RF AND ADT AFTER LS1

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Abstract

During LS1 a number of consolidations and upgrades have been undertaken in the LHC RF, including replacement of a cryomodule (four cavities, beam 2), upgrade of klystron collectors and new solid state crowbar systems. The RF parameters will be outlined in view of the consequences of the increased beam current and energy, and the exotic bunch spacing for the scrubbing beams.

The LHC Transverse feedback system (ADT) is also undergoing a major upgrade during LS1, with double the total number of pickups to reduce the noise floor of the system, new beam position electronics and an upgraded digital signal processing system to accommodate all of the extra functionality that had been introduced during LHC Run I, and more sophisticated signal processing algorithms to be deployed for Run II. An external "observation box" to record transverse and longitudinal data from the RF and ADT systems is being implemented.

RF UPGRADES DURING LS1

Replacement of Faulty Cavity Module

During Run I, cavity 3 of beam 2 could not be operated reliably above a voltage of 1.2 MV, compared with the nominal value of 2 MV, and it was decided to replace the cavity cryomodule M1B2 ("America") with the spare ("Europa"). This was done at the start of 2014, and the new module will be commissioned along with the remaining three. No special issues with this module are anticipated.

Upgrades for Improved Reliability

A number of upgrades to the RF systems have been performed with the aim of improving reliability:

Crowbar systems: The old thyratron based crowbars [1] have been replaced by a new solid state thyristor stack design, which is less prone to misfiring.

Klystron HV cables: Faulty spring contacts and poor welding in the HV connectors frequently led to spurious drops in the klystron filament current. The connectors have all been replaced using an improved induction welding technique which avoids damaging the cable insulation.

Waveguide arc detectors: These are based on photodiode sensors which detect the light emitted by an arc in the waveguide [2]. The radiation sensitivity of the diodes led to frequent spurious trips. A mitigation was put in place during Run I using an AND logic between the detectors to eliminate the spurious trips. A new design with a more sophisticated voting logic between multiple detectors has been developed, is used in Linac4, and is the object of a knowledge transfer to industry. The new system will be installed on the new cavity module; however, there are no plans to install it systematically in all LHC cavities before LS2.

Klystron collectors: During Run I, the DC power handling of the klystrons was limited to 400 kW by a design fault in the collector water cooling assembly. All klystrons have now been upgraded by Thales to handle the design DC power of 500 kW. In addition, eight of the sixteen klystrons have been swapped with spares for purposes of wear levelling.

Renovation of RF zone in SR4: During Run I the RF racks in SR4 were open to the hall, making them subject to phase and frequency drifts due to temperature and humidity variations. A roof has now been installed on the RF zone and a new air conditioning system installed to maintain constant conditions.

Remaining Items for Run II Startup

RF noise monitoring: On a few occasions, malfunctioning LLRF has resulted in severe RF noise, debunching and population of the abort gap. A Phase Noise Power Spectral Density (PSD) display was made available in CCC, which compares the vector sum of the 8 cavities for each beam against a reference spectrum and generates audible warnings in the case of excessive noise. After LS1 (mid 2015) we aim to have a measurement of the amplitude and phase noise PSD for each individual cavity implemented in custom-design VME module, to allow immediate identification of the problem cavity.

Studies on shaping of the longitudinal distribution with RF phase noise: Controlled injection of RF phase noise is used to increase longitudinal stability via emittance blow-up [3]. This technique can also be used to shape the bunch according to the noise spectrum chosen. Controlled blowup may be needed to compensate the synchrotron radiation damping at 6.5 TeV. Many data are available from Run I, but several observations are not understood. The first goal of the study is to reproduce the Run I blow-up measurements with the simulations. Studies are ongoing to find an optimum noise spectrum for a targeted bunch profile. A simulation code, BLonD (Beam Longitudinal Dynamics) [4], is being implemented into PyHEADTAIL [5].

Bunch-by-bunch phase measurement: The LLRF measures the phase of each bunch individually, then averages over the beam to correct the phase of the RF drive. Bunch-by-bunch phase measurements have been used in electron cloud studies to give information on the energy loss for each bunch [6]. Individual bunch phase observations has also been used to estimate longitudinal coupled-bunch instability growth rate [7] and will become extremely important if we suffer from longitudinal instabilities with high intensity 25 ns operation. It is measured in the custom-designed LLRF VME module but it was not practically feasible to extract the data in real time, nor to store it for analysis. These issues are being addressed via the "observation box" development described later in this paper.

Outstanding RF Controls Items

Replacement of CPUs and move to Linux: All RIO3 VME crate CPUs running LynxOS are being replaced by the new MEN A20 boards running Linux. Around 95% of the FESA classes have already been migrated, but a large campaign of installation and test is still required.

FESA3 upgrade: At LHC startup, only the new signal processing hardware of the Transverse Damper system will have front-end software under FESA3 [8]. Other LHC systems will remain on FESA 2.10 but will be migrated to FESA3 during 2015 technical stops and the winter shutdown.

Expert RF application software: The LabVIEW panels used by RF experts to configure the hardware, as well as the MATLAB scripts used for setting-up the LLRF, are using version 2 of Remote Device Access (RDA2). In order to follow the programmed FESA evolution to FESA3 version 2, these applications must be upgraded to use RDA3 [9] or JAPC (Java API for parameter control) [10]. However, as a medium-term solution, the BE-CO middleware team offers a proxy service to enable RDA2 clients to access RDA3 servers, and we will use this facility in 2015. In addition, it is desirable to use the LSA settings management rather than directly accessing the FESA devices.

It has not yet been decided whether to progressively migrate the LabVIEW applications to RDA3 and LSA, or to re-implement them using another tool such as Inspector [11].

RF RE-COMMISSIONING

The re-commissioning of the RF system will be performed in four distinct steps:

1. *Re-commissioning of the High-Voltage:* The HV (50-60 kV) supply for the klystrons will be commissioned, including tests of the HV interlocks and commissioning of the new crowbars.
2. *Re-commissioning of the High-Power RF:* The klystrons will be re-commissioned with the waveguide short-circuits in place, including the 8 new klystrons installed during LS1. Tests of the klystron interlocks and power calibrations will be performed.
3. *Re-commissioning of the cavities:* The cavities will be re-commissioned, including the new module (4 cavities) installed during LS1. The cavity interlocks will be tested, the cavities conditioned, and voltage calibrations performed.
4. *Re-commissioning of the Low-Level RF:* The tuning and feedback loops will be commissioned, with calibration of the cavity loaded Q vs. power coupler position, and optimization of the LLRF parameters.

In order for commissioning to start, a certain number of pre-conditions are necessary: general services (240/400 V) should be available, as well as demineralized water. Access to UX45 will be required, which is incompatible with magnet powering. The 18 kV cells must be powered, and the HV power converters operational, including power converter controls. The front-end crates and controls software must be operational for the RF equipment, with the expert application software available. Cavity commissioning requires in addition the cavities to be cold and filled with liquid He under stable cryogenic conditions.

RF PARAMETERS FOR 2015

Capture Voltage

Extensive measurements of SPS longitudinal emittance and bunch length exist from the 2012 proton run with 50 ns bunch spacing (Table 1). At SPS extraction with the Q20 optics, the Δp/p is about 15% less than with the classic Q26, but the bunch length is slightly longer. The beam was captured with an RF voltage of 6 MV in LHC, giving a bucket area of 1.24 eVs.

SPS optics	Longitudinal emittance (mean)	4 sigma bunch length (mean)
Q26	0.5 eVs	1.45 ns
Q20	0.45 eVs	1.6 ns

Table 1: SPS longitudinal emittance and bunch length from 2012 run (50 ns):

Under these conditions, the measured capture losses were consistently below 0.5 % [12].

In 2015, with 25 ns spacing, the bunch intensity will be lower ($1.1\ 10^{11}$ compared with $1.4\text{-}1.65\ 10^{11}$) but the total current will be higher (0.55A DC compared with 0.35 A DC). We do not expect lower longitudinal emittance and bunch length from the SPS than in 2012, and it is therefore proposed to start with a capture voltage of 6 MV.

Flat-top Voltage and Power

The cavity loaded Q can be optimized giving the minimal required power

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

where V is the total RF voltage and $I_{rf,pk}$ is the 400 MHz RF component of the beam current during the beam segment.

Each LHC klystron can provide 300 kW RF with the nominal DC settings of 8.8A and 58 kV. Keeping 20%

margin for RF voltage regulation limits the theoretical power to 250 kW, which determines the maximum voltage per cavity (Table 2).

With 8 cavities, taking a cosine^2 bunch profile with a nominal 1.25 ns bunch length [13], the maximum achievable total voltage is 13.4 MV with 0.55 A DC beam current, and 14.9 MV with 0.5 A DC beam current.

I_{DC}/A	4 sigma bunch length/ns	$I_{rf,pk}$/A (cosine^2 profile)	V @ 250 kW (MV)
0.55	1.0	1.269	**1.58**
	1.25	1.196	**1.67**
0.50	1.0	1.142	**1.75**
	1.25	1.076	**1.86**

Table 2: Maximum achievable voltage per cavity for different DC beam currents and bunch lengths

Bunch Spacing: 25ns and 5+20ns

The RF beam control was designed for the nominal LHC beam, and thus should function without problem with 25 ns bunch spacing [14]. With the 5+20 ns spacing of the doublet scrubbing beams, the wavelets produced by the two bunches passing in the same 25ns sampling window superpose to produce a valid sum signal, providing the signal is sampled at the correct instant (Fig. 1). Therefore with careful adjustment the beam control can be made to function correctly with the doublet scrubbing beams.

The same considerations apply to the beam position measurements of the Transverse Damper.

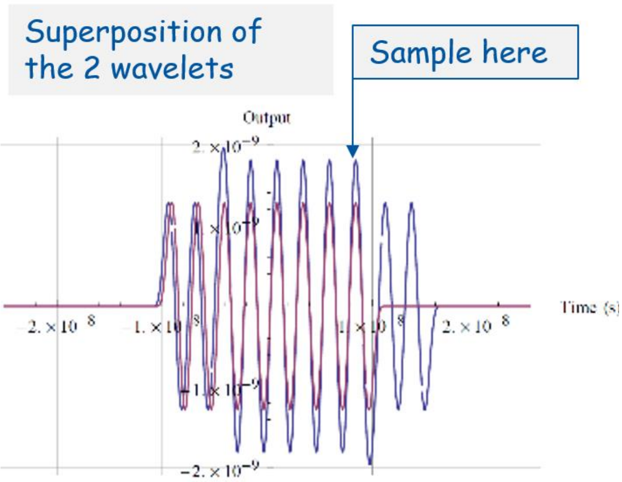

Figure 1: Adjustment of sampling in beam phase measurement for 5+20ns bunch spacing

ADT NEW FEATURES FOR RUN II

The LHC Transverse Damper (ADT) was primarily designed for damping of injection oscillations and of oscillations driven by coupled bunch instability. It plays an important role in the preservation of the transverse beam emittance.

Digital Processing Hardware

Since the LHC start in 2008 the feature set has grown to include injection and abort gap cleaning, transverse blowup used for loss map measurements, detection of instabilities using the damper pickups, and extraction of tune signals with the aim of eventually alleviating some of the co-existence problems between the damper and the BBQ [15].

The ADT upgrade foreseen for Run II provides more powerful digital signal processing hardware in a larger FPGA in order to accommodate all of the features added during Run I and some new additional functionality (Fig. 2). Three independent output DACs allow combination of the main damper loop signal with those for excitation and abort gap cleaning, each with independent gain control [16].

The new ADT Low level RF hardware is being developed in synergy with the SPS transverse damper upgrade, which is now installed and operational in SPS.

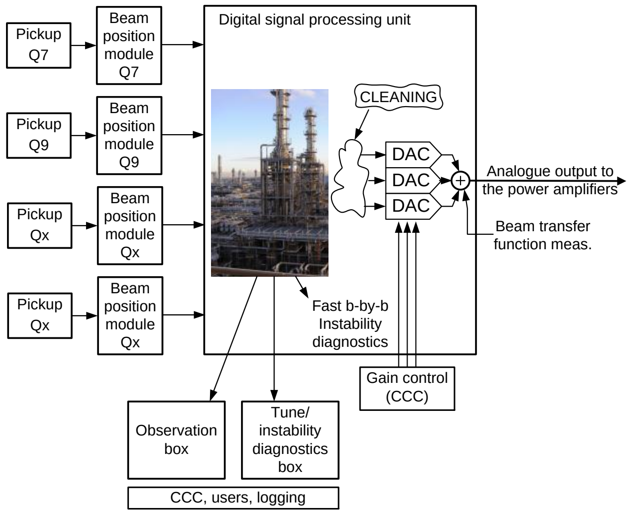

Figure 2: Signal processing in new ADT hardware

Signal to Noise Ratio and Pickup Layout

The number of pickups used by ADT has been doubled to four pick-ups per beam per plane. The signal to noise ratio for N pickups with respect to a single pickup at β=100m can be expressed by

$$\left(\frac{S}{N}\right)_{improvement} = 20\text{dB}\times\log_{10}\frac{\sum_{n=1}^{N}\sqrt{\beta_n/100\text{m}}}{\sqrt{N}}$$

In agreement with the BI group, the BPMC coupler-type pickups at Q7 and Q8 either side of Point 4 have been swapped with those of the Beam Presence Flag system in order to benefit from the higher beta values at these pickups. Table 3 shows the estimated improvement signal-to-noise with respect to the Run I situation.

New Data Processing Algorithm Features

The current normalization scheme sees only even-symmetric oscillation patterns which are needed for the closed loop feedback. If the longitudinal bunch profile is symmetric, the odd-symmetric transverse oscillation modes are not visible to the damper, since they do not produce a movement of the bunch centroid [17]. The new data processing implementation has an additional algorithm which can detect odd-mode head-tail & higher order oscillations. It cannot resolve the original oscillation nor the absolute oscillation amplitude accurately, but it can detect oscillation activity and distinguish between the symmetric and asymmetric modes of every bunch. This information can be used in real time to generate a measurement trigger.

	Run I (2 PU) Q7,Q9	**Run II (4 PU) Q7,Q9,Q10**	**After BI swap Q7,Q8, Q9,Q10**	**Run I → II dB (relative)**
H.B1	3.8 dB	5.6 dB	7.0 dB	**3.2**
V.B1	4.2 dB	7.4 dB	8.0 dB	**3.8**
H.B2	4.4 dB	5.9 dB	8.0 dB	**3.6**
V.B2	4.9 dB	6.6 dB	8.2 dB	**3.3**

Table 3. Estimated improvement in S/N wrt a single pick-up at beta =100 m

Compatibility with New UPS

The ADT base-band signals, from 3 kHz to 20 MHz, are transmitted over coaxial lines from SR4 to the driver amplifiers in UX45. These signals were perturbed by ground currents from the uninterruptible power supplies (UPS) which had a switching frequency of 5, 8 or 16 kHz. A measurement campaign in 2010 followed by the installation of noise suppression chokes allowed the problem to be mitigated [18]. However, the newly installed UPSs produce very different noise spectra, with some frequencies less prominent, but some components up to 40 times stronger.

The ADT team is in contact with the EN/EL group, and a measurement campaign will be carried out in order to identify and quantify a possible perturbation of the ADT by the new UPS.

RF OBSERVATION BOX

New Facilities for Signal Observation

The ADT and RF VME hardware incorporates memory buffers for the acquisition of bunch-by-bunch diagnostic data. However, these buffers are limited in size, and the demand for bunch-by-bunch data for use in beam studies has overtaken the technical possibilities. This has motivated the launch of an “Observation Box” development which aims to make available the bunch-by-bunch data to external applications. The sample data from the ADT and RF VME boards is streamed over optical fibre links to an external PC with large memory & processing capabilities, allowing data to be made available for a quasi-unlimited number of turns. On-the-fly data analysis opens the possibility of tune measurements and instability detection, which can in turn be connected to the LHC instability trigger network [19].

The data transmission and reception firmware has been developed, and the front-end software implementation is well advanced. Discussions are underway with OP for the development of an application for bunch-by-bunch beam phase measurements.

CONCLUSIONS

Large-scale modifications to the high-power RF are being implemented: a new cryomodule has been installed to replace one with a defective cavity, new solid-state crowbars aim to reduce spurious trips, and all klystrons have now been upgraded for full DC power handling.

It is envisaged to capture with 6 MV at injection as in 2011-2012, and the maximum available RF voltage at flat-top will be 13.4 MV with the nominal DC beam current of 0.55 A DC, or 14.9 MV with 0.5 A DC, assuming a $cosine^2$ profile and the baseline value for the 4 sigma bunch length of 1.25 ns. Operation with 250 kW of effective RF power requires the maximum 8.8A/58 kV klystron DC settings.

With a minor adjustment the RF will cope with the 5-20 ns bunch spacing of the doublet scrubbing beams.

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

The ADT system is undergoing a major upgrade during LS1 to further improve flexibility and performance. An increased number of pickups and optimisation of the pickup locations result in an improved signal to noise ratio. More powerful signal processing permits the implementation of additional algorithms for fast bunch-by-bunch symmetric and anti-symmetric intra bunch instability detection. Dedicated signal paths are provided for witness bunches or cleaning.

The new hardware is developed in synergy with the new SPS damper which is currently being commissioned in the SPS machine.

New diagnostics are in preparation for measurements in the transverse and longitudinal planes which will make large-volume bunch-by-bunch data available to external software applications. New facilities are also being developed for monitoring of the RF noise.

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