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# Commissioning of CW digital low-level RF for 50 MHz cyclotrons at PSI

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## Abstract

In the long-term project frame of the HIPA (High Intensity Proton Accelerator) RF systems, the replacement of analogue LLRF from the 1980 with a digital system is ongoing. This new digital LLRF system will be used the first time in HIPA for beam operation with a new resonator in autumn 2023. The tuning system, with hydraulic aggregate and valve actor for the plunger, is working in closed loop. Regulated operation is keeping the resonator on resonance under all changing environmental conditions. The tuning system controls two independent plungers for the same resonator, which are used in different operation schemes. Phase detection between the accelerating voltage and RF input Power acts as the input to the tuning loop. Phase error Offset, fixed position control, independent plunger tuning and position offset offers the variety of operation scenarios. The RF system is working with amplitude and phase regulation to maintain the precision and performance of the accelerating field. For the start-up sequence and also for the operation of the system there are various exception handling procedures implemented. This poster shows the first test results at the Injector-II / Resonator-2 system.

## Operation Scenario

During the RF-startup into a detuned resonator the forward power is regulated to fill the resonator with RF and to introduce an accelerating voltage over the accelerating gap. After reaching an acceptable level of reflected power with RF-pulsing and continuous automatic tuning, the forward power is increased until the nominal voltage is reached on the pickup measurement. At this moment the feedback control loop for the amplitude regulation is changing seamless from resonator input coupler to pick up signal for the input signal to the closed amplitude regulation loop.
The closed loop phase and amplitude regulation (Figure 1) with resonator pickup signal is used in beam operation to maintain the stability of the accelerating voltage and phase. The absolute phase noise (Figure 2) and amplitude noise (Figure 3) level from 10 Hz – 10 kHz (resonator bw = ~5 kHz) have been measured and compared between open- and closed loop operation. The 50 MHz Master Oscillator signal source for the LLRF system has been measured and displayed as reference.

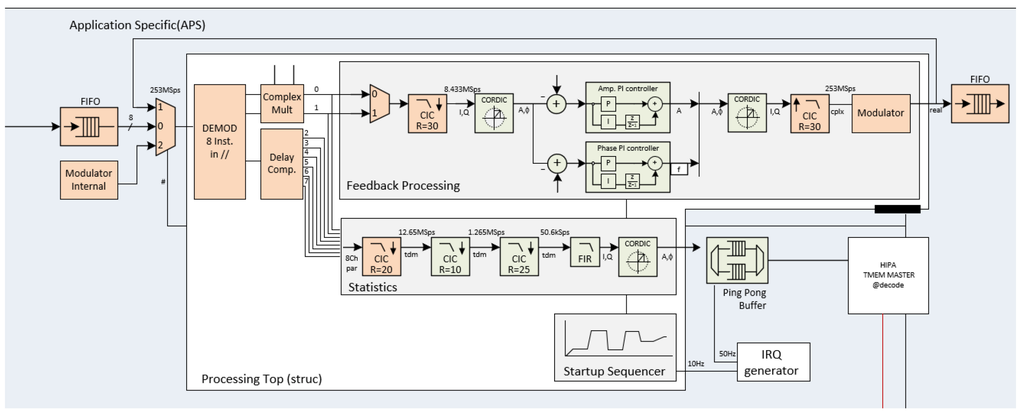


Figure 1: Architecture of the signal processing in the FPGA for the fast feedback controllers and the DAQ

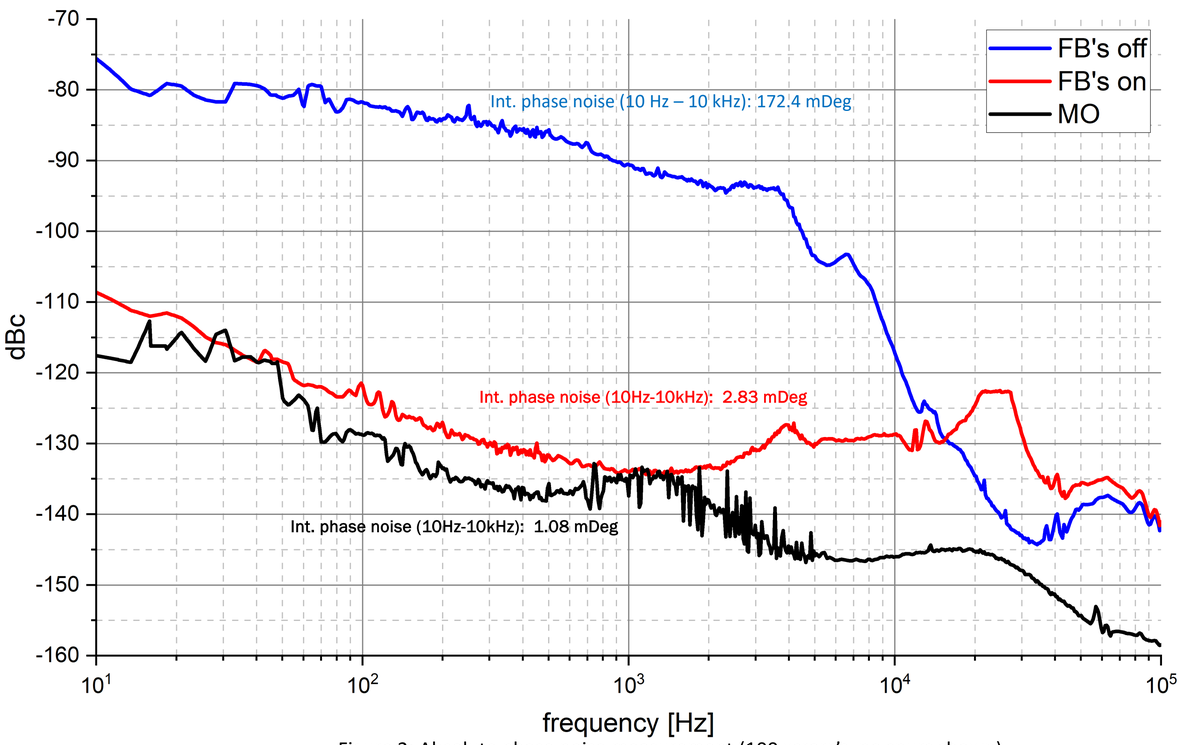


Figure 2: Absolute phase noise measurement (100 xcrorr's, no spurs shown)

## Signal processing

The ADC converter is working on 253 Msps rate. The amplitude and phase regulation is working after down sampling of factor 30 at a signal rate of 8.43 Msps. For the tuning processing and the startup electronic the data is down sampled in 3 stages from 253 Msps down to 50.6 ksps. A real time software furthermore reduces the data stream down to 25 sps for cavity resonance tuning and 10 sps for DAQ.
The output of the amplitude and phase PI controller actuators are up sampled by factor 30 and the DAC data rate is again 253 Msps for the LLRF DAC output.

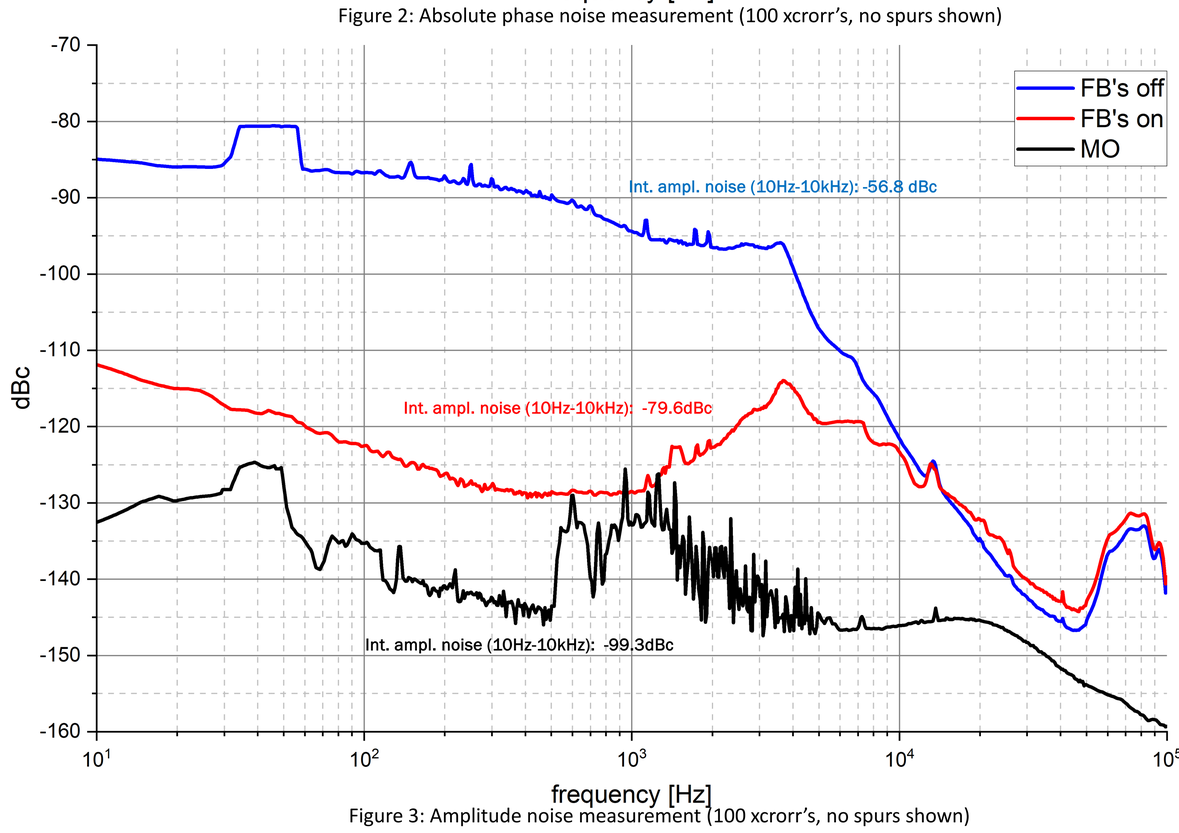


Figure 3: Amplitude noise measurement (100 xcrorr's, no spurs shown)

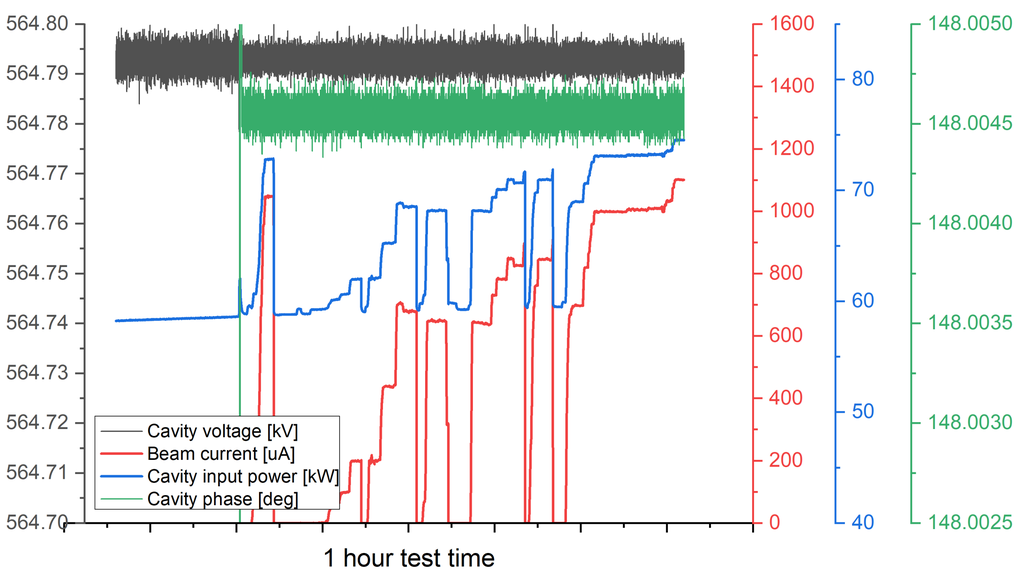


Figure 4: Initial beam tests (LLRF DAQ data points @ 10 sps, avg. of 50.6 ksps data stream)

### Beam operation INJ-II with four resonators

During the recent testing phase, it was the first time possible to operate INJ-II cyclotron with again all four resonator's; the Resonator-1,-3,-4 with their existing analog LLRF and the Resonantor-2 with the new digital LLRF. The beam current could be increased gradually up to more than 1000 µA. The additional acceleration voltage lead to less turns required for the same energy level of 72 MeV at the output of the INJ-II cyclotron. The reduction of turns results in more distance between the beam orbits and reduce the space charge effects between the proton packets during the acceleration inside the cyclotron.

## Conclusion / Outlook

The new digital LLRF system was tested successfully with the new tetrode based 150 kW high-power RF amplifier chain using the already installed new Resonator-2 with two contactless plunger units for resonance tuning . Together with the three other existing cavities with their analog LLRF's, a four cavity operation with a beam current up to 1000 µA was demonstrated.

The goal and next step is to bring all four resonators to the new type digital LLRF system in automated operation. All the manual steps that were still required actual to operate resonator 2 LLRF system, need to be updated for the RF on/off sequences to allow automated remote control operation from the control room.

Revision 1.2 , Matthias Stoll matthias.stoll@psi.ch 12.10.2023, presented at LLRF Workshop 2023 (LLRF2023)