COMMISSIONING OF THE LINAC4 LOW LEVEL RF AND FUTURE PLANS

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Abstract

Linac4 is a new 86-m long normal-conducting linear accelerator that will provide 160 MeV H^- to the CERN PS Booster (PSB), and replace the present 50 MeV proton Linac2. The Low Level RF (LLRF) system has to control the RFQ, two choppers, three bunching cavities, twenty two accelerating cavities and one debuncher in the transfer line to the PSB. To optimize the transfer into the 1 MHz PSB bucket, the machine includes fast choppers (synchronized with the PSB RF) and a voltage modulation of the last two cavities that will provide Longitudinal Painting for optimum filling. The commissioning in the tunnel with beam has started in October 2013. So far the part consisting of the RFQ, the three bunching cavities, and the first DTL is operational. The rest of the machine will be progressively commissioned till end 2015. The paper presents the LLRF system. First results from the commissioning (with a prototype regulation system) are shown and the more sophisticated algorithms under development are presented.

PRESENTATION OF LINAC4 RF

The Linac4 machine will pulse at a 2 Hz maximum repetition rate, with a 400 µs maximum beam pulse length and 40 mA DC current. The machine operates at 352.2 MHz RF. The klystron-powered RFQ (3 MeV) is followed by a Medium Energy Beam Transfer line (MEBT), that includes three bunching cavities (pillbox geometry) powered by solid-state amplifiers (30 kW). The beam is then accelerated to 160 MeV by a succession of three Drift Tube Linacs (DTL), seven Cell-Coupled DTLs (CCDTL) and twelve PI Mode Structures (PIMS). A debunching cavity is inserted in the transfer line to the PSB. Except for the three bunchers, the RF power is generated by 1.3 MW and 2.8 MW klystrons. The 2.8 MW models are used with DTL2 and 3 (2 MW required power) and in other instances where they feed two cavities (1 MW per cavity). To make the beam density uniform in the PSB receiving bucket, longitudinal painting is implemented by modulating the accelerating field in the last two PIMS cavities, with a 40 µs period [1]. Given the 10 µs filling time of the PIMS, precise tracking of the voltage and phase will be a challenge. The target cavity voltage is a flat function for all cavities except the last two PIMS (triangular voltage modulation, constant phase) and the debuncher (constant voltage, triangular phase modulation). The LLRF consists of a **tuning system** that keeps the cavity at the tune that minimizes the required power (function of voltage, beam current and stable phase), and a **fast regulation** (Cavity Loops) that modifies the generator drive to keep the cavity field at the desired value.

TUNING SYSTEMS

The required power is minimized when the cavity is detuned such that generator current and cavity voltage are in phase. During each pulse, the cavity voltage (V) and the forward signal from a coupler at the cavity entrance (C_{fwd}) are demodulated to generate baseband I-Q pairs at 44.025 M-samples per second (MSps). They are then filtered and decimated (CIC decimators [2]) reducing the rate to 2.75 MSps. The cross-product is computed* and, after further filtering and decimation, the error data are passed to a DSP (ADSP-21369). The DSP normalizes the error signal to make tuning speed independent of the magnitude of cavity voltage and, at the end of the RF pulse, sends a correction to the motor piloting a plunger (except for the RFQ that is tuned by regulating the cooling water flow).

FIELD REGULATION

The loop delay from LLRF drive to the antenna signal (measured by the LLRF), is around 1 µs. That includes generator and circulator group delay, waveguide to cavity, and cable delay in the antenna signal path. Allowing 200 ns for processing in the LLRF, the closed-loop delay amounts to 1.2 µs. Fig.1 shows the regulation loops. We have four main sub-systems (shaded areas in Fig.1).

The RF is switched on 100 µs before injection. The **Cavity Filling Ramp** raises the cavity voltage in 50 µs.

The **Linear Quadratic Gaussian regulator** (LQG [3]) is then switched on and stabilizes the field in the remaining 50 µs until the beam batch is injected. Although we cannot measure the *present* cavity voltage, we can estimate it because the cavity response is well known and the generator drive is generated by the LLRF, and therefore known as well (except for the generator noise). The *optimal* estimator is the Kalman Predictor [3], a model of the cavity response with delay, driven by the same drive as the generator. The (delayed) cavity voltage measurements are used to update the predictor's estimates, and correct for the inexact model and the unknown noise sources. The measurement noise is caused by the imperfect demodulation. The process noise is mainly caused by the generator and beam loading.

* The cross-product is proportional to the sine of the phase angle:

$$V \times C_{fwd} = V_I\, C_{fwd,Q} - V_Q\, C_{fwd,I} = \sqrt{V_I^2 + V_Q^2}\,\sqrt{C_{fwd,I}^2 + C_{fwd,Q}^2}\,\sin\psi$$

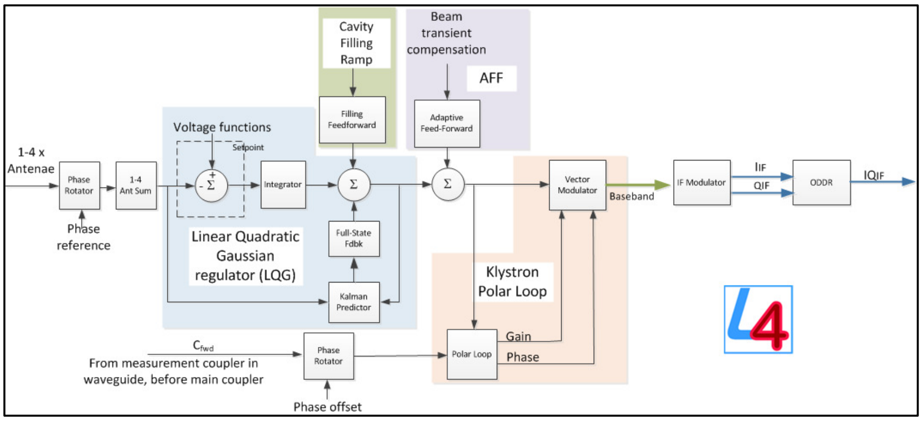

Figure 1: Field regulation loops (Cavity Loops module).

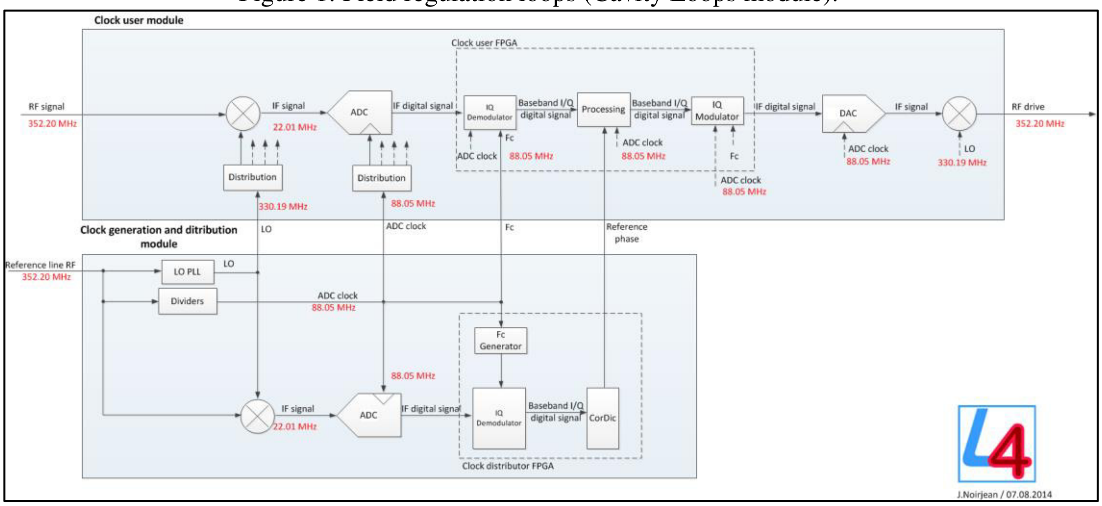

Figure 2: Demodulation, processing and modulation.

The predictor is expected to generate an accurate estimate of the inaccessible present and (recent) past cavity voltage values (1.2 µs history), that can be used to implement a full-state feedback. In order to track the reference input (desired cavity voltage set point), an integral feedback is added, using the difference between the measured cavity voltage and the set point. The integrator and full-state feedback gains are optimized using Linear Quadratic Regulator theory (LQR [3]).

To compensate for the beam loading transient at the head of the beam batch (hopefully fairly reproducible from pulse to pulse) an **Adaptive Feed-Forward** (AFF) correction is added to the generator drive (Fig. 1). It is updated before every pulse, from measurements on past pulses.

Klystrons transform the ripples present on their High Voltage (HV) supply into RF magnitude and phase noise. Similarly, their gain and phase shift are drifting, in the likely case of a drift of the DC parameters. This can cause much problem with the LQG feedback: as the open loop phase rotates, the phase margin decreases and the loop can go unstable. The effect of DC fluctuations on the RF parameters is multiplicative noise (modulation of gain and phase), and it is best compensated by a Polar Feedback acting on the overall gain and phase shift (**Klystron Polar Loop**, Fig.1). The forward current measured with a coupler at the cavity input is compared to the klystron drive, generating a gain and phase shift data. After subtraction of set values, the error signals are integrated and control a vector modulator. Such a Klystron Polar Loop is in operation in the LHC [4].

When we drive two cavities with a single klystron, the regulation loops receive the antenna signals from both cavities. A slow mechanical phase shifter is inserted in one of the two waveguides and will be controlled to adjust the relative phase. The common drive will be regulated by the fast loops (Fig. 1). Most fast perturbations being common to both cavities (klystron noise and transient beam loading), the overall performances should not be degraded much. Mechanical vibrations could however be problematic.

HARDWARE IMPLEMENTATION

We use the classic I-Q Digital demodulation scheme first proposed in 1995 [5]; refer to Fig. 2. The RF signal (antenna, coupler or reference line) at f_{RF} (352.2 MHz) is first down-mixed to an IF at 1/16 f_{RF} (22.01 MHz) by mixing with an LO at 15/16 f_{RF} (330.2 MHz). The analog IF signal is sampled by an ADC whose clock runs at ¼ f_{RF} (88.05 MHz). After time de-multiplexing and sign inversion, a stream of baseband (I,Q) pairs is generated at 44.025 MSps [5]. The stability and precision of the

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harmonically related clocks (LO and ADC clock) are critical for the overall performances. Linac4 has a coaxial reference line, powered with a 100 W signal, and running in the tunnel, with -30 dB coupler adjacent to each cavity. The signal from these couplers are routed to the LLRF on cables (~100 m long) running together with the corresponding antenna signals. This layout is intended to minimize phase variations caused by temperature changes[†]. On the surface, the reference line signal is used to generate the demodulations clocks (LO and ADC clock). This is realized in the Clock Distribution module (lower block on Fig. 2). A reference phase is measured from the demodulation of the reference signal. The reference phase is subtracted from the antenna demodulation, so that the scheme is not sensitive to drift in the generation of the LO and ADC clocks. After processing in baseband (field regulation loops shown in Fig. 1, implemented in an FPGA clocked at 88.05 MHz), the output is mixed to the 22.01 MHz IF frequency, converted to analog and mixed up to generate a 352.2 MHz generator drive. The same LO is used for demodulation and modulation so that the open-loop transfer function is not sensitive to LO phase drift.

RESULTS FROM FIRST COMMISSIONING

So far we have commissioned the RFQ, the three bunching cavities and the first DTL. The tuning system installed is the final version described above. The regulation loop is a prototype version, including only the Cavity Filling facility and a simple Proportional-Integral (PI) feedback. The closed-loop response time is around 3 µs. Fig. 3 shows the antenna signal of the DTL1, without beam, with 10 MV demanded voltage.

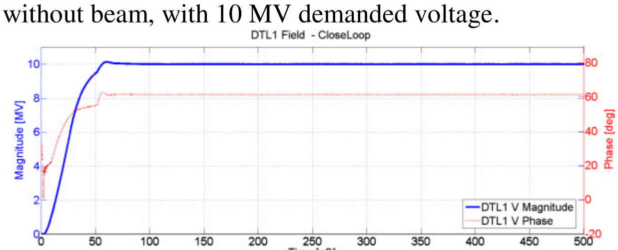

Figure 3: Magnitude and phase of DTL1 field. No beam.

The Cavity Filling ramp is active for the first 50 µs. At that time the RF feedback is closed resulting in a small visible transient. The beam is expected after 100 µs. Fig. 4 shows the field stability during the beam window (but without beam). With regulation (Closed Loop), the ripple is 6 kV pk-pk (0.06%) and 0.05 deg pk-pk. Without regulation (Open Loop) we measure 60 kV amplitude and 0.2 deg phase drifts. The dominant 10 kHz ripple was traced to the switching frequency of the HV power converters. While the simple PI feedback fully compensates for the slow drifts, it reduces the 10 kHz phase ripple by a factor of 5 only (linear). The future Klystron Polar Loop will not have much effect at 10 kHz. Two improvements can be considered: either stop the switching of the High Voltage supply during the beam pulse or synchronize it with the repetition rate so that the AFF can reduce its effect.

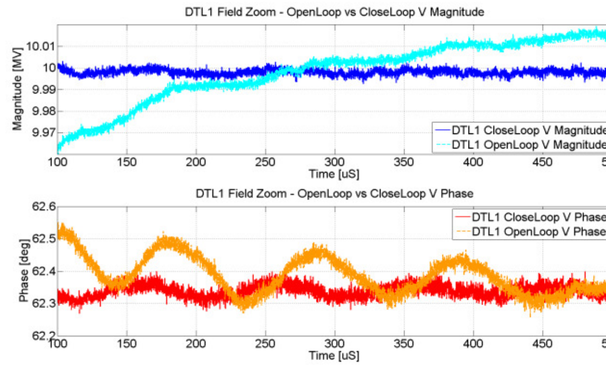

Figure 4: Top: stability of the field magnitude. Bottom: field phase. With regulation (Closed Loop) and without (Open Loop). No beam.

Also of interest is the phase reproducibility from pulse to pulse. From a histogram of the DTL1 phase (averaged over the 100-500 µs window), taken over 859 consecutive cycles, a standard deviation of 0.03 degree has been measured. This measurement can be trusted as it was not using any of the LLRF electronics (out-of-loop measurement).

CONCLUSIONS

A prototype LLRF system has been installed on the first five Linac4 cavities. The results are very promising in term of voltage noise and stability. The final system is under development and will be commissioned with the installation of more cavities in the coming months.

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[†] To guarantee a similar thermal behaviour, the antenna and reference signal cables came from the same cable roll, for a given cavity.