A STABLE PHASE REFERENCE FOR THE APS SHORT-PULSE X-RAY PROJECT *

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Abstract

The Argonne Advanced Photon Source is in the process of developing a short-pulse x-ray (SPX) beamline capable of producing picosecond-scale x-ray pulses for use in time-resolved studies. To accomplish this, transverse deflecting cavities (crab cavities) [1] operating at eight times the storage ring rfwill be installed to enable production of short x-ray pulses at a selected beamline.

Analysis reveals demanding phase and amplitude stability requirements for the cavity fields. The common-mode cavity field phase error relative to bunch arrival time is +/- 10 degrees at the 2815-MHz cavity frequency while the cavity-to-cavity phase difference must be held to +/- 0.07 degrees. The phase differential between the cavity phase and beamline timing must be held to +/- 1 picosecond.

A phase stabilized link is under development to transport a phase stable 351.9-MHz reference low level rf (LLRF) located at the beamline end. The delivered phase-stable reference will be used to develop rf references for the cavity LLRF, beamline laser, and streak camera. This paper will discuss the details of the design and report preliminary performance of the prototype.

INTRODUCTION

Beamlines performing time-resolved studies at the APS will benefit from a shorter (~ 1 picosecond) x-ray pulse. The proposed Short-Pulse X-Ray project (SPX) will use multiple deflecting cavities operating at 2815 MHz (eight time the storage ring rf frequency), to chirp and unchirp charge bunches in the APS storage ring at a specific sector. The chirping process is used in conjunction with x-ray optics to select a small slice of the x-ray pulse to propagate down the beamline [1]. It is critical that the deflecting cavity fields maintain a stable phase relationship relative to the stored beam. This requirement imposes the requirement that the correlated cavity field phases be maintained to +/- 10 degrees at 2815 MHz relative to electron beam arrival time.

To meet the requirements for the correlated phase error, a fiber-optic link with active phase stabilization is being developed to transport the storage ring rf 351.9 MHz phase reference signal to the SPX sector low level RF system [2]. This phase stabilized reference will be multiplied by eight to produce the 2815 MHz reference required for the cavities and divided by four to produce the 88 MHz for the beamline laser. The system builds on prior investigations done at NLC and TELSA and uses commercial off-the-shelf components [3, 4].

DISCUSSION

Single-mode fiber has a temperature coefficient of approximately 7 to 10 ppm /^{o}C. For the 300-meter length of fiber required to transport a phase reference to the SPX beamline, a phase deviation of 10.4 degrees/^{o}C at 2815 MHz is expected. Any temperature deviation greater than 1^{o}C would cause the phase at the receiving end to exceed the specification of 10 degrees of phase shift allowed; i.e., an integrated one-degree change in environmental temperature will consume the entire common-mode cavity phase error budget

Figure 1 shows a diagram of the phase-stabilized fiber-optic link. An optical transmitter is amplitude modulated

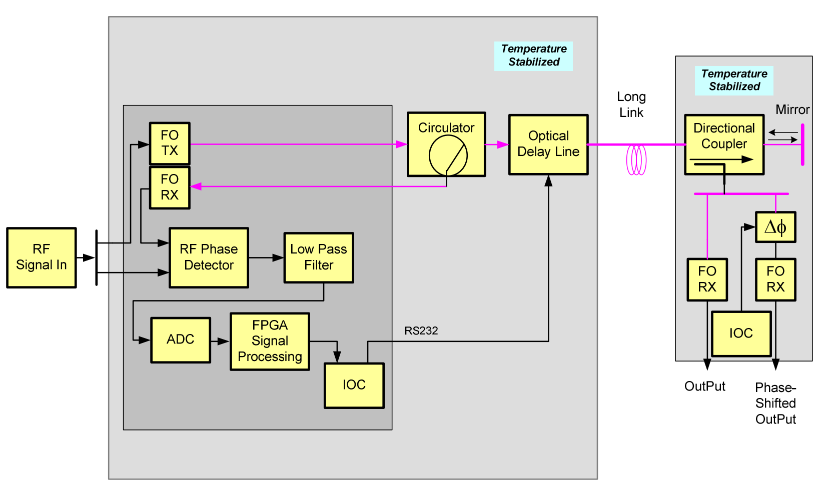

Figure 1: Phase Stable Link block diagram showing the transmitter, receiver, and optical components. The pink lines are optical fiber lines.

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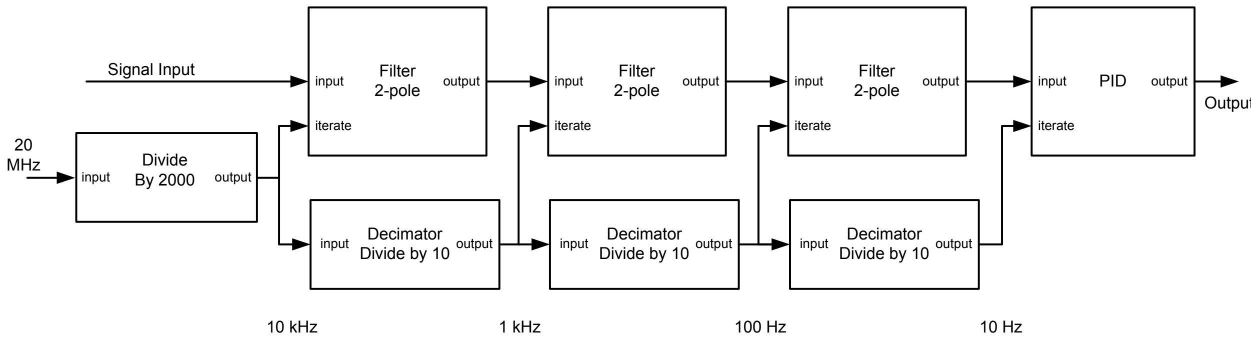

Figure 2: Block diagram of FPGA logic showing 3 2-pole filters with decimators.

with the phase reference frequency. The modulated light from the laser passes thorough a circulator and phase shifter and is then launched on to the long fiber to be phase stabilized. At the receiving end, the modulated light passes through a directional coupler that diverts a portion of the light to an optical receiver for local use. The remainder of the light is reflected by a mirror back through the directional coupler, down the long fiber, and back to the transmitting end. This reflected light signal passes through the phase shifter into the circulator. The circulator diverts essentially all the reflected light to a port that has an optical receiver connected. The phase of this received signal is compared to the phase of the reference frequency to generate a phase error signal. This signal is processed and used to control a phase shifter to compensate for temperature induced phase shifts. In this manner, the phase at the receiving end is maintained at a constant value.

A phase-locked loop (PLL) will be used at the receiving end to phase lock a 2815-MHz voltage-controlled crystal oscillator (VCXO) to generate the deflecting cavity phase reference. The VCXO also provides "jitter cleaning"; i.e., the PLL/VCXO combination reduces phase noise introduced by the fiber-optic transmission of the 351.9-MHz reference.

SIGNAL PROCESSING

The phase detector output is passed through a low-pass filter to a 16-bit ADC. The ADC samples the phase error at a 10-kHz sample rate. The digitized phase error is processed by logic in an FPGA shown in Fig 2. The digitized phase error is passed through three stages of 2-pole IIR low-pass filter/decimator combinations. The final filter output is passed to a PID (proportional-integral-derivative) controller. The final output sample rate is 10 Hz with a 1-Hz bandwidth.

The FPGA processed phase-error signal is sampled at 10 Hz by an embedded EPICS IOC (Input/Output Controller). The IOC further processes the phase error by performing a rolling average and down sampling to 0.1 Hz. The IOC drives an optical delay line [5] via an RS232 link. This delay line acts as a phase shifter and provides the feedback element to control phase.

PRELIMINARY PERFORMANCE

All the required components became available shortly prior to this publication. Testing is in the very preliminary stages.

Figures 3 and 4 show open-loop and closed-loop performance. A three-thousand-foot spool of single-mode fiber was used for the test. Each test was run in an office environment overnight for about 14 hours. The measured variable is the phase detector output voltage. The open-loop plot shows a variation at the phase detector of about 23 degrees of phase for a temperature swing of about 4.5 degrees overnight. The closed-loop plot shows that the controller maintained the phase detector output at a fixed value for over 14 hours. Note that the closed-loop plot (Fig. 4) has a much different scale. The scale of Fig. 4 corresponds to about +/- 0.2 degrees peak deviation. This corresponds to about +/- 1.6 degrees peak deviation at 2815 MHz.

The wide-band rms jitter between the reference signal and the phase stabilized link receiver output is about 4 picoseconds. In the final design a 2815-MHz VCXO in a phase-locked loop will perform jitter cleaning.

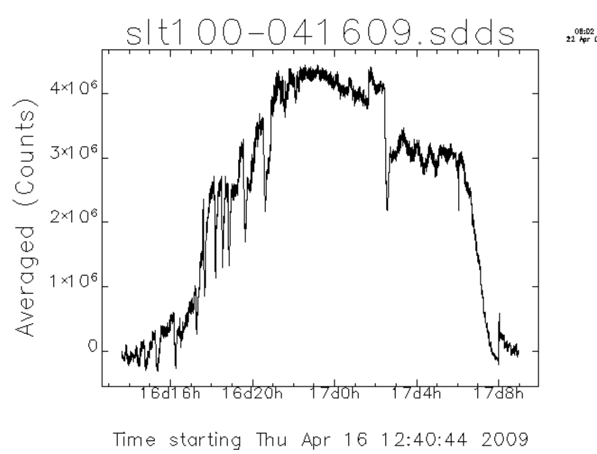

Figure 3: Open loop phase detector output for an overnight. The deviation corresponds to about 10 degrees of phase. The temperature varied by about 4.5 degrees.

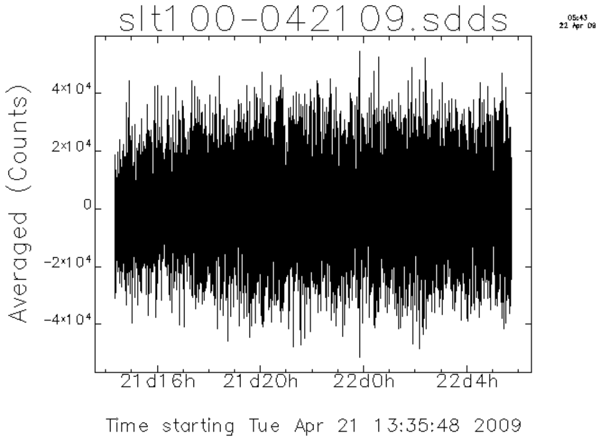

Figure 4: Closed loop phase detector output over a 14-hour run. The peak deviation corresponds to about +/- 0.2 degrees of phase.

FUTURE DIRECTIONS

Much work is yet to be done. We plan to use our environmental chamber to quantify phase stable link performance by heating and cooling the fiber spool. In addition, the feedback controller parameters still need to be optimized. Once the prototype operation has been characterized and optimized, the fiber will be installed in the accelerator for in situ testing.

CONCLUSION

A phase stable link has been prototyped and preliminary testing completed. Further work is needed to characterize and optimize the link performance. We believe the link will meet the performance requirements of the SPX beamline.

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