



## Balancing machine availability and preventive maintenance for HL-LHC

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Many thanks to the AWG

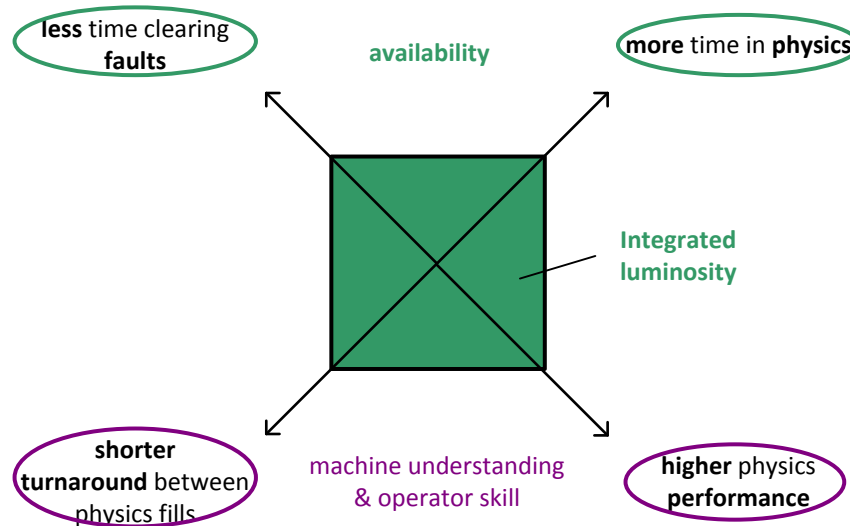


7<sup>th</sup> HL-LHC Collaboration Meeting, 13.-16.11. 2017, CIEMAT Madrid

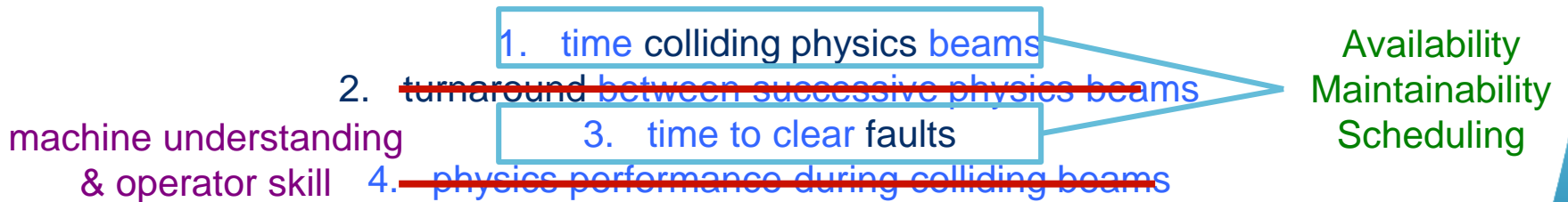
# Outline

- ❑ 'Charge' questions:
  - ❑ Availability: what do we gain (or loose) if we modify the allocation of preventive maintenance in the year?
  - ❑ The access in UR for the LSS does it help ?
- ❑ Maximising the physics output of the (HL-)LHC
- ❑ What is preventive maintenance? Do we do preventive maintenance and how does it impact availability?
- ❑ Conceiving the ideal maintenance plan
  - ❑ Can or should we change the time allocated to preventive maintenance?
  - ❑ Should we consequently adapt our machine schedules?
- ❑ Can we increase the (HL-)LHC availability by allowing access to the URs?

# Context of Availability



integrated luminosity is a function of...

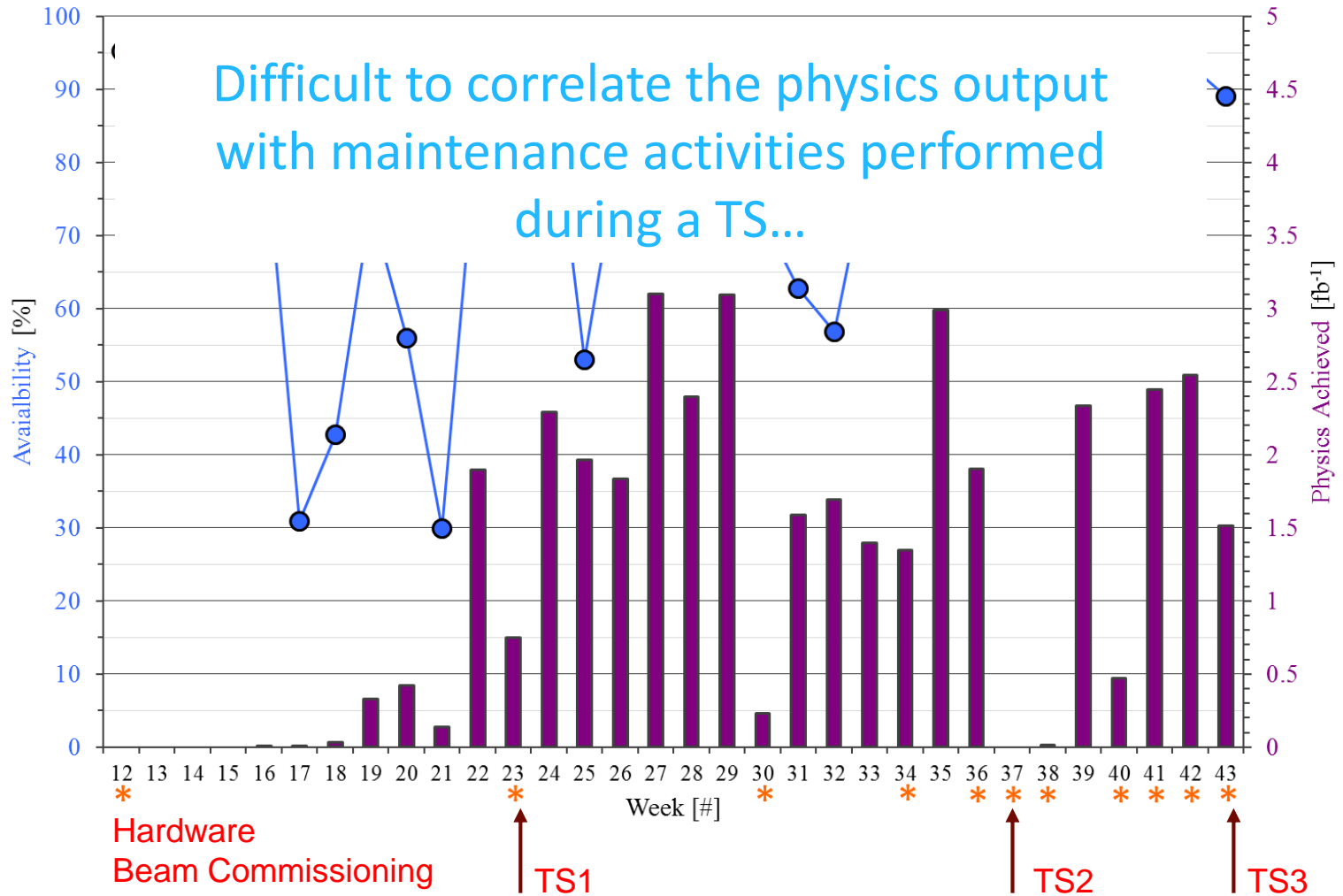


These are not independent variables

# A typical (good) year of physics production (2016)

\* = incomplete weeks

Availability and Physics Achieved by Week



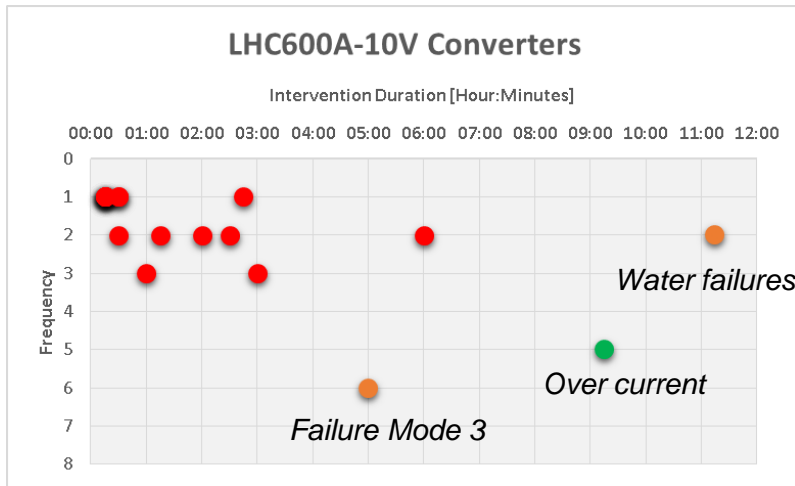
# Types of Maintenance

- Breakdown/reactive Maintenance:
  - Waiting until equipment fails before repairing or servicing it (most of today's LHC failures)
- Preventive Maintenance (PM):
  - (Time-based or run-based) Periodically inspecting, servicing, cleaning, or replacing parts to prevent sudden failure (Cryogenics, Cooling & Ventilation..)
  - (Predictive) **On-line monitoring of equipment** in order to use important/expensive parts to the limit of their serviceable life (RF components, klystrons,...)
- Corrective Maintenance:
  - Improving equipment and its components so that preventive maintenance can be carried out reliably  
-> Long-term feed forward from fault tracking into consolidation

Low initial cost  
Faults piling up

High initial cost  
Fault rates kept ~ constant

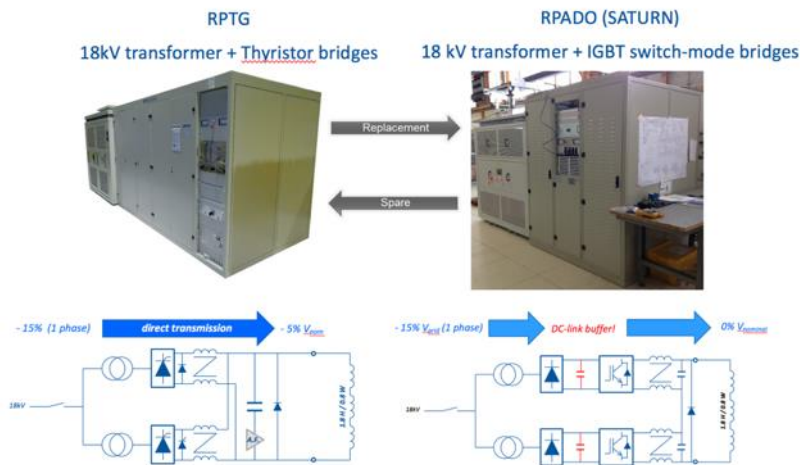
# Examples of successful corrective maintenance



LHC600A-10V Converters

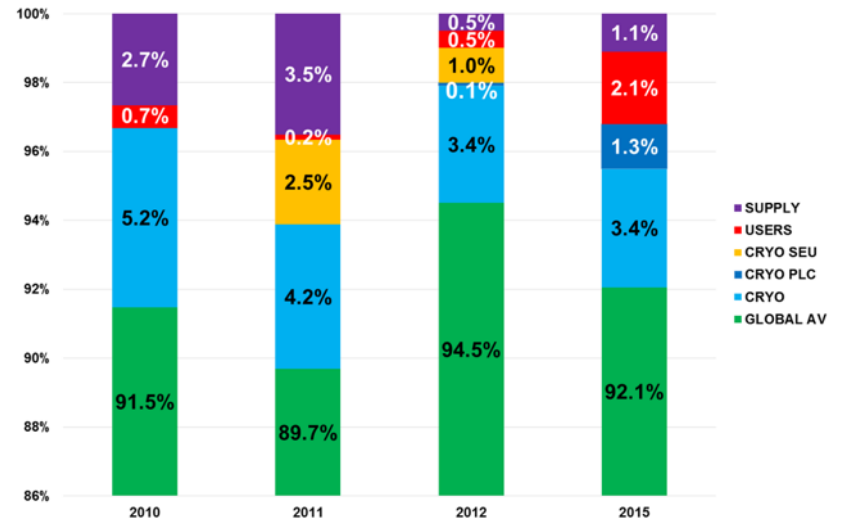
Consolidation of the Auxiliary Power Supply against SEUs

Exploiting AFT data to establish Availability Matrix



Replacing Thyristor PC for D1 and D34 to decrease effect of network perturbations

LHC CRYO AVAILABILITY SUMMARY FROM RUN 1 TO RUN 2



Cryogenic availability – reduction of power plants, exchange of PLCs,...

# Benefits of Preventive Maintenance

- “...the (long-term) cost of breakdown maintenance is usually much greater than preventive maintenance.”
- Preventive maintenance...
  - Keeps equipment in good condition to prevent large problems
  - Extends the useful life of equipment
  - Finds small problems before they become big ones
  - Is an excellent training tool for technicians
  - Helps eliminate rework/scrap and reduces process variability
  - Keeps equipment safer
  - Parts stocking levels can be optimized
  - Greatly reduces unplanned downtime

<http://www.prenhall.com/divisions/bp/app/russellcd/PROTECT/CHAPTERS/C HAP15/HEAD01.HTM>

# When does PM make sense?

- PM makes sense if Cost of DoingPM < Cost of NotDoingPM
  - **CDoingPM** = f(hours of not running equipment, loss in staff motivation when doing PM instead of “real work”, materials and man-hours consumed in PM, potential for making things worse, etc.)
  - **CNotDoingPM** = f(cost of losing/reworking a failed batch (unless PM makes no difference in preventing the failure), materials and man-hours spent repairing equipment, loss of equipment lifetime, loss in staff motivation from NOT doing PM, reduced staff familiarity with equipment, etc.)
- In a 24x7 manufacturing operation, it is typically better to perform the hours of activities in several smaller periods of time
  - Duration and variability in preventive maintenance are key factors in whether equipment will be able to maintain a steady flow of output
- Performing PMs inconsistently is functionally equivalent to consistently having much longer downtime durations

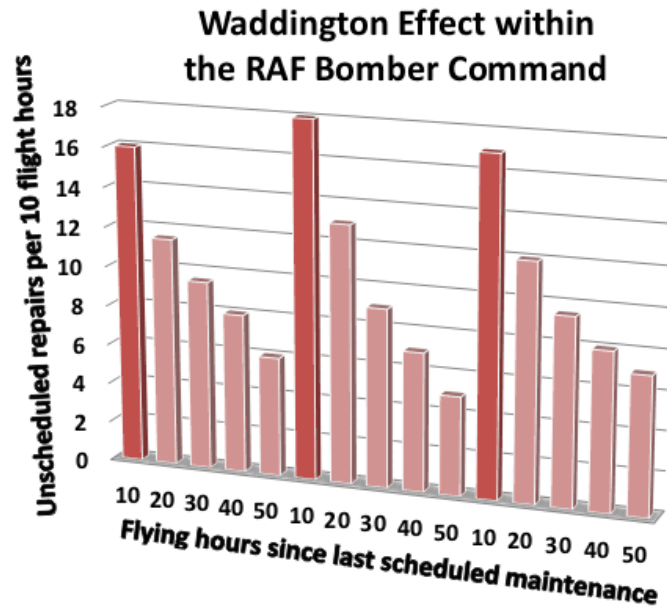
# Waddington effect

- First observed by C.H. Waddington during the 2<sup>nd</sup> world war studying British aircraft maintenance
- Background theory: **unscheduled downtime should be a random phenomenon**
- If all **unscheduled downtime events are plotted with respect to the last PM, there should not be any pattern evident**



**Conrad Hal (C.H.)  
Waddington**

# Waddington effect

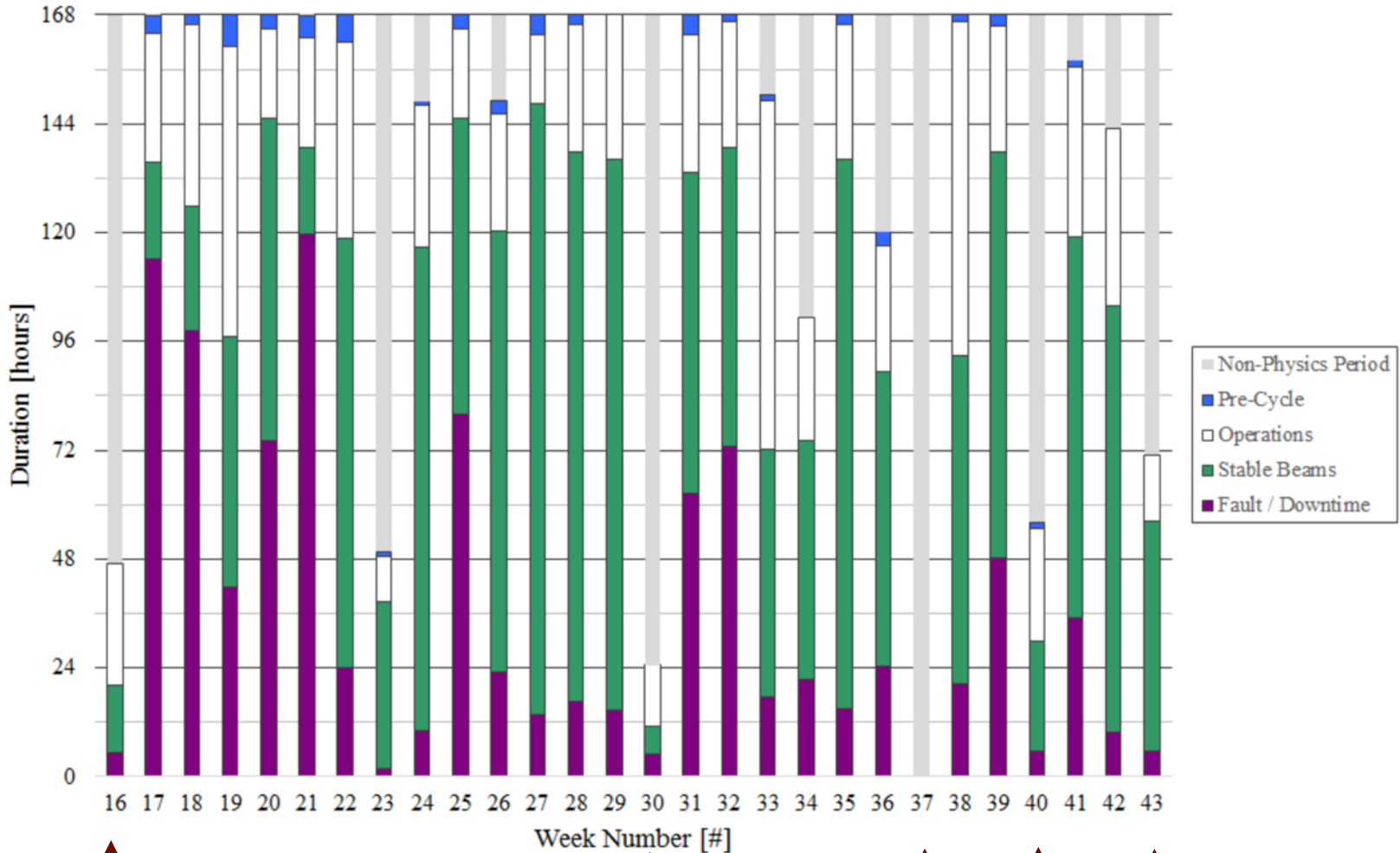


A pattern of increased unscheduled downtime immediately following PM's is a "Waddington Effect"

- Increase the time interval between scheduled maintenance cycles, and eliminate all preventive maintenance tasks that couldn't be demonstrably proven to be beneficial.  
-> effective flying hours of fleet increased by 60 percent!
- Maintenance isn't an inherently good thing, but it's a necessary evil (like surgery). We have to do it from time to time, but we sure don't want to do more than absolutely necessary to keep our aircraft safe and reliable. Doing more maintenance than necessary actually degrades safety and reliability

# Machine Mode by week for 2016

Breakdown of Machine Mode by Week for 2016 LHC Proton Physics

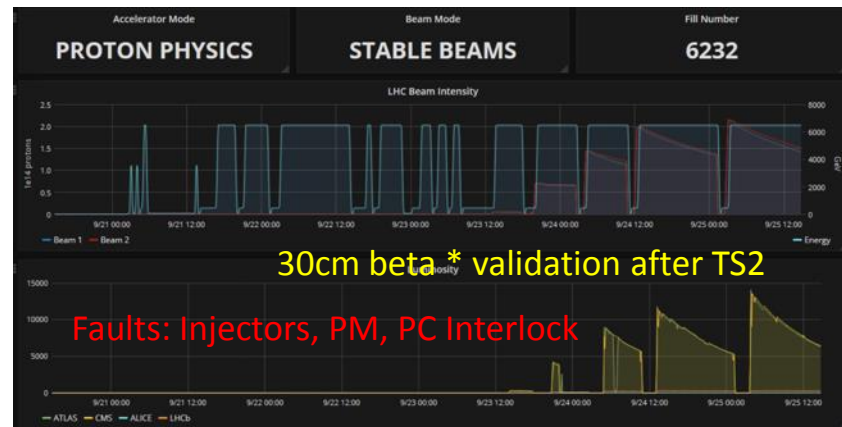
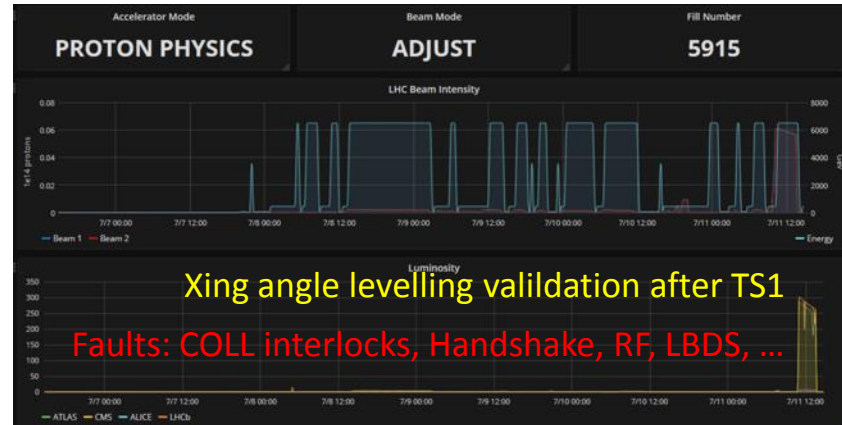


↑ End Beam Commissioning    ↑ TS1    ↑ MD1    ↑ TS2    ↑ MD4    ↑ TS3



# Recovery from TS in 2017

- Maintenance is not all that bad....! We also piggy-back on the TS to do a number of other changes....



# Machine Schedules today and tomorrow?

- Today a technical stop comes at a loss of physicist's time of 5 days (intervention) + 1-2 days (recovery and revalidation)
  - Time for planned TS vs physics time ~ 14%
- More frequent maintenance but shorter periods of 1-2 days could allow to better accommodate for (true) preventive maintenance actions
  - Shorter stops will naturally limit the extent of applied changes + reduce the extend of re-validation
  - Major interventions (unless for urgencies) only during long (E)YETS
- For a sc machine like the LHC, the overhead of (re-)commissioning is considerable, should one foresee 2 x 1.5 years (or 2 x 2 years) of beam operation (see FCC scenarios)?

Machine Mode	Restart to TS1	TS1 to TS2	TS2 to TS3	Σ
Beam Commissioning	29	1 ½	2 ½	33
Ion Cycle Setup	0	0	2	2
Special Physics Commissioning	0	3	0	3
Scrubbing	2	0	0	2
Machine Development	0	11	9	20
Special Physics	3	0	4	7
Physics	40	79	27	146
Σ	74	94 ½	44 ½	

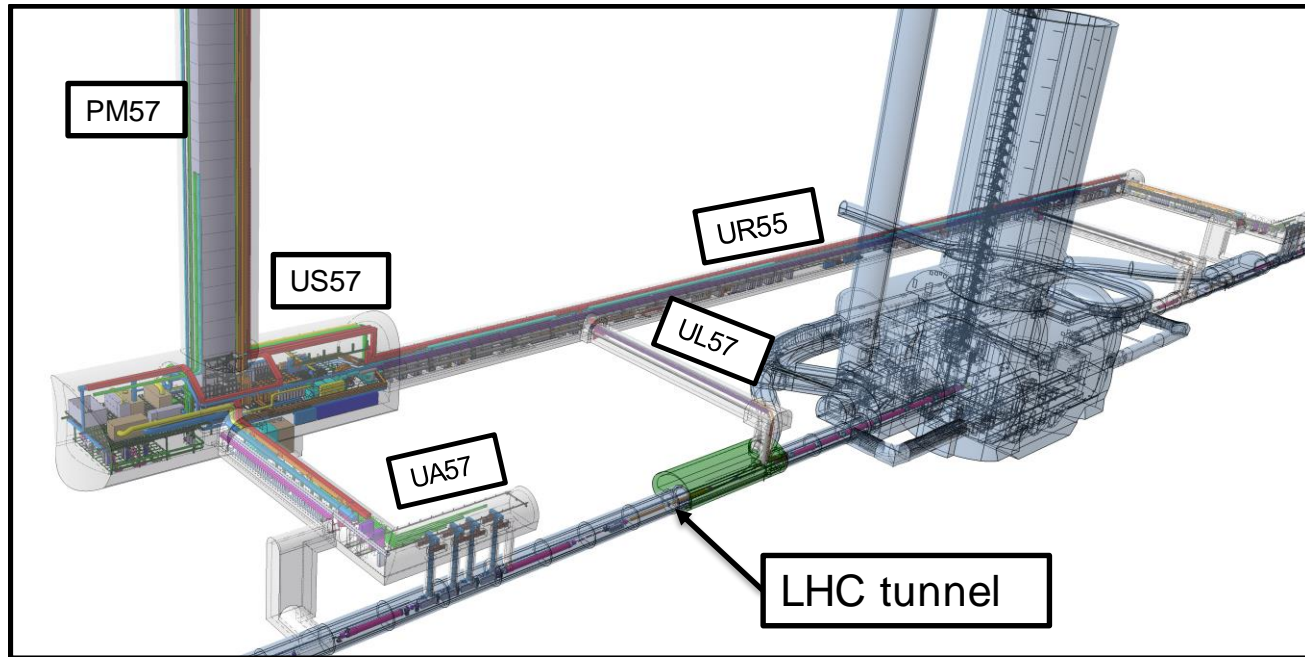
Typical allocation of beam time during an operational year

# Accessing the LHC during operation

- Due to **cryogenic, electrical and radiation risks**, different scenarios are being applied for the LHC when accessing underground areas
- **Experimental caverns, surface areas**
  - Access possible just after dump of beams, no RP piquet, no pre-cycle (a priori)
- **UA galleries**
  - Up to 4 adjacent sectors have to be powered down due to cryogenic risk
- **Tunnel, RRs, UJs**
  - Up to 4 adjacent sectors have to be powered down due to cryogenic risk
  - Radiation survey required for intervention during operation (and at start of TS, YETS...)
  - Access to inner triplet regions only possible with special derogation and well defined interventions
- **Following access, a pre-cycle has to be done** (since 2017 to 3.5 TeV only)

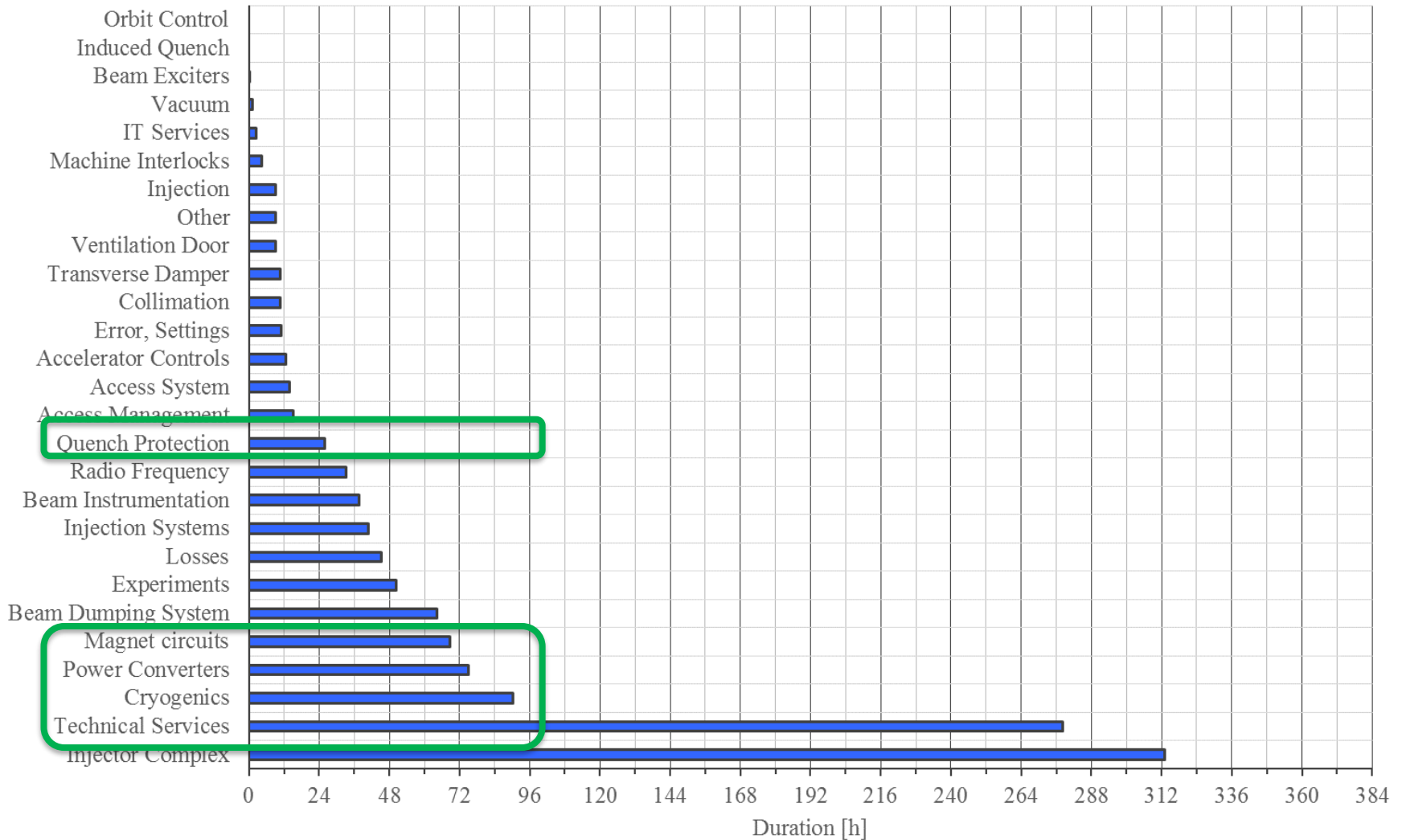
# New HL caverns, will they help?

- ❑ New caverns to hold most of powering and protection equipment (power converters, quench protection, cryogenics, interlocks,...), however most systems are not redundant / hot-swappable, hence primary gain is with early diagnostics and intervention time  
-> What will be the cryogenic rules for the new HL caverns?



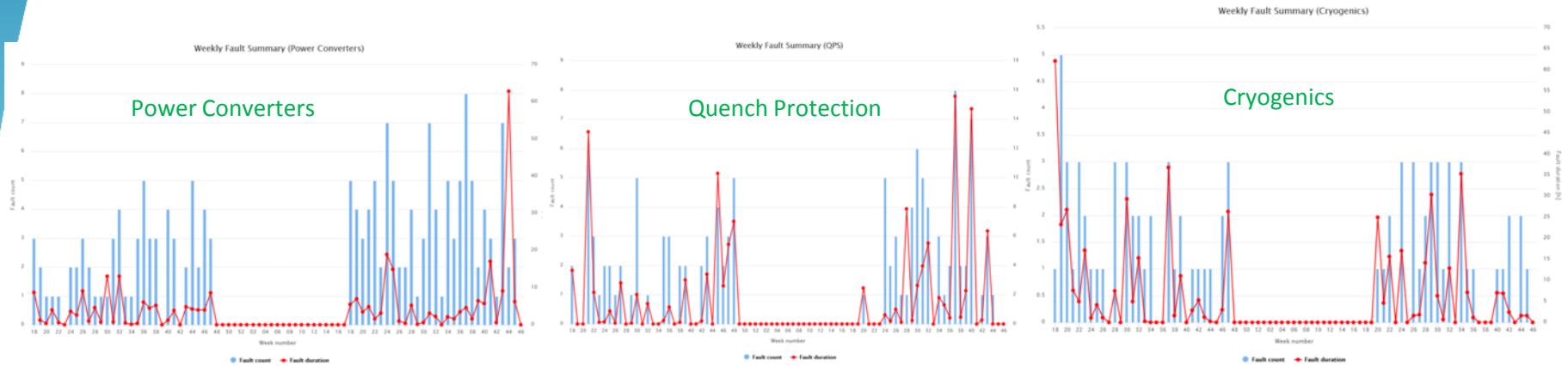
# 2016 Downtime Distribution

Stacked Pareto - Fault Duration, Machine Downtime and Root Cause Duration vs Root Cause System



[h]

# Statistics of powering system failures in IR1/5



## Power Converters:

32h of fault time out of 302h in high-lumi IRs (3-4 x FGC/R2E + communication loss, over-voltage, collateral trips due to EMC, water leaks,)

## Quench Protection:

6h of fault time out of 127h in high-lumi IRs (R2E for controller resets, heater firings due to EMC and thunderstorms, trips due to OP parameters)

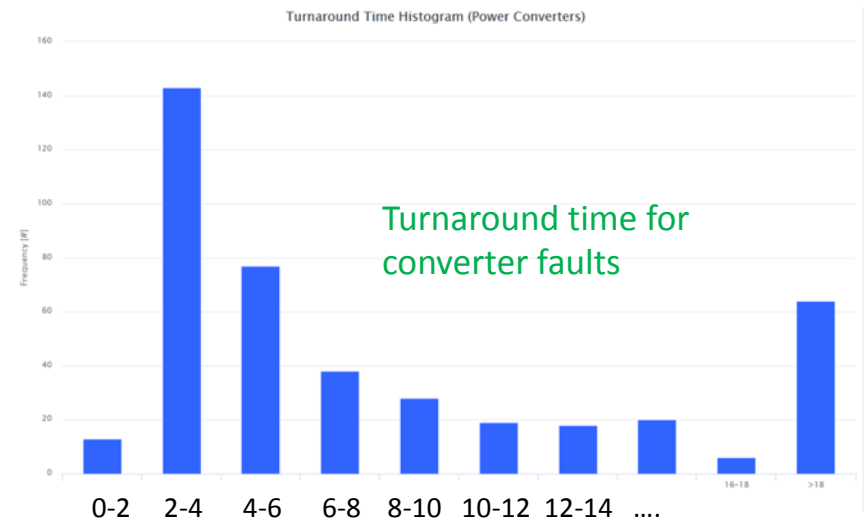
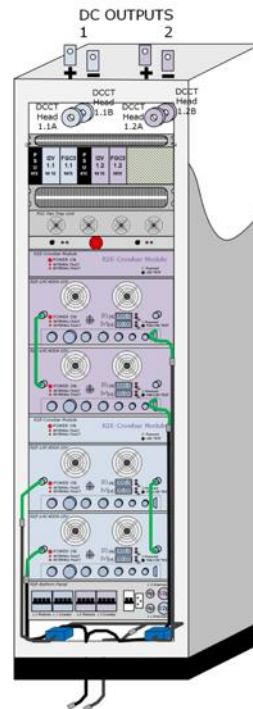
## Cryogenics:

53h of fault time out of 570h in high-lumi IRs

23h due to PM18 PLC communication issue (2016), 2x7 due to QURCB-18-CC1 Frequency drive communication card (2017), respectively temperature probe of RQ4.R5B2.

# How to profit best from access possibilities?

- ❑ For most (recurring) faults interventions are well optimized
- ❑ Only minor availability gain expected from relocation (R2E)
- ❑ To truly profit from access we should increase our capability of doing preventive maintenance
  - ❑ Monitoring and diagnostics of arising issues !!!
  - ❑ Fault tolerant designs / hot swaps



# Conclusions

- Preventive maintenance is important to assure the long-term reliability of systems, but...
  - An ideal preventive maintenance plan of equipment depends on its nature and availability figures
  - There cannot be a unique plan for a complex system of systems
    - Based on the AFT data set this could be modelled (for the main systems) to derive an optimized overall plan  
-> Reliability Centered Maintenance plans
  - Arbitration of PM actions should be increased to reduce the interventions to those considered beneficial for availability
- If integrated luminosity is highest priority, one should quantify the cost and benefits of a different operational scenario (e.g. 2x2 years of operation between LS)
- Pushing further the availability of very reliable systems (and profiting from accessibility to equipment) will require incorporating early fault detection and fault tolerance into the designs of future systems and upgrades

Thanks a lot for your attention!  
Questions?

