LCLS-II Beam Stay-Clear *

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1 Introduction

This note addresses the theory and details that go into the Beam Stay-Clear (BSC) requirements for LCLS-II [1]. At a minimum a BSC boundary is needed to keep the desired beam from being lost or degraded by striking or passing too close to accelerator components. But, in addition, accelerator components must be kept outside of the BSC defined by the acceptance of the halo collimator system which scrapes off the tails of the beam. Since halo collimators determine a larger boundary than would be set by the desired beam, they serve as the basis for the BSC requirements. If machine components were allowed to inside the collimator defined BSC they could be subject to high radiation from beam loss and scatter secondary radiation into radiation sensitive areas.

The BSC determined by the collimator system acceptance is determined by the collimator gaps and the optical functions. The collimator gaps and optical functions are optimized to make the collimator acceptance well within the acceptance of the undulator vacuum chamber. The gaps must not be allowed to be so small that they cause wake field degradation to the beam quality. In the dispersive regions, where the desired beam size due to energy spread is quite substantial and the betatron size negligible, the collimators serve mainly to limit energy acceptance. With limited energy acceptance, the only propagating beam halo is close to the design energy and can be efficiently stopped by the nearby betatron halo collimators.

The stay-clear needed for betatron motion and for energy acceptance are discussed separately in the next two sections, and in the following section they are combined to form an overall BSC that is suitable for design purposes. In the two last sections the detailed assumptions and the resulting stay-clear are discussed.

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2 Betatron Stay-Clear

In this section we are only considering particles that have no energy error. The betatron stay-clear is defined so as to make the betatron collimator jaws define the betatron acceptance of the machine. First consider a single collimator jaw intruding on the beam from one side and presenting an aperture that limits transmitted beam phase space. Figure 1 illustrates the definition of an effective emittance g_i^2/β_i for the i-th collimator whose jaw face is a distance g_i from the beam center and is at a position where $\beta = \beta_i$ [2]. It defines the largest emittance at the i-th collimator that does not hit the jaw, independent of the orientation of the emittance ellipse. At the i-th collimator particles with

$$\epsilon = \gamma x^2 + 2\alpha x x' + \beta x'^2 < \frac{g_i^2}{\beta_i},$$

where α, β, and γ are the usual Courant-Snyder parameters, should have 100% transmission past the jaw. If $\epsilon > g^2/\beta_i$ some particles may hit the collimator jaw.

We make the assumption that the energy-normalized emittance (usually called the invariant emittance) of halo particles does not change with beam energy. However particles with large amplitude will sample nonlinear fields from the magnets and RF and may be transported to larger amplitude. A study of this effect is underway. Also coherent synchrotron radiation and micro-bunching effects can distort and enlarge the transverse phase space in certain conditions. Generally these effects are relatively small for the desired beam compared with halo.

We define a 'collimator emittance'

$$\epsilon_i = \frac{\gamma_i}{\gamma}\frac{g_i^2}{\beta_i}$$

where γ now refers to the beam energy at any point in the beamline and γ_i is the beam energy at the i-th collimator. ϵ_i represent the largest (absolute) emittance at any point in the beamline that passes (either forward or backward) completely by the collimator jaw without loss. Note that with ϵ_n the invariant emmitance the ratio of the ordinary (absolute) emittance to the collimator emittance,

$$\frac{\epsilon}{\epsilon_i} = \frac{\epsilon_n \beta_i}{\gamma_i g_i^2}$$

depends only on the the parameters at the i-th collimator and is independent of energy along the beamline.

This picture leads to a natural definition for betatron Collimator Stay-clear (C_i) that is equal to g_i at the location of the i-th collimator and elsewhere in the beamline is

$$C_i = \sqrt{\beta\epsilon_i} = g\sqrt{\frac{\beta}{\beta_i}\frac{\gamma_i}{\gamma}}.$$

Assuming symmetric betatron collimator gaps, all components except for collimators should be located outside of the boundary described by $\pm C_i$. If an upstream component is within the collimator stay-clear it will intercept halo that would otherwise be stopped by the collimator. If a downstream component is within the collimator stay-clear it will intercept halo that the collimator allowed to pass and would otherwise safely go through the undulator. If the beam is steered, it is assumed that position of the jaws relative to the beam is precisely maintained so as to keep the proper gap. In the usual case of more than one collimator, the betatron Collimator Stayclear at any point along the beamline must be the maximum C_i of the different jaws.

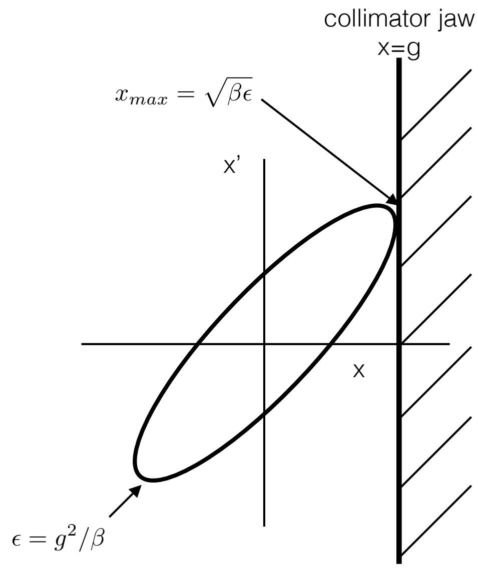

Figure 1: The location of the collimator jaw defines maximum emittance $\epsilon(g)$ for a given half-gap g that can be transmitted without loss.

3 Energy Stay-Clear

Unlike the case of betatron motion, it is a poor approximation to assume for LCLS-II that longitudinal phase space $(z, \delta\ )$ is conserved. Nonlinear compression, wakefields, and CSR interactions result in complex changes to the z, δ distribution of a bunch often resulting in asymmetric, non-gaussian energy distributions with significant tails. To estimate an energy stay-clear boundary that will just contain all of the desired particles the energy distributions are first be calculated in detail by specialized codes; e.g. Litrack or Elegant, and then non-modeled effects such as energy jitter or an allowance for an RF trip is added to the calculated energy deviations. The required clearance is then be calculated from net energy deviations of the particles and the dispersion functions.

Since the dispersion function is nonzero at only a few places, the energy distributions need only be calculated at those places. In reality wakefields change energy distributions continuously, but are of no consequence to the transverse motion of the the particles in the dispersion free areas. We ignore the relatively minor effects of dispersion errors that can propagate along the beamline where there is no design dispersion.

A beam envelope for the desired beam that includes only the transverse position due to energy deviation alone can be expressed as

$$E = \eta[\delta_{min}, \delta_{max}]$$

where η is the appropriate dispersion function and δ refers to the relative energy deviation of the particles. δ_{min} and δ_{max} are the minimum and maximum acceptable energy deviations. In practice all the energy collimators are horizontal.

Clearly all components, including energy collimators, should be outside of the boundary E or they will intercept desired beam. Ideally energy collimators should intercept particles with energy outside $[\delta_{min}, \delta_{max}]$.

Thus, as with the betatron case, we are led to define an energy BSC based on the i-th energy collimator gap g_i such that the extreme energy particles would just hit the jaws, i.e $[\delta_{min}, \delta_{max}] = g_i/\eta_i$. Here g_i should be thought of as a two-component vector containing values for either of the opposing jaws depending on the sign of the dispersion, thus allowing for asymmetric energy collimation.) The energy Collimator Stayclear can be extended to the nearby components (where the energy distribution is the same) as such

$$E_i = \eta[\delta_{min}, \delta_{max}] = \eta\frac{g_i}{\eta_i}.$$

4 Overall Beam Stay-Clear

To define an overall BSC it is necessary to combine the collimator betatron and energy stay-clear functions. Where dispersion is non-zero the net spatial distribution is the result of the superposition of pure betatron displacements and the displacements due to energy alone. We assume the overall BSC should accommodate the combined displacements. Thus we define

$$BSC_{xp} = C_x + max(E_x) \quad (1)$$

$$BSC_{xn} = -C_x + min(E_x) \quad (2)$$

where ‘p’ and ‘n’ stand for ‘positive’ and ‘negative’, corresponding to maximum and minimum energy displacements. Analogous defintions hold for the y coordinate.

The strategy for energy collimation is to set the energy acceptance just large enough to accommodate all of the desired beam. This means that the energy collimator gaps must be increased over that needed for the nominal minimum and maximum particle energy to allow for some betatron motion and a steering allowance. As a result the energy collimators will pass some particles with larger than nominal energy acceptance.

The overall BSC is calculated at each element of the MAD optics and the numerical results are put in the LCLS2 database. Entries are given for a diameter, and for positive and negative horizontal and vertical extents. The diameter entry represents the smallest circle that encloses a rectangle formed from the horizontal vertical extents. Normally it is sufficient to know the diameter, but in special cases where there is strong motivation to get a close to the beam as possible, a rectangular BSC can be constructed from the horizontal and vertical values.

5 Assumptions

Assumptions that go into generating the BSC must insure that the boundary is sufficiently outside of the ideal betatron and energy collimator stayclears to include allowance for β mis-match and orbit excursions that are normally part of operation, as well are a reasonable allowance for changes to the beam optics design. The detailed inputs used to determine the BSC are given in Tables 1 - 3. The BSC allows for:

- at least 16 σ_β for a 1 μm normalized emittance

- 100% of calculated energy spread for the 300 pC case using ideal optics
- an optics mis-match (BMAG) of a factor of 2 everywhere, except in the undulator
- a steering allowance of ±2 mm, except in the undulator where it is ±1 mm.
- allowance for an RF trip of one klystron anywhere after BC1
- a 'vernier' energy adjustment of ±1%
- a 2% energy loss (simple shift) after the undulator due to FEL production
- a minimum half-gap of 1 mm to avoid wakefield degradation of beam quality.
- a maximum relative energy jitter of ±0.0001.
- a maximum applied chirp (beyond what is in the simulation) of ±0.01 relative energy spread
- an allowance for dispersion errors up to 30%.

Table 1: Energy inputs used to generate the BSC

Location	Relative Energy Deviation		
	rms	min	max
ASTRA-Elegant Simulation			
'Gun'	0	-0.0001	0.0001
'Laser Heater'	0.0008	-0.0051	0.0011
'BC1'	0.0201	-0.0601	0.0701
'BC2'	0.006	-0.0151	0.0251
'Dogleg'	0.0022	-0.0261	0.0291
'DL1'	0.0019	-0.0181	0.0221
'DL3'	0.002	-0.0181	0.0221
'DL14'	0.0008	-0.0246	0.0321
'DL18'	0.0008	-0.0246	0.0321
'Undulator'	0.0008	-0.0246	0.0321
'Dump'	0.0058	-0.0401	0.0321
Other Inputs			
Energy jitter		-0.0001	0.0001
FEL		$-.02$	0
Chrip		-0.01	0.01
Vernier		-0.01	0.01
Laser Heater Energy		-0.0051	0.0011
RF trip after BC1		19 MeV loss	

6 Results

Most vacuum chambers have an circular cross-section and can use the Radial Stay-Clear shown Figure 2. In some unusual cases where the beam aspect ratio is particularly distorted by high dispersion and energy spread, or where it is necessary to approach the beam as closely as possible, the Horizontal and Vertical Stay-Clear boundaries, shown in Figure 3 can be used and the Radial ignored.

6.1 Collimator gaps

The betatron collimator gaps are determine using the parameters in Table 2 and the assumptions stated in Section 5. For betatron collimators the gaps, normalized to the beam size, is set to insure the collimated beam easily passes through the undulator; unless the resulting gap is so small wakefield effects are important, in which case the gap is set to the minimum

Table 2: Transverse inputs to Stay-Clear calculations.

Lattice:	LCLS2sc (Dec 12, 2014)		
			Note No.
Normalized emittance	1	μm	1
Und. horz. eff. aperture	±3.5	mm	2
Und. vert. eff. aperture	±2.5	mm	3
Und. average beta	30	m	4
Min coll. half-gap	1	mm	5
'Horz. Steering Max'	2	mm	6
'Vert. Steering Max'	2	mm	
Und. Horz. Steering Max	1	mm	
Und. Vert Steering Max	1	mm	
'BMAG'	2		
'DMAG'	1.3		7

Notes	
1	Projected emittance; slice emittance 0.2-0.7 μm [5] .
2	RF BPM radius -0.5 mm for tolerances.
3	Chamber half-height -1 mm for tolerances.
4	Largest value over the energy range 2-4 GeV.
5	FEL measured performance degrades with half-gap below about 1 mm. Simulations are underway to estimate the transverse and longitudinal wakefield effects. [6]
6	Steering allowance everywhere except in undulators. Absolute, not scaled with beta functions.
7	'DMAG' is a factor multiplying the design dispersion to account for dispersion errors and tuning.

Table 3: Collimator energy acceptance at various locations.

Location	Collimator Energy Acceptance	
	min	max
'Laser Heater'	-0.066	0.062
'BC1'	-0.071	0.081
'BC2'	-0.033	0.031
'Dogleg'	-0.037	0.036
'DL1'	-0.037	0.036
'DL3'	-0.037	0.036
LCLS2scS		
'DL14'	-0.033	0.036
'DL18'	-0.033	0.036

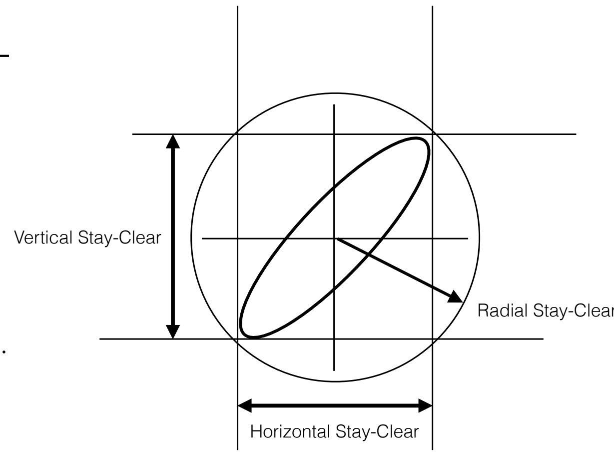

Figure 2: The Radial Stay-Clear is the smallest circle that can encompass the Horzontal and Vertical Stay-Clear boundariers.

physical gap stated in the assumptions. The undulator acceptance is calculated from the effective undulator aperture and the average undulator beta — both values are conservatively chosen.

Originally it was thought that sequentially increasing the normalized gaps would avoid creating more halo consisting of secondary particles created when the primary halo hits the collimators. However extensive modeling of such secondaries [4] has shown that such effects are neglible for LCLS-II. Keeping the normalized gaps constant minimizes the required beam stay-clear.

Figures 3 shows the BSC plotted as a function of the distance along the entire HXR beamline from source to main dump, based on simulations [7] and the MAD deck as of December 12, 2014.

6.2 Energy Acceptance

Energy collimators gaps are set so the energy acceptance of these collimator contains the maximum energy excursions given the assumptions in Tables 1. The jitter and RF trip inputs serve to shift the limits derived from simulations. The result is an energy acceptance defined by the energy collimators and shown in Table 3. In the Laser heater the actual energy acceptance is quite a bit larger than is required to accept the spread in particle because the dispersion is quite modest and the beams betatron size dominates. This is not the case in BC1 or BC2. There the dispersion dominates and the collimators CEBC1 and CEBC2 perform a relatively clean energy collimation.

In Figure 4 the BSC is display for the part of the machine containing the Laser Heater, BC1 and BC2. The BSC for the other end of the machine is shown in Figure 5. In the spreader region the BSC varies erratically with smaller values where kicker or septum magnets are located, modest values in the LTU region and small values in the undulator. It takes off in the dump line because of the high vertical dispersion.

The energy extrema used are shown in Figure 6 and are based on the input from Table 1. At time of this writing no allowance has been made for 2-bunch 2-energy beams, over-compression, or highly chirped beams.

6.3 Optics Mis-match Allowance

An deliberate mis-match of the optics has been found to be necessary at LCLS to produce the highest quality FEL beams. Figure 7 shows the history of the mis-match parameter 'BMAG', measured at the end of the Linac, for a one month period of recent LCLS operation. Deliberately mis-matching the beam often results in a factor of two gain in FEL pulse energy. Typically the BMAG in the y plane is well over 2 while the in the x plane it is around 1.5 - 2. When the optics is mis-matched relative to the design the gaps have to be adjusted to maintain the (normalized) design acceptance. A factor of 2 in BMAG implies approximately a factor of 4 increase in the peak beta functions and a factor of two betatron beam size. As there is no systematic way to determine exactly what mis-match will be desired for LCLS-II, the Collimator betatron stayclear based on the design optics is multiplied by a factor of 2 when included into the BSC.

Dispersion errors are also part of ordinary operation as quadrupoles in the dispersive regions are frequently subject to tuning. Based ocassional measurements at LCLS an allowance of 30% dispersion error was assumed in the energy stay-clear.

References

[1] J. Welch, 'Residual Gas and Beam Stay-Clear', LCLS-II project document LCLSII-2.1-PR-0234-R0

[2] Chao, et. al. *Handlbook of Acclerator Physics and Engineering*, 2nd edition [2012], p73.

[3] 'LCLS-II Parameters', T. Raubenheimer, LCLSII-1.1-PR-0133-R0

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[6] K. Bane, personal communication

[7] P. Emma and L. Wang, personal communication.

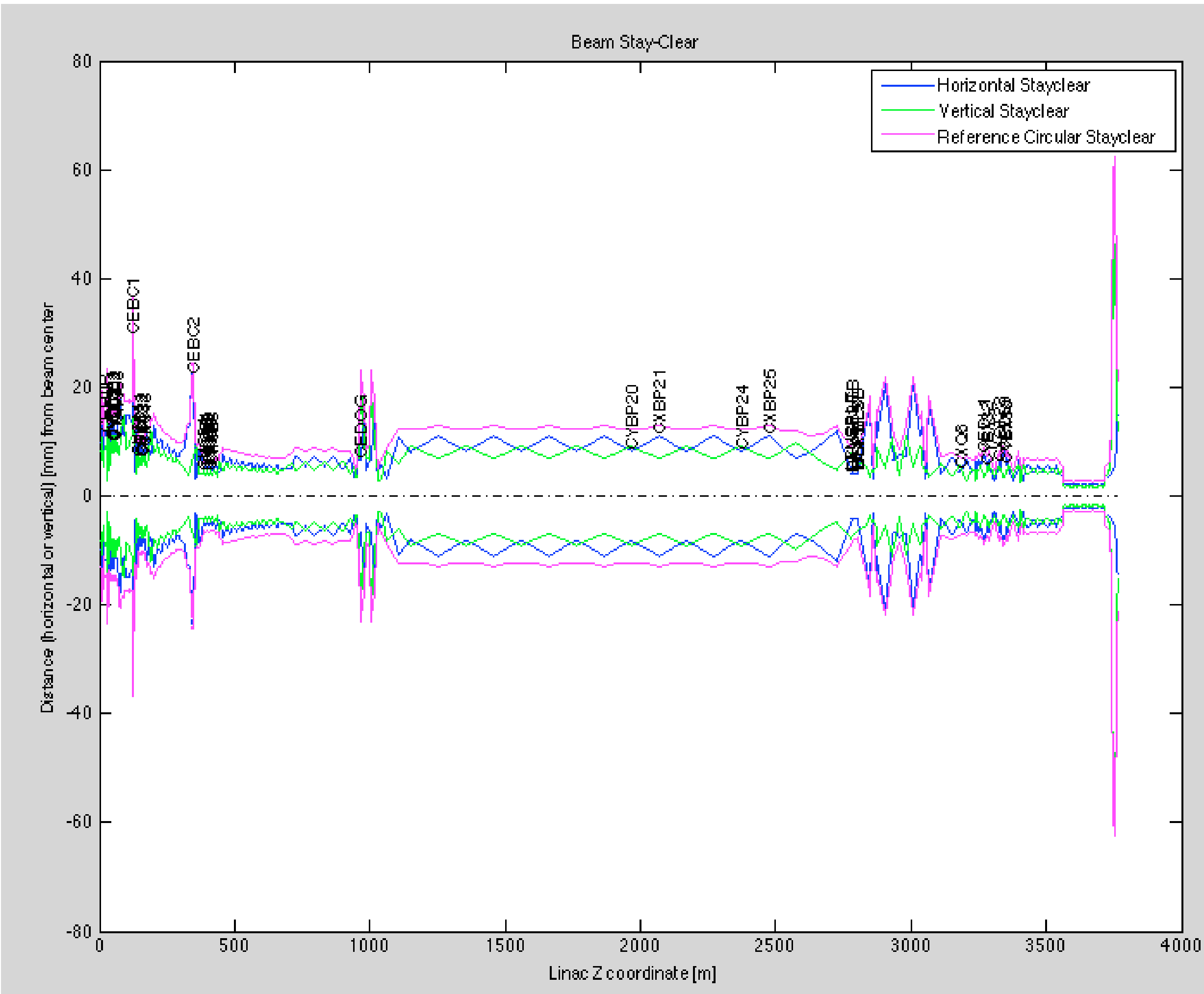

Figure 3: Stayclears and acceptances for the entire HXR beamline.

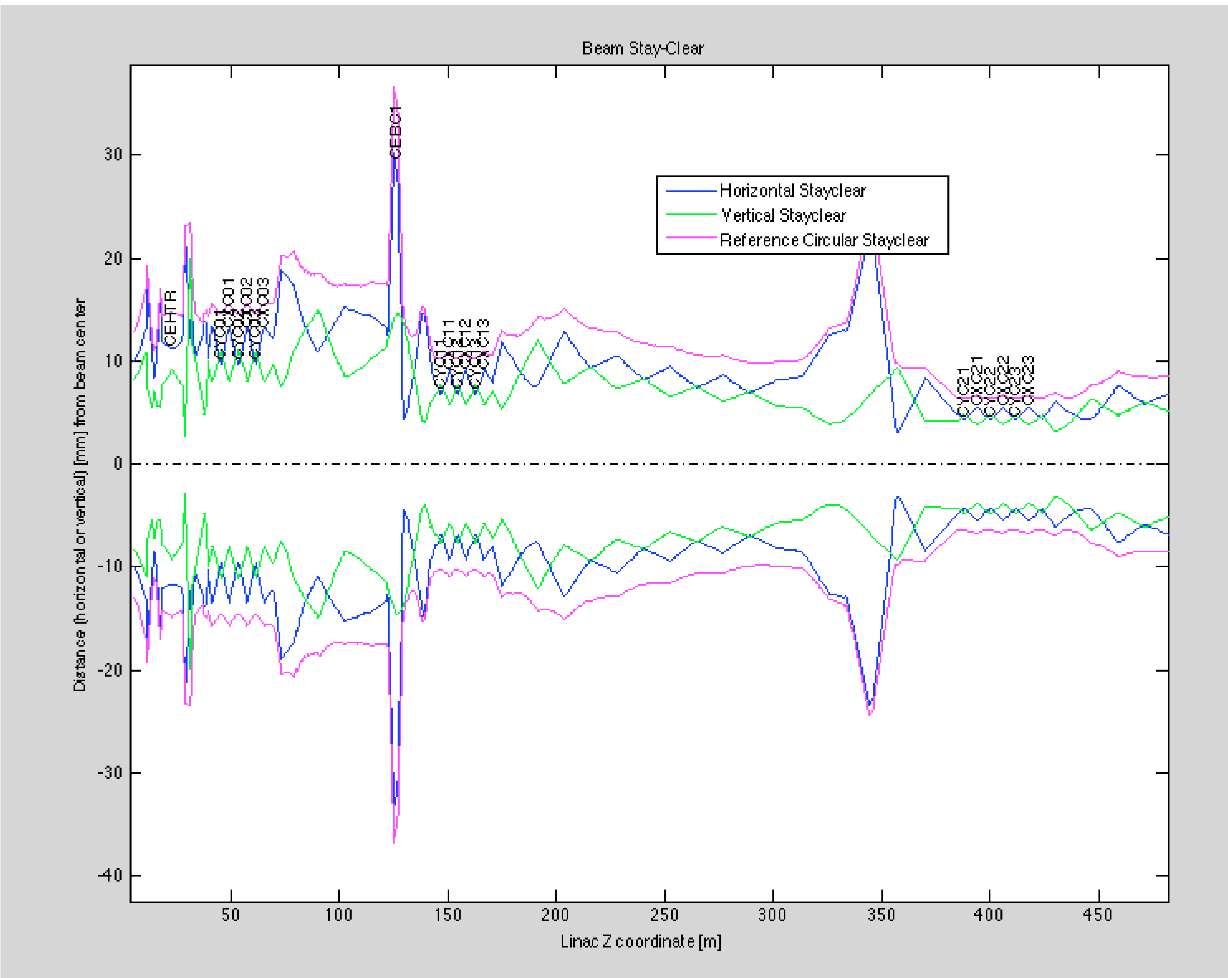

Figure 4: Stayclears and acceptances for the front end of the HXR beamline.

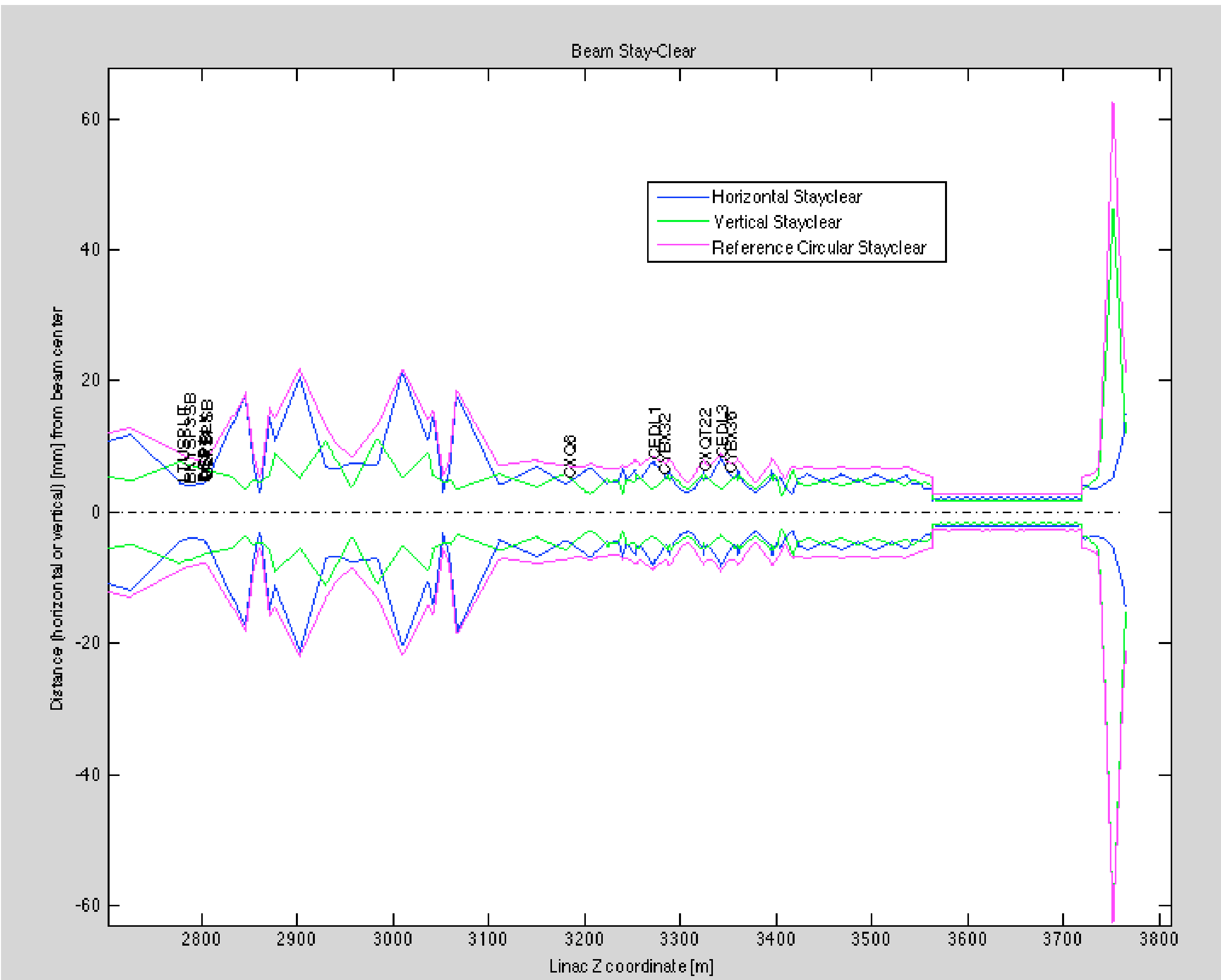

Figure 5: Stayclears and acceptances and beam excursions for the downstream end the HXR beamline.

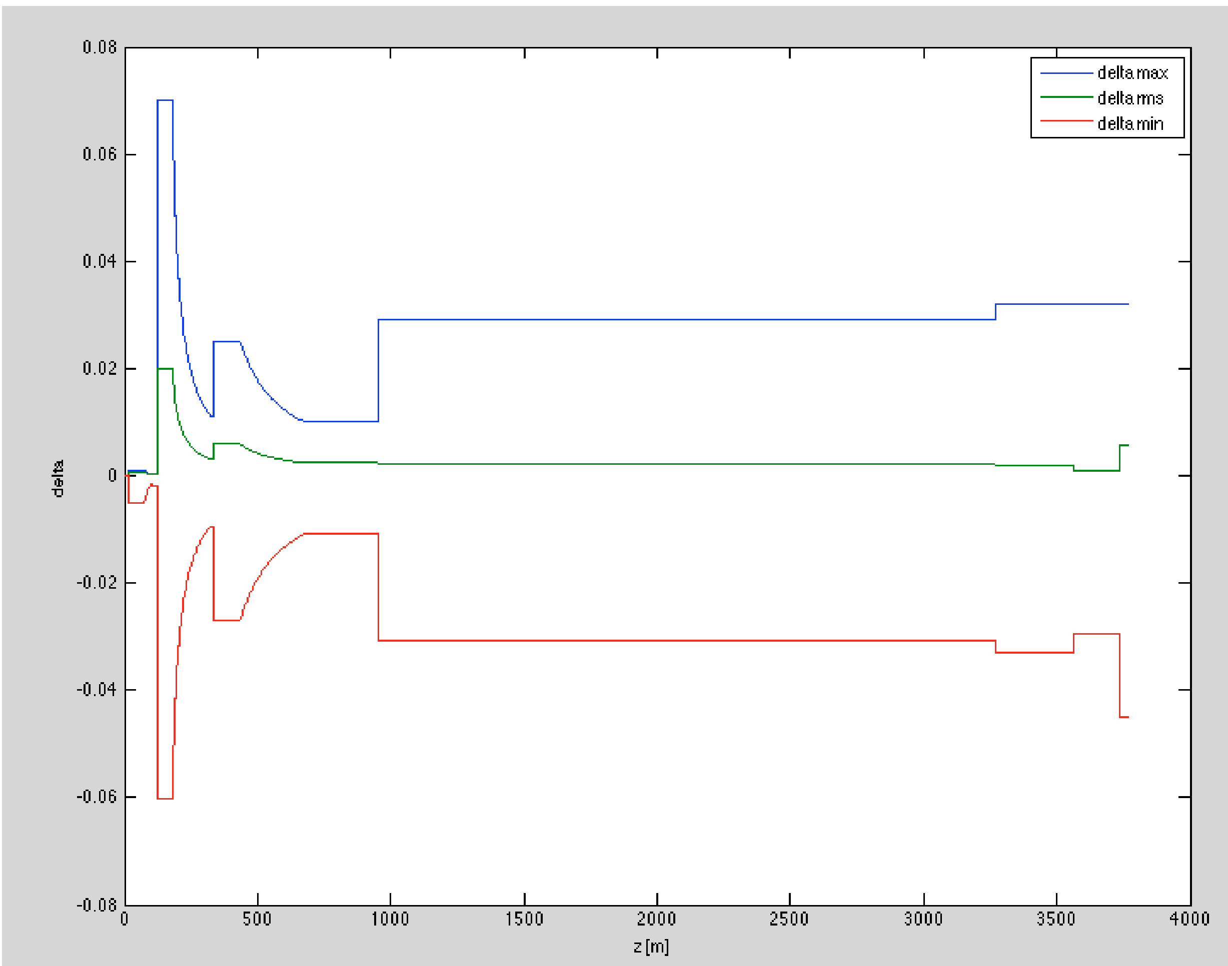

Figure 6: Maximum, minimum, and rms values for relative energy spread used in the generation of the stay clear.

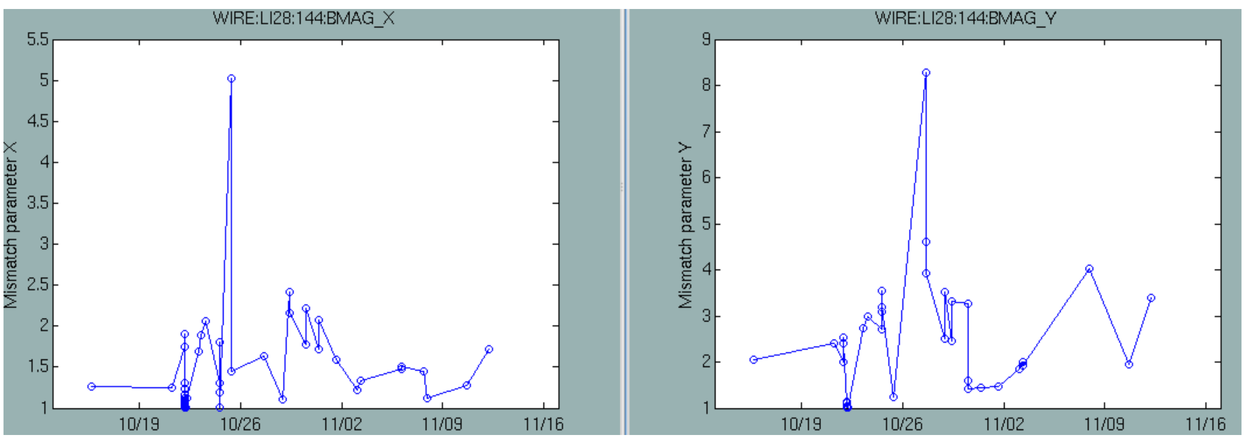

Figure 7: Measured BMAG values at LCLS during normal operation for a one month period starting October 16, 2014.