PHOTON BEAM TRANSPORT SYSTEM AT FERMI@ELETTRA: MICROFOCUSING FEL BEAM WITH A K-B ACTIVE OPTICS SYSTEM

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**FEL 1** from ~100 nm down to 20 nm - source distance (to spectrometer) 57.5 m
Divergence $\sigma(\mu\text{rad}) = 1.25 \lambda(\text{nm})$ - Source dimension = 60 $\mu\text{m}$ (sigma)

**FEL 2** from 20 nm down to ~4 nm - source distance (to spectrometer) 49.8 m
Divergence $\sigma(\mu\text{rad}) = 1.5 \lambda(\text{nm})$ - Source dimension = 123 $\mu\text{m}$ (sigma)
K-B active optic system - DiProI

K-B system configuration

End-stations need high flux - great demagnification

K-B system advantages

- Decoupling vertical and horizontal beam components
- Thick ellipsoidal mirrors with the great demagnification request are difficult to realize

K-B bendable system advantages

- Focalization of the 2 sources at different distance with the same couple of mirrors
- Improvement of the FEL beam wavefront
K-B active optic system - DiProI

Profile surface characterization with Long Trace Profilometer

- LTP profile measurements 1mm step
- Best possible profile reached through the Adaptive Correction Tool software
- Measurements with Zygo interferometer and AFM - rms under specifications (<3Å spatial range 2µm - 0.5mm)
- Proof of the system stability

K-B Vertical mirror - residual surface profile  
K-B Horizontal mirror - residual surface profile
K-B active optic system - DiProI

Ray tracing simulations with Shadow code

- K-B vertical mirror at best focus (+2mm to the nominal focus)
  - $\text{FWHM}_{\text{ray-tracing}} = 18 \, \mu\text{m}$

- K-B horizontal mirror at best focus (-2mm to the nominal focus)
  - $\text{FWHM}_{\text{ray-tracing}} = 10.5 \, \mu\text{m}$
Focal spot measurements - DiProl
Phosphorus screen and PMMA ablation

First phase
- rough angle alignment
- optimized mirror bending
- best spot achieved on Phosphorus screen $\text{FWHM}_{32\text{nm}}=60 \times 70 \ \mu\text{m}$

Second phase
- refine angle alignment
- optimized mirror bending
- best spot achieved:
  Phosphorus screen $\text{FWHM}_{32\text{nm}}=40 \times 42 \ \mu\text{m}$
  seen with PMMA ablation $\text{FWHM}_{32\text{nm}}=15 \times 26 \ \mu\text{m}$

Suggestion - Shadow predictions would be a lower limit of the optical system performance
PSF WITH FRESNEL DIFFRACTION

- PSF computation from surface metrology
- At any energy
- Approximations:
  - Work in scalar approximation
  - Computation using the meridional profiles (1Dimension)

Work in grazing incidence
Kirchoff-Fresnel diffraction equation

\[ U(P) = \frac{Ae^{ikr_0}}{r_0} \iint_S e^{iks'} K(\chi) dS' \]

\[ PSF(x) = \frac{\Delta R}{f \lambda L^2} \left| \int_L e^{-i \frac{2\pi}{\lambda} \left( \sqrt{(x-x_p)^2+z_p^2} - z_p \right)} dl \right|^2 \]
Two or more reflections

Double reflection

\[ E_h(x_h, z_h) = \frac{E_0 \Delta R}{L \sqrt{\lambda x_h}} \int_{f}^{f+L} \sqrt{\frac{x_p}{d_2}} e^{-\frac{2\pi i}{\lambda}(d_1 - z_p)} \, dz_p \]

\[ PSF(x) = \frac{\Delta R}{E_0^2 f \lambda L^2} \left| E_h(x_h, z_h) e^{-i \frac{2\pi}{\lambda} \left( \sqrt{(x-x_h)^2 + z_h^2} \right)} \right|^2 \]
Focal spot computation with Fresnel diffraction: FEL case

\[
E_h(x_h, z_h) = \frac{E_0 \Delta R}{L \sqrt{\lambda x_h}} \int_{f}^{f+L} \sqrt{\frac{x_p}{d_2}} e^{-\frac{2\pi i}{\lambda} (d_2 - z_p)} d z_p
\]

\[
PSF(x) = \frac{\Delta R}{E_0^2 f \lambda L^2} e^{-i \frac{2\pi}{\lambda} \sqrt{(x-x_h)^2 + z_h^2}}
\]

\[
u(x, z) = \frac{\omega_0}{\omega} e^{\left[-j(kz - \Phi) - x^2 \left(\frac{1}{\omega^2} + \frac{jk}{2R}\right)\right]}
\]

\[k = \frac{2\pi}{\lambda}, \quad \Phi = \arctan(\lambda z / \pi \omega_0^2)\]
Focal spot simulations - DiProl

32 nm wavelenght

- K-B vertical best focus -2 mm from nominal $\text{FWHM}_{32\text{nm}} = 5.8 \, \mu\text{m}$
- K-B horizontal best focus 0 mm from nominal $\text{FWHM}_{32\text{nm}} = 4.4 \, \mu\text{m}$

Suggestion - the system limit in terms of the spot size should be lower than shadow predictions
FEL 1 wavefront measurements

WAVEFRONT MEASUREMENTS BEFORE K-B SYSTEM

- FEL 1
- wavelength - 32 nm
- distance from the source - 90 m
- Gaussian intensity distribution
- nominal divergence 40 urad $\Rightarrow$ FWHM$_{90m} = 8.5$ mm

Wavefront = isophase surface
deforation from ideal shape (Gaussian beam) due to:

- Small instabilities of the Source
- photon transport optics
FEL 1 wavefront measurements

Effect of these wavefront deformations is not negligible in terms of focal spot degradation.

Work still in progress.
Focal spot measurements at DiProI end-station

Wavefront sensor measurements

- FEL 1
- Wavelength - 32 nm
- Measuring of Intensity and Wavefront at 1m out of nominal focus
- Reconstruction of the spot in focal plane
- RMS wavefront of best spot 12 nm
Focal spot measurements at DiProI end-station

Wavefront sensor measurements

Fresnel diffraction simulations

- FEL 1
- Wavelength - 32 nm
- Diffraction limit spot-size at 32 nm FWHM = 4x5 µm
- Best spot-size measured FWHM = 5x8 µm
- Spot-size simulated with ray-tracing FWHM = 10.5x18 µm
- Spot-size simulated with Fresnel diffraction at the common best focus (-1mm from the nominal focus) FWHM = 5.2x7.7 µm
CONCLUSIONS

- We performed surface profile characterization of the K-B bendable system mounted in the DiProI chamber with Long Trace Profilometer.

- We extended the Fresnel diffraction method to FEL applications - non isotropic sources - focal spot given the best measured profile at LTP - FWHM = 4.4x7.7 µm

- We provided several measurement campaigns of K-B system focalization in the DiProi end-station, 40x42 µm on the P-screen 15x26 µm on PMMA

- We performed wavefront measurements of the FEL before K-B optics. The study of the focal spot degradation due to wavefront deformations is still under investigation

- Through a wavefront sensor we went further in the optimization of the mirror shape. Focal spot (reconstructed via software) FWHM = 5x8 µm

- From the comparison between simulations and measures we conclude that the focal spot in a FEL can now be predicted by using the Fresnel diffraction method.
People involved in this work:

• L.Raimondi, N.Mahne, C.Svetina, S.Gerusina, C.Fava, L. Rumiz, R.Gobessi and M.Zangrando – PADReS

• F.Capotondi, E.Pedersoli, M.Kiskinova – DiProI

• B. Mahieu, G. De Ninno, C. Spezzani, E. Allaria, M. Trovò, E. Ferrari – FERMI team

• G.Sostero – Metrology LAB

• D.Cocco – SLAC


THANKS FOR YOUR ATTENTION
Adaptive correction tool software

Adaptive Correction Tool

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Approximations:

- Work in scalar approximation
- Computation using the meridional profiles

- The same slope errors along the azimuth result in an angular spread of rays smaller by a factor of $\tan^2 \alpha$

- The X-ray scattering pattern in grazing incidence is $100$-$1000$ times more extended in the incidence plane than in the perpendicular direction

- Aperture diffraction resembles the diffraction pattern of a long, straight slit, which can be computed monodimensionally (visible in UV)

\[ \Delta l \approx \frac{\lambda f^2}{2\pi R_0 r} \]
\[ \Delta x \approx \frac{\lambda f^2}{\pi R_0 L} \]
Kirchoff-Fresnel diffraction equation

\[ U(P) = \frac{A e^{i k r_0}}{r_0} \int \int_S \frac{e^{i k s'}}{s'} K(\chi) dS' \]

\[ E(x, y) = \int_S \frac{E_0}{d_2 \lambda} \exp \left[-2i\pi \frac{d_1 + d_2}{\lambda}\right] d^2 s \]

\[ E(x, y) = \frac{E_0}{f \lambda} \int_L e^{-i \frac{2\pi}{\lambda} (L + f - z_p + \sqrt{(x-x_p)^2 + z_p^2})} dl \int_{-\Delta y/2}^{+\Delta y/2} e^{-i \frac{2\pi y}{\lambda f} y_p} dy_p \]

\[ I(x, y) = \frac{E_0^2}{f^2 \lambda^2 (\Delta y)^2} \frac{\sin^2 \delta}{\delta^2} \left| \int_L e^{-i \frac{2\pi}{\lambda} \left(\sqrt{(x-x_p)^2 + z_p^2} - z_p\right)} dx \right|^2 \]

Integration over \( y \) and normalizing with flux intensity

\[ PSF(x) = \frac{\Delta R}{f \lambda L^2} \left| \int_L e^{-i \frac{2\pi}{\lambda} \left(\sqrt{(x-x_p)^2 + z_p^2} - z_p\right)} dl \right|^2 \]
FIGURE ERRORS

$2\theta \longleftrightarrow \theta(\alpha)$

SCATTERING

$$\frac{(\theta_s - \theta_i)^2}{2} + \frac{\varphi_s^2}{\tan \theta_i} \approx \frac{f^2 \lambda^2}{\cos \theta_i \sin \theta_i}$$

APERTURE DIFFRACTION

$$I(\theta) \propto \frac{\sin^2\left(\frac{\pi d}{\lambda} \sin \theta\right)}{\left(\frac{\pi d}{\lambda} \sin \theta\right)^2}$$
ELECTRIC FIELD DIFFRACTED ON THE HYPERBOLA

\[ \text{PSF}(x) = \frac{\Delta R}{E_0^2 f \lambda L^2} \left| \int_{f-L}^{f} E_h(x_h, z_h) e^{-i \frac{2\pi}{\lambda} \left( \sqrt{(x-x_h)^2 + z_h^2} \right)} d z_h \right|^2 \]

SCATTERING: THEORETICAL APPROACH

1. XRS is an effect strongly dependent of the photon energy
2. It cannot be simulated using geometrical optics
3. The scattering intensity is proportional to the surface PSD (Power Spectral Density of the roughness)
   \[ \frac{dI_s}{d\theta_s} \propto \text{PSD} \]

   \[ \sigma^2 = \int \text{PSD} \, df \]

   However, we cannot extend the proportionality to the low frequency range!

   \[ 4\pi \sigma \sin \alpha < \lambda \]

   E.g. \( \lambda = 1\text{Å} \quad \alpha = 0.5^\circ \quad \sigma < 9\text{Å} \)