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DEVELOPMENT OF THE DIGITAL LOW LEVEL RF SYSTEM FOR THE LANSCE PROTON STORAGE RING*

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Abstract

As part of the modernization of the Los Alamos Neutron Science Center (LANSCE), a digital low level RF (LLRF) control system for the LANSCE proton storage ring (PSR) is designed. The LLRF control system is implemented on a Field Programmable Gate Array (FPGA). The high resolution tunable 2.8MHz reference RF is generated by a direct digital synthesizer (DDS) at the LANSCE front end and is transmitted to the PSR control system located half mile away. Since the digital LLRF control system is synthesized in the In-phase/Quadrature (I/Q) coordinate, the I/Q RF signals are generated by the Hilbert Transformer (HT) based finite impulse response (FIR) filter. For the stabilization of the cavity field, a Proportional-Integral (PI) feedback controller is implemented. In order to verify the performance of the LLRF control system before it is applied to the PSR, a FPGA based PSR cavity simulator is designed and its parameters are identified using the cavity field data obtained during the PSR beam operation. The low power LLRF testbench based on the simulator is constructed and the amplitude and phase stabilities of the digital LLRF system are verified.

INTRODUCTION

The modernization of the LANSCE PSR LLRF system is under way [1]. Analog low level RF control and electronics is to be replaced with FPGA based control system. The legacy LANSCE PSR LLRF system is an analog PI feedback control system, which provides reliable amplitude and phase error of < ±1.0% and ±1.0°, respectively. However, it doesn't provide operational flexibility and data communication between the LLRF system and the supervising host. The new design of the LLRF system uses a FPGA, on which a softcore processor embedded with the real-time operating system and the EPICS IOC provides the capabilities of algorithm and digital signal processing modifications and upgrades. In this note, the new digital LLRF system of the LANSCE PSR and its performance are addressed.

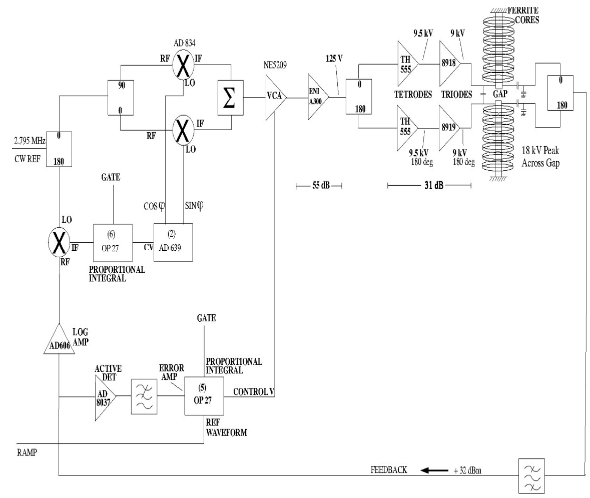

Figure 1: Legacy Analog Low Level RF Control System of the LANSCE PSR [2].

LANSCE PROTON STORAGE RING

The LANSCE PSR is a fast-cycling high current ring designed to accumulate beam over a macropulse from the LANSCE linac, with multi-turn injection [2]. The circumference of the ring is 90.2 meter and the rotational frequency is 2.7924024001 MHz. Figure 1 shows the analog low level control system. The RF system provides up to 18 kV of 2.79242001 MHz voltage to the buncher gap [3]. The buncher gap is a 1cm break in the PSR beam pipe, which is insulated with an outer alumina cylinder. The RF structure consists of a pair of opposing horizontal stubs approximately 79 cm long. These beam pipes are grounded at the far ends to the enclosure cshell, and open-circuited at the center and the insulator bridges the structure at the center [3]. Twenty water-cooled Philips type 4H ferrite toroids are stacked on each pipe to raise the inductance, and foreshorten the resonance [3]. Direct current is routed through a bias winding to tune resonance to 2.79242001 MHz. The proton beam is delivered to a target after passing through the PSR. The time it takes an 800 MeV proton to travel one circuit of the PSR is 360 nsec. The beam entering the PSR is filled with micropulses separated by 5 nsec (the minimum separation) for a duration of 270 nsec. There is then a gap of no beam for 90 nsec for each 360 nsec cycle. This pattern is repeated for the entire macropulse or 625µsec / 360 nsec = 1736 times. The 90 nsec gap is required for the magnets to switch, then the beam is extracted from the ring [2].

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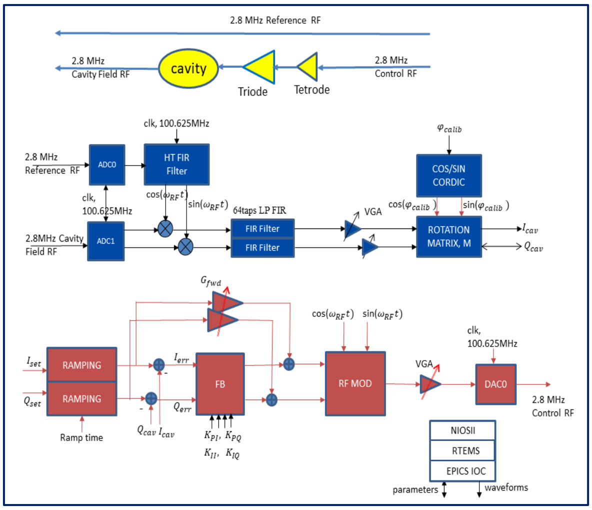

Figure 2: Schematic block diagram of the digital Low Level RF system of the LANSCE PSR

DIGITAL LLRF CONTROL SYSTEM

The LLRF control system is a fully digitized system which is implemented on a FPGA (Figure 2). The cavity RF and the reference RF are directly sampled with the 16 bit ADCs. The sampled reference RF is used for generation of the quadrature signals (cosine and sine sinusoids) in the Hilbert Transformer (HT) based FIR filter. These sinusoids are used in the digital downconverter to transform the sampled cavity RF to the baseband I/Q signals of the cavity field. The I and Q stream outputs of the downconverter are processed to remove the DC offsets and then filtered by 64-tap linear-phase low pass FIR filters. A rotation matrix is introduced to decouple the I/Q channels and hence, the Two-Input Two-Output (TITO) system becomes two decoupled Single-Input Single-Output (SISO) systems. In addition, for both I/Q channels, gain control amplifiers are implemented to achieve the overall loop gains of each channel unity. The feedback controller provides the corrections for the cavity field I/Q signals to track the set point I/Q signals. The feedback controller outputs are up-converted to the drive RF through the digital upconverter which uses the HT based FIR filter output sinusoids. The LLRF control system parameters are loaded to the memory mapped-registers on the FPGA through the EPICS IOC over the LANSCE control system (LCS) network. For the register reads and writes, and waveform uploads, a softcore CPU, NIOS II processor, embedded with the EPICS IOC and the Real-Time Executive for Multiprocessor Systems (RTEMS) is implemented on the FPGA.

HILBERT TRANSFORM BASED FIR FILTER

The RF frequency of the LANSCE PSR is 201.25MHz/72.07=2.792424001 MHz. This reference RF is generated with a DDS which is placed at the LANSCE LINAC front end. The DDS input clock is 201.25 MHz and it is synchronized with 10MHz master clock.

The control system design is performed with the baseband signal. In order to downconvert the RF input to the baseband I/Q signals or the baseband amplitude and phase signals, the quadrature signals of the same frequency as the reference RF of the PSR are necessary. A Hilbert transformer is a filter that generates a pair of quadrature signals (cosine and sine sinusoids) which have identical amplitudes but 90 degree phase difference [4]. Digital FIR filters achieve this by creating a parallel network that includes a real path and an imaginary path.

Consider a HT based FIR filter with the length N+1. The filter is designed with Matlab function firpm using Parks-Macmillan algorithm. The filter is characterized by the odd-symmetricity of coefficients and the interleaved zero coefficients, that is, h(0)=h(2)=...=h(N)=0 as shown in Figure 3. For N=20, the transfer function of the HT based FIR filter is expressed as

$$\begin{aligned} H(z) = z^{-1}[&h(1)(1-z^{-18}) + h(3)(z^{-2}-z^{-16}) \\ &+h(5)(z^{-4}-z^{-14}) + h(7)(z^{-6}-z^{-12}) \\ &+h(9)(z^{-8}-z^{-10})]. \end{aligned} \quad (1)$$

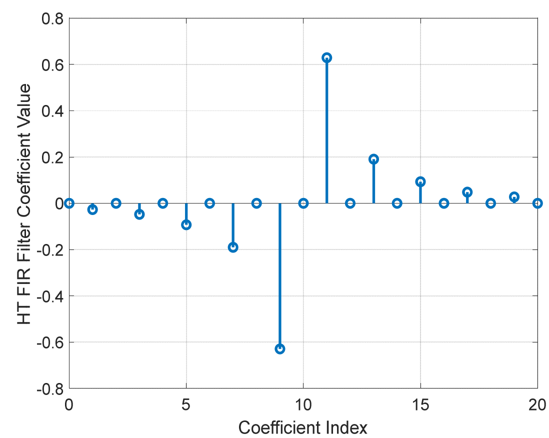

Figure 3: Coefficients of the HT based FIR Filter of the order of 21. Figure 4 shows the performance of the filter.

CAVITY SIMULATOR

The PSR cavity is not available for the performance test of the new LLRF control system since the PSR is under the beam production. Hence, a PSR cavity simulator is implemented on a FGPA.

When beam is not loaded, the transfer function of the cavity in the basesband I/Q coordinate is expressed as

$$G(s) = \begin{bmatrix} \frac{g_{I0}}{\tau s+1} e^{-T_d s} & 0 \\ 0 & \frac{g_{Q0}}{\tau s+1} e^{-T_d s} \end{bmatrix} \quad (2)$$

where T_d is the loop delay, g_{I0}, g_{Q0} are I channel and Q channel steady state gains and τ is the time constant, which can be estimated based on the step response data.

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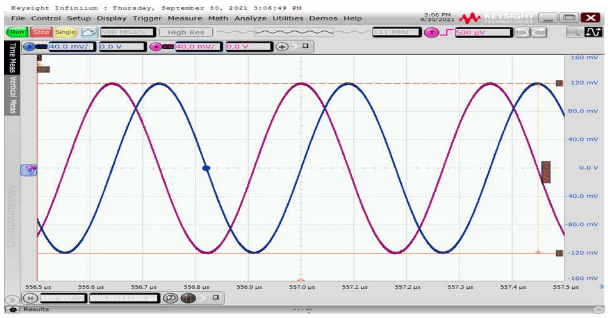

Figure 4**:** The oscilloscope screen shot of the quadrature signals (cosine and sine sinusoids) of the implemented HT based FIR filter.

When the RF is turned off after the cavity field reaches its steady state, the cavity field is decaying naturally. The decaying cavity field signal is used to obtain the time constant of the cavity. Figure 5 shows the decaying cavity field amplitude waveform of the PSR cavity. The time constant and the 3db bandwidth of the cavity are obtained: $\tau = 23.94 usec$, $f_{3dB} = 6648 Hz$. The calculated Q-factor is 210. A RF-band model of the PSR cavity can be realized with a bandpass filter where the center frequency of the filter is the cavity resonance frequency f_o (= 2.7924024001 MHz) and the two-sided bandwidth is $2f_{3dB}$.

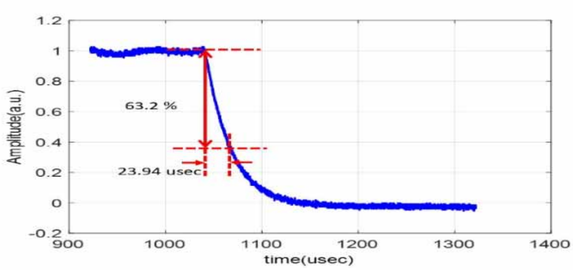

Figure 5: The decaying Cavity Field Amplitude of the LANSCE PSR when the RF is turned off.

FIELD CONTROL PERFORMANCE

The transfer function $C_D(z)$ of the implemented discrete time PI controller is expressed as

$$C_D(z) = \frac{K_P}{2^{15}} + \frac{K_I}{2^{15}} \frac{1}{1-z^{-1}}. \quad (3)$$

Here, the proportional gain K_P and integral gain K_I are 16 bit unsigned integers. The performance of the PI control system is shown Figure 6. Note that with higher PI gains, better performance is obtained. However, since there is a loop delay of a few µsec, gains are chosen not to degrades robustness stability of the controlled system. For fixed proportional gains of I and Q channels, as the integral gains are increased, the peak magnitude of the sensitivity function, $S(s) = \left(1 + G(s)C(s)\right)^{-1}$ of the closed loop system [5], is pushed toward the higher frequency region and the excitation amount of the modes of the loop delay is increased, resulting in oscillating time response of the closed loop system.

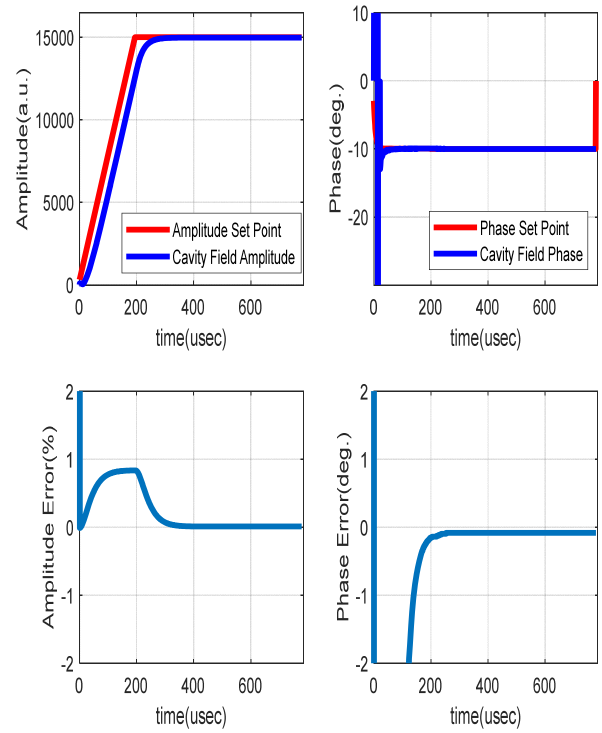

Figure 6: Amplitude and phase stabilization performance of the digital LLRF system. Top left : Cavity Field Amplitude, Bottom left : Amplitude Error, Top right : Cavity Field Phase, Bottom right : Phase Error.

CLOSE LOOP PHASE SCAN

In order to accelerate a beam, it is necessary to find the optimal acceleration field point. This is performed by scanning the phase under the constant amplitude. During the phase scan, the cavity field amplitude variation should be as small as possible. Figure 7 shows the amplitude variation versus the phase set points. Small amplitude variation is observed though it is within ±0.105%. This is caused by mixer nonlinearity, channel crosstalk in the downconverter, other nonlinear distortion in the RF receiving path.

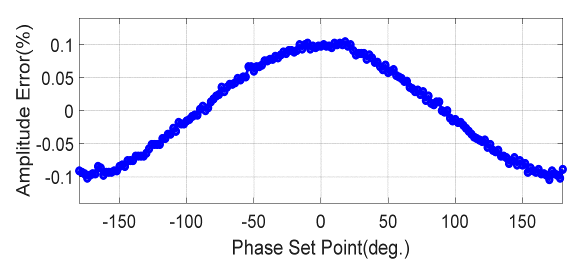

Figure 7: Amplitude Stability at 360 degree phase scan.

CONCLUSION

The preliminary digital LLRF system for the LANSCE PSR is designed and tested at the low power testbench. The direct sampling, the HT FIR filter based up/down-converters, and the PI feedback controller achieve promising amplitude and phase stabilities.

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REFERENCES

[1] D. Rees *et al*., "LANSCE RF Systems Improvements for Current and Future Programs," *in Proc. 2nd Int. Particle Accelerator Conf. (IPAC'11)*, San Sebastian, Spain, Sep. 2011, paper MOPC068, pp. 238-240.

[2] J. Lyles and J. Davis, "Low Level RF Control for the LANSCE Proton Storage Ring Buncher," *in Proc. of 2001 Particle Accelerator Conf. (PAC'01)*, Chicago, IL, USA, Jun. 2001, paper MPPH098, pp. 999-1001.

[3] J. Lyles and J. Davis, "Improvements to the Cathode-Follower RF Amplifier System for the LANSCE Proton Storage Ring Buncher," *in Proc. of 1999 Particle Accelerator Conf. (PAC'99)*, New York, NY, USA, 1999, paper MOP142, pp. 1001-1003.

[4] S. K. Mitra, *Digital Signal Processing-A Computer-Based Approach*. McGraw-Hill, New York, NY, USA, 2001.

[5] S. Skogestad and I. Postlethwaite, *Multivariable Feedback Control: Analysis and Design*, John Wiley & Sons, Ltd., 1996.