PAUL SCHERRER INSTITUT

Diffractive optics for photon beam diagnostics at hard XFELs

Wir schaffen Wissen – heute für morgen

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ESRF: A. Rack

SOLEIL: T. Weitkamp

APS: A.T. Macrander

SACLA: M. Yabashi, T. Katayama, H. Ohashi

EuroXFEL L. Samoylova, J. Grünert, H. Sinn

Diffractive optics for photon beam diagnostics at hard XFELs

Outline:

Grating-based wavefront sensor

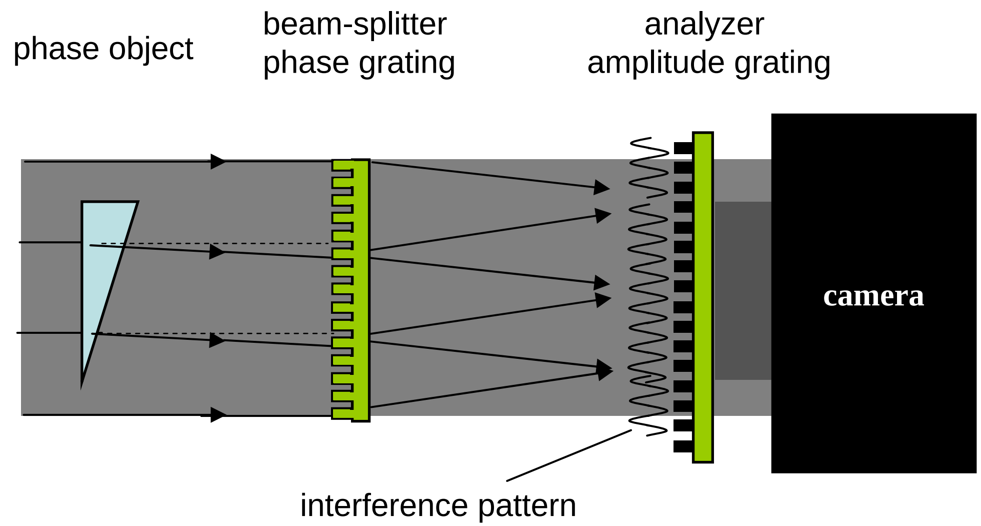
- Introduction and working principle
- Metrology on synchrotrons
- Single-shot metrology on LCLS & SACLA

Grating-based spectral monitor

- Principle and design
- Single-shot spectral monitoring at LCLS
- Future: Improved set-up – best of both worlds

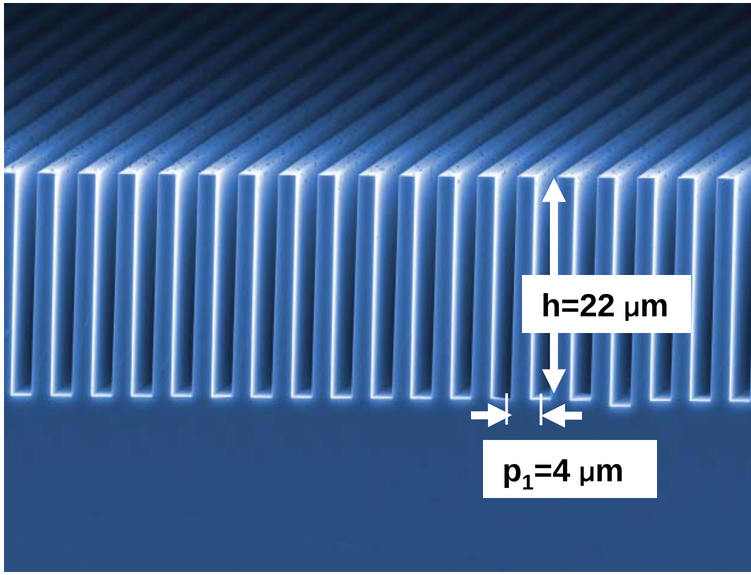
X-ray grating interferometry

- Was initially developed for phase contrast imaging
- Grating based interferometry detects small refraction of x-rays on phase gradients
- Phase gradients are converted into intensity changes using a set of two gratings

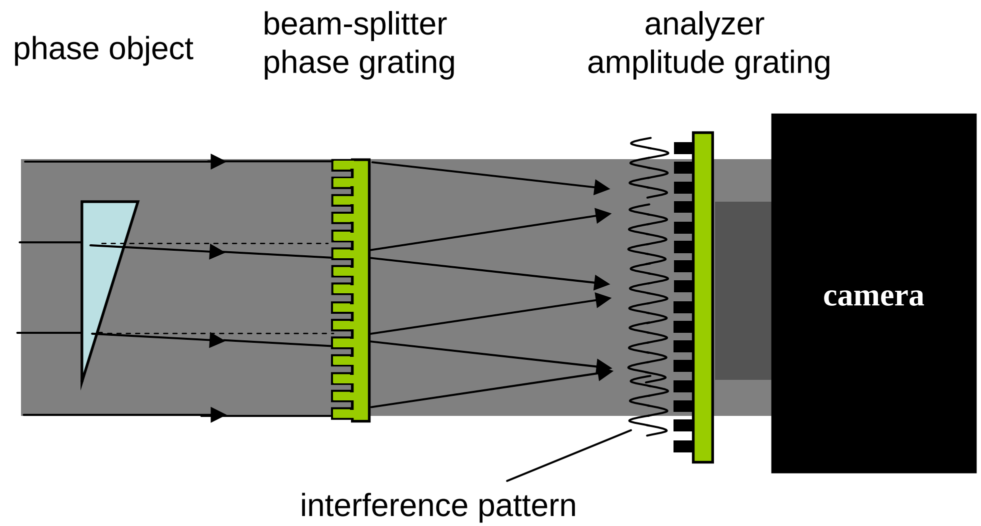


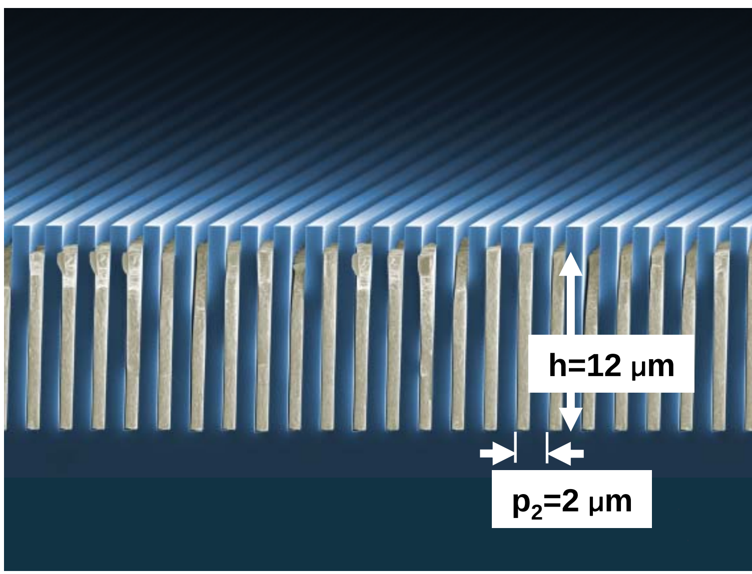
Differential phase contrast imaging

X-ray grating interferometry



beam splitter grating G_1

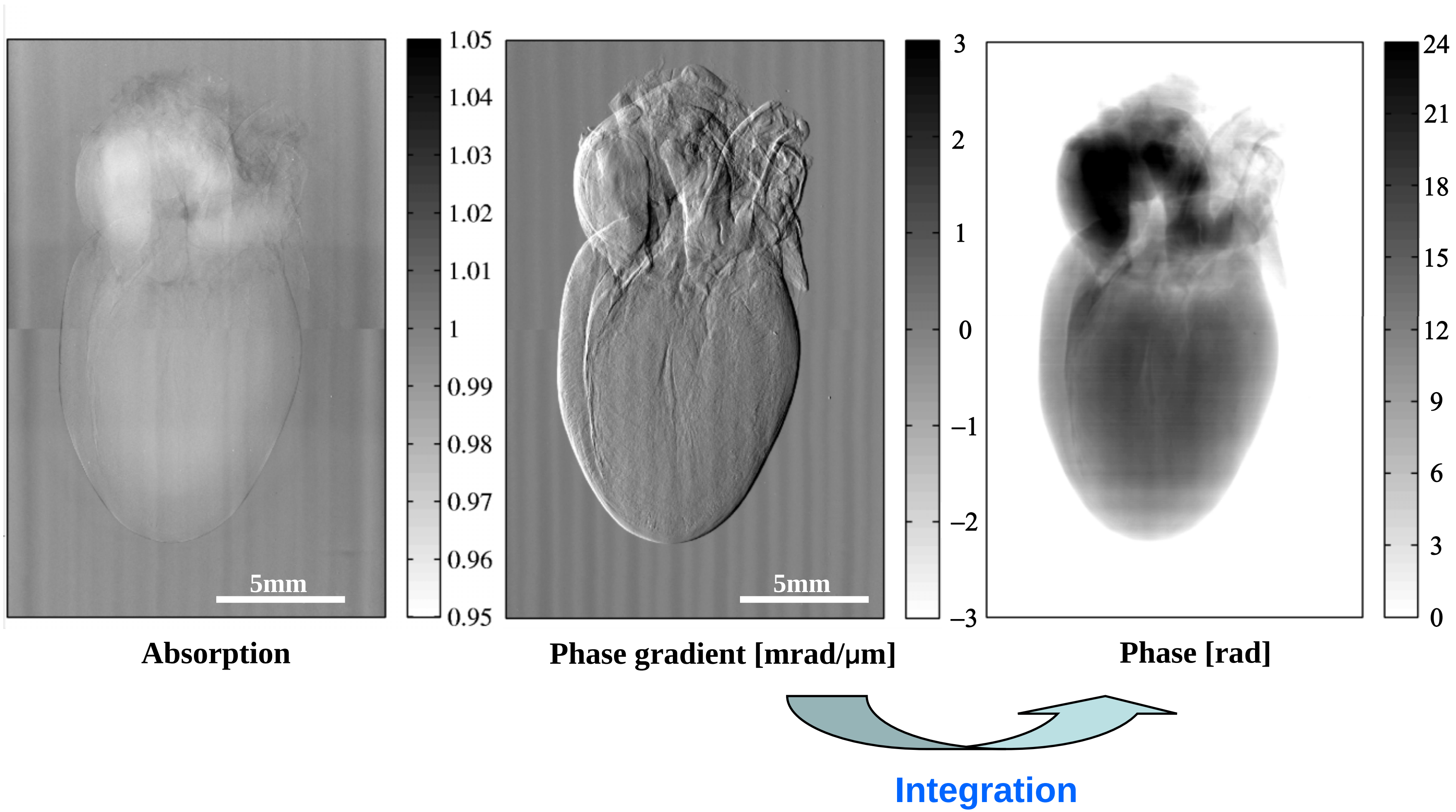




analyzer grating G_2

Phase contrast imaging

Rat heart in formalin solution, ESRF, ID19, 17.8 keV

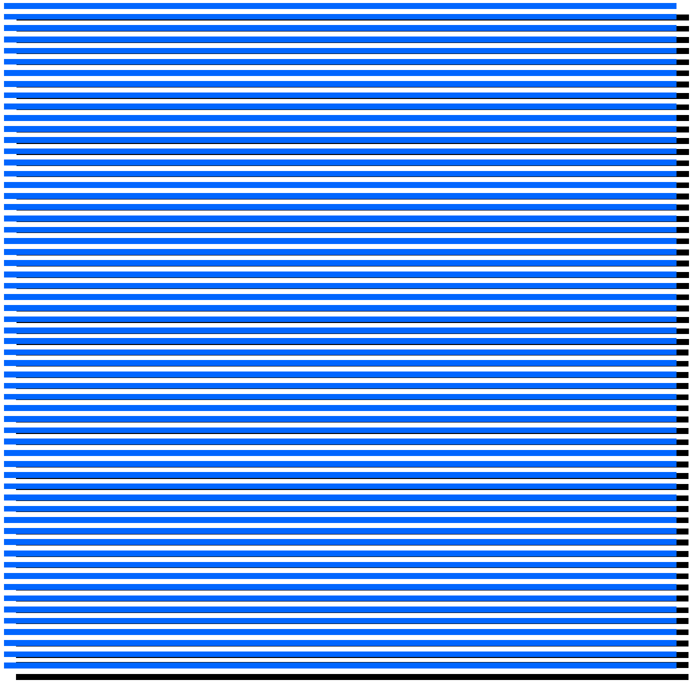


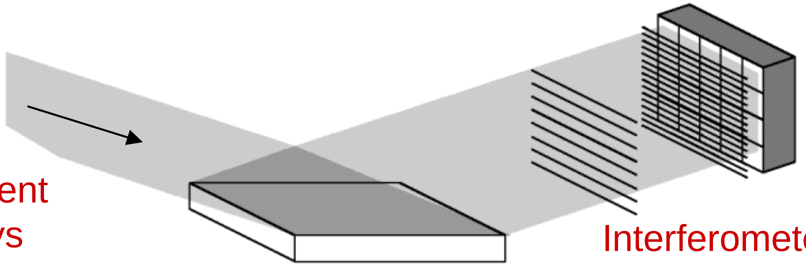
Mirror metrology

T. Weitkamp, B. Nöhammer, A. Diaz, C. David, E. Ziegler

X-ray wavefront analysis and optics characterization with a grating interferometer

Appl. Phys. Lett. 86 (2005) 054101





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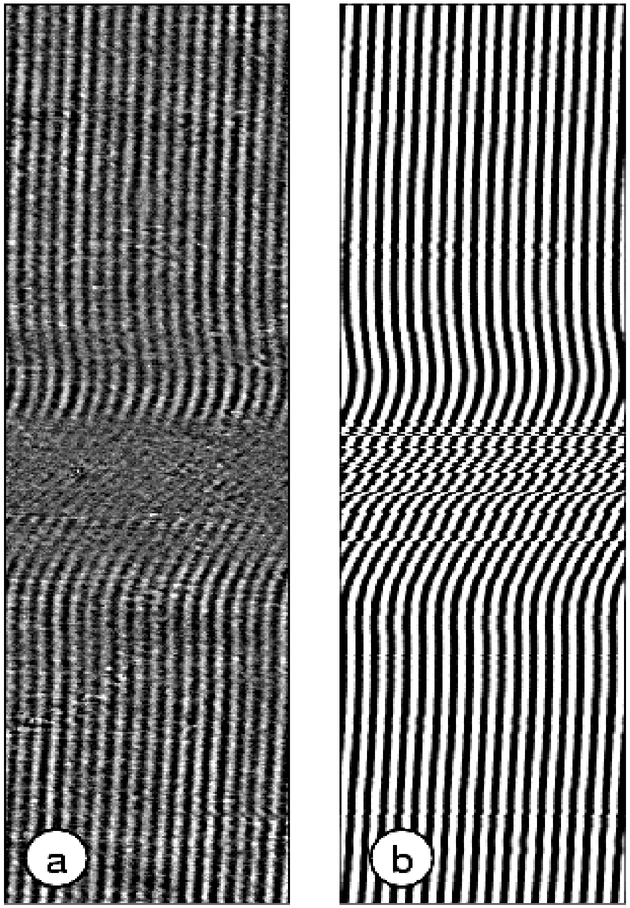
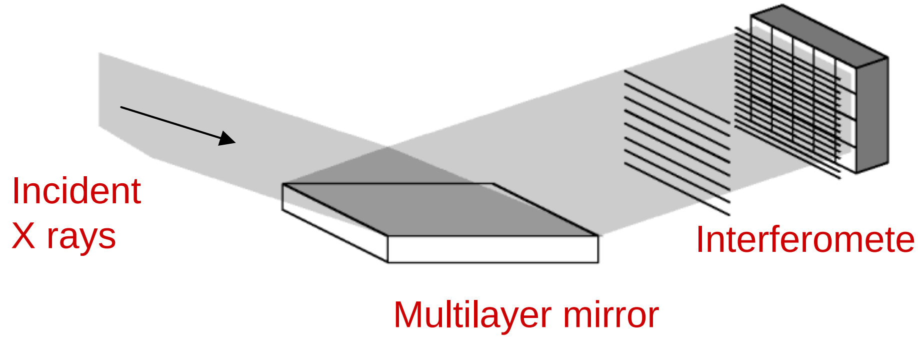
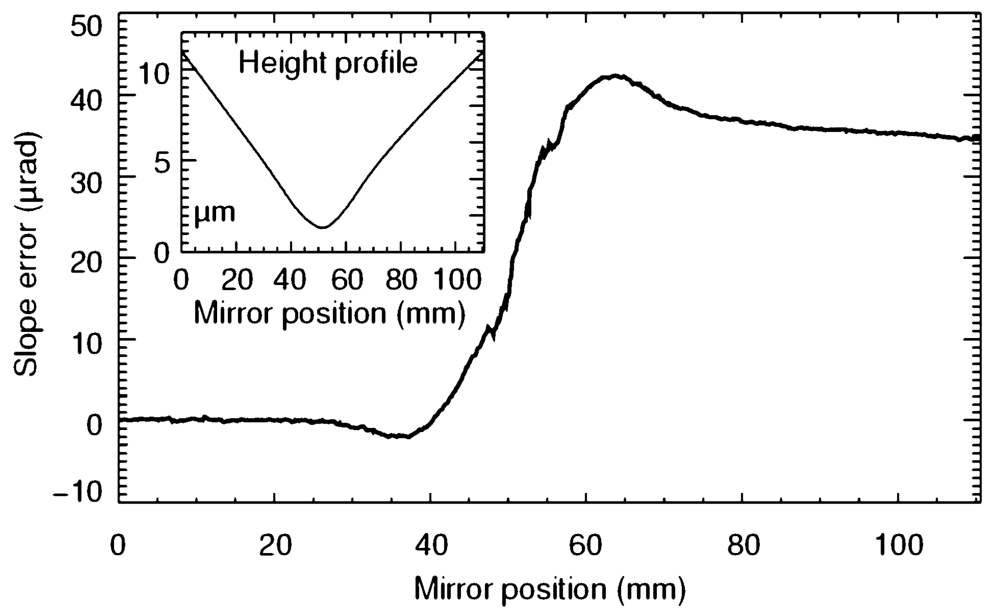


detected interferogram

analyze main Fourier component





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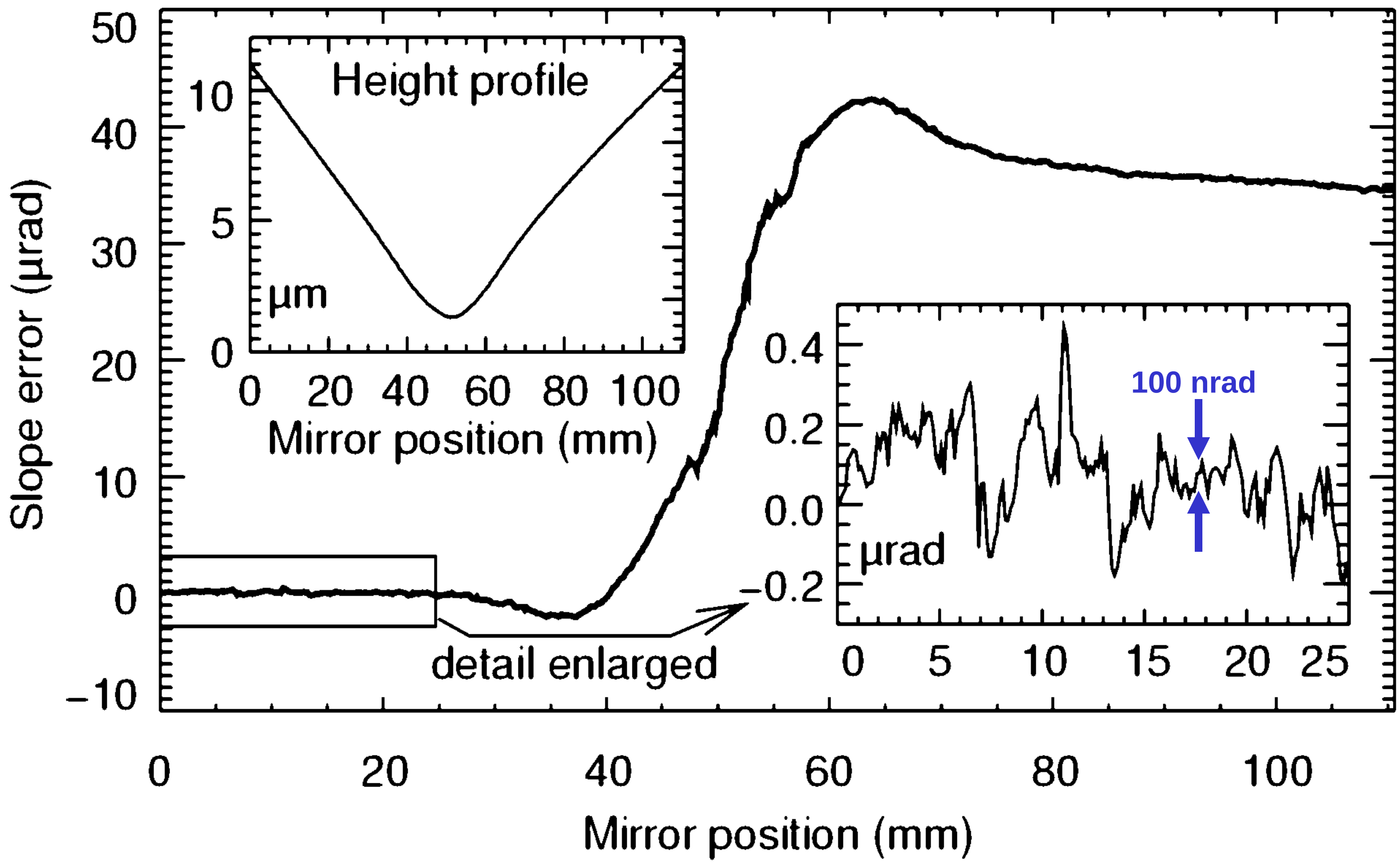
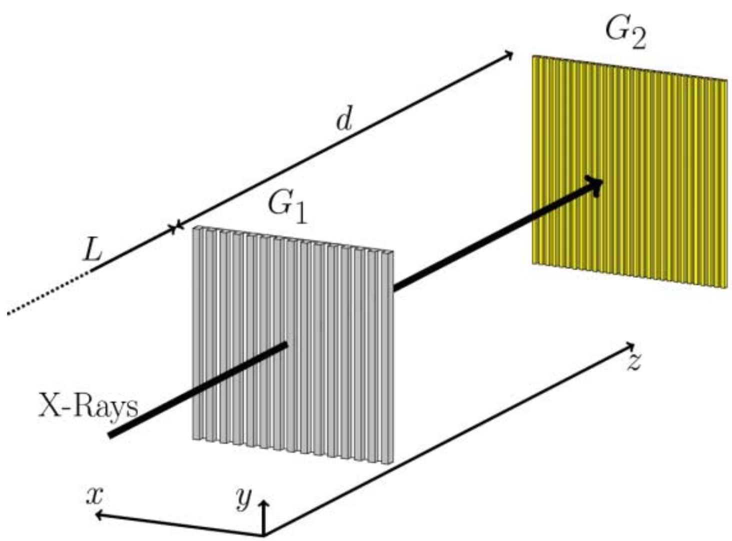
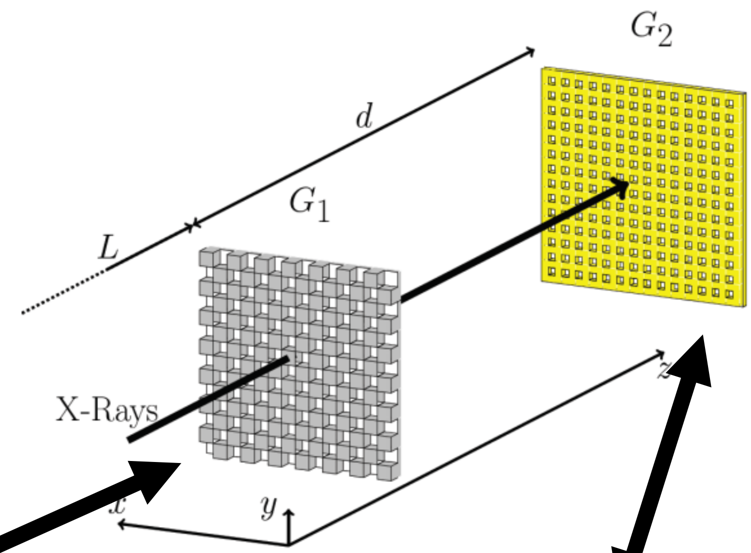


From 1D to 2D….





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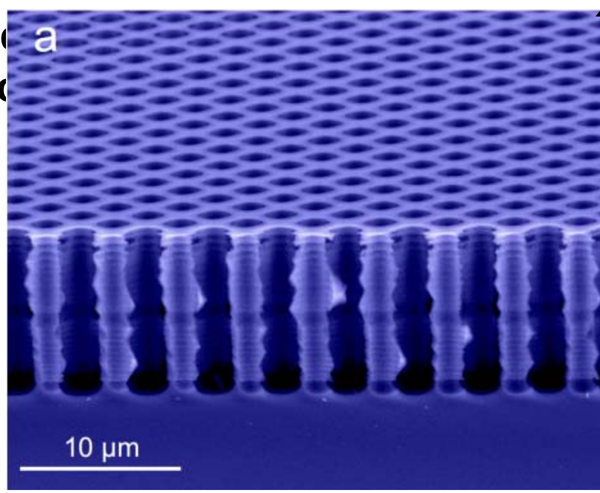
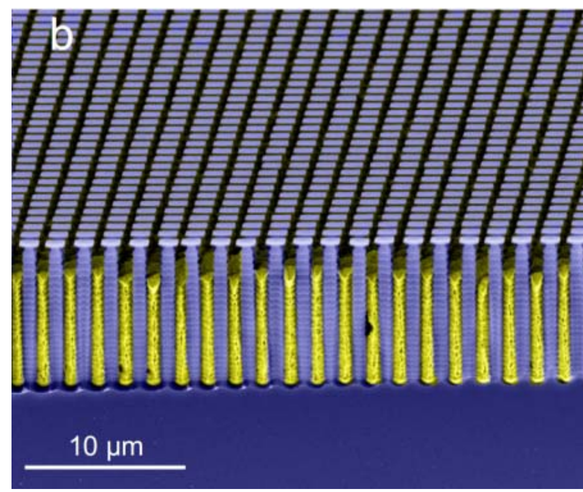




In-situ measurement of heat load effects on a DCM

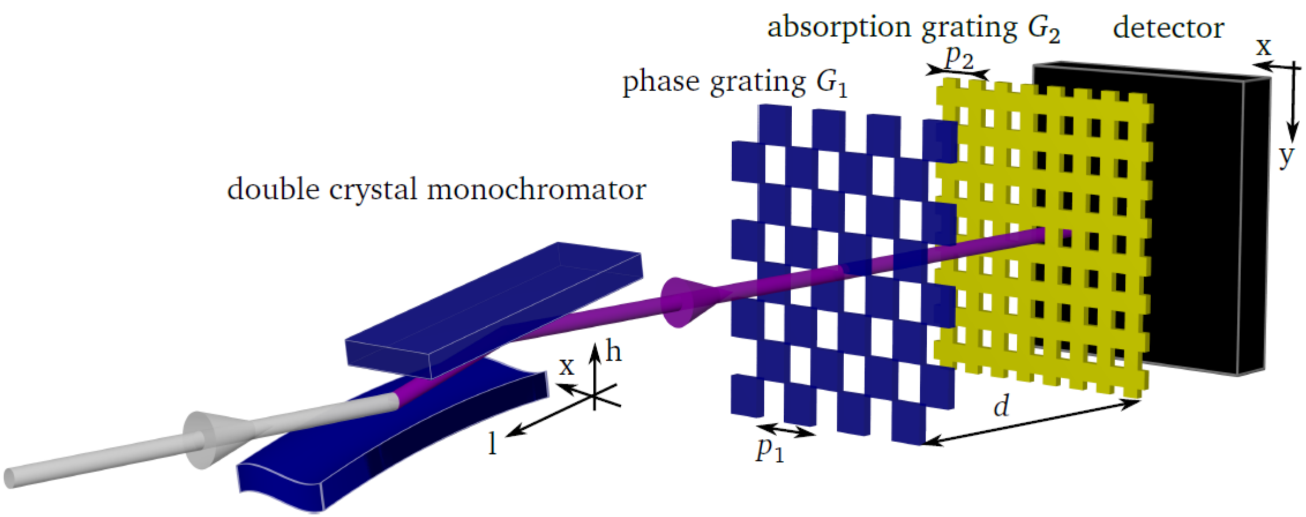
with S. Rutishauser, Y. Kayser (PSI) A. Rack (ESRF-ID19), T. Weitkamp (SOLEIL), A.T. Macrander (APS)

Goal:

In-situ observation of heat-load induced deformations of a DCM („heat bump“)

Experimental parameters:

- **Photon energy: 17.6 keV**
- **Interferometer:** **p_1=4.785 μm, p_2=2.4 μm, d=448 mm**
- **Wiggler source, P= 0-40 W**
- **Source distance: 150 m**



Set-up at ESRF ID19

(S. Rutishauser et al., accepted in J. Synchrotron Rad.)

In-situ measurement of heat load effects on a DCM

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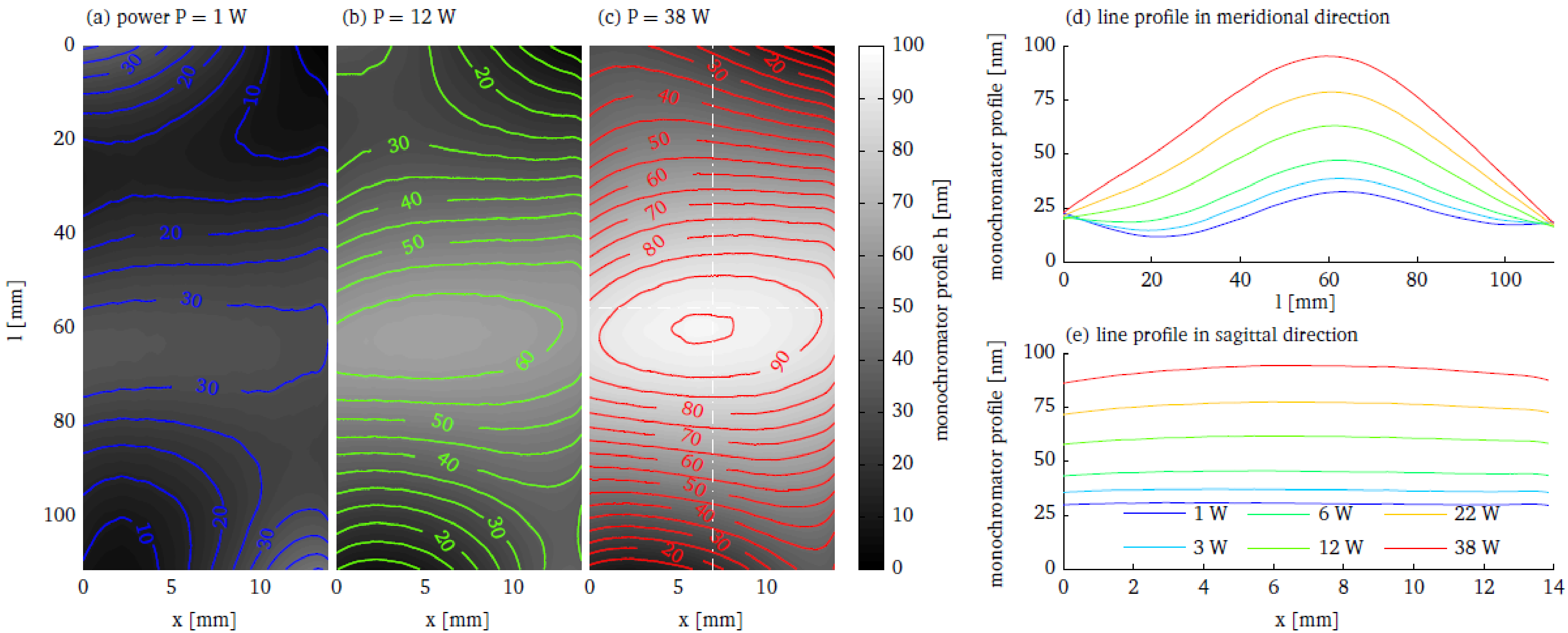
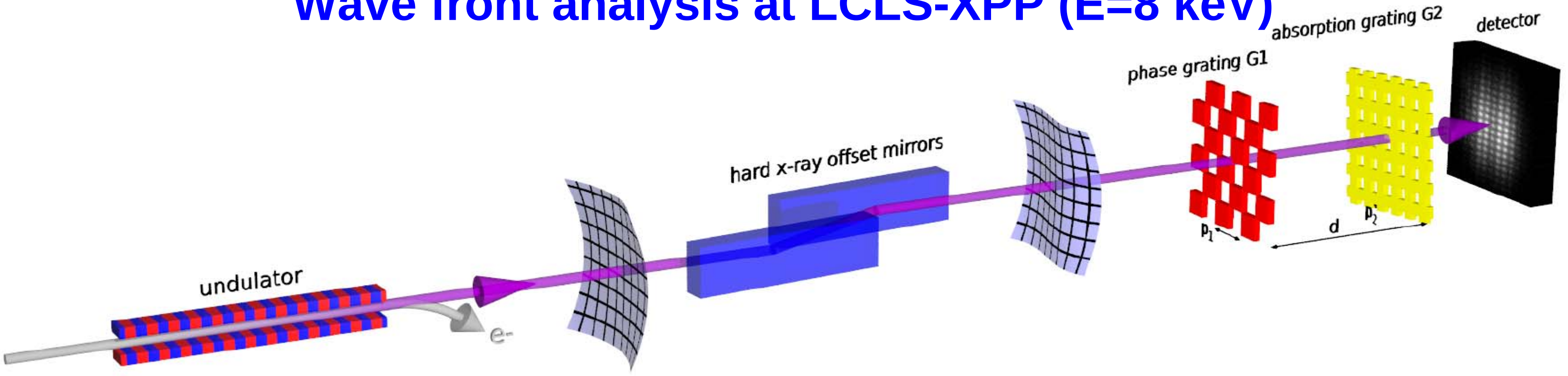


Crystal shape for 1 W, 12 W and 38 W incident power

(S. Rutishauser et al., accepted in J. Synchrotron Rad.)

Wave front analysis at LCLS-XPP (E=8 keV)



nature COMMUNICATIONS

ARTICLE

Received 3 Apr 2012 | Accepted 11 Jun 2012 | Published 10 Jul 2012

DOI: 10.1038/ncomms1950

Exploring the wavefront of hard X-ray free-electron laser radiation

Simon Rutishauser[1], Liubov Samoylova[2], Jacek Krzywinski[3], Oliver Bunk[1], Jan Grünert[2], Harald Sinn[2], Marco Cammarata[3], David M. Fritz[3] & Christian David[1]

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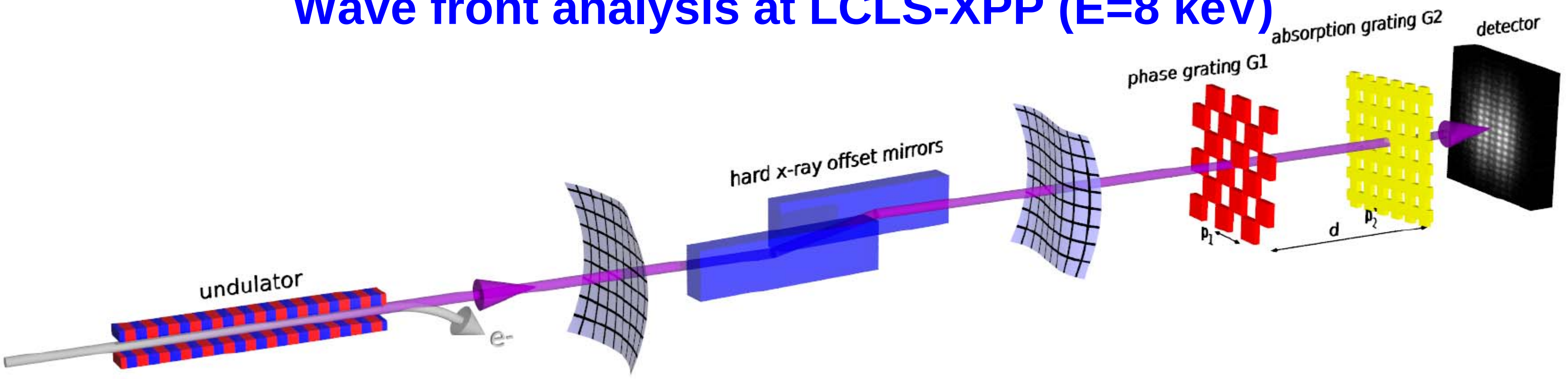
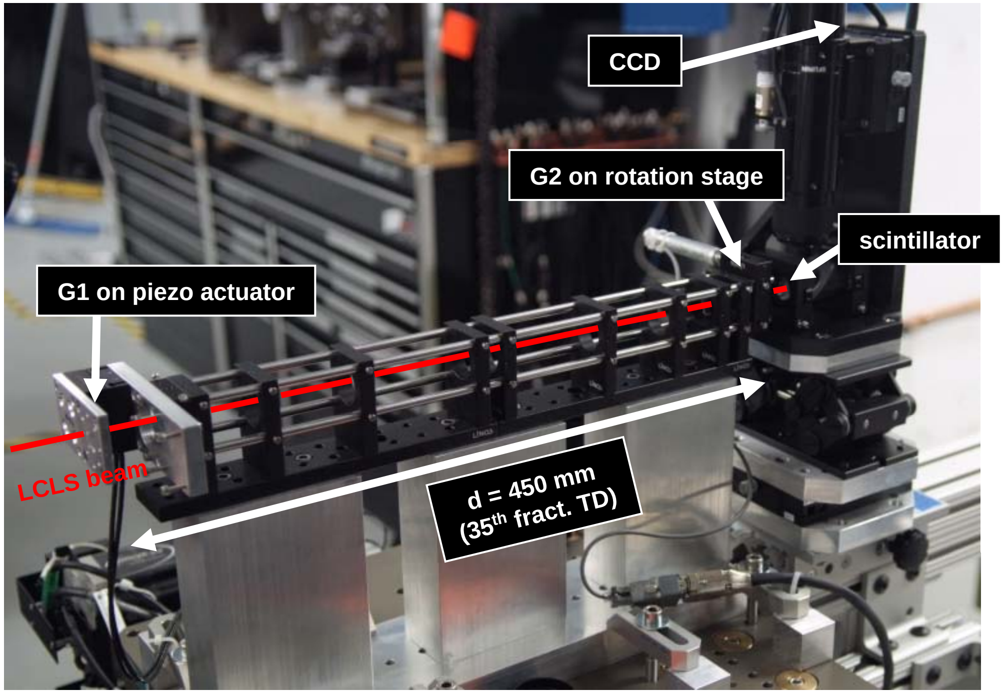
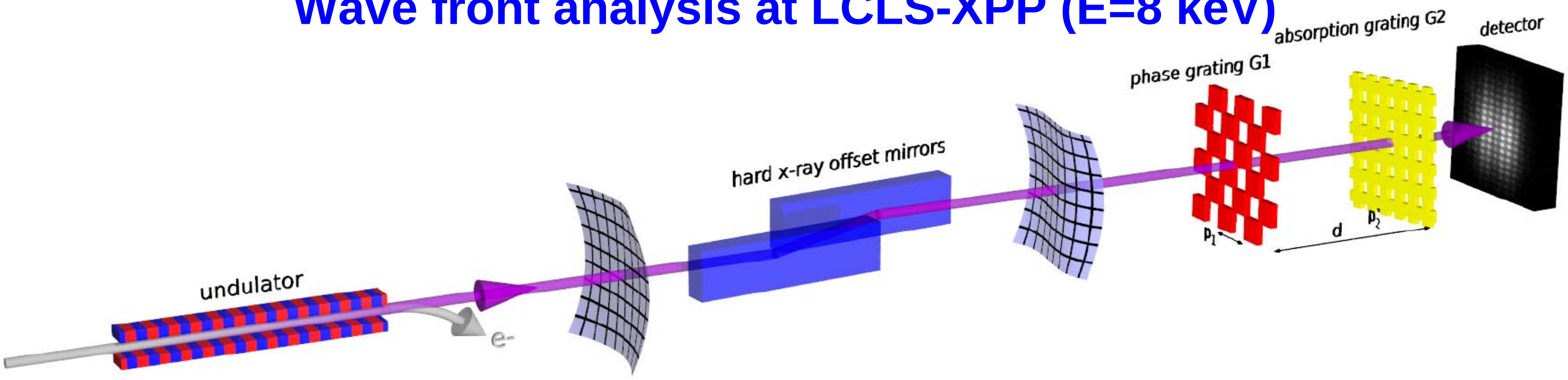


Goals:

- Single-shot investigation of *source point stability*
- *Effects of machine parameters* (e.g. driving laser into saturation)
- Single-shot measurements of the *wave front aberrations* caused by optical components



Wave front analysis at LCLS-XPP (E=8 keV)



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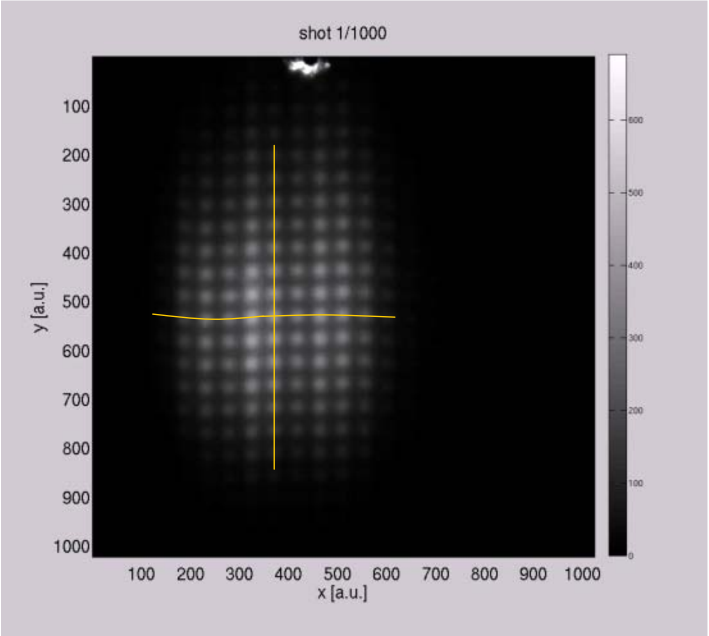
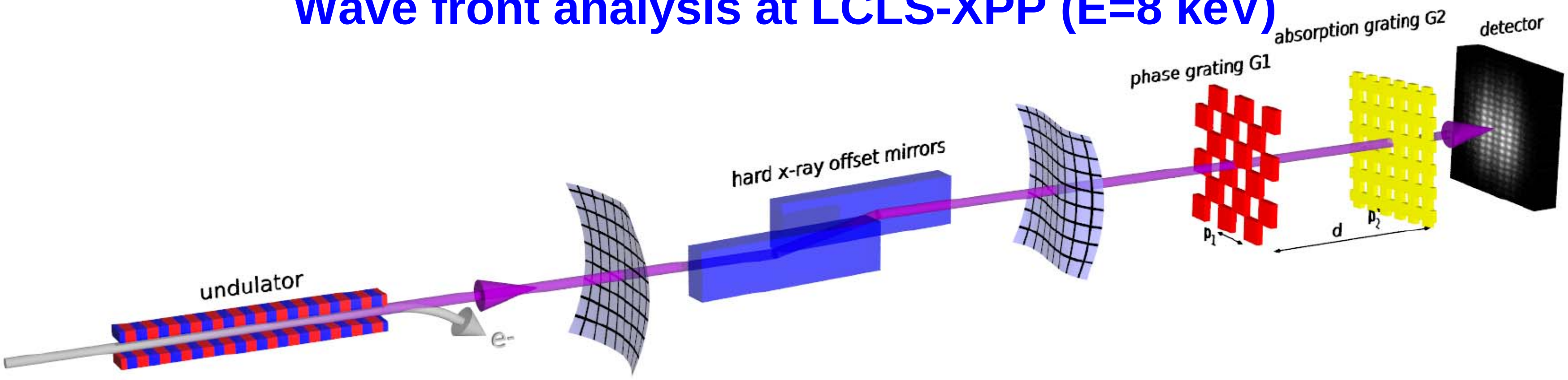
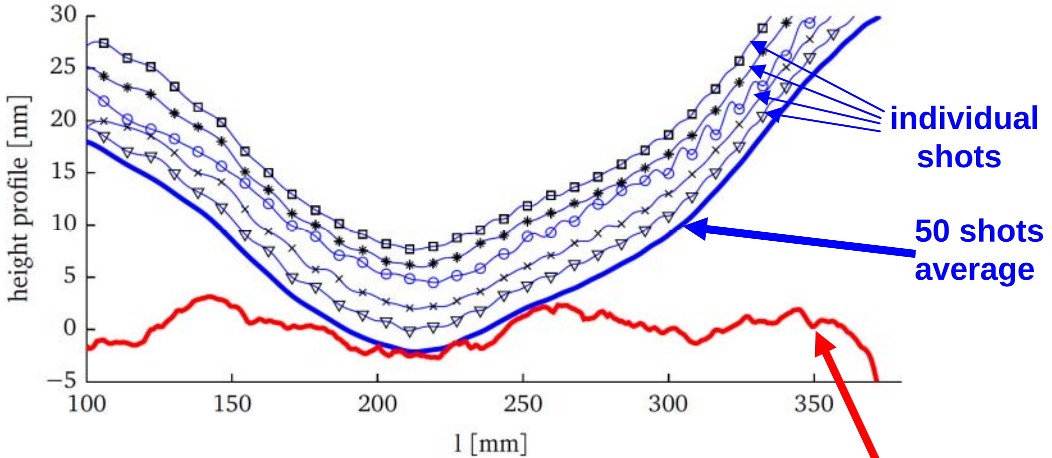


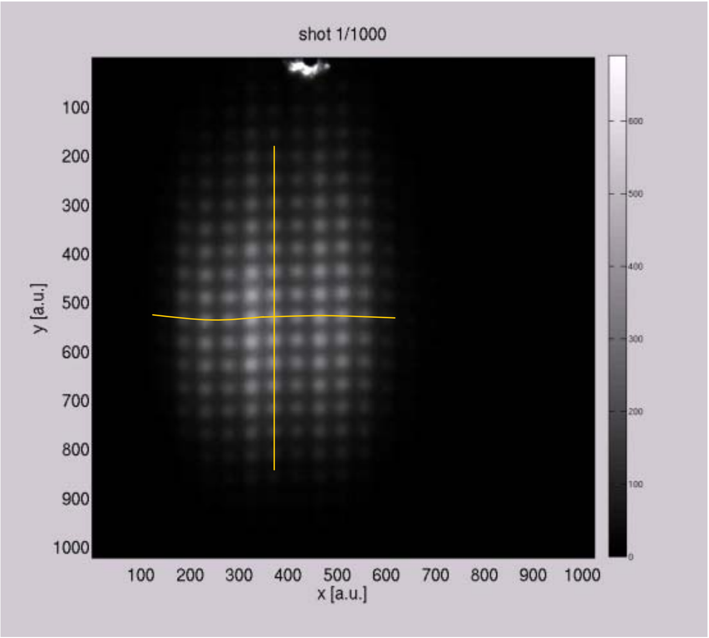
Field of view ≈ 1mm x 1mm

Wave front analysis at LCLS-XPP (E=8 keV)



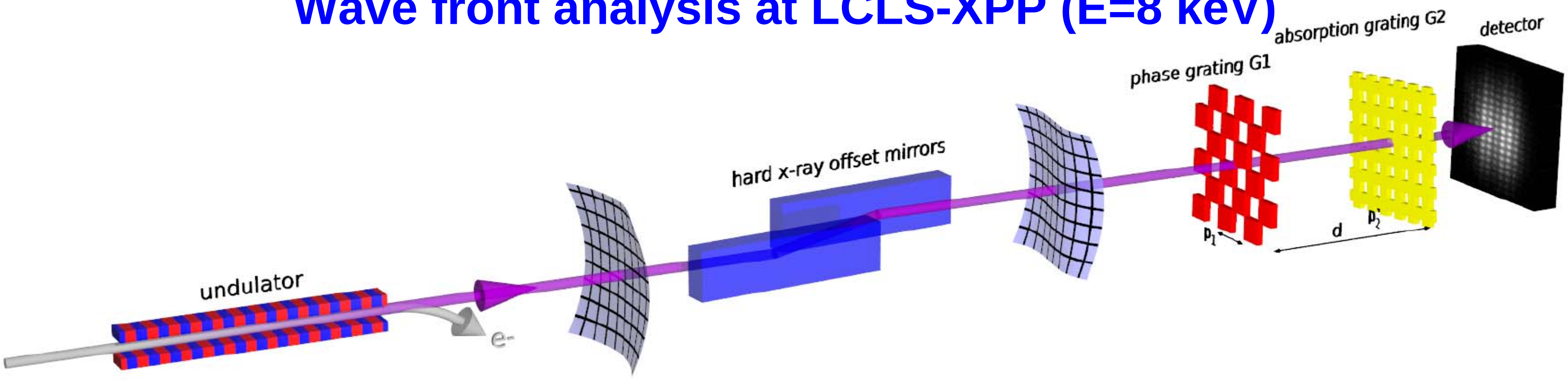


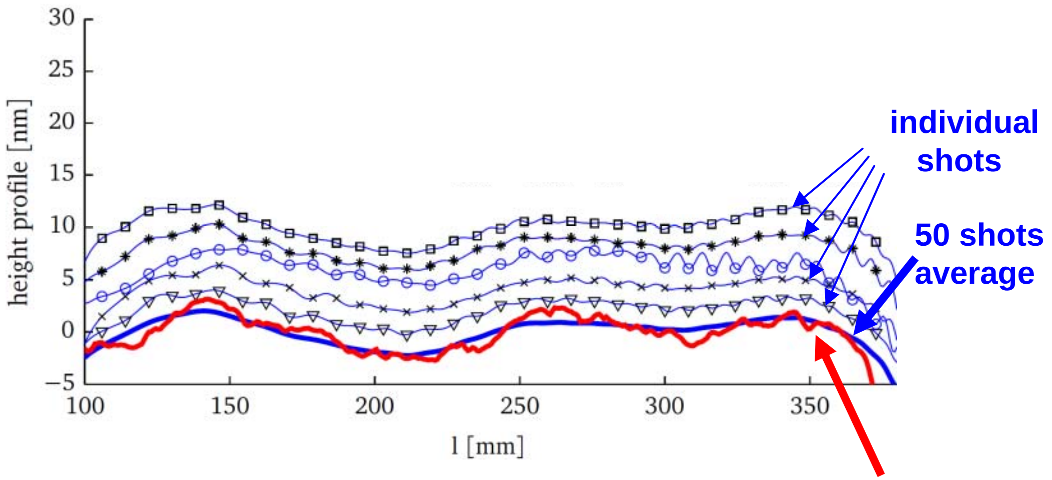
height profile of combined mirrors



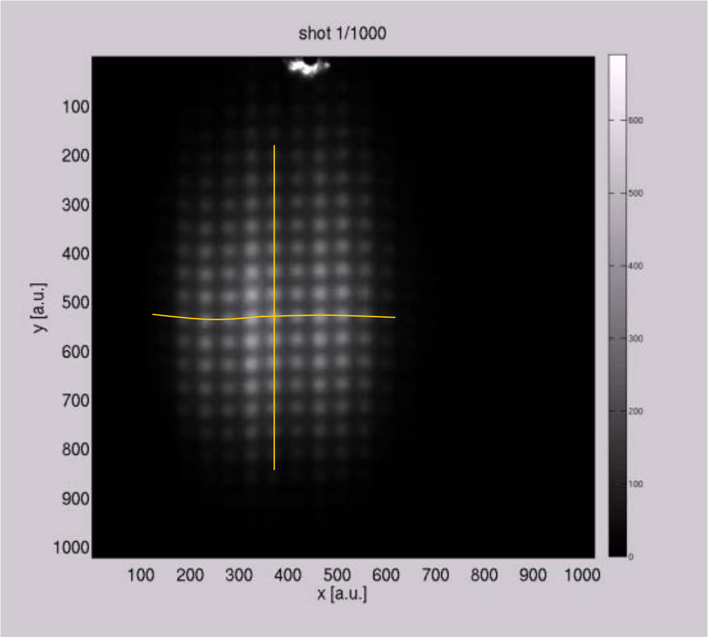
Field of view ≈ 1mm x 1mm

Wave front analysis at LCLS-XPP (E=8 keV)





height profile of combined mirrors
aspheric component only



Field of view ≈ 1mm x 1mm

- **Collimating effect of HOMS: 30 nm shape error**
- **Aspheric component of mirror profile: 5 nm, matches LTP**
- **In-situ, single-shot metrology with angular sensitivity *down to ~10 nrad***

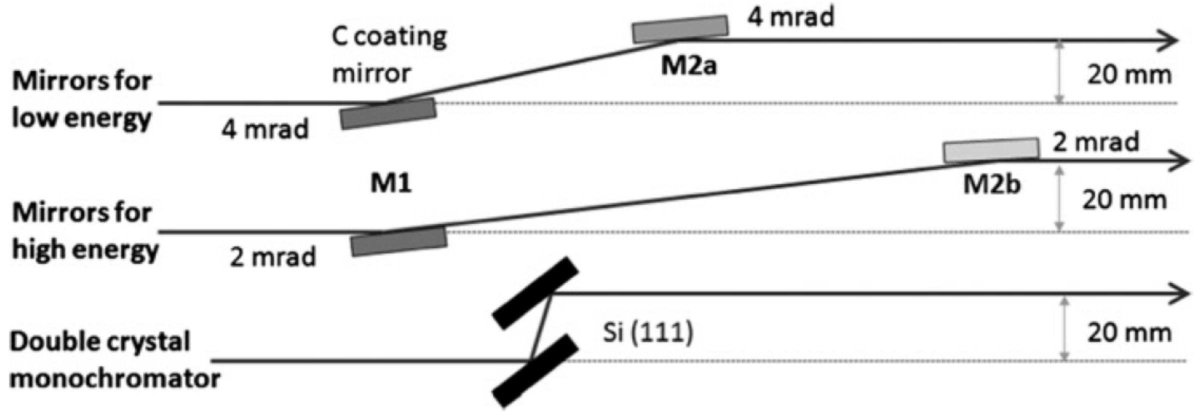
Wave front analysis at SACLA

with T. Katayama, M. Yabashi, H. Ohashi

E<7.5 keV

E>7.5 keV

4 keV < E <30 keV

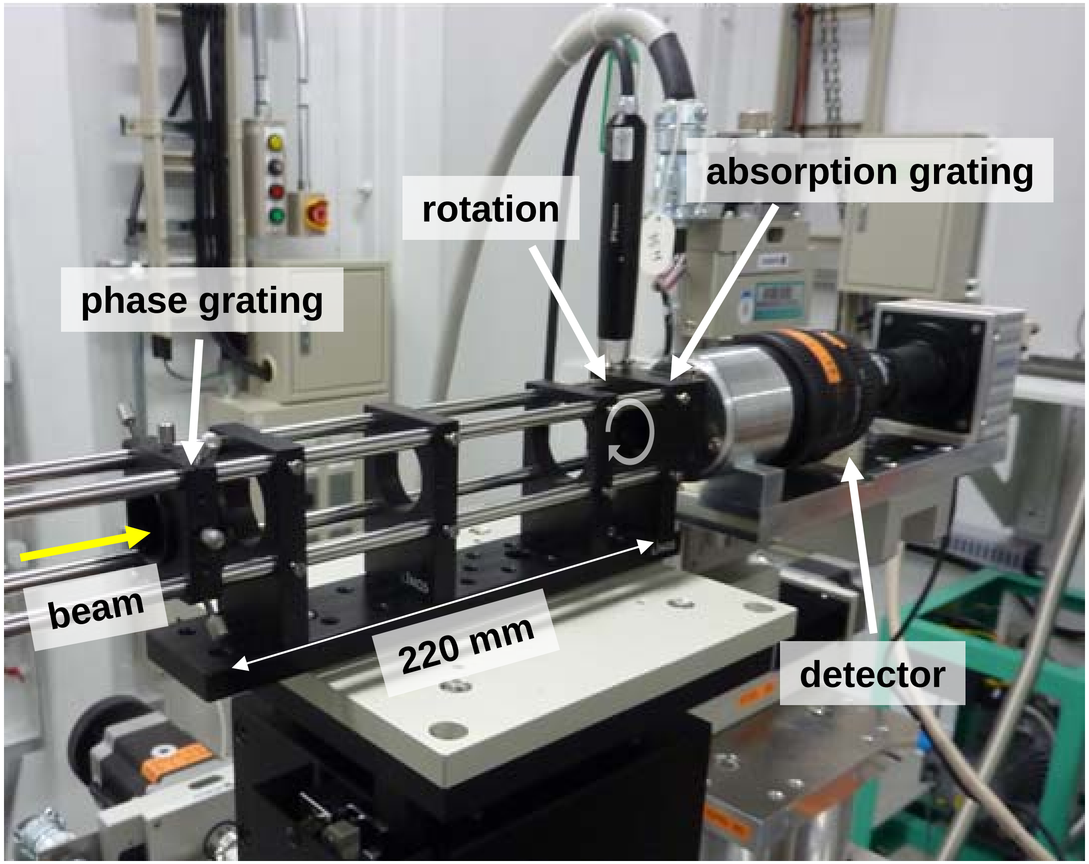


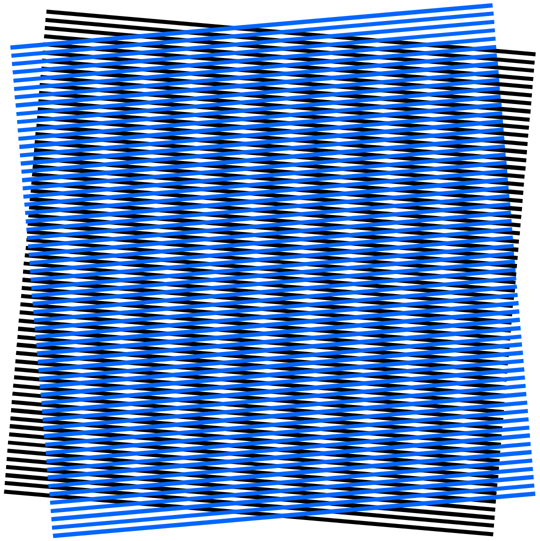
Beamline optics at SACLA. The beam is deflected in vertical direction.

(from H. Ohashi et al., NIMA 2012, in press)

Wave front analysis at SACLA

with T. Katayama, M. Yabashi, H. Ohashi



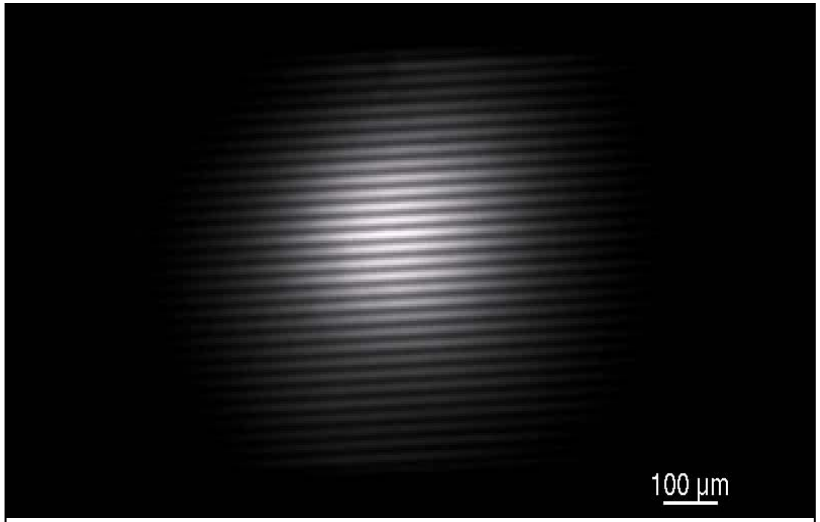


Measurement: observe angle of moiré fringes while rotating grating

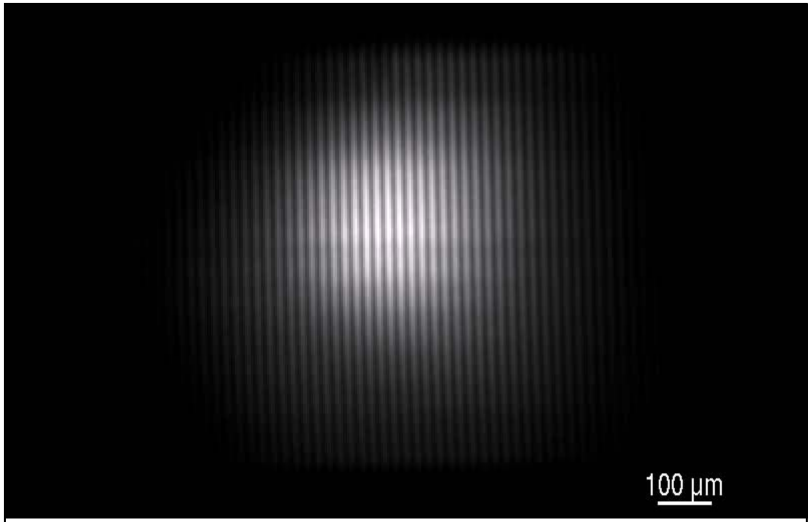
Radius of curvature (ROC) of the wavefront

Wave front analysis at SACLA

with T. Katayama, M. Yabashi, H. Ohashi



vertical orientation of grating lines



horizontal orientation of grating lines

horizontal ROC: R_x = 156 m

corresponds to expected source distance

vertical ROC: R_y = 74 m

mirrors have slightly defocusing effect

Shape of J-TEC mirrors?

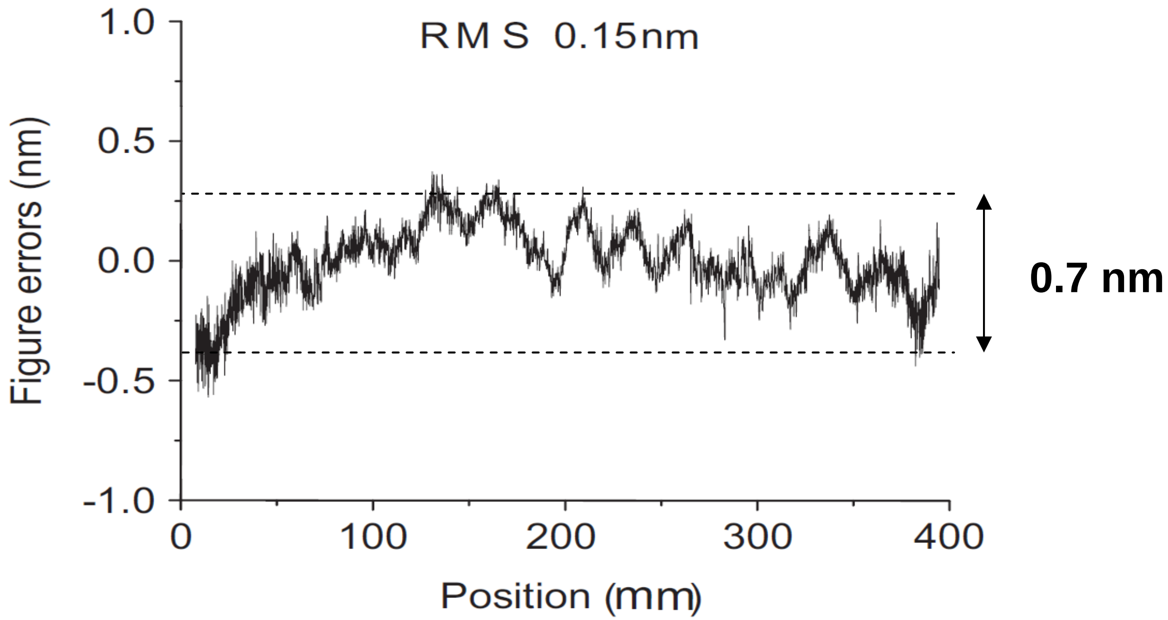
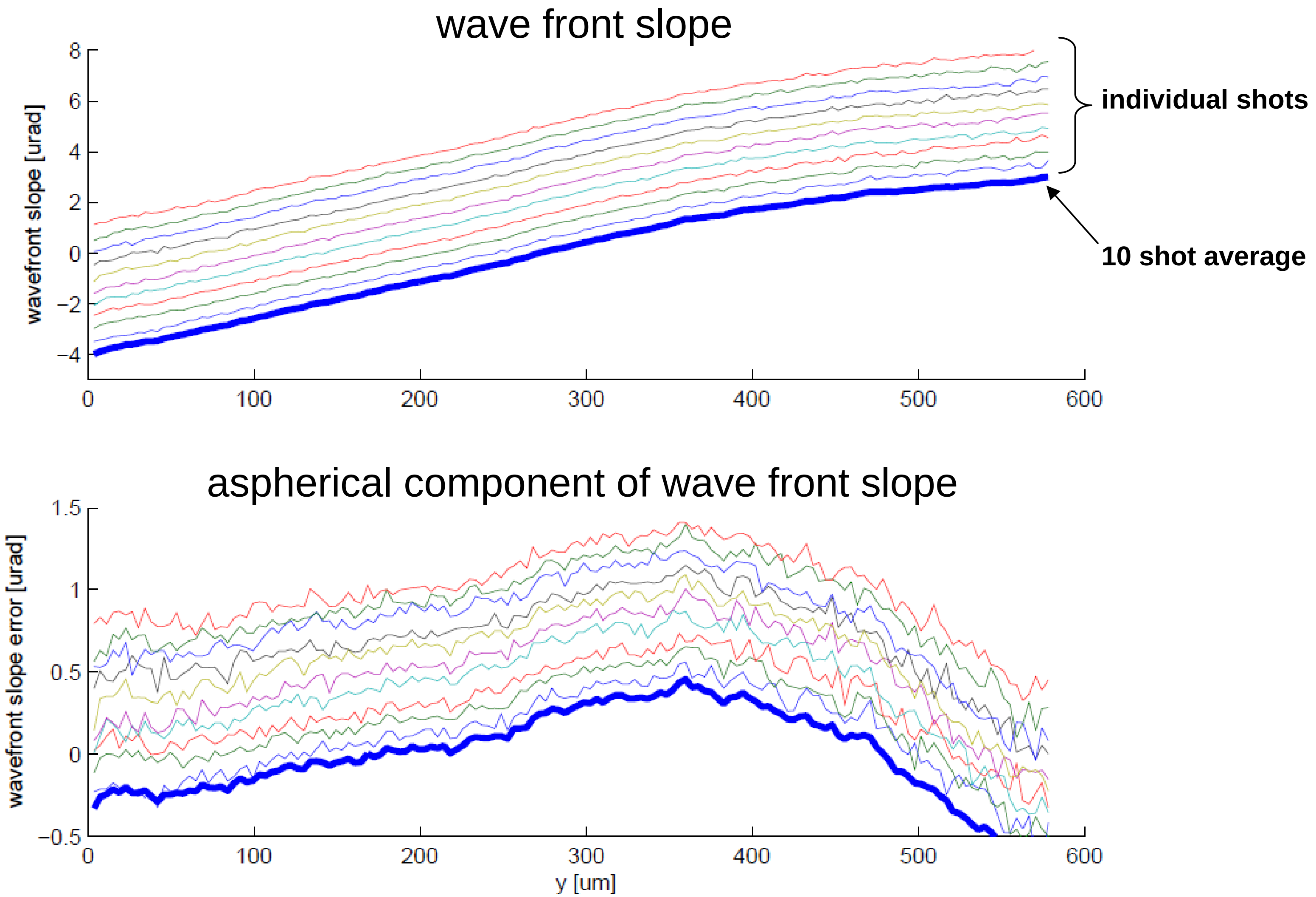


Figure error of J-TEC mirror M2a
measured ex-situ with stitching interferometry
(from H. Ohashi et al., NIMA 2012, in press)

Grating inteferomety results: mirrors M1 & M2b

Photon energy: 12.4 keV



Grating inteferomety results: mirrors M1 & M2b

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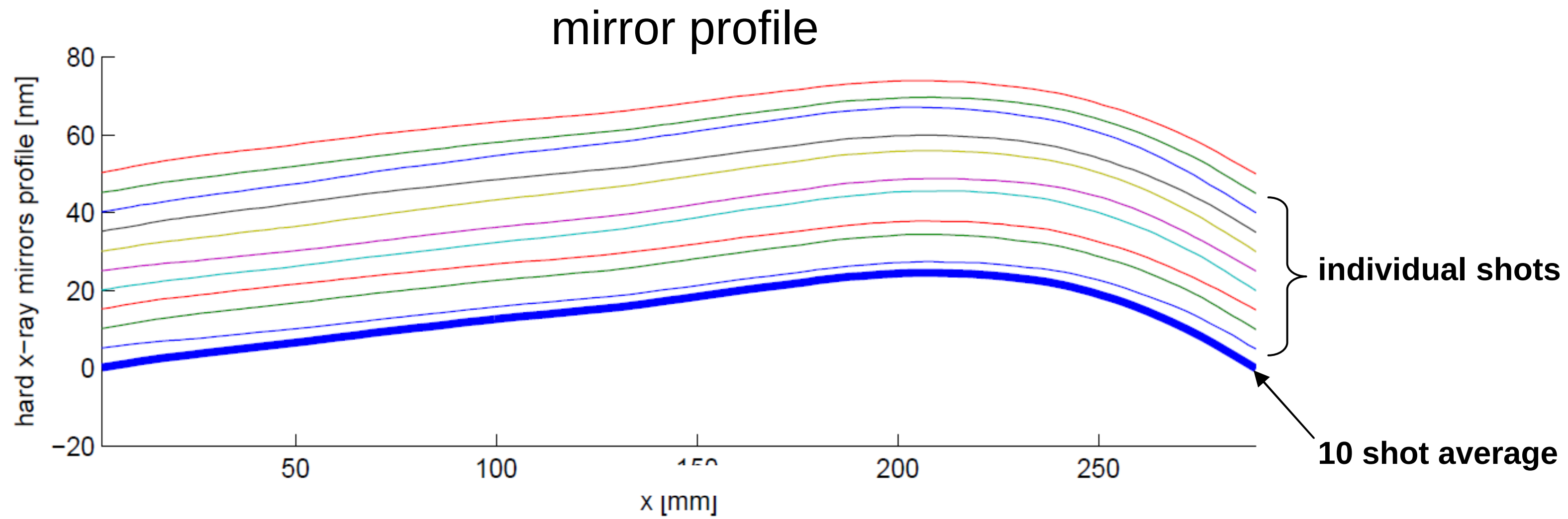
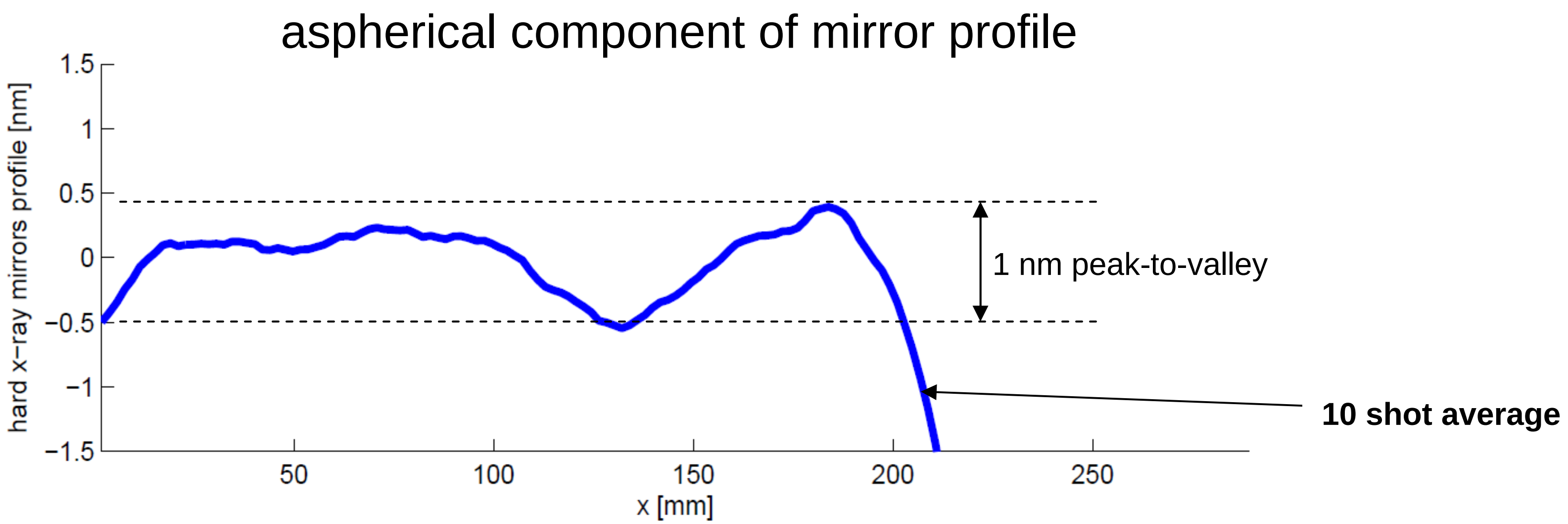


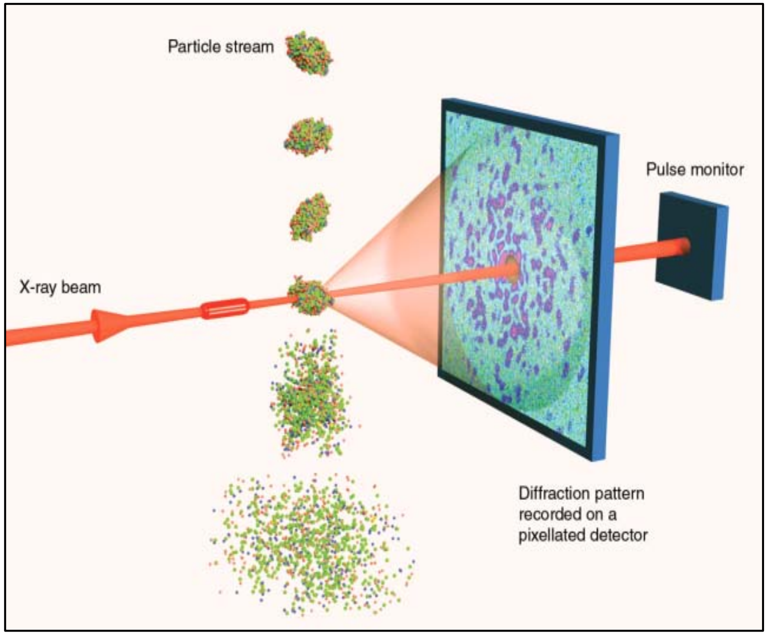


Wave-front sensor at European XFEL

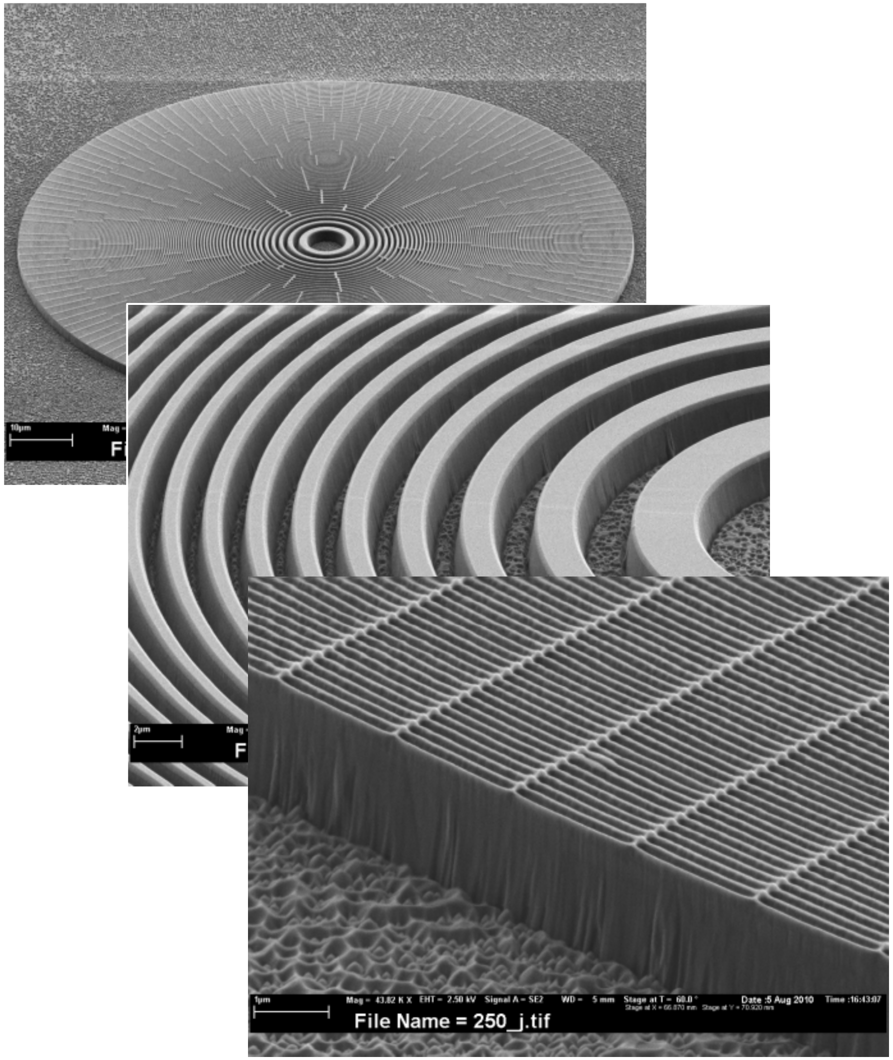
- Simple, robust, light-weight device
- Could be easily used as (invasive) diagnostics tool
- Could be installed downstream of a (running) experiment
- Provides information on optics and source
- Speed is limited by detector
- Radiation load may require other materials
  when running at full pulse rate

Part 2 – A grating-based spectral monitor

- We developed zone plates for nanofocusing of hard XFEL radiation
- Advantages: high resolution, simplicity, clean wave front
- Problem: radiation damage



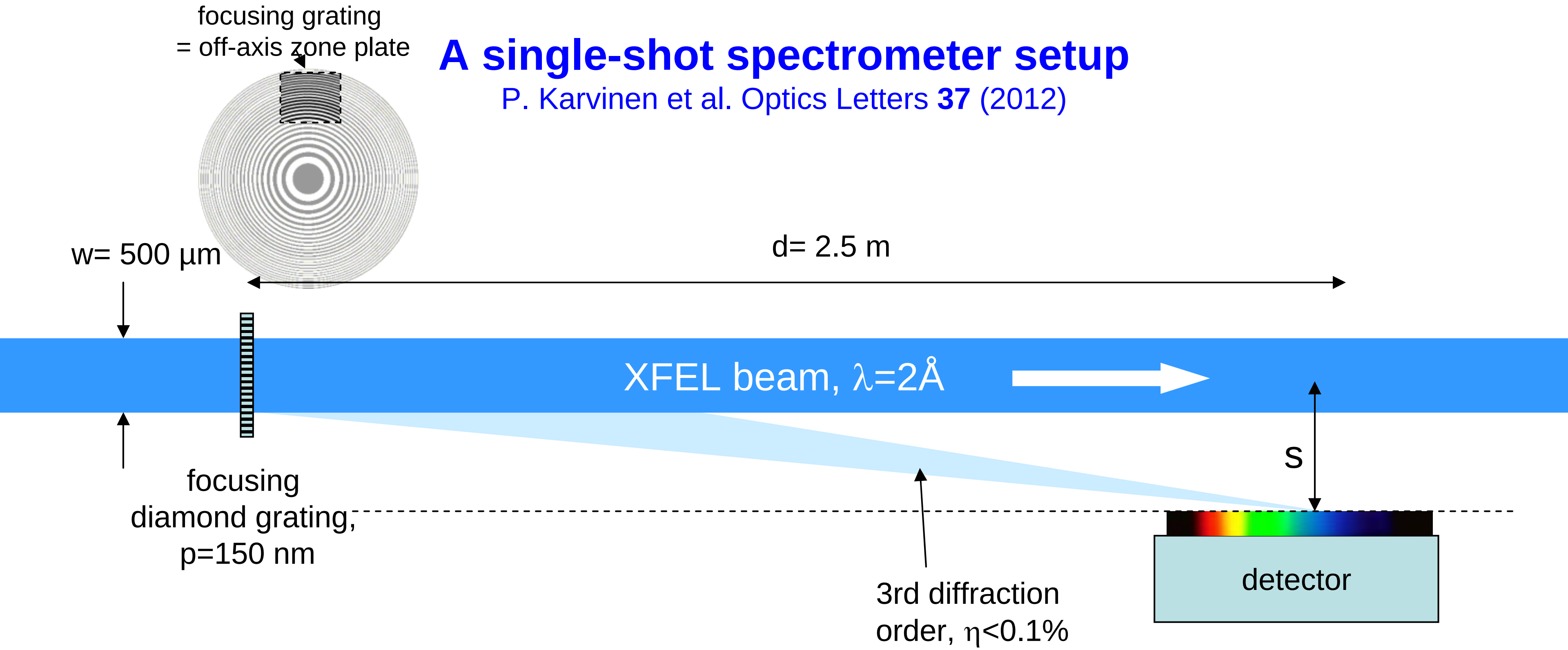
***(K. J. Gaffney and H.N. Chapman, Science* 316 (2007) 1444)**



Zone plate structures (100 nm wide, 2 µm high) etched into diamond

A single-shot spectrometer setup

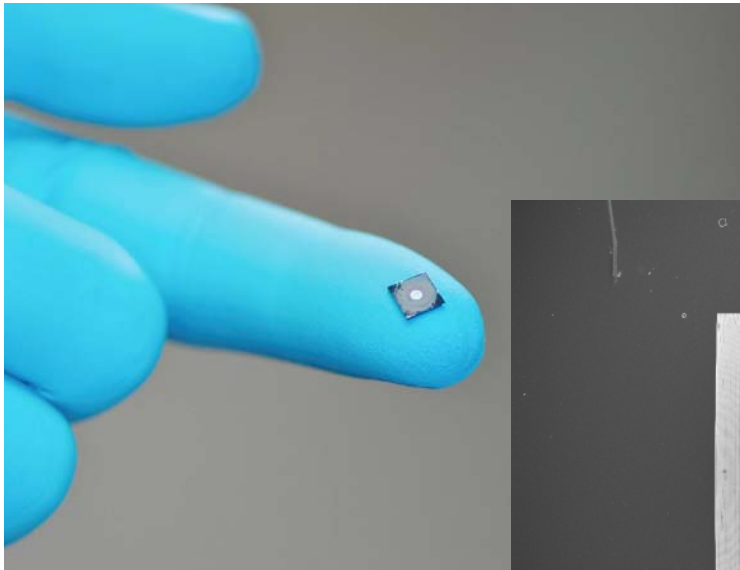
P. Karvinen et al. Optics Letters **37** (2012)

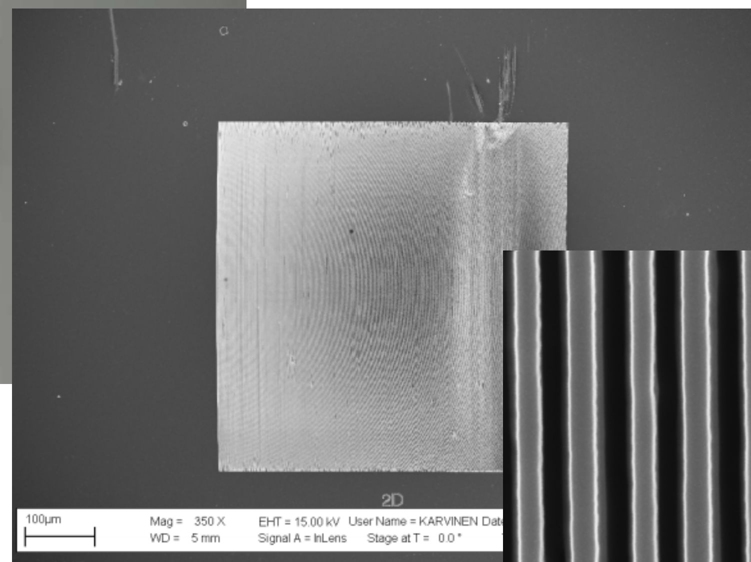


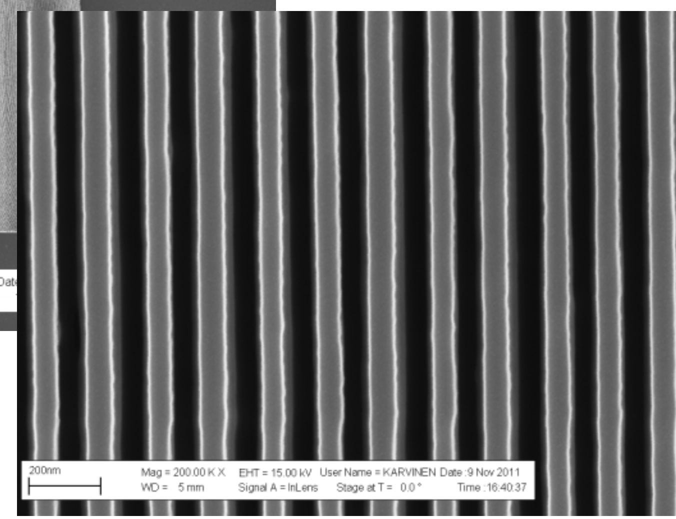
diffraction angle:	**$\alpha = \lambda/p$ = 4 mrad**
separation:	**$s = d \times \alpha$ = 10 mm**
diffraction limit of spectral resolution (equal to number of lines x diffraction order):	**$\lambda/\delta\lambda$ = 10'000 => δE = 0.6 eV**
Used detector:	**GOTTHARD strip detector, 50 µm pitch**

A single-shot spectrometer setup

P. Karvinen et al. Optics Letters **37** (2012)

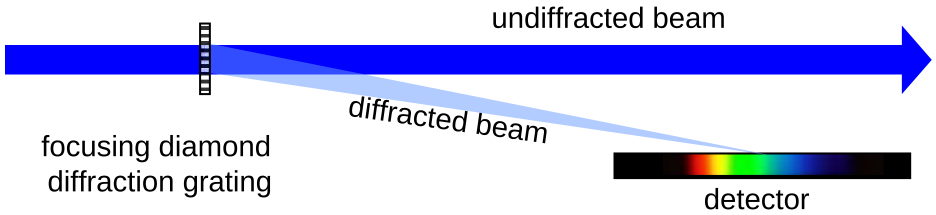


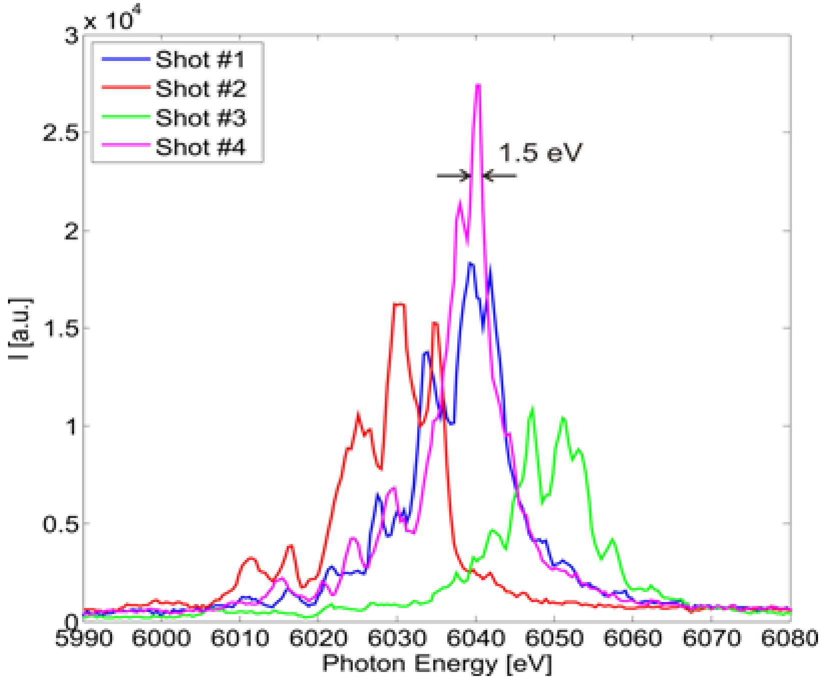




Diamond grating with p=150 nm
etched into a 5 µm thick diamond membrane

Shot-to-shot spectral analysis

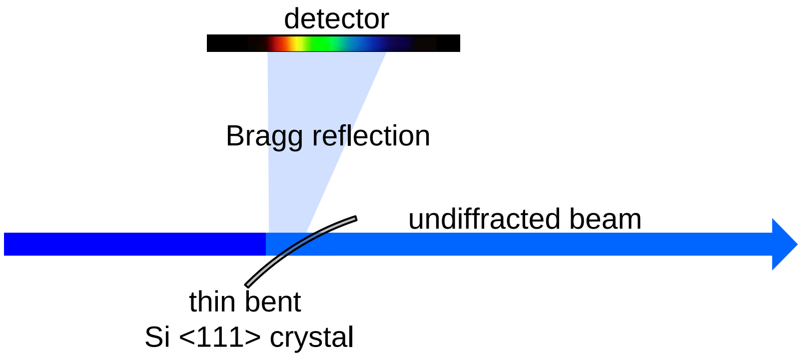


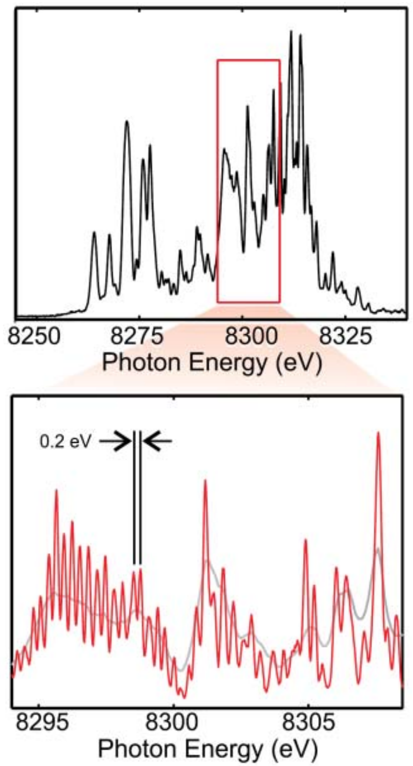


- Spectral resolution of 1.5 eV (close to diffraction limit)
- Simple, robust, radiation-hard,…
- *Problem 1:* Focal length of grating changes proportional to photon energy.

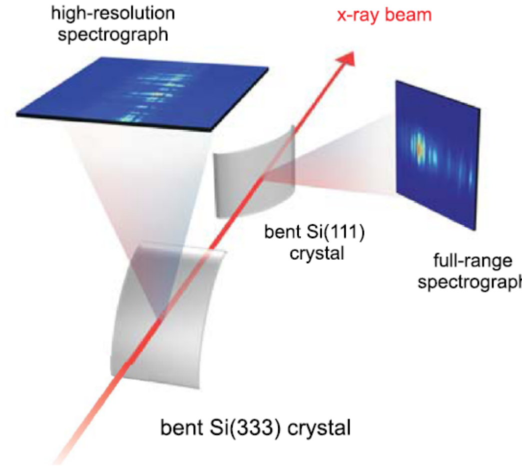
  => need to move components over large distances to cover wide range
- *Problem 2:* Detector resolution degrades at higher energies under shallow incidence

Shot-to-shot spectral analysis



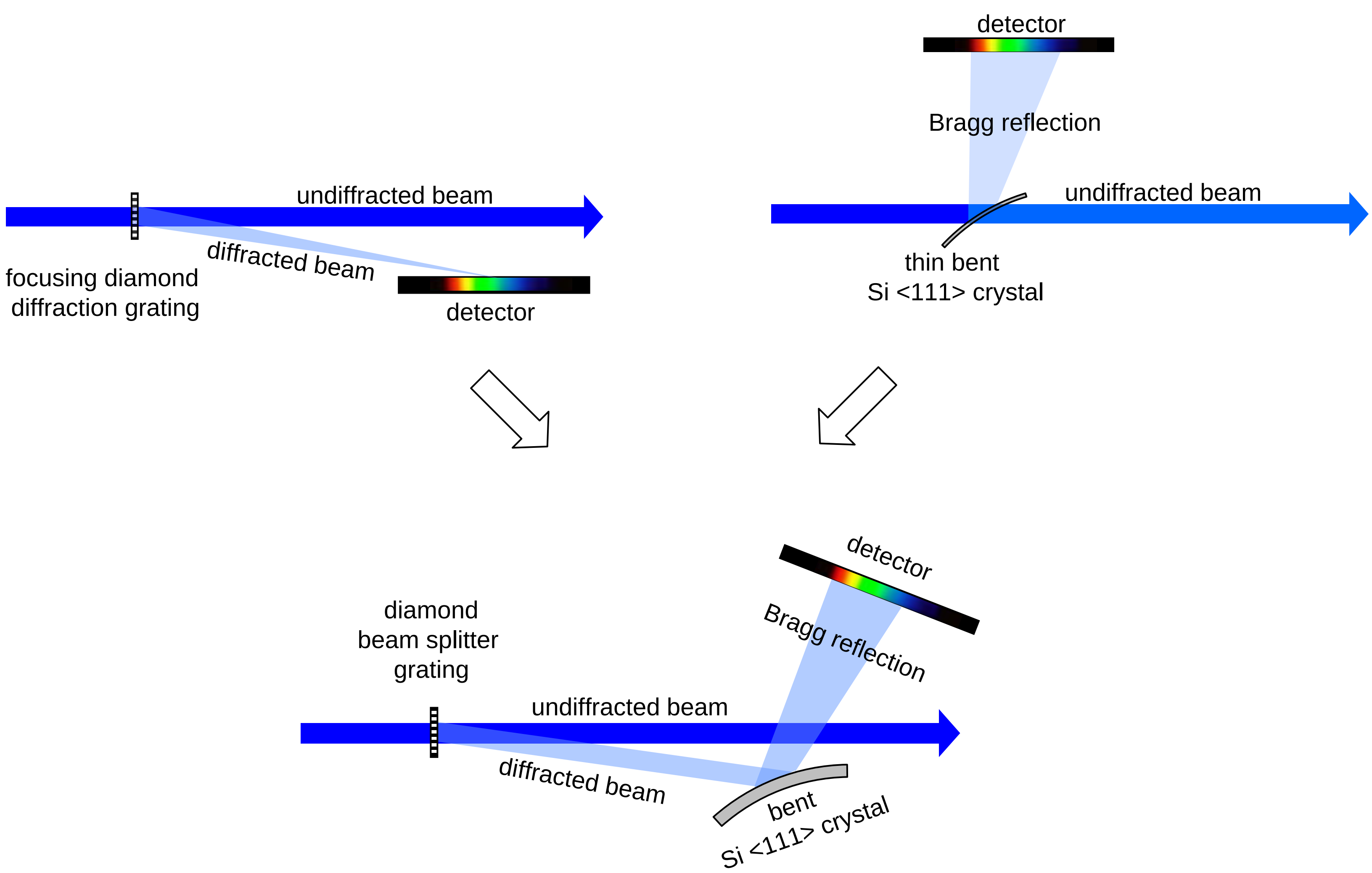


D. Zhu et al., APL **101** (2012)



- **Alternative: Spectrometer based on thin, bent Si crystal analyzer (developed by LCLS)**
- **Spectral resolution <u>down to 0.2 eV</u> @ 8 keV!!!**
- **Simple**
- ***Problem 1:* High losses (up to 50%), especially at high resolution (<333> reflection)**
- ***Problem 2:* will be damaged at the European XFEL**

Best of both worlds – a solution for XFEL.EU



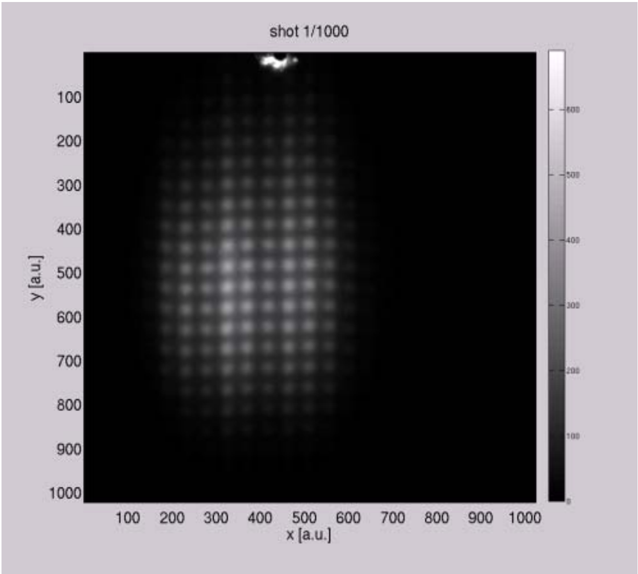
Best of both worlds – a solution for XFEL.EU

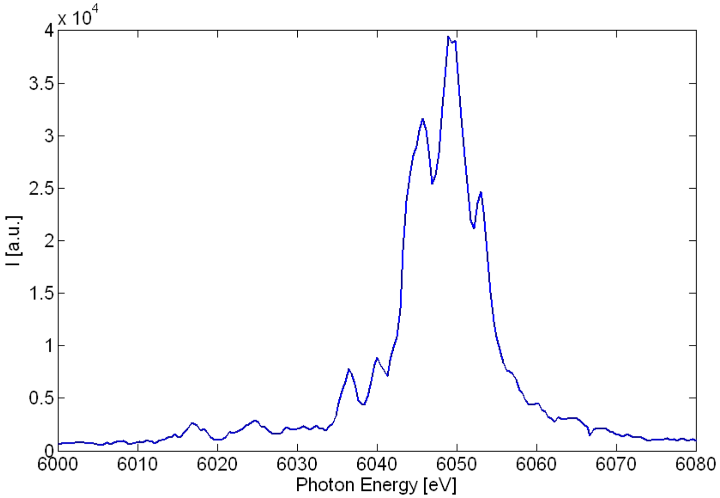
Problem:	**Solution:**
Speed	Gotthard has 1 MHz frame rate 5 MHz version under development
Non-invasive	OK – zeroth order wave of grating should not be affected
Radiation hardness	- Diamond should work for E>5 keV, SACLA proposal submitted to investigate damage - Silicon analyzer receives only small fraction of full beam (0.1%)
Tunability	5 keV – 15 keV should work, possibly extendable to higher energies
Resolution	excellent – Si crystal analyzer

=> LCLS proposal submitted for testing

=> In-kind contribution under preparation to develop a spectral monitor for XFEL.EU

Summary





Grating interferometry:

- Can measure wave front distortions with sensitivities of 10 … 100 nrad
- Can give in-situ, at-wavelength, single-shot information on the effect of optical elements
- Can provide diagnostics on the source like transverse and longitudinal jitter etc.

Grating based spectral monitor:

- Gives single-shot spectra
- Non invasive monitor
- Should be able to work with 4 MHz for energies E>4 keV
- Diamond gratings should be combined with bent silicon crystal analyzer