Initial Beam Phasing of the SRF Cavities in LCLS-II

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Introduction

One of the more challenging aspects of commissioning the LCLS-II accelerator is in the initial phasing of the SRF linac. Before any beam has been transported or accelerated through the SRF cavities, the RF phase of each cavity can be at any random phase, from 0 to 360°, with respect to beam arrival time. Therefore, with the actual acceleration profile completely unknown, and no information immediately available on the true RF phases, it is worth developing a plan to phase all of the cavities in an automated way using the electron beam position monitor (BPM) readings in the chicanes and transport-line bends downstream of each main linac section (*e.g.*, L1). Here each section (see Figure 1) is examined with appropriate parameters for each case (see Table 1).

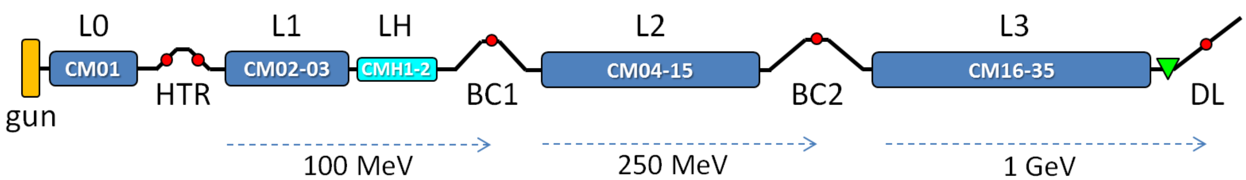

Figure 1: Layout of LCLS-II accelerator showing the five main SRF linac sections, the bend systems, and their BPMs (red dots). The three coasting beam energy settings for L1/LH, L2, and L3, up to their respective BPMs, are shown as dashed lines.

Table 1: SRF, bend system, BPM, and collimators for phase scans in each linac section.

Parameter	**L1/BC1**	**LH/BC1**	**L2/BC2**	**L3/DL**
Cryomodules	CM02-03	CMH1-H2	CM04-15	CM16-35
N cavities	16	16	96	160
Energy (MeV)	100	100	250	1000
Dispersion (mm)	-275	-275	443	437
Gradient (MV/m)	2.0	6.0	5.0	16
Cavity Length (m)	1.038	0.346	1.038	1.038
Beta (m)	13	13	64	30
BPM resolution (mm)	0.1	0.1	0.1	0.1
BPM position (*X* or *Y*)	*X*	*X*	*X*	*Y*
BPM name	BPM11	BPM11	BPM21	BPMDOG2
Collimator beam stop	CEBC1	CEBC1	CEBC2	CEDOG

Cavity Phasing Procedure

The cavity phasing procedure is the same for each main linac section, although the parameters and device names are somewhat different, as shown in Table 1.

1. Start this procedure with beam already established after CM01 at ~100 MeV. (The CM01 cavity phasing requires a special procedure.)

2. Set the beam rate to 1-10 Hz with 20-50 pC/bunch ($P_{avg} \leq 0.5$ W).

3. Set the HTR, BC1, and BC2 bends to their nominal settings (see "Dispersion" values in Table 1). Close the local energy collimator (see Table 1) as a dump for that bend system.

4. Switch off all cavities in and beyond the linac section of interest (*e.g.*, for L2 phase scans, switch off all 96 SSAs in L2 and all 160 SSAs in L3).

5. Scale the bends to the low, constant energy established by switching the SSAs off (*e.g.*, scale the BC2 bends to 250 MeV, maintaining the nominal dispersion there).

6. Scale the quadrupole magnets in the section of interest, maintaining their focal lengths (*e.g.*, scale all quadrupoles located between BC1 and BC2 to 250 MeV settings).

7. Transport a low-energy coasting electron beam through the linac section to the collimator (*e.g.*, transport a 250-MeV constant energy beam from BC1 to BC2, stopping at CEBC2).

8. Adjust the energy at the start of the section in order to 'zero' the BPM position reading (*e.g.*, adjust the energy at BC1 to set the BC2 BPM X-reading to zero).

9. Switch on one SSA at a time at the RF gradient listed in Table 1 (*e.g.*, switch on one of the L2 SSAs at 5 MV/m).

10. Scan the RF phase of this cavity over 360 degrees in 10-deg steps and read the BPM (X or Y) position as listed in Table 1 (*e.g.*, scan the RF phase of one L2 cavity and record the BC2 BPM X-position reading at each step – possibly averaging several readings).

11. Set the phase offset PV such that the cavity phase reads zero at accelerating crest phase.

12. In addition, the cavity can then be set at crest phase, switched *on* and *off*, noting the BPM position change, and thereby roughly calibrating the cavity amplitude (update ampl. PV).

13. Turn off that cavity and proceed to the next cavity, one at a time.

14. Do this phasing for each cavity in that linac section and then repeat for all linac sections.

15. This rough phasing and amplitude calibration procedure can be followed with a more precise process after all of the SRF is set at crest and powered up fully.

Phasing the L0-Linac Section

The single cryomodule, CM01, includes 8 L-band cavities. Due to the very low energy entering the L0-linac (< 1 MeV), the RF phasing here requires a special procedure based on beam transmission with RF phase. This procedure is not outlined here but should not be particularly difficult. Care should be taken no to bombard the cathode with back-acceleration at high rate.

Phasing the L1-Linac Section

This section covers the RF phasing for the two L1 cryomodules CM02 and CM03, which include 16 total L-band cavities. The procedure is as described above, with the beam coasting though the L1-linac section at 100 MeV up to the BC1 BPM and collimator. The phase of one of the 16 L1 L-band cavities is scanned while reading the X-position of "BPM11" at each step, forming a plot as in Figure 2. Each cavity gradient here is limited to 2 MV/m in order to vary the relative beam energy by no more than ±2%.

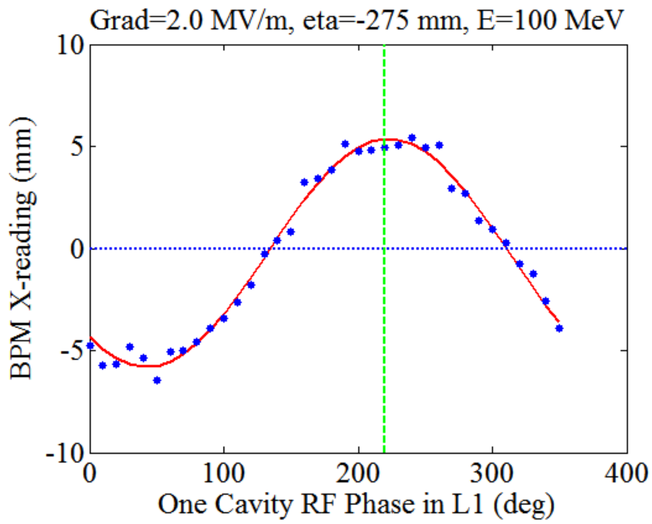

Figure 2: SRF phasing simulation for one of 16 L-band cavities in the L1 linac. The beam coasts from CM01 to BC1 at 100 MeV and the BPM in the BC1 chicane has a horizontal dispersion of -275 mm. The simulation includes a one-sigma rms betatron jitter, 0.2% rms energy jitter, 0.1-mm BPM position resolution, and includes a static phase and BPM position offset error.

Phasing the 3.9-GHz Section

This section covers the RF phasing for the two 3.9-GHz cryomodules CMH1 and CMH2, which include 16 total harmonic cavities. The procedure is as described above, with the beam coasting though the L1 and LH-linac sections at 100 MeV up to the BC1 BPM. The phase scan proceeds using one of the 16 LH harmonic cavities while reading the X-position of "BPM11" at each step, forming a plot as shown in Figure 3. The cavity gradient used here is 6 MV/m for this linac section (with shorter cavities) in order to vary the relative beam energy by no more than ±2%.

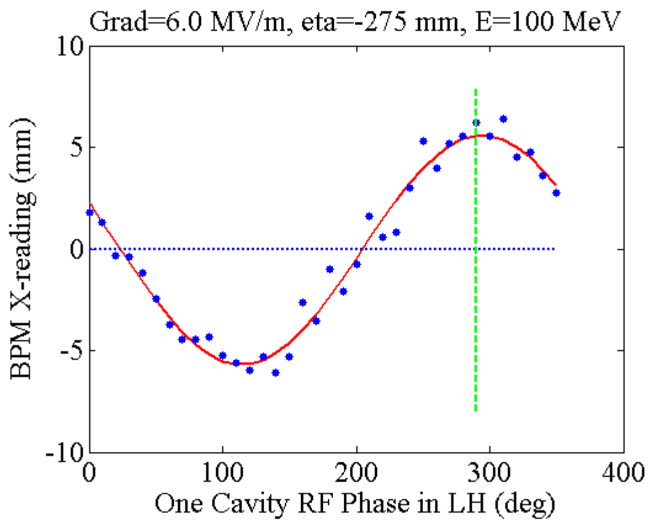

Figure 3: SRF phasing simulation for one of 16 3.9-GHz cavities in the LH linac. The beam coasts from CM01 to BC1 at 100 MeV and the BPM is in the BC1 chicane where the horizontal dispersion is -275 mm. The simulation includes a one-sigma rms betatron jitter, 0.2% rms energy jitter, 0.1-mm BPM position resolution, and includes static phase and BPM position offset errors.

Phasing the L2-Linac Section

This section covers the RF phasing for the 12 L2 cryomodules, CM04-CM15, which include 96 L-band cavities. The procedure is as described above, with the beam coasting though the L2-linac at 250 MeV to the BC2 BPM. One of the 96 L2 cavities is scanned in phase while reading the X-position of "BPM21" at each step, forming a plot as in Figure 4. The cavity gradient used here is 5 MV/m in order to vary the relative beam energy by no more than ±2%.

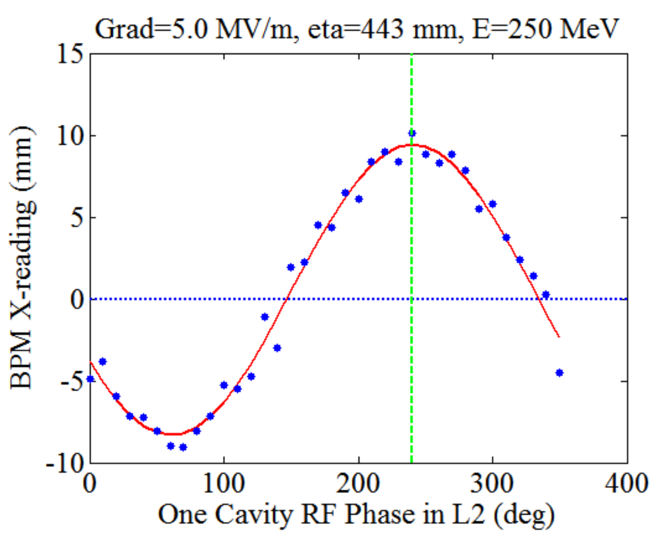

Figure 4: SRF phasing simulation for one of 96 L-band cavities in the L2 linac. The beam coasts from BC1 to BC2 at 250 MeV and the BPM is in the BC2 chicane where the horizontal dispersion is 443 mm. The simulation includes a one-sigma rms betatron jitter, 0.2% rms energy jitter, 0.1-mm BPM position resolution, and includes static phase and BPM position offset errors.

Phasing the L3-Linac Section

This section covers the RF phasing for the 20 L3 cryomodules, CM16-CM35, which include 160 L-band cavities. The procedure is as described above, with the beam coasting though the L3-linac section at 1 GeV up to the Dog-Leg (DL) BPM. The phase scan proceeds using one of the 160 L3 L-band cavities while reading the X-position of "BPMDOG2" at each step, forming a plot as shown in Figure 5. The cavity gradient used here is 16 MV/m for this linac section setting the maximum relative beam energy variation to no more than ±1.7%.

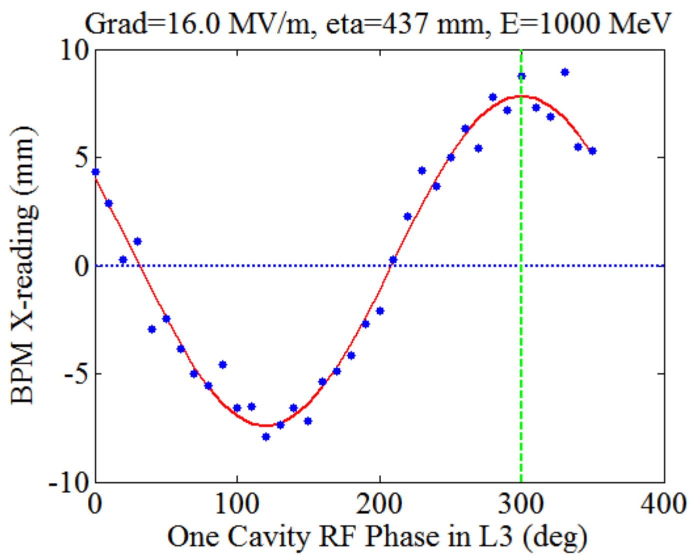

Figure 5: SRF phasing simulation for one of 160 L-band cavities in the L3 linac. The beam coasts from BC2 to the dog-leg at 1 GeV and the BPM is in the dog-leg bends where the vertical dispersion is 437 mm. The simulation includes a one-sigma rms betatron jitter, 0.2% rms energy jitter, 0.1-mm BPM position resolution, and includes static phase and BPM position offset errors.