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PERFORMANCE OF THE SLAC-PAL-VITZROTECH X-BAND CAVITY BPMs IN THE LCLS-II UNDULATOR BEAM LINES*

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Abstract

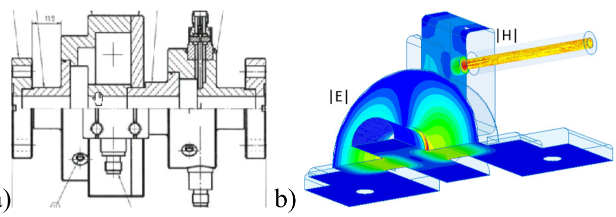
The hard X-ray and soft X-ray undulator beamlines of the LCLS-II X-ray FEL incorporate 65 X-band cavity beam position monitors for accurate tracking of the electron beam trajectories and Beam-Based Alignment. For this crucial function, a design was jointly developed between PAL and SLAC, consisting of a monopole reference cavity and a dipole position cavity, with signals coupled out through coaxial vacuum feed-throughs. For the relatively large quantity needed, the production of completed units was contracted to the Korean company Vitzrotech, who developed the manufacturing process to successfully fabricate the needed quantity. Herein, an overview is given of the production experience, tuning, installation and performance of these devices.

INTRODUCTION

The LCLS-II free electron laser at SLAC requires monitoring of the beam position with sub-micron level resolution in both x and y. The device chosen by the project to achieve this is an X-band cavity beam position monitor, or RFBPM, of a unique configuration whose design was developed over the last couple of decades [1-3]. It consists of two independent resonant cavities, dipole and reference, with signals coupled out through coaxial vacuum feedthroughs. A distinguishing feature benefiting sensitivity is the magnetic coupling of the dipole cavity fields into side waveguide stubs in a way that shields the pickups from the monopole mode [4]. The design adopted had been recently deployed in the PAL-XFEL in Pohang, Korea. For production of the 65 units required in the soft X-ray and hard X-ray undulator beamlines of LCLS-II, the technology was transferred to the Korean industrial firm Vitzrotech in Gyeonggi-do. The full complement of RFBPMs was completed, installed and recently commissioned at SLAC.

DEVICE DESCRIPTION

Developed through a Cooperative Research and Development Agreement (CRADA), with final design by PAL, the 10 cm beamline device passes the beampipe through two resonant pillbox cavities (Fig. 1a). As sensitivity roughly scales with wavelength, an X-band cavity frequency of nominally 11.424 GHz was chosen, equal to four times that of the SLAC normal conducting and PAL S-band linacs. The main cavity operates in the TM_{110} mode. Each polarization component, excited by either an x or y offset of the beam, couples through its radial magnetic field into a pair of slot-coupled longitudinal waveguide stub resonators. Capacitive probes couple signal out through coaxial feedthroughs brazed into the sides of these in a pin-wheel pattern. The smaller second cavity, excited on axis in the fundamental TM_{010} mode, provides a phase reference for the sign of the position cavity signals and an amplitude reference for their bunch charge dependence. Its signal is coupled out through a pair of coaxial feedthroughs magnetically coupled through the edge of its end wall.



a) b)

Figure 1: a) cutaway and external view of RFBPM geometry and b) field simulation of dipole cavity coupling.

Two feedthroughs couple to each of the three cavity modes. Each incorporates a ceramic coaxial vacuum window. Four threaded tuning pins are provided around the edge of each cavity at the 45° positions. Split-ring collars are used with special tuning tools to provide push-pull capability on these pins for fine-tuning of the cavity frequencies (Fig. 2b).

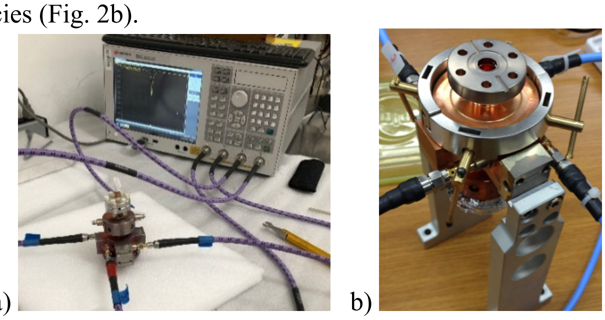

a) b)

Figure 2: a) RF testing on 4-port network analyzer and b) fine tuning of cavity with tuning collar and tools.

PRODUCTION EXPERIENCE

After an initial 3 prototypes were received and one was beam tested, fabrication of production units began at Vitzrotech, in batches of about 15–25. Upon receipt of each batch, acceptance testing at SLAC would proceed via mechanical inspection, vacuum testing and RF characterization (Fig. 2a). Over the 2–3 year production span, with roughly a hundred units produced, problems were encountered and overcome by the vendor, with advisory input from SLAC and from PAL via regular video meetings and a couple of factory visits.

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Some units were lost or needed to be reworked due to learning curve issues with the complicated, multi-stage procedure of brazing together the multiple body parts, flanges, holding blocks, tuning pins and feed-throughs. These were addressed largely by adjustments to temperatures, jigging and the number and arrangement of units in the furnace.

Another issue that required attention was achieving the desired RF coupling, β. The sensitivity of the cavity β to the final brazed pin position was simulated to be on the order of 10% per 100 µms. With fairly broad specification ranges and improved consistency, this concern was overcome. Having two ports per cavity mode allows us to choose the better-coupled one in each pair for cabling, the other being terminated with a coax load.

Cross-talk in the dipole cavity, defined as the relative coupling between orthogonal ports and opposite ports (i.e. *x-y* vs. *x-x* or *y-y*) is required to be below -20 dB in order to independently resolve x and y beam position. Coupling can result from an asymmetry in the dipole cavity where the defining normal mode orientations are not perfectly aligned with the port axes. Some units were received out of specification, despite having passed the factory testing. Fortunately, our tuning procedure at SLAC allowed the coupling to be re-adjusted within specification, along with the mode frequencies themselves.

In addition to the specification of the cavity frequencies all being within 10 MHz of nominal, it is also required that the x and y resonances each be within a couple of megahertz of the reference cavity frequency, due to the effect on the commonly downmixed signal amplitudes. (Toward the end of the program, it became standard procedure to fine-tune the reference cavity during acceptance testing to midway between the dipole frequencies.) Though the dipole cavity frequency can be tuned and cross-talk suppressed, the arrangement of the tuning pins does not facilitate differential tuning along the x and y axes. A handful of units ended up being deemed unusable or held in reserve due to excessive *x-y* frequency spread.

By far the greatest obstacle encountered in the production was the reliability of the feedthrough vacuum windows. With six fragile SMA feedthroughs per RFBPM, this Achilles' heel led to quite a few units either failing acceptance or needing to be replaced due to vacuum leaks showing up during or after installation. Much attention and a number of meetings were focused on this problem, considering such issues as the ceramic braze and the connector pin depth. The infant mortality rate was reduced without significant design modification largely by a combination of a more selective feedthrough quality assurance protocol by Vitzrotech and a more delicate handling protocol at SLAC. The latter included leak-checking one unit at a time, adding straight or angled SMA connectors to the ports to avoid undue stress from multiple cable connections, transporting holder mounted units in a padded Pelican™ case and anchoring the signal cables with a base clamp at installation for stress relief and contact avoidance.

Though the above technical challenges faced in the course of this program are worth documenting, it should be noted that the vendor was always very professional, technically accomplished, accommodating and responsive to concerns. They were a pleasure to interact with on this extended scale production of a laboratory-developed design. It is worth noting to their credit that in the final batch of 18 units delivered not a single failure was encountered.

RF BENCH TESTING RESULTS

Each received RFBPM was cold tested at SLAC for comparison with the vendor factory test data. They were kept under vacuum during this process, which can make a difference on the order of 0.5 MHz in frequency). A 4-port network analyzer (Fig. 2a) facilitated measurement of return loss plots from each dipole port as well as all couplings between ports. The cavity frequencies are found from the dips in the plots, and the apparent port couplings β_{measN} from the standard VSWR technique (after level correction of feed-through round-trip loss, typically ~-0.15 dB. In this calculation, the power emitted from the opposite port is seen as indistinguishably combined with ohmic wall loss. Thus, for each pair of ports coupled to the same mode, the actual port couplings are then calculated as:

$$\beta_{p1} = \frac{1+\beta_{meas2}}{1-\beta_{meas1}\beta_{meas2}}\beta_{meas1}, \text{ and similarly for } \beta_{p2},$$

after which the total external coupling is determined from:

$$\beta_{tot} = \beta_{p1} + \beta_{p2} = \frac{\beta_{meas1}+\beta_{meas2}+2\beta_{meas1}\beta_{meas2}}{1-\beta_{meas1}\beta_{meas2}}.$$

The loaded quality factors are calculated from the 3 dB drop off points of the coupling plots between opposite ports from $Q_L = f_r/\Delta f_{3dB}$, and from these and the total couplings, Q_0 is determined. Table 1 lists the main parameter specifications along with the average values achieved and standard deviations based on data from 84 units.

Table 1: Parameter Specifications and Unit Statistics

Cavity	Param.	Specification	Average	SD
ref.	f_r (GHz)	11.424±0.010	11.4234	.0012
	Q_L	1,700–2,800	2,511	180
	β_{tot}	1.25–2.1	1.486	0.219
	Q_0	5,200–6,700	6,227	542
dipole	f_r (GHz)	11.424±0.010	11.4234	.0017
	Q_L	1,900–3,000	2,425	204
	β_{tot}	1.25–2.1	1.729	0.174
	Q_0	5,800–7,300	6,619	592

INSTALLATION

In preparation for each installation, an RFBPM that has passed all testing and received any required tuning was fitted with straight or an elbow SMA connectors in the orientation appropriate for the installation cable direction (for SXR or HXR), with termination loads on the opposite ports. It was then mounted in an adjustable beamline holder stand (see Fig. 3) integrated with other beamline interspace components, re-checked for vacuum integrity and installed on a girder.

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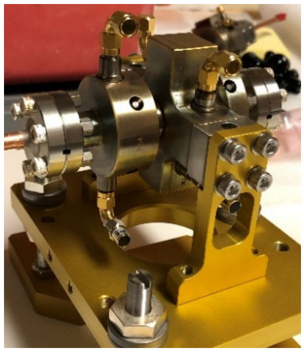

Figure 3: RFBPM ready for beamline integration.

After girder installation and under vacuum, the cavity BPM is measured again to determine the resonant frequencies. If tuning is needed for the front-end electronics, this is performed at this stage.

ELECTRONICS DESIGN

In order to achieve the required performance, the SLAC Technical Innovation Directorate has developed a common hardware and firmware platform for beam instrumentation based on the Advanced Telecommunication Computing Architecture (ATCA) platform with a SLAC built advanced mezzanine card (AMC) along with a common carrier FPGA board.

The cavity BPM signals are downmixed from 11.424 GHz to 40 MHz using a super heterodyne receiver as shown in the block diagram in Fig. 4. This technique has been used on LCLS-I, LCLS-II and PAL X-FEL. To meet the dynamic range requirement and maintain good linear response, there are digitally controlled attenuators that provide 30 dB of dynamic range.

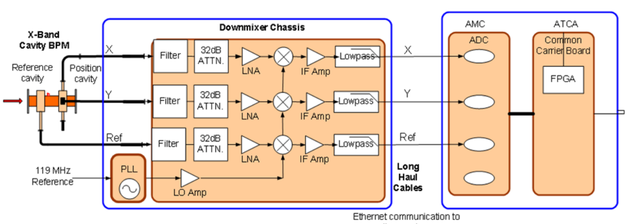

Figure 4: Block diagram of the cavity BPM electronics.

After the signals have been downmixed to the IF frequency, the signals are digitized using a TI-JESD 350 MHz digitizer. The BPM system uses a common carrier module containing an FPGA (Xilinx Kintex Ultrascale XCKU040 or XCKU060). It has serial connections to the backplane Ethernet, and to the RTM and AMC cards. JESD204b is used to the AMC cards. The carrier card also contains DC-DC power supplies from the -48 V to a variety of voltages used by the AMC cards. A slot of an ATCA crate consists of a carrier card, which supports two AMC cards and one, RTM card. The ATCA backplane features a dual-star network that provides 10 Gb Ethernet connectivity from each carrier module to a switch in slot 1. Timing data broadcasted from slot 2 to all carriers uses a proprietary protocol in order to support beam-synchronous data acquisition.

The BPM system is calibrated using the mover system on each girder. We instruct the movers to move ±100 µm steps with a total transverse distance of 1 mm. Using a Matlab script, we coordinate the move and the acquisition of the BPM reading. The Matlab program calculates the scale factors and polarity of the BPM electronics (see Fig. 5). We use the model to compensate for second order effects from the magnets due to the quadrupole offsets. Also, jitter correction is compensated by measuring orbit drifts of the upstream BPMs.

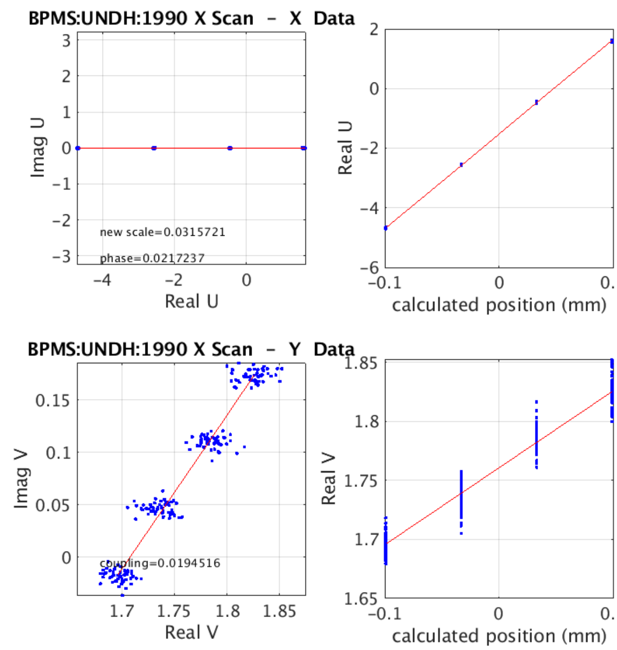

Figure 5: Calibration and Coupling measurement.

PERFORMANCE RESULTS

Using the beam-synchronous data acquisition features of the electronics and the intrinsic beam jitter we can determine the BPM resolution by predicting where the beam is supposed to be downstream and where it was measured to be using a linear predictor. The next set of figures illustrate the resolution at 165 pC, 82 pC and 26 pC. The BPM system show good linearity with respect to charge.

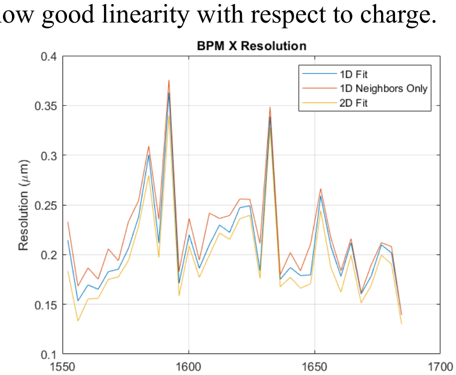

Figure 6: X-plane resolution for HXR undulator at 165 pC.

Figures 6 and 7 illustrate that most BPMs have a resolution of 200 nm in both X-Y plane. However, one BPM had a Y-plane resolution that was drastically worse. It was discovered this was due to an oscillation on the Monopole cavity electronics which has since been repaired. The next figures illustrate the resolution of 82 pC.

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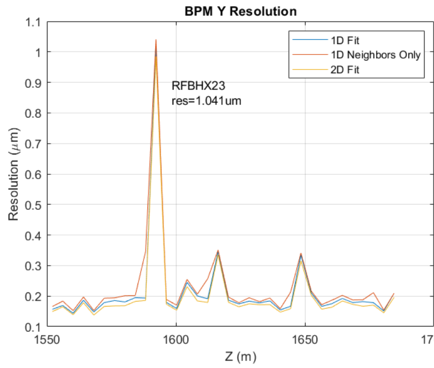

Figure 7: Y-plane resolution for HXR undulator at 165 pC.

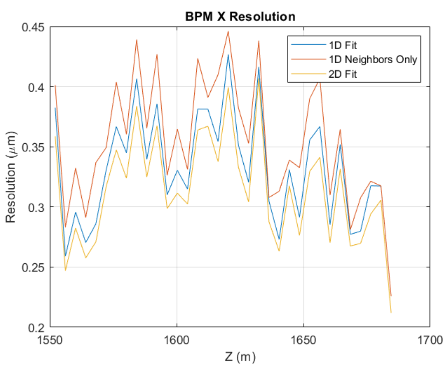

Figure 8: X-plane resolution for HXR undulator at 82 pC.

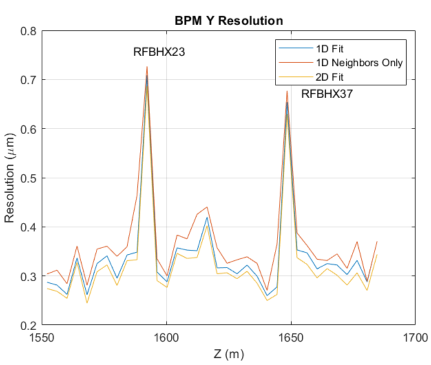

Figure 9: Y-plane resolution for HXR undulator at 82 pC.

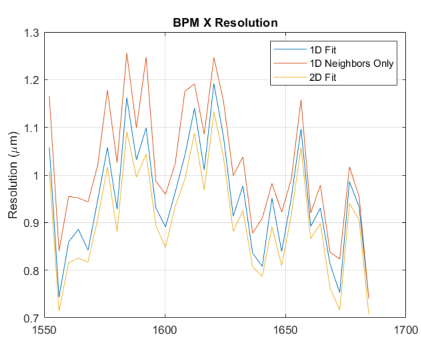

Figure 10: X-plane resolution for HXR undulator at 26 pC.

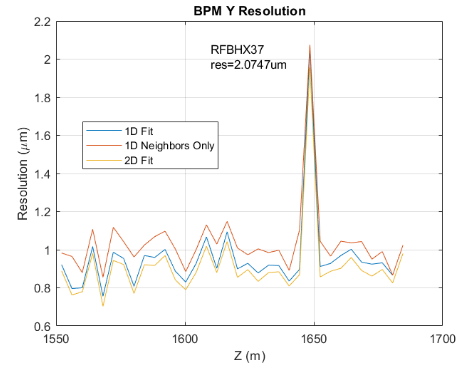

Figure 11: Y-plane resolution for HXR undulator at 26 pC.

At 26 pC the resolution for most BPMs is 1 µm. The data was taken with the electronics calibrated and optimized at 180 pC. Thus, some improvements can still be made to increase the resolution at low bunch charge.

CONCLUSION

The CRADA and industrial partnership with Pohang and Viztrotech has been very successful. We have installed 65 BPMs in LCLS-II HXR and SXR. LCLS-II cavity BPMs work as specified and are recording shot to shot data at 120 Hz. Future operations will include running at 1 MHz repetition rates.

ACKNOWLEDGEMENTS

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