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The LHC Low Level RF

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Abstract

The LHC RF consists of eight 400 MHz superconducting cavities per ring, with each cavity independently powered by a 300 kW klystron, via a circulator. The challenge for the Low Level is to cope with very high beam current (more than 1 A RF component) and achieve excellent beam lifetime (emittance growth time in excess of 25 hours). Each cavity has an associated Cavity Controller rack consisting of two VME crates which implement high gain RF Feedback, a Tuner Loop with a new algorithm, a Klystron Ripple Loop and a Conditioning system. In addition each ring has a Beam Control system (four VME crates) which includes a Frequency Program, Phase Loop, Radial Loop and Synchronization Loop. A Longitudinal Damper (dipole and quadrupole mode) acting via the 400 MHz cavities is included to reduce emittance blow-up due to filamentation from phase and energy errors at injection. Finally an RF Synchronization system implements the bunch into bucket transfer from the SPS into each LHC ring. When fully installed in 2007, the whole system will count over three hundred home-designed VME cards of twenty-three different models installed in forty-five VME crates. The paper presents the various loops: it outlines the expected performances, summarizes the algorithms and the implementation. Thanks to a full scale test set-up including klystron and cavity we have measured the response of the RF Feedback and Tuner Loop; and these will be presented and compared to the expectations.

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THE LHC LOW LEVEL RF

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LAYOUT

The sixteen cavities (eight cavities per ring) are installed in the Intersection Point 4 (IP4) of the LHC. A huge cavern, 150 m below ground level, houses the sixteen klystrons (one per cavity) and the Cavity Controller part of the Low Level RF (LLRF), responsible for the RF feedback and Tuner loop around each individual klystron-cavity pair. On the surface, the Beam Controllers (one per ring) are responsible for the generation of the Master 400 MHz sent to the Cavity Controllers via fiber links. They implement the classic Low Level loops using three reference signals per ring: the Cavity Sum, the Radial Pick-up and Phase Pick-up outputs. Finally the RF Synchronization system is responsible for the beam transfer from the injector (SPS).

CAVITY CONTROLLER

There is one Cavity Controller per cavity (two VME crates). It provides control of the phase and amplitude of the cavity voltage, ideally bunch by bunch (with a bunch spacing of 25 ns), and keeps the power demanded at acceptable levels via the mechanical tuner.

The RF feedback

The very high beam current (0.6 A DC nominal) together with a very uneven beam distribution around the ring (3 μs beam dump gap plus a series of 0.94 μs gaps due to kicker rise time limits) induces huge and broadband beam loading in the cavities [1]. The RF feedback can reduce the effective impedance of the cavity (as seen by the beam) to a minimum value R_{min} [2]

$$R_{\min} = \frac{2}{\pi}\frac{R}{Q}\omega_0 T \qquad (1)$$

achieved when the open loop gain is set to G_{opt}

$$G_{opt} \approx \frac{Q}{\omega_0 T} \qquad (2)$$

and resulting in a closed loop bandwidth

$$\Delta\omega_{2sided} = \frac{2.6}{T} \qquad (3)$$

where ω_0 is the RF frequency (2π x 400 MHz), *R/Q* is defined by the cavity geometry (45 Ω) and *T* is the loop group delay. The klystron and circulator contribute less than 200 ns to *T*. The cable and waveguide add another 400 ns, and the LLRF is designed to contribute only 10 ns extra. This results in an effective cavity impedance of 44 kΩ, and a closed loop two-sided bandwidth of 680 kHz. The cavities are equipped with movable couplers so that the loaded Q can be varied from 20000 to 180000 [1]. In order to keep the effective impedance at 44 kΩ while the loaded Q is changed, the gain of the RF feedback must be changed according to equation (2). This keeps the 680 kHz closed loop bandwidth constant.

During the summer of 2005 a full-scale test set-up including klystron, cavity, prototype RF feedback, cable and waveguide, was tested. The RF feedback was optimized, with 1 MV accelerating voltage, for all values of the cavity loaded Q, resulting in a closed loop two-sided bandwidth of 600 kHz. The optimal open-loop gain was experimentally found to be 20 and 120 (linear) for Q values from 20000 to 180000 respectively. The bandwidth fits very well with the theory. The gain values from equation (2) are 13 and 117 respectively.

Figure 1 shows the implementation of the cavity controller. It realizes an I/Q (or cartesian) feedback. The cavity antenna signal is first demodulated to generate an (I,Q) pair of base-band signals that are processed by a pair of base-band amplifiers, then fed into an I/Q Modulator to generate the 400 MHz drive to the klystron. Notice that there is a fully analogue path from antenna to klystron, thereby keeping the electronic group delay below 10 ns (yellow blocks on figure 1). The key component is the Merrimac IQ demodulator IQG-20E-400, quoted for 1 degree, 0.2 dB accuracy and 80 MHz RF BW. As its precision can degrade due to drifts, the analogue RF

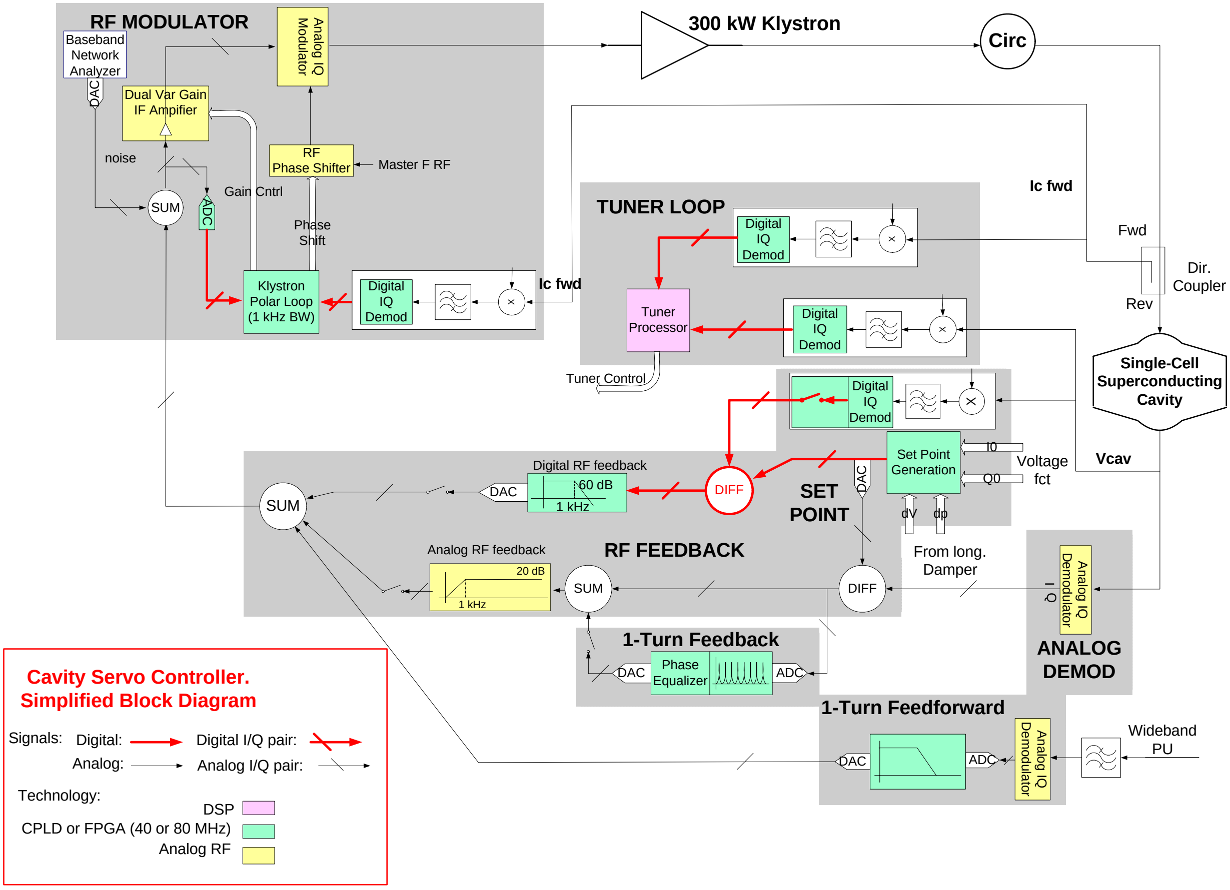

Figure 1: The Cavity Controller

feedback is paralleled by a digital feedback with an IF BW of a few kHz (around the 400 MHz RF). In the LHC the revolution frequency is 11 kHz. The analogue feedback is therefore responsible for the compensation of the transient beam loading (revolution frequency sidebands of the RF carrier) while the digital feedback takes care of the spectral component at the exact RF frequency. It is limited to the very low frequencies (1 kHz), and its gain can therefore be further increased to improve precision with no risk of instability caused by the 600 ns loop delay. This method is called Integral Compensation in classic controls theory. Such a hybrid RF feedback has already been proposed in the past [3]. The implementation of the digital part relies on classic narrowband digital IQ demodulators [4]. The 400 MHz antenna signal is first mixed with a 380MHz LO to generate a 20MHz IF. This analogue IF is then sampled with 14 bits ADC clocked at 80 MHz to generate (I,Q) pairs at the 40 MHz rate. All above clocks are phase locked. The desired cavity voltage is generated by the Set Point Module and compared to the antenna signal (see figure 1). It is the responsibility of the RF feedback to make the set-point value and the antenna signal equal. The set point need not be identical for all bunches. Sophisticated schemes are being studied to individually set the reference bunch per bunch in order to minimize the klystron current transients [5]. This architecture also provides an easy point for injecting the longitudinal damper signal, meant to damp phase and energy errors at injection [1]. With a constant 1MV in the cavity (Q=20000), a 70 kV step can be applied in quadrature, with a rise time of 1 µs (field measured in the cavity on the test stand). This measurement is relevant to the use of the RF system as a damper at injection (dipole mode). On successive injections from the SPS the batches will be spaced by 0.94 µs. It is important that the damper rise time be short enough so that it does not kick the circulating beam while damping the phase and energy error of the freshly injected batch. For larger steps (> kV) the klystron saturates and the rise time increases. While this test shows that the cavity voltage can be quickly modulated via the strong RF feedback, a large RF power peak is pulled out of the cavity during the 1 µs transient. To prevent the klystron from being over-driven, and therefore exhibiting negative differential gain characteristics, a fast limiter is inserted between the modulator output and the klystron (not shown on figure 1).

The Klystron Polar Loop

The RF feedback is well suited to compensate additive perturbations such as the beam induced voltage. Another major perturbation is the variation of the klystron gain and phase with the klystron beam voltage, nominally set at 58 kV. A one percent drift of this voltage induces 8.4 degrees phase shift at 400 MHz. The high voltage rectifiers (12 poles type) introduce noise at 50 Hz and its harmonics (dominant 600 Hz) that transform into phase noise at the RF output. On the test stand a 4 degrees peak-peak phase noise is measured at the klystron output. The RF feedback will reduce this noise (see below) but if the open loop phase rotates by 45 degrees (5% drift in the high voltage) the loops gets close to instability. So a klystron polar loop is included in the RF Modulator of figure 1. It compares the cavity input to the modulator input and corrects the gain (via a variable gain amplifier) and the phase shift (via a phase shifter acting on the LO of the IQ modulator) to keep the overall gain and phase shift constant. The expected attenuation of the phase ripple is 200 (linear) at 50 Hz and 30 at 600 Hz. The klystron polar loop is not implemented yet in the test set-up.

As mentioned above the RF feedback also provides reduction of the phase noise. Its effectiveness has been measured on the test set-up. With 2 MV and a loaded Q of 60000 (conditions during physics), the 4 degrees peak-peak ripple is reduced to 0.4 degrees as the feedback gain is raised to 40 (linear).

The Tuner Loop

The mechanical tuner is actuated via a step motor (25 Hz per step) that covers a 250 kHz range [1]. The tuning is based on the phase shift between cavity drive and antenna (figure 1). The RF signals are demodulated via a digital IQ demodulator, and then sampled at 80 MHz. A series of decimating filters are inserted to finally pilot the tuner with a time constant of the order of 1 second. This high over-sampling results in a very sensitive tuner loop whose performance has been measured on the test set-up. With a fixed klystron drive the tuner locks from end-stop to end-stop (measured with Q=60000, 180 kW CW). Once locked it can track minute fluctuations of the cavity tune (probably caused by helium pressure ripples) with the 25 Hz resolution of the step motor (measured with RF feedback on, 1 MV, Q=20000). This 25 Hz corresponds to 0.11 degrees at 400 MHz with a Q equal to 20000. The details of the implementation are presented in a companion paper [7].

BEAM CONTROL AND RF SYNCHRONIZATION

Beam Control

Each ring has a dedicated Beam Control system. Its goal is to keep the beam centred and to minimize emittance blow-up due to phase noise. It generates a Master 400 MHz signal of fixed amplitude whose phase is adjusted continuously.

First a dual Direct Digital Synthesizer (DDS) generates a 400 MHz reference for each ring. It is driven by two functions whose values are computed off-line from the magnetic field ramp and the desired radial steering (frequency program). The two rings can be ramped independently, but for physics they will ramp synchronously. For each ring, a Master 400 MHz signal is generated by a VCXO and sent on a fibre optic link to the eight cavity controllers. A Beam Control Loop DSP pilots the VCXO. It implements the classic three loops: phase, radial and synchronization. The phase loop is intended to be on at all times. The last two loops are exclusive.

The phase loop input is the phase error between the total eight cavities voltage and the beam phase, measured with a pickup. We measure the phase of each bunch at each turn, and an average is computed as input to the phase loop. On successive injections this averaging will include the freshly injected batch only after stabilization by the longitudinal damper.

The synchronization loop locks the VCXO output on the DDS output (frequency program). Its dynamics will be adjusted to track the changing synchrotron frequency during acceleration.

The transverse position of each bunch is also measured at each turn. Normally this signal is used for observation only but it can be used by the Beam Control DSP to implement a radial loop. This is foreseen for commissioning and machine development sessions only.

The processing is slow (update rate at the revolution frequency of 11 kHz) so that a DSP can be used. An interpolation filter smoothes the DSP output fed to the VCXO. The two Master 400 MHz signals are sent to the cavity controllers via fibre optic links.

RF Synchronization

The three main functions are the synchronization of the SPS to the LHC, the generation of beam synchronous signals and the fine re-phasing of the two rings before physics. As the method used for bunch into bucket transfer is identical throughout the CERN injector chain it will not be detailed.

CONCLUSION

Series production of the Tuner Loop and RF Feedback electronics is launched. They will be installed at the end of 2006. The Klystron Polar Loop is currently under development and will be validated on the test set-up in autumn 2006.

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