RF System: availability and general performance - Run II

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and the entire piquet team
Content

- RF system availability
- Software and diagnostics
- System limitations during run II
- Upcoming system limitations
- Forthcoming studies and improvements
RF system availability
RF System Availability 2018

- Improved reliability over 2017
  - 2017 run (29 weeks): 32 faults, 45.5h → 5.7% root caused duration
  - 2018 run (32 weeks): 59 faults, 49.2h → 4.9% root caused duration
- Longest intervention: 2018 → 4h22min, 2017 → 14h
- Several weeks when no faults at all were recorded
RF System faults summary 2018

Root Cause Fault Times by System (RF)

- **Hardware**: 24 faults, 38.10h, avg 1h32m
- **Controls**: 17 faults, 10.15h, avg 52min
- **Longitudinal Instabilities**: 1 fault (bunch length oscillation), 0.05h
- **Other**: 1 fault (MD RF setup), 0.01h
Hardware faults

- Accumulation of faults in weeks 25 - 29
  - Broken water flowmeter (1)
  - BIC intrlk $\rightarrow$ FESA class migration $\rightarrow$ control fault
  - New firmware for ALLSetPoint $\rightarrow$ cavity phasing $\rightarrow$ reflected power $\rightarrow$ arcs (5)
  - Electrical glitches

- Cavity trips during RF MD (6)
- LLRF crate down (1)
- LLRF module replacement (1)
- Crowbars (3)

**4 faults:**
- klystron drive, crowbar and klystron vac intlk $\rightarrow$
- SWAP and FB off
Controls faults

- Longitudinal blow-up (4)
- Lost communication (2)
- Accumulation of faults in weeks 25-29
  - New firmware for ALLSetPoint → cavity phasing
- LLRF crate down (1)
- XPOC error (2)
- Power glitch (2)
- Server issue (1)
- Sequencer issue (1)
- Power Supply (HW) (1)
Other faults

- Longitudinal instabilities – bunch length oscillation (1)
- Caused by electrical glitch (2)
- During MD set-up (1)

Total faults duration less than 1h
Summary of faults and availability

- Hardware related faults were dominating and they are expected to be more frequent with ageing equipment.
- Software constantly evolves or is migrated, leading to some faults → deployment of modifications often limited to TS.
- LHC requests evolve with time as well, requiring new solutions → MDs.
- Significant number of faults were diagnosed and fixed remotely → access only needed for hardware faults.
Software and diagnostics

RF Expert tools
Yearly commissioning and lessons learned
RF Expert tools

Expert acquisition interfaces (previously LabVIEW, now Inspector)
LHC Control > LHC Equipment Control > RF > Expert

- Improvements to existing monitoring systems
  - Crowbar detection
  - Arc detection
- Additional diagnostics: power supplies, interlocks, temp., radiation ...
- LHC RF OP Viewer → https://lhc-rf-op.web.cern.ch/lhc-rf-op/
  - Last 3h of data, archive, faults, SMS notification
Cavity conditioning tools

Cavity and coupler conditioning (better control and set-up of conditioning process):

- Automatized set-up of conditioning process
- Detailed procedures

Pulsed FM RF power is applied to the cavity in a controlled way with vacuum FB

- Pulse length from 200us to CW
- Power from 10kW to 300kW
- Various coupler positions
  - $Q_L = 20000$, flat bottom $\rightarrow$ 1.5 MV/cavity (0.75 MV/cavity)
  - $Q_L = 60000$, flat top $\rightarrow$ up to 2.2 MV/cavity (1.5MV/ cavity)
  - $Q_L = 40,000$ (intermediate position)
Recommissioning scripts

LLRF Commissioning scripts were migrated from MATLAB to Python

- No MATLAB license needed
- PyJapc instead of JavaCoInterface
- Automatic backup/restore
- Improved data processing
- New algorithms added
- Step-by-step procedure and documentation

They were successfully used during recommissioning in 2018
Recommissioning timeline

STEP 1: Re-commissioning of the High Voltage (2 weeks)
- HV Bunkers: crowbars, modulator, cables... Interlocks and signals checks

STEP 2: Re-commissioning of the High Power (3 weeks)
- Klystron, Circulator, Loads, Power supplies, Power meters, Water Flowmeters – validation
- Klystron power calibration
  - Calibration of klystron DC power against collector thermal power
  - Circulator, arc detector, interlock levels, etc. adjustment

STEP 3: Re-commissioning of Cavities (4 weeks) + DSO test

STEP 4: Re-commissioning of LLRF (2 weeks)
- Calibration of offsets, delays, phases, gains, etc..

FIRST BEAM

STEP 5: First Pilot Capture and Beam Control Adjustment

STEP 6: First Nominal Bunches

STEP 7: Intensity RAMP-UP, Adjustment for The Beam Loading Compensation

STEP 8: Ion Setting up (in ion run)
Commissioning experience

- Many things can be automatised, but still human intervention is necessary: a few lines will always show unexpected behaviour at some stage of the commissioning.
- Many diagnostic tools and expert panels have been developed to ensure smooth operation, but trained people are still needed.
- Technical stops are shortened to a minimum and often commissioning has to be performed with modified hardware & software.
  - Many activities are carried out one after another and depending on the previous results, some in parallel.
  - The LLRF commissioning is the last in the line and has to absorb potential delays in the schedule.
  - Good coordination and communication.
System limitations during Run II

Antenna problem
C1B1 Antenna problem

- Detected during the cavity conditioning in 2017 → the field level ~10 dB less than expected (wrong tune and coupler position were ruled out)

- Measuring the transmission between operational and spare antenna showed indeed 10 dB less signal on C1B1 than on other cavities, TDR measurement has also been performed

- Since April 2017 the cavity is operated using the spare antenna
C1B1 Antenna problem

TDR measurements at cold and at warm have been performed annually

- All measurements very consistent → no significant impedance changes between different antennae were observed

Actions to be taken:

- **Opening of the CM insulation vacuum** → an visual inspection of the connecting cables and the pick-up connectors, followed by a leak check on the pick-up and probably installation of a new cable → a detailed plan is discussed

- If replacing the antenna turns out to be necessary, this operation would almost certainly have to take place in a clean room and then **we may have to exchange this module.**
Upcoming system limitation

Anticipated limitations and actions taken
RF power limitation at injection

Initially the energy ramp and flat top were considered as a limitation for the HL-LHC (target intensity of $2.3 \times 10^{11}$ ppb) → full-detuning beam loading compensation scheme since 2017

Available klystron power

<table>
<thead>
<tr>
<th>Klystron HV</th>
<th>Cathode current</th>
<th>DC power</th>
<th>RF power(*)</th>
<th>Measured saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 kV</td>
<td>7.8 A</td>
<td>390 kW</td>
<td>230 kW</td>
<td>190 – 220 kW</td>
</tr>
<tr>
<td>58 kV</td>
<td>8.6 A</td>
<td>500 kW</td>
<td>300 kW</td>
<td>250 – 280 kW</td>
</tr>
</tbody>
</table>

* assuming a klystron efficiency 60% (the expected ageing effect may reduce performance)

MD#3 and MD#4 on power consumption at injection (optimized loaded Q and cavity tune)

- MD#3 at 50kV, $1.15 \times 10^{11}$ ppb
  - 9MV → all lines saturated
- MD#4 at 58kV, $1.3 \times 10^{11}$ ppb (with circulating beam instead of injection transient)
  - 10MV → with the voltage partition

To be continued [see Helga’s talk]
Static heat load (?)

- Boil off test in SM18: flowmeter saturated at 10 g/s, much higher than expected

- Values measured for modules in LHC tunnel using a different method are lower: (measuring needed time between closing of supply valve and start of TTmax raising in concerned module)
  - S34_B1: P=135.3kPa, emptying time=88min → heat load 131.1W
  - S34_B2: P=135.5kPa, emptying time=103min → heat load 111.9W
  - S45_B1: P=135.5kPa, emptying time=93min → heat load 123.9W

(Courtesy of K. Brodziński)

- Meeting with TE-CRG colleagues: we think we understood the discrepancy.

- A 2nd measurement in SM18 in February, with the same settings as in the LHC
  - CM is already cold
Forthcoming actions
Maintenance and operational spares

Hardware
- Crowbar (Solid State): 4 units (LHC needs 4 units) → 3 to 5 additional units by the end of LS2
- Modulator MAC10 (tetrode): 2 units + 3 units used on tests stand → tetrode replacement system is under development

Controls
- Replacement/maintenance of a large number of PLC processors, interlock cards, power supplies, etc..
- LLRF modules → spare production campaign ongoing
- Replacement of the power supplies (LLRF)

Software
- FESA2 → FESA3 migration (e.g. beam control classes → difficult to debug without a beam)
Maintenance and operational spares

Test stand infrastructure
- ACS test stand in SM18 → partially done in 2018 but work should continue (controls upgrade)

ACS module and cavities
- 1 spare dressed cavity (90s production) → successfully tested in 2018
- 1 spare LHC ACS module (with new pumping crosses)
- 4 dressed spare cavities and 1/4 test CM will be available for Run3

and more see Helga’s talk
Successful test of the spare LHC ACS CM

Test of spare LHC ACS module with new pumping crosses in October 2018 (America, taken out in LS1)

- 2.5MV @ Qx=60k (flat top) and 1.5MV @ Qx=20k (injection position), all cavities were able to work stably for several hours
- Additional studies and tests such as HOM measurement and TDR of field antenna have been performed
- The M9 horizontal test bench in SM18 was brought back in operation → to be continued
- A significant number of software updates and improvements have been introduced following the user interface adaptation → to be continued
Summary

- The LHC RF system is working reliably and successfully throughout the years
- Flexibility of the RF system has been proved: MD requirements, special runs
- Huge amount of work has been performed in 2018
- Preparation for post-LS2 operation under way
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References:

H. Timko et al., ‘Estimated LHC RF system performance reach at injection during Run III and beyond’, to be published, (2019)
