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LHC Performance Workshop 2016
Session 3 + 4
LHC Hardware Performance

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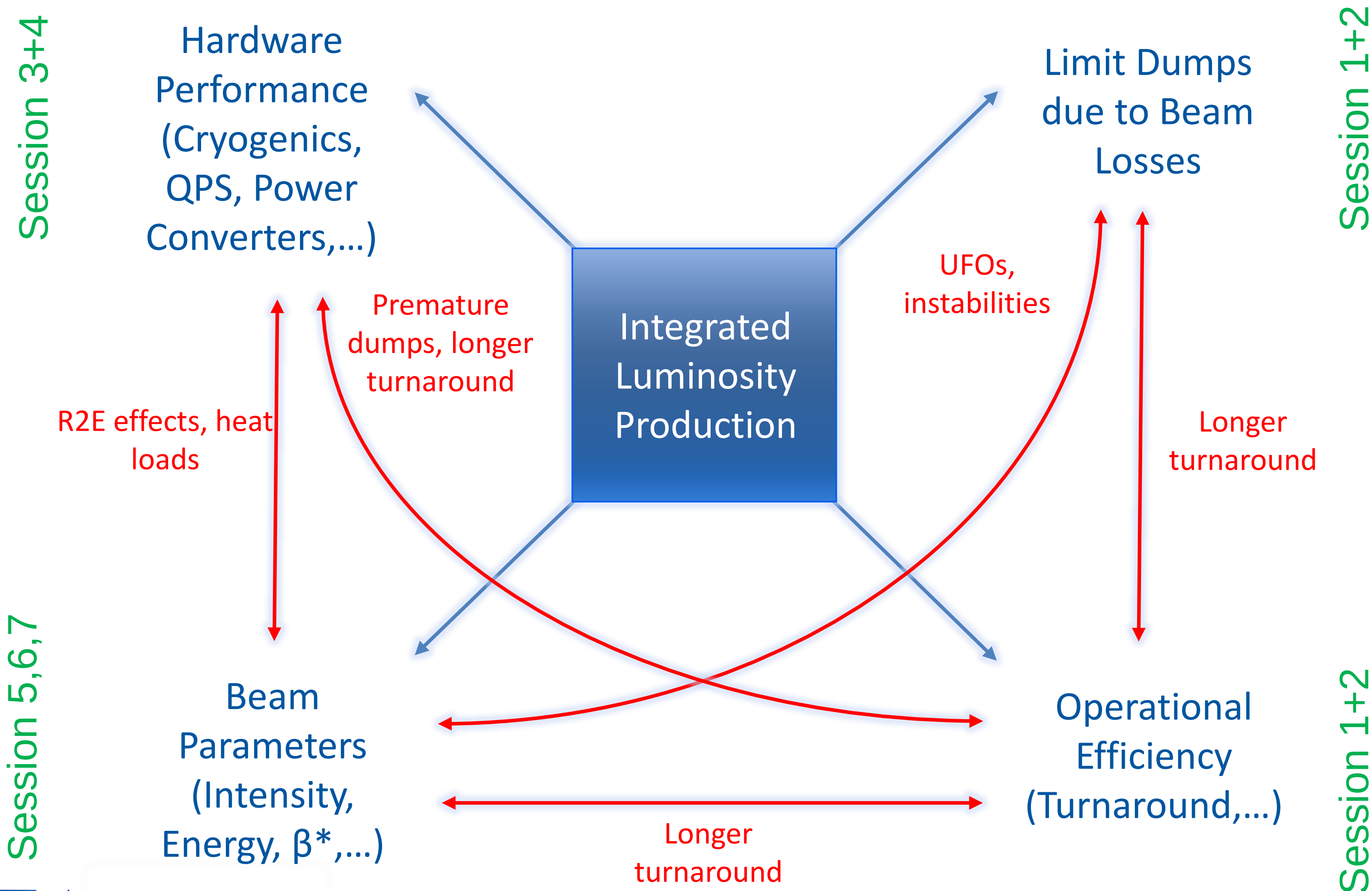
Outline session #3

6 talks:

- Accelerator Fault Tracker & Availability Working Group Where do we go from here? — **B.Todd**
- LHC Availability – Status and Prospects — **A.Apollonio**
- Cryogenics — **G.Ferlin**
- Quench Detection System — **R.Denz**
- Electrical Performance of Magnet Circuits — **F.Rodriguez Mateos**
- Power Converters — **V.Montabonnet**

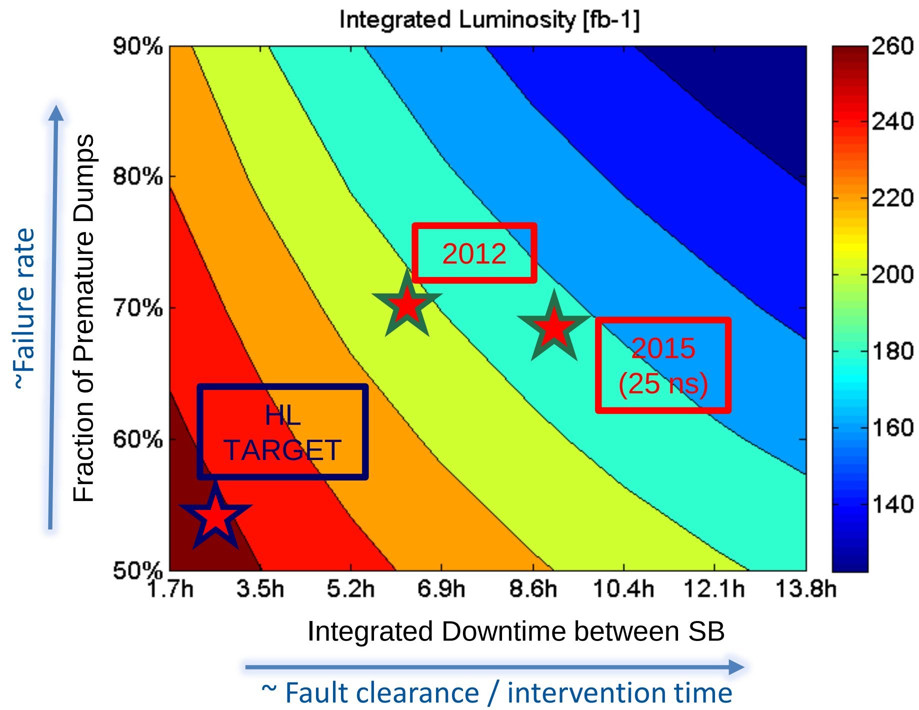
Integrated Luminosity Production



Maximizing physics output of the LHC

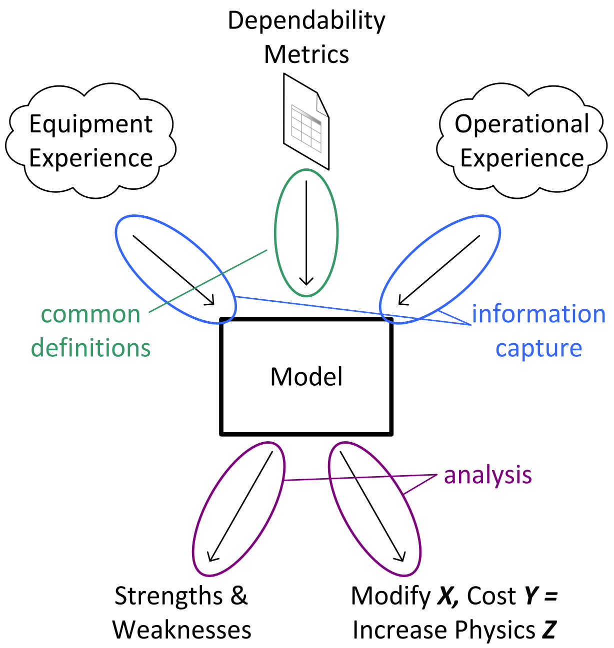
- Dependability of LHC systems is one of key drivers of physics output (integrated L)
- While machine safety cannot be compromised, one of priorities for future years (and conception of HL-LHC, FCC) will be to maximize system availability to meet physics goals
- Availability is the only means to increase integrated luminosity once a machine is levelled
- Past experience is key to understanding of equipment failures (root cause) and assessing impact and cost of mitigations

Monte-Carlo simulation of HL-LHC performance based on availability achieved in 2012 / 2015



Availability Working Group

- LHC Availability Working Group (AWG) launched in 2012
- 2010-2012: objective view of availability not possible = weaknesses in data captured -> coherent & objective information capture is primary concern – biggest challenge of AWG
- 2012-2013: AWG proposed the Accelerator Fault Tracker to solve data issues
- 2014: Accelerator Fault Tracker (AFT) launched by BE/CO, BE/OP and TE/MPE
- 2015: AFT was extensively used for availability data analysis → See later



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Coherent & objective = viewpoint from both operations & equipment

"Cardiogram"

Operations Viewpoint

Impact on Physics

Duration of No Beam

Fault Duration

Fault Root Cause

System

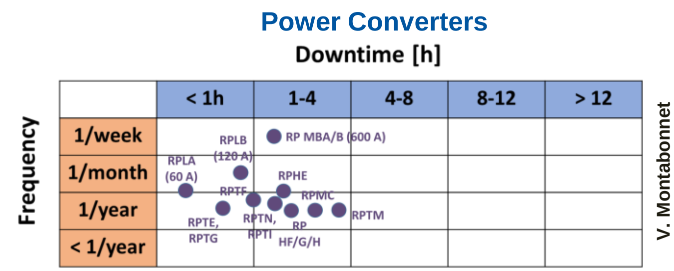
Sub-System

Equipment Code

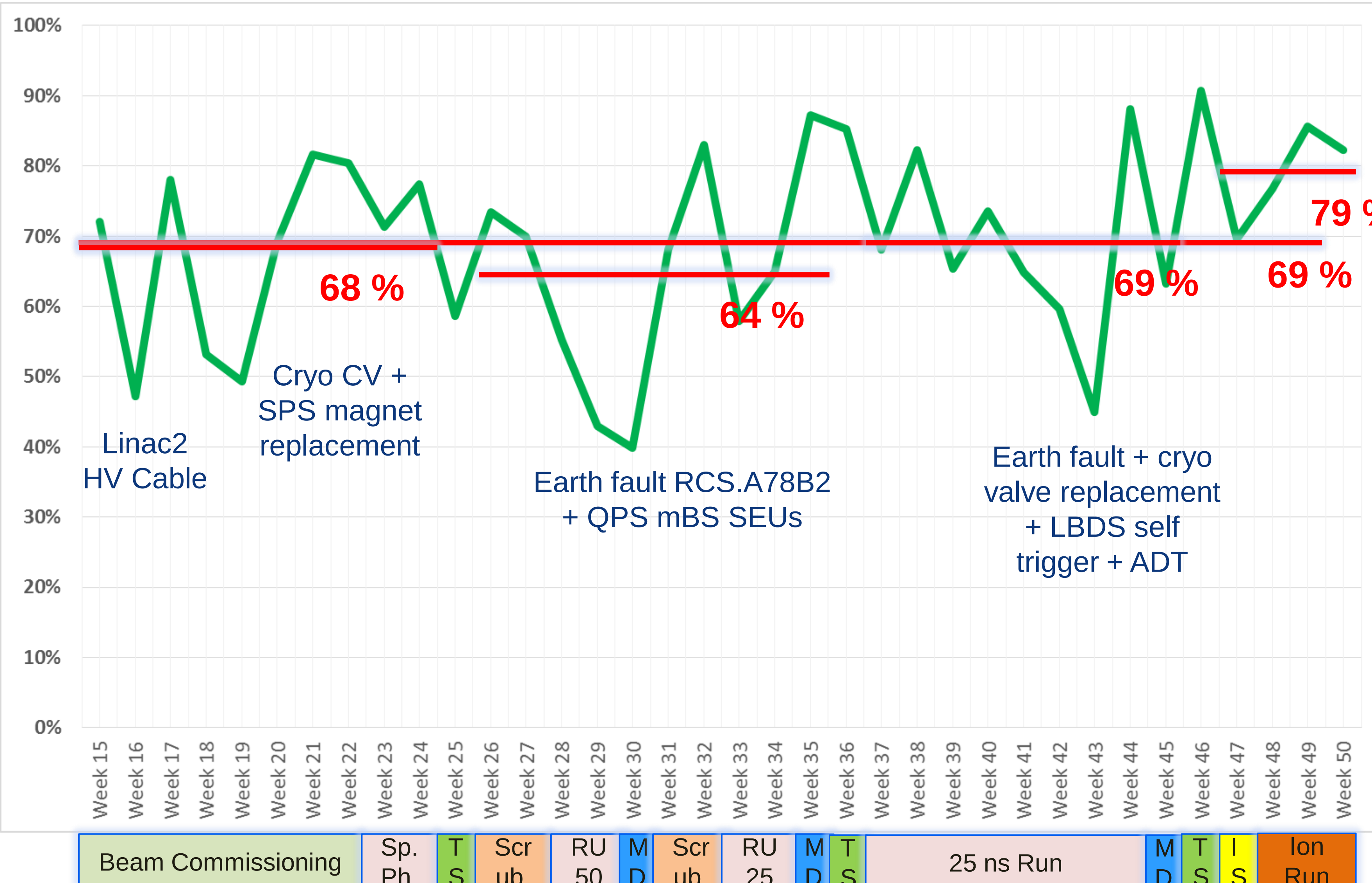
Failure Mode

Equipment Viewpoint

"Availability Matrix"



2015 Availability



Next steps for AWG

AFT 1.0 → AFT 2.0: Add equipment group information TE/MPE and TE/EPC already started work

New Analysis Requests

E.g. "what is the influence of energy / intensity on availability?"

E.g. "why was the ion run having such high availability?"

AFT & AWG in the Injectors: It is possible to propagate the AFT tool, primary focus of AWG is the LHC

How to approach this?

Day to Day

data validation and continuous improvement of the AFT remains a core aspect of the AWG

effort to maintain fault data increased x3 – used to be a part-time job…

Dedicated (long-term) resources required!

Strategic View

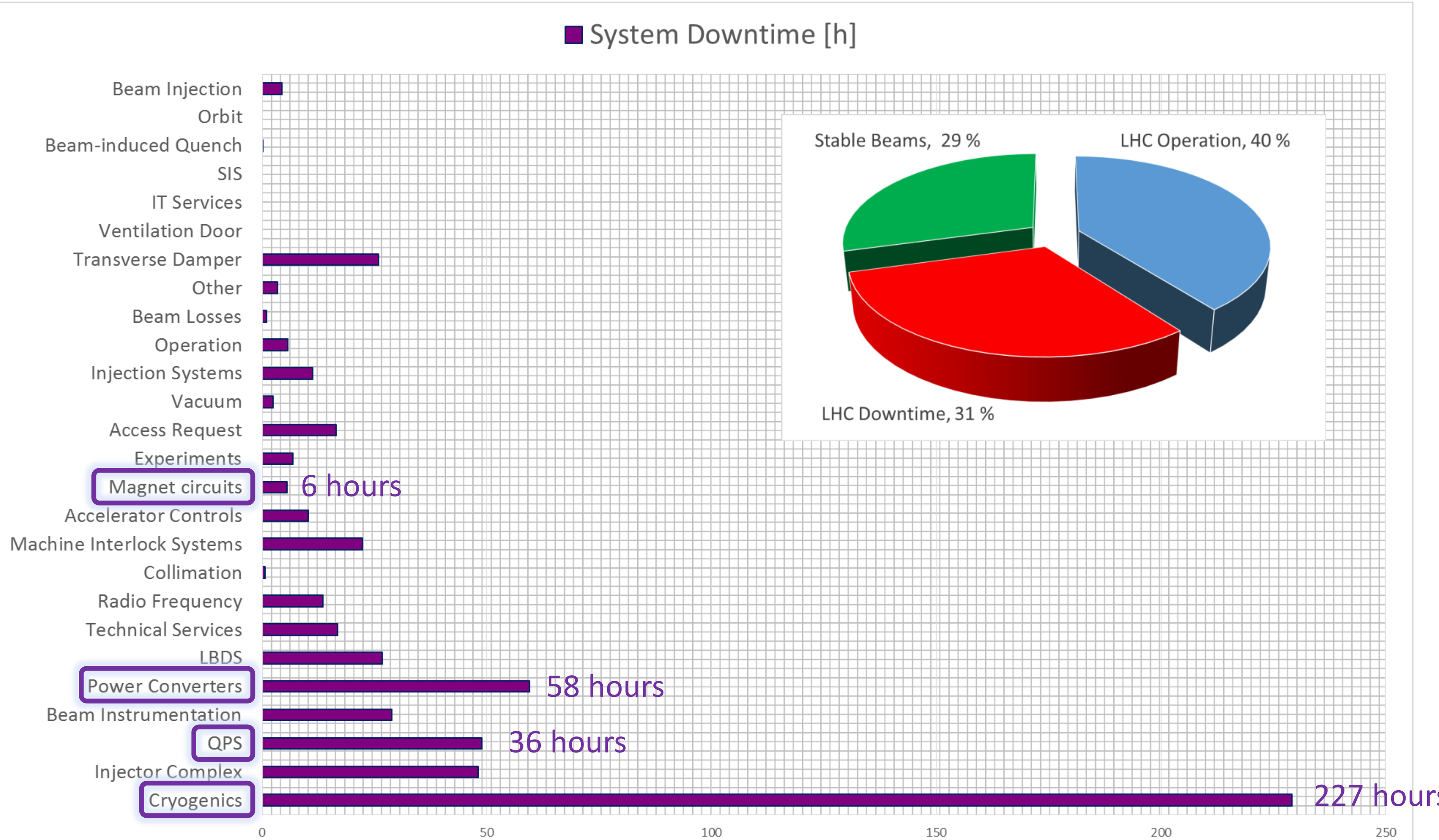
information created for the LHC can be exploited for HL-LHC, FCC, …

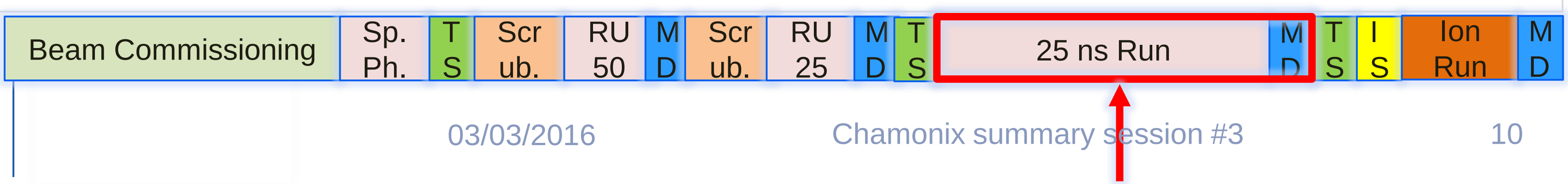
new and existing machines are being designed facing availability as a primary deliverable.

AFT information should be able to be used to create generic models

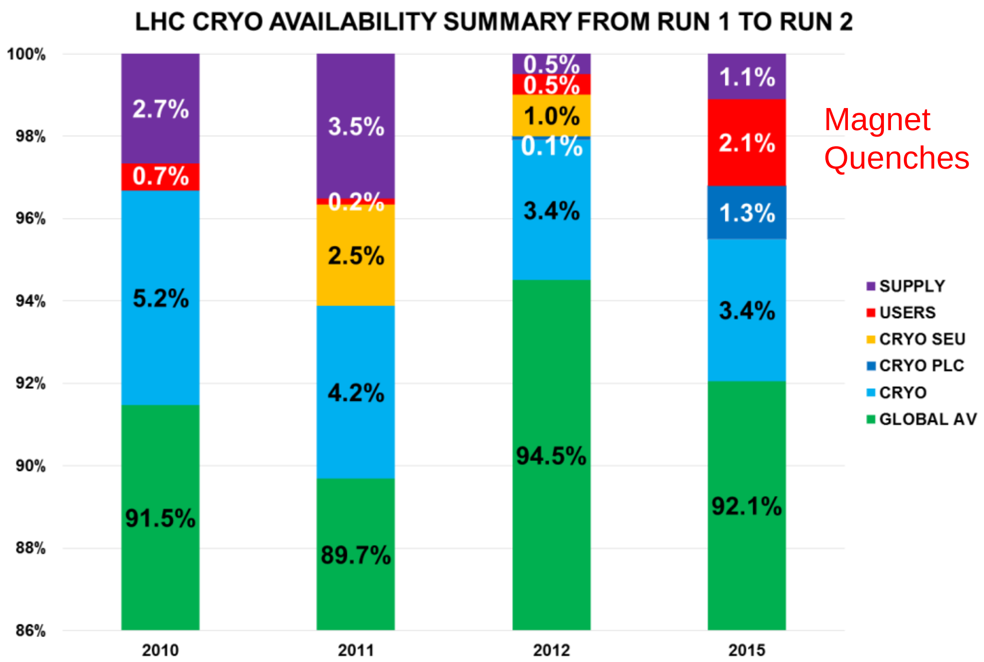
Centralised modelling & strategy into a different dedicated (sub-) working group

2015 Availability – TS2 to TS3





Cryogenics in 2015



Most frequent CM losses:

- **DFBMI**: 39 losses; addressed during YETS
- **DFBAF**: 29 losses; Trigger origin tbd with stakeholders (thresholds, timer…)

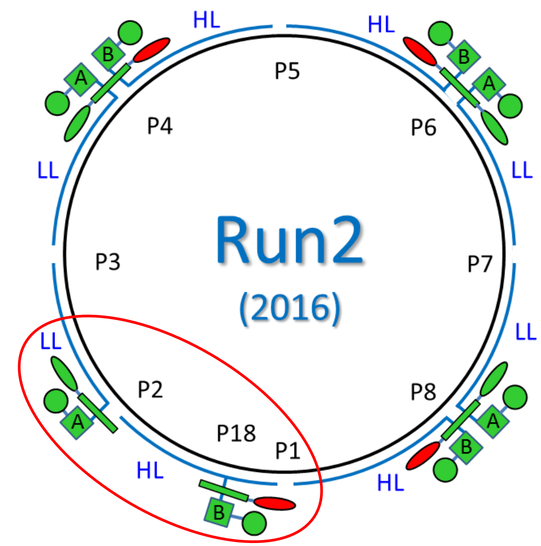
Most time-consuming CM losses:

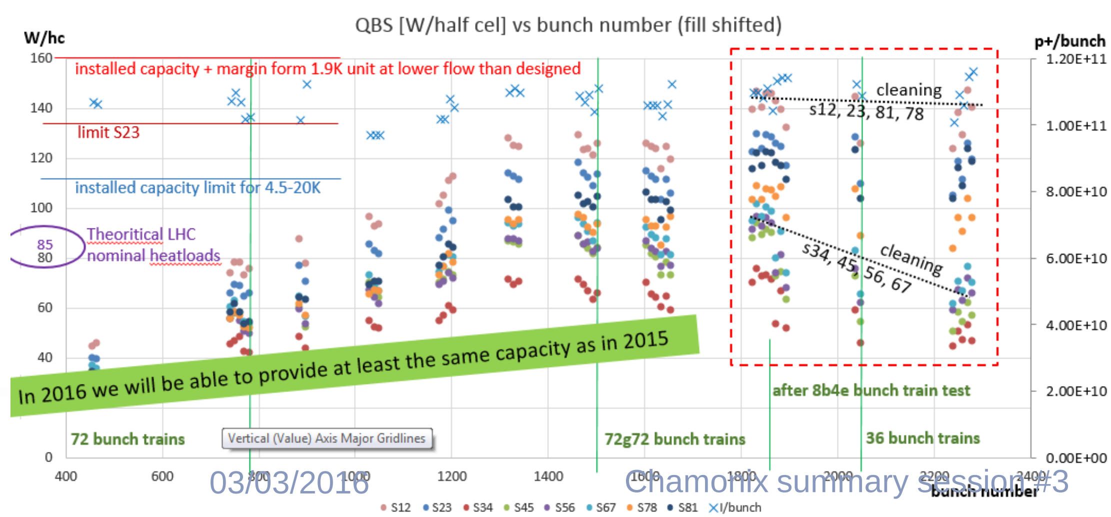
- **1.8 K units**: 8 losses, Average equivalent to Run1; should decrease if new configuration P18/P2 works well.
- **PLCs**: 4 losses, should be solved with new firmware during YETS
- **OP/Human factor**: 9 losses; should be partially solved by process optimization under high BS load
- **Elec/Instrumentation/Tunnel**: 22 losses; Average equivalent to Run 1

Downtime in line with Run1, despite higher beam induced heat loads

Cryogenic outlook for 2016 operation

- Further testing during cool-down
  - to minimize number of rotating machinery to improve the global availability
  - boost cooling capacity of cryo-plant in P2 and BS cooling power for S23 (non symmetric configuration)
- Continuous improvement of software to fulfil cryogenic power increase (anticipation of thermal load on BS,...)
- Data mining to detect drifts and anticipate issues
- Expecting 93-95% of availability during 2016





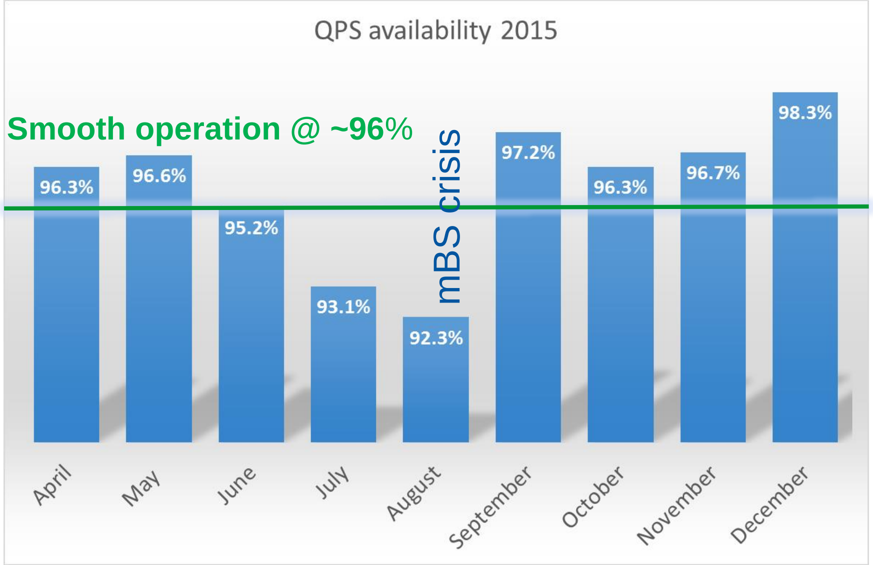
QDS system dependability in 2015

Challenging year after major system upgrades during LS1

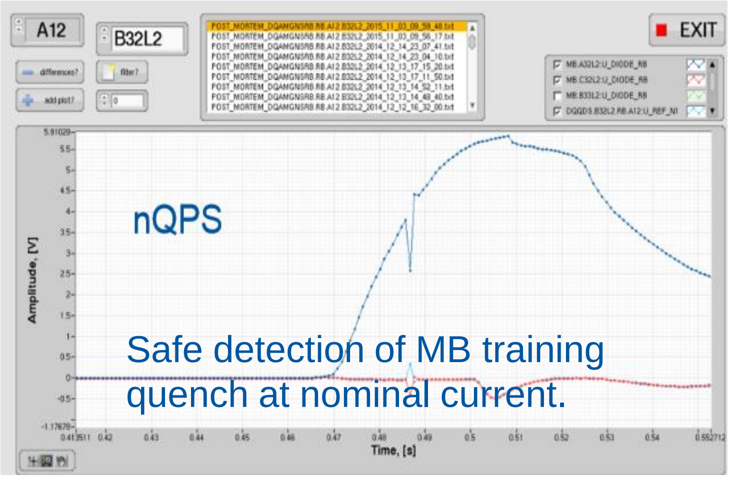
- Overhaul of MB protection system (yellow racks)
- Revision of safety critical firmware
- Automatic system configuration and verification
- Relocation of equipment (Inner Triplet protection)
- Deployment of radiation tolerant electronics (IPQ, IPD)

Enhancement of supervision & diagnostic capabilities

- Enhanced quench heater circuit supervision
- Earth voltage feelers
- QPS fieldbus upgrade
- CSCM for all sectors (objective added in 2014)



Note: $A_{QPS} = (T_{OPERATION} - T_{FAULT(AFT)})/T_{OPERATION}$



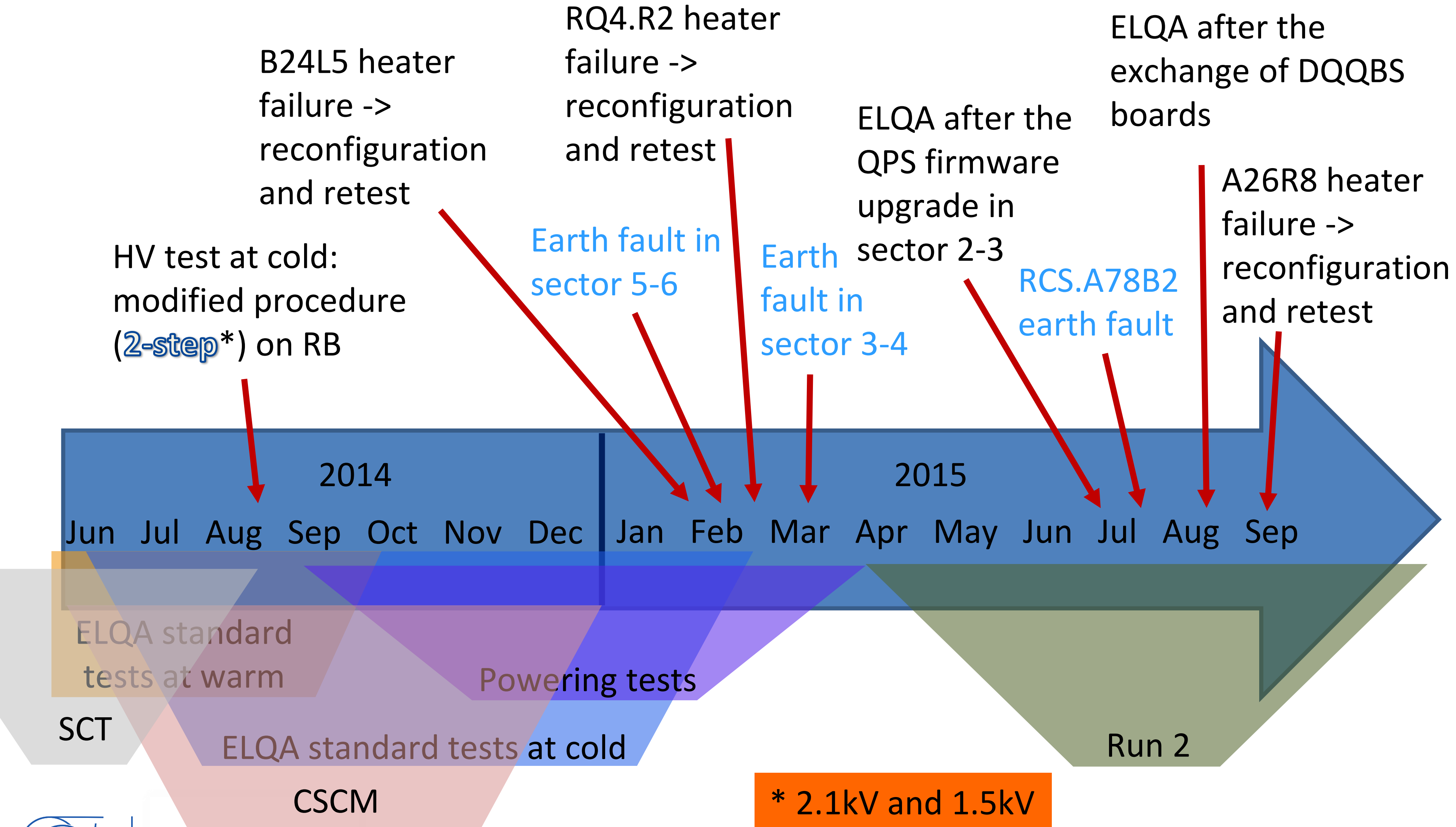
Very (=100%) reliable operation and effective protection of superconducting circuits

Detection of 40 main dipole quenches during proton run 2015

QDS Outlook for 2016 operation

- Firmware upgrade for nQPS DAQ systems
  - Sampling rate for earth voltage feelers increased to 10 Hz
  - Better detection and recovery of local communication faults; transparent error handling
- Deployment of radiation tolerant QDS for 600 A circuits
  - Mandatory for radiation exposed areas in point 1, 5 and 7
- Considering a successfully implementation of the ongoing upgrades:
  - The same level of availability as in 2015 after TS#2 (~98%) should be feasible despite the increasing radiation load
  - The system maintainability is expected to improve, mainly to the better handling of certain error types
- The complexity of the system remains a challenge

Magnet Circuits chronology (highlights)



Outlook & Actions Magnet Circuits 1/2

- Completing feasibility studies for new methods on earth faults localization with use of additional signals:
  - U_{diode} to be triggered by earth faults
  - Current measurement transformers at the level of the current leads
  - Current measurement in grounding loops
- New hardware for “curing” known fault cases:

  “weak-spot blower” – new, more controllable version required, possibility to cover larger V-range as shorts may occur above the HDS level (900 V)

- Studying the margin with respect to lifetime for some large scale systems (e.g. capacitors in HDS)
  - Special aging tests should allow to get an estimation of the remaining (statistical) lifetime

Outlook & Actions Magnet Circuits 2/2

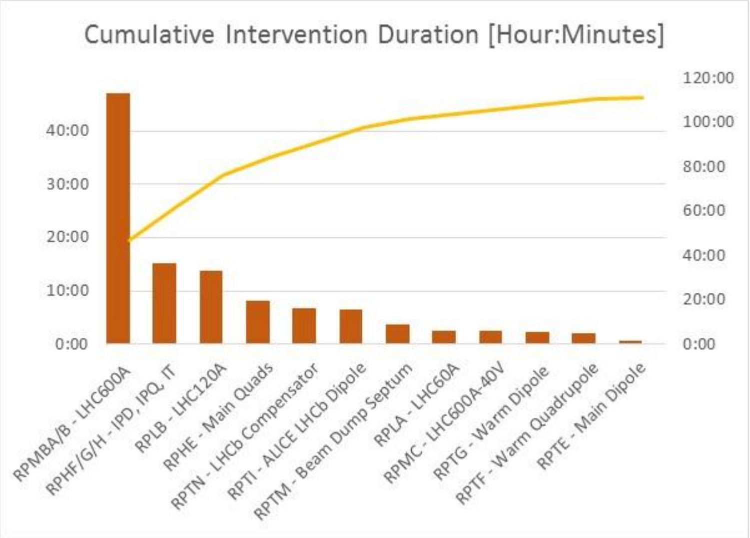
- Monitoring of the long term evolution of high-current joints' resistance in main circuits + possible design of appropriate tooling for applying torques in a controlled manner
- Spares for 600A switches should be envisaged
- Galvanic separation in an automated manner of warm and cold parts of the main circuits by means of a 'disconnector' would help reducing intervention times, minimizing manipulation risks and improving safety. Technical and financial feasibility of this in the LHC main circuits should be analyzed
- Some of above tasks are not yet programmed, manpower efforts should be properly estimated

Courtesy Kurt Artoos, EN

Power converter 2015 performance

- Important consolidation activities during LS1 (R2E relocation, diode replacement in IPD/IPQ/RQF/RQD output, auxiliary power supplies…)
- Top 3 of the main downtime contributors (80% of the intervention duration) :
  - LHC600A-10V converters
  - LHC4-6-8kA / IPD, IPQ, Inner Triplets converters
  - LHC120A-10V converters

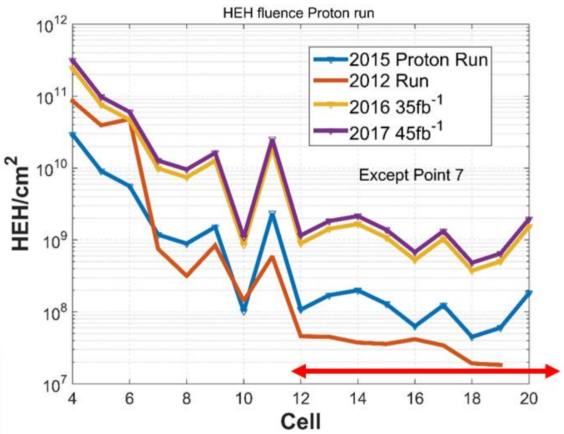
CONVERTER TYPE	CUMULATIVE INTERVENTION DURATION [H:MN]	NUMBER OF INTERVENTIONS	CONVERTER QUANTITY
RPMBA/B - LHC600A	47:00	38	394
RPHF/G/H - IPD, IPQ, IT	15:15	12	188
RPLB - LHC120A	13:45	15	291
RPHE - Main Quadrupoles	8:15	4	16
RPTN - LHCb Compensator	6:45	5	3
RPTI - ALICE LHCb Dipole	6:30	4	2
RPTM - Beam Dump Septum	3:45	1	2
RPLA - LHC60A	2:30	5	750
RPMC - LHC600A-40V	2:30	1	36
RPTG - Warm Dipole	2:15	3	4
RPTF - Warm Quadrupole	2:00	2	4
RPTE - Main Dipole	0:45	1	8



Important for orbit stability/FB!

Power converter outlook for 2016 operation

- Several mitigations (software, interlock masks and procedure improvements) put in place during YETS to further increase availability
- R2E remains concern, FGClite will progressively replace the FGC2 until 2017



Year	Control Part	Power Part	Beam Dump
2015	5	0	3
2016	31	4*	21
2017	1	6*	4

FGClite Installation

** Pessimistic Case : 0 fault in 2015*

Ratio linked to Operational redundancy

Outline session #4

6 talks:

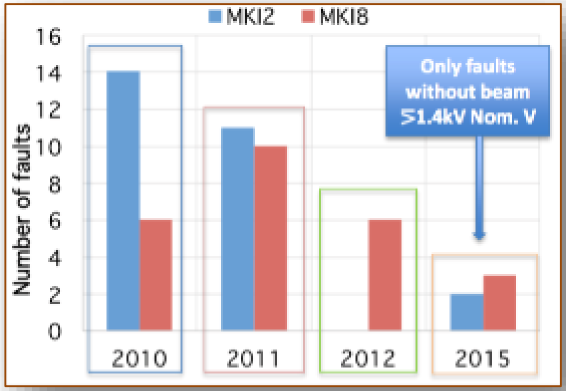
- LBDS and injection protection **C.Bracco**
- RF/ADT **A.Butterworth**
- Beam Instrumentation **W.Vigano**
- Technical infrastructure **R.Ledru**
- Radiation to electronics – R2E **S.Danzeca**
- Availability in view of increasing beam energy to 7 TeV **R.Schmidt**

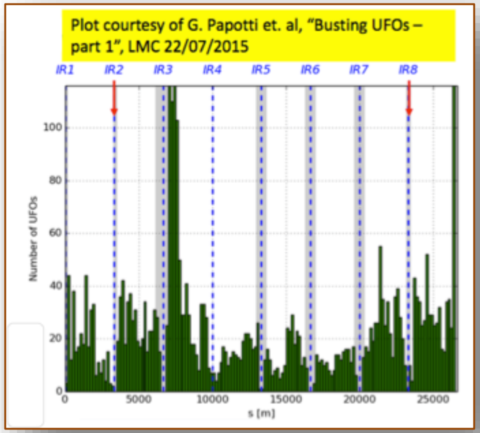
Injection - MKI

25 ns downtime = 25 hours
(for all beam transfer systems)

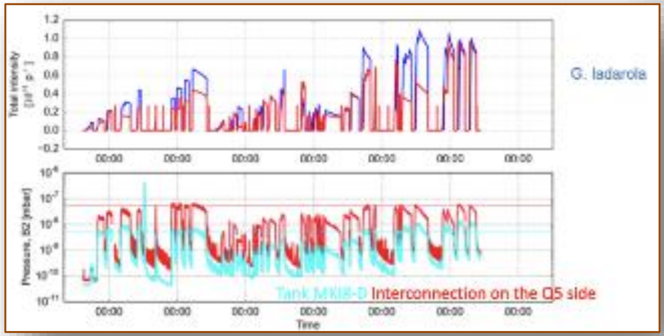
Main goals of LS1 activities:

- Improve high voltage performance
- Reduce:
  - Ferrite MKI yoke heating
  - Pressure rise and e-cloud
  - Number of UFOs

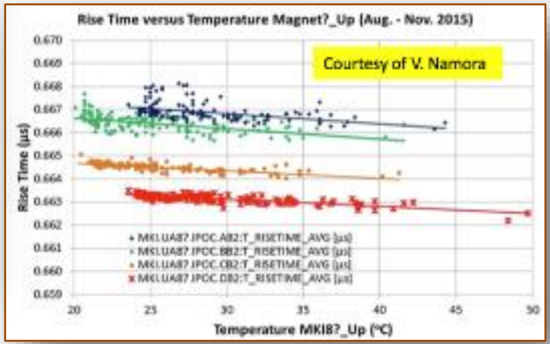




UFOs @MKI
have disappeared



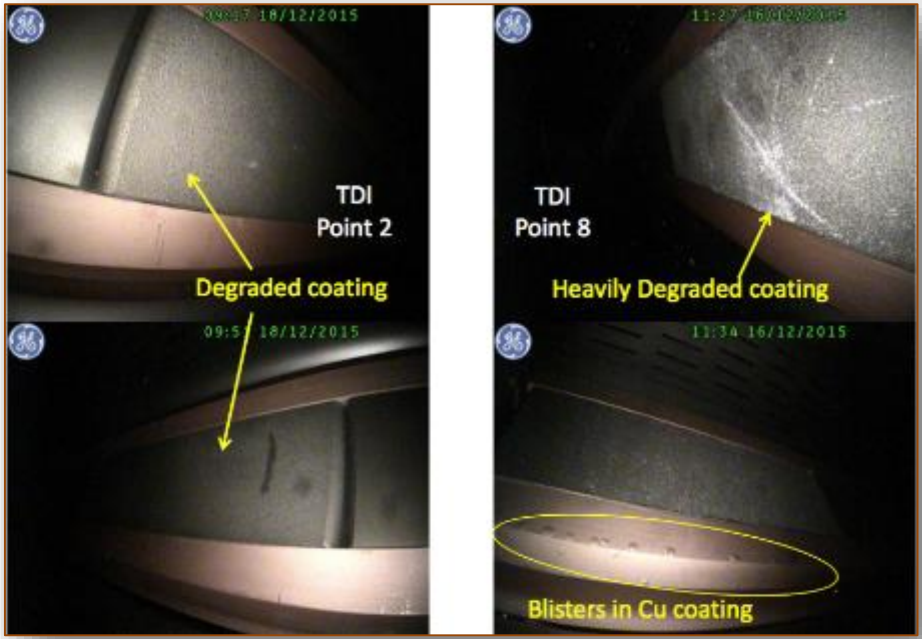
Q5 interconnect occasionally limited operation.
Improvements under study

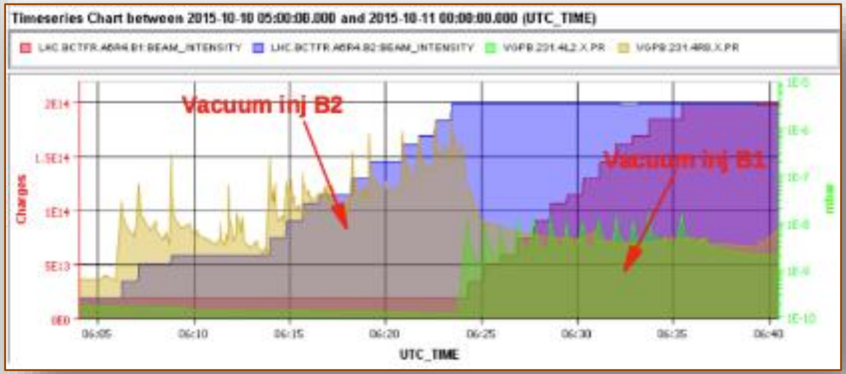


No stop/delay in
2015 operation

Injection - TDI

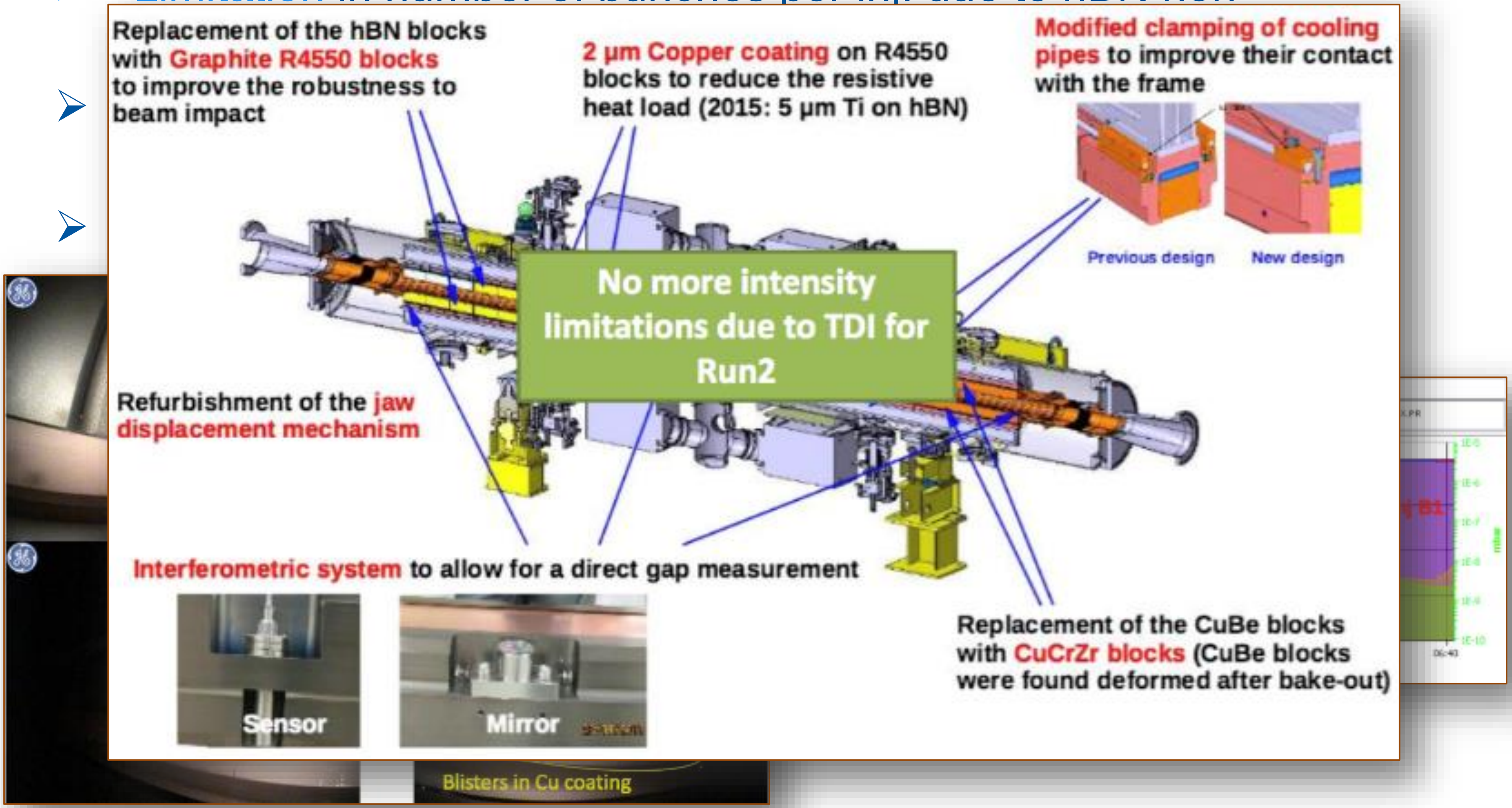
- Limitation in number of bunches per inj. due to hBN non-conformities
- Significant pressure rise during injection and spurious spikes during fill with jaws retracted
- Much worse behavior for TDI in IP8





Injection - TDI

- Limitation in number of bunches per inj. due to hBN non-



LBDS

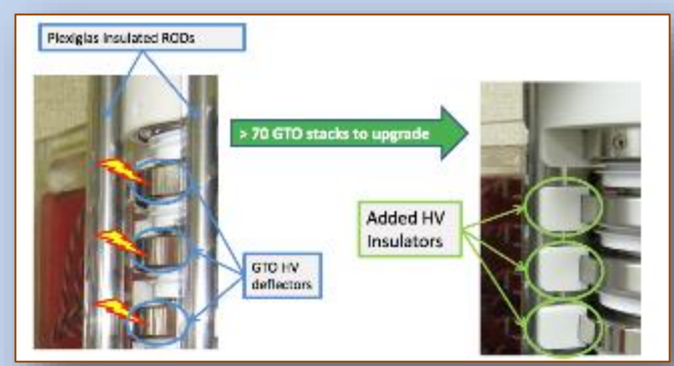
Estimated false dumps: 8 (±2) per year

➔ 24 false dumps foreseen for 3 years of LHC operation (2010-2013)

Observed 29 false dumps

MKD

Main aim:
Reduce spontaneous triggers (reliability) and radiation resistance



Correlation between dust presence inside generators and sparking activity was found…as result of the cleaning **only one asynchronous dump** with beam in 2015

Estimated async. dumps @ 6.5 TeV:
3 per beam per year

Modifications planned in LS2 to allow operation at 7 TeV

R2E: No SEB in 2015 (no limitation for 7 TeV)

Future activities for LBDS and injection

Run 2

- **TCDI:** < 144 BCMS bunches before LS2 (transmission problems)
- **TDE:** HW interlock on N_2 pressure to be added as soon as possible

Run 3

- **TDI:** new hardware will be installed during LS2
- **TCDI:** new HW with 2.1 m jaws in LS2
- **MKB/MKD:** switch modification needed to go to 7 TeV

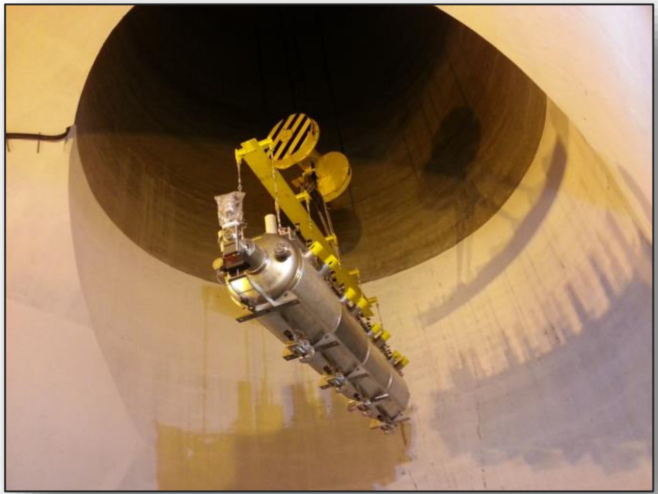
HL-LHC

- **MKI:** Several interventions are foreseen for LS2 and LS3
- **TCDD:** additional mask at D1 is needed
- **TCDQ/TCSP/TCDS/TDE:** ongoing studies to define optics constraints and if any HW issues are present
- **TDE:** solution to avoid overheating is being studied

RF

RF - LS1 ACTIVITIES

- All HV connectors repaired ➔ no more klystron filament glitches
- 8/16 klystrons replaced to avoiding aging
- Crowbars: Thyratrons replaced by Solid State devices (better performance & reliability) ➔ no more spurious crowbar trip
- Replacement of faulty cavity
  - Cavity 3 B2 was quenching at 2 MV (clamped at 1.2 MV during Run1)
  - Decided to replace *America* cryomodule by the spare module *Europa*
  - Conditioning in pulsed mode to burn emitters was successful ➔ Nominal performance re-gained…***America* is now a valid spare!**



Potential limitation in spare production in case *America* is used

RF

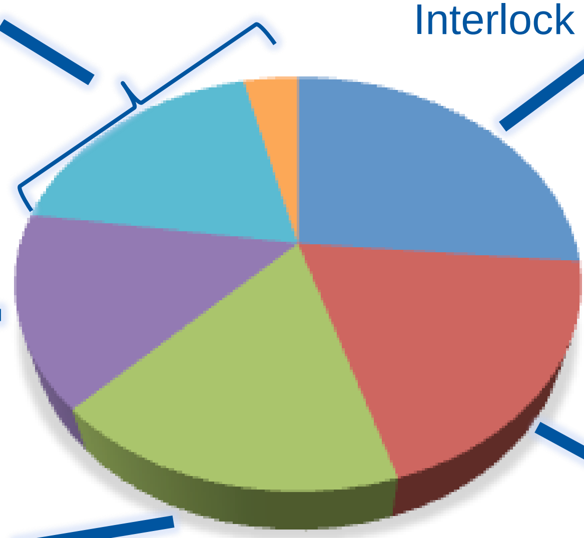
25 ns downtime = 13 hours

RF FAULTS IN 2015

- **57 RF and HV trips** recorded, 76 hours downtime
- **13 beam dumps** (all during 25 ns run)

23% LLRF and control
Several components replaced

26% Mitigated faults
Interlock levels, T glitches,…



15% beam related faults
Conditioning to 300 MW in 2016

17% HV faults
Real crowbar issue, soon after restarting RF

26% Child faults
Cryo loss, electrical glitches,…

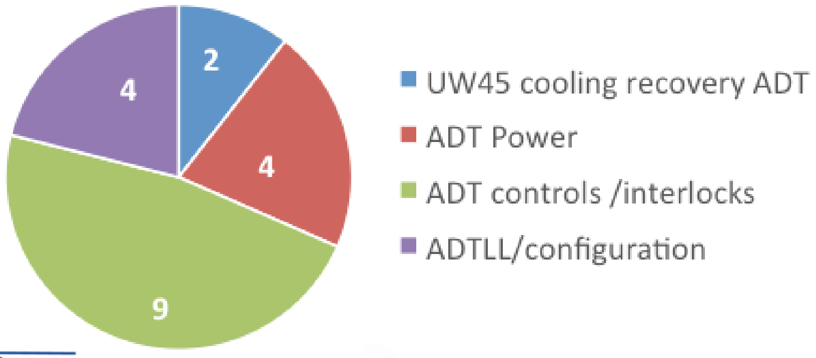
ADT

25 ns downtime = 23 hours

ADT - LS1 ACTIVITIES

- More performant signal processing HW
- Proper integration of all new functionality added during Run 1:
  - Fully independent feedbacks for main loop and witness bunches
  - Abort gap and injection gap cleaning
  - Blow-up
  - Excitation functionality through the whole cycle

18 ADT faults in 2015



Good hardware availability

- Few minor isolated issues

Few operational issues identified

- Monitoring of performance
- Settings management

Beam Instrumentation

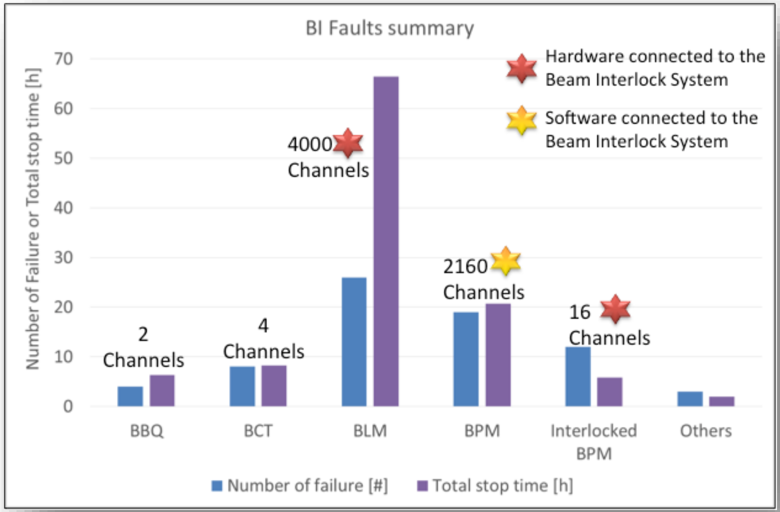
ACTIVITIES TO INCREASE AVAILABILITY

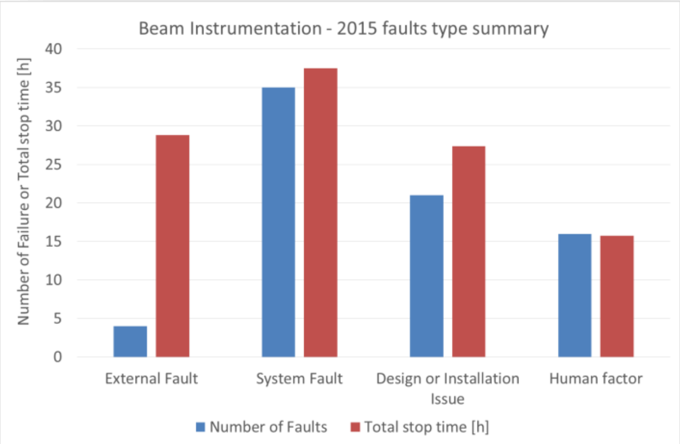
- **Online monitoring**
  - Improving analysis tools to quickly understand system status
- **Offline monitoring**
  - Daily checks to control parameter degradation
- **New event warning**
  - Automatic alert to experts in case of parameter change
- **Test benches**
  - e.g. Orbit feedback software test bench
- **Intervention time reduction**
  - Creation of dedicated piquet service with piquet manual

Among others, BE-BI Group would profit from a longer term Reliability Analysis team

Beam Instrumentation

25 ns downtime = 20 hours





All **75 faults** analyzed and divided in 4 categories:

- External faults
- System faults
- Design and installation
- Human factor

Failure Type	Number of failures [#]	Total stop time [h]	Contribution Percentage
External Fault	4	28.8	26%
System Fault	35	37.5	34%
Design Issue	21	27.4	25%
Human factor	16	15.7	14%

No R2E failures thanks to heavy testing at design stage

Technical infrastructure

A **Major Event** is created when a technical problem stops an accelerator

DATA QUALITY IS CRUCIAL

TI has well established process to analyze and handle Major Events

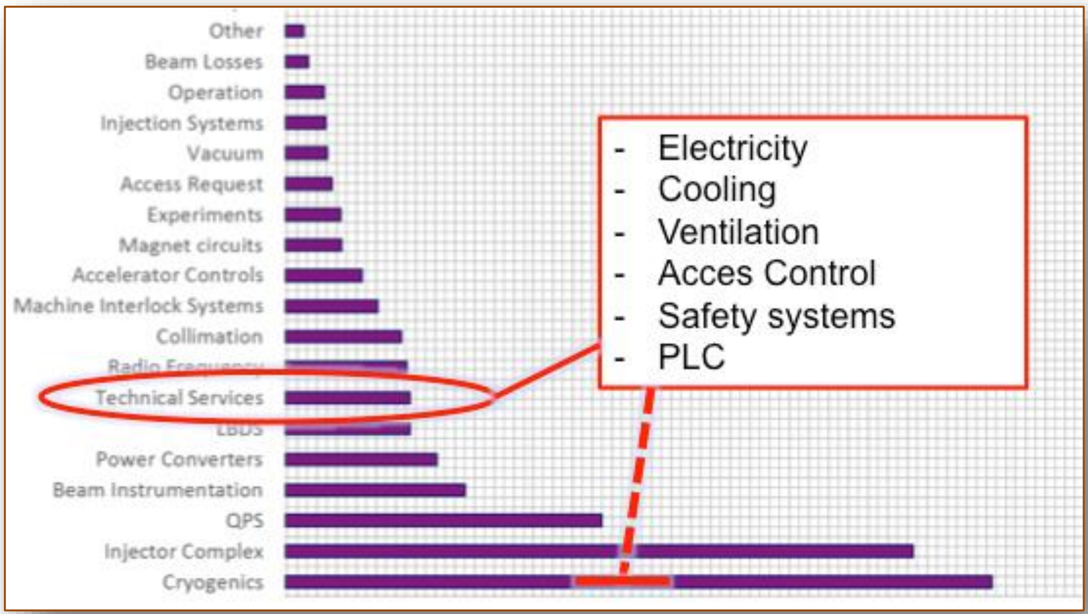
- Link to data from the machine logbooks
- Associate the fault to a precise device (Computerized Maintenance Management System)
- Determine fault category
- Major events review by Technical Infrastructure Operations Committee (TIOC) weekly

Technical infrastructure

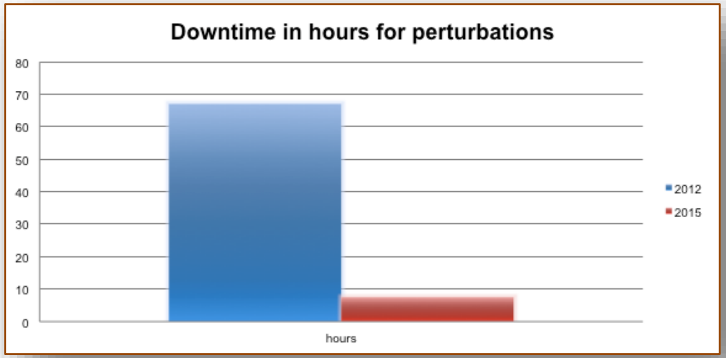
25 ns downtime = 12 hours

101 major events on LHC in 2015

(57 needing access)



Big efforts in LS1 to make equipment less sensitive to perturbations

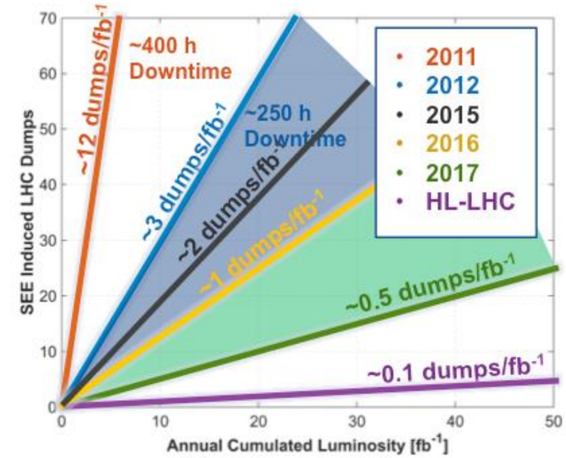


R2E

Equipment	Dumps 2012	Dumps 2015 (After TS2)	Dumps 2016 35fb-1	Dumps 2017 45fb-1
QPS	32	2+1	0-5	0-5
Power Converter	15	5+2	~25	0-10
Cryo	4	0	0	0
EN/EL	1	0	0	0
Vacuum	4	0	0	0
Collimation	1	0	0	0
RF	1	4*	?	?
Others (hidden)	-	-	0-10	0-10
Total	3 /fb^{-1}	~3.4 /fb^{-1}* 2.3 /fb^{-1}	~1-1.5 /fb^{-1}	~0.5 /fb^{-1}

* To be confirmed

R2E limitation strategy



- Failure rates proportional to radiation level
- Several equipment installed in the tunnel: QPS, EPC, Cryo,…

LHC Era	Machine Energy	Integrated Luminosity	Radiation Dose in Arc	Radiation Dose in DS
	[GeV]	[fb-1]	[Gy/year]	[Gy/year]
Run 1	3.5/4.0	~30	<<1	~10
Run 2	6.5/7.0	~100	~1	~20
Run 3	7	~300	~2-4	~40
HL-LHC	7	~3000	~4-8	~80-160

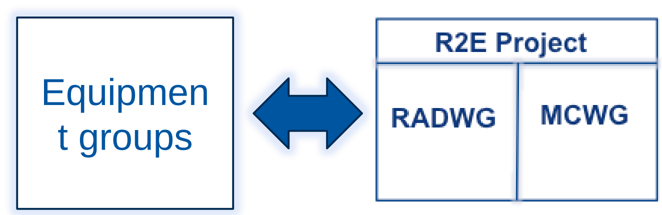
from R2E Availability workshop 2014

R2E – recipe for the future

- **Equipment inventory**
  - Knowledge of installation in critical areas and failure tracking
  - Radiation testing coordination
- **Radiation Monitoring**
  - Global and local level (failure points, DS and ARC) in order to foresee an equipment rotation
- **Follow new component developments**
  - Radiation Hardness Assurance (**RHA**) dedicated guidelines should be used for development of new HW

Strong collaboration is mandatory!!!

- Equipment groups
- Radiation Working Group (RADWG)
- Monitoring & Calculation Working Group (MCWG)



Availability for 7 TeV

- It is premature to run today the LHC at 7 TeV
- The long time needed for training (400 to 700 quenches expected) will eventually affect integrated luminosity
- Several aspects to be studied and better knowledge to be acquired on:
  - Magnet system
  - UFOs
  - MKD
  - Cryogenic system
- Increasing availability is possible by small steps, but they contribute to higher availability when integrated over many years

Availability for 7 TeV

	Systems	Impact of 7 TeV operation on availability
1	Injector complex	No change
2	Injection systems	No change
3	Beam injection	No change
4	Access system	No change
5	Machine Interlock Systems	No change
6	Accelerator Controls	No change
7	Technical services (electricity supplies, ..)	No change
8	Beam Instrumentation	No change
9	Transverse damper	No change
10	Magnet protection system (QPS)	No change
11	Experiments	No change
12	Vacuum	No change
13	RF	No change
14	Cooling and ventilation	No change
15	Collimation	No change
16	Beam Dumping System	Potentially worse
17	Power converters	Potentially worse
18	Cryogenics	Potentially worse
19	Beam Losses (incl. UFOs)	Expected to become worse
20	Beam induced quenches (UFOs)	Expected to become worse
21	Magnet circuits	Expected to become worse

Priority for studies on availability increase!!

Availability in general

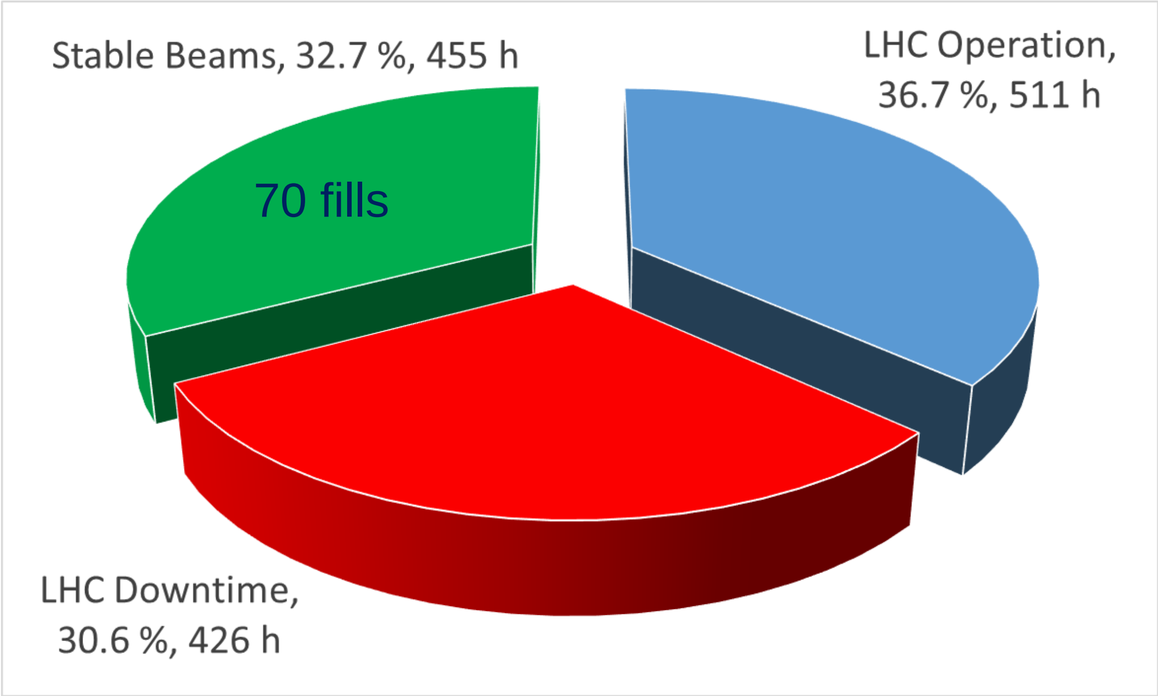
- An **availability working group** has been set up to pursue the studies on availability improvement
- The Accelerator Fault Tracking (AFT) is a fundamental tool to study availability and will soon be extended to other accelerators
- Information exchange between the different groups is a crucial ingredient (e.g. Single Event Upsets)
- Collaboration with many institutes has been started and proved to be very fruitful

Conclusions

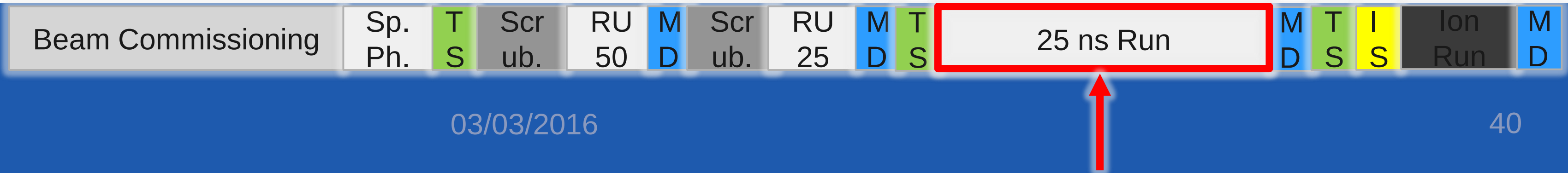
- Many efforts have been done to establish an "Availability culture" at CERN, but **further long-term efforts + resources are mandatory to meet ambitious goals**
- Availability plays a crucial role in complex accelerators, defining performance and ultimately the integrated luminosity
- Some points requiring thorough follow-up have been identified:
  - Potential limitations for 7 TeV (MKD, UFOs) – 2016 statistics
  - RF facility for spare generation
  - 'creative' ideas for availability increase
- LS1 activities have largely demonstrated beneficial for system availability
- AFT has proven to be the essential tool for availability studies and will be a powerful tool to identify priorities for future efforts

Backup Slides

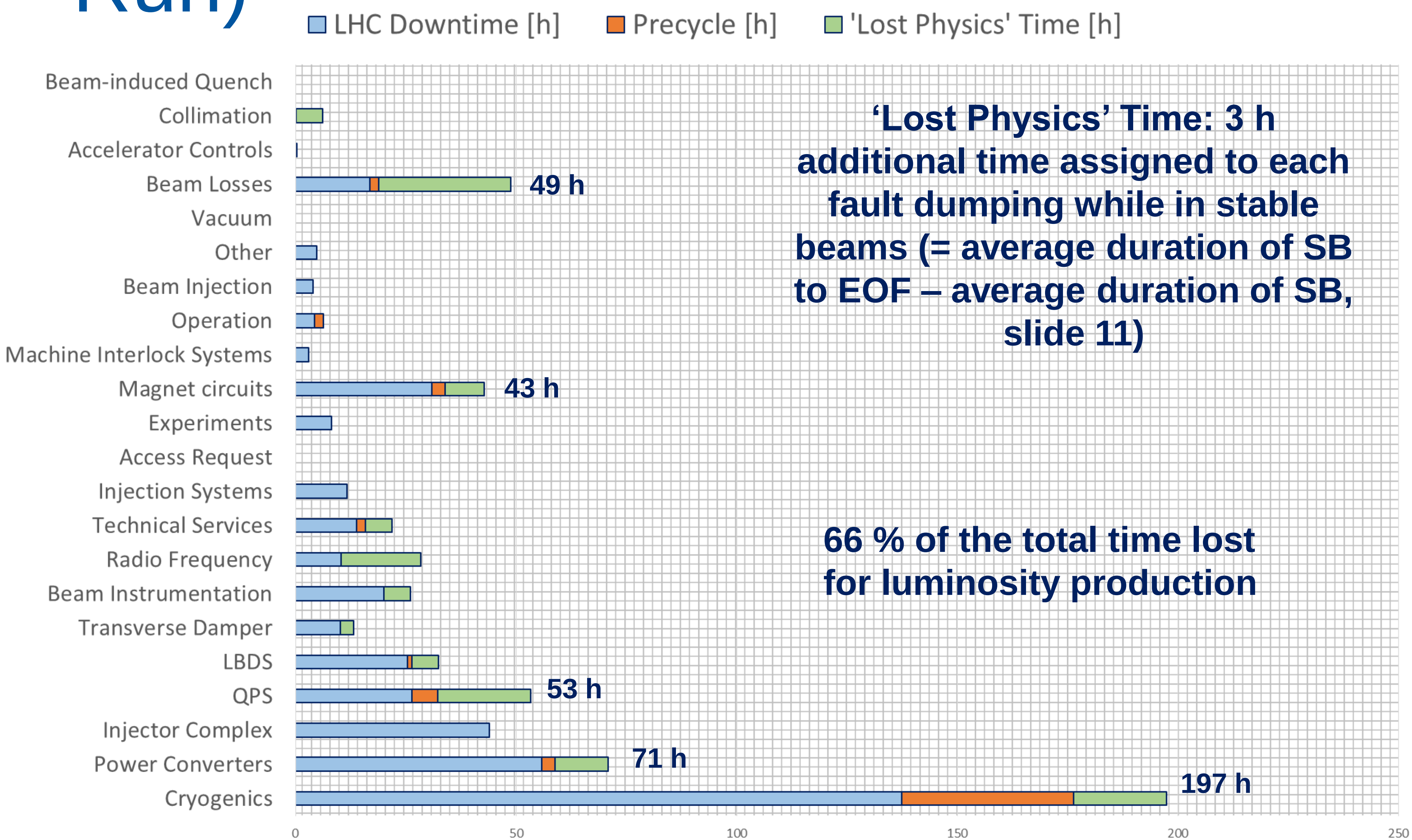
Availability for Physics – 25 ns Run



- 22 End-Of-Fill, 48 dumped due to faults
- Fraction of premature dumps: 48/70 = 68.6 %
- Average operational turnaround (per SB) = 511/70 = 7.3 h
- Average Fault time (per SB) = 426/70 = 6 h



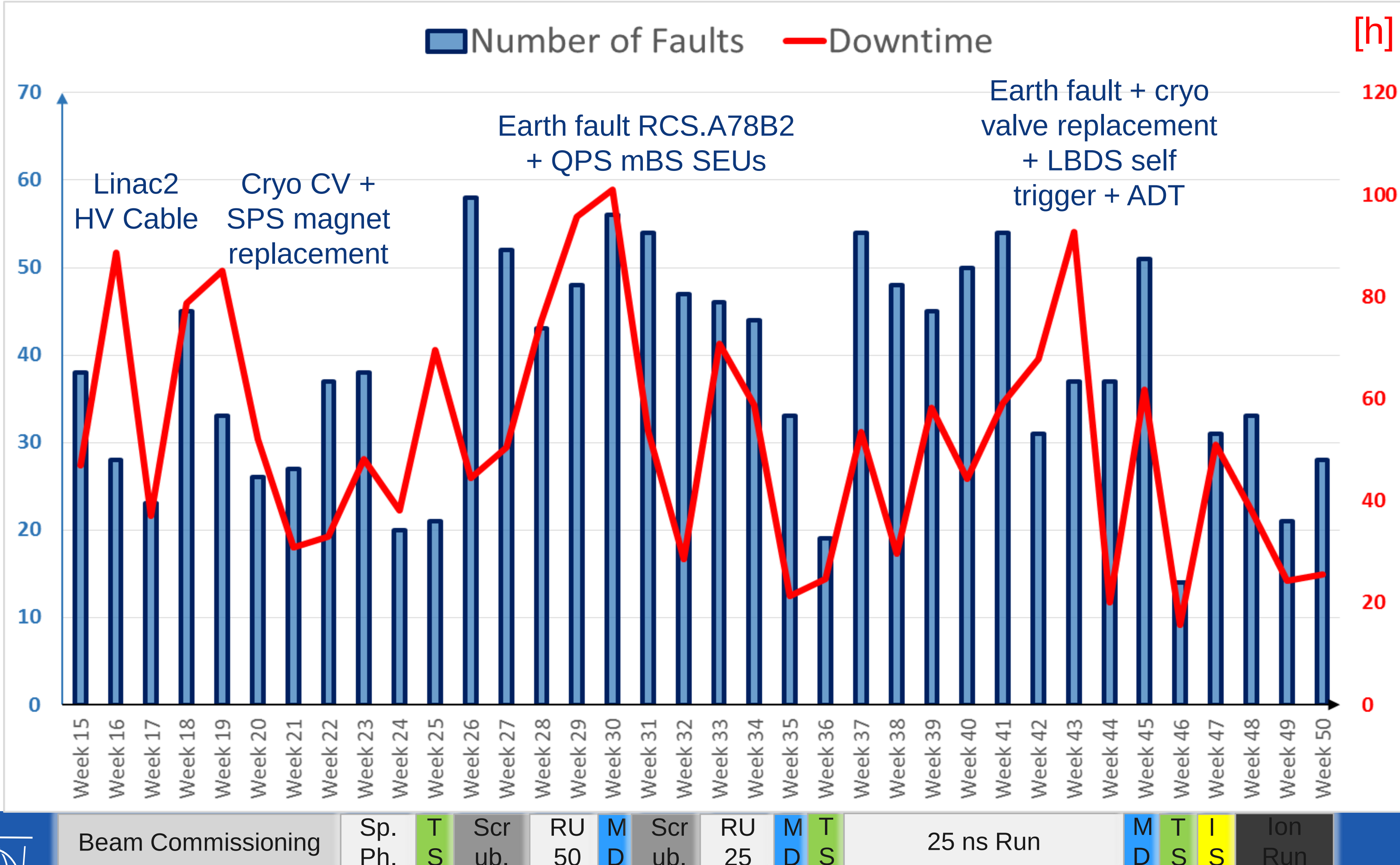
…Impact on LHC Operation (25 ns Run)



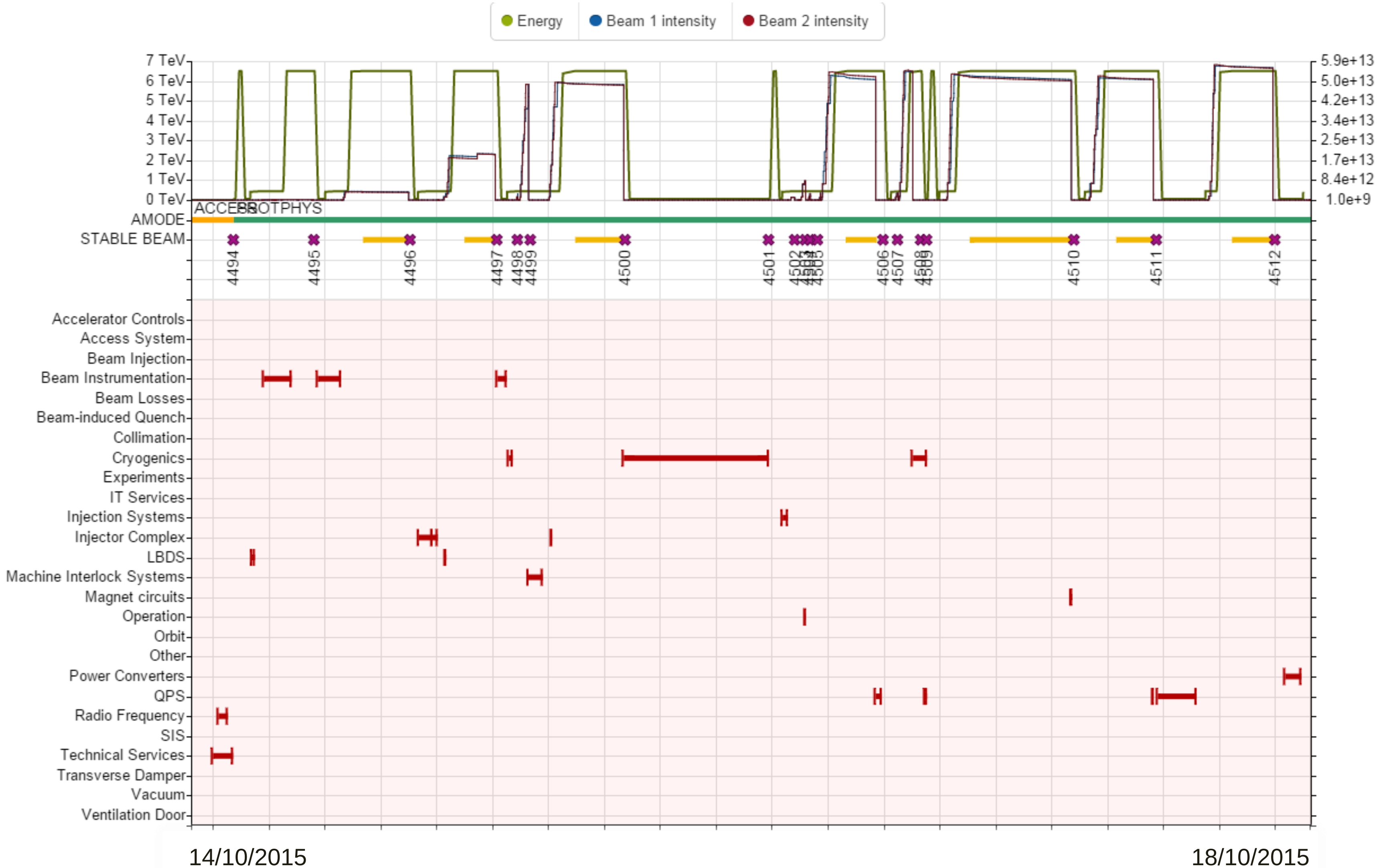
'Lost Physics' Time: 3 h additional time assigned to each fault dumping while in stable beams (= average duration of SB to EOF – average duration of SB, slide 11)

66 % of the total time lost for luminosity production

2015 Fault + Downtime Overview

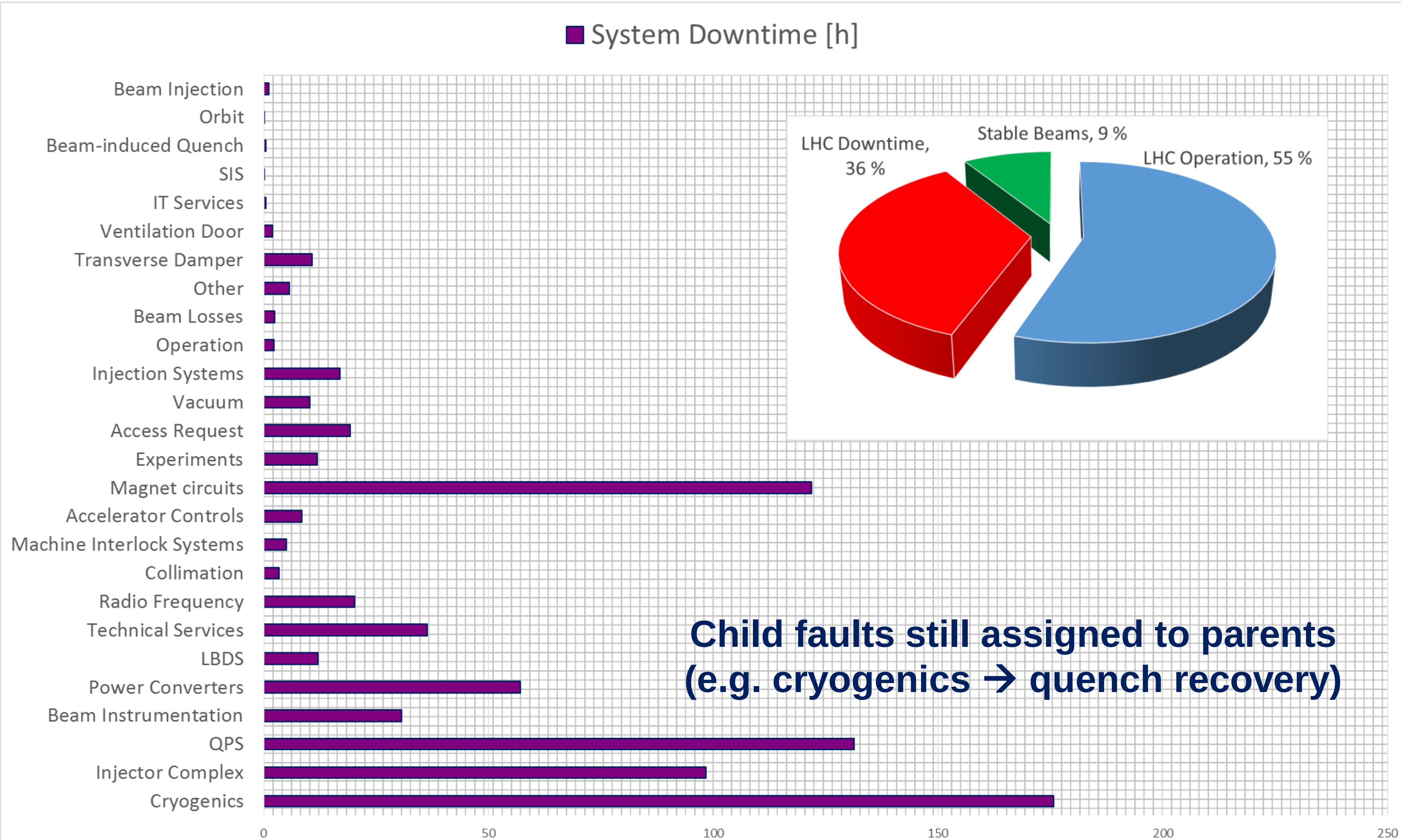


Standardized Availability Summary

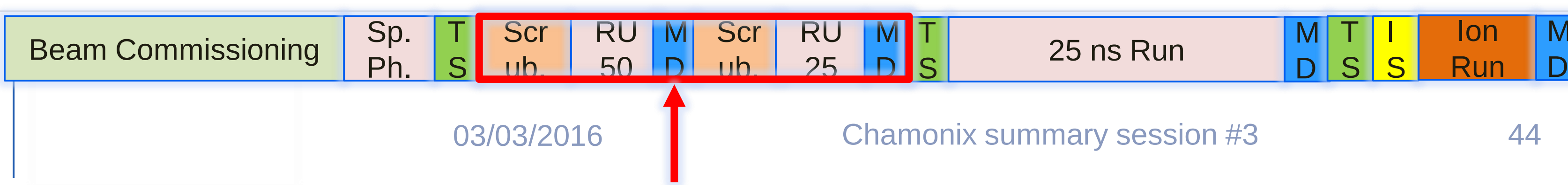


“Cardiogram” of LHC operation

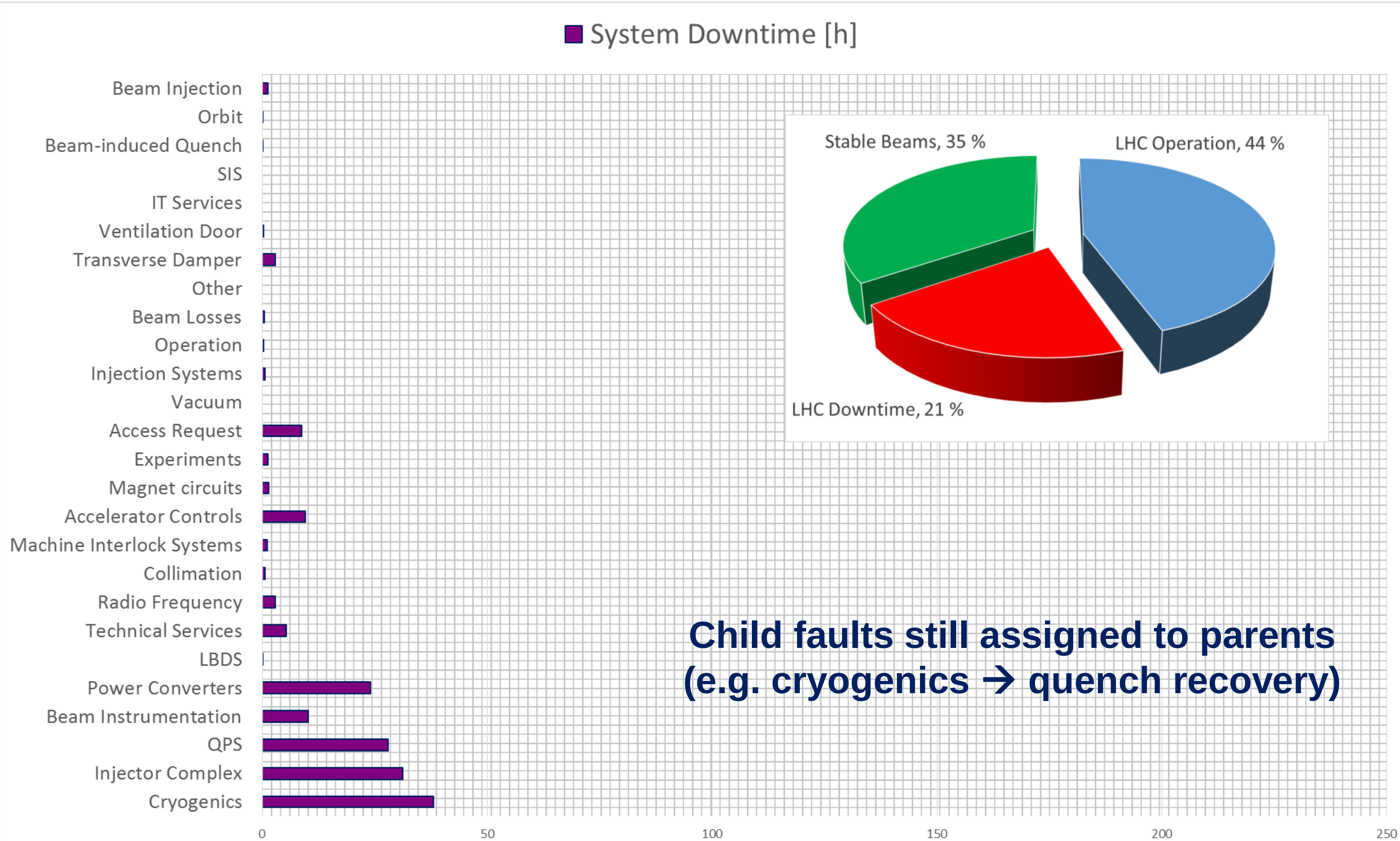
2015 Availability – TS1 to TS2



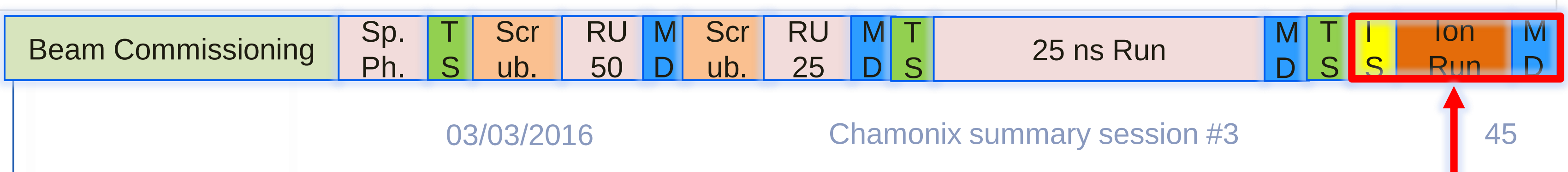
Child faults still assigned to parents (e.g. cryogenics → quench recovery)



2015 Availability – after TS3



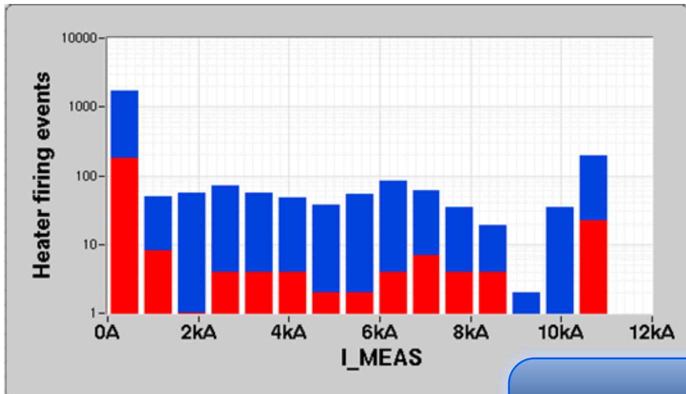
Child faults still assigned to parents (e.g. cryogenics → quench recovery)



Statistics for Heater Discharges on LHC main dipoles, 2014-2015

- Data provided by Zinur Charifoulline:

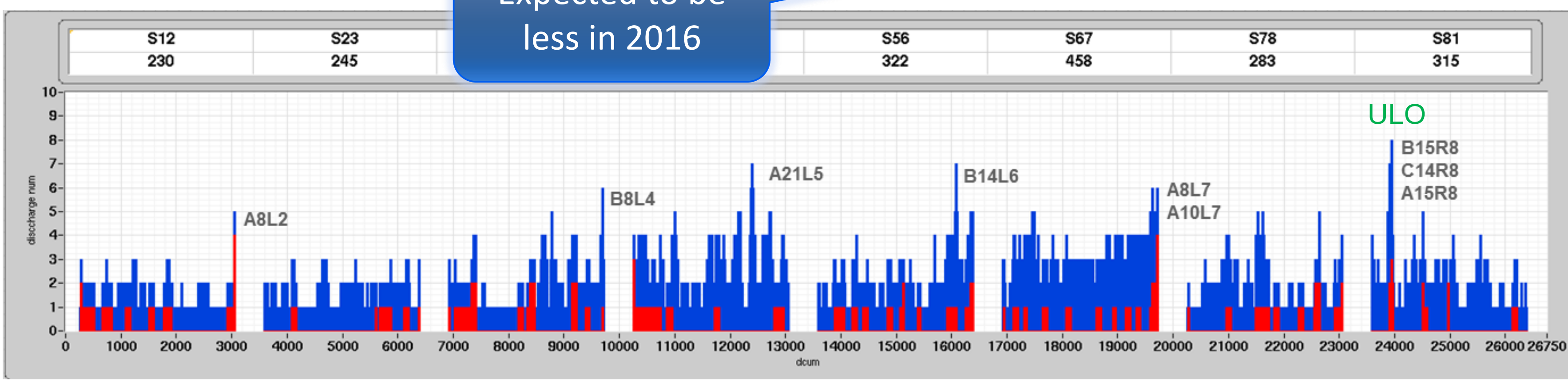
No firing campaign scheduled for 2016



Since October 2014 (QPS-IST included):
- ✓ 2533 full charge firings in total
- ✓ about 1660 firings at zero current

Since April 2015 (1st beam in the machine):
- ✓ 247 full charge firings in total
- ✓ about 175 firings at zero current

Expected to be less in 2016

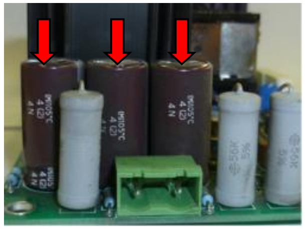


Power converters – Main LS1 activities

- Relocation of power converters [in UL14/16, UL557, TZ76]
  - Mitigation measure for Single Event Effect induced by radiation [R2E project]

- LHC600A-10V Converters
  - Consolidation of the Auxiliary Power Supply as mitigation measure for Single Event Effect [R2E project]
- IPD/IPQ and RQD/RQF converters
  - Output module consolidation due to diode case reliability issue and improvement of the thermal environment for a better reliability at 7TeV (full current)

- LHC60A converters
  - Consolidation of the Auxiliary Power Supply due to capacitor ageing



Availability increase, some ‘creative’ ideas

- Shorter shut-downs or less shut-downs?
- Very short technical stop over Christmas? Compatible with injectors?
- Reduced time for “Hardware and Beam Commissioning”?
- Reduced time for “Intensity ramp-up”?
- Do we need to switch off a sector when a fast power abort is generated?
- Can we delay the abort of a circuit in case of training quenches to generate multiple quenches (idea from 2007)?