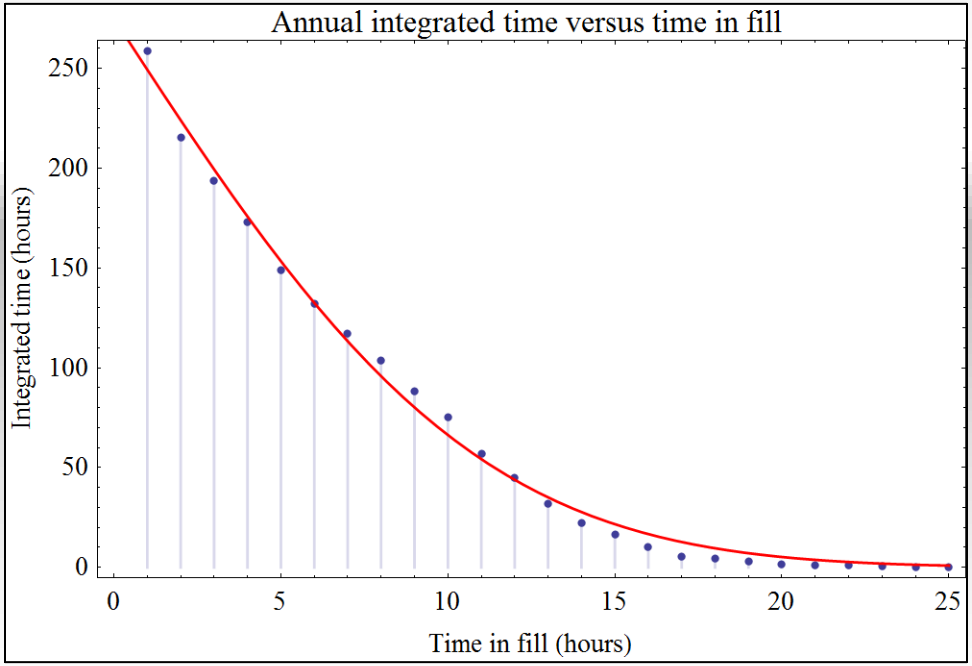
* Including SEUs

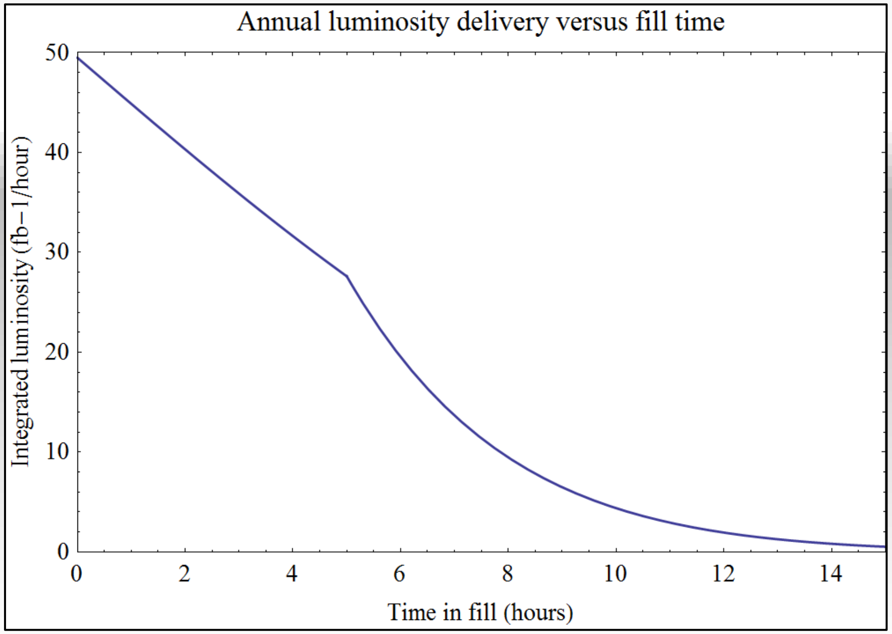
Required availability?



- 2012 fill time distribution naively scaled to 160 days (=> same availability, turnaround)
- 5 hours levelling at 5 x 10^{34} $cm^{-2}s^{-1}$
- 5 hour luminosity lifetime thereafter
- Dump fill after 13 hours

~210 fb^{-1}

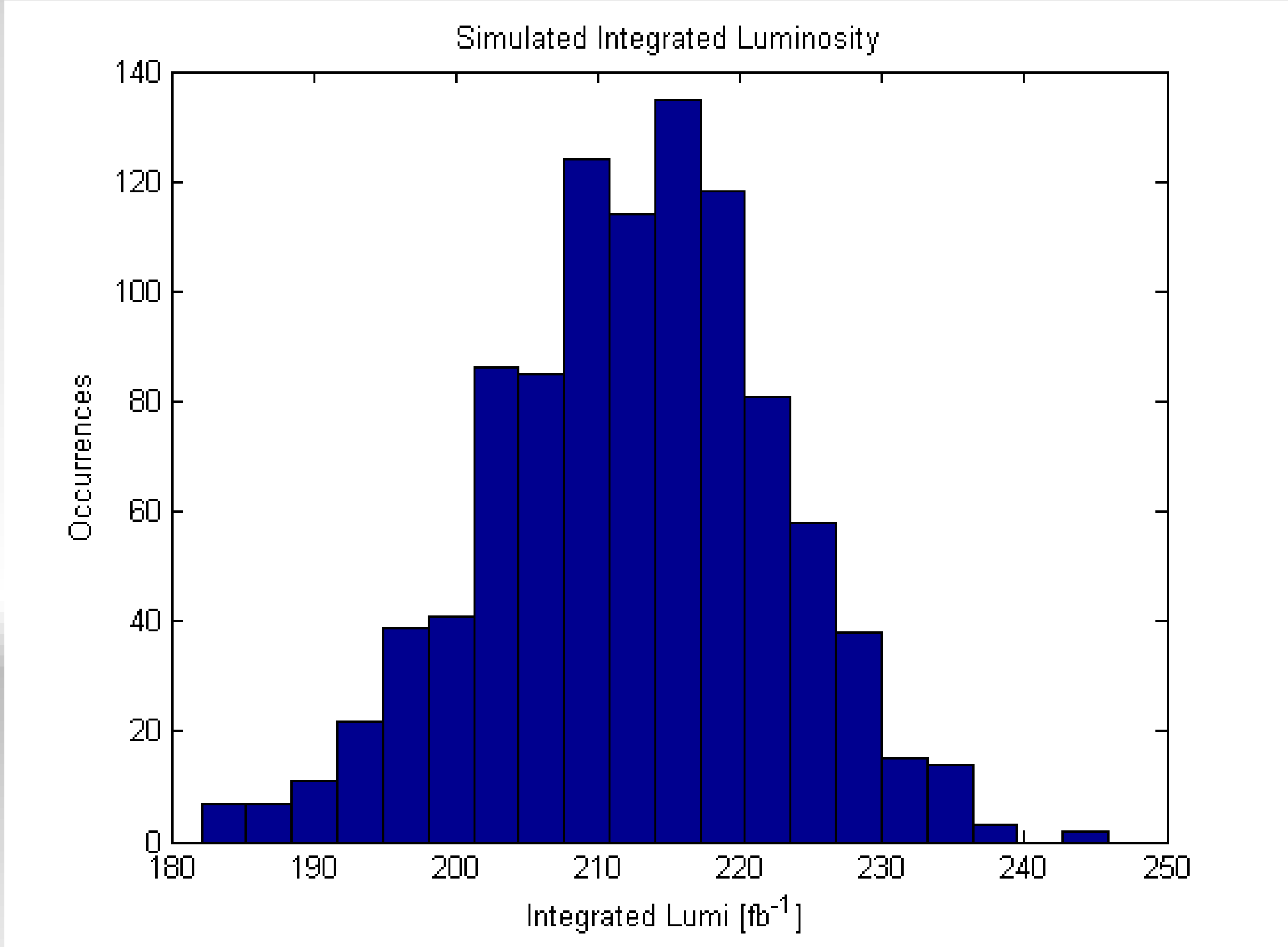




Andrea Apollonio, Daniel Wollmann

High-Luminosity LHC and Availability

- Extension of 2012 figures to HL-LHC (Full HL)



AVG SIMULATED:

- 213 [fb^{-1}] (*reference*)

Only the average turnaround time is increased from 5.5 to 6.2 h

Simulated years of operation: 1000, ~1.5 min Simulation Time

Simulated impact on Integrated Luminosity of SEUs, UFOs, quenches: 180 – 220 fb^{-1}

Identified some main areas:

- Reduce number of faults (HW & SW)
- Reduce time to fix faults, reduce intervention times, reduce number of interventions
- Reduce number of beam induced faults
- Reduce mean turn around time (besides reducing number of unwanted dumps before stable beams)

WHAT CAN BE DONE?

What has been done

- Clear that the groups involved have been working hard to target areas of improvement:
  – Cryogenics, QPS, power converters, vacuum, BLMs, RF, collimation, injection, LBDS, feedbacks, controls, TI…

- Major combined effort to alleviate the serious problem of single event effects – R2E

- With considerable success

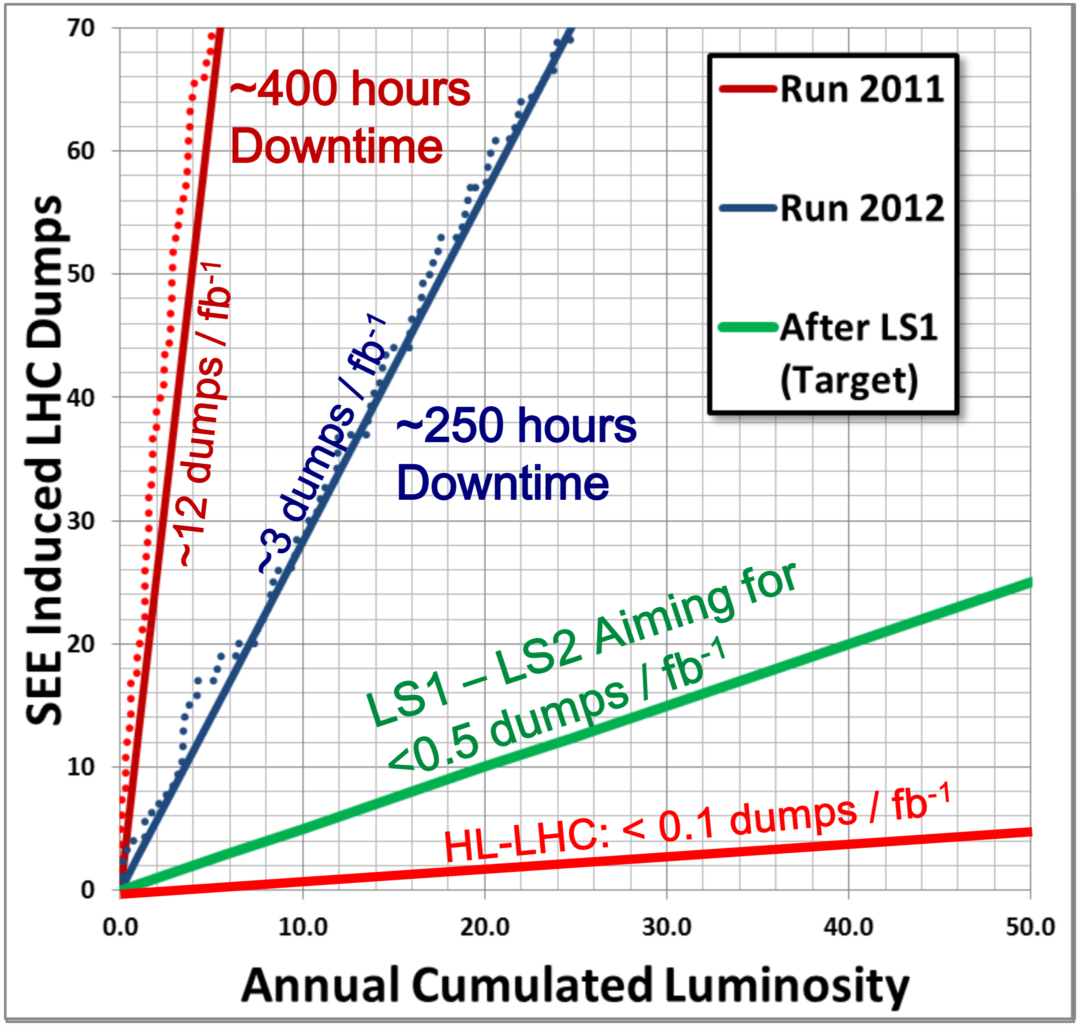
By category

August 2011 – availability brainstorm

Cause	Category	System effected	
Dumped by SW interlock on BLM HV channel (1.3e11/bunch)	BLM		FIXED
CMS BCM2	CMS		FIXED
CMS BCM2	CMS		FIXED
Electrical network glitch	EL		SH
Electrical network glitch	EL		SH
Electrical network perturbation	EL		SH
Electrical network perturbation	EL		SH
El network glitch	EL		SH
Losses 83s RS on TCSG.A6L7.B1	OP		SH
RCBXH.R1 tripped, PC changed	PC		SH
Loss of cryogenic conditions in Sector 34 – PLC crash	PLC	CRYO	
Lost cryo compressors in Pt8 PLC problem	PLC	CRYO	
QTF trip: QFB versus QPS	QFB		FIXABLE
QPS trigger, trip of RQTL7.L7B1	QPS		
QPS – WorldFIP/UPS/?	QPS		
QPS communication problem	QPS		
QPS RCO/RCD/RCS cross-talk S56	QPS		
False trip of 600A QPS RQTL7.R7B1.	QPS		
RF Module trip	RF	RF	
RF - klystron	RF	RF	
RF klystron vacuum	RF	RF	
RF interlock on HOM line 2 B2	RF	RF	
Valve controller IT.R1 – possible SEU	SEU	CRYO	
Controller IT5 Possible SEU	SEU	CRYO	
DFB valve controller (SEU)	SEU	CRYO	
Problem on valve on DFB in arc 8.1 Possible SEU	SEU	CRYO	
QPS trigger RCBXV3.R1 (SEU?)	SEU	QPS	
Collimator crate UJ16 (SEU?)	SEU	COLL	
Cryo lost S56, SEU on a thermometer at a current lead	SEU	CRYO	
Cryo – R1 24V supply Possible SEU	SEU	CRYO	
Cryo valve PROFIBUS (UJ76) (SEU?)	SEU	CRYO	
Cryo valve PROFIBUS (UJ16) (SEU?)	SEU	CRYO	
UFO 31L8 on B1	UFO		SH
Mini UFO in triplet R1 from B1	UFO		SH
Vacuum spike 4L8	VAC		CON
Vacuum spike 4L8	VAC		CON
Vacuum spike R2	VAC		CON

LHC R2E: Past/Present/Future

R2E SEE Failure Analysis



- **2008-2011**
  - Analyze and mitigate all safety relevant cases and limit global impact
- **2011-2012**
  - Focus on long downtimes and shielding
- **LS1 (2013/2014)**
  - Final relocation and shielding
- **LS1-LS2 (2015-2018)**
  - Tunnel equipment and power converters

Courtesy Markus Brugger

Availability/performance – R2E

- Vitally important job so far
  - including test facilities, external companies…
- Extremely important for the HL-LHC era that this effort continues:
- Long term strategy includes:
  - superconducting links, with feedboxes, main power converters on the surface (IR1,5-UJ,7-RR)
  - 120 A, 60 A (exposed in tunnel)
  - power converter R&D for rad tol, then decision about what else to bring up
  - QPS and cryogenics that remains in tunnel and RRs - rad-tol solutions
- Some 10,000 units in the tunnel – robust solution required for both radiation and no radiation – stringent demands on MTBF
- Beam instrumentation – targeted rad-tol design, upgrades etc.

Worry about knowledge continuity through LS3 (rad tol design etc.)

What will have been done

2012 only partially representative

- Another ~8 years of debugging, consolidation, understanding and flushing out of system problem
- ~8 years of beam dynamics, understanding, control, instrumentation, diagnostics, combat tools at 6.5 to 7 TeV with 25 ns beam
- Certainly to be quantified in the next 8 years or so
  - Higher energy operation: power converters, cryogenics nearer limits, beam induced quenches
  - Training – de-training after thermal cycling
  - E-cloud, scrubbing, conditioning, de-conditioning after LS
- UFOs
  - Conditioning, thresholds adjustment, clean MKI…

Availability - cryogenics

- We did: 90% 5 wks in 2009, 90% in 2010, 89% in 2011 (SEU), 95% in 2012-13. This includes MDs and physics, with typical 260 days/year
- Our forecasts would be for post-LS1: 90% in 2015, 92% in 2016, 95% in 2017 considering:
  - Correct understanding of cryo process & equipment (now well tuned and with procedures), experienced staff and shift organisation
  - "quick" fixes will be required, but not often and with pre-defined protocols, therefore with minor impacts on integrated availability
- Considerations for post-LS1 beam operation parameters w.r.t "reduced parameters pre-LS1:
  - for sure increased heat loads, in particular higher "dynamic" (resistive-Ri2 and beam related) w.r.t to static, but still in the range of "nominal mode w.r.t design" and below "installed capacity“

Baseline target 95% for HL-LHC era

NB: 3 additional facilities

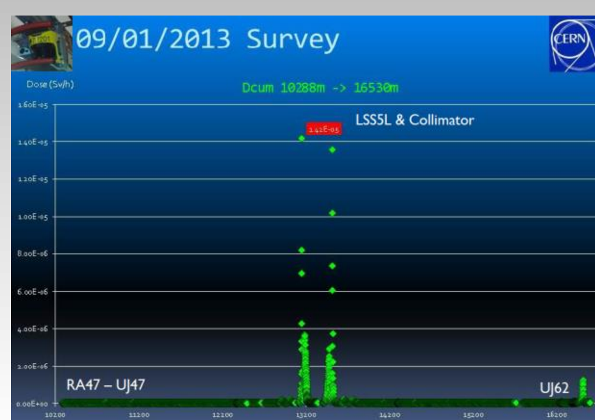
Serge Claudet

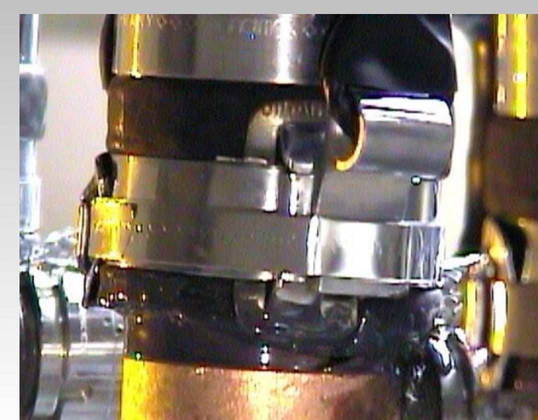
Less faults

- More rigorous preventive maintenance – technical stops to allow said.
- Sustained, well-planned consolidation of injectors
- Plant redundancy e.g. back-up cooling pumps, fully reliable UPS
- Updated design for reliability, targeted rad-tol, robust, redundant system upgrades given experience and testing

Reduced fault overhead

- Better diagnostics
- Less tunnel interventions
  - Remote resets, redundancy, remote inspection
  - Stuff on surface, 21st century technology
- Faster interventions
  - TIM radiation surveys, visual inspections etc.





Operational efficiency

- Fully and robustly establish all necessary procedures required in HL era
- BLM thresholds completely optimized across all time scales
- Compress the cycle e.g. Combined ramp & squeeze, reduced injection time (dedicated – singe batch injection)
- More efficient and fully optimized set-up in place:
  - Injectors
  - Transfer & injection
  - Collimators, squeeze, optics,
  - Less test ramps, squeezes, adjust
  - Optimum fill length
  - Pre-cycle:, optimized pre-cycles/dynamic use of model
- Upgraded system performance: e.g. 2Q triplet power supplies

Worry about…

It will be a mature system but with major upgrades operating with unprecedented bunch and beam intensities.

- Aging, long-term radiation damage, robustness of systems such as QPS, power converters (that remain in tunnel)
- Intervention overheads:
  - Radiation: cool-down requirements etc. – remote handling requirements etc. Fully examine radiation protection in the HL era intervention space
  - Personal doses
- The cost of deconditioning (UFOs, e-cloud) following long shutdowns

Publicity

With the focus of LHC exploitation increasingly shifting towards machine availability, the workshop will:

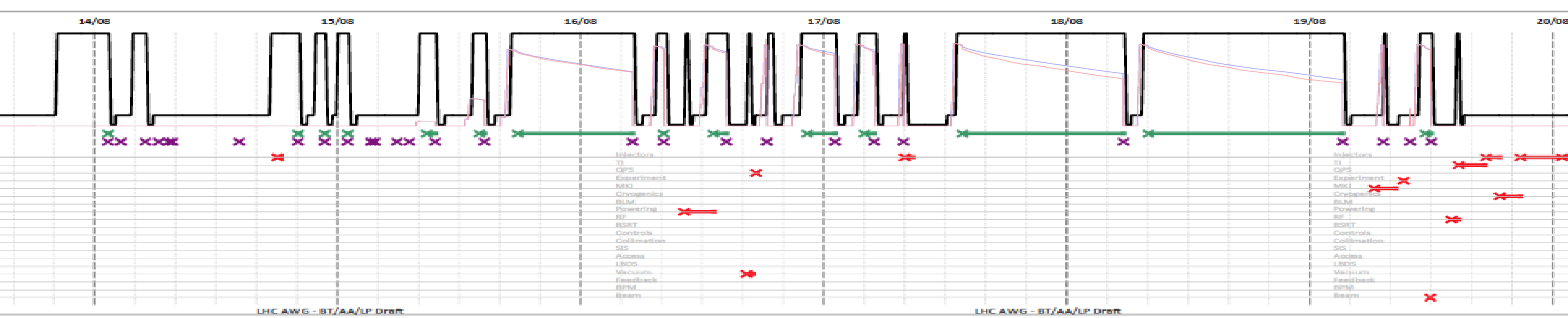
- Provide a forum for exchange on ongoing dependability work between equipment teams (ABT, BI, CRG, EL, EPC, MPE, OP, RF...) and guarantee coherence
- Define the tools and methodologies required to reliably track and quantify the dependability of equipment systems
- Investigate possibilities to optimize balance between operational availability and machine protection
- Quantify the impact of ongoing improvements and their effect on integrated luminosity in the post LS1 and HL-LHC era
- Identify synergies and input for tools provided by Maintenance Management Project

Organizers: Andrea Apollonio, Christophe Mugnier, Laurette Ponce, Benjamin Todd, Jan Uythoven, Jorg Wenninger, Daniel Wollmann, Markus Zerlauth

Ben Todd et al

Fault tracking

- It is vital that an adequate fault tracking tool be developed and implemented for the LHC restart after LS1.
  - R1. A new LHC fault tracking tool and fault database is needed.
  - R2. Defined and agreed reference metrics are needed to consolidate views on definitions used in availability calculations.
  - R3. Reliability tracking of the critical elements of the MPS is needed to ensure that LHC machine protection integrity is acceptable.
- Fully assign downtime
  - Downtime = Fault-time and lost-physics
  - Develop metric to reflect lost integrated luminosity



Conclusions

- Challenging HL demands on availability and operational efficiency
  - 2012 encouraging but…
- Known unknowns to be evaluated
  - 8 years more operations will surely see a concerted effort to address these issues
- Unknown unknowns ("new physics") to be discovered
- R2E will continue to be important
- System improvements will continue to be important
- RP/interventions to be anticipated
- More formal approach to availability – fully support AWG
  - Tracking, accounting, coherency

Going have to run it like we mean it cf. Tevatron – working on on the 1%

Price for flexibility or a recipe

Beniamino di Girolamo

- The price: x ab^{-1} not reached on human affordable time
- A possible personal recipe: in view of the scenarios that can moderate the pile-up density (crab kissing) we may need to decide
- to accept higher pile-up than 140 to be able to integrate more luminosity in less time.
  - HL-LHC will provide 10^{35} lumi to be leveled
- Or ask for more efficient