Propagation of Coherent X-rays

Liubov Samoylova

WP73   X-Ray Optics and Beam Transport System

Outline

- Properties of XFEL radiation
- Optics layout of European XFEL beamlines
- Heat bump on mirrors
- Influence of surface imperfections
- Impact of monochromator on time structure
- Outlook

European XFEL Radiation Parameters

Photon beam properties at the European XFEL, 17.5 GeV electron energy, normalized emittance 1.4 μm, bunch charge 1nC, peak current 5 kA

	Units	SASE1	SASE2	SASE3
Undulator period	mm	35.6	47.9	65-68
Undulator magnetic field	T	1	0.6-1.3	0.8-1.7
Undulator gap	mm	10	19-10	20-10
Wavelength range	nm	0.1	0.1-0.4	0.4-1.6
Source size (FWHM)	μm	70	85-55	60-70
Divergence (FWHM)	μrad	1	0.84-3.4	3.4-11.4
Bandwidth (FWHM)	%	0.08	0.08-0.18	0.2-0.3
Coherence time	fs	0.2	0.22-0.38	0.34-0.88
Pulse duration (FWHM)	fs	100	100	100
Photons per pulse	#	10^{12}	$1\text{-}16\times10^{12}$	$1.6\text{-}10\times10^{13}$
Peak brilliance	B	5×10^{33}	$5\text{-}2.2\times10^{33}$	$2\text{-}.5\times10^{33}$

T.Tschentscher, et al, to be published 2010

design beam parameters are at *saturation point*,
most stable and the highest degree of coherence

XFEL Radiation : Comparison with other sources

Common with SR sources:

- experience of preserving the coherence
- experience of high heat load resistance

Difference to SR:

- coherence is the key design feature
- ultra-short pulse structure
- unprecedented peak heat loads

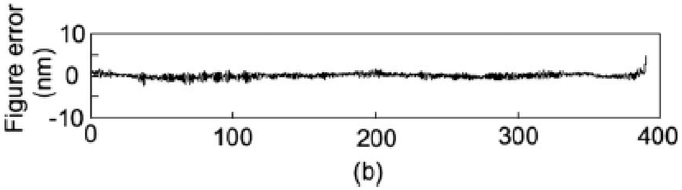
Optical laser community

- common: coherence and short pulses
- different: the wavelengths

Focusing optics, CRL, FZP,

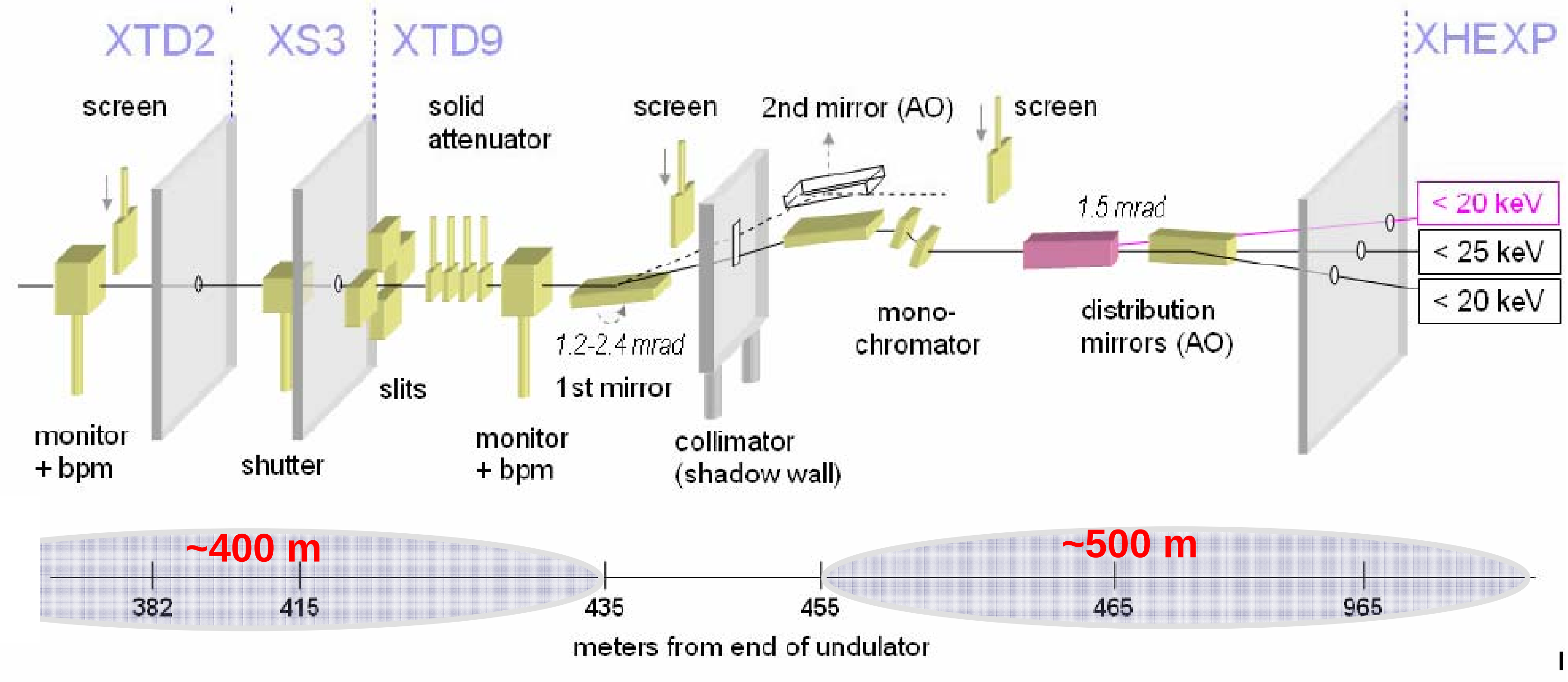
Active optics – bimorph mirrors

EEM polishing, micro-stitching interferometry



Mimura et al. Rev.Sci.Instrum 2008

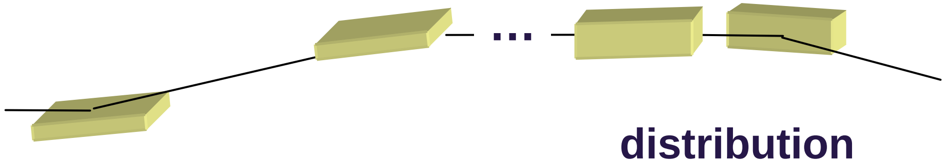
SASE 1



Optical elements:

- **free propagation**
- slits
- attenuators
- **grazing incidence mirrors**
- **crystals**
- *multilayers*
- *lenses, zone plates, …*

Wavefront Propagation Simulation



offset mirrors

distribution mirrors

basic mirror system

Computation methods :

- **numerical solution of Kirchhoff integral**
- **Fourier optics**

  FFT for Fresnel diffraction,
  phase screen approach
- **stationary phase approximation**
- **for Bragg diffraction – new formalism for short pulses with complex time structure**

Software

PHASE, PHASE4IDL
J.Bahrdt, Phys.Rev.Special Topics (2007)

SRW – Fourier optics
O.Chubar, P. Elleaume (1998)

Wave Optics: Distances make the difference

LCLS, hard x-ray beamlines, FEH

~0.2mm/1μrad

~ 100 m

~ 300 m

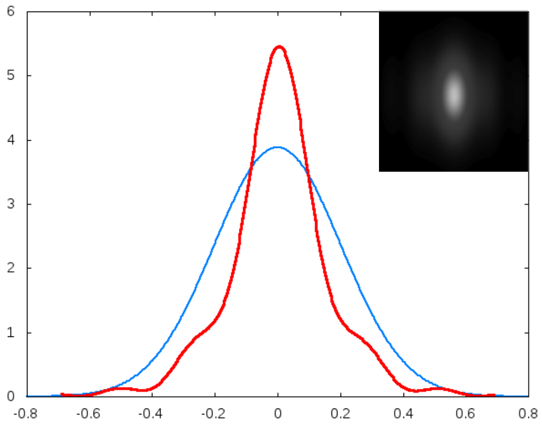
λ=1.5 Å

source

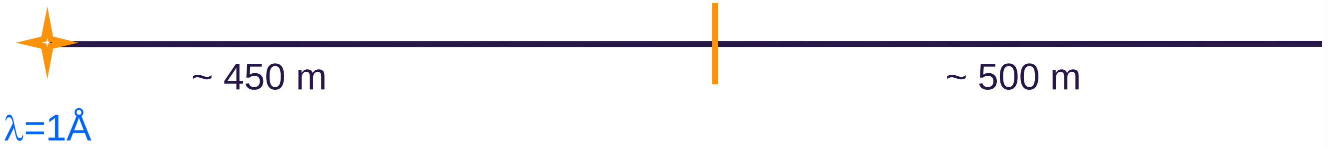
slit

sample

$N_F \approx 0.8$



European XFEL, SASE 1



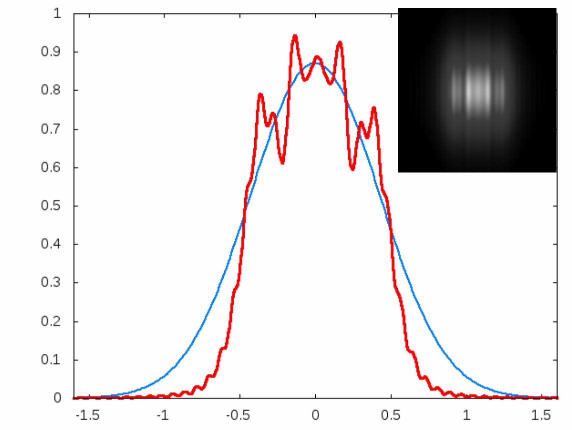
~0.5 mm/1 μrad

~ 450 m

~ 500 m

λ=1Å

$N_F \approx 5$

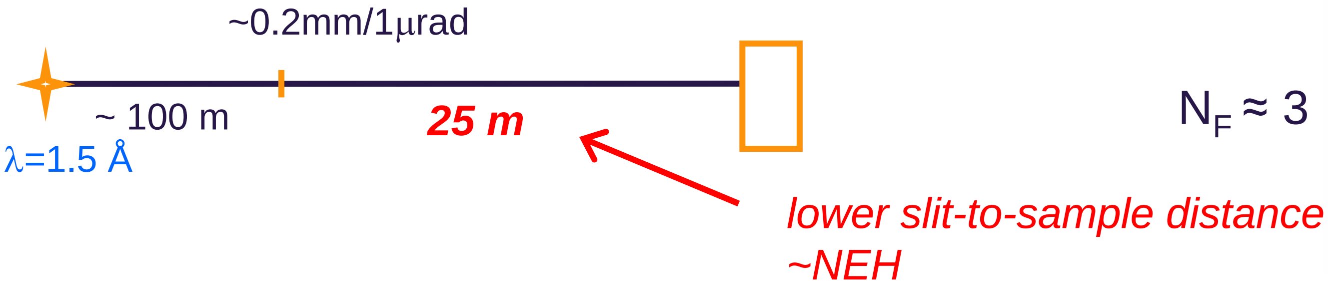


— free space propagation

— slit width 3σ of beam

Wave Optics: Distances make the difference

LCLS, hard x-ray beamlines



~0.2mm/1μrad

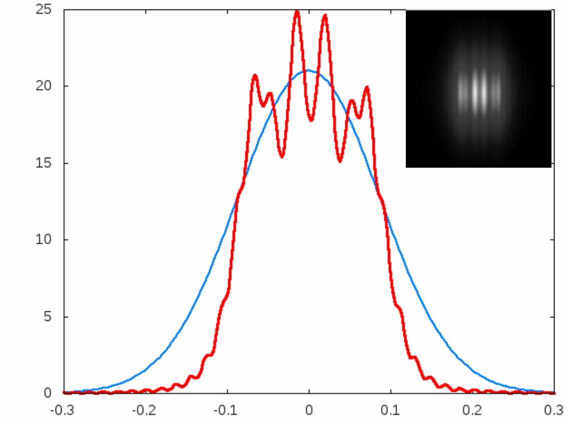
~ 100 m

25 m

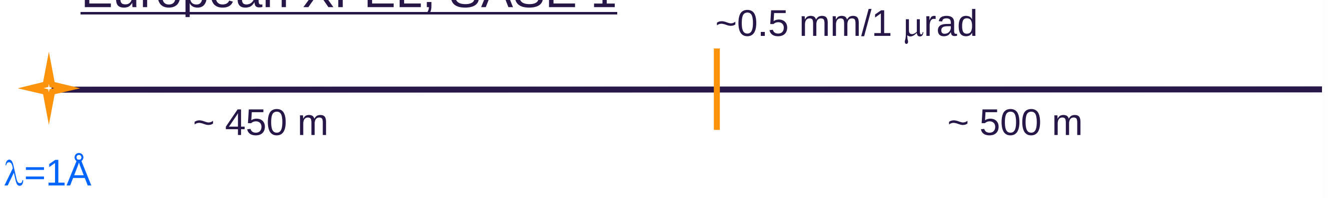
λ=1.5 Å

lower slit-to-sample distance ~NEH

$N_F \approx 3$



European XFEL, SASE 1



~0.5 mm/1 μrad

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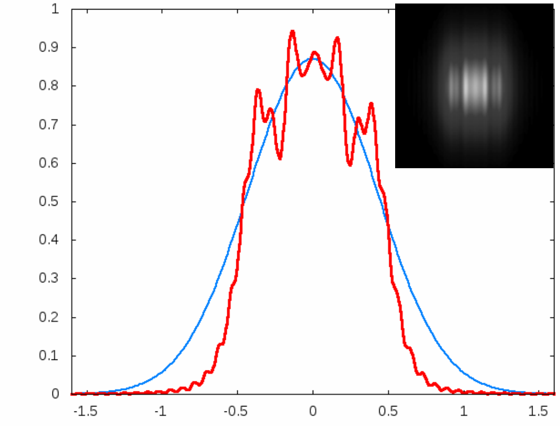
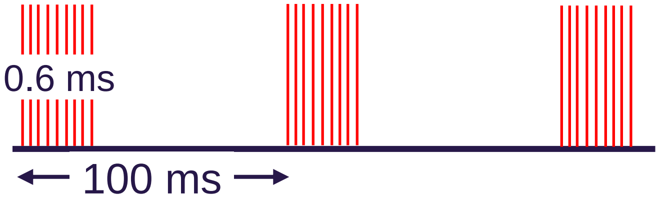
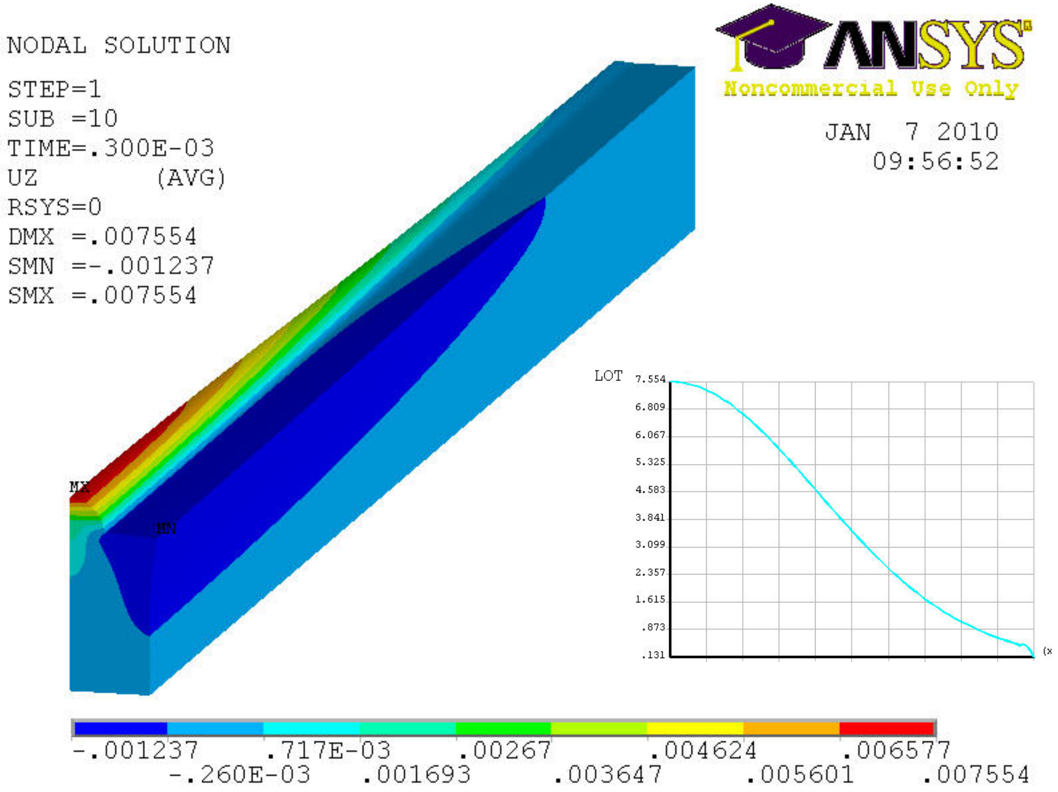


Influence of mirror surface imperfections

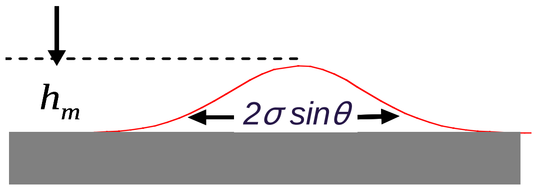
Offset Mirrors: dynamic heat load bump

- average power during pulse train >10kW
- reversible deformation due to heat load on time scales ~0.6ms
- slope error leads to wavefront distortions





Bump profile geometry



FEM calculations (Fan Yang)

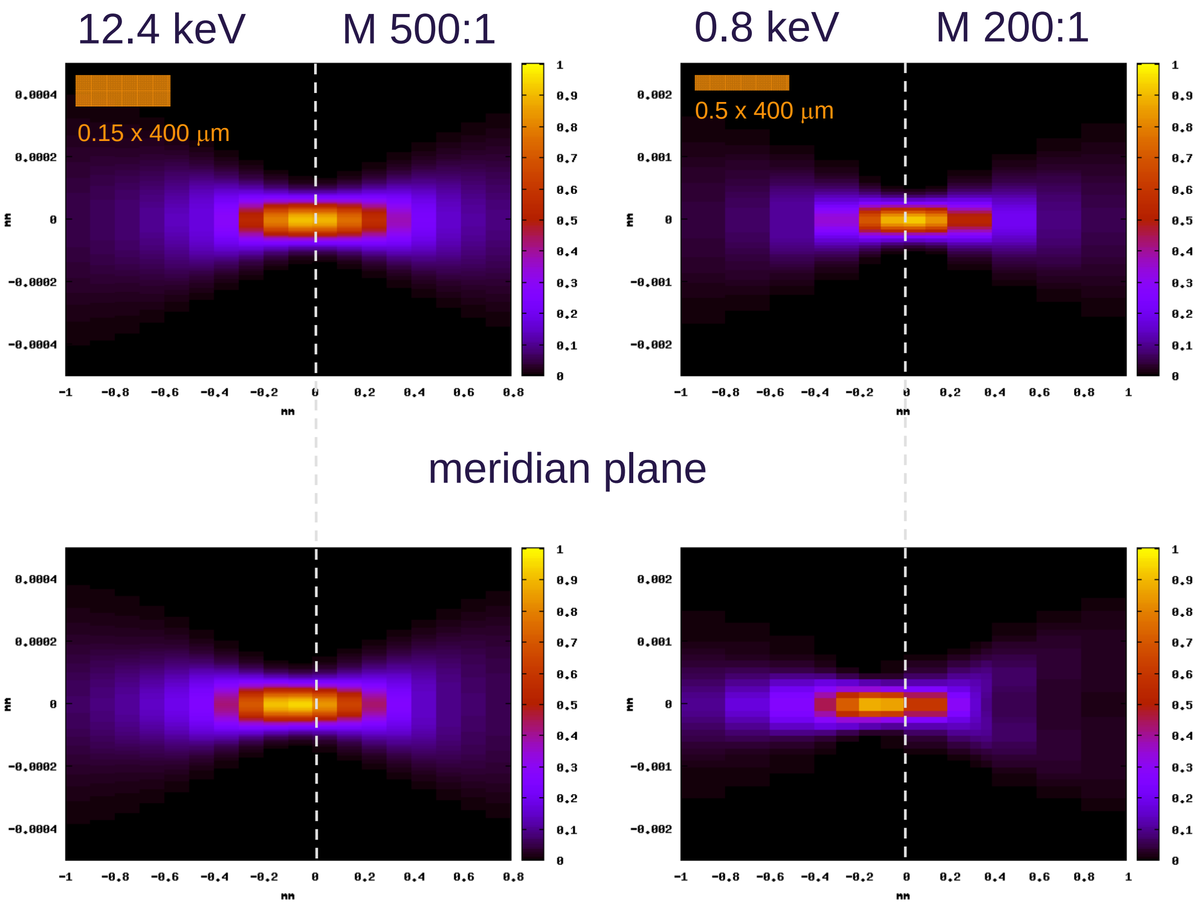
- 12.4keV, 3000 pulses 10kW/ 0.6 ms train, T 300K: max bump height 1.5 nm
- 0.8keV, 3000 pulses 80kW/0.6 ms, T 300K: max bump height ~20 nm

Offset Mirror: heat load bump, spherical aberrations

Focusing with ideal elliptical mirror after 2 offset mirrors with bumps

Focal distance 2 m,
no heat load bump, h_m=0

Focal distance 2 m,
with heat load bump:
12.4 kev h_m=3nm
0.8 keV h_m=20nm



no problems for submicron focus, *extreme focusing under investigation*

Offset mirrors: non-ideal surface

Surface
Power Spectrum Density
(PSD) components:

- high spatial frequencies: *microroughness*

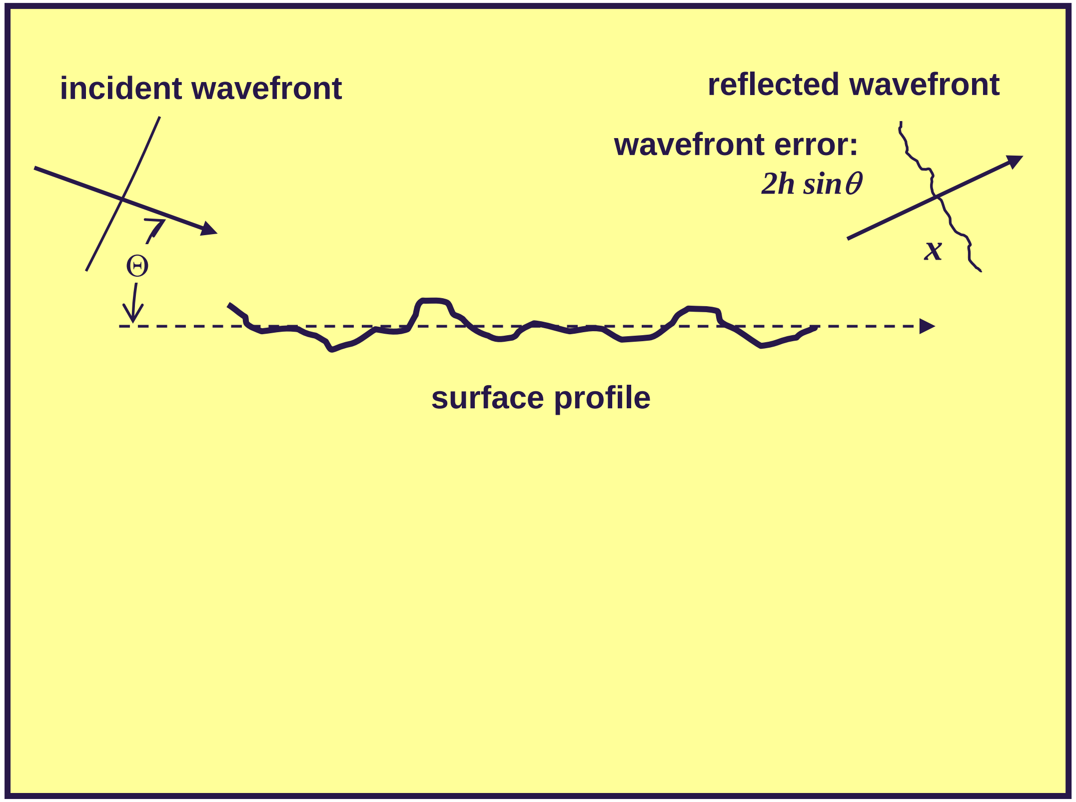
  →diffuse scattering

- low spatial-frequencies: *form/figure errors*

  →focusing/defocusing

- mid spatial-frequencies: *waviness*

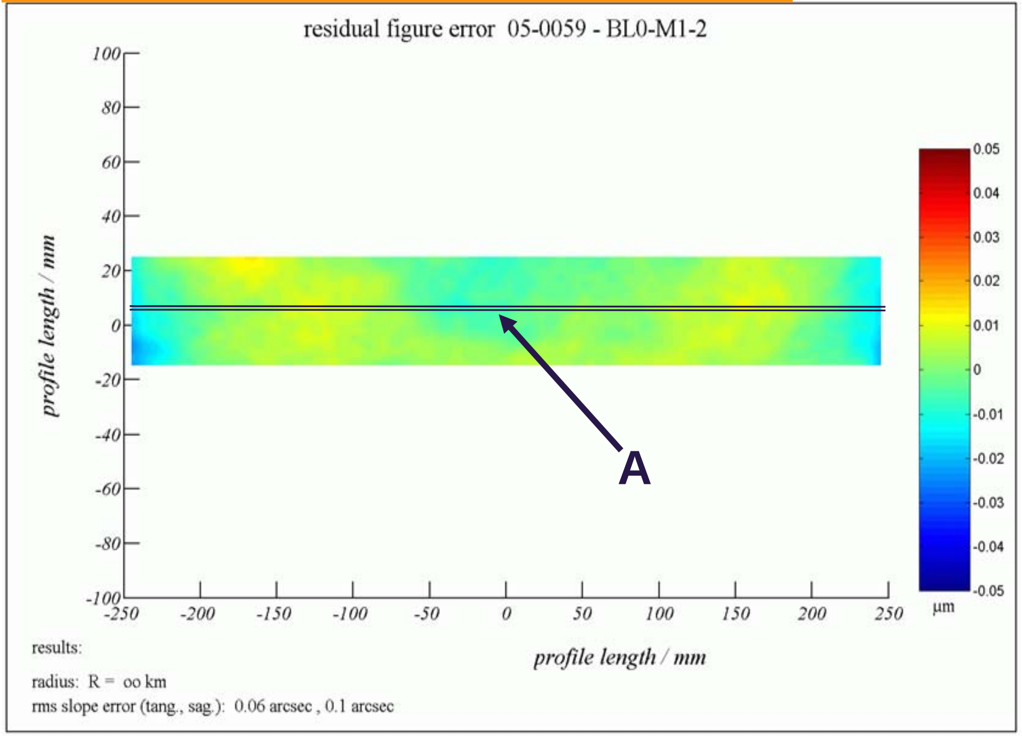
→wavefront distortions



λ ~1 Å: PV < 3 nm for >10 mm spatial frequencies

Offset mirrors: metrology data

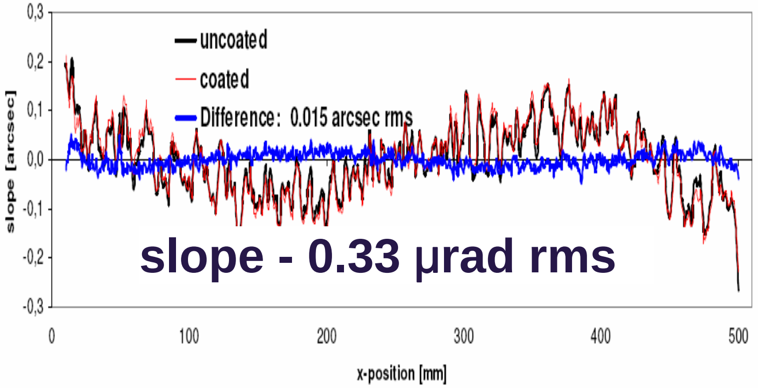
510 mm long plane mirror for a VUV FEL-beamline at FLASH / DESY



long trace profilometry (LTP) data

510 mm long plane mirror

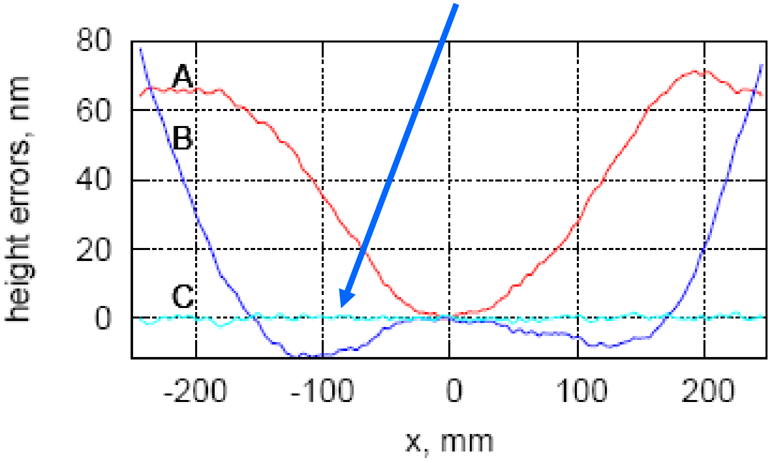
manufactured by Zeiss



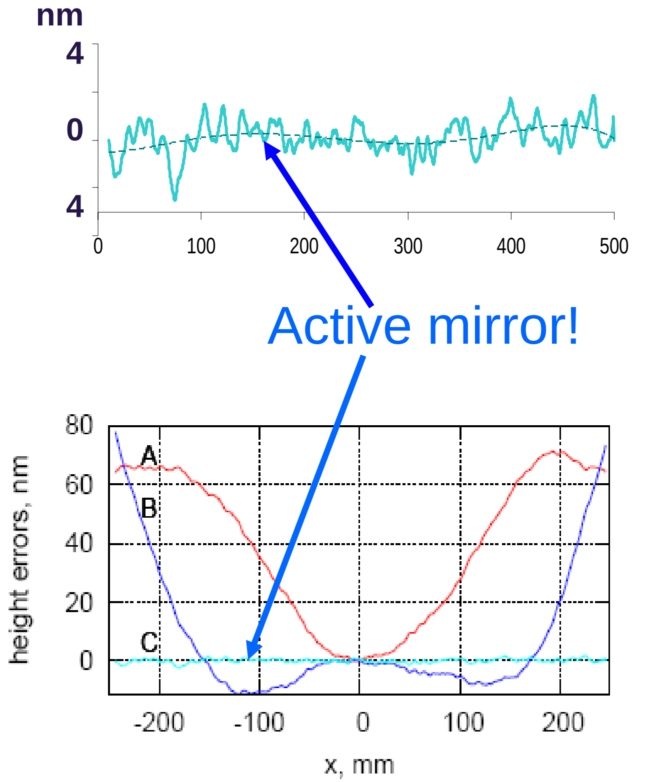
slope - 0.33 µrad rms

BESSY-NOM measurements for meridian line

Active mirror!



Offset mirrors: intensity distribution vs quality



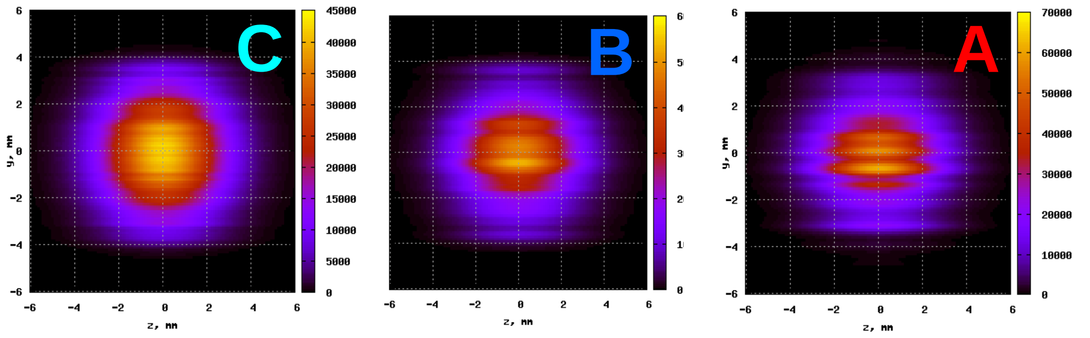
Active mirror!

A: original surface profile measured with NOM

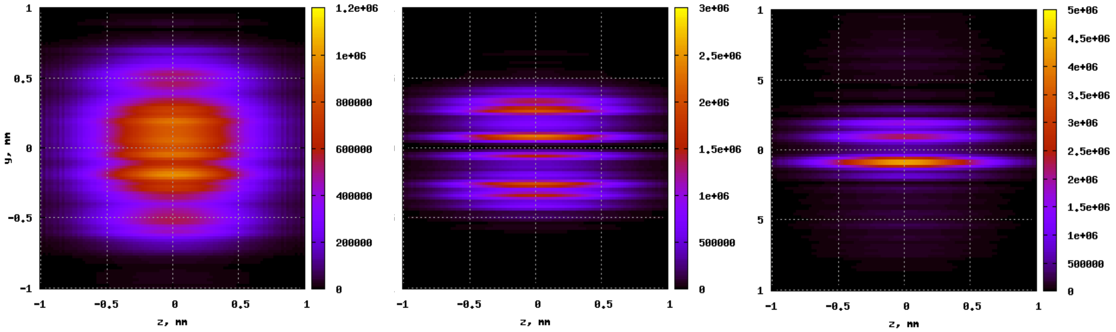
B: ~200 km radius is subtracted from A : makes the central part almost flat

C: the residual height errors of profile A, modeling a mirror surface correction with bender actuators technique (25 mm)

SASE 3: 16Å, divergence 11.4 μrad, incidence angle 10 mrad, source-to-mirror distance 234 m, total distance 400 m



SASE1: 1Å, divergence 1 μrad, incidence angle 1.8 mrad, source-to-mirror distance 525 m, total distance 955 m

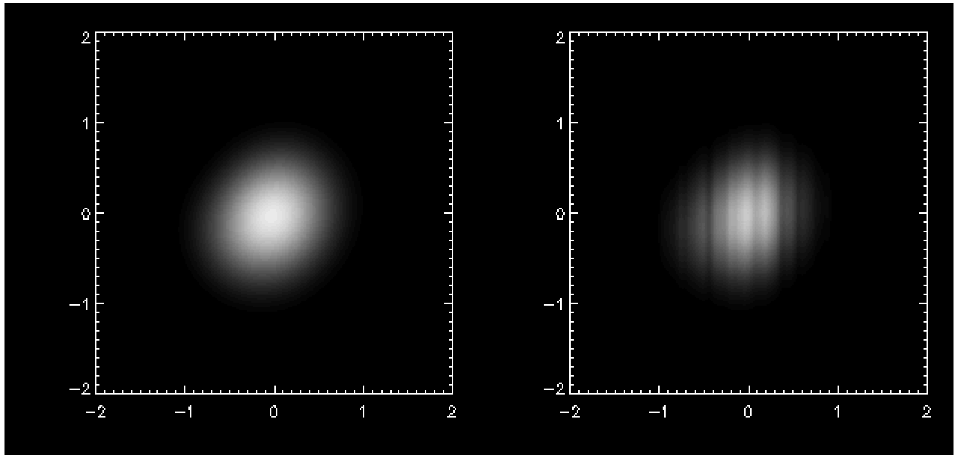


Model pulse propagation

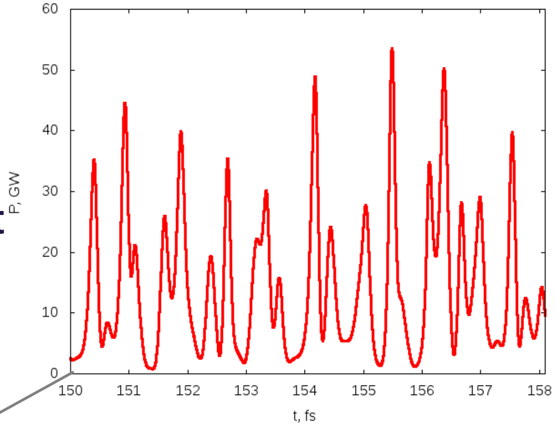
SASE 1, 12.4 keV: propagation to end station, 965 m

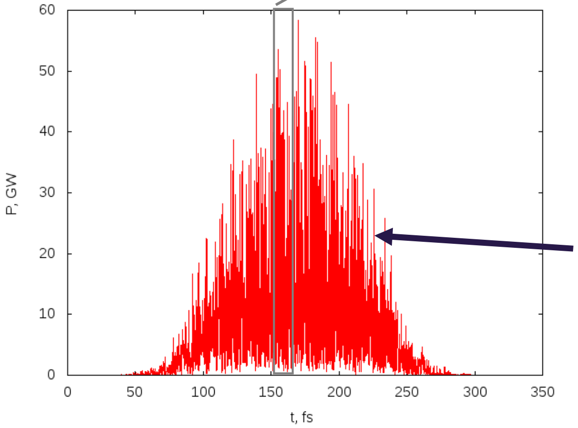
Free space propagation

Propagation through offset mirrors



time structure of pulse fragment



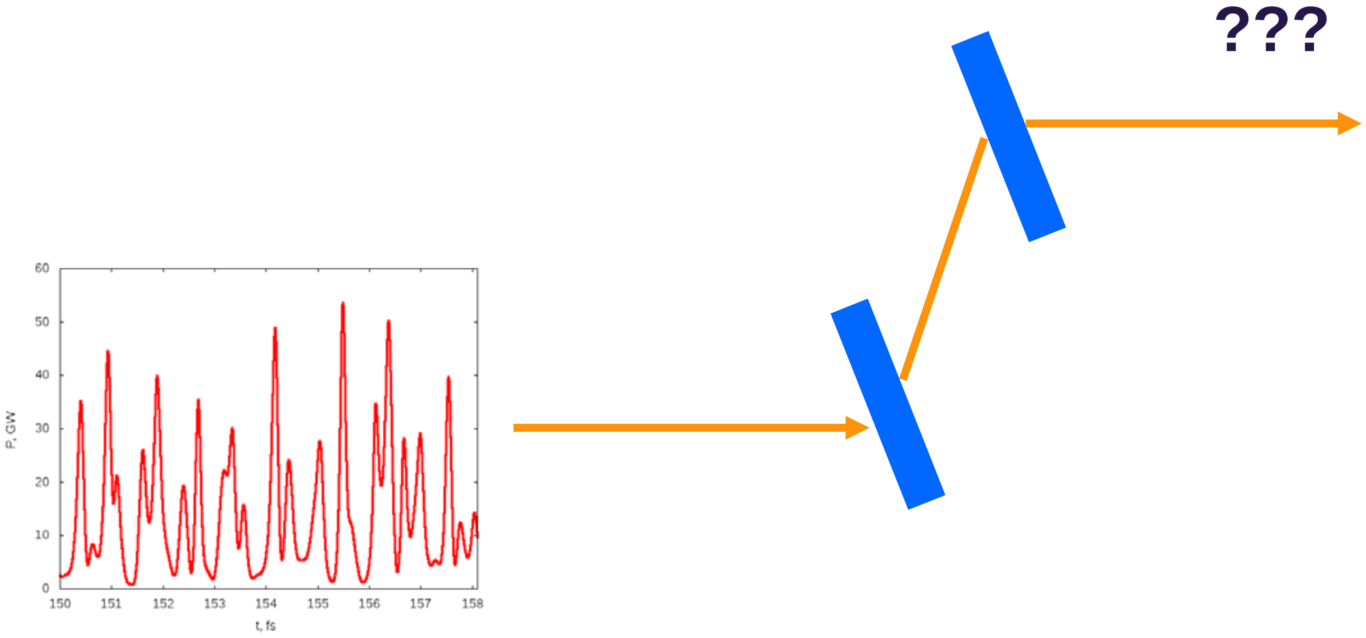


SASE 1 pulse at saturation length,
M.Yurkov's data set,
simulation with FAST code
E.Saldin, E.Schneidmiller, M.Yurkov, NIM 1999

win

full

Impact of monochromator on time structure



Double crystal diamond monochromator: influence on time structure

- dynamical Bragg reflection changes the time structure

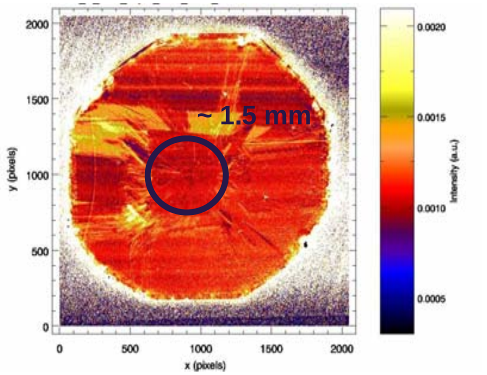
- double crystal Laue geometry provides a compact pulse with increased time duration

withheld, not yet published

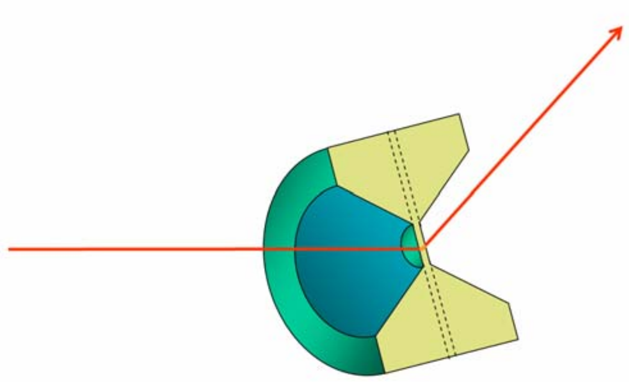
Courtesy of V. Bushuev

Double crystal diamond monochromator

- Unprecedented heat load, solutions from other sources do not work
- our approach: diamond monochromator in Laue geometry

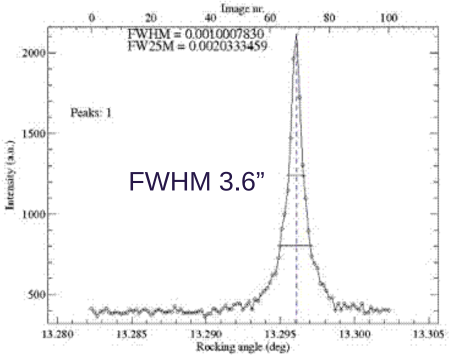


Thin Diamond single crystals between two CVD ‘head buffers’



TDR 2006

rocking curve mapping results see Poster #253



Conclusions and Outlook

Coherence effects control the propagation of XFEL beams through optical systems

Coherence requires full wavefront propagation calculations,
even for “non-coherent” beamlines

- Deterministic polishing and active mirror technologies open a good prospects for producing good enough mirrors.
- Monochromators have a strong impact on time structure, but can be optimized by double crystal setup

- Our next steps:
  - simulation of full XFEL beamline optics
  - prototypes of mirrors and monochromators will be tested

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