Integration of a Digital PLL in LLRF Systems for Advanced Cavity Characterization

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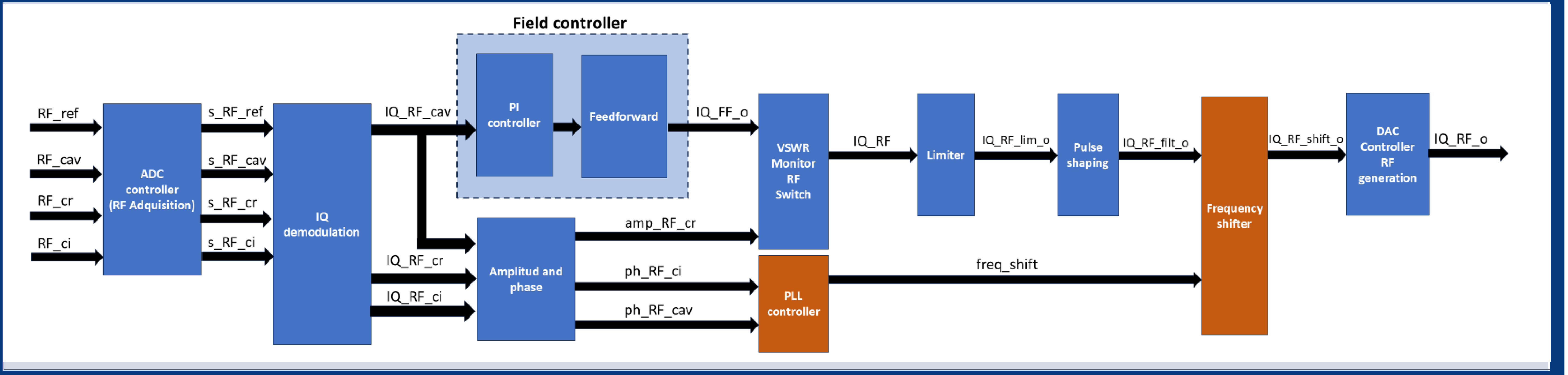
Abstract

The Low-Level Radio Frequency (LLRF) system is a vital subsystem in particle accelerator facilities, tasked with generating and maintaining a stable electric field within accelerator cavities by precisely controlling both amplitude and phase. As facilities transition from legacy analogue LLRF systems to modern digital counterparts, the enhanced computational power of current Field-Programmable Gate Arrays (FPGAs) presents opportunities to introduce new, sophisticated functionalities.

In this work, we explore the design and implementation of a fully digital Phase-Locked Loop (PLL) integrated within the LLRF system. This digital PLL is capable of automatically tracking the resonant frequency of the accelerator cavities, ensuring that the system continuously adapts to any deviations from the nominal resonant frequency. Moreover, this feature extends beyond simple frequency monitoring; it can also be leveraged for detailed characterization of the magnitude response of the cavity.

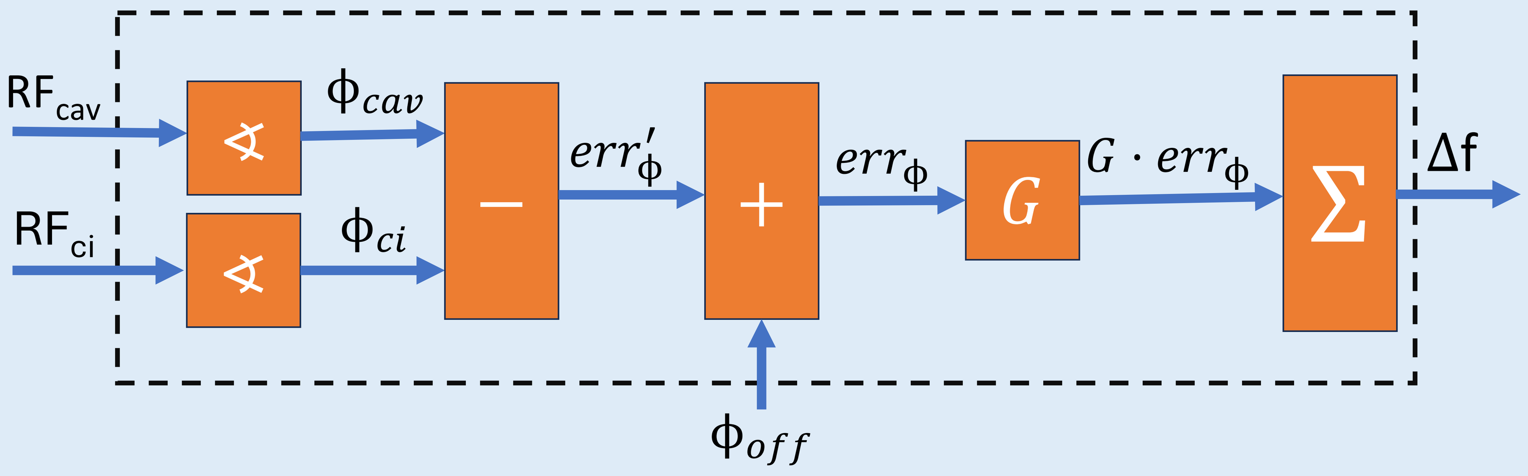
The implementation details and performance evaluation of this digital PLL feature will be thoroughly discussed in this work.

LLRF Functional diagram



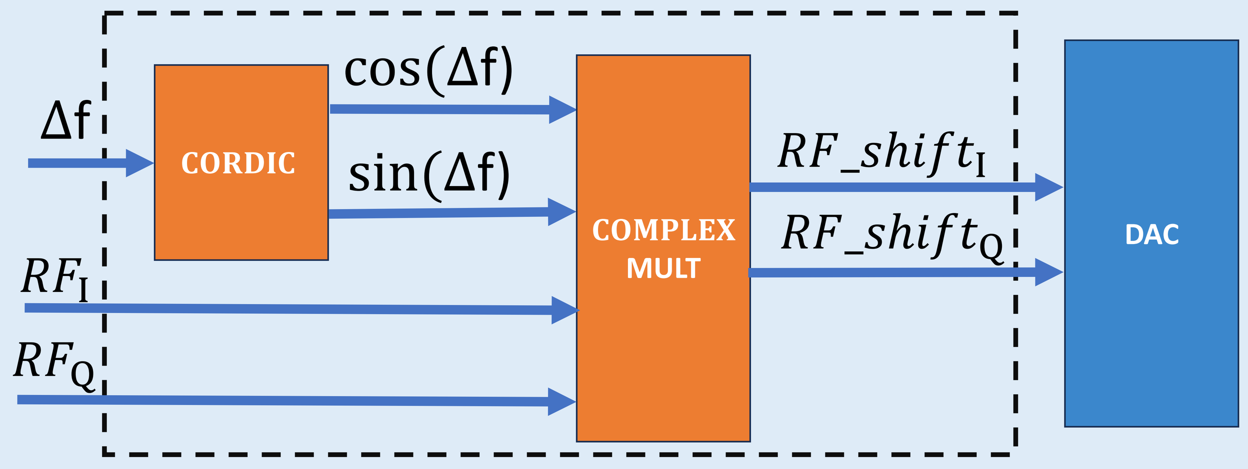
PLL controller

The PLL controller block measures the phase error between the RF signal injected into the cavity and the cavity's measured field. An offset phase (ϕ_{off}) is added to this error for calibration purposes. The resulting phase error is then multiplied by a configurable gain constant (G) and integrated to function as an integrated loop controller. The final output (Δf) represents the frequency adjustment needed to minimize the phase error.



Frequency Shifter

The output from the PLL controller block (Δf) is fed into a CORDIC core, which generates the corresponding complex exponential from its sine and cosine components. The IQ components of the RF signal produced by the LLRF are then multiplied by this complex exponential before being sent to the DAC controller. Within the DAC, the IQ signals are modulated with the nominal RF frequency, resulting in an RF output with a frequency of $f_{nom} + \Delta f$

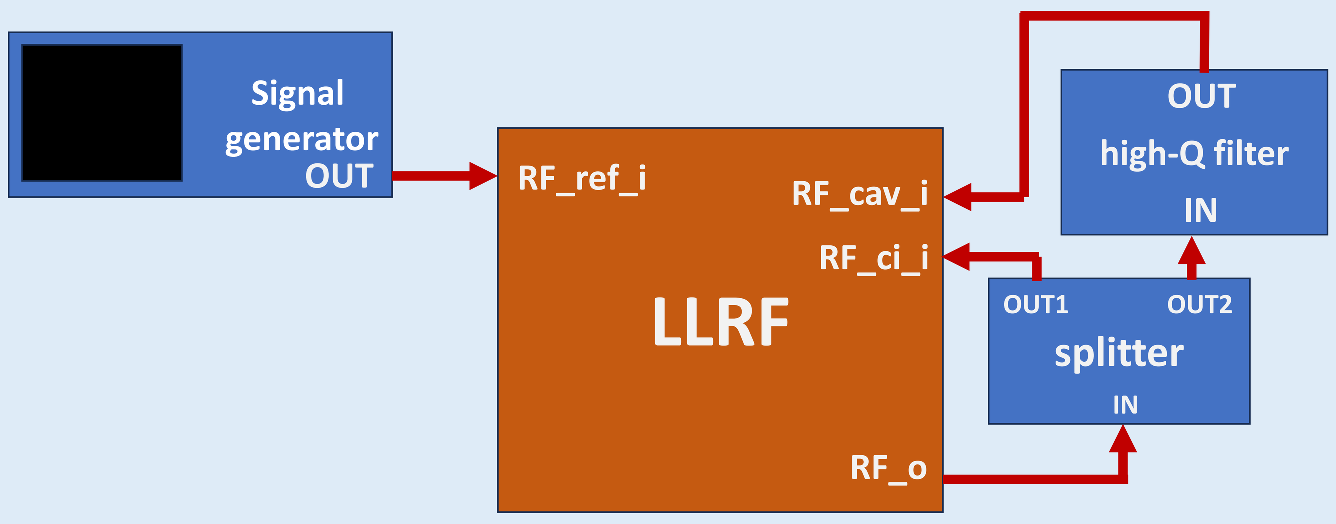


Set-up

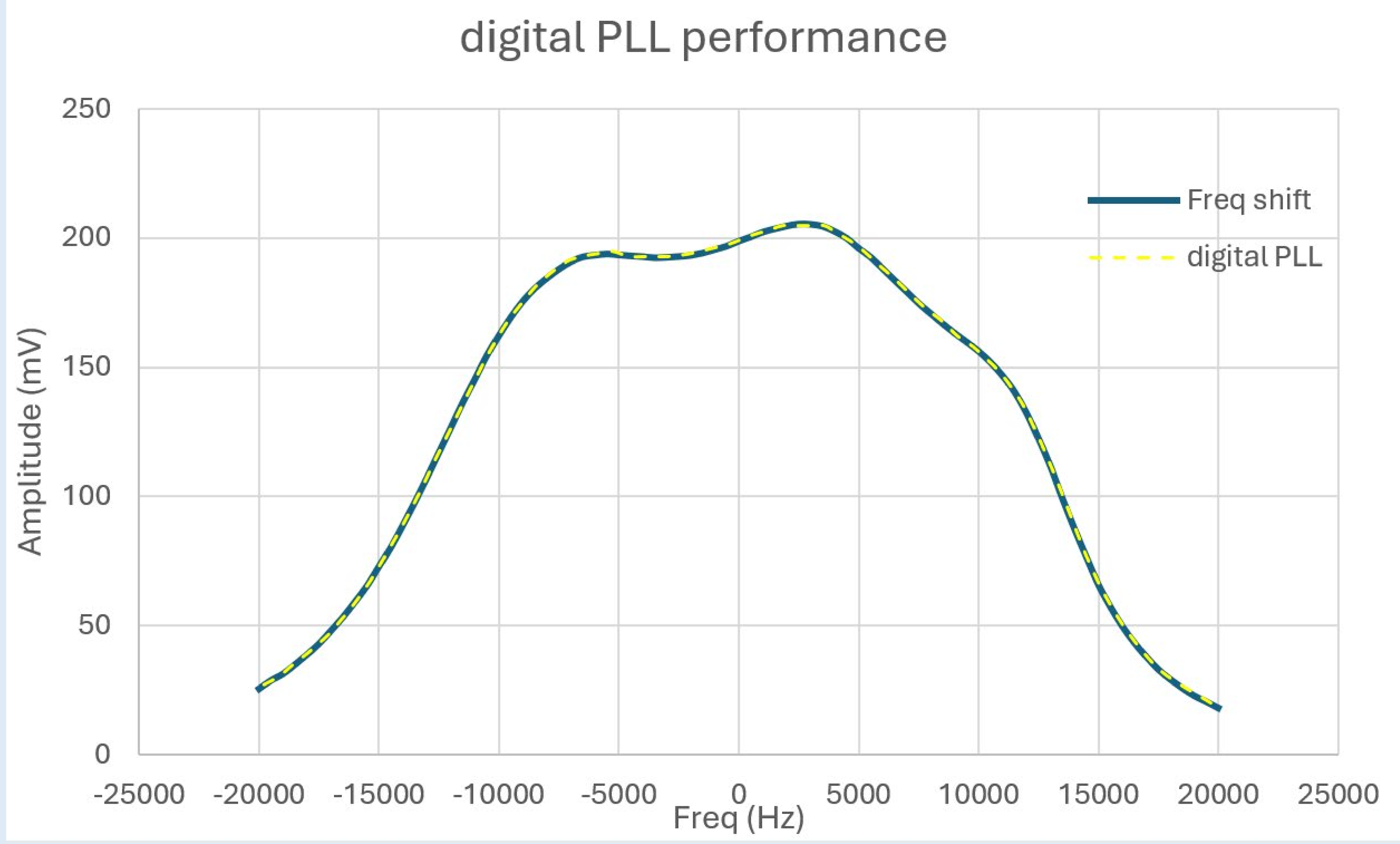
To evaluate the performance of the digital PLL, a high-Q filter was utilized to simulate the response of a cavity. The characterization of the filter's magnitude response is depicted in the image on the right, obtained through two distinct methods:

- Conducting a frequency sweep using only the frequency shift capability of the LLRF system.
- Performing a ϕ_{off} sweep, which forces the digital PLL to converge to different frequencies.

As illustrated, both curves align perfectly, demonstrating the effective performance of the digital PLL. This capability enables tracking of the resonant frequency of actual accelerating cavities, even as it varies due to thermal and other effects.



Results



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