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Revision History

Revision	Date Released	Description of Change
R0	4/7/2014	Original Release.

1 Purpose

This document describes the physics requirements for the electron beam position monitors (BPMs) in the LCLS-II injector, linac, both undulators, the five off-axis diagnostic lines, and the various electron transport lines to and from each of the SXR and HXR undulators.

2 Scope

This covers all non-invasive electron beam position monitors, not including intercepting beam screens, wire-scammers, x-ray monitors, or other non-electron-based position monitoring systems. Beam screens and wire-scanners are covered in a separate document.

3 Definitions

BPM	Beam Position Monitor
HXR	Hard X-Rays
SXR	Soft X-Rays
SL	Strip Line (type of BPM)
CV	Cavity (type of BPM)

4 References

LCLSII-2.1-PR-0134	Beamline Boundaries PRD

5 Responsibilities

N/A	N/A

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6 Document Content

6.1 Introduction

Many BPMs are required throughout the LCLS-II accelerator, from the injector, through the linac, transport lines, off-axis diagnostic lines, FEL undulators, and electron beam dump lines. BPMs are non-invasive measurement devices on the electron beamline which sense the transverse position of (ideally) each electron bunch with respect to the center of a set of pick-up electrodes, or a cavity, and report the beam position (ideally zero) to the control system for each passing electron bunch. Each BPM also reports the estimated bunch charge, although a separate calibration is typically required for absolute charge accuracy.

As a rough guideline, there is typically one BPM associated with each quadrupole magnet (frequently within the magnet bore), with ~250 quadrupole magnets in the LCLS-II. There are two basic types of BPMs in the LCLS-II: stripline (SL) BPMs, and cavity (CV) BPMs. Stripline BPMs offer a low-cost, well-tested option, while cavity BPMs offer superior beam position resolution (typically sub-micron) and require a beam-based calibration of position and charge. The linac BPMs are cold L-band cavities with one BPM inside each cryomodule at the downstream end. The cavities will need to be calibrated using beam, but mounting each one on an *x* and *y* translation stage for convenient position calibration purposes is not an economic solution. Therefore it is suggested that the upstream steering correctors be used to swing the beam position in *x* and *y* to calibrate each cavity BPM, as done at the LCLS-I in some of the undulator X-band cavity BPMs (the few without movers).

The BPM system can be divided into several components:

- The BPM pick-up on the beam line
- Cabling to the processor
- BPM processor module
- Timing inputs to the BPM processor module
- Data transfer from the processor to other applications

This document does not address all components, but concentrates on the BPM pick-up and timing requirements.

6.2 Position and Charge Resolution Requirements

Each BPM is required to read electron beam position (*x* and *y*) as well as bunch charge for each passing bunch, with a minimum 1-μs bunch spacing. It is not absolutely necessary to read all BPMs at full rate, but further compromise discussions will eventually determine the best tradeoff. A future possibility of 10-MHz operation (100-ns bunch spacing) can be accommodated by simply averaging over ~10 bunches so that individual bunch reporting at 100 ns is not required. The bunch charge setting will be controlled by operations personnel and will be variable from 10-300 pC, with 100-pC defined as the nominal LCLS-II operating charge, but 10-20 pC as a real option. Position and charge resolution requirements are listed in **Table 3** for each group of BPMs (same name except last index numbers) and are defined at 10 pC of bunch charge (lowest value with the most challenging resolution demand), where it is understood that the resolution scales inversely with bunch charge and that the

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position and charge resolution at higher charge levels (> 10 pC) will be improved, with nearly 10-times better position resolution (*i.e.*, smaller numerical value) at 100 pC. Higher charge (100 pC < $Q \leq$ 300 pC) is expected to produce similar or better resolution.

6.3 Installation Roll Angle of Stripline BPMs

Stripline BPMs can be oriented as shown in **Figure 1** below, with a possible roll angle of zero (left), or a roll angle of 45° (right). Most of the BPMs in the existing LCLS-I are unrolled (left), but some of the BPMs (~10%) in and around bending magnets are rolled by 45° (right) so that the synchrotron radiation and off-energy halo beams do not strike the stripline, possibly damaging it or biasing the position and/or charge measurement. However, in LCLS-II, in order to avoid the possible confusion where specific BPMs are rolled and others are not, we adopt the strategy in LCLS-II where all strip-line BPMs, except a few in the sector-10 dog-leg, are rolled by 45 deg, as show at the right side of **Figure 1**. The BPM database will include the roll angle for each BPM in order for the control system to process the BPM signals into horizontal and vertical positions as two separate linear combinations of the four strips. With no performance penalty in this rolled configuration, we hope to minimize installation and database entry errors. The roll angle requirements for each stripline BPM are listed in the master requirements list of **Table 3** with almost all striplines rolled 45 deg. The eight sector-10 dog-leg BPMs are unrolled ($\varphi = 0$) since the dog-leg itself is rolled by 45 deg (see row in **Table 3** labeled: "BPMBD1-8").

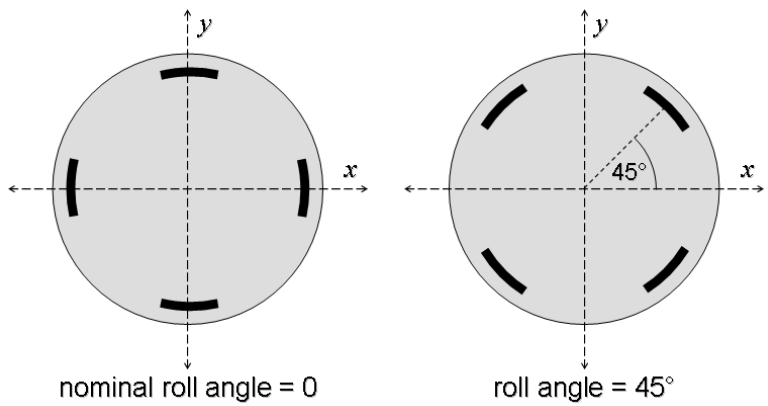

Figure 1: All BPM striplines will be rotated by 45 degrees in the *x-y* plane (right) so that synchrotron radiation and low-energy halo does not strike the stripline. Beam travels into the figure here.

Note that several more LCLS-II electron transport lines sections are guided by rolled bends, defining a beamline section that does not lie purely in the horizontal or vertical planes. In such cases (e.g., the sector-10 dog-leg, the HXR spreader branch, and both main beam dump lines), the installation angle of the BPMs (as well as the quadrupole magnets and other components) must be clearly specified. The table below (Table 1) lists the four beamlines where this stripline BPM installation angle (and the database angle used to untangle the nominal 45-deg roll) must be explicitly noted.

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Table 1: Stripline BPM installation and database roll angle requirements.

Beamline Description	Area	Installation Roll Angle (deg)	Database Roll Angle (deg)
Sector-10 Dog-Leg	BYP	0	0
HXR Spreader Line	SPH	45	45
SXR Main Dumpline	DMPS	45 + 10	45
HXR Main Dumpline	DMPH	45 – 10	45
All other areas	*all*	45	45

Note that a roll angle of 45 deg here is defined with respect to the global linac coordinates and therefore indicates that no additional roll angle is required for that particular system, whereas a roll of other than 45 deg (*i.e.*, both dumplines) implies that the BPM is rotated by the standard 45 deg (as for all stripline BPMs), plus an additional roll angle such that the BPM reports the *x* and *y* positions in the local coordinate system of that beamline. For the main dumplines (SXR and HXR) this additional roll angle is ±10 deg (= $\Delta\varphi$) and the BPMs, beam screens, and quadrupole magnets must be installed with this 55-deg roll in the global linac coordinates, but a 45-deg roll in the local dumpline coordinates.

6.4 Machine Protection System (MPS) Functions

The cavity BPMs in each undulator (both SXR and HXR) must communicate to the MPS system to trip the beam off as fast as possible (<100 μs, if possible) if any *x* or *y* position reads more than 1 mm in absolute value. The MPS-triggered beam shut-off mechanism can be the beam spreader system with beam switched into the high-power BSY dump until the latched condition is reset by operations personnel. In addition, the cold cavity BPMs in the cryomodules should also be interlocked to the MPS system, again tripping the beam off as fast as possible (<100 μs, if possible) if any *x* or *y* position reads more than (for example) 3 mm in absolute value. At present, these are the only MPS-connected functions required for the BPM systems.

6.5 Trajectory Feedback Functions

Some fraction of the BPMs will be used to supply position and charge readings from each bunch passed to several (slow and fast) transverse feedback loops in order to stabilize (fast) and also recover (slow) the nominal beam trajectories at several key locations. These feedback loop locations and requirements are not yet laid out in any detail, but it is expected that the BPMs leading into the undulators (including the first few undulator BPMs) will be used in a fast-feedback loop for each of the SXR and HXR undulator trajectories, independently. In addition, the position and charge readings of a few key energy-sensitive BPMs (one in the laser heater chicane, the BC1 chicane, the BC2 chicane, and a few of the BPMs in each of the two dog-leg bend systems near the SXR and HXR undulator entrances) will be used as input to a global longitudinal fast-feedback system, stabilizing the electron energy and bunch length at each of these locations, and also stabilizing the final peak current and beam arrival time in the undulators. For this case, it will be useful to take advantage of the high beam rate in the LCLS-II to optimally stabilize the machine, with up to 1-MHz sampling of position and charge fed to the feedback-loop processors and making corrections at a lower rate (using RF phase and

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amplitude), while averaging the high-rate BPM data for better resolution and excellent machine stability. Finally, many of the BPMs (10-20%) will be used in several slow (< 10 Hz) transverse feedback loops (*e.g.*, in the injector, linac, and transport lines), mostly dedicated to rapidly recovering the trajectory during machine startup, or eliminating steering effects that arise while tuning, for example due to small, but inevitable magnet misalignments. These slow-feedback BPMs do not need to be read at a full 1-MHz level, but perhaps just a 1-10 kHz level.

6.6 Alignment, Drift, and Electrical Offsets

In reality, each BPM will be misaligned to some degree, its position and charge readbacks will drift over time, and even a perfectly aligned BPM will have some small electrical offset. The following table lists the estimated requirements for these types of errors:

Table 2: Estimated BPM transverse alignment, drift, and electrical offset maxima.

Accelerator Area	Alignment (mm)	Drift (mm/week)	Offset (mm)
Injector (striplines)	0.2	0.1	0.1
Linac (cold cavities)	0.5	0.2	0.2
Transport/Diagnostic Lines (striplines)	0.2	0.1	0.1
SXR Undulator (cavities)	0.1	0.02	0.10
HXR Undulator (cavities)	0.05	0.01	0.05
Large Aperture (*e.g.*, BC1, BC2, dumps)	0.5	0.2	0.5

The detailed BPM requirements are in **Table 3**, with all LCLS-II BPMs listed by name, specifying their locations (see MAD files or naming-PRD for definitions), type, resolution requirements, installed roll angle of pick-up (linac coordinates), and estimated minimum stay-clear inner-diameter.

Table 3: BPM specifications defined at a 10-pC bunch charge. It is understood that the position and charge resolution at higher charge levels (>10 pC) will be improved (smaller values) as the resolution scales inversely with bunch charge.

BPM Name (MAD)	No. BPMs per group	Acc. Area (MAD)	BPM Type	RMS Position Resolution (microns)	RMS Charge Resolution (pC)	Roll Angle (deg)	Stay-Clear Min. ID Estimate (mm)
All BPMs in main line from gun to "LTUSPLIT" (below).							
BPM01-2	2	GUNB	SL	20	0.1	45	50
MCM01	1	L0B	CV-cold	50	0.2	0	70
BPM0H01-06	6	HTR	SL	20	0.1	45	25
BPMHD01-04	4	HTR	SL	20	0.1	45	25

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BPMDC01-04	4	INJ	SL	20	0.1	45	25
BPMC001-04	4	COL0	SL	20	0.1	45	25
MCM02-03	2	L1B	CV-cold	50	0.2	0	70
MHCM01-02	2	L1B	CV-cold	50	0.2	0	70
BPM1C01	1	BC1B	SL	20	0.1	45	25
BPMS11B	1	BC1B	SL	20	0.1	45	100 (hor.)
BPMC201-2	2	BC1B	SL	20	0.1	45	25
BPMC203-11	9	COL1	SL	20	0.1	45	25
MCM04-15	12	L2B	CV-cold	50	0.2	0	70
BPM2C01	1	BC2B	SL	20	0.1	45	25
BPMS21B	1	BC2B	SL	20	0.1	45	100 (hor.)
BPMC301-2	2	BC2B	SL	20	0.1	45	25
BPMC303-10	8	COL2	SL	20	0.1	45	25
MCM16-35	20	L3B	CV-cold	50	0.2	0	70
BPMX01-14	14	EXT	SL	20	0.1	45	25
BPMBD1-8	8	DOG	SL	20	0.1	0	25
BPML1P-4P	4	BC3	SL	30	0.1	45	50
BPMS31	1	BC3	SL	20	0.2	45	70 (hor.)
BPMBP13-27	15	BYP	SL	30	0.1	45	50
BPMBP35	1	BYP	SL	30	0.1	45	50
BPMBP28	1	BYP	SL	30	0.1	45	50
All BPMs in SXR lines from "LTUSPLIT" to main SXR dump (below).							
BPMSP1S-9S	9	SPS	SL	20	0.1	45	25
BPMBP37	1	SPS	SL	20	0.1	45	25
BPMBP30-34	5	SPS	SL	20	0.1	45	25
BPMDBL1-L2	2	LTUS	SL	20	0.1	45	25
BPMDL11-22	12	LTUS	SL	20	0.1	45	25
BPMVB1B-3B	3	LTUS	SL	20	0.1	45	25
BPMVM3B-4B	2	LTUS	SL	20	0.1	45	25
BPMEM1B-4B	4	LTUS	SL	20	0.1	45	25
BPME31B-36B	6	LTUS	SL	20	0.1	45	25
BPMUM1B-4B	4	LTUS	SL	20	0.1	45	25
RFB07B-8B	2	LTUS	CV	2	0.1	0	10

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BPMSX15	1	SXX	CV	2	0.1	0	10
BPMSX19	1	SXX	CV	2	0.1	0	10
BPMSX22	1	SXX	CV	2	0.1	0	10
RFBSX24-25	2	SXX	CV	2	0.1	0	10
RFBSX26-47	22	SXR	CV	2	0.1	0	10
RFBSX51	1	DMPS	CV	2	0.1	0	10
BPMUE1B-3B	3	DMPS	SL	10	0.1	45	25
BPMQDB	1	DMPS	SL	10	0.2	45	70 (ver.)
BPMDDB	1	DMPS	SL	10	0.2	45	70 (ver.)
All BPMs in HXR lines from "LTUSPLIT" to main HXR dump (below).							
BPMSP1H-13H	13	SPH	SL	20	0.1	45	25
BPMBSY39	1	SPH	SL	20	0.1	45	25
BPMBSY85	1	SPH	SL	20	0.1	45	25
BPMBSY88	1	SPH	SL	20	0.1	45	25
BPMBSY92	1	SPH	SL	20	0.1	45	25
BPMVM1-2	2	LTUH	SL	20	0.1	45	25
BPMVB1-3	3	LTUH	SL	20	0.1	45	25
BPMVM3-4	2	LTUH	SL	20	0.1	45	25
BPMDL1	1	LTUH	SL	20	0.1	45	25
BPMT12	1	LTUH	SL	20	0.1	45	25
BPMDL2	1	LTUH	SL	20	0.1	45	25
BPMT22	1	LTUH	SL	20	0.1	45	25
BPMDL3	1	LTUH	SL	20	0.1	45	25
BPMT32	1	LTUH	SL	20	0.1	45	25
BPMDL4	1	LTUH	SL	20	0.1	45	25
BPMT42	1	LTUH	SL	20	0.1	45	25
BPMEM1-4	4	LTUH	SL	20	0.1	45	25
BPME31-36	6	LTUH	SL	20	0.1	45	25
BPMUM1-4	4	LTUH	SL	20	0.1	45	25
RFB07-8	2	LTUH	CV	1	0.1	0	10
RFBHX15-50	36	HXR	CV	1	0.1	0	10
RFBHX51	1	DMPH	CV	1	0.1	0	10
BPMUE1-3	3	DMPH	SL	20	0.1	45	25

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BPMQD	1	DMPH	SL	10	0.2	45	70 (ver.)
BPMDD	1	DMPH	SL	10	0.2	45	70 (ver.)
All BPMs in D10 line from "LTUSPLIT" to D10 dump (below).							
BPMSP1D-4D	4	SPD	SL	20	0.1	45	25
All BPMs in off-axis DIAG0 line from KDG0 kicker to DG0DUMP (below).							
BPMDG000	1	DIAG0	SL	20	0.1	45	25
BPMDG002	1	DIAG0	SL	20	0.1	45	25
BPMDG003	1	DIAG0	SL	20	0.1	45	25
BPMDG004	1	DIAG0	SL	20	0.1	45	25
BPMDG005	1	DIAG0	SL	20	0.1	45	25
BPMDG0RF	1	DIAG0	SL	20	0.1	45	25
BPMDG008	1	DIAG0	SL	20	0.1	45	25
BPMDG009	1	DIAG0	SL	20	0.1	45	25
BPMDG0PR	1	DIAG0	SL	20	0.1	45	25
BPMDG011	1	DIAG0	SL	20	0.1	45	25
BPMDG0DU	1	DIAG0	SL	20	0.1	45	25
All BPMs in off-axis DIAG1 line from KDG1 kicker to DG1DUMP (below).							
BPMDG1*nn*	1	DIAG1	SL	20	0.1	45	25
BPMDG1*nn*	1	DIAG1	SL	20	0.1	45	25
BPMDG1*nn*	1	DIAG1	SL	20	0.1	45	25
BPMDG1*nn*	1	DIAG1	SL	20	0.1	45	25
BPMDG1*nn*	1	DIAG1	SL	20	0.1	45	25
BPMDG1*nn*	1	DIAG1	SL	20	0.1	45	25
BPMDG1*nn*	1	DIAG1	SL	20	0.1	45	25
BPMDG1*nn*	1	DIAG1	SL	20	0.1	45	25
BPMDG1*nn*	1	DIAG1	SL	20	0.1	45	25
BPMDG1*nn*	1	DIAG1	SL	20	0.1	45	25
BPMDG1*nn*	1	DIAG1	SL	20	0.1	45	25
All BPMs in off-axis DIAG2 line from KDG3 kicker to DG3DUMP (below).							
BPMDG3*nn*	1	DIAG2	SL	20	0.1	45	25
BPMDG3*nn*	1	DIAG2	SL	20	0.1	45	25
BPMDG3*nn*	1	DIAG2	SL	20	0.1	45	25
BPMDG3*nn*	1	DIAG2	SL	20	0.1	45	25

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BPMDG3*nn*	1	DIAG2	SL	20	0.1	45	25
BPMDG3*nn*	1	DIAG2	SL	20	0.1	45	25
BPMDG3*nn*	1	DIAG2	SL	20	0.1	45	25
BPMDG3*nn*	1	DIAG2	SL	20	0.1	45	25
BPMDG3*nn*	1	DIAG2	SL	20	0.1	45	25
BPMDG3*nn*	1	DIAG2	SL	20	0.1	45	25
BPMDG3*nn*	1	DIAG2	SL	20	0.1	45	25
All BPMs in off-axis DIAGS line from KDGS kicker to DGSDUMP (below).							
BPMDGS*nn*	1	DIAGS	SL	20	0.1	45	25
BPMDGS*nn*	1	DIAGS	SL	20	0.1	45	25
BPMDGS*nn*	1	DIAGS	SL	20	0.1	45	25
BPMDGS*nn*	1	DIAGS	SL	20	0.1	45	25
BPMDGS*nn*	1	DIAGS	SL	20	0.1	45	25
BPMDGS*nn*	1	DIAGS	SL	20	0.1	45	25
BPMDGS*nn*	1	DIAGS	SL	20	0.1	45	25
BPMDGS*nn*	1	DIAGS	SL	20	0.1	45	25
BPMDGS*nn*	1	DIAGS	SL	20	0.1	45	25
BPMDGS*nn*	1	DIAGS	SL	20	0.1	45	25
BPMDGS*nn*	1	DIAGS	SL	20	0.1	45	25
All BPMs in off-axis DIAGH line from KDGH kicker to DGHDUMP (below).							
BPMDGH*nn*	1	DIAGH	SL	20	0.1	45	25
BPMDGH*nn*	1	DIAGH	SL	20	0.1	45	25
BPMDGH*nn*	1	DIAGH	SL	20	0.1	45	25
BPMDGH*nn*	1	DIAGH	SL	20	0.1	45	25
BPMDGH*nn*	1	DIAGH	SL	20	0.1	45	25
BPMDGH*nn*	1	DIAGH	SL	20	0.1	45	25
BPMDGH*nn*	1	DIAGH	SL	20	0.1	45	25
BPMDGH*nn*	1	DIAGH	SL	20	0.1	45	25
BPMDGH*nn*	1	DIAGH	SL	20	0.1	45	25
BPMDGH*nn*	1	DIAGH	SL	20	0.1	45	25
BPMDGH*nn*	1	DIAGH	SL	20	0.1	45	25
Total =	**358**						

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