

RF specific hardware - software issues and outlook for the LHC chain

Joint Accelerator Performance Workshop

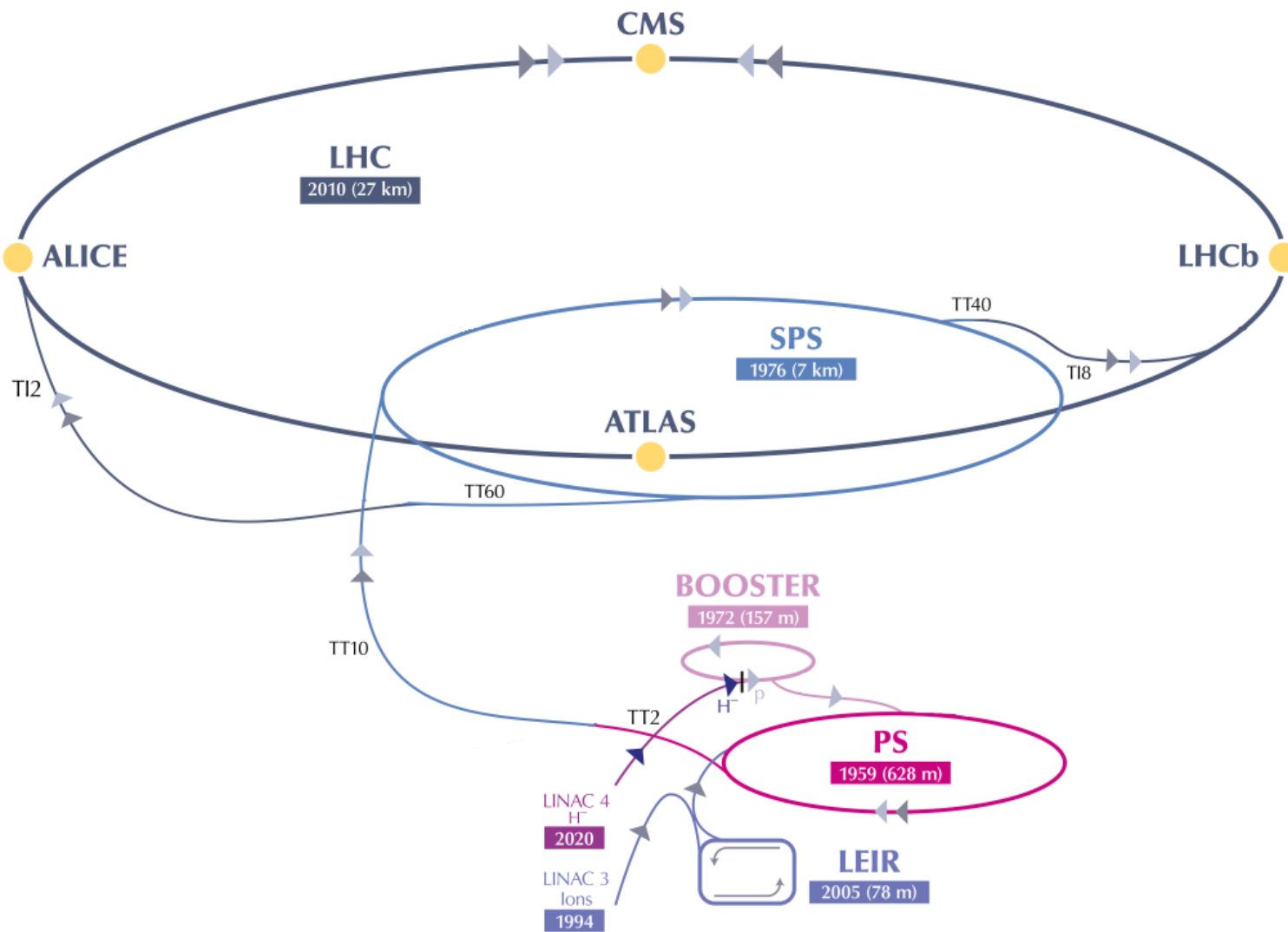
05/12/2022 – 08/12/2022

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and many more RF and OP colleagues!

Introduction

- The 2022 run is the first year after the Long Shutdown 2 of operation with the complete CERN Accelerator Complex, intensive year for RF operation...
- In the injectors, the upgraded RF systems during LS2 are reaching their target performance and even pushed beyond their design parameters, while LHC operation resumes.
- After the upgrades an important effort is ongoing to improve the reliability of the RF systems, to cope with single fault events and lingering teething/ageing issues.
- Some upgrade items are also continuing in view of their deployment during the Run 3.
- This talk covers the work and possible actions in view of improving the reliability and operation of the RF systems in the LHC chain in 2023+.

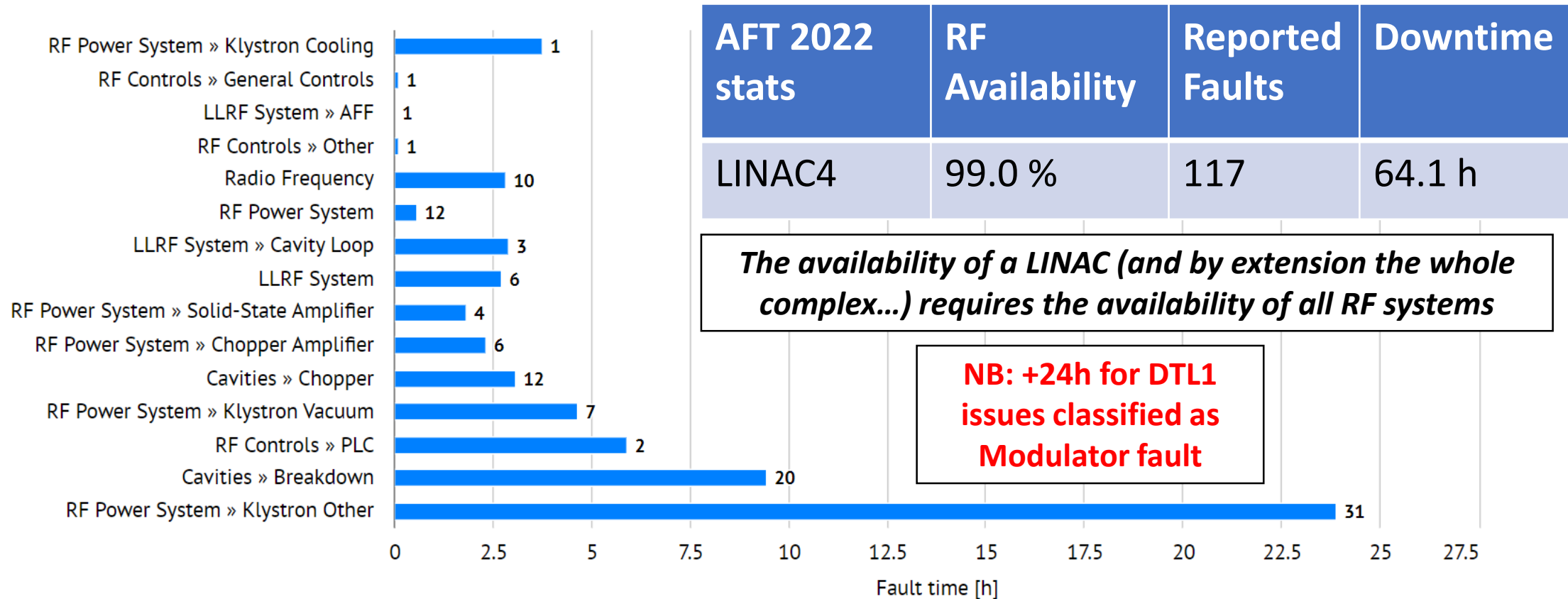
Outline



LLRF: Low *power* Level RF (controls, feedbacks)
HLRF: High *power* Level RF (power, amplification)

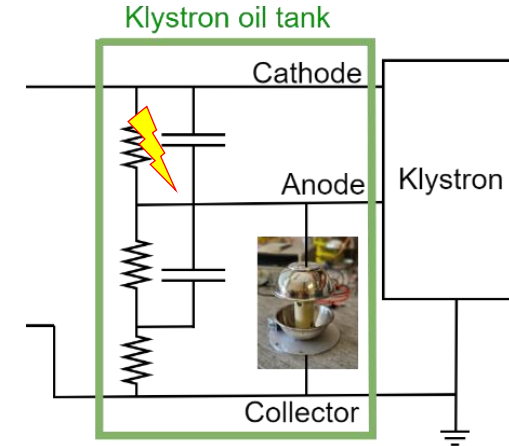
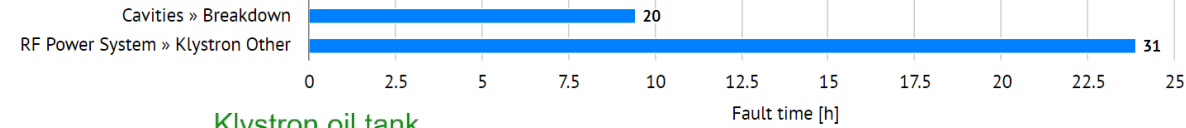
- Introduction
- Overview per machine
 - LINACs
 - Low energy rings
 - PS
 - SPS
 - LHC
 - *Bunch charge limitation*
-> *Theodoros in this WS*
 - *Rupture discs*
-> *LMC*
- Reliability, performance, operability of RF systems
- Conclusions

LINAC4 – Fault Tracking

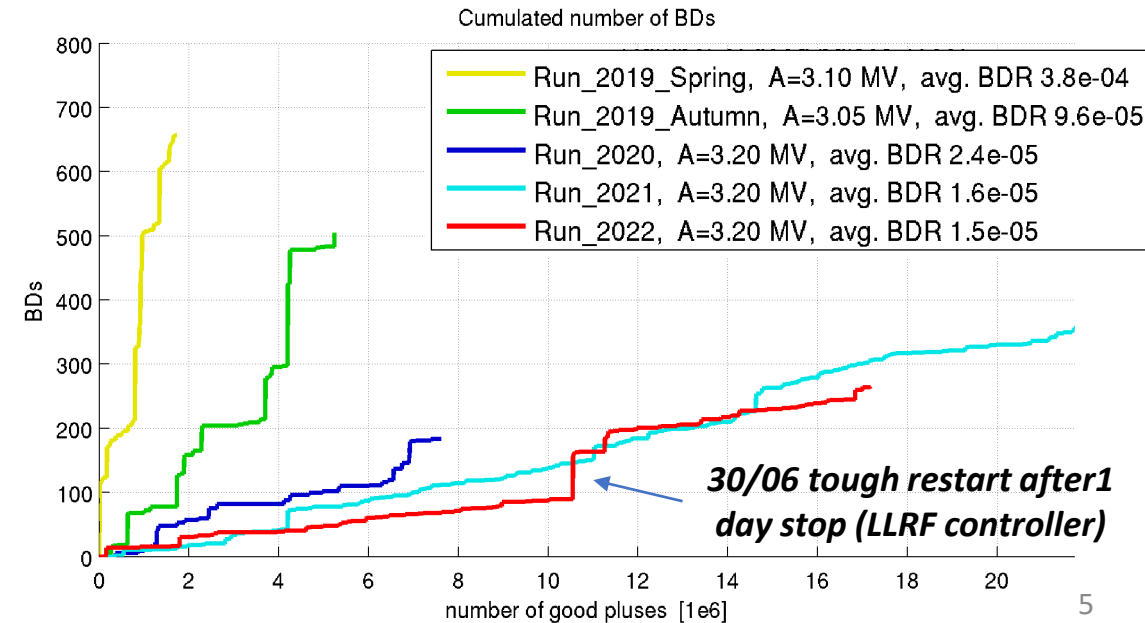


- **Excellent availability of the LINAC4 RF systems overall**, teething issues have tremendously improved over the years.
- **Main driving sources of downtime** were the issues with the **DTL1 Klystron/Modulator and breakdowns**.

LINAC4 – Main faults



318th IEF meeting (18 November 2022) · Indico (cern.ch)



DTL1 Klystron/Modulator

- Thorough investigations by RF/EPC after two important faults in June, fault classified in EPC equivalent to 1/3 of the overall L4 RF downtime in 2022.
- Mitigation of the faults after oil exchange in the klystron tank, likely arcs in the klystron oil tank.
- Consolidated action plan during YETS (RF): Exchange of the DTL1 klystron-tank assembly (LEP klystron), exchange of the oil (Silicone), evaluation to install oil circulator with filter.

Breakdowns and RFQ protection

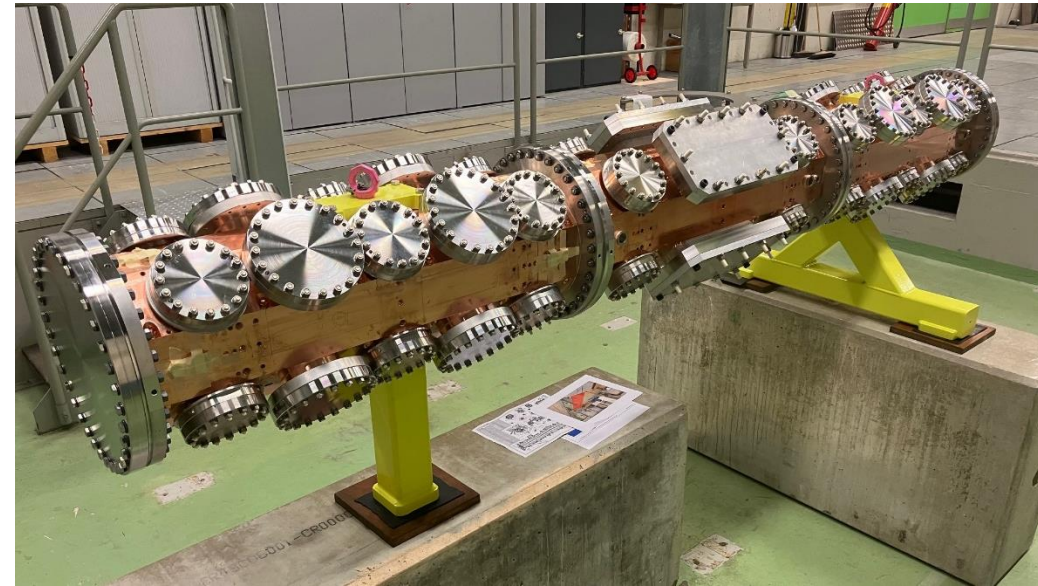
- Continuous reduction of the breakdown rate along the years.
- Breakdown protection shown to be effective will be extended to further cavities.

LINAC4 – Status of spares and strategy



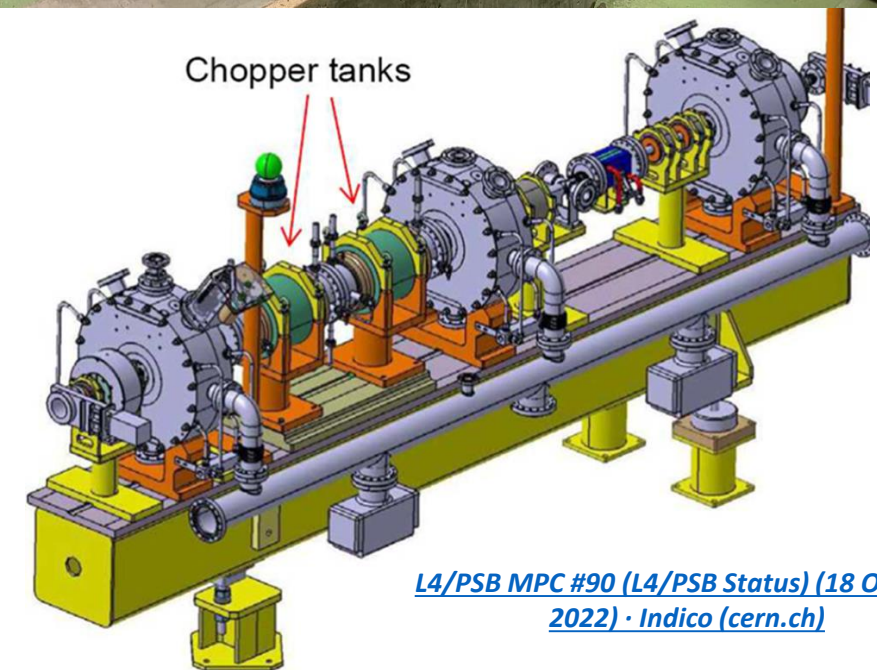
■ Spare RFQ2 and spare chopper structure

- Spare RFQ2 built as carbon copy of RFQ1 **available for beam tests in 2023**. Material studies ongoing to understand surface changes.
- Spare chopper structure will be **ready in 2023**.



■ Chopper driver amplifiers

- Present availability of the chopper driver amplifier **not expected to be sustainable until LS4** (ok until LS3), in particular if pulse rate would be increased.
- R&D for a new chopper driver started. **No 1-to-1 replacement possible.**
- Resources for R&D need to be secured for chopper driver replacement and **long-term operation of LINAC4**.



LINAC3 – Amplifier consolidation and LLRF

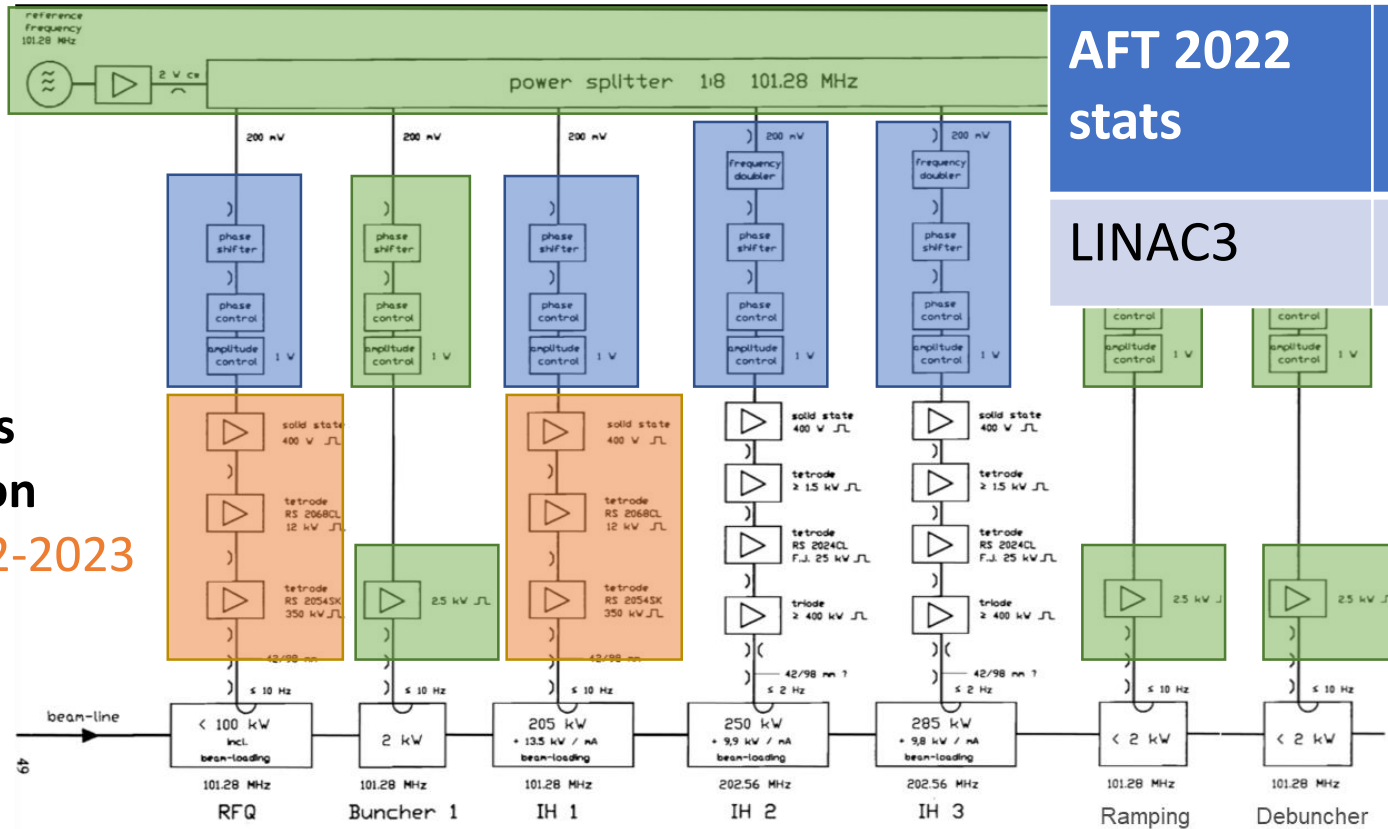


LLRF

Installed
Upgrade
Pending

Amplifiers
Installation

YETS 2022-2023



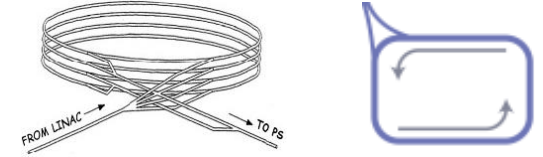
AFT 2022 stats	RF Availability	Reported Faults	Downtime
LINAC3	99.8 %	6	6.5 h



New amplifier test stand

- **New high-power solid-state amplifiers ready** for installation during the YETS. Expected 1-to-1 change of hardware with **no modification of controls** but **expected improvement in reliability**.
- **Linac3 LLRF ready to be deployed**. **Installation date** of the remaining LLRF systems **to be defined**.

PSB, LEIR - Aparté on low energy rings



■ Excellent availability and performance of the Finemet-based RF systems installed in low energy rings.

■ Continuation of amplifier update during YETS and ITS

- Modification of the upgraded amplifiers to improve RF stability is still ongoing (Rings 1 and 2), no major impact expected on operations based on 2022 experience.

■ Defects on RF bypasses and open circuits

- Defective RF bypasses agreed to be left after YETS 21-22 to avoid delay for PSB restart.
- Discharge on the flange seal leading to vacuum leak during high beam intensity tests.
- Detailed plan of activity proposed for the YETS (two rounds of measurements and replacement of broken bypasses)

• Digital transverse damper, spares, ObsBox

- The transverse damper is presently not on digital system: proposal for renovation during LS3 and check of spare strategy (not included in CONS).
- ObsBox for RF observation deployed in AD/ELENA (longitudinal obs.), requires dedicated funding to be extended to LEIR/PSB.

AFT 2022 stats	RF+TFB Availability	Reported Faults	Downtime
PSB	99.7 %	22	17.6 h



PS – Performance of PS RF systems



- The upgraded PS RF system was pushed to the limits in 2022 to accelerate high intensity beams.

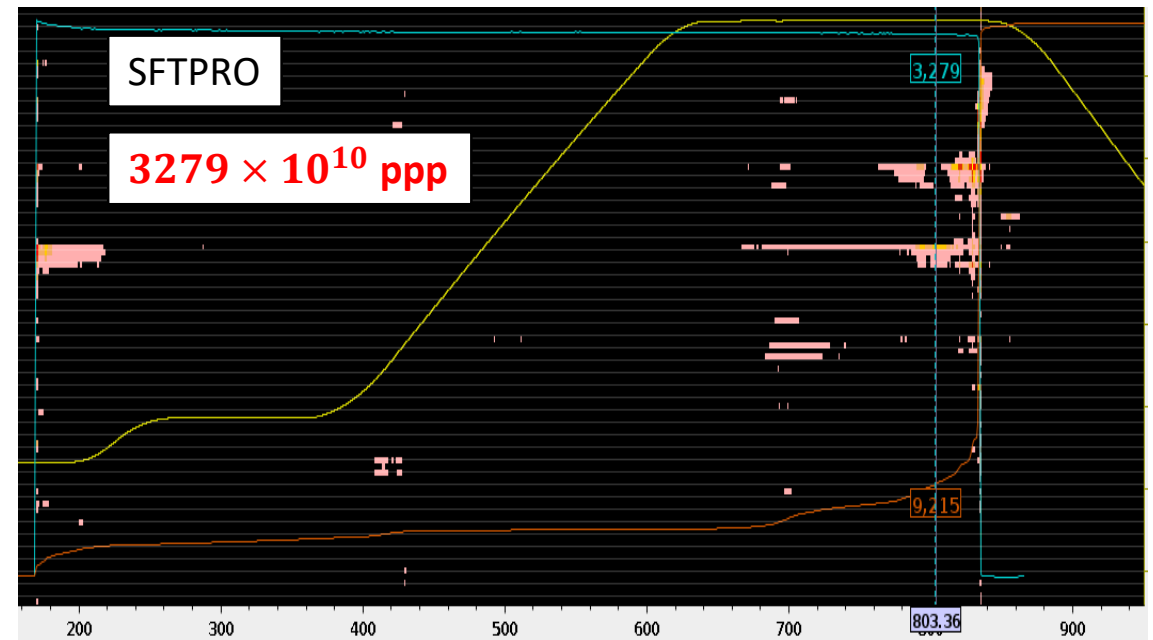
- LIU beam up to 3.2×10^{11} protons per bunch.

- SFTPRO beam up to 3200×10^{10} protons per cycle.

- AD beam up to 2100×10^{10} protons per cycle.

- After fine tuning of the RF system settings, no major bottleneck identified in terms of power even beyond operational requirements.

AFT 2022 stats	RF+TFB Availability	Reported Faults	Downtime
PS	98.5 %	172	93.3 h



PS – Investigations on PS RF trips



■ Frequent trips of PS RF Systems in 2022

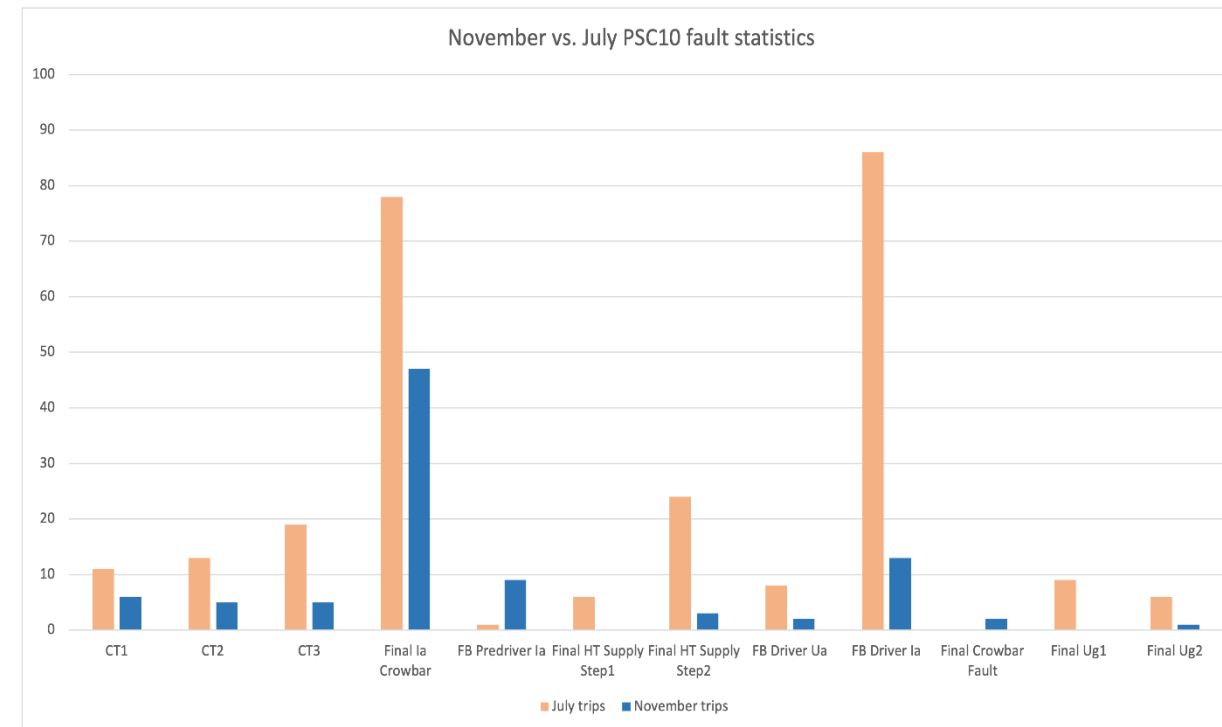
- **New interlock systems** installed during LS2 with upgraded PLCs.
- **Faults have minor impact on overall beam availability** (resets and spare cavities) but **causes daily operation to stutter**.

AFT 2022 stats	RF+TFB Availability	Reported Faults	Downtime
PS	98.5 %	172 *	93.3 h

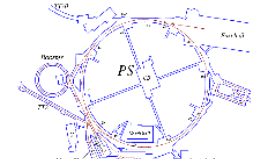
* Faults > 2min downtime

■ Actions taken on PSC10 RF Systems

- **Interlock levels originally set without beam**, and gradually **adapted during the beam intensity ramp up** from start of Run 3 (signal noise levels, filter spikes).
- **Identified under-dimensioning of amplifier electronics**, more powerful version installed on 6/11 cavities (remaining **installation during YETS**).
- **Investigations are ongoing** on two important categories of faults (final amplifier crowbar and on the coarse tuning system), and **corrections on the design will be deployed during YETS**.

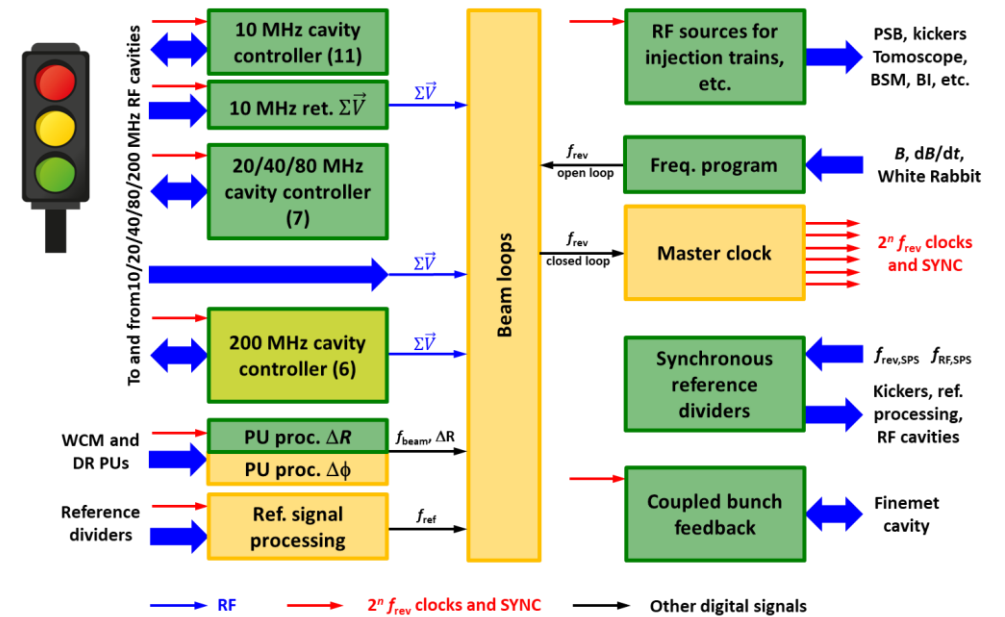


PS – Plans for LLRF in 2023



Handling digital and analog LLRF

- Firmware development of the beam loops continued in 2023.
- Main objective is to perform beam phase measurements and first locking of phase loop with digital LLRF.
- A cost-effective solution for monitoring and logging of analog LLRF signals (phase, radial, synchronization loops) is planned for deployment during YETS (improved diagnostics for piquet interventions).



Improved integration of RF systems in operations

- A thorough review of the PS RF settings and operability will be required for the good integration of digital LLRF, new power converters for cavity tuning, flexible cycle length (major overhaul of RF settings on the long term).
- Present integration relies on heterogenous applications, increased number of expert settings and scripts for which support cannot be ensured.

Heterogeneous integration of RF settings

		Cavity Number							
		11	36	48	51	56	66	76	81
Spare									
Global		1	1	1	1	1	1	1	1
Modif. 1									1
Modif. 2						1	1		
Modif. 3		1	1	1					
Modif. 4									
Modif. 5								1	
Modif. 6					1				
Modif. 7									1
Modif. 8									

Phase offset ▲▲▲ 0.0 deg ▼▼▼

Back to Init

Splitting Adjustments

CPS.USER.LHC3
LHC25#48b_BCMS_22

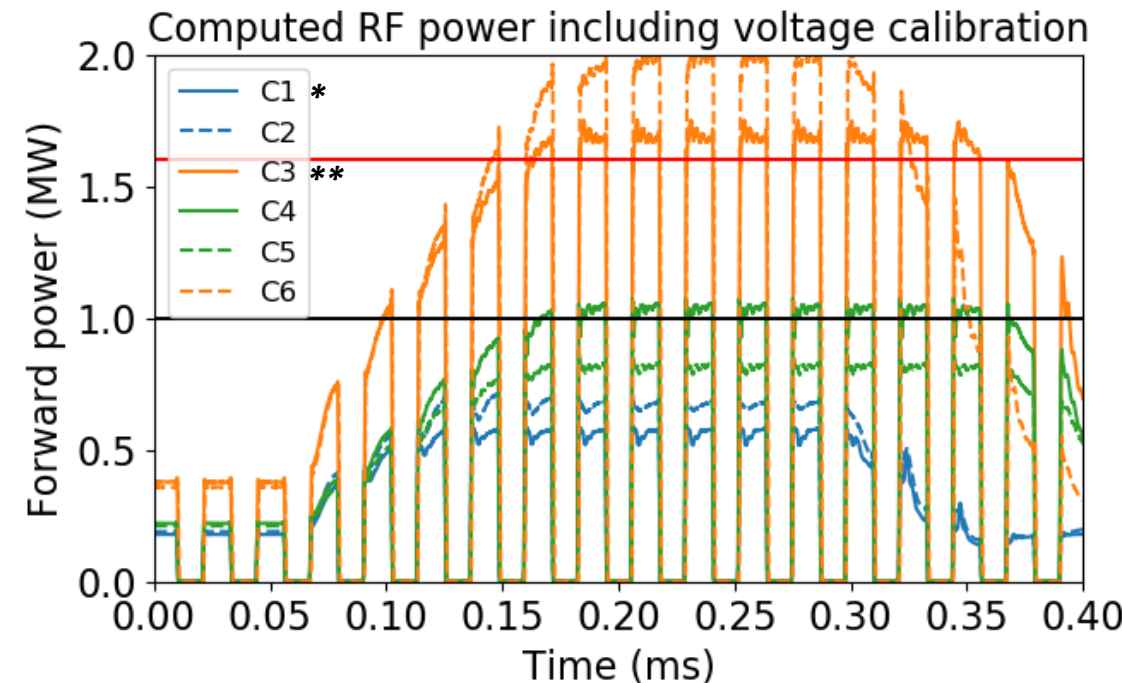
	Init values	Previous trim	After last trim
DPC_20:	35.42 deg	35.42 deg	...
DPC_40-77:	256.75 deg	256.75 deg	...
DPC_40-78:	10.75 deg	10.75 deg	...
DPC_80-08:	220.50 deg	220.50 deg	...
DPC_80-88:	126.50 deg	126.50 deg	...
DPC_80-89:	2.50 deg	2.50 deg	...

SPS – HLRF Conditioning and faults



- The SPS RF Systems have gradually been reaching their design peak power performance with conditioning throughout the year.
- Siemens amplifiers HV issues
 - Three incidents on high voltage resistors leading to damaged amplifiers. Root cause identified, already addressed at 317th IEFC meeting with detailed action plan (EDMS 2791153).
- Thalès transistors increased breakage
 - Present breakage rate of 1 transistors /day, while design is 1 transistor /week.
 - Transistor breakage is transparent to operation (load balancing between transistors). Spares situation is reasonable (recent delivery, 30% spare increase) but investigations required to understand increased breakage.
- Remaining arcing in the transmission line will be investigated during YETS (all lines).
- Transverse feedback faults root cause traced down to missing kicker magnet pulses in TT2 transfer line (large deviations). Cross-machine and equipment group investigations!

AFT 2022 stats	RF+TFB Availability	Reported Faults	Downtime
SPS RF	97.9 %	623	110.4 h
SPS TFB	99.9 %	34	5.4 h



* ageing tubes

** (14/16) towers

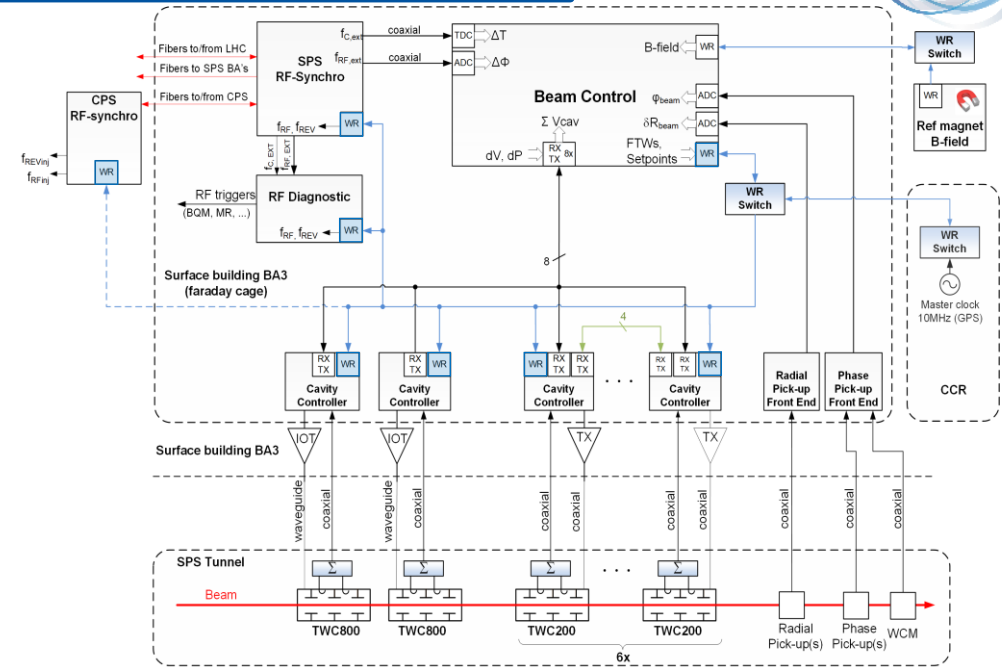
Short pulses, average power achievable is lower

SPS – LLRF latest developments



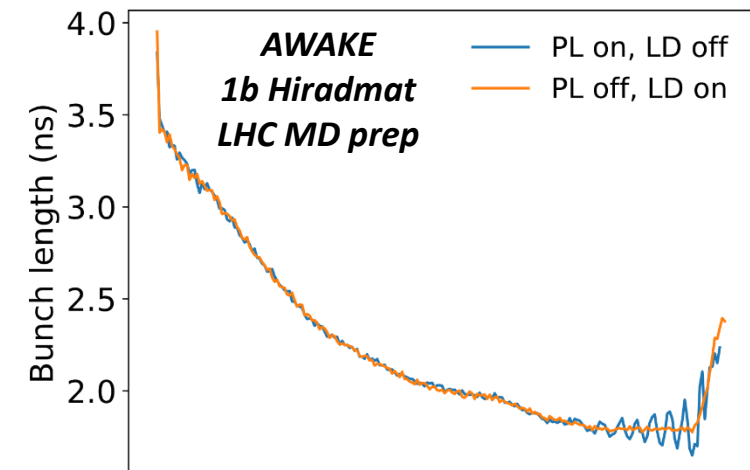
Completion of the LIU baseline digital LLRF

- Successful commissioning of the **longitudinal damper and feedforward in 2022**.
- Remaining items for YETS and 2023 are to upgrade the **feedforward for compatibility with the amplitude modulation**, and usage of the **wideband pick-up for bunch-by-bunch measurements** (longitudinal damper and slip stacking).
- **Instability related to phase loop with single bunches** at high energies observed. **Non-linear simulation model designed, attempting to reproduce the observations**.



LIU-SPS Architecture

[Injectors Performance Panel: Mini workshop on LIU ramp-up \(17 November 2022\) · Indico \(cern.ch\)](#)



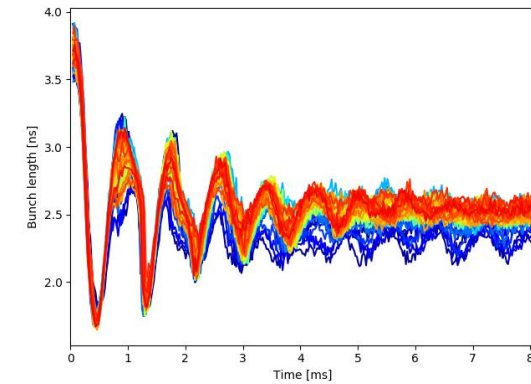
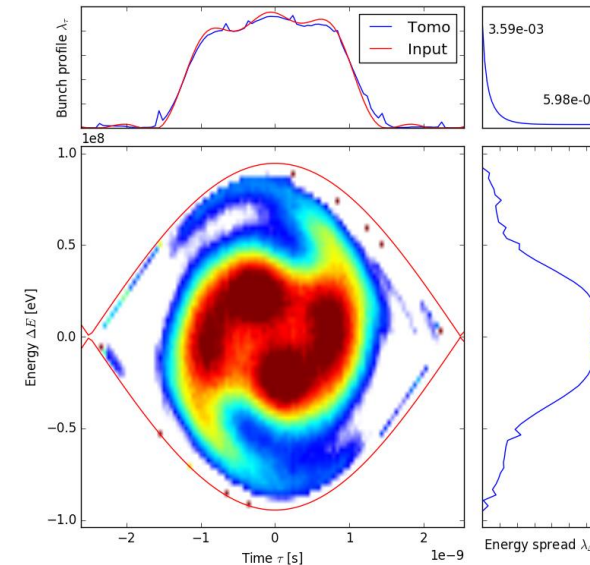
Successful beam commissioning of the SFTION beam with digital LLRF

SPS – RF Beam observation and pick-ups



■ SPS beam observation

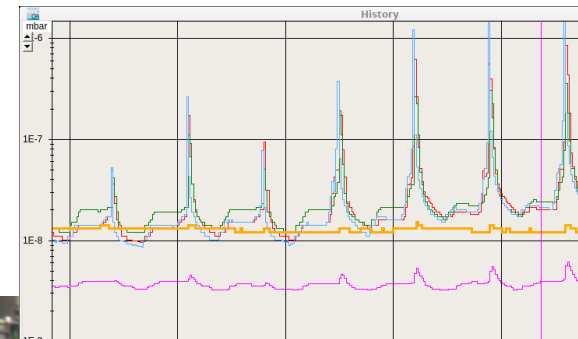
- Re-configuration of the SPS beam observation pick-up lines proposed to accommodate a channel for an SPS Tomoscope application and PS-SPS beam observation system.
- **Further splitting of the lines is challenging** to keep high quality signal for existing applications (BQM) and **will require checks during YETS**.



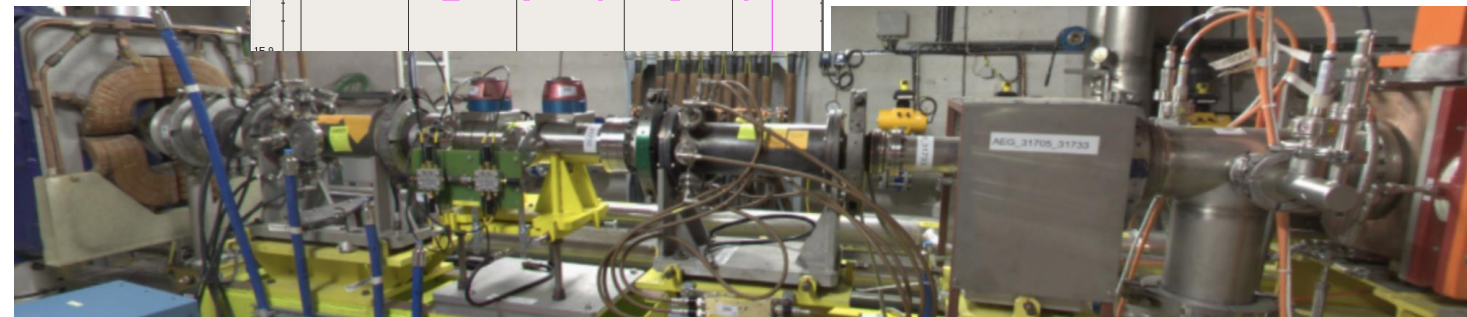
[Injectors Performance Panel: Mini workshop on KPIs \(29 April 2022\) · Indico \(cern.ch\)](#)

■ Pressure rise in LSS3 with 8b4e beam

- **Significant intensity limitation for multibatch 8b4e beam**, dependent on the batch spacing, suspected beam impedance issue.
- Access on last week of the run to **attempt various methods to detect sparking** (sonometer, temperature sensors...).
- **Proposals for actions and studies during YETS under preparation.**



[SPS MPC #31 - Special MPC on pressure spikes in LSS3 \(29 November 2022\) · Indico \(cern.ch\)](#)



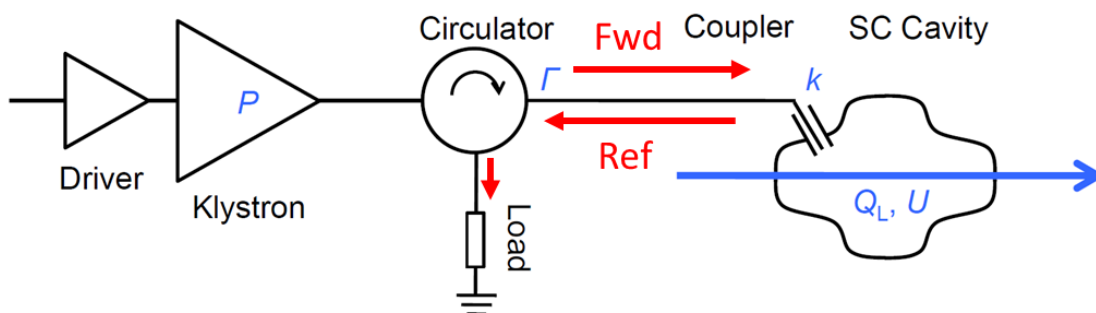
LHC – Arcs in amplifier chain



▪ L8B2 Broken ferrite in circulator

- Finding and removal of broken ferrite after **arcs in the L8B2 circulator (klystron protection)**. Klystron able to **resume normal operation after removal of the ferrite pieces**.
- **L8B2 circulator faults represent about 15% of the RF downtime (8 faults reported).**
- **Klystron exchanged. Circulator exchange and investigations during YETS** by the manufacturer of the circulator (AFT microwave).

AFT 2022 stats	RF Availability	Reported Faults	Downtime
LHC	81.9 %	27	760.7 h
LHC (excl. rupture discs)	97.3 %	26	112.6 h



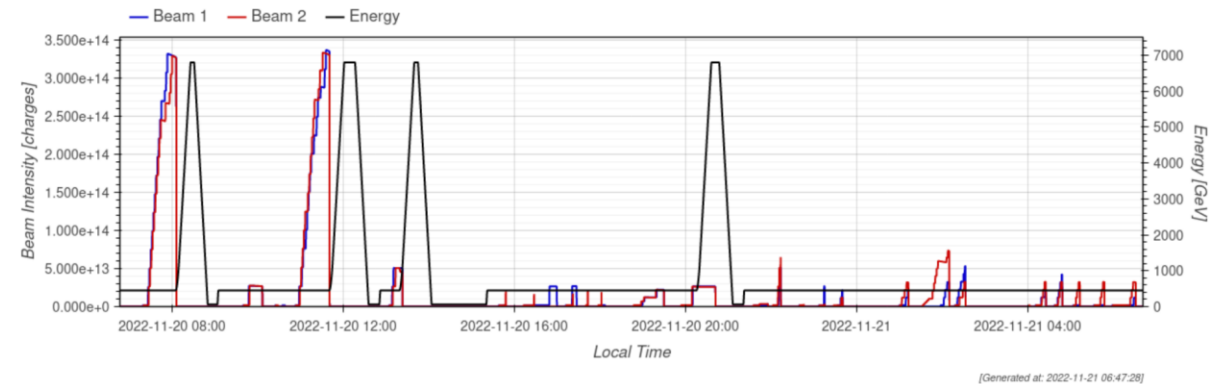
LHC – Beam control and ADT



■ “R3” Rocky RF Recovery

- **Difficult restart after** LHC beam tests with **ions**. Issues affecting both **beam control and transverse damper (ADT)**. **Beam dump on losses at start of ramp**. Detailed investigations presented at [LMC #453](#).
- **Power cycle of RF beam control and RF ADT** allowed to remove the issue and resume **proper operation**. **Supposed corruption of FPGA memory** after power perturbation in SR4.
- **Loop signals degradation**
 - **Phase loop pickup signal degrading over last weeks of operation**, before R3 event (raised thresholds, **no detection of pilots for phase loop**). **Will be fixed during YETS**.
 - Settings thoroughly investigated during the R3 event. **Review of the RF settings in LSA needed in the future**.

AFT 2022 stats	ADT Availability	Reported Faults	Downtime
LHC	99.5 %	2	20.5 h



Overview RF availability

Overall good availability of the RF systems across the complex in 2022

- Many issues already tackled by committees, operational and coordination meetings **or included in the CONS project.**
- What is the **effective fault impact** on operations and physics, **beyond availability statistics and perception from the CCC?**
- How to **better guide equipment experts** for their investigations?

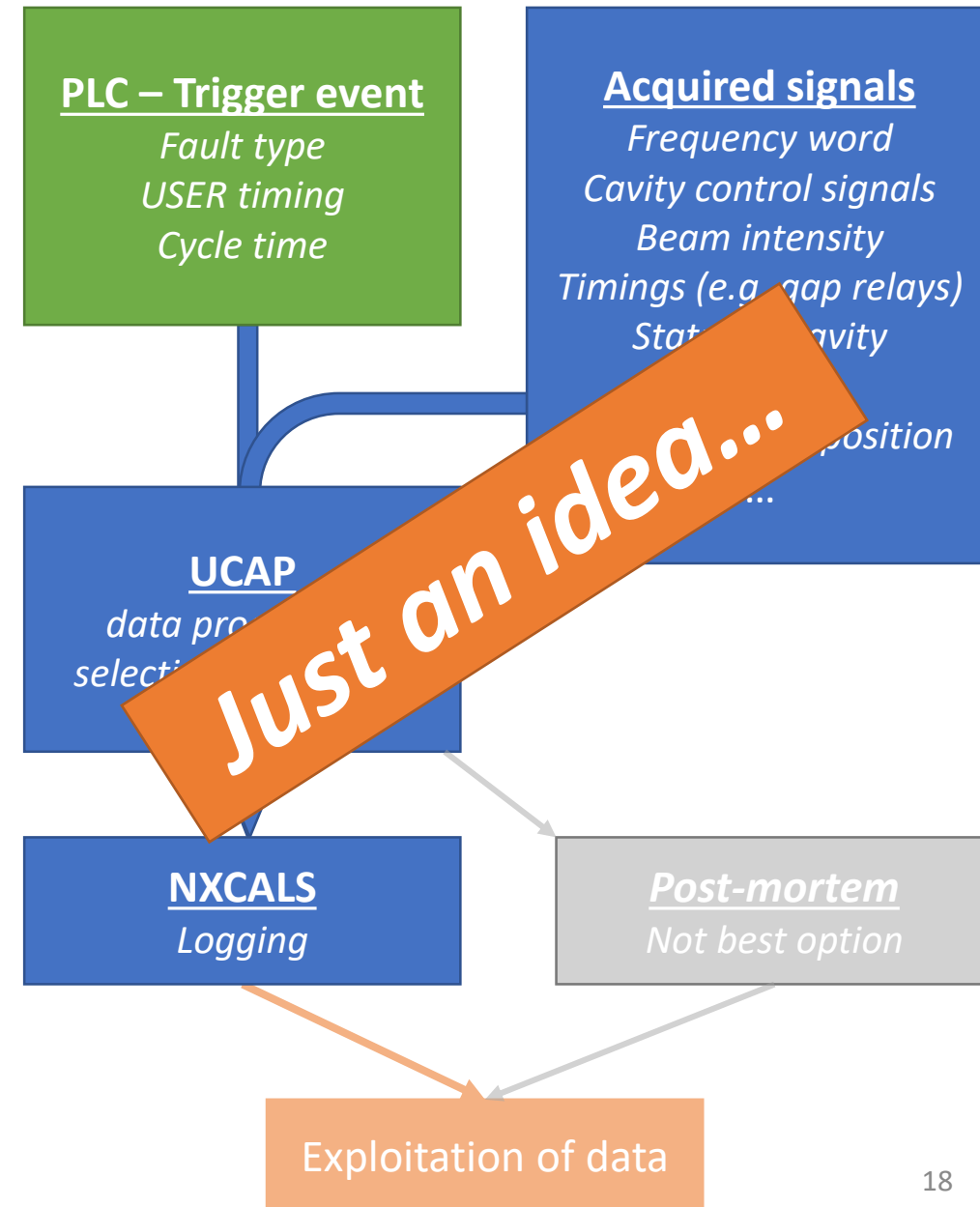


AFT 2022 stats	RF+TFB Availability	Reported Faults	Downtime
LINAC4	99.0 %	117	64.1 h
LINAC3	99.8 %	6	6.5 h
PSB	99.7 %	22	17.6 h
LEIR	-	-	
PS	98.5 %	172 *	93.3 h
SPS	97.8 %	657	115.8 h
LHC	81.4 %	29	781.2 h
LHC (excl. rupture discs)	96.8 %	28	133.1 h

RF systems reliability and fault analysis

Development of detailed fault analysis

- **Investigations of root cause of faults** in the PS and SPS are necessary but tedious as dependent from
 - The **played cycles in the supercycle and beam intensities** (MDs, increase in intensity required by the operation...)
 - Parameters of the **cavity feedbacks**
 - Cycle **settings** and possible settings faults
- **More information is required to the RF expert** to disentangle between a **fault due to hardware** required to be fixed and a **fault due to operational conditions**.
- Both **PS and SPS share the same design of PLCs** recording fault types and could be **extended to provide with more precise (10s ms level) timing of the event**.
- **Present data extraction relies on individual scripts** and would **benefit from a more global approach**. **It would nonetheless require planned joint effort for development**.



Conclusions

- The upgraded RF systems across the complex are **reaching unprecedented performances and availability**.
- **Many items already addressed** in 2022 by the committees and operation meeting, **and tackled timely by the equipment experts** or included in the **CONS project**.
- Some remaining hardware/software items (**L4 chopper driver, PS LLRF, SPS solid-state amplifier breakage...**) are exposed in this talk for future consideration.
- Beyond core performance of the RF systems, **the integration in operation** (settings...) and **identification of root causes of frequent trips** will require **development of improved tools** to help both RF experts and operators.

*Thank you
for your
attention...*



...Questions?