LCLS-II KB Mirror Systems: Technical Challenges and Solutions
(Practice of Design Optimization)

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LCLS: Linac Coherent Light Source
LCLS vs. LCLS-II

14 GeV LCLS Linac used for x-rays up to 25 keV

1.0 - 25 keV (120 Hz, “copper” Linac)
LCLS vs. LCLS-II

South side source:
- 1.0 - 25 keV (120 Hz, “copper” Linac)
- 1.0 - 5 keV (≥100 kHz, SC Linac)

North side source:
- 0.2-1.2 keV (≥100 kHz, SC Linac)

4 GeV SC Linac in sectors 0-10
14 GeV LCLS Linac used for x-rays up to 25 keV

LCLS: Linac Coherent Light Source

MEDSI 2016, Sept. 11-19, 2016, L. ZHANG
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### Table: LCLS-I Vs. LCLS-II

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#### 4 GeV SC Linac in sectors 0-10

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#### South side source:
- 1.0 - 5 keV (≥ 100 kHz, SC Linac)

#### North side source:
- 0.2-1.2 keV (≥ 100 kHz, SC Linac)

**Baselines:**
- LCLS-I
- Now

**HXU - Cu**
- 400 - 25,000
- 1000 - 5000

**HXU - SC**
- 200 - 1300

**SXU - SC**
- 250 - 6000

**SXU – Cu (TBC)**

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### LCLS vs. LCLS-II

**South side source:**
- 1.0 - 5 keV \((\geq 100\) kHz, SC Linac\)
- 1.0 - 25 keV \(120\) Hz, “copper” Linac)

**North side source:**
- 0.2-1.2 keV \(\geq 100\) kHz, SC Linac\)

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X-ray instrument plans for LCLS-II

- 7 instruments fed by a single undulator at present
- 9 instruments available for LCLS-II

- NEH 1.1: Atomic, Molecular and Optical
- NEH 2.1: Resonant Inelastic X-ray Scattering
- NEH 2.2: Soft X-ray Research
- NEH 1.2: Tender X-ray Instrument
- XPP: X-ray Pump Probe
- XCS: X-ray Correlation Spectroscopy
- MFX: Macromolecular Femtosecond Crystallography
- CXI: Coherent X-ray Imaging
- MEC: Matter in Extreme Conditions

- SXU
- HXU

- 3 Soft X-ray
- 1 “tender” x-ray
- 5 Hard X-ray
KB mirror systems for Soft and Tender X-ray

NEH 1.1
- High Flux Soft X-ray
- Bendable K-B Pair — 1 μm
- Fixed Figure K-B Pair — 300nm
- 250-1300 eV

NEH 1.2
- Tender X-ray Instrument
- SXR Bendable K-B Pair — 1 μm
- HXR Bendable K-B Pair — 1 μm
- 400-6000 eV

NEH 1.2
- Tender X-ray Instrument
- SXR Bendable K-B Pair — 1 μm
- HXR Bendable K-B Pair — 1 μm
- 400-6000 eV

NEH 2.1
- RIXS
- Bendable K-B Pair — 2x10μm
- 250-1350 eV

NEH 2.2
- Mono Soft X-Ray
- Bendable K-B Pair — 1x4 μm
- 250-1350 eV

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KB mirror systems for Soft and Tender X-ray

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NEH 2.2
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→ 6 pairs of KB mirror systems
Some properties of XFEL, optics requirements

- Nearly monochromatic beam (especially with self-seeding)
  - K-B mirrors absorbs ~ 10% XFEL beam power, → to be actively cooled
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- Nearly monochromatic beam (especially with self-seeding)
  - K-B mirrors absorbs ~ 10% XFEL beam power, \( \rightarrow \) to be actively cooled

- Fully coherent photon beam \( \rightarrow \) Wavefront preservation
  - 2*FWHM beam size needed

\[
\theta = 14 \text{ mrad}
\]

\[
\begin{align*}
\text{Unfocussed beam} & \quad 2 \text{ FWHM accept.} & \quad 1 \text{ FWHM accept.}
\end{align*}
\]
Some properties of XFEL, optics requirements

- Nearly monochromatic beam (especially with self-seeding)
  - K-B mirrors absorb ~ 10% XFEL beam power, → to be actively cooled

- Fully coherent photon beam → Wavefront preservation
  - 2*FWHM beam size needed

- Shape error requirement (SR ≥ 0.97)

![Diagram showing beam properties](image-url)
LCLS-II K-B mirror system

- Dynamically bendable
- Water cooled

WEPE33  KB Mirror Design for the LCLS-II
SXR Beam Line

FRBA04  LCLS-II KB Mirror Systems:
Technical Challenges and Solutions
KB mirror system, technical challenges

- Kirkpatrick-Baez (K-B) mirror configuration

- Ellipsoidal shape

- Technical challenges
  - Large Acceptance $\Rightarrow$ Long mirror
  - Variable Source & Focal Points $\Rightarrow$ Bendable Mirror
  - **Sub Nanometer Shape Error** $\Rightarrow$ Limited Suppliers
  - High Demagnification $\Rightarrow$ Tight Bending (stress issues, …)
  - Few tenth nrad residual bending error $\Rightarrow$ **Variable Mirror Width**
  - High Thermal Loads & Variable Footprint $\Rightarrow$ **Innovated Cooling**
  - Minimize the coupling between the mirror Bending & Cooling
Technical challenges

- Large Acceptance → Long mirror
- Variable Source & Focal Points → Bendable Mirror
- Sub Nanometer Shape Error → Limited Suppliers
- High Demagnification → Tight Bending (stress issues, …)

**Sub-μrad residual bending error → Variable Mirror Width**

- High Thermal Loads & Variable Footprint → Innovated Cooling
- Minimize the coupling between the mirror Bending & Cooling
Mirror profile optimization

- **Width profile defined by Bending Equation (BE)**

$$w(x) = \frac{12M(x)}{Et^3} R(x)$$

$$z(x) = \frac{\sin \theta(p+q)}{4pq+(p-q)^2 \cos^2 \theta} \times \left\{2pq-2[pq]^2-pqx^2-xpq(p-q)\cos \theta\right\}^{1/2} - x \cos \theta(p-q)$$

- **Residual Slope Error (RSE):**

$$\Delta \text{slope} = \text{slope} - \text{slope}_{\text{ellipse}}$$

$$F_1 = F_2 = 60 \text{ N}$$

$$F_1 = 62.92 \text{ N}$$

$$F_2 = 63.58 \text{ N}$$

- **Limitation of the analytical formula (Beam theory approximation)**
Mirror profile optimization

FE model with bending forces (VFM)

ANSYS Release 16.0
AUG 4 2015
08:31:00
ELEMENTS
/EXPANDED
PowerGraphics
EFACET=1
F

LCLS-II KB mirror: VFM, Fin=60, Fout=60 N, Ndxc=8, i=5

Silicon crystal orientation
(low stress & bending force)
- Mirror optical surface // Si (110) plan
- Tangential-axis // [001]

Optimized Mirror Profile (VFM, q=2m)

- L. Zhang, SMEXOS (2009), Grenoble, France
Optimized Mirror Profile – bending performance

Following effects to be taken into account

- Bender stiffness (not negligible)
- Anticlastic-bending effects
- Anisotropy of the Si crystal
- Geometrical non-linear effects in the simulation
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\[
\text{RMS}_{\Delta \text{slope}} \quad \text{(reduction factor: } \sim 10^4) \\
\begin{align*}
\text{43.7 } \mu\text{rad} & \quad \text{(with the profile defined by BE)} \\
\text{0.005 } \mu\text{rad} & \quad \text{(with the optimized profile by FEA)}
\end{align*}
\]

\[
\text{RMS}_{\Delta \text{slope-opt}} / \text{slope}_{PV-ellipse} \sim 2 \times 10^{-6}
\]
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- Sub-µrad residual bending error $\rightarrow$ Variable Mirror Width

- High Thermal Loads & Variable Footprint $\rightarrow$ Innovated Cooling
- Minimize the coupling between the mirror Bending & Cooling
Final cooling design

- Contact (Top-up-side), one single length water cooling based on SSRL designs for contact cooled mirror

Silicon intermediate Blocks (SiB)

Contact surface with mirror at a nominal gap (50µm) of GaIn

Cu cooling Block (CuB)

Bonded contact interface with GaIn or Indium foil

based on SSRL designs for contact cooled mirror
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Preliminary Design Review of the KB mirrors for LCLS-II SXR
August 27, 2015, L. Zhang & D. Morton
Mirror cooling design – 3 schemes

➢ Top-up-side water cooling

1. Single-length cooling

- L. Zhang et al., SRI 2015 Conference
Mirror cooling design – 3 schemes

- **Top-up-side water cooling**

1. Single-length cooling

   ![Diagram of single-length cooling](image)

2. Variable-length cooling

   ![Diagram of variable-length cooling](image)

- L. Zhang et al., *SRI 2015 Conference*
Mirror cooling design – 3 schemes

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Mirror cooling design – 3 schemes

1. Single-length cooling

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3. Electric heater + Single-length cooling

\[ RMS_{\text{thermal}} : = f \left( L_{\text{heater}}, P_{\text{aheater}}, x \right) \]

- L. Zhang et al., *SRI 2015 Conference*
Mirror cooling design – performance

- LCLS-II SXR K-B mirrors
  - For 20 W of XFEL beam power, full-length (top-up-side) cooling is sufficient
  - For 200 W of XFEL beam power, optimal, variable-length cooling is needed
Mirror cooling design – performance

LCLS-II SXR K-B mirrors
- For 20 W of XFEL beam power, full-length (top-up-side) cooling is sufficient
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Resistive Element Adjustable Length
REAL Cooled Optics
(DoE funded R&D project, 2017-2018 FY)
Technical challenges

- Large Acceptance $\Rightarrow$ Long mirror
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- Sub Nanometer Shape Error $\Rightarrow$ Limited Suppliers
- High Demagnification $\Rightarrow$ Tight Bending (stress issues, $\ldots$)
- Sub-µrad residual bending error $\Rightarrow$ Variable Mirror Width
- High Thermal Loads & Variable Footprint $\Rightarrow$ Innovated Cooling

- Minimize the coupling between the mirror Bending & Cooling
  - Minimization of mechanical constraint effects of Eutectic GaIn as thermal interface (*presented* WEBA02)
  - Bend cooling blocks (design optimization practice)
Cooling blocks bending and translation

Single pusher: bending + translation

$F$

$y$

$x$

$k_1$

$F$

$bending + translation$

$k_2$

Flexor (spring) support
Cooling blocks bending and translation

Single pusher: bending + translation

$F$

$k_1$

Flexor (spring) support

$k_2$

KB mirrors for LCLS-II SXR beamline - progress report
Jan 25, 2016
Cooling blocks bending and translation

- Cooling block bent shape: \( y_{\text{CB}}(x, F, k_1, k_2) \)
- Mirror shape (ideal ellipse): \( y_{\text{mir}}(x, q) \)
- For given value of \( F, k_1, k_2, q \)
  - Minimization:
    - \( dU_y(x) = y_{\text{CB}}(x) - y_{\text{mir}}(x) \)
  - \( dU_y(x) \rightarrow \text{RMS, } d_{pv} \)
  - \( d_{pv} < 5 \, \mu\text{m} \)
Cooling block bent shape:

\[ y_{CB}(x, F, k_1, k_2) \]

Mirror shape (ideal ellipse):

\[ y_{mir}(x, q) \]

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  \[ dU_y(x) = y_{CB}(x) - y_{mir}(x) \]
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Objective function:

\[ f(F, k_1, k_2, q) \]

\( d_{pv} < 5 \mu m \)
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- Objective function: \( f(F, k_1, k_2, q) = RMS * d_{pv} \)

\( d_{pv} < 5 \mu m \)
1 pusher: $F$
2 flexor supports: $k_1$, $k_2$
- $F$: 6 ~ 10 N
- $k_1 = 52.93$ N/mm, $k_2 = 48.15$ N/mm

Uniform cross section

KB mirrors for LCLS-II SXR beamline - progress report
February 8, 2016
Cooling blocks: single pusher + elastic supports

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2 flexor supports: \( k_1, k_2 \)

- \( F \): 6 \( \sim \) 10 N
- \( k_1 = 52.93 \text{ N/mm} \), \( k_2 = 48.15 \text{ N/mm} \)
Flexor Supports

Stainless steel thin blade

\[ k = \frac{192EI}{L^3} = 16Ew\left(\frac{t}{L}\right)^3 \]

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<tr>
<th></th>
<th>(k_1)</th>
<th>(k_2)</th>
<th>(\Delta%)</th>
<th>(\Delta_0)</th>
<th>(\Delta_{\text{req}})</th>
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<tr>
<td>target</td>
<td>52.93</td>
<td>48.15</td>
<td>1%</td>
<td>(mm)</td>
<td>(mm)</td>
</tr>
<tr>
<td>(E) (N/mm²)</td>
<td>2.00E+05</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(t) (mm)</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3%</td>
<td>(0.0006)</td>
<td>±0.01</td>
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<tr>
<td>(L) (mm)</td>
<td>20</td>
<td>20</td>
<td>0.3%</td>
<td>0.06</td>
<td>±0.05</td>
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<tr>
<td>(w) (mm)</td>
<td>16.54</td>
<td>15.05</td>
<td>1%</td>
<td>0.150</td>
<td>±0.1</td>
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- Width \(w\) (add 10% to initial values) can be adjusted (re-machined) to fit exact \(k\)-values
- \(1\%\) accuracy for the values of \(k_1, k_2\) should be achievable
Cooling blocks: translation + rotation
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\[ dU_y(x) = y_{CB}(x) - y_{mir}(x) \]
Cooling blocks: translation + rotation

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Summary

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- Variable Source & Focal Points → Bendable Mirror
- Sub Nanometer Shape Error → Limited Suppliers
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**LCLS-II K-B mirror system**
- Dynamically bendable
- Water cooled

**Prototype testing**
- 2016 Q4

**Final KB mirror system**
- Mirror procurement 2017 Q1
- Mechanics procurement 2017 Q2
- Delivery 2018 Q1
- Assembly, Metrology and Tests 2018 Q2
- Installation & commission 2018 Q3
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