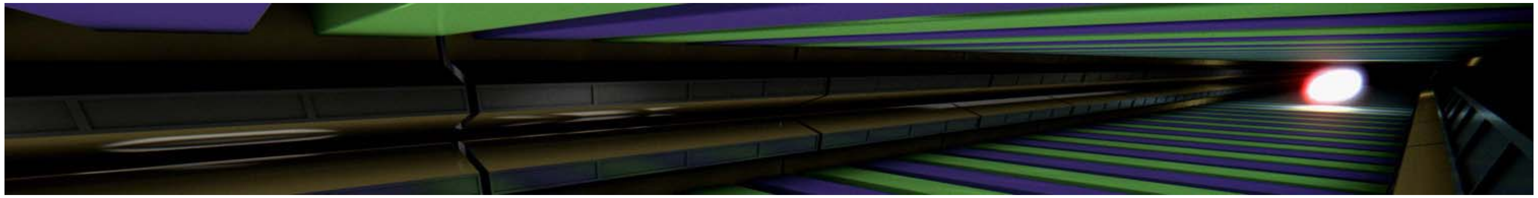


Challenges of Optics for High Repetition Rate XFEL Source

Liubov Samoylova, *European XFEL GmbH*

ACTOP11, DIAMOND, April 5th, 2011

- European XFEL photon transport system - overview
- X-ray optics for XFEL: requirements and challenges
- Grazing incidence mirrors: wavefront simulations and first measurements
- Summary and outlook

European XFEL

European XFEL @DESY

www.xfel.eu www.desy.de

- 10-15 experiments (start-up 6)
- 27,000 pulses/sec (2-100 fs long)
- 10^{10} - 3.7×10^{14} phs/pulse @ 0.5Å – 49 Å
- flux: 1.7×10^{16} phts/(0.1% sec) @ 12.3 keV
- 10^{9} € (start-up 850 M€)

Timeline:

June 5, 2007: Official funding of project by Germany and 12 international partners

Nov. 2008: Award of construction contracts

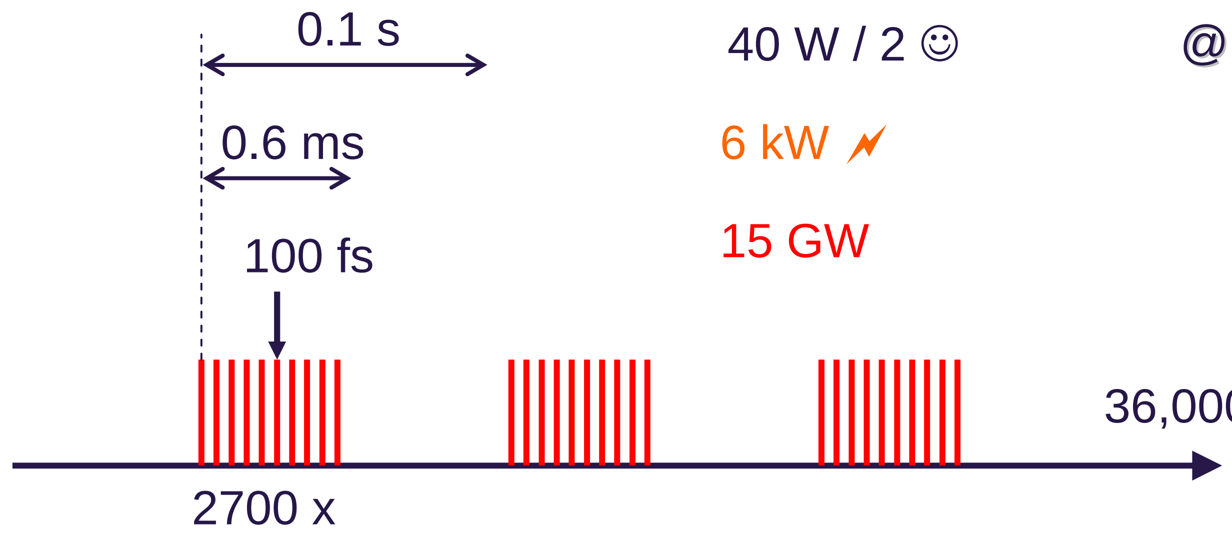
Oct 2009: Foundation of XFEL Company

mid 2013: All buildings finished, start installation of components

mid 2015: first beam

December 2015: User operation, SASE 1

XFEL pulse structure



0.1 s

0.6 ms

100 fs

2700 x

40 W / 2 ☺

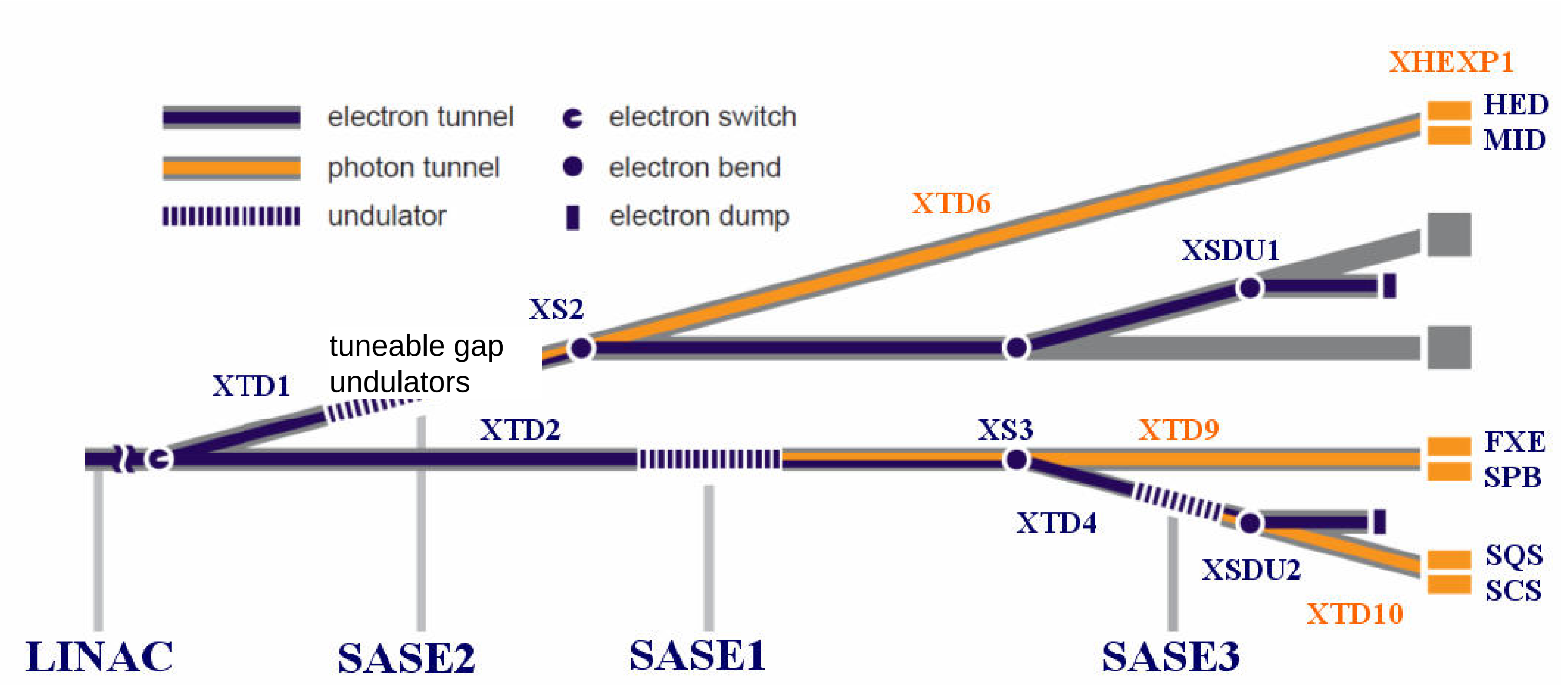
6 kW ⚡

15 GW

@12.39keV

36,000 W/mm²

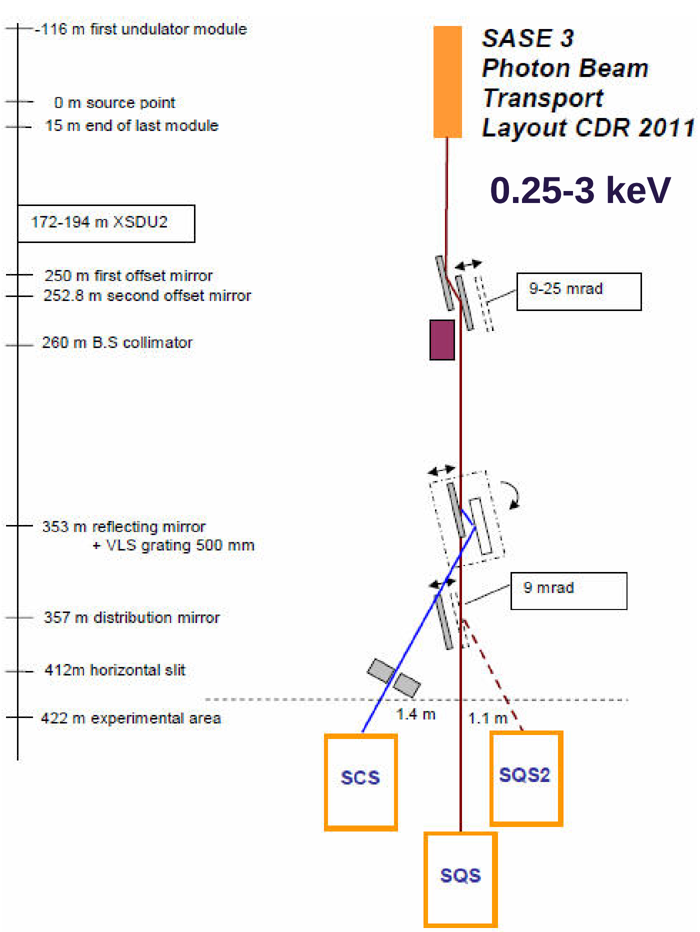
European XFEL Photon Beam Systems



Experimental stations:

- **HED: H**igh **E**nergy **D**ensity matter experiments
- **MID: M**aterial **I**maging and **D**ynamics
- **FXE: F**emtosecond **X**-ray **E**xperiments
- **SPB: S**ingle **P**article, clusters & **B**iomolecules
- **SQS: S**mall **Q**uantum **S**ystems
- **SCS: S**pectroscopy & **C**oherent **S**cattering

Photon transport systems

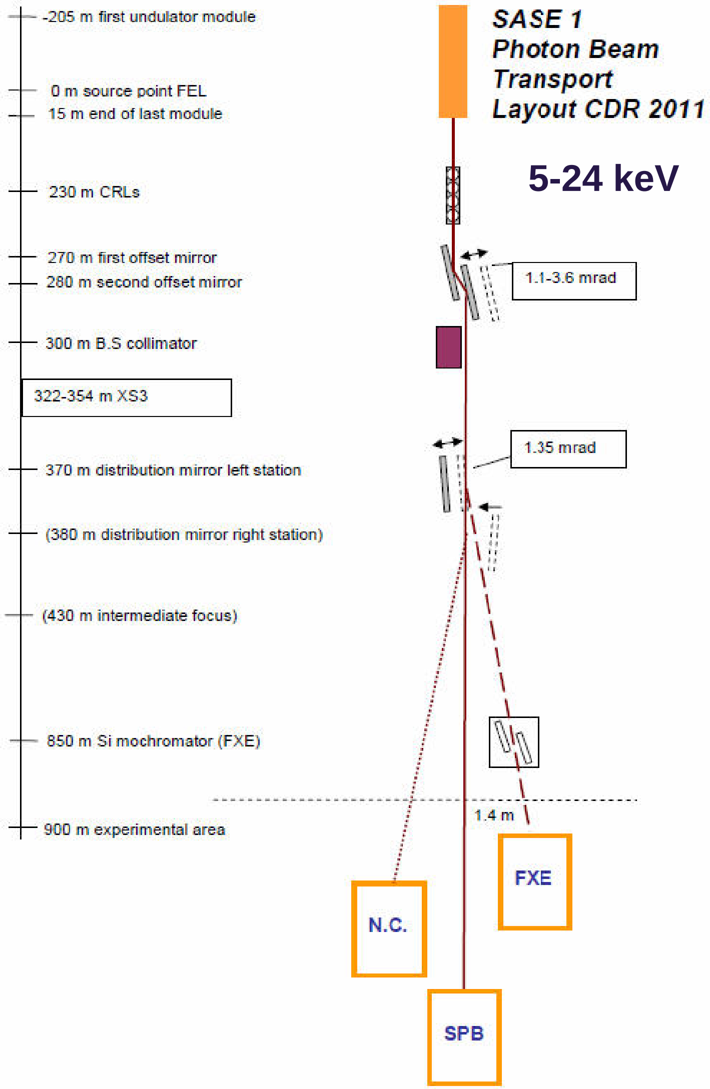


SASE 3
Photon Beam
Transport
Layout CDR 2011

0.25-3 keV

-116 m first undulator module
0 m source point
15 m end of last module
172-194 m XSDU2
250 m first offset mirror
252.8 m second offset mirror
260 m B.S collimator
353 m reflecting mirror
+ VLS grating 500 mm
357 m distribution mirror
412m horizontal slit
422 m experimental area

9-25 mrad
9 mrad
1.4 m
1.1 m
SCS
SQS2
SQS



SASE 1
Photon Beam
Transport
Layout CDR 2011

5-24 keV

-205 m first undulator module
0 m source point FEL
15 m end of last module
230 m CRLs
270 m first offset mirror
280 m second offset mirror
300 m B.S collimator
322-354 m XS3
370 m distribution mirror left station
(380 m distribution mirror right station)
(430 m intermediate focus)
850 m Si mochromator (FXE)
900 m experimental area

1.1-3.6 mrad
1.35 mrad
1.4 m
FXE
N.C.
SPB

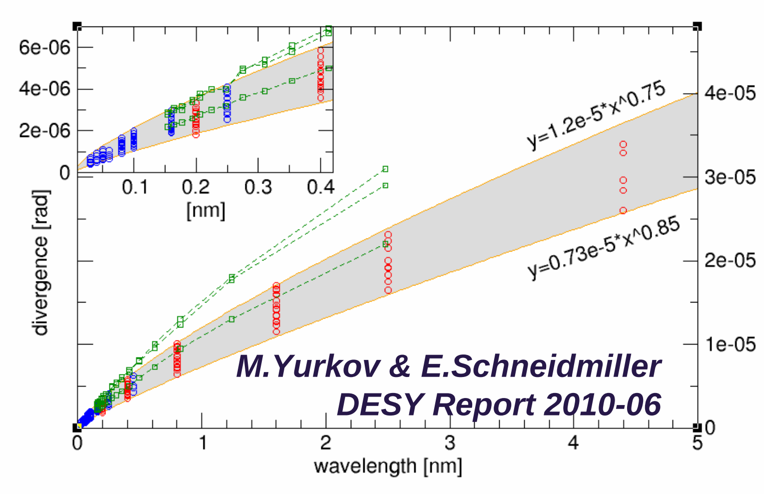
0.25-0.5 keV limited performance:
< 4σ transmission, damage limited

Requirements to Photon Transport System

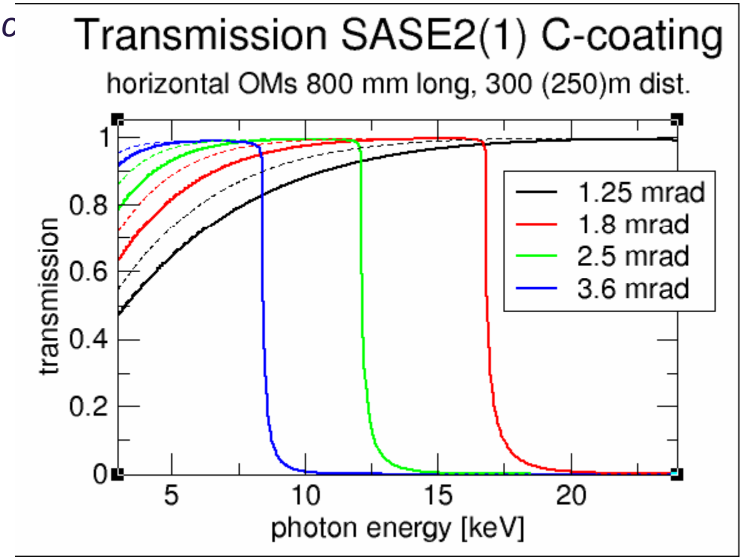
- Maximal possible transmission
  single pulses / full pulse train
- Minimal possible distortion of wavefronts
- Extensive/ redundant monitoring of the system status
  motor encoders, temperatures, bending radii of mirrors …
- Safe operation
  single pulse damage, heat load damage during the pulse trains
- Fast change in between experiments
- Reliable & fast change of photon energy – tuning of mirror system
- Stability of beam positions *cp jitter of SASE*
- Radiation protection

Mirror Optics Optimization

- Diffraction effects on mirror apertures
  can be reduced with increasing θ_{inc}
- Wave front distortions due to surface height errors
  ~2 h_{PV} sin(θ_{inc}) grow proportional to θ_{inc}
- Ultra smooth mirrors, <2-3 nm PV, length 800 mm
- Single pulse damage
- Heat load



M.Yurkov & E.Schneidmiller
DESY Report 2010-06



Mirror Optics Optimization

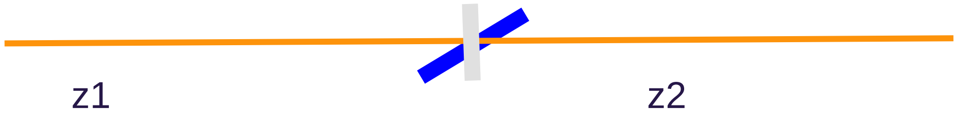
- Is 4 σ clear aperture sufficient?
- Is it possible to minimize WF distortions and provide maximum beamline transmission for whole operation ranges?

Wave front simulation

- Fourier optics approach to propagation of XFEL pulses through the X-ray grazing incidence optics
- Alternatives (used mostly for cross-checking):
  - stationary phase method
  - Fresnel Kirchhoff numerical integration

- PHASE software*:* ***HZB, J. Bahrdt***
- SRW ***O. Chubar, P. Elleaume***

Wave front simulation
Effect of 'too short' mirrors



Fresnel number for aperture:

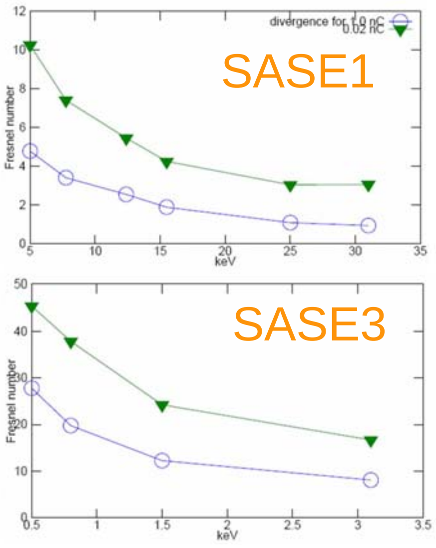
NF = $w^2/(4\lambda z)$

SASE1:

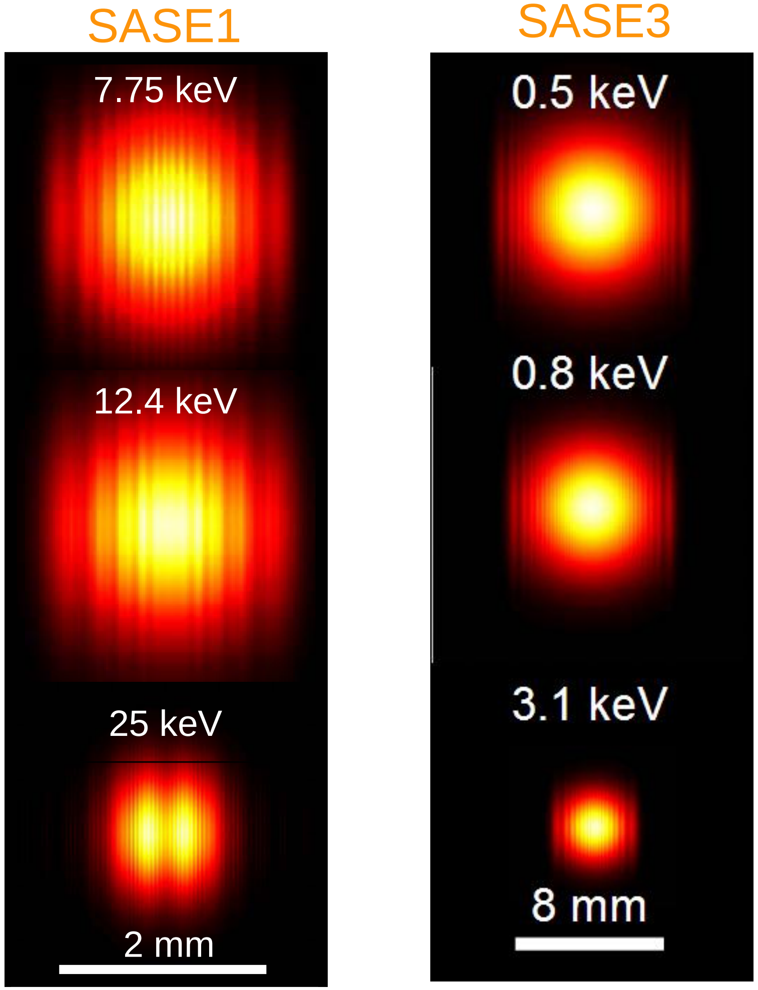
Z1=300m, z2=600m

SASE3:

Z1=250m, Z2=160m

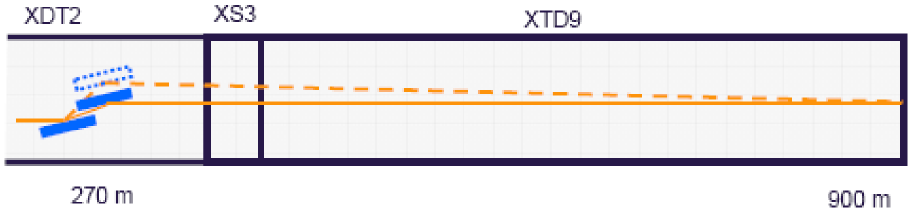


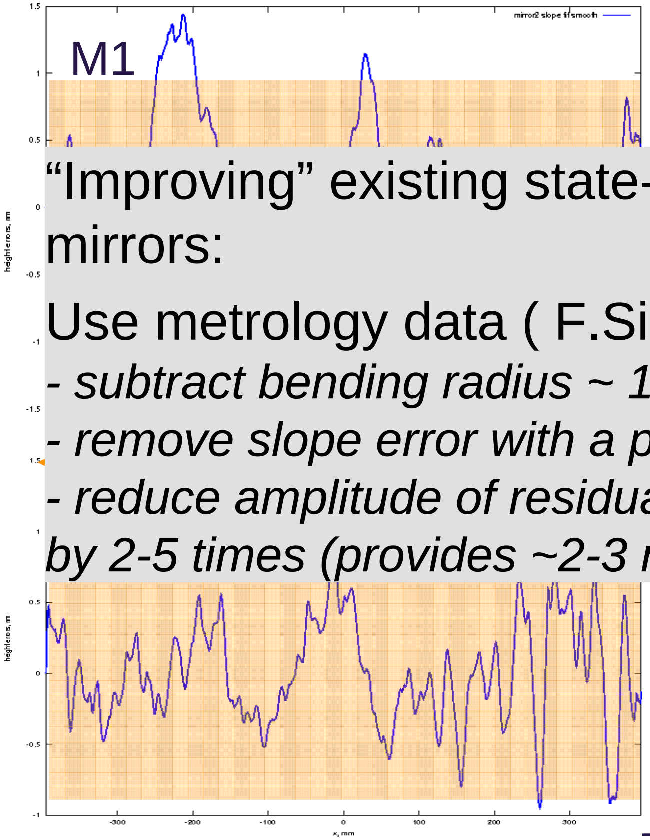
4σ footprint on offset mirror



The diffraction effects become noticeable for footprints of 4σ or less.

SASE1 central station (SPB)





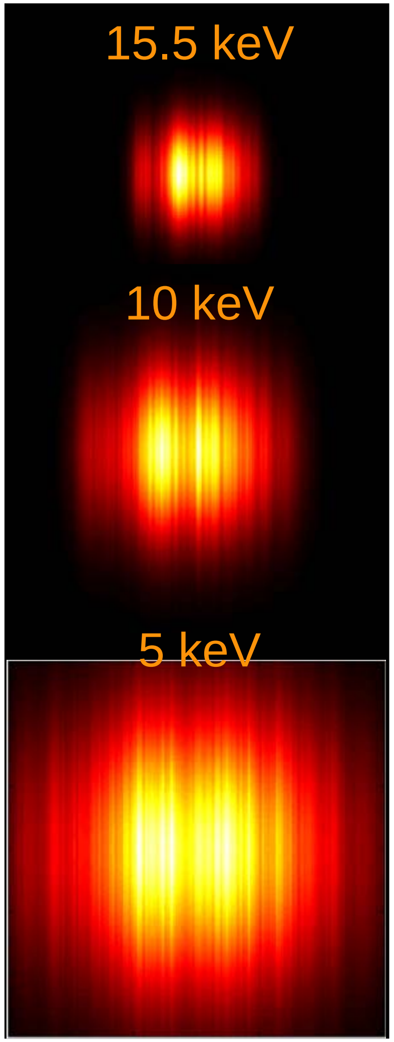
“Improving” existing state-of-the-art mirrors:

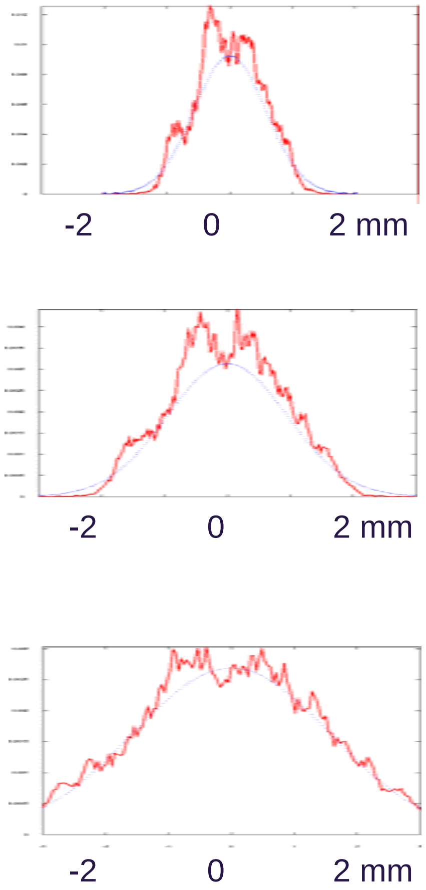
Use metrology data (F.Siewert) and:

- subtract bending radius ~ 100-200 km

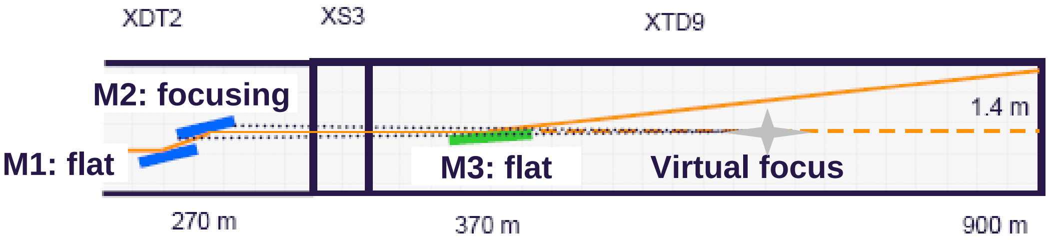
- remove slope error with a polynomial

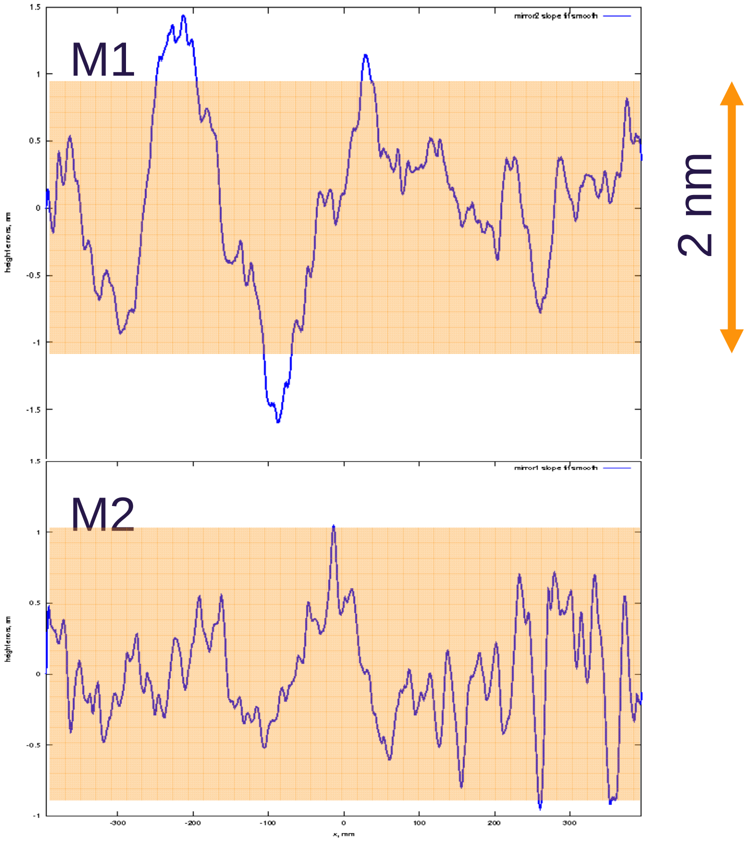
- reduce amplitude of residual height errors by 2-5 times (provides ~2-3 nm PV)





SASE1 side station (FXE)

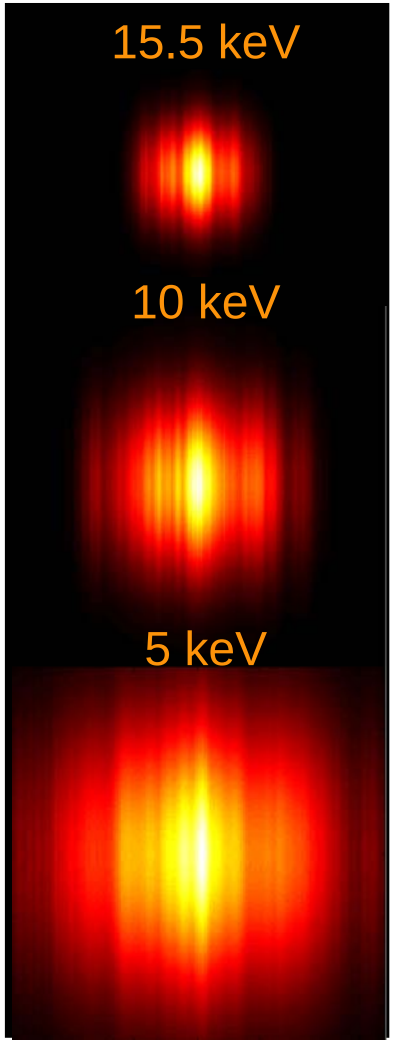


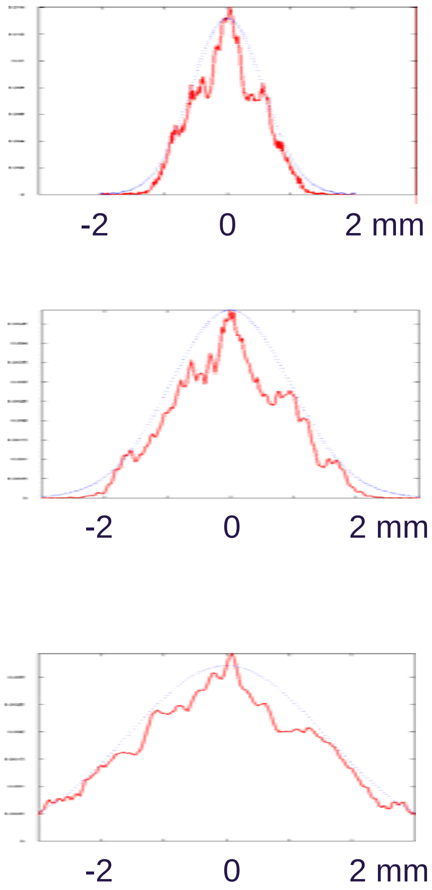


R = 200 km

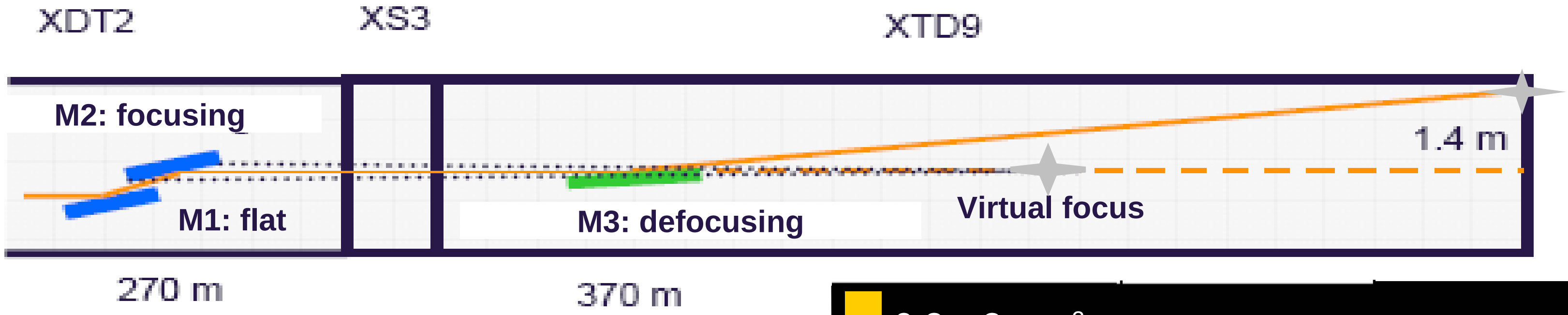
120 km

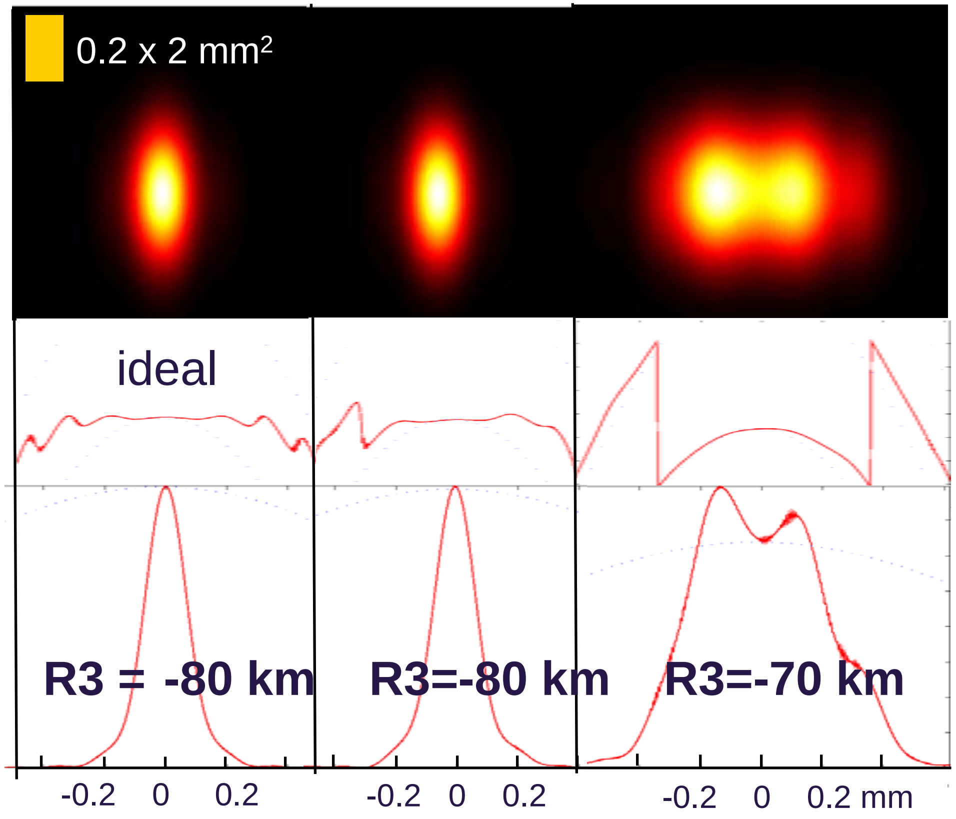
72 km





SASE1 side station (FXE): focused beam



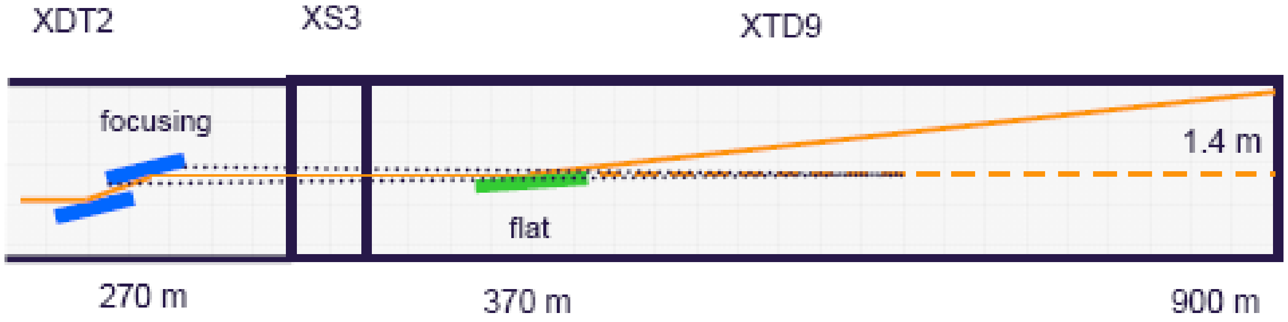


10 keV

R2 = 120 km

4.5 σ footprint

Focusing conditions



for lowest energies

	z_{m2}	z_{m3}	z_{exp}	f	R_{m2}	R_{m3} round	R_{m3} focus	M central	M branch
SASE1	280	370	900	150	54 km	flat	-100 km	2.2	4.7
SASE2	300	390	940	160	58 km	flat	-123 km	2.1	4.2
SASE3	252.8	357	422	162	7.9 km	-3.5 km	-116 km	0.67	0.72

Height difference in the center of the mirror

$$h[nm] = \frac{l_{mirr}^2[mm]}{8\,R[km]}$$

10% size variation of focused beam (20µm) - 3 nm stability of distribution mirror curvature

10% size variation of a round beam @ 12 keV ~30 nm of offset mirror

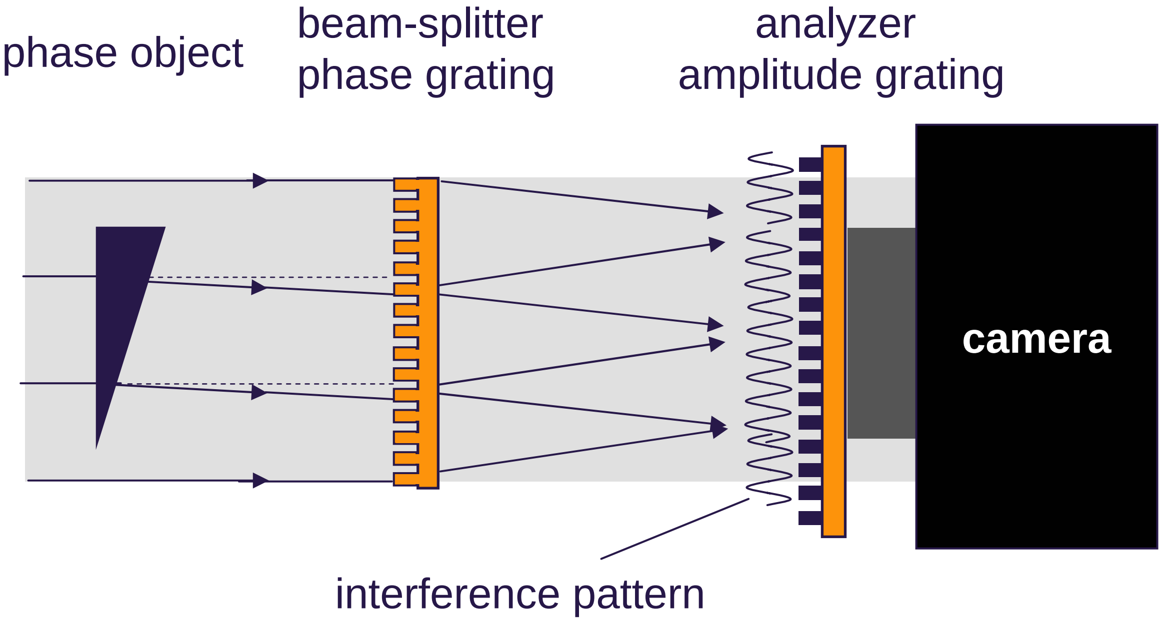
Comparison with experiment

Wave front analysis

at LCLS XPP station, 9 keV

Measuring Wavefronts: Grating X-ray Interferometry

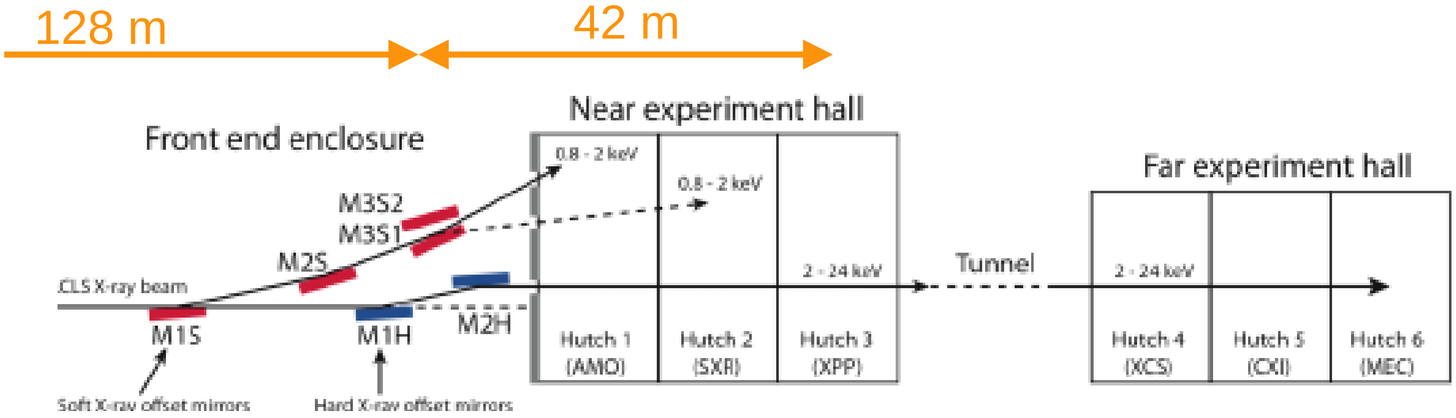
Differential phase contrast imaging!

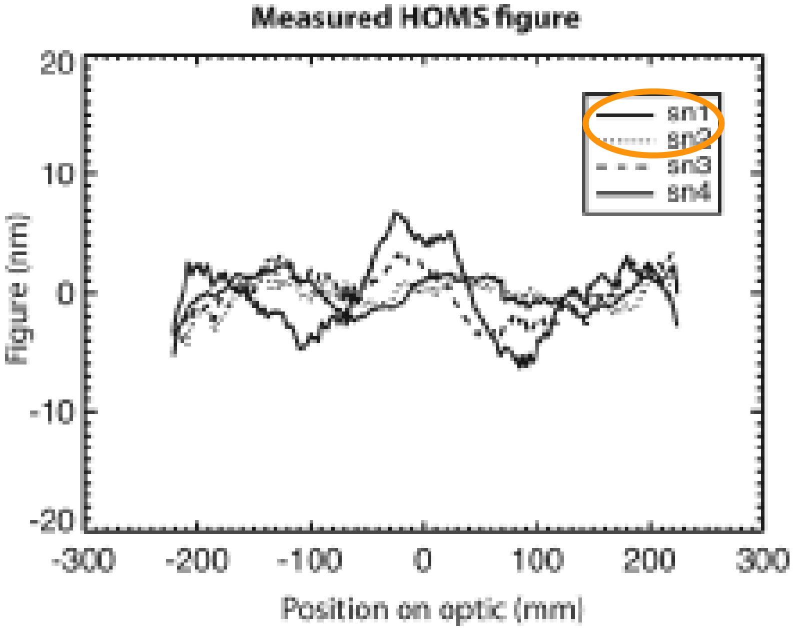


sketch courtesy of C.David, PSI

First results from X-ray wavefront measurements at LCLS

Project leader C. David

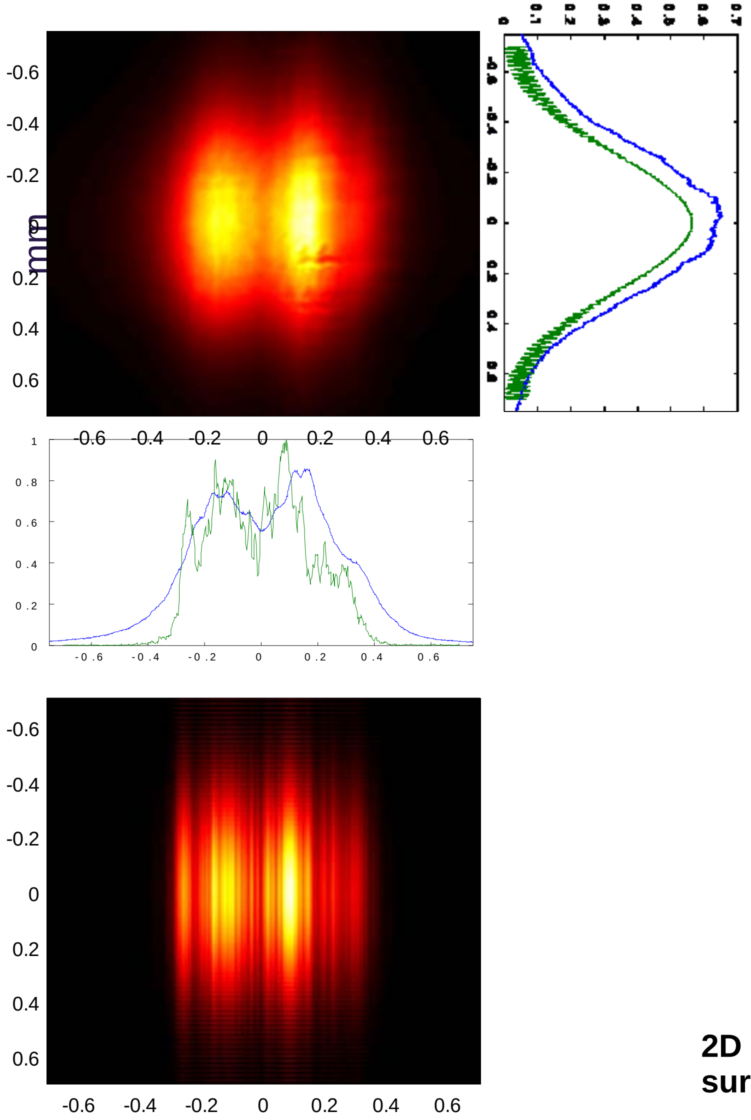




A.Barty et al, Opt.Express (2009)

Wave front analysis at LCLS XPP, 9 keV

Intensity distribution after two HOMs mirrors



XPP wavefront measurements with 1D grating interferometer

- ❑ phase stepping mode (~100 shots per step)

Calculations:

- ❑ Gaussian beam with far field divergence 3.5 µrad FWHM

2D grating interferometer data processing by Simon Rutishauser
surface profiles by LLNL/Jacek Krzywinski

Summary

- Photon transport systems can transmit single XFEL pulses and pulse trains with reasonable wavefronts distortions by beamline optics
- Design relies on novel optical components.
  In particular, 800 mm long mirrors, with profile errors < 2nm PV, ~20 nm slope errors and with bending control precision up to 10 nm and better.
- First experience with grazing incidence X-ray optics at LCLS:

  - coherent X-ray laser radiation brings problems,
  - good news: we can predict and analyze them in advance

… and Outlook

- precise and mechanically stable (~1 nm) *active* optics

F. Siewert
T. Noll
HZB

- in-situ metrology and control are crucial!

  optical and X-ray grating interferometry, precision up to 10nm/10nrad

In-situ X-ray metrology
C. David, PSI

- user-friendly wave optics software for design, commissioning and optimisation of beamlines and instruments

J.Bahrdt HZB
O.Chubar, BNL

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Frank Siewert, Johannes Bahrdt

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Christian David, Simon Ruthhauser

SLAC

Jacek Krzywinski

BNL

Oleg Chubar

MPY, DESY

Mikhail Yurkov, Evgeny Schneidmiller

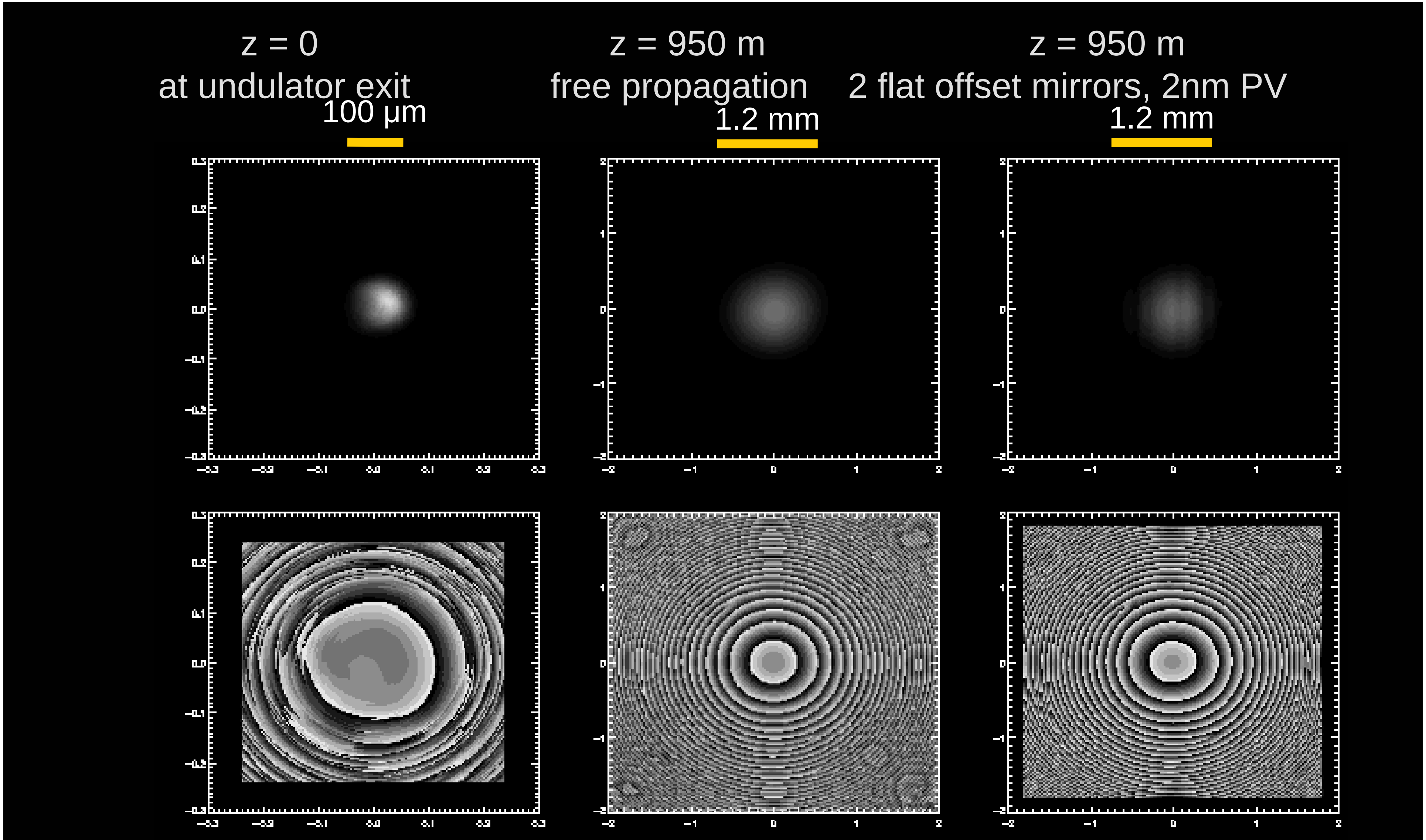
European XFEL:

Harald Sinn

Jerome Gaudin, Antje Trapp, Fan Yang, Germano Galasso, Nicole Kohlstrunk, Martin Dommach, Idoia Freijo, Shafagh Dastjani Farahani

Thomas Tschentscher

Thank you for your attention!



M.Yurkov data (FAST code) SASE pulse, 2010