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# DIGITAL LOW-LEVEL RF SYSTEM FOR THE CERN Linac3 ACCELERATOR

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*Abstract*

A major consolidation of the aging RF system of the CERN Linac3, the ion source for the whole CERN accelerator chain, started during the Long Shutdown II. The main changes were an upgrade of the analogue Low-Level RF system (LLRF) and replacement of the 350 kW tube amplifiers by a solid-state equivalent. The state-of-the-art digital LLRF system enabled new sophisticated features in field manipulations, significantly increased the operational flexibility and improved operational reliability and availability. The paper presents the new architecture, a low noise master clock generator, digital signal processing with direct sampling of the RF signals, pulse parameter measurement and cavity resonance control.

## LINAC3 RF SYSTEM

Linac3, commissioned in 1994 is the ion source for the whole CERN accelerator chain. Seven different RF structures accelerate the beam: RFQ, Buncher, Cavity 1, Cavity 2, Cavity 3, Ramping and Debunching cavities. The Linac operates at a fundamental frequency of 101.28 MHz, with cavities 2 and 3 run at the second harmonic 202.56 MHz. Field in the accelerating structures was controlled by an analogue LLRF system, based on the Linac2 design, which became obsolete. The system provided no operational flexibility, it was very demanding to set up, or sensitive to environmental aspects. Spare parts for the aging system became difficult to obtain and maintain. Nevertheless, the analogue system was very robust. It is worth to mention that some of the LLRF boards removed during the upgrade campaign in the summer 2020 were marked ”OK, 26.10.1977” and still operating properly.

The LLRF system for the Ramping cavity and the Debuncher was replaced in 2003 by a VME-based digital LLRF installed in a temporary movable rack [1, 2]. The main motivation was needed energy ramping capability by phase sweeping the field in these structures. The 350 kW tube power amplifiers for RFQ and Cavity 1 also became difficult to maintain and operate, so a consolidation project to replace the obsolete LLRF and power amplifiers was launched. The Linac3 uses its own, free running frequency reference and it is not frequency locked to the downstream LEIR accelerator [3].

## FULLY DIGITAL LOW LEVEL RF SYSTEM

A fully digital LLRF system allows implementation of very sophisticated control algorithms and digital signal processing. With the measurement and observation capabilities, it provides a lot of operational flexibility which is needed in machines serving multiple beam users and dynamically changing the output beam parameters. An example of a newly added capacity is the active control of the momentum spread based on the measurements of beam injected into LEIR [4].

When the project started in 2017, it was clear the new LLRF system will be fully digital, however it was not yet clear what platform should be used. The VME LLRF technology was mature at CERN, with all resources available. The uTCA LLRF platform was only emerging at CERN and it was not guaranteed to be available within the expected project timeline. A conservative approach was adopted. The new, Linac3 digital LLRF was designed on VME platform.

### *RF Pulse Stability and Other Requirements*

Due to the beam dynamics requirements in the RFQ and the IH structures (KONUS [5]), highly accurate physical parameters of the accelerating field are not a constraint, however high stability and reproducibility of the RF fields (phase and amplitude) are a requirement [6]. This high stability and reproducibility requirement is necessary over all time-scales. The stability required in the original design report [7] is 0.3° in phase and 0.3% in amplitude. The design report did not take into account how stable the future performance requirements might be for LEIR and LHC, these are listed in [6]. The updated performance is stricter for Cavity 1 and Cavity 2 amplitudes, however more relaxed on other parameters. In terms of other requirements, the new system must provide a pulse-by-pulse capability of RF phase and amplitude control. In terms of diagnostics the system should deliver a measurement of pulse RF parameters - one value per pulse, but also an on demand full rate acquisition of the executed RF pulse for diagnostics and accelerator physics purposes.

### *Direct RF Sampling and Quadrature Demodulation*

The Linac3 operating frequencies, 101.28 MHz and the second harmonic 202.56 MHz, are compatible with full power bandwidth of modern, high speed analogue to digital converters. The new LLRF system was therefore designed to use direct RF sampling. The regulation bandwidth of the feedback loops is defined by the cavity bandwidth (tens of kHz), and it is negligible with respect to the operating RF frequency. An undersampling can also be employed to our advantage.

A direct quadrature demodulation can easily be obtained if the sampling frequency and the signal frequencies are locked in a defined ratio. It was desirable to use only one sampling

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frequency, even if the RF structures operate at two different harmonics. When sampling-to-input frequency ratio is defined by Equation 1 we obtain exactly four samples per input signal period; the commonly used 90° demodulation technique.

$$f_{SAMPLE} = \frac{4f_{RF}}{4k+1} \tag{1}$$

The sampling frequency was therefore selected to fulfill the 90° operation for the higher frequency (202.56 MHz) structures, but for the fundamental it means 45° sampling intervals. Typically, a very low total feedback loop delay is critical for operation in normal conducting linacs. Therefore a maximum sampling and signal processing frequency supported by the used ADCs (Analog Devices LTC2185), was chosen with k = 2, $f_{SAMPLE} = 4/9 \quad 202.56\,\text{MHz} = 90.02\overline{6}$ MHz. We have also implemented a quadrature demodulator, which outputs one I-Q pair every half period of the sampled signal to reduce the demodulator pipeline delay.

A vector rotation matrix was used to derive the demodulation formula for arbitrary sampling increments. If n is the number of equally spaced samples acquired per one period of the input signal, and the input vector is $[I_{IN}, Q_{IN}]$, then the output vector at every phase increment will be:

$$\begin{bmatrix} I_n \\ Q_n \end{bmatrix} = \begin{bmatrix} \cos(\phi_n) - \sin(\phi_n) \\ \sin(\phi_n) \cos(\phi_n) \end{bmatrix} \begin{bmatrix} I_{IN} \\ Q_{IN} \end{bmatrix} \tag{2}$$

An ideal ADC will output a stream of consecutive samples, x[n], spaced by phase increments $\phi_n$.

$$x[n] = [I(\phi_0), I(\phi_1), I(\phi_2), ...I(\phi_n), ...] \tag{3}$$

In case of 45° intervals we obtain the following values. A real world ADC will also add a DC offset to the data.

$$\begin{aligned} x[n] = [&I_{IN}, \sqrt{2}I_{IN} + \sqrt{2}Q_{IN}, Q_{IN}, -\sqrt{2}I_{IN} + \sqrt{2}Q_{IN}, \\ &-I_{IN}, -\sqrt{2}I_{IN} - \sqrt{2}Q_{IN}, -Q_{IN}, +\sqrt{2}I_{IN} - \sqrt{2}Q_{IN}] \\ &+DCOffset \end{aligned} \tag{4}$$

The "fast" demodulator can reconstruct the initial values of $I_{IN}$, $Q_{IN}$ only from a fraction of the samples and does not need to wait the full signal period. In phase 1, using the first four samples:

$$\begin{aligned} I_{DEMOD} &= x_0 + x_1 + 0 \cdot x_2 - x_3 = \\ &= I_{IN} \cdot (1+\sqrt{2}) + DCOffset \\ Q_{DEMOD} &= 0 \cdot x_0 + x_1 + x_2 + x_3 = \\ &= Q_{IN} \cdot (1+\sqrt{2}) + 3 \cdot DCOffset \end{aligned} \tag{5}$$

And in phase 2, using the next four samples:

$$\begin{aligned} I_{DEMODphase2} &= -x_4 - x_5 + 0 \cdot x_6 + x_7 \\ &= I_{IN} \cdot (1+\sqrt{2}) - DCOffset \\ Q_{DEMODphase2} &= 0 \cdot x_4 - x_5 - x_6 - x_7 \\ &= Q_{IN} \cdot (1+\sqrt{2}) - 3 \cdot DCOffset \end{aligned} \tag{6}$$

It can be seen that the fast demodulator does not treat the ADC offset equally for both quadrature channels, and the sign is inverted for the phase 1 and 2. As the ADC offset is assumed constant at the time scale of the demodulation period, the problem can be fixed by calculating the ADC offset separately and subtracting it from the ADC stream before it reaches the demodulation stage:

$$DCoffset = \frac{1}{8}(x_{-8}+x_{-7}+x_{-6}+x_{-5}+x_{-4}+x_{-3}+x_{-2}+x_{-1}) \tag{7}$$

### *Master Clock Generator*

In order to profit from the direct RF sampling, the sampling clock must have a very low jitter [8]. The new master clock generator uses the Axtal AXIOM75ULN ultra low noise, oven controlled oscillators (OCXO) to produce the 101.28 MHz Linac RF frequency and the $90.02\overline{6}$ MHz sampling frequency [9]. These are locked to an AXIOM145ULN, 10 MHz ultra low noise and high stability reference oscillator [10]. The two frequencies must be locked to the 10 MHz reference, but at the same time, their mutual ratio $f_{sample}/f_{RF}$ must be exactly 8/9 in order to achieve synchronous sampling and quadrature demodulation as explained in the previous section. At the same time, the phase locked loop (PLL) must not degrade the noise performance of any of the oscillators.

In order to achieve the exact 8/9 frequency ratio, two direct digital synthesizers (DDS) with carefully chosen frequency tuning words were used as a rational frequency dividers. The RF and sampling frequencies are divided down to 10 MHz where they are compared and locked to the 10 MHz reference. However, the quantized and integer nature of DDS causes the absolute value of the output frequency to be slightly off with respect to the ideal 101 280 000.000 Hz, namely 101 280 000.685 Hz. It could be trimmed to the exact value by lowering the frequency of the 10 MHz reference (by about 7 parts per billion), but as the Linac3 is a free running machine, it does not represent a problem if left uncorrected. Important is to have the two frequencies perfectly locked in an exact ratio (here 8/9), which was achieved.

The phase noise performance of each oscillator was measured and the PLL bandwidths were carefully and individually adjusted to obtain the best possible phase noise values for the complete system. Integrated jitter of the sampling clock, measured in the band of 1 Hz to 3 MHz is approximately 3.2 ps. Very narrow PLL bandwidths and rather limited tune range of the high performance OCXOs require a sophisticated locking procedure controlled by a microcontroller. The master clock generator also serves as clock distributor and a reference line for the Linac3.

### *RF Feedbacks and Generation of Functions*

One of the changes introduced by the new digital LLRF system was the way the RF pulse parameters are defined in the machine. The former analogue system used so called knobs, which were directly outputting an analogue voltage

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to control phase shifters and attenuators in the feedback. The translation of the knob value to a phase, or amplitude was not linear and setpoints and other parameters were defined in arbitrary units. The new digital LLRF system is designed to use calibrated physical units (degrees, kiloVolts etc.) to control the setpoints or loop gain values what is appreciated by the Accelerator Beam Physics group operating Linac3.

As beam loading in Linac3 is negligible, a simple proportional-integral regulation loop is sufficient to control the field in the accelerating structures. The feedback is implemented entirely in Cartesian coordinates. Setpoint and loop gain values during the RF pulse are dynamically generated by an on-chip function generator. A function consisting of up to 16 piece wise linear segments for each parameter provides great flexibility in RF pulse shaping. The currently adopted control strategy is to start the RF pulse in an open loop mode (by setting both gains to zero) at a ramp rate compatible with the cavity filling time and gradually increase the feedback gain. To prevent accumulation of a large error during the cavity filling time, the integral gain is ramped from an intermediate value to the final value only when the pulse reaches the plateau and the field precision is needed. Controlled cavity filling and loop gain scheduling minimizes the transients (both in amplitude and time) optimally using the power amplifiers. This will become even more important for the 350 kW solid state amplifiers foreseen for the RFQ and Cavity 1 structures.

### *RF Pulse Parameter Measurement*

A state of the art digital LLRF system offers the possibility to acquire a time series of important signals in the feedback controller and use them for monitoring or real time analysis. An adaptive algorithm was implemented in the LLRF controller FPGA to measure numerous pulse parameters like amplitude/power, peak amplitude/power, phase, phase modulation, or deviation from setpoint just to name few.

Pulse analysis in the FPGA also allowed to implement the RF breakdown interlock. The system monitors the reflected power waveform. In case an activity is detected at the portion of the RF pulse where it is not expected, the breakdown interlock records the event. A single RF breakdown is not considered dangerous for the machine, however more frequent breakdowns indicate a degradation or emerging problem. Limits for 10-minute and 24-hour are implemented.

### *Cavity Resonance Control*

Cavity resonance control in machines which are playing dynamically changing cycles might be a challenging problem. In case of CERN's Linac3, the resonant frequency is controlled by piston tuners (one or two per structure). In order to reduce the number of tuner movements, it is not desirable to move the tuners after each RF pulse, or cycle. Instead the pulse measurement subsystem described in the previous section provides an information about the overall level of reflected power within defined time windows and the tuning system slowly follows to keep the reflected power within acceptable values for the solid state amplifiers.

Normal conducting linacs which do not have sophisticated control systems are typically difficult to start from cold, e.g. after a planned shutdown, or simply a longer duration RF fault. The new Linac3 digital LLRF system is capable to measure the cavity tune state and calculate the exact resonant frequency using controlled, low power RF pulsing and a cavity model. The tuning system then prepares the cavity for pulsing at cold, significantly reducing the cavity start up time.

## AUTOMATION OF OPERATION

The new, consolidated Linac3 RF system is fully automated, greatly facilitating its operation. A sophisticated sequencer goes through four fundamental states: OFF, Standby, Ready for RF and ON. Each state has defined actions to transit to the state, actions when in the state, conditions to transit to the state and conditions to stay in the state. The sequencer continuously checks hundreds of conditions and when transiting states it executes defined actions in a precisely defined order. Such a sequencer allowed only two control buttons be exposed to the operation team "RF ON" and "RF OFF" (plus cavity voltage and phase program of course). Our approach simplifies the Linac operation and guarantees that the RF system easily starts and recovers after any fault, intervention, or a technical stop. The faults are recorded, logged and communicated to the operators in a human readable form reducing number of calls to RF specialists.

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## CONCLUSION

CERN's Linac3 RF system underwent a major renovation and consolidation during the Long Shutdown II (2018-2020). The obsolete analogue LLRF system of Bunching, Ramping and Debunching cavities was replaced by a state of the art, fully digital one, providing significantly improved operational flexibility, comfort and robustness, as well as improved precision and stability.

The project will continue by the second phase during the year-end-technical-stop of 2022-2023. It is foreseen to replace the 350 kW tube amplifiers of RFQ and Cavity 1 by a solid state equivalent. The new amplifiers will be accompanied by a new digital LLRF and modern PLC controls.

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