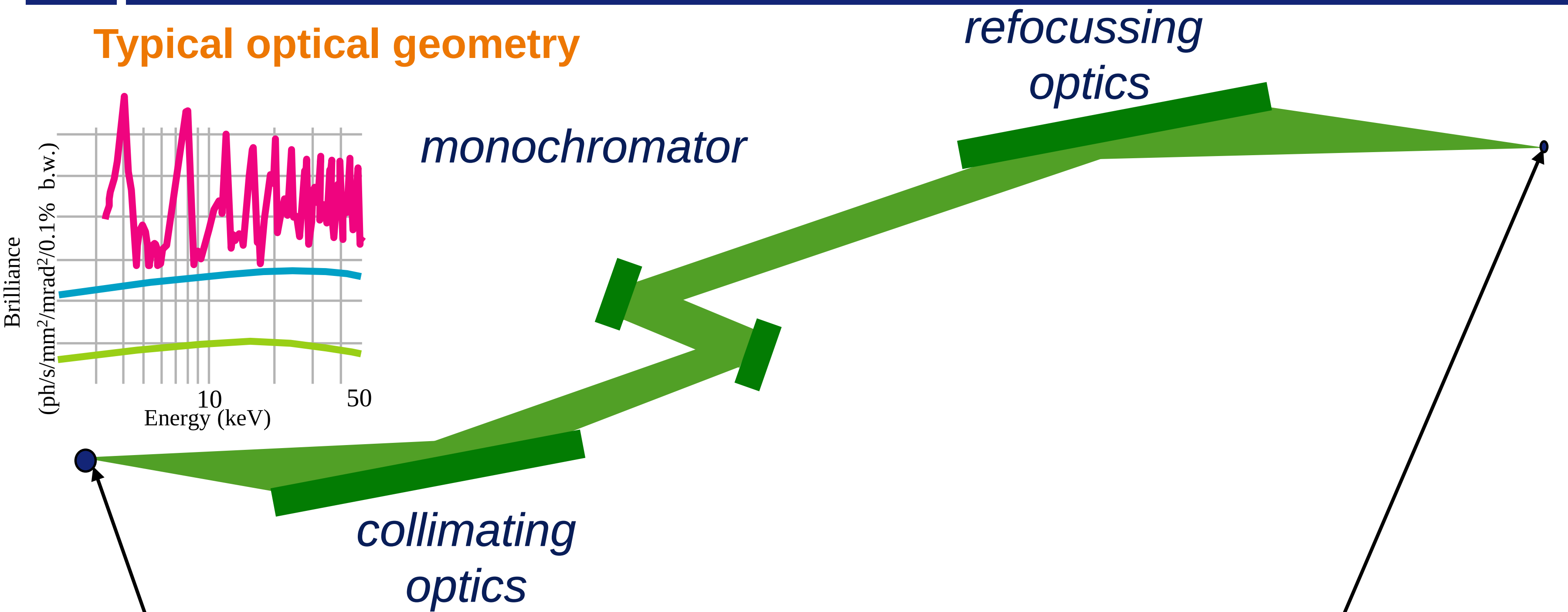
BEAMLINE OPTICS FOR SMALL ROUND BEAMS

- *Overview*
- *Impact of emittance reduction for X-ray optics*
- *Requirements*
- *Current limitations*

Ray Barrett
X-ray Optics Group Leader
Instrument Services & Development Division (ISDD)
ESRF

Typical optical geometry



OPTICS

?

Source

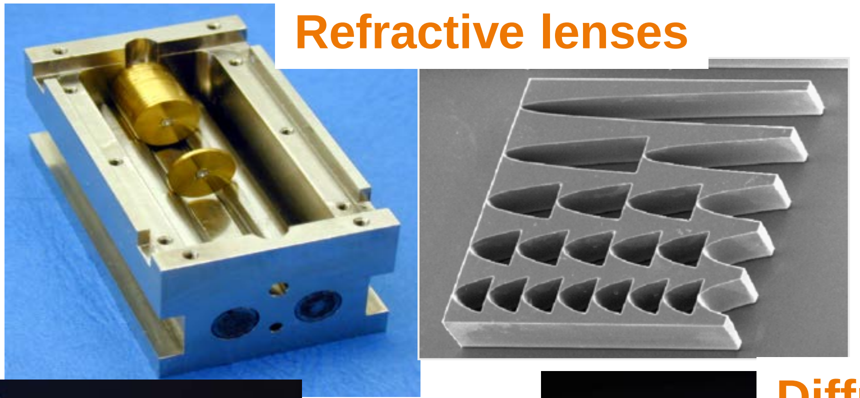
- spectrum (ΔE/E)
- emittance (size x divergence)
- degree of spatial coherence
- brilliance (ph/s/mm^2/mrad^2/0.1%bw)
- polarisation (linear, circular, elliptic)

Sample

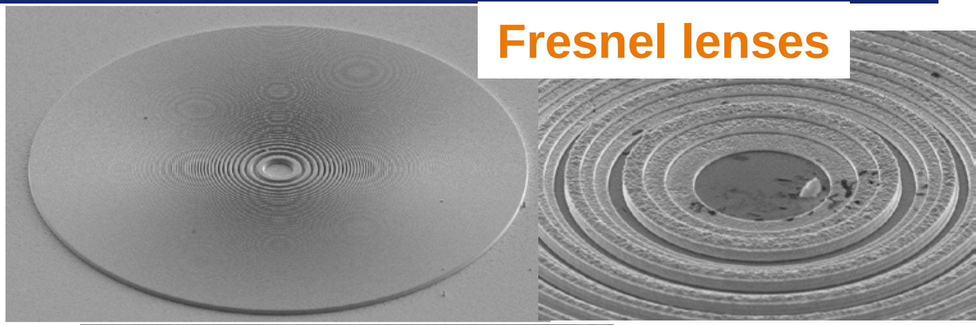
- beam size (μm)
- beam divergence (μrad)
- flux (ph/s)
- temporal coherence: ΔE/E
- spatial coherence
- polarisation

X-RAY OPTICS

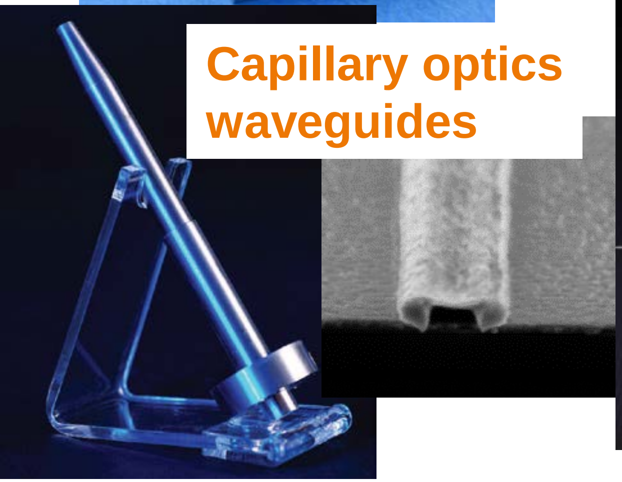
Refractive lenses



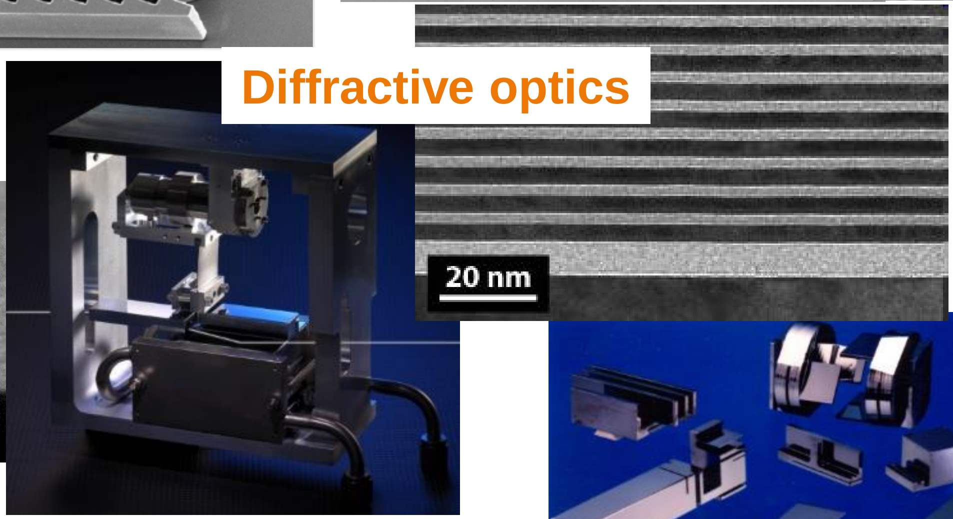
Fresnel lenses



Capillary optics waveguides

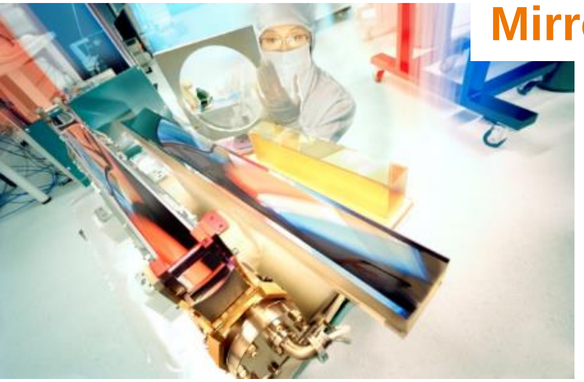


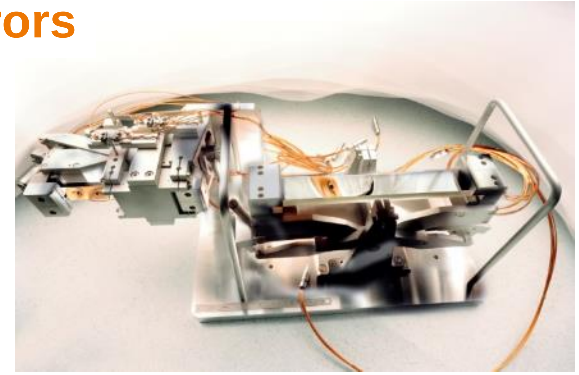
Diffractive optics

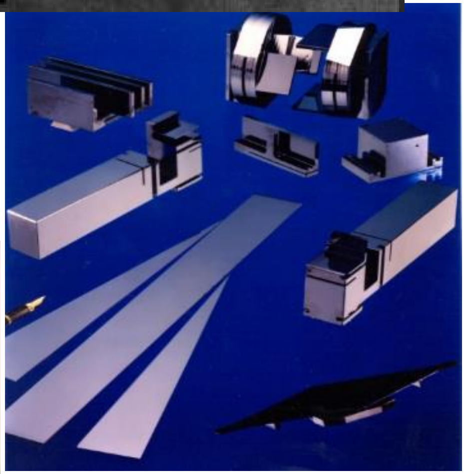


Filters

Mirrors







+ polarising optics, interferometers, …

AIM IS TO CONSERVE THE EMITTANCE

imperfect optics increase emittance

The tolerable increase of emittance should be comparable to the stability of the source parameters (~ 10%)

- optical aberrations
- manufacturing errors
  - ✓ mirror slope errors
  - ✓ imperfect multilayer coatings
  - ✓ crystal imperfections (strain)
  - ✓ imperfect lenses
- mechanical & thermal deformations
- vibrations

- ❖ high quality polishing
  - Slope & figure errors
- ❖ interfaces must be smooth and flat
  - micro-roughness, slope & figure errors
- ❖ use of perfect crystals
  - Silicon, Germanium, …
- ❖ high accuracy lens profiling
  - mechanical tolerances, lithography…
- ❖ special mounting strategies
  - benders, supports, ...
- ❖ cooling strategies
  - water,LN2 cooling, ...

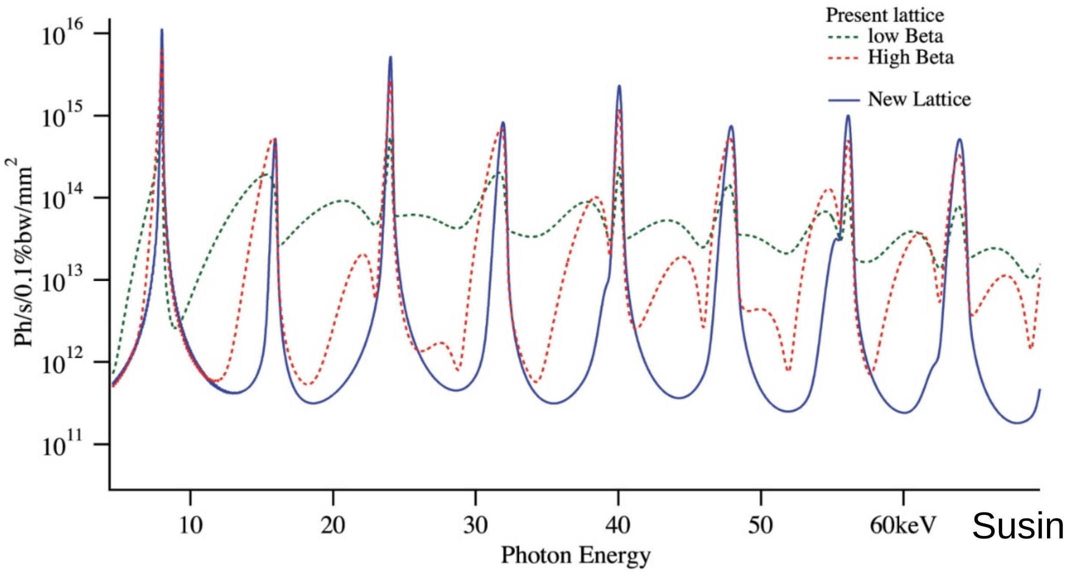
ESRF 'Extremely Brilliant Source' EBS Project

ESRF X-RAY SOURCE PARAMETERS: CURRENT AND ESRF-EBS LATTICES

2m U18 undulator

Energy	Lattice	RMS size (µm)		RMS divergence (µrad)	
		H	V	H	V
10 keV	Current low β section	49	5.0	107	6.1
	Current high β section	410	4.9	11.5	6.1
	EBS lattice	30	5.1	7.4	6.1
50 keV	Current low β section	50	3.8	105.5	4.5
	Current high β section	410	3.8	11.2	4.5
	EBS lattice	30.3	4	6.1	4.5

relatively little change



Improved spectral purity
~1.5x reduction in undulator peak width

Susini et al., J. *Synch. Rad.* **21**, (2014) 986–95

WHAT ABOUT THE X-RAY OPTICS FOR THE ESRF EBS?

- **Reduction in horizontal beam divergence + source size**

❖ **Shorter mirrors (-> better quality)**

❖ **Lower demagnification/smaller apertures: replace some mirrors by refractive lenses**

- **Narrowing of energy width of undulator peaks**

❖ **Improved monochromator motor control for continuous energy scanning**

- **Wavefront (‘coherence’)/ Emittance preservation**

❖ **Vertically little/no change, horizontal large improvements**

❖ **Vertically deflecting reflective, monochromator optics still performance limiting (see later)**

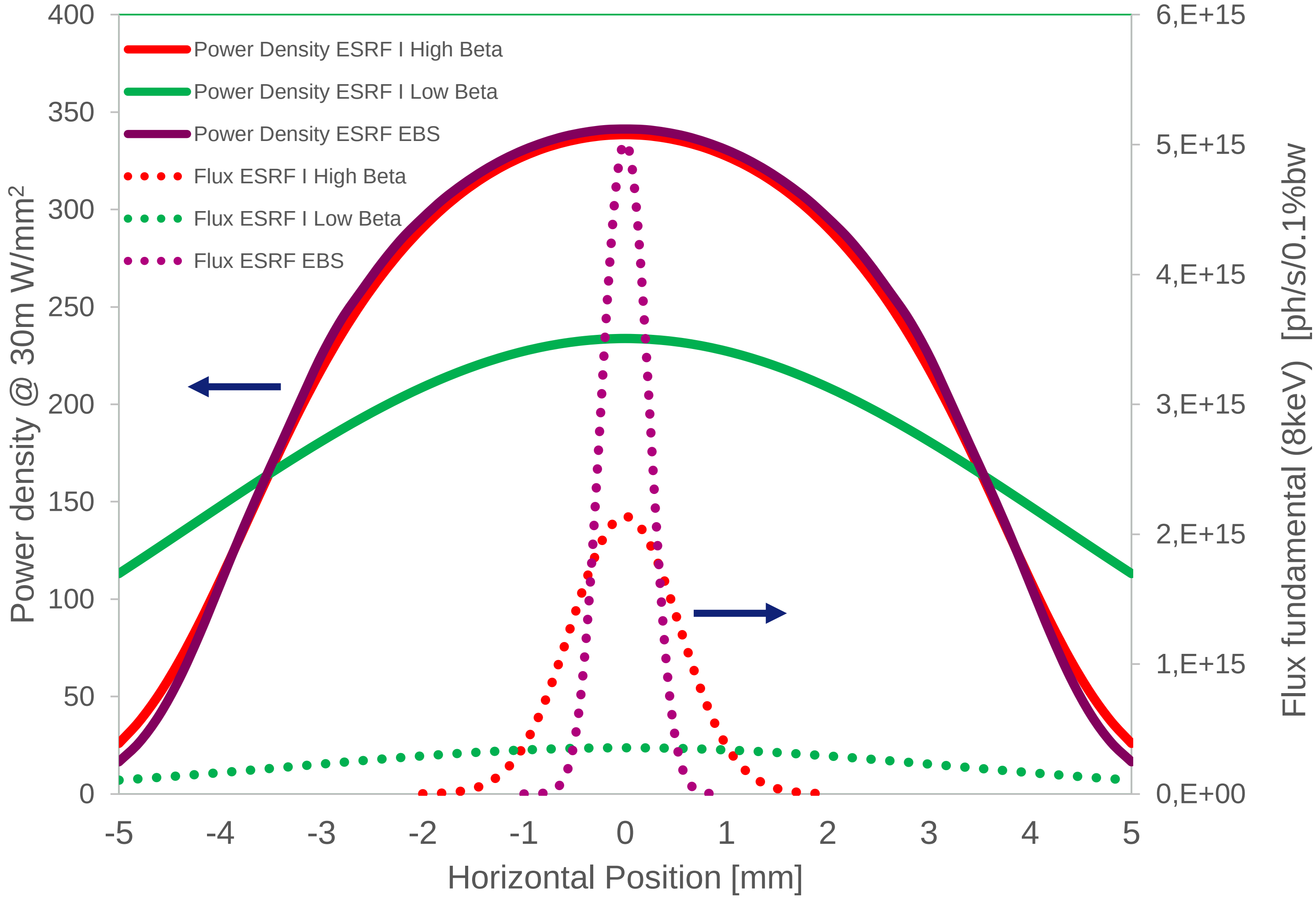
❖ **Requires improved quality of horizontally deflecting mirror (but shorter is generally better)**

❖ **Replace some mirrors by refractive lenses**

- **Heat Load?**

POWER DISTRIBUTION AND FUNDAMENTAL PEAK WIDTH

Spatial distribution of power density is primarily driven by the deflection parameter K of the undulator



30m from source,
2 m CPMU18
K=1.67,
E=6.04GeV

Peak power density comparable with existing lattice… but narrower emission cone

Characteristics of 2m-long, 18mm-period undulator at 10keV:

Lattice	RMS Photon beam size at 30m (µm)		Integrated Power over central cone (W)	Integrated Power in 0.1% BW (W)
	H	V		
Low β	3100	150	180	0.77
High β	530	150	42	0.77
EBS	220	150	17	0.77

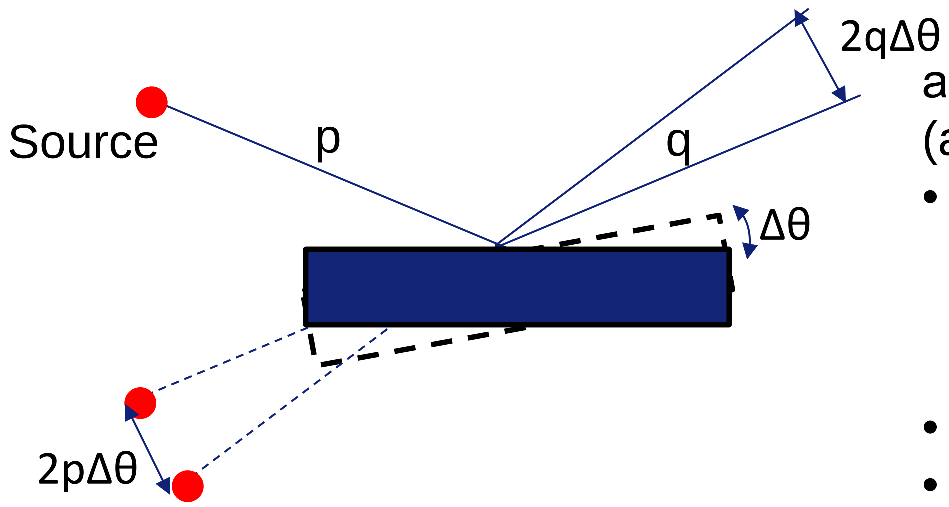
'round' beam!

Integrated power: total power integrated over the RMS beamsize

Current cooling strategies will remain applicable ☺

Susini et al., J. *Synch. Rad.* **21**, (2014) 986–95

Angular errors: slope errors, vibrations degrade apparent source size



angles ≡ source movement/magnification (amplified by lever arm)

- Due to long lever arms at SR sources usually dominant cause of beam/effective source size degradation for both **static** and **dynamic systems**
- Resolution degradation (spatial, energy)
- Degraded wavefront

Aim for effective source size increase < 10%

e.g. Single mirror at 30m from low-β source (10keV):

ESRF 1996: σ_v= 11µm: $\Delta\theta_{rms}$ < 80 nrad
σ_h= 58µm: $\Delta\theta_{rms}$ < 440 nrad

ESRF 2014: σ_v= 4.3µm: $\Delta\theta_{rms}$ < 32 nrad
σ_h= 49µm: $\Delta\theta_{rms}$ < 370 nrad

EBS: σ_v= 3.8 µm: $\Delta\theta_{rms}$ < 29 nrad
σ_h= 25 µm: $\Delta\theta_{rms}$ < 190 nrad

Non-reflective optics similar issues –but smaller, lighter

HOW DID WE SURVIVE UNTIL NOW?

Even in 1996 we needed 80 nrad angular stability – how did we survive?

- Optical quality and diversity much less developed (mirrors ~5µrad rms slope errors, high energy zone plates had lower resolutions, no refractive lenses)
- Often other optical aberrations dominated (e.g. toroidal mirrors)
- Cooling technologies less well developed
- Vibrations/drifts at this level were secondary concerns
- Use horizontally deflecting mirrors (also helped for heat-load deformation) preferably double reflection on common support
- Put the optic closer to the source. ESRF limit is ~ 30m + increased power density. Not possible for micro/nanofocusing optics – place on common support with sample.
- Use secondary source after (most) unstable optics
- Replace (some) double crystal monochromators with channel cut crystals

REQUIRED QUALITY OF X-RAY OPTICS (DIFFRACTION LIMITED FOCUSING)

Strehl ratio: > 80% (i.e. <20% of intensity outside spot)

Maréchal Criterion: rms wavefront error $\lambda/13$

Reflective Optics: Any deviation *h* from the ideal surface introduces a phase distortion φ. At grazing angle θ, $\varphi = (4\pi/\lambda)\cdot h\cdot\sin\theta$

X-ray energy (keV)	Coating material	Incidence angle θ (mrad)	Figure specification σ (nm, rms)
8	Rhodium	6.0	1.0
20	Platinum	3.0	0.8
50	Multilayer (W/B_4C)	5.9	0.15

e.g. O. Hignette *et al*., Proc. SPIE 4501:43–53. San Diego 2001

Refractive Optics: Cumulated thickness errors, t, of lenses introduce phase distortion φ. For material with $n=1-\delta-i\beta$, $\varphi = 2\pi\delta t/\lambda$

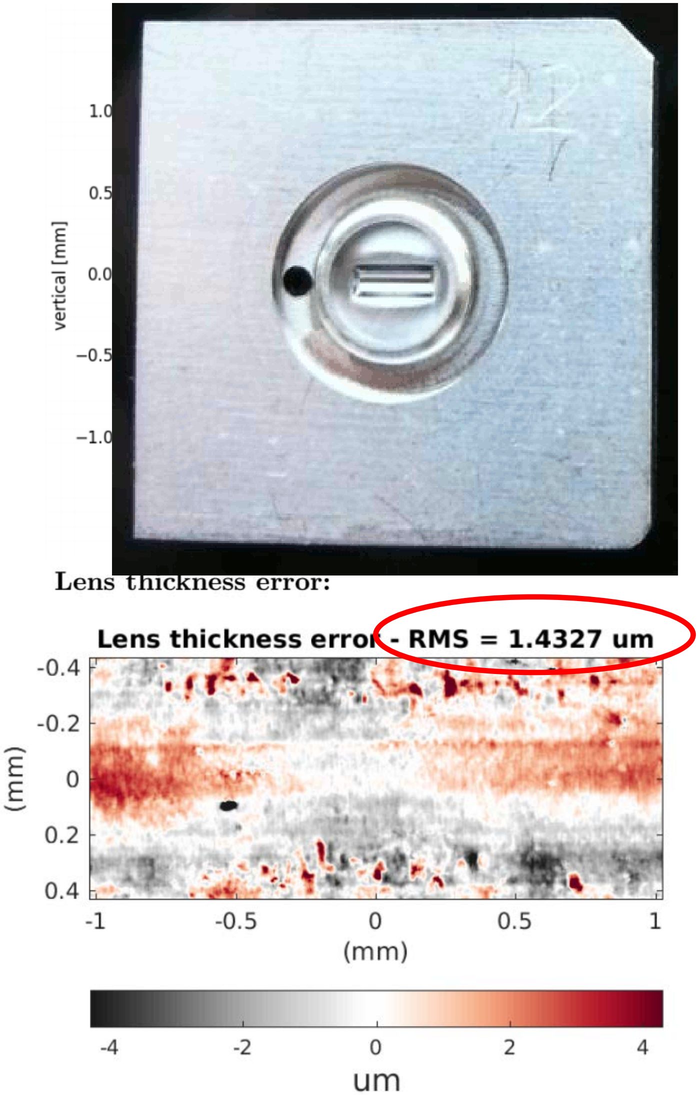
X-ray energy (keV)	Lens material	delta	Figure specification σ (nm, rms) (full stack)	Figure specification σ (nm, rms) (per lens *)
8	Be	5.3E-06	2200	980
20	Be	8.5E-07	5600	1000
50	Al	2.2E-07	8700	810

*** Assumes focal length of 1m with lenses R=50µm**

Fresnel Zone Plates: Zone placement accuracy ~ 1/3 zone width (3-4 nm!)

e.g. A.G. Michette, *Optical Systems for Soft X Rays*. Plenum Press, 1986

Figure errors of 1D Be lens (R_0 = 200 µm)



Corrective 'glasses'

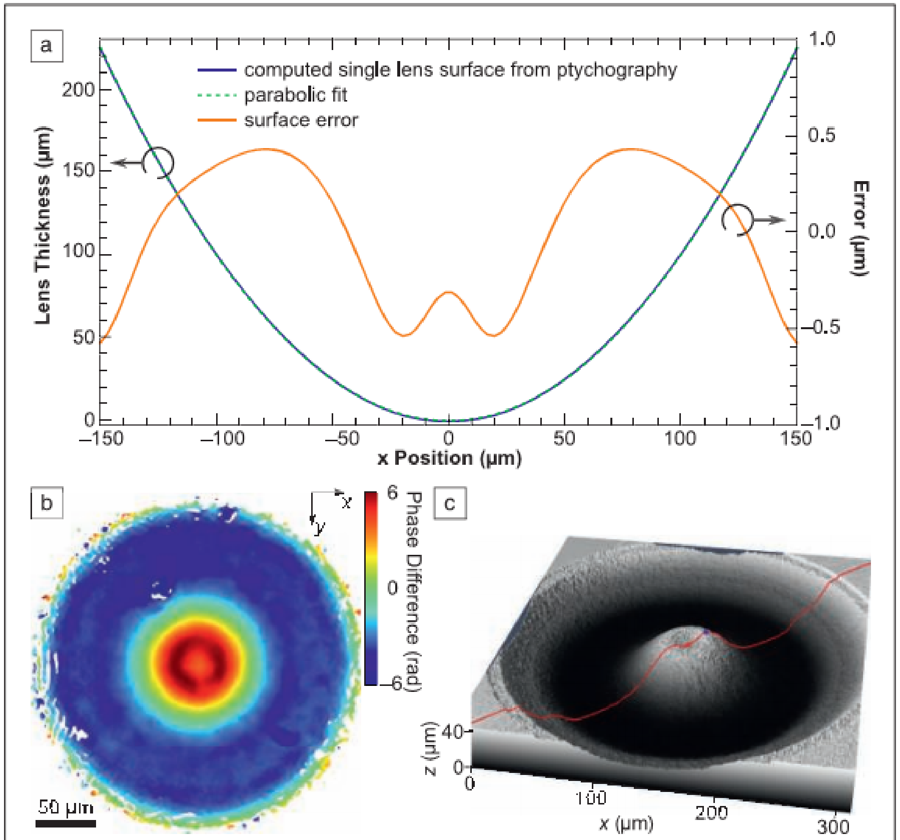
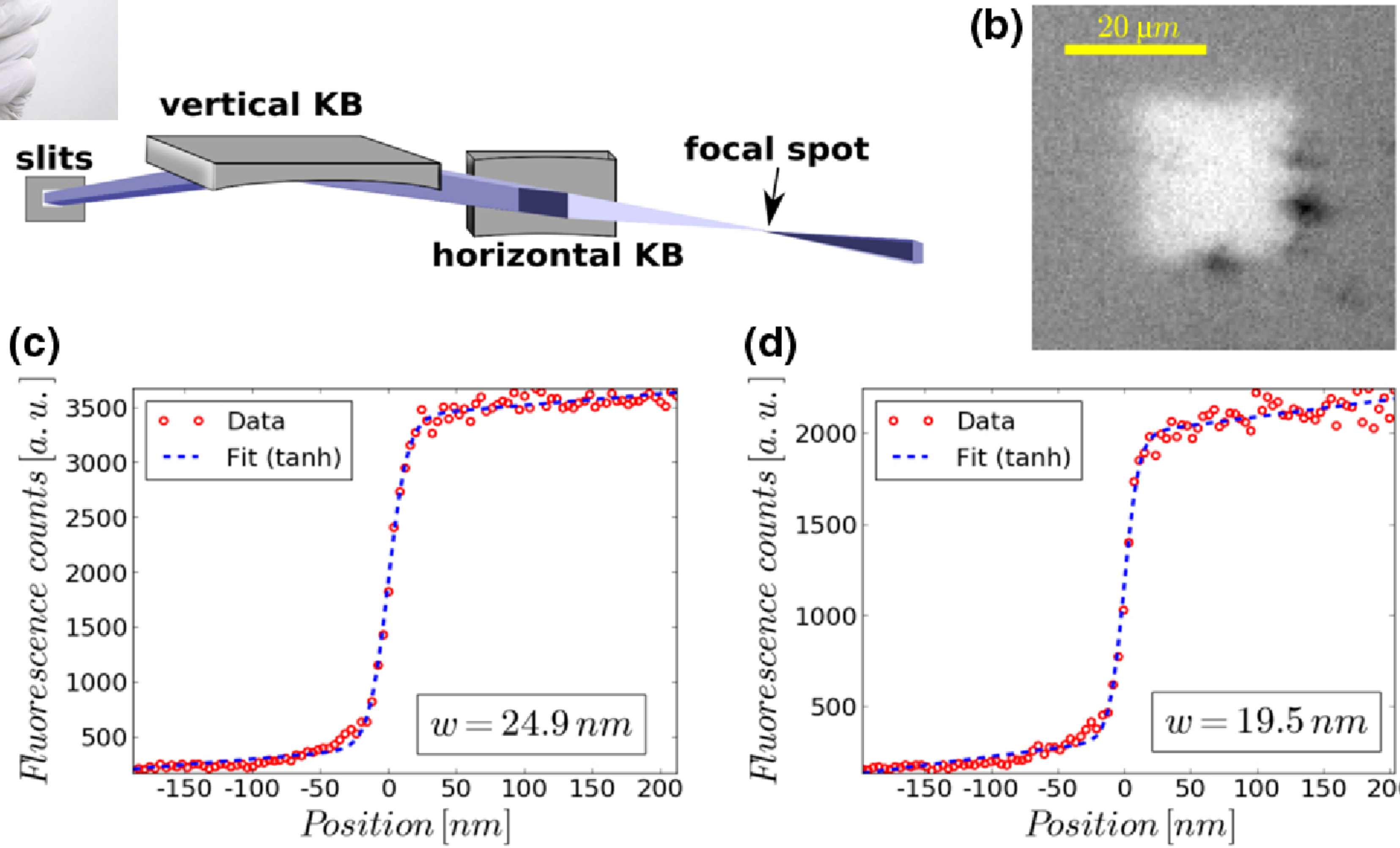


Figure 3. (a) Reconstructed lens profile and error. (b) Reconstructed phase error of the beam exiting an *N* = 20 lens stack. (c) SiO_2 phase plate to correct for the aberration.

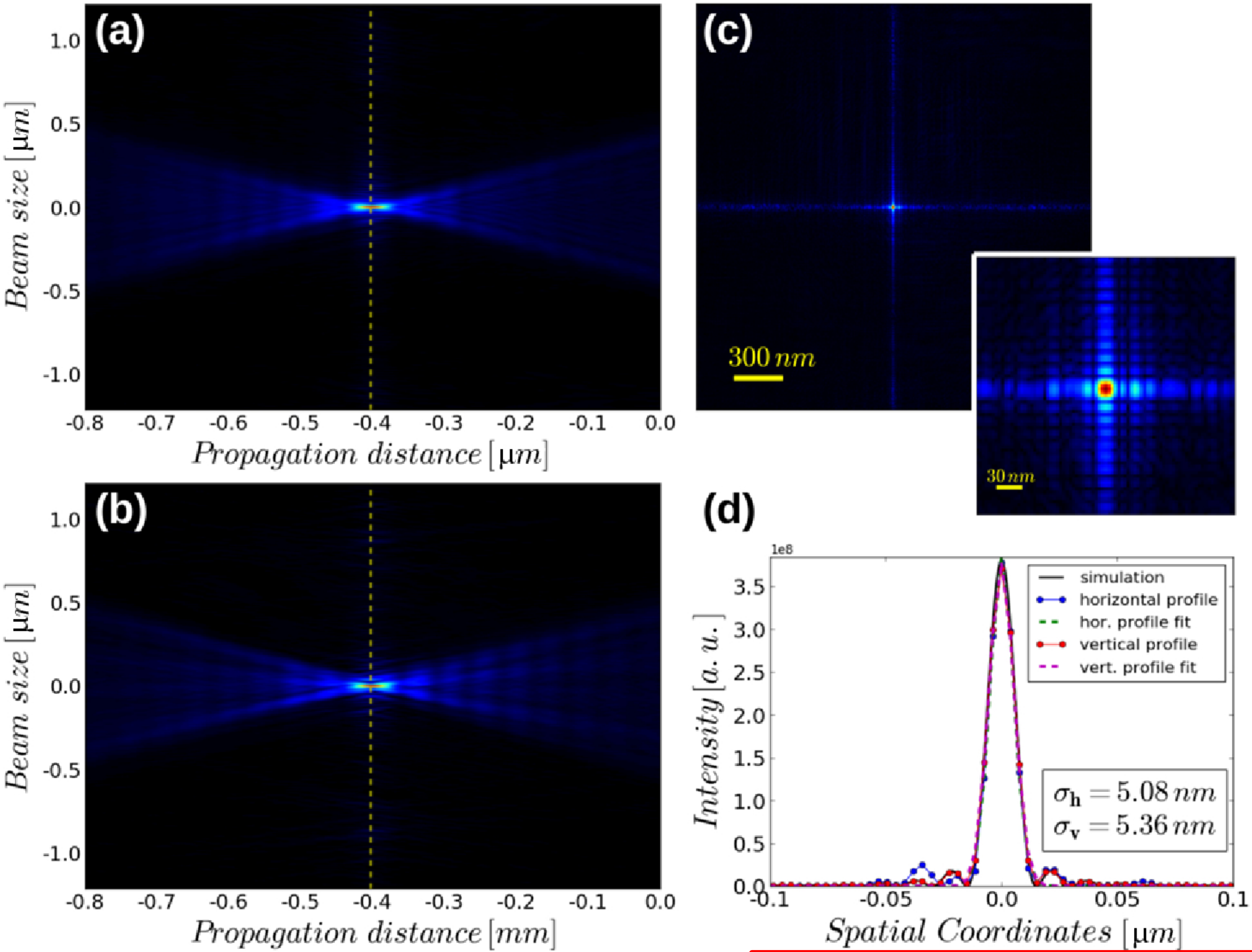
F. Seiboth *et al*, Nat. Commun. 8, 14623 (2017)

Elliptical Cylinder Mirrors: Figure errors < 1nm pv, roughness < 1Å
Multilayer coatings



J. Cesar da Silva et al, Optica **4,** 492-495 (2017);

BEAM PROFILE RECONSTRUCTION BY PTYCHOGRAPHY



13 x 13 nm^2 fwhm beam size

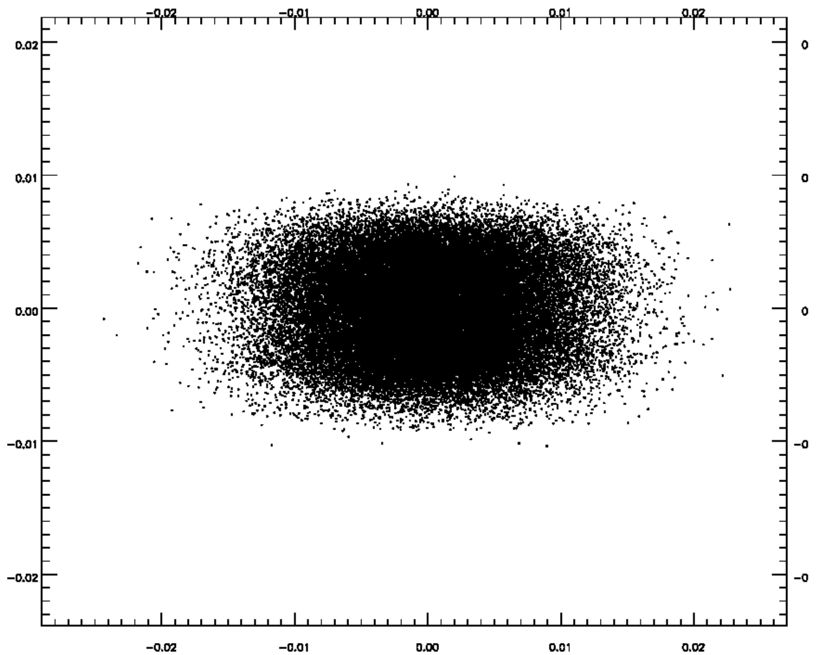
J. Cesar da Silva et al, Optica **4,** 492-495 (2017);

PRINCIPAL LIMITATIONS TODAY

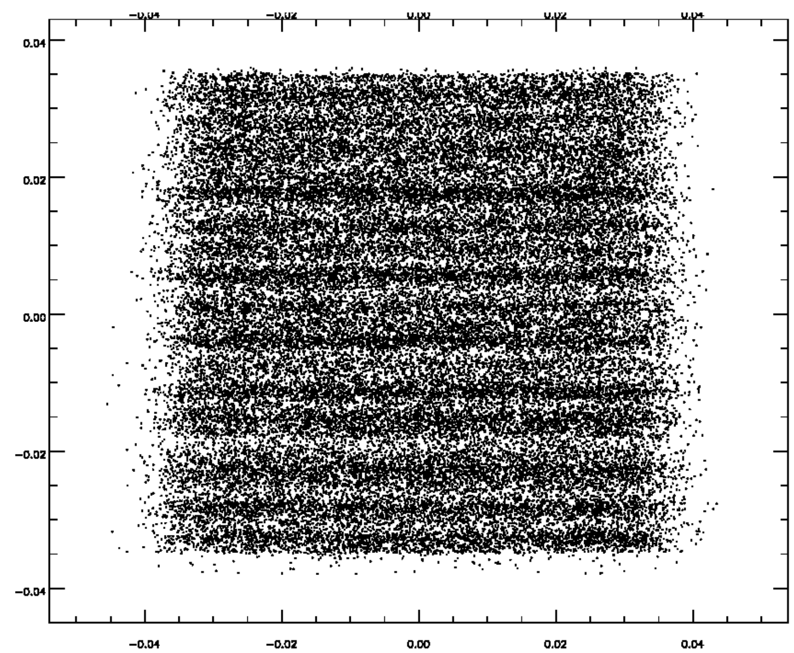
- **Current mirror/substrate polishing quality:** slope errors < 100 nrad rms, < 1nm p.v. but still performance limiting and few suppliers. Issues particularly in production of non-planar figures. Limits performance of ML systems too.
- **Crystal technologies:** energy resolutions ~0.5 meV (➔ rocking curve < 85 nrad rms) polishing essentially ok but some distortions due to absorbed power. Diamond may still be of interest...
- **Refractive lenses:** Not perfect in terms of optical quality and numerical aperture – current activity to improve lens quality and develop diamond lenses
- **Diffractive lenses:** Tend to suffer from limited efficiency (<1%) at higher energies, Multilayer Laue lenses can overcome this but currently small apertures
- **Crystal monochromator technologies:** Particularly for applications requiring energy scanning (crystal parallelism ~10µrad during energy scan)

Ray tracing simulations of mirror focused beam

in-focus



defocused

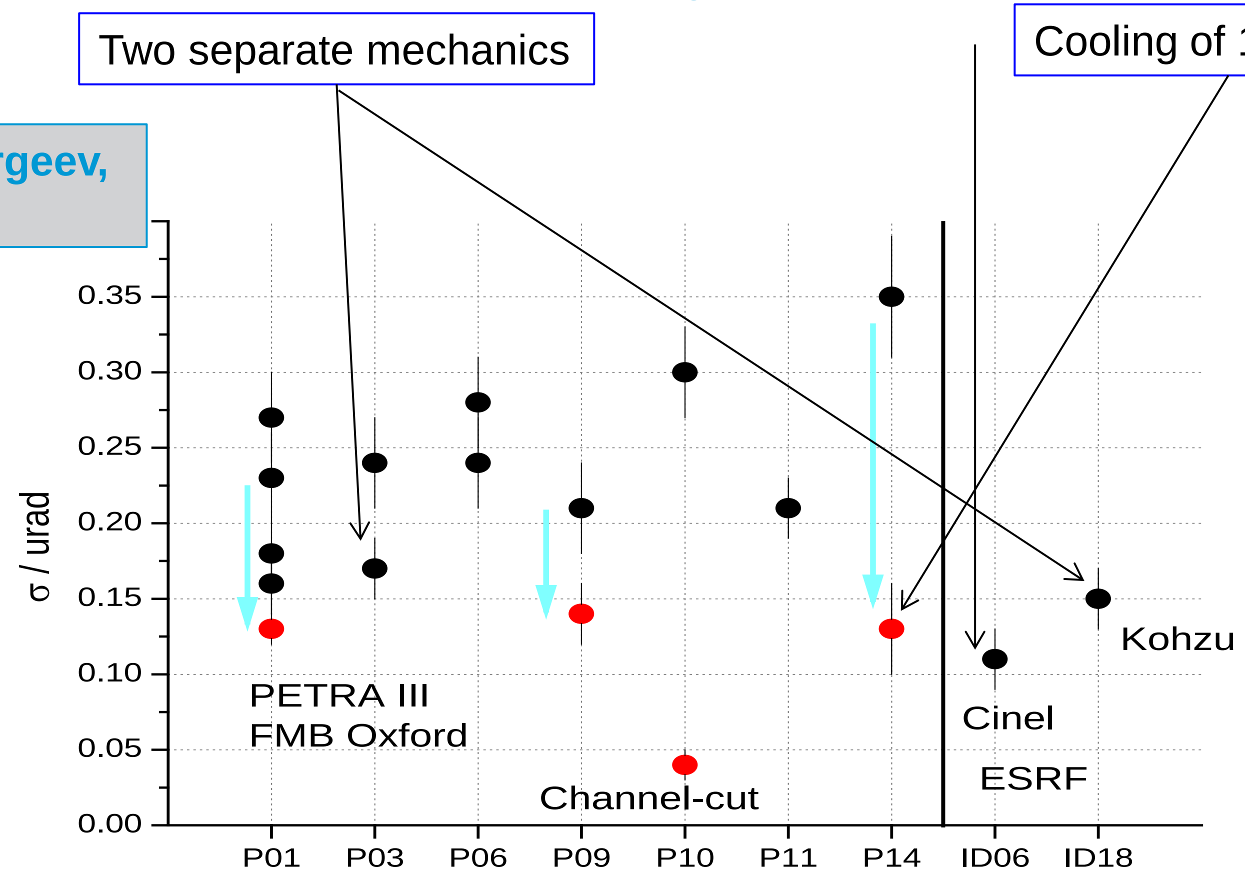


Actively corrected mirrors may be a partial solution

Sources aiming for high energy/spatial resolution and energy stability mostly experience limitations with current generation of commercial devices

e.g. crystal parallelism stability at fixed energy (measured in-situ):

Courtesy: Ilya Sergeev, PETRA III

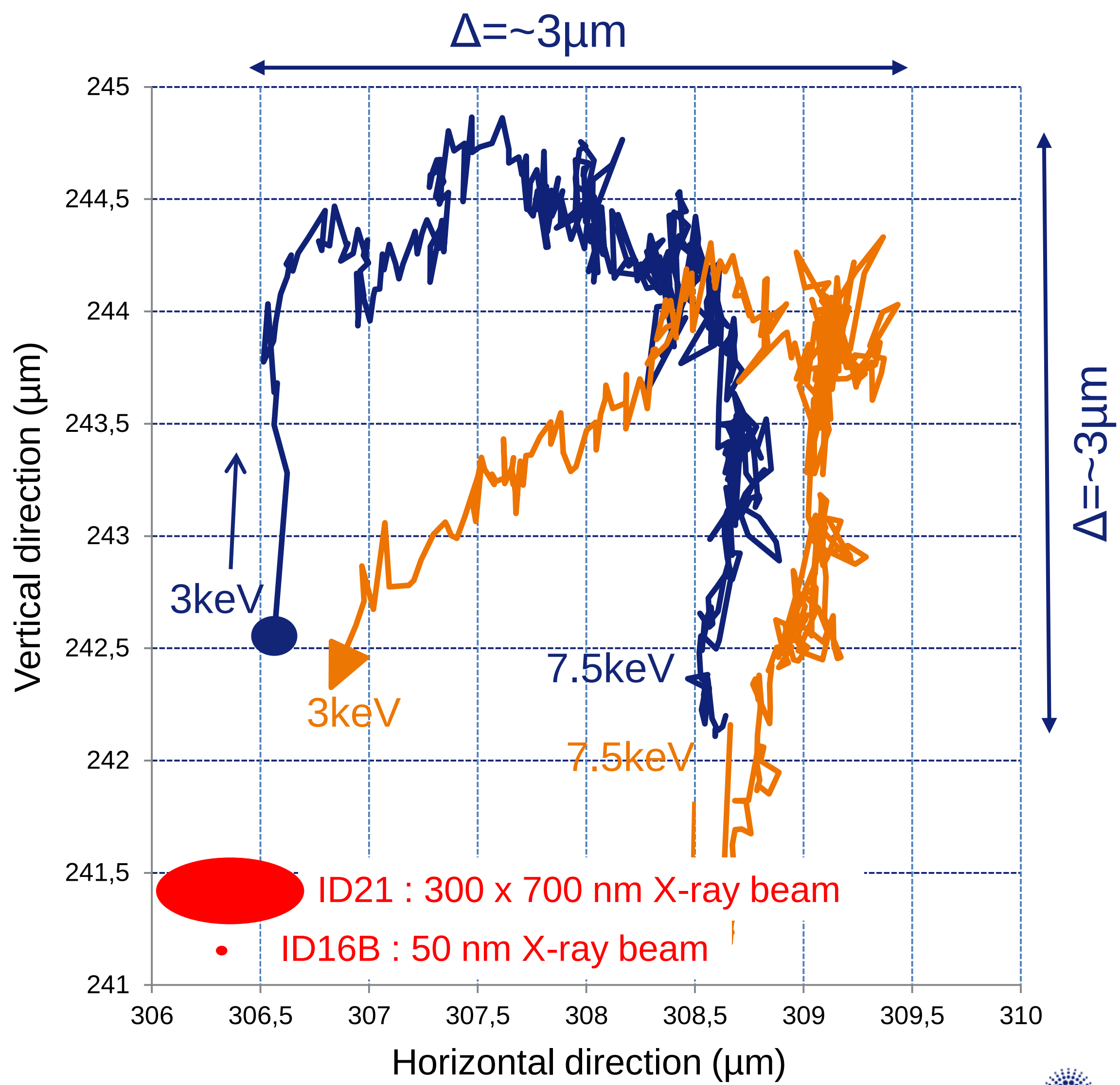


Some DCM systems give sub-50 nrad rms with LN2 cooling/beam but at fixed energy

BEAM STABILITY DURING ENERGY SCAN – MORE CHALLENGING

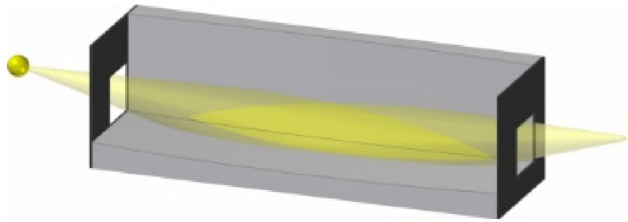
Micro-beam trajectory in sample plane during an energy scan: *Courtesy M. Salome*

- Kohzu Si (111) monochromator
- KB focused micro-beam
- Energy range : 3 keV to 7.5 keV and back,10 eV steps
- Angular range: 41.23 to 15.28 º
- Micro-beam position measured on fluorescence screen in KB focal plane with video-microscope in BPM mode
- Δ=3µm in focal plane corresponds to crystal parallelism variation ~10µrad



"FLAT" VS "ROUND" BEAMS

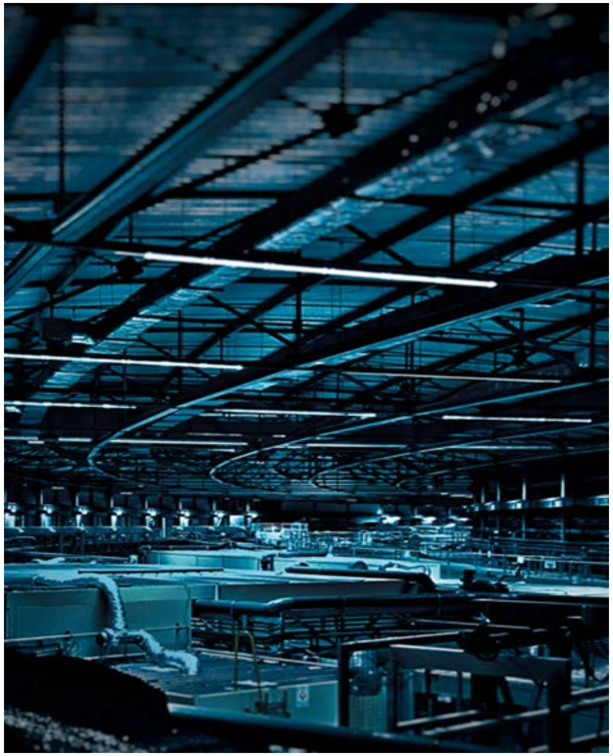
- Often mirrors used in horizontal deflecting geometry to mitigate the effects of 'moderate' mirror quality - this benefit would be lost (but relaxed for vertical deflection)
- Highest flux nanoprobe beams tend to be formed using KB mirror pairs which partially compensate the beam asymmetry. Montel mirrors as alternative?



- Increase of vertical source size would penalize beamlines aiming for highest energy resolutions and those aiming to maximise transverse coherence

CONCLUSIONS

- **X-ray optics are constantly improving but do not yet preserve the source emittance**
- **An increase in the vertical emittance in a round beam scheme might relax some of the optical constraints but would not be desirable for certain applications**



Thank you!
Merci!