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LCLS-II KB Mirror Systems: Technical Challenges and Solutions

(Practice of Design Optimization)

***L. Zhang**, D. Cocco, N. Kelez, D.S. Morton*

LCLS, SLAC National Accelerator Laboratory

2575 Sand Hill Road, Menlo Park, CA, 94025, United States

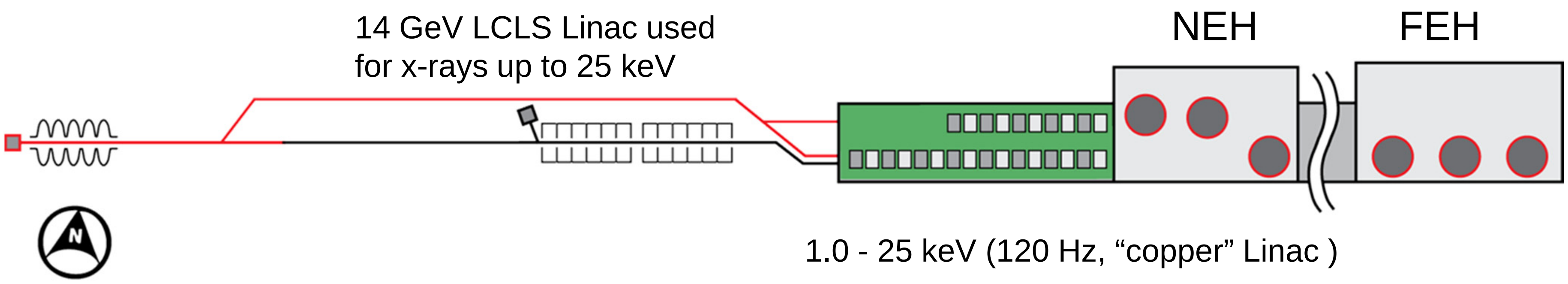
zhanglin@slac.stanford.edu

U.S. DEPARTMENT OF ENERGY
Office of Science

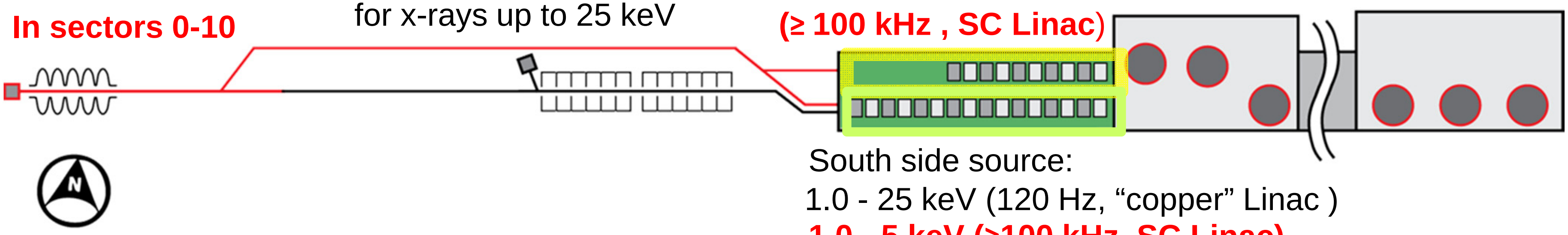
SLAC NATIONAL ACCELERATOR LABORATORY

LCLS: Linac Coherent Light Source

LCLS vs. LCLS-II



LCLS vs. LCLS-II



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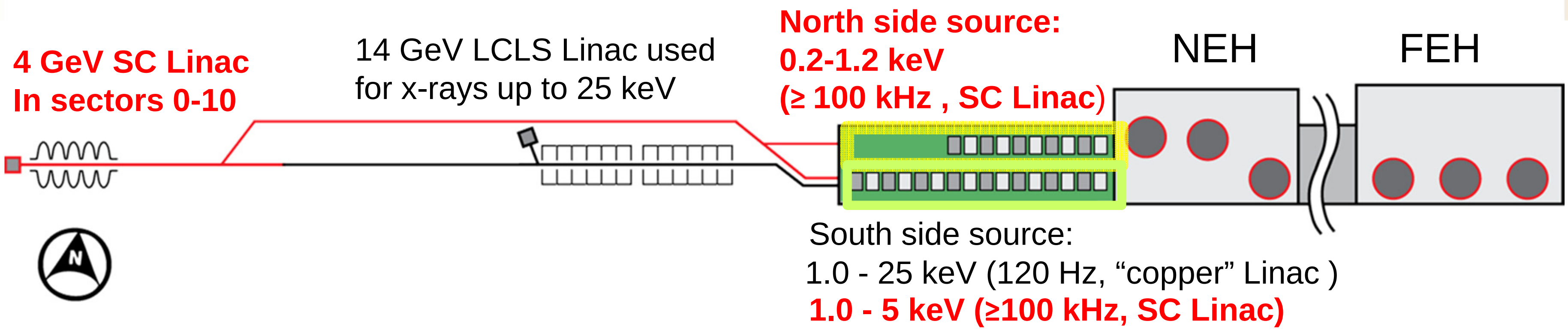
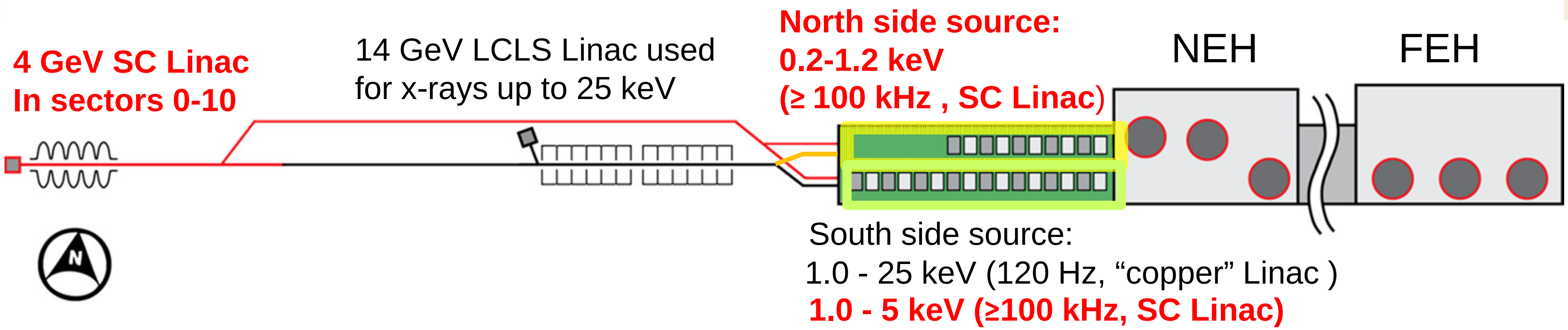


	LCLS-I Baseline	Now	HXU - Cu	HXU - SC	SXU - SC	SXU – Cu (TBC)
Photon Energy Range (eV)	800 - 8,000	250 - 12,800	400 - 25,000	**1000 - 5000**	**200 - 1300**	250 - 6000
Repetition Rate (Hz)	120	120	120	**929,000**	**929,000**	120
Per Pulse Energy (mJ)	~ 2	~ 4	~ 4	**~ 0.2**	**~ 2**	~ 8
Maximum average power (W)	0.24	0.48	0.48	**200**	**600**	0.96
Photons/Second	~ 10^{14}	~ 10^{14}	~ 10^{14}	**~ 10^{16}**	**~ 10^{17}**	~ 10^{14}

LCLS vs. LCLS-II



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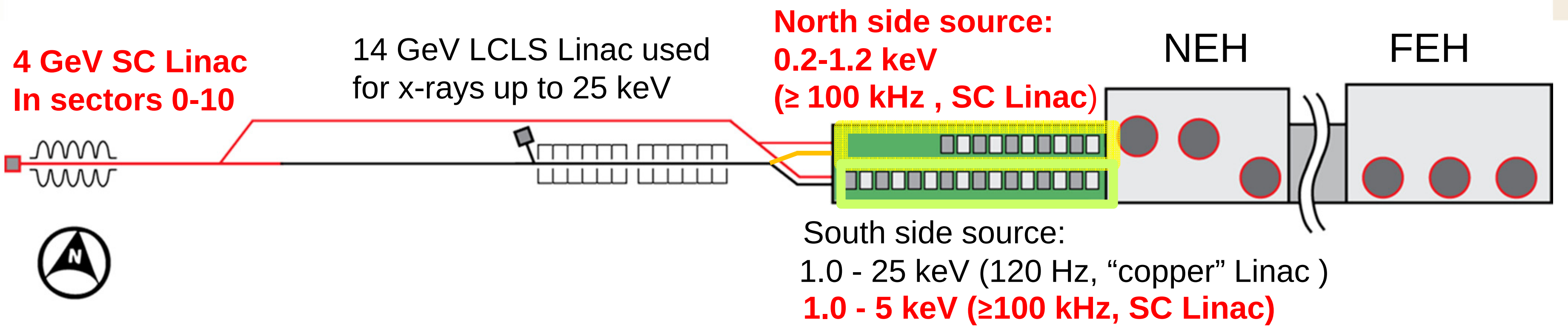

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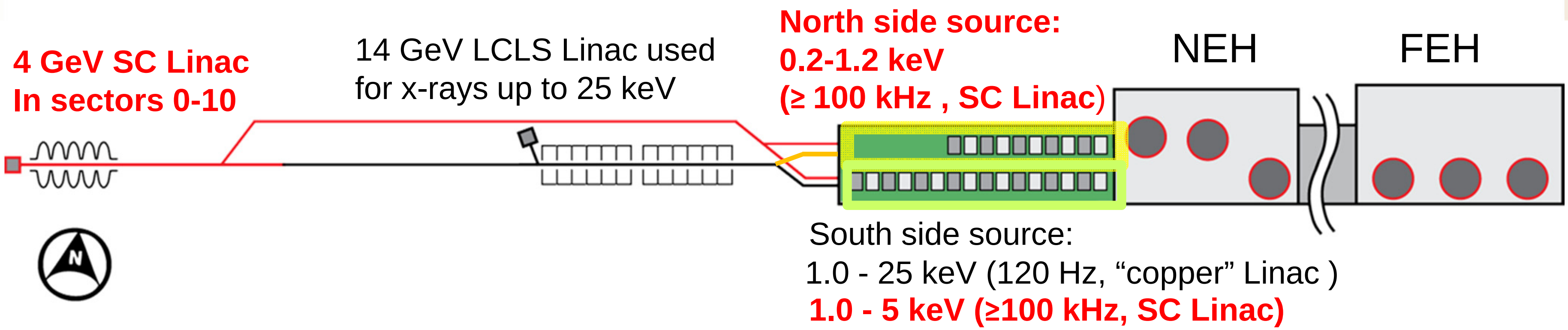
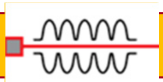
LCLS vs. LCLS-II

SLAC





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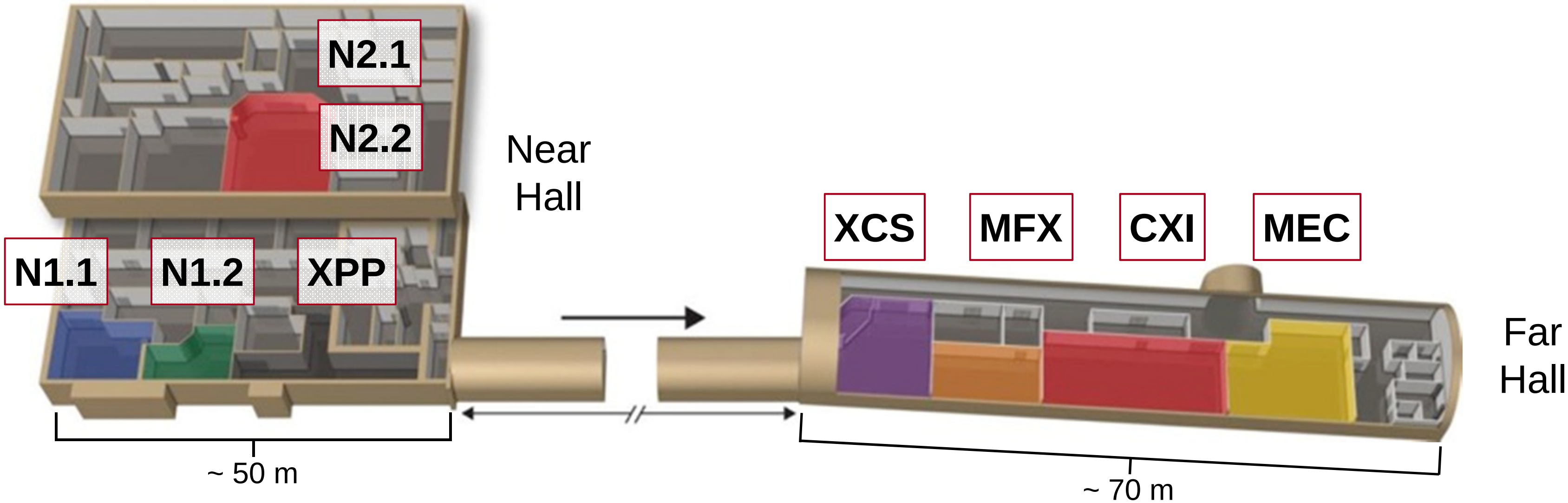
X-ray instrument plans for LCLS-II

- **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 → NEH 1.1, NEH 2.1, NEH 2.2, NEH 1.2

HXU → NEH 1.2, XPP, XCS, MFX, CXI, MEC

NEH 1.1, NEH 2.1, NEH 2.2: 3 Soft X-ray

NEH 1.2: 1 “tender” x-ray

XPP, XCS, MFX, CXI, MEC: 5 Hard X-ray

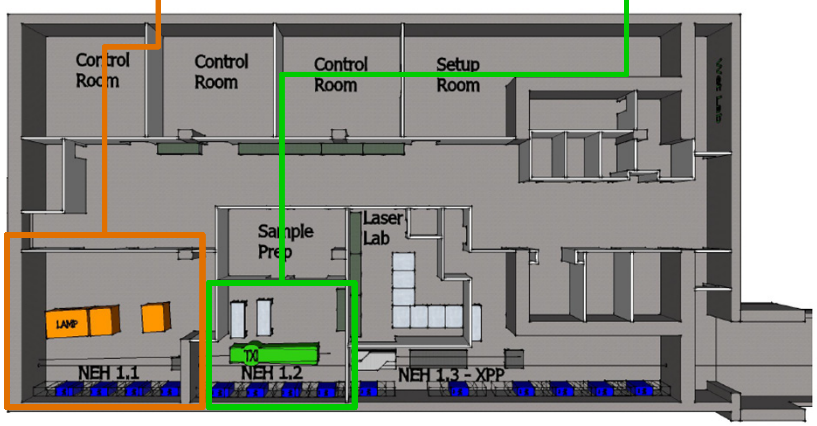
KB mirror systems for Soft and Tender X-ray

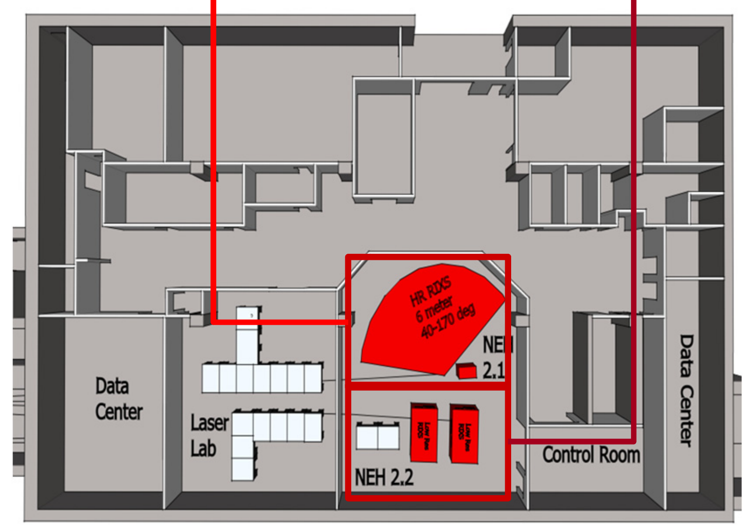
NEH 1.1
- High Flux Soft X-ray
- **Bendable K-B Pair**
  - 1 μm
- **Fixed Figure K-B Pair**
  - 300nm
- 250-1300 eV

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 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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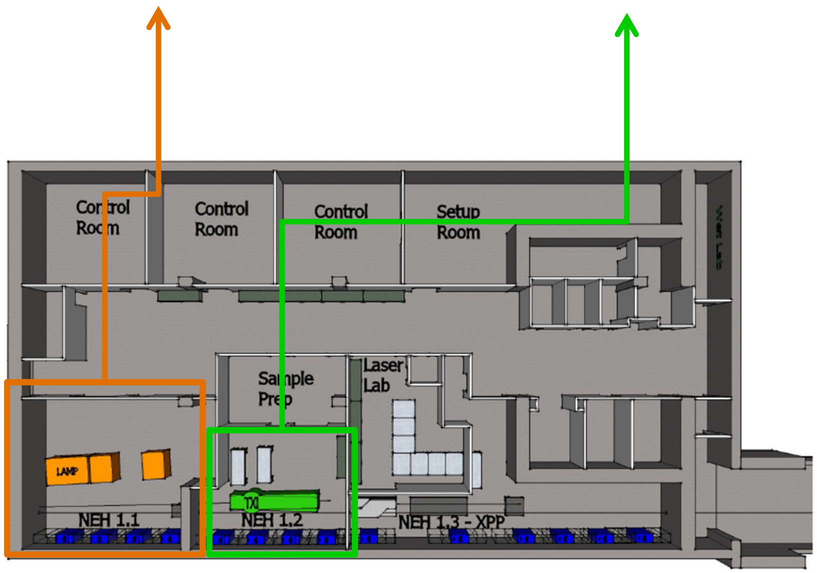

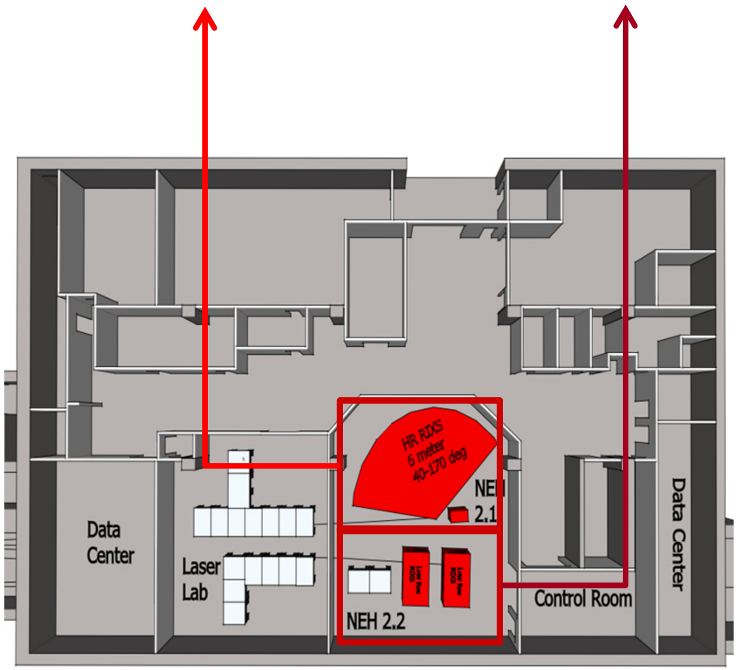

→ 6 pairs of KB mirror systems

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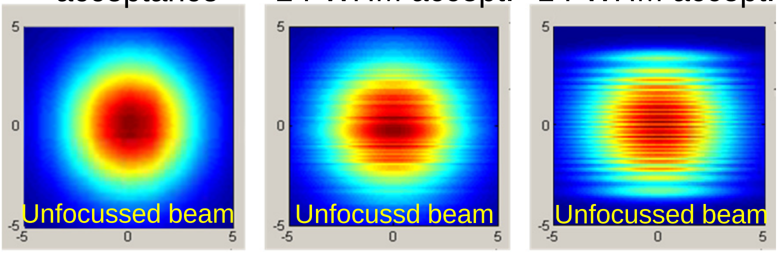
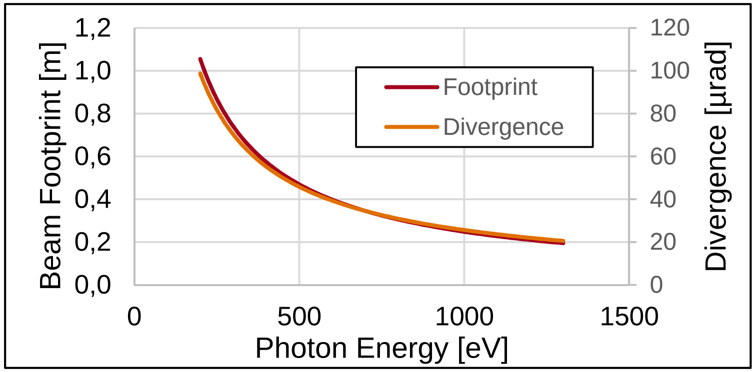
- **Fully coherent photon beam → Wavefront preservation**
  - **2*FWHM beam size needed**

∞ acceptance 2 FWHM accept. 1 FWHM accept.



θ=14 mrad



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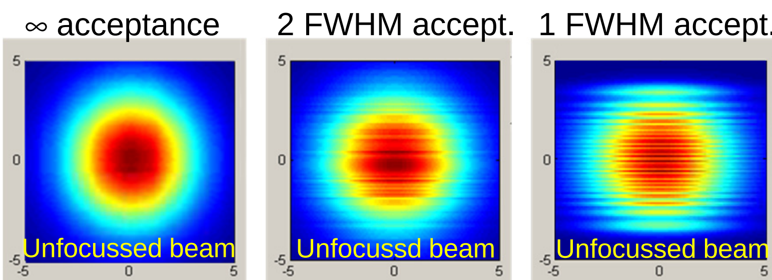

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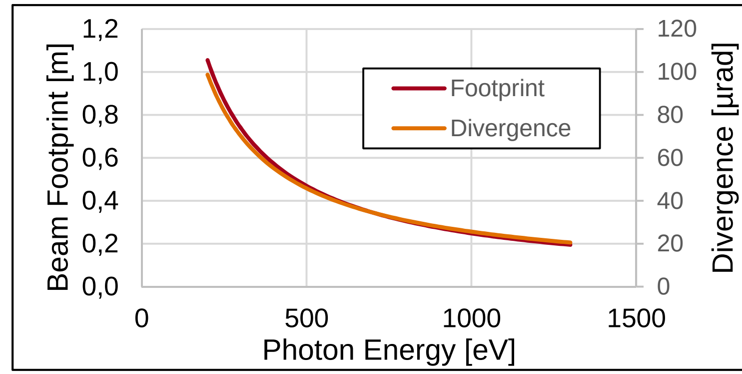
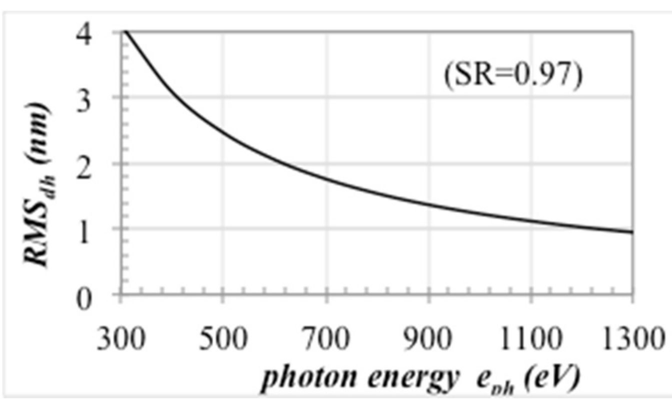
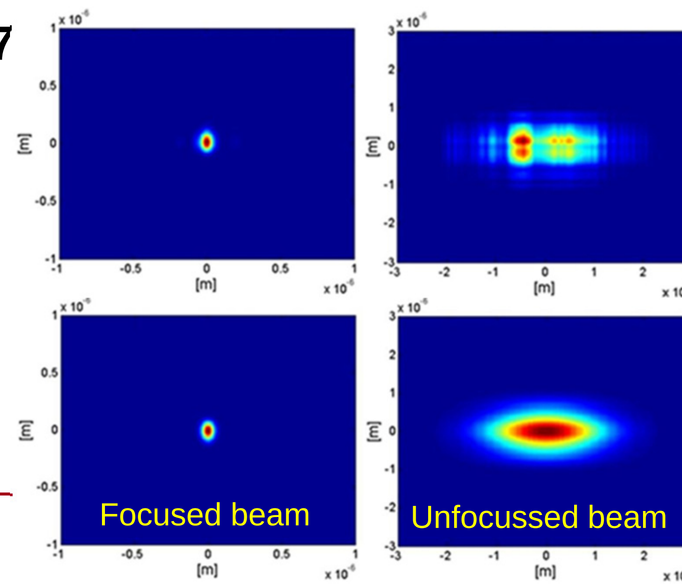


  - **Shape error requirement (SR ≥ 0.97**

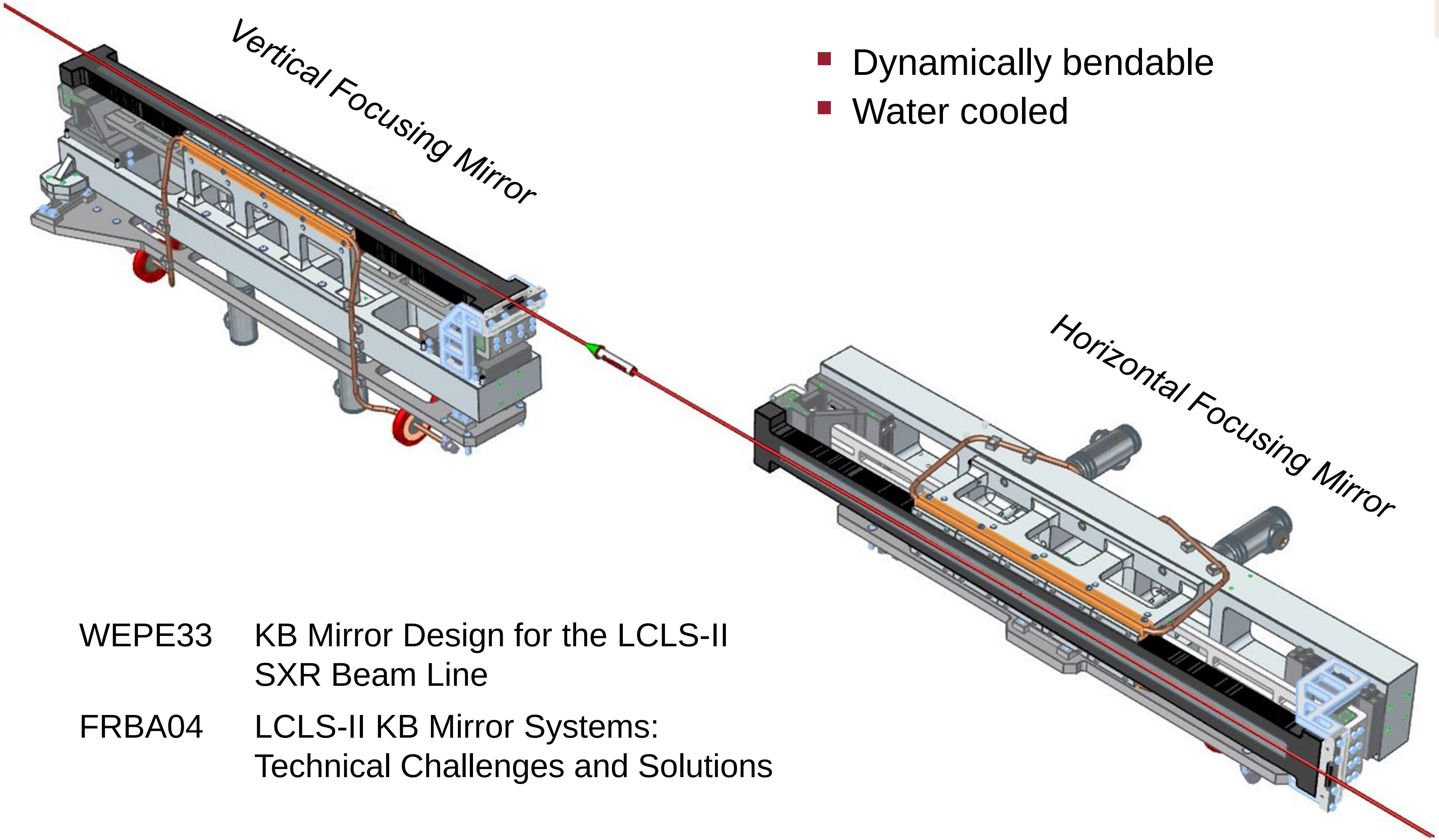




SR=0.80

SR=0.97

LCLS-II K-B mirror system

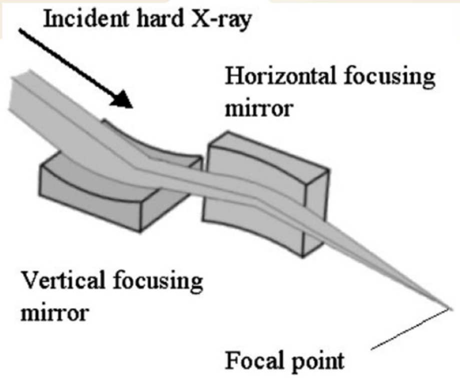


- Dynamically bendable
- Water cooled

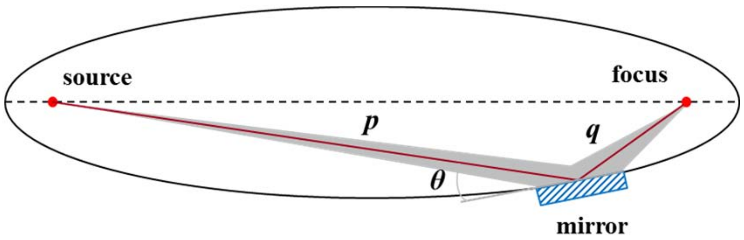
WEPE33	KB Mirror Design for the LCLS-II SXR Beam Line
FRBA04	LCLS-II KB Mirror Systems: Technical Challenges and Solutions

KB mirror system, technical challenges

- Kirkpatrick-Baez (K-B) mirror configuration



- Ellipsoidal shape



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

Technical challenges

SLAC

- 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
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Mirror profile optimization

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

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

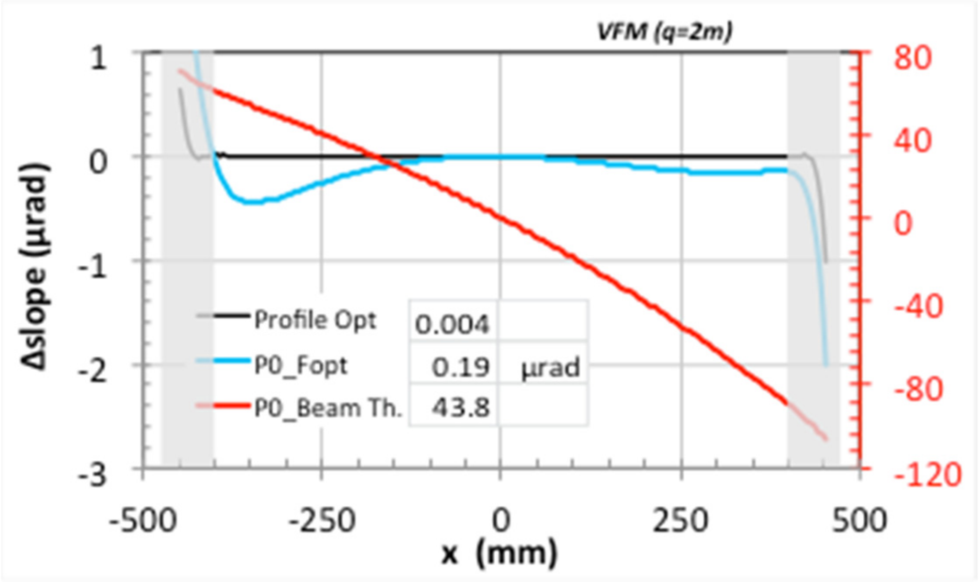
$$z(x) = \frac{\sin\theta(p+q)}{4pq + (p-q)^2 \cos^2\theta} \times \{2pq - 2[(pq)^2 - pqx^2 - xpq(p-q)\cos\theta]^{1/2} - x\cos\theta(p-q)\}$$

Residual Slope Error (RSE) :

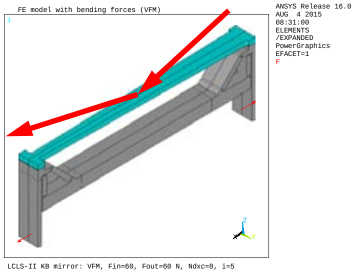
$\Delta slope = slope - slope_{ellipse}$

$F_1 = F_2 = 60$ N

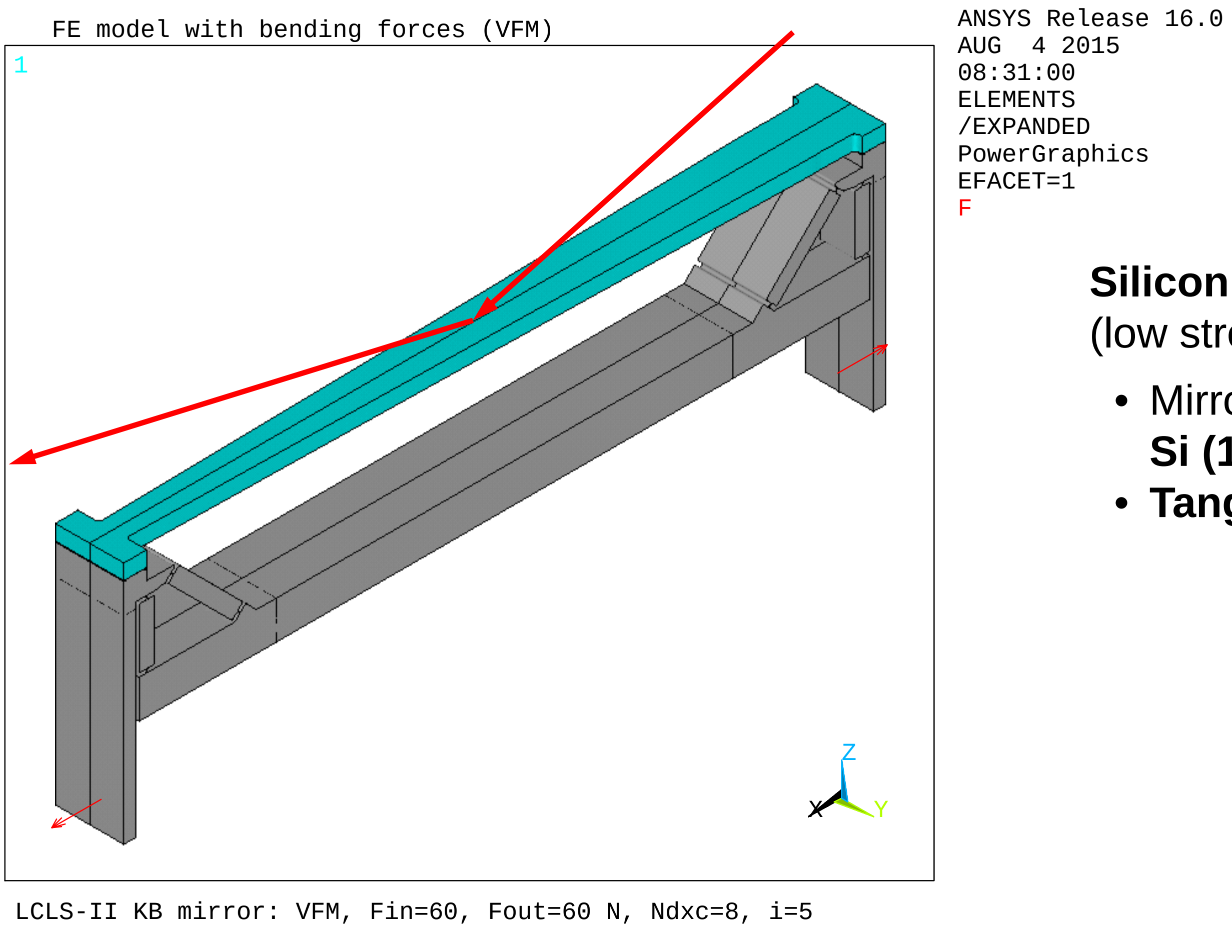
$F_1 = 62.92$ N
$F_2 = 63.58$ N



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

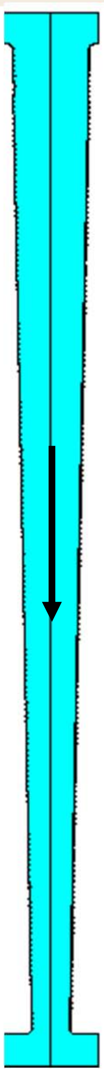


Mirror profile optimization



Silicon crystal orientation
(low stress & bending force)

- Mirror optical surface *//* **Si (110)** plan
- **Tangential-axis *//* [001]**

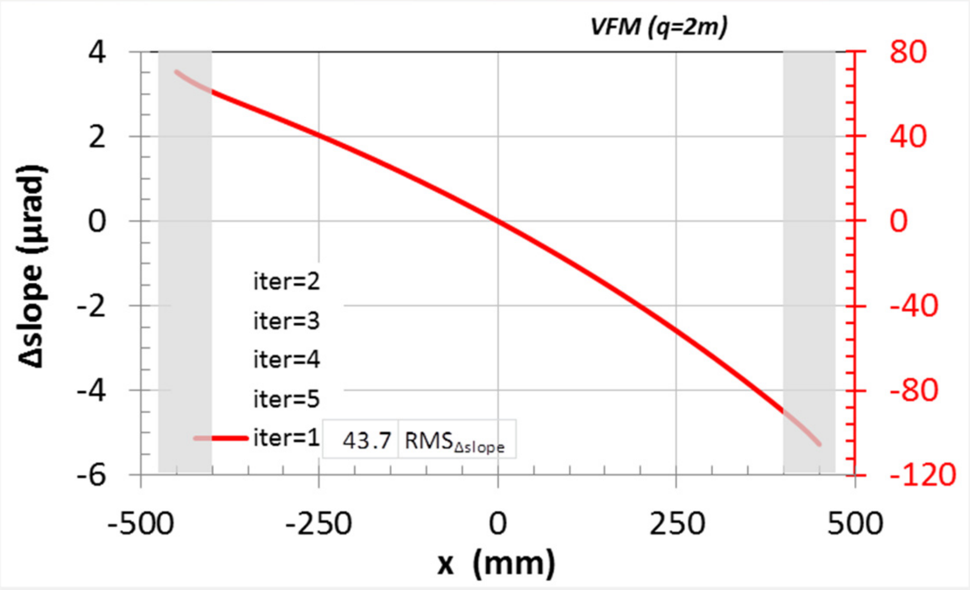


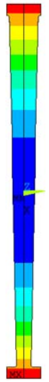
- *L. Zhang, **SMEXOS** (2009), Grenoble, France*
- *L. Zhang et al., **AIP Conference Proceedings** 1234, 801 (2010); doi: 10.1063/1.3463335*

Optimized Mirror Profile (VFM, q=2m)

V_{201505}

Optimized Mirror Profile – bending performance



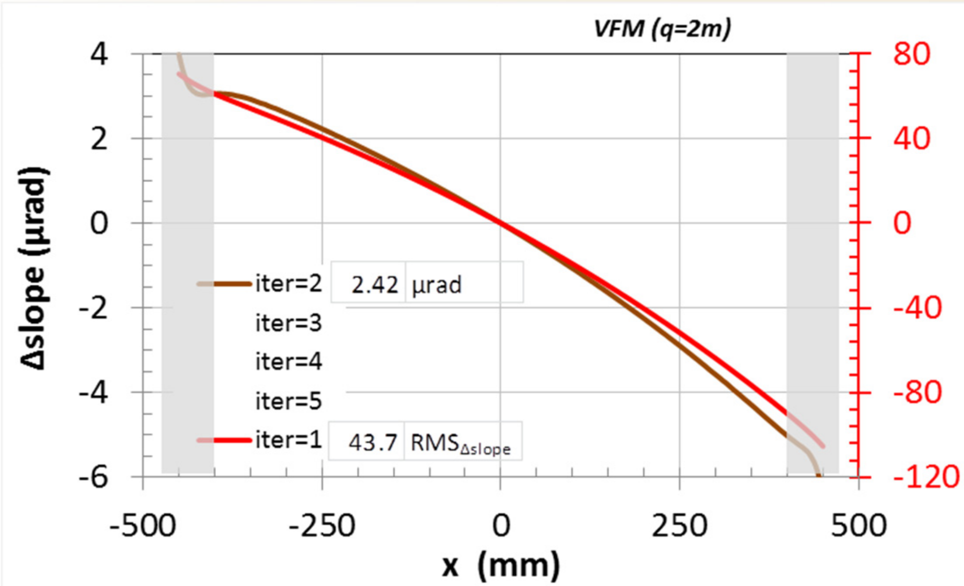


iter=1

→ **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

Optimized Mirror Profile – bending performance



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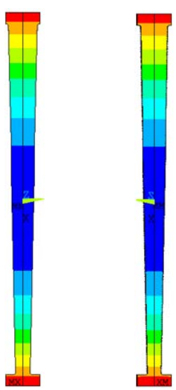
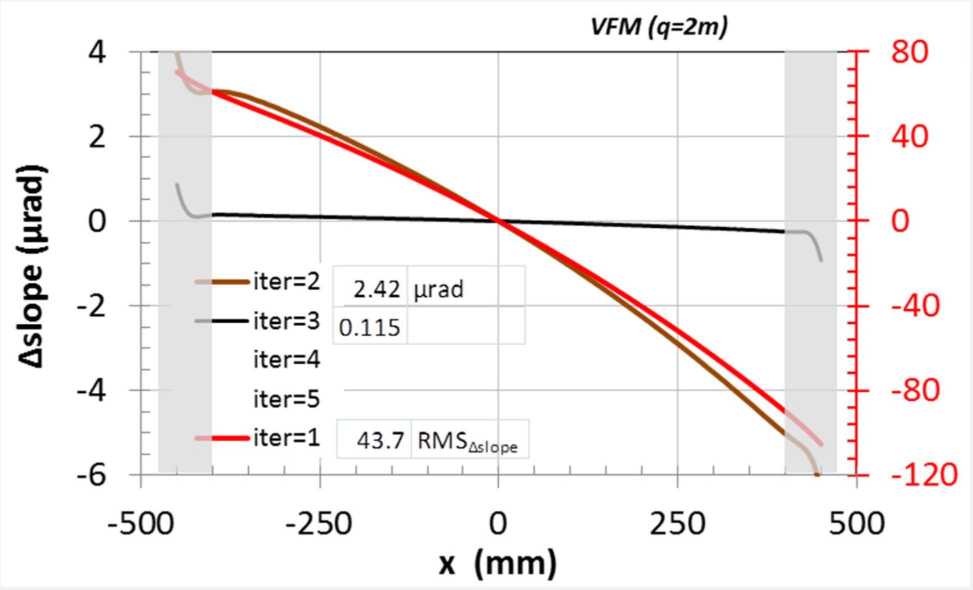


iter=1 iter=2

Optimized Mirror Profile – bending performance



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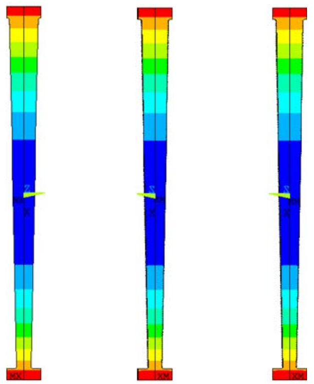
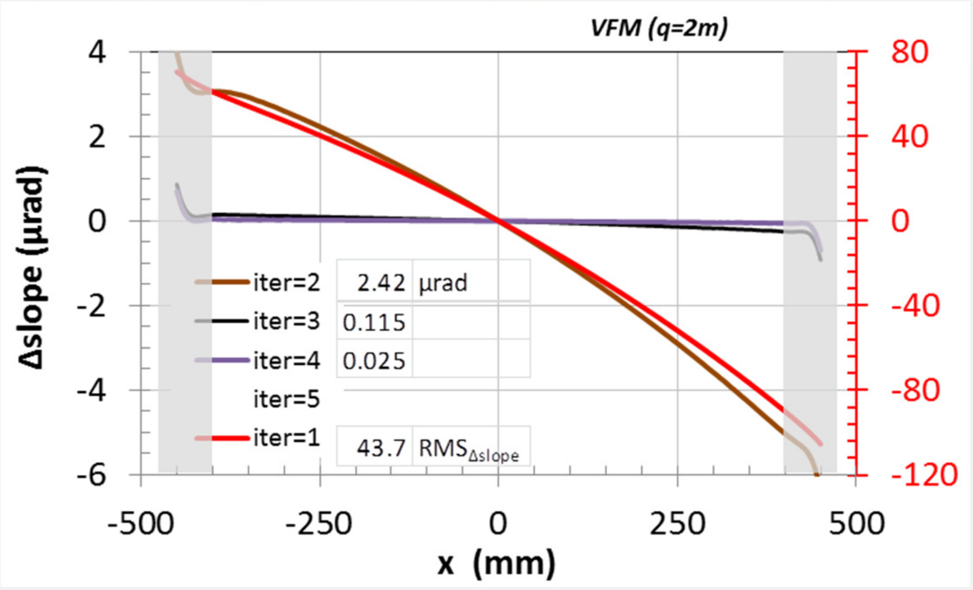


iter=1 iter=2 iter=3

Optimized Mirror Profile – bending performance

SLAC



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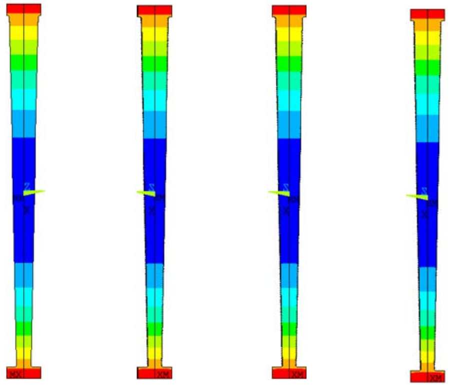
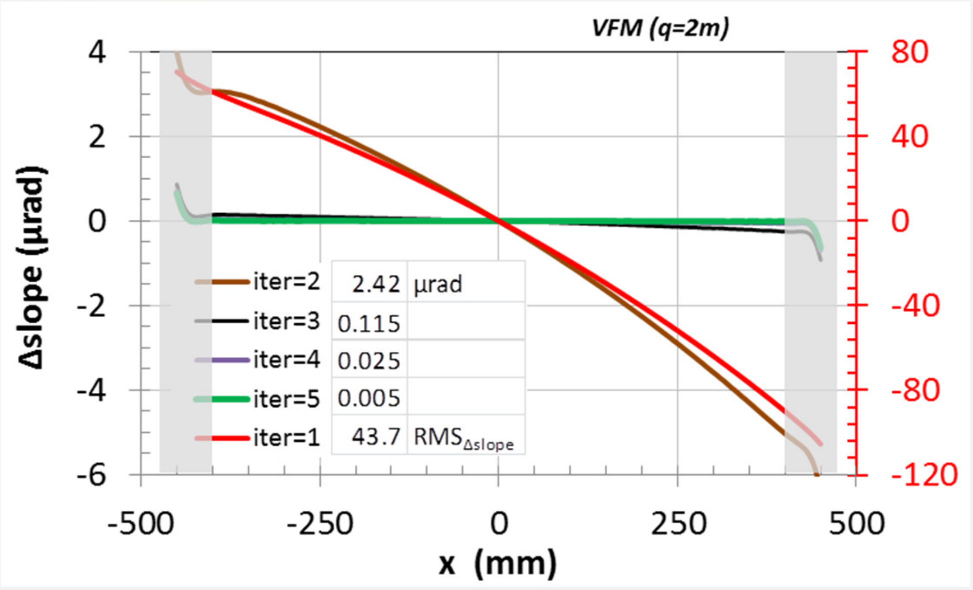


iter=1 iter=2 iter=3 iter=4

Optimized Mirror Profile – bending performance



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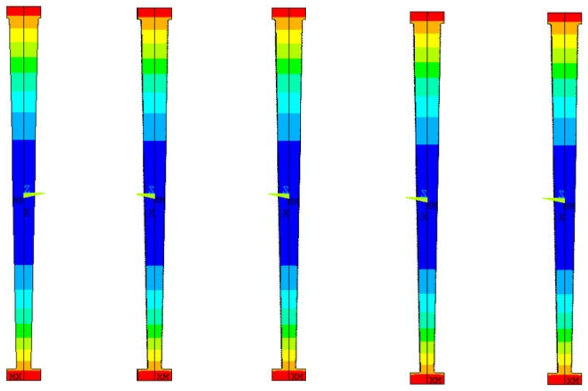

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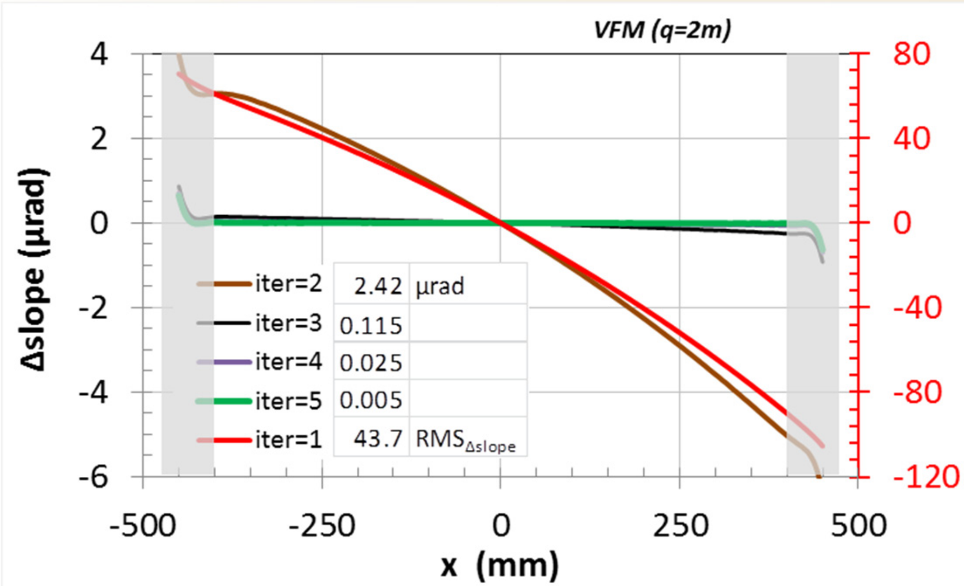

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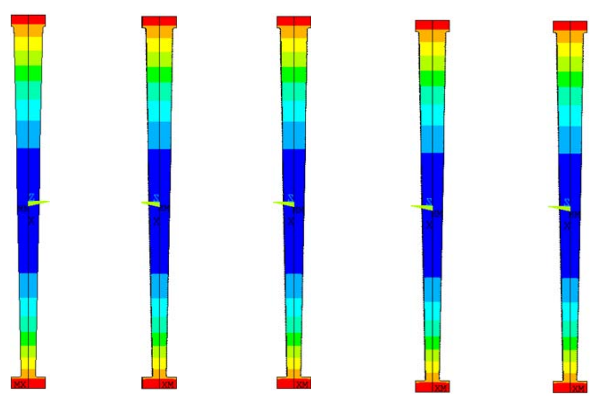


iter=1 iter=2 iter=3 iter=4 iter=5

RMS$_{\Delta slope}$ (reduction factor : **~ 10^4**)

- **43.7 μrad** (with the profile defined by BE)
- **0.005 μrad** (with the optimized profile by FEA)

RMS$_{\Delta slope\text{-}opt}$ /*slope*$_{PV\text{-}ellipse}$ ~ **2 10^{-6}**

Technical challenges

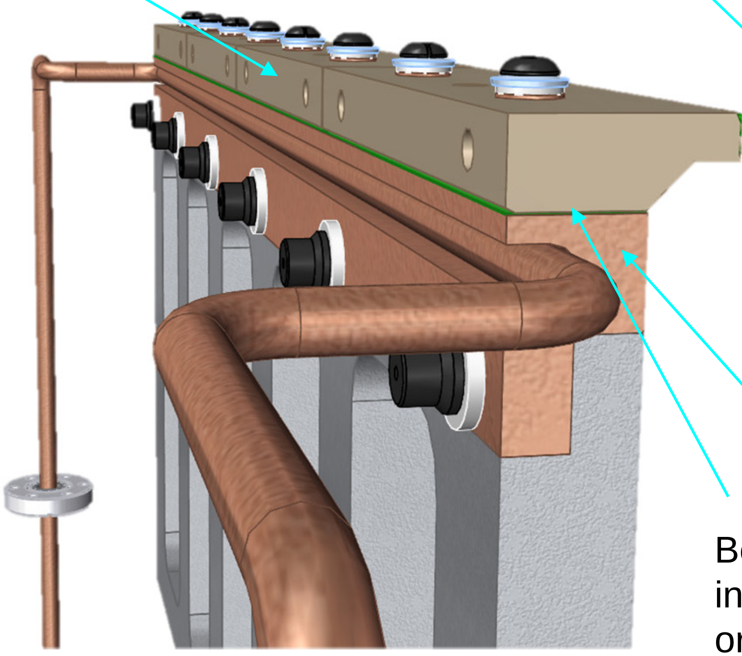
- Large Acceptance → Long mirror
- Variable Source & Focal Points → Bendable Mirror
- Sub Nanometer Shape Error → Limited Suppliers
- High Demagnification → Tight Bending (stress issues,…)
- Sub-μrad residual bending error → Variable Mirror Width
- **High Thermal Loads & Variable Footprint → Innovated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

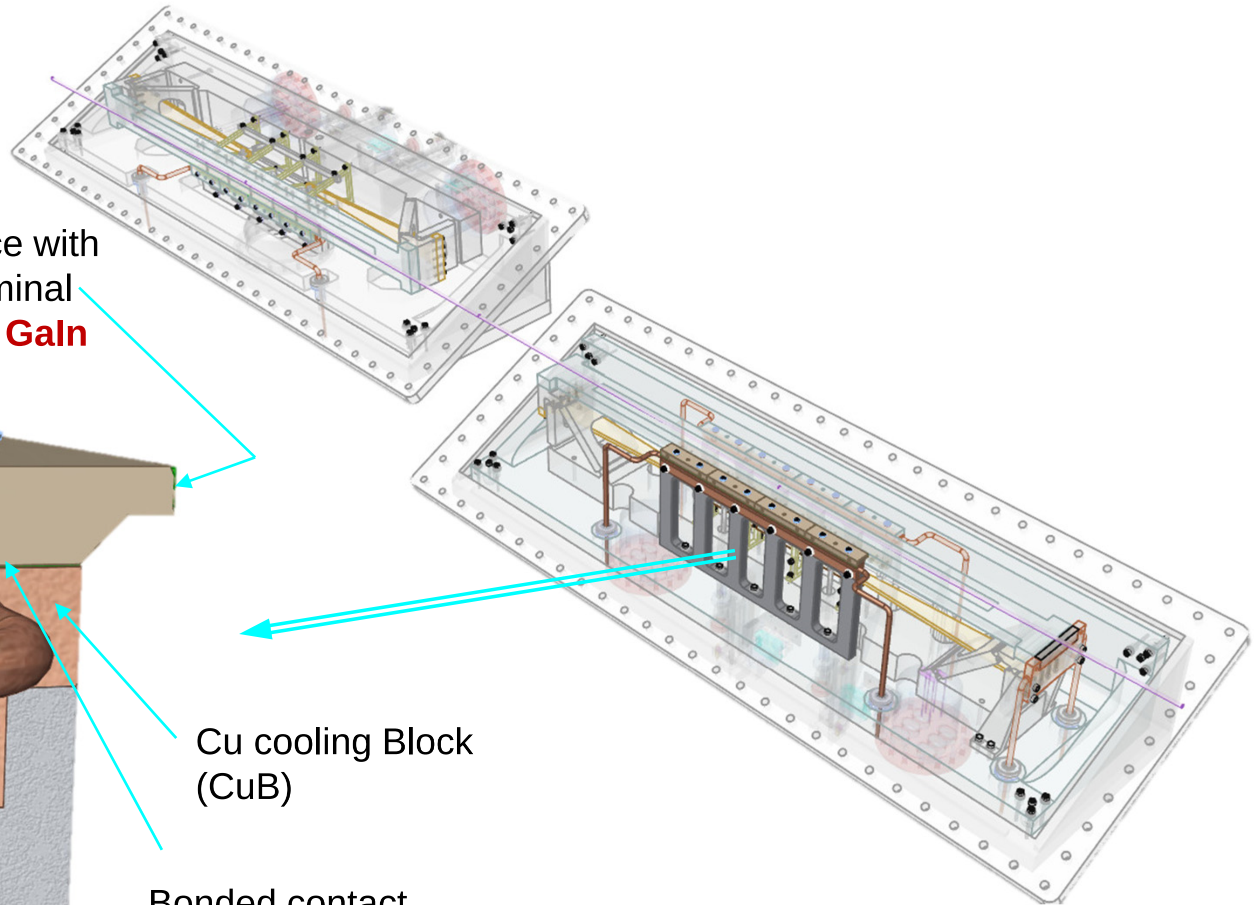
Final cooling design

- **Contact (Top-up-side), one single length water cooling**

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

Final cooling design

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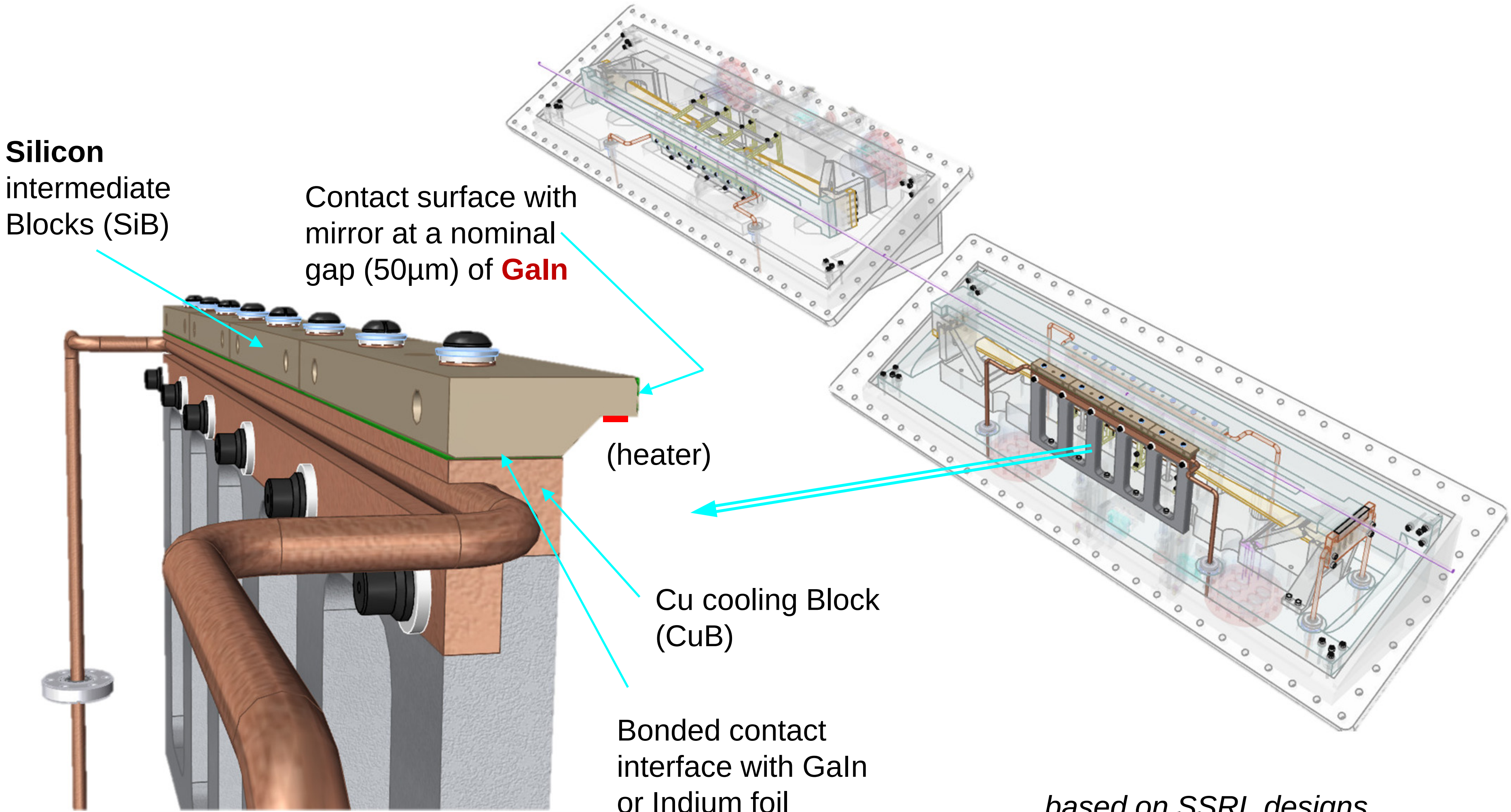


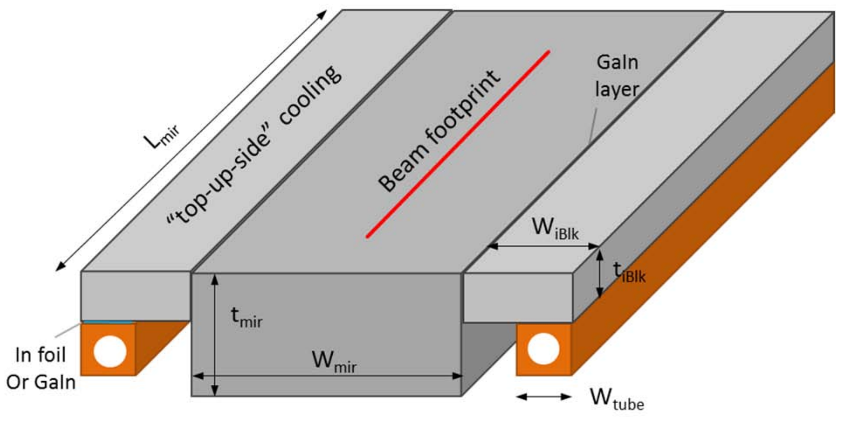
based on SSRL designs for contact cooled mirror

Mirror cooling design – 3 schemes

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

- *L. Zhang et al.* ***J. Syn. Rad.*** *(2015).* ***22****,1170–1181*
- *L. Zhang et al. ,* ***SRI 2015 Conference***

1. Single-length cooling



Mirror cooling design – 3 schemes

➢ Top-up-side water cooling

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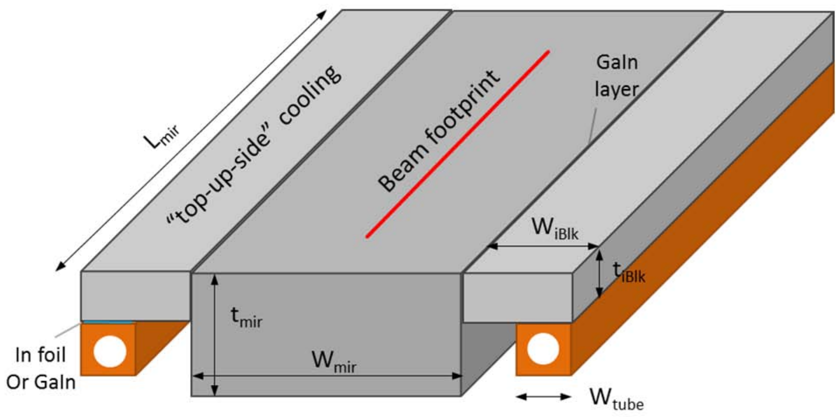
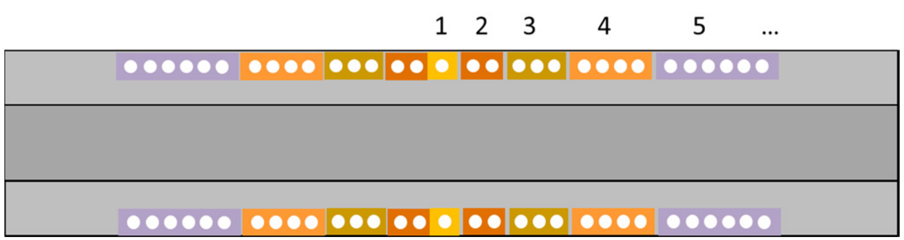


2. Variable-length cooling



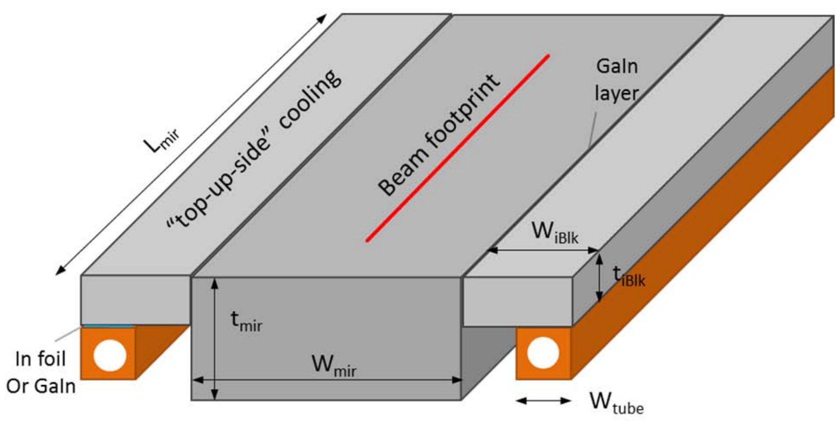
back face view

Mirror cooling design – 3 schemes

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

- *L. Zhang et al.* ***J. Syn. Rad.*** *(2015).* ***22****,1170–1181*
- *L. Zhang et al. ,* ***SRI 2015 Conference***

1. Single-length cooling



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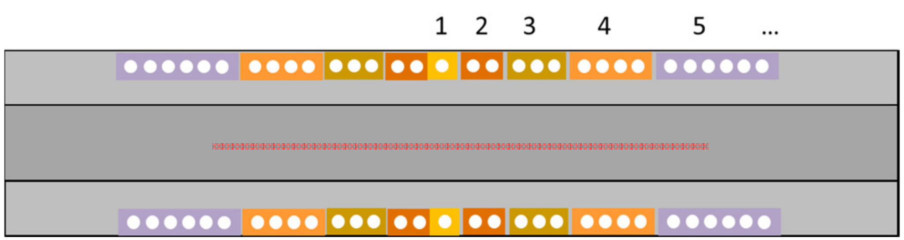

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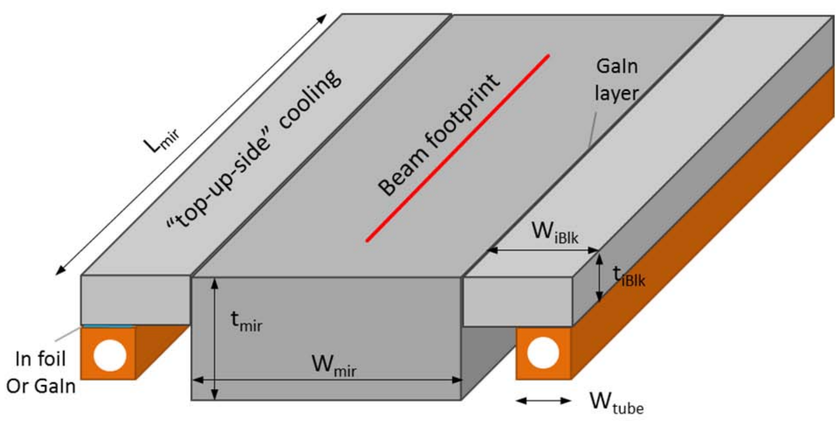

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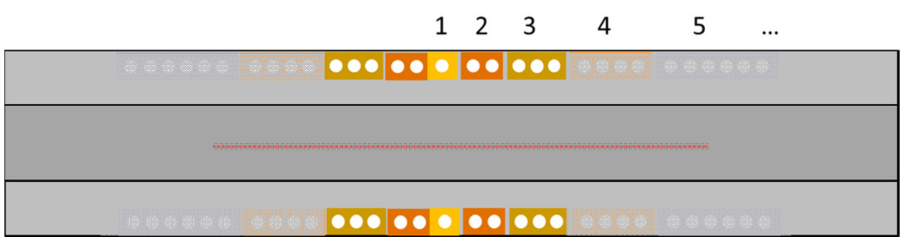

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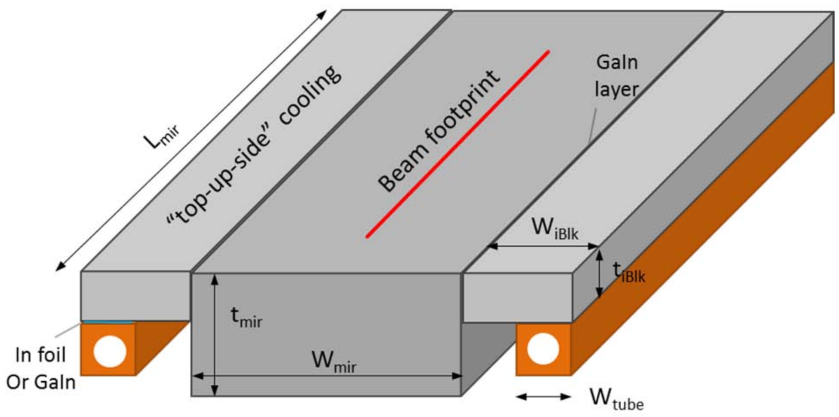

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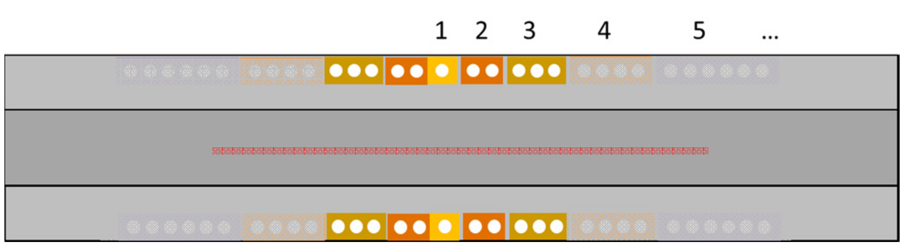
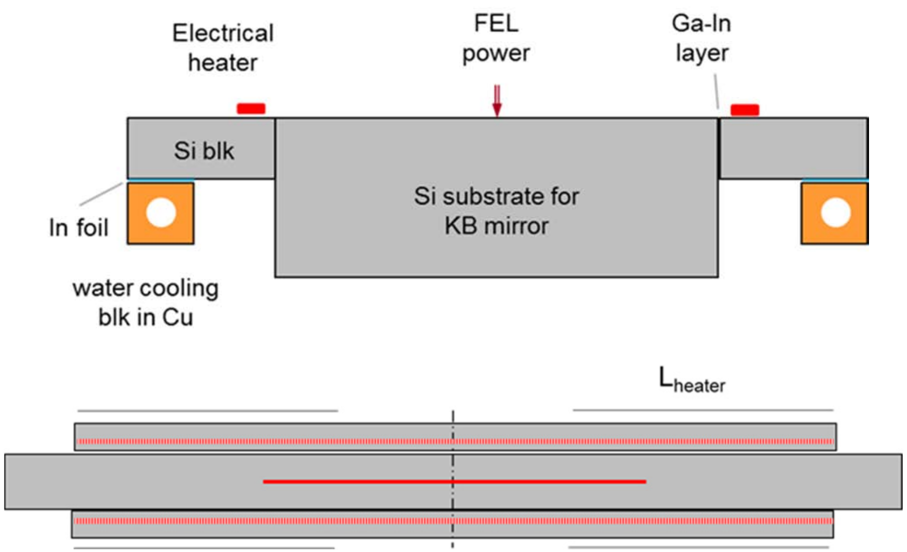


back face view

3. Electric heater + Single-length cooling



optical face view

Mirror cooling design – 3 schemes

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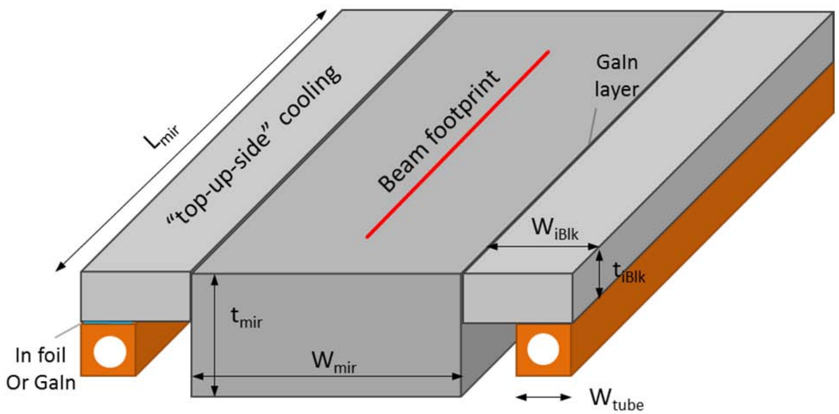

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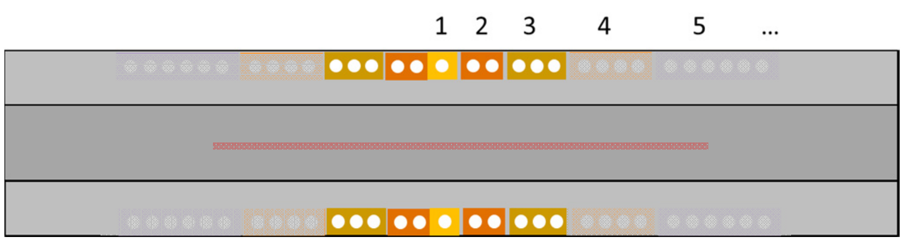

back face view

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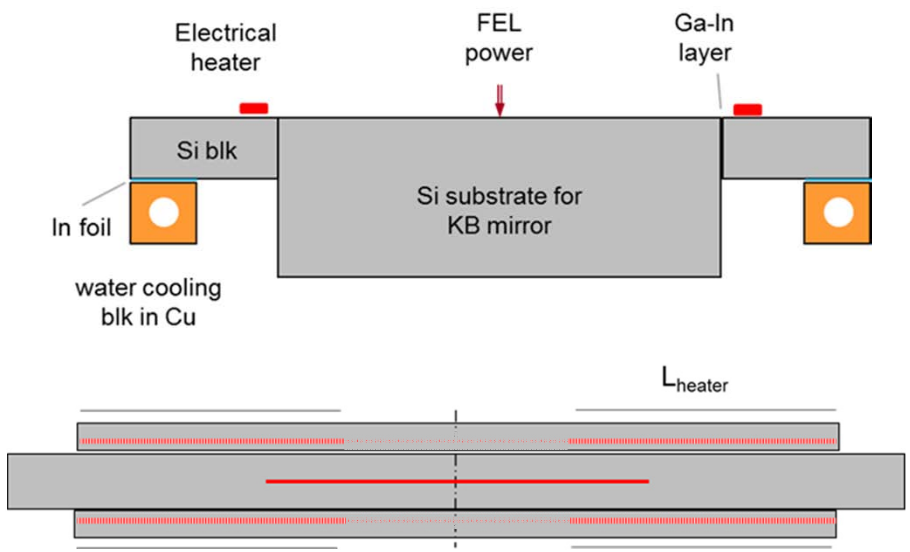

optical face view

Mirror cooling design – 3 schemes

SLAC

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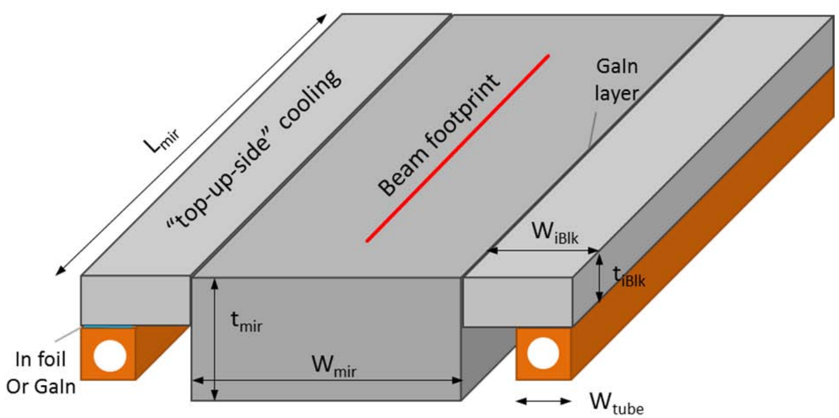

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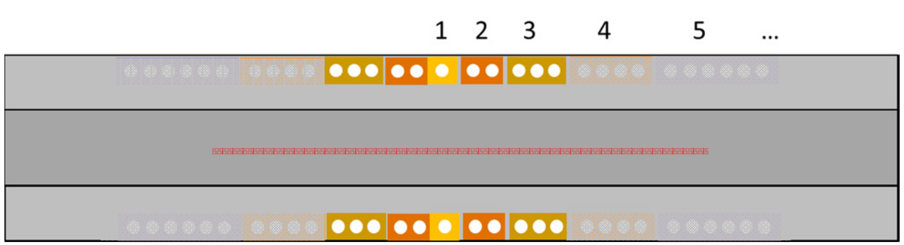

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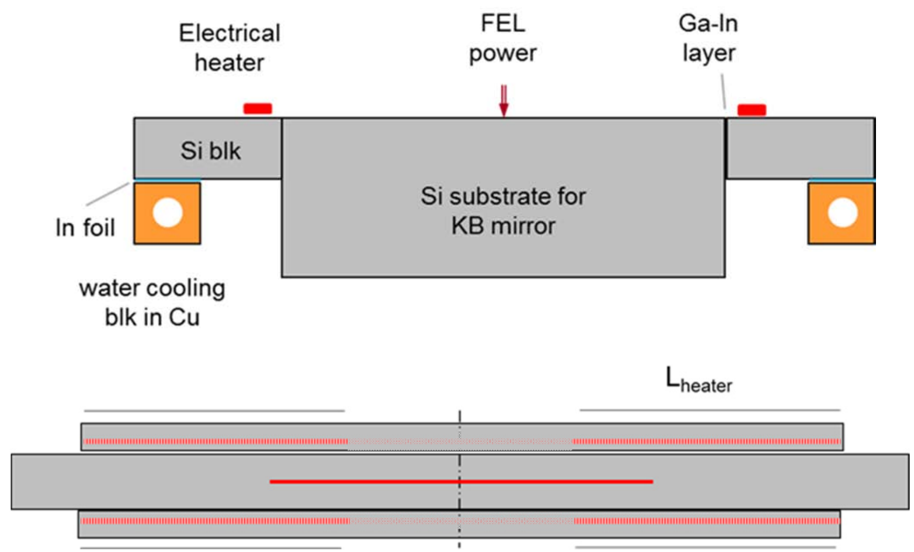
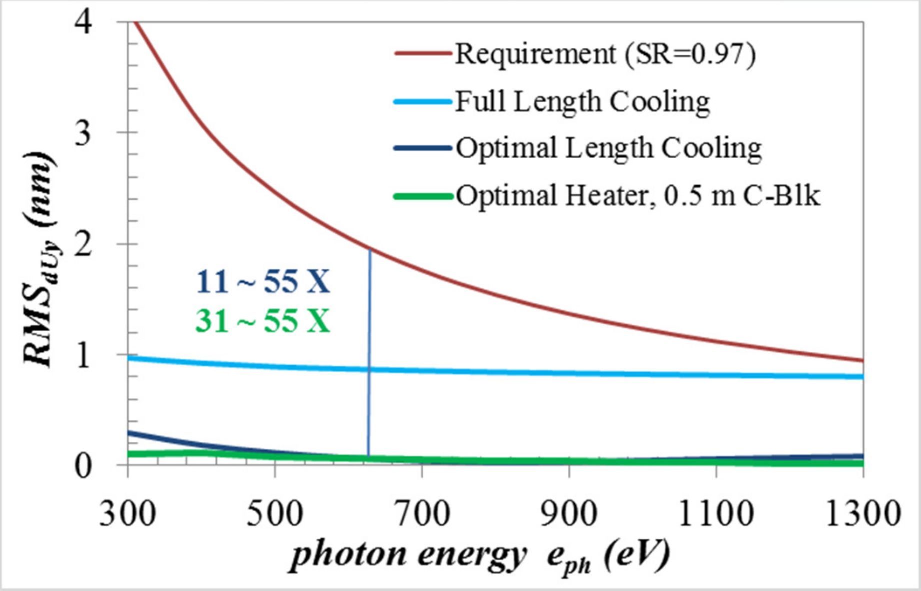


optical face view

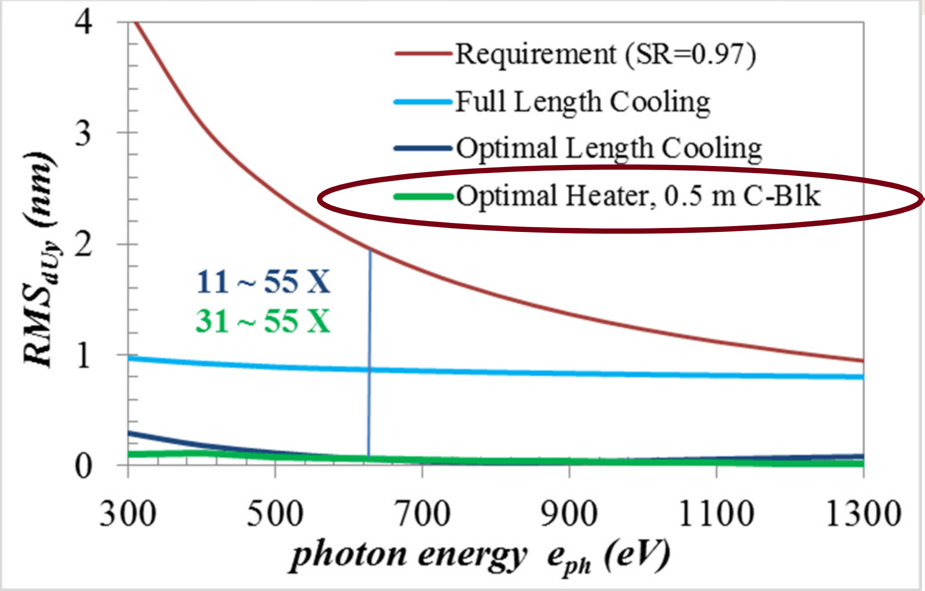
$$RMS_{thermal} := f\,(L_{heater}, Pa_{heater}, x)$$

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



Resistive Element Adjustable Length

REAL Cooled Optics

(DoE funded R&D project, 2017-2018 FY)

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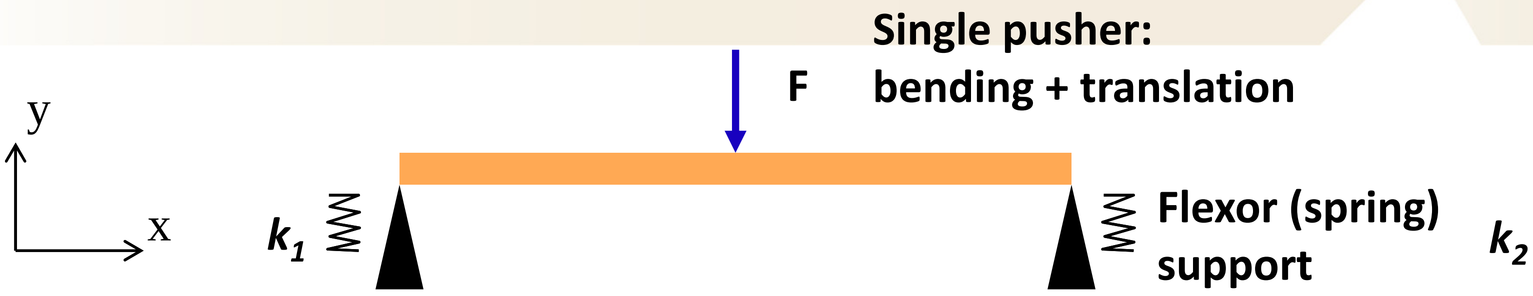
  - For 200 W of XFEL beam power, optimal, variable-length cooling is needed

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**
  - Minimization of mechanical constraint effects of Eutectic GaIn as thermal interface *(presented WEBA02)*
  - **Bend cooling blocks (design optimization practice)**

Cooling blocks bending and translation



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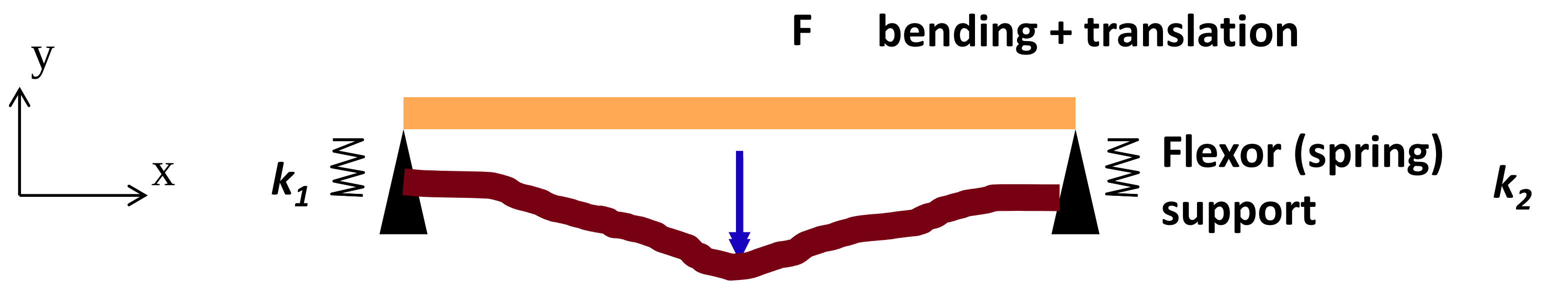
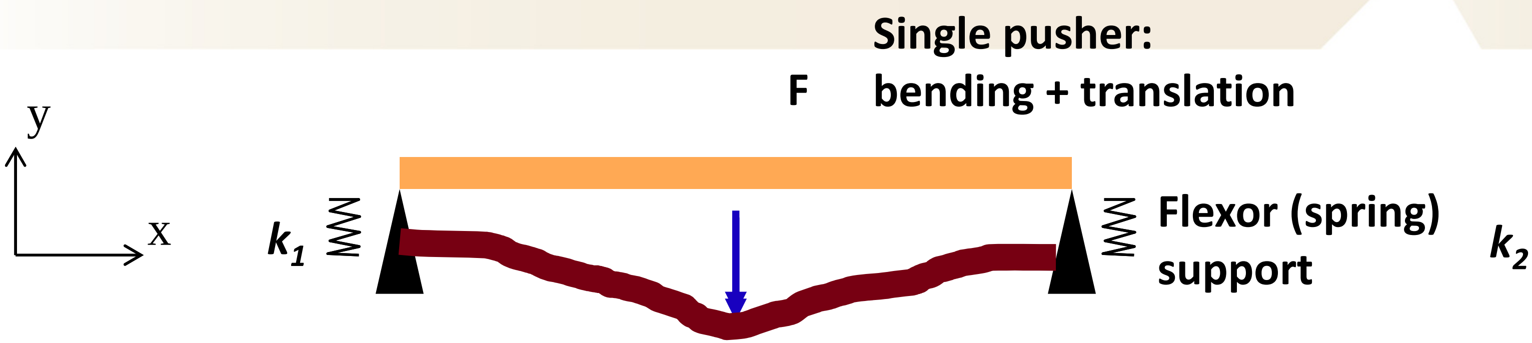


Single pusher: bending + translation

Flexor (spring) support

Cooling blocks bending and translation



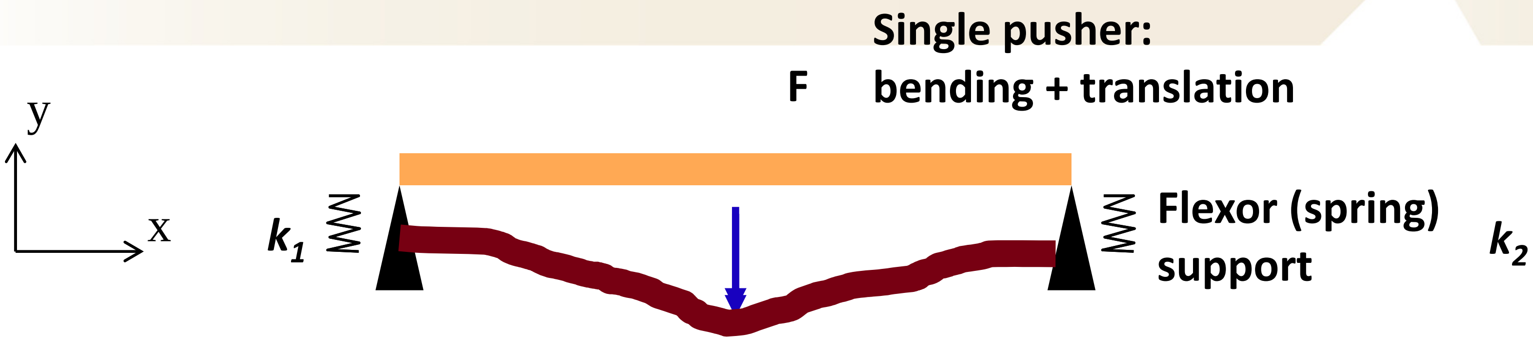
- Cooling block bent shape: $\mathbf{y_{CB}(x, \mathit{F}, \mathit{k_1}, \mathit{k_2})}$
- Mirror shape (ideal ellipse): $\mathbf{y_{mir}(x, q)}$

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

- For given value of $\mathbf{\mathit{F}, \mathit{k_1}, \mathit{k_2}, q}$
  - Minimization : $dU_y(x) = y_{CB}(x) - y_{mir}(x)$
  - $dU_y(x)$ → RMS, d_{pv}

d_{pv} < 5 µm

Cooling blocks bending and translation



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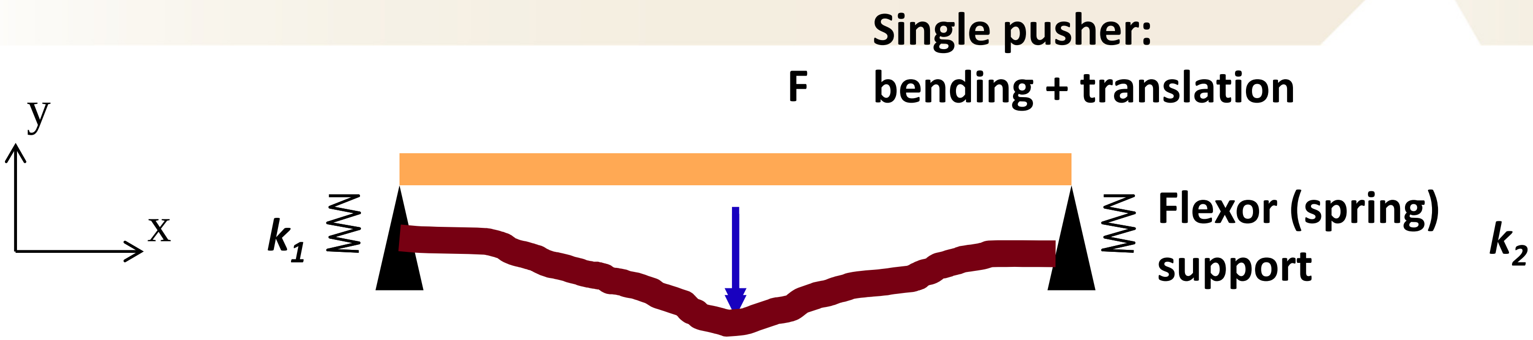
- For given value of F, k_1, k_2, q
  - Minimization : $dU_y(x) = y_{CB}(x) - y_{mir}(x)$
  - $dU_y(x) \rightarrow RMS, d_{pv}$

$d_{pv} < 5$ μm

- **Objective function:** $f\,(F, k_1, k_2, q)$

Cooling blocks bending and translation



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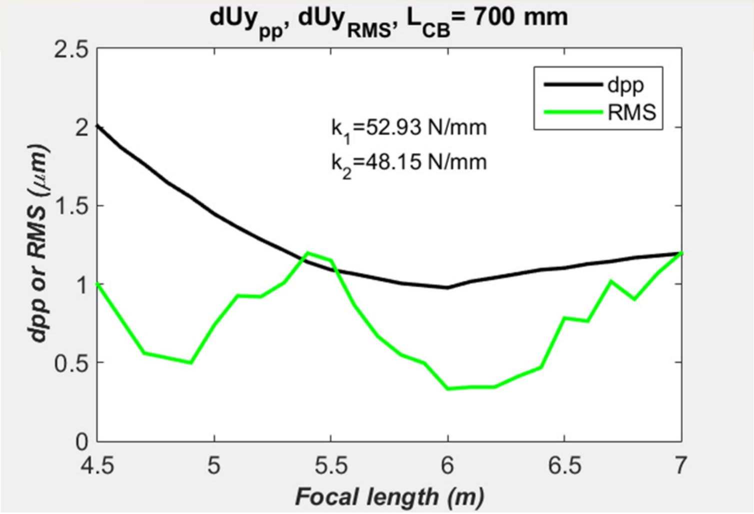
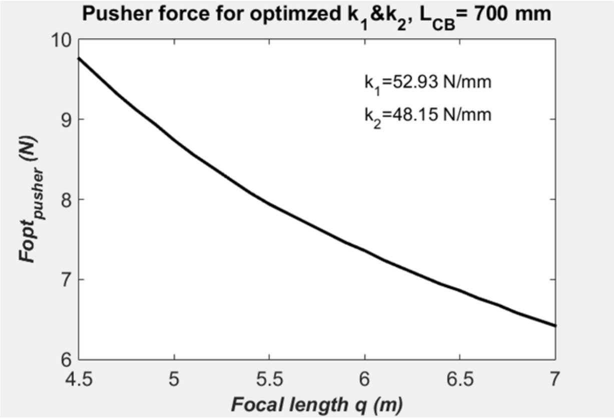
$d_{pv} < 5\ \mu m$

- **Objective function:** $\boldsymbol{f\,(F, k_1, k_2, q) = RMS*d_{pv}}$

Cooling blocks: single pusher + elastic supports

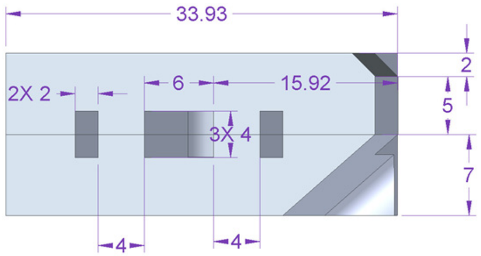
SLAC



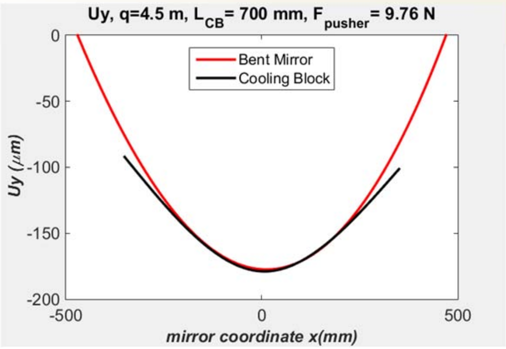


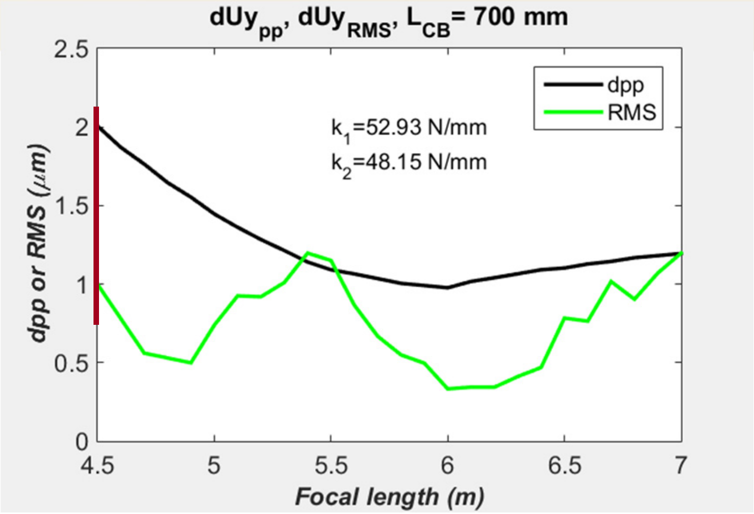
- 1 pusher: F
  2 flexor supports: k_1, k_2
  - F : 6 ~ 10 N
  - k_1 = 52.93 N/mm, k_2 = 48.15 N/mm

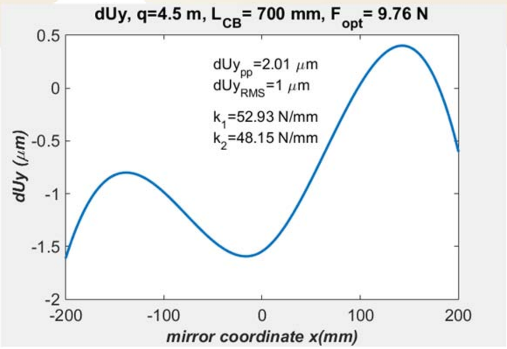
Uniform cross section

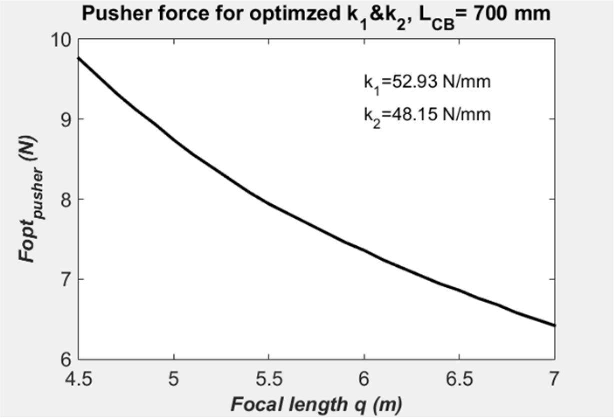


Cooling blocks: single pusher + elastic supports









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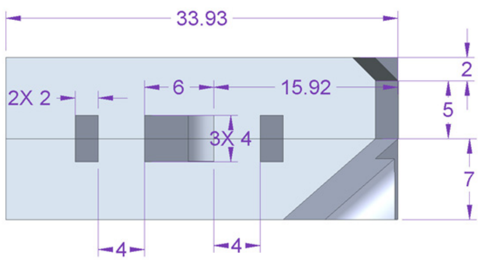

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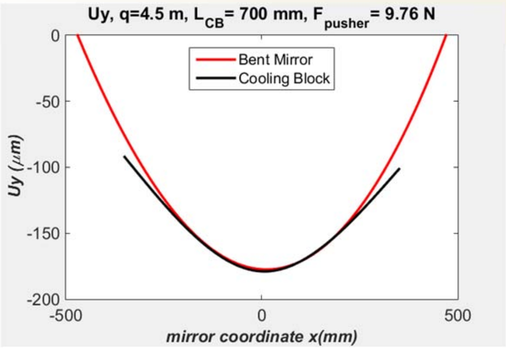

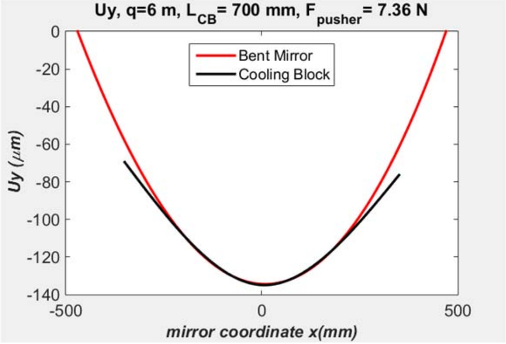

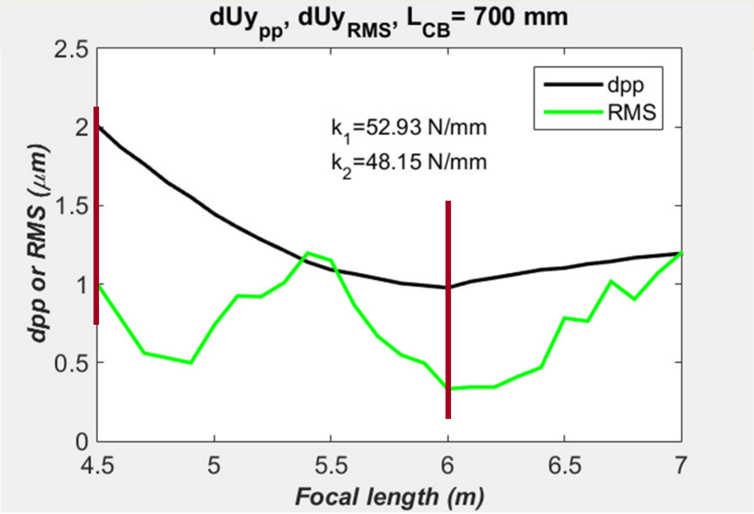

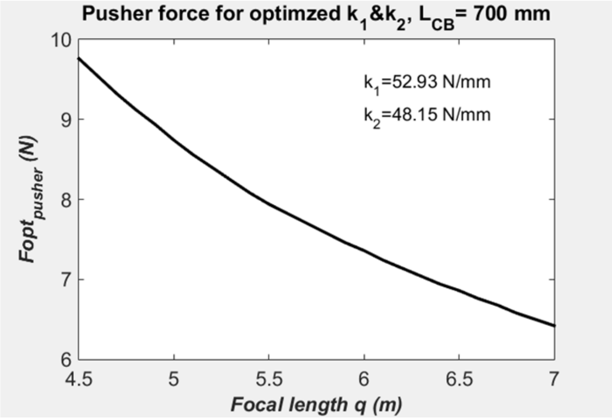

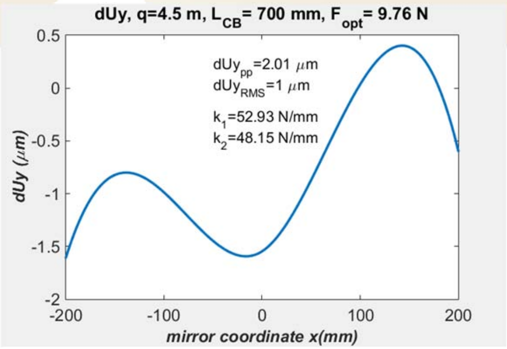

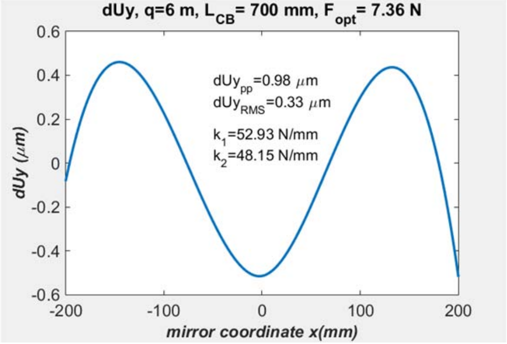

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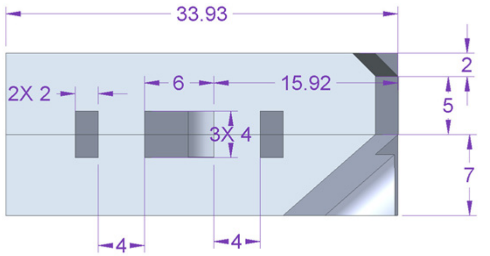


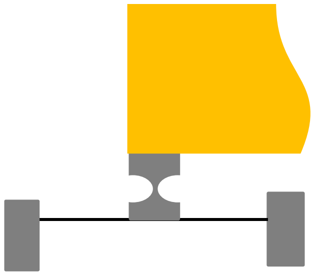
Cooling blocks: single pusher + elastic supports

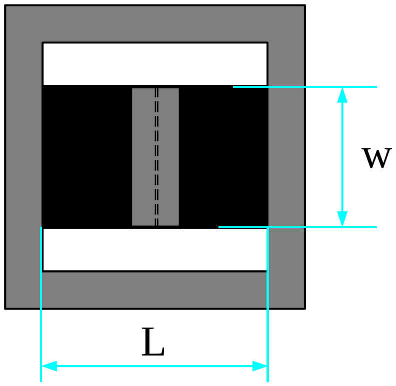
Flexor Supports

- Stainless steel thin blade

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

k_N (N/mm)	k_1	k_2	$\Delta_{\%}$	Δ_0	Δ_{req}
target	52.93	48.15			
			1%	*mm*	*mm*
E (N/mm^2)	2.00E+05	2.00E+05			
t (mm)	0.2	0.2	0.3%	**0.0006**	±0.01
L (mm)	20	20	0.3%	0.06	±0.05
w (mm)	16.54	15.05	1%	0.150	±0.1

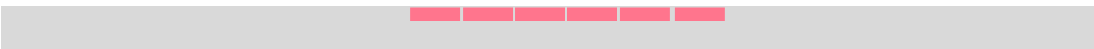




- Width w (add 10% to initial values) can be adjusted (re-machined) to fit exact k-values

→ 1% accuracy for the values of k_1, k_2 should be achievable

Cooling blocks: translation + rotation



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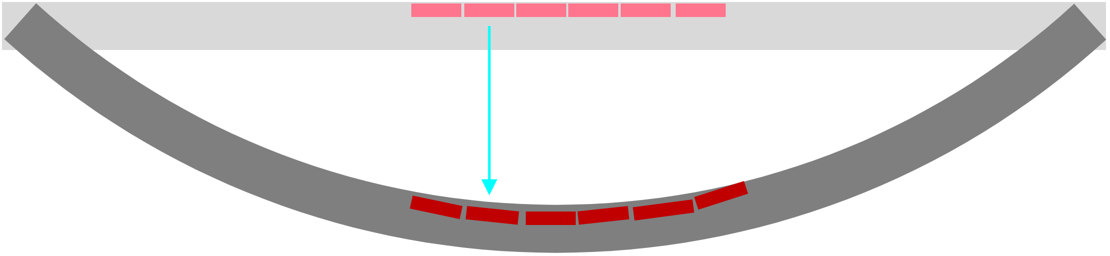

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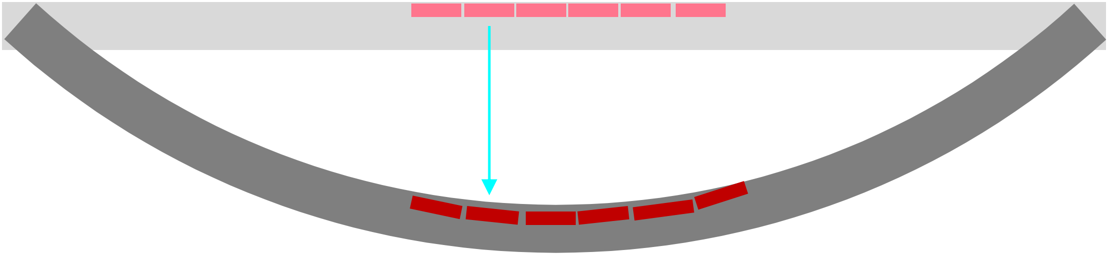
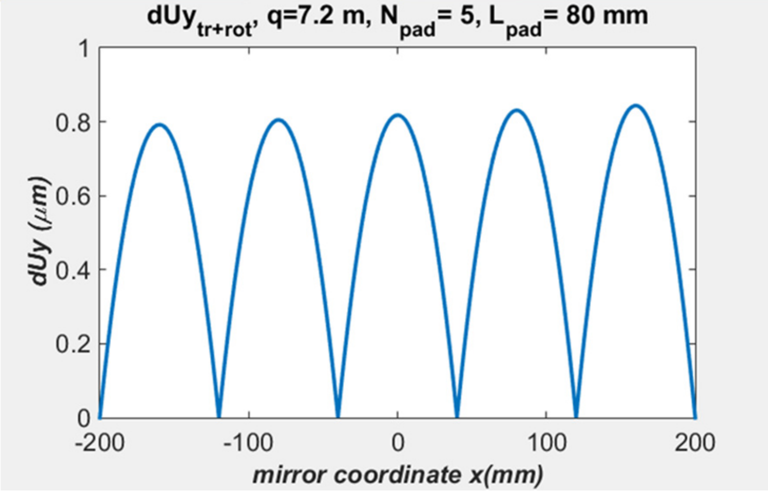
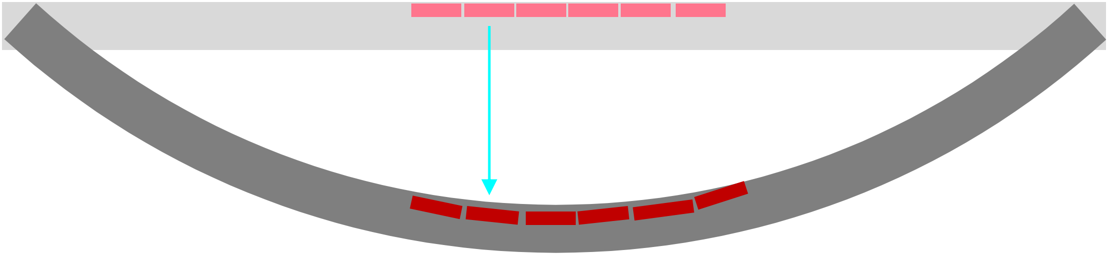
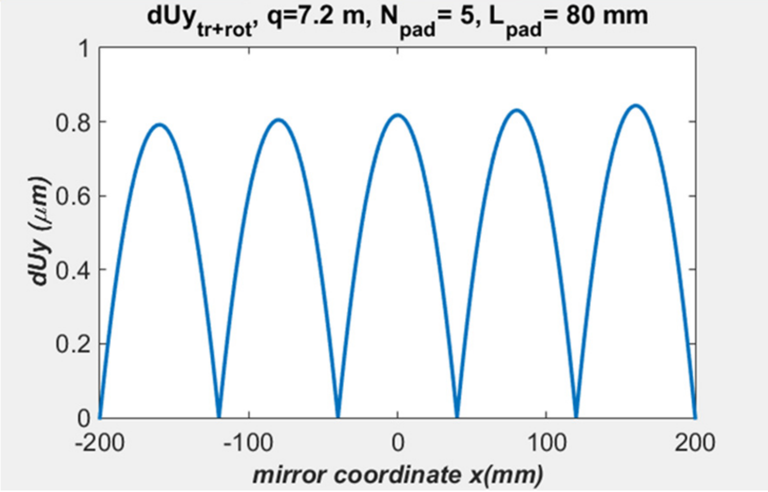




$$dU_y(x) = y_{CB}(x) - y_{mir}(x)$$

Cooling blocks: translation + rotation





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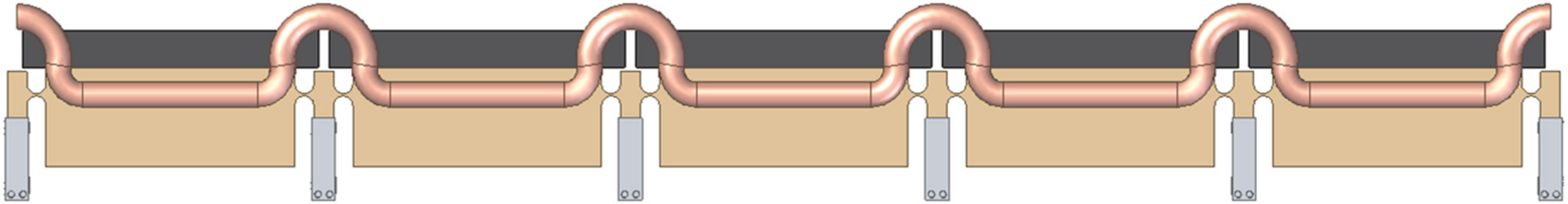
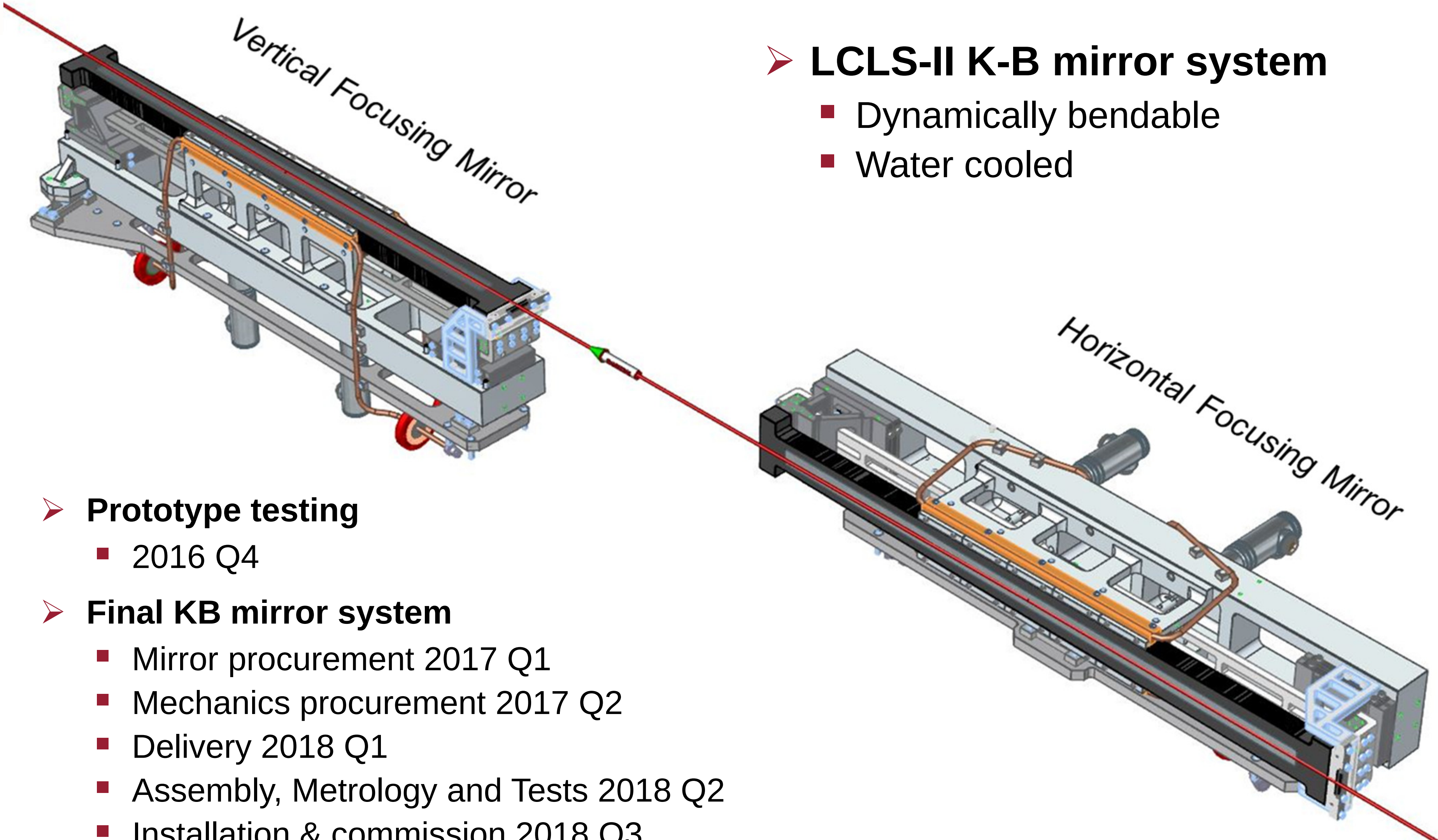


Summary



- **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

Acknowledgement

- **E. Anderssen** LBNL
- **R. Baker** ESRF
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- **M. Church** SLAC/SSRL
- **R. Duarte** LBNL
- **D. Harrington** SLAC/SSRL
- **J. Krzywinski** SLAC/SSRL
- **T. Rabedeau** SLAC/SSRL
- **A. Ringwall** SLAC/SSRL
- **E. Ortiz** SLAC/LCLS-II
- **B. Schlotter** SLAC/LCLS-II
- **V. Srinivasan** SLAC/LCLS, now India
- **P. Stefan** SLAC/LCLS
- **Randy Whitney** SLAC/LCLS

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