EVALUATION OF THE ANALOG AND DIGITAL RECEIVER SECTION IN THE LIBERA LLRF SYSTEM

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Abstract

In a LLRF feedback system the disturbances added in the receiver section are one of the major contributors to the amplitude and phase fluctuations of the fields in the RF cavities that are being controlled. It is therefore crucial to thoroughly evaluate the receiver section of the control system. Measurement results of parameters like amplitude noise, phase noise, coupling between RF channels, linearity and temperature dependent drifts of the receiver are presented. We also discuss what the influences of some of the measured parameters on phase and amplitude stability of the RF fields are. Finally, we summarize the results of the measurements and their impact on the future development of the Libera LLRF system.

INTRODUCTION

Libera LLRF is an industrial digital RF stabilization system developed for applications demanding a high level of RF field stabilization. The system's performance meets 4th generation light sources' requirements. The flexible architecture and high performance RF design enable RF field stabilization from few MHz up to 12 GHz. Moreover the system architecture supports different RF system topologies from single-transmitter-single-cavity to up to 32 cavities per transmitter. The Libera LLRF supports both pulsed and CW operation modes.

A powerful low latency FPGA-based processing scheme together with a computing module enable the implementation of sophisticated control and diagnostics algorithms. The basic version of the software already includes RF system diagnostics and automatic vector-sum calibration, which are implemented in the frame of the Nyquist stability analysis algorithm. A robust interlock system is also implemented for machine protection.

The first part of the paper summarizes the measurements of the receiver. The second part describes the results demonstrated with Libera LLRF on the field at Daresbury laboratory, at high power, on a test set-up of the EMMA FFAG RF system. During the tests the system was controlling a peak power of 10 kW. The Libera LLRF provided an RMS amplitude and phase stabilization of 0.005 % and 0.008 deg respectively.

A brief description is also given of preliminary tests of Libera LLRF system on the ILC 3.9 GHz SC crab cavity set-up.

Figure 1: Libera LLRF, an industrial 19" 2U rack-mount chassis digital RF stabilization system, controlling the 1.3 GHz EMMA test set-up with 10 kW.

RECEIVER MEASUREMENTS

The LLRF receiver, other than the master oscillator (global phase reference), presents the ultimate limitation in terms of uncorrelated noise performance, when all the other perturbation sources are reduced and feedback successfully is correcting for the perturbations added in the transmitter section. In what follows some typical measurements that characterize the performance of the receiver are presented.

Residual Amplitude and Phase Noise

Residual phase noise measurements were carried out using the measurement technique presented in [1]. The main contributors are the amplifiers in the Local Oscillator (LO) distribution circuit. Figure 2 shows the measured spectrum and integrated cumulative phase and amplitude uncertainty.
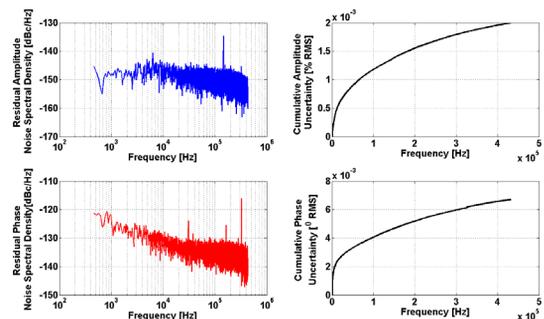
Figure 2: Measured amplitude and phase uncertainty added by the receiver.

The integration of the noise spectral density is performed in the range between 500 Hz and 500 kHz. The amplitude noise is dominated by the ADC noise floor (-147dBc/Hz).

DEMONSTRATION OF LIBERA LLRF AT DARESBURY LABORATORY

1.3 GHz Test Set-Up Description

Libera LLRF was tested in the accelerator environment on a set-up of two NC EMMA FFAG cavities at 1.3 GHz.

The test set-up consisted of an AM87 60 dB pre-amplifier, a 30 kW CPI IOT, a Q-par Angus 3dB hybrid waveguide distribution section, a phase shifter and two 1.3 GHz Niowave copper cavities. After the IOT and in front of the cavities, directional couplers were installed for power monitoring purposes.

A circulator was installed between the IOT and the hybrid. For these measurements a high performance Master Oscillator (MO) based on Wenzel and Vectron components was used as reference.

Figure 3: EMMA FFAG test setup. In the background the two copper cavities, the waveguide hybrid distribution system in the middle, the IOT and the HVPS on the right, the Libera LLRF with the MO reference on the left are visible.

RF System Diagnostics

The Libera LLRF unit updated with calibration coefficients for the cables was connected to the EMMA RF system. The declared input signals were: a probe signal for each cavity, two forward and two reflected signals. When the circulator was mounted, additional forward and reflected signals were added for diagnostic purposes.

When the system was turned on, the Libera LLRF performed a low power RF system diagnostics for full characterization of the RF system and cavity tuning purposes.
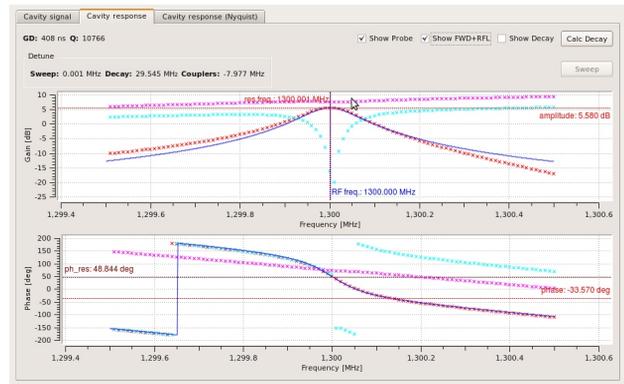
Figure 4: Results of the first EMMA cavity RF system diagnostics. The forward, reflected and transmission responses are characterized versus frequency. The Libera LLRF provides the cavity detuning and the QL factor available either from the sweep analysis or the decay analysis.

The IOT linearity was also characterized by means of a power sweep that can be used for calibration or transmitter linearization purposes.
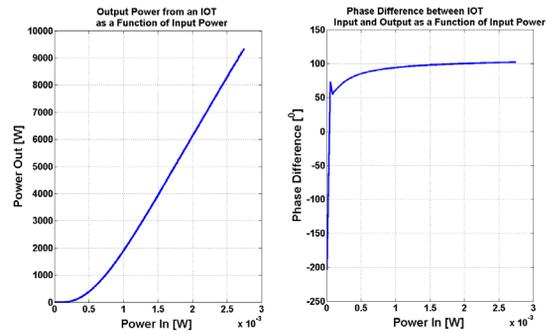
Figure 5: Measured nonlinear effects of the IOT by using the Libera LLRF system. In order to maximize the performance of the control loop the high power amplifier needs to be linearised.

After that the RF system response was automatically processed by means of the Nyquist stability algorithm in order to define a stable vector sum calibration. The resulting stability margins are displayed to the operator for confirmation.

The loop was closed with the Libera LLRF system configured for 1.6 ms long RF pulses with a repetition rate of 10 Hz. The IOT output power was progressively raised up to 10 kW, corresponding to a vector sum of 300 kV across the two cavities.
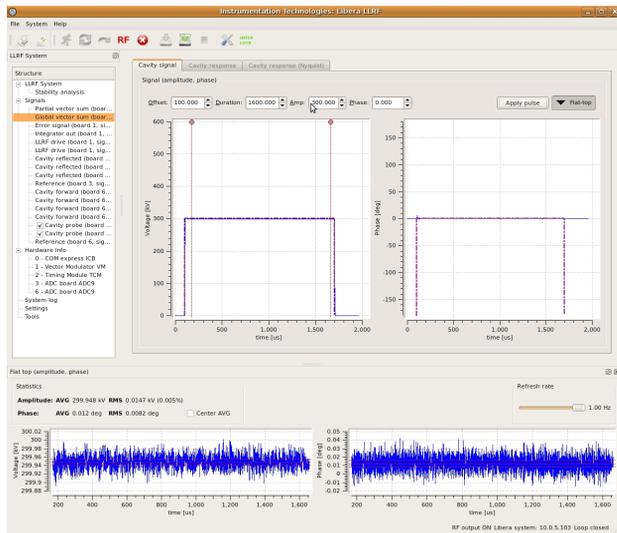
Figure 6: Libera LLRF controlling 300 kV (10 kW)

In Table 1 the results are summarized in terms of RMS amplitude and phase uncertainty measured at the IOT peak output power of 10 kW.

Table 1: RMS Vector Sum Uncertainty at 300 kV (10 kW peak power) Vver 1 MHz Bandwidth

Amplitude dA/A	0.005 %
Phase	0.008 deg

The Libera LLRF system triggers an interlock when one of the signals exceeds a predefined threshold.

During the test, at 3 kW, the loop was intentionally driven towards instability in order to test the interlock system.
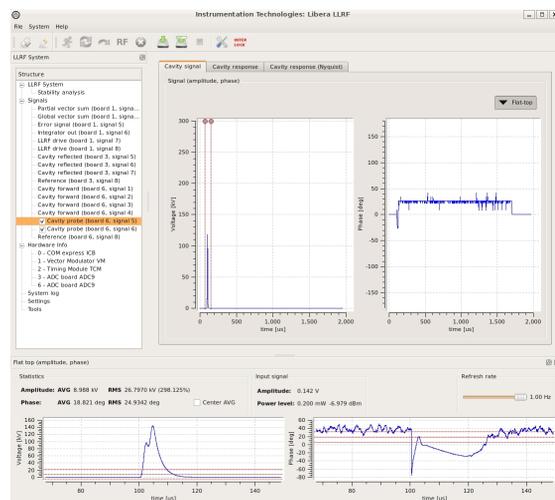
Figure 7: The interlock was triggered by Libera LLRF during high power tests at 3 kW. The loop was intentionally destabilized and the cavity field exceeded the interlock threshold of 120 kV. The interlock system reaction time is the order of few us.

MEASUREMENTS ON THE 3.9 GHZ SRF CRAB CAVITY

Several tests were performed on the vertical test-stand that includes two one-cell 3.9 GHz cavities cooled down to 4K. With minor and easy modifications of the hardware and software we reconfigured the same system that was being used at 1.3 GHz, to operate at 3.9 GHz.

Figure 8 shows the regulated amplitude and phase response at the vector-sum. The optimum performance was achieved with a loop gain of ~80. The strong correlation between the amplitude and phase response is caused by the fact that the resonance frequency of the two cavities was affected by microphonics. The fluctuation in resonance frequency and the detuning can be deduced by the slope of the phase when the RF switches off (see phase plot on Fig. 8). The standard deviation of the regulated amplitude and phase, at the vector sum, over 1MHz of bandwidth equals 0.07 % and 0.06 °. The major contributor to uncertainty is microphonics.
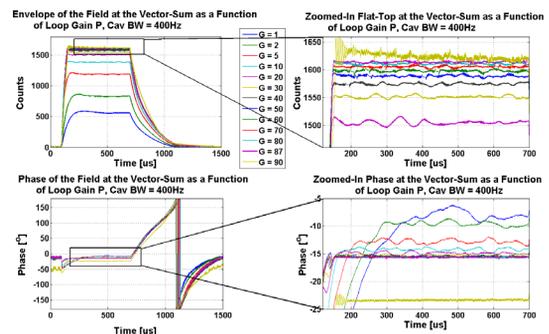
Figure 8: Amplitude and phase as a function of proportional loop gain. The zoomed-in region shows a strong correlation between amplitude and phase disturbances.

CONCLUSIONS

The results of a field demonstration of Libera LLRF have been presented showing high performance RF field stabilization capabilities. The flexible architecture integrated by the software makes Libera LLRF an valuable RF stabilization and diagnostic tool for robust and algorithmically controlled RF system operation.

ACKNOWLEDGEMENTS

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REFERENCES

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