RF Demodulation Theory

SLAC NATIONAL ACCELERATOR LABORATORY

K. Kim, A. E. Romero

Abstract

Four signal processing methods to measure the accelerating amplitude and phase of particle accelerator radio-frequency fields are derived. Each demodulation method is thoroughly chronicled theoretically, concerns addressed, and demonstrations given within the context of the SLAC RF gun and linear accelerator. We argue that the method "IQ demodulation" is inferior to "Non-IQ demodulation."

Introduction

In theoretical londigudinal dynamics, particle acceleration is achieved by precisely designing the accelerating voltage V_{design}. There are several well-described constraints on V_{design}, for example the synchronicity condition and phase-space stability condition [1] which contrain the amplitude A_{design} and angular frequency ω_{design} of V_{design}.

$$V_{design} = A_{design}\sin(\omega_{design}t)$$

However, this scheme is not perfect, and at any moment there may be errors in the generation of the design voltage, prohibiting the scientist from designing the acceleration of their charged particles.

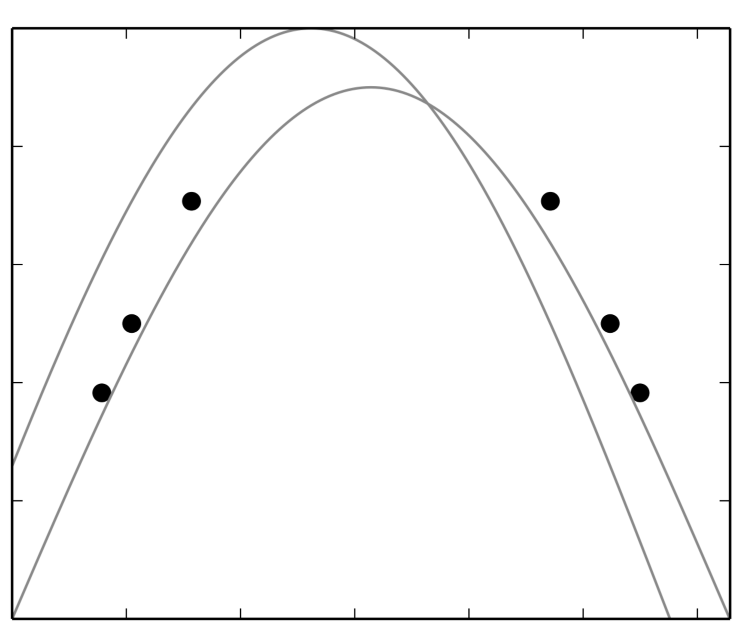


Figure 1. Diagram. In the standard treatment of longitudinal dynamics, consider two kinds of imperfections of the design voltage V_{design}. Errors in amplitude, and errors in phase. To be clear, the term synchronous phase pertains to the placement of the particles, while here ϕ refers to the placement of the accelerating voltage itself.

With these two errors in mind, admit the real accelerating voltage has some imperfect amplitude A_{RF} and undesirable error in phase ϕ.

$$V_{RF} = A_{RF}\sin(\omega t + \phi)$$

Measuring A_{RF} and ϕ is the responsibility of the SLAC low-level RF system (LLRF). It begins after the injector, and ends before the electrons are provided to the undulators where photons are created for experiments. This system is cyclic, where generation of the fields is influenced by feedback systems that actively measure the fields. Devices that measure A_{RF} and ϕ are named demodulators. Since at least 1996 [2] have demodulators been developed at SLAC, each design evolved from the next. Thorough exposition is given to the following four methods, with additional information on how SLAC currently implements each.

Direct Demodulation

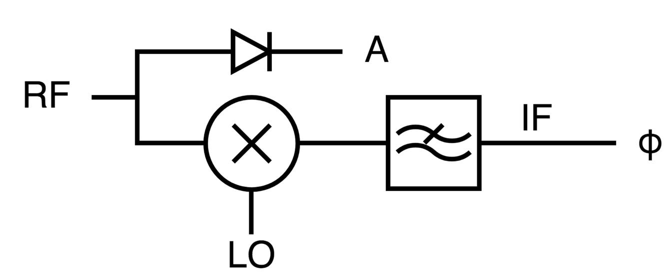
Direct demodulation is the simplest method. The diode measures amplitude directly [3]. The local oscillator (LO) is

$$V_{LO} = A_{LO}\cos(\omega t)$$

The signal is mixed and passed through one LPF to obtain

$$V_{IF} = A_{RF}A_{LO}\frac{1}{2}\sin(\phi)$$

Notwithstanding the constant factor and sine factor, phase is easily acquired by measuring VIF.



Analog IQ Demodulation

Analog IQ demodulation uses two signals, one shifted one quarter period in phase from the other. The input VRF is the same, but suppose the LO is somehow imaginary

$$\begin{aligned} V_{LO} &= A_{LO}e^{-i\omega t} \\ &= A_{LO}(\cos\omega t - i\sin\omega t) \end{aligned}$$

Suppose the signal is mixed with the real and imaginary part passed through independent LPFs. The resulting signal is

$$V_{IF} = A_{RF}A_{LO}\frac{1}{2}(\sin\phi + i\cos\phi)$$

Call the real part I and imaginary part Q.

$$V_{IF} = I + iQ$$

Amplitude and phase are therefore calculable.

$$A_{RF} = \sqrt{I^2 + Q^2}$$

$$\phi = \tan^{-1}(\frac{Q}{I})$$

Commonly, the LO for I is delayed by one–quarter period to obtain the LO for Q. This gives the names in-phase and quadrature.

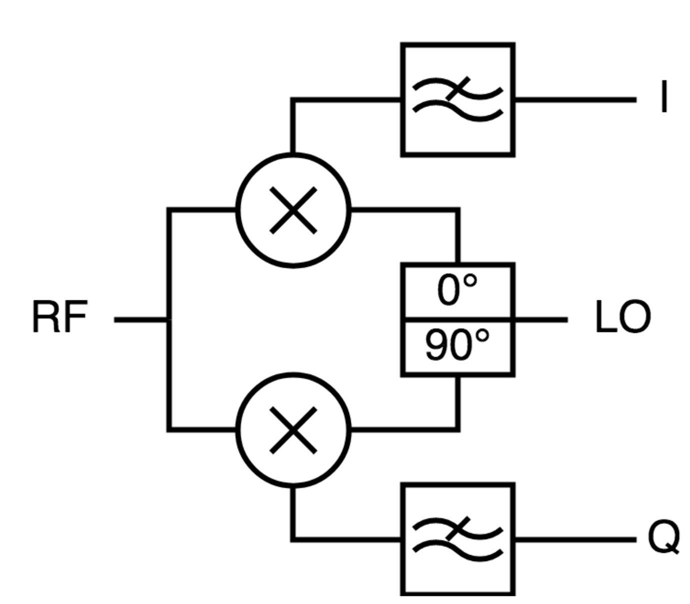


Figure 3. Delay the I signal by one quarter phase to obtain the Q signal. By measuring I and Q simultaneously, the amplitude and phase of the RF signal can be reconstructed.

Digital IQ Demodulation

Digital IQ demodulation tries to perform the quadrature phase shift another way, and attempts to resolve I and Q not simultaneously but in alternating fashion. By requiring one measurement per π 2 period of the signal, the ADC must sample at four times the IF angular frequency.

$$\omega_{ADC} = 4\omega_{IF}$$

In pursuit of measuring ϕ we oversample V_{IF}. Because the sampling frequency is integer multiple of the signal, higher harmonics of the signal overlap into the fundamental frequency.

Digital Non-IQ Demodulation

Digital Non-IQ demodulation attempts to reformulate the amplitude and phase of VRF to avoid the quarter period phase shift requirement, hence the name "not IQ." Rewrite V_{RF} as

$$V_{RF} = A_{RF}(\sin(\phi)\cos(\omega t) + \cos(\phi)\sin(\omega t))$$

The signal can be Fourier decomposed into

$$f(x) = a_\omega\cos(\omega t) + b_\omega\sin(\omega t)$$

$$a_\omega = \frac{1}{\pi}\int_0^{2\pi} f(x)\cos(\omega x)\,dx = A_{RF}\sin(\phi)$$

$$b_\omega = \frac{1}{\pi}\int_0^{2\pi} f(x)\cos(\omega x)\,dx = A_{RF}\sin(\phi)$$

Acquire amplitude and phase.

$$A_{RF} = \sqrt{a_\omega^2 + b_\omega^2}$$

$$\phi = \tan^{-1}(\frac{a_\omega}{b_\omega})$$

To compute a_ω and b_ω, measure n samples every m periods

$$m\omega_{ADC} = n\omega_{IF}$$

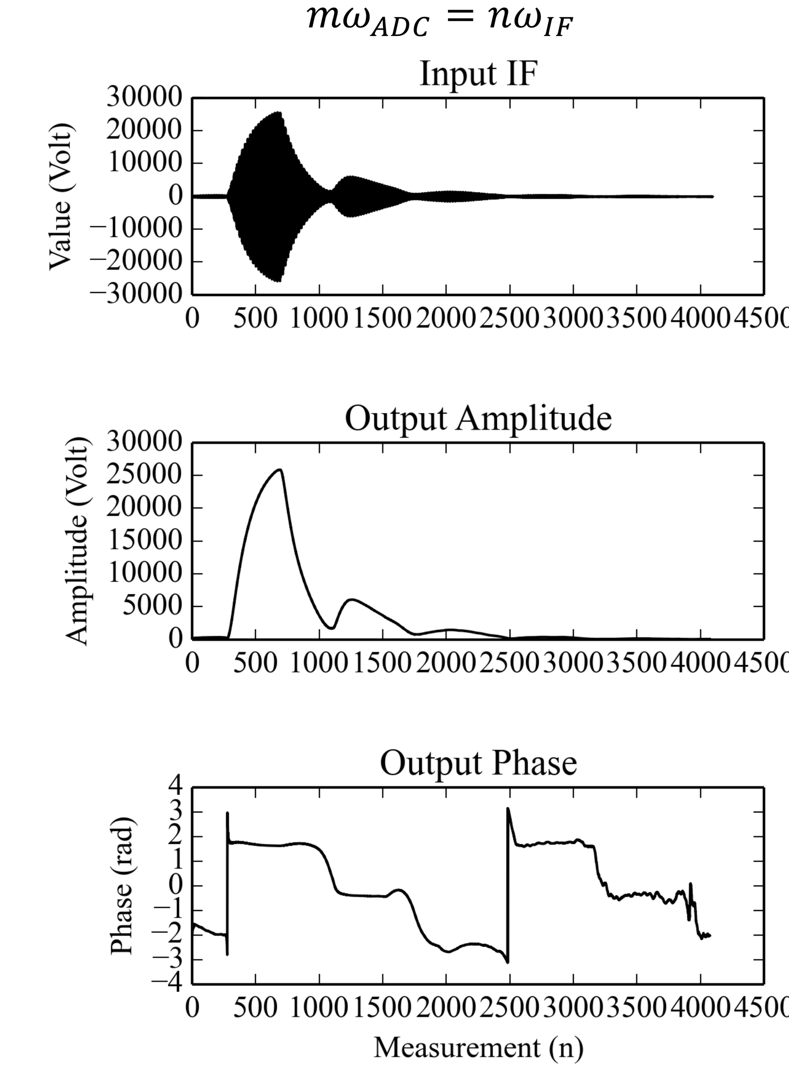


Figure 4. Demonstration. The subject is the measured V_{IF} signal over one full RF pulse, Gun Probe 1, LCLS-I. The IF frequency is 85 MHz and ADC frequency of 357 MHz, satisfying the earlier relation.

Discussion

Digital Non-IQ Demodultion avoids aliasing in comparison to Digital IQ Demodulation. Observe that when m and n are multiples of each other, the higher order harmonics sample into the fundamental frequency of the IF signal.

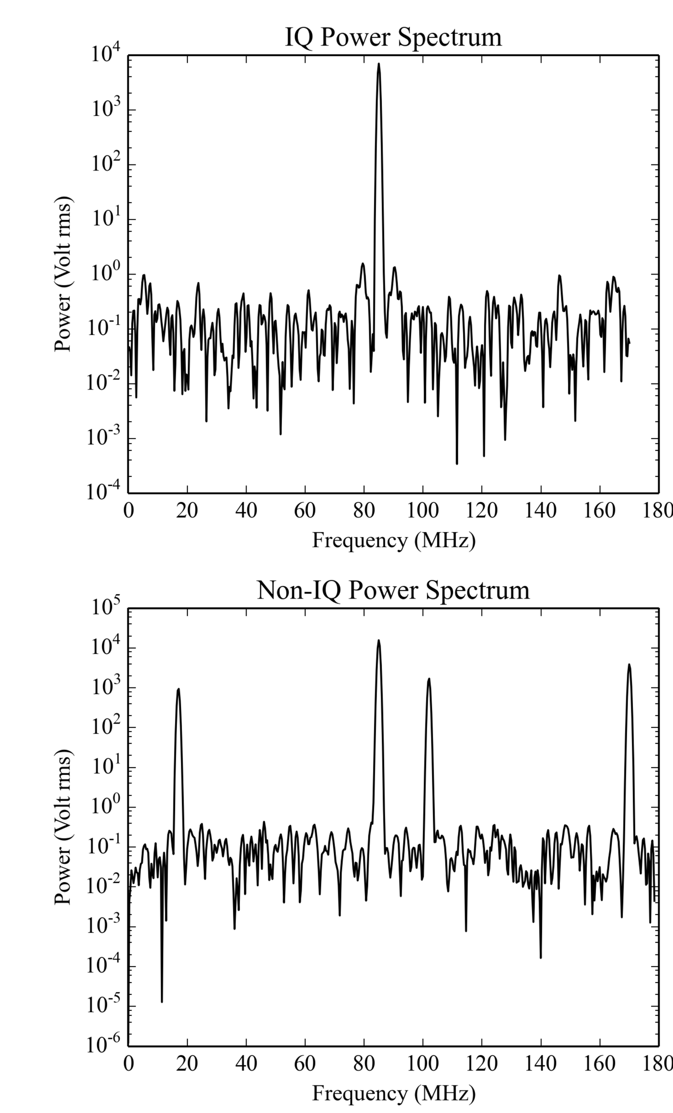


Figure 5. Demonstration. This signal is simulated, with fundamental frequency 85 MHz, has weaker harmonics up to 425 Mhz, with frequency noise and oscillating DC. The top is sampled with m = 1, n = 4, and the bottom with m = 5, n = 21. For both analog and digital IQ demodulation, it is impossible to determine which frequency obtains the highest power.

Conclusion

In summary, the problem of extracting useful information from accelerating RF cavities has merited careful research and development at SLAC. This paper summarizes both defunct and modern methods for this problem, with the hope that other accelerator facilities reconsider the measurement devices of their own radio-frequency cavities.

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