LCLS-TN-12-6

Ray-Trace Study for the LCLS-II Safety Dump Lines *

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1 Summary

Collimator sizes and locations are determined such that the LCLS-II electron beam will be always be safely absorbed, even if the BYD magnet in either the HXR or SXR lines is mis-wired, or if any of the QUE magnets is mis-wired as a dipole.

2 Safety Dump Lines in LCLS-II

In LCLS-II, as in LCLS-I, the primary electron beam is directed toward the experimental area until it is deflected downward into the main beam dump where there is adequate shielding and it is safely absorbed. If for some reason the electron beam were to escape its prescribed channel and proceed directly towards the often occupied experimental area, the shielding protecting the experimental area would not sufficiently attenuate the radiation that would be produced when the beam strikes the experimental area wall and dangerous levels of radiation would be produced inside the experimental area. To prevent this possibility various measures are taken, such as wiring the vertically deflecting dipole (BYD) in series with an horizontally deflecting dipole far upstream, to insure that the electron beam will not be present if there is any fault in the BYD dipole current. With this arrangement, the current has to be correct for the beam energy, or the beam will not make it through the first dipole. However, there is the remote possibility that the BYD dipole is mis-wired and this measure is defeated. Also, there are two quadrupole magnets downstream of the undulators in each of the two LCLS-II beamlines, each of which could be mis-wired to produce a deflecting dipole field. For these possibilities, and for others that haven't been imagined, a system of collimators and permanent magnets called the Safety Dump Line is specified that would safely stop the electron beam if it should escape due to the above-mentioned mis-wirings.

3 Fundmental Assumptions

Below is a list of fundmental assumptions made in the ray trace analysis used to determine the Safety Dump Line design. These apply to the range of cases considered and the particular parameters assumed for the various devices and beams. They were chosen to be conservative and inclusive. Additional assumed parameters are given in Table 1.

1. BYD magnets may be mis-wired, or otherwise modified, such that they can produce field that is anywhere from the nominal for the maximum energy beam to negative that value, while beam is present in the dump line.
2. BYD magnets can only deflect the beam in the vertical plane. There is no possibility of a horizontal kick from a BYD magnet no matter how it is mis-wired.
3. QUE1 or QUE2 can be mis-wired as a dipole of either polarity in either the horizontal or vertical direction.
4. Only one mis-wiring event at a time is possible. That is, we do not look at cases where two QUE's are both mis-wired, nor where one QUE is mis-wired and the BYD is mis-wired.

4 Analysis

Critical rays are constructed which represent extreme limits of possible electron beam trajectories based on the assumptions and parameters given above. The rays are extrapolated as straight lines until they are absorbed. The collimation system insures that all possible beam paths that could arise as a result of mis-wiring of the BYD dipoles or either of the QUE quadrupoles results in a path that terminates on a collimator, or the floor, or the main electron beam dump.

4.1 Effect of Earth's magnetic field

Normally the electron beam travels in a straight line unless it is deflected by a magnet. However, due to small ambient magnetic fields that is not precisely true. The largest ambient field is the Earth's fields, which is about 0.4 G in magnitude. It will have the most effect on the lowest energy electron. In this case the deviation of the beam from a straight line varies as the square of the distance along the beamline, and for 88 m of travel can amount to 11 mm. In all but two cases, the collimation system does not allow rays to propagate more than 15 m, which implies the deviation from straight is less than 0.3 mm and can be ignored. There are two cases in the SXR line where the deviation is more significant, and these are dealt with explicitly.

4.2 Mis-wiring QUE quadrupoles as dipoles

It is possible to mis-wire a QUE quadruple magnet to form a crude dipole that deflects the beam either horizontally or vertical in either direction. A conservative estimate of the maximum effective dipole field strength is that it is less than the product of the gradient (normally wired) and the bore radius, assuming the same current. This is the estimate used in this study. A more accurate estimate is that the field is about 70% as much as the conservative estimate.

4.3 HXR ray-trace

The layout of the collimators and magnets, and the ray-traces for the HXR beamline are shown in Figure 1 and 2. The following paragraphs explain how,

Figure 1: Plan view of collimators (green lines) and ray-traces (purple lines) for the HXR beamline. The horizontally deflecting permanent magnet is represented as a blue triangle. The vertically deflecting electromagnet is represented by a red triangle.

in the various cases stated, all electron beam paths terminated.

Mis-wired QUE1 as a horizontally deflecting dipole Referring to Figure 1 the leftmost blue diamond represent QUE1. Four rays are shown emanating from it. The two outer rays represent the maximum angle the electron beam could get by passing through QUE1 if it is wired as a dipole and set to the maximum current and the beam is at the minimum energy. They are clearly intercepted by collimator C00. This indicates outer diameter of C00 is adequately sized [1]. The two inner rays just touch the inside edges of C00 and continue to QUE2 where they are bent by the defocussing fields in QUE2 and then intercepted on C0. The bending by QUE2 is calculated for the worst case of maximum field and defocussing, so these rays represents the worst case with respect to horizontal or vertical mis-wirings. All possible beam paths that lie inside of the two inner rays would be intercepted by C0 or pass through the BYD magnets and be deflected into the electron beam dump.

Mis-wired QUE1 as a vertically deflecting dipole As in the horizontally deflecting case, rays not intercepted by C00 and C0 are directed into the trench or beam dump by BYD.

Mis-wired QUE2 as a horizontally deflecting dipole Similar to the case for QUE1 mis-wiring, rays not intercepted C0 pass through BYD and are directed into the trench or beam dump.

Mis-wired QUE2 as a vertically deflecting dipole Similar to the case for QUE1 mis-wiring, rays not intercepted C0 pass through BYD and are directed into the beam dump. The vertical angle of the dumpline is -0.087866 radians. The maximum kick angle for a QUE mis-wire is 0.021 implying the in the worst case the beam would have a vertical angle downward of a $0.087866 - 0.021 = 0.067$ radians. Such a beam would pass below the floor level after 21 m — well before EH2 wall — after which it would be absorbed in the trench or in the electron beam dump.

BYD mis-wired, wrong, or no vertical deflection It is conceivable that the BYD electromagnets could be mis-wired and produce no field, or a field in the opposite direction from what was intended. The result would be that the electron beam would either continue in a straight line along the x-ray beampath, or would be deflected upward if the polarity was incorrect. However, there is no conceivable horizontal deflection. The safety dump line scheme relies on a single horizontally deflecting permanent magnet and a system of collimators to intercept all possible electron beams that might arise from a BYD mis-wire event.

Referring Figure 1, which is in the plan view and shows only horizontal deflections, all possible beam paths (QUE1 and QUE2 are assumed to be wired normally) passing through BYD are either terminated by C1, C2, or pass through the gap in the permanent magnet PM. Those that pass through the gap are deflected to either C3 or C4. The two rays emanating from the aisle side of the PM represent the paths for highest and lowest energy beams. The ray striking the C4 collimator represents the highest energy case. It strikes the collimator 10 mm from the inner edge.

Referring Figure 2, which is in the elevation view, four rays emanate from just after BYD1. The outer two rays represent the extreme rays if the beam energy is at a minimum and the BYD magnets are power at the nominal maximum and mis-wired. The inner two rays just touch the outside edges of collimator C1 and are extrapolated in a straight line thereafter. It can be seen that these forward-most rays strike the tunnel ceiling or floor well before they reach the EH2 wall. A close-up elevation view shown in Figure 3. In this case the innermost pair of rays represent the extreme beam paths that pass through

[1] The four rays are calculated as if they start exactly on axis and do not take into account an initial angle or position prior to QUE1. The actual range of possible angles is less than of order 1 mm/ 30 m = 30 μrad, (30 m is a typical beta function value and 1 mm is the maximum allowed orbit deviation by MPS) which is negligible compared to the kick angle of the QUE mis-wire. Similarly the 1 mm orbit allowance is negligible compared with the maximum allowed beam excursion.

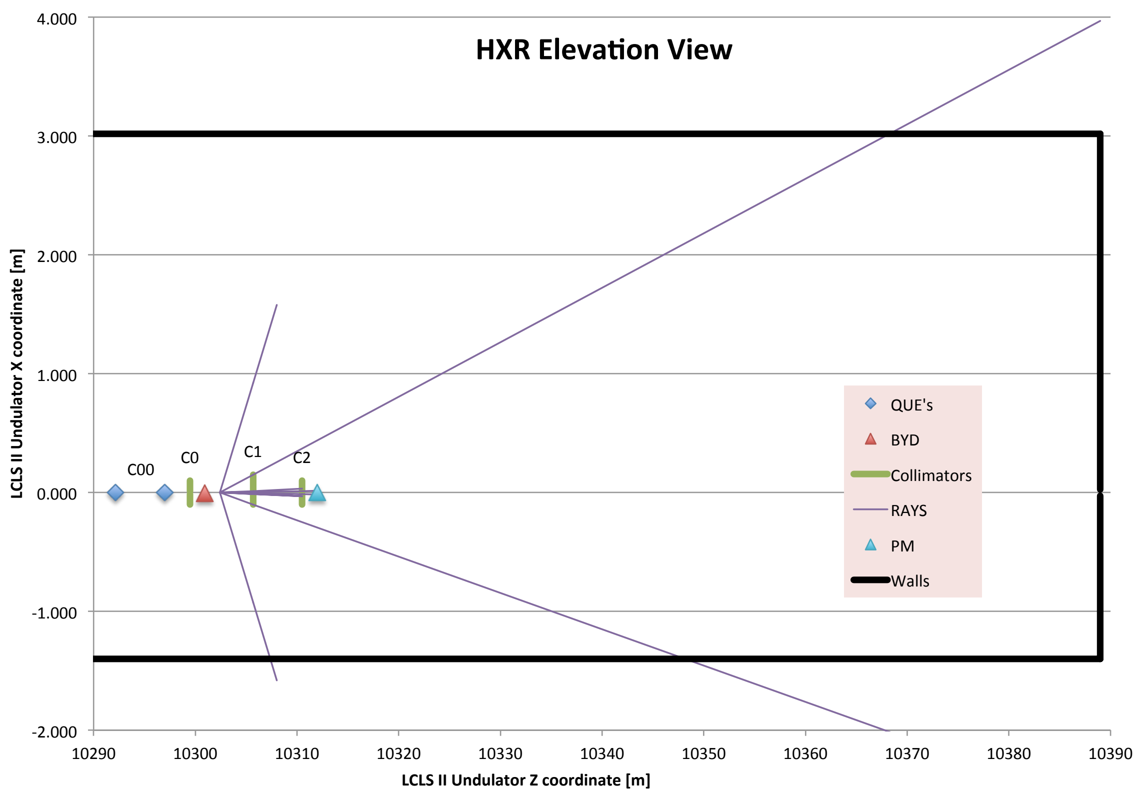

Figure 2: Elevation view of collimators and ray-traces for the HXR beamline.

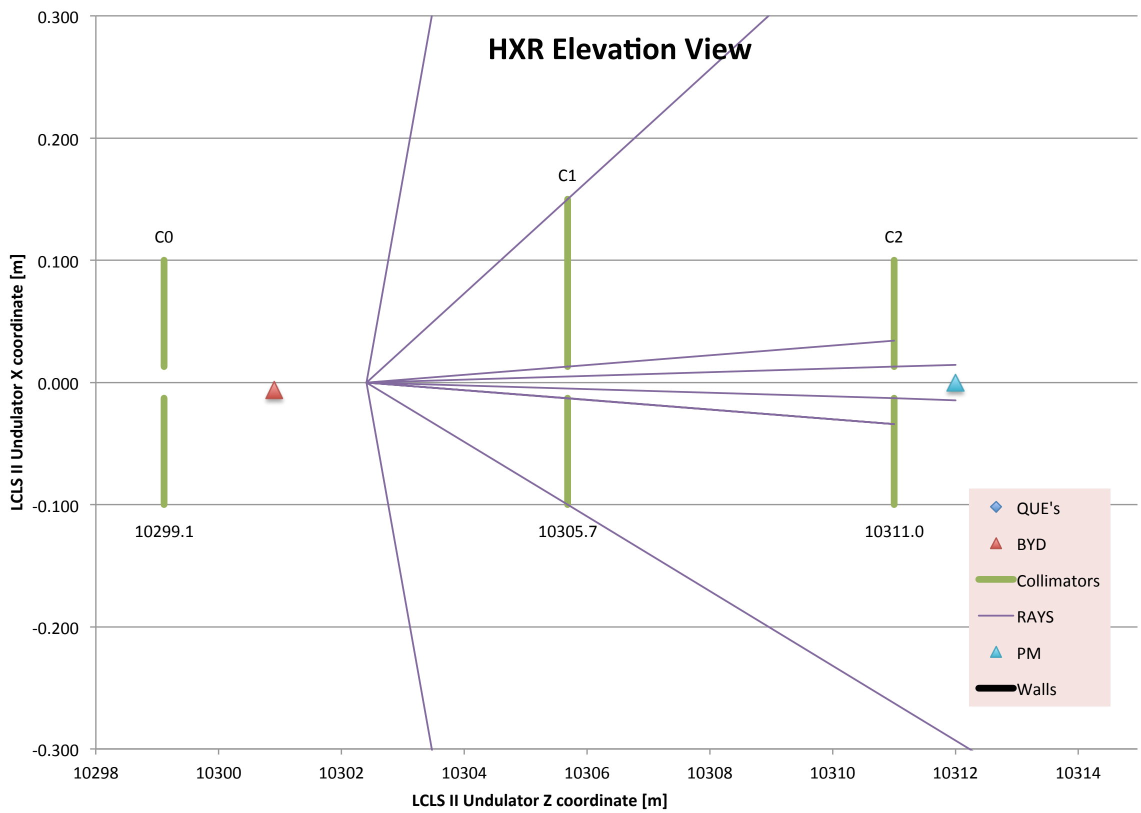

Figure 3: Close-up elevation view of the collimators and ray-traces for the HXR beamline.

C1. These rays are collimated on C2 such that they either terminate on C2 or pass through the gap in the permanent magnet and are deflected horizontally and absorbed on C3 and C4 (not shown in this view). The source point for rays hitting the outer edges of the C1 collimator represent beams that escape the field in the middle of the BYD1 magnet. The extent of the rays passing through the PM is 30 mm while the gap is 38 mm, so no beam paths can strike the permanent magnet poles.

Though not shown in Figure 2, the electron beam passes below C1. There is a nominal clearance between the bottom of C1 and the electron beam centerline of 172 mm.

4.4 SXR ray-trace

Compared with the HXR photon beamline, the optical path of the SXR photon beamline has a much larger offset. This feature allows collimators to block the errant electron beam without the need for a horizontally deflecting permanent magnet. The plan view of the SXR collimation scheme is shown in Figure 4. Note that the size and location of the C00 and C0 collimators and the position of the BYD magnet are identical for the HXR and SXR lines. (See Tables 2 and 3)

Mis-wired QUE1 or QUE2 In the HXR analysis it was conservatively assumed that the mis-wired QUE magnet was powered for the highest energy but the beam energy was the lowest. The same assumption is made for the SXR analysis. Therefore the ray trace analysis given for the HXR cases of mis-wiring QUE1 or QUE2 is the same as for the SXR beam for the rays terminating on C00 and C0, (which are also identical, see Table 2). The rays which pass through C0 pass through the gap in the BYD magnet are are deflected downward into the dump.

BYD mis-wired, wrong or no vertical deflection Referring to Figure 4, the horizontal projection of all possible beam paths is encompassed by a pair of rays emanating from C0 and terminating on C2. Two more pairs of rays start at C0, just touch the inner opening of C1 and terminate on C3. These rays encompass all possible rays passing through C2. Therefore, even if the BYD magnet is mis-wired, all rays passing through C0 are terminated on collimators and none escape, provided collimators C1, C2, and C3 have adequate vertical extent.

The SXR elevation view in Figure 5 and the close-up elevation view in Figure 6 show that the vertical extent of the C1 collimator is adequate. Any rays not stopped by C1 either hit the ceiling, floor, or the trench; or are stopped on C2, or pas through C2 and hit C3. The source point for rays hitting the outer edges of the C1 collimator represent beams that escape the field in the middle of the BYD1 magnet.

The earth's magnetic field will have a small effect on the lowest energy beams. In the SXR case a beam originating at a zero-field BYD magnet would develop a horizontal offset of 3 mm at the C2 collimator and 8 mm at the C3 collimator relative to the same beam without earth's field acting on it. These offsets are small enough that the C2 and C3 collimators can easily accommodate them.

The inner dimensions of the SXR collimators C1,C2, and C3 do not match their counterparts in the HXR line because a larger beam stayclear is required.

5 Design

5.1 Collimators

Collimators are required that occlude the physical dimensions designated in Table 2. The meaning of the physical dimensions is explained in Figure 7. Though a rectangular shape is depicted, it is permissible to use round or other shaped collimators provided the shape described by the parameters is completely covered by the chosen shape as shown in Figure 8. Generally the collimator shape dimensions were chosen to include the beam stayclear, a standard vacuum tube size, and a few millimeters of position tolerance. The relationship between the model used for the ray-trace study and the physical requirements of the collimators is shown in Figure 9.

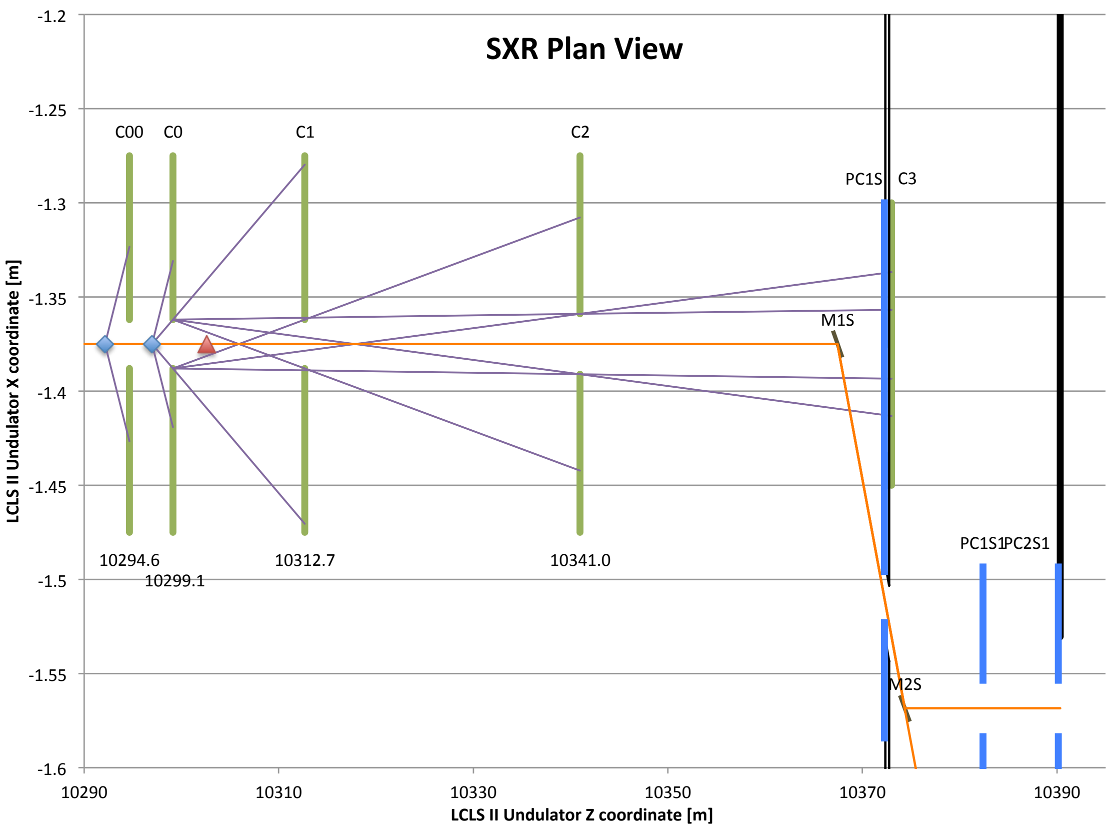

Figure 4: Plan view of the collimators and ray-traces for the SXR beamline.

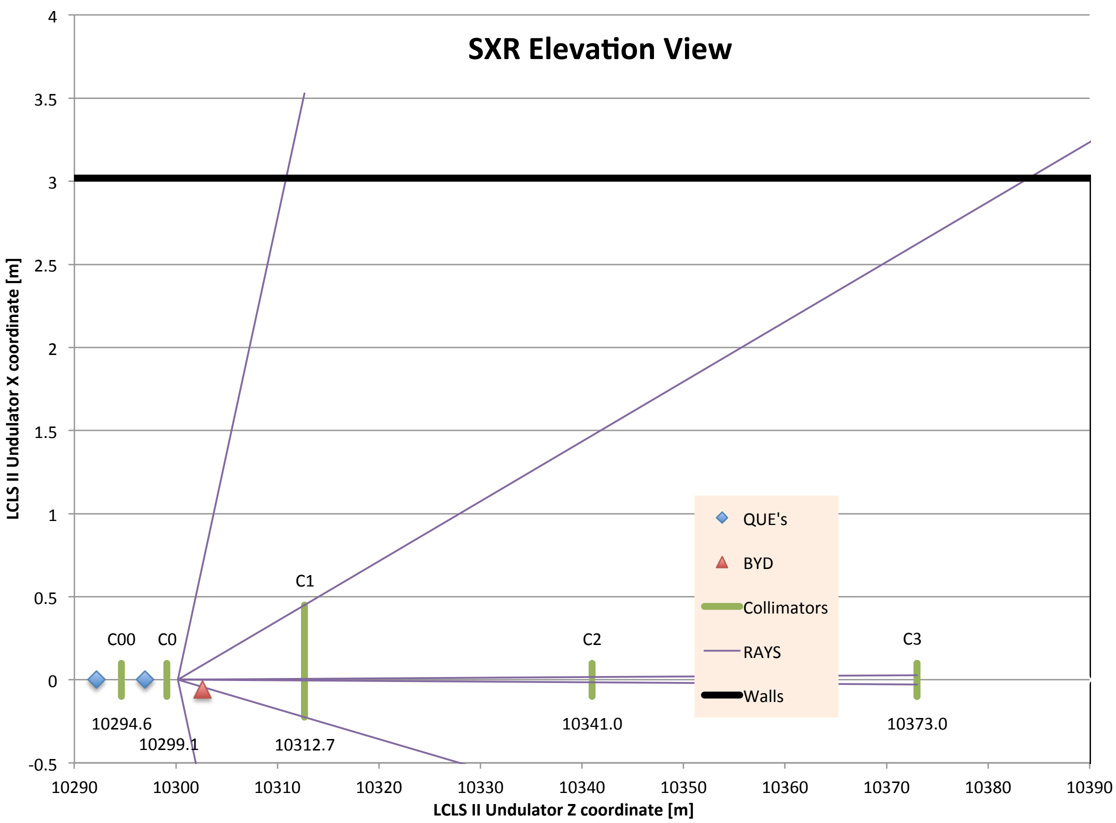

Figure 5: Elevation view of the collimators and ray-traces for the SXR beamline, ceiling, floor, and west wall.

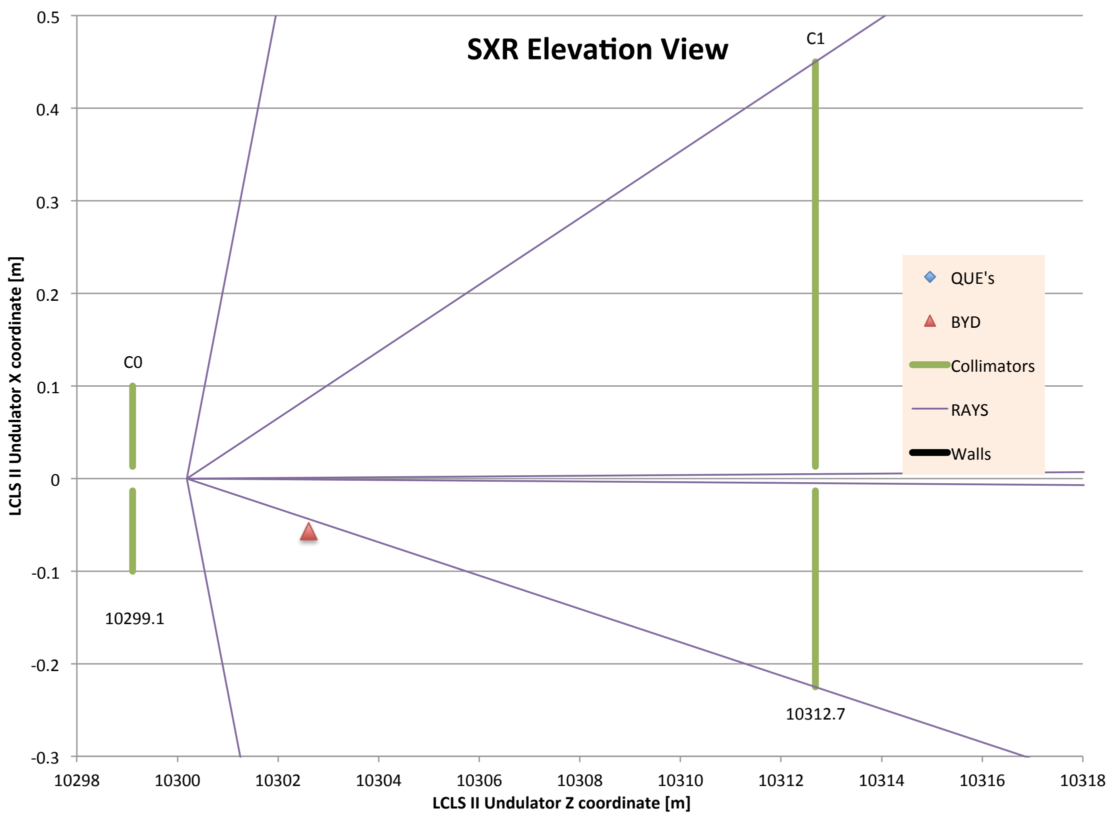

Figure 6: Close-up elevation view of the collimators and ray-traces for the SXR beamline, ceiling, floor, and west wall.

5.2 Permanent magnet

A single permanent magnet is required for the HXR line and the relevant parameters are defined in Table 3. This is requirement is in contrast to that of LCLS-I where three permanent magnets were required.

Acknowledgment

The design of the collimators was developed with helpful feedback from Mario Santana, who ran a sophisticated single-point simulation of the beam and collimator arrangements and pointed several deficiencies.

References

[1] J. Galayda, Linac Coherent Light Source II Global Project Requirements, SLAC-I-060-105-000-00-R000, performance goals for Linac, p.7.

[2] P. Emma, Electron Beam Loss in the LCLS, PRD 1.1-011-Rev-8, (2008)

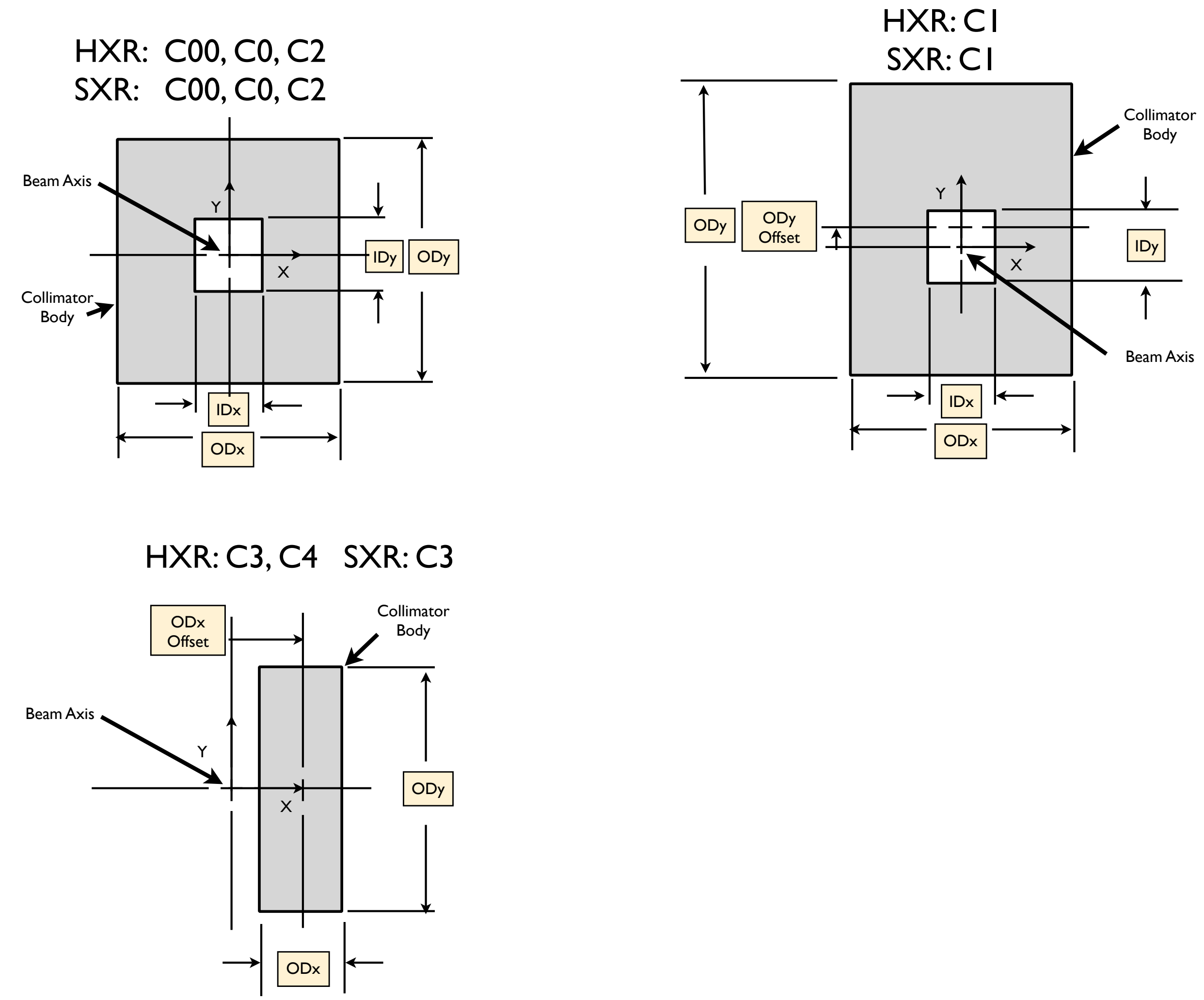

Figure 7: Collimator shape parameter definitions. Coordinates refer to the LCLS-II Undulator coordinate system and the beam is in the Z-direction coming out of the paper.

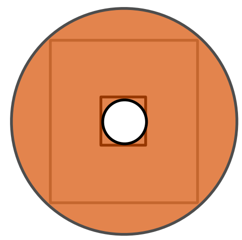

Figure 8: Example of collimator profile that would cover the defined rectangular shape.

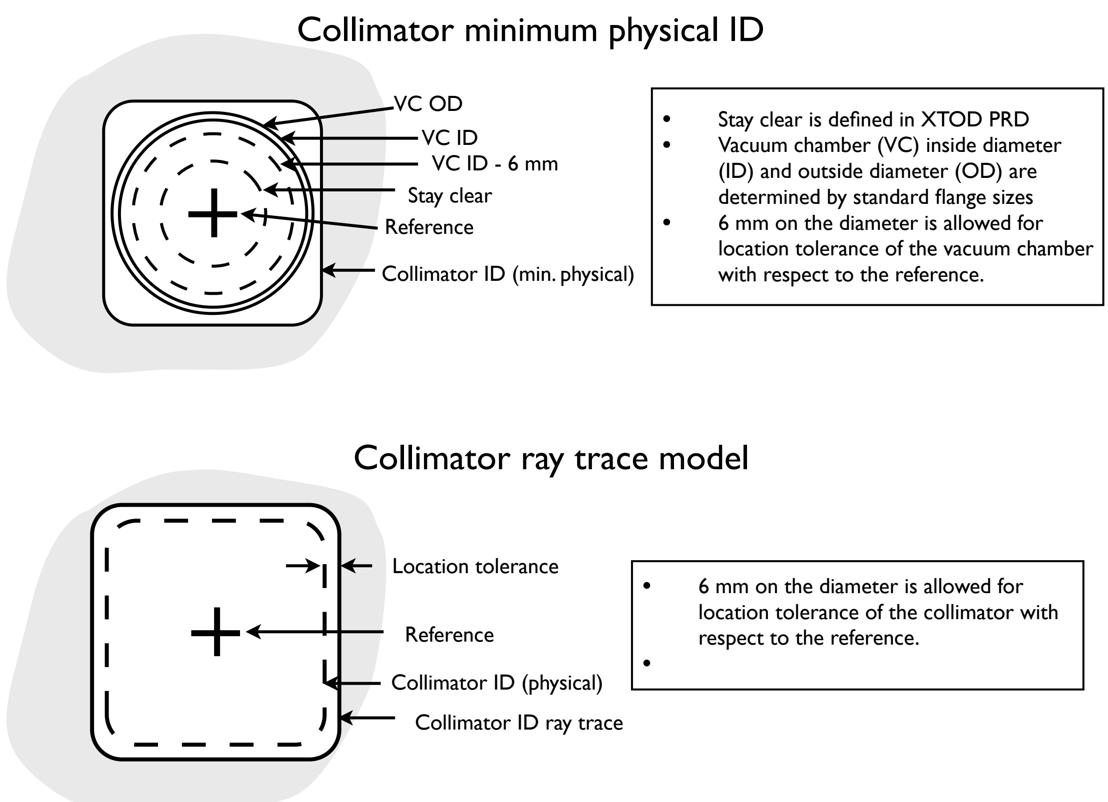

Figure 9: The relationship of the stayclear diameters, collimator physics size requirements and sizes used in the ray-trace study are shown.

Table 1: Parameters assumed for the ray trace analysis.

Parameter	Value	Unit	Note
BYD nominal kick angle	−0.088	radians	MAD deck LCLSII01FEB12
BYD mis-wire kick angle	±0.282	radians	Scaled from Max GeV.
QUE mis-wire integrated field	0.289	Tm	Estimated from max gradient and bore
QUE mis-wire max kick	±0.021	radians	Max. range, either horz. or vert.
QUE max gradient	±7	T	SLAC-I-060-103-055-00-R000
QUE bore radius	41.3	mm	sa9026140200.pdf
PM field	0.4	Tm	LCLS PRD 1.3-117-r1, scaled to 38 mm gap
Min. GeV	4.2	GeV	Min. electron beam energy [1]
Max. GeV	13.5	GeV	Max. electron beam energy [1]
Collimator tolerance	3	mm	Max. radial error in position

Table 2: Collimator locations, and ray-trace and physical shape dimensions.

MAD	Figure	Z	Ray-Trace [mm]				Physical [mm]				Offsets [mm]		
Name	Label	[m]	IDx	ODx	IDy	ODy	IDx	ODx	IDy	ODy	ODx	IDx	ODy
PCPM00H	C00	10294.6	26	200	26	200	20	206	20	206	0	0	0
PCPM0H	C0	10299.1	26	200	26	200	20	206	20	206	0	0	0
PCPM1H	C1	10305.7	26	200	26	300	20	206	20	306	0	0	50
PCPM2H	C2	10311.1	26	200	26	200	20	206	20	206	0	0	0
PCPM3H	C3	10314.0	0	87	0	200	0	93	0	206	56.5	0	0
PCPM4H	C4	10318.0	0	87	0	200	0	93	0	206	56.5	0	0
PCPM00S	C00	10294.6	26	200	26	200	20	206	20	206	0	0	0
PCPM0S	C0	10299.1	26	200	26	200	20	206	20	206	0	0	0
PCPM1S	C1	10312.7	26	200	32	675	20	206	26	681	0	0	112.5
PCPM2S	C2	10341.0	32	200	32	200	26	206	26	206	0	0	0
SFTDMPS	C3	10373.0	0	150	0	200	0	156	0	206	0	0	0

Table 3: Magnet parameters

MAD Name	Figure Label	Z center [m]	Integ. Field [Tm]	Integ. Gradient [T]	Gap [mm]
QUE1H	QUE1	10292.1	0	7	82.55
QUE2H	QUE1	10297.0	0	7	82.55
BYD1HA	BYD	10300.9	-	0	43.992
BXPM1HA	PM	10312.0	0.4	0	38
QUE1S	QUE1	10292.1	0	7	82.55
QUE2S	QUE1	10297.0	0	7	82.55
BYD1SA	BYD	10300.9	-	0	43.992