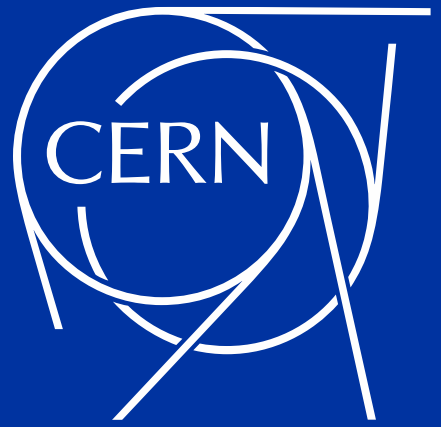


Recurring Faults in the Injectors Evolution over the Years and Plans

JAPW ’23, Montreux 5th – 7th of December 2023

R. Alemany Fernandez, T. Argyropoulos, A. Asko, F. Boattini, G.P. Di Giovanni, L. Felsberger, J. Heron, A. Lasheen, K. Li, B. Mikulec, R. Scrivens, P. Skowronski, R. Wegner.

Introduction

- Machine availability is the **primordial KPI** for the users in the injector complex:
  - **Direct correlation** (almost causation) with **users' experience satisfaction**.
  - **Is it the only one?** Of course not.
    - **Machine performance** is for instance an essential one. But more uptime allows for more optimization.
    - Ongoing effort to **track periods of degraded mode.**

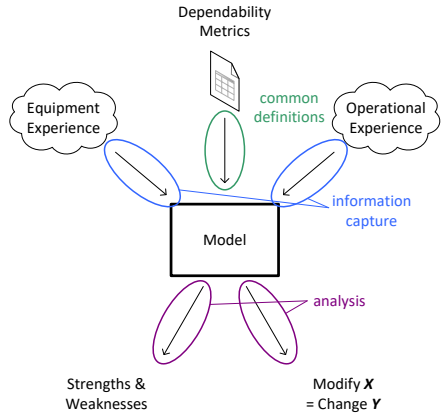
- **How to correctly evaluate machine availability?**
  - Establish **common metrics.**
  - Capture **information from equipment and operation**.

Good quality data are a crucial ingredient!

- **End goals:**
  - Identify **strengths and weakness** in today's machines.
  - Identify **areas to address for the future** (resources allocation, CONSolidation, new projects).

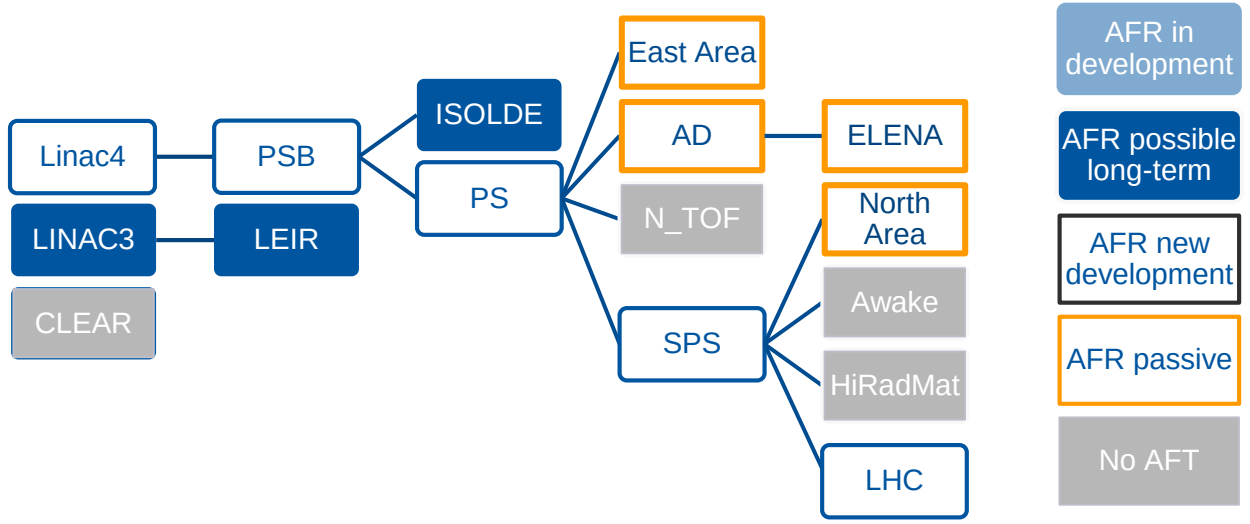
- The overall orchestration, including regular reviews of the data as well as the long-term strategies for the data exploitation fall under the umbrella of the **Reliability and Availability WG** (https://indico.cern.ch/category/9071/).

Data Capture



- **A**ccelerator **F**ault **T**racking (**AFT**) inherited **from the LHC** since 2017 (outcome of Chamonix ’16).

- **More than 10k faults** recorded and reviewed in 2023 (LHC included) → **Automation necessary**
  - Significant **effort done by OP** in integrating the machines of the CERN complex.
  - The data automatically/manually stored are **first reviewed by the coordinators/supervisors of the week.**
  - **Weekly fault reviews** throughout the year, driven by Lukas/Jack.



Support

- Accelerator Fault Tracking (AFT) inherited from the LHC since 2017 (outcome of Chamonix ’16).

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- A major goal for this year was to raise expert review rate and participation by increasing:
  - Experts’ awareness and notification mechanisms on fault existence.
  - Clarify responsibility throughout the systems in the accelerator complex
  - Make UI/UX better for the experts.

Great effort from Anti/Lukas

User Training and Onboarding:

Multiple demos have been given to different expert groups

	L4	PSB	PS	SPS	LHC	EA
2022	78%	59%	58%	25%	46%	39%
2023	94%	78%	54%	17%	50%	70%

Culture

- **A**ccelerator **F**ault **T**racking (**AFT**) inherited **from the LHC** since 2017 (outcome of Chamonix ’16).

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  - Experts’ **awareness** and **notification** mechanisms on fault existence.
  - Clarify **responsibility** throughout the systems in the accelerator complex
  - Make **UI/UX better for the experts.**

- **Cultural shift:**
  - AFT is not a blaming machine.
  - **Industrial approach** necessary when looking at the data both for **equipment groups and management:**
    - Could resources be diverted to teams to address short-medium term issues which have a quantified impact?

2023 in a Glance

Slide presented by Rende at the OP group meeting in Dec. 2023

Facility	Destination	'21/'22 Overall [%]	Achieved 2023		Period
			Overall [%]	Per destination [%]	
LINAC4	PSB	96.7/97.1	**98.0**	**98.0**	2023 – 12.11.2023
PSB	PS	94.4/95.1	**96.1**	**96.4**	23 – 12.11.2023
	ISOLDE				03.2023 – 30.10.2023
PS	SPS	88.6/88.7			17.03.2023 – 30.10.2023
	East Area			3.5	27.03.2023 – 01.11.2023
	nTOF			**92.8**	03.04.2023 – 30.10.2023
	AD			**93.9**	12.06.2023* – 12.11.2023
ELENA	AD-Hall		**90.4**	**90.4**	12.06.2023* – 12.11.2023
SPS	LHC	74.5/73.3	**86.4**	**94.8**	27.03.2023 – 30.10.2023
	North Are			**87.3**	24.04.2023 – 30.10.2023
	AWAKE			**98.4**	01.05.2023 – 22.10.2023
	HiRadMat			**99.0**	22.05.2023 – 27.08.2023

You are doing GREAT!

Cumulative availability

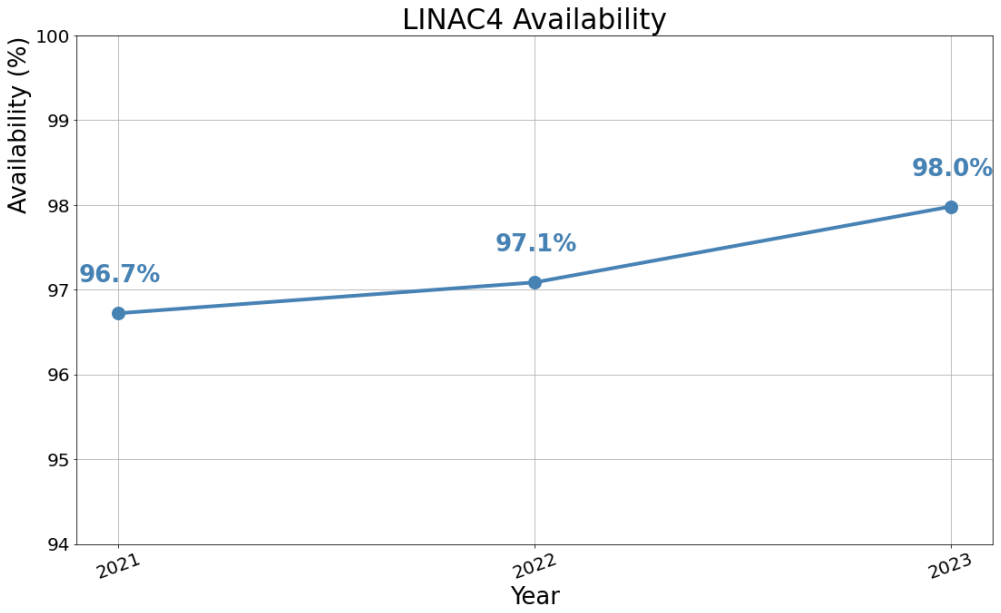
In the injectors overall very good availability

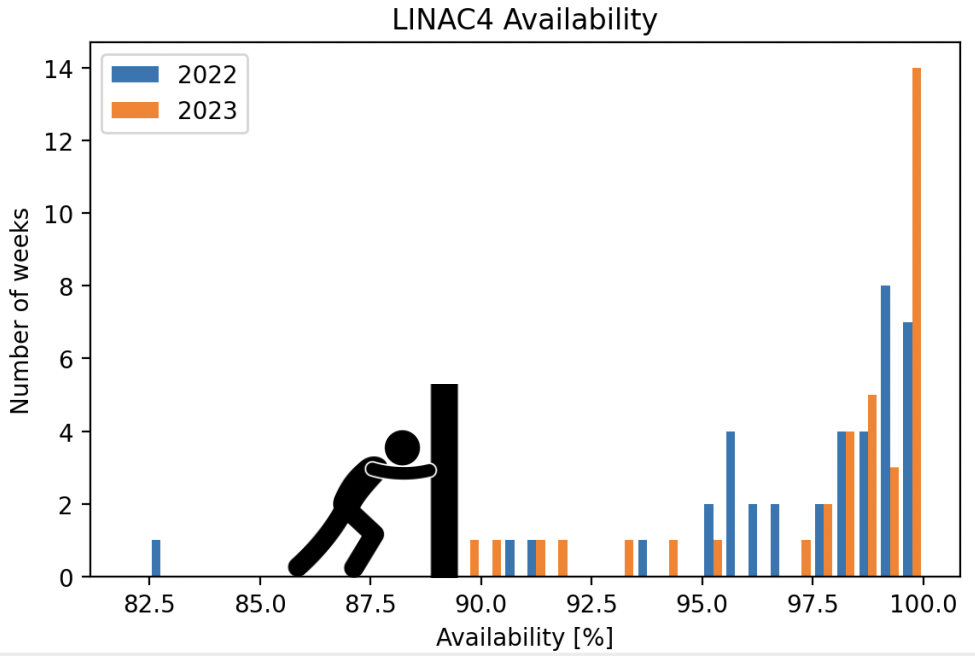
- *Better than in previous years*

Overall includes the whole period and all other beams such as MD etc.

**Revised AD start date following quadrupole water leak*

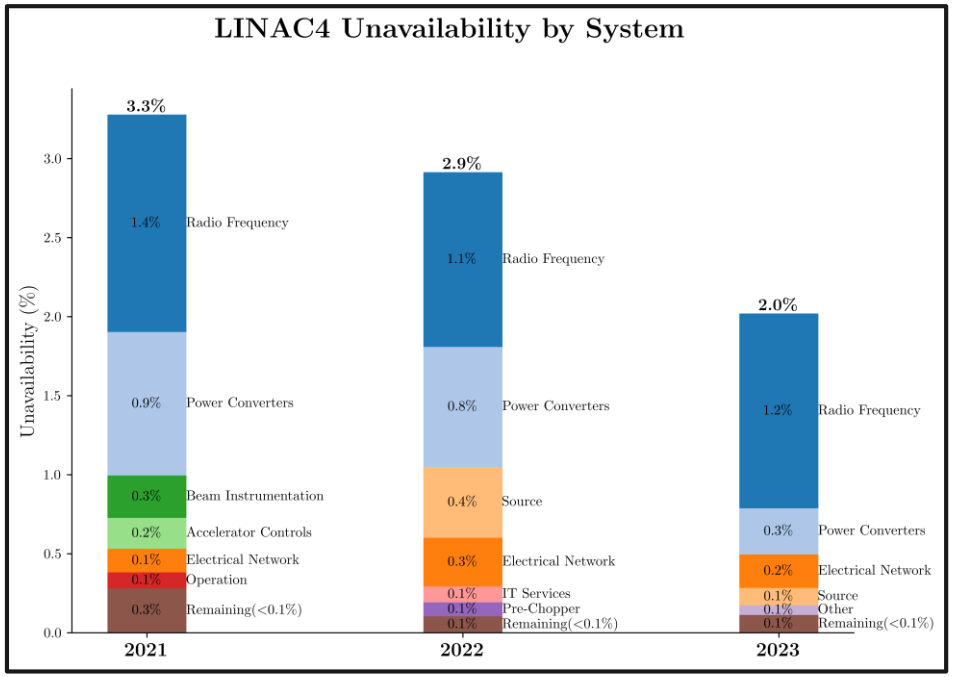
Linac4 in a Nutshell





- **Excellent performance**, availability increasing over time.
  - Experts continue **solving issues** which repeatedly cause downtime **at the source**, when possible.
- Machine is still relatively new, and we (still) do **not see many aging effects:**
  - **Reduced the number of faults, in particular the major ones**, i.e., longer than 2h.
  - Excellent **support and collaboration within the groups**.
  - Increasing (and keeping the) **experience** also plays a role.

Linac4



- **RF is the main** (>70% of the) equipment, and by far the **most challenging system,** so it must be the main downtime contributor:
  - ➢ **Still an impressive availability of 98.8%!**

- **Modulators** are power supplies that **deliver above 100 kV** voltage for klystrons. De facto, they are **integral part of RF powering system**:
  - They interlock with fast abort if RF lines stop.
  - They suffer from any high voltage sparking in the modulator-klystron systems.
  - Therefore, it is not a surprise that they are the 2nd contributor to the downtime.

- **Implemented several improvements throughout the years.** Only in 2022:
  - **Contained sparking** in modulator-klystron interface.
    - Minimized modulator voltages and layout modifications.
  - Extended **cavity break down** protection across **LINAC4.**
  - **Chopper trips from 2022 addressed**:
    - PLC FW & interlock logic update.
    - Chopper dump alignment line and better steering in MEBT.
  - **DTL1 klystron exchanged** in EYETS22/23.
  - **Source valve validation in test stand** and modification the **gas injection system** for a faster valve exchange.

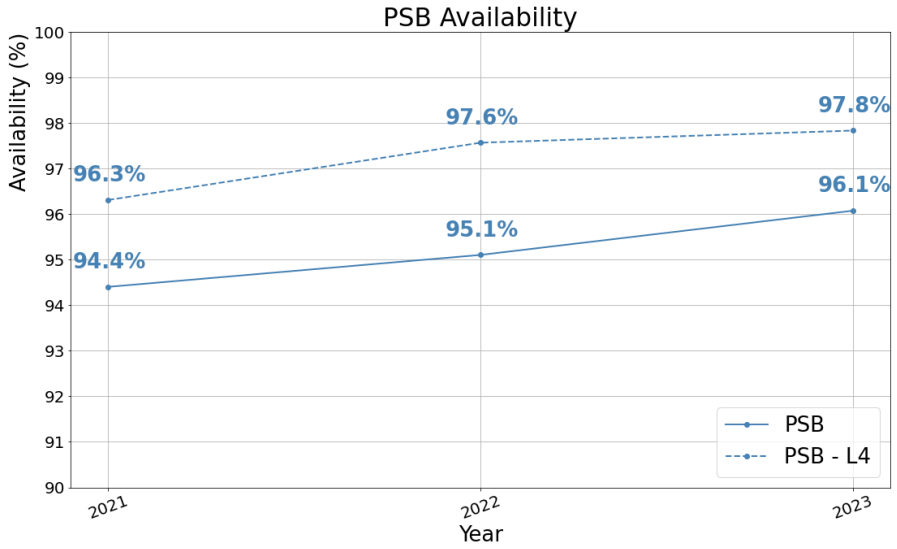
Linac4

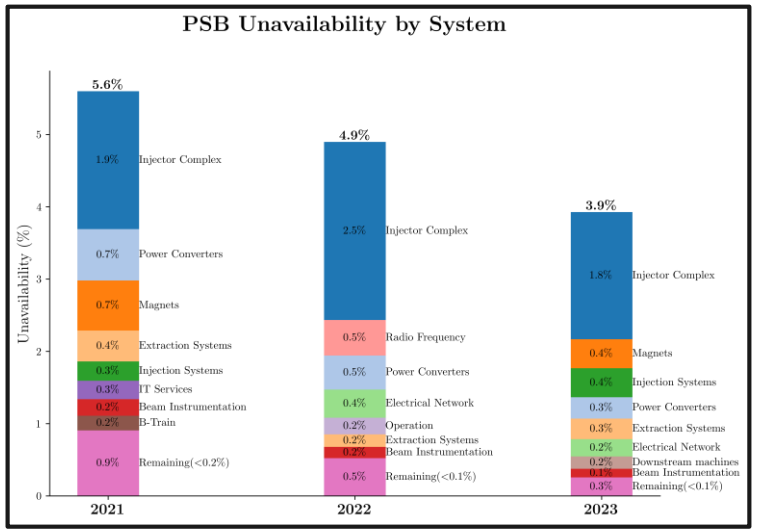
- **2x burned connector on focus circuit:**
  - Other connectors were verified during iTS.
  - Consolidation during YETS.
- **Hydrogen valve in the source.**
- **Aftermath of LEIR 18 kV circuit breaker fault.**
- **Card measuring filament current (interlock).**
- **Water pressure sensor (interlock).**
- **Card measuring focus current (interlock) + difficulties in the system restart.**
- **Sensor checking socket connection (interlock).**

Date	Equipment	Downtime
Mar 15	PIMS1112	9 hours
Apr 15	PIMS0102	8 hours
Apr 28	Source	5 hours
Jun 27	Multiple	7 hours
Jun 1	CCDTL1	4.5 hours
Jun 12	CCDTL1	13.5 hours
Oct 17	CCDTL7	10.5 hours
Nov 2	Pre-chopper	4.5 hours

4 out of 7 are related to faulty sensors interlocking the machine (being followed-up by experts)

PSB in a Nutshell



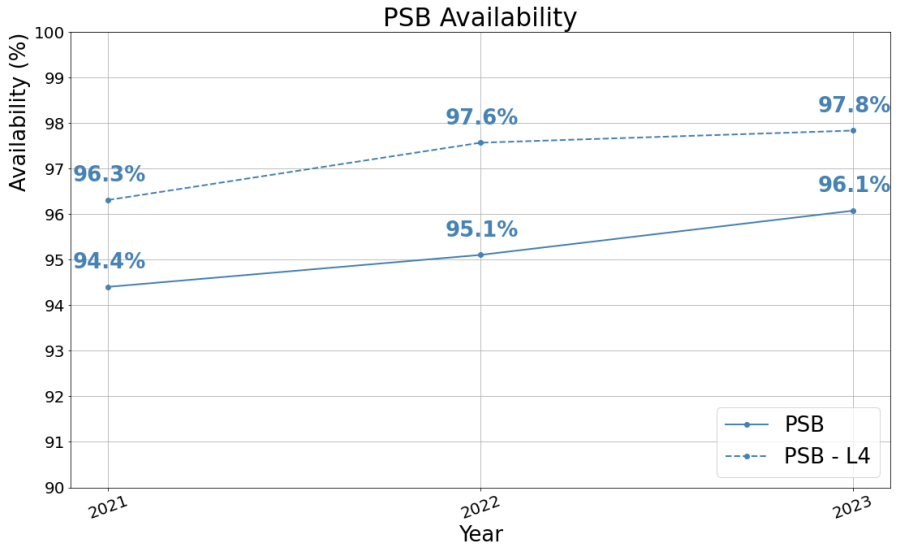


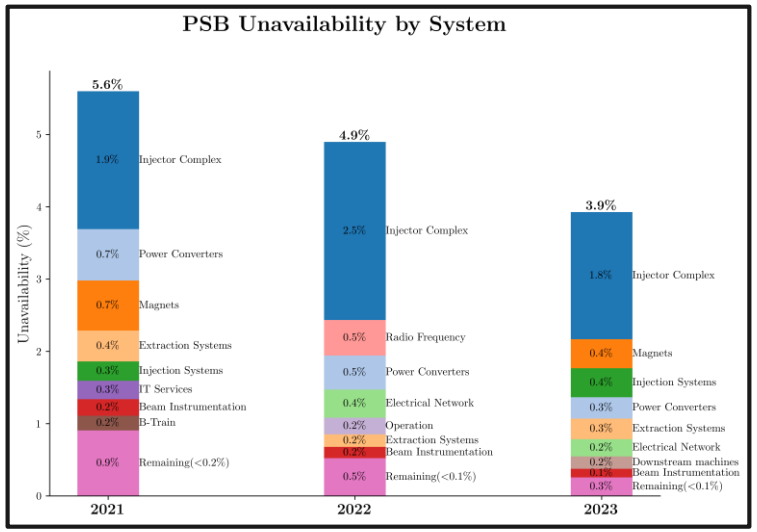
- PSB only availability is **comparable to Linac4** (~98% in 2023!).
  - Even more impressive counting that PSB extracted the same # of protons in 2022 with ~20% less days.
- PSB is a **mix of new** (LIU) and **LEGACY equipment**.
- Some of the equipment is still > 50y, e.g. the main magnets, …

- Excluding the single event in 2022 of a vacuum leak caused by an arc in a RF bypass in 16L1 R2 (intensity push) the pattern of downtime is generally the same:

1) Linac4.
2) Magnets issues (mainly water leaks).
3) BI.BSW water leaks and equipment replacement.
4) Power converters (every POPS-B trip takes at least 20 mins to recover from).
5) Electo-valve failures in recombination septa/losses on extraction septa.

PSB in a Nutshell





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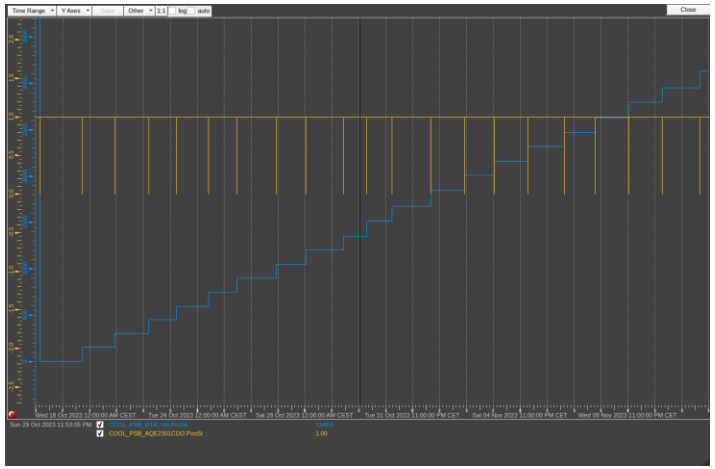
PSB Main Magnets

Water leaks in the PSB main magnets:

- 2 leaks in 2021, 3 leaks in 2022, 1 (and so far, only 1!) in 2023.
- This is **legacy equipment** (1972) and expected to pulse **+200M times by 2040**.
- A task force built to investigate and mitigate the issue, see here
- Source of the leaks due to **galvanic corrosion which attacks the brazed joints.**
- In the **short-term future, we could experience more leaks. Options are:**
  - Patching the magnet in situ and regularly monitor.
  - Replacing the leaking magnet.

➢ **Q: In the future could we early detect leaks without access?**

BR.QFO11 fencing, regular measurements, remote monitoring (cameras).



PSB water refills monitoring (EN-CV).

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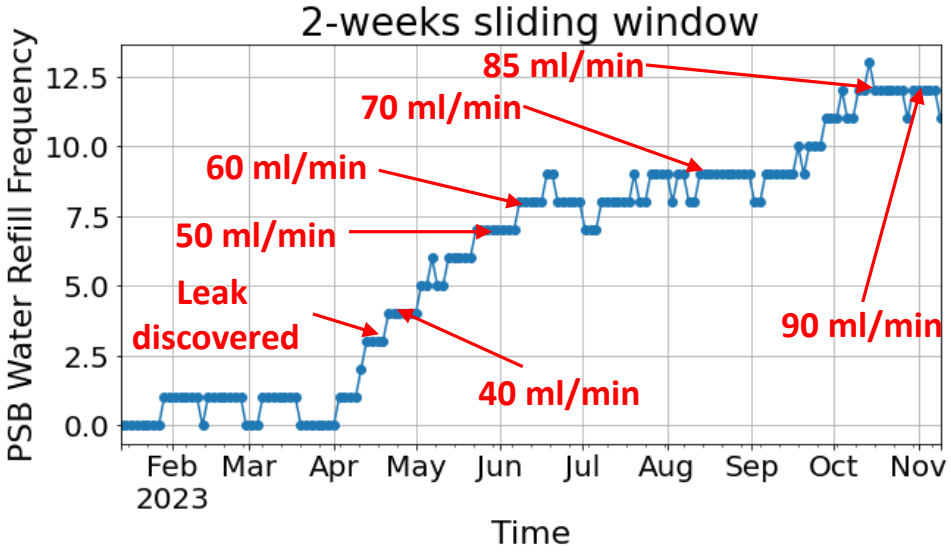
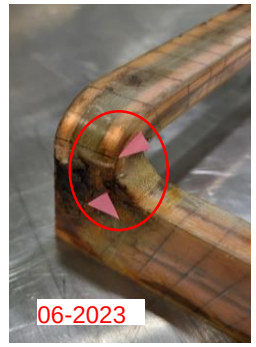


- **Data indicates that in 2023 lucky to spot the leak during a shadow access and the MSC team creative to patch it in situ.**
  It could have been a showstopper.

PSB BI.BSW

BI3.BSW1L1.1

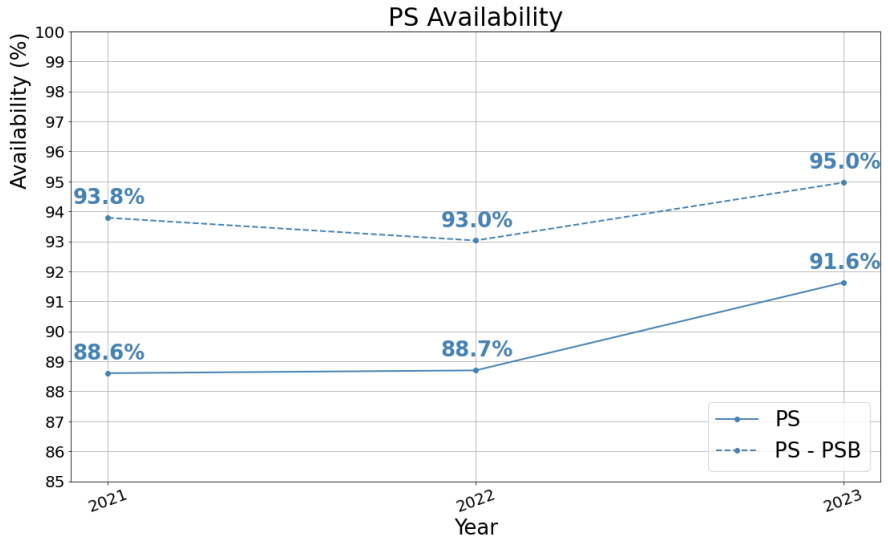


BI1.BSW1L1.4

- **BI.BSW coil failure, 7 since 2020 (16 bumpers in injection, 4 per ring).**
- This is LIU equipment, so brand new.
- Account of the history and mitigation measures (reinforced coils) presented at IEFC
- Coil reinforced and upgraded, still **leak this year on BI1.BSW1L1.4 was latest failure was on the upgraded braze, but too early to draw conclusions.**
- Downtime breakdown in 2023:
  - First issue identified on **BI1.BSW1L1.4** during iTS1. **Replacement during iTS (30h) so additional 4h30m without beam and ~10h in degraded mode** (no R1).
  - Second event on the same **BI1.BSW1L1.4** on 14th of August → **11h for the intervention.** Beam to beam in all rings.
  - After that **5 access, once every 2 weeks** to monitor for a total of ~4h30m downtime.

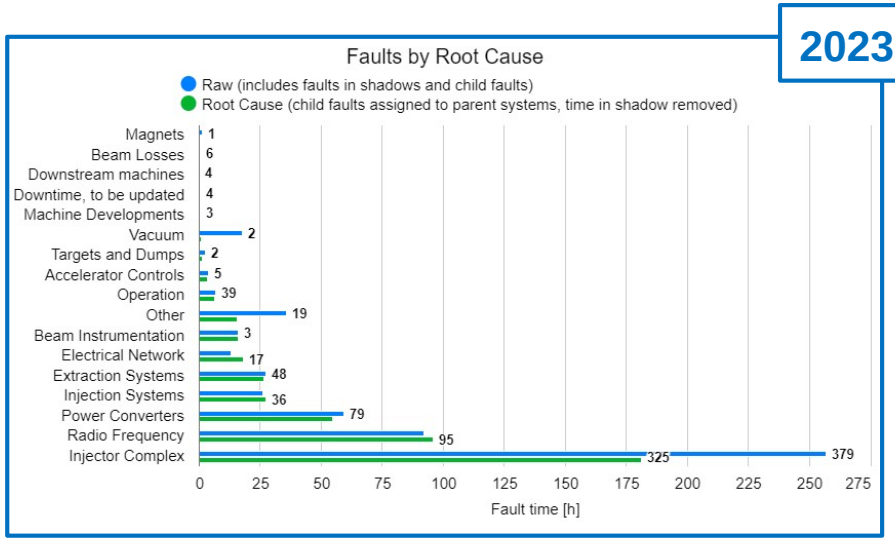
➢ **Mitigate mechanical stresses: ongoing study (IEFC endorsed) to review the interlock strategy.**

PS in a Nutshell



- Destination availability in 2023 between ~92% (SPS) - 94% (AD).
- Clear **improvement since LS2.**
- **Availability above pre-LS2 value** (90.7% in 2018).
- **Mostly standard maintenance in YETS23/24:**
  - ➢ No high expectations to improve availability in 2024.
- **Several improvements planned for LS3** (POPS+, HL+LLRF, PCs…).

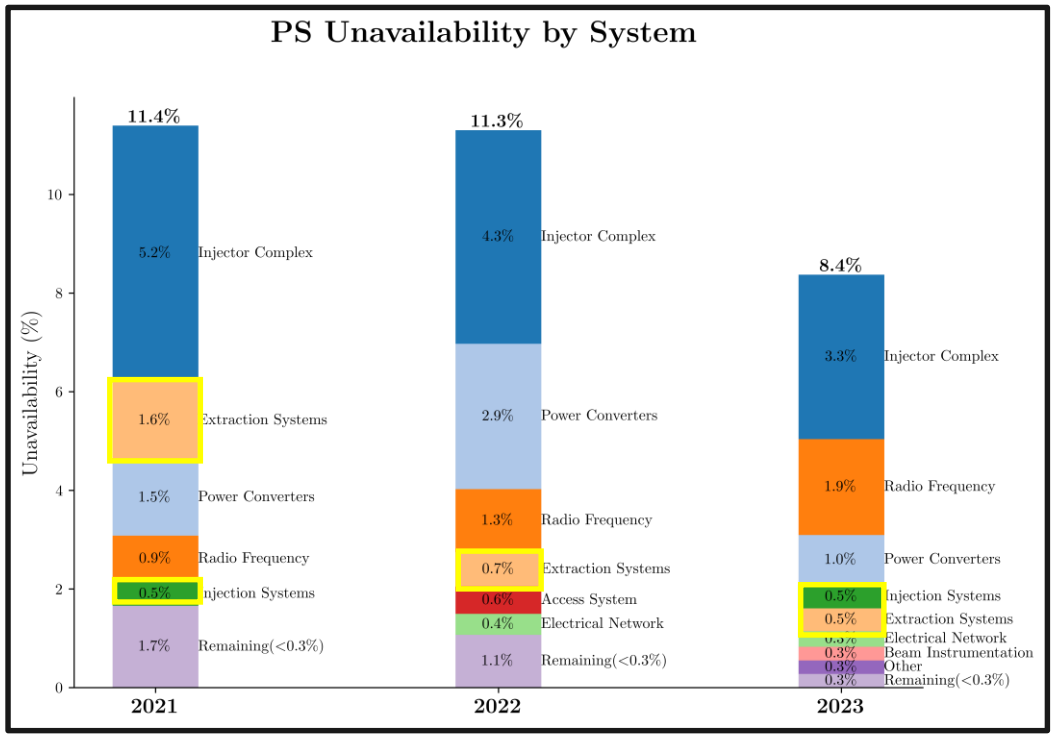
2023



- Besides injector faults, longest root downtime due to:
  1) Radio-frequency.
  2) Power converters.
  3) Injection/extraction systems.

➢ In the following slides we will analyse the trend in reverse order.

PS – Injection/Extraction Systems

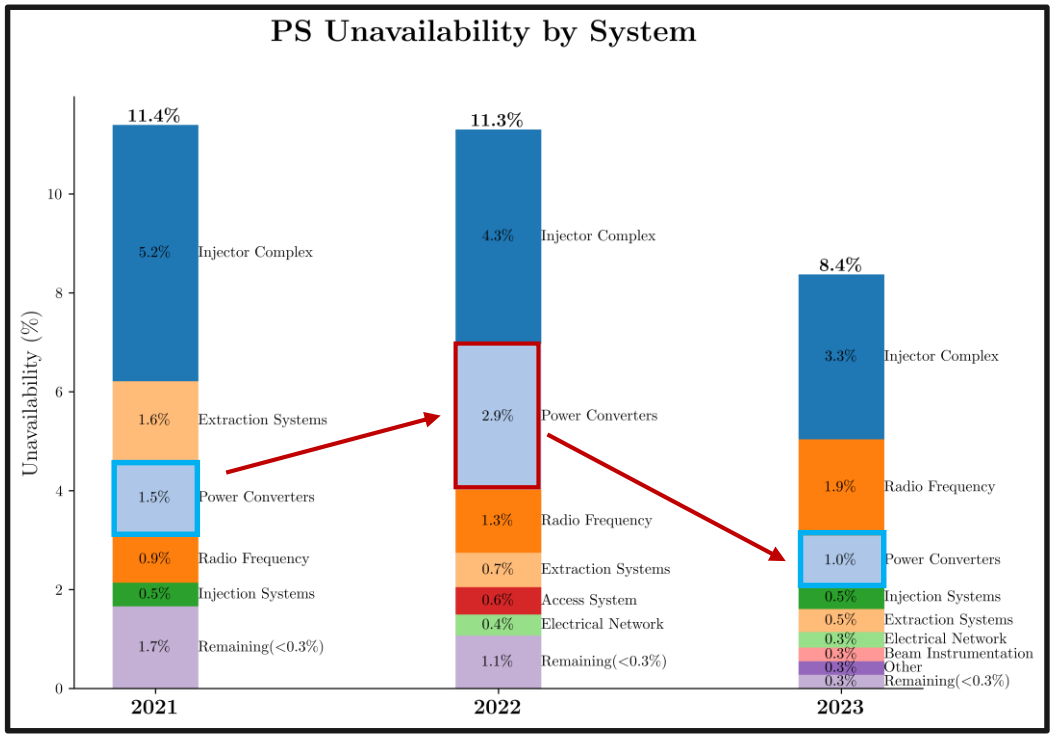


- Longest fault duration moved **from 2d in 2021** (**SMH57** condensation on cables, replacement affecting EA) **to ~7h30m in 2023 for ion injection kicker KFA28** burnt transformer (and power outage following smoke formation in B362).

- **The year 2023 was a difficult one for extraction kicker KFA71/79**, which does not really show up in AFT.
  - Recurrently, missing pulses leading to **radiation alarms** (beam lost at FT), but quick resets.
  - **Staggered consolidation of 3 generators** every YETS.
  - **Lessons learnt in 2023 to improve reliability in 2024.**

- A few faults on KFA13 affecting SPS NA (MTE).

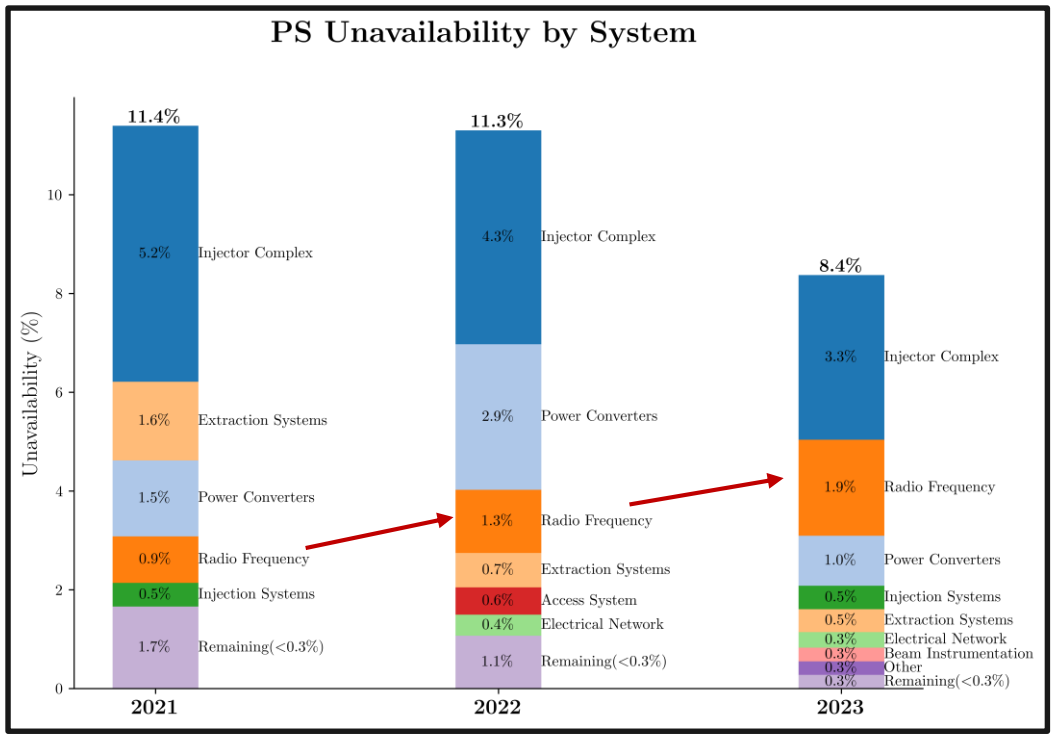
PS – POPS



- Increase of “Power Converters faults“ in 2022 due to **POPS communication issues between FGC and main controller:**
  - Massive effort throughout the year and EPC piquet solicited
  - Issue understood at the end of October: the **replacement of crate power supplies** to **3 independent power supplies** made the ripple disappear.
  - ➢ **Benefit of the modification visible in 2023.**

- Worth mentionining that **a few POPS trip in 2023 were due to new demanding cycles:** TOF double-extraction, special low-energy cycles, degaussing of pole-face windings etc.
- **Feedback** from operational years to be used for **POPS+ (LS3)**, i.e. improved diagnostics, etc, etc
- Improve HW reliability with additional AD/DC and DC/DC converters (one per type).

PS – RF Systems



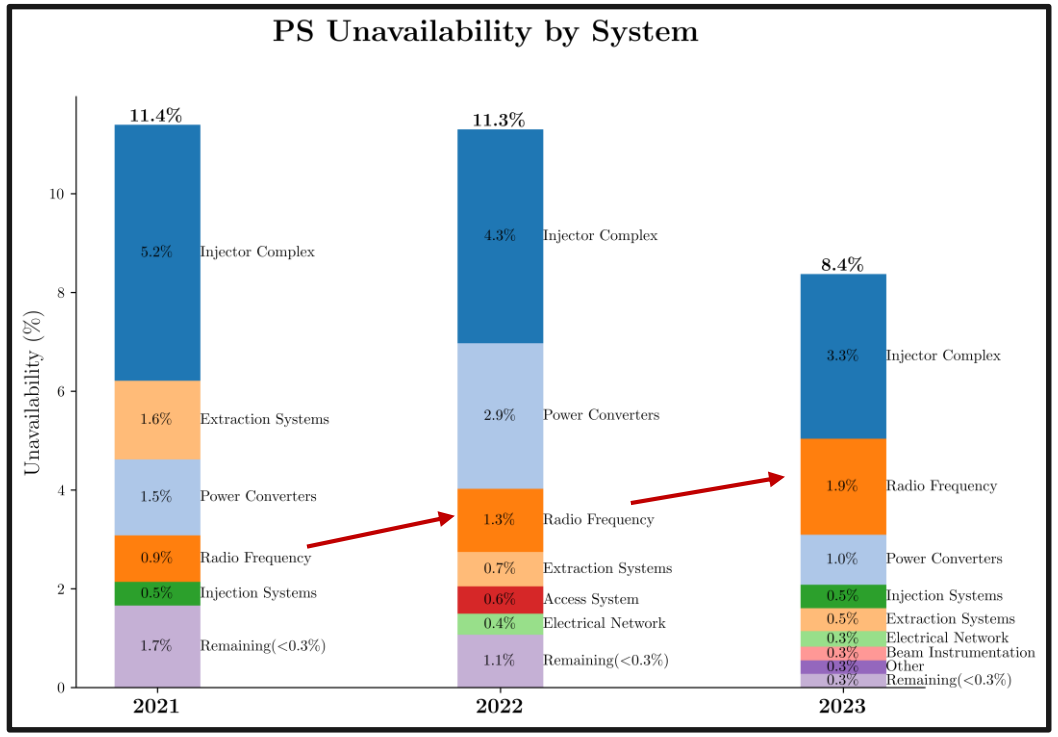
- Percentage of **RF faults seems increasing over time**:
  - Carefully **monitored by the RF team**, see here
  - RF is working on **better classification** to more effectively identify which part of the systems to focus on.
  - Some faults affect beam quality, so are not automatically recorded.

- **PS is CERN's most complex/flexible accelerator in the RF domain!**

- Much of the **RF system has been upgraded since LS1:**
  - Steady but gradual move to a fully digital LLRF system.
  - Digital beam control upgrade under preparation, MDs in 2024.
  - From **2024 all cavity controllers will be digital** (except 200 MHz).
  - HLRF upgrades to improve direct feedback and remote control/monitoring.
  - **More to come in LS3**: Tuning PSUs, driver amps, LLRF…

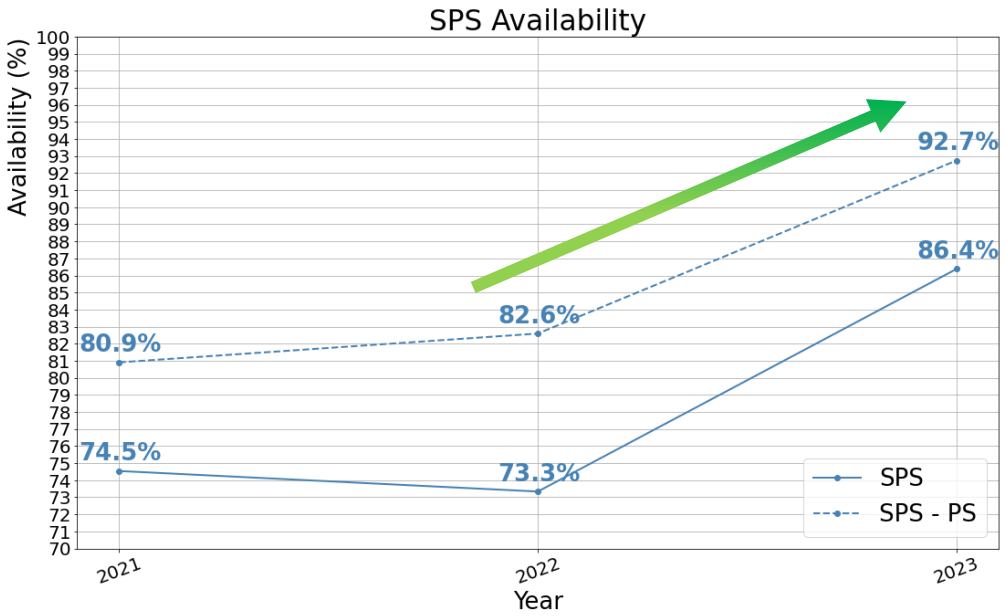
PS – RF Systems

Large # of interlock signals per year but few are equipment disorders



- **Over 2000 faults in 2023 on 10 MHz system:**
  - Gap relay. Short reset or switch to spare if available.
  - **Ring access for 9 gap relays and 8 amplifiers replacements.**
  - RF tubes of the 10 MHz driver amplifiers obsolete and not on the market anymore. **Renovation needed in LS3 (CONS). Prototype tests in 2024.**
  - 10 MHz power converters:
    - Old, **CONSolidation by SY-EPC prepared for LS3.**
  - Tuning power converter for the 10 MHz cavities:
    - Old, **CONSolidation by SY-EPC prepared for LS3.**
- **Over 1000 faults in 2023 on 40/80 MHz systems:**
  - Easily resettable. Mostly **affecting beam quality and can remain unnoticed.**
  - EPC fixed issue with PC but **should be CONSolidated**.
- **Longest downtime:**
  - Non-conforming (prototype design) bypass in SS03 caused 16h of downtime. **Fixed for 2024 and no bypass of this type left in the machine.**
- In **2023 intermittent issues on the H16 barrier bucket prototype controller** causing the controller to crash and not distributing the rev. Frequency:
  - **FESA class modification** in August **fixed the issue.**

SPS in a Nutshell



Context:

- 2021, a commissioning year.
- 2022, running at the highest intensities (SPS NA).
- 2023, post-commissioning and running at standard intensities.

+ Positive trend over the years

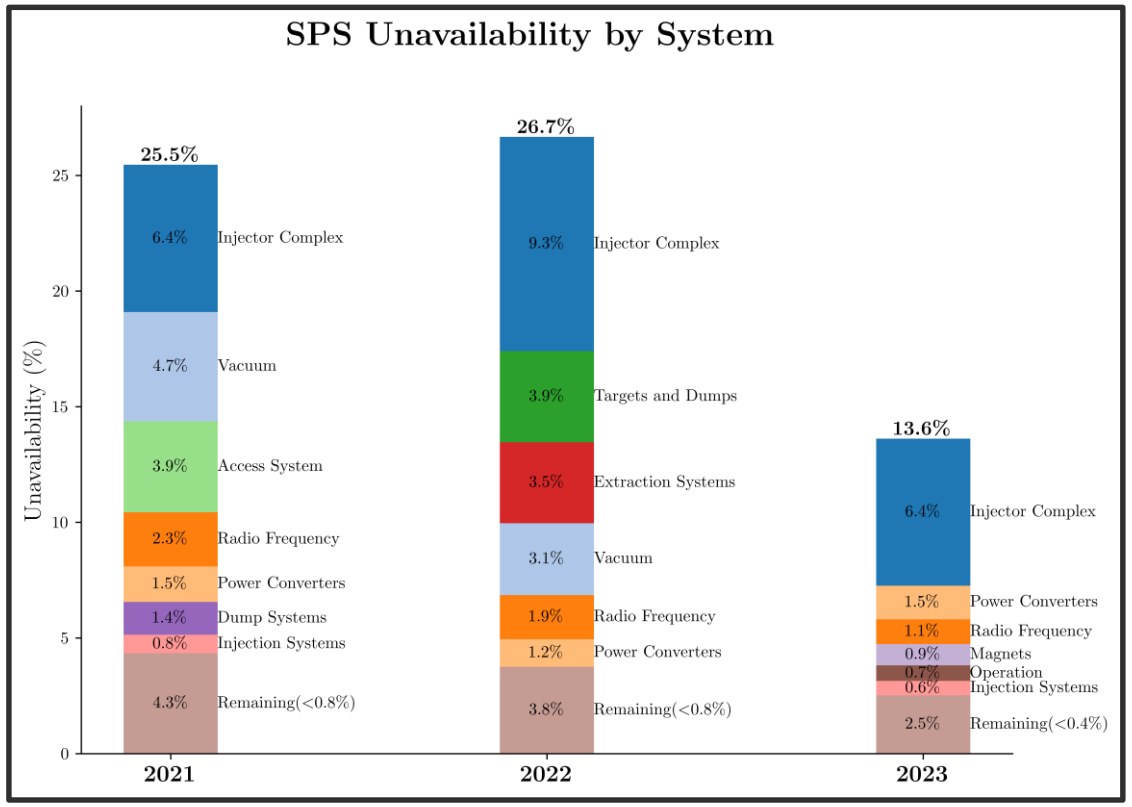
- Faults maximum downtime moved from mulitple days in 2021/2022 to max 1d in 2023 (excluding the MSN.X0220031 as it is EA).

- The SPS remains an RP challenging environment:

- Equipment interventions require long RP cool-down time and careful planning (ALARA).

- **Do not expect major improvements for 2024.**
  - Availability should improve with the NA CONS, but not in the immediate future.

SPS in 2021



- **Several single event upset (SEU) like events.**

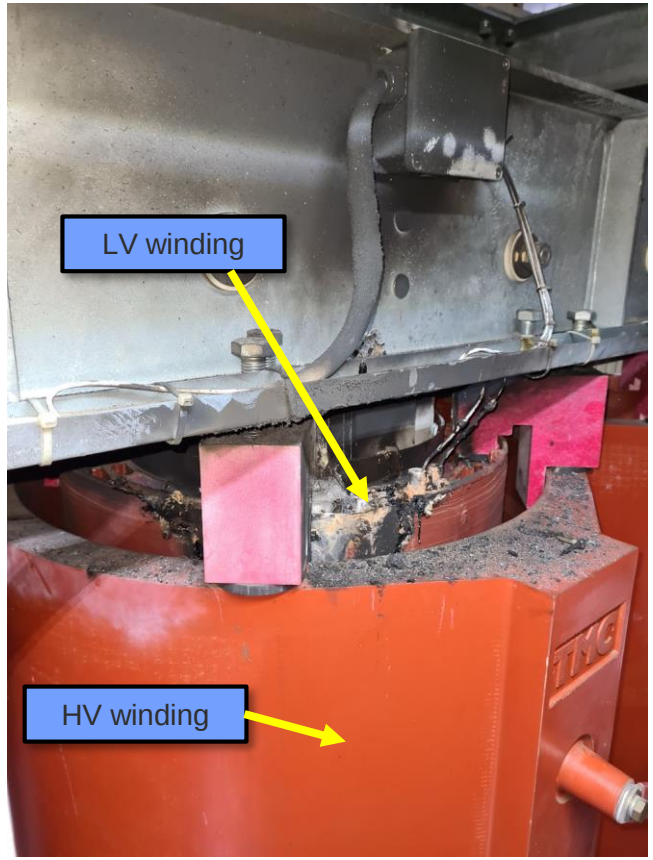
- A couple of **vacuum system issues due to corrosion.**
- **Dump kicker MKDV1:** weak high voltage behaviour due to broken insulating ceramic spacer.
- **Arcing in transmission lines for RF cavities.**

- And **design issues** for **access system crates (radiation)**:
  - Mitigated in 2022 adding a **shielding in front**.

All these issues have been addressed and did not recur in the following years.

SMD Transformers

- In February 2021, **LV insulation failure on a BA2 transformer**.
  - It happened during HWC, so not registered as downtime.



***Damaged area** RMT123-1/A2 (BA2)*

SMD Transformers

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- In March 2023 **a second failure of another BA2 transformer.**
  - 🔥 This time causing a **fire**.
  - It happened during HWC, so not registered as downtime.

RMT123-3/A2 – BA2

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  - 🔥 This time causing a **fire**.
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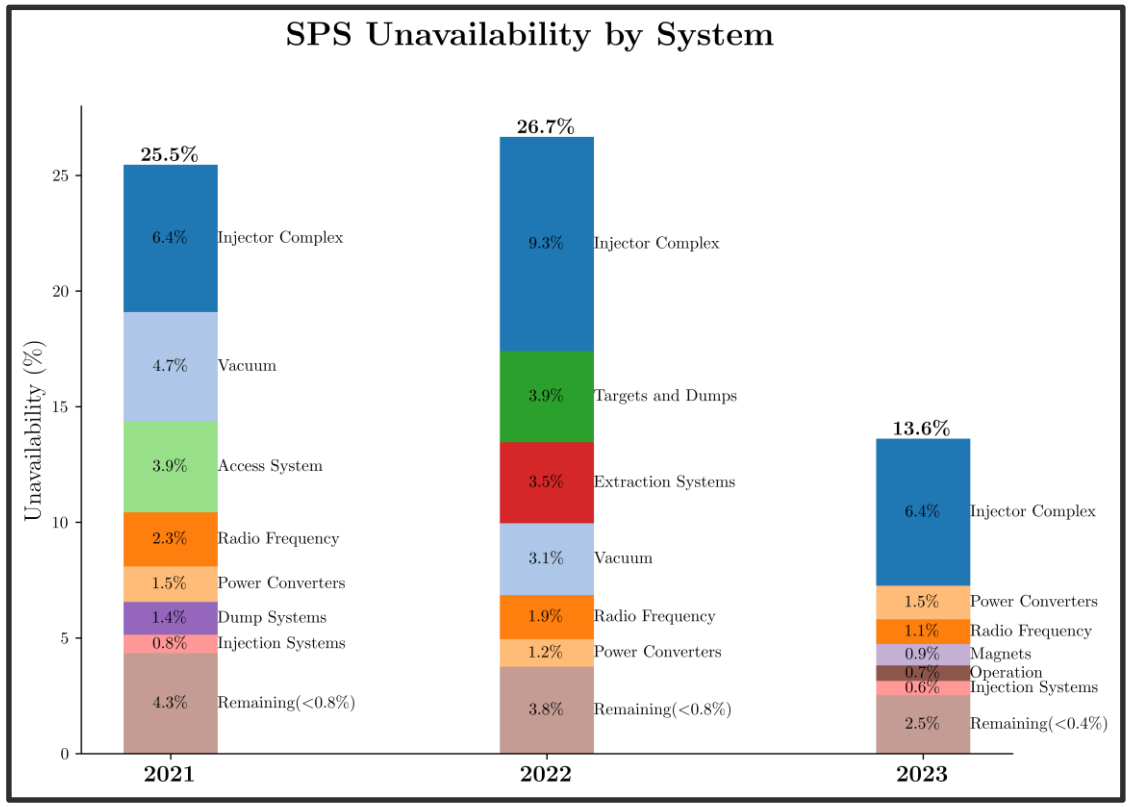
Transformers cut and analysed.

- **SY-EPC spent signifcant effort** on analysing the faulty transformers:
  - **Comprehensive investigations** have been done already, but **no obvious cause stood out.**
  - The possibility of **systematic failures** cannot be excluded as of today.
  - Strategy focuses **on early detection**, e.g. advanced temperature monitoring systems.
  - **Spare strategy** in place to mitigate machine downtime:
    - No fire risk for BA building → All **cast resin transformers are Fire Class F1.**
    - Eased the access and procedure updated.
  - Full report at the IEFC #335

SPS in 2022



April: **Water leak on TCSC**. SPS NA beam stopped for ***~9d***

May: **MBB22090 inter-turn short** (***~2d***)

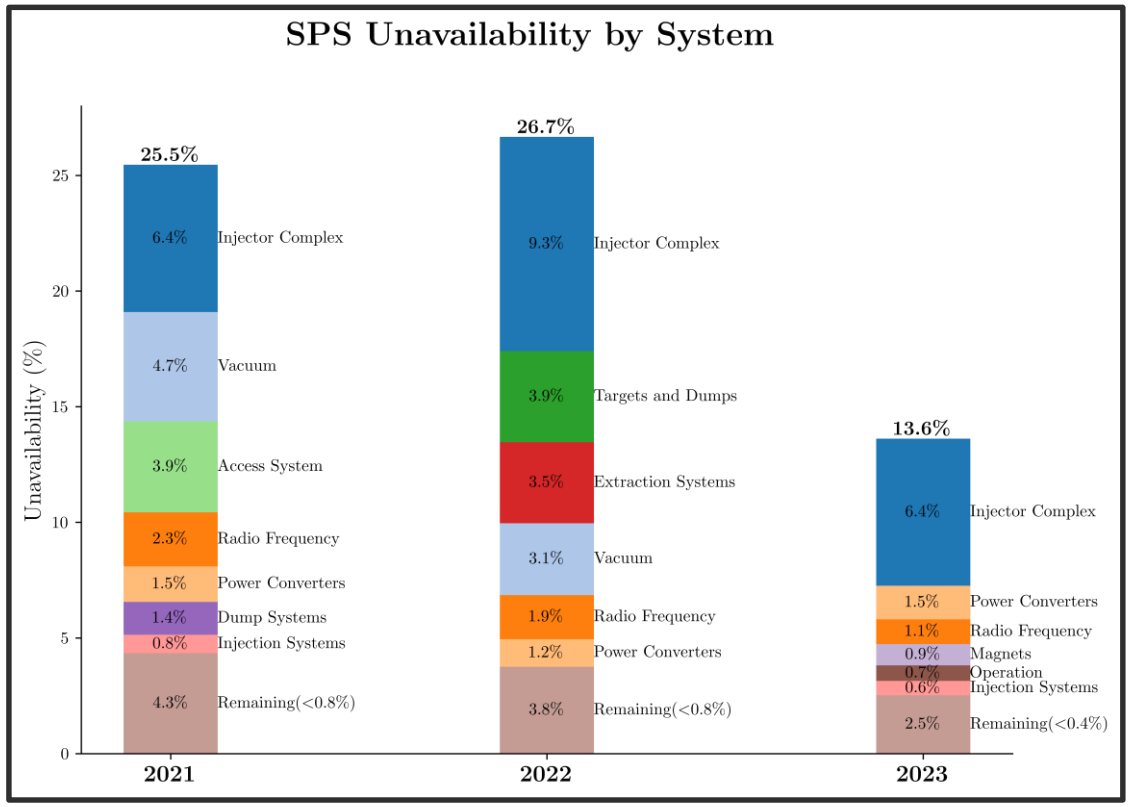
June: **ZS ion trap bottom voltage fault *(>5d integrated)***

- **High sparking rate** for some weeks followed by further degradation.
- Device **not able to keep the voltage** on the **ZS2 bottom** anymore.
- **Long cool-down time** and **several accesses** needed.
- Finally, **issue with the 4 cables of the ZS1 and ZS2 circuits**
  - **Root cause not yet clear**, high dose rates in-situ.
  - **Did not reoccur** in 2023.

July: **T2 TIBU vacuum leak** (***~6d***):

- Wobbling magnet in T2 tripped, followed by TBIU pressure rise.
- Replaced (plug-&-play) + time for cooldown

SPS in 2023



- **Good availability.** No systems or major faults
- The faults assigned to **operation are setting-up** and are not strictly speaking faults, as this time was scheduled:
  - ➢ **Is a less invasive integration of the SPS ions activities possible?** (see K. Li's talk)

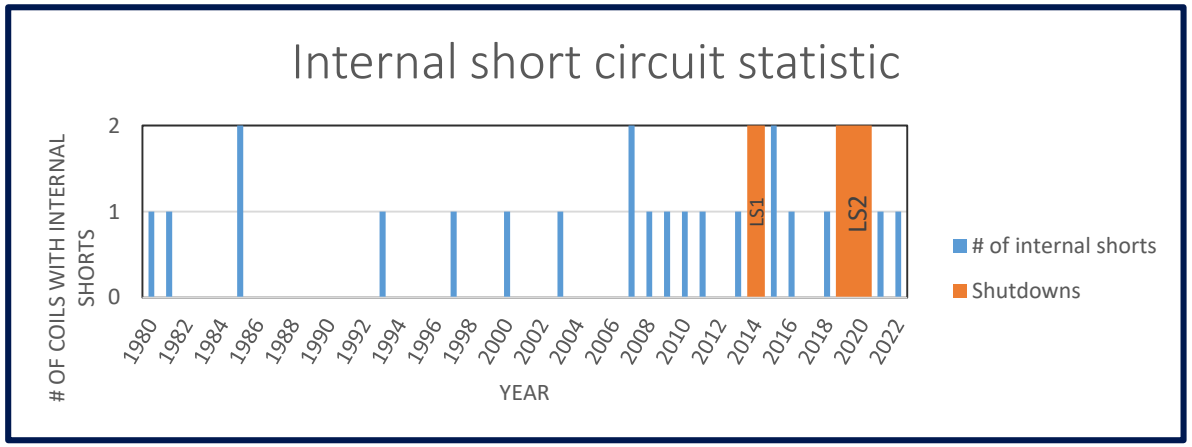
- **Worth mentioning:**
  - September: **MBB.43550 inter-turn shorts**.
  - October: **MSN.X0220031** magnet on fire (**inter-turn short**).
  - October: Fire alarm long which took time to reset.
    - BIW returned **false fire alarm** in SPS Ring (BA5).
    - **Bypassed** following risk assessment.
    - **Third-party piquet could not intervene** during the night.
      - ➢ **Being followed up.**

SPS Magnets Inter-Shorts

- **Increasing failure rate** of SPS main bending coils. → Spare stock is being depleted.
  - Statistics presented at IEFC #331 (and to be updated with 2 failures in 2023).

- Concerns coils produced by **Lintott on MBB** (249/385 in the SPS).
- Inter-turn shorts seem due to **poor internal brazing quality.**

- **Difficulty of finding industrial suppliers** to produce small series of large coils.
- **Set-up of a larger coil production facility within TE-MSC:**
  - Dedicated space in **B181.**
  - **R&D activities** are already **ongoing**.
  - Main components are now under **procurement.**
  - **Prototyping** should start in **mid-2024.**
  - **Budget** and **resources** have been **defined and secured.**
  - Possible future knowledge transfer to industry.



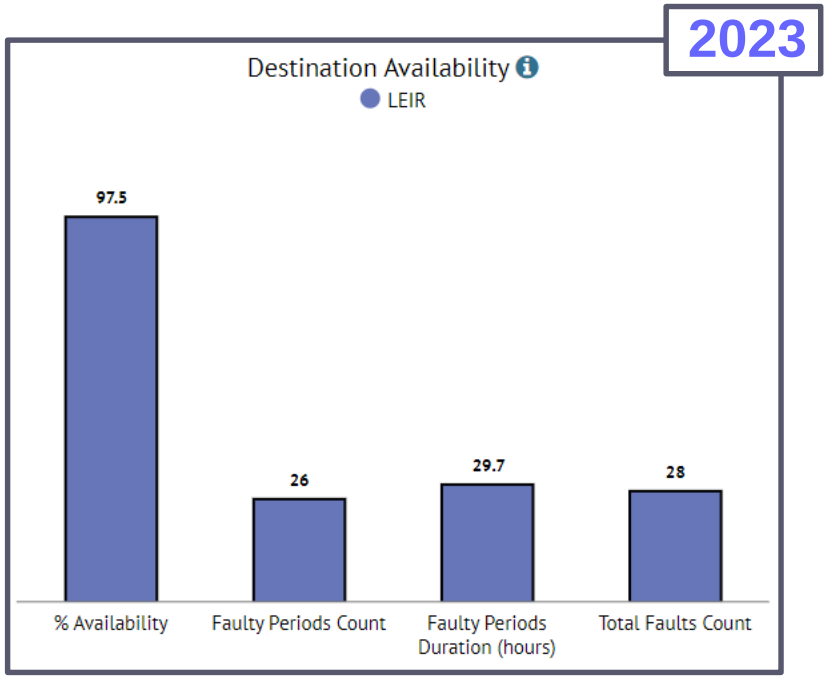
Linac3

- The year **2021** was a **commissioning** year for Linac3 and LEIR.
- The year **2022** included **2 weeks of physics run for SPS NA** during which **2 days of LHC tests with Pb ions.**
- The year **2023** included **~5 weeks of LHC physics and 4 weeks of SPS NA + 2d extension for CHIMERA**.
- Outside of physics periods Linac3 (and LEIR) operation is only during **daytime** and is **not followed up systematically with AFT:**
  - ➢ It makes sense to analyse the availability only during the physics runs.

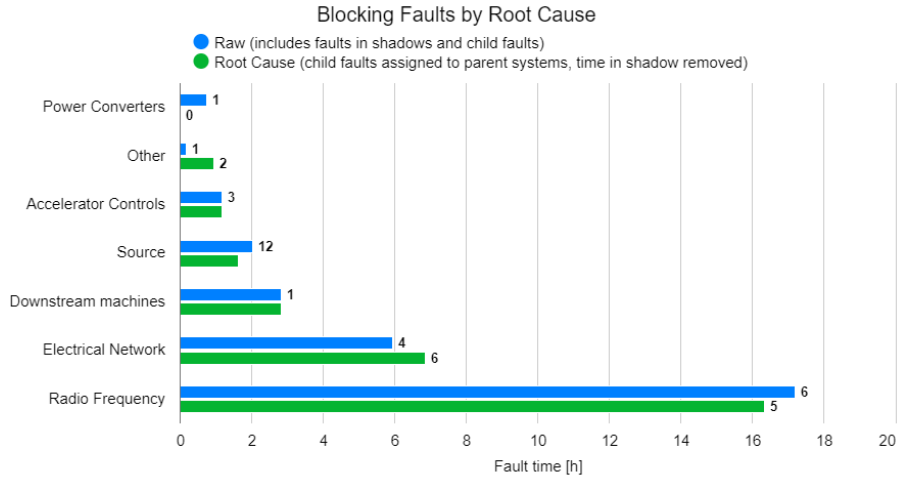
Global Availability in 2023: 97.5% (7 weeks)

A high availability:

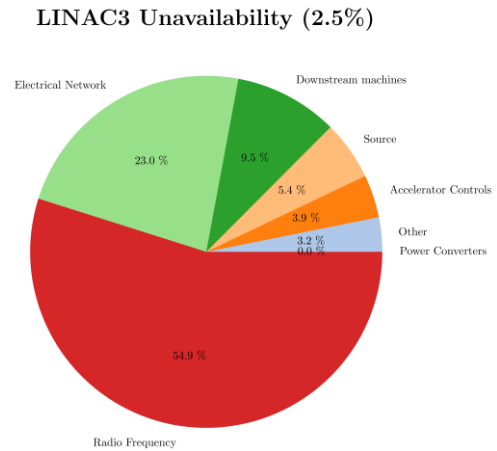
- 2018: 92.7% (5 week physics run).
- 2022: 97.3% (2 week physics run).



Linac3 in 2023



- **No equipment displayed faults demonstrating long term issues.**
- Most of **RF downtime caused by issues with sequencing/interlock:**
  - Learning from experience → Expected modifications during EYETS23-24.
  - No major hardware issues with new amplifier in RFQ and Cavity1.
- **Source:**
  - **Excellent year.**
  - Experienced **unstable periods of 5-10 minutes**, recovering without intervention.
  - Oven refills extended from **2 weeks in 2018 to 4 weeks post LS2**, with **improved design** of the oven to **reduce Pb-oxide build up**.
  - Oven refills **not counted as downtime** (included as planning activities).
  - **No diagnostics to quantify the Pb still available in an oven**. First sign of running out can be an unstable beam which cannot be recovered. Trying to push to longer than 4 weeks between refills increases the risk of needing an unexpected refill that leads to longer downtime.

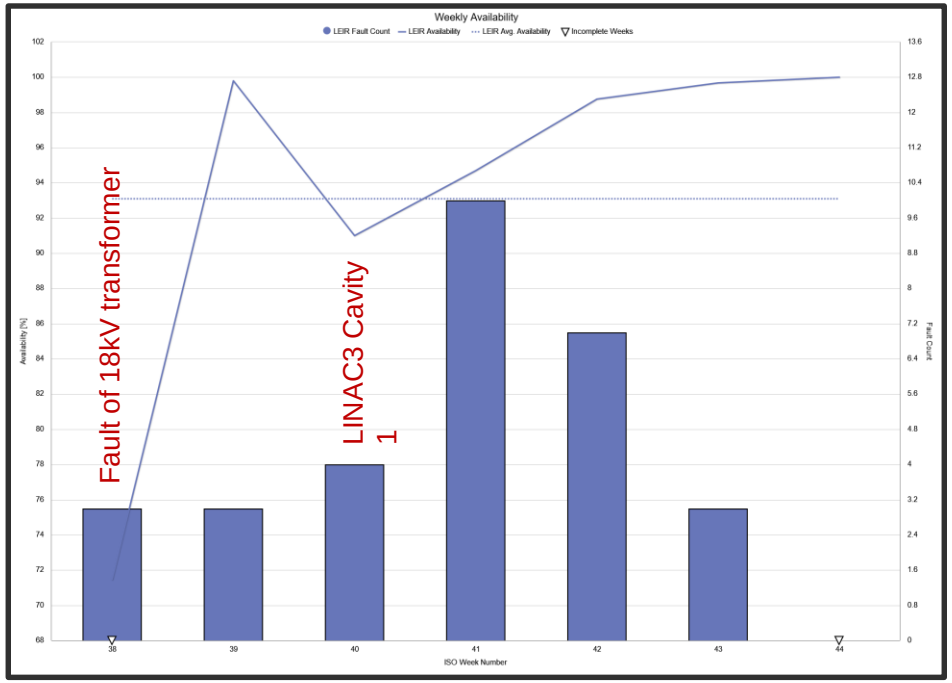


LEIR

- Just looking at AFT LEIR is **a rather solid machine!**

- **2022: 95.7%** (**97.8% excluding Linac3 downtime**):
  - Availability **compatible with Linac3.**
  - A few power converters issues (<1h to fix).

- **2023: 93.1%** (**95.6% excluding Linac3 downtime**)
- **High availability apart from week 38!**
  - **Major event**: fault of the **18kV breaker** and the consequent recovery of other equipments and beam performance.
    - Several outdated electronics cards (**PowM1553**) which needed **to be replaced** (CONSolidation).
  - Remaining (minor) issues with power converters tripping.



- Looking beyond the mere statistics:
  - A few **equipment missing a spare** or even **spare components**.
  - Ions program currently scheduled until 2043 (as long as HL-LHC):
    - We must **ensure long term reliability of LEIR**.

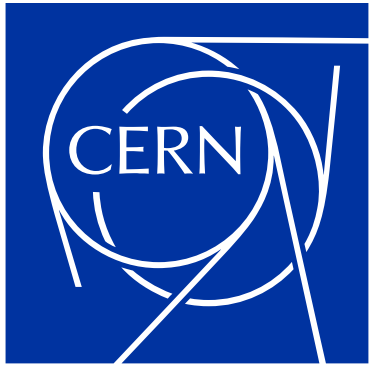
Summary

- **Data in AFT** are currently **widely accepted at CERN**, as result of a common effort!
  - Teams working improved diagnostics, automatic resets and fault recording.

- **Virtuous feeback loop among teams** to address machine‘s issues at the source.
  - Long term strategy/needs for **recurrent issues followed-up within the IEFC framework**.

➢ As a result the **machines are performing rather well:**
  - General feeling is that we will **not be able to easily improve the 2023 figures before LS3**.
  - We need strike a balance between **pushing the performance** to the limit and the **machine reliability**.
  - Personal suggestion to **document yearly the machine availability**, observations, expectations, etc, etc...

- **RAWG surveying the usage of AFT with the equipment groups** to define the next steps:
  - AFT data **quality/categorization** to be improved → automation should help.
  - Agree on a way to **exploit captured data** to improve performance – definition of **complexity** and **consolidation**.
  - AFT is currently a container isolated data:
    - **Correlate** the data with external databases, e.g. RP, losses, beam/cycle types, API to NXCALS missing.
  - **The exciting news is that there is so much potential in the tool which could be exploited.**
    - Ongoing EPA effort, e.g. WP 8, could be a force multiplier to the AFT growth.



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BI.BSW Coil Failure History

Time / cycles	Magnet	Observation	Root cause	Down time [h]
28/09/'20 ~ $1*10^3$	BI3.BSW1	Brazing alloy blockage of cooling tube: Repaired by re-drilling, but damaged copper tube	Repair damage	LS2
21/4/'21 ~ $1*10^6$	BI4.BSW1	Fatigue damage with microcrack on cooling tube	Fatigue crack cooling pipe	TS
7/12/'21 / ~ $21*10^6$	BI3.BSW4	Brazing failure – hydraulic connector 2 water block	Brazing joint	YETS
13/1/'22 ~ $21*10^6$	BI3.BSW4	Brazing failure - hydraulic connector 2 water block	Brazing joint	YETS
17/1/'22 ~ $21*10^6$	BI1.BSW3	Brazing failure – Coil 2 water block	Brazing joint	YETS
21/6/'23 ~ $44*10^6$	BI1.BSW4	Fatigue damage with microcrack on cooling tube	Fatigue crack cooling pipe	TS+14h
14/8/'23 ~ $4*10^6$	BI1.BSW4	Brazing failure – Coil 2 water block	Brazing joint	11h