LCLS X-ray mirror measurements using a large aperture visible light interferometer

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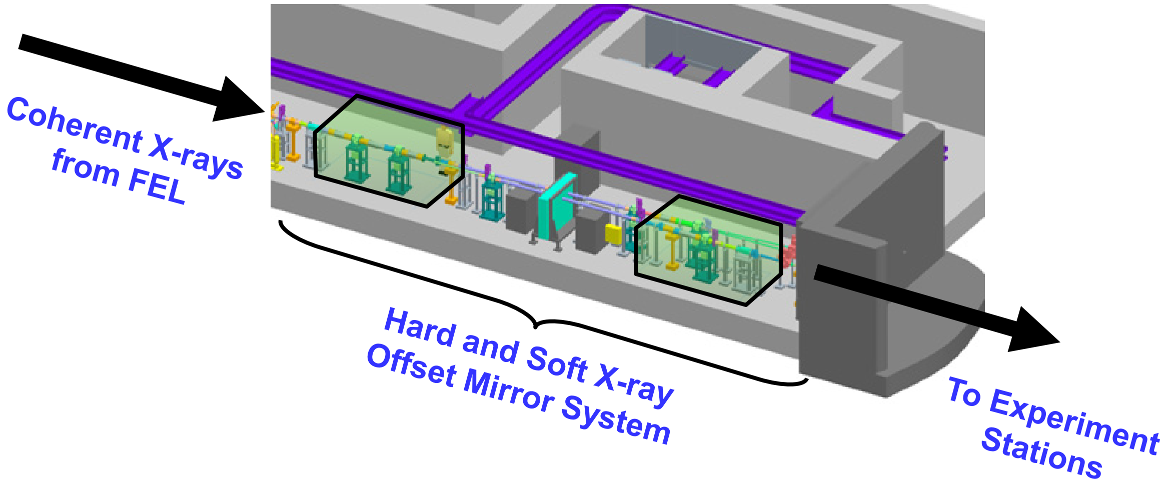
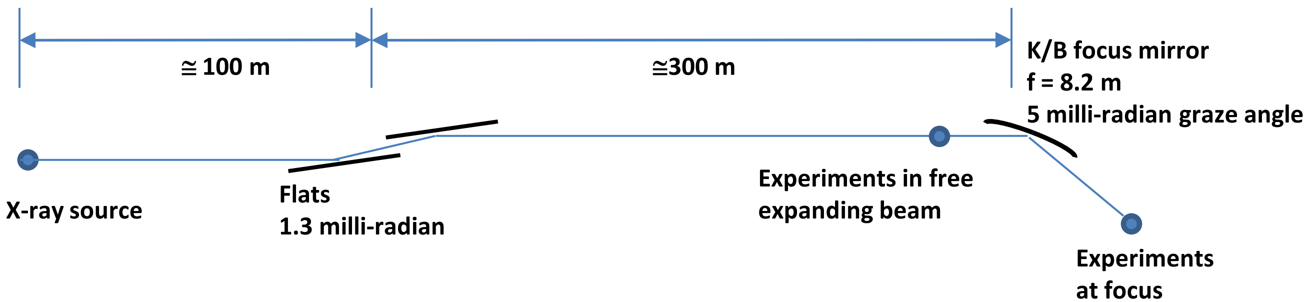
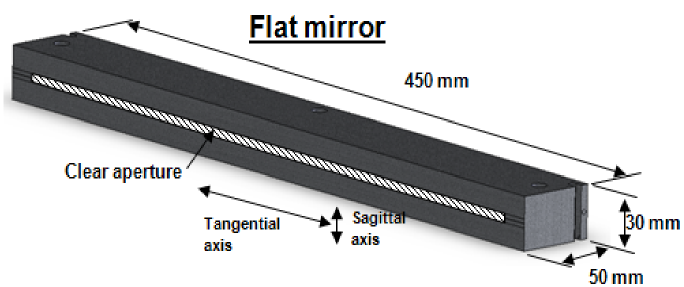


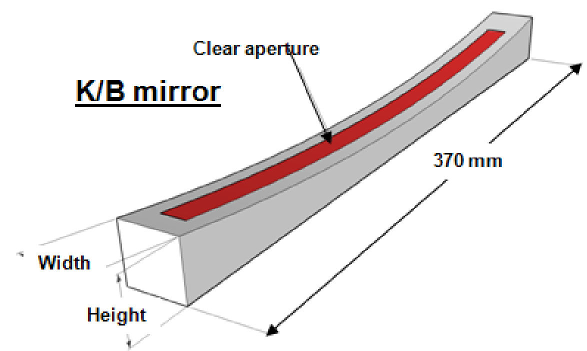
This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 in support of LCLS Project at Stanford Linear Accelerator Center.

This talk describes how we arrived at mirror figure tolerances for LCLS hard X-ray mirrors, and how they where measured

Nominal high energy beam line layout





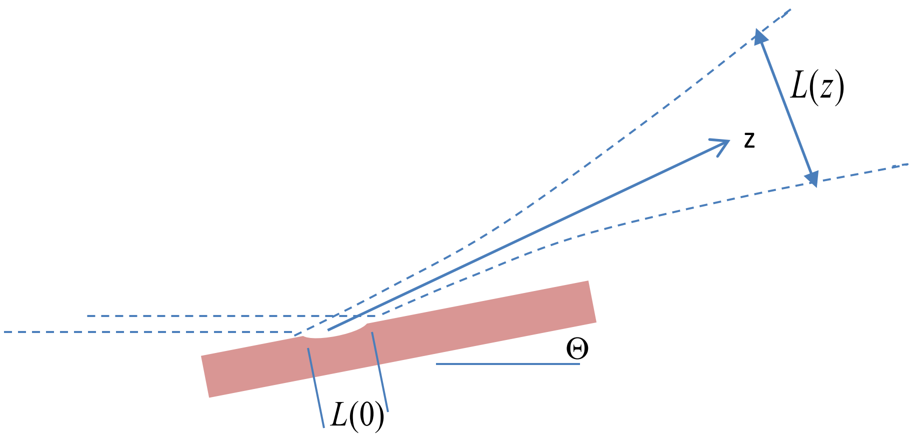


Mirror type	Tangential Sphere (peak/valley)	Tangential A-sphere (rms)
Flats	< +/- 10 nm	< 2 nm
K/B focus mirror	< +/- 3 nm	< 1 nm

The affect of figure errors on phase/intensity depends on the figure error length scale

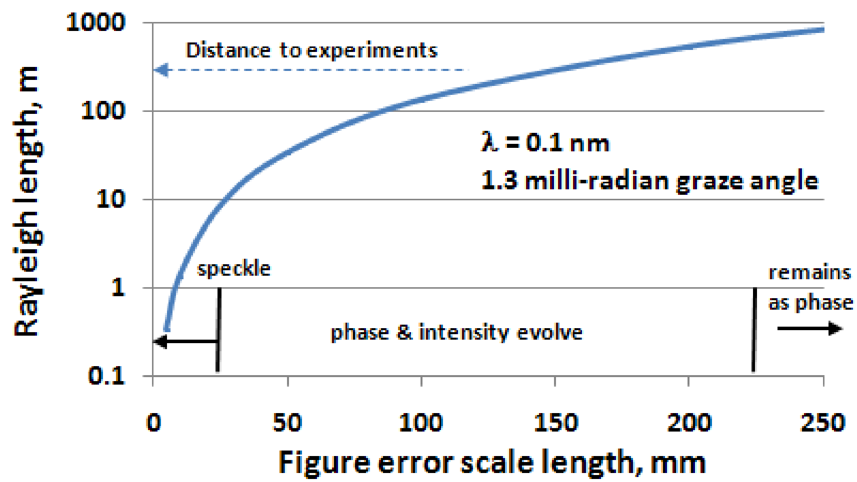
- **A figure error of length** $L(0)$ **initiates a phase disturbance of length** $L(0)\sin\Theta$

- **The disturbance grows in size as** $L(z) = L(0)(\sin\Theta)\left[1+(z/Ra)^2\right]^{1/2}$, **where the Rayleigh length** $Ra = \pi(L(0)\sin\Theta)^2/(4\lambda)$



- **Between the flat and the focus mirror, initial disturbances may**

  (1) rapidly expand and intermingle
  (2) gradually evolve in both phase and intensity
  (3) propagate as a phase-only disturbance



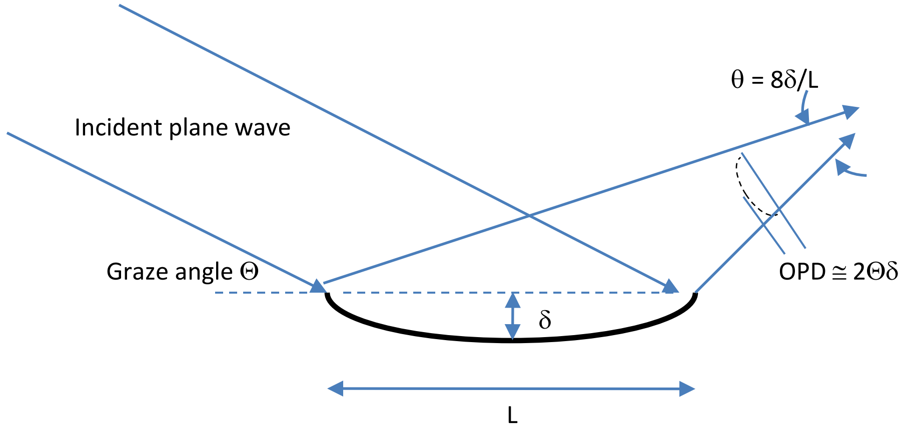
- **Most figure errors of interest lead to gradual evolution**

  - examined by solving the Fresnel equation

A tolerance for spherical error in flats and focus mirrors can be arrived at analytically – using peak intensity at focus as the metric

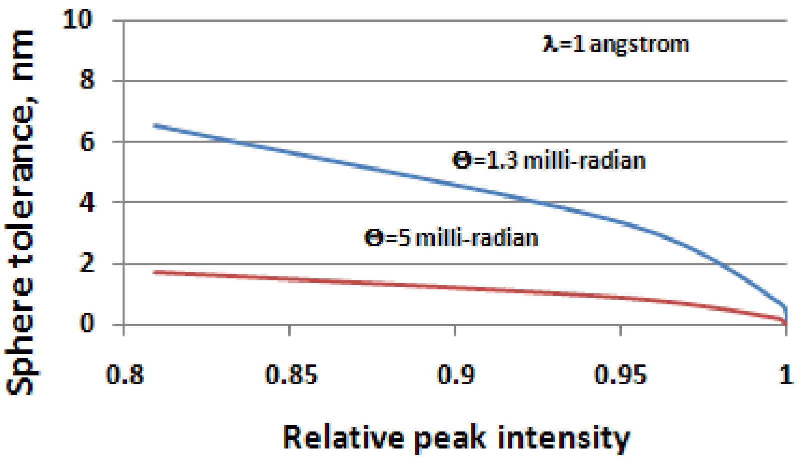
- **An Optical Path Difference (OPD) results when mirror spherical curvature differs in sagittal and tangential planes by an amount δ, peak/valley**

  - OPD $\cong 2\Theta\delta$ upon reflection
  - results in astigmatism at focus, reducing the peak intensity



- **For astigmatism, the relative peak intensity I at focus scales as (Born & Wolf, sec. 9.3):** $I > 1 - \frac{\pi^2}{6\lambda^2}\sin^2(2\Theta\delta)$

  - Maintaining < 80% peak intensity limits the spherical error in flats to < 6 nm (peak/valley)
  - < 2 nm relative error between focus mirrors



Once the spherical error is known, it can be reduced to a focus shift Δf by translating K/B focusing optics relative to one another

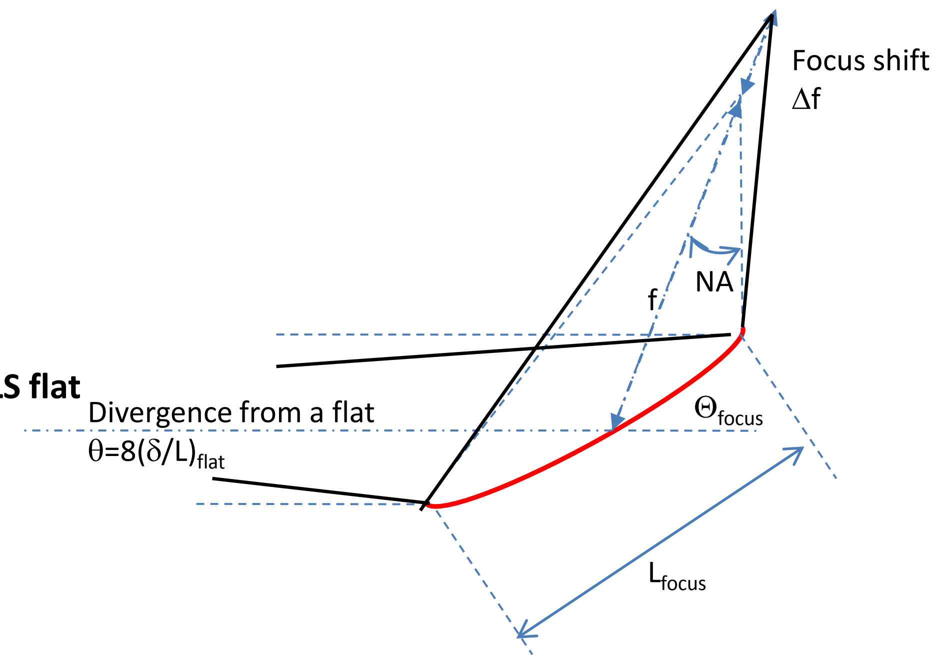
- **The focus shift is proportional to the spherical errors in the mirrors**

$$\Delta f/f = \theta/NA$$

- **In terms of flat and focus mirror geometry,**

$$\Delta f = 16f^2(\delta/L)_{flat} / (L\Theta)_{focus}$$

= 7 mm shift per nm of spherical error in an LCLS flat



- **the 10 nm of sphere allowed in the flats can be corrected by a shifting a K/B mirror 70 mm**

Measuring sphere accurately enables a focus shift to be pre-planned prior to mirror installation

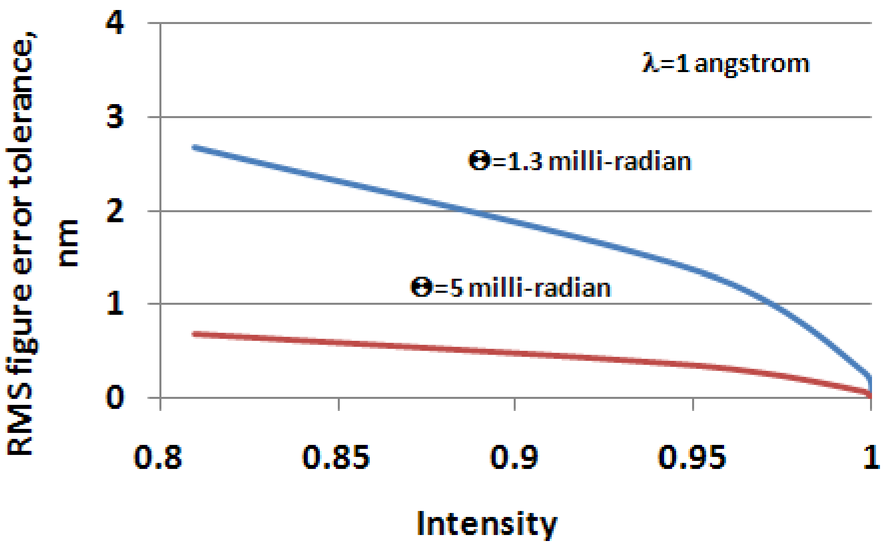
Tolerances for a-sphere in LCLS flats were specified using the Maréchal criterion

• The criterion describes the reduction in peak intensity at focus due to a random figure error distribution of rms amplitude δ_{rms}

$$I < 1 - \left(\frac{2\pi}{\lambda}\right)^2 (2\delta_{rms} \sin\Theta)^2$$

• The error must be < 3 nm rms to achieve > 80% of the diffraction limited intensity at focus

• A smaller number applies to focus mirrors, due to larger graze angle



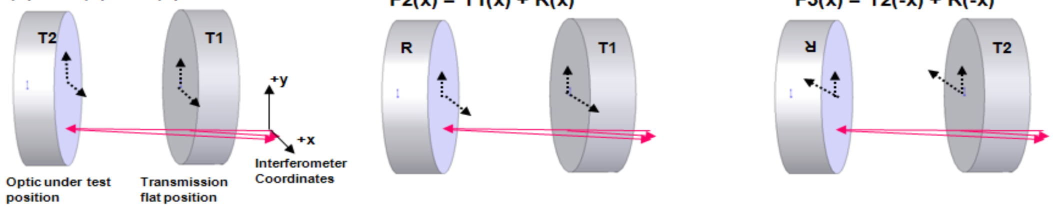
• Measuring these tolerances with a visible light interferometer requires:

- Measurement noise << 1 nm (must be a phasing interferometer)
- Normal incidence, using only the essential optics (no turning flats, etc.)
- Careful attention to mirror distortion while mounting
- Absolute calibration to < 1 nm with a three-flat test

A three flat test was used to calibrate a 300 mm diameter interferometer transmission flat to < 0.5 nm (rms) along the horizontal axis

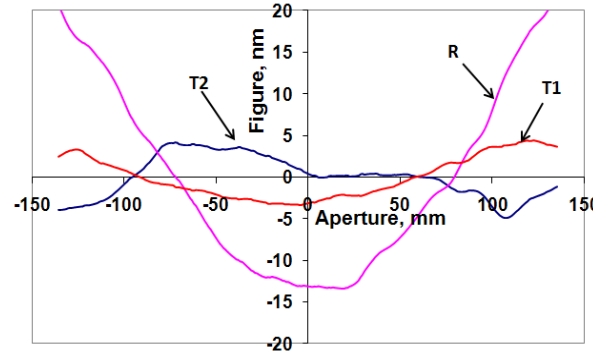
• **The figure of transmission flats T1, T2, and reflection flat R were solved along a horizontal line using the geometries shown**

F1(x) = T1(x) + T2(x) F2(x) = T1(x) + R(x) F3(x) = T2(-x) + R(-x)



• To solve for T1(x), T2(x), R(x), convert T2(-x) to T2(x), R(-x) to R(x)

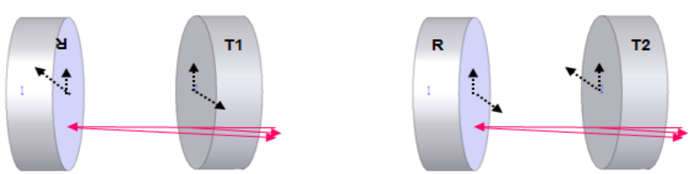
T1(x)=1/2[F1(x)+F2(x)-F3(-x)] T2(x)=1/2[F1(x)-F2(x)+F3(-x)] R(x)=1/2[-F1(x)+F2(x)+F3(-x)]



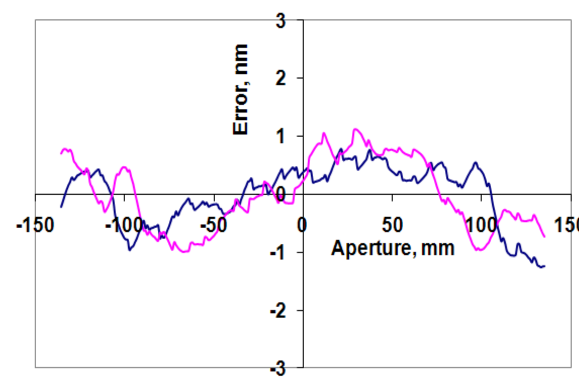
• **The solution error was sampled using two additional independent configurations**

- both error samples indicate < 0.5 nm rms calibration error
- 0.01 μradian slope

F4(x) = T1(x) + R(-x)+Error(-x) F5(x) = T2(-x) + R(x)+Error(x)



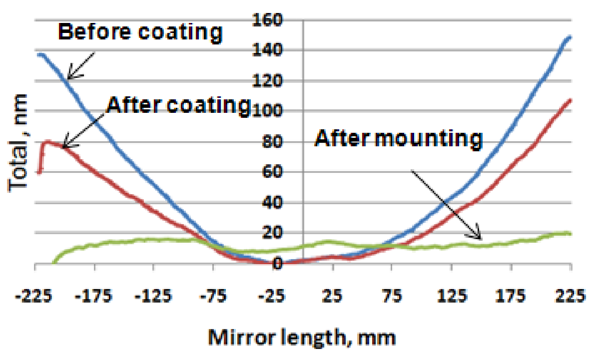
Error check
Error(x) = F4(-x)-T1(-x)-R(x)
Error(x) = F5(x)-T2(-x)-R(x)

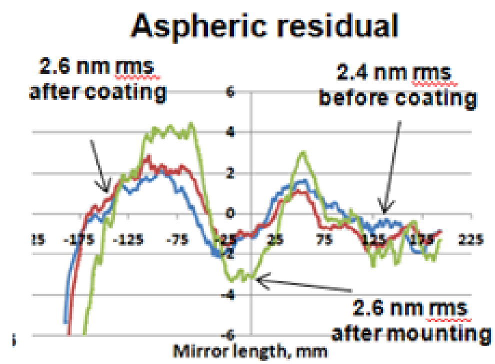


The a-sphere figure error varies from 1 to 2.6 nm (rms) for four 450 mm long flats

- The flats are fabricated by Zeiss with 150 nm of concave spherical curvature, and < 2 nm rms a-sphere

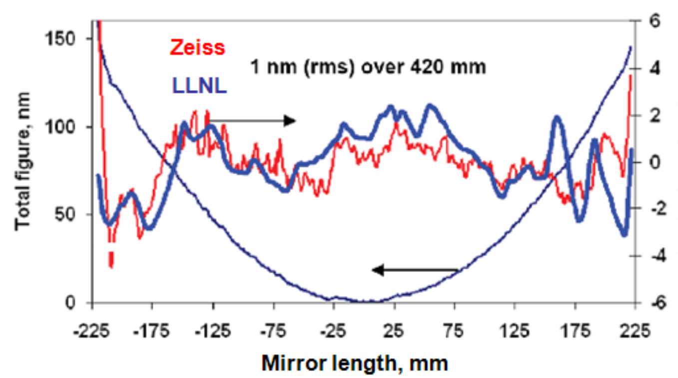
  - they are then coated by Regina Soufli at LLNL, reducing the curvature by about 10 nm
  - the sphere is mechanically reduced to < 10 nm peak/valley during mounting, in front of an interferometer
  - a-sphere is monitored throughout to make sure it is not increased my mounting forces



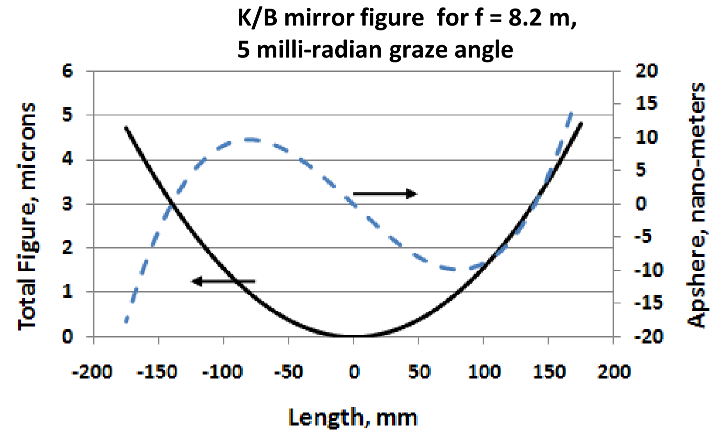


- Zeiss measures the a-sphere independently prior shipping

  - Zeiss & LLNL measurements are in good agreement



Focus mirrors with high fringe density can be accurately measured by calibrating the “trace back” error

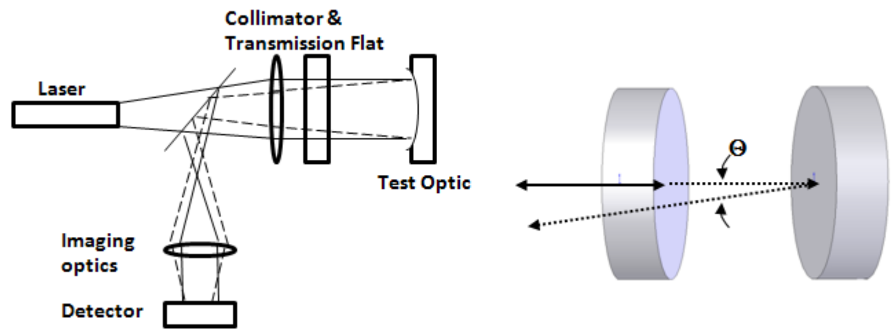


• Pixel density limits the maximum curvature that can measured

- Nyquist limit requires > 3 pixels/fringe
- Limits measurements to < 25 microns (peak/valley) across the aperture

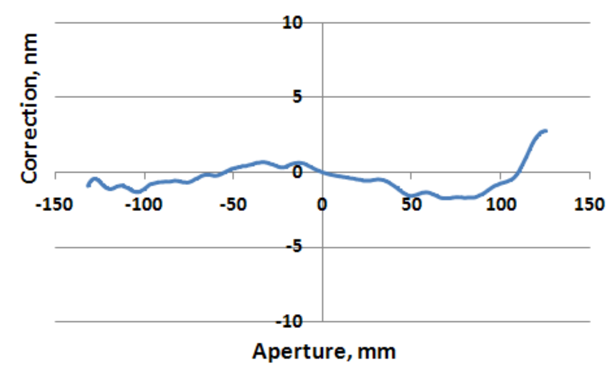
• At high fringe density, sample rays and reference rays travel different paths through the interferometer

- a measurement error is observed when a test flat is tilted off null fringe



• The correction that would be applied to the f=8.2 m K/B mirror is shown

- note a slight miss-alignment in the imaging optics
- the correction is small, but significant compared to 1 nm tolerance for a-sphere



Conclusions and Future Efforts

- A visible light interferometer was used to accurately measure 450 mm long flats for LCLS

  - bend mirrors flat to < 10 nm peak/valley
  - measured a-spheric figure ranging from 1 – 2.6 nm rms for four flats

- Focus mirrors can be measured accurately by applying a correction for systematic errors of the interferometer imaging optics

  - the correction is significant compared to focus mirror figure tolerances

- The interferometers 300 mm aperture requires file stitching, which limits measurement accuracy

  - plans are underway to calibrate a 600 mm instrument
  - 900 mm aperture instruments are becoming available

Acknowledgements

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