LINAC AUTOMATED BEAM PHASE CONTROL SYSTEM

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Abstract

Adjustment of the rf phase in a linear accelerator is crucial for maintaining optimal performance. If phasing is incorrect, the beam will in general have an energy error and increased energy spread. While an energy error can be readily detected and corrected using position readings from beam position monitors at dispersion locations, this is not helpful for correcting energy spread in a system with many possible phase errors. Uncorrected energy spread results in poor capture efficiency in downstream accelerators, such as the Advanced Photon Source's (APS's) particle accumulator ring (PAR) or booster synchrotron. To address this issue, APS has implemented beam-to-rf phase detectors in the linac, along with software for automatic correction of phase errors. We discuss the design, implementation, and performance of these detectors and how they improved APS top-up operations.

INTRODUCTION

The Advanced Photon Source (APS), at Argonne National Laboratory is a high-brightness, third-generation synchrotron light source that operates in top-up mode 75% of the time to maintain a storage ring current of 102 mA to 1% tolerance. The APS operating availability reached greater than 98% last year. The excellent machine performance is due to many hardware and software improvements including software automation of machine operations. This paper will describe one of many automated tools used by APS specifically for our new linac beam phase control system. This system measures and corrects the phase of the beam relative to each rf system that provides acceleration in the particle accelerator. We will also cover the beam position monitors (BPMs), related electronics, and how the bpm information is interfaced with our automated software to maintain hands- free injector beam phasing.

APS LINAC LAYOUT AND PHASE DETECTOR LOCATIONS

Linear accelerators consist of a linear sequence of many accelerating structures where accelerating fields are generated and timed such that particles accumulate energy from each accelerating structure. The APS linear accelerator, or linac, was designed with five accelerating sectors known as Linac One through Linac Five or (L1 - L5). Three of the five sectors are SLEDed [1] sectors—L2, L4, and L5 support four accelerating structures each for particle acceleration up to ~ 450 MeV. L1 and L3 have the capability of driving one of our two thermionic rf guns [2].

Phase detectors for the phase detection system are configured so that the beam phase is actually measured by a BPM upstream of the accelerating structure as shown in Figure 1. This configuration ensures that the ability to measure and correct phase errors is not dependent on having beam transport through the linac structures that are being phased. Hence, we can measure and correct the beam-to-rf phase for a set of structures as soon as beam arrives at the entrance to the first structure. The only exception to this configuration is in the case of the rf gun phase detector.

The first phase detector measures the phase of the beam using linac BPM L1:P1 relative to the RG1 or RG2 rf and the L2 rf measured at the first L2 accelerating structure. The L4 and L5 phase detectors operate using the first accelerating structures in L4 and L5 rf waveforms and BPMs L3:P3 and L4:P1, respectively.

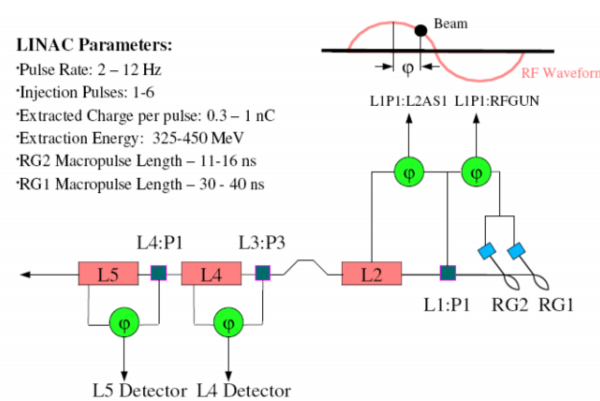

Figure 1: Linac layout.

BEAM-PHASE CONTROL OPERATION

Operation of the linac beam-phase control is mathematically very similar to our linac trajectory controls. For the case of the linac trajectory, the horizontal or vertical beam position at each BPM is held fixed by changing correctors along the linac depending on the deviation of the measured BPM position from the desired BPM position. An analogous longitudinal beam "trajectory" is given by the output of each phase detector along the linac. The linac beam-phase control acts to keep the phase deviation at each detector fixed by changing the linac sector phases or, in the case of the RFGun phase detector, the RFGun power, depending on the deviation of the measured phase at each detector from crest.

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The operation of the RFGun phase detector is worth special mention here. In the case of the L2, L4, and L5 phase detectors, the phase detector output depends on the position of the phase setpoint of the klystron powering these sectors. This is apparent since the phase of each linac sector waveform is independent of all the other sectors and the RFGun. Since the beam is created at the RFGun, phase is defined by the RFGun rf waveform, and hence the time the beam arrives at the BPM is the same for all L1 klystron phase setpoints. Changing the L1 klystron phase setpoint will therefore have no effect on the output of the RFGun phase detector. The only way to change the RFGun phase detector output is to change the power of the klystron powering L1 or the current in the alpha magnet between the gun and the phase detector. Changing the L1 klystron power results in a different RFGun beam energy and hence a different time-of-flight from the RFGun to L1:P1. This time-of-flight difference is directly related to the RFGun phase detector output. The linac beam-phase control therefore uses the L1 klystron power to keep the phase detector output constant, which has the beneficial effect of keeping the beam energy out of the RFGun constant.

Initial setup of the system requires manual phasing and setting of RFGun power to establish the desired operating points for each detector. Once this is completed, a PEMtool [3] application (Figure 2) is used to transfer the phase detector readbacks to the feedback setpoints.

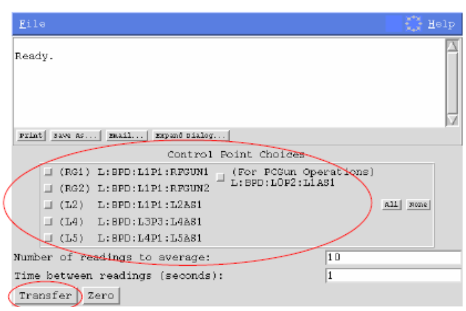

Figure 2: Phase detector transfer phase feedback readings to setpoints tool.

Transferring the readbacks to the setpoints zeros the errors. With the errors zeroed, the control program then acts to keep phase errors zeroed and the beam's longitudinal trajectory fixed. The control-loop software application is shown in Figure 3 and is similar to others used in the injector. From this application, the operator can start, resume, suspend, or abort the control-loop. Figure 4, left display, shows a linac beam-phase control-loop runcontrol screen with an adjacent display of predetermined process variables (PVs) that have minimum and maximum operating values defined. When the entire list of test PVs are within their operating range, the control-loop will function.

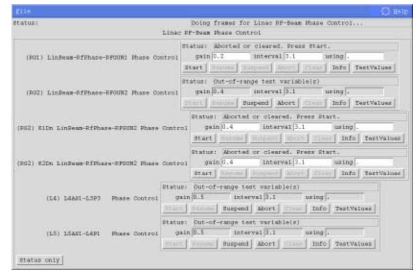

Figure 3: Linac phase control application.

Figure 4: Linac phase control runcontrol screens and test condition screen.

LINAC BPM ELECTRONICS

We have just covered how the beam phase control system software works; we now discuss some of the hardware.

Signals from linac beam position monitors are carried over 0.141-inch hard-line cable to a feedthrough bracket. There they connect to ¼-inch helix cable for the rest of the journey from the linac tunnel to electronics located in the klystron gallery. The phase detection system is basically partitioned into subsystems, as shown in Figure 5 [4]. The stripline detector and bandpass filters are external to the phase detector receiver. The receiver comprises a summing network, phase detector, and control and regulation boards.

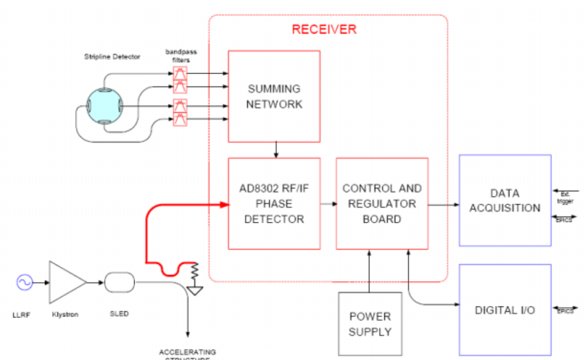

Figure 5: High-power rf-to-beam phase detector electronics.

High-Power RF-to-Beam Phase Detector Electronics

The summing network front-end board combines four signals from the BPM stripline. The stripline signal blades are combined to minimize position dependence. This is accomplished by three Wilkinson 2-way power combiners that are printed on the Rogers RO3006 microwave board substrate. The dielectric constant of the ceramic PTFE composite substrate is 6.15 and the loss tangent is 0.0025 @ 10 GHz. One of the design goals was to keep the rf board construction process as simple as possible by avoiding bonding substrates. This equates to a two-layer board with a thickness of 0.025 inch to insure the trace width of 0.036 inch for 50-Ω lines.

The summing network board also provides the gain and self-test capabilities for the system. The two signals are sampled via 15-dB directional couplers, which are printed on the circuit board. This provides the ability to trouble-shoot the system without disconnecting any cables. The directional couplers also serve as feeds for the self-test oscillators. In the self-test mode the coupler is switched from a 50-Ω termination to a voltage-controlled oscillator. The oscillator drives a two-way equal power divider that is also printed on the circuit board and provides equal inputs to the phase detector. The board employs a selectable gain stage to shift the operating range by 20 dB. This amplification will shift the input operating range while maintaining the same system gain. This feature will be used in some applications and has the effect of extending the dynamic range.

The phase detector board also uses the Rogers 3006 ceramic PTFE composite substrate. The input signals are fed into matching networks and then fed into the Analog Devices AD8302. The AD8302, shown in Figure 6, integrates two closely matched wideband logarithmic amplifiers, a wideband linear multiplier/phase detector, precision 1.8-V reference, and analog output scaling circuits. The gain and phase video output signals are then filtered and scaled to ± 1.0 into 50 Ω. The signals are then fed into the digitizer.

The control and regulator board is constructed on standard FR-4 board and provides conditioned input power and housekeeping for the system.

The boards are housed in an EMI-shielded aluminum case. The receivers are installed in a 19-inch-wide, 4-U-height card crate where up to eight receivers can be installed

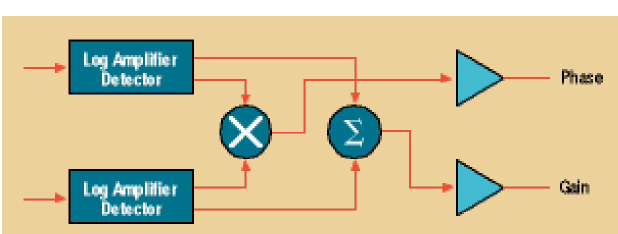

Figure 6: AD8302 block diagram.

ENGINEERING TOOLS

Acquired data from the beam phase control system receiver card is analyzed by a data acquisition and digital I/O card and then graphically displayed. This graphical display is known as the engineering phase detector calibration screen, shown in Figure 7. Here phase and amplitude waveforms are provided along with raw and conditioned values of voltage and phase including values smoothed for use by the phase control loop.

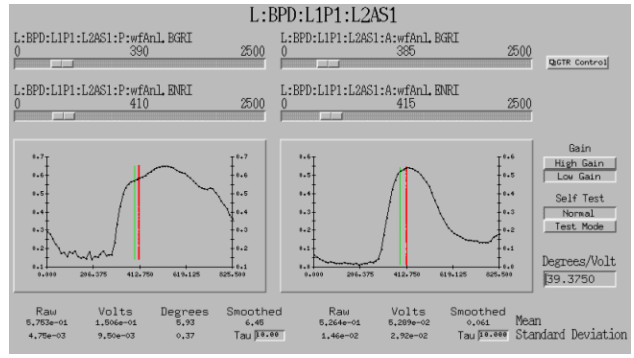

Figure 7: Phase detector calibration screen

CONCLUSION

Initial measurements and tests of the linac beam-to-rf phase detector system were found to have good performance over a wide range of linac operating conditions. Once the beam phase control-law was interfaced with the hardware, beam injection efficiency dramatically improved for top-up operation, and manual phasing is no longer needed by operations personnel. I should note that additional changes will be made in the near future to use a single feedback matrix with the control loop instead of three separate matrices with individual control loops. This should improve injector phase response when power fluctuations of L1 occur.

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