LHC Availability in 2023

”LHC - is it falling apart? How to get out of the series of unfortunate events?”

Lukas Felsberger, Jack Heron, Jan Uythoven, Daniel Wollmann

Acknowledgements to Machine Coordinators & Operators, System Experts, AFT team

Joint Accelerator Performance Workshop 2023, Montreux, Dec 7th 2023

Structure

- 2023 LHC availability statistics & trends
- Analysis of
  - Recurring faults
  - Longest faults in 2023
  - Cryo-eco mode
- Summary & Conclusions

Accelerator Fault Tracking

AFT data captured by OP and reviewed together with equipment experts and RAWG

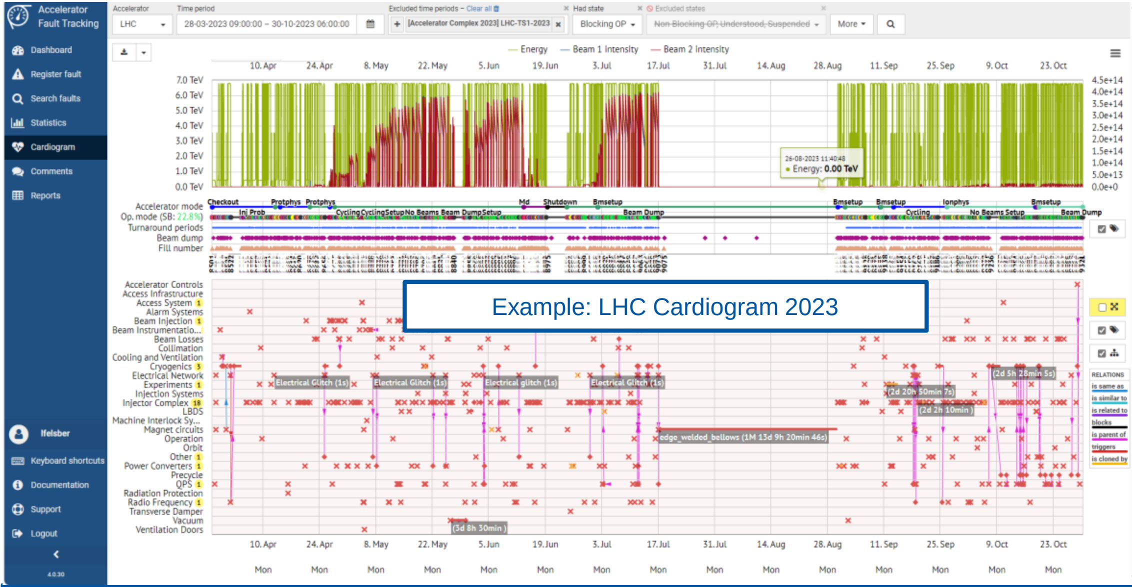
- **Acknowledgements for significant efforts!**

Fault: Deviation from nominal operation as defined in accelerator schedule

- During physics: every downtime
- During TS, MD, beam-commissioning: unexpected delays

Root-cause statistics used:

- downtime attributed to system causing the downtime
- E.g. flat-top training quench → cryo recovery: counted towards magnet circuits

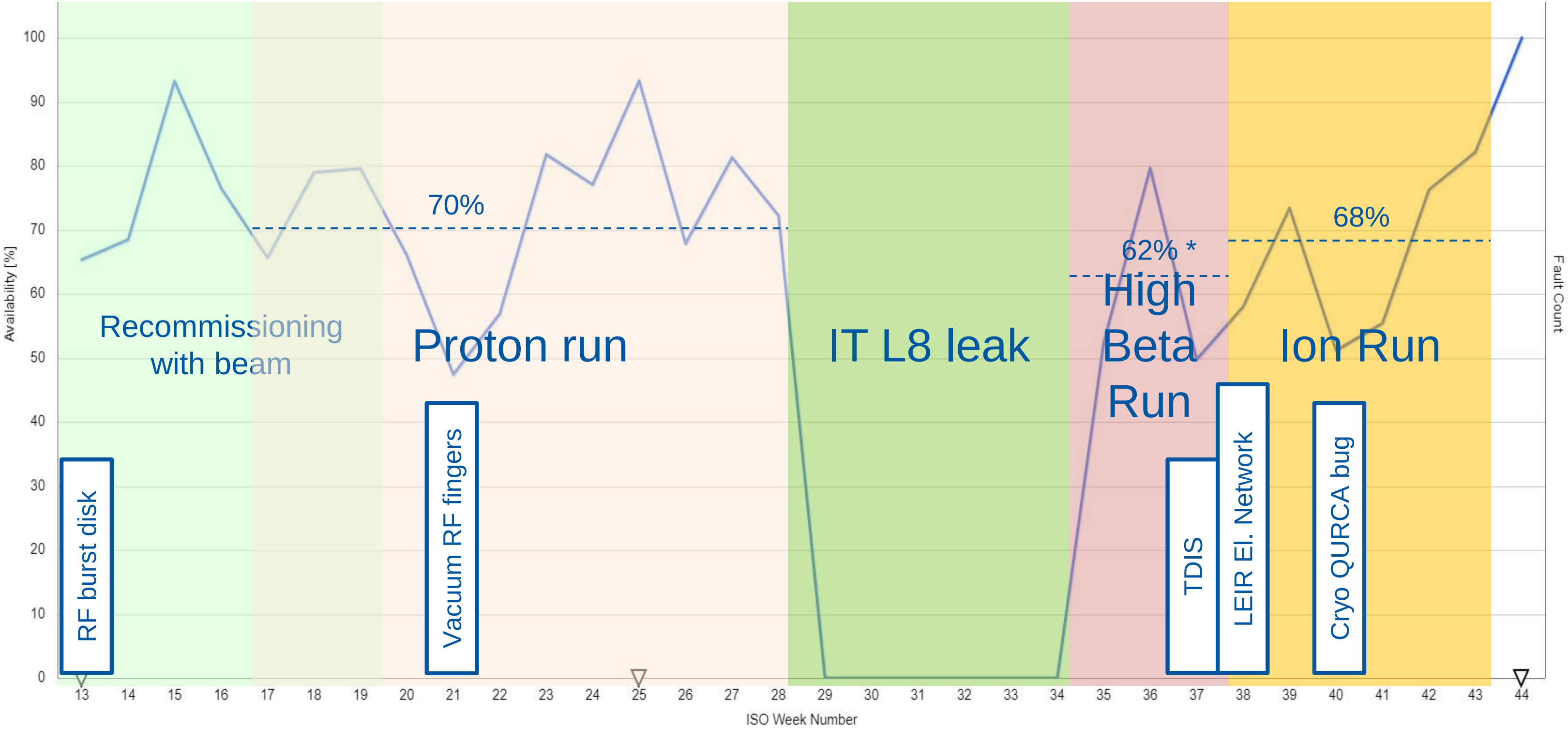


Fault tracking centrally managed with AFT tool (provided by BE-CSS)

Weekly Availability

AFT – Statistics (cern.ch)

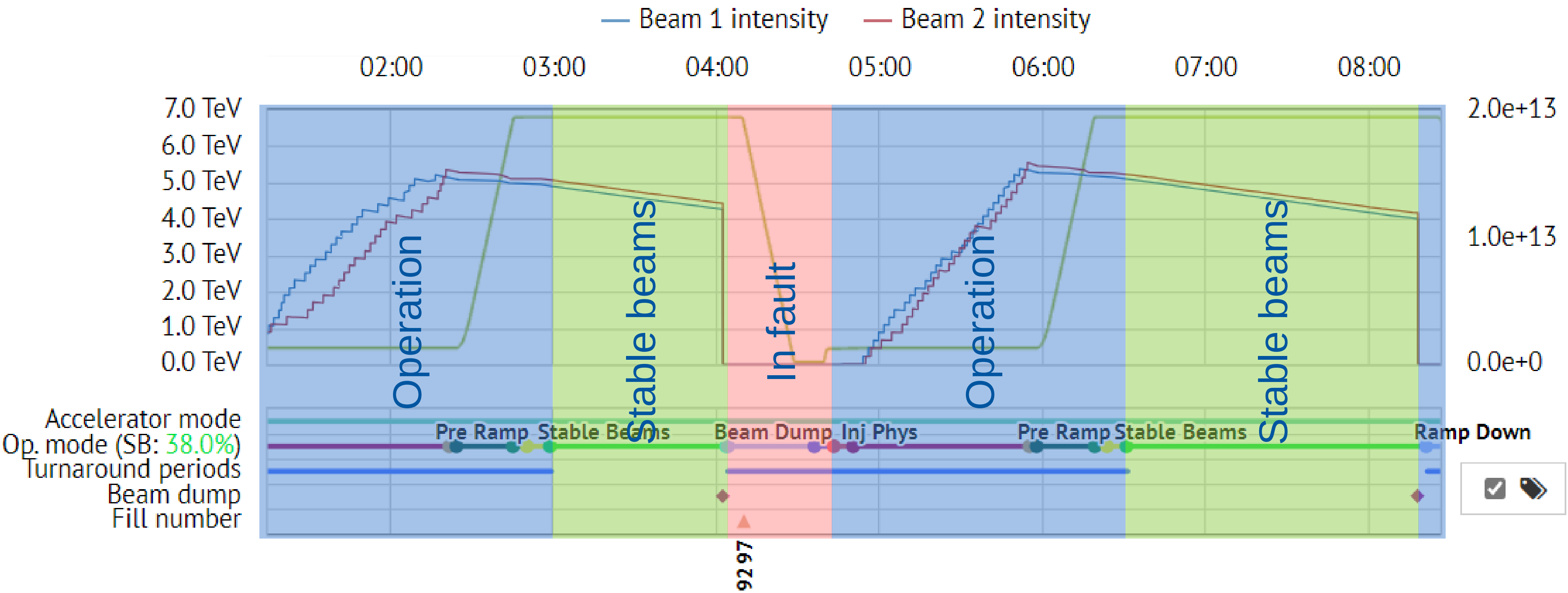
Availability: Fraction of scheduled operational time that machine is available for operation



*includes set-up periods

Proton Run

AFT – Dashboard (cern.ch)



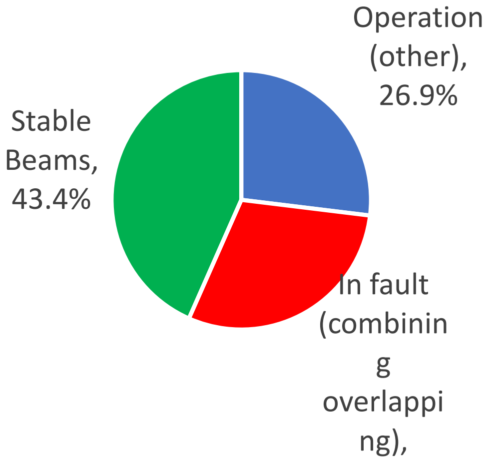
[AFT – Dashboard (cern.ch)]

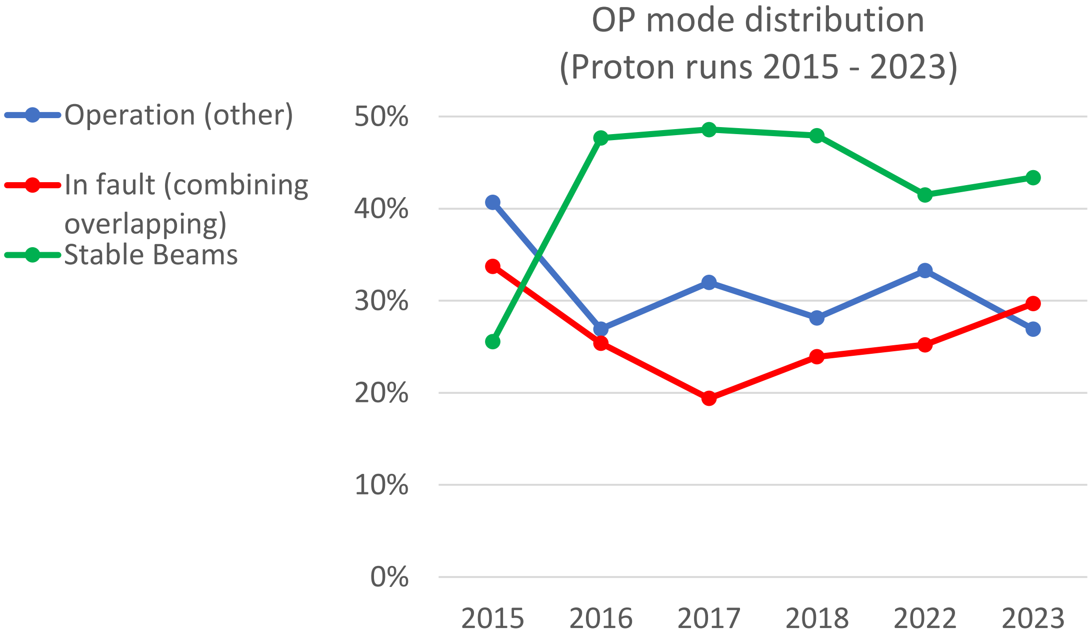
Proton Run

2023
Time period from first stable beams until IT.L8 leak. MD & TS excluded

Downtime ratio ~5% higher than in previous years

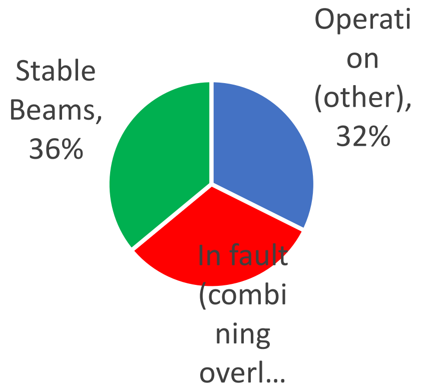
- Vacuum RF finger event alone contributes ~5 % downtime
- Much bigger impact by ITL8 event, resulting in reduction of run length



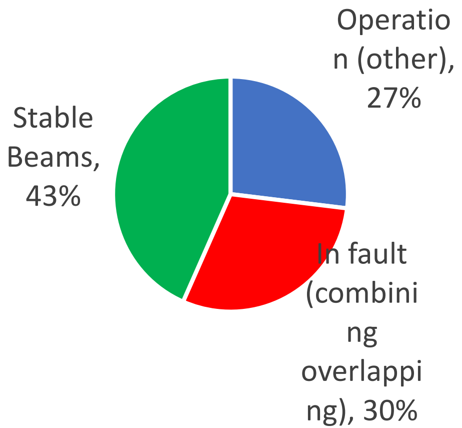


Ion Run

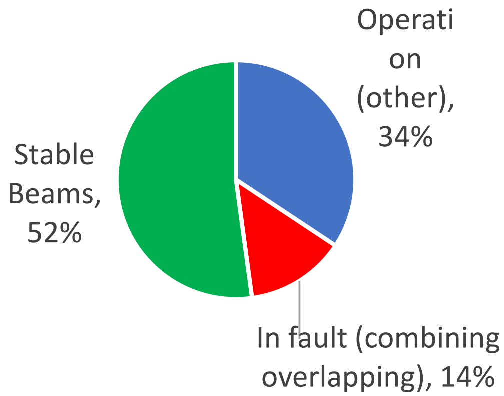
2023 Ion run
From end of ion set-up (26.09.) until end of run (30.10.)
L3 oven refill, MD, VIP visits excluded



2023 Proton run
Taken as reference:

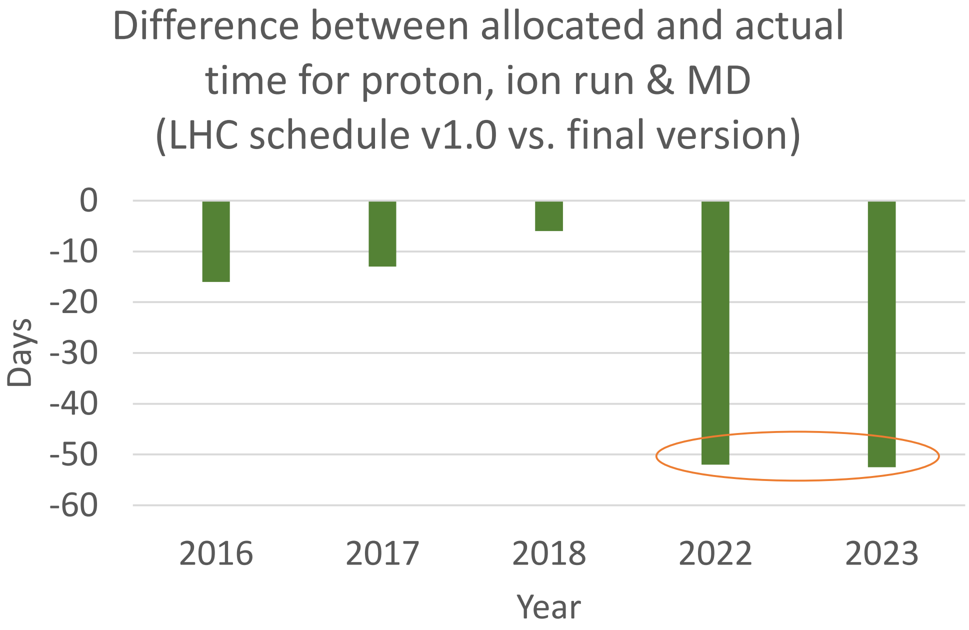


2018 Ion run
Taken as reference:



- Longer filling + shorter stable beams in ion run 2023 compared to proton run 2023
  - This year difficult set-up: High losses in the ramp around 6 TeV & High background in ALICE inner tracker
- Higher downtime fraction in ion run 2023 compared to proton run 2023
  - Mainly due to QPS R2E events & delays in cryogenics recovery – details in talk by J. Steckert

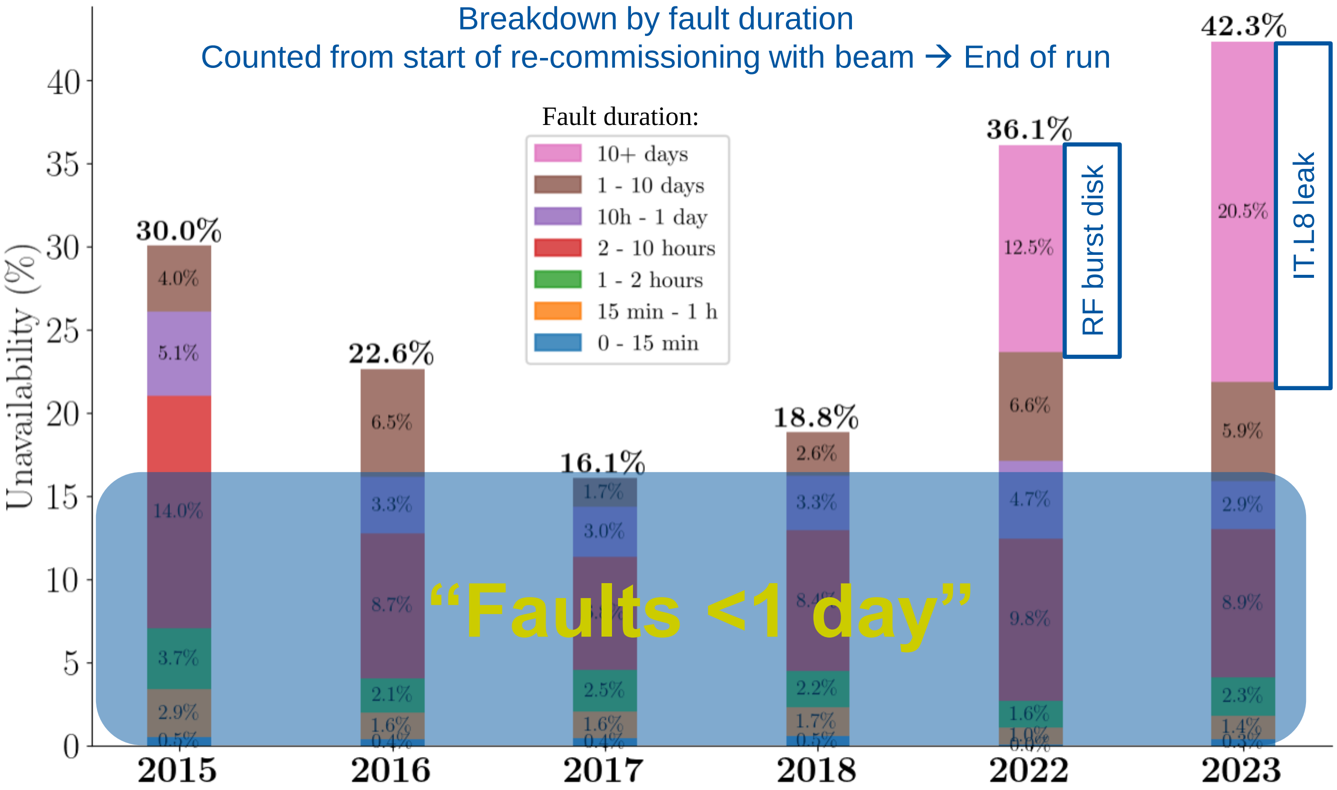
Looking beyond the proton and ion run - Initial Schedule vs Final Schedule



Comparison of initial and final LHC schedule each year shows:

- Significant differences appearing in last two years
- Further emphasized by shortened run in 2022 and 2023

Distribution of Fault Durations over Years



LHC downtime in 2022 and 2023 is dominated by long faults

- Faults > 10 days start to appear during run in 2022
- Faults < 1 day fairly stable

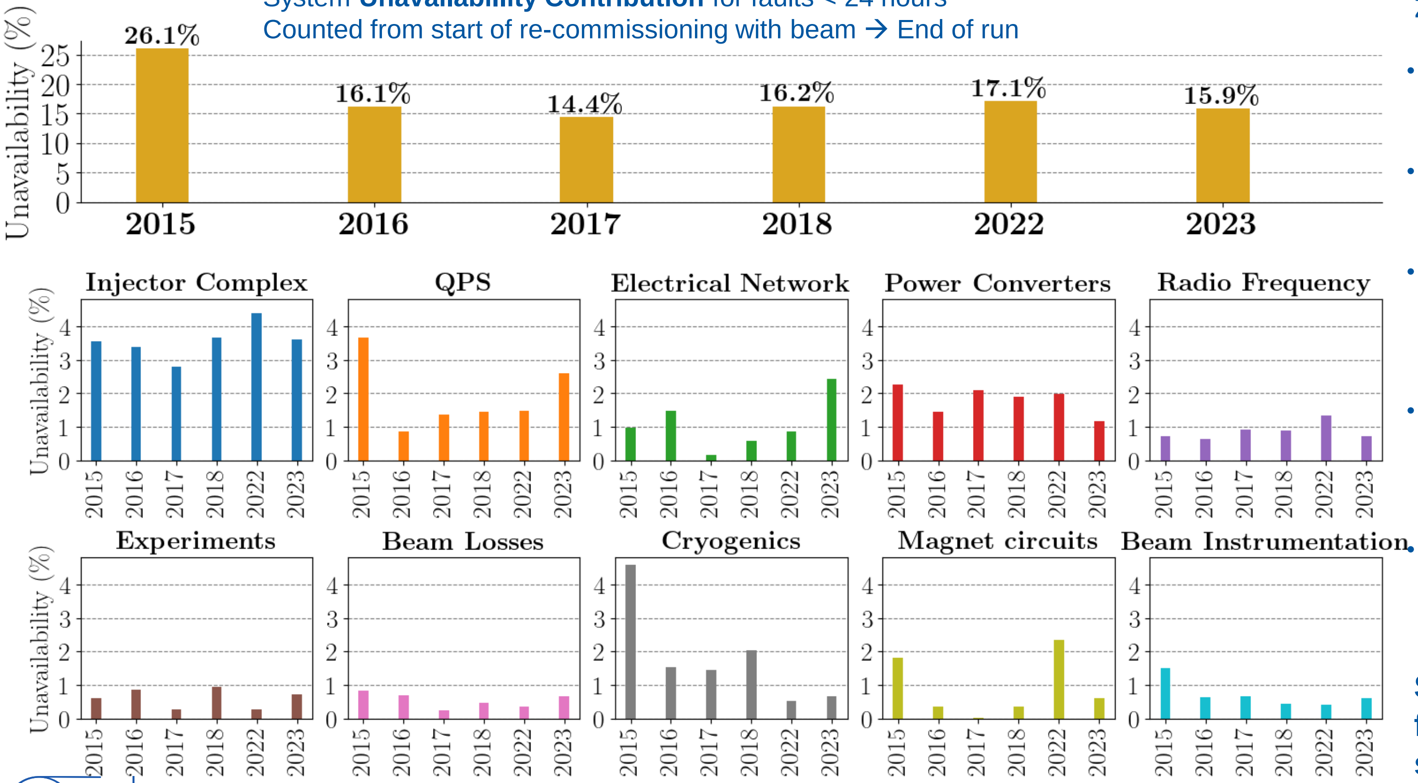
→ Split analysis in faults shorter and longer than 1 day

Faults > 1 day are rare:
→ qualitative analysis

Faults < 1 day are frequent:
→ statistical analysis

Faults < 1 day: Downtime Contribution by system

System **Unavailabillity Contribution** for faults < 24 hours
Counted from start of re-commissioning with beam → End of run



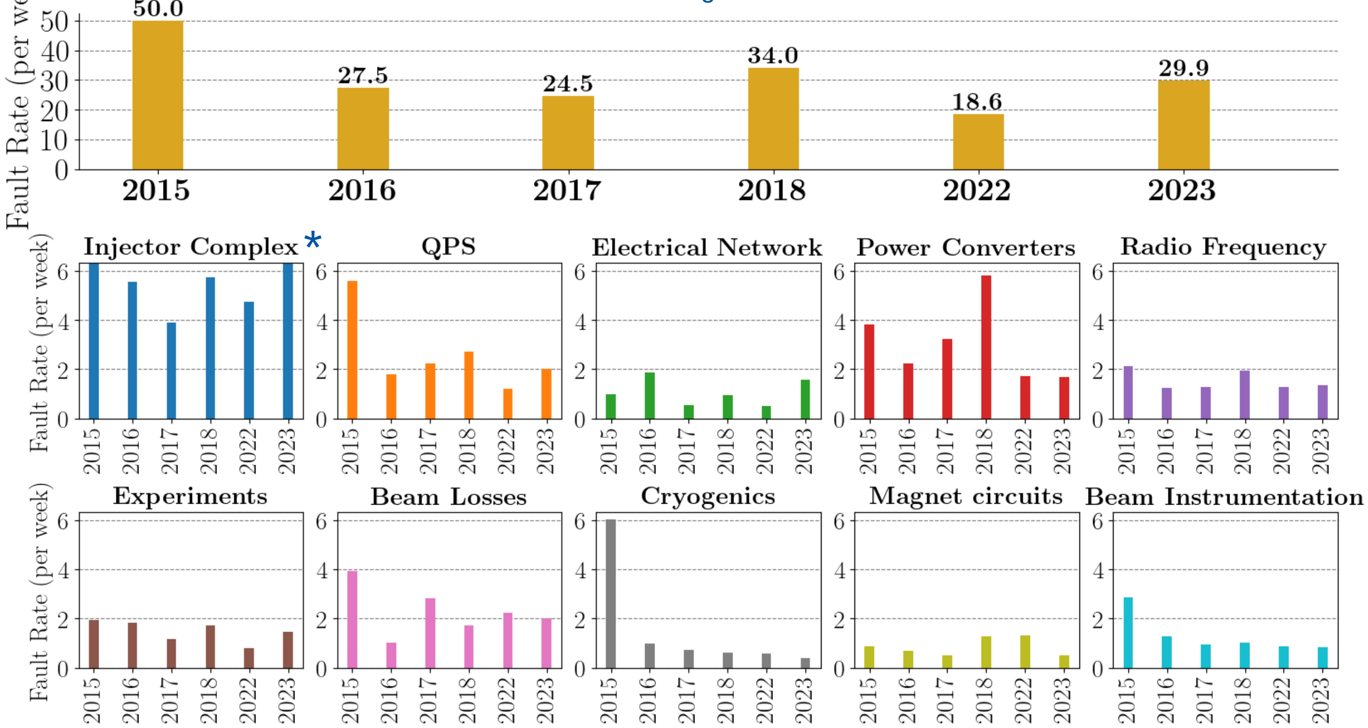
2023 statistics:

- Injector complex: Downtime improved since 2022
- QPS: Strong impact of R2E during ion run.
- Electrical Network: 30% of downtime from external perturbations.
- Power Converters: improved in comparison to previous years
- RF: improved in comparison to 2022

Sum of unavailability evolution fairly constant. However, strong shifts between systems.

Faults < 1 day: Failure rate by system

System **Failure Rate per week (of uptime)** for faults < 24 hours
Counted from start of re-commissioning with beam → End of run



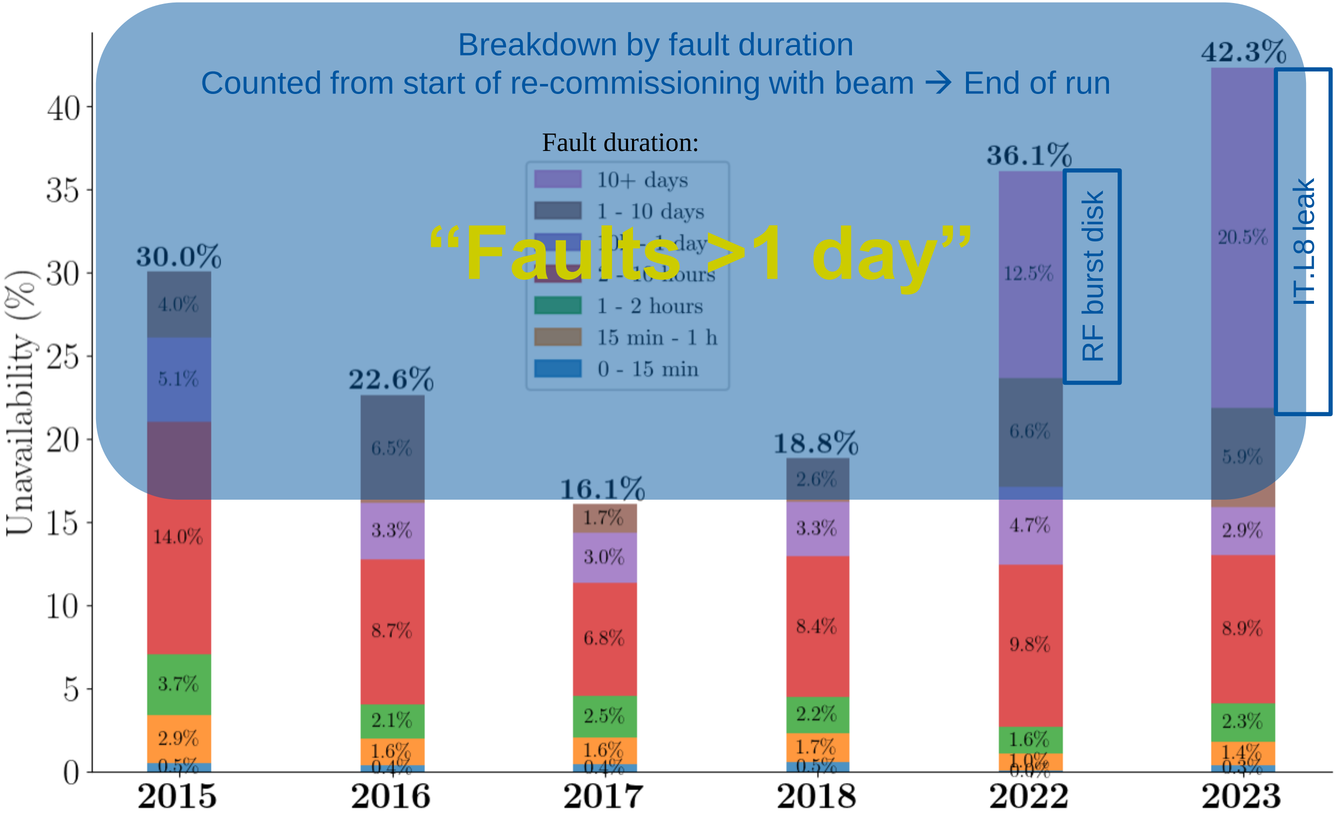
2023 statistics:

- Injector complex: Artificial increase due to automatic recording of short faults.
- QPS: Improved in comparison to run 2. Strong impact of R2E during ion run in 2023.
- Electrical Network: increased since 2022. 50% external.
- Power Converters: improved in comparison to run 2
- RF: similar to 2022

Strong shifts between systems.

* Y-axis clipped. Artificial increase due to automatic recording of short faults. Is 11 per week for 2023.

Distribution of Fault Durations over Years



LHC downtime in 2022 and 2023 is dominated by long faults

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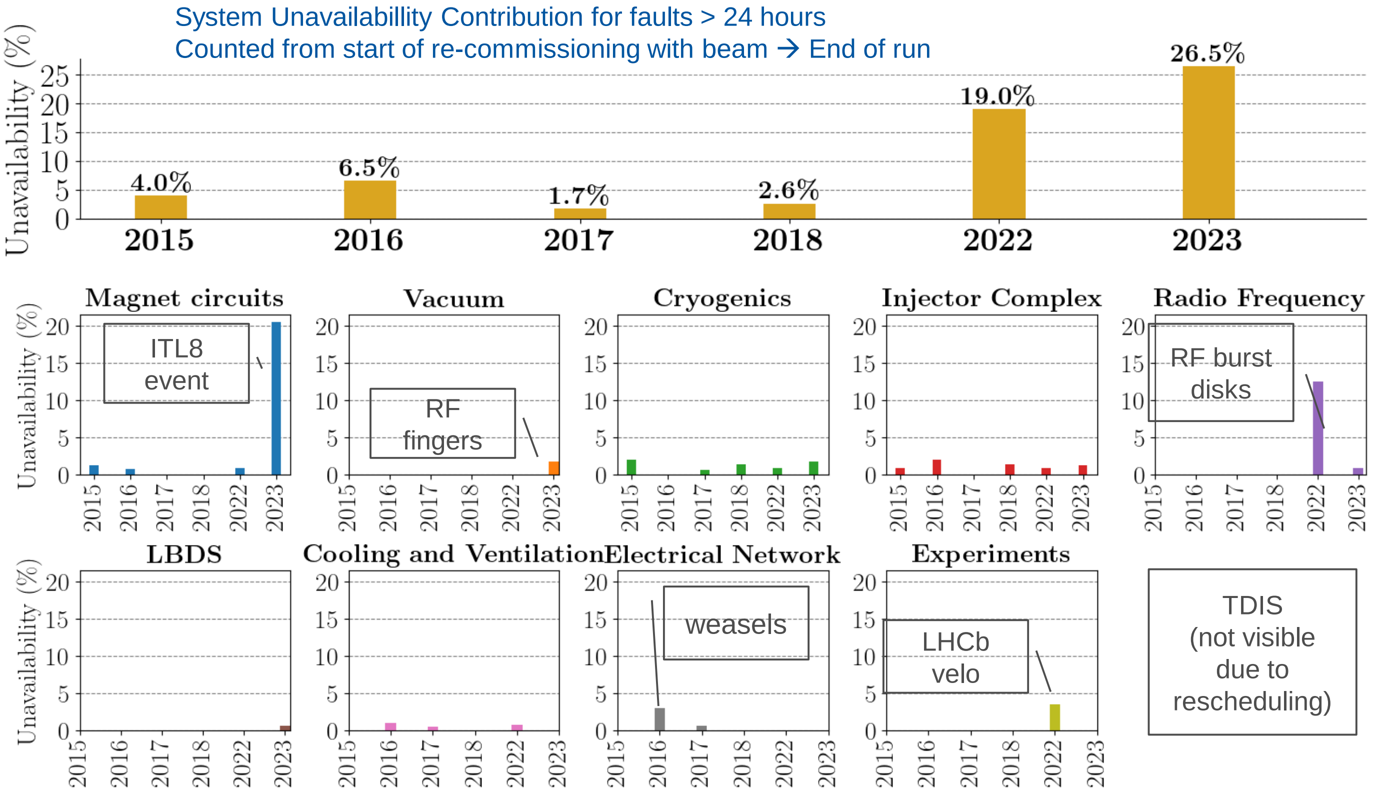


2023:

- Magnet circuits: ITL8 leak – singular event
- Vacuum: RF fingers - singular event
- Cryogenics: dominated by equipment trips during cryo recovery in ion run
- Injector complex: LINAC3 electrical network event at beginning of ion run
- RF: burst disk events

Very long events appear during run in 2022/3

Long Faults: Qualitative Analysis of Main Events in 2023

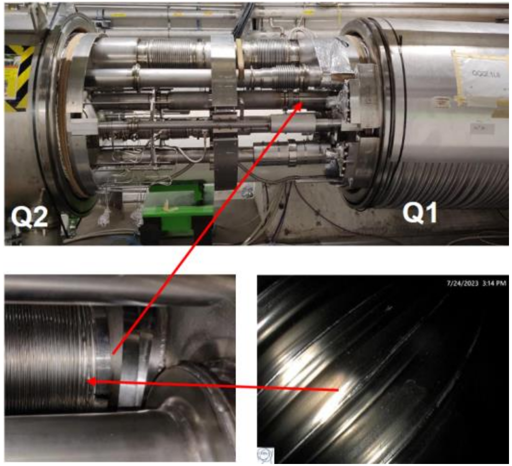
- 5 longest events of 2023 contribute 60% of downtime!
- For each of these events, a set of questions was asked to experts.
- Qualitative analysis performed based on answers.

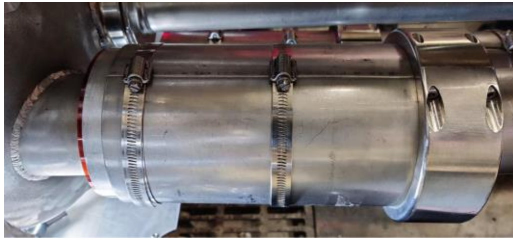
Event	*Impact on run*
ITL8 vacuum leak	50 days
Vacuum RF fingers	3.5 days
TDIS Vacuum Leak	End of high-intensity pp run
Delayed Cryo Recovery due to SW bug	2 days
RF burst disk	2 days

Acknowledgements to inputs from S. Le Naour
* More details in dedicated flash talk

IT.L8 Vacuum Leak (July 17th)

Description & Root Cause	Due to electrical network glitch, the **quench heaters of a few LHC magnets correctly triggered**, including the ones of the IT.L8. As expected, the pressure inside the cold masses increased up to 18 bars but **provoked a leak in an edge-welded bellow of the Q1-Q2 interconnection**. The pressure in the vacuum vessel degraded, preventing the running of the LHC and demanding the bellow repair. It was found that a few bellow convolutions were partially blocked.				
Impact	~ 50 days total impact on physics runs.				
Wear-Out or Aging phenomenon?	Beam intensity related?	Random Hardware Failure?	Due to modifications or upgrades?	Inadequate specifi-cation?	Production non-conformity?
Possibly mech. fatigue (due to partially blocked convolutions)	No	No. Few bellow convolutions partially blocked, increasing stress on others	No	**Yes, of the guiding shell of the bellow**	No
Mitigation strategy & status	IT.L8: in-situ repair & mitigation by adapting bellow protection Others: none until LS3 (would need complete warm-up for mechanical repair)				
Outlook	**Similar events possible** on all triplets and mainly in Q1-Q2 interconnection until LS3, more details in dedicated talk by S. Le Naour.				



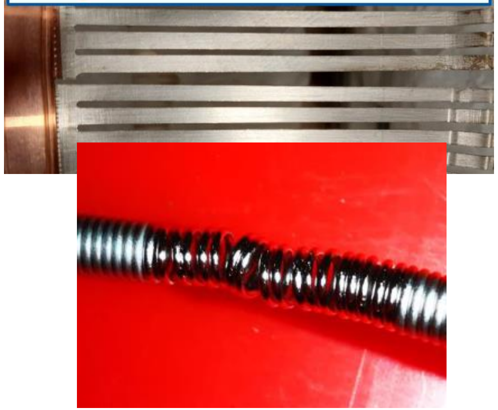


Acknowledgements to inputs from G. Bregliozzi
More details in talk by P. Krkotic & C. Antuono

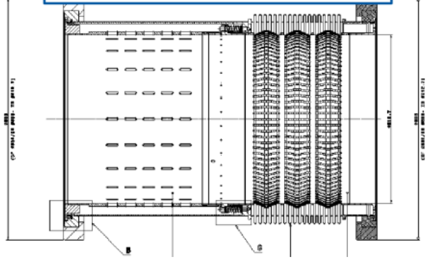
Vacuum RF Fingers Incident (May 26th)

<table>
<tr><td>Description & Root Cause</td><td colspan="5">Localized heating (>500°C) of spring triggers localized plasticization with consequent loss of electrical contact. Heating due to small irregularities between finger gaps enhancing impedance and power dissipation (tbc).</td></tr>
<tr><td>Impact</td><td colspan="5">3 days 13 hours blocking & performance impact during recovery
Thereafter, operation limited by intensity < 1.6x10^{11} ppb</td></tr>
<tr><td>Wear-Out or Aging phenomenon?</td><td>Beam intensity related?</td><td>Random Hardware Failure?</td><td>Due to modifications or upgrades?</td><td>Inadequate specification ?</td><td>Production non-conformity?</td></tr>
<tr><td>Possibly</td><td>Yes</td><td>No</td><td>No</td><td>No or maybe *</td><td>Likely **</td></tr>
<tr><td>Mitigation strategy & status</td><td colspan="5">Replace all (71) old ID212 RF contacts in YETS23/24 and 24/25 with the HL-LHC baseline that is the new DRF (deformable RF bridges) design.</td></tr>
<tr><td>Outlook</td><td colspan="5">Similar problems can be expected at same order of magnitude (until DRF deployed). For the other warm modules in the LHC machine (> 1800 units and different family) a detailed impedance study should be carried out.</td></tr>
</table>

Example of damaged RF finger of A4L1 warm module



New DRF LHCVM___0098

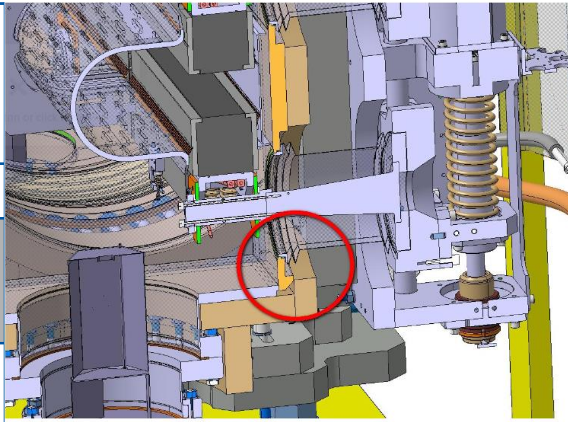


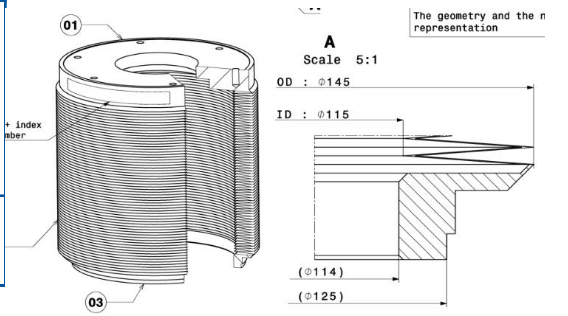
*there was not a clear specification in 2002-2003 apart the one done by the old vacuum group about the pumping speed and the design was for the LHC era.
** From vacuum and mechanical point of view there are no non-conformities, but apparently with high intensity beam small deviation from the design could trigger some impedance problems

Acknowledgements to inputs from A. Perillo Marcone
More details in talk by C. Sharp

TDIS Vacuum Leak (Aug./Sept.)

Description & Root Cause	**Two TDIS jaw actuator bellows developed vacuum leaks**. Repaired by applying varnish and blocking movement. Resulted in degraded function, allowing ion run but preventing proton run at nominal intensity. Root cause was a **misspecification of the bellow**, causing wear-out after 2-3 years.				
Impact	End of high-intensity proton physics (Compensated by extended ion run)				
Wear-Out or Aging phenomenon?	Beam intensity related?	Random Hardware Failure?	Due to modifications or upgrades?	Inadequate specification ?	Production non-conformity?
Mech. fatigue (due to inadequate spec.)	No	No	**Installed in LS2**	**Yes**	No?*
Mitigation strategy & status	Both TDIS (points 2 and 8) will be replaced by (non-conform) spares during YETS-23/24. Will be replaced again during YETS-24/25 by conform spares (based on refurbished TDIS with new bellows). **Until then, movement should be limited (spares available only from summer 2024)**. New spare TDIS tanks will be built in parallel as back-up.				
Outlook	**Risk until YETS-24/25. Thereafter, corrective measures should avoid similar problems until the end of the devices' lifetime (i.e. ~20 years).**				





* Cannot exclude a non-conformity until the faulty bellows have been analysed in detail (to be done during the next months).

Acknowledgements to inputs from B. Bradu & L. Delprat

Delayed Cryo Recovery (Oct. 7th)

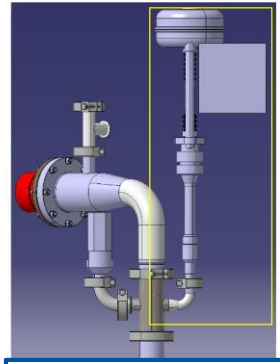
Description & Root Cause	SEU triggered quench heater discharge in S23. During cryo recovery**, bug in Cryo PLC software unexpectedly provoked the opening of a bypass valve,** propagating a warm wave in the line, while the cold compressors were pumping on the sectors, leading to long delay in recovery. Root cause is that **threshold for a valve (3CV796) to be considered closed got accidentally changed during LS2**, most likely during a PLC software reload				
Impact	~50 hours				
Wear-Out or Aging phenomenon?	Beam intensity related?	Random Hardware Failure?	Due to modifications or upgrades?	Inadequate specification?	Production non-conformity?
No	No	No	**Bug most likely introduced in LS2**	No	No
Mitigation strategy & status	- Until EYETS: P18/P2 were decoupled, and correct thresholds applied **DONE**. - During EYETS: correction of QUIA/QUIB logic to properly manage the quench protection in all configurations for S12 & S23 and consolidation of QURC logic for CV235. **DONE.**				
Outlook	**No similar issues expected.**				

Acknowledgements to inputs from W. Venturi Delsolaro

RF Burst Disk (April. 2nd)

Description & Root Cause	**Triggered by power cut in point 4 following a wrong manipulation after issue with compensator**, which led to a well-known chain of events: the ACS modules are automatically isolated from the helium input and output lines, consequently the cryomodule pressure increases due to the static heat loads and the safety valves open and maintain the **pressure around 1.9 bar**. Unfortunately, **two of the new SS burst disks** installed during the previous YETS **did not withstand the pressure and opened**. After the event, a test campaign on the spare disk confirmed that likely these **two disks were outliers**.				
Impact	45 hours				
Wear-Out or Aging phenomenon?	Beam intensity related?	Random Hardware Failure?	Due to modifications or upgrades?	Inadequate specification?	Production non-conformity?
No	No	(Yes)	**Yes**	No	**Yes**
Mitigation strategy & status	The task force on RF burst disk recommended the **installation of fast depressurizing valves** to back up the warm recovery line in cases when this is not available. ECR was approved, VIC was done, and hardware is expected on time for installation in the coming YETS.				
Outlook	**Mitigation reduces risk. Similar events may still happen** given small pressure margin between opening of safety valve and burst disk, which is necessary to able to protect the RF cavities against major events, for which the bust disks were foreseen.				

Installed RF burst disk type



Depressurizing valve

Main Events – Comparative Analysis

Event	Wear-Out or Aging phenomenon?	Beam intensity related?	Random Hardware Failure?	Due to modifications or upgrades?	Inadequate specification ?	Production non-conformity?	*Similar problems to be exected?*
ITL8 vacuum leak	Possibly mech. fatigue (due to partially blocked convolutions)	No	No (due to partially blocked convolutions, increasing stress on others)	No	Yes, of the guiding shell of the bellow	No	*Yes (until LS3)*
Vacuum RF fingers	*Possibly*	Yes	No	*No*	No or maybe	Likely	*Yes*
TDIS Vacuum Leak	Mech. fatigue (due to inadequate spec.)	No	No	Installed in LS2	Yes	No	*Until YETS24/25*
Delayed Cryo Recovery due to SW bug	No	No	No	Bug most likely introduced in LS2	No	No	*Not of the same type*
RF burst disk	No	No	(Yes)	Yes (LS2)	No	Yes	*Yes, but fewer*

- 4 of 5 events due to inadequate specifications or non-conformities
- 3 of 5 events due to more recent changes (LS2)
- 2 of 5 events possibly related to aging of LHC, in combination with a non-conformity or increased intensity

→ **Age of LHC is not predominant cause of analyzed events. Pushing the machine parameters reveals new weaknesses.**

→ **Mitigations are being implemented, but risks remain and need to be carefully considered for machine exploitation until LS3**

→ **Can we invest even more in specifying, testing and validation of machine & equipment (HW & SW) upgrades for changes foreseen in LS3?**

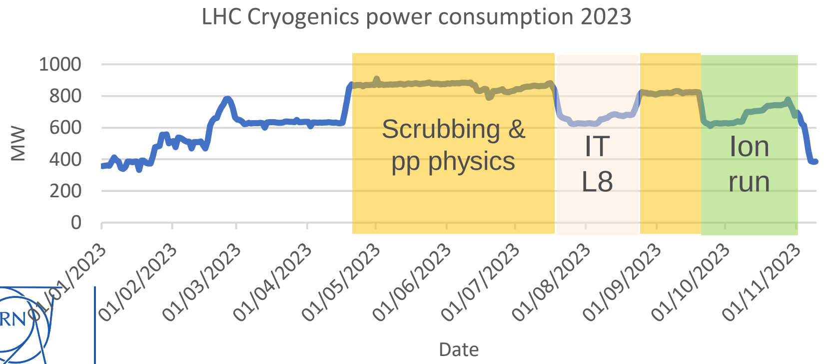
Structure

- 2023 LHC availability statistics & trends
- Analysis of
  - Recurring faults
  - Longest faults in 2023
  - Cryo-eco mode
- Summary & Conclusions

Acknowledgements to inputs from B. Bradu & L. Delprat

Cryogenics Eco Mode (2023 Ion Run recap)

- Eco mode implemented (on Sept 20th) for ion run due to reduced heat load
  - **Reduced power consumption by ~ 10.5 MW in comparison to proton run** (~ 10% of LHC incl. Experiments)
- Two events during „full“ Eco-Mode
  - Sept. 24th: P4 - loss of QSCA-4 PLC led to loss of Cryogenics (33 hours)
  - Oct. 7th: P2(/18) SEU triggered quench heater discharge + Bug in control system leading to unexpectedly long delay in recovery (67.5 hours)
  - Both delays would have happened irrespectively of eco mode. Length of delay partially impacted by eco mode
- Following event on Oct. 7th, point 2 re-configured in full power mode
  - Power consumption still 5.8 MW reduced
  - No other events on points configured in eco-mode for rest of ion run



Elec Power meas. in 2023	P18/P2	P4	P6	P8	LHC
Full Power	9.8 MW	9.4 MW	7.7 MW	9.8 MW	36.7 MW
Eco mode (savings)	6.9 MW (-2.9 MW)	7.3 MW (-2.1 MW)	5.5 MW (-2.2 MW)	6.5 MW (-3.3 MW)	26.2 MW (-10.5 MW)

Acknowledgements to inputs from B. Bradu & L. Delprat

Cryogenics Eco Mode – Key Points

- All cryo points and cryoplants have specificities and one **cannot setup a general rule** about the eco mode for all LHC cryo points.
- The needed **reconfiguration time** to switch between Eco & Full Power **must be kept at 24 hours**, which is already challenging.
  - Preliminary notice >1 day needed to pass from the eco mode to full power (need to first re-cooldown one cryoplant at nominal temperature)
  - Without prior notice, it will probably take ~2 days
- **Most of the cryo recovery durations are not impacted by the eco mode**, only the “biggest ones” are concerned. Also risk of RF burst disk events is completely independent of eco mode.
- What can be learned from recent experience:
  - **P6 & P8: Eco mode is suitable** and should be used as much as possible
  - **P2(/18): Eco mode is not suitable** due to the special arrangement of cryoplants→use the full power mode during beam operation
  - **P4: Not obvious -** Special due to the RF cavities and because in most of the trips, even during a “cold compressor trip”, the recovery time in eco mode will be satisfactory. Nevertheless, for a trip of all P4 cryoplants emptying the RF cavities for a significant amount of time (like after a long power/water cut - occurs about once per year), the recovery time will be impacted by the eco mode.

Conclusions I

LHC - is it falling apart?

- It’s in better shape than this meeting room…

Conclusions I

LHC - is it falling apart?

- No, but ….
- Since 2022 the machine availability is dominated by a small number of long faults.
- Qualitative analysis of the five longest events of 2023 suggests
  - 2 events possibly due to aging but also non-conformities.
  - 3 events due to more recent changes.
  - 4 events due to inadequate specifications and/or non-conformities

Conclusions II

How to get out of the series of unfortunate events?

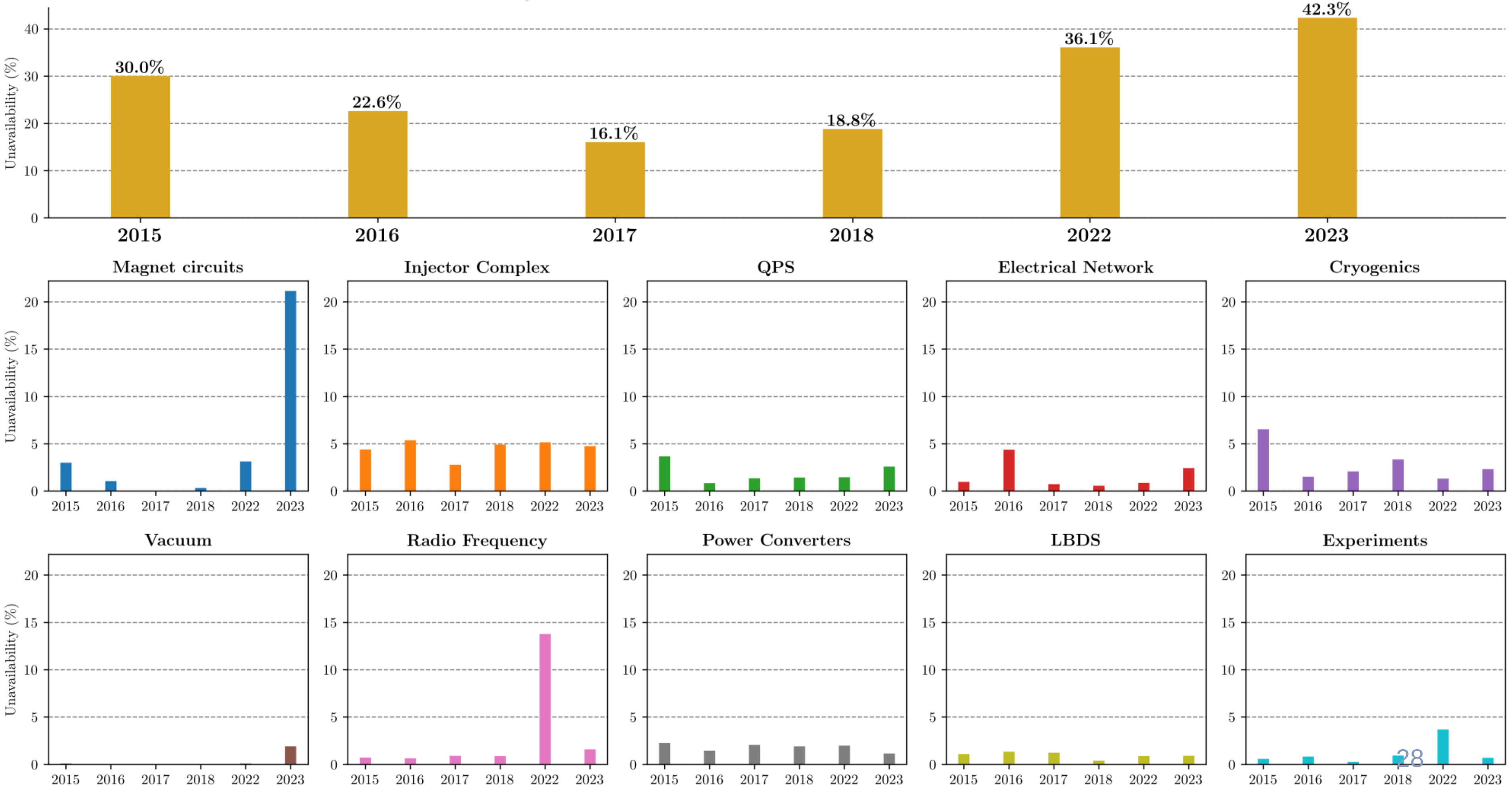
- If we push operational parameters, we will probably find new weaknesses. This is important as we want to find them before LS3. However, **we have to balance producing luminosity and finding limits**.
- For known weaknesses, **identified risks should be carefully considered**. Additional monitoring may help to prevent further damage (especially for systems at cold or in radiation areas).
- Can we invest even more in specification, testing and validation of machine & equipment (HW & SW) upgrades to avoid new non-conformities of HL equipment? IT-String is important!

Besides that:

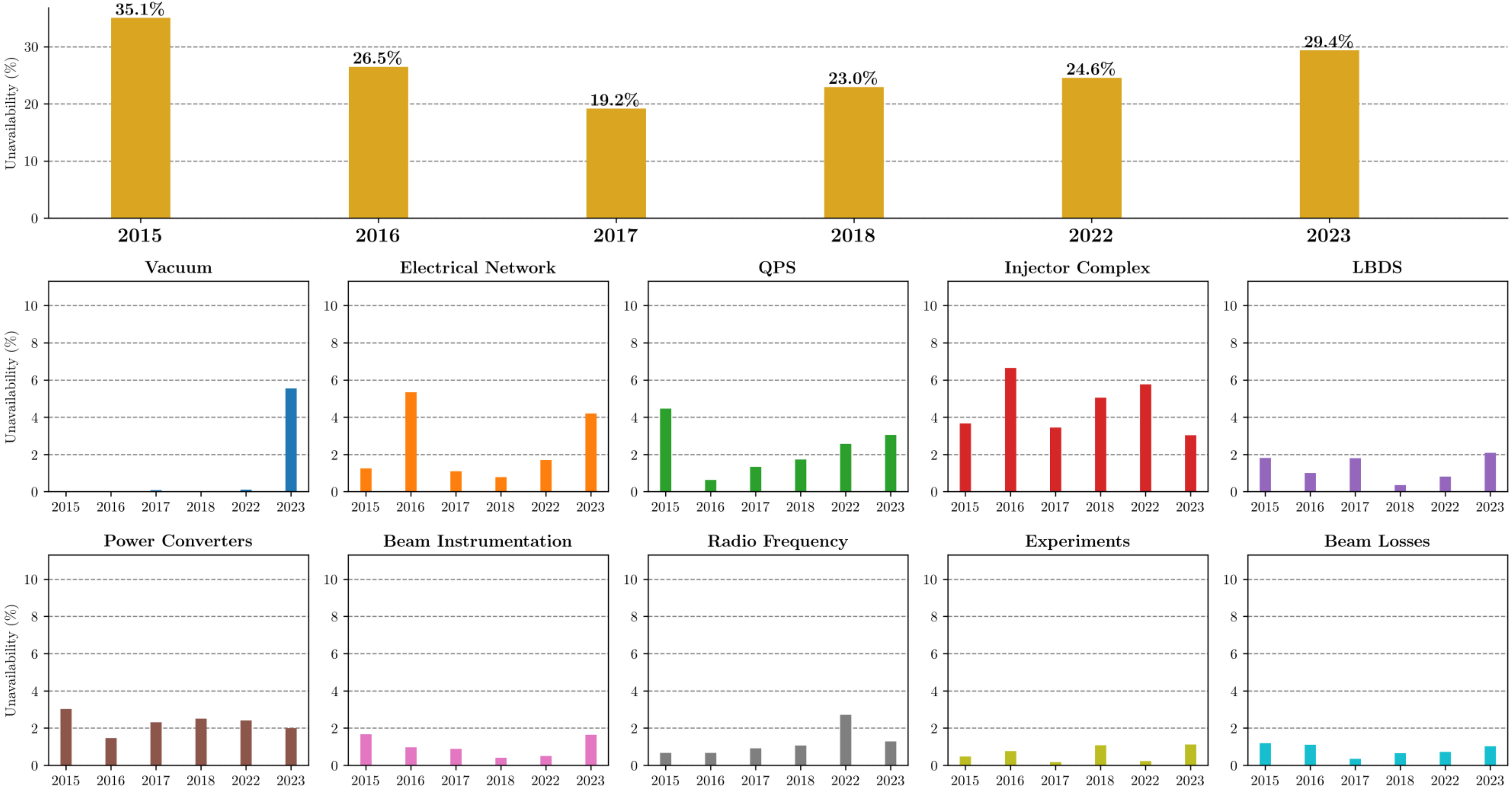
- Faults <1 day: Significant differences in unavailability trends between systems over years → **Continuous efforts to maintain high availability are extremely important.**
- Many systems are expected to reach end-of-life in LS3, following 20 years of operation. Replacements of some systems are already taking place. **A careful choice for consolidation will be important in the coming years.**

Backup slides

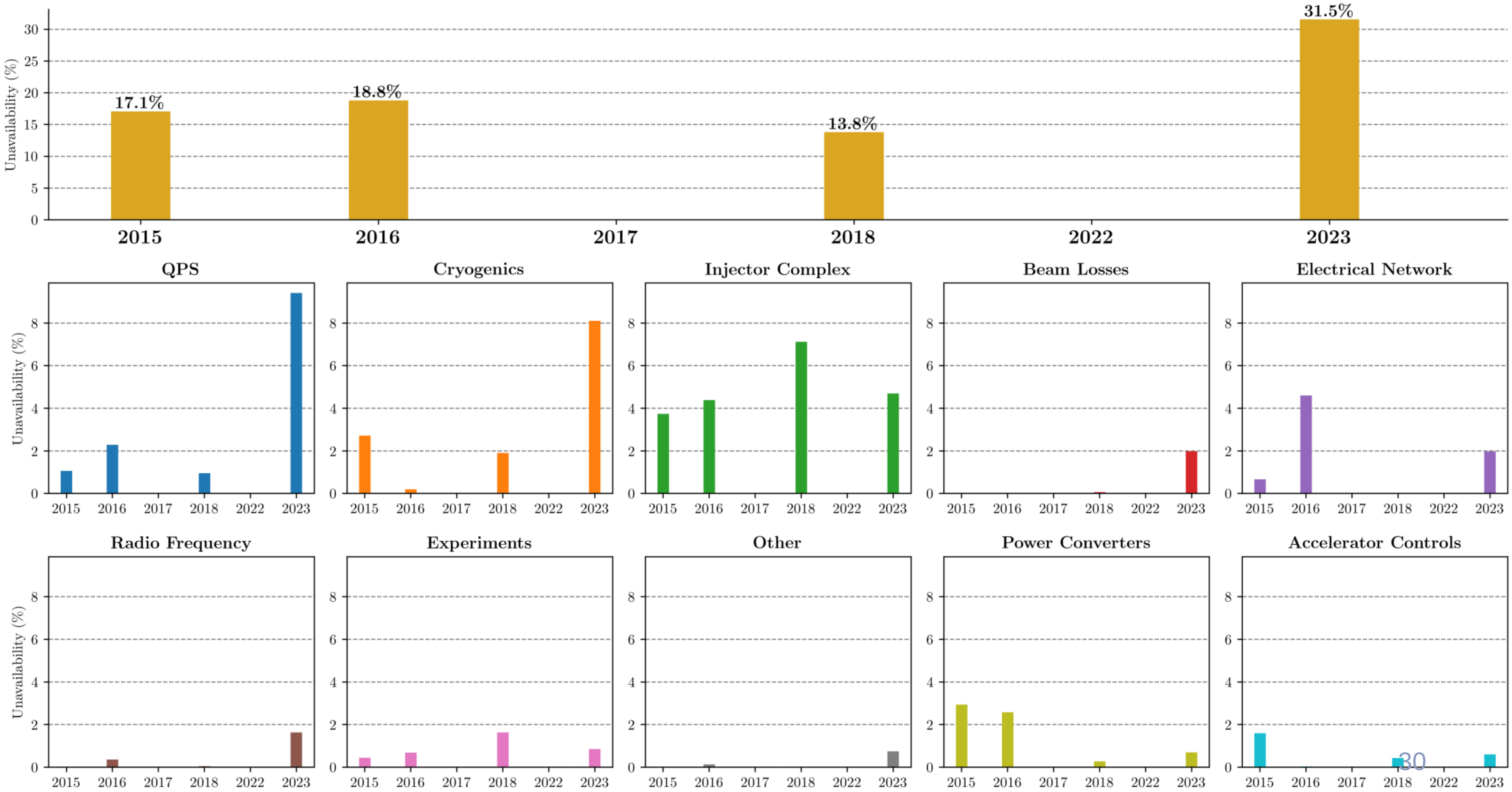
System Unavailabillity Contribution
Counted from start of re-commissioning with beam → End of run



System Unavailabillity Contribution
Proton runs



System Unavailabillity Contribution
Ion runs



Considered times

```
#proton run
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                    ('07:45 03/06/2015','00:00 15/06/2015'),
                    ('01:00 20/06/2015','15:00 20/07/2015'),
                    ('03:00 13/08/2015','14:00 26/08/2015'),
                    ('19:30 06/09/2015','10:00 04/11/2015'),
                    ('01:00 24/04/2016','09:00 06/06/2016'),
                    ('08:18 11/06/2016','04:24 16/06/2016'),
                    ('23:32 16/06/2016','08:24 01/07/2016'),
                    ('03:14 02/07/2016','23:26 25/07/2016'),
                    ('22:49 31/07/2016','06:32 21/08/2016'),
                    ('18:38 24/08/2016','00:17 10/09/2016'),
                    ('00:00 19/09/2016','07:00 03/10/2016'),
                    ('23:00 07/10/2016','14:00 13/10/2016'),
                    ('00:00 14/10/2016','09:00 20/10/2016'),
                    ('00:00 21/10/2016','11:00 21/10/2016'),
                    ('21:00 21/10/2016','23:00 26/10/2016'),
                    ('15:20 23/05/2017','10:00 29/05/2017'),
                    ('07:30 30/05/2017','15:00 06/06/2017'),
                    ('09:00 12/06/2017','09:00 30/06/2017'),
                    ('19:00 09/07/2017','06:00 24/07/2017'),
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                    ('17:30 13/10/2017','07:00 08/11/2017'),
                    ('23:00 08/11/2017','15:00 10/11/2017'),
                    ('11:30 17/04/2018','08:00 23/04/2018'),
                    ('14:45 24/04/2018','07:00 12/06/2018'),
                    ('17:30 21/06/2018','06:50 23/07/2018'),
                    ('06:30 28/07/2018','07:20 12/09/2018'),
                    ('01:09 22/09/2018','06:30 10/10/2018'),
                    ('06:30 10/10/2018','21:22 14/10/2018'),
                    ('21:22 14/10/2018','06:02 24/10/2018'),
                   ('00:00 04/07/2022','18:00 23/08/2022'),
                   ('00:00 27/09/2022','07:43 17/10/2022'),
                   ('08:03 19/10/2022','18:37 05/11/2022'),
                   ('08:42 09/11/2022','11:23 17/11/2022'),
                   ('16:46 19/11/2022','08:00 22/11/2022'),
                   ('19:50 23/11/2022','06:00 28/11/2022'),
                   ('17:15 22/04/2023','16:00 13/06/2023'),#first stable beams declaration - start of MD1
                   ('00:00 01/07/2023','01:00 17/07/2023')]

#ion run
time_interval_str_ion = [('08:00 23/11/2015','16:30 13/12/2015'),
                         ('00:00 11/11/2016','00:00 04/12/2016'),
                         ('18:00 08/11/2018','09:00 27/11/2018'),
                         ('20:22 27/11/2018','17:45 02/12/2018'),
                         ('18:00 26/09/2023','09:30 29/09/2023'),
                         ('15:30 29/09/2023','06:00 07/10/2023'),
                         ('18:00 07/10/2023','13:30 12/10/2023'),
                         ('16:30 12/10/2023','08:00 18/10/2023'),
                         ('12:00 19/10/2023','00:00 30/10/2023')]

#all OP
time_interval_str_all = [('00:00 05/04/2015','00:00 14/12/2015'),
                         ('00:00 29/03/2016','06:00 05/12/2016'),
                         ('00:00 01/05/2017','06:00 04/12/2017'),
                         ('00:00 30/03/2018','06:00 03/12/2018'),
                         ('00:00 26/04/2022','09:30 28/11/2022'),
                         ('00:00 28/03/2023','06:00 30/10/2023')
                         ]
```

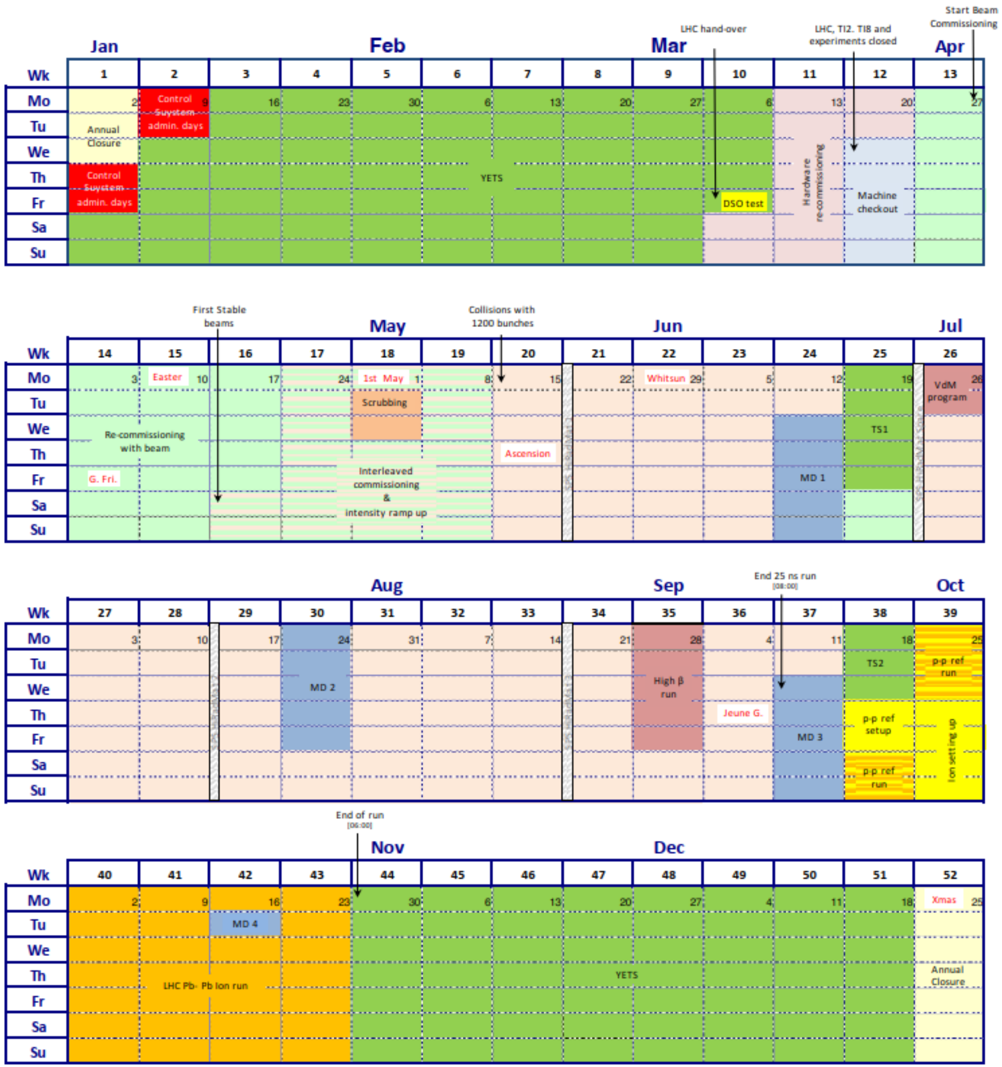
Questions asked to experts

- Please provide a short description of the failure and the root cause (or the most likely explanation for the root-cause).
- Please state whether or not the fault was:
  - Wear-Out or Aging phenomenon?
  - Beam intensity related?
  - Random Hardware Failure?
  - Consequence of modifications or upgrades of the concerned equipment (e.g. in LS2)?
  - Inadequate specification?
  - Production non-conformity?
- What is the mitigation status of the fault (including any plans for YETS23/24 24/25)?
- Can similar problems be expected in the next years on same or similar equipment elsewhere in the machine?

Schedule v1.0

Nov 7th, 2022

Programme	Days
proton run	118
ion run	27
MD	16
pp-ref run	5
high beta run	5



Schedule v1.7

Oct 12th, 2023

Programme	Days
proton run	118 → 68.5
ion run	27 → 33
MD	16 → 7
pp-ref run	5 → 0
high beta run	5 → 11

Faults in AFT recorded according to latest available schedule

Impact of large faults outside beam operation or that triggered re-scheduling not always visible → considered separately