DESIGN REVIEW REPORT

The Design Review Report Shall include at a minimum:
- The title of the item or system;
- A description of the item;
- Design Review Report Number;
- The type of design review;
- The date of the review;
- The names of the presenters
- The names, institutions and department of the reviewers
- The names of all the attendees

- Findings/List of Action Items – these are items that require formal action and closure in writing for the review to be approved. See SLAC Document AP-391-000-59 for LUSI Design Review Guidelines.
- Concerns – these are comments that require action by the design/engineering team, but a response is not required to approve the review.
- Observations – these are general comments and require no response.

TYPE OF REVIEW: Advance Procurement Technical Review

WBS: 1.3 Coherent X-ray Imaging

Title of the Review: CXI 1 Micron K-B Mirror System Advanced Procurement Technical Review

Presented By: Sebastian Boutet, P. Montanez

Report Prepared By: Al Macrander

Date: 22 October 2008

Reviewers/Lab: N. Kelez (LBL), A. Khounsary (ANL), A. Macrander (ANL) (chair), T. McCarville (LLNL), R. Soufli (LLNL), P. Takacs (BNL)

Distribution:

Attachments: □Review Slides □Design Checklist □Calculations □Other

Purpose/Goal of the Review:

Provide a technical review of the procurement specifications, statements of work and procurement strategy for the CXI 1 Micron K-B Mirror System.
Report from the committee to review procurement plans for the LUSI/CXI KB systems as presented to the committee at SLAC on Oct. 8, 2008

Committee: N. Kelez, A. Khounsary, A. Macrander (chair), T. McCarville, R. Soufli, P. Takacs

Date of report: Oct. 22, 2008

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II. Collections of comments that have a common theme
III. Full texts of individual comments by all committee members

I. Specific Recommendations/Action Items

1) Closer communication with vendors involving local visits is recommended.

2) An arrangement should be made to obtain independent metrology data for mirrors mounted in the manipulator. Such data should be used to check the figure of the delivered mirror assembly independent from the vendor’s own metrology and assurances.

3) The feasibility of a Cr or Ti underlayer that can be used to float off a damaged surface coating should be explored for the CXI mirrors.

4) Consideration of an enclosure for each K-B system to improve temperature stability is recommended.

II. Common Themes/Comments

Vendors

A.K.: "A more substantive discussion with these and other potential vendors is necessary to gain a deeper understanding of what they can or cannot do, key technical issues, metrology systems they use, how the measurements would be made, who the technical person(s) involved are, what fabrication method is used to figure and finish the parts, vendor detail schedule, what technical challenges the vendors envisions, do they need to go beyond their “comfort zone” to deliver the product, what other projects they have, what are their backlogs, what are their prior experience, etc., including a host of what ifs... // The formal RFP/RFQ should be considered as a formality. Almost all the real work has to be done prior to that. Procurement people would not let us to talk to vendors after the request is issued. If these are written loosely, many questions will arise and one may be forced to rewrite it and that delays the process."
R.S.: "The capabilities of the various candidate vendors (for the substrate polishing and for the engineering of the system), and their impact on cost, quality, schedule and other risks, should be further explored and understood, prior to placing the procurements."

P.T.: "Although it would be nice to have a single vendor provide the complete instrument package, mirrors and mechanical parts, the RFQ should be structured in such a way as to not preclude separating the optical and mechanical parts. This will open the procurement up to other vendors who specialize in one or the other capability. In particular, the Physical Sciences Laboratory at the U of Wisconsin should be added to the list of vendors. They have extensive experience in synchrotron beamline instrumentation and have built many monochromators and other systems for various synchrotrons in the past. Also, the capabilities of WinlightX should not be discounted just because they are new players in the game. The same criticism can be made of Jtech."

T.M.: “The preferred procurement strategy and the requirements presented at the review were reasonable and clear. But the specification read by the reviewers does not accurately reflect the procurement strategy and design requirements described at the review. The specification was initially written as a starting point for expression of interest from suppliers. The present draft has served this purpose, but it should be updated to reflect your current strategy and requirements. It will be much more concise once redundant and outdated sections are eliminated.”

N.K.: "While the reported performance of the JTEC fixed figured optics is quite promising, the notion that only one (as suggested in the presentation) of the required length has been fabricated to date makes this an inherently risky procurement path. Significant thought, care and diligence is required to effectively manage this process to a satisfactory performance and schedule delivery. // Engage and evaluate potential vendors as deeply as possible prior to formal procurement process. Examine options for procurement of second vendor (Zeiss, etc.) optics as insurance for delivery and performance issues with primary contractor. Additionally, since these optics will likely have a shorter delivery time, they can be used as both spares and test pieces for coating, metrology and assembly testing. Prior to award of contract, develop and manage meaningful and demonstrable milestones with associated cost, performance, and schedule implications. This should include development of contingency plans and specific decision point(s) to abandon and/or reevaluate options. Develop a valid test plan for key performance requirements that is consistent with vendor and SLAC capabilities (both in house and via sub-contractor)."

A.M.: "The vendors under consideration are credible, but the information so far obtained is incomplete and insufficient to make a selection. In the case of WinlightX, the supplier and fabrication method for the mirrors needs to be known in order to judge the likelihood of a successful delivery. In the case of JTEC, the schedule demands on the CVM and EEM machines need to be known in order to understand more fully the quoted 12 month delivery time."
**Metrology**

A.K.: "Different vendors use different metrologies, yielding different results for the same surface. This means that metrology methodologies must be checked and agreed on with the vendors in advance. It is also best if the metrology procedure is spelled out in advance. // Logistics and the practical aspects of the independent metrology to verify vendor’s results need to be worked out between the three parties in advance. Agreement of the vendor is needed. Also, consider possible outcomes and scenarios: What would be LUSI response, if, for example, the verification results are different from those of the vendor?"

T.M.: "The complexity of calibrating an interferometer to accurately measure nm scale figure error at 45 degrees is formidable. I would not encourage measuring these mirror at use angle with an interferometer. It would seem that a linear trace profiler is a more natural fit. This suggestion should be coordinated with your collaborators at LBL."

P.T.: " Attempting to do metrology on the final assembly is a daunting task. Assuming that the full length of each mirror surface can be viewed at normal incidence, it may be possible to do either stitching interferometry or profilometry on the surface in the final assembly orientation. This will give you information about figure distortions which should be enough to see if any changes have occurred during mounting and assembly. The cost for doing these kinds of measurements is reasonable, as they can be done off line in a metrology laboratory. The other metrology possibility is to do at-wavelength testing at a facility like the X-ray Calibration Facility (XRCF) at Marshall Space Flight Center. This facility has a 518 meter long vacuum pipe connecting the x-ray source to the end station vacuum chamber. Measuring the image from this source through the KB mirror pair would provide an unambiguous measurement of the real system performance and give one a good idea of the tolerances in the motion devices. Unfortunately, this would probably be a very costly metrology effort. Perhaps a similar setup can be rigged with the LCLS beam pipe, inserting an x-ray tube source far upstream from the mirror chamber.

A.M.: " The metrology tool most appropriate to check the figure after mounting is the long trace profiler (LTP). The 45 deg geometry should pose no serious problems for an LTP measurement. However, no specific LTP was defined as the one to be employed."

**Release layer**

A.K.: " If appropriate, consider having a Cr underlayer coating (under some or all coating strips). In the case of damage to the coating (due to radiation, etc.), I could remove the damage (lift off) the damaged coating by etching away the Cr underlayer to have the mirror re-coated, instead of the EXPENSIVE and time-consuming alternative of re-polishing / re-figuring. If Cr is unacceptable, other sub layers such as titanium may be considered."
R.S.: "During the review, Ali Khounsary made the suggestion of using a Cr underlayer in the mirror coating, that could be later etched and render the mirror re-usable (SPIE Proc. Vol. 5193, 2003). This is an excellent suggestion and its feasibility should be investigated for the LUSI K-B mirrors. Two issues should be explored: (i) the survivability of the Cr underlayer material under peak FEL beam conditions (instantaneous dose) that would be applicable for the LUSI K-B mirrors (ii) verification of the substrate mid- and high-spatial frequency roughness properties (using AFM and Zygo metrology) after a coating-and-etching iteration. Both issues (i) and (ii) above could be explored by performing experiments on small-size Si witness substrates, polished by the manufacturer of the LUSI K-B mirror substrates. The authors of the project should consider ordering a few additional witness coupons by the substrate vendor, for the purposes of this experiment."

A.M.: "Experience at the Advanced Photon Source has shown that many mirrors designed with a thin Cr first layer can be reused if they experience damage to the coating because the entire surface coating can be floated off in a standard Cr etch bath. The ability to float off a damaged surface coating from the K-B mirrors for the CXI instrument may result in the ability to reuse the expensive mirrors after recoating should there be damage to the coating."

**Temperature Controlled Enclosure**

A.K.: "Provide specification and design for a microenvironment, preferably a double walled system to maintain the inside temperature to within +/- 0.1 degrees C. Provide this information to the vendor designing the KB holders and chambers."

T.M.: "It is reasonable to relieve the system supplier from responsibility for the temperature control system that provides thermal pointing stability, because similar temperature control environments will already deployed around the offset mirror systems. Nevertheless, the system supplier must still abide by and demonstrate a specification for thermally induced pointing error. Temperature around the offset mirrors is controlled within +/- 0.01 C, which is a practical limit for commercially available controllers. To achieve pointing stability around 10 nano-radians under temperature control, the devices that affect pointing should have an error coefficient of 10 nanoradians/0.01 C = 1 microradian/C. Thus, the requirement in the system spec. is that the supplier must demonstrate the mechanical devices that affect pointing produce an error < 1 microradian per degree Celcius of ambient air temperature change. A suggestion as to how this can be measured by the supplier is provided below.

**Specific Concerns**

R.S.: "In the Engineering Specification Document, Table 4 (mirror coating requirements): The high-spatial frequency roughness specification of the 1st and 2nd coating layers is the same as the substrate (0.25 nm rms). For DC-magnetron sputtered coatings in the thickness range 40-70 nm (as is the case for these mirrors), without an additional smoothing process implemented during deposition, the above roughness
specification is non-physical. The coating should be allowed to add some roughness to the substrate. Especially for the B₄C coatings which have inherently high compressive stress, the coating deposition parameters may need to be modified to relax the stress, at the expense of an increase in roughness. For example, with these modified deposition parameters, a 30 nm-thick B₄C coating deposited on a substrate with 0.25 nm rms high-spatial frequency roughness, may result in a 0.6-0.7 nm rms top surface roughness. To be on the conservative side, the top surface roughness of the mirror coating should be relaxed to about 0.8 nm rms."

P.T.: "Mounting the mirrors at 45° roll angles relative to gravity is extremely risky. This design concept needs to be fully justified in terms of meeting the physics requirements. Unless there is some compelling physics requirement, I don’t see any need to orient the mirrors in this position. It will require extraordinary engineering design and analysis to prove that the mounting methods don’t produce excessive distortion in the mirror. Vendors already have experience in mounting mirrors either parallel or perpendicular to the gravity vector and can rely on previous experience and analyses to predict what will happen. Asking for a 45° rotation throws most of this experience out the window, making the subsequent design process very costly and introducing unnecessary uncertainty into the result.

A.M.: " The most daunting and worrisome specification is for nanoradian stability on the incident angles for the mirrors. This specification will likely drive the design of the manipulator, and places great importance on the choice of vendor for the manipulator. A possibility to deflect vertically instead of horizontally may be a flexibility needed to meet the nanorad specification. "

III. Full texts of individual comments by all committee members follow below.
Comments / Questions:

1- The presentation was excellent. It showed that a substantial amount of work had been done on the project, including the development of specifications and contacting various vendors.

2- What kind of silicon (FZ or CZ) is to be used, why, and why the (111) direction, why < 10 Ohm-cm?

3- Was SiC (instead of Si) substrate considered? How about Be?

4- Given the large demagnification (~ 400:8), are aberrations too large if two identical but optimized elliptical mirrors are used (for both horizontal and vertical focusing)? There could be some cost savings if this was possible.

5- The requirement of zero digs and scratches on mirror surfaces seems unreasonable and not well defined.

6- Different vendors use different metrologies, yielding different results for the same surface. This means that metrology methodologies must be checked and agreed on with the vendors in advance. It is also best if the metrology procedure is spelled out in advance.

7- Logistics and the practical aspects of the independent metrology to verify vendor’s results need to be worked out between the three parties in advance. Agreement of the vendor is needed. Also, consider possible outcomes and scenarios: What would be LUSI response, if, for example, the verification results are different from those of the vendor?

Recommendations:

1- A more substantive discussion with these and other potential vendors is necessary to gain a deeper understanding of what they can or cannot do, key technical issues, metrology systems they use, how the measurements would be made, who they technical person(s) involved are, what fabrication method is used to figure and finish the parts, vendor detail schedule, what technical challenges the vendors envisions, do they need to go beyond their “comfort zone” to deliver the product, what other projects they have, what are their backlogs, what are their prior experience, etc., including a host of what ifs…
2- Figuring and finishing of mirrors for many vendors are statistical and not deterministic processes. As such, some scheduling flexibility must be built in and expected, in anticipation of delays beyond the vendors’ control.

3- Consider segmenting the SiC (as well as Rh/SiC) coating stripes into two or more strips, to arrest possible radiation damage / peeling off. In this case, another fresh strip coating is available for use (without the need to open the chamber immediately to repair).

4- If appropriate, consider having a Cr underlayer coating (under some or all coating strips). In the case of damage to the coating (due to radiation, etc.), I could remove the damage (lift off) the damaged coating by etching away the Cr underlayer to have the mirror re-coated, instead of the EXPENSIVE and time-consuming alternative of re-polishing / re-figuring. If Cr is unacceptable, other sub layers such as titanium may be considered.

5- A flat “dummy” blank mirror for coating and then for practicing assembly is helpful.

6- The beam line photon energy ranges from 2 to 8 keV. This energy affects the size of the optics (a shorter mirror is needed for 8 keV), etc. It is very helpful if a matrix of load factors for these energies is developed. For example, what fraction of the time 8 keV energy will be used? This is important when trade offs (design, cost, performance) are being considered.

7- The formal RFP/RFQ should be considered as a formality. Almost all the real work has to be done prior to that. Procurement people would not let us to talk to vendors after the request is issued. If these are written loosely, many questions will arise and one may be forced to rewrite it and that delays the process.

8- Relax the sagittal slope error requirement. In fact, the mirrors can have a radius in that direction (some vendors figure the substrates from a spherical one). This would not affect performance.

9- While simplicity is important, one should not shy away from motorizing motions if that is appropriate. In case of drifts, it would be a pain to enter the radiation area to move screws manually to align mirrors.

**Action Items**

1- Necessary warranties and guarantees must be specified in the RFQ because there is a cost associated with them. Recommend a two-year warranty.
2- Provide specification and design for a microenvironment, preferably a double walled system to maintain the inside temperature to within +/- 0.1 degrees C. Provide this information to the vendor designing the KB holders and chambers.

3- A clean room or a clean area is needed to install the mirrors in the chamber (or later on to maintain, repair, replace, re-coat, etc.). I suggest combining this with item 2 above, if adequate real estate is available.

4- Prepare a pre-alignment plan at SLAC to be used by the chamber vendor or LUSI itself.

5- Specifications should require the vendor to etch the entire mirror and polish all sides to some reasonable specs (to be determined by the mirror holder design), and fine polish the reflecting surface. Bevel specs are also needed.

6- Procurement of spare mirrors should be given serious thoughts, especially given the radiation damage risk and the long procurement lead-time.
The presentation on this project was very well-prepared and organized. The people responsible for this project understand well the physics requirements of their experiments and the issues related with the construction of this mirror system. A few comments and suggestions for improvement follow below:

1) In the Engineering Specification Document, Table 4 (mirror coating requirements): The high-spatial frequency roughness specification of the 1\textsuperscript{st} and 2\textsuperscript{nd} coating layers is the same as the substrate (0.25 nm rms). For DC-magnetron sputtered coatings in the thickness range 40-70 nm (as is the case for these mirrors), without an additional smoothing process implemented during deposition, the above roughness specification is non-physical. The coating should be allowed to add some roughness to the substrate. Especially for the B4C coatings which have inherently high compressive stress, the coating deposition parameters may need to be modified to relax the stress, at the expense of an increase in roughness. For example, with these modified deposition parameters, a 30 nm-thick B4C coating deposited on a substrate with 0.25 nm rms high-spatial frequency roughness, may result in a 0.6-0.7 nm rms top surface roughness. To be on the conservative side, the top surface roughness of the mirror coating should be relaxed to about 0.8 nm rms.

2) In the Engineering Specification Document, Table 4 (mirror coating requirements): As has been shown in the literature, and verified in recent work for the LCLS SOMS mirrors, the mid-spatial frequency roughness of the substrate (in the frequency range defined for the LUSI K-B mirrors) is exactly replicated by DC-magnetron sputtered coatings in the 30-70 nm thickness range. So specifying mid-frequency roughness for the coatings is somewhat redundant, since it is expected to be identical to the substrate mid-roughness.

3) In the Engineering Specification Document, Table 2: The clear aperture width for each coating strip should be closer to 10 mm (rather than 5 mm stated in the Table), to ensure best surface coverage and thickness uniformity. If the strip width is too narrow, it could complicate the deposition process and the coating thickness could be dominated by near-edge “shadowing effects”.

4) During the review, Ali Khounsary made the suggestion of using a Cr underlayer in the mirror coating, that could be later etched and render the mirror re-usable (SPIE Proc. Vol. 5193, 2003). This is an excellent suggestion and its feasibility should be investigated for the LUSI K-B mirrors. Two issues should be explored: (i) the survivability of the Cr underlayer material under peak FEL beam conditions (instantaneous dose) that would be applicable for the LUSI K-B mirrors (ii) verification of the substrate mid- and high-spatial frequency roughness properties (using AFM and Zygo metrology) after a coating-and-etching iteration. Both issues (i) and (ii) above could be explored by performing experiments on small-size Si witness substrates, polished by the manufacturer of the
LUSI K-B mirror substrates. The authors of the project should consider ordering a few additional witness coupons by the substrate vendor, for the purposes of this experiment.

5) In the presentation slides nos. 68-83, a wavefront propagation model was presented to explore the effect of mirror surface errors on the beam wavefront. While it is very useful that the authors of the project are performing this modeling, the provenance of the “LLNL HOMS metrology” data (type of sample, date) is not clear. Our group at LLNL that is responsible for HOMS metrology has not officially released any metrology data corresponding to HOMS mirrors or coupons. In any event, if earlier data from a coupon-type of substrate were used, then the surface errors included in the model would be limited by the size (length) of the coupon and by the relevance of the polishing methods to the HOMS. This should be clearly mentioned in the slides.

6) The capabilities of the various candidate vendors (for the substrate polishing and for the engineering of the system), and their impact on cost, quality, schedule and other risks, should be further explored and understood, prior to placing the procurements.


**Recommendation Regarding Near Term Mirror Procurement:** The need to procure the mirrors within the next few months is the result of a schedule constraint imposed by one particular mirror vendor. While it is wise to recognize this vendor’s constraint, it should not subvert over an orderly design sequence for the rest of the system.

1. You have already defined a mounting geometry, substrate features, and dimension’s that preserves mirror fabrication figure specifications. This is a good start, but it has implications on the mirror procurement and system spec ((2) and (3) below).

2. While your calculations show mirror figure can be preserved, the substrate features you require should be discussed with mirror fabricators before they are procured. They may have useful input regarding these features.

3. The fact that you intend to procure the mirrors early, and thus define the substrate features and mounting approach, lets the supplier for the mechanical system “off the hook” for mirror figure. If you are defining the mirror and the mounting approach, and they will no longer be accountable for figure of the mounted mirror. The specification should be modified to reflect this by stating the mirror and mounting approach will be specified by you.

**Recommendation Regarding Specification Organization:** The preferred procurement strategy and the requirements presented at the review were reasonable and clear. But the specification read by the reviewers does not accurately reflect the procurement strategy and design requirements described at the review. The specification was initially written as a starting point for expression of interest from suppliers. The present draft has served this purpose, but it should be updated to reflect you current strategy and requirements. It will be much more concise once redundant and outdated sections are eliminated.

**Recommendation Regarding Thermal Stability:** It is reasonable to relieve the system supplier from responsibility for the temperature control system that provides thermal pointing stability, because similar temperature control environments will already deployed around the offset mirror systems.

Nevertheless, the system supplier must still abide by and demonstrate a specification for thermally induced pointing error. Temperature around the offset mirrors is controlled within +/- 0.01 C, which is a practical limit for commercially available controllers. To achieve pointing stability around 10 nano-radians under temperature control, the devices that affect pointing should have an error coefficient of 10 nanoradians/0.01 C = 1 microradian/C.

Thus, the requirement in the system spec. is that the supplier must demonstrate the mechanical devices that affect pointing produce an error < 1 microradian per degree Celsius of ambient air temperature change. A suggestion as to how this can be measured by the supplier is provided below.
Suggestion Regarding Pointing Stability Requirements: The KB mirror system pointing stability requirements are not trivial to design for, or demonstrate by measurement. The designs and metrology techniques used to meet these requirements for the offset mirror systems will be useful background for the KB mirror system supplier. Potential KB system suppliers should be provided with this information. They can take whatever advantage of that experience they see fit.

Suggestion Regarding Metrology of Mounted Mirrors: The complexity of calibrating an interferometer to accurately measure nm scale figure error at 45 degrees is formidable. I would not encourage measuring these mirror at use angle with an interferometer. It would seem that a linear trace profiler is a more natural fit. This suggestion should be coordinated with your collaborators at LBL.

Comment regarding the need for a “blank” mirror: The HOMS/SOMS mirror specifications called for an early mirror substrate finished to a ¼ wave at HeNe wave length. This is repeated in your spec. This early mirror prototype was (marginally) useful for measuring the figure change of a mounted mirror. It turned out our mirror supplier could make a real mirror almost as soon as they delivered the blank, so it was of relatively small value.

In my opinion, you should evaluate whether this needs to be in your specification with potential suppliers. If you do not have a need for it, and they don’t either, then it just adds confusion to the specification.

Recommendation Regarding Motor Controls: While your system spec calls for motor controlled functions, it does not specify stepper motors. You control people will insist on that. Your system supplier is probably not responsible for the motor control cards and racks that run these motors (you need to coordinate with your control people of this decision). If that is true, this spec should state where there responsibility for motor control ends.

Comment Regarding Motion Specifications: The minimum set of motion specifications presented in the view graphs seems reasonable and clear. This is much better than the ten degrees of freedom approach implied in the specification we reviewed. Each degree of freedom is a stability threat that will take substantial effort to mitigate.
Notes from CXI KB system review at SLAC

P.Z. Takacs

1.) Mounting the mirrors at 45° roll angles relative to gravity is extremely risky. This design concept needs to be fully justified in terms of meeting the physics requirements. Unless there is some compelling physics requirement, I don’t see any need to orient the mirrors in this position. It will require extraordinary engineering design and analysis to prove that the mounting methods don’t produce excessive distortion in the mirror. Vendors already have experience in mounting mirrors either parallel or perpendicular to the gravity vector and can rely on previous experience and analyses to predict what will happen. Asking for a 45° rotation throws most of this experience out the window, making the subsequent design process very costly and introducing unnecessary uncertainty into the result.

2.) Although it would be nice to have a single vendor provide the complete instrument package, mirrors and mechanical parts, the RFQ should be structured in such a way as to not preclude separating the optical and mechanical parts. This will open the procurement up to other vendors who specialize in one or the other capability. In particular, the Physical Sciences Laboratory at the U of Wisconsin should be added to the list of vendors. They have extensive experience in synchrotron beamline instrumentation and have built many monochromators and other systems for various synchrotrons in the past. Also, the capabilities of WinlightX should not be discounted just because they are new players in the game. The same criticism can be made of Jtech.

3.) The engineering requirements document is too bloated. The essential parameters need to be distilled into a few lucid paragraphs with tables. The extraneous boilerplate that is duplicated many times should be condensed into one section.

4.) What is missing is a simple strawman conceptual design drawing that illustrates the essential parameters. It only needs to be a simple solid model CAD drawing, but it should illustrate the recommended location and placement of various elements.

5.) Attempting to do metrology on the final assembly is a daunting task. Assuming that the full length of each mirror surface can be viewed at normal incidence, it may be possible to do either stitching interferometry or profilometry on the surface in the final assembly orientation. This will give you information about figure distortions which should be enough to see if any changes have occurred during mounting and assembly. The cost for doing these kinds of measurements is reasonable, as they can be done off line in a metrology laboratory. The other metrology possibility is to do at-wavelength testing at a facility like the X-ray Calibration Facility (XRCF) at Marshall Space Flight Center. This facility has a 518 meter long vacuum pipe connecting the x-ray source to the end station vacuum chamber. Measuring the image from this source through the KB mirror pair would provide an unambiguous measurement of the real system performance and give one a good idea of the tolerances in the motion devices. Unfortunately, this would probably be a very costly metrology effort. Perhaps a similar setup can be rigged.
with the LCLS beam pipe, inserting an x-ray tube source far upstream from the mirror chamber.
Re: Review of LUSI/CXI K-B system
From: A.T. Macrander

Findings

The result of a great deal of diligent work was presented. The overall plan for the K-B system was thoughtful and the project is ready to proceed to the step of opening serious discussions with vendors. The decision to plan on a prefigured mirror in place of a bender arrangement is supported. The simulations of the Rayleigh length as well as beyond the focus were illuminating. The specifications as presented appeared appropriate and needed.

Comments

The most daunting and worrisome specification is for nanoradian stability on the incident angles for the mirrors. This specification will likely drive the design of the manipulator, and places great importance on the choice of vendor for the manipulator. A possibility to deflect vertically instead of horizontally may be a flexibility needed to meet the nanorad specification.

The specifications for the mirror figure and finish have already been demonstrated by one of the vendors under consideration (JTEC), but preservation of the figure once the mirrors are installed in the manipulator will be needed. This also places importance on the selection of the vendor for the manipulator. As a corollary, metrology after mounting will be needed. The metrology tool most appropriate to check the figure after mounting is the long trace profiler (LTP). The 45 deg geometry should pose no serious problems for an LTP measurement. However, no specific LTP was defined as the one to be employed.

Simulations for a surface constructed in accordance with a likely spatial power spectrum were presented. However, other quite different surface profiles are consistent with the same power spectrum, and simulations of an actually produced mirror would be best.

The vendors under consideration are credible, but the information so far obtained is incomplete and insufficient to make a selection. In the case of WinlightX, the supplier and fabrication method for the mirrors needs to be known in order to judge the likelihood of a successful delivery. In the case of JTEC, the schedule demands on the CVM and EEM machines need to be known in order to understand more fully the quoted 12 month delivery time.

Experience at the Advanced Photon Source has shown that many mirrors designed with a thin Cr first layer can be reused if they experience damage to the coating because the entire surface coating can be floated off in a standard Cr etch bath. The ability to float off a damaged surface coating from the K-B mirrors for the CXI instrument may result in
the ability to reuse the expensive mirrors after recoating should there be damage to the coating.

**Recommendations**

1) The decision for a purely horizontal K-B deflection geometry should be left open until a full manipulator design that meets the nanorad specification is decided upon.

2) An arrangement should be made to obtain independent LTP data for mirrors mounted in the manipulator. Such data should be used to check the figure of the delivered mirror assembly independent from the vendor’s own metrology and assurances.

3) A coating underlayer that can be used to float off a damaged surface coating should be engineered into at least one stripe on each mirror.
Findings

The material for the review was extremely thorough and well presented. It was clearly evident that significant effort has been directed at determining system requirements, associated performance impact and resulting tolerances.

Comments

While the reported performance of the JTEC fixed figured optics is quite promising, the notion that only one (as suggested in the presentation) of the required length has been fabricated to date makes this an inherently risky procurement path. Significant thought, care and diligence is required to effectively manage this process to a satisfactory performance and schedule delivery.

The specification contains information beyond the reach of typical documents and risks contrary, redundant and confusing information.

The evaluation matrix is not necessarily appropriate for the technical requirements of this procurement.

The nature of the system performance requirements lead to serious concerns regarding validating performance prior to delivery, and more importantly, after delivery and installation. Additionally, based on comments at the review, the current plan for a wave front sensor has (likely) insufficient sensitivity to adequately diagnose specific issues with the mirror assemblies.

Recommendations

Engage and evaluate potential vendors as deeply as possible prior to formal procurement process.

Examine options for procurement of second vendor (Zeiss, etc.) optics as insurance for delivery and performance issues with primary contractor. Additionally, since these optics will likely have a shorter delivery time, they can be used as both spares and test pieces for coating, metrology and assembly testing.

Prior to award of contract, develop and manage meaningful and demonstrable milestones with associated cost, performance, and schedule implications. This should include development of contingency plans and specific decision point(s) to abandon and/or reevaluate options.

The specification(s) should be nominally limited to functional specification and requirements, tolerances, and validation requirements. Items like "Reporting" and other
process management elements should be contained in the SOW or other supporting documentation.

Change "Evaluation Matrix" to reflect more value (~30-40%) in capabilities, historical performance and facilities for actually achieving and validating performance requirements.

Develop a valid test plan for key performance requirements that is consistent with vendor and SLAC capabilities (both in house and via sub-contractor).
Responses to Recommendations/Action Items from the CXI KB System
Procurement Review

1) Closer communication with vendors involving local visits is recommended.

    Communications with vendors has been ongoing for many months and visits to
the vendors were always in the LUSI plans, especially for status updates after the
award of the contract. In addition, since the review has occurred, the facilities of 3
of the 4 potential vendors were visited by the LUSI team. A visit to the fourth
vendor is planned for early December.

2) An arrangement should be made to obtain independent metrology data for mirrors
mounted in the manipulator. Such data should be used to check the figure of the delivered
mirror assembly independent from the vendor’s own metrology and assurances.

    Such an arrangement has been included in the LUSI plans since prior to the CD-2
review. We have done a preliminary identification of potential groups with the
capabilities to make such measurements. LUSI plans to enter into an agreement
with one such group with demonstrated metrology capabilities.

3) The feasibility of a Cr or Ti underlayer that can be used to float off a damaged surface
coating should be explored for the CXI mirrors.

    This option was discussed at the Facilities Advisory Committee meeting in
November 2008 and will be explored further with potential coating vendors. This
however requires some level of technique development and there is no guarantee
at this point that such a coating can meet the tight figure and roughness
requirements of the CXI mirrors. If this proves to not be easily feasible, then the
mirrors will be coated without the underlayer, which has been demonstrated for
the LCLS offset mirrors.

4) Consideration of an enclosure for each K-B system to improve temperature stability is
recommended.

    Such an enclosure will likely prove necessary to meet the thermal stability
requirements and the CXI team will make plans to include it. It will be based on a
very similar enclosure that will be used for the LCLS HOMS mirrors.
LUSI
Coherent X-ray Imaging Instrument
KB System Review

Sébastien Boutet – CXI Instrument Scientist
Paul A. Montanez, P.E. – CXI Lead Engineer
KB System Review
October 8, 2008
Outline

- Purpose of the review
- Scientific Scope of CXI Instrument
- LCLS Overview
- Instrument Overview
- Focusing Requirements
- Specifications
  - Mirror Substrate Specifications
  - Coating Specifications
  - Metrology Requirements
  - Mechanical System Requirements
- Safety
- Major Interfaces
- Acquisition Plan
  - Bid Process
  - Statements of Work
  - Timeline
- Status of Discussions with Vendors
- Vendor Selection Criteria
- Summary
Specifications and instrument concept developed with the science team.

The CXI team leaders
- Janos Hajdu, Photon Science-SLAC, Uppsala University (leader)
- Henry Chapman, DESY, University of Hamburg
- John Miao, UCLA

Thanks to Jacek Krzywinski for some simulations
Purpose of the Review

- We are planning a design-build contract with an outside vendor
  - We are not doing the design ourselves
  - This is not a design review
- A design-build contract is considered a procurement
- We require advanced procurement approval since the LUSI project has not reached CD-3 yet
- We plan to go out on bids
  - Due to the expected high price tag, we expect the bid process (approval by DOE) to take 3 months
  - Time wasted during which no design occurs
- DOE wishes to review all our procurement specifications
  - Make sure we don’t waste their money
- Therefore, this review seeks approval of the specifications, the procurement process and the potential vendors
- This review must occur before we can submit the paperwork to go out on bids for the design-build contract
Scope of Review

- Specifications for complete mirror system
- Quality assurance plans
- Acquisition strategy
  - Going out on bids for a design-build contract
- Potential vendors
- Vendor selection process
How we got here

- Started out looking for single vendor to provide complete system
  - As a design-build contract with all the coating and metrology required
  - With independent metrology to verify the vendor claims
- Initial discussions with vendors revealed no vendor that could do everything
- We chose to separate the specifications in 7 parts since we wanted to give every vendor a chance to propose the system they saw fit
  - Mirrors
  - Coating
  - Metrology
  - Mirror mounting
  - Mirror bending
  - Vacuum Chamber
  - Stand
- Sent these specs as a Request for Information to 10 vendors
- Responses ruled out a few vendors immediately
- It became clear that
  - All mechanical components would be better done by a single vendor
  - Specs may still not reflect that thinking and language may need to be cleaned up
  - A bender system was not likely to be the right solution
  - Mirrors may need to be ordered separately and early due to long lead-time
  - All mechanical vendors, except 1, do not make their own mirrors
    - Who orders the mirrors (us or the mechanical vendor) does not really matter
- Specs were refined and iterated with vendors and we have converged on final specifications
CXI Instrument Motivation

- Imaging of ANY micron-sized object with atomic resolution
  - Specifically biological samples
    - Structure of biomolecules
      - Proteins
      - Protein complexes
      - Viruses
      - Molecular machines
  - Nanoparticles
    - Quantum dots
    - Amorphous nanoparticles
- Current techniques with atomic resolution:
  - Surface techniques
  - Limited to very thin sample (Electron microscopy)
  - Crystallography
    - Extremely successful
    - Requires crystalline material
- The LCLS beam offers unique capabilities
Coherent Diffractive Imaging of Biomolecules

One pulse, one measurement

LCLS pulse

Particle injection

Wavefront sensor or second detector

Noisy diffraction pattern

Combine $10^5$-$10^7$ measurements into 3D dataset

Classification

Averaging

Orientation

Reconstruction

Gösta Huldt, Abraham Szöke, Janos Hajdu (J.Struct Biol, 2003 02-ERD-047)
CXI Science

- 3D bio imaging beyond the damage limit
  - Single injected reproducible biomolecules that can’t be crystallized
    - Proteins
    - Membrane Proteins
    - Viruses
    - Molecular complexes
    - Molecular machines
  - Biomolecular structure determination from nanocrystals
    - No need for large high quality crystals

- 2D bio imaging beyond the damage limit
  - Live hydrated cells with particle injector
  - Nanoparticles
    - Quantum dots
    - Amorphous nanoparticles

- High fluence X-ray-matter interactions
  - Damage studies during the pulse
    - Effect of tamper layers on damage
**Key Design Considerations**

- **Most measurements will be single shots**
  - No chance to increase signal with multiple exposures
  - Every device must be able to handle the full beam
  - Need to maximize signal on every shot
    - Every photon is precious

- **Ability to perform multiple shot experiments adds extra capabilities to the instrument**
  - Compare low fluence to high fluence for damage measurements
  - Requires high stability over a short period of time which is not necessary for single shots
Linac-to-Undulator (227m)

Undulator Hall (175m)
Beam Dump (40M)

Front End (29m)

Near Expt’l. Hall

X-ray Transport (200m)

Far Expt’l. Hall

Near Experimental Hall

LCLS Ultrafast Science Instruments
Linac-to-Undulator (227m)

Undulator Hall (175m)

Front End Encl.

Near Expt. Hall

X-ray Transport (230m)

Far Expt. Hall

Source to Sample distance: ~ 440 m
LUSI project is funded separately from the LCLS construction project

LCLS is responsible for
- Civil construction
- Accelerator
- Front End Enclosure optics and diagnostics
- AMO Instrument in Hutch 1
- Beam transport to the Far Experimental Hall

LUSI is responsible for
- Designing and building the optics, diagnostics and experimental systems in hutches 3, 4 and 5
Front end X-ray optics being assembled at LLNL

Optics/diagnostics through preliminary or final design review

Front End Enclosure

Solid Attenuator
Gas Attenuator
Slit
Gas Detector
Hard x-ray Monochromator (K Spectrometer)
5 mm collimator
Soft X-Ray Offset mirror system
Hard X-Ray Offset mirror system
Start of Experimental Hutches
Direct Imager
Pulse Energy Thermal Detector
Gas Detector

Muon Shield

Front End Enclosure
LCLS Beam Parameters

- LCLS energy range (fundamental): 800 – 8265 eV
  - 3rd harmonic up to 24.9 keV (1% of the fundamental)
- Repetition rate: 120 Hz
- Source size and location vary with energy
- Unfocused beam will damage most materials with a single shot

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon energy</td>
<td>24795</td>
<td>8265</td>
<td>6000</td>
<td>4000</td>
<td>2000</td>
<td>eV</td>
</tr>
<tr>
<td>Wavelength</td>
<td>0.05</td>
<td>0.15</td>
<td>0.21</td>
<td>0.31</td>
<td>0.62</td>
<td>nm</td>
</tr>
<tr>
<td>Source size (FWHM)</td>
<td>60</td>
<td>60</td>
<td>67</td>
<td>73</td>
<td>78</td>
<td>µm</td>
</tr>
<tr>
<td>CXI Hutch distance from undulator exit</td>
<td>385.5</td>
<td>385.5</td>
<td>385.5</td>
<td>385.5</td>
<td>385.5</td>
<td>meters</td>
</tr>
<tr>
<td>CXI Hutch distance from source</td>
<td>437.3</td>
<td>437.3</td>
<td>428.7</td>
<td>418</td>
<td>404.1</td>
<td>meters</td>
</tr>
<tr>
<td>Source divergence (FWHM)</td>
<td>0.73</td>
<td>1.1</td>
<td>1.34</td>
<td>1.89</td>
<td>3.47</td>
<td>µrad</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>~100</td>
<td>~100</td>
<td>~100</td>
<td>~100</td>
<td>~100</td>
<td>fsec</td>
</tr>
<tr>
<td>Number of photons</td>
<td>1.7E+10</td>
<td>1.7E+12</td>
<td>2.7E+12</td>
<td>4E+12</td>
<td>8E+12</td>
<td>photons</td>
</tr>
</tbody>
</table>
Assume source is fully coherent
- In reality, simulations show the beam will be ~80% coherent

Assume source is Gaussian
- Simulations show slight distortions from Gaussian profile
  - Simulated FEL source using Genesis Code by Sven Reiche
    includes simulation of electron orbits in the linac and the undulator

Intensity of the FEL output radiation
Intensity of the Gaussian source

From Jacek Krzywinski
Source position varies with photon energy
- Source is assumed to be 1 Rayleigh length inside the undulator

Source size varies with photon energy
- This means the focal size and position of the focus will vary with photon energy
  - Also the beam size at the optic varies greatly with energy

Fundamental up to 8265 eV
- 3rd harmonic source size and location is assumed to be the same as the fundamental
## Expected Fluctuations of LCLS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Origin*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse intensity fluctuation</td>
<td>~ 30 %</td>
<td>Varying # of FEL producing SASE spikes; 100% intensity fluctuation/per-spike; etc.</td>
</tr>
<tr>
<td>Position &amp; pointing jitter (x, y, α, β)</td>
<td>~ 25 % of beam diameter</td>
<td>Varying trajectory per pulse; Saturation at different locations of β-tron curvature</td>
</tr>
<tr>
<td>Source point jitter (z)</td>
<td>~ 5 m</td>
<td>SASE process reaching saturation at different z-points in undulator</td>
</tr>
<tr>
<td>X-ray pulse timing (arrival time) jitter</td>
<td>~ 1 ps FWHM</td>
<td>Timing jitter btw injection laser and RF; Varying e-energy per-pulse</td>
</tr>
<tr>
<td>X-ray pulse width variation</td>
<td>~ 15 %</td>
<td>Varying e-energy leading to varying path (compression) in bunch compressors</td>
</tr>
<tr>
<td>Center wavelength variation</td>
<td>~ 0.2 % (comparable to FEL bandwidth)</td>
<td>Varying e-energy leading to varying FEL fundamental wavelength and higher order</td>
</tr>
</tbody>
</table>

- Every pulse is a new experiment
- Require diagnostics on every pulse
- Fluctuations have implications on focusing system
LCLS Offset Mirror Systems

- Soft X-ray Offset Mirror System (SOMS) selects 800-2000 eV range for soft X-ray line
- Hard X-ray Offset Mirror System (HOMS) selects 2-25 keV range.
- HOMS periscope located just upstream of the Near Experimental Hall
- 385 mm clear aperture mirrors → >70% transmission at 2 keV and >98% at 8.3 keV
HOMS Mirror Specifications

Figure A1: Pictorial definition of terms

<table>
<thead>
<tr>
<th>Surface Radius</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tangential</td>
<td>$150 \text{ km} \leq R_{\text{Tm}} \leq 195 \text{ km}$</td>
</tr>
<tr>
<td>Sagittal</td>
<td>$&gt; 4 \text{ km}$</td>
</tr>
</tbody>
</table>
## HOMS Mirror Specifications

<table>
<thead>
<tr>
<th>Clear Aperture</th>
<th>Figure Error</th>
<th>Specification</th>
<th>Measurement Bandwidth</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>Height Error</td>
<td>≤ 2.0 nm rms</td>
<td>$2.6 \times 10^{-6} \mu$m$^{-1}$ to $10^{-3} \mu$m$^{-1}$</td>
<td>1 mm to 385 mm</td>
</tr>
<tr>
<td></td>
<td>Tangential Slope Error</td>
<td>≤ 0.25 μrad rms</td>
<td>$2.6 \times 10^{-6} \mu$m$^{-1}$ to $10^{-3} \mu$m$^{-1}$</td>
<td>1 mm to 385 mm</td>
</tr>
<tr>
<td></td>
<td>Sagittal Slope Error</td>
<td>≤ 2 μrad rms</td>
<td>$2.0 \times 10^{-4} \mu$m$^{-1}$ to $10^{-3} \mu$m$^{-1}$</td>
<td>1 mm to 5 mm</td>
</tr>
<tr>
<td>Zone 2</td>
<td>Height Error</td>
<td>≤ 5.0 nm rms</td>
<td>$2.3 \times 10^{-6} \mu$m$^{-1}$ to $10^{-3} \mu$m$^{-1}$</td>
<td>1 mm to 430 mm</td>
</tr>
<tr>
<td></td>
<td>Tangential Slope Error</td>
<td>≤ 0.63 μrad rms</td>
<td>$2.3 \times 10^{-6} \mu$m$^{-1}$ to $10^{-3} \mu$m$^{-1}$</td>
<td>1 mm to 430 mm</td>
</tr>
<tr>
<td></td>
<td>Sagittal Slope Error</td>
<td>≤ 2 μrad rms</td>
<td>$6.7 \times 10^{-5} \mu$m$^{-1}$ to $10^{-3} \mu$m$^{-1}$</td>
<td>1 mm to 15 mm</td>
</tr>
</tbody>
</table>

LCLS ESD 1.5-121-r1, “Engineering Specifications for the XTOD Hard X-Ray Offset Mirrors”
## HOMS Mirror Specifications

<table>
<thead>
<tr>
<th>Roughness</th>
<th>Specification</th>
<th>Measurement Bandwidth</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-Spatial</td>
<td>$\leq 0.25$ nm rms</td>
<td>$10^{-3} \mu m^{-1}$ to $0.5 \mu m^{-1}$</td>
<td>$2 \mu m$ to $1 mm$ See Figure A2 below (to be used together with the LCLS/LLNL drawing) for locations of roughness measurement sites. The roughness measured at each site shall be compared for compliance with the specifications.</td>
</tr>
<tr>
<td>High-Spatial</td>
<td>$\leq 0.4$ nm rms</td>
<td>$0.5 \mu m^{-1}$ to $50 \mu m^{-1}$</td>
<td>$20 \text{ nm to } 2 \mu m$</td>
</tr>
</tbody>
</table>

Figure A2: Definition of Clear Aperture Zones and Roughness Measurement Sites

LCLS ESD 1.5-121-r1, “Engineering Specifications for the XTOD Hard X-Ray Offset Mirrors”
Expected Impact of HOMS Mirrors

- Satisfy the Maréchal criterion up to 12 keV
  - Small wavefront distortions to central Gaussian peak
  - Presence of HOMS distortions increase the figure requirements of the CXI KB System

- Limited aperture
  - Diffraction effects at energies below ~4 keV

- Large radius of curvature
  - Increase of beam divergence by less than 10%

- Good pointing stability
  - Beam stable to within a fraction of its size over many days
  - Mirror stability comparable to the intrinsic beam stability
CXI Instrument Location

Near Experimental Hall

X-ray Transport Tunnel

Source to Sample distance: ~ 440 m

Far Experimental Hall

AMO (LCLS)  XPP

CXI Diagnostics & Common Optics

CXI Endstation
Goals

- Perform imaging of single particles at highest spatial resolution achievable using single LCLS pulses
- Image biological nanoparticles beyond the classical damage limit using single LCLS pulses

Tailor and characterize X-ray beam parameters

- Spatial Profile
- Intensity
- Repetition rate

Deliver the sample to the beam and control its environment
## CXI Physics Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remove X-ray beam halo</td>
<td>X-ray Guard Slits/Apertures</td>
</tr>
<tr>
<td>Tailor X-ray intensity</td>
<td>Attenuators</td>
</tr>
<tr>
<td>Tailor X-ray repetition rate</td>
<td>Pulse Picker</td>
</tr>
<tr>
<td>Characterize X-ray pulse intensity</td>
<td>Intensity Monitor</td>
</tr>
<tr>
<td>Characterize X-ray spatial profile</td>
<td>Profile Monitor</td>
</tr>
<tr>
<td>Characterize X-ray pulse intensity before the</td>
<td>Non-destructive Intensity Monitor</td>
</tr>
<tr>
<td>sample on every shot</td>
<td></td>
</tr>
<tr>
<td>Characterize X-ray focus</td>
<td>Wavefront Monitor</td>
</tr>
<tr>
<td>Align experiment without X-ray beam</td>
<td>Reference Laser</td>
</tr>
<tr>
<td>Maximize X-ray flux on sample</td>
<td>Focusing optics 1 micron Kirkpatrick-Baez Mirrors</td>
</tr>
<tr>
<td>Tailor focal spot size to the sample</td>
<td>0.1 micron Kirkpatrick-Baez Mirrors</td>
</tr>
<tr>
<td>Minimize air scatter and background</td>
<td>Sample environment</td>
</tr>
<tr>
<td>Position sample and final apertures</td>
<td></td>
</tr>
<tr>
<td>Position sample environment</td>
<td>Instrument Stand</td>
</tr>
<tr>
<td>Deliver single particles to the X-ray beam in the</td>
<td>Particle Injector</td>
</tr>
<tr>
<td>gas phase</td>
<td></td>
</tr>
<tr>
<td>Measure X-ray scattering pattern</td>
<td>2D X-ray Detector (Utilizing the LCLS Detector)</td>
</tr>
<tr>
<td>Position X-ray area detector</td>
<td>Detector Stage</td>
</tr>
<tr>
<td>Analysis of sample fragments after Coulomb</td>
<td>Ion Time-of-Flight</td>
</tr>
<tr>
<td>explosion</td>
<td></td>
</tr>
</tbody>
</table>
Optics near the tunnel exit
- Slits
- Diagnostics
  - Pop-in Profile Monitors (Beam viewers)
  - Pop-in Intensity monitors
  - Intensity-Position Monitors (Non-destructive intensity monitors)
- Attenuators
- Pulse Picker
- Reference Laser
CXI Instrument Layout (FEH Hutch #5)

- 2 KB systems to produce 1000 and 100 nm focus
  - Each KB deflects the beam and the sample chamber must move with the beam
  - 3 beam locations
- Precision Instrument Stand holds the Sample Chamber, the Detector Stage and the 0.1 micron KB system
- 10 meters of space behind sample chamber
  - Wavefront Monitor to characterize the focus
  - Used as a second detector for low q data
- Diagnostics
- Slits
Instrument Configuration

CXI Components in the X-ray Transport Tunnel (XRT)

Reference Laser

Diagnostics

Beam Direction

CXI Components in Far Experimental Hall Hutch 5 (FEH H5)

FEH Common Room

CXI Control Room

Laser Table

Gas Cabinet

Focusing Optics

Sample Environment

2X Double Racks

5X Single Racks

FEH H5

Note: Overhead crane in H5 not shown for clarity
Two separate focusing systems
Use one or the other to produce the desired focus
  Beam damage issues prevent using both sets of mirrors together

**CXI 0.1 micron KB System**

- **Purpose**
  - Produce a 100 nm focal spot at sample
    - Located 0.7 meters (mid-point between mirrors) upstream of sample
    - For samples smaller than 50 nm
    - Beam as small as possible while still having enough space for chamber components

**CXI 1 micron KB System**

- **Purpose**
  - Produce a 1 micron focal spot at sample
    - Located 8 meters (mid-point between mirrors) upstream of sample
    - For samples smaller than 0.5 micron
    - Beam no smaller than 1 micron at all energies

Today’s review focuses on 1 micron System but some of the requirements are specified because of the 0.1 micron system.

- We want both systems to be as identical as possible and therefore the shorter focal length system must be considered as well in the specifications.
Major Subsystems

- Mirror system specifications are separated in 4 subsystems
  - Mirror Substrates
    - A vendor will provide 2 Si substrate polished to the required figure and roughness accuracy
  - Mechanical System
    - A vendor will design and build
      - The mechanical system to support and position the mirrors
      - The vacuum enclosure
      - The support stand
    - This vendor is also responsible for demonstrating the performance of the complete system and verifying the figure of the mirrors when mounted.
  - Mirror Coating
    - A vendor will coat the Si substrates with the desired materials
  - Metrology
    - A vendor will independently verify the surface quality of the mirror substrates and the coated mirrors

- Hope that a single vendor can do everything
  - Except for independent metrology verification
- Discussions with vendors indicate we will need a separate vendor for coating
- Options are limited for a single entity doing the mechanical system and the optics
Mirror Substrates Requirements and Specifications

- Overview
- Requirements
- Specifications
- Quality Assurance
- Summary
General Mirror Requirements

- >75% reflectivity over the widest energy range possible
  - Every photon is important for single shot measurements
    - Determines coating and incidence angle

- Energy Range
  - At least up to 4-8.5 keV
  - Goal: 2-15 keV
    - Determines coating and incidence angle

- Accept 4 sigmas or more over the widest energy range possible
  - Needed to minimize diffraction effects
    - Determines the mirror length, given an angle of incidence

- Withstand full power of the LCLS beam without damage
  - Single shot ablation is a big issue with FEL beam
    - Determines coating

- Ultra-High vacuum
  - < 10^{-9} Torr

- Preserve coherence
  - Meet at least the Maréchal criterion at 8.3 keV, the highest fundamental energy
  - >80% of incident intensity in the central peak at the focal plane
    - h_{rms} = \text{rms height error over entire length of the mirror}
    - \lambda = \text{wavelength}
    - N = \text{number of reflective optics (2 in this case)}
    - \alpha = \text{incidence angle}
    - h_{rms} \leq \frac{\lambda}{14\sqrt{N2\alpha}}

- Pointing stability to within a fraction of focal spot
  - Allows multiple shot experiments

- Minimal figure distortions from mounting system

- Minimize scattering
  - Reduce background signal on detector

KB System Review Coherent X-Ray Imaging October 8 2008

S. Boutet (sboutet@slac.stanford.edu)
P. Montanez (montanez@slac.stanford.edu)
Key Technical Choices

- **Coating material**
  - Affects reflectivity
  - Determines maximum incidence angle
  - Damage issues with high Z materials

- **Incidence angle**
  - Determines the energy range
  - Determines mirror length

- **Mirror length**
  - How long can you make the mirrors and still polish them to the required accuracy?
Beam Parameters at the Optic

- Propagate the Gaussian source to the optic
  - Distance from source: 437 meters at 8.3 keV
  - Peak Power: $\sim 10^{12}$ W/cm$^2$

![Intensity Profile at Mirror Entrance](image1.png)

- 8.3 keV
  - FWHM = 507.3 μm

![Intensity Profile at Mirror Entrance](image2.png)

- 2 keV
  - FWHM = 1495.34 μm
Beam Size at Optic

![Graph showing the beam size at optic as a function of energy. The graph indicates a decrease in FWHM (full width at half maximum) with increasing energy. The x-axis represents energy in eV, ranging from 2000 to 14000, and the y-axis represents FWHM in microns, ranging from 1600 to 200,000. The graph shows a steep decline in FWHM as energy increases.]
Assuming focal lengths of 8.2 and 7.8 meters,

Focal spot size from geometrical optics varies with photon energy.
Mirror Substrate Specifications

- **Material**
  - Si <100> Single crystal

- **Shape**
  - Tangential ellipse
    - Focal lengths
      - 8.2 m
      - 7.8 m

---

Kewish et al, Applied Optics 46, 2007

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KB System Review  
October 8 2008
Coherent X-Ray Imaging
Mirror Substrate Specifications

Max incidence angle
- 3.4 mrad
  - Reflects up to 10.8 keV with SiC coating
  - More details in coating part of the presentation

Average incidence angle
- Mirror 1
  - 3.364 mrad
- Mirror 2
  - 3.363 mrad

Figure
- Ellipse parameters
  - Mirror 1
    - a=214.1 m
    - b=197.4 mm
  - Mirror 2
    - a=213.9 m
    - b=192.4 mm
- Maximum height of surface
  - Mirror 1
    - 3.24 μm
  - Mirror 2
    - 3.40 μm
- Tangential radius of curvature
  - Mirror 1
    - 4632-4932 m
  - Mirror 2
    - 4405-4706 m
- Mean tangential radius tolerance
  - 0.1 %
- Sagital radius of curvature
  - > 400 m
- Sagital radius tolerance
  - 1 %

Kewish et al, Applied Optics 46, 2007
Radius of curvature of the surface

First mirror, focal length=8.2 m, incidence Angle=3.364 mrad

Second mirror, focal length=7.8 m, Incidence Angle=3.363 mrad
Mirror Dimensions

Wavefront propagation simulations
- Gaussian source, 1 Rayleigh length inside the undulator

8.265 keV

Intensity Profile at Source

FWHM = 60.8 μm
Mirror Dimensions

Wavefront propagation simulations
- Gaussian source, 1 Rayleigh length inside the undulator
- Propagate to the mirror, located 383 meters from undulator

Intensity Profile at Mirror Entrance

8.265 keV

FWHM=507.24 μm
Wavefront propagation simulations
- Gaussian source, 1 Rayleigh length inside the undulator
- Propagate to the mirror, located 383 meters from undulator
- Apply phase shift to wavefront for a given mirror curvature

Kewish et al, Applied Optics 46, 2007
Wavefront propagation simulations

- Gaussian source, 1 Rayleigh length inside the undulator
- Propagate to the mirror, located 383 meters from undulator
- Apply phase shift to wavefront for a given mirror curvature
- Limit the aperture

Mirror length = 100 mm

![Graph showing intensity profile at mirror exit for mirror length 100 mm with FWHM=336.5 μm.](image)

Mirror length = 350 mm

![Graph showing intensity profile at mirror exit for mirror length 350 mm with FWHM=507.3 μm.](image)
Wavefront propagation simulations

- Beam profile through the focus for different mirror lengths
- Propagated wavefront after phase shift at the optic

Mirror length = 400 mm
Wavefront propagation simulations

- FWHM vs distance along the beam for various mirror lengths

Minimum not at zero because source is at z=-438 m while mirror curvature was generated for Z=-420 m

The focus location varies as

\[ dz = \frac{f^2 z^2}{z^2 + ds^2} \]

where \( ds \) is the source point fluctuation

- \( f \) is the focal length
- \( z \) is the average source location
- For 5 m source point jitter
  - \( dz \sim 4 \text{ mm} \)
  - Well within the Rayleigh length
Mirror Dimensions

- Wavefront propagation simulations
  - FWHM vs distance along the beam for various mirror lengths

Mirror length = 400 mm
Mirror Dimensions

- Long mirrors are required to produce the small focus
- Long mirrors are required to produce high peak intensity

- Ratio of peak intensities between 350 mm and 100 mm mirrors
  - \((9/2)^2 = 20\)
  - Using a 100 mm mirror is equivalent to throwing away 95% of the photons at 8.3 keV
  - Situation is even worse for lower photon energies

![Graphs showing FWHM and peak intensity vs mirror size](image-url)
Ideally, we would at least match the acceptance of the HOMS mirror system with the KB System.
Acceptance of 350 mm long mirrors

Mirror length = 350 mm

Energy (eV)

KB Acceptance (sigmas)

4 sigma minimum target

2.5 mrad
2.786 mrad
3.067 mrad
3.36 mrad
3.4 mrad
3.6 mrad
Mirror Substrate Specifications

**Dimensions**

- **Clear Aperture**
  - **Width**
    - 12 mm
    - Allows 2 coating strips
  - **Length**
    - 350 mm
    - Largest mirrors that can be made and meet figure specs

- **Substrate**
  - **Width**
    - 50 mm
  - **Length**
    - 360 mm < length < 390 mm
  - **Thickness**
    - 50 mm
    - Thickest mirror vendor says they can do metrology on
Focus gets larger with decreasing energy due to the reduced mirror acceptance.

8.3 keV
Preserve the coherence of the beam

- Satisfy the Maréchal criterion at least at 8.3 keV and if possible up to 11 keV
  - >80% of incident intensity in the central peak at the focal plane

  - $h_{\text{rms}} = \text{rms height error over entire length of the mirror}$
  - $\lambda = \text{wavelength}$
  - $N = \text{number of reflective optics}$
  - $\alpha = \text{incidence angle}$

$$h_{\text{rms}} \leq \frac{\lambda}{14\sqrt{N} 2\alpha}$$

- With HOMS mirrors, we have a total of 3 mirrors horizontally
  - Some wavefront distortions are present due to the HOMS

- Without HOMS
  - At 8.3 keV
    - $h_{\text{rms}} = 1.57 \text{ nm}$
  - At 11 keV
    - $h_{\text{rms}} = 1.18 \text{ nm}$

- With HOMS
  - At 8.3 keV
    - $h_{\text{rms}} = 1.1 \text{ nm}$
  - At 11 keV
    - $h_{\text{rms}} = 0.83 \text{ nm}$

- Difficult height error to achieve
  - 0.56 nm achieved on 100 mm mirrors
  - Possible to achieve < 1 nm rms
Why not use a single KB system?

- With 0.1 micron focus, Rayleigh length ~ 40 microns
  - Beam size increases 1 micron every mm
- Could move sample by 10 mm to get 1 micron spot
  - A single KB system could be sufficient
- However, the wavefront distortions out of focus are too large
Source parameters

1) Gaussian source
   - 60 microns FWHM

2) FEL source
   - Simulated with Genesis Code, by Sven Reiche

Distance to optic
- 437 m

Wavelength
- 0.15 nm

Mirror parameters

Parameters for 0.1 micron KB system
- Focal length (mirror 1) : 0.9 m
- Focal length (mirror 2) : 0.5 m
- Mirror length : 0.4 m
- Grazing angle : 3.5 mrad

Simulations performed by Jacek Krzywinski
Without optics errors, Gaussian source, at the focus

Gaussian beam - 50% of flux has fluence above 50% of maximum fluence
Without optics errors, FEL source at the focus

~47% of flux has fluence above 50% of maximum fluence
Simulations by Jacek Krzywinski

Intensity profiles for Gaussian and FEL sources at the focus

Max intensity $\sim 5.4 \cdot 10^5$ of the source max intensity

![Graphs showing intensity profiles for Gaussian and FEL sources at the focus.](image-url)
Without optics errors, Gaussian source, intensity distribution 10 mm behind the focus

Gaussian beam - 50% of flux has fluence above 50% of maximum fluence
Without optics errors, FEL source, intensity distribution 10 mm behind the focus

~42% of flux has fluence above 50% of maximum fluence
Simulations by Jacek Krzywinski

Intensity profiles for Gaussian and FEL sources 10 mm behind the focus
Model of surface roughness

Model for figure, low frequency errors, based on Zeiss metrology of HOMS mirror samples

Power distribution function (PSD) for surface height errors

RMS height error: 2 nm

Generated surface errors

Fractal model for mid and high frequency errors, based on LLNL metrology of HOMS mirror samples
HOMS 2nm rms errors, no KB errors

intensity distribution at the focus

~ 46% of flux has fluence above 50% of maximum fluence
Simulations by Jacek Krzywinski

HOMS 2nm rms errors, 0.5nm rms KB errors

intensity distribution at the focus

No effect!

Gaussian beam

~ 46% of flux has fluence above
50% of maximum fluence
HOMS 2nm rms errors, 1 nm rms KB errors

intensity distribution @ the focus

Small effect!

Gaussian beam

~ 41% of flux has fluence above
50% of maximum fluence
HOMS 2nm rms errors, 2 nm rms KB errors
intensity distribution @ the focus

With optics errors
No optics errors

~ 33% of flux has fluence above 50% of maximum fluence
HOMS 2nm rms errors, no KB errors

intensity distribution at the focus

~ 46% of flux has fluence above 50% of maximum fluence
HOMS 2nm rms errors, 0.5nm rms KB errors

intensity distribution at the focus

Small effect!
FEL beam

\[ \approx 43\% \text{ of flux has fluence above} \]
\[ 50\% \text{ of maximum fluence} \]
HOMS 2nm rms errors, 1 nm rms KB errors

intensity distribution @ the focus

Small effect!

~ 40% of flux has fluence above 50% of maximum fluence
HOMS 2nm rms errors, 2 nm rms KB errors

intensity distribution @ the focus.

- X profile
- Y profile

With optics errors
No optics errors

FEL beam

~ 24% of flux has fluence above 50% of maximum fluence
Wavefront through focus

HOMS 2nm rms errors, 1 nm rms KB errors

Intensity distribution 150 um behind the focus

~26% of flux has fluence above 50% of maximum fluence
Wavefront through focus

HOMS 2nm rms errors, 1 nm rms KB errors
intensity distribution 300 um behind the focus

~ 18% of flux has fluence above 50% of maximum fluence
Wavefront through focus

HOMS 2nm rms errors, 1 nm rms KB errors
intensity distribution 600 um behind the focus

~ 11% of flux has fluence above
50% of maximum fluence
HOMS 2nm rms errors, 1 nm rms KB errors
intensity distribution 1000 um behind the focus

~ 8% of flux has fluence above
50% of maximum fluence
HOMS 2nm rms errors, 1 nm rms KB errors

Intensity distribution 3000 um behind the focus

~ 17% of flux has fluence above 50% of maximum fluence
Wavefront through focus

HOMS 2nm rms errors, 1 nm rms KB errors
intensity distribution 6000 um behind the focus

~ 9% of flux has fluence above 50% of maximum fluence

75 um
Wavefront through focus

HOMS 2nm rms errors, 1 nm rms KB errors, intensity distribution 10000 um behind the focus

Max intensity 100% higher than without optics errors!!

~ 6% of flux has fluence above 50% of maximum fluence
Wavefront through focus

Without optics errors, FEL source, intensity distribution 10 mm behind the focus

~42% of flux has fluence above 50% of maximum fluence
Acceptable wavefront distortions and reduction of intensity at the focus for <1 nm rms

With current HOMS system and state of the art KB system, cannot use single KB system out of focus
  - Intensity fluctuations out of focus are > 50% within FWHM

Height error is the most important parameter
**Figure Error Specifications**

### Height Error
- **1 nm rms**
  - Beyond the capabilities of most vendors
    - 2 nm rms is typically the best number quoted by vendors
  - A few vendors claim to be able to do 1 nm
    - Only 1 vendor has demonstrated 0.56 nm on 100 mm mirror

### Slope Error
- **Tangential**
  - < 0.25 μrad rms
    - State of the art vendor capability
- **Sagittal**
  - < 2 μrad rms
    - State of the art vendor capability
    - Limited by metrology capabilities
    - Sagittal divergence induced by 1 mirror is compensated by focusing with other mirror
Roughness

**Mid-spatial**
- $< 0.25 \text{ nm rms}$
  - State of the art vendor capability
  - Important to limit flares off mirror
    - Not as crucial as the figure error since we can partially remove the flares with apertures

**High-spatial**
- $< 0.25 \text{ nm rms}$
  - State of the art vendor capability
  - Important to minimize wide angle scattering which creates background on the detector
    - Not as crucial as the figure error since we can partially remove the wide angle scattering with apertures
## Mirror Parameter Tables

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Mirror Shape</td>
<td>Tangential ellipse</td>
<td></td>
<td>For pre-figured mirrors Or flat</td>
</tr>
<tr>
<td>2 Clear aperture length</td>
<td>350</td>
<td>mm</td>
<td>Length over which the coating will be applied and the surface specifications must be met</td>
</tr>
<tr>
<td>3 Clear aperture width</td>
<td>&gt;12</td>
<td>mm</td>
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<tr>
<td>4 Mirror Length</td>
<td>390 ≥ length ≥ 360</td>
<td>mm</td>
<td>Extra length is to allow mounting during the coating process and mirror use</td>
</tr>
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<td>&gt;45</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>6 Mirror Thickness</td>
<td>&gt;50</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>7 Substrate material</td>
<td>Si &lt;100&gt;</td>
<td>Single crystal</td>
<td></td>
</tr>
<tr>
<td>8 Figure height error</td>
<td>&lt;1.00</td>
<td>mm rms</td>
<td>Over dimensions from 1mm to the clear aperture size</td>
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<td>9 Mid-spatial roughness</td>
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<td>&lt;2</td>
<td>μrad ms</td>
<td></td>
</tr>
<tr>
<td>13 Tangential Radius of curvature</td>
<td>4632-4932</td>
<td>m</td>
<td>Elliptical profile (see Figure 3 below). For pre-figure mirrors only</td>
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<tr>
<td>14 Mean Tangential Radius of curvature tolerance</td>
<td>0.1</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>15 Sagittal radius of curvature</td>
<td>&gt;400</td>
<td>m</td>
<td></td>
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<tr>
<td>16 Mean Sagittal Radius of curvature tolerance</td>
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<td>%</td>
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<tr>
<td>17 Maximum height of surface</td>
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<td>μm</td>
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<td>mrad</td>
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<td>mrad</td>
<td>Angle of incidence at the mid-point of the mirror</td>
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<td>21 Distance from source</td>
<td>406-439</td>
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<tr>
<td>22 Ellipse parameter (a)</td>
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<td>m</td>
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<tr>
<td>23 Ellipse parameter (b)</td>
<td>197.4</td>
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<td></td>
</tr>
<tr>
<td>24 Vacuum pressure</td>
<td>&lt;10⁻⁵</td>
<td>Torr</td>
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<tr>
<td>25 Temperature</td>
<td>22</td>
<td>°C</td>
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Table 1: Parameters for first mirror of KB1 system.

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Table 2: Parameters for second mirror of KB1 system.
Other Specifications

- **Optical surface**
  - Controlled grinding and polishing
    - Stress-free surface
    - Remove residual sub-surface damage
  - No visible striae
  - Meet requirement 10/5 per MILPRF-13830B
    - No digs and scratches

- **Non-optical Surfaces**
  - Controlled grinding and polishing
    - Stress-free surface
    - Remove residual sub-surface damage
  - Wet-chemical-etched

- **Vacuum (UHV)**
  - Compatible with $10^{-9}$ torr

- **Handling**
  - Full UHV handling practices
  - Vendor to submit a Handling and Process plan before award
    - Approved by SLAC

- **Cleaning**
  - Vendor to submit a Handling and Process plan before award
    - Approved by SLAC

- **Packaging**
  - Protection against shock and vibration
  - All metal
  - Dust-free
  - Vendor to submit a Handling and Process plan before award
    - Approved by SLAC
Other Specifications

Test Coupons
- 3 test coupons
  - Shape and size approved by SLAC
  - Used by SLAC (via subcontractor) to characterize the polishing process
    - May also be used for coating process development
  - Polished and figured using the same process as the full-size mirrors
    - Mid-spatial and high-spatial roughness to meet requirements
    - Figure relaxed to peak-to-valley height error < 158 nm
- Delivered to SLAC as soon as possible

Blank Substrate
- Vendor to provide a blank substrate for development of mechanical system
  - Delivered to SLAC as soon as possible
- Prepare the same way as real mirrors
  - Cut to size with all mounting features (grooves, holes)
  - Wet-chemical etched
- Flat figure instead of elliptical
- Peak-to-valley height error of 158 nm
- Mid and high-spatial roughness of 1 nm rms
Quality Assurance

- **General**
  - SLAC reserves right to perform audit of vendor before award
  - Vendor to maintain all documentation for processes and measurements

- **Handling and Process Plan**
  - Submitted in response to Request for Proposal
  - Approved by SLAC
  - Includes
    - Fabrication process
    - UHV handling procedures
    - Mirror cleaning procedure
    - Packaging and shipping arrangements

- **Program Management**
  - A single individual shall be named Program Manager at vendor's facility
    - Single point of contact with SLAC
  - Vendor to provide a detailed project schedule
    - Vendor to report against the schedule monthly
  - SLAC reserves the right to perform reviews and audits, if necessary

- **Progress Reporting**
  - At a minimum, monthly teleconferences with SLAC
    - Report on status
    - Discussion of any item requiring immediate attention

- **Inspection and Tests**
  - Vendor is responsible for all tests and metrology
    - Submit Inspection Test Procedure to SLAC before award
  - SLAC reserves the right to perform in-process inspections
  - Vendor to notify SLAC 5 days before final testing
    - SLAC may chose to take part in testing

- **In-process Inspections**
  - Specified in Inspection Test Procedure
  - At a minimum, will include
    - Inspection after initial shaping of the non-optical surface areas
    - Selected points during mirror surface polishing
    - Final inspection after the mirror is finished
Quality Assurance

- **Visual Inspection**
  - Visual inspection for digs/scratches prior to metrology
    - Any digs/scratches to be removed

- **Metrology by vendor**
  - All optical surface requirements to be verified by vendor
    - Results provided to SLAC in Inspection Test Report
  - All measurement procedures pre-approved by SLAC via the Inspection Test Procedure
  - Measurements to be performed at
    - 20°C ± 2°C
    - 30% to 70% humidity
    - Equipment and optic to be at thermal equilibrium
    - Mid and high-spatial roughness to be measured at specified points

- **Inspection Test Report**
  - Include all metrology results
  - Provide machine-readable raw data to SLAC
    - Vendor to describe the file format and supply all necessary parameters for independent analysis

*Figure 6: Location of roughness measurement sites, marked in blue. The clear aperture zone is marked in red.*
Mirror Substrate Summary

- 350 mm long clear aperture
  - Between 360 mm and 390 mm long substrate
  - Shorter the better
- 50 mm wide
- >45 mm thick
- 1 nm rms height error
- 3.4 mrad maximum incidence angle
- Figure specs fully developed
- Limited number of vendors exist with the required capabilities
Mirror Coating

- Overview
- Requirements
- Specifications
- Quality Assurance
- Summary
Coating Requirements

- Energy range
  - > 75% reflectivity (for mirror pair) up to at least 8.3 keV
    - > 86% reflectivity for each mirror

- Damage resistance
  - Capable of withstanding the full beam without any attenuation
  - Stable over many years

- Preserves the figure and roughness of the substrate
  - Figure is more important than roughness

- Flexibility for the future
  - LCLS could lase, with the current accelerator, up to 10.8 keV if the emittance is good enough
  - We require at least some safety margin on the coating so it will still be reflective if the maximum fundamental energy of LCLS is larger than 8.3 keV
    - Preferably, we should be capable of using a 10.8 keV beam as well

- Capable of reflecting the 3rd harmonic up to as high an energy as possible
  - Reduced radiation damage requirements for 3rd harmonic
### Coating Options

#### Materials

- **B₄C**
  - Excellent reflectivity (>99%)
  - Light material
    - High damage threshold
  - Small energy range at 3.4 mrad incidence

- **SiC**
  - Reflectivity not as good as B₄C
  - Light material
    - High damage threshold
    - Lower than B₄C
  - Energy range larger than B₄C for same incidence

- **Rh or Ru**
  - High reflectivity over much larger energy range
    - If it could be used, we could make shorter mirrors with larger incidence
  - Low damage threshold
    - Too close for comfort without actual measurements
  - This approach is too risky

- **Rh/SiC, Ru/SiC, Rh/B₄C Ru/B₄C bilayers**
  - Combine the high damage threshold of low Z material with high reflectivity of high Z material
  - Beam is reflected off top layer for fundamental energy
    - Reflection off bottom (high Z) layer for 3rd harmonic
  - Coating stability issues
    - Requires R&D
Reflectivity of B$_4$C at 3.4 mrad

- 50 nm B$_4$C
- 3.4 mrad incidence
  - Low angle
  - Long mirrors
  - Or poor performance at low energies where the beam is larger
- Reflective up to ~9 keV
- Low Z material
  - Damage resistance
  - No damage issues are expected
50 nm SiC

3.4 mrad incidence
  - Low angle
    - Long mirrors
    - Or poor performance at low energies where the beam is larger

Reflective up to ~10.5 keV
  - Larger energy range for same incidence makes it a better choice than B4C

Low Z material
  - Damage resistance
  - No damage issues are expected
Reflectivity of Rh at 3.4 mrad

- 50 nm Rh
- 3.4 mrad incidence
- Reflective up to ~18 keV
  - Absorption edge at 3 keV is a concern
- High Z material
  - Possible damage issues
  - Requires measurements of damage at LCLS
- Very risky approach
  - Could destroy the coating on first shot
Reflectivity of Rh/SiC at 3.4 mrad

- Bilayer
  - Top layer: 20 nm SiC
  - Bottom layer: 30 nm Rh
- 3.4 mrad incidence
- Reflective up to ~18 keV
  - Reflects off SiC up to 10.5 keV
  - Removes the problem with the Rh edge at 3 keV
- No damage problems
  - SiC protects Rh at energies below 11 keV
    - Rh “sees” the beam only for the 3rd harmonic
- Possible bilayer stability issues
Radiation Damage Issues

Calculations shown on plots assume normal incidence
- Grazing incidence reduces peak dose by ~ 3 orders of magnitude
- SiC has a safety factor of ~ 400
- Rh has a safety factor of ~ 10
- Lots of uncertainty in the calculations
- Need to measure damage thresholds under LCLS conditions

Rh coating alone can only be used above 4 keV
- Based on these uncertain calculations
- Measurements may reveal Rh is safe below the critical angle
- Could potentially be used as a monolayer but not before damage thresholds are measured experimentally
- Other similar material (like Ru which has a higher melting temperature) could be used instead of Rh

Thermal fatigue threshold
- Thermal cycling can lead to cracking
- Depends on the mechanical properties of the material

\[ \delta T = \frac{3(1-\nu)G}{\alpha E} \]

\( \nu \) = Poisson ratio
\( G \) = Yield strength
\( E \) = Young’s modulus
\( \alpha \) = Coefficient of thermal expansion

Coating Material Choice

2 Strips

First Strip
- 50 nm SiC
- Only this strip will be deposited for sure

Second Strip
- Choice 1
  - 20 nm Rh
  - 30 nm SiC
- Choice 2
  - 50 nm Rh only

Perform early damage experiments at LCLS before choosing second coating strip material
- We may choose to leave it blank
## Coating Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coating material</td>
<td>SiC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coating thickness</td>
<td>50</td>
<td>nm</td>
<td></td>
</tr>
<tr>
<td>Figure height error</td>
<td>&lt;1.00</td>
<td>nm rms</td>
<td>Over dimensions from 1mm to the clear aperture size</td>
</tr>
<tr>
<td>Mid-spatial roughness</td>
<td>&lt;0.25</td>
<td>nm rms</td>
<td>Over the $10^{-3}$ to $0.5 \mu m^{-1}$ frequency range</td>
</tr>
<tr>
<td>High-spatial roughness</td>
<td>&lt;0.25</td>
<td>nm rms</td>
<td>Over the 0.5 to 50 $\mu m^{-1}$ frequency range</td>
</tr>
<tr>
<td>Coating Strip width</td>
<td>5</td>
<td>mm</td>
<td></td>
</tr>
</tbody>
</table>

**Table 3:** Mirror coating requirements for the first strip
## Coating Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>First coating layer material</td>
<td>Rh or Ru</td>
<td></td>
<td></td>
</tr>
<tr>
<td>First coating layer thickness</td>
<td>30</td>
<td>nm</td>
<td></td>
</tr>
<tr>
<td>Figure height error (1\textsuperscript{st} layer)</td>
<td>&lt;1.00</td>
<td>nm rms</td>
<td>Over dimensions from 1mm to the clear aperture size</td>
</tr>
<tr>
<td>Mid-spatial roughness (1\textsuperscript{st} layer)</td>
<td>&lt;0.25</td>
<td>nm rms</td>
<td>Over the 10\textsuperscript{-3} to 0.5 (\mu\text{m}\textsuperscript{-1} ) frequency range</td>
</tr>
<tr>
<td>High-spatial roughness (1\textsuperscript{st} layer)</td>
<td>&lt;0.25</td>
<td>nm rms</td>
<td>Over the 0.5 to 50 (\mu\text{m}\textsuperscript{-1} ) frequency range</td>
</tr>
<tr>
<td>Second coating layer material</td>
<td>SiC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Second coating layer thickness</td>
<td>20</td>
<td>nm</td>
<td></td>
</tr>
<tr>
<td>Figure height error (2\textsuperscript{nd} layer)</td>
<td>&lt;1.00</td>
<td>nm rms</td>
<td>Over dimensions from 1mm to the clear aperture size</td>
</tr>
<tr>
<td>Mid-spatial roughness (2\textsuperscript{nd} layer)</td>
<td>&lt;0.25</td>
<td>nm rms</td>
<td>Over the 10\textsuperscript{-3} to 0.5 (\mu\text{m}\textsuperscript{-1} ) frequency range</td>
</tr>
<tr>
<td>High-spatial roughness (2\textsuperscript{nd} layer)</td>
<td>&lt;0.25</td>
<td>nm rms</td>
<td>Over the 0.5 to 50 (\mu\text{m}\textsuperscript{-1} ) frequency range</td>
</tr>
<tr>
<td>Coating Strip width</td>
<td>5</td>
<td>mm</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4:** Mirror coating requirements for the second strip
Other Coating Specifications

- **Test Coupons**
  - Test coupons will be made available for the process development

- **Process development**
  - Vendor to develop and demonstrate the coating process before coating mirrors
  - Perform same metrology on test coatings as for final mirrors

- **Vacuum (UHV)**
  - Compatible with 10^-9 torr

- **Handling**
  - Full UHV handling practices
  - Vendor to submit a Handling and Process plan
    - Approved by SLAC

- **Cleaning**
  - Vendor to submit a Handling and Process plan before award
    - Approved by SLAC

- **Packaging and shipping**
  - Protection against shock and vibration
  - All metal
  - Dust-free
  - Vendor to follow same Handling and Process plan as substrate vendor
    - Approved by SLAC
Coating Quality Assurance

- **General**
  - SLAC reserves right to perform audit of vendor before award
  - Vendor to maintain all documentation for processes and measurements

- **Handling and Coating Process Plan**
  - Submitted in response to Request for Proposal
  - Follow the same Handling and Process Plan as mirror substrate vendor
    - Approved by SLAC
  - Includes
    - Coating process
    - UHV handling procedures
    - Mirror cleaning procedure
    - Packaging and shipping arrangements

- **Program Management**
  - A single individual shall be named Program Manager at vendor’s facility
    - Single point of contact with SLAC
  - Vendor to provide a detailed project schedule after award
  - SLAC reserves the right to perform reviews and audits, if necessary

- **Progress Reporting**
  - At a minimum, twice monthly teleconferences with SLAC
    - Report on status
    - Discussion of any item requiring immediate attention

- **Inspections and Tests**
Coating Inspection and Test Procedure
- Submitted to SLAC in response of Request for Proposals

In-Process Inspection Points
- Specified in Inspection Test Procedure
- At a minimum, will include
  - Inspection upon receipt of the mirror substrates
  - After deposition of each strip
  - Final inspection after the mirror coating is finished

Metrology by vendor
- All optical surface requirements to be verified by vendor
  - Results provided to SLAC in Inspection Test Report
- All measurement procedures pre-approved by SLAC via the Inspection Test Procedure
- Measurements to be performed at
  - 20°C ± 2°C
  - 30% to 70% humidity
  - Equipment and optic to be at thermal equilibrium
  - Mid and high-spatial roughness to be measured at specified points

Coating Inspection Test Report
- Include all metrology results
- Provide machine-readable raw data to SLAC
  - Vendor to describe the file format and supply all necessary parameters for independent analysis
Coating Summary

- 2 coating strips
  - Each 5 mm wide
- First strip
  - 50 nm SiC
- Second strip
  - 30 nm Rh or Ru
  - 20 nm SiC
  - Will only deposit this strip after LCLS damage measurements
Metrology

- Overview
- Requirements
- Specifications
- Quality Assurance
- Summary
Metrology Requirements

- We require independent verification of
  - Mirror substrate figure and roughness
  - Coating figure and roughness
  - Mirror figure when assembled in complete system

- We may choose to participate in the vendor final assembly and tests to verify the final performance of the system.

- We plan to hire an external vendor with suitable metrology capabilities to independently verify the performance of subsystems and possibly the completed system.
Metrology Specifications

- **Frequency of Measurements**
  - Upon receipt of the test coupons
  - After the delivery of the substrates
  - After deposition of the first coating strip
  - After deposition of the second coating strip

- **Figure Measurements**
  - Full-aperture visible-light interferometry
  - Long trace profiler
  - Stitching interferometry

- **Roughness Measurements**
  - Mid-spatial frequencies
    - Interferometer
    - Profiling microscope
  - High-spatial frequencies
    - AFM

- **Power Spectral Density**
  - A PSD combining all the metrology will be provided by vendor

---

*Figure 6: Location of roughness measurement sites, marked in blue. The clear aperture zone is marked in red.*
**Metrology Specifications**

- **Handling**
  - Consistent with the Handling and Process Plan developed by Substrate vendor and approved by SLAC

- **Packaging and Shipping**
  - Consistent with the Handling and Process Plan developed by Substrate vendor and approved by SLAC

- **Handling and Metrology Process Plan**
  - Contains description of all metrology processes
  - To be approved by SLAC as a response to the Request for Proposals

- **Characterization Metrology**
  - All optical surface requirements to be verified by vendor
    - Results provided to SLAC in Inspection Test Report
  - All measurement procedures pre-approved by SLAC via the Inspection Test Procedure
  - Measurements to be performed at
    - 20°C ± 2°C
    - 30% to 70% humidity
    - Equipment and optic to be at thermal equilibrium
    - Mid and high-spatial roughness to be measured at specified points
Metrology Quality Assurance

- General
  - SLAC reserves right to perform audit of vendor before award
  - Vendor to maintain all documentation for processes and measurements

- Program Management
  - A single individual shall be named Program Manager at vendor’s facility
    - Single point of contact with SLAC
  - Vendor to provide a detailed project schedule after award
  - SLAC reserves the right to perform reviews and audits, if necessary

- Progress Reporting
  - At a minimum, twice monthly teleconferences with SLAC
    - Report on status
    - Discussion of any item requiring immediate attention

- Metrology Procedure
  - Outlines all the measurements and equipment to be used
    - Submitted in response to Request for Proposals

- Metrology Report
  - Include all metrology results
  - Provide machine-readable raw data to SLAC
    - Vendor to describe the file format and supply all necessary parameters for independent analysis
Metrology Summary

- Metrology vendor to independently verify optical surface specifications
  - Test coupons
  - Mirrors before coating
  - Mirrors after coating
- Independent verification of mirror figure in final assembled system
  - Best way to do this may be to participate in the vendor final tests
Mechanical System

- Overview
- Requirements
- Specifications
  - Mirror Support System
  - Vacuum Enclosure
  - Support Stand
- Ultimate specifications vs Realistic/minimum specifications
- Quality Assurance
- Summary
Subsystems

- Mirror support
  - Bender system
    - Likely will not be necessary since we will likely go with pre-figured mirrors

- Vacuum enclosure

- Support stand

- We will seek a single vendor to design and integrate all components

- This vendor is responsible to demonstrate the final capabilities of the system and that the specs are met
45 Degree Arrangement

- Large mirror to sample distance
  - 8 meters
- Large distance from sample to final diagnostics behind the focus
  - 10 meters
- We need to track the beam to 3 different positions and directions
  - 1 micron focus displaces the beam by 175 mm at the end of the hutch
  - 0.1 micron focus displaces the beam by 105 mm at the end of the hutch
  - Direct beam has zero displacement
- Much simpler mechanics if the deflection from the KBs is in the horizontal only

---

**Upstream mirror**

**LCLS Beam**

**Downstream mirror**
Degrees of Freedom

- Each mirror has 3 positions and 3 angles
- Some angles and positions can be fixed but others must be motorized
- Translation along surface normal: $y$
- Translation along the beam: $z$
- Translation perpendicular to beam and normal: $x$
- Incidence (grazing) angle (pitch): $\theta$
- In-plane rotation (yaw): $\psi$
- Perpendicularity (roll): $\phi$
Degrees of Freedom

- Need to move from 1 coating strip to the other
  - x1 and x2 must be motorized
  - Total width of clear aperture: 12 mm
    - Translation range: 14 mm

- Need to move the mirrors out of the beam to use other KB system
  - y1 and y2 must be motorized
  - Nominal position: 0 mm
  - Clear aperture at 3.4 mrad: 1 mm
  - Range: 2 mm to -10 mm when mirror is retracted
    - Gives ~ ½ inch of clearance for the beam

- Need to fine tune the incidence angle
  - θ1 and θ2 must be motorized
  - Simulation results will show required resolution

- All other axes can be manual or positioned with machining tolerances if possible
  - Need to control Z to better than the Rayleigh length of the focus so both mirrors focus at the same plane
    - 4 mm for 1 micron KB System
    - 16 μm for 0.1 micron KB System
  - We pick the tighter of the 2 requirements
    - 8 μm accuracy (may require motorization of z for 1 mirror)
Simulations show slightly relaxed Z positioning specs than simple Rayleigh length calculations.
Mechanical Requirements

- **Incidence angle**
  - Wavefront propagation for different incidence angle
  - Rotate the ideal elliptical surface and recalculate the height function
    - Good focus achieved only over a narrow range of incidence

Kewish et al, Applied Optics 46, 2007
Incidence Angle

- Focal length = 8.2 m
- Focal length = 7.8 m
- Focal length = 0.9 m
- Focal length = 0.5 m

< 1 μrad resolution is required
Comparison with Existing Systems

- Ray-tracing calculations for 100 mm long mirrors
  - Incidence angle requirements are more stringent than other 2 angles
  - Built system by this group matched the simulations well

They also performed wavefront propagation calculations for incidence angle.

Requires similar accuracy as our system:

- **Incidence**
  - $< 1 \mu$rad

- **Perpendicularity**
  - 5 $\mu$rad

- **In-plane**
  - 1 mrad

Mechanical Requirements

- **Stability**
  - Keep the focal position stable to within 10% of the focal width
  - Stable to within 100 nm at 8.2 meters away
    - Y-translation
      - Stable to within 100 nm (short term)
      - Stable to within 1 μm (long term)
    - Incidence angle
      - 10 nrad stability
        - Same for 0.1 micron KB System
        - Stable to within 10 nm at 0.9 meters away
      - Very difficult to achieve
      - This stability is required over only a short period of time (~10 minutes) for experiments requiring multiple exposures
      - Since most experiments are single shots, we can tolerate long term drifts comparable to the FWHM of the focus
        - 100 nrad long term (1 day) stability requirement would be great
        - 1 μrad long term would mean the beam moves by 10 times its size and would require realignment every few hours but it is not a show stopper for single shot measurements, provided the short term stability is met
  - Roll stability
    - 2 μrad
    - Same for both KB systems
  - In-plane rotation
    - Does not directly affect the position of the focus
      - Leads to wavefront distortions
      - Stability requirement : 0.1 mrad
Mechanical Support Specifications

- **Scope**
  - UHV mirror mounting system
  - Vacuum chamber
  - Support stand

- **Design and Analysis**
  - Vendor design and analysis will include
    - Interface definition
    - Component design
    - Stress and thermal analysis
    - Reliability analysis
    - System performance analysis
    - Verification and test plans

- This vendor, with SLAC oversight, is responsible for the whole system integration
Perpendicularity may be achieved by fixing 1 mirror and moving the second.
Only the first 3 motions need to be motorized.

<table>
<thead>
<tr>
<th>Motion</th>
<th>Nominal Position</th>
<th>Range</th>
<th>Resolution</th>
<th>Repeatability</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>x2</td>
<td>0</td>
<td>-7 mm &lt; x &lt; 7 mm</td>
<td>4 μm</td>
<td>4 μm</td>
<td>1 (10) μm</td>
</tr>
<tr>
<td>y2</td>
<td>0</td>
<td>-10 mm &lt; y &lt; 2 mm</td>
<td>4 μm</td>
<td>4 μm</td>
<td>0.1 (1) μm</td>
</tr>
<tr>
<td>Grazing angle (θ2)</td>
<td>3.363 mrad</td>
<td>2 mrad &lt; θ &lt; 5 mrad</td>
<td>0.5 μrad</td>
<td>0.5 μrad</td>
<td>0.01 (0.1) μrad</td>
</tr>
<tr>
<td>In-plane rotation (ψ2)</td>
<td>3.4 mrad</td>
<td>-10 mrad &lt; ψ &lt; 10 mrad</td>
<td>1 μrad</td>
<td>1 μrad</td>
<td>0.1 (0.1) mrad</td>
</tr>
<tr>
<td>Perpendicularity (φ2)</td>
<td>0</td>
<td>-100 μrad &lt; φ &lt; 100 μrad</td>
<td>5 μrad</td>
<td>5 μrad</td>
<td>1 (1) μrad</td>
</tr>
</tbody>
</table>

**Table 6:** Motion requirements for the downstream mirror. The stability number corresponds to short term (10 minutes) stability while the number in parentheses correspond to long term stability (over 1 day).
Mechanical Support Specifications

Positioning
- The z position and the roll angle of the second mirror must be adjusted to the first mirror
  - \( z_2 = z_1 + 400 \pm 0.008 \text{ mm} \)
  - Motorization of mirror 1 seems like the best solution
  - \( \phi_2 = \phi_1 + 90 \text{ degrees } \pm 5 \mu \text{rad} \)
  - Motorization of mirror 1 would allow beam based alignment

Dimensions
- Z length must be limited for 0.1 micron system
  - Limited distance from mirror to focal plane
  - Limit z length for both systems so they are identical
  - 400 mm distance between the centers of the mirrors is a hard requirement with fixed figure
- Second beamline passing through the hutch limits the size of the entire system in \(-x\) direction
  - \(< 450 \text{ mm from beam center line in } -x \text{ direction} \)
Orientation (45 degrees)
Orientation (45 degrees)
Orientation (45 degrees)

370 mm

50 mm

50 mm

50 mm
ANSYS Analysis

NODAL SOLUTION
STEP=1
SUB =1
TIME=1
UZ (AVG)
RSYS=20
DMX =.200E-04
SMX =.148E-04
ACEL

Units: mm, gm, N, MPa, g=9.806E-3 mm/ms**2
ANSYS Analysis

NODAL SOLUTION

STEP=1
SUB =1
TIME=1
/EXPANDED
UZ (AVG)
RSYS=20
DMX =.200E-04
SMX =.148E-04

Units: mm, gm, N, MPa, g=9.806E-3 mm/ms**2
**ANSYS Analysis**

**NODAL SOLUTION**

STEP = 1
SUB = 1
TIME = 1
EPELX (AVG)
RSYS = 20
DMX = .200E-04
SMN = -.232E-06
SMX = .621E-07

**Plot Description**

The plot shows a 3D representation of a structure with color-coded data indicating stress distribution. The axes are labeled as x, y, and z. The color bar ranges from negative to positive values, indicating varying degrees of stress.

**Units**

- Units: mm, gm, N, MPa, g = 9.806E-3 mm/ms**2

**Date and Time**

OCT 7 2008
17:31:10
mirror_defl_symm
ANSYS Analysis

NODAL SOLUTION

STEP=1
SUB =1
TIME=1
EPELY (AVG)
RSYS=20
DMX = .200E-04
SMN = -.623E-06
SMX = .116E-06

Units: mm, gm, N, MPa, g=9.806E-3 mm/ms**2
ANSYS Analysis

NODAL SOLUTION
STEP=1
SUB =1
TIME=1
EPOL2 (AVG)
RSYS=20
DMX =.200E-04
SMN =-.480E-06
SMX =.132E-06

x
y
z

Units: mm, gm, N, MPa, g=9.806E-3 mm/ms**2
Surface displacement

![Graph showing the relationship between position along the mirror and surface displacement](image-url)
Wavefront Simulations

With Distortions

Without Distortions

Focal length=8.2 m

Distance from optical axis (µm)

Distance from focus (mm)
Wavefront Simulations

With Distortions

Without Distortions

FWHM=1.21 \mu m

Intensity (ph/m)

Distance from optical axis (\mu m)

FWHM=1.21 \mu m

Intensity (ph/m)

Distance from optical axis (\mu m)
Wavefront Simulations

With Distortions

Without Distortions

[Graphs showing FWHM (μm) vs Distance from focus (mm)]
Mirror mounting induced distortions

- The mounting of the mirrors shall not distort the natural figure of the mirrors by more than the figure error requirements described before
  - This applies to the aspheric component of the distortions
    - 1 nm rms height error
  - The natural spheric component of the mirror figure is huge and a small extra sphere will only slightly change the focal length
    - We can compensate for that
- Vendor to demonstrate with calculations and, if necessary, prototype
  - To be reviewed by SLAC before final fabrication
- Clear aperture of mounting system
  - At least 2 mm x 12 mm
**Mechanical Support Specifications**

### Motion Limits
- **Limits on fine motion**
  - When the system is aligned, set limit switches to prevent large moves
- **Limits and hard stops on large motions**
  - When the system is being aligned or when switching to the other KB system
  - Allow full range of motion

### Cyclic Requirements
- **Actuation 500 over a few days**
  - During alignment
- **Small corrective actuations for 2 months**
  - To correct for drifts
- **Actuation 3000 times/yr for each motion for 10 yrs**
Mechanical Support Specifications

- **Mechanical Interfaces**
  - Support system interfaces with vacuum enclosure

- **Vacuum**
  - Compatible with UHV ($10^{-9}$ Torr)
  - Consistent with SLAC document SC-700-866-47
  - All parts cleaned for UHV

- **Materials**
  - Compatible with UHV ($10^{-9}$ Torr)
  - List of materials to be communicated to SLAC in response of Request for Proposals

- **Thermal Issues**
  - 240 mW thermal load from X-ray beam
    - Each mirror must reflect $> 86\%$ of beam
      - $< 34$ mW absorbed heat
  - No active cooling is expected to be necessary
  - Vendor to demonstrate that system allows for proper heat removal
  - Vendor to demonstrate that the system meets the stability, positioning, repeatability requirements given this heat deposited.
  - Vendor also to demonstrate that the figure requirements will be met given this heat load
Mechanical Support Specifications

Radiation Damage Issues
- Grazing incidence and SiC coating will protect the optical surface from damage
- Leading edge must be protected with a 10 mm thick B$_4$C
  - Control position relative to mirror to within 10 microns
- Every exposed surface of the mounting system that can be exposed to the beam shall be made of low Z material that can withstand the beam or be covered by a low Z material

Alignment/Fiducialization
- Fine align of motorized motions to be beam-based
- Other motions to be surveyed to within the requirements
- Fiducials to be provided to locate the mirrors within the support system

Stability
- Vibrational stability and short term (10 minutes) thermal stability
  - Focus stable to within 10% of the FWHM
- Long term thermal stability (1 day)
  - Focus stable to within the FWHM
- It may be necessary for SLAC to enclose the system in a well-controlled environment for temperature stability
  - The vendor may communicate this need to SLAC
    - It will be SLAC responsibility to build the A/C system
Other Mechanical Support Specifications

- Handling and Cleaning
  - Vendor to submit a Handling and Process Plan
    - Approved by SLAC
- Packaging and Shipping
  - Vendor responsible for designing and building shipping containers
  - Protection against vibrations and shocks
  - Described in the Handling and Process Plan
- Mirror Support Handling and Process Plan
  - Approved by SLAC
  - Submitted in response to the Request for Proposals
  - Includes
    - Fabrication process
    - List of materials
    - UHV handling procedures
    - Cleaning procedures
    - Packaging and shipping arrangements
- Electrical Requirements
  - If any in-vacuum motors, electronics are used, terminate all wires and cables with proper UHV connectors
  - All electrical components shall comply, if possible, with codes (NRTL)
- On-site Installation Assistance by Vendor
  - Vendor to assist in installation at SLAC
Mechanical Support Quality Assurance

**General**
- SLAC reserves right to perform audit of vendor before award
- Vendor to maintain all documentation for processes and measurements
- SLAC intends to use the vendor’s existing QA procedures, to include at least

**Configuration Control**
- Vendor to establish a document control process
- A formal change process must be followed before fabrication

**Program Management**
- A single individual shall be named Program Manager at vendor’s facility
  - Single point of contact with SLAC
- Vendor to provide a detailed project schedule after award
- SLAC reserves the right to perform reviews and audits, if necessary

**Progress Reporting**
- At a minimum, monthly teleconferences with SLAC
  - Report on status
  - Discussion of any item requiring immediate attention
Technical Interface Meeting
- Vendor to host a meeting to discuss contract planning with SLAC no later than 1 month after Receipt of Order

Design Reviews
- Conceptual Design Review
  - Within 2 months of award
- Preliminary Design Review
  - Within 4 months of award
- Final Design Review
  - Prior to finalizing drawings
  - Within 10 months of award (goal)
- Manufacturing Readiness Review
  - Prior to starting fabrication
- Pre-Ship Review
  - Review how the system performs against the specs prior to shipping
Mechanical Support Quality Assurance

Manufacturing and Assembly
- Vendor to submit a Fabrication, Assembly and Inspection Plan prior to MRR
- Vendor to provide subcontractor scope
- System shipped as a whole if deemed safe to do so
- Vendor to provide all drawings to SLAC
  - In a format agreed upon with SLAC

Verification and Test Plans
- Vendor to provide a qualification and verification matrix
  - List each requirement, a pass/fail grade and how they were tested

Inspection Requirements
- Vendor to submit an Inspection Plan which includes
  - Fabrication steps
  - In-process and end item inspection points
  - References to applicable inspection criteria

Non-Conformance Control
- Nonconformance reports to be provided to SLAC with final documentation

Documentation
- Vendor to provide all drawings to SLAC in PDF
- All models in a format agreed upon with SLAC
- A detailed assembly procedure

Part Marking
- Vendor to inscribe all parts, assemblies and sub-assemblies with a unique serial number, whenever possible
Mirror Bending System

- Offered as an option to vendors during Request for Information.
- Single vendor must take responsibility for both mirror substrates and mechanical system if bent mirrors are to be the solution.
- Preferred solution is pre-figured mirrors and most vendors agree.
- Most likely, there will be no bender system.
Due to space constraints along the beam for the 0.1 micron system, a single chamber for both mirrors is preferred.

- No space for flanges and bellows between the 2 mirrors.

With single vendor designing the entire mechanical system, the stages controlling the motions of the mirrors can all be located outside vacuum.
Vacuum Enclosure Specifications

Vacuum Requirements
- Compatible with UHV (10^-9 Torr)
- Consistent with SLAC document SC-700-866-47
- All parts cleaned for UHV
- Only metal seals

Dimensions
- At least 0.8 m long on the inside
  - As short as possible on downstream end
- < 450 mm in –x direction
  - Due to other beam pipe
- No other size restrictions

Kinematics/Supports
- Mounting on stand reproducible to within 100 microns
### Viewports

<table>
<thead>
<tr>
<th>Port type or use</th>
<th>Orientation</th>
<th>Location</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viewport (4.5&quot;)</td>
<td>Along ψ1 axis</td>
<td>Midpoint along z of mirror 1</td>
<td>Future addition of interferometer</td>
</tr>
<tr>
<td>Viewport (4.5&quot;)</td>
<td>Along θ1 axis</td>
<td>Midpoint along z of mirror 1</td>
<td>Future addition of interferometer</td>
</tr>
<tr>
<td>Viewport (4.5&quot;)</td>
<td>Along ψ2 axis</td>
<td>Midpoint along z of mirror 2</td>
<td>Future addition of interferometer</td>
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<tr>
<td>Viewport (4.5&quot;)</td>
<td>Along θ2 axis</td>
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<td>Future addition of interferometer</td>
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<tr>
<td>Vacuum gauge (2.75&quot;)</td>
<td>Any</td>
<td>Anywhere</td>
<td>Measure the pressure</td>
</tr>
<tr>
<td>Vacuum gauge (2.75&quot;)</td>
<td>Any</td>
<td>Anywhere</td>
<td>Measure the pressure</td>
</tr>
<tr>
<td>Rough pumping (2.75&quot;)</td>
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<td>Anywhere</td>
<td>Pump down the enclosure from atmosphere</td>
</tr>
<tr>
<td>Ion Pump (6&quot;)</td>
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<td>Bottom of enclosure</td>
<td>Create Ultra-high vacuum</td>
</tr>
<tr>
<td>Feedthrough (6&quot;)</td>
<td>Any</td>
<td>Near the back side of mirror 1</td>
<td>Connect cables for motorized motions</td>
</tr>
<tr>
<td>Feedthrough (6&quot;)</td>
<td>Any</td>
<td>Near the back side of mirror 2</td>
<td>Connect cables for motorized motions</td>
</tr>
<tr>
<td>Miscellaneous (6&quot;)</td>
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<td>Anywhere</td>
<td>Future expansion</td>
</tr>
<tr>
<td>Miscellaneous (6&quot;)</td>
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<td>Miscellaneous (2.75&quot;)</td>
<td>Any</td>
<td>Anywhere</td>
<td>Future expansion</td>
</tr>
</tbody>
</table>

**Table 7:** List of ports required on the vacuum enclosure of the KB mirror system.
Vacuum Enclosure Specifications

- **Mechanical Interfaces**
  - **Entrance port**
    - 6” non-rotatable
    - At beam height 1400 mm
    - Mated to a gate valve
  - **Exit port**
    - 6” rotatable
    - At beam height 1398.1 mm
    - Lateral offset = 9.6 mm in +x direction
    - Mated to a gate valve
  - Bellows on each side of chamber for 1 micron system
  - Bellows only on upstream side for 0.1 micron system

- **Thermal Issues and Stability**
  - ±1 degree Fahrenheit thermal stability inside the hutch
  - Stability requirements of all axes must be met with this temperature fluctuation
  - May require a small controlled enclosure around the KB system
    - This option does not work for the 0.1 micron KB system since it is integrated with the sample chamber
Vacuum Enclosure Specifications

- **Alignment/Fiducialization**
  - External fiducials on chamber
    - Referenced to the mirrors inside
    - 6 x ¼ inch holes for tooling balls

- **Handling and Cleaning**
  - Vendor to submit a Handling and Process Plan
    - Approved by SLAC

- **Packaging and Shipping**
  - Same as discussed for the mirror support system

- **Electrical Requirements**
  - If any in-vacuum motors, electronics are used, terminate all wires and cables with proper UHV connectors
  - Provide the vacuum feedthroughs
  - All electrical components shall comply, if possible, with codes (NRTL)

- **Maintenance and Accessibility**
  - Design to allow, to the extent possible, the removal of the mirror support system without removing the entire vacuum enclosure from the beamline
    - Large access ports if possible
  - Access to the mirrors in vacuum with removal of a single CF flange
    - For minor maintenance
  - Access to the front and back sides of each mirrors
    - Example: removal lid on top of the chamber
  - Lifting fixtures to be provided on vacuum enclosure
  - No trip hazards, pinch points, loose cables
Vacuum Enclosure Quality Assurance

Same as for the mirror support system
Support Stand Specifications

- **Performance**
  - Must meet the thermal and vibration requirements described before

- **Mechanical Interfaces**
  - Interface with the vacuum enclosure/mirror support system

- **Materials**
  - Material to be chosen for their thermal and vibrational stability

- **Thermal Issues and Stability**
  - Stability requirements described before are all relative to the sample chamber
    - Maybe possible to match the thermal expansion of the chamber and stand

- **Structural Issues**
  - Certification by the SLAC Earthquake Safety Committee if weight supported by the stand exceeds 400 pounds
    - Vendor to allow 6 weeks for SLAC approval

- **Motion**
  - Mount of vacuum enclosure to allow ± 12.5 mm of coarse manual adjustment in x and y
    - With steps of 0.1 mm or less
    - For future drifts of the beam

- **Color**
  - Stand to be painted red (FS11140), the official CXI color
Stand Quality Assurance

- Same as for the mirror support system and vacuum enclosure
Mechanical System Summary

First mirror
- Motorized
  - x₁, y₁, θ₁
- May be motorized (design decision by vendor and SLAC)
  - z₁, φ₁
- Manually adjusted or fixed with manufacturing tolerance
  - ψ₁

Second mirror
- Motorized
  - x₂, y₂, θ₂
- Manually adjusted or fixed with manufacturing tolerance
  - ψ₂, z₂, φ₂

Mechanical Specs are defined and supported with simulations
- 2 major difficulties
  - Thermal stability
  - Mirror mounting without distorting the mirrors beyond the specs
- 45 degree arrangement has big advantages
  - Worth pursuing but it is more important to meet the figure specs than to have the 45 degree system

Vendor to be in charge of entire system design
- Except for optics which are to be set in size and shape before award
- Vendor to demonstrate with metrology that all the specs are met
Safety

- **Beam confinement**
  - Ray tracing calculations will be performed by SLAC to define the beam stay-clear
  - Every exposed surface will be protected with B₄C
  - Software and limit switches will also be implemented to limit the beam motions
  - The KB system is located in a hutch that will always be closed when there’s beam on
    - Beam confinement is expected to be a Machine Protection issue and not a Personnel Protection issue
    - The fixed figure will prevent the beam from being focused on the hutch walls

- **Seismic**
  - The entire system will be reviewed and approved by SLAC for seismic safety if it exceeds 400 pounds

- **Pressure Vessels**
  - Vacuum enclosure to conform to Chapter 14 of SLAC document I-720-0A29Z-001
    - Specifically, it will conform to 10CFR851
Controls Requirements

- Requiring vendor to use actuators with existing EPICS drivers to the extent possible
- All controls software to be written in-house by LUSI Controls Group lead by Gunther Haller
  - Scanning
  - Software limits
  - Position feedback
  - Locking positions when system is aligned
Acquisition Plan

4 Statements of Work

- **Mirrors**
  - Meet all the requirements for the optics
  - Delivery time
    - 12 months

- **Mechanical System**
  - Meet all the mechanical requirements
    - Mirror support system
    - Mirror bender (if applicable)
    - Vacuum enclosure
    - Stand
  - Delivery time
    - 12 months

- **Coating**
  - Coating for the first strip only at first
  - Delivery time
    - 2 months

- **Metrology**
  - Independent in-process metrology and possibly metrology of end product
  - Duration of work
    - 2 months

Bid Process

- Submit Request for Proposals for
  - Mirrors
  - Mechanical System as a Design & Build Contract

- Encourage vendors to submit bid for both combined
  - Also accept bids for mirrors only and mechanical system only

- Evaluate the technical aspects of the bids

- Coating & Metrology will likely not be Request for Proposals
  - We plan on entering into an agreement with another lab (MOU) with proper capabilities
Acquisition Plan

Timeline

- Review the specs and the plan
  - Today
- Place Purchase order paperwork
  - October
- Wait for DOE approval (likely all the way to Oak Ridge due to high price tag)
  - November-January
    - During that time, we will refine our concepts for mounting the mirrors and perform more analysis to build confidence that the shape of the mirror substrates is adequate
- Submit Request for Proposals
  - February
- Evaluate proposals
  - February
- Award (if we have money)
  - March
- Design and Fabrication Phase
  - 16 months
  - Delivery in July 2010

We must start the procurement process very soon

- Since this is envisioned as a design-build contract, we can’t start the detailed design until we award the contract
Preliminary Design Reviews
- Detector Stage – September 2008
- Reference Laser – October 2008
- 1 micron Sample Chamber – December 2008
- Particle Injector – August 2009
- 1 micron KB System – October 2009
- 1 micron Instrument Stand – December 2009
- 0.1 micron KB System – October 2009
- 0.1 micron Sample Chamber – March 2010
- 0.1 micron Instrument Stand – May 2010
- Ion TOF – June 2010

Final Instrument Design Review – October 2009

Final Design Reviews
- Reference Laser – December 2008
- Detector Stage – May 2009
- 1 micron Sample Chamber – June 2009
- Particle Injector – December 2009
- 1 micron KB System – March 2010
- 1 micron Instrument Stand – March 2010
- 0.1 micron KB System – June 2010
- Ion TOF – July 2010
- 0.1 micron Instrument Stand – August 2010
- 0.1 micron Sample Chamber – October 2010

Project Ready for CD-3 - October 2009

Award PO
- 1 micron KB System – April 2009
- 0.1 micron KB System – July 2009
- 1 micron Sample Chamber – January 2010
- Detector Stage – January 2010
- Reference Laser – March 2010
- 1 micron Precision Instrument Stand – May 2010
- Particle Injector – May 2010
- Ion TOF – September 2010
- 0.1 micron Precision Instrument Stand – October 2010
- 0.1 micron Sample Chamber – February 2011

Receive
- 1 micron Sample Chamber – April 2010
- Reference Laser – May 2010
- Detector Stage – June 2010

Project Ready for CD-4 - April 2011

All dates are early finish
## CXI Critical Path

**Driving Milestones:**
LL Approval, CD-3 & CD-4

**KB Mirrors Design Effort**

**KB Mirrors Award & Vendor Design**

**Post Vendor Effort and Installation**

### Table: CXI Critical Path

<table>
<thead>
<tr>
<th>Activity ID</th>
<th>Activity Description</th>
<th>Total Float</th>
<th>Early Finish</th>
<th>Late Finish</th>
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<td>05/25/11</td>
<td>05/25/11</td>
</tr>
</tbody>
</table>

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**KB Mirrors Design Effort**

**KB Mirrors Award & Vendor Design**

**Post Vendor Effort and Installation**

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**LUSI Ultrafast Science Instruments**

S. Boutet (sboutet@slac.stanford.edu)
P. Montanez (montanez@slac.stanford.edu)
KB systems are “long duration procurement” items – requesting DOE long lead approval for 1μm KB system prior to CD-3

Critical path (through 1μm KB System) has 117d of schedule contingency
Status of Discussions with Vendors

- **JTEC** ([http://j-tec.co.jp/english/index.html](http://j-tec.co.jp/english/index.html))

  - **Point of Contact**
    - Makina Yabashi & Tsumura-sensei
  - **Mirrors only**
  - Started discussions in 2007
  - Originally, we thought they could build the full system
  - Have since told us they cannot build the mechanical system
    - They cannot meet our deadline
  - Demonstrated polishing capabilities, with Osaka University group, beyond everyone else
  - Recently produced a sub 100 nm focus with 400 mm mirrors
  - Reviewed our mirror specs
    - Are in full agreement with the specs
    - Say they require 12 months to finish the 2 mirrors
  - Provided a rough quote for 2 mirrors 6 months ago

- **Pros**
  - Make the best mirrors in the world
    - Demonstrated capabilities
  - Highly motivated because they will soon need to make the mirrors for the Japanese FEL
    - Very interested in making our mirrors as their prototype
      - We need to move fairly fast before they start work on the Japanese mirrors and lose interest in us
  - Will perform tests on mirrors at the kilometer-long beamline at SPRING8 as part of the contract
    - Direct performance characterization

- **Cons**
  - Expensive
  - Mirrors only
  - Long lead time
Zeiss

- Point of Contact
  - Helge Thiess
- Mirrors only
- Vendor of the LCLS HOMS mirrors
- Will guarantee only 2 nm rms height error
  - Reports of LCLS HOMS metrology indicate they have done better
- Provided a quote in September
- Willing to perform feasibility tests to reach 1 nm rms
  - Would cost us $21K
- Can meet all other specs
- Pros
  - Cheap
  - Relatively short lead time, based on LCLS experience
- Cons
  - Don’t meet our most critical specification
  - Mirrors only
Status of Discussions with Vendors

- InSync ([http://www.insyncoptics.com/index.html](http://www.insyncoptics.com/index.html))
  - Point of Contact
    - Tom Tenneson
  - Mirrors only
  - Reviewed the specs
  - No capabilities to make pre-figure ellipse
    - Would provide flat mirrors to be bent
  - Pros
    - Probably cheap
  - Cons
    - Flat mirrors only
    - Don’t meet our most critical specification
Status of Discussions with Vendors

- **SESO** ([http://www.seso.com/uk/infos.htm](http://www.seso.com/uk/infos.htm))
  - Point of Contact
    - JJ Ferme
  - Mirrors only
  - Reviewed the mirror specs
  - Can only guarantee 5 nm rms
  - Said they would study this some more
  - Not replying to emails lately

- **Crystal Scientific** ([http://www.crystal-scientific.com/](http://www.crystal-scientific.com/))
  - Point of Contact
    - Simon Cockerton
  - Mirrors only
  - Had a phone conversation in July 2008
  - Sent the specs by email
  - No response to multiple emails since

- **Tinsley** ([http://www.asphere.com/](http://www.asphere.com/))
  - Point of Contact
    - Clay Sylvester
  - Reviewed the specs and they are not interested
Status of Discussions with Vendors

- **Accel** ([http://www.accel.de/](http://www.accel.de/))
  - **Point of Contact**
    - Riccardo Signoratto
  - **Interested in entire system**
    - Mirrors sub-contracted to outside firm
  - **Had multiple phone conversations with them**
  - **Concerned with difficult mechanical specs**
    - Would like to discuss reduced deliverables with incentives for ultimate specs
  - **Collaborators with JTEC and Osaka people for many years**
    - Would be interested in testing the whole system at km beamline
    - Could purchase the mirrors directly from JTEC and take responsibility for complete system
      - Except for coating

- **Pros**
  - Full system
  - Years of experience with KBs
  - Good relationship with JTEC
  - Open to multiple sources for mirrors

- **Cons**
  - Want to share the risks with us with reduced deliverables
    - That’s understandable
WinlightX (http://www.winlightx.com/)

- Point of Contact
  - Olivier Hignette
- Interested in entire system
- Provided quote for full system
  - Without coating
- Many years of experience with KB optics when he was at ESRF
- Started this new small company
- Claims he can make his own mirrors with 1 nm rms height error
- Sounds like we would be his first clients
- Agrees with the specs

Pros
- Full system
- Years of experience building KB systems
- Open to any mirror vendor
  - But prefers to make his own
- Cheap

Cons
- New company
Status of Discussions with Vendors

  - Point of Contact
    - Scott Mowat
  - Full system
  - Mirrors only from SESO
    - SESO cannot meet our figure specs

- **ADC** ([http://www.adc9001.com/](http://www.adc9001.com/))
  - Point of Contact
    - Alex Dehim
  - Mirror mechanics only
  - Have never built a KB system
  - Say they would license a design from someone else
  - Claim they can meet all the specs
  - Have a dubious reputation
Vendor Selection Process

Selection Process

- Panel of experts will review all aspects, other than costs, of the vendor proposals
  - Panel to include
    - CXI Instrument Scientist
    - CXI Lead Engineer
    - A few internal and external experts
- Independent evaluation by each reviewer
- Cursory search for major weaknesses
  - Totally deficient proposals may be eliminated at this point
- Submit initial evaluations to Chairman
- Meeting after initial review
  - Discuss until a consensus is reached
- Chairman with Purchasing Department will evaluate the cost aspects of the proposals
  - Panel is not involved in this
- All communications with vendors done through Chairman
  - Ensures communication is sent to all vendors at the same time
- Proposals reevaluated after receipt of any responses to Panel questions

Evaluation Criteria

- Only technical aspects to be rated by the panel
- No costs
## Vendor Selection Process

### Evaluation Standards Guide Sheet

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Max</th>
<th>Excellent</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
<th>Unacceptable</th>
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<tbody>
<tr>
<td>Compliance With Technical Requirements &amp; Specifications</td>
<td>45</td>
<td>40-45</td>
<td>30-39</td>
<td>20-29</td>
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<td>10-12</td>
<td>7-9</td>
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<td>Personnel, Experience, Facilities</td>
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</tbody>
</table>

**Excellent** - comprehensive and complete; meets or exceeds all RFP requirements; exemplifies complete understanding of the requirements; and demonstrates in detail how to accomplish the task.

**Good** - generally meets or exceeds RFP requirements; omissions are of minor consequence or small; would be likely to produce an acceptable end item.

**Fair** - omissions are of significance, but are correctable; substantiation of points is weak or lacking; probability of successful effort is marginal.

**Poor** - gross omissions; failure to understand problem areas; failure to respond to requirements; little or no chance of success in completing the end item.

**Unacceptable** - does not meet the specifications.
Summary

Only a few valid options have been identified
- Accel mechanics with JTEC mirrors
  - Can be arranged as a single contract through Accel
- WinlightX complete system
- WinlightX or Accel mechanics with Zeiss mirrors
  - Zeiss does not meet the specs but they are cheaper

Preferred option
- Accel with JTEC mirrors as a single design-build contract
  - KB experience
  - Characterization of the complete setup using X-rays
- MOU with other labs for coating and independent metrology

Need to get approval to proceed with procurement so the design by the vendor can start as soon as possible
- A few months earlier is a big deal at LCLS since there will be only 1 hard x-ray instrument operational
- Mirrors have a long lead time and we cannot wait until the mechanical design is complete to order them
- We believe a monolithic Si block with strain relief features can meet the specs and should be ordered in early 2009