Preliminary plane mirror analysis for LCLS-II high repetition rate soft X-ray FEL beam

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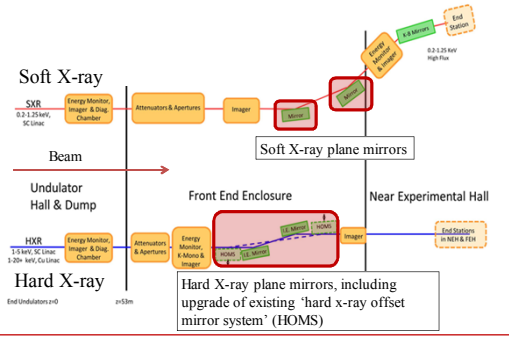
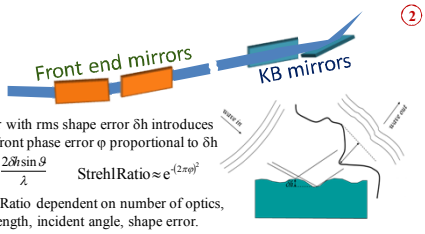
Introduction ①

The Linac Coherent Light Source – II is a free electron laser (FEL) project to build a 4 GeV superconducting (SC) linear accelerator, and with two variable gap undulators for soft and hard x-rays (SXR and HXR). With FEL pulse repetition rates up to 1 MHz, it will enable a new range of high resolution coherent 'pump probe' experiments in the 0.2 to 5 keV photon energy range. A pair of SXR and HXR flat distribution mirrors and an Kirkpatrick-Baez (KB) mirror system for the SXR line will be needed to absorb the spontaneous radiation, higher harmonic energies and deflect the x-ray beam to the end station optics. To deliver an FEL beam (20 W incident) with minimal flux loss and less than five percent wavefront distortion, one will need mirrors of height error as low as 0.3 nm across an aperture of 300 mm and 1 nm across the length of the mirror. The mirror system is also expected to perform at the highest repetition rate (200 W incident) with reduced performance. We discuss preliminary analysis (work in progress) for a potential side-mounted water-cooled geometry with two cooling footprints for variable beam footprint, and using gallium-indium eutectic interface between the mirror and the cooling assembly.



Requirements ②

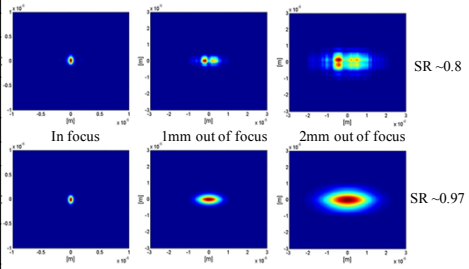
Range	SXR: 0.2-1.25 keV HXR: 1-5 keV
Incident power	20 W to 200 W
Mirror bulk	Silicon, <100> tangential orientation
Coating	SXR: Bare silicon HXR: To be decided
Angle	SXR: 12 mrad HXR: 3 mrad
Mirror length	800-1000 mm
Clear aperture	20 mm (sagittal)
Radius	≥ 500 km (tangential) ≥ 2 km (sagittal)
Wavefront	<5% distortion in /out of focus
Strehl Ratio	0.97 or higher (combined)
Shape error	<0.3 nm rms center 300mm tangential < 1 nm overall in clear aperture
Slope error	<0.2 urad rms (tangential) <1 urad rms (sagittal)
Roughness	<0.3 nm rms (20 nm - 0.5 mm sampling frequency)



Mirror with rms shape error δh introduces wavefront phase error φ proportional to δh

$$\varphi = \frac{2\delta h \sin\vartheta}{\lambda} \qquad \text{Strehl Ratio} \approx e^{-(2\pi\varphi)^2}$$

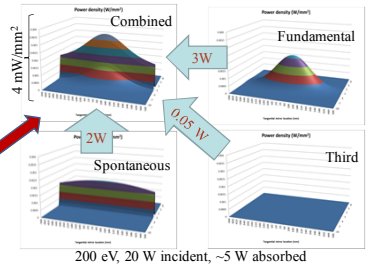
Strehl Ratio dependent on number of optics, wavelength, incident angle, shape error.



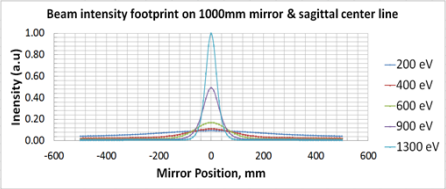
Simulation for effect on beam profile for combined Strehl ratio of four mirrors

Beam Parameters for Analysis ③

Third harmonic	3 % of incident power
Fundamental, absorbed	Energy dependent
Third harmonic, absorbed	Energy dependent
Spontaneous radiation correction factor	Energy dependent * 35% of electrons
Divergence, fundamental	Energy dependent
Divergence, third harmonic	~58 % of fundamental
Sample case	
Energy	200 eV
Incident power	20 W (100 kHz)
Incidence angle	12 mrad
Source distance	100 m
Divergence, fundamental	19.8 urad
Divergence, third	11.4 urad
2*FWHM	~780 mm
Absorbed, fundamental	15 % (3 W)
Absorbed, third harmonic	8 % (0.05 W)
Absorbed, spontaneous	2 W
Absorbed, total	5.05 W

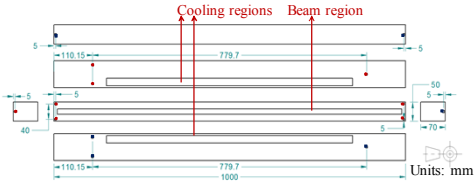


200 eV, 20 W incident, ~5 W absorbed



Mirror Geometry and Parameters ④

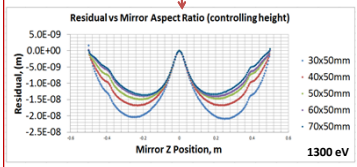
Material	Silicon <100>
Density	2330 kg/m³
Thermal expansion coefficient	2.5x10⁻⁶ / K at 295.15 K
Young's Modulus	129 GPa
Poisson's Ratio	0.28
Thermal Conductivity	141 W/m.K
Radiation emissivity	0.1 (very low doping Si)
Length	1000 mm
Cross Section	70 x 50 mm

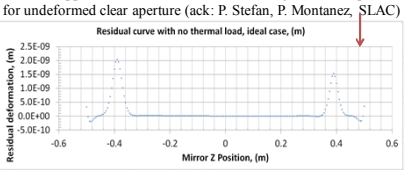


Mirror schematic: 1000x70x50 mm cross section

- Supports
- Restraining load positions (<10 N) with potential 'Z' concave bender location

Vertical supports/loads mid-distant between edge & Bessel points for undeformed clear aperture (ack: P. Stefan, P. Montanez, SLAC)





b = 70 mm

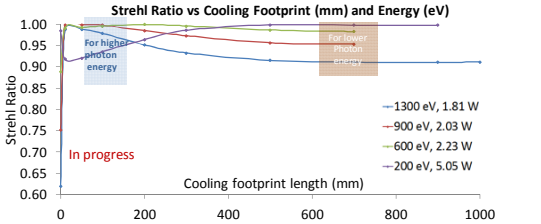
h

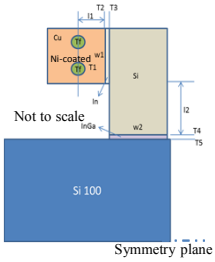
- 70 mm x 50 mm cross section to maximize stiffness (within vendor limits)
- Gravity-induced deflection not affected since 'b' term cancels out.
- Sag ~ (load/inertia). Inertia ~ $bh^3/12$. Load = ρ*(b*h*l).

Y (Vertical)
Z (Beam) X (Deformation axis)

Cooling Geometry and Parameters ⑤

Conductance, Indium (In) foil (50 um)	10,000 W/m².K
Conductance, Indium gallium (InGa) eutectic (50 um)	100,000 W/m².K
Conductivity, Silicon	141 W/m.K
Convection coefficient, water tubes	10,000 W/m².K
Copper length, l1	5 mm
Silicon length, l2	14.5 mm
Copper contact width, w1	24 mm
Silicon contact width, w2	10 mm
Water tube diameter	5 mm
Number of tubes	2
Effective cooling coefficient	~5100 W/m².K

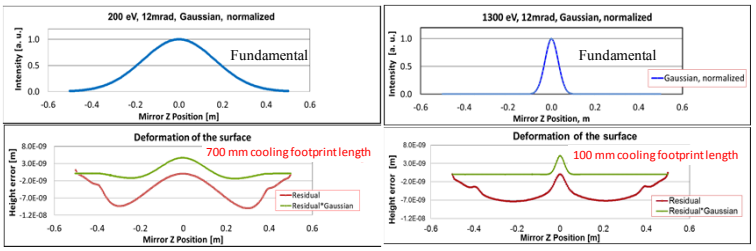




- Water-cooled copper tubes mechanically separated from mirror with combination of silicon adapter blocks, indium foil and indium gallium eutectic.
- Using 5000 W/m².K as effective cooling coefficient at optic
- Preliminary FE analysis shows benefit in developing a cooling geometry with variable contact length.
- Due to complexity of beam footprint geometry and difficulty in getting highly variable cooling geometry, we are working toward developing a two-length cooling circuit with valves, to get a ~100 mm length for high photon energy and ~700 mm for low photon energy.

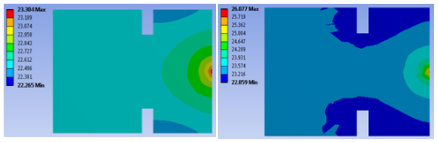
Simulations: ANSYS

Weighting residual error with beam intensity ⑥



Deformation convoluted with intensity profile is used for calculating the Strehl ratio

High Power Parameters ⑦



200 eV, 200 W incident
T_{max} ~ 23.3°C, ΔT ~ 1°C

1300 eV, 200 W incident
T_{max} ~ 26.1°C, ΔT ~ 3.2°C

- Introducing a notch in mirror cross section to induce a thermal moment and mitigate high power effects.
- Not detrimental in low power scenario.
- Notch depth: 3-10 mm (Optimization in progress)
- Notch width: 5 mm
- Notch distance from mirror surface: 12-26 mm (Optimization in progress)