Photons At the Next Generation Storage rings
Trieste , December 5th, 2017

Beamline design issues related to the future SOLEIL upgrade

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outline

- **Present /upgraded source**
  - Electron / photons source parameters
- **Light collection**
  - Collection efficiency
  - Unwanted light : heat load
- **Tolerances**
  - Stability
  - Optics quality
- **Some case studies**

Machine parameters SOLEIL/ Upgrade

SS	long	medium	short	*upgrade*
σ_x (µm)	281	182	388	7
σ_z (µm)	17.3	8.1	8.1	7
σ'_x (µrad)	19.2	30	14.5	7
σ'_z (µrad)	2.2	4.6	4.6	7

	β_x (m)	β_z (m)	η_x (m)
Long SS	10	8	0.2
Medium SS	4	1.8	0.13
Short SS	18	1.8	0.28
Upgrade	1	1	0

Natural horizontal emittance = 3900 → 72 pm.rad

Energy dispersion = 1.03 / 0.86 10^{-3}

Coupling = 1% /100%

Courtesy P. Brunelle

From electron to experiment

- **Photon source emittance gain**
  - electron emittance gain is ~ 4 10^3
  - What is transfer to the photon source ?
- **What will be the benefit for beamlines ?**
  - Smaller beam size on sample
    higher flux/ unit area (illumination)
    high coherence fraction
  - Better flux collection
  - Smaller optics size
  - Optics simplifications :
    less elements, shorter, more stable, beamlines
  - Requirements on optics quality

Monochromatic Photon emittance

- **Photon source = Electron beam + Undulator**
- **Independent convolution of divergence and source size contributions**
  for central cone $\sigma'_{ph} \approx \sqrt{\lambda / L}$ $\sigma_{ph} \approx \sqrt{\lambda L} \,/4\pi$ *(diffraction limit)*
- **Parameters for a 4m long undulator**

Energy	300 eV	3 keV	30 keV
σ_{ph} (µm)	10	3.2	1
σ'_{ph} (µrad)	32	10	3

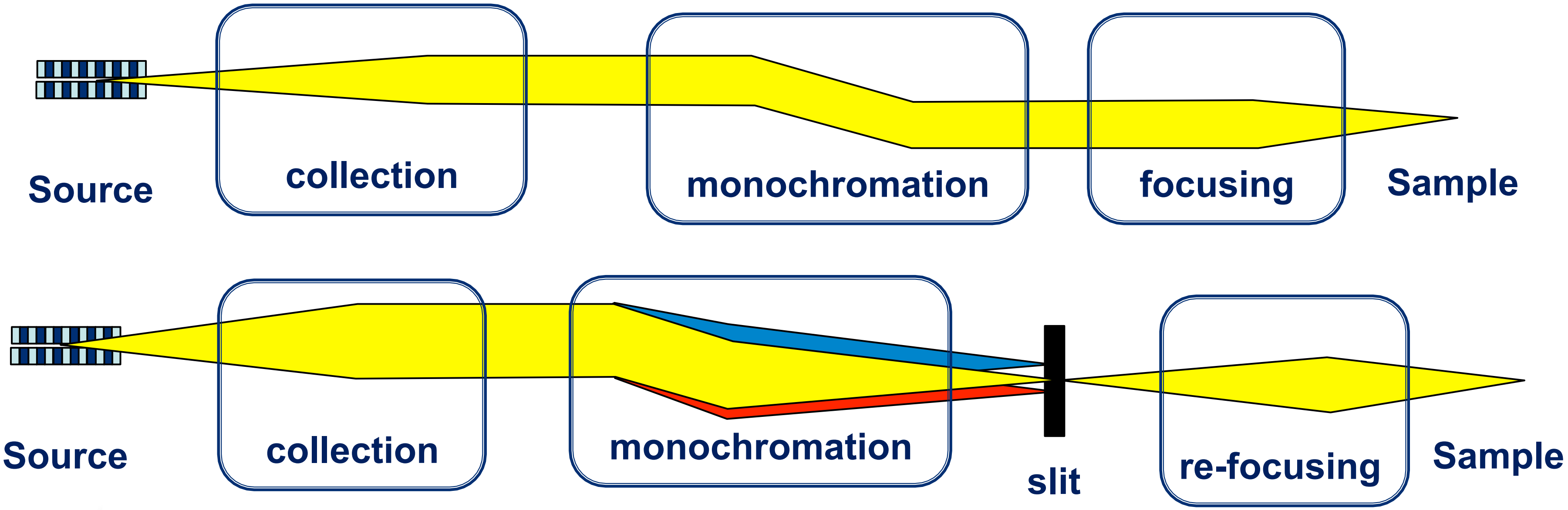
coherence

- **Electron and photon source size and divergence convolute independently**
- **Energy spread widening**

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right) \Rightarrow \text{shift emission peak @ } \lambda \qquad \Delta\theta \approx \frac{N}{2\gamma}\frac{\Delta E}{E}\left(1 + \frac{K^2}{2}\right)$$

~ 10 -20 µrad

Beamlines from a designer point of view



We want to preserve the small source size throughout

- for soft X-rays to hard X-rays

We used to rely mostly on reflective optics

- Because they are achromatic
- What do we need to change ?

Elimination of 1st optics vignetting

- **Small divergence beams have long waists**

$$\sigma^2 = \sigma_0^2 + (\sigma' Z)^2 \quad \Longrightarrow \quad \text{waist length} \sim 3\ \boxed{?}/\boxed{?}'$$

  - With present β > 10m and non zero horizontal dispersion, the first optics at 20 m is often vignetting on high energy BL

- **With β= 1m**
  - All optics are in the far field of the source
  - Size of the optics match the source divergence

Thermal load

- **Total radiated Power**

$$P\left[kW\right] = 0.633\, E^2\left[GeV\right] B_0^2\left[T\right] I\left[A\right] L\left[m\right]$$

Undulator length

- **On axis Power density**

$$dP/d\Omega\left[W/mrad^2\right] = 10.84\, B_0\left[T\right] E^4\left[GeV\right] I\left[A\right] N$$

Number of periods

Expected increase

L $\longrightarrow$ x 2 ; $B{\downarrow}0 \longrightarrow$ x 1.5

Power density do not depend on electron beam size and divergence

But useful collection aperture does.

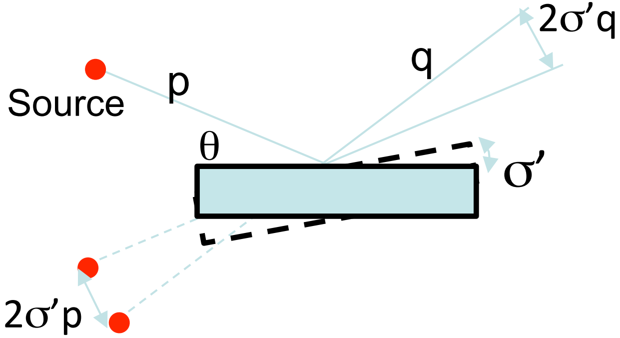
Reduction of the collection aperture in hard X-rays

Stability issues

- **Stability requirements scale with the source size**
  - On the upgraded machine they will be ~7 µm in both planes
  - This is almost the present vertical size
  - Stability level required for the 1st optics at 20 m :
    0.5 µm in position ; 10 -20 nrad in angle
- **Presently most beamline are sensitive to vertical thermal drifts**
  - Improvement of the hutches temperature stability and
  - more rigorous mechanical design requested
- **Vibration stability**
  - Angular vibration induced by the cooling systems are the most critical.
  - Rigidity of the cooling lines is hardly compatible with precise position and angle adjustment of the optics under beam.
  - Thermo-mechanical engineering is highly required

Mirror slope errors

- **Mirror imperfections can be characterized by slope errors**
  - Small wavelengths ⟶ geometrical optics
  - Image widening ∝ focus distance (q)
    - Tangential : $w_t = 2\,\sigma'_t\,q$
    - Sagittal : $w_s = 2\,\sigma'_s\,\sin\theta\,q$



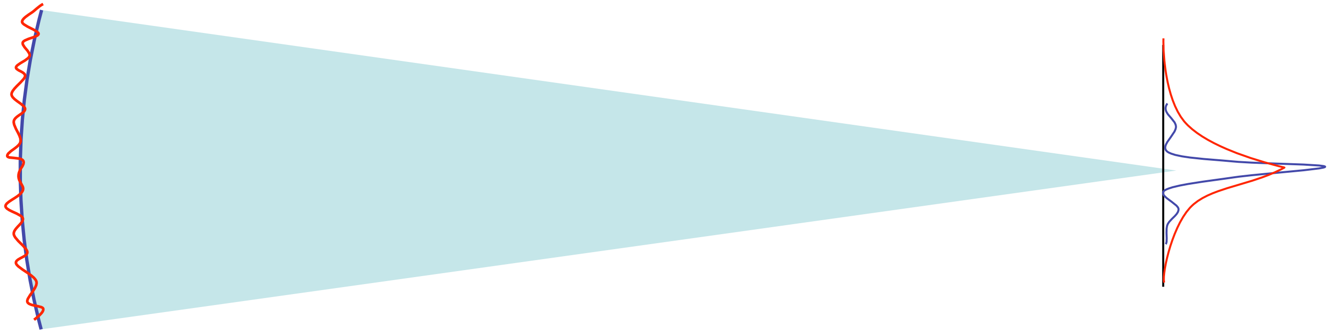
Two ways of reducing slope error influence

1. **Choose a short focus distance**
   - Focusing stage only
   - Diaphragm in a intermediate image may help decoupling beamline optics influence (flux cost)
2. **Use sagittal focusing geometry**
   - Only in the most sensitive (dispersion) direction
   - Widely used on present machine due to source size asymmetry

- **Upgraded SOLEIL will require tighter tangential tolerances**

  Source at 20 m & $\sigma_h = 7\ \mu m \Rightarrow \sigma'_t << 0.2\ \mu rad$

Wavefront preservation



- **Light scattered from wavefront imperfections**
  - Reduces peak (specular) intensity ; generate a halo around it.
- **Wavefront quality often expressed by Strehl ratio**

$$S = \mathit{specular\ flux}/\mathit{total\ flux} = (\mathit{total\ flux} - \mathit{scattered\ flux})/\mathit{total\ flux}$$

= 1 – TIS *(Total Integrated Scatter)*

- **Scatter is related to the power spectral density of phase fluctuations**

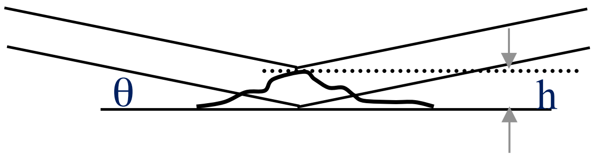
TIS=*exp*(−2⍰ ⍰↓⍰)↑2 =*exp*(−2⍰ ⍰↓⍰ /⍰)↑2 ⍰↓⍰ ↓↑2 = variance of optical path

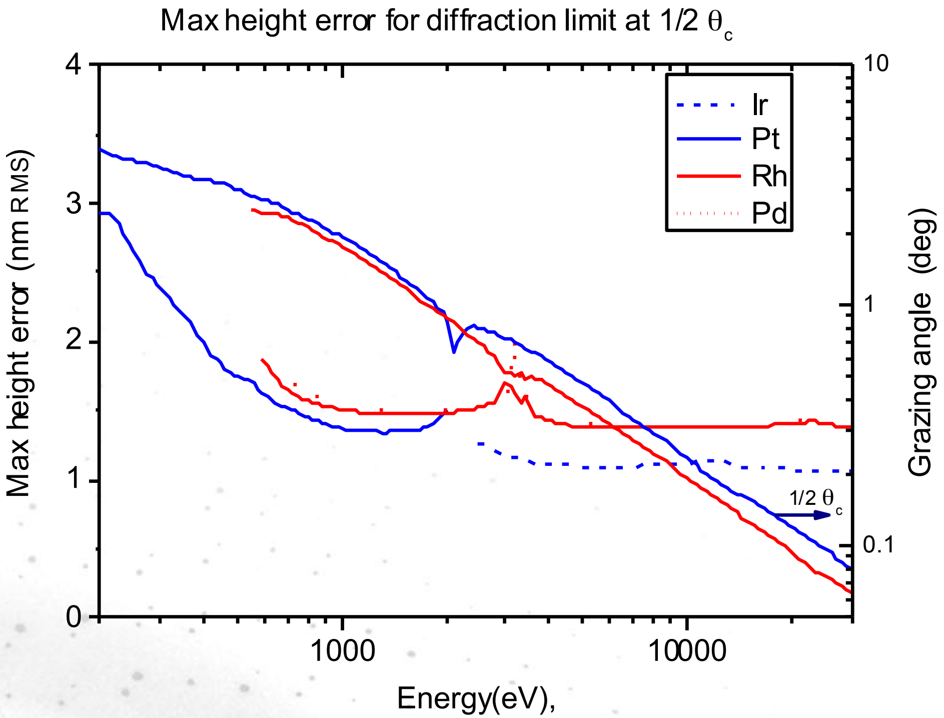
For imaging :

S>0.8 ⟺ ⍰↓⍰ ↓↑2 > ⍰↑2 /180 Maréchal criterion

Diffraction limited optics

- **For focusing: phase errors must meet Maréchal criterion**
  - $\sigma_\Delta = 2\sin\theta\,\sigma_h < \dfrac{\lambda}{14}$ (total for all surfaces)
  - Tolerances are relaxed by grazing angle
  - Rough estimate using $\theta = \theta_c/2$ for simple metal coating





Consequences of small grazing angles

- **Incidence changes along a curved surface**
  - Difficult to exceed ± 30% of central value θ_0
  - ➢ Image aperture angle NA < 0.3 sin θ_0

- **Reduced aperture angle impacts spatial resolution**

  Minimum focus size is inversely proportional to aperture angle

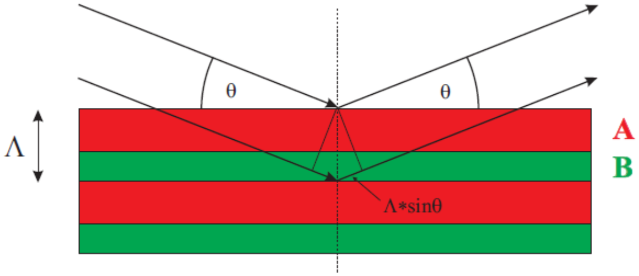
  even for a perfect surface $\rho = \lambda / 2\,NA$

  eg: E= 20 keV ; grazing angle 0.09 deg $\Longrightarrow$ $\mathrm{NA} = 0.47\ 10^{-3}$ $\rho = 66\ \mathrm{nm}$

  Transverse aperture size is also very small

  eg : F= 100 mm $\Longrightarrow$ aperture size= 100 µm

Multilayer coatings



- **Tuning condition**

$$m\lambda = 2\Lambda\sqrt{\bar{n}^2 - \cos\theta^2}$$

$$m\lambda = 2\Lambda\sin\theta \;\; if \; \theta >> \theta_c$$

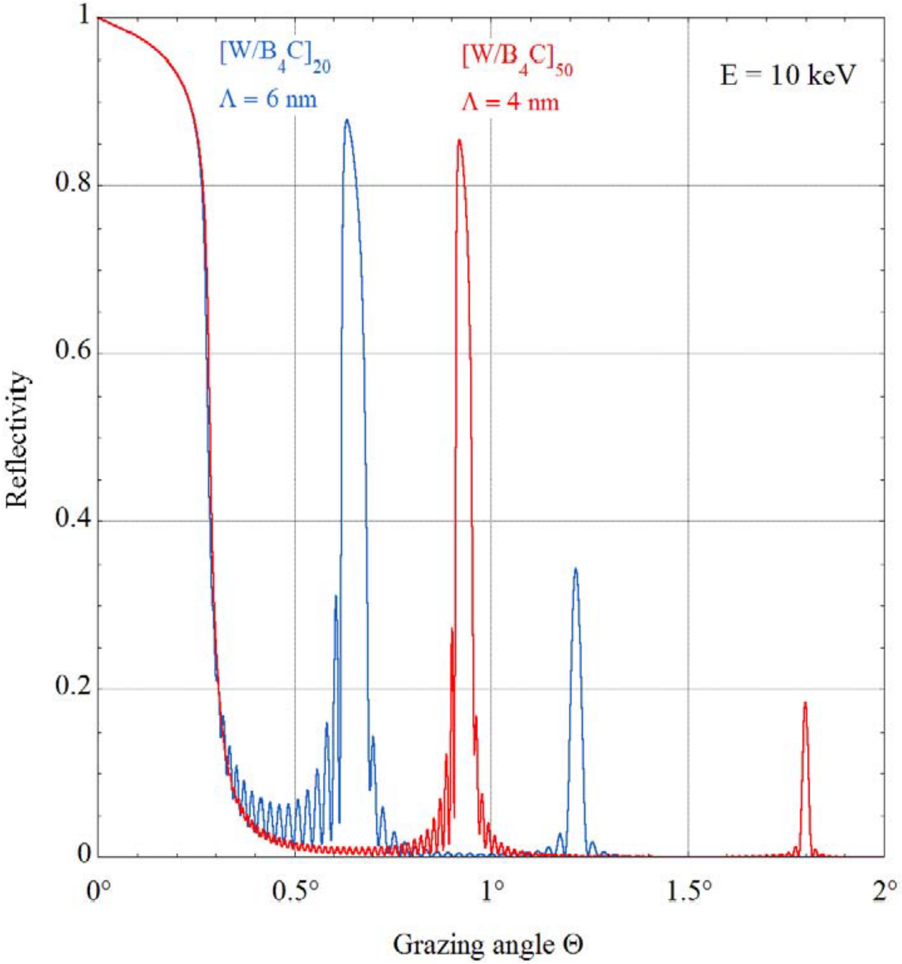
- **Standard material pairs**

  Mo/B4C Cr/B4C W/B4C

- **Stable down to ~ 2.5 nm period**

- **Bandpass / reflectivity tradeoff**

  Number of effective periods



From C. Morawe , ESRF Friday seminar 25-05-10

Multilayer / single layer mirror

	Single layer	multilayer
Grazing angle θ	$\sim\boxed{?}/35\ nm$	$\boxed{?}/2\boxed{?} < \boxed{?}/4\ nm$
Max Aperture ~ θ/3	$<\boxed{?}/100\ nm$	$<\boxed{?}/12\ nm$ *requires ML gradient*
Ultimate Resolution	*50 nm*	*6 nm*
RMS shape errors *(Maréchal)*	*< 1.3 nm*	*< 0.15 nm*

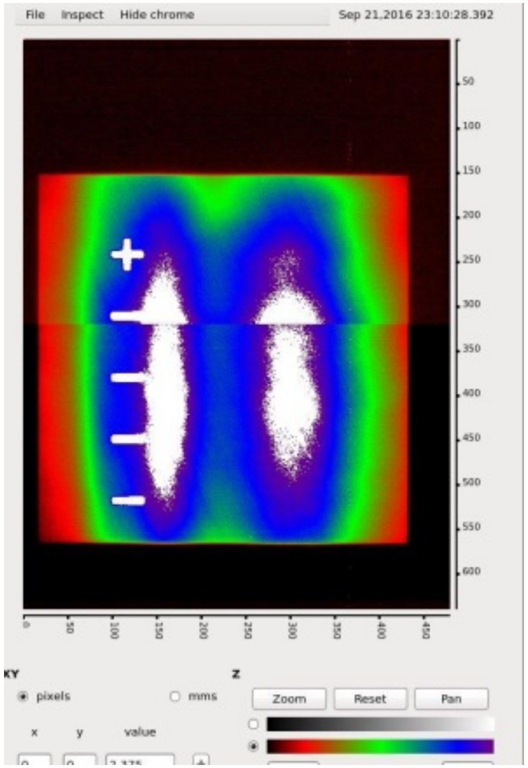
Mirror quality progress

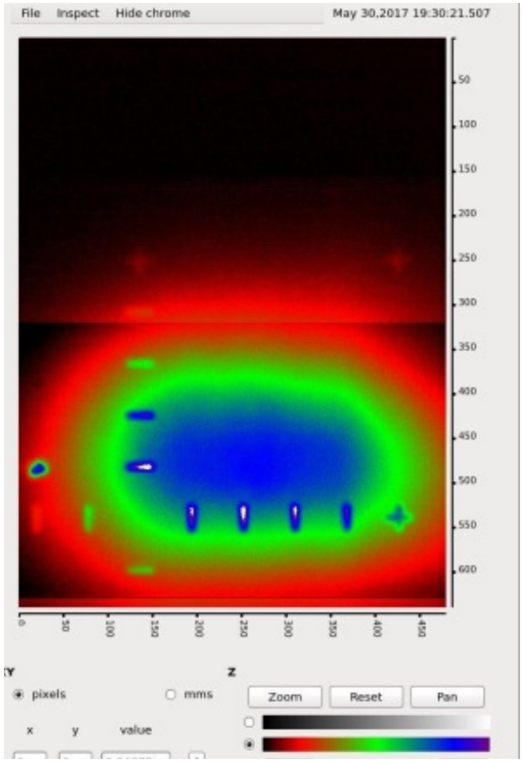
- **SOLEIL Beamline mirrors**
  - **Conventional polishing + Ion figuring correction**
  - Best tangential RMS slope errors on length 200 – 300
    2006 : 0.5 µrad
    2011: 0.25 µrad
    2016: 0.23 µrad
  - **Fluid Jet polishing**
    2014: 50 nrad (0.2 nm RMS) - length 300 mm
  - Fluid jet polishing is mastered by one manufacturer only !

Mirrors are the only achromatic X-ray optics

- Also required as blanks for non achromatic optics:
  gratings and multilayer mirrors

Effect of shape errors on a fully coherent beam





Beam on LCLS CXI station on Sept 2016

KB mirrors are 450 mm long
with 2 nm RMS shape errors.

Beam on LCLS CXI station on May 2017

New KB mirrors, 1 m long, fluid jet polished
0.3 nm RMS measured by manufacturer
(0.5 nm measured at LCLS)

Courtesy Daniele Cocco (SLAC)

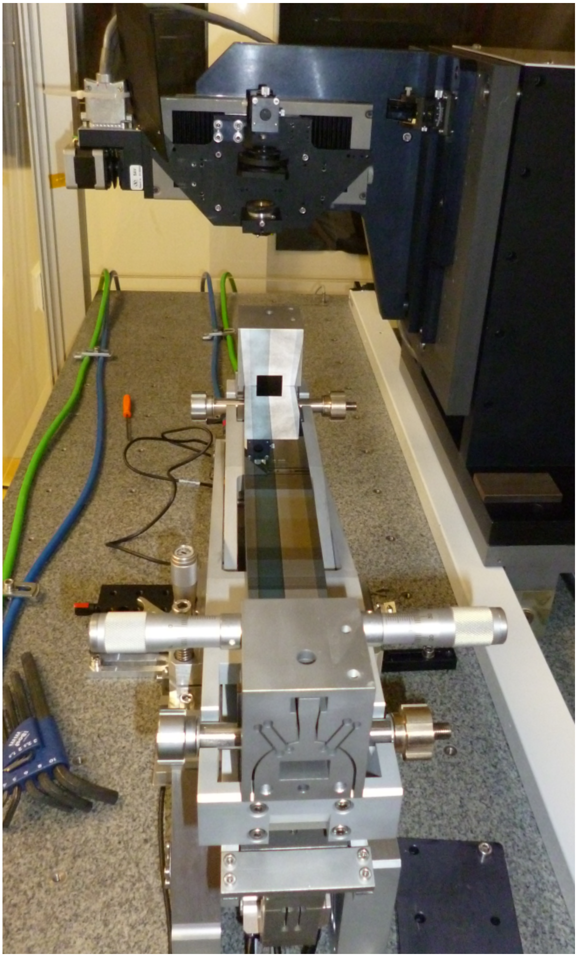
Laboratory Metrology

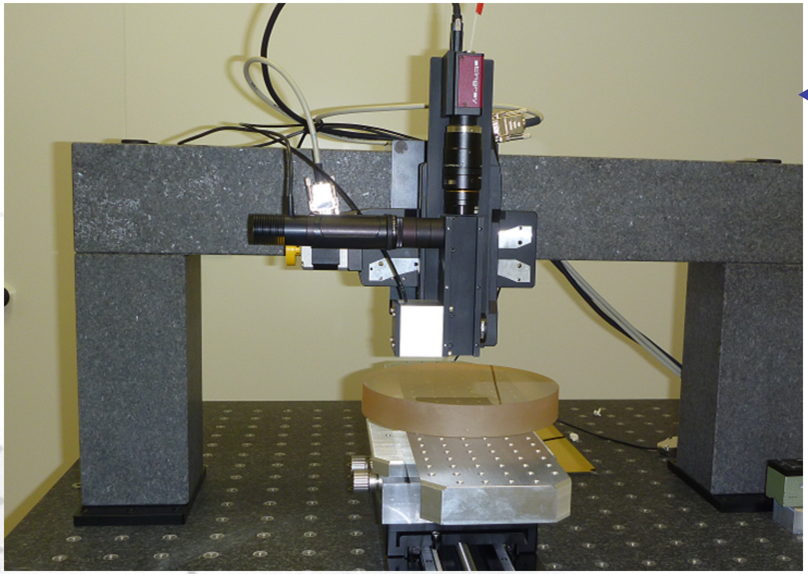
- **LTP or NOM**

  Slope measurement on linear traces

- **Phase shift interferometer**

  2D height maps (with field stitching)





LTP

Sensitivity: ~ 50 nrad

Accuracy: ± 0.1 – 0.2 µrad

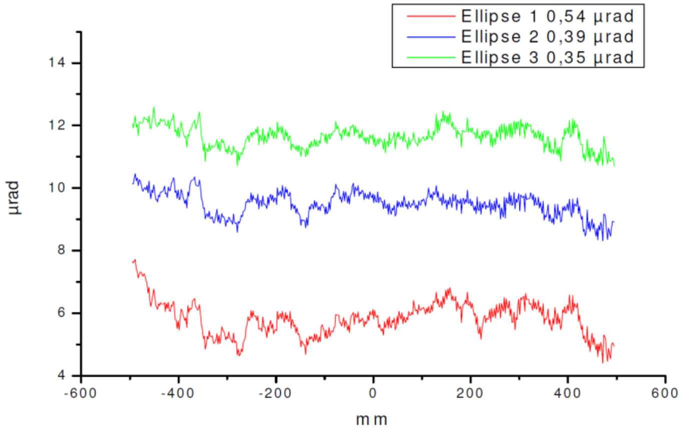
Deflection response is not perfectly linear

- must be calibrated
- can be corrected by measuring the surface with a series of tilts

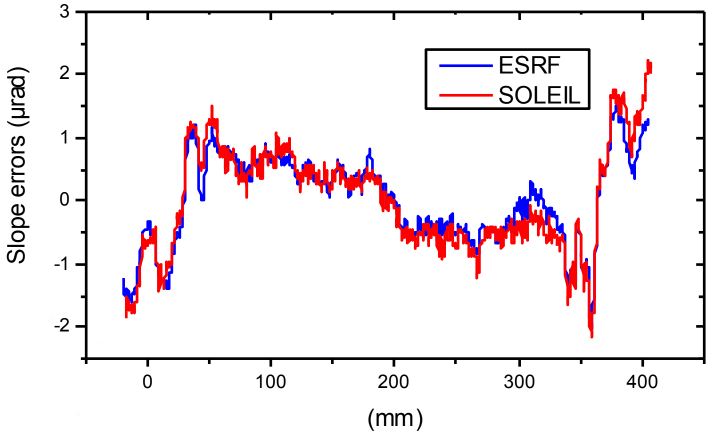
Sensitive to thermal drift

- requires a thermally stabilized enclosure (± 0.1 °C !!)
- repeated measurements needed for ultimate accuracy

Height errors computed by integration



Tuning of a 1m long bender



LTP cross-check on a 22 m radius mirror

Phase shift interferometry

Small field required to reach 10 mm^{-1} spatial frequency ⟹ **Stitching**

Sensitivity: ~ 0.1 nm = $\lambda/5000$

Accuracy: ± 0.3 – 0.5 nm

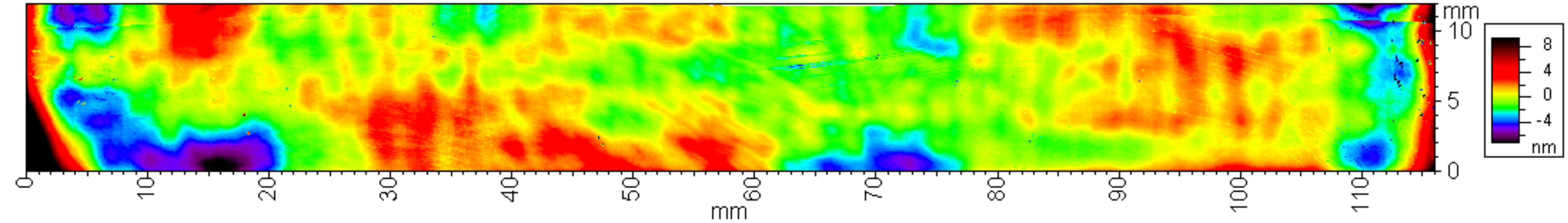
Uses a reference surface which is not perfectly known

- must be calibrated
- can be extracted from a set of overlapping measurements of a good flat surface

Stitching procedures

- cannot rely on relief correlation (smooth surfaces)
- Must be guided by other measurements to avoid long range distortion of the shape

wide pupil interferometer (RADSI)
autocollimator or LTP trace



SiO_2 differential coated mirror

Case study 1 : microfocus 20 KeV

- **Present state**
  - Source 650 µm x 20 µm (HxV FWHM)
  - Transfer to secondary source in extension building
    - p= 27 m , q =58 m M=2.1
    - Secondary source slit cut to 40 x 40µm flux loss ~ 40
  - KB demagnification
    - p=83 m , q =0.15m M=1/550
    - Spot size ~ 70 -100 nm
  - Total length : 165 m

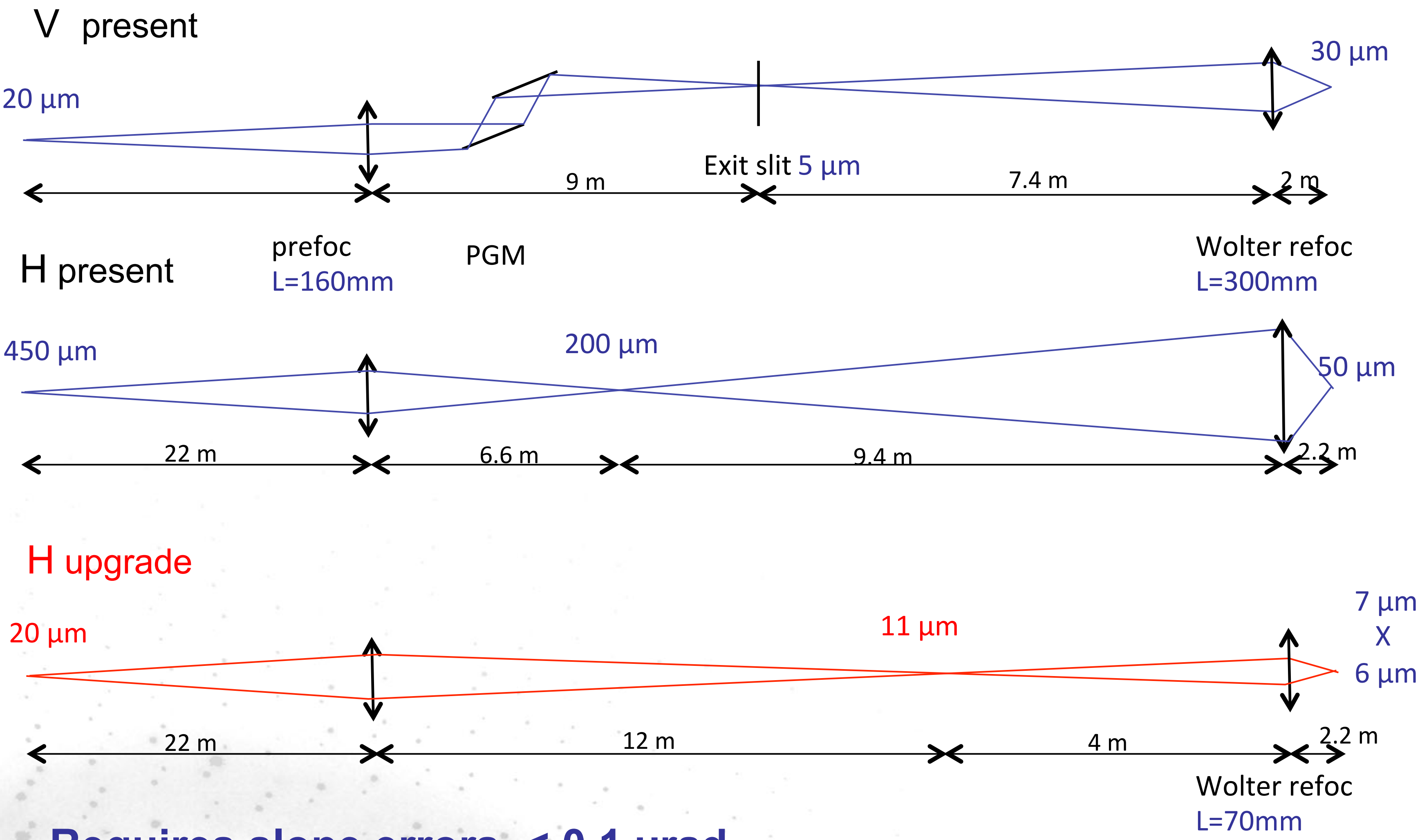
- **Upgrade**
  - Source 15 µm x 15 µm (HxV FWHM)
  - Direct KB demagnification
    - p= 40 m , q =0.2 m M=1/200
    - Spot size ~ 70 -100 nm
  - Total length :40 m
  - Fit on the experimental floor
  - Shorter length ⟹
    better thermal stability
    less vibration issues

Case study 2 : VUV beamline

- **Energy range 5 - 40 eV**
- **Present state**
  - Electromagnetic 10 m long undulator 16 periods of 64 cm
  - Collection aperture 0.6 x0.6 mrad^2 *(oversized)*
  - @5 eV K ~ 6.7 ; B_{max}= 0.15 T
  - Total radiated power ~500 W : incident power on optics <100 W

- **Upgrade**
  - Permanent magnet undulator, 4 m long 16 periods of 25 cm
  - @ 5 eV K~ 11 ; B_0= 0.47 T
  - Radiated power density ~2 kW :
    need to reduce the aperture to keep P <100 W

Case study 3: photoemission beamline ~ 1 keV



Requires slope errors < 0.1 µrad

Conclusion

- **The close match of electron and undulator divergence** (small β) **enables a good transfer of source size gains to image size**
- **Smaller source size mean less demagnification**
  - More compact design
  - Smaller aperture and optics size
- **This size change directly affects the requirements on optics quality**
  - slope errors < 0.1 µrad RMS
  - Shape errors < 1 nm RMS
  - Synchrotron facilities should develop the metrology to control such specifications
- **Stability requirements scale in the same proportions**
  - Thermal drift
  - Vibrations (eg induced by cooling)