FIRST BEAM COMMISSIONING OF THE 400 MHz LHC RF SYSTEM

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Abstract

Hardware commissioning of the LHC RF system was successfully completed in time for first beams in LHC in September 2008. All cavities were conditioned to nominal field, power systems tested and all Low level synchronization systems, cavity controllers and beam control electronics were tested and calibrated. Beam was successfully captured in ring 2, cavities phased, and a number of initial measurements made. These results are presented and tests and preparation for colliding beams in 2009 are outlined.

INTRODUCTION

The 400 MHz RF accelerating system [1], situated around Point 4 of the LHC, consists of sixteen single-cell SC cavities, eight per beam. Each cavity provides a nominal 2 MV accelerating voltage and is individually powered by a 300 kW klystron.

Each cavity has a Cavity Controller rack with two VME crates containing cavity tuner loop, RF feedback loop and klystron feedbacks to minimise noise and ripple [2]. Each ring has a beam control system (four VME crates) which includes a Frequency Program, Phase Loop, Radial Loop and Synchronization Loop.

Before installation all cavities were conditioned to a gradient of 8 MV/m, over 1.5 times nominal voltage [3]. The main power couplers had already been pre-conditioned to full klystron power, at all reflected RF power phases, before fitting to the modules [4]. Between November 2007 and August 2008, the cavities were conditioned in LHC and all Cavity Controller equipment was set up and calibrated without beam for a single loaded cavity Q of 60000 [5].

COMMISSIONING WITH BEAM

Measurement and Adjustments with RF Off

On the morning of the LHC start-up day a single bunch of ~ 2 x 10^9, injected into ring 1, reached the APWL wideband longitudinal pickup in Point 4 (Fig. 1).

About 45 minutes later, the beam made two turns in the machine and shortly afterwards three.

A few hours later Beam 2 was being injected and making a few turns. With 6 turns the Beam Phase module [6] of the Beam Control system was used to measure the turn by turn phase slip between beam and RF, giving a first estimate of the LHC ring 2 frequency of 400.788933 MHz.

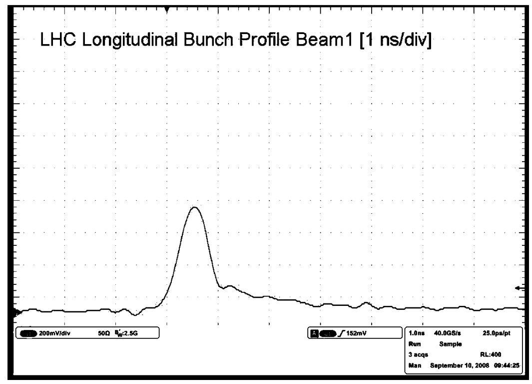

Figure 1: First Longitudinal bunch profile of Beam 1 acquired from the APWL wall-current monitor. 1 ns/div.

A fit of a Gaussian pulse to the first turn data gave after correction a bunch length of 4σ = 0.9 ns, as expected from the SPS measurements on this beam.

By the end of the first day of commissioning, Beam 2 was making more than a few hundred turns without RF.

RF Capture

By the evening of the second day, Beam 2 was circulating for more than one hundred turns in “inject and dump after 10 ms” mode, and the RF team was given priority to set up the capture.

With RF still off, Fig. 2 shows the beam-RF phase slip as measured by the Beam Phase module. The blue trace shows the pickup signal filtered at 400 MHz as the beam repeatedly traverses the pick-up. The red trace shows the individual bunch-RF phase at each turn and the yellow trace is the average phase over one turn (in this case there is only one bunch). Note the excellent Signal-to-Noise ratio for only 2x10^9 protons/bunch. The frequency error is easily derived from the tilt in the phase slip trace.

Once the RF frequency had been corrected, a trajectory measurement showed the beam close to the central orbit with an average displacement of -0.52 mm and dp/p of ± 0.68 x 10^{-3}.

After switching on the RF at 2 MV/cavity, 16 MV total, the beam was captured immediately. After several shots the settings for injection phase and stable phase were correctly adjusted and the synchrotron oscillation could be seen to develop along a horizontal and zeroed baseline, (Fig. 3).

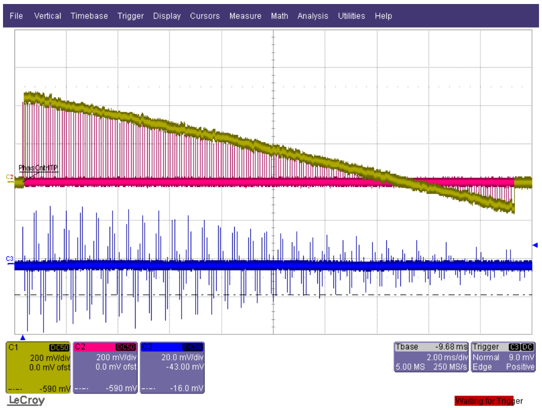

Figure 2: RF OFF, Injection frequency at 400.788933 MHz (error of -30Hz), 2 ms/Div

Yellow: average bunch-RF phase, red: bunch by bunch phase, blue: filtered pickup signal (under-sampled)

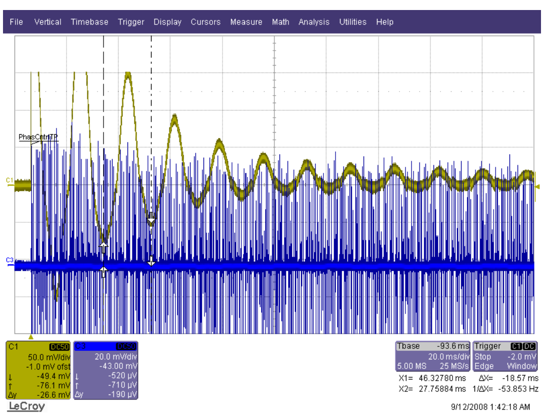

Figure 3: Same signals as the previous figure. RF frequency, injection phase and stable phase correctly set: 20 ms/Div.

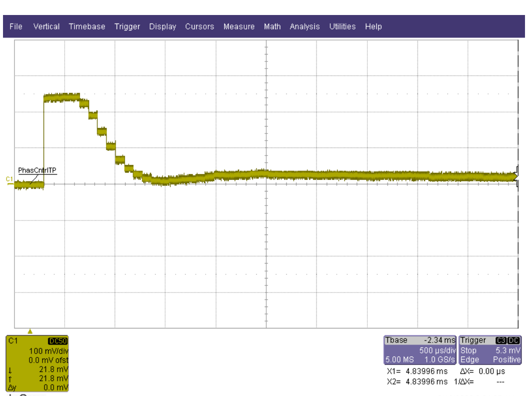

Figure 4: Bunch-RF phase at injection in the presence of an injection phase error and with phase loop ON. 500 µs/div.

Phase Loop

The phase loop could now be closed. The phase loop is intended to quickly correct for potential injection phase error, thereby preventing emittance blow-up through filamentation. Figure 4 shows the evolution of the bunch-RF phase as the loop was closed just after injection. The phase was intentionally offset by 45 degrees to observe the transient and adjust the loop gain accordingly. Figure 4 shows the correction of the phase loop in ~10 turns, as designed.

Figure 5 shows the corresponding Mountain Range display. Notice the 300 ps phase error and the correction in the first ten turns.

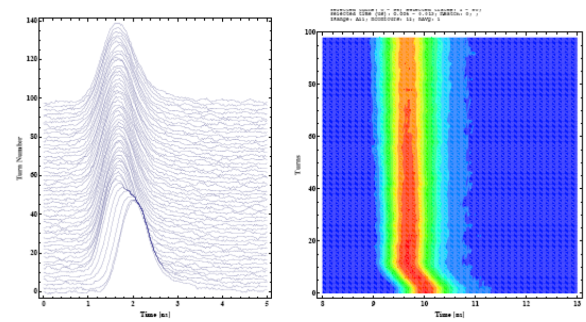

Figure 5: Mountain Range display of one of the very first captured beams in the presence of injection phase error and with phase loop ON at injection.

Phasing of Cavities

The relative cavity phases had previously been set up without beam [5]. The phasing for ring 2 was verified with a pilot beam and the phase loop off. By ramping up and down the individual cavity voltages, the beam was transferred between the bucket of a single reference cavity and each of the other cavities in turn, while measuring the longitudinal position of the beam given by the phase between the pickup and the Master RF reference. For a perfect phasing, the longitudinal position of the beam should come back to a constant value after each transfer. Only one cavity phase had to be corrected, by -8°, confirming the accuracy of the calibrations.

Synchrotron Frequency and Beam Lifetime from Schottky Measurements

A peak detected Schottky spectrum [7] was acquired using the APWL longitudinal wideband pickup, with the phase loop off and 8 MV total cavity voltage (Fig. 6). It shows a maximum dipole frequency, f_s, of (60±1) Hz.

For a nominal RF voltage of 8 MV, the small amplitude synchrotron frequency f_{s0} should be 66 Hz, which is in agreement with the measurement since it is expected that $f_s < f_{s0}$ [8].

A recording of the peak detected signal versus time gave a lifetime of τ = (82±30) minutes, measured over a time t_{obs} = 189 s.

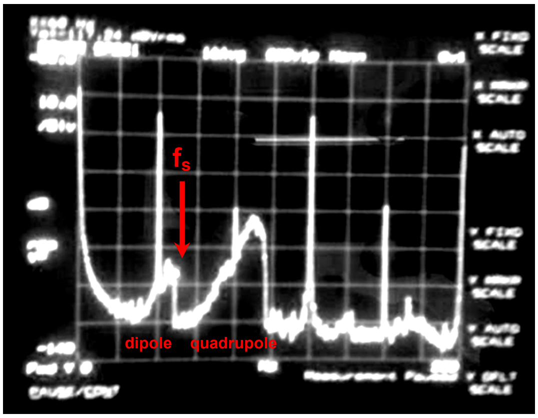

Figure 6: Peak detected Schottky frequency spectrum. Horizontal scale 0 to 250 Hz. The two broad humps are the dipole and quadrupole lines.

PLANS FOR 2009 STARTUP AND 2010 RUN

- The cavities will be conditioned and the whole RF chain re-commissioned, including cavity low-level (for a range of loaded Q from 20000 to 60000) and beam control. The setting up will be facilitated by new remote software tools under Matlab developed by an ongoing LARP collaboration [9].
- A 1-Turn feedback (further reducing the effective cavity impedance) will be installed and commissioned on all sixteen cavities before first beam [10].
- A Longitudinal Feedback acting through the cavities is being developed for installation mid-2010. This may be necessary for equalizing the longitudinal emittances when injecting several bunches from successive SPS cycles.
- The capture of beam 2 will be re-commissioned and that of beam 1 commissioned. The SPS-LHC RF Synchro settings will be adjusted to have both bunches colliding in IP1 and IP5.
- The radial loop for both beams will be commissioned.
- All beam observation equipment will be re-commissioned and more accurate measurements of bunch lifetime will be made on both beams. Bunch lifetime in collision should be measured.
- RF rephasing before physics of both rings to the fixed reference clock used by the experimental detectors.
- First tests of controlled emittance blow-up during acceleration using programmed noise will be made.
- Many enhancements are being made to application software including user-friendly acquisition of the critical signals for setting-up and diagnostics.

CONCLUSIONS

For the RF, following an intense hardware commissioning period, the first few days of beam were very successful with few surprises. Beam 2 was quickly captured and found to exhibit good lifetime. Due to the lack of time, diagnostics and observation tools were minimal in September 2008. The situation will be much improved for the next commissioning run.

ACKNOWLEDGEMENTS

The authors wish to thank all the members of the RF installation and commissioning teams, including D. Landre, D. Glenat, C. Julie, F. Killing, P. Martinez-Yanez, C. Nicou, G. Pechaud, J. Pradier and C. Renaud.

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