Phase Noise Cancellation Impact on IQ Measurement Accuracy in LLRF Systems with Frequency Downconversion

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ABSTRACT

High performance synchrotron light sources like Soleil-II or Lunex-5 require LLRF systems with high IQ accuracy (rms): typically 0.01° in phase and 10^{-4} relative error in amplitude. This accuracy is ultimately limited by the phase noise of the reference and RF signals. In most LLRF systems, frequency downconversion to an IF signal of 10 MHz is used before the digital IQ-demodulation. It can be shown by simulation and experimental measurements that the phase noise information is largely lost when the local signal is produced by mixing the reference RF signal with a spectrally ultrapure 10-MHz signal. In that usual case, the RF and local signals have almost the same phase noise, which will cancel out in the downconversion process.

INTRODUCTION

Even though the final IQ accuracy of a LLRF system will depend on the nature and amplitude of the disturbances, it is desirable to seek the highest accuracy on IQ measurement, as well as the shortest latency as a prerequisite. Among the parameters that determine the accuracy of the digital IQ demodulation, the phase noise of signals (reference, RF and clocks) certainly brings the ultimate limitation. Additive phase noise effects on LLRF systems with frequency conversion have been analyzed by Rutkowski and Czuba [1]. However, to the knowledge of the authors, the cancellation of phase noise in downconversion has not been discussed, at least in the LLRF community. This effect is presented in simulation and experimental measurements in this communication.

METHODS

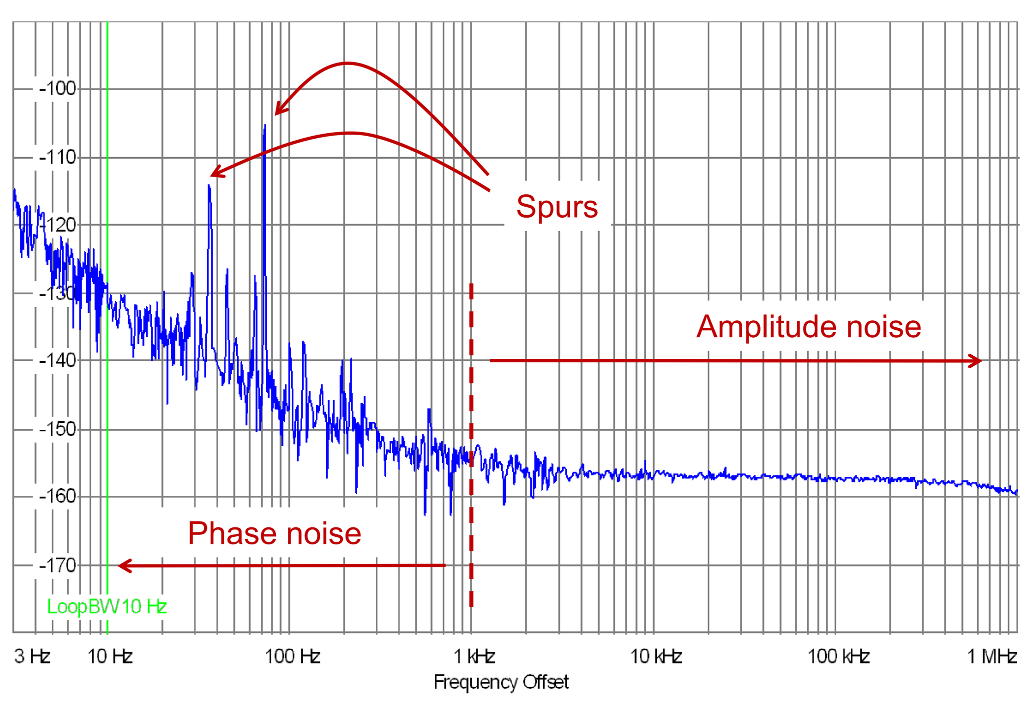
A. Definitions and formulae

$$s(t) = A\sin\left(2\pi f_c t + \varphi_j(t)\right) = A\sin\left(2\pi f_c\left(t + \frac{\varphi_j(t)}{2\pi f_c}\right)\right)$$

$$\tau_j(t) = \frac{\varphi_j(t)}{2\pi f_c}$$

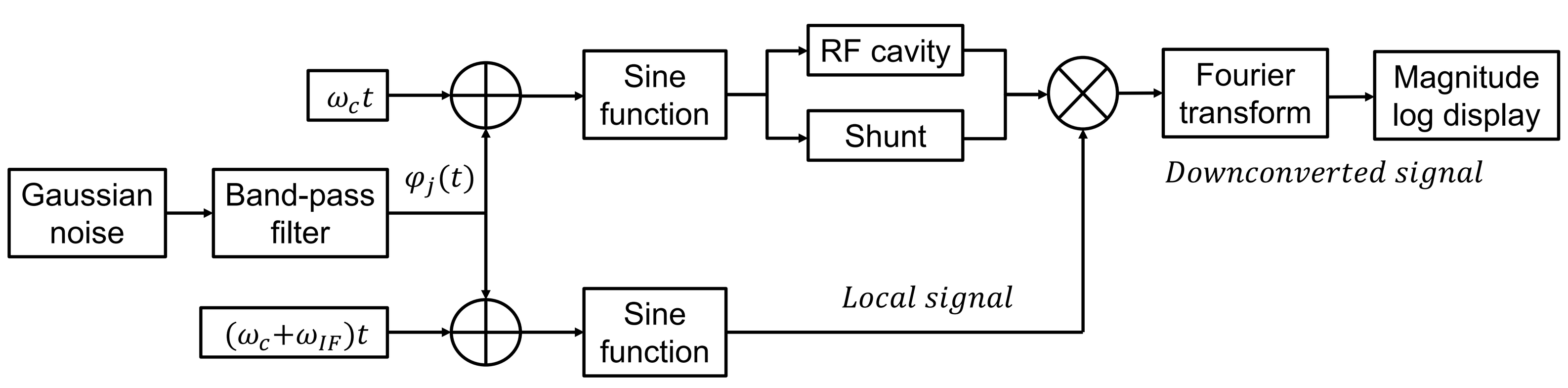
$$L(f - f_c) = 10\log\left(\frac{S(f)}{S(f_c)}\right)$$

$$\tau_{jrms} = \frac{\varphi_{jrms}}{2\pi f_c} = \frac{1}{2\pi f_c}\sqrt{2\int_{f1}^{f2} 10^{\frac{L(f)}{10}}\,df}$$



where φ_j, τ_j, $S(f)$ and $L(f - f_c)$ are respectively the phase jitter, time jitter, power spectrum density of s(t) and the phase noise.

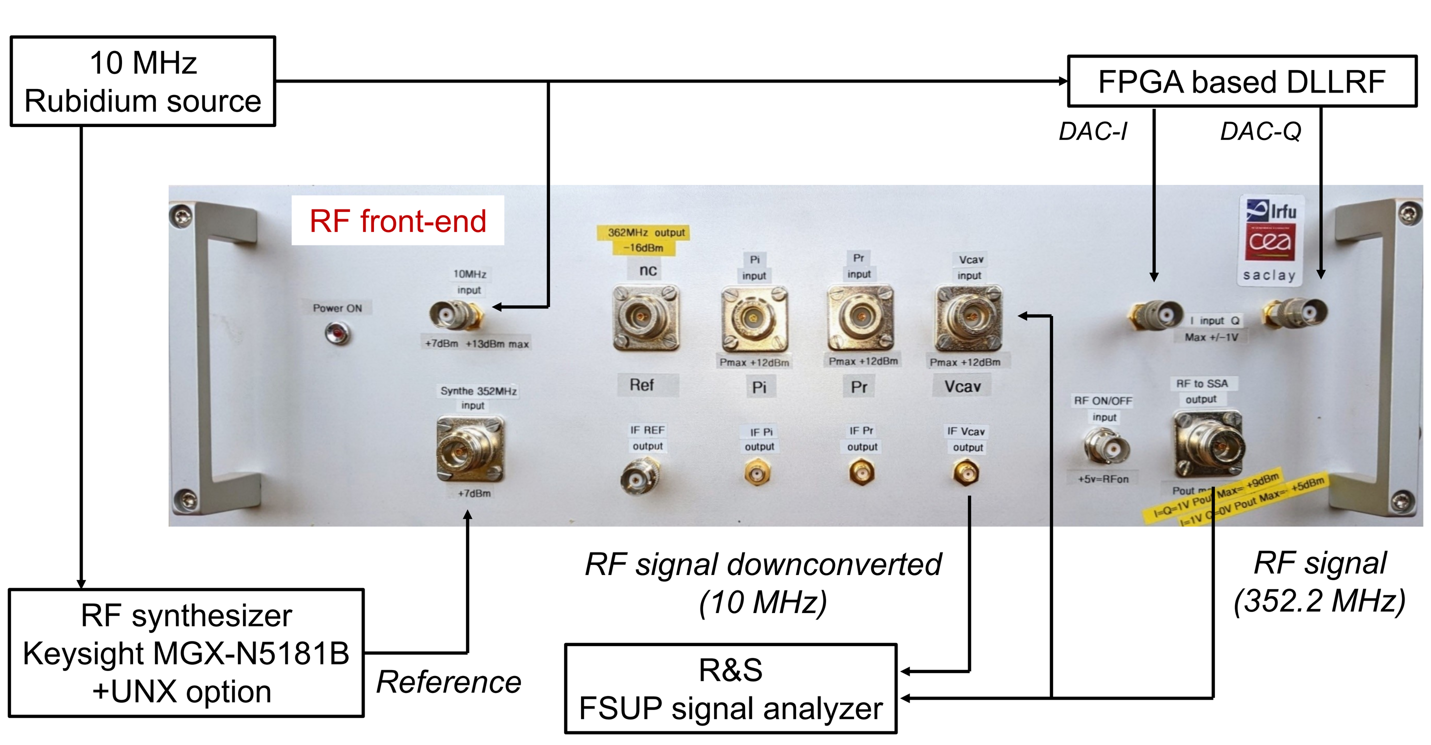
B. Numerical simulations: an arbitrary case study (Scilab v2023)



Carrier frequency: 80 MHz, IF frequency: 20 MHz, colored noise bandwidth: 1MHz, RF cavity bandwidth: 320 kHz. Number of RF periods simulated: 10^6.

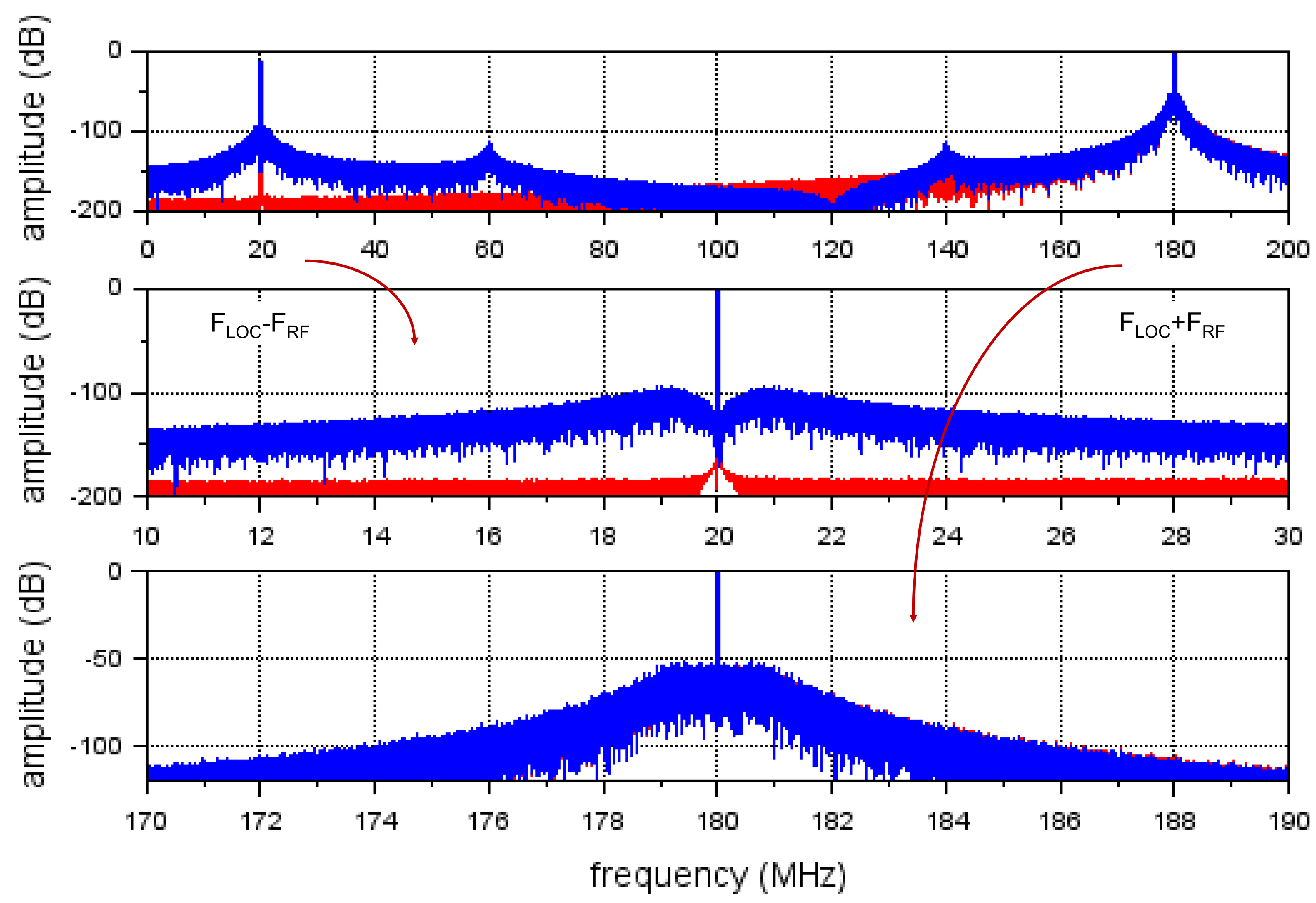
C. Experimental evidence of phase noise cancellation

Phase noise measurements are carried out with a R&S®FSUP signal analyzer [2] on the LLRF system developed for the upgrade of the Soleil synchrotron [3]. The RF and IF frequencies are respectively 352.2 MHz and 10 MHz. The RF cavity is not connected and the system operates in open-loop configuration.



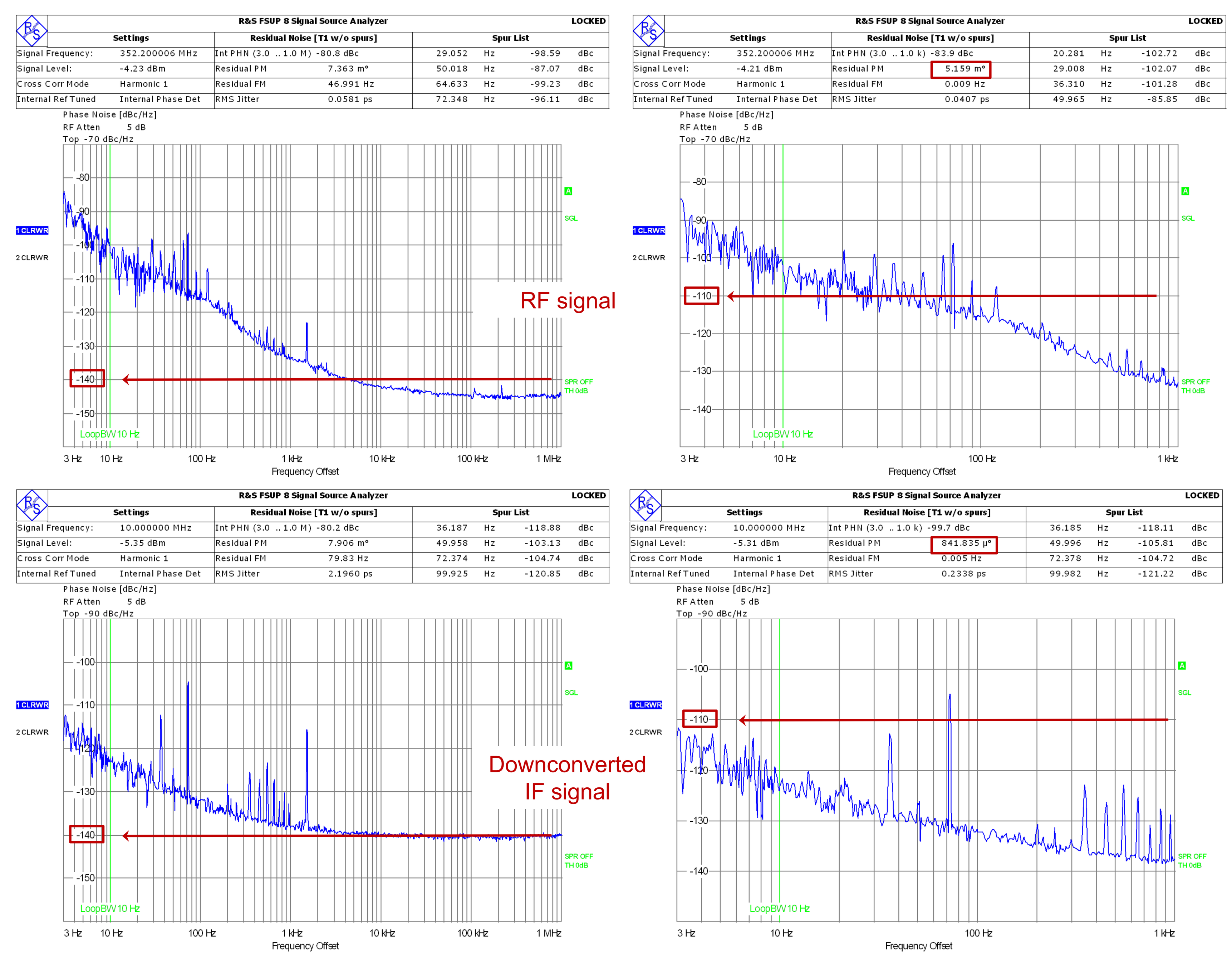
Phase noise measurements

RESULTS



Downconverted signal spectrum from simulation
Red: without the RF cavity, Blue: with the RF cavity

Phase noise cancellation only occurs on downconverted signal and not on upconverted signal. With an RF cavity on the signal path, this cancellation is limited to the passband of the cavity.



Amplitude noise slightly increased, due to the additive amplitude noise (NF) of both the mixer and IQ modulator that generates the local signal, but phase noise strongly decreased (by about a factor 6 in terms of phase jitter) in the down-converted signal. Power line spurs (50 Hz and its harmonics) are removed.

DISCUSSION

Phase noise cancellation may appear at first sight as an advantage that increases the IQ measurement accuracy but it corresponds actually to a loss of the phase noise information. It can mislead on the true performance of a LLRF system. If the particle bunches were clocked by a much lower phase noise source than the reference and RF signal, then energy spread and emittance grow would occur. When the same reference signal is used to trigger the bunches, the result will depend on the dispersion of the cables that carry the signals: same degradation in case of significant dispersion, no such a degradation otherwise. However, in the latter case, the synchrotron light source time resolution may be jeopardized. In LLRF system with frequency downconversion, an ultra-low phase noise source should be used for the reference signal, especially at frequency above 1 GHz.

References

[1] Rutkowski, Igor, and Czuba, Krzysztof. "Additive phase-noise in frequency conversion in LLRF systems." arXiv preprint arXiv:1806.09247 (2018).
[2] https://www.rohde-schwarz.com/fr/produits/test-et-mesure/analyseurs-de-spectre-et-signaux/rs-fsup-signal-source-analyzer_63493-8429.html.
[3] Sreedharan, Rajesh et al. "Status of DLLRF System Development for Soleil-II Project. Poster presentation at the LLRF Workshop, Gyeongju (2024).