LCLS RESONANT CAVITY BEAM POSITION MONITORS *

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Abstract

The Linac Coherent Light Source (LCLS) is a free-electron laser (FEL) at SLAC producing coherent 1.5 Å x-rays. This requires precise, stable alignment of the electron and photon beams in the undulator. We describe construction and operational experience of the beam position monitor (BPM) system which allows the required alignment to be established and maintained. Each X-band cavity BPM employs a TM_{010} monopole reference cavity and a single TM_{110} dipole cavity detecting both horizontal and vertical beam position. The processing electronics feature low-noise single-stage three-channel heterodyne receivers with selectable gain and a phase-locked local oscillator. Sub-micron position resolution is required for a single-bunch beam of 200 pC. We discuss the specifications, commissioning and performance of 36 installed BPMs. Single shot resolutions have been measured to be about 200 nm rms at a beam charge of 200 pC.

FEL COMMISSIONING

LCLS photocathode RF gun and injector systems were commissioned in 2007, followed by linac and bunch compressor systems in 2008. Beam was first taken through the undulator beamline (with no undulators installed) in December, 2008. After aligning each undulator segment individually, 21 undulator magnets were inserted in April 2009. We observed lasing at 1.5 Angstroms essentially immediately [1].

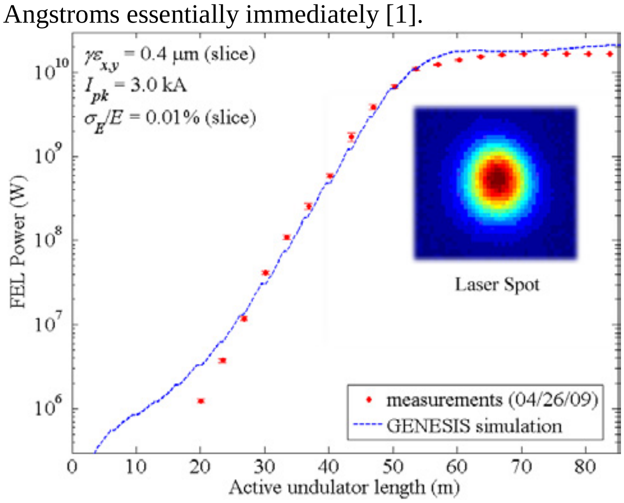

Figure 1: FEL gain length measurement at 1.5 Å made by kicking the beam after each undulator sequentially (red points), prediction (blue line) and YAG screen laser spot.

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BPM REQUIREMENTS

Laser saturation in the LCLS FEL requires the electron and photon beams be collinear in the 131 meter-long undulator to about 10% of the 37 µm rms transverse beam spot size over scales of the FEL amplitude gain length (~4m) [2,3]. BPM system requirements include centering accuracy, reproducibility, small physical size, radiation hardness, and sub-micron resolution at 200 pC.

SYSTEM DESIGN

The major subsystems for the LCLS undulator BPM system are the cavity BPM, receiver, and data acquisition components. The cavity BPM and downconverter reside in the tunnel while the analog-to-digital converters (ADC) and processing electronics are in surface buildings.

Thirty-four BPMs are installed on undulator girders while two are placed in the linac-to-undulator (LTU) transport line. The BPMs provide stable and repeatable beam position data for both planes on a pulse-to-pulse basis for up to a 120-Hz repetition rate.

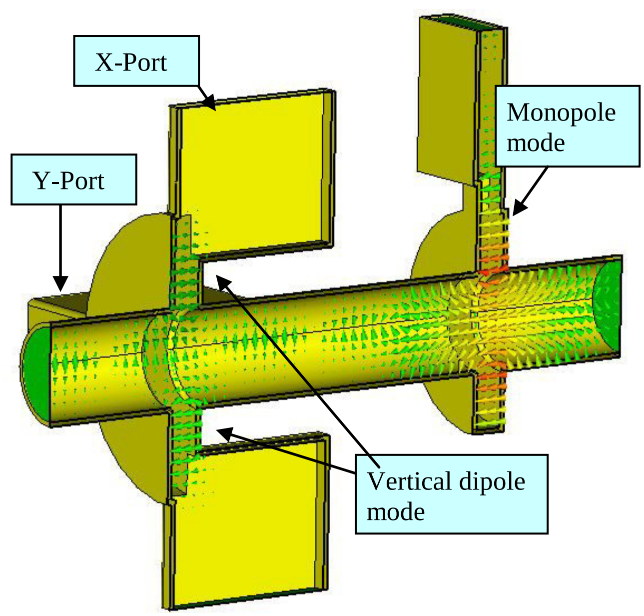

Figure 2: BPM Cavity schematic with electric fields of position (dipole) and reference (monopole) cavities.

X-Band Cavity

Figure 2 shows the electric field vectors in the cavity BPM simulated when the beam is offset[4,5]. Beam passes through the monopole reference cavity on the right, exciting the TM_{010} monopole mode signal resonant at 11.384 GHz. The TM_{110} dipole cavity is located 36 mm downstream through the 10-mm-diameter beam pipe. Monopole-dipole isolation is 130 dB, due to a below-cutoff beampipe, copper losses, and poor coupling of the TM beampipe mode to the cavity dipole mode.

The position cavity dipole mode is resonant at 11.384 GHz, its output proportional to the product of beam position and bunch charge. The X and Y position modes are nominally degenerate in frequency, with the appropriate component chosen by the geometry of the couplers. The dipole coupler geometry is chosen to reject (the generally larger) monopole modes[4-8].

Iris couplers are precisely electrical discharge machined (EDM) into a solid copper block to ensure repeatable and accurate coupling. This technique ensures that the waveguide braze has little or no effect on the cavity performance. The dipole cavity was designed as a 4-port device with two opposing X couplers orthogonal to two opposing Y couplers. This is useful for cold testing and preserves symmetry. Unused ports are terminated with the potential for using them for future diagnostics.

Forty BPMs were built to a tolerance of ±10 MHz of design frequency. Accomplishing this without demanding unrealistic machining tolerances requires tuning. First, parts are inspected and cleaned. End caps are fitted to the body and clamped to a test fixture. Frequency and bandwidths are measured, then endcap beam pipe inner diameters are micro-machined as needed. BPMs are reassembled and checked to ensure the cavities are within the tolerance of +0, -10 MHz to compensate for frequency shift in the brazing process. End cap brazing was strictly controlled and a 10 MHz frequency shift was typically measured after the braze.

Dipole cavity final tuning was done with a sliding hammer in up to eight boss locations in the endcap to dimple the wall of the cavity. Four tuners in-line with the iris couplers are used for frequency adjustment. Four cross-talk tuners on the dipole cavity end cap are located at 45 degrees to the couplers. They reorient the dipole mode such that the modes are symmetric about the vertical and horizontal planes. These tuners are used to set the symmetry of the modes and optimize the isolation between planes.

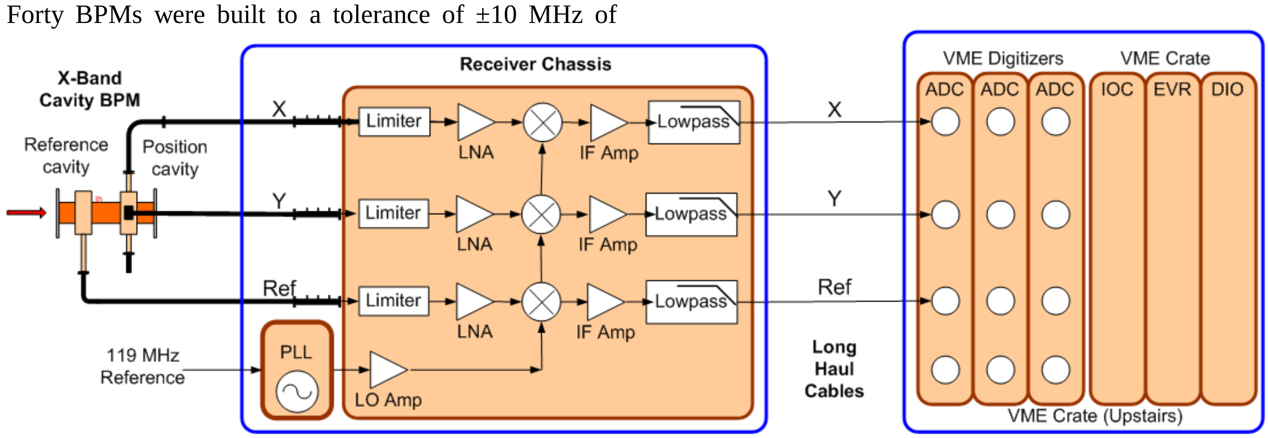

Figure 3: System block diagram. The receiver is mounted on the undulator stand while the digitizers are upstairs.

Receiver

A three-channel heterodyne receiver (Figure 3) mixes incoming X-band signals to a 25-50 MHz intermediate (IF) frequency. Each receiver input is limited to a 35 MHz bandwidth around 11.384 GHz. Filters also provide a broadband -10 dB return loss match to the cavities. Out-of-band filtering of -60 dB prevents higher modes from saturating the receiver input. Signals are first amplified in a low noise stage (LNA), then translated to the lower IF by mixing with a local oscillator (LO). The LNA is protected against high-power surges by a limiter that is rated at 50 W peak. The dynamic range of the electronics is extended by switching the gain of the receiver. Overall conversion gain/loss is +10 dB in the high gain mode and -15 dB in low gain. The LO is a low noise phase-locked dielectric resonant oscillator (PDRO) locked to the 119-MHz timing reference [9].

Digitizer

The X, Y, and Reference signals are digitized to 16 bits at a 119 MHz sampling rate in 4-channel VME digitizers designed and built at SLAC. Waveforms are transmitted over the backplane to a VME processor which reduces raw waveforms to beam position and charge.

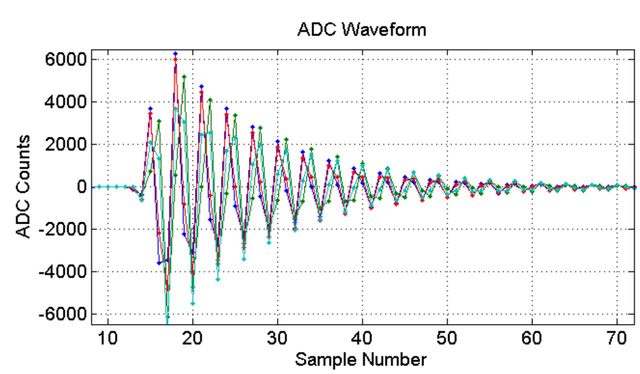

Figure 4: BPM raw waveforms sampled at 119 MHz.

ALGORITHM

Beam charge at each BPM is estimated by scaling the amplitude of the reference cavity. Each position waveform is reduced to amplitude and phase in an appropriate bandwidth around the cavity frequency. Normalized amplitudes are formed by dividing by the amplitude of the reference cavity and rotating by its phase. Position is estimated by rotating this complex normalized amplitude by a phase established with beam calibration, projecting out the position component, and scaling to microns. Finally a linear transformation accounts for potential physical rotations of the BPM, non-orthogonality of the X and Y ports, and coupling between the ports.

CALIBRATION

Recovering beam position and charge from the digitized cavity waveforms requires knowledge of cavity phases and scales. Undulator BPMs are calibrated by mechanically moving the girder on which the BPM is fixed, fitting the phase and amplitude of the position signals normalized in phase and amplitude to the reference. Presently production BPM code calibrates by moving BPMs in 100 micron steps, much larger than typical 10 to 20 micron beam jitter. In principle we can use uncalibrated measurements from nearby BPMs to remove beam jitter during calibration, and calibrate with motion below alignment tolerances. The results of such a small-move calibration are shown in Figure 5. Transfer line BPMs, which are not mounted on movers, are calibrated by moving the beam on the BPM with a corrector.

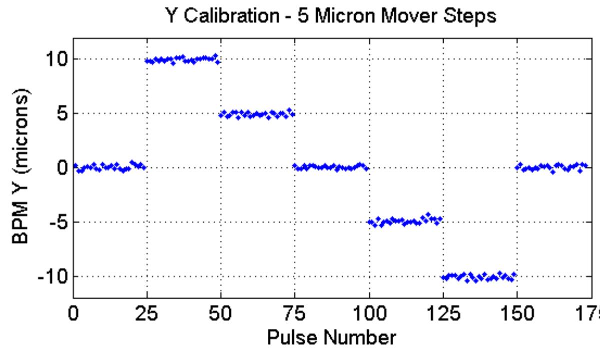

Figure 5: Calibration moving BPM in 5 micron steps.

PERFORMANCE

Resolution

We evaluate BPM resolution in the presence of >10 micron beam jitter by acquiring beam position synchronously over many beam pulses from many BPMs. A least-squares fit predicts position in each BPM as a linear combination of position measured in neighboring BPMs. Figure 6 shows this procedure applied to the 26th cavity BPM. It shows Y measured 120 times in 3 adjacent BPMs, Y versus that predicted from four closest neighbors, and the fit residual, or difference between measurement and prediction. The scatter of fit residual is an estimate of BPM resolution. Also plotted is a histogram of Y resolutions for 33 BPMs.

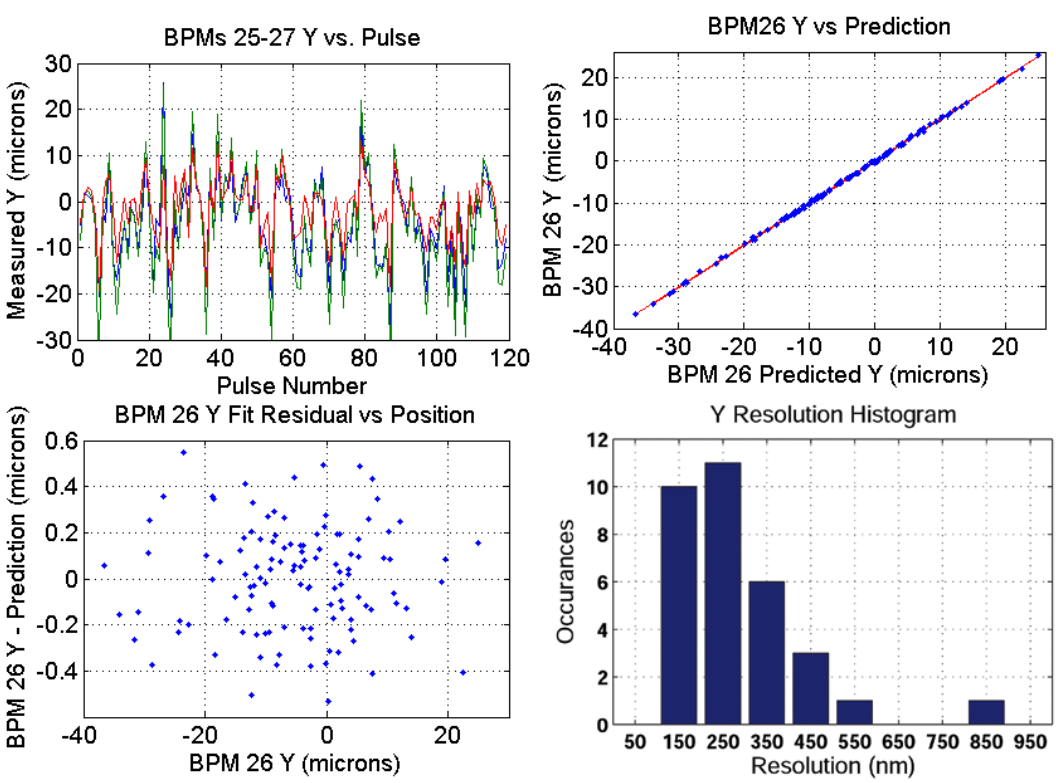

Figure 6: Upper-left: Y position measured at adjacent BPMs for 120 pulses. Upper right: Y at BPM26 vs. best fit prediction from its neighbors. Lower left: Fit residual, Lower right: Histogram of measured BPM resolutions.

Stability

We evaluate two aspects of BPM stability. Calibration stability is evaluated by repeatedly calibrating about once a shift over three days. We find the scale drifting by less than 0.5% in 24 hours and the phase stable to 0.1 degree. Secondly we record groups of about 100 beam pulses every 20 minutes over a 3.5 day period using a single calibration. Using adjacent BPMs to remove beam jitter, we plot measured beam position at each BPM. Typical stability is better than 1 micron drift over 24 hours.

Gain Drifts

Since LCLS turn-on the cavity BPM receivers have been losing gain. Figure 7 shows gains of all the BPMs as of April 20th. There were several theories why the gain was changing: radiation, over-voltage, beam excursion, higher-order modes (HOM), or hydrogen poisoning of the GaAs MMIC and mixers. Radiation damage seems unlikely; the dose rate was measured to be less than 0.1R/week. GaAs devices are radiation hard to ~10kR. The receiver sits below the beam pipe. The damage units are not correlated with high dose areas. Likewise over-voltage damage seems unlikely, as both the reference and position channel saw damage. The reference channel is sensitive to charge not position. With extremely short bunches in the LCLS, this excites HOMs in the THz region. It is important to note, that the reference cavity channel has a 12dB pad on it input and it was getting damaged.

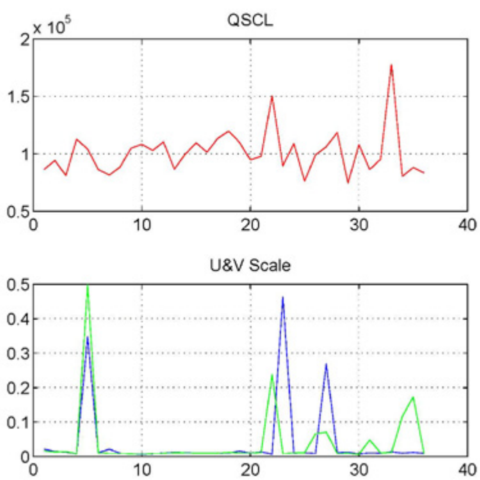

Figure 7: After ten receivers were modified this is the gains of all BPMs. The red curve is the gain of the reference channel and the blue and green are the gain of the position channels.

The most likely scenarios have the GaAs MMIC amplifiers getting damaged due to hydrogen poisoning. The front-end receiver was made by MITEQ using a GaAs MMIC low-noise amplifier (LNA) from Hittite. The datasheet warns that if these amplifiers are installed in a hermetically sealed package then hydrogen getter material should be incorporated [10]. Figure 8 is a picture of the front-end receiver with the covers off the LNA.

Figure 8: Cavity BPM recevier module

The belief is that molecular hydrogen is converted to atomic hydrogen through a catalytic reaction with platinum or palladium in the gate structure and diffuses into the Schottky metal and channel. There have been at least eighteen receivers affected so far. Some of the LNA amplifiers have had the drain source current change as much as 20%. With the use of GaAs devices on the rise due to the higher speed performance and low power consumption, the reliability of GaAS devices have been analyzed [11]. The Hittite GaAs MMIC has a structure shown in figure 9. The gate width of the device is 0.2um and a length of 0.4mm with a noise figure of 1.75dB. The gate length is what set the high frequency limit while the gate width defines the gain and the drain source current. Thus the hydrogen affects the gate width which changes the gain and the drain source current. The Isolation implant maximizes the gate isolation.

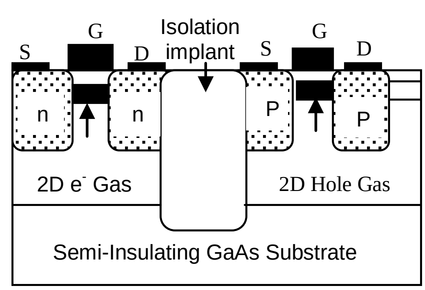

Figure 9: Block Diagram of the GaAs Structure

Before the 2010 downtime, we recorded the gain change on BPM17 and is illustrated in figure 9. In the 180days the gain changed by a factor of 6.

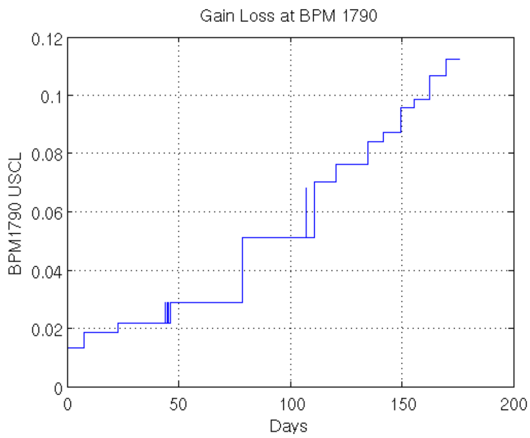

Figure 10: Gain variation over 180 days for BPM17

The solution to the hydrogen poisoning problem that was chosen was to replace the all of the LNA that have shown a decrease in gain in ten RF receivers. To lower the Hydrogen level trapped in the enclosure by baking the enclosure at 100 degree C for 100 hours in a dry nitrogen environment. After the enclosures were baked, the Hydrogen getter material was adhered to the enclosure lid. Finally the RF circuit was assembled to the housing. The LNA was tested before the getter material was activated. Due to the delayed turn on of the LCLS and the completion of CD4 we have not been able to do long time gain studies of the repaired receivers. We hope to accomplish this in the near future.

REFERENCES

[1] P. Emma, "First Lasing of the LCLS X-Ray FEL at 1.5 A", to be published in Proceedings of PAC09, May, 2009.

[2] R. Hettel, et al, "Investigation of Beam Alignment Monitor Technologies for the LCLS FEL Undulator," BIW98, Stanford CA, May 1998, p. 413.

[3] P. Emma, J. Wu, "Trajectory Stability Modelling and Tolerances in the LCLS," EPAC06, Edinburgh, Scotland, June 2006, p. 151.

[4] R. Lill, et al, "Linac Coherent Light Source Undulator RF BPM System," FEL06, Berlin, Germany, July 2006, p. 706.

[5] G. Waldschmidt, R. Lill, L. Morrison, "Electromagnetic Design of the RF Cavity Beam Position Monitor for the LCLS", PAC 07, Albuquerque NM, May 2007, p. 1153.

[6] V. Balakin, "Experimental Results From a Microwave Cavity Beam Position Monitor", PAC99, New York, May 1999, p. 461.

[7] Z. Li, et al "Cavity BPM with Dipole-Mode-Selective Coupler", PAC03, Portland OR, May 2003, http://accelconf.web.cern.ch/AccelConf/p03/PAPERS/ROAB004.PDF

[8] S. Walston, et al, "Performance of a High Resolution Cavity Beam Position Monitor System." NIM A578, 2007.

[9] R. Lill, G. Waldschmidt, D. Walters, L. Morrison, S. Smith, "Design and Performance of the LCLS Cavity BPM System", PAC07, Albuquerque NM, p. 1153.

[10] Hittite application note: Hydrogen Effects On GaAs pHEMT Devices: v00.010

[11] S. Kayali, "Hydrogen Effects on GaAs Device Reliability,"Int. Conf. On GaAs Manufacturing Technology, San Diego,CA, 1996, pp. 80-82.