# STATUS AND COMMISSIONING PLANS FOR LHC RUN2.
# THE RF SYSTEM

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## *Abstract*

The paper presents the work done on the LHC RF system during Long Shutdown 1 (LS1). On the High Level side we have replaced a cryomodule (four cavities, beam 2), which could not operate reliably at the design voltage (2 MV per cavity). The upgrade of klystron collectors has been completed and new crowbar systems have been installed (solid state thyristors replacing the old thyratrons). On the Controls side, all RIO3 CPUs are beeing replaced and the new ones are now using Linux. The new FESA classes are being designed with FESA3. The consequences of the increased beam current (0.55 A DC compared to 0.35 A in 2012), the increased energy (physics planned at 6.5 TeV/c per beam), and the exotic bunch spacing (5-20 ns for the scrubbing beams) will be analyzed from an RF hardware point of view. A tracking code is being developed to understand the effect of coloured phase noise on the longitudinal bunch profile. The expected benefits are the optimization of the blow-up and the possible shaping of bunch profile (flatter bunches) to avoid beam induced heating and improve beam stability. Upgraded longitudinal bunch-by-bunch measurements are being implemented.

## UPGRADES DONE DURING LS1

The LHC RF design called for 16 MV total voltage at 7 TeV/c, providing a 7.9 eVs bucket area containing a bunch of 2.5 eVs longitudinal emittance (1.05 ns 4σ bunch length) [1]. At 3.5 TeV (2011) and 4 TeV (2012) we have operated with 12 MV total voltage. For beam 1, the eight cavities were operated at 1.5 MV, but one of the beam 2 cavities (C3B2) could not be operated reliably above 1.2 MV, resulting in uneven cavity voltage settings: 1.2 MV in C3B2 and 1.54 MV in the other beam 2 cavities. This situation is not optimal: unequal voltages result in unequal voltage phase slip caused by transient beam loading, a situation that would be problematic for the future RF phase modulation scheme [2]. Also, a higher voltage may be needed at 6.5 TeV/c. The LHC cavities are housed in cryomodules in groups of four. A complete module has been replaced in the beginning of 2014 (see Fig. 1), hopefully allowing for 16 MV per beam in the future, if needed.

Figure 1: The spare RF cryomodule (four cavities) being lowered down into the UX45 cavern (Feb. 2014).

Every LHC cavity is supplied by an individual 300 kW klystron. Each unit of four klystrons is powered by a power converter (60 kV/40A DC). A fast protection system (crowbar) protects the four klystrons: in case of arcing inside a klystron, the protection system (thyratron) grounds the High Voltage (HV) in less than a few microseconds thereby avoiding damage in the tube [3]. The diversion of the HV energy is achieved by triggering the thyratron, which then becomes conducting and acts as a short circuit of the HV power supply to the ground. The thyratrons in use during the LHC Run1 require very fine adjustment and are very sensitive to noise. Although they proved to be reliable from the point of view of protecting the klystron, from time to time they have suffered from auto-firing that resulted in LHC beam dumps. Figure 2 shows an RF power fault summary for year 2012, with eleven beam dumps triggered by the crowbar (weeks 20 and 28); the majority of these were false alarms.

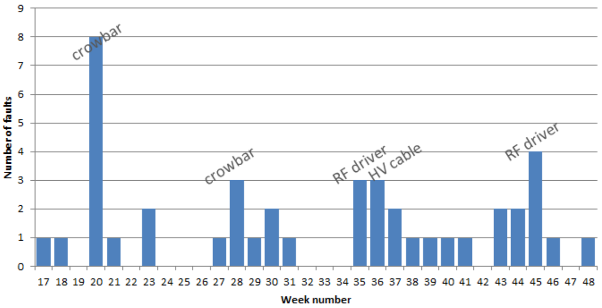


Figure 2: RF power fault summary (2012).

All four thyratron tubes have been replaced with their solid state equivalent (thyristor). One such system had been installed in Sept. 2012 and performed reliably till the LHC stop in March 2013. Compared to the thyratron, the new system is simpler (little controls electronics), requires no cooling, and is not prone to auto-firing. In addition it is a more modern technology with a large industrial choice. Figure 3 shows both systems.

Figure 3: Thyratron (old system) left and thyristor (new system).

The klystron cathode is raised to a high voltage (50-60 kV) with respect to the klystron body. Electrons are extracted from the cathode filament, resulting in a DC current (8-9 A) from cathode to the anode (collector). As electron emission depends on the cathode's temperature, the filament is heated by an added AC current that is monitored, resulting in klystron trip and beam dump if it deviates from the set value. Several fills were dumped following a "glitch" in the monitoring of the filament heater current. The cause was traced to the poor soldering of the high voltage cables. These have been redone, with new connectors re-weld, using induction welding, without damaging the insulation material (Fig. 4).

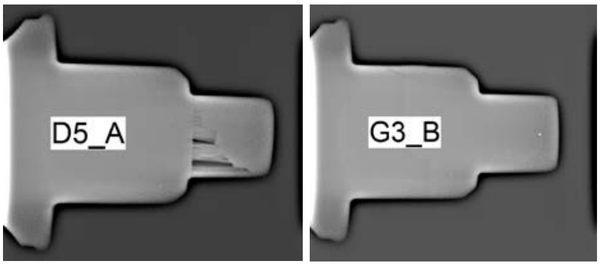


Figure 4: X-ray of the High-Voltage connector before (left) and after replacement.

Photo-diodes are installed inside the RF waveguides to detect possible arcing. They are linked to an interlock that would trip the corresponding klystron and eventually dump the beam. There were many false alarms during LHC Run1, due to photo-diodes detecting radiation instead of a real arc. They have now been replaced with a new design, more resistant to radiation.

The design klystron working point is 58 kV cathode voltage and 9 A beam current, resulting in a DC power of 520 kW, and an RF power of approximately 300 kW. In a klystron, the residual DC power not consumed as RF output power is dissipated in the collector, and with the low RF power required in operation (below 200 kW during Run1), the collector power resulted in overheating (Fig. 5). An upgrade program was launched in 2010, to improve the collector's cooling circuitry and all klystrons are now capable to sustain the full DC power. We have also replaced eight klystrons with spares to make the aging profile more favourable (avoid that all klystrons present aging problem around the same time).

Figure 5: Klystron collector showing traces of overheating (2010).

Several upgrades to the RF Controls are being deployed during LS1: all RIO3 CPUs are being replaced with MEN A20 models, and the Operating System changed from Lynx OS to Linux. Front-End software developments for the new boards are now done with FESA3. Old systems remain on FESA2.10 but will be migrated to FESA3 during 2015.

Tools are being developed as diagnostics in the longitudinal plane. The Low Level RF (LLRF) includes a Beam-Based Phase Loop: for each ring, the phase of each individual bunch is measured, and an average over one turn is computed to correct the phase of the RF drive of the corresponding beam. Originally, the individual bunch phase measurements were not intended as diagnostics, but they have been used to study electron cloud, as they provide useful information on the energy loss per bunch [4][9]. This application will be very useful during the 2015 scrubbing run. Bunch-by-bunch phase acquisition has also been used to estimate longitudinal coupled-bunch instability growth rate [5], a study that will be continued during LHC Run2. Finally, this diagnostic tool will be essential if the LHC will ever suffer from longitudinal instabilities in operation. With careful post-processing to remove systematics and reduce random errors, the measurement accuracy is adequate but the limited storage (73 turns only) was a problem during Run1. In 2015, we will export a stream of single bunch phase measurements at 40 M samples per second (one measurement per bunch at 25 ns spacing), for monitoring and analysis by an application running in the Control Room. The implementation will be similar to the one developed for the diagnostic of transverse instabilities.

RF noise was a major concern during the design of the LHC, with fears that it would limit the luminosity lifetime. This is not the case, thanks to a careful low-noise design, but on a few occasions in 2011, a malfunctioning LLRF has led to severe RF noise with debunching and populating the abort gap as a consequence. In 2012, a commercial instrument was installed to measure the Phase Noise Power Spectral Density (PSD) of the sum of the eight cavities for each beam. An application displayed plots of the spectrum in the Control Room, compared the measurements with references and generated an audio message in case of excess noise. A better diagnostic is being developed for installation during 2015: it will measure the amplitude and phase noise PSD for each cavity individually, will include an interlock and could trigger the beam dump if needed. It will ease the diagnostic by identifying the faulty cavity directly.

## RF PARAMETERS FOR 2015

At injection, the LHC capture voltage was initially set in 2010 to 3.5 MV. With the increased injection current, the injection dump would fire on occasion, triggered by radiation measured by the Beam Loss Monitors (BLM) [6]. To reduce capture losses the voltage was raised to 6 MV at the restart in 2011 [7] and has remained at that value through the rest of Run1. From October 2012 on the SPS was operated with the new Q20 optics. Compared to the classic Q26 optics, the $\Delta p/p$ at SPS extraction was 15% smaller, but the bunch length was slightly longer (Table 1). The capture voltage was therefore not changed.

Table 1: Longitudinal emittance and 4σ bunch length measured in the SPS before transfer to the LHC (mean over the injected batch) with the old SPS optics (Q26) and the new optics (Q20). 7.5 MV 200 MHz and 640 kV 800 MHz SPS RF, 50 ns bunch spacing.

| SPS optics | Mean longitudinal emittance | Mean bunch length (4σ) |
|---|---|---|
| Q26 | 0.5 eVs | 1.45 ns |
| Q20 | 0.45 eVs | 1.6 ns |

With 25 ns spacing in 2015, the bunch intensity will be lower (1.1E11 p per bunch vs. 1.4E11-1.65E11 p for 50 ns spacing in 2012), but the total current will be higher (0.55A DC vs. 0.35 A DC). So we do not expect lower longitudinal emittance and bunch length from the SPS and propose to restart the LHC with unchanged 6 MV capture voltage.

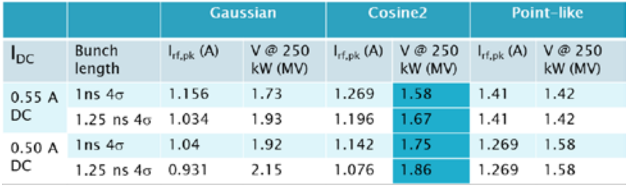
An important beam parameter is the bunch length at top energy. Since a low pileup density is essential for tracker detectors, it is not desirable to reduce the 4σ length below 1.25 ns in physics [8]. With this constraint, the remaining free parameter is the RF voltage during physics. If we operate with the bunch length used in 2012 (1.25 ns), 10 MV at 6.5 TeV/c will provide the same longitudinal stability margin as in 2012 (12 MV at 4 TeV/c) [9]. A higher voltage would provide a larger bucket area and allow for a larger longitudinal emittance. This would be beneficial as it reduces the transverse emittance growth caused by Intra Beam Scattering. But it also increases the momentum spread causing a larger betatron tune spread (footprint) due to chromaticity, and therefore potential losses. Final optimization in physics will be done by experimenting.

On the hardware side, the maximum RF voltage is limited by the available klystron power. During the LHC Run2 we will use the same algorithm as in Run1, that is, trying to fully compensate the transient beam loading caused by the no-beam segments*. We keep the voltage strictly constant over one turn. After optimizing the cavity coupling (adjustable in the LHC cavities), the required RF power per cavity is [10]

$$P = \frac{V\, I_{rf,pk}}{8} \tag{1}$$

$I_{rf,pk}$ is the RF component of the beam current during the beam segment. It depends on the DC beam current, the bunch length and the longitudinal distribution. LHC klystrons are designed for a 300 kW RF output. We wish to keep a safe 20% power margin for regulation, therefore limiting the operational RF power at 250 kW. This sets the maximum voltage per cavity as listed in Table 2.

Table 2: Cavity voltage produced by a 250 kW klystron for different beam DC currents, bunch lengths and longitudinal distributions: Gaussian, cosine-square and point-like (Dirac pulse).



| | | Gaussian | | Cosine2 | | Point-like | |
|---|---|---|---|---|---|---|---|
| $I_{DC}$ | Bunch length | $I_{rf,pk}$ (A) | V @ 250 kW (MV) | $I_{rf,pk}$ (A) | V @ 250 kW (MV) | $I_{rf,pk}$ (A) | V @ 250 kW (MV) |
| 0.55 A DC | 1ns 4σ | 1.156 | 1.73 | 1.269 | 1.58 | 1.41 | 1.42 |
| | 1.25 ns 4σ | 1.034 | 1.93 | 1.196 | 1.67 | 1.41 | 1.42 |
| 0.50 A DC | 1ns 4σ | 1.04 | 1.92 | 1.142 | 1.75 | 1.269 | 1.58 |
| | 1.25 ns 4σ | 0.931 | 2.15 | 1.076 | 1.86 | 1.269 | 1.58 |

The longitudinal distribution in LHC is determined by the controlled emittance blow-up [14]. The cosine-square shape is a good match. With 1.25 ns bunch length we can operate with 1.67 MV per cavity (13.4 MV total) at nominal beam intensity and with 1.86 MV per cavity (14.9 MV total) at 0.5 A DC. Comparing to the 10 MV lower limit (longitudinal stability margin as in Run1), we have some flexibility in the choice of voltage in physics. We propose to optimize it, by testing a few physics fills with different voltages.

For Run2, we will operate with 25 ns bunch spacing. This was the original specification for the LHC RF and the hardware is fully compatible [1]. To make the e-cloud scrubbing faster, it is proposed to work with 5 ns-20 ns spacing, that is, pairs of bunches spaced by 5 ns, with

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* Above nominal LHC beam (0.55 A DC) the klystron power will not be sufficient to compensate the transient beam loading and we will modulate the phase of the RF following the beam gaps [2]. With this scheme the required RF power will be significantly lower than given by equation (1).

25 ns spacing between pairs. The LHC Beam Based Phase Loop has been introduced above: it measures the phase of each bunch, averages over one-turn and updates the phase of the corresponding beam RF. This scheme is classic in Hadron machines. It provides fast damping of the longitudinal oscillation mode zero (all bunches oscillating in phase). When the RF is generated by an oscillator, the phase noise is particularly large at low frequency offset from the carrier. In a large collider the synchrotron frequency is small (just above 20 Hz in the LHC) and the noise will excite coherent longitudinal oscillations. Due to the non-linearity of the RF potential, the oscillations will result in growth of longitudinal emittance and losses as the RF bucket gets full [11]. With 25 ns spacing the electronics measures the phase of each bunch. For 5-20 ns spacing it will give an average over the two paired bunch. As the measurements are then averaged over one turn to generate an update for the RF drive, the performance is expected to be similar with the scrubbing beam [12].

## STUDIES ON CONTROLLED RF NOISE

If we apply only adiabatic variations of the RF parameters, the longitudinal emittance (expressed in eVs) remains constant during the acceleration. Since the longitudinal stability threshold decreases with energy, the beam would be unstable at high energy without intentional emittance growth during the ramp [13]. This controlled blow-up is achieved by injecting band-limited RF phase noise in the cavities, while monitoring the mean bunch length [14]. The method has been in operation since summer 2010. Various implementations have been tried: the phase noise can be injected in the LLRF loops or directly in the cavity. It can cover a narrow spectral band around the RF frequency or around a revolution sideband. Blow-up was also tested with and without Beam Phase Loop [15]. In spring 2014 a study was started to explain the observations with blow-up recorded during Run1. The PyHEADTAIL tracking code has been upgraded to allow for injection of colored RF phase noise. With this modelling, we hope to gain better understanding of the blow-up in order to make it more reproducible from ramp to ramp, more uniform among the bunches, and to produce longitudinal profiles that create less machine heating in 2015. It was also proposed to use RF phase modulation to create flat bunches (flat longitudinal distribution) [16]. Such a profile would reduce the beam-induced heating [†] and could be beneficial for transverse stability, and thus luminosity. At 7 TeV/c the synchrotron radiation damping time is 24 hours (for $\sigma_z$). Ignoring all other blow-up sources, the bunch length would shrink to 80% of its initial value in 6 h [18]. Although Intra Beam Scattering and, to a lesser extent, RF noise will counteract, the net effect may still be shortening that could be compensated by periodically injected bursts of RF phase noise during physics. These manipulations require a better understanding of the effect of controlled RF noise in the LHC.

## CONCLUSIONS

The high-power RF equipment underwent a major upgrade during LS1: installation of a spare cryomodule complete with four cavities, new solid-state crowbar systems replacing the old thyratrons, klystrons upgraded for full DC power and improved arc detectors. These should improve the RF availability.

During Run2, we plan to operate initially with 1.25 ns bunch length in physics. Capture voltage will be 6 MV. At 6.5 TeV/c, the RF voltage can be chosen between 10 MV (conservative stability threshold) and 14 MV (RF power limit). The lower value is defined by the loss of Landau damping, scaled from MD results at 4 TeV/c. We plan to measure the stability threshold at 6.5 TeV/c at the beginning of run2. During most of run1[‡], we used 12 MV in physics as C3B2 could not provide more than 1.2 MV. For constant bunch length, a high voltage value is beneficial as it reduces transverse emittance growth caused by Intra Beam Scattering, but it results in a large momentum spread that may reduce lifetime in collision (betatron tune spread caused by chromaticity). Optimization should be done in 2015, in physics. We do not anticipate hardware problems with the 25 ns spacing, neither with the exotic 5-20 ns (scrubbing beams).

New diagnostics are in preparation: bunch-by-bunch phase measurement (hopefully available at start-up) and monitoring of the RF noise (second half of 2015).

The controlled injection of RF phase noise is being implemented in the PyHEADTAIL simulation code. The goal is to improve longitudinal blow-up and design RF manipulations to precisely control bunch profile in physics.

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[‡] We used 10 MV for a few fills towards the end of Run1.

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