Beam Containment in the Offset Mirror System Region of the LCLS Front End Enclosure

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Brief Summary: This document summarizes the methodology and assumptions used in constructing the FEL photon beam containment ray traces for the Offset Mirror System (OMS) region of the LCLS Front End Enclosure (FEE).

Change History Log

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<th>Sections Affected</th>
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<td>2009/6/23</td>
<td>All</td>
<td>Initial Version</td>
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1. Introduction:

1.1. Overview:

This ESD summarizes the methodology and approximations used in constructing the FEL photon beam containment ray traces for the Offset Mirror System (OMS) region of the LCLS Front End Enclosure (FEE). The ray traces appear as sheets 1-3 of "LCLS Front End Enclosure Ray Trace", GP-380-001-03.

The downstream half of the FEE is occupied by the OMS. Within the FEE, the OMS comprises six mirrors and five collimators. While the five collimators have fixed apertures and are fixed in position, the six mirrors are not; each can both rotate and translate. The extreme rays generated as the FEL x-ray beam is relayed from mirror to mirror are generally prevented from overfilling the transport beam pipe by restricting the rotation and translation ranges of the mirrors. Even with such restrictions, however, additional restricting apertures are required in a few special locations. Nevertheless, when taken altogether, these motion restrictions and special apertures permit full, passive containment of the FEL beam within the FEE vacuum transport, without communication/interface with the LCLS Beam Containment System electronics. This is a practical simplification of the overall requirement for containment of the FEL beam within the FEE.

In what follows, the photon beam ray traces will be introduced, and the methods, assumptions, and approximations made to generate them presented.

1.2. Boron Carbide, the "FEL-Proof" Material:

As has been previously described elsewhere, the LCLS FEL beam is capable of ablation-damaging almost any material it intercepts. The few materials that are presently thought to be "FEL-proof" tend to have high melting temperatures and are comprised of low-atomic-number elements. Of these, boron carbide ($\text{B}_4\text{C}$) appears to be the best suited for cost-effective application within the LCLS vacuum system. In addition, for the present photon energy range of the LCLS FEL beam, 10 mm of $\text{B}_4\text{C}$ produces adequate attenuation of the FEL beam such that subsequent conventional materials downstream require no additional protection. As a result, all locations within the FEE where the FEL beam may terminate on the vacuum system must be composed of 10 mm of $\text{B}_4\text{C}$.

2. Ray Trace Results:

In order to better understand subsequent descriptions of how the ray traces are constructed, some initial familiarity with the ray trace results themselves will be helpful. A simplified plan view ray trace for the OMS is illustrated in Figure 1. The mirrors and collimators of the OMS are illustrated, together with an outline of the
vacuum transport envelope. In addition, four special $B_4C$ apertures, the Photon Stoppers, and major shielding components are also illustrated. Each collimator utilizes $B_4C$ on its upstream face. All mirrors include a $B_4C$ "chin guard" to protect the upstream-facing surface of the mirror substrate. All possible trajectories of the FEL beam are illustrated as the fan-shaped regions linking the mirrors and collimators. As can be seen from Figure 1, the FEL trajectory never impinges upon the unprotected vacuum system envelope.

A list of all OMS $B_4C$ components is presented in Table 1. The item numbers listed are taken from ESD 1.5-120. While many items serve a "beam containment" function (BCS), others are not required for beam containment and only serve to prevent component damage, i.e. "machine protection" (MPS). This distinction is indicated in the "Function" column.

<table>
<thead>
<tr>
<th>Item #</th>
<th>Function</th>
<th>Hard X-Ray Branch Beam Line</th>
<th>Soft X-Ray Branch Beam Line 1</th>
<th>Soft X-Ray Branch Beam Line 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>BCS</td>
<td>Collimator C1, upstream face</td>
<td>Collimator C1, upstream face</td>
<td>Collimator C1, upstream face</td>
</tr>
<tr>
<td>12</td>
<td>MPS</td>
<td>Mirror M1H, chin guard</td>
<td>Mirror M1S, chin guard</td>
<td>Mirror M1S, chin guard</td>
</tr>
<tr>
<td>15</td>
<td>BCS</td>
<td>Collimator C2H, upstream face</td>
<td>Collimator C2S, upstream face</td>
<td>Collimator C2S, upstream face</td>
</tr>
<tr>
<td>16</td>
<td>MPS</td>
<td>Mirror M2H, chin guard</td>
<td>Mirror M2S, chin guard</td>
<td>Mirror M2S, chin guard</td>
</tr>
<tr>
<td>18</td>
<td>MPS</td>
<td>Differential Pump, pumping throttle protection aperture</td>
<td>Differential Pump, pumping throttle protection aperture</td>
<td>Differential Pump, pumping throttle protection aperture</td>
</tr>
<tr>
<td>19</td>
<td>BCS</td>
<td>Stopper SH1, upstream block faces, 2X</td>
<td>Stopper S1, upstream block faces, 2X</td>
<td>Stopper S1, upstream block faces, 2X</td>
</tr>
<tr>
<td>20</td>
<td>BCS</td>
<td>Collimator C3H, upstream face</td>
<td>Collimator C3S1, upstream face</td>
<td>Collimator C3S2, upstream face</td>
</tr>
</tbody>
</table>

Table 1: $B_4C$ Components
Figure 1: Illustration plan view ray trace for the OMS in the FEE.
Figure 2 provides similar information for an elevation view. In this case, the anamorphic magnification is considerably greater (500:1, vs. 10:1). Separate illustrations are presented for each branch beam line, i.e., the two soft x-ray branch beam lines and the hard x-ray branch beam line. These illustrations are made along the ideal centerline of each branch beam line in the horizontal, that is, the illustration "straightens out" the beam line. Only the mirrors and collimators are illustrated, and then in a more schematic fashion. Note that the full vertical scale for each illustration is only $\pm 5$ mm. Consequently, the FEL trajectory never impinges upon the unprotected vacuum system hardware, which is far off scale in the drawing.
Figure 2: Illustration elevation view ray trace for the OMS.
3. Ray Trace Preparation Methodology:

This section details the methodology used in constructing the ray trace drawings. Initially, some general definitions and terminology are presented, along with the required geometrical inputs. Following these, a step-by-step outline of the plan view ray trace construction is presented, with the primary purpose of explaining the assumptions and approximations used in each step, as the FEL beam is relayed from element to element. A similar explanation is then made for the elevation view.

3.1. Treatment of Apertures: As was mentioned previously, 10 mm of B₄C is necessary to adequately attenuate the incident FEL beam. As a result, to identify an "extreme ray" within a fan of possible trajectories incident at the edge of a B₄C aperture, the ray which just penetrates the entire 10 mm of B₄C is the defining extreme ray. For the present situation, in which the apertures are encountered at nearly normal incidence, the extreme ray will be the one entering the upstream corner of the aperture edge, as illustrated in Figure 3.

![Treatment of Apertures](image)

Figure 3: The extreme ray just passes through the full 10 mm of B₄C in the aperture.
3.2. **The "Acceptance Region" of a Mirror:** In estimating the extreme output trajectories of an incident optical beam on a movable mirror, it would be helpful if the number of incident beam and mirror settings that must be considered could be reduced to a small, finite set and still be assured of obtaining conservative extreme output rays. This leads to the concept of an "acceptance region" for a mirror. This region is constructed from coordinates on the mirror surface and combinations of the allowable mirror rotations and translations. Figure 4 below illustrates development of 8 extreme points that arise for mirrors having the degrees of freedom available in the XTOD OMS, i.e. translation in the x-direction and yaw rotation.

![Figure 4: The Extreme Points of a Mirror.](image)

As long as the entire mirror can be illuminated by the source, the extreme output rays will come either from the upstream corner of the mirror or from the downstream corner, as illustrated in the upper left panel. Again, as long as the source can illuminate the entire mirror throughout its entire x-translation range, the extremes of the translation will be required to produce the extreme output rays. In a similar fashion, the extremes of the mirror yaw rotation will also be required to produce the extreme output rays. Taking all possible combinations of these three parameters yields the eight points illustrated in the bottom right panel. They are the upstream and downstream corners of the mirror surface for the extremes of mirror translation and for the extremes of mirror rotation, taken in all possible combinations.
Although calculations can be performed using the eight extreme points, additional, conservative simplifications can still be made. As illustrated in Figure 5, an "acceptance region" can be constructed to enclose all the extreme points. Furthermore, one can assume that any incident ray entering this region will encounter the extreme settings of mirror rotation. (This is clearly conservative, since only the corners of the acceptance region actually correspond to extreme mirror rotation, but then only in one of the two possible rotation directions.)

Using the acceptance region concept, one finds that two "corner points" are responsible for the extreme output rays in the general case. These are illustrated for "upward-deflecting" and "downward-deflecting" mirror cases in the lower portion of Figure 5. Therefore, as long as these corner points are illuminated by the incident source, they will serve as the source points for the output extreme rays, whether those rays are simply propagated downstream to a target, or threaded through an intermediate aperture on their way to a downstream target. This level of simplification allows the entire ray trace to be constructed graphically, with minimal reliance on numerical calculations.

Figure 5: The Acceptance Region and the Corner Points for two mirror orientations.
3.3. **The BCS Construction:** The inputs and operations performed in the BCS construction are now detailed.

3.3.1. **Input Parameters:** The primary input parameters for the BCS construction are summarized in Table 2, Table 3, and Table 4, for the FEE mirrors, collimators, and apertures respectively.

### Table 2: Mirror Parameters in the FEE

<table>
<thead>
<tr>
<th></th>
<th>M1S</th>
<th>M1H</th>
<th>M2S</th>
<th>M3S1</th>
<th>M3S2</th>
<th>M2H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z (m)</td>
<td>739.185</td>
<td>740.510</td>
<td>741.835</td>
<td>750.751</td>
<td>750.751</td>
<td>751.843</td>
</tr>
<tr>
<td>X (mm)</td>
<td>0.0</td>
<td>0.0</td>
<td>73.4</td>
<td>567.9</td>
<td>567.9</td>
<td>30.6</td>
</tr>
<tr>
<td>θ (mrad)</td>
<td>13.850</td>
<td>1.350</td>
<td>41.550</td>
<td>69.250</td>
<td>41.550</td>
<td>1.350</td>
</tr>
<tr>
<td>&quot;orientation&quot;</td>
<td>north</td>
<td>north</td>
<td>north</td>
<td>north</td>
<td>south</td>
<td>south</td>
</tr>
<tr>
<td>L (mm)</td>
<td>250</td>
<td>450</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>450</td>
</tr>
<tr>
<td>Δx (mm) †</td>
<td>+2.5</td>
<td>±2.5</td>
<td>±1.0</td>
<td>+2.5</td>
<td>+12.0</td>
<td>±2.5</td>
</tr>
<tr>
<td>Δθ (mrad) ‡</td>
<td>±3.0</td>
<td>±1.2</td>
<td>±3.0</td>
<td>±3.0</td>
<td>±3.0</td>
<td>±1.2</td>
</tr>
</tbody>
</table>

† The Δx range is restricted by hard stops and limit switch interlocks.
‡ The Δθ range is inherently restricted by the rotating-cam actuator design.

Referring to Table 2, the z-coordinate is the mirror center location in LCLS coordinates, i.e. from Station 100. The x-coordinate is the mirror center displacement perpendicular to the theoretical input beam entering the FEE from the Electron Beam Dump. The angle θ is the counter clockwise yaw rotation relative to the z-direction. The optical surfaces of the OMS mirrors tend to point either at the north wall or the south wall of the FEE. This is the parameter in the table listed as "orientation". The overall length of the mirror is given as L. The translation range of the mirror along the x-direction is given as Δx, while the yaw rotation range is given as Δθ.
Collimator and Aperture location and rotation parameters given in Table 3 and Table 4 have the same meanings as in Table 2. The variable \( \phi \) is the aperture diameter in the Collimator/Aperture.

3.3.2. Construction of the Plan View:

3.3.2.1. Undulator Source Extreme Rays through Collimator C1: The geometry utilized to obtain the undulator source horizontal extreme rays through Collimator C1 is illustrated in Figure 6.
Rays are drawn from the extreme vertical edges of an effective undulator beam tube (located at LCLS Z coordinates of 647.000 m) to opposite edges of the aperture in Collimator C1, at the upstream collimator surface. Such a procedure certainly results in a worst-case deviation from the beam centerline, since if these rays are projected back toward the undulator, they soon run into the wall of the undulator beam tube. Therefore, it is highly unlikely that the entire FEL beam could exit the undulator beam tube in such an orientation and direction, unless the beam could be specularly reflected. The deviations of these extreme rays, and the values actually used in the BCS calculation, are summarized in Table 5.

A similar construction, but contained in a vertical plane rather than in the horizontal plane, is performed to obtain the extreme rays for the elevation view. The numerical results are also summarized in Table 5.

### Table 5: Undulator Source Extreme Ray Angles through Collimator C1

<table>
<thead>
<tr>
<th>View</th>
<th>From Geometry</th>
<th>Used in Calculation</th>
</tr>
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<tbody>
<tr>
<td>Plan</td>
<td>± 99 µrad</td>
<td>± 100 µrad</td>
</tr>
<tr>
<td>Elevation</td>
<td>± 72 µrad</td>
<td>± 75 µrad</td>
</tr>
</tbody>
</table>

3.3.2.2. Define the Acceptance Regions and Corner Points for Each Mirror:
The acceptance regions and corner points for the six OMS mirrors are derived according to the concepts outlined in Section 3.2 and the data presented in Table 2.

3.3.2.2.1. Re-define Corner Points for the M1's: The limited source divergence through Collimator C1 makes it impossible to illuminate the typical corner points of M1S and M1H (see Figure 5) for the entire Δx translation range. The effective corner points which can actually be illuminated (altered x-coordinates) are obtained.

3.3.2.3. Beam Clearance Requirements: The vacuum transport hardware (stainless steel tubing and flanges) is likely to be damaged if it intercepts the FEL beam. Therefore, sufficient clearance must be provided between the worst-case FEL beam trajectories and the inner surfaces of the vacuum transport system. That clearance requirement is specified in LCLS XTOD PRD 1.5-002, Section 6: A 3 mm minimum clearance is required. 5 mm is desired. 2 mm is allowable only with special consideration and means to assure
clearance. For this OMS BCS design, a minimum 5 mm clearance is generally required to components that might be damaged by the FEL beam, i.e. anything except the mirror surfaces and B\(_4\)C.

3.3.2.3.1. The one exception is the clearance to throttle assemblies in two differential ion pumps. These two pumps are located immediately downstream of C1 and between M2H and C3H. To be effective, the throttle assemblies through which the FEL beam will pass, must be as small as possible. A 2 mm nominal clearance is established by using throttle diameters of 9 mm, and fiducializing the assemblies and carefully aligning them to upstream B\(_4\)C protection apertures. The 5 mm aperture in C1 protects the upstream pump. A separate B\(_4\)C aperture, attached directly to the throttle of the downstream pump, protects it.

Even if the FEL beam were to strike the throttle assemblies, or the internal components of the differential ion pumps, these are not elements of the vacuum enclosure, and are located 10’s of mm from the nearest vacuum structure. Therefore, beam containment is not compromised even if these components should be damaged.

3.3.2.4. Propagate Beam from M1S toward M2S and C2S: FEL light passing through C1 illuminates M1S. The corner points on M1S, defined by the edges of the incident FEL beam fan, become the source points for the extreme rays towards M2S and C2S. The incident undulator source rays are mirror-reflected and propagated to M2S and C2S. The north ray passes over M2S and terminates on C2S, while the south ray terminates on the chin guard of M2S

3.3.2.5. Propagate Beam from M1S, Reflect from M2S, to C2S: The corner points of M1S and M2S are linked in all their possible combinations to obtain input rays to M2S. These input rays are then mirror reflected from M2S and propagated to C2S. The two worst-case rays are retained.

3.3.2.6. Propagate Beam Past M2S: This ray is obtained by linking pairs of corner points from M1S and M2S and extending the resulting rays to C2S. The worst-case ray is retained.

3.3.2.7. Propagate Beam from M2S through C2S to the M3's: The corner points of M2S are linked to the extreme edges of the aperture in C2S. The resulting rays are extended to the chin guards of the M3's. The worst-case rays are retained. This process implicitly assumes that beam can be mirror-reflected from M1S to M2S and directed to
either edge of the C2S aperture. A separate numerical study confirmed that this assumption is valid.

3.3.2.8. Propagate Beam from C2S Past the M3's to B4C1: The two edges of the C2S aperture become sources of rays to the extreme edges of the acceptance regions associated with both M3S1 and M3S2. The resulting rays are propagated to B4C1, which in this case serves as a beam stop. The two extreme rays are retained.

3.3.2.9. Propagate Beam from C2S through the M3's to B4C1: The aperture edges of C2S again provide the source points. These points are linked to the corner points of M3S1 and M3S2. The resulting rays are extended to B4C1. The worst-case rays are retained.

3.3.2.10. Propagate Beam from the M3's through B4C1 to B4C2 and B4C3: The corner points of M3S1 and M3S2 are linked to their respective apertures in B4C1. The resulting rays are extended to B4C2 in the case of M3S1, and to B4C3 in the case of M3S2. The worst-case rays are retained. This process implicitly assumes that source rays originating at the aperture edges in C2S, linked to the corner points of the M3's, can be mirror-reflected through the appropriate aperture edges in B4C1. This, in fact, is not the case. Specifically, for the north ray at B4C2 and the south ray at B4C3, the required mirror rotation exceeds the rotation limits specified in Table 2, even when a reasonable installation error is also included. Therefore, these rays represent a very conservative worst-case.

3.3.2.11. Propagate Beam from M3S1 through B4C1 and B4C2 to C3S1: The corner points of M3S1 are linked to the aperture edges in B4C2 and propagated to C3S1. The worst-case rays are selected. However, the north ray arriving at C3S1 from such a construction fails to pass through the aperture in B4C1. Therefore, the actual worst-case ray is instead defined by opposite aperture edges in B4C1 and B4C2, propagated to C3S1.

3.3.2.12. Propagate Beam from M3S2 through B4C1 and B4C3 to C3S2: The corner points of M3S2 are linked to the aperture edges in B4C3 and propagated to C3S2. The worst-case rays are selected. However, the south ray arriving at C3S2 from such a construction fails to pass through the aperture in B4C1. Therefore, the actual worst-case ray is instead defined by opposite aperture edges in B4C1 and B4C3, propagated to C3S2.

3.3.2.13. Propagate Beam from M3S1 through B4C1, B4C2, and C3S1 to C4S1: As in Section 3.3.2.11 above, one corner point on M3S1 and an aperture edge on B4C1 are linked to the aperture edges in C3S1 and propagated to C4S1 to obtain the extreme rays.
3.3.2.14. Propagate Beam from M3S2 through B4C1, B4C3, and C3S2 to C4S2: As in Section 3.3.2.12 above, one corner point on M3S2 and an aperture edge on B4C1 are linked to the aperture edges in C3S2 and propagated to C4S2 to obtain the extreme rays.

3.3.2.15. Propagate Beam from M1H to C2H: Using much the same procedure given in Section 3.3.2.4 above, extreme rays from M1H are projected to C2H. In addition, M1H can be retracted such that most of the incident beam from the undulator source can pass over the mirror surface and directly terminate on C2H. These rays are also shown.

3.3.2.16. Propagate Beam from M1H through C2H to M2H and beyond to C3H: The corner points of M1H are linked to the aperture edges of C2H and the rays obtained propagated to M2H. Due to the close proximity of C2H to M2H, all of these rays pass through the M2H mirror acceptance region, i.e. the M2H mirror acceptance region is not fully illuminated. Therefore, the corner points for M2H must be defined somewhat differently. A crossover set of rays illuminates the largest portion of the M2H mirror acceptance region. This set of rays is used to define the corner points of M2H, and when reflected, produces the extreme-case output rays to C3H. These corner points are also used as the sources for subsequent apertures downstream. Finally, because M2H can be substantially withdrawn from the incident beam, this crossover set of rays is also propagated directly to C3H, and produces the north extreme ray at C3H.

3.3.2.17. Obtain Trajectory Fan for the Differential Pump Protection Aperture: A special differential ion pump is located between M2H and C3H. It isolates the ultrahigh vacuum of the OMS from downstream portions of the hard x-ray branch beam line. The inlet aperture of the differential ion pump is 9 mm in diameter, which is less than the width of the trajectory fan obtained above in Section 3.3.2.16 at the inlet aperture location. Therefore, the trajectory fan information from this Section is used to design a B4C protection aperture. The extreme rays through the protection aperture are obtained using the corner points of M2H and the edges of the protection aperture.

3.3.2.18. Propagate Beam from M2H through C3H to C4H: The corner points of M2H are coupled to the aperture edges of C3H and propagated to C4H. The extreme rays are retained.

3.3.3. Construction of the Elevation View: Unlike the plan view, in the elevation view there are essentially no movable optical elements. Neither the x-translation nor the yaw rotation of the OMS mirrors should ideally
affect the beam trajectory within a vertical plane. Under such ideal conditions, consider the appearance of the ray trace (see Figure 2): Extreme rays through collimator C1 appear at the collimator edges. Away from the collimator edges, towards the ideal beam centerline, possible rays make a smaller maximum angle with the ideal beam centerline. As the fan of rays through C1 is propagated through mirrors, it expands, and the extreme ray angles are preserved. However, when a downstream collimator is encountered, and "trims" the beam to a smaller overall diameter, the resulting maximum extreme ray angle is also decreased, since the extreme edges have been removed. Keeping this ideal ray trace in mind, consider the construction described below:

3.3.3.1. Extreme Rays through Collimator C1: The extreme rays through C1 for the elevation view are derived using the same construction detailed in Section 3.3.2.1 above, and summarized in Table 5.

3.3.3.2. The Effect of a Mirror Roll Angle: The OMS mirrors will not be perfectly aligned. There may be a roll angle error in the mirror alignment, essentially a rotation about the z-axis. Such an error deflects the beam out of the ideal horizontal plane, through a pitch rotation, i.e. a rotation about the x-axis. The geometry used to estimate the resulting pitch error from a mirror alignment roll error is illustrated in Figure 7 below.
Three orthogonal views of a mirror and its incident and reflected beams are illustrated in the figure. The upper left panel is a simple plan view. The incident beam makes a grazing angle $\alpha$ with the mirror surface and reflects at an equal angle to a target a distance $S_{\text{tar}}$ away. The view below, in the lower left, is an elevation view looking through the mirror itself. Although the incident beam is in the horizontal plane, the exit beam has been deflected through a pitch angle $\Delta \psi$. The origin of the pitch angle is evident from the remaining view, another elevation view, with the reflected beam coming out of the page. The mirror has an alignment error in the roll axis, $\delta_{\text{roll}}$. Using the diagram, one can determine, in the small-angle approximation, that:

$$\Delta \psi = 2 \alpha \delta_{\text{roll}}$$

Numerical values for the OMS are summarized in Table 6. The $\delta_{\text{roll, max}}$ value noted is a conservative alignment error for the OMS mirrors.
Table 6: Vertical Beam Steering through Mirror Roll Alignment Errors

<table>
<thead>
<tr>
<th>δ_{roll max}</th>
<th>Soft X-Ray Mirrors</th>
<th>Hard X-Ray Mirrors</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0 mrad</td>
<td>55.40 µrad</td>
<td>5.40 µrad</td>
</tr>
</tbody>
</table>

3.3.3.3. Conservative Construction of the Elevation View: This ray trace (simplified version illustrated in Figure 2) is conservatively constructed using the following assumptions: The initial extreme ray angles through collimator C1 are those listed in Table 5. Whenever the beam is reflected from a mirror, an additional angle, given in Table 6, accounts for the maximum possible additional deflection due to the mirror alignment roll error. When a collimator is encountered, and the beam fan diameter is reduced, the extreme ray angle of the exit beam is set equal to that of the incoming beam to the collimator; it is not reduced. As a result, the ray trace approach illustrated in Figure 2 is certainly a worst-case, as long as the mirror roll alignment allowance can be reasonably met.

4. Summary:

An introduction to the FEL photon BCS ray trace for the OMS region of the FEE has been presented through the illustrations in Figure 1 and Figure 2. The remainder of this document summarized the methodology and approximations used in the ray trace construction.

The FEL beam can be transported through the OMS without approaching within 5 mm of any vulnerable portion of the vacuum transport system, in either the horizontal or the vertical. This requires the use of B₄C on the upstream faces of all the components listed in Table 1, all the collimators, all the mirrors, all the stopper blocks, and the inclusion of three special B₄C apertures. In addition, it requires restriction of the mirror motions, as detailed in Table 2 for mirror translation and rotation.

References: