OPERATION EXPERIENCE WITH THE LHC RF SYSTEM

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Abstract

The LHC ACS RF system is composed of 16 superconducting cavities, eight per ring, housed in a total of four cryomodules each containing four cavities. Each cavity is powered by a 300 kW klystron. The ACS RF power control system is based on industrial Programmable Logic Controllers (PLCs), with additional fast RF interlock protection systems. The Low Level RF (LLRF) is implemented in VME crates. Operational performance and reliability are described. A full set of user interfaces, both for experts and operators has been developed, with user feedback and maintenance issues as key points. Operational experience with the full RF chain, including the low level system, the beam control, the synchronization system and optical fibers distribution is presented. Last but not least overall performance and reliability based on experience with first beam are reviewed and perspectives for future improvement outlined.

INTRODUCTION

The RF superconducting system is composed of:

- Two times eight superconducting single-cell cavities, on two independent rings, all installed in the straight section in point 4
- Four power converters (100kV, 40A ex-LEP) located in a surface building (SR4)
- Sixteen 330 kW max Klystron (58 kV, 8.4 A), 130 ns group delay (~ 10 MHz BW), CW gain 39 dB, located in an underground cavern in point 4 (UX45)
- Sixteen HV modulators and fast protection systems located in four bunkers in UX45
- WR2300 HH WG distribution system between cavities and their individual klystrons
- The Cavity Controllers comprising forty VME crates of Low level RF electronics located underground in two Faraday Cages close to the cavities and implementing an RF feedback, a klystron polar loop (amplitude and phase), and a cavity tuning loop [1],[2],[9].
- One Beam Control per ring, consisting of two VME crates located in the surface building SR4, implementing a Frequency Program, a Synchro Loop which locks the RF frequency to it, and a Phase Loop which compares the measured beam phase with the Vector Sum Voltage of the eight cavities.

OPERATION WITH FIRST BEAMS

RF Synchronization and Cogging

So far we have operated in single-bunch transfer only, with one bunch injected per SPS cycle. Physics has routinely operated with two bunches per ring, the minimum needed to have one collision per turn in all four experiments.

The collision point was fine-adjusted shortly after the 2010 startup and has not needed to be retuned in the two months since. Figure 1 shows the ATLAS luminous region during one fill at 3.5 TeV. The centre is offset by 1 mm only and the width is 100 mm at the base, in perfect agreement with a 470 ps long bunch with 12 MV. Concerns about possible ring to ring phase noise that would increase the vertex distribution width have proved to be unfounded.

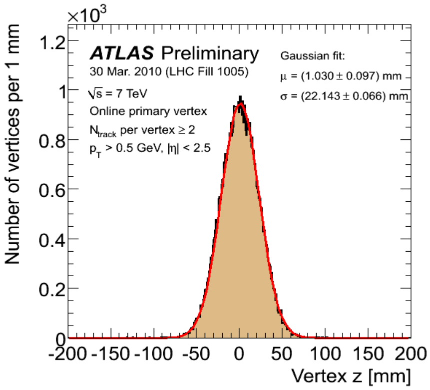

Figure 1 : ATLAS vertex longitudinal distribution. Courtesy of [3]. Two pilots 5E9/bunch, 3.5 TeV

Capture

In 2008 it took only three hours to realize the very first capture of the LHC ring 2 beam [4], capture has consistently proven very easy in both re-starts 2009 and 2010. The injection frequency of 400.788860 MHz, a figure derived in November 2009 and not trimmed since, is optimum for ring 2. On ring 1 we observe a small frequency error on first turns (~ 15 Hz @ 400 MHz).

Table 1: Matched capture voltage for different beam characteristics.

Beam	*Intensity /protons per bunch*	*Logitudinal emittance/eVs*	*Matched capture voltage/MV*
Pilot	$5\text{x}10^9$	< 0.2	2.5
Nominal	$1.1\text{x}10^{11}$	0.4	5
Nominal (design)	$1.1\text{x}10^{11}$	0.7	8

Table 1 shows the matched capture voltages obtained experimentally for pilot and nominal bunch intensities, compared with the LHC design value. We have decided to work with a fixed 5 MV, using only six cavities per ring (with two kept as spare) and about 100 kW per klystron.

With the maximum voltage at extraction in the SPS (7MV @ 200 MHz), the bunches are comfortably short, less than 1 ns long, which minimizes the risk of capture losses. Optimization of the injector chain parameters will be done as problems arise in the LHC.

The phase loop, immediately after injection, moves the RF phase onto the beam. The injection transients are continuously monitored in the CERN Control Centre (Fig. 2). Over the past two months of operation we have observed a continuous drift of the injection phase, probably caused by temperature induced phase shift in the 10 km long fibre optic link transmitting the LHC 400 MHz reference to the SPS. The operation crew has typically fine-trimmed this phase once a week. Automated adjustment is foreseen for the future.

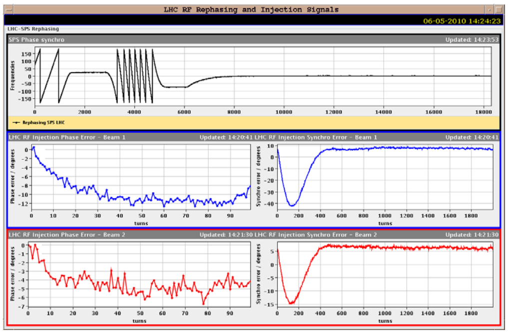

Figure 2: Control room display of injection synchronisation, phase and synchro loop transients

The cavity main couplers are set for low loaded Q (20k) to maximize the bandwidth for the longitudinal damper (to be commissioned in second half 2010) and for the phase loop at injection.

Ramping

The LHC ramp takes 45 minutes from 450 GeV to 3.5 TeV, and the frequency swing is less than 1 kHz at 400 MHz. The frequency program is driven by a pre-calculated function, without direct measurement of the magnetic field over the full ramp. Before the start of the ramp, the main couplers are moved to a high loaded Q (60k) position, to allow an increase in cavity voltage, currently to 8MV but this ultimately be 16MV with nominal beam intensity. The larger bucket will be necessary to accommodate the 2.5eVs emittance required to achieve the design 25 hours luminosity lifetime by sufficiently reducing intra-beam scattering (IBS) [5]. Hardware for emittance blow-up [8] is being designed and will be commissioned in the second half of 2010.

Coupler motion implies much gymnastics: an application continuously monitors the coupler position and changes parameters in the RF feedback (gain and phase shift) and in the Tuner loop (phase offset) according to individual calibration curves established during hardware commissioning in Feb 2010 [6]. This mechanism has worked perfectly so far.

Physics

The RF is doing nothing special during physics. IBS is not an issue yet and we make no attempt to blow up the longitudinal emittance. The 8 MV bucket is enormous compared to the low emittance bunch, and thus a klystron trip during physics currently goes completely unnoticed.

RF noise

In reviews, the choice of klystrons for powering a hadron collider was much debated. However the first results are very encouraging.

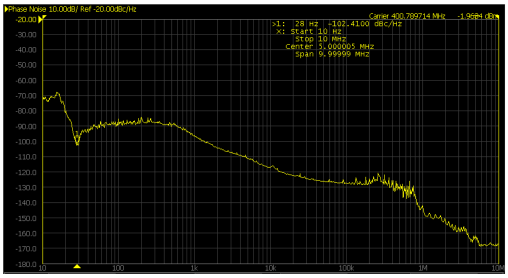

Figure 3 : Phase Noise PSD, ring 2, 3.5 TeV, 12 MV

Figure 3 shows the Power Spectral Density (PSD) of the Phase Noise in the vector sum of the antenna signals from the eight cavities of beam 2. A single bunch of $6x10^9$ protons is circulating at 3.5 TeV. The synchrotron frequency is 28 Hz and we clearly see the effect of the phase loop that digs a hole in the phase noise spectrum at that frequency.

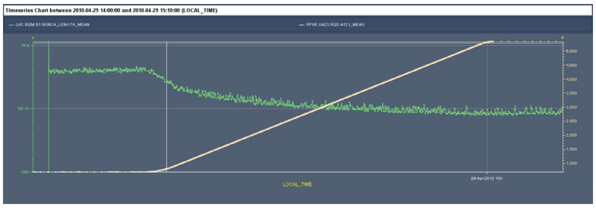

Figure 4 : Bunch length evolution (green) during ramp (70 min total). Left vertical axis is 1 ns full scale.

Figure 4 shows the evolution of the bunch length during the ramp. We have one bunch of $1.0x10^{10}$ protons. The beige trace shows the momentum ramp. The green trace is the bunch length of beam 1 showing the decrease from 850 ps to 500 ps during the ramp as expected from adiabatic evolution. In stable conditions, the observed bunch lengthening is 30 ps/hour at 450 GeV and 6 ps/hour at 3.5 TeV. We have observed no significant effect from the synchrotron frequency crossing the 50 Hz line [10] during the ramp. A study of the LHC RF noise and its effect on beam is being conducted as a part of the LARP program. [7].

KLYSTRON POWER

Due to a deficiency in water flow rate in the klystron collector cooling, the first period of operation is limited to 220KW of RF power, klystron DC parameters 50kV 8A. This is not a limit with the present beam intensity.

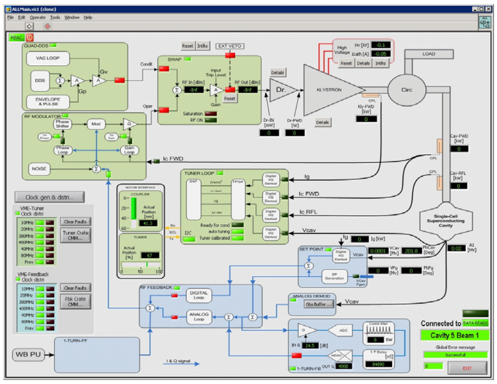

Figure 6 : Low level system user interface

The mismatch at the power circulator output influences the cavity loaded Q and results in a large dispersion in klystron demanded power for the same requested cavity voltage (at present +/- 25 % in power). This is not a limitation yet as the klystrons are driven far from saturation, but it will be when moving to nominal intensity. A project is going on to measure the klystron output mismatch on a test stand and, eventually, develop an appropriate regulation for the circulator bias current.

RELIABILITY

During the first period of operation a series of recurrent faults has affected the RF availability without any impact on the beam.

Communication problems with the High voltage power converters were solved by more robust front-end software. High voltage crowbars were reduced to almost zero after a careful setting of the thyratron parameters. Main coupler blower glitches are still an issue under investigation.

From the graph below we can see long periods, days, without a single RF power cut. The RF system is very reliable with the present beam conditions, we are confident for the future high intensity runs.

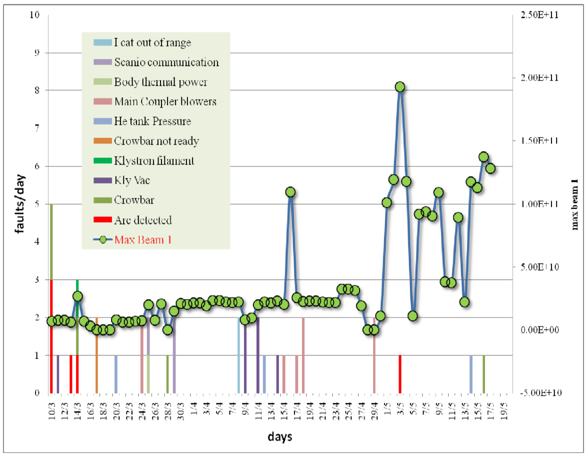

Figure 5 : Superconducting RF faults summary

USER INTERFACES

A large suite of applications (Fig. 6), both for operation (Java) and RF expert (LabView) has been written and has proven to be crucial for the day to day operation of the whole RF system.

CONCLUSIONS

The paper is based on the first four months of beam operation since September 2008. Many improvements have been made during the commissioning period and we are confident for the future. Several projects are under development and will be commissioned as the intensity is increased.

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