BEAM POSITION MONITORS: HOW TO MEET THE SPECIFICATIONS OF THE MOST RECENT ACCELERATORS*

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Abstract

Modern particle accelerators must operate with increasingly restrictive beam stability requirements. Synchrotron light sources require sub-micron stability for time periods extending to one week and for frequencies up to 1 kHz and beyond, and FELs need similar levels of shot-to-shot reproducibility. A variety of beam position monitor (BPM) technologies used at synchrotron light sources, FEL facilities, and other accelerators will be reviewed and future areas of development outlined. This will include an overview of analog vs. digital downconversion, including data acquisition and processing techniques. Orbit and trajectory feedback systems using modern field-programmable gate array technology and dedicated fast data networks have been developed to take advantage of high-speed BPM data streams and will be described.

INTRODUCTION

Of recent accelerators, synchrotron light sources, including storage rings, free-electron lasers (FELs) and energy recovery linacs (ERLs) have some of the strictest requirements on transverse beam stability. Shown in Table 1 are requirements collected from various design documents.

Table 1: Stability Requirements

Facility	Stability Requirement (microns rms)	Bandwidth
Cornell ERL [1]	0.3	1 kHz
LCLS-II FEL [2]	< 1.0	60 Hz
E-XFEL [3]	3.0	> 1 kHz
SwissFEL [4]	< 1.0	50 Hz
APS upgrade [5]	0.4 / 0.8	200 Hz / 1 kHz

PICKUP ELECTRODES

Depending on the pulse structure and beam intensity, three types of pickup electrodes are typically used. For high-intensity high-duty-cycle beams such as those seen in a storage ring or ERL, capacitive button pickups are used for beam position monitoring, while stripline pickups can be used for high-sensitivity applications such as tune measurement or multibunch feedback. With a superconducting linac (for example the European x-ray FEL, which uses lower-duty-cycle (< 1%) high-intensity pulse trains), stripline pickups present larger signals to the processing electronics for intra-bunch-train feedback, while cavity BPMs are needed to achieve 100 nanoradian-scale trajectory straightness in the undulator hall. For low-intensity and low-duty-cycle machines, such as LCLS (single pulse, 120 Hz maximum), cavity-based BPMs are used to allow for sub-micron resolution on a single shot within the undulator hall, while stripline pickups are used in the upstream linac.

Button-style Pickup Electrodes

Shown in Fig. 1 are typical flange-mounted pickup electrodes. Often they are welded directly to the vacuum chamber. They are usually used in sets of four to detect both horizontal and vertical position.

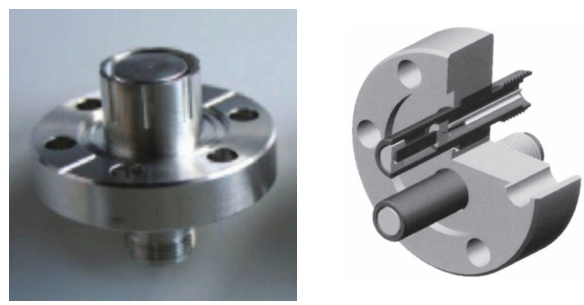

Figure 1: Examples of capacitive button pickup electrodes. Warm flange-mounted E-XFEL design (left), and small-aperture 4-mm-diameter double-button design used on small-gap insertion device vacuum chambers at the Advanced Photon Source (APS) (right).

Capacitive pickups range in size from 4 mm up to a few cm, and have weak coupling to the beam. They are most useful with bunch charge ranging from a nC up to tens of nC, with bunch duty cycle ranging from hundreds of kHz (e.g., the revolution frequency) to hundreds of MHz (the rf frequency). Their low impedance allows many of them to be used with small-aperture vacuum chambers for enhanced position resolution.

Stripline Pickup Electrodes

Shown in Fig. 2 is an example of a stripline pickup / kicker [6].

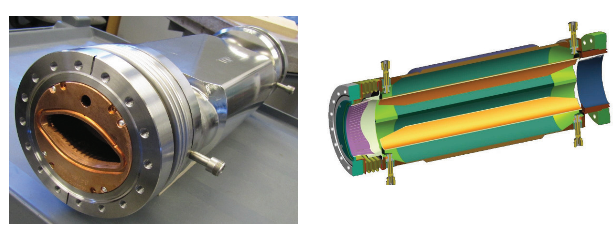

Figure 2: APS horizontal stripline used for fast feedback.

Striplines are sometimes known as traveling wave devices or directional coupler pickups since they can be used in colliding-beam machines to detect counter-propagating beams. In this instance, access to both ends of the device

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allow for its use either as a pickup (from the upstream connectors) or as a kicker (driving into the downstream connectors). This particular device is optimized as a kicker, with the upstream port terminated into a high-power attenuator from which both the beam signal and the drive amplifier can be simultaneously monitored. When used strictly as pickups, the port opposite to the signal port can be shorted, left open, or terminated. If shorted or opened, the device orientation is immaterial, since the power has nowhere to go but out the provided connector, perhaps after a reflection.

For a single bunch, striplines generate a bipolar pulse, with the time between upward- and downward-going half-pulses determined by the stripline length. Striplines usually couple quite strongly to the beam and, as such, care is required to account for beam-generated heating. The fact that they produce relatively large signals allows for high sensitivity to beam position even for relatively large apertures and small bunch intensity. Determination of beam position involves computing a difference of large numbers accurately, which is difficult considering small variabilities in downconversion stages, hybrids, buffer amplifiers, attenuators, connectors, and the like. While striplines have adequate sensitivity to small beam motions with small bunch charge, it is challenging to obtain long-term DC stability using them, or to provide an accurate absolute position measurement relative to external fiducials.

Cavity-Based Pickup Electrodes

Shown in Fig. 3 and 4 is the LCLS cavity BPM [7].

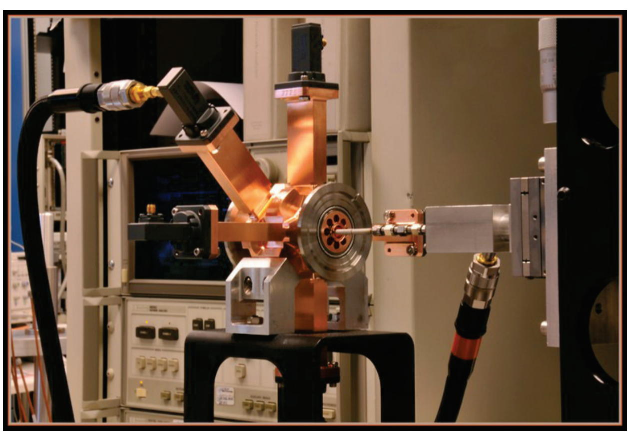

Figure 3: LCLS cavity BPM under test.

The LCLS was one of the first modern accelerators to employ large numbers of cavity BPMs in a trajectory feedback system. Due to the dipole mode symmetry, the signal generated is directly proportional to the product of transverse beam position and intensity, obviating the need for rf hybrids or other differencing schemes necessary for buttons or striplines. A second nearby monopole cavity set to resonate at the same frequency as the dipole cavity is generally used to provide pulse intensity for normalization. The LCLS design was demonstrated to have single-pulse resolution in the range from 150 nm to 0.5 microns at 200-pC pulse charge for a set of 33 BPMs, with highly repeatable electrical center [8].

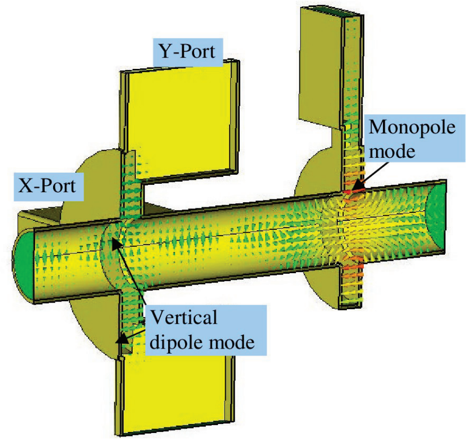

Figure 4: LCLS cavity BPM electromagnetic model.

For the LCLS cavity BPMs, copper was chosen to have a relatively high Q, and waveguides vs. coaxial cables were used to maximize available signal at the in-tunnel processing electronics. LCLS uses single pulses arriving at 120 Hz maximum duty cycle, so the high Q (3500) results in a damped sinusoid at 11.384 GHz lasting a few hundred nanoseconds.

In parallel with the LCLS cavity BPM development, a steel C-band (4.76 GHz) cavity BPM was developed at the SPring-8 SCSS prototype accelerator for the presently-operating SPring-8 Angstrom Compact Free-Electron Laser (SACLA) facility [9]. The European X-ray FEL (E-XFEL) project is adopting a very similar design, scaled up to S-band (3.30 GHz). Shown in Fig. 5 is the small-aperture S-band version [10].

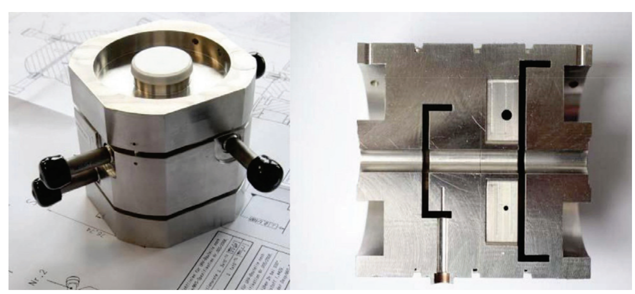

Figure 5: Steel S-band cavity BPM for E-XFEL.

By going to steel vs. copper, the Q is lowered from 3500 to about 70, implying an impulse response on the order of tens of nanoseconds. This allows sufficient bandwidth to resolve closely spaced bunches. This design also makes use of coaxial connectors that are more convenient and acceptable at C- or S-band vs. X-band for which they are generally too lossy.

Cylindrical cavity BPMs have the characteristic of the horizontal and vertical modes being very nearly degenerate. Very tight machining tolerances are required to achieve sufficient isolation between nominally orthogonal ports.

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ELECTRONICS AND DATA ACQUISITION

Shown in Table 2 is a summary of the styles of rf front ends for presently operating in-progress accelerator facilities and commercially available hardware.

Table 2: BPM rf Front-End Methodologies

Facility	Operating Frequency	Method
LCLS	11.384 GHz	RF Downconversion to 20-40 MHz
NSLS-II	500 MHz	Digital Downconversion $F_s = 117$ MHz
E-XFEL[3]	3.30 GHz	RF Downconversion to DC; I/Q
SACLA	4.76 GHz	
I-Tech Libera Brilliance+	500 MHz, 352 MHz, others	Digital Downconversion
APS	352 MHz	AM / PM Log/Limiter + 88 MS/sec sampling

Nearly all beam position monitor systems use some form of buffering or rf signal processing prior to digitization. The trend has been to move the digitizers closer and closer to the pickup electrodes in the signal processing chain. Digitizers with 250 MS/sec sample rate at 16 bits are now becoming available, with input analog signal bandwidth exceeding 650 MHz (e.g., reference [11]). Dropping to 12 bits, ADCs that sample above 3.5 GS/sec are available. In an ideal world, the pickup electrodes would be sampled directly by identical ADCs, perhaps with some simple analog filtering, using all digital processing thereafter. Unfortunately, if the intent is to use real-time digital signal processing, field-programmable gate arrays (FPGAs) are limited to cycle times of a few hundred MHz, explaining the need for undersampling / digital downconversion with signals above about 500 MHz.

Storage Ring BPMs

It is essential to keep the overall purpose of a BPM system in mind at the design phase [12,13]. One argument for fast sampling in a multibunch storage ring where correction bandwidth below 1 kHz is desired is to improve noise floor in the narrow correction bandwidth. There are, however, many capable digitizers operating with 24 bits and sample rates of hundreds of kHz. From a white noise perspective, the slower 24-bit solution wins: noise floor reduction going from 100 MS/sec to 100 kS/sec goes as the square root of the ratio of bandwidths, i.e., a factor of 31 in this case, while the bit resolution going from 16 to 24 bits gives an improvement factor of 256. Once the electronics noise floor is sufficiently below the desired stability level, emphasis should move from noise floor reductions to available feature set, which fast sampling and FPGAs offer in spades. Turn-by-turn and even bunch-by-bunch data streams open up a lot of potential, e.g., real-time betatron tune monitoring, multi-bunch instability monitoring, injection trajectory tracking and correction, post-mortem analysis, and many other capabilities.

Because BPMs in storage rings generally use buttons or striplines, channel matching is critical in the determination of beam position from individual buttons or striplines. This has been a hot topic for the past couple of decades, since long-term stability requires channel matching at the level of 0.01 dB and below. A number of strategies are used for this: rf hybrids; injection of pilot tones or pulses, either off frequency or between beam pulses; or multiplexing schemes.

At the APS, in-tunnel rf hybrids transmit button difference and sum signals at 352-MHz center frequency and 10-MHz bandwidth to amplitude-to-phase (AM/PM) conversion electronics outside the tunnel, the so-called monopulse receivers [14]. The AM/PM technique is a nice method to compute the ratio delta / sum at the IF (10 MHz) signal bandwidth, although it suffers from intensity dependence and timing sensitivity. After sampling at 88 MHz, sample selection and digital filtering are applied before sending the signals on to the fast closed-orbit feedback system and other data streams [15]. A clever trick developed at CERN is to use an rf hybrid combiner with a delay line on one leg to put two pickup signal pulses onto the same coaxial line. Doing this twice to get e.g., A + delayed B vs. B + delayed A, results in a pair of bipolar signals. The time between zero crossings of these two signals then becomes a measure of normalized beam position, i.e., a differential amplitude-to-time converter [16]. Use of narrowband rf filters could be used to acquire a narrower-band amplitude-to-phase system.

At NSLS-II, a pilot tone scheme is used to combine off-frequency calibration signals in the tunnel with the beam signals. Their detection is used in the digital domain to correct for variations in channel gain [17]. Sensitivity of the rf front end to small changes in frequency makes the off-frequency pilot tone method rather challenging.

A well-known multiplexing scheme is engendered by the multiplexed receiver invented by Bittner and Biscardi in the 1980s [18] and now marketed by Bergoz instrumentation. In this scheme, each of four button signals are switched in turn to a common rf receiver at some tens of kHz. An analog difference coupled to an automatic gain control regulating the receiver gain for constant analog sum provides an accurate DC measurement of normalized beam position, albeit with poor noise performance in comparison to modern systems. The rf front end for the Instrumentation Technologies (I-Tech) electron, brilliance, and brilliance+ series of BPM processors makes use of a proprietary cross-bar switching system that cycles the four pickup signals through a set of four rf channels in sequence. Fast sampling at approx. 120 MS/sec together with FPGA logic to deal with the switching, attenuation, filtering, and other logistical tasks provide a high-performance system with excellent noise floor (2 nm /√Hz) and long-term stability at the level of hundreds of nanometers over a 24-

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hour period [19]. Many synchrotron light sources use I-Tech components almost exclusively.

BPMs for Linacs and FEL Facilities

The challenges for linacs and FELs are significantly different than for storage rings. For FELs, the particle and photon beams must overlap on the scale of a gain length, usually some tens of meters, to support lasing, but transverse beam sizes are at the level of tens of microns. They tend to use small (< 1 nC), relatively widely spaced bunches or bunch trains, so there is insufficient signal strength for storage ring BPM systems, which are geared more for cw-type processing, e.g., narrow-band detection and processing. The LCLS operates with a fraction of a nC of charge in a single bunch and maximum repetition rate of 120 Hz. For superconducting linacs such as that being built for the European XFEL, much higher duty cycles are planned, with 650-microsecond-long 1.3-GHz bunch trains pulsed at 10 Hz. This is still less than 1% duty cycle, and the average current is 5 mA vs. hundreds of mA for storage rings. The intent is to perform trajectory control within the same bunch train.

FEL beam characteristics drove the development of cavity-style BPMs, which couple very strongly to the beam in comparison to button-style pickups. Because the position-sensitive cavity mode outputs a signal directly proportional to the product of beam position offset and beam intensity, and because they can be machined to extremely tight tolerances, they provide excellent absolute position determination with respect to external fiducials. Beam-based alignment techniques are also used in addition to further optimize FEL performance.

Using electronics developed at the Paul Scherrer Institute, the electronics shown in Fig. 6 together with the cavity BPM design shown in Fig. 5 were demonstrated to have a single-shot resolution of 183 nm rms. This was accomplished using steel vs. copper, and in spite of an operating frequency significantly below that for LCLS [20].

To give an idea of the types of approaches being taken, shown in Figs. 6 - 10 show a variety of linac BPM electronics configurations that are either in use or have been tested with beam. Note that the E-XFEL and SACLA facilities have taken the path using in-phase / quadrature (I/Q) downconversion, while the LCLS is directly digitizing the down-converted signals and working with amplitudes and phases of the BPM and reference cavities to extract normalized beam position.

At SLAC, the data acquisition shown in Fig. 8 is now in the µTCA form factor, which is used generally for low-level rf control and diagnostics. In this instance the rear transition module (RTM) on the left relays up to ten rf signals to the commercial 119 MS/sec digitizer on the right. In this application, the cavity difference and reference cavity signals are digitized, and an FPGA on the digitizer board performs the computation of normalized beam position.

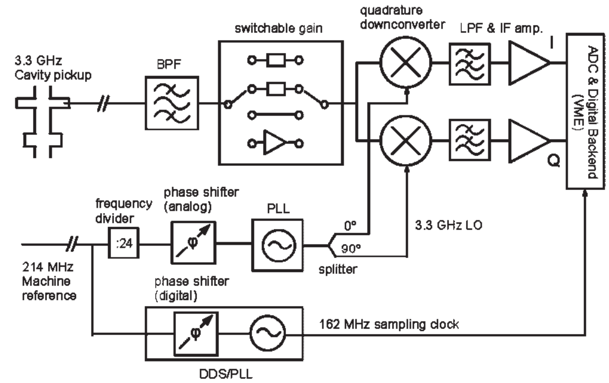

Figure 6: E-XFEL cavity BPM test electronics [20].

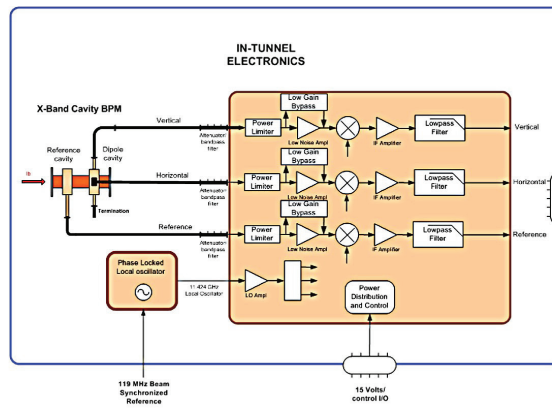

Figure 7: LCLS cavity BPM electronics [8].

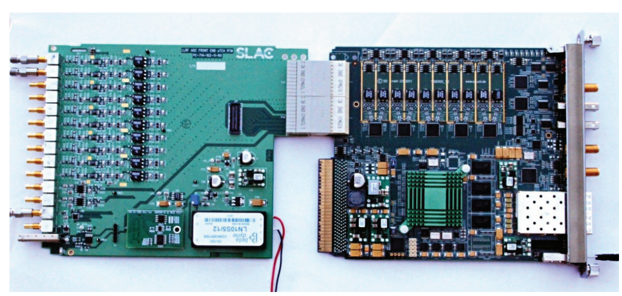

Figure 8: Upgraded µTCA LCLS BPM rear transition module (RTM, left), and 119 MS/sec 16-bit digitizer and FPGA processor (right) [21].

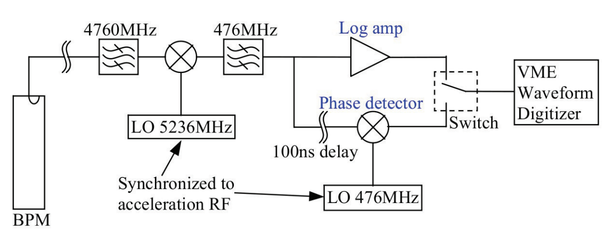

Figure 9: SCSS prototype cavity BPM electronics [9].

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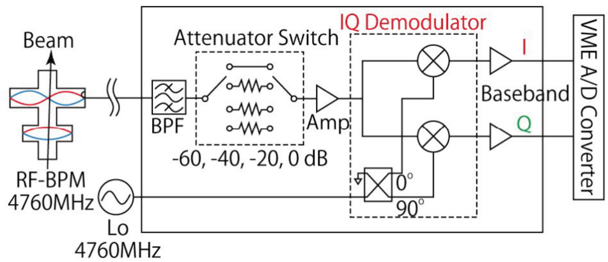

Figure 10: SACLA cavity BPM electronics [22].

Shown in Fig. 11. is an example of a modern FPGA, the Xilinx ZC706 evaluation board. The signal processing potential of these modern components is immense, including features like dual on-chip ARM CPUs, loads of memory, and many interfacing options. The FPGA mezzanine card (FMC) connectors along the top edge of the board can be connected to digitizers, digital-to-analog converters (DACs), small-form-factor pluggable (SFP) ports, etc., with many new off-the-shelf components becoming available.

Data can be clocked into the FPGA via the FMC ports in parallel, or using new serial protocols such as the Joint Electron Devices Engineering 204 (JESD204) standard, which allows line data rates above 10 Gb/sec using multi-gigabit transceivers. Many reference designs are available from the FPGA vendors, which aids considerably in the design effort. With great power comes great responsibility, however, and a significant comittment in terms of human effort is needed to synthesize advanced functionality using these devices. For example, shown in Fig. 12 is an implementation of the FPGA above, applied to a global closed-orbit feedback system upgrade at the APS.

MECHANICAL STABILITY

At the level of beam stability required for modern accelerators, having the best BPM electronics and data acquisition is of no avail if the pickup electrodes / vacuum components are mechanically unstable. Sub-micron mechanical stability in the presence of variable air and water temperature, beam current, vibration, and diffusive ground motion is particularly challenging. With regard to thermally induced motion, given that most materials that accelerators are contructed from have thermal expansion coefficients near 10^{-5} / deg. C, it would require temperature stability at the level of +/- 0.01 °C to achieve mechanical stability down below 0.2 microns. Heroic measures can result in air temperature stability at "only" the level of +/- 0.05 °C, so additional methods are necessary [23,24]. A critical development for storage ring-based light sources is top-up operation, used to regulate the stored beam current and consequently the beam-induced thermal loads at the level of 1% or better. Even so, micron-scale mechanical motion has been clearly seen at the APS when top-up is interrupted, resulting in a 2% drop in beam current [25].

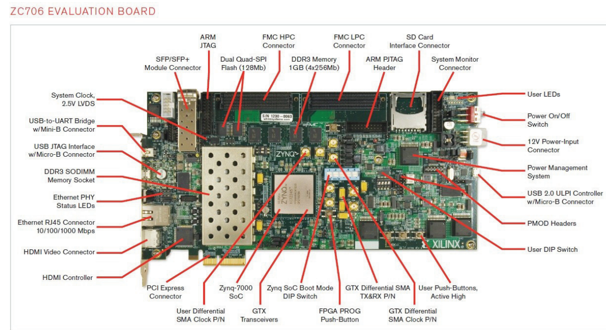

Figure 11: A modern FPGA evaluation board.

Shown in Fig. 13 is the mechanical motion sensing concept implemented at LCLS [23]. In this case a hydrostatic leveling system (HLS) was used in conjunction with a pair of wires strung through a network of wire position monitors (WPMs) to assure the straightness of critical components along the length of the FEL undulator. The WPM sensors physically resemble BPM pickup electrodes, but with a current-carrying wire in place of the charged-particle beam. Sytematic errors impacting the WPM array have to do also with tunnel temperature variations, wire sag, etc. The hydrostatic leveling sensors used were integrated with a movable support structure. Settling times following girder motion are on the order of several hours, making any closed-loop mechanical feedback system problematic.

Hydrostatic leveling systems are best suited for tracking of small motions over longer time scales, such as diffusive ground motion [25]. Their use, in combination with capacitive proximity sensors and super-invar supports, is planned to monitor the vertical mechanical motion of critical BPM pickup electrodes at the APS [26]. Ground motion has been measured at the SOLEIL light source to be at the level of 50 µm/10 m/year using a hydrostatic leveling system[27] . Achieving long-term stability below 0.5 microns with an HLS is extremely challenging and a subject of ongoing research.

CONCLUSIONS

Modern accelerators will require a degree of beam stability at the level of hundreds of nanometers or less in the coming years. There are a number of new and old technologies that are now necessary to meet these tight specifications, including fast-sampling digitizers, advanced realt-time digital processing methods using both conventional CPUs and FPGAs, and auxiliary equipment to compensate for thermal and mechanical instability.

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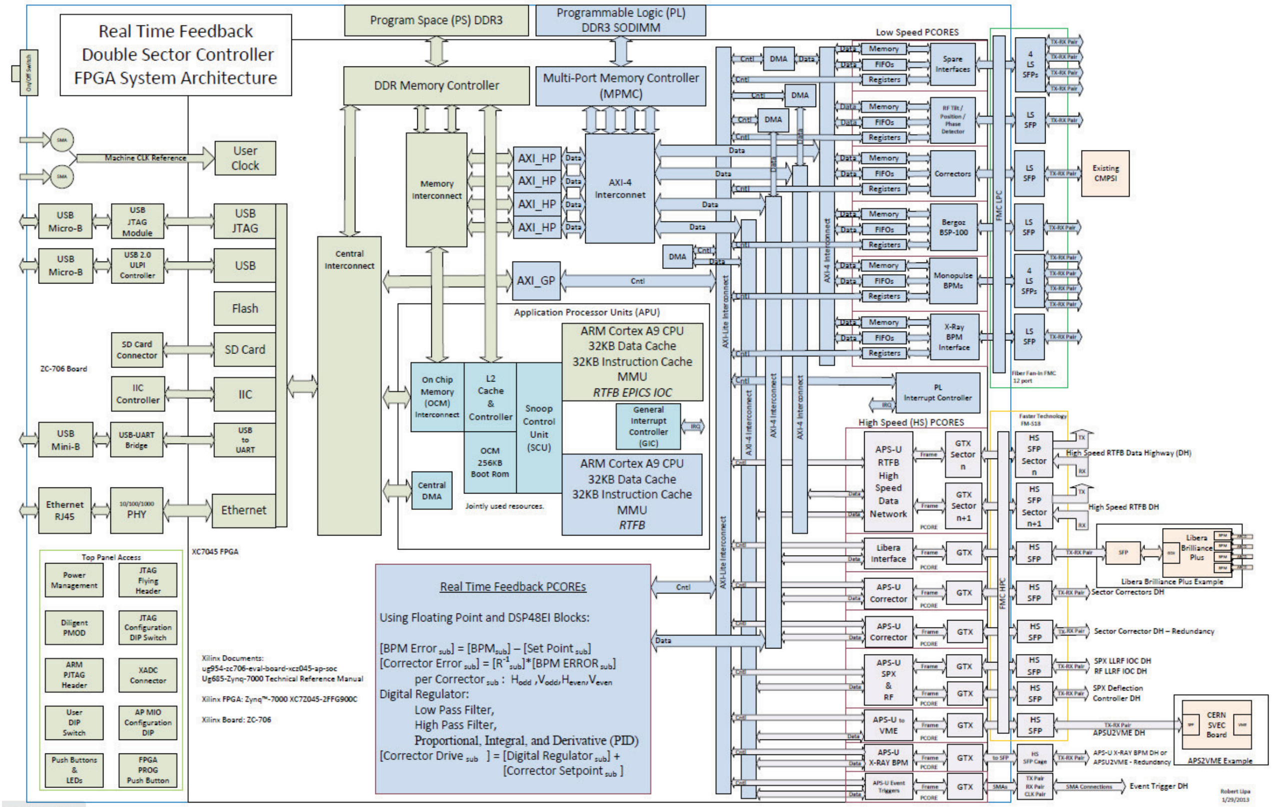

Figure 12: Advanced Photon Source real-time feedback system upgrade FPGA architecture.

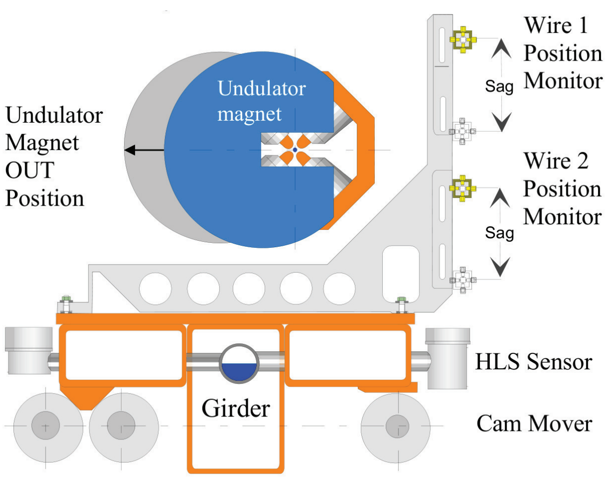

Figure 13: Mechanical motion sensing for LCLS.

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