LHC AVAILABILITY FOR POST LS1 OPERATION

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Acknowledgements: L. Ponce, C. Roderick, R. Schmidt, B. Todd, D. Wollmann, M. Zerlauth, AWG members

Outline

- Introduction
- LHC Availability in 2012
- Summary of the Dependability Workshop
- Fault Tracking Project
- Luminosity predictions vs Availability
- Conclusions

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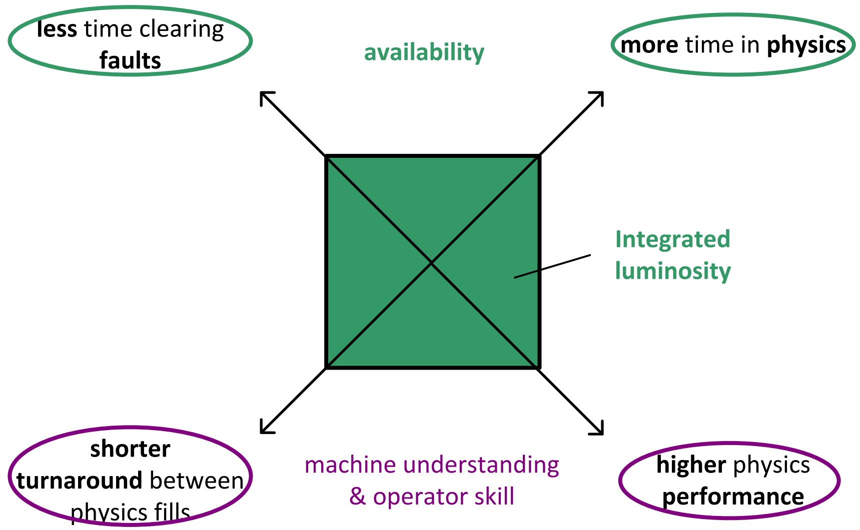
Introduction

- The increasing interest in the study of Availability at CERN is directly linked to pushing the LHC performance to the limits
- Major efforts towards increasing LHC luminosity:
  - LIU: injectors upgrade, Linac4
  - HL-LHC project
- Having a deep understanding of the factors driving LHC availability can be one of the keys to achieve better performance in the future
- Consistent data capturing is at the base of availability studies

Luminosity and Availability: definitions



integrated luminosity is a function of…

1. time colliding physics beams
2. ~~turnaround between successive physics beams~~
3. time to clear faults
4. ~~physics performance during colliding beams~~

availability!

machine understanding & operator skill

These are not independent variables

B. Todd & AWG, LMC February 2014

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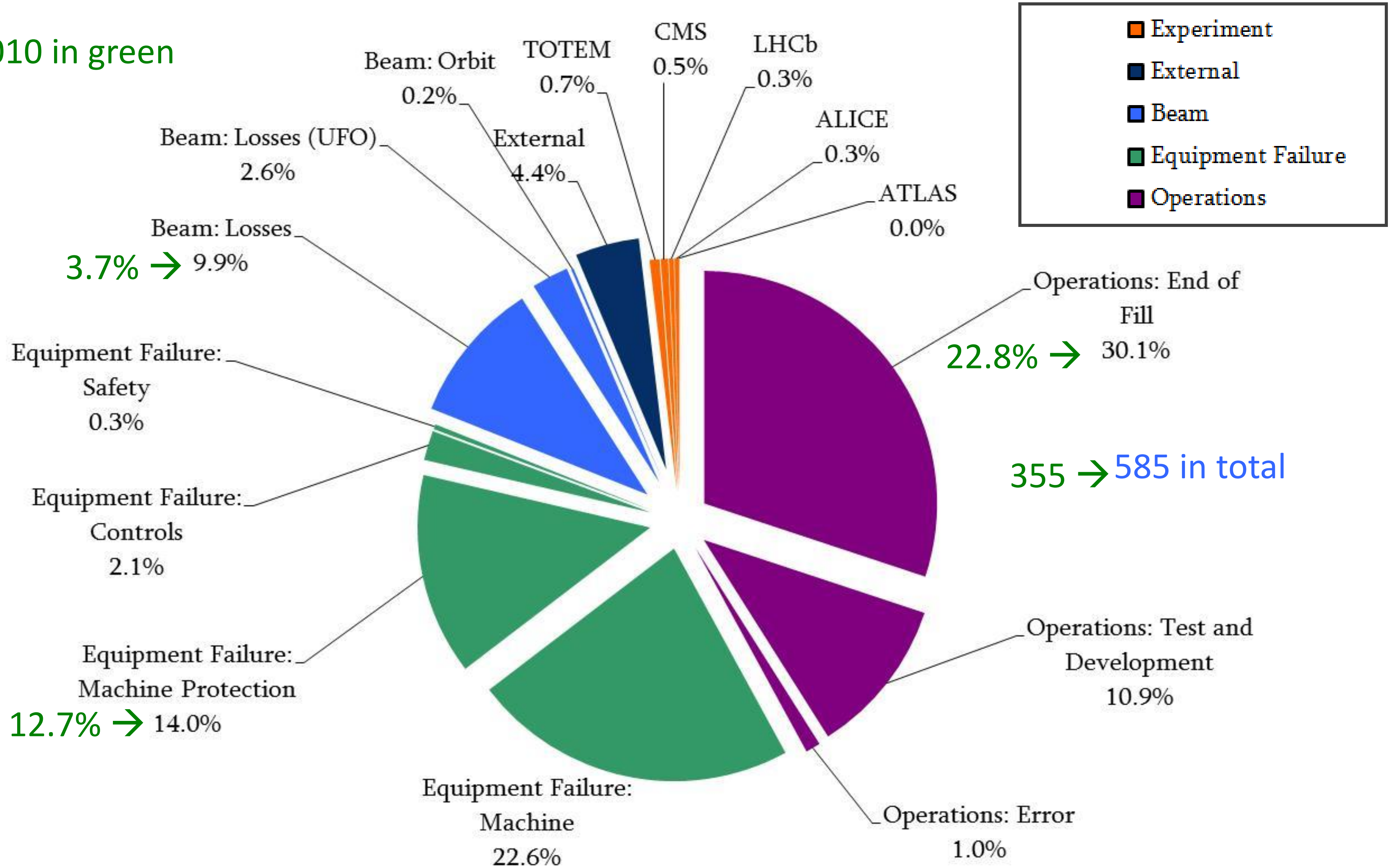
2012 – Dump Cause Classification

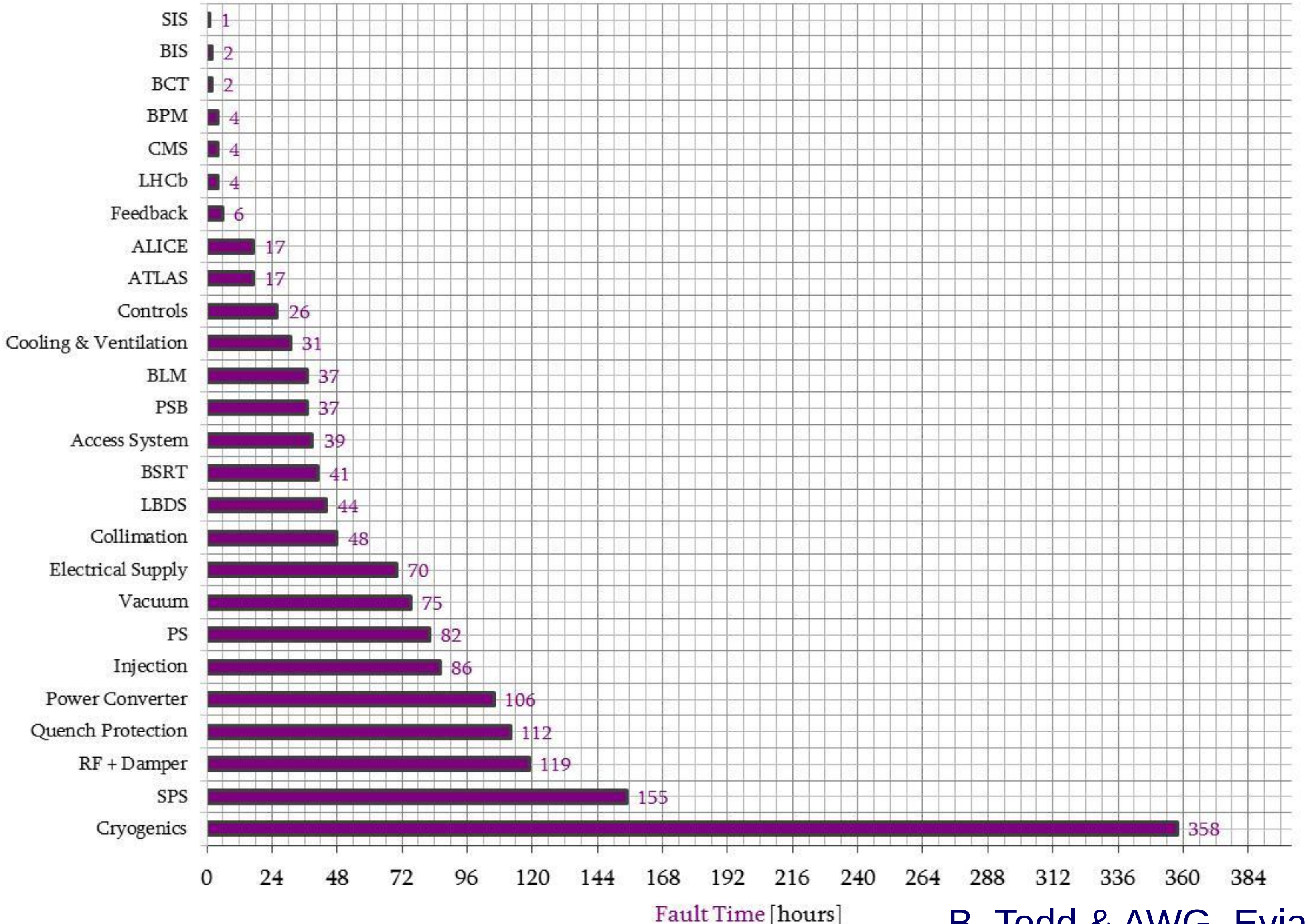
2010 in green



355 → 585 in total

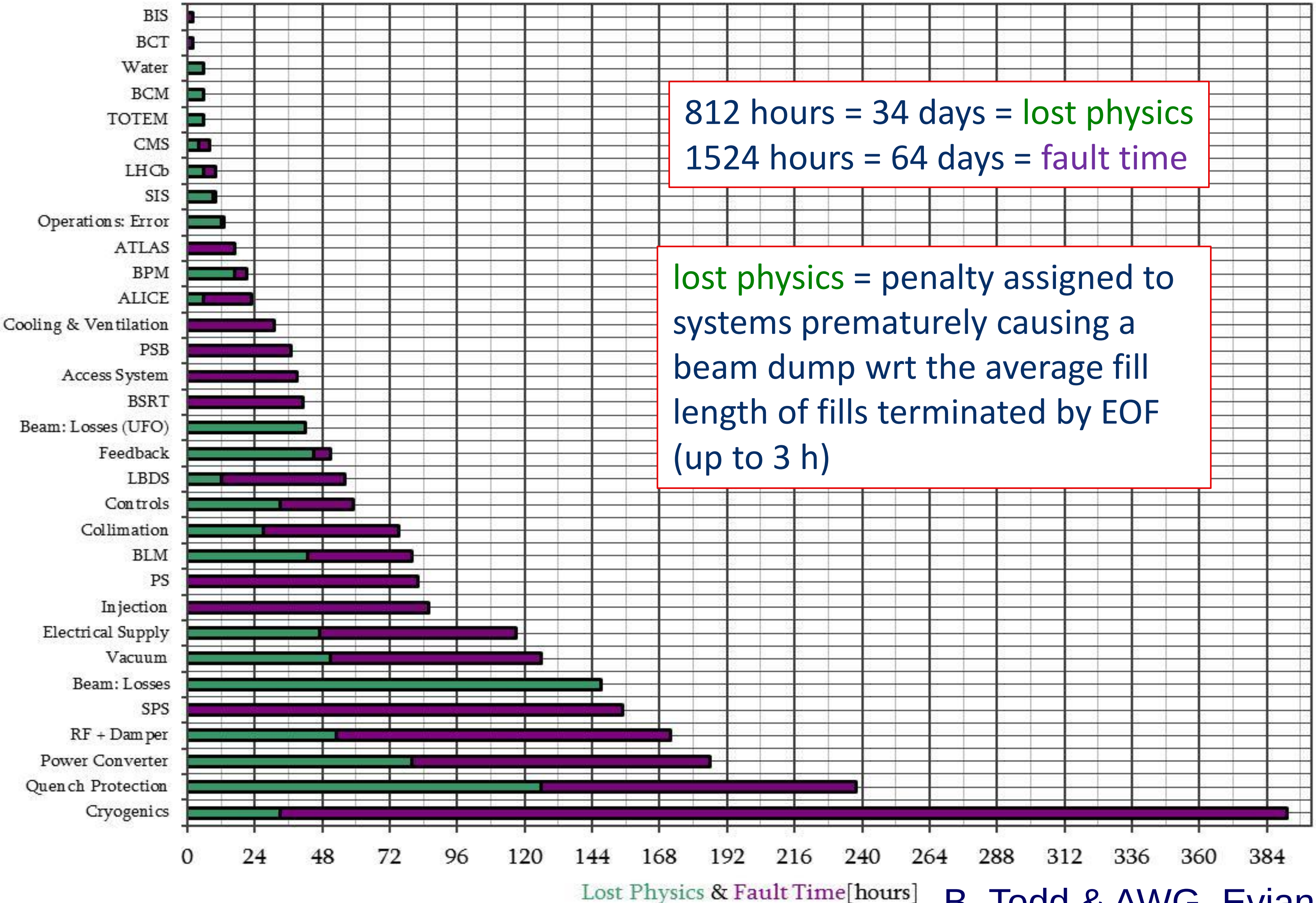
B. Todd & AWG, Evian 2012

2012 – Fault Time Distributions



B. Todd & AWG, Evian 2012

2012 – 'Lost physics time'

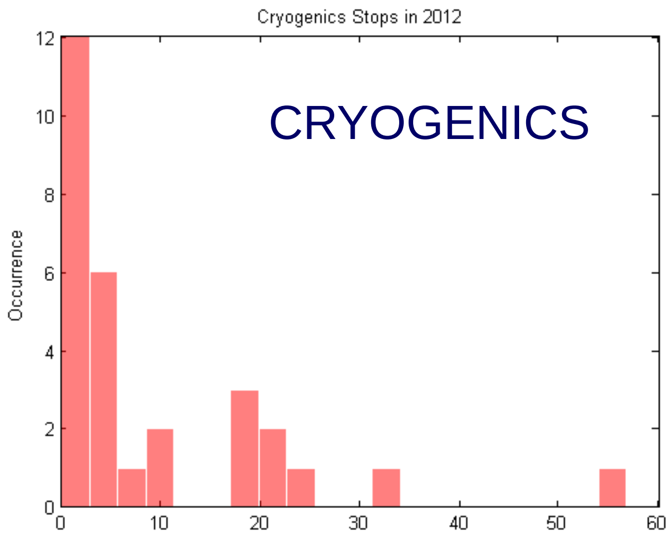


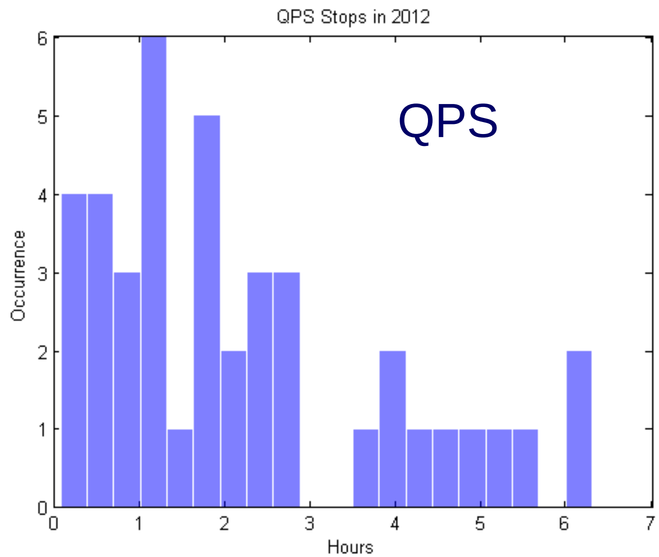
812 hours = 34 days = lost physics
1524 hours = 64 days = fault time

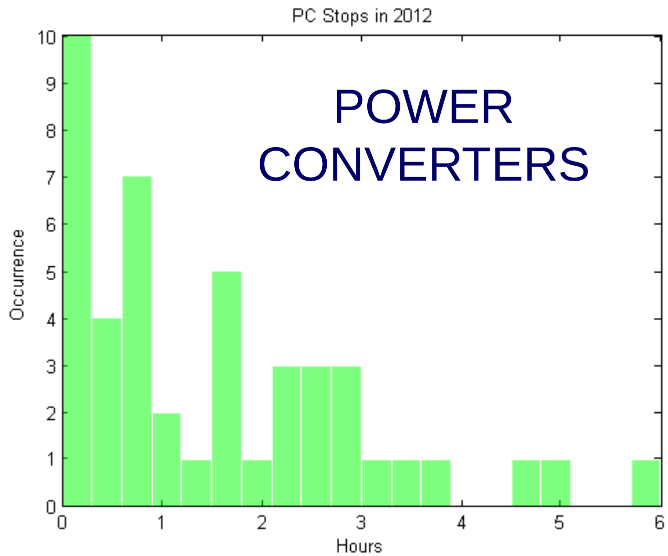
lost physics = penalty assigned to systems prematurely causing a beam dump wrt the average fill length of fills terminated by EOF (up to 3 h)

B. Todd & AWG, Evian 2012

Top 3 contributors to machine downtime in 2012:



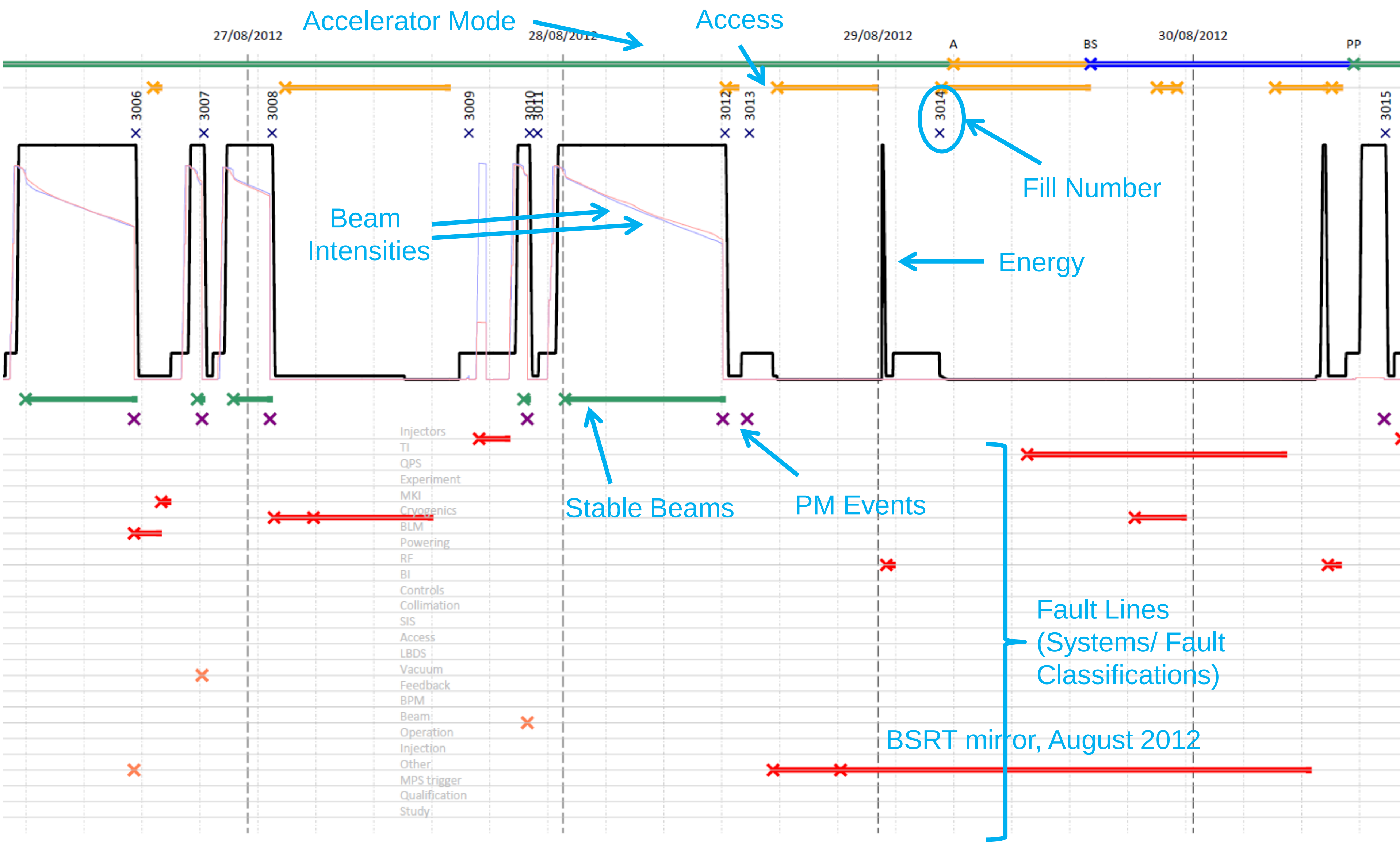




- Understanding system failure modes is crucial for availability and reliability analyses
- It is important to keep trace of all failures to infer wear out or observe systematic effects
- A Fault Tracking Project was launched at CERN to consistently store this information

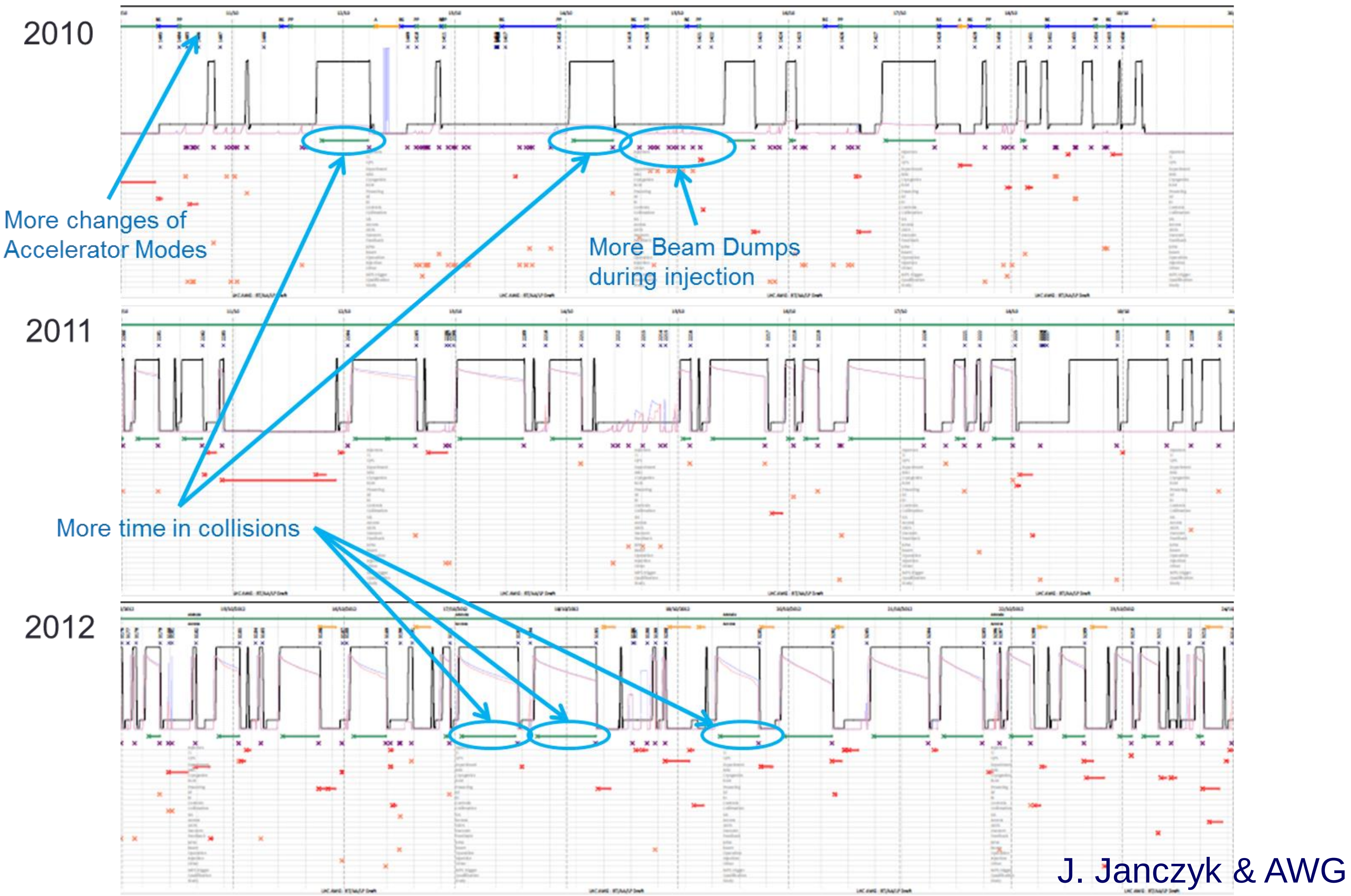
* Faults: registered in the eLogbook

“Cardiogram”: 2010-2012



B. Todd, J. Janczyk & AWG

Cardiogram 2010-2012



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Dependability Workshop Summary (1/2)

- Cryogenics – E. Duret & S. Claudet

+ rotating machine overhauls	- Less tolerance to 3.3kV glitches
+ magnetic bearing controllers EMC reinforcement	- Higher operating point at 7TeV
+ remote reset for R2E	- Longer quench recovery

- Power Converters – S. Uznanski

+ radiation tolerant controller being designed	- Higher operating point at 7TeV

- Beam Dump – R. Filippini

+ vacuum gauges replaced	- BIS retrigger line added
+ HV insulated against sparking	- More surveillance on trigger unit
+ IGBT upgrade	- Common cause failures addressed in power
+ shielding for R2E	- Two more MKB per beam

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Dependability Workshop Summary (2/2)

- Magnet Protection & Interlocks – S. Gabourin
  - + BIS: monitoring = preventive maintenance
  - + QPS upgrades: EMC, R2E, remote reset
  - - BIS retrigger line added
- Beam Instrumentation – L. Jensen
  - + BLM: monitoring, fans
  - + BPM: upgrades, attenuator remote control
  - + BSRA/T: redesign for reliability
  - + BGI: repaired and corrected
  - - Abort gap monitoring added to SIS
  - - Tune feedback interaction with QPS
- RF & Damper – P. Maesen
  - + thyratron crowbar becomes solid state
  - + connectors improved
  - + relocation for R2E
  - - FESA 3

B. Todd & AWG, LMC February 2014

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Accelerator Fault Tracking (AFT)

- Goals:
  - Know why machines are not in use when they should be
  - Know what are the causes of un-planned downtime
  - Look for patterns, relations between systems, operational modes, etc.

- Project launched in February 2014, based on inputs from:
  - Evian Workshops
  - Availability Working Group
  - Workshop on Machine Availability and Dependability for post-LS1 LHC

- Scope:
  - Initial focus on LHC, but aim to provide a generic infrastructure capable of handling fault data of any CERN accelerator.
  - Easy exploitation and visualization of existing data, highlighting inconsistencies and missing information

C. Roderick, LMC 30/4/2014

AFT: Project Stages

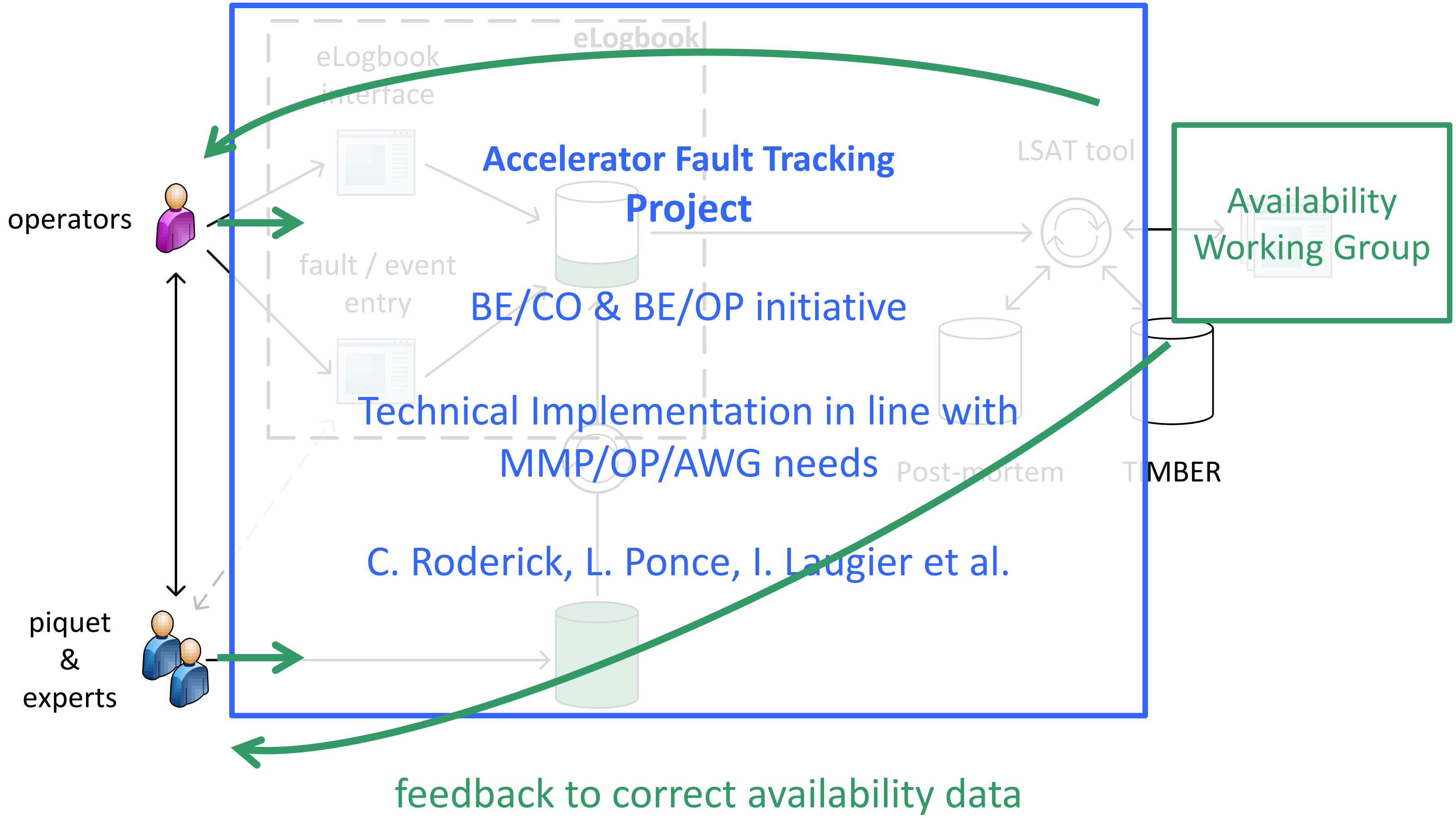
1. Put in place a fault tracking infrastructure to capture LHC fault data from an operational perspective
   - Enable data exploitation and review by others (e.g. AWG and OP) to identify areas to improve accelerator availability for physics
   - Ready before LHC restart (January 2015)
   - Infrastructure should already support capture of equipment group fault data, but not primary focus

2. Focus on equipment group fault data capture

3. Explore integration with other CERN data management systems
   - potential to perform deeper analyses of system and equipment availability
   - in turn - start predicting and improving dependability

C. Roderick, LMC 30/4/2014

Future



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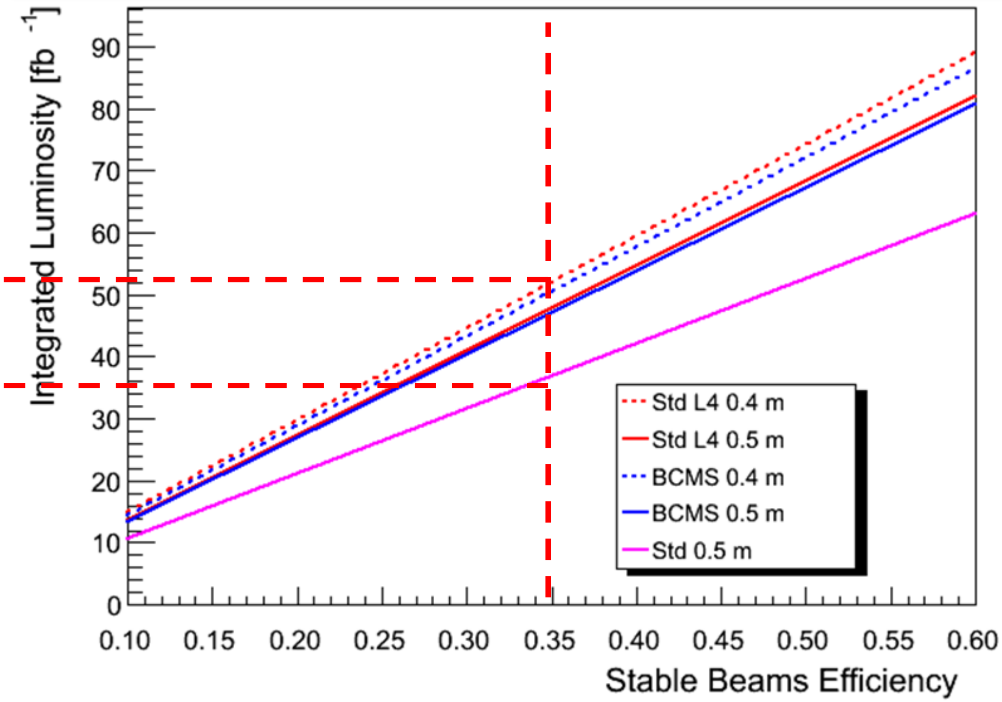
Post LS1 LHC Operation

Beam	β* (m)	Leveled L (10^{34} cm^{-2}s^{-1})	Peak L (10^{34} cm^{-2}s^{-1})	Leveling time (h)
Standard L4	0.4	1.65	2.1	~1.4
BCMS	0.4	1.54	2.2	~2.1
Standard L4	0.5	1.65	1.9	~0.7
BCMS	0.5	1.54	2.0	~1.5
Standard	0.5	1.65	1.2	--



- BCMS & standard are very close in performance.
- Leveled L ~at the triplet limit, peak lumi BCMS / L4 above limit.
- With 2011 emittance model, values increase ~2%.

Add 5-10% to account for mixed fill length distribution

J. Wenninger, RLIUP October 2013

Baseline for Performance Evaluation

- Sequence of LHC Operational states:

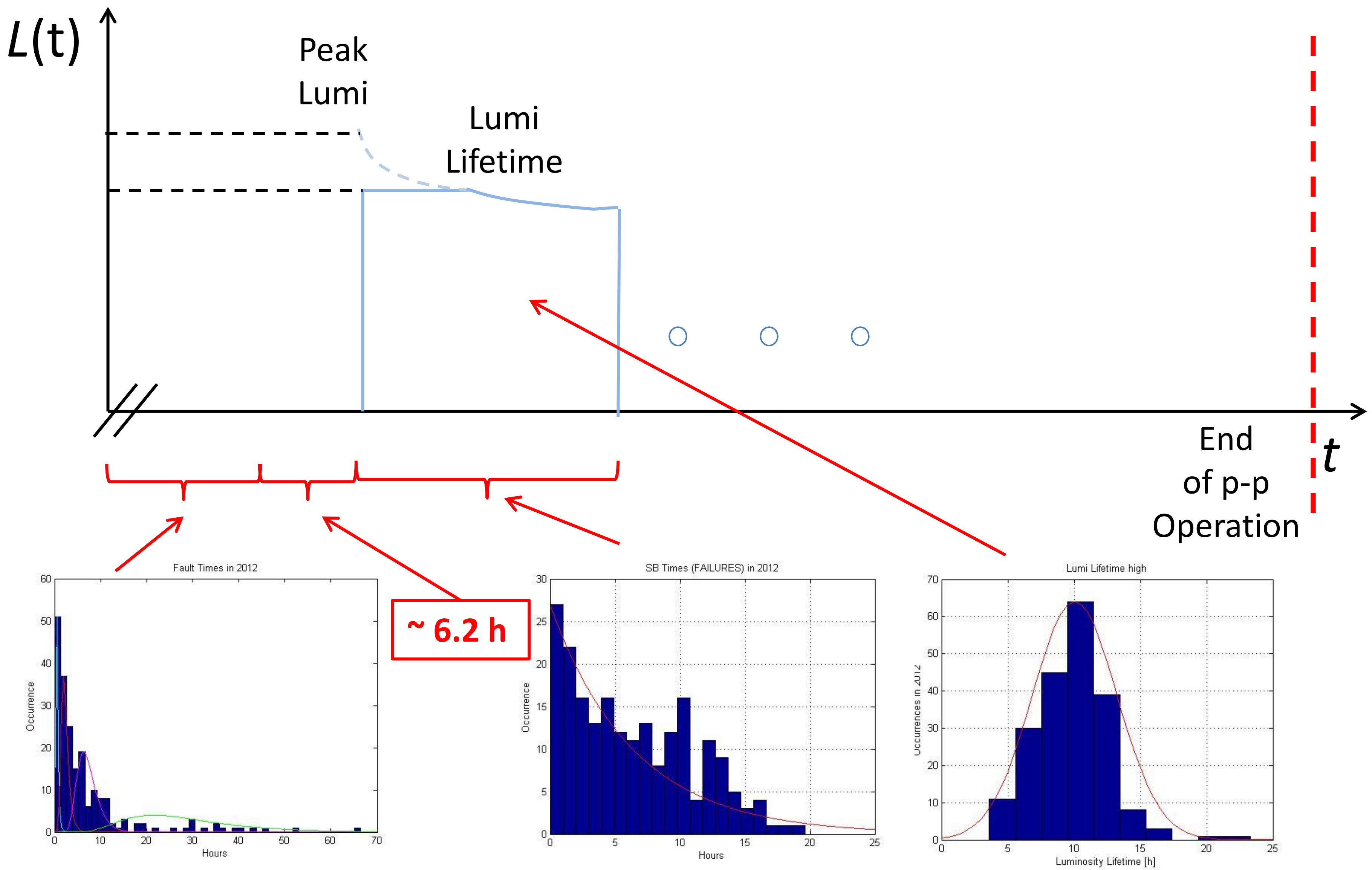
Turnaround	**Stable Beams**	**Machine Fault**

- **2012 Observations** (average values):
  - ❑ Turnaround: 5.5 h
  - ❑ Fault time per fill: 4.8 h
  - ❑ Stable Beams: 6.1 h

- **Monte Carlo model** for performance evaluation (MATLAB):
  - ❑ Generation of random numbers based on 2012 distributions

- The model reproduces a **realistic timeline** of 1 year of LHC OP:
  - ❑ Assumes 2012 parameters as reference
  - ❑ Includes intensity Ramp-up
  - ❑ Allows for sensitivity analyses to relevant parameters

Monte Carlo Model: Levelling



Post-LS1 Availability: 'Abstract' Scenarios

1. **No machine faults** (i.e. max theoretical luminosity)
   (MFR=0 %, FAT=0 h, TAT=4 h)
2. **Only external faults**
   (MFR=9 %, FAT=2.6 h, TAT=4 h)
3. **Extension of 2012 fault distributions**
   (MFR=70 %, FAT=7 h, TAT=6.2 h)
4. **All faults require no access**
   (MFR=70 %, FAT=1 h, TAT=6.2 h)
5. **All faults require 1 access**
   (MFR=70 %, FAT=4 h, TAT=6.2 h)
6. **All faults require major interventions**
   (MFR=70 %, FAT=12 h, TAT=6.2 h)

MFR: Machine Failure rate = fills with failures / total # of fills

FAT: Average Fault time per fill to Stable Beams with failures

TAT: Average Turnaround time per fill to Stable Beams

160 days of operation

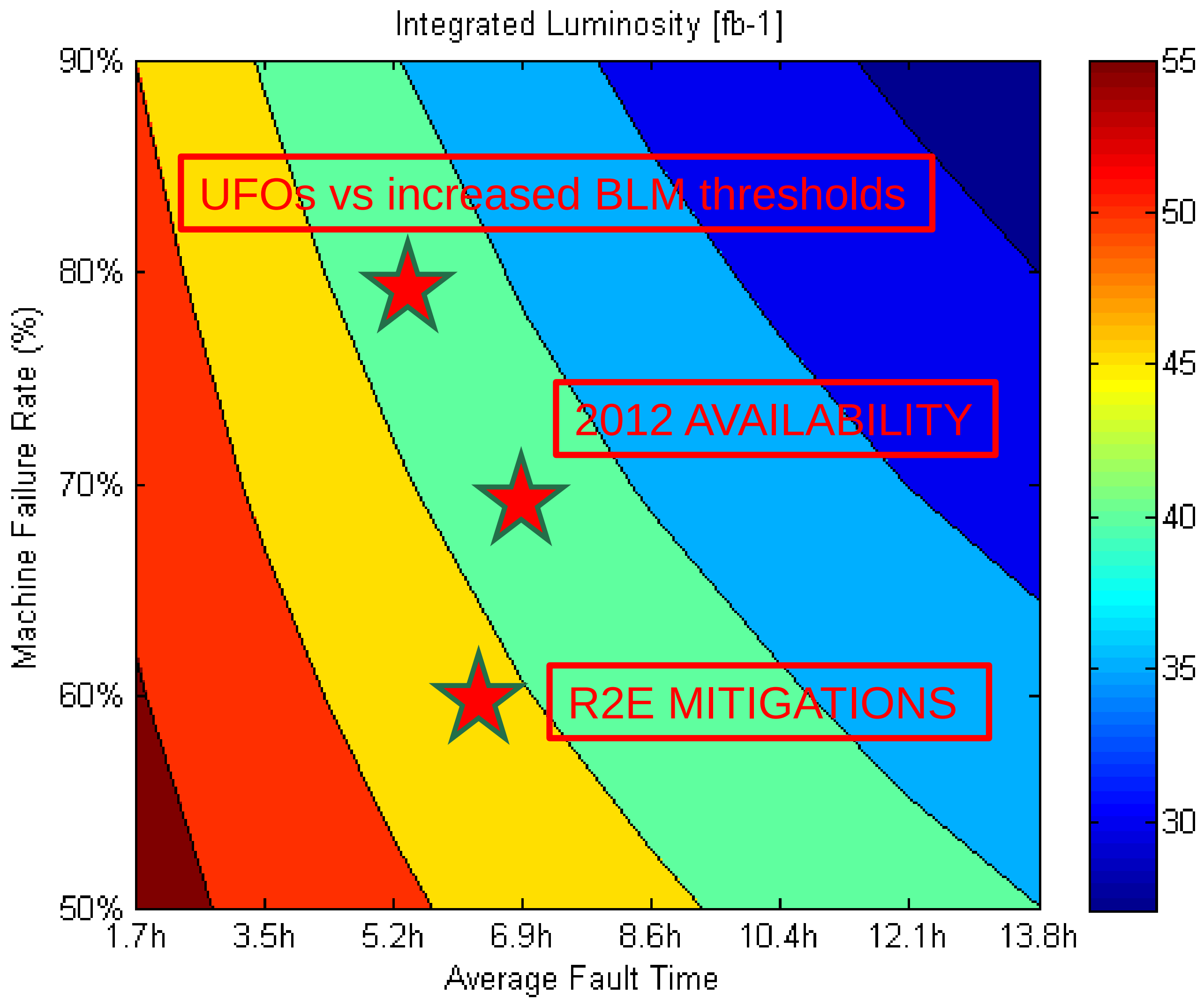
Post LS1 LHC: Opt Integrated Luminosity

Scenario	Integrated Luminosity (BCMS)	Opt. # fills		Opt. Stable beams	
		EOF	Failures	Levelling	Exp decay
1. No faults	100.5 [fb^{-1}]	405	0	2.1 h	3.4 h
2. External faults	98.3 [fb^{-1}]	364	32	2.1 h	3.5 h
3. 2012 distributions	56.4 [fb^{-1}]	69	160	2.1 h	5.9 h
4. Faults - no access	75.9 [fb^{-1}]	95	221	2.1 h	4.7 h
5. Faults – 1 access	64.5 [fb^{-1}]	80	186	2.1 h	5.4 h
6. Major interventions	52.3 [fb^{-1}]	63	148	2.1 h	6.3 h

- Optimum time in stable beams is for fills terminated by EOF only (average fill length for fills terminated by failures is 4.6 h)

Lumi Predictions: Realistic Scenarios

- Using the Monte Carlo model, starting from 2012 distributions:



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Conclusions

- The LHC had a **remarkable** availability in 2012
- Availability models are currently being developed to make luminosity **predictions** for future operational scenarios
- The AFT project will allow capturing availability-related data in a more **consistent** way
- Failures having the highest impact on LHC availability during run 1 are currently being addressed in the LS1 with dedicated **mitigation** strategies
- **Extrapolation** of failure behaviors for future operational scenarios is not trivial
- A **strategic view** on how to improve LHC performance through availability optimization must be studied in the future

THANKS A LOT FOR YOUR ATTENTION!

References:

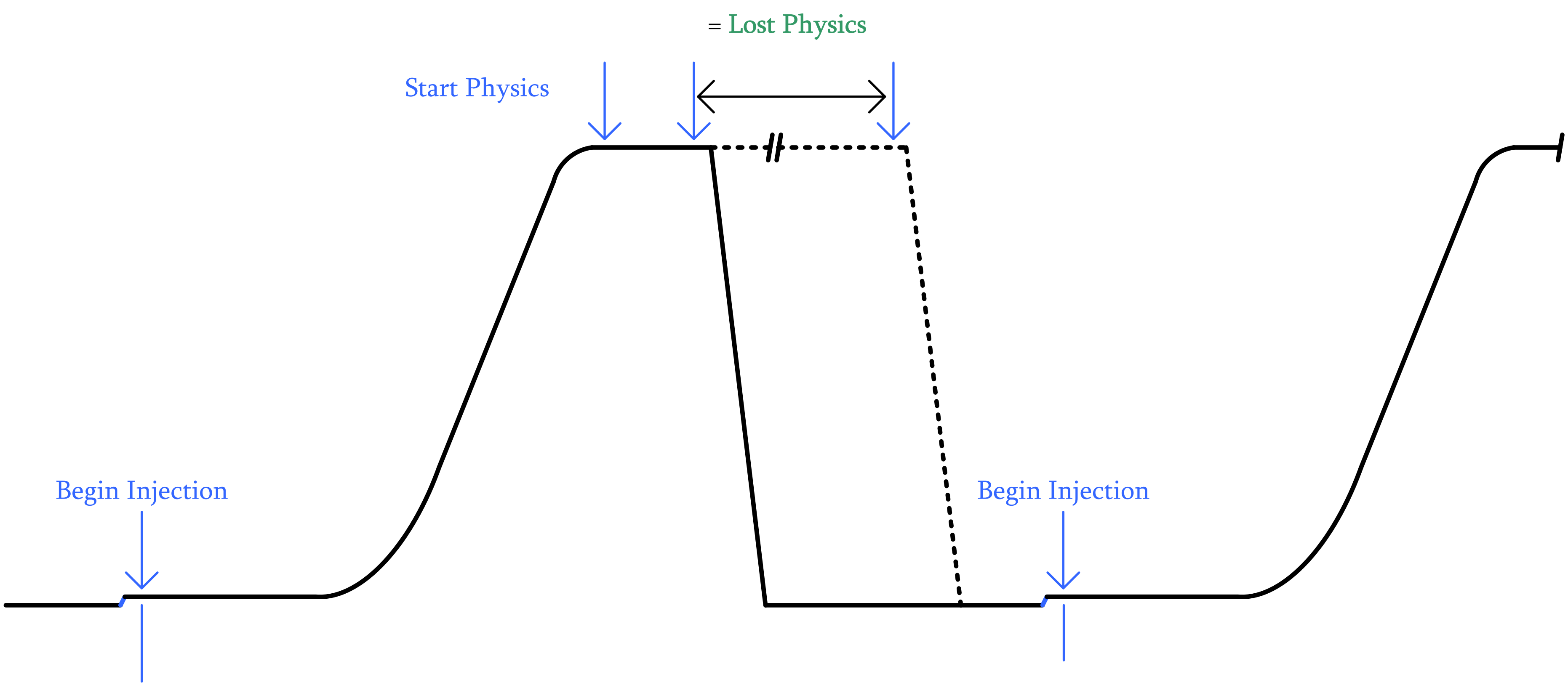
- The proceedings of the 2012 Evian Workshop on LHC beam operation, 17 – 20 December 2012, Evian-Les-Bains, France, https://cds.cern.ch/record/1562028/files/CERN-ATS-2013-045.pdf
- The proceedings of the Availability and Dependability Workshop for Post-LS1 LHC, 28th November 2013, CERN, https://indico.cern.ch/event/277684/material/2/0.pdf
- AWG website: https://espace.cern.ch/LHC-Availability-Working-Group/Meetings/SitePages/Home.aspx

Lost Physics

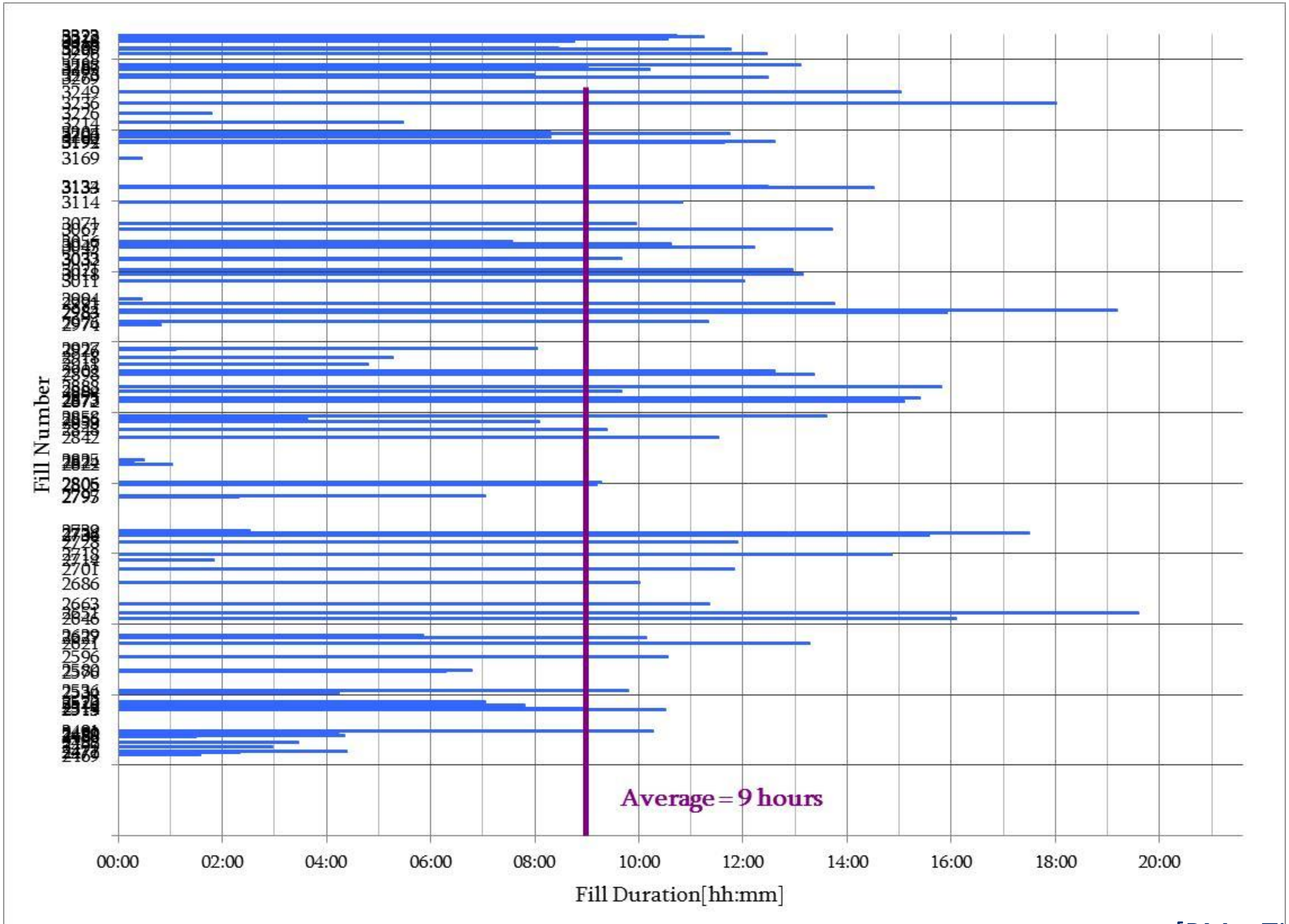
Lost Physics = stable beams cut short by faults

Average time in physics when reaching End of Fill = 9 hours … good turnaround = 3 hours

if fill did not have 9 hours stable beams : dump cause is assigned up to 3 hours lost physics



Mean Stable Beams 9 Hours @ End of Fill



[PM + TIMBER]

Considering Complexity

Can we compare systems by their complexity?

Asked each system to give “number of hardware signals which can provoke beam abort”…

initial informal attempt:

System	Approximate Number	Reference
RF	800	O. Brunner
Beam Interlock System	2000	B. Todd
Cryogenics	3500	S. Claudet
Quench Protection	14000	R. Denz
BLM (surveillance of protection function)	18000	C. Zamantzas
BLM (protection function)	48000	C. Zamantzas

Better metric for complexity…
TE/MPE & AWG – student 2013

Study by A. Apollonio

[10]

2005 Predictions…

2005 – Reliability Sub-Working Group

Predicted false dumps and safety of Machine Protection System

safety: no events

false dumps: used to determine whether predictions were accurate

System	Predicted 2005	Observed 2010	Observed 2011	Observed 2012
LBDS	6.8 ± 3.6	9	11	4
BIS	0.5 ± 0.5	2	1	0
BLM	17.0 ± 4.0	0	4	15
PIC	1.5 ± 1.2	2	5	0
QPS	15.8 ± 3.9	24	48	56
SIS	-	4	2	4

radiation induced effects are included in the figures above

false dumps – in line with expectations…

safety –therefore in line with expectations… if ratio false dumps to safety is ok.

Study by A. Apollonio

[11]

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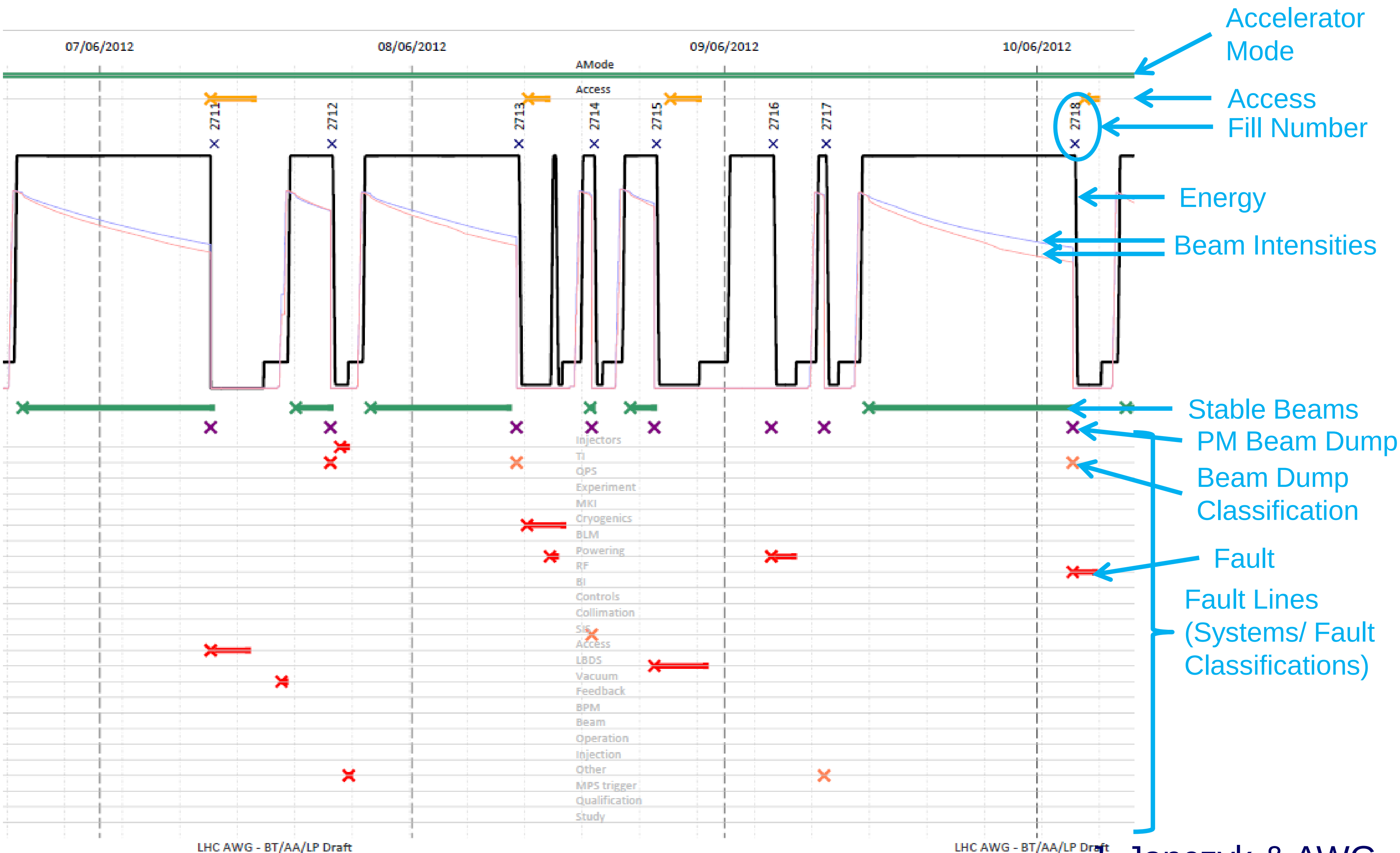
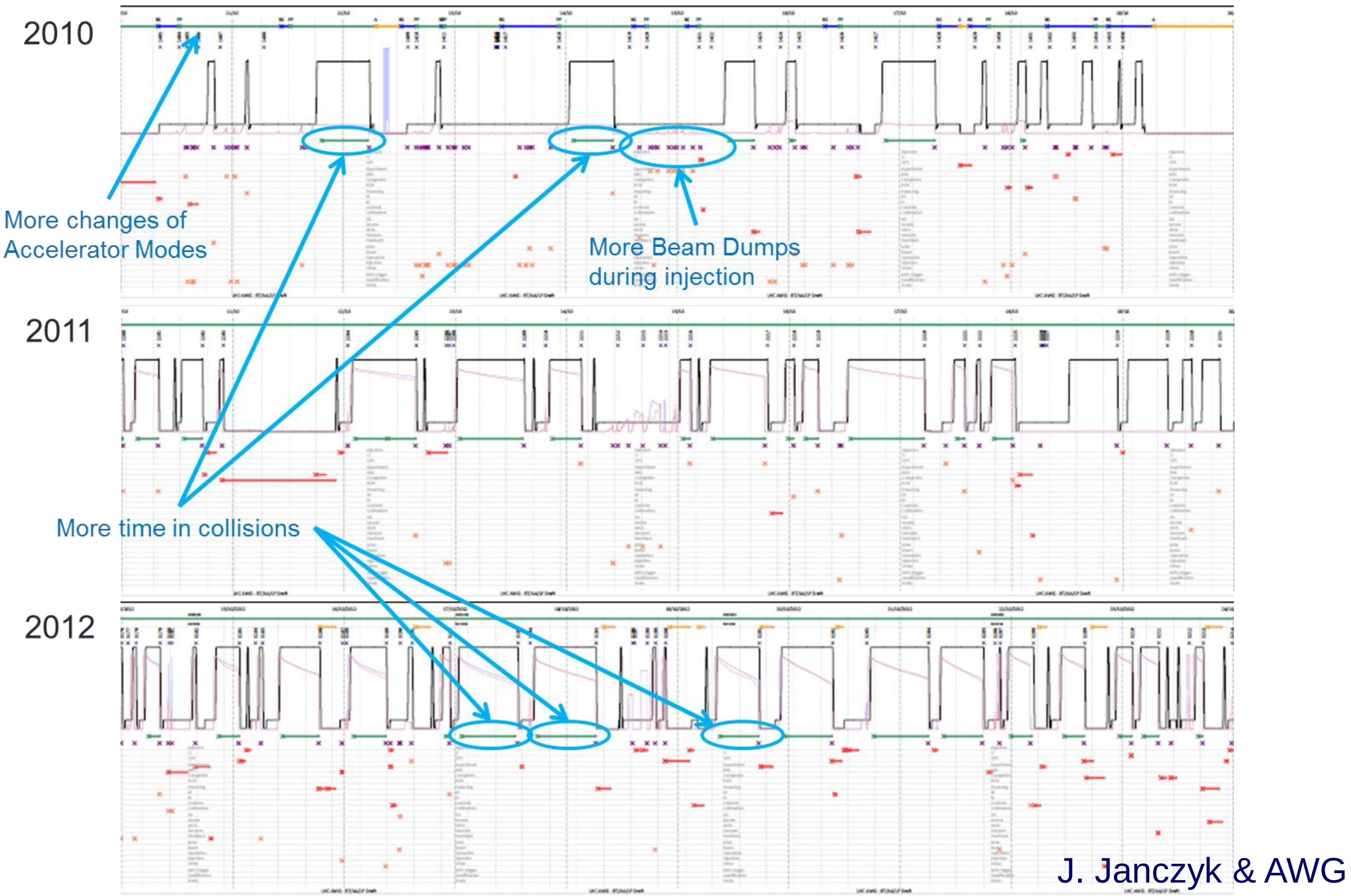


J. Janczyk & AWG

Cardiogram 2010-2012



Dependability Workshop: Cryogenics

- Changes during LS1 increasing availability:
  - Major overhauls of rotating machinery, to avoid end of life wear-out.
  - Magnetic bearing controllers in the cold compressors, reinforced against EMC.
  - Remote reset and R2E mitigations in P2, 4 and 6.
- Changes during LS1 decreasing availability:
  - The re-adjustment of tolerance to 3.3kV glitches, which is necessary for motor protection may induce additional downtime.
- Sensitivity to Operating Conditions:
  - Higher energy means that resistive heat loads will increase (factor 4). Operating point moved closer to the maximum possible, although still within design values.
  - Failures of rotating machinery will be more visible; near misses from before will now cause a stop with an impact on availability or physics.
  - Quenches will take longer to recover from

Dependability Workshop: PC

- Changes during LS1 increasing availability:
  - Known unreliable parts in the VS have been fixed.
  - A new radiation tolerant power converter controller is being designed (FGClite) which is expected to be 20 times more reliable in radiation than the current FGC.
- Changes during LS1 decreasing availability:
  - The FGClite will not be ready for the restart of LHC after LS1. Therefore it is possible that the FGC2 remains in place, with the known failure rate.
  - After the FGClite installation, an initial period of infant mortality with higher failure rate is to be expected.
- Sensitivity to Operating Conditions:
  - Higher current in the magnets mean that the VS will run at a higher operating point, which is expected to decrease the MTBF of the VS.
  - Higher beam loading and local radiation mean that the current FGC will suffer more failures due to radiation induced effects until its replacement by the FGClite.

Dependability Workshop: QPS

- Changes during LS1 increasing availability:
  - QPS, relocation of equipment will mitigate around 30% of the single event effects.
  - QPS, upgrade of electronics to be more radiation tolerant.
  - QPS, a campaign has been initiated to check for bad cabling, which is the reason for spurious energy extraction opening.
  - QPS, cable routing and twisting improved to increase the system robustness against EMC type problems.
  - QPS, firmware upgrade allowing automatic reset when communications lost, remote reset for the local quench detectors.
- Changes during LS1 decreasing availability:
  - None.

Dependability Workshop: other systems

- Some examples of changes during LS1 increasing availability:
  - BLM, replacement of all fans in all VME power supplies (BI)
  - BIS, addition of fibre optic monitoring system to predict failure of the optical infrastructure.
  - BSRA, light extraction system is being re-designed to reduce the risk of failure (BI)
  - A solid state replacement for the Thyratron crowbar has been prototyped and tested, showing much higher availability (RF)
  - …
- Changes during LS1 decreasing availability:
  - BIS, an additional interlock between the BIS and the LBDS, to ensure the protection of the LHC even in the case of failure of the TSU (MPS)
  - Abort gap monitoring system will be added to the Software Interlock System (SIS).
  - The change to FESA 3 risks to have some unavailability problems due to the number of classes which have to be migrated and the little time available (RF)

Assumptions for post-LS1 LHC Operation

- **160 days of operation**
- **25 ns operation** with and without Linac4 (BCMS and Standard + Linac4)
- **4.5 h average luminosity lifetime** (~10 h in 2012)
- **6.2 h average turnaround time** (5.5 h in 2012)
- **4 logn distributions for the fault time** + future scenarios
- **2 stable beams time distributions:**
  - ❑ END OF FILL: gauss(mean 9.6 h)
  - ❑ EMERGENCY DUMPS: exp(mean 4.6 h)

Post-LS1 Availability: Possible Scenarios

Possible future scenarios:

1. **Extension of 2012 fault distributions** to Post-LS1 operation
2. **Impact of UFOs** at 6.5/7 TeV
3. **Impact of increased BLM thresholds** and Beam-Induced Quenches (BIQ)
4. **Impact of LS1 mitigations wrt SEUs**
5. Possible **impact of increased energy on SEUs**
6. **Combination of 3 and 4:** Impact of increased BLM thresholds and Beam-Induced Quenches (BIQ)+ SEUs mitigations

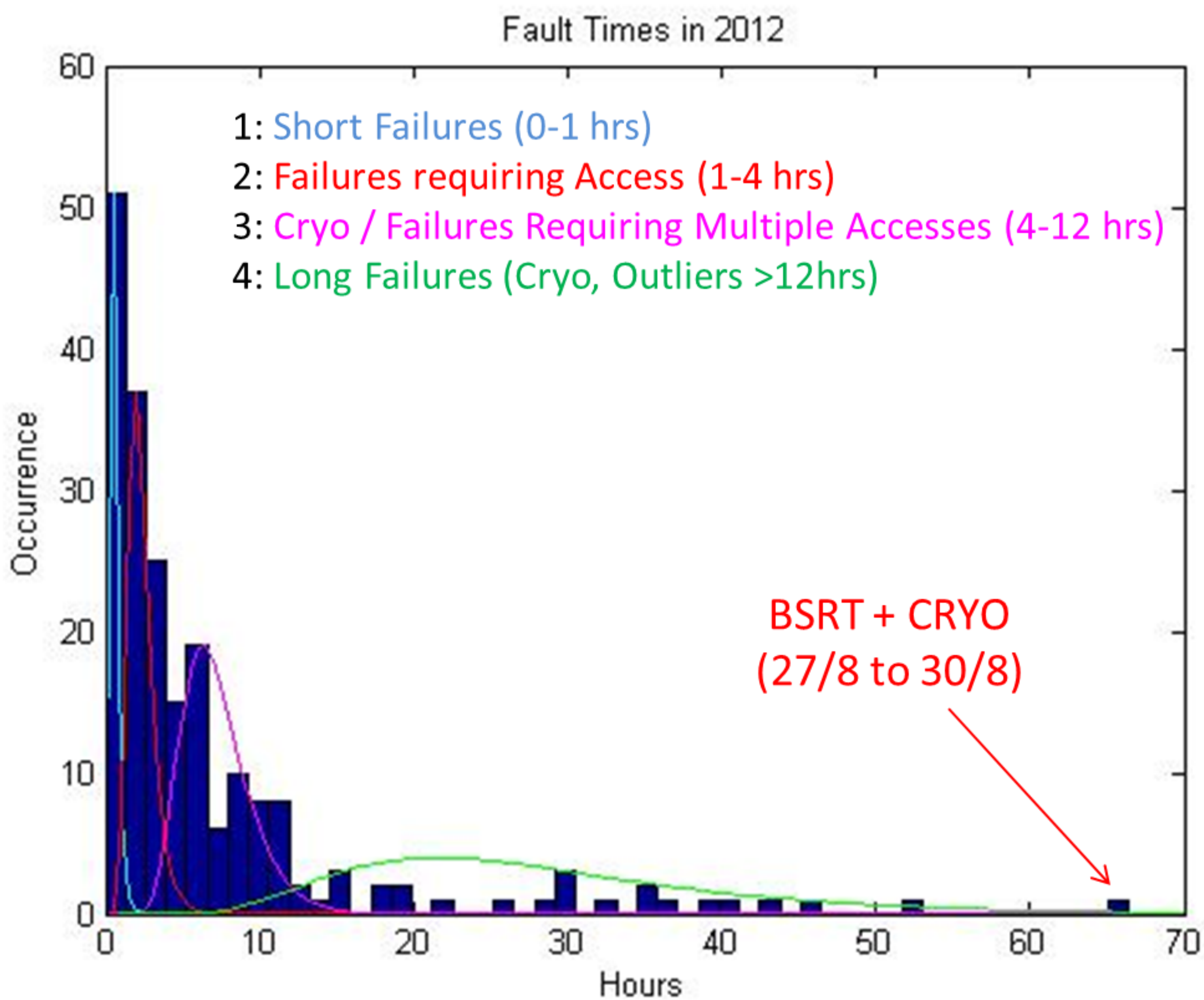
Post LS1 LHC Operation and Availability

- Summary of fault scenarios and impacts:

Failure Scenario/ Mitigation	Assumption	Simulated impact on Integrated Luminosity (BCMS)	Simulated impact on Integrated Luminosity (LINAC4)
1. 2012 Fault distributions	-	42.5 [fb^{-1}] (*reference*)	42.7 [fb^{-1}] (*reference*)
2. UFOs (6.5/7TeV)	100 UFO dumps	38.6 [fb^{-1}] (-*10 %*)	39.0 [fb^{-1}] (-*10 %*)
3. UFOs + BIQ	Factor 3 higher BLM thresholds, 33 UFOs, 3 BIQ	41.4 [fb^{-1}] (-*2.6 %*)	41.5 [fb^{-1}] (-*2.8 %*)
4. SEU mitigations	20 SEU dumps	43.3 [fb^{-1}] (*+1.8 %*)	43.6 [fb^{-1}] (*+2.1 %*)
5. SEU increase due to higher energy	60 SEU dumps (+50% wrt 2012)	41.7 [fb^{-1}] (-*1.8 %*)	41.9 [fb^{-1}] (-*1.8 %*)
6. Combined impact of scenarios 3 and 4	-	41.8 [fb^{-1}] (-*1.6 %*)	42.1 [fb^{-1}] (-*1.4 %*)

Fault time distributions in 2012

4 lognormal distributions were adopted to model the failures in 2012:



"Shaping" these distributions allows making predictions for possible future operational scenarios