SUPERFLAT

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Open Market Consultation

19 November, 2021

Introduction to the Technical Content

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Co-funded by the European Union

LEAPS INNOVATION

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 101004728

Mirrors for the next generation of Synchrotron and FEL sources

- Progress on electron accelerator design allows nearly diffraction limited photon sources over a large energy range.
- Among LEAPS* members, several facilities have upgraded to such sources and many are planning upgrades in a near future

- Quality of mirror surfaces is a major limiting factor for transferring the source brightness to the sample.
- Next generation beamlines will increasingly require "*nanometer precision*" optical surfaces

* League of European Accelerator-based Photon Sources (https://leaps-initiative.eu/)

An X-ray beamline optics wish list

- Optics that have no measurable impact on the wavefront
- Optics that have surface microroughness compatible with the deposition of high-performance short period multilayers
- Such optics with sizes up to 1 m long
- Strongly aspheric surfaces for short focal length focusing of X-rays
- Ability to figure the optical surface to tailor the wavefront
- Optics that could withstand the high radiation power of our sources

Aim of Superflat PCP

- Incite and help the development of production processes compatible with the forthcoming X-ray optics demand in the EU
- These processes may include sequences of
  - Full-size tool polishing
  - Computer controlled abrasive or slurry polishing (CMP , pads, …)
  - Deterministic local tool figuring (Ion beam, fluid jet, EEM, …)
- Surface metrology is required to guide deterministic figuring
  - Suppliers should demonstrate adequate metrology
  - Cross-calibration will be done with the metrology of the buyers group

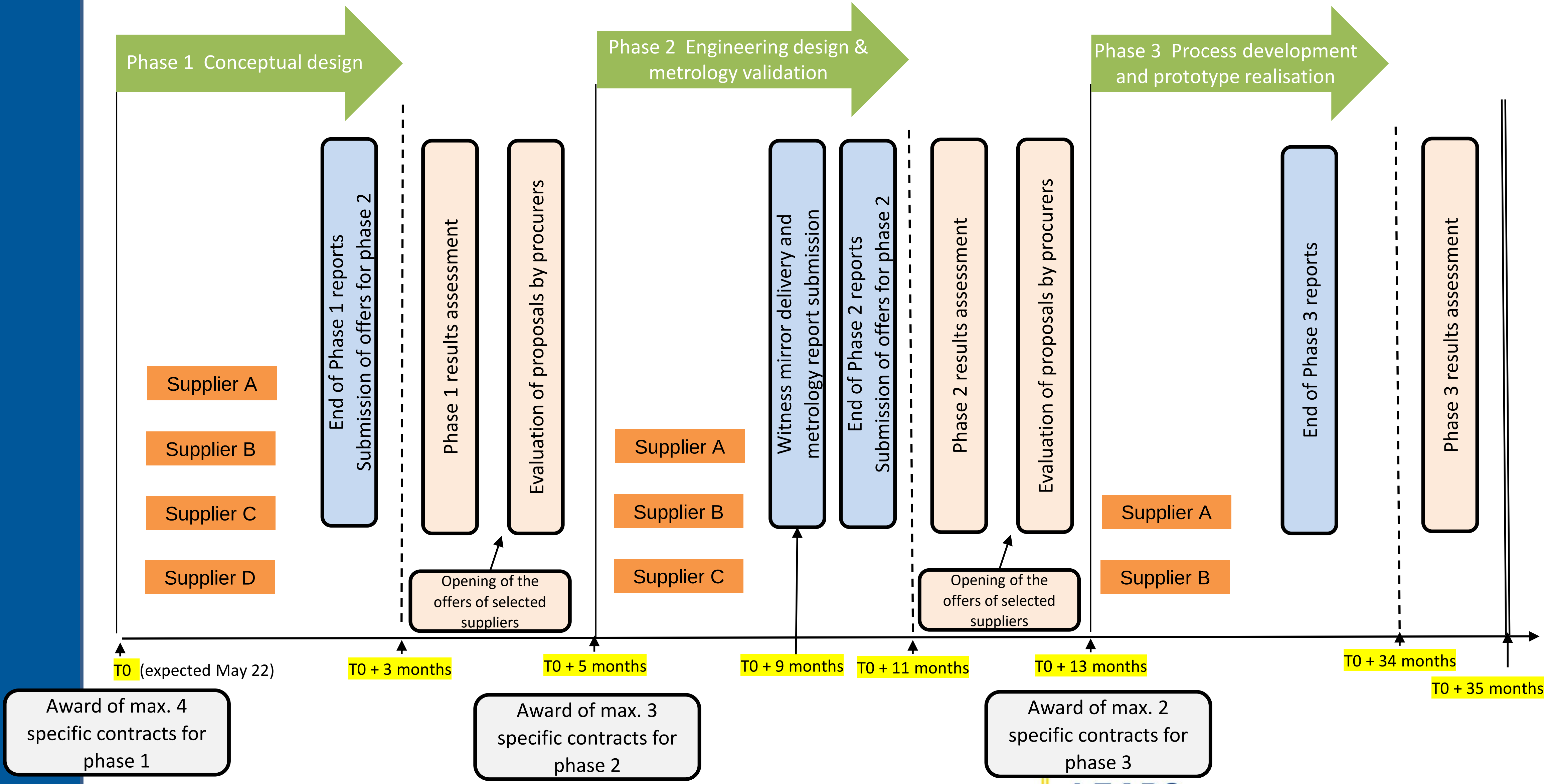
Summary of Specifications for Superflat Call

- Flat surface
  - Average curvature < 0.02 km^{-1}
- Minimum clear area 500 mm x 20 mm
- Figure error
  - Height error < 1 nm PV
- Slope error
  - RMS slope error < 50 nrad
- Roughness < 0.1 nm RMS
- Figure and slope errors are evaluated on the clear aperture after subtraction of the "best fitting toroid" approximated by a 2nd order polynomial

Scope of Superflat

- Development of a fabrication process for high-quality flat mirrors in 3 phases
  - Conceptual design
  - Engineering design and metrology validation
  - Process development and prototype realisation

Superflat timeline



Scope of Phase 1 (3 months)

- A conceptual design study presenting
  - – manufacturing technologies– figuring machines, tool heads, processing algorithms – either pre-existing or which will be developed or upgraded in phases 2 and 3
  - – metrology technologies - either pre-existing or requiring development and their integration into the production process.
  - – All computations and simulation needed to justify the above proposals (i.e. describing why existing tools or processes are considered sufficient or new developments are required)
- A detailed risk analysis from preliminary studies

Scope of Phase 2 (6 months)

- Engineering documents of the planned production means
- Technical study supporting the process choices
- A reduced scale evaluation report of processes, machining algorithms and metrology under development
- An update of risk analysis for phase 3

- Deliverables (at month 4)
  - A sample mirror of reduced area and specifications
  - A report on the metrology performed on an identified 75 mm x 15 mm area of this mirror with metrology equipment representative of that to be used in the proposed manufacturing process
  - ➢ The sample mirror will be cross-measured by the buyers group and a report sent to the manufacturer with the evaluation of phase 2. It will remain the property of the manufacturer and returned before phase 3

Scope of phase 3 (21 months)

- Development of an operational mirror manufacturing process
  - supported by a visit of production means by the buyers group on the supplier’s premises
- Documentation of the developed process
- An analysis report on the limits of the process at the end of phase 3 with directions and prospects for improvement
- Deliverables :
  - Progress reports (M 6, 12, 18) ; final report (M21)
  - A full-size prototype mirror (M21)
  - A metrology report of the prototype (M21)

Cooperation between suppliers and the buyers group

- The members of the buyers group are developing and maintaining high performance surface metrology equipment and methods
- These metrology facilities are cross-checked on a regular basis
- They will be used for evaluation of the results
- Suppliers may ask for cross-checks with their own metrology means during phase 2 and phase 3

- Assessment of optical surface quality is not fully normalized.
- Cooperation is also expected to converge toward a common mutually agreed metrology data collection and processing protocol

Defining optical surface quality

- Surface quality of X-ray mirrors is classically evaluated by 3 global values:
  - figure errors, slope errors, roughness
  - after detrending with a best fitting polynomial surface
- Issues
  - Spatial frequency of the defects is not always specified
  - Frequency filters can yield very different results especially for RMS slopes
  - Filtering can be hidden in data acquisition and processing

As a result intercomparison can be strongly biased

Impact of surface imperfections on wavefronts

- Surface imperfections characterized by the height error

  $h(X,Y)$ = distance to the design surface

➢ Local phase error of the reflected wavefront

  $\varphi(X,Y) = 4\pi \frac{\sin\theta}{\lambda} h(X,Y)$, where θ is the grazing incidence angle

- *Single material reflection*

  θ must be below the critical angle of reflection $\theta_c \cong \sqrt{2\,\Re(1-n)}$

  $\delta = \Re(1-n)$ varies roughly as E^{-2} over the X-ray range

  Hence the scaling factor $\frac{\lambda}{\sin\theta_c}$ is nearly constant ~ 30 nm

- *Multilayer reflection*

  The scaling factor $\frac{\lambda}{\sin\theta} = \Lambda_{mc}$ is the multilayer period $\gtrsim$ 2 nm

Height variance, Total Integrated Scatter (TIS) and Strehl Ratio

- Light scattered from a rough surface is evaluated by the TIS

$$\text{TIS}=\frac{Total\ scattered\ intensity\ outside\ the\ specular\ reflected\ \ peak}{Total\ specular\ intenstity\ in\ absence\ of\ roughness}$$

- If the height distribution is Gaussian (variance= σ^2) it was shown that[1]

$$TIS = 1 - \ exp\left[-\left(4\pi\ sin\theta\,\frac{\sigma}{\lambda}\right)^2\right]$$

- The Strehl ratio complements TIS
  It is the ratio in the peak with / without roughness

$$Strehl = 1 - TIS = \ exp\left[-\left(4\pi\ sin\theta\,\frac{\sigma}{\lambda}\right)^2\right] \approx 1 - \left(4\pi\ sin\theta\,\frac{\sigma}{\lambda}\right)^2$$

The formula still gives reasonable estimate though Gaussian assumption may not be fully valid while Strehl > 0.1

Maréchal criterion $\sigma_w^2 < \frac{\lambda^2}{180}$ *is equivalent to Strehl > 0.8*

[1] Bennett, H.E., Porteus, J.O., 1961. Relation Between Surface Roughness and Specular Reflectance at Normal Incidence. J. Opt. Soc. Am., JOSA 51, 123–129. https://doi.org/10.1364/JOSA.51.000123

Slope variance, Slope errors and PSF broadening

- The PSF is the FT of the autocorrelation of the pupil

➢ if the pupil is multiplied by a phase factor $f = e^{i\varphi}$, then the PSF is convoluted by a broadening function equal to $|FT[f]|^2$

- The RMS width of the broadening function is generally calculable
(it is not the case of the diffraction limited PSF, the integral being divergent)

- $\sigma_{kx}^2 = \iint \left|\hat{f}(\boldsymbol{k})\right|^2 k_x^2 \, dk_x dk_y - \left|\iint \left|\hat{f}(\boldsymbol{k})\right|^2 k_x \, dk_x dk_y\right|^2 = \iint \left|\frac{\partial f}{\partial x}\right|^2 dx\, dy - \left|\iint \frac{\partial f}{\partial x} f^* \, dx\, dy\right|^2$

- Which for $f = e^{i\varphi}$, reduces to $\sigma_{kx}^2 = \langle \left(\frac{\partial \varphi}{\partial x}\right)^2 \rangle - \langle \frac{\partial \varphi}{\partial x} \rangle^2$

- Converting from wavefront (x, y) to surface coordinates $x = X\, sin\theta, y = Y$

  and from wavevector to angular broadening $\sigma_{\theta x} = \frac{\lambda}{2\pi} \sigma_{kx}$ one finally gets

- $\sigma_{\theta x} = 2\, \sigma'_x$, and $\sigma_{\theta y} = 2\, sin\theta\, \sigma'_y$; $\sigma'_x = \left\langle \left(\frac{dh}{dx}\right)^2 \right\rangle$

- This is the geometrical broadening factor; it must be compared to the width of the diffraction limited PSF : $\frac{\lambda}{\sin\theta\, L} \approx 50\, nrad$ – *L is the coherently illuminated length*

Power Spectral Density (PSD)

- Definition:
  - $PSD := |FT[h(x,y)]|^2 \quad \Leftrightarrow \quad PSD = FT[h \otimes h]$

    FT of the autocorrelation function
  - Distinction must be done between 1D and 2D transforms
    - Area PSD (APSD) corresponds to 2D FT of a height map. It has units of type d^4 (e.g. μm^4)
    - Linear PSD (L-PSD or usually PSD) for 1D FT of a profile. It has units of type d^3 (e.g. μm^3)
  - Relation to variances:
    - Height variance: $\sigma^2 = \iint PSD(f)\, d^2 f$ over all meaningful frequencies
    - Slope variance: $\sigma'^2_{x,y} = 4\pi^2 \iint f^2_{x,y} PSD(f) d^2 f$

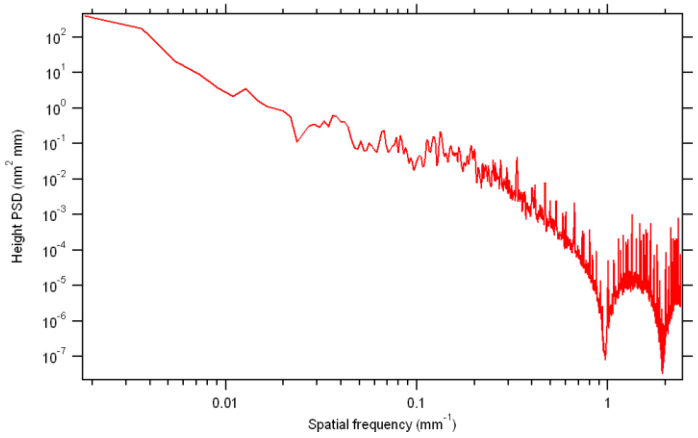
The APSD provides a full statistical representation of a surface,

but because of the grazing incidence, we are more sensitive to tangential gradients and an **average tangential line PSD is statistically meaningful**

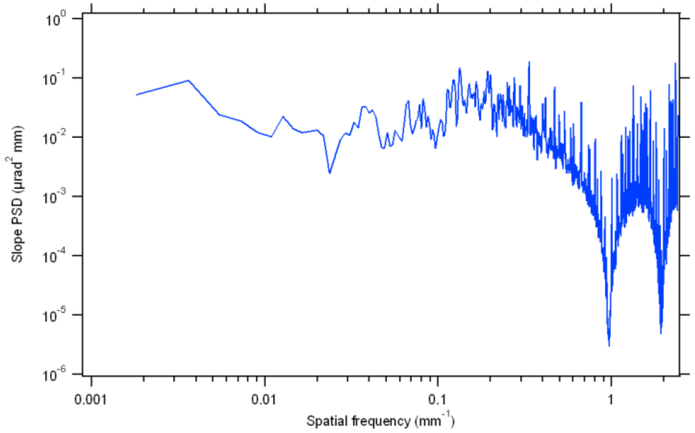
An interesting evaluation tool : the Cumulated Power Spectral Density

- Definition
  - CPSD is the integral over frequency of the One-sided Line PSD
    - One sided PSD = k $PSD(f)$; k=1 if $f = 0$; k=2 if $f \neq 0$;
  - CPSD is a graphic representation of the contribution of frequency content to the total variance

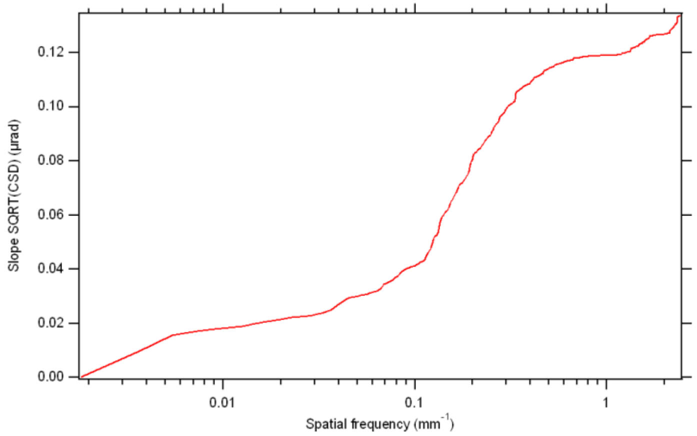
Height $L - PSD$



$Slope\ L - PSD$



$\sqrt[2]{Slope\ CPSD}$



PSD are sensitive to data acquisition and processing

- Fourier transforms of finite length generate aliasing
- Proper windowing is required to limit aliasing
  - Should be normalized not disturb a uniform statistical distribution
- Frequency content is sensitive to filtering
  - Applied filtering and measurement noise are usually apparent on PSD
  - No filtering should be applied before FT
  - The meaningful frequency range must be defined

A common protocol to evaluate optical surfaces

- Measurement:
  - Surfaces will be measured on a regular XY grid covering the full clear area
  - Height measurements will be preferred. Slope measurements will be accepted if given a proof that twist deformation is preserved
  - **No filtering** will be applied
  - If stitching is used, individual sub-area measurement will be provided
- Fourier transform
  - **FT** will be performed **on individual tangential lines** after windowing
    - *Choice of a window function needs further discussion before the call for tender*
  - **All line-PSDs will be averaged** to preserve the global RMS value
  - Slope PSD will be computed from height PSD and integrated for CPSD
- A Python computation script will be provided to ensure identical processing

Specifications assessment (still being refined)

- Figure error
  - Height error PV and RMS on the whole active area
- RMS Slope error
  - PV and Rms values on the whole surface after application of a low-pass filter
    - script to be provided by the buyers group
  - Two frequency bands will be considered in slope CPSD
    - frequencies below 0.1 mm^{-1} (band A)
    - frequencies between 0.1 mm^{-1} and 1 mm^{-1} (band B)
  - the cumulated RMS slope errors of the 2 bands should be below 50 nrad
  - contribution of band B should be less than 60% of total
- Roughness
  - Will be evaluated as average RMS height errors on at least 9 subareas of minimum size 1.4 x 1 mm^2

Technical questions to be answered in the OMC report (15/12/21)

- Are the challenge goals pertinent ? Reasonable ?
  - In particular, are the height, slope and roughness targets compatible ?
- Are the phase scopes and durations properly distributed ?
- Is the budget per phase appropriate ?
- Are the proposed evaluation criteria
  - clear ?
  - pertinent ?
  - reliable ?
- Which other criteria should be proposed ?
- Any other question .....