Characterization and Improvement of Phase Noise in the RHIC 197 MHz RF System

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Abstract

The Relativistic Heavy Ion Collider (RHIC) is a hadron collider currently in operation at Brookhaven National Lab that collides both proton beams and heavy ion beams at energies of up to 250 GeV. The use of a low phase noise RF system is important to the operation of the collider, as phase noise will cause beam emittance growth over time as beam is circulated. In an effort to reduce the phase noise seen by the beam, an ultra-low phase noise source consisting of a DAC being clocked by an ultra-quiet 2 GHz clock was developed and tested for RHIC's 197 MHz RF systems. Using this source, the current High Level RF system's phase noise performance was characterized. This source optimized noise performance at high frequency offsets, while the current RF system is optimized for low frequency offsets. It will have applications in the future Electron-Ion Collider Crab Cavities, as wideband noise is critical in limiting the transverse emittance growth of the beam.

RHIC Cavity Control

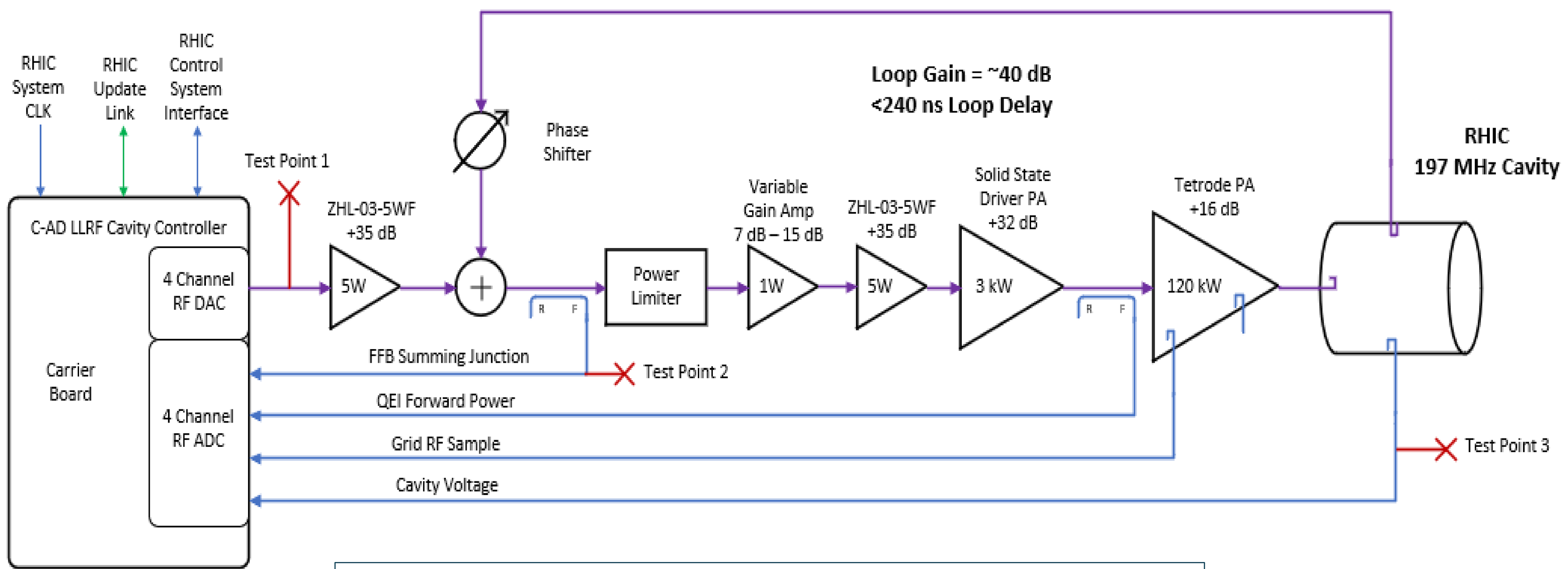

Figure 1 – RHIC 197 MHz Cavity Control Loops

To control cavity stability in the RHIC 197 MHz RF system, an analog Fast Feedback loop is employed in conjunction with a digital IQ Loop. The Fast Feedback Loop has extremely low latency, with less than 240 ns of loop delay, which leads to a generous phase margin of ~135° typically. As can be seen in Figure 1, the loop reference is the LLRF Drive signal that has been amplified by a 5W amplifier, the ZHL-03-5WF. Measurements were made at the test points specified in Figure 1.

Methodology

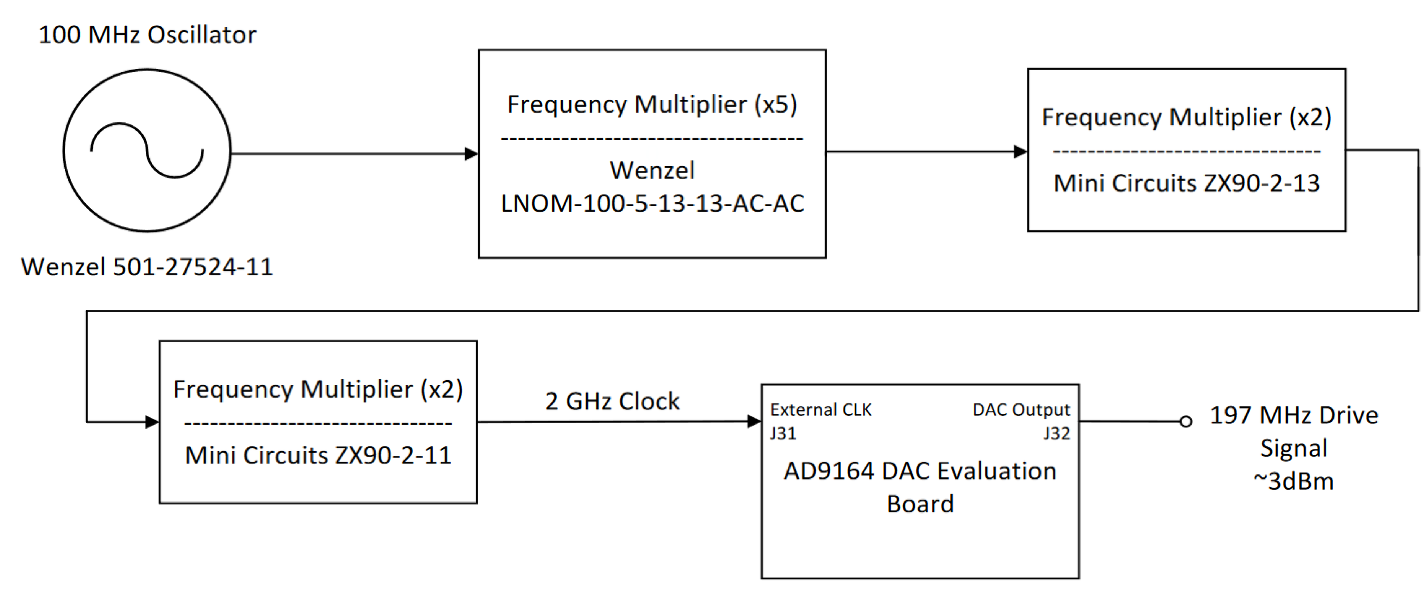

Figure 2 – Ultra-Low Noise LLRF Source

To characterize the performance of the 197 MHz signal chain, a sufficiently quiet drive signal is needed, as well as a Signal Source Analyzer for measurement. The source described in Figure 2 was developed to be an ultra-low noise LLRF Drive Signal, whose phase noise at 197 MHz can be seen in Figure 4.

The 197 MHz system was driven using the ultra-low noise source, and the Agilent E5052B was used to measure coupled signals from the cavity field and 5W amplifier output.

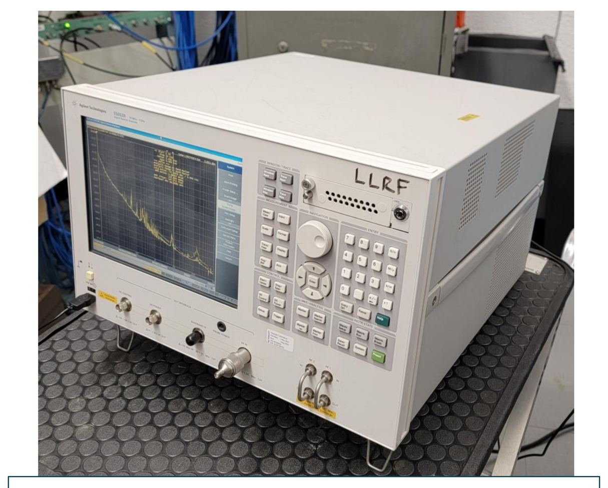

Figure 3 – Agilent E5052B SSA

Future Work

Although an improvement was observed after replacing the 5W amplifier, the signal chain is still observed to have some additive noise after this change. To rectify this, a new amplifier is being chosen to replace the 2 5W amplifiers in the signal chain. Once this amplifier is installed, new measurements will be taken which might show further improved noise performance.

This work is applicable to future efforts involving Crab Cavity control for the EIC, as an ultra-low noise source is needed to combat beam emittance growth generated by the Crabs. To support this, a low noise, high gain RF Feedback Loop will need to be designed. A noise propagation simulation is being developed in conjunction with this research to better understand how to design such a system.

Expected Behavior

Generally, the phase noise seen on the cavity should be dominated by the phase noise of the LLRF reference, as the amplifiers included in the loop are expected to add only small amounts of white and flicker noise. In the presence of residual amplifier noise, the propagation of that noise in the context of an amplifier chain is expected to follow Frii's Formula,

$$F_{\text{total}} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \cdots + \frac{F_n - 1}{G_1 G_2 \cdots G_{n-1}}$$

Where F_n and G_n are the Noise Factor and Gain of amplifier n, respectively. Therefore, it follows that the most impactful amplifier when it comes to noise performance the first.

Results

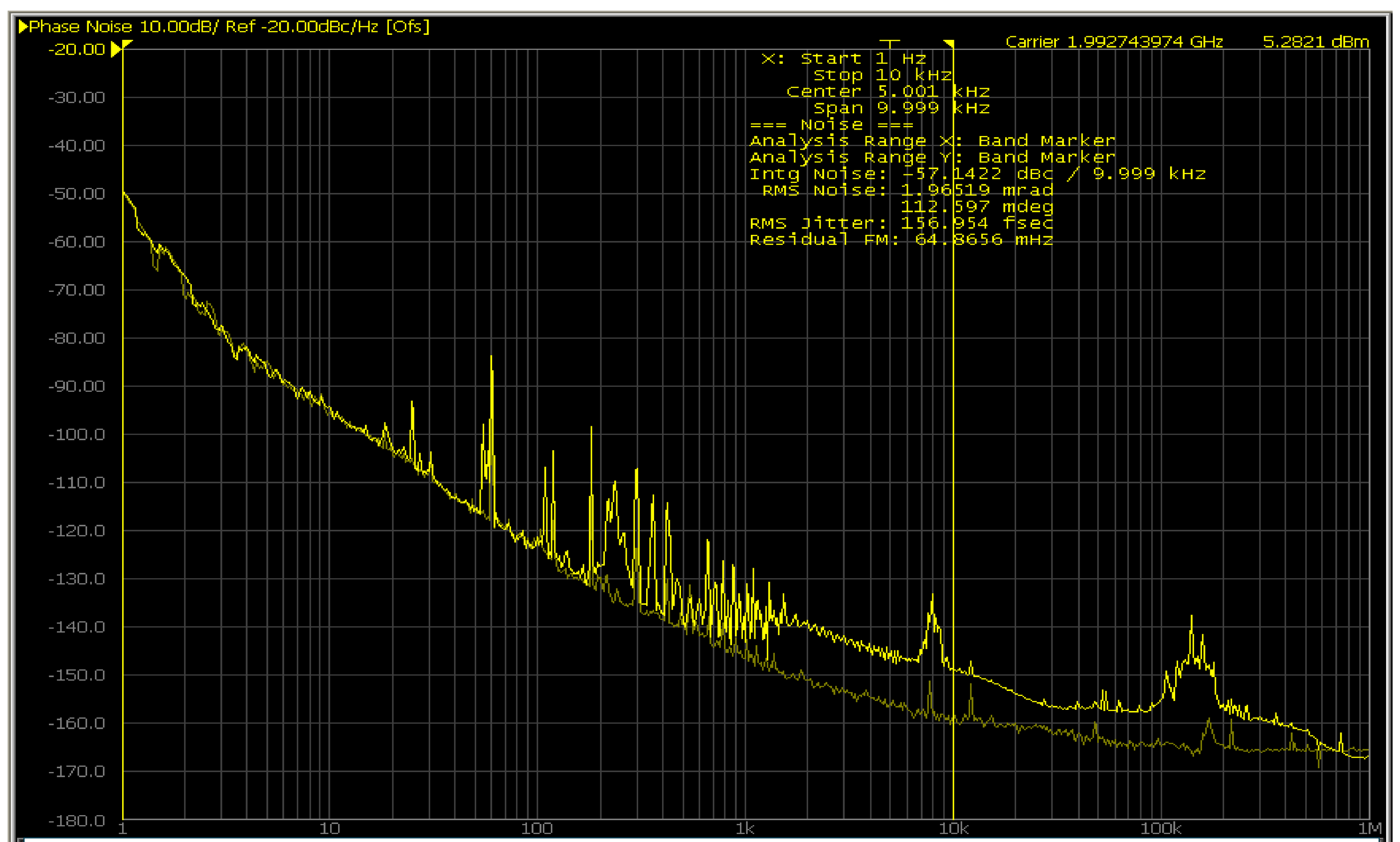

Figure 4 – Cavity Voltage Coupled Signal (front) vs. LLRF Drive (back) PN

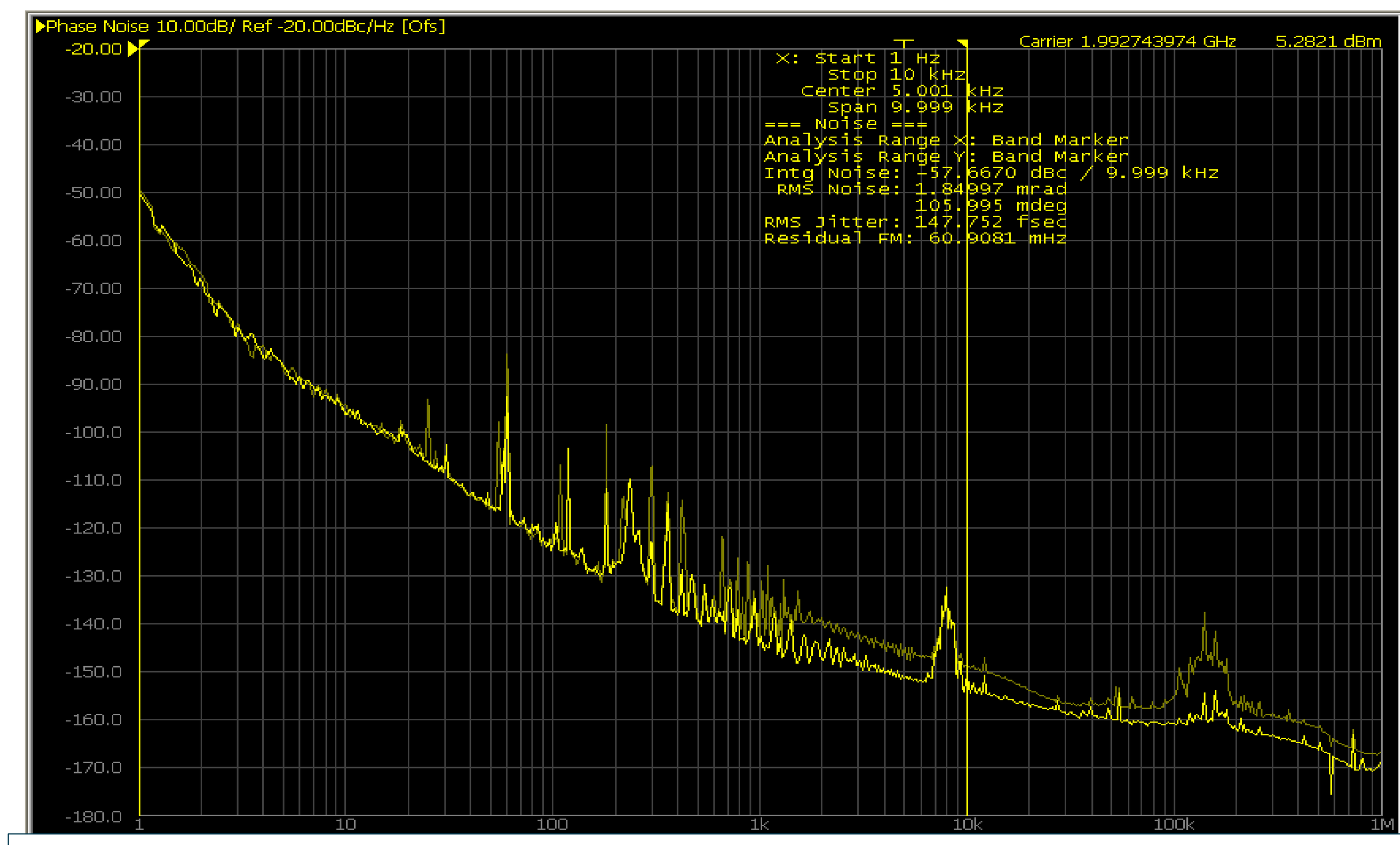

Figure 5 – Cavity Voltage Coupled Signal with (back) and without (front) 5W Amp

Figure 4 shows the performance of the 197 MHz High-Level RF system without modification when using the new Ultra-Low Noise LLRF Source as the drive. As can be seen, the signal chain has a significant amount of additive noise, with performance being as much as 15 dBs worse in the 100 – 200 kHz range.

To combat this, the first amplifier in the chain, the ZHL-03-5WF, was replaced with the RFMD S100403340, a similar amplifier with slightly less gain which has been observed to add little noise. Figure 5 shows the improvement in performance after making this change, with the darker trace being the original measurement.

The original measurement had 156.954 fs of RMS jitter from 1 Hz to 10 kHz, while the new measurement had 147.752 fs. This simple change netted a modest improvement of 9.202 fs of RMS jitter.

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