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

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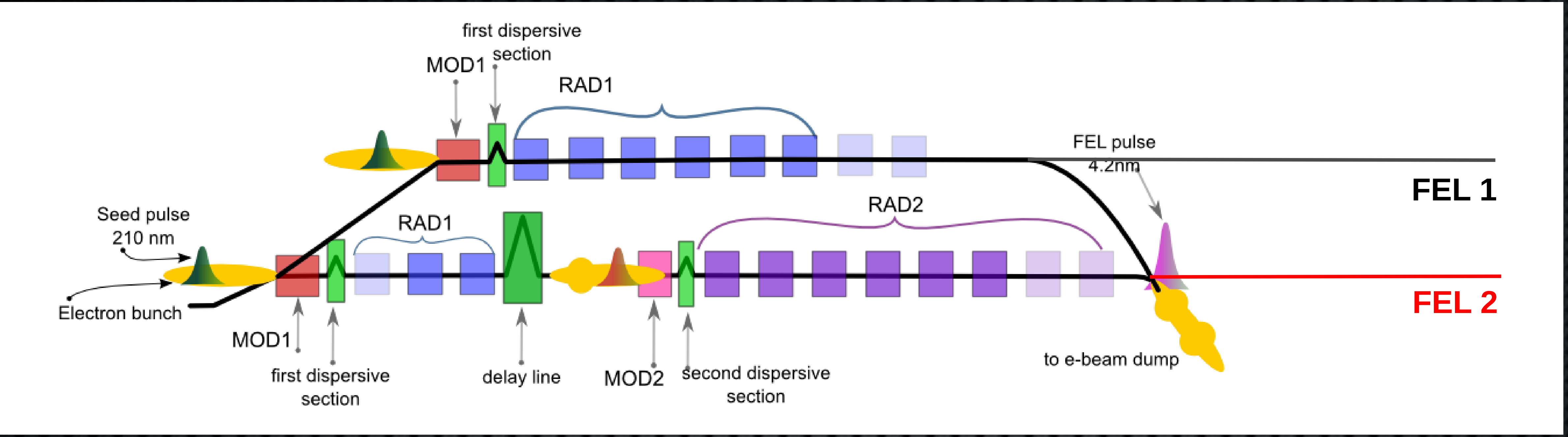
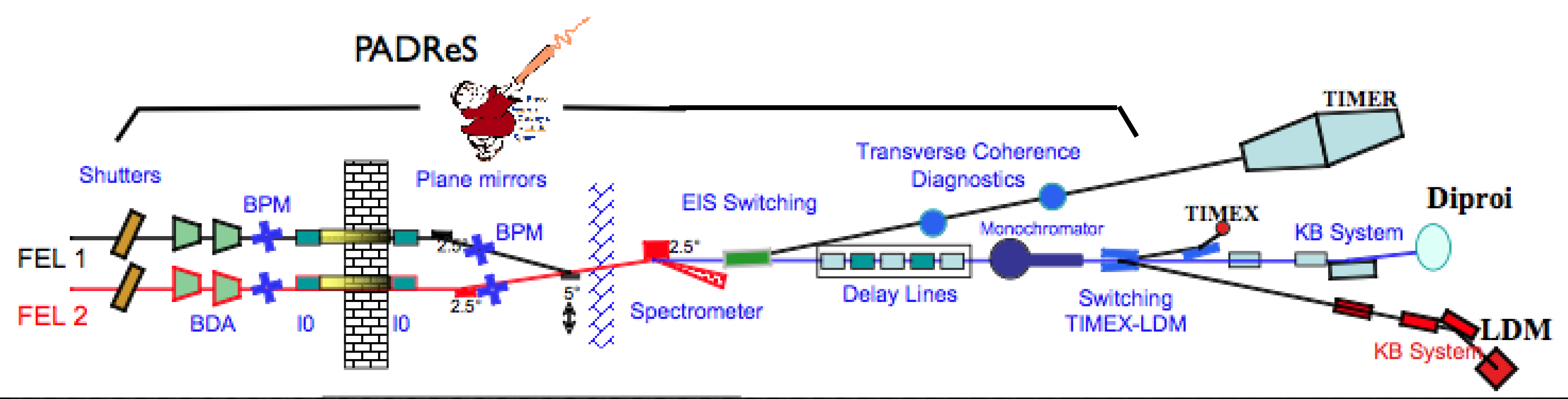
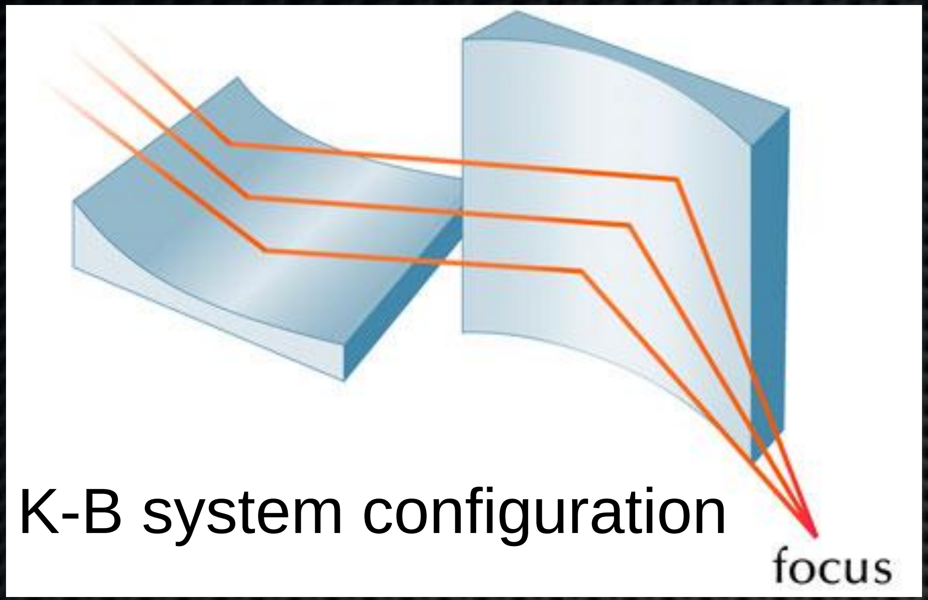
FERMI@Elettra seeded FEL

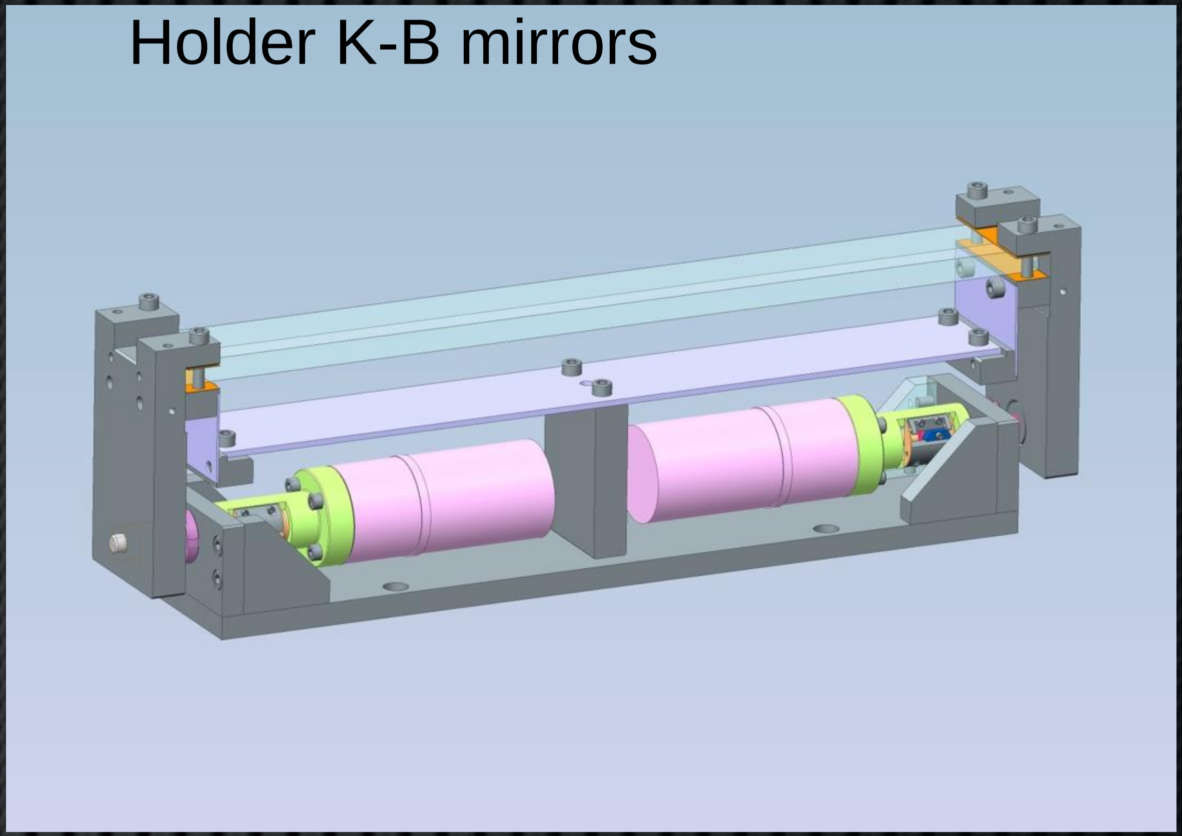


- FEL 1 from ~100 nm down to 20 nm - source distance (to spectrometer) 57.5 m
  Divergence σ(μrad) = 1.25 λ(nm) - Source dimension = 60 μm (sigma)
- FEL 2 from 20 nm down to ~4 nm - source distance (to spectrometer) 49.8 m
  Divergence σ(μrad) = 1.5 λ(nm) - Source dimension = 123 μm (sigma)



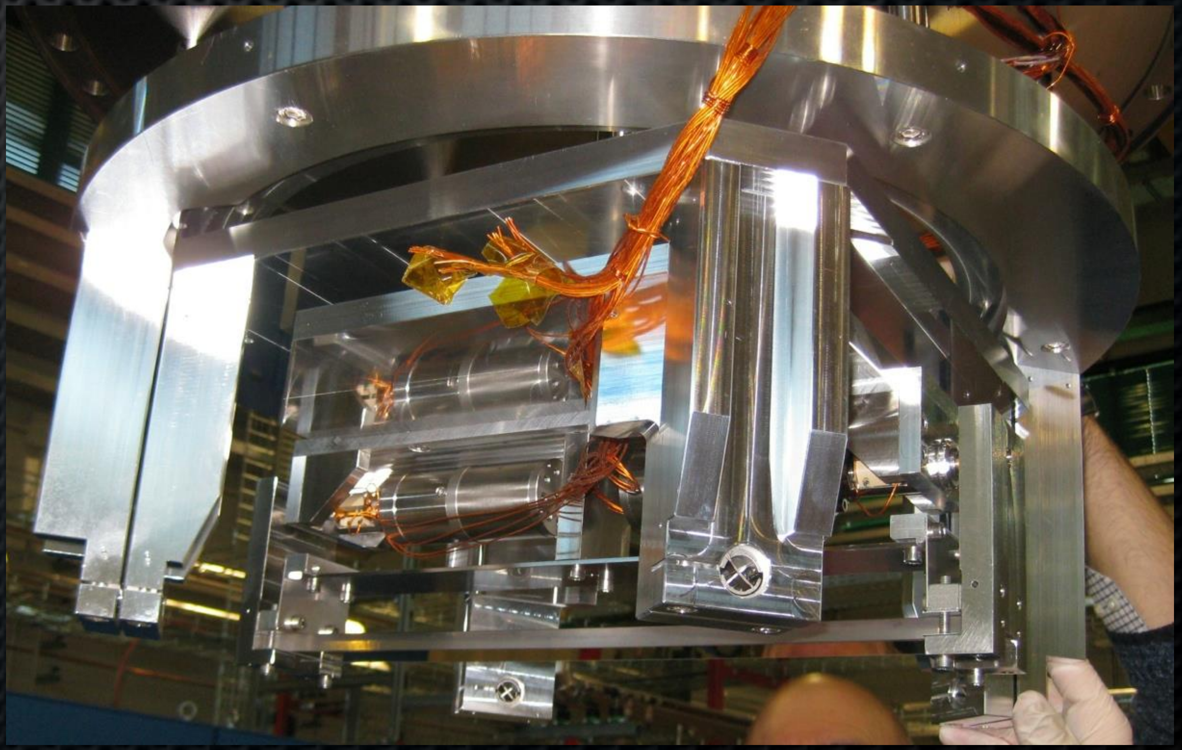
K-B active optic system - DiProI





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

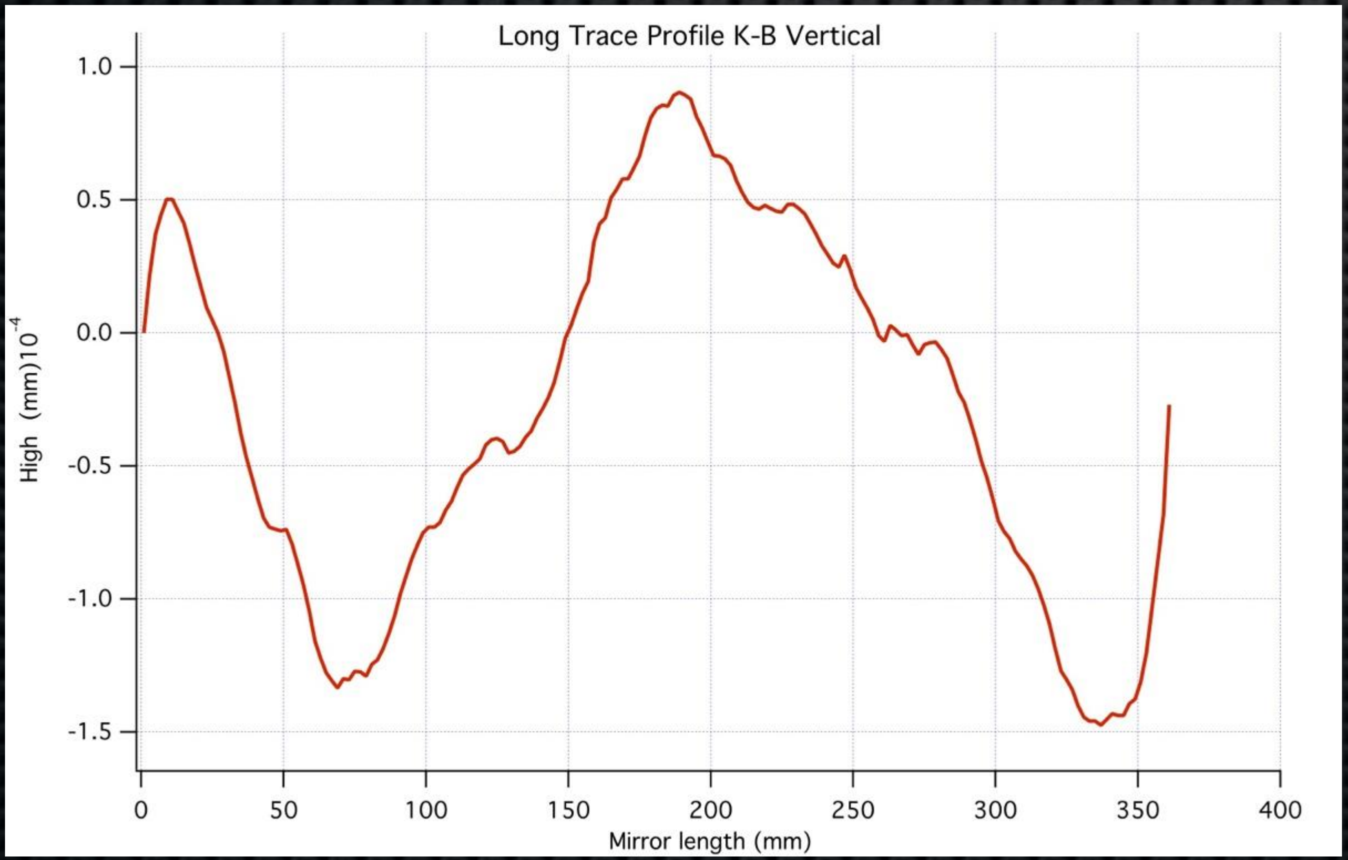


K-B active optic system - DiProI

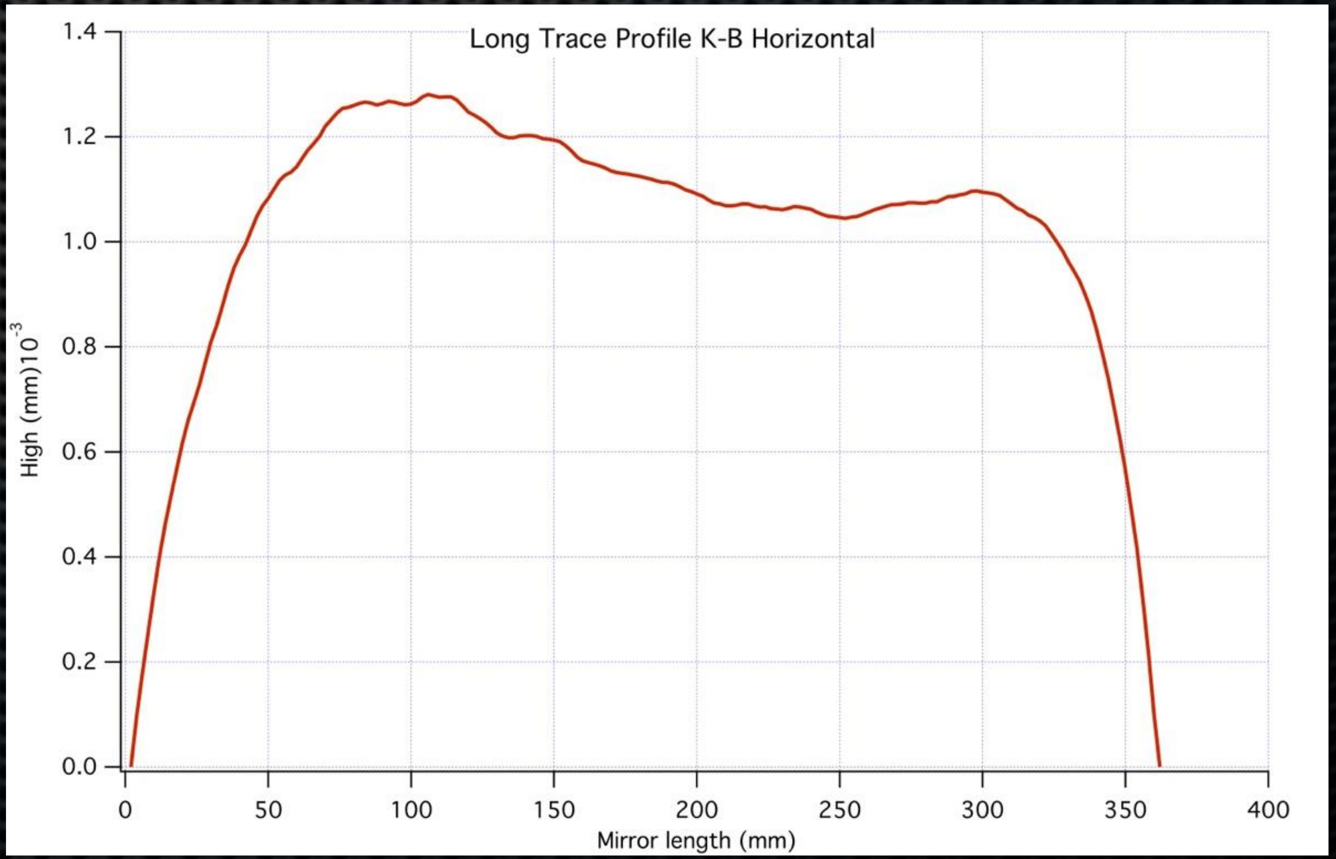
Profile surface characterization with Long Trace Profilometer

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

K-B Vertical mirror - residual surface profile



K-B Horizontal mirror - residual surface profile



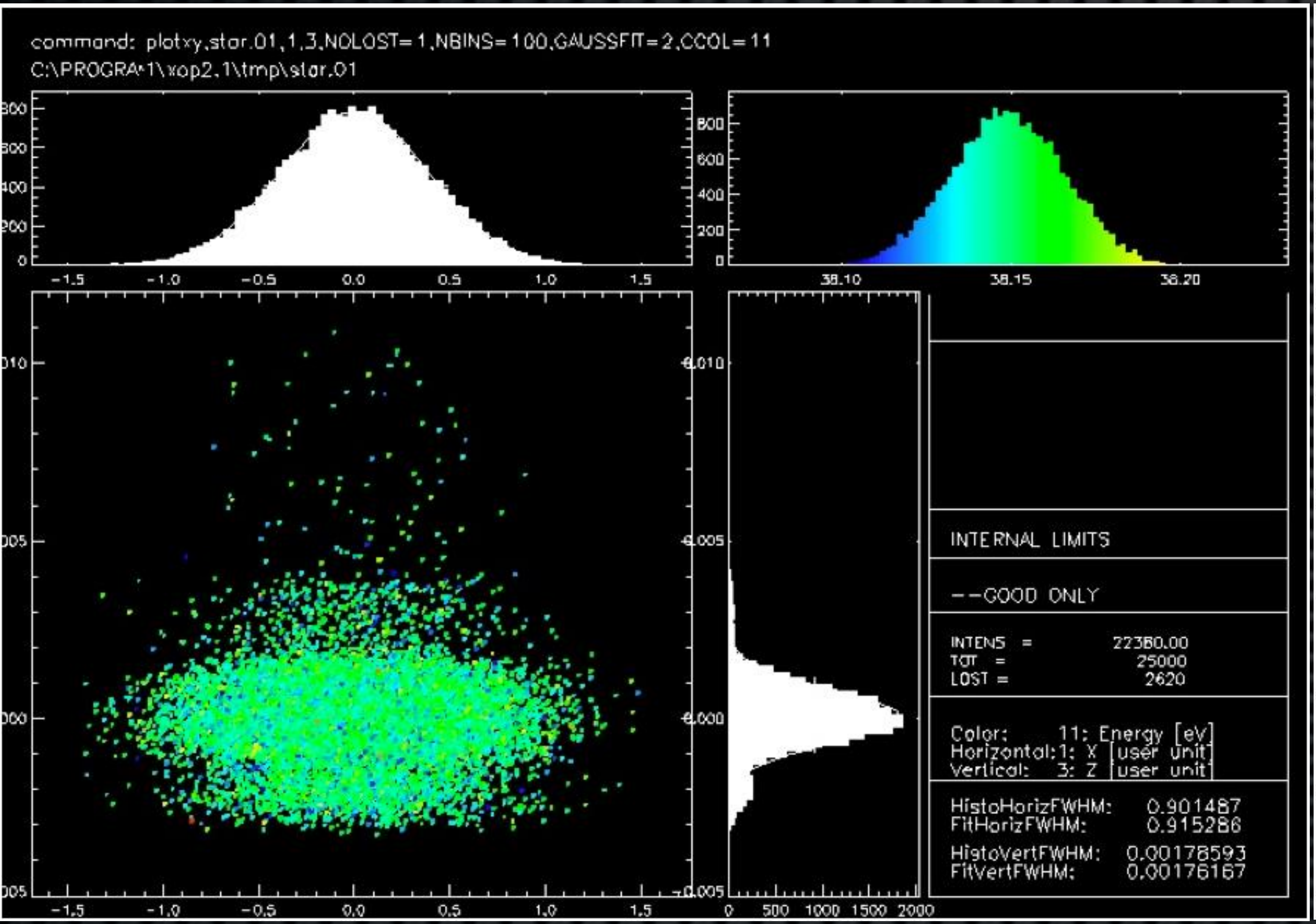
K-B active optic system - DiProI

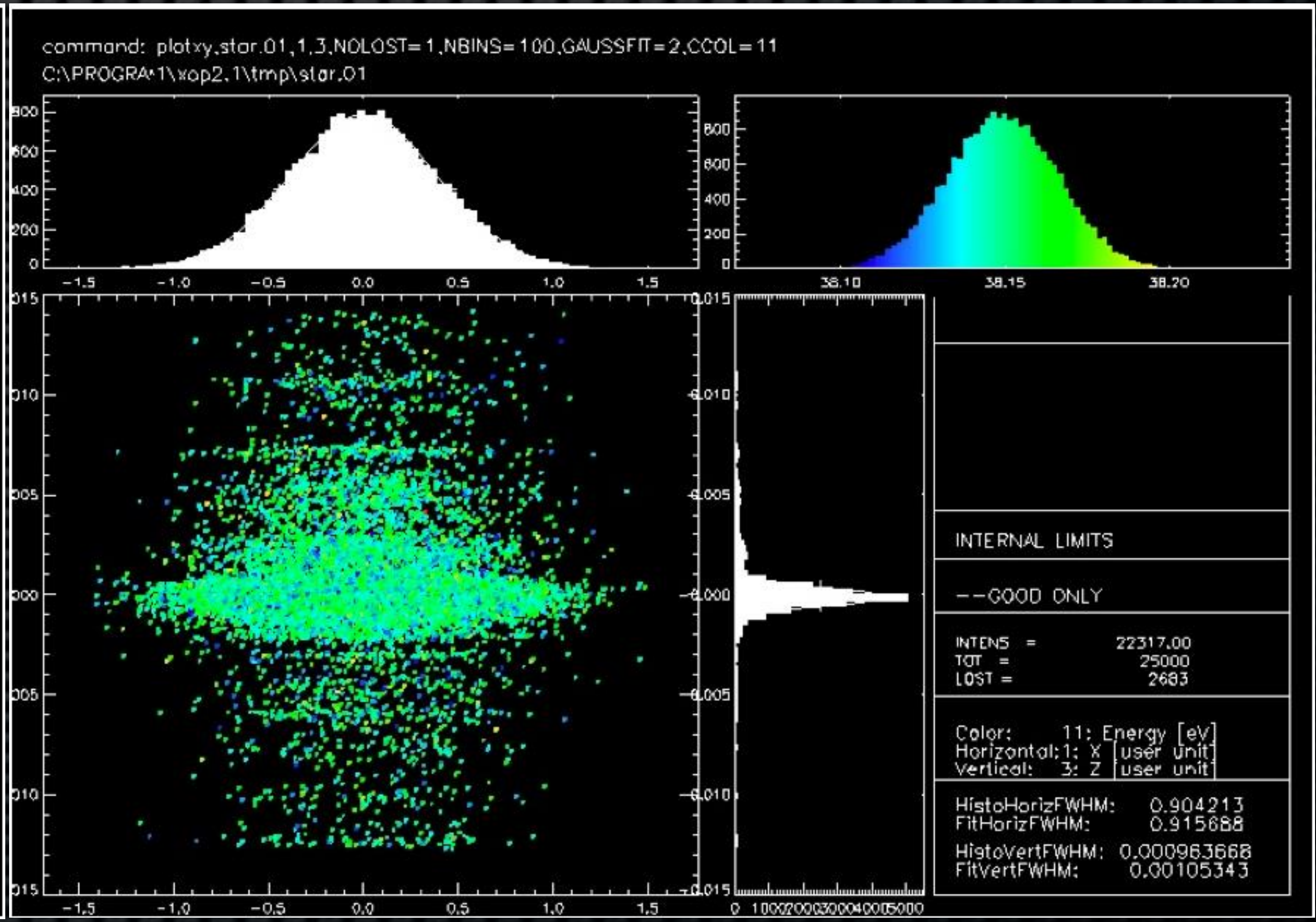
Ray tracing simulations with Shadow code

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

K-B horizontal mirror at best focus (-2mm to the nominal focus)

FWHM$_{\text{ray-tracing}}$ = 10.5 µm





Focal spot measurements - DiProI

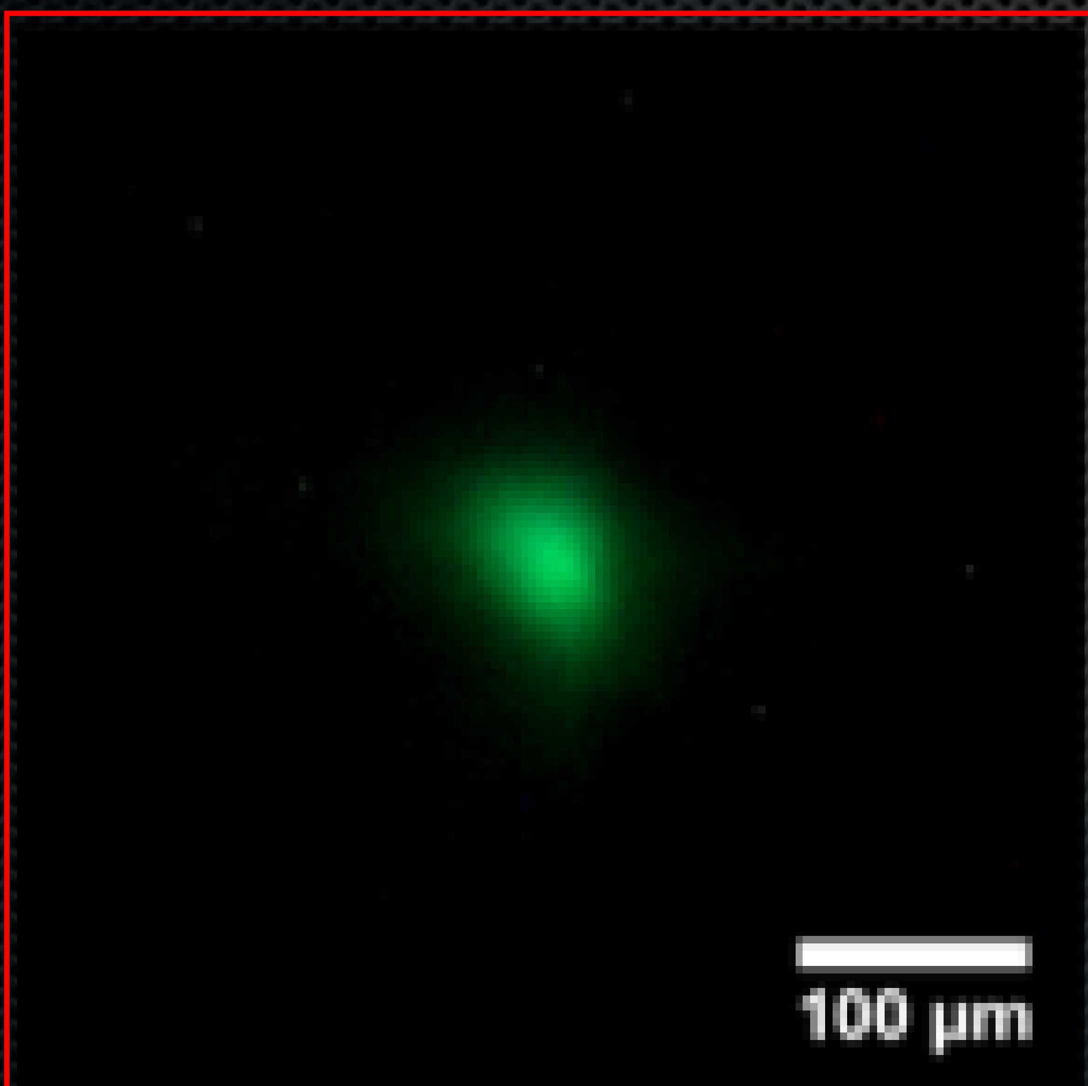
Phosphorus screen and PMMA ablation

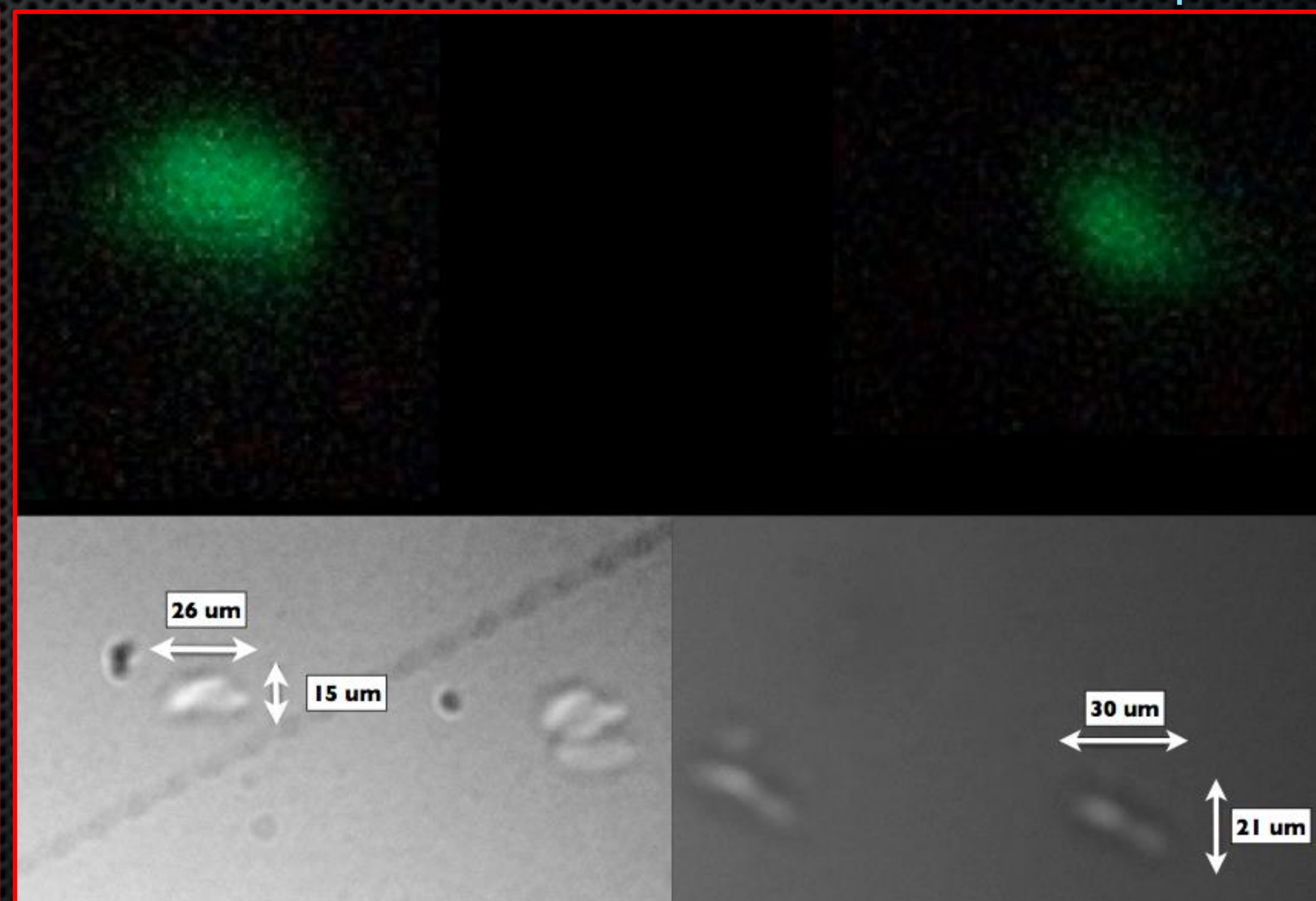
First phase

- rough angle alignment
- optimized mirror bending
- best spot achieved on Phosphorus screen $FWHM_{32nm}$=60x70 μm

Second phase

- refine angle alignment
- optimized mirror bending
- best spot achieved:
  Phosphorus screen $FWHM_{32nm}$=40x42 μm
  seen with PMMA ablation $FWHM_{32nm}$=15x26 μm





Suggestion - Shadow predictions would be a lower limit of the optical system performance

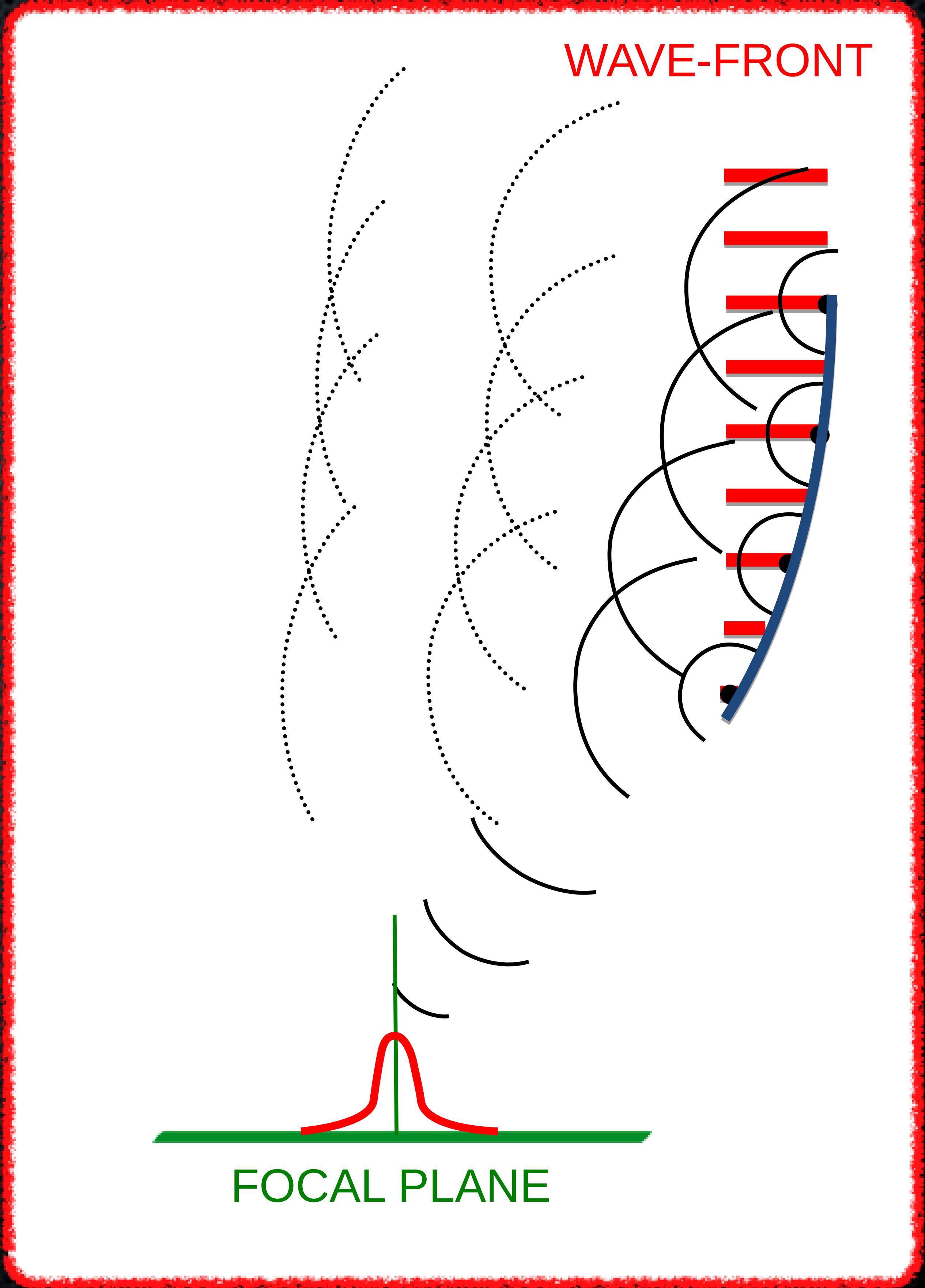
PSF WITH FRESNEL DIFFRACTION

L. Raimondi, D. Spiga, SPIE Proc., 8147 (2010)

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

↓

Work in grazing incidence



PSF WITH FRESNEL DIFFRACTION

L. Raimondi, D. Spiga, SPIE Proc., 8147 (2010)

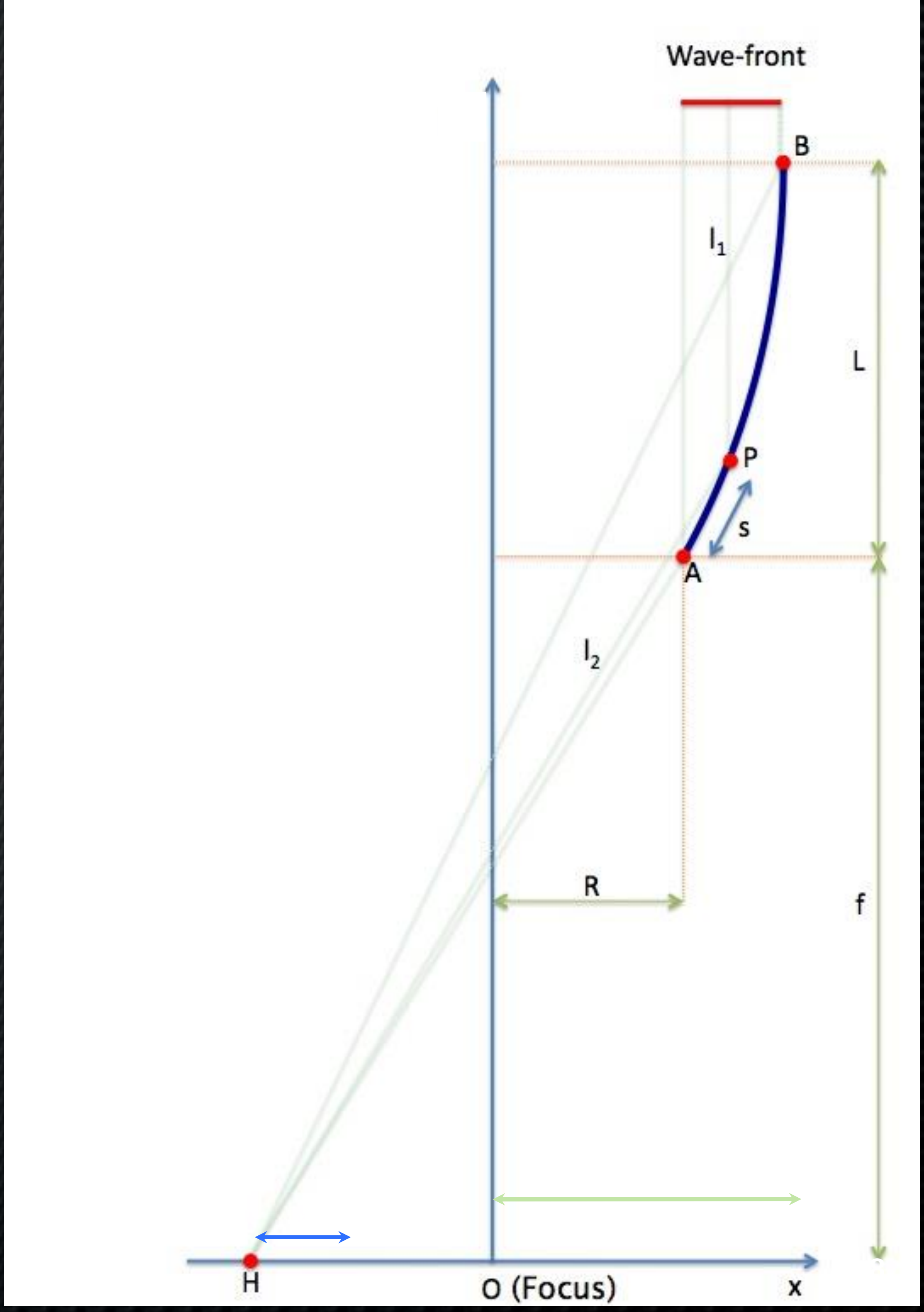
SINGLE REFLECTION PARABOLA – ISOTROPIC SOURCE

ELECTRIC FIELD ON THE FOCAL PLANE OBTAINED BY THE CONSTRUCTIVE INTERFERENCE BETWEEN THE SPHERICAL WAVES GENERATED IN EACH POINTS OF THE MIRROR.

Kirchoff-Fresnel diffraction equation

$$U(P) = \frac{Ae^{ikr_0}}{r_0} \int\int_S \frac{e^{iks'}}{s'} K(\chi) dS'$$

$$PSF(x) = \frac{\Delta R}{f \lambda L^2} \left| \int_L e^{-i\frac{2\pi}{\lambda}\left(\sqrt{(x-x_\mathrm{p})^2+z_\mathrm{p}^2}-z_\mathrm{p}\right)} \mathrm{d}l \right|^2$$

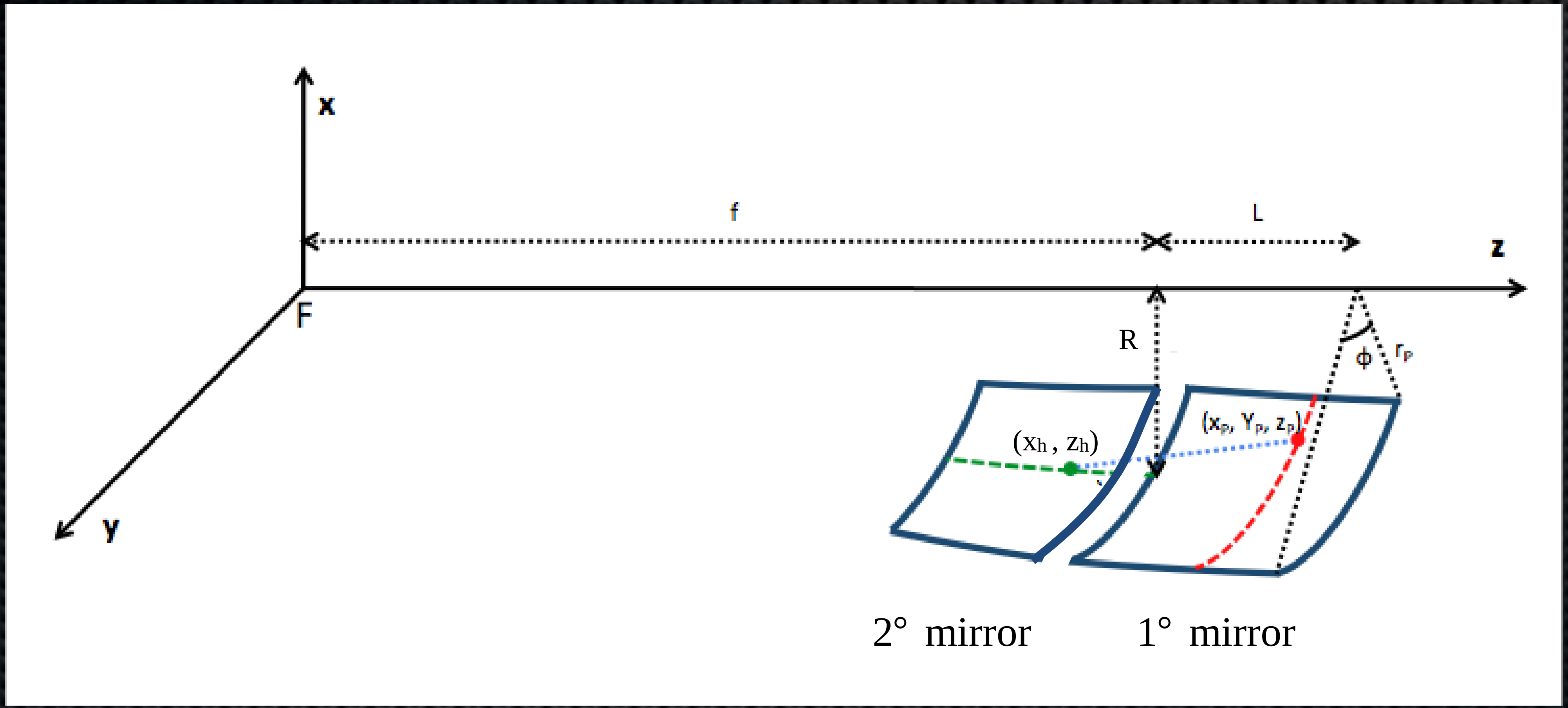


PSF WITH FRESNEL DIFFRACTION

L. Raimondi, D. Spiga, SPIE Proc., 8147 (2011)

Two or more reflections

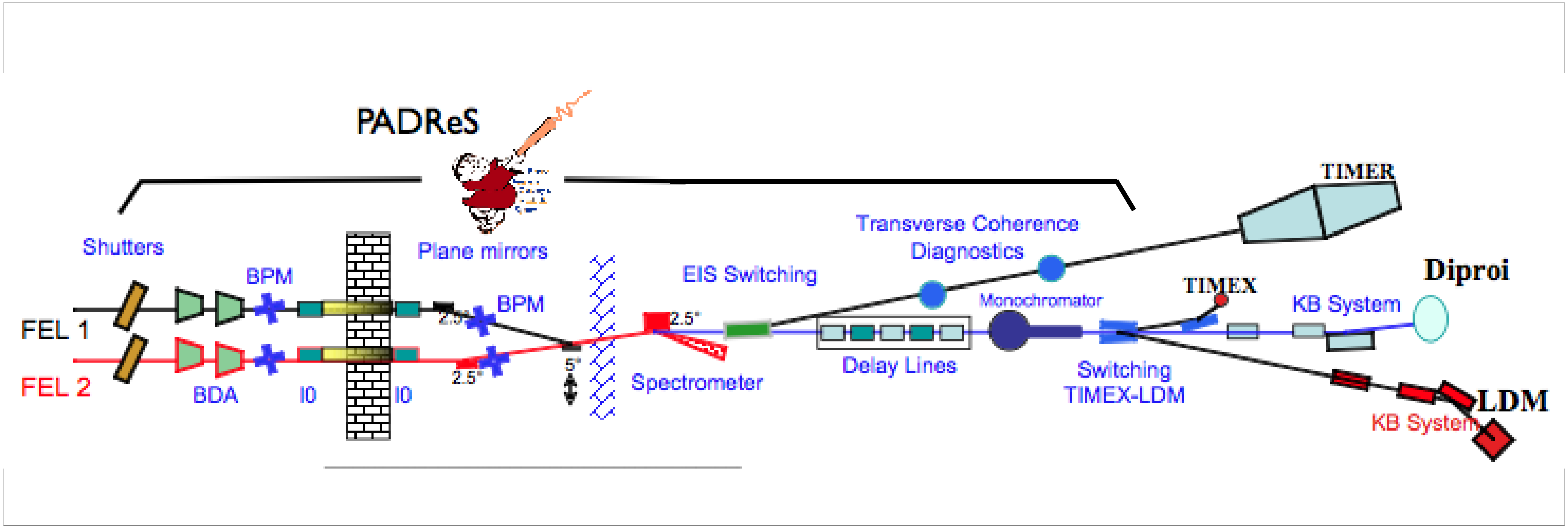
Double reflection



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

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

Focal spot computation with Fresnel diffraction: FEL case



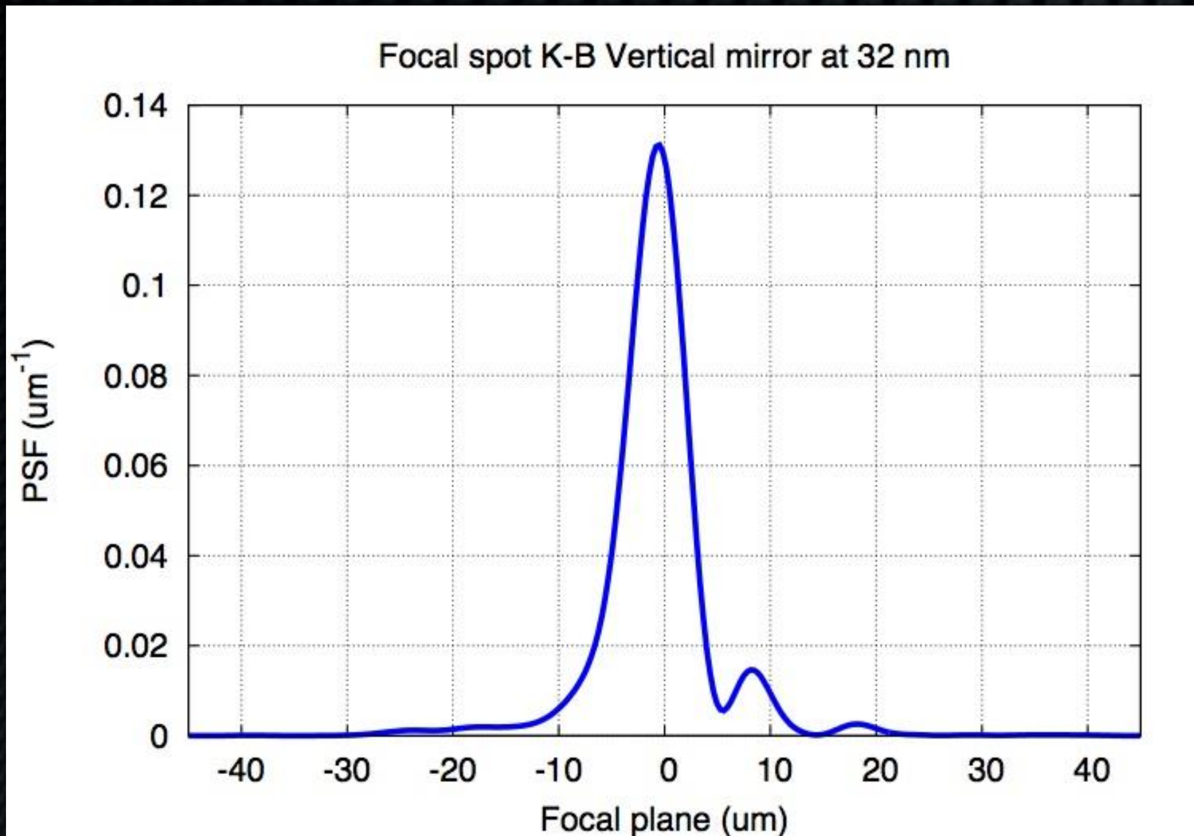
$$u(x,z) = \frac{\omega_0}{\omega} e^{\left[-j(kz-\Phi)-x^2\left(\frac{1}{\omega^2}+\frac{jk}{2R}\right)\right]}$$

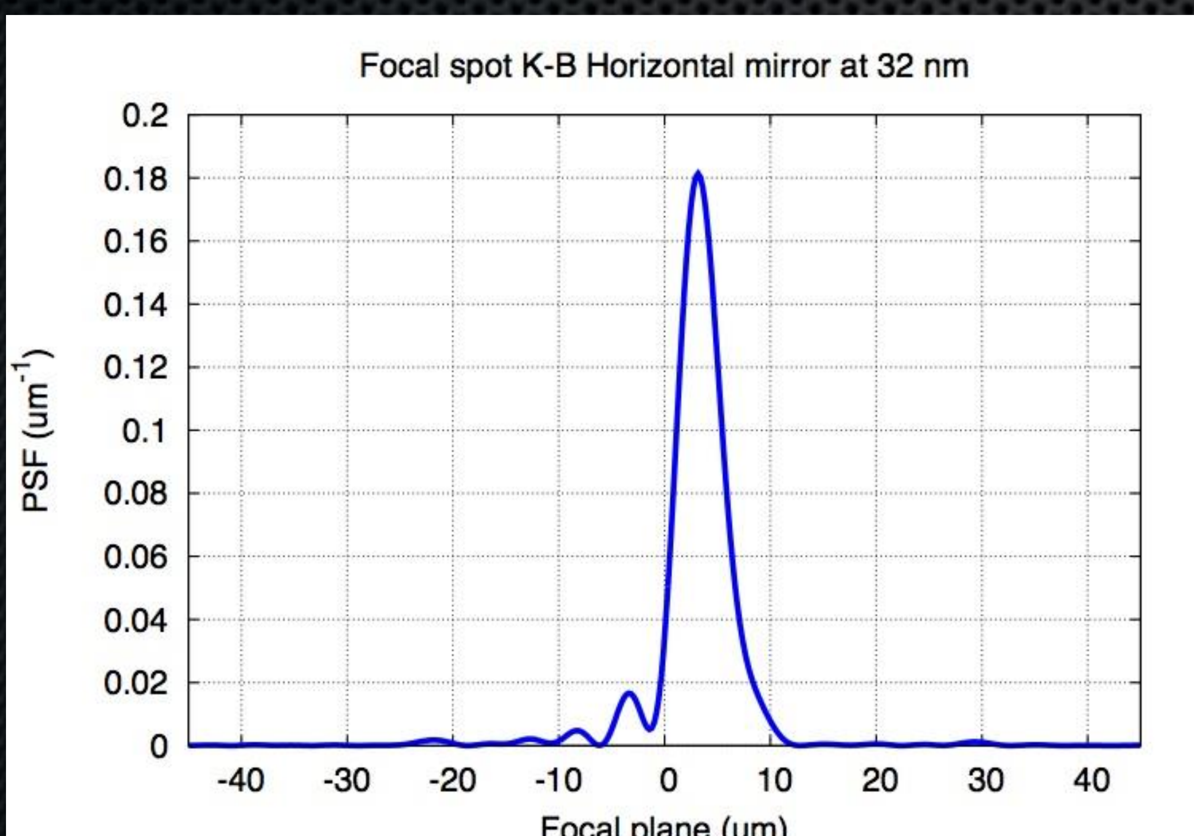
$$k = 2\pi/\lambda \quad \Phi = \arctan(\lambda z / \pi\omega_0^2)$$

$$E_h(x_h, z_h) = \frac{E_0 \Delta R}{L\sqrt{\lambda x_h}} \int_f^{f+L} \mathbf{u(x,z)} \sqrt{\frac{x_p}{d_2}}\, e^{-\frac{2\pi i}{\lambda}(d_2 - z_p)}\, dz_p$$

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

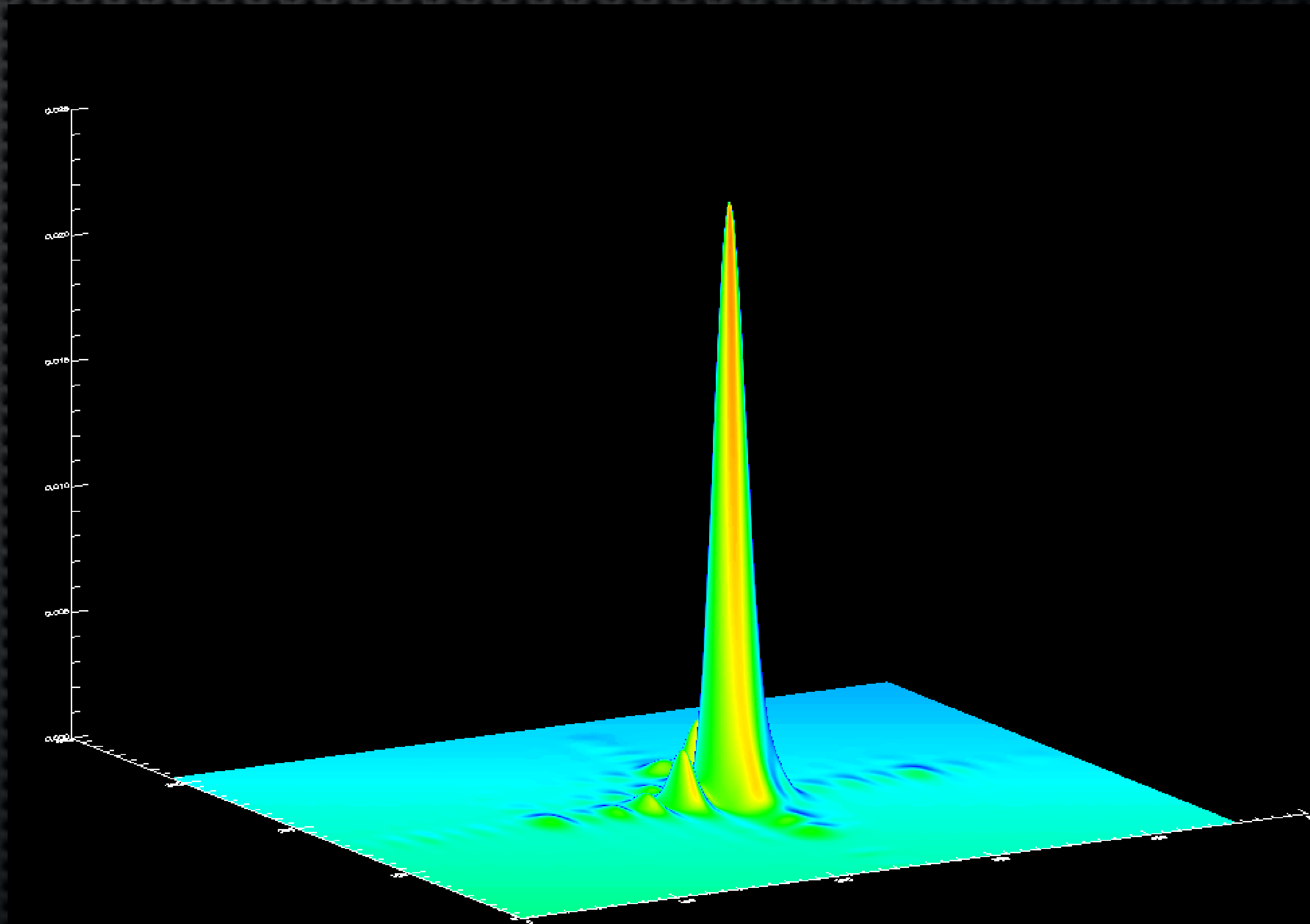
Focal spot simulations - DiProI





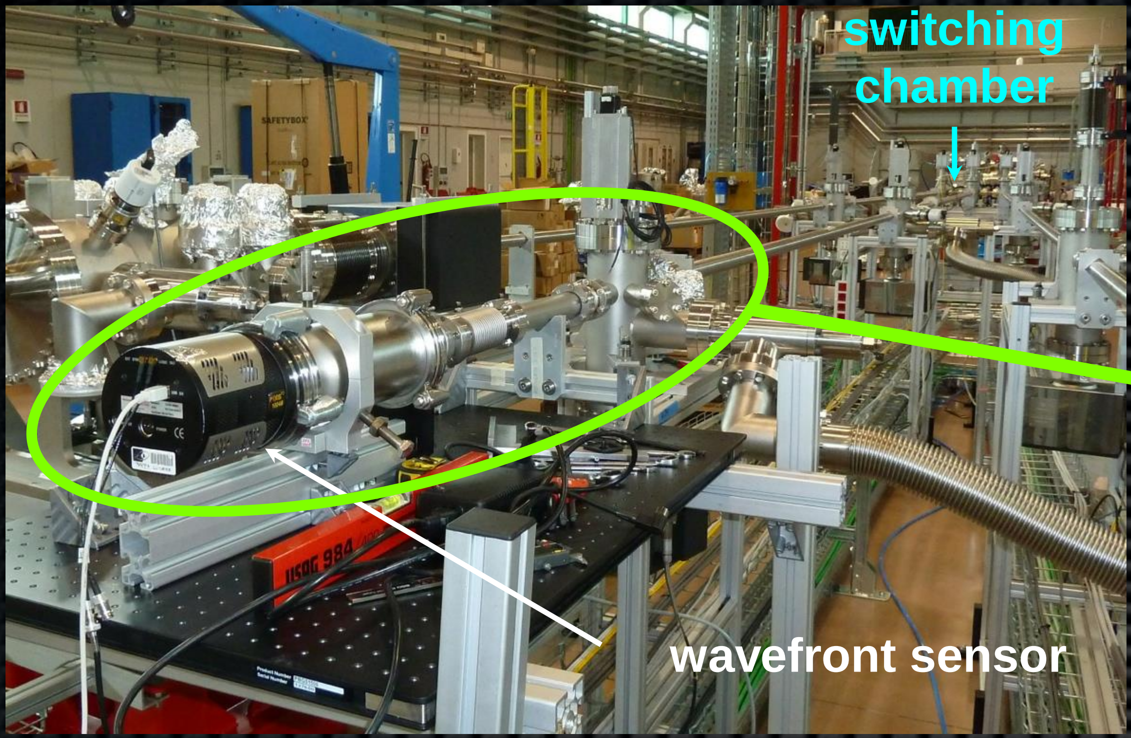
32 nm wavelenght

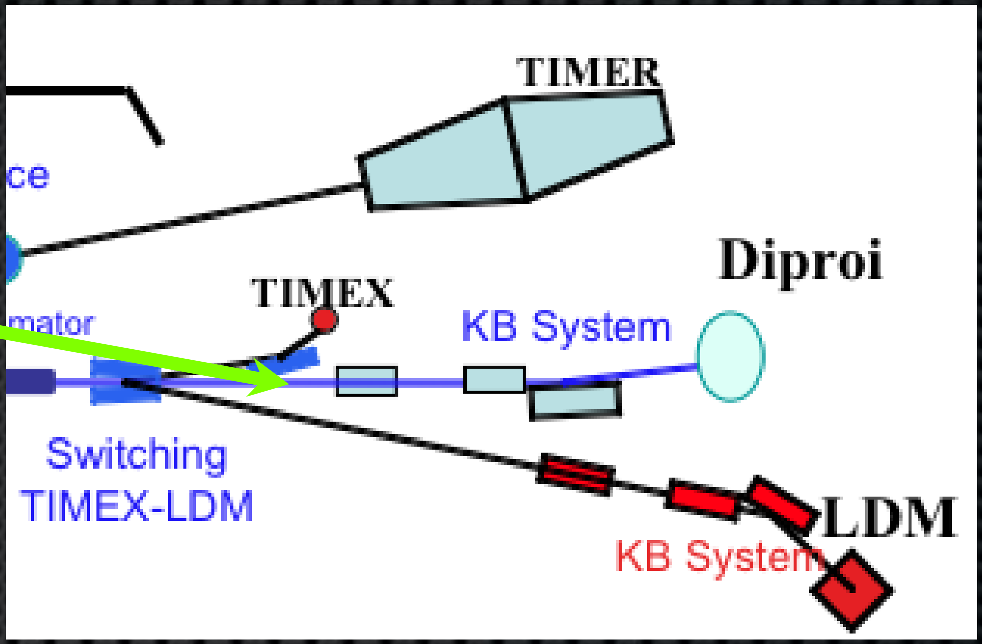
- K-B vertical best focus -2 mm from nominal $FWHM_{32nm}$ = 5.8 µm
- K-B horizontal best focus 0 mm from nominal $FWHM_{32nm}$ = 4.4 µm



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

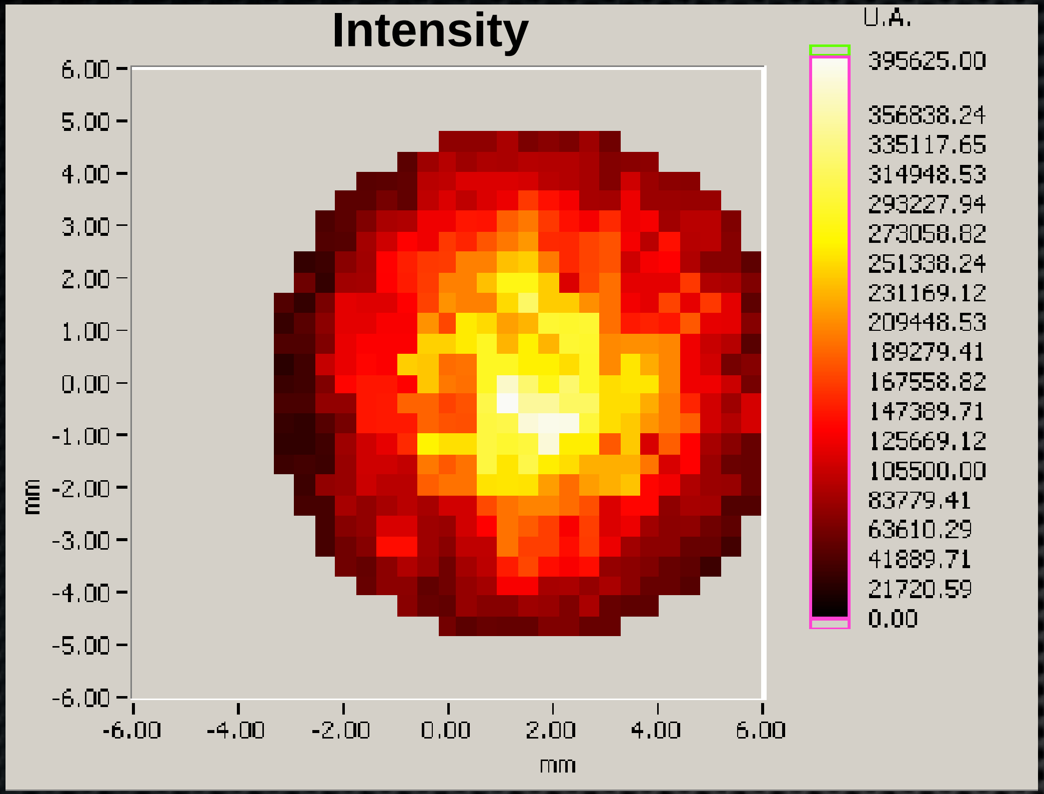
- FEL 1
- wavelength - 32 nm
- distance from the source - 90 m
- Gaussian intensity distribution
- nominal divergence 40 urad → $FWHM_{90m}$ = 8.5 mm

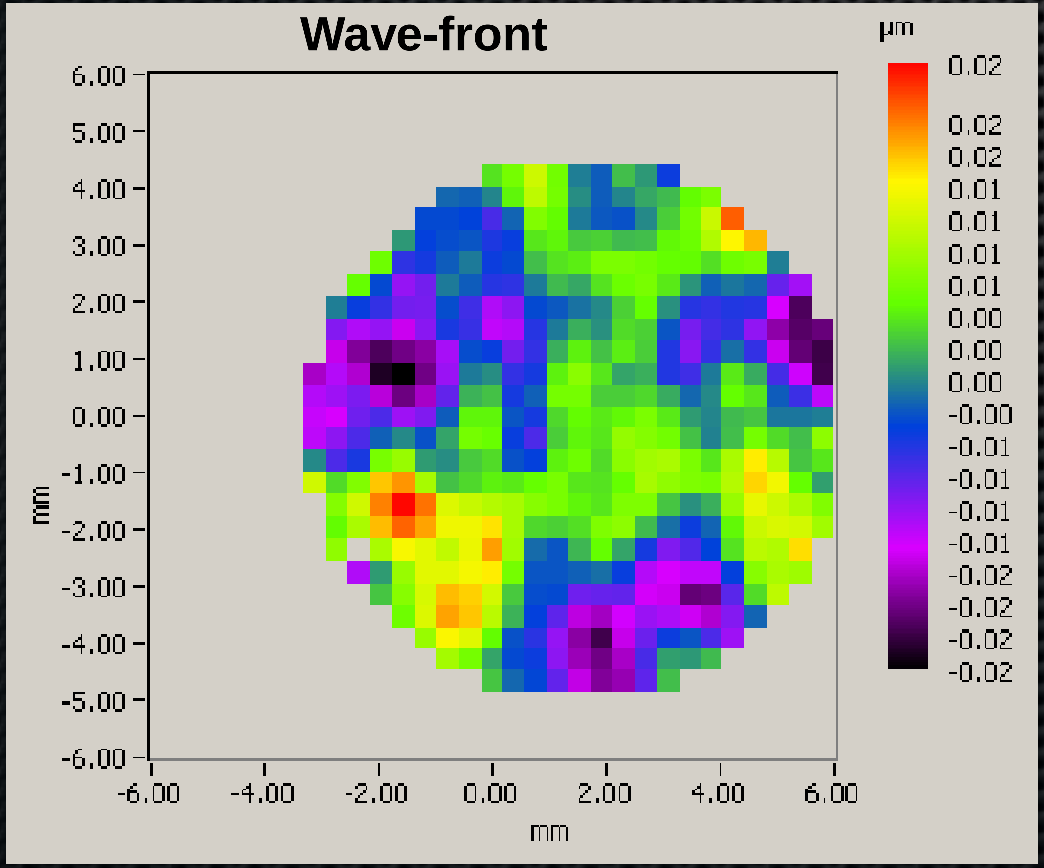
Wavefront = isophase surface

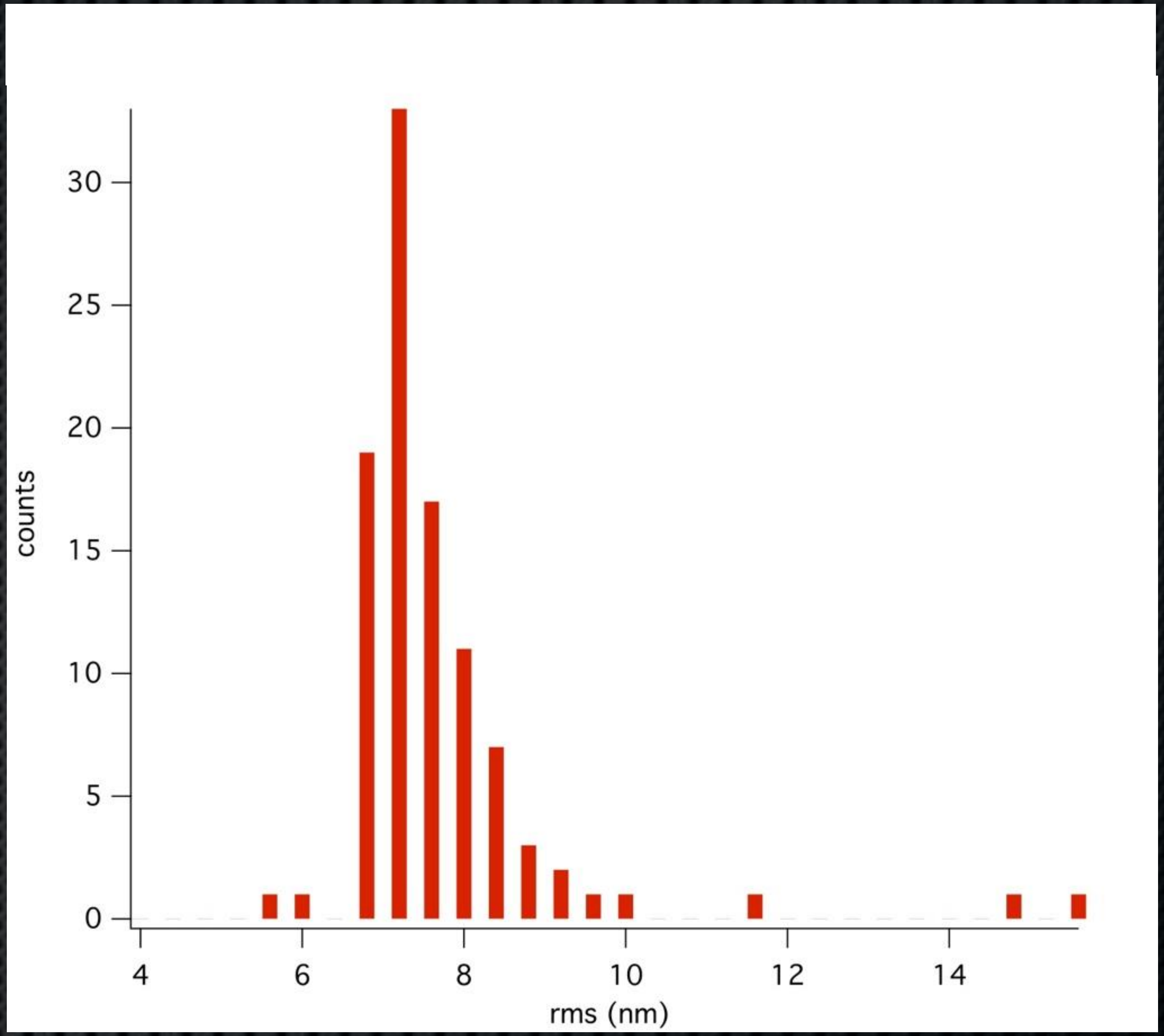
deformation from ideal shape (Gaussian beam) due to:

- Small instabilities of the Source
- photon transport optics

FEL 1 wavefront measurements





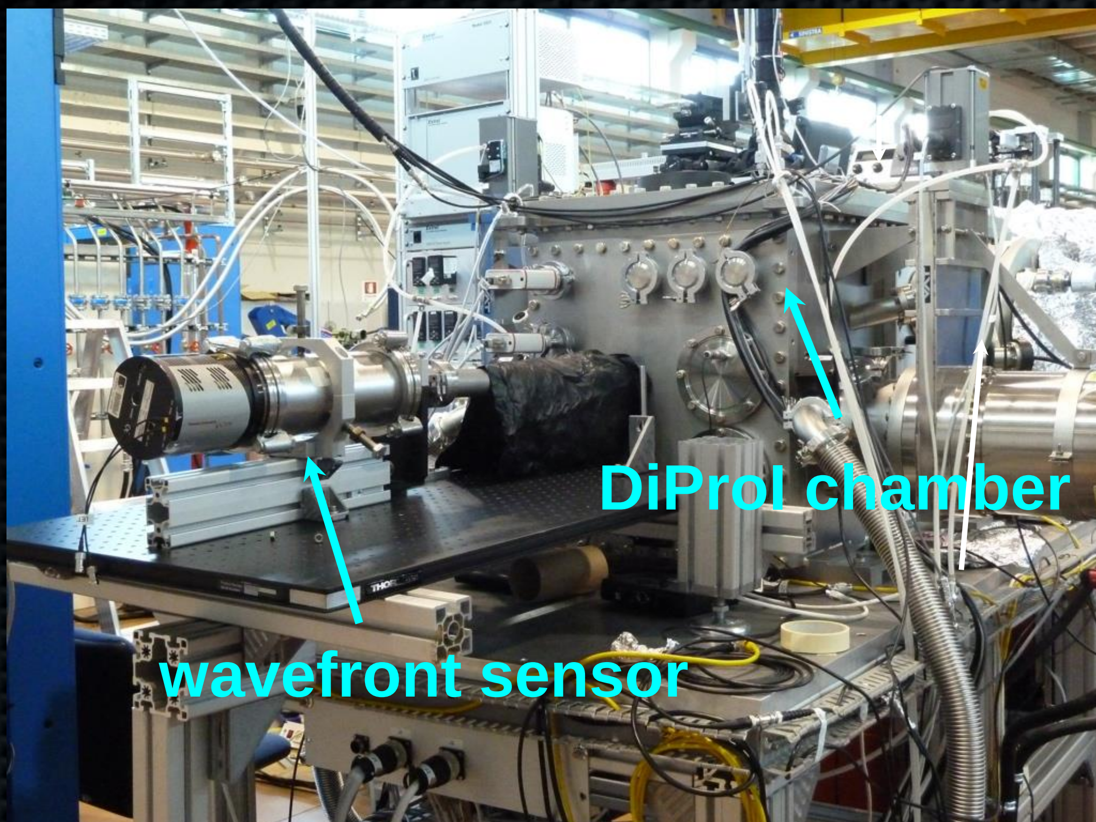


effect of these wavefront deformations is <u>not negligible</u> in terms of focal spot degradation

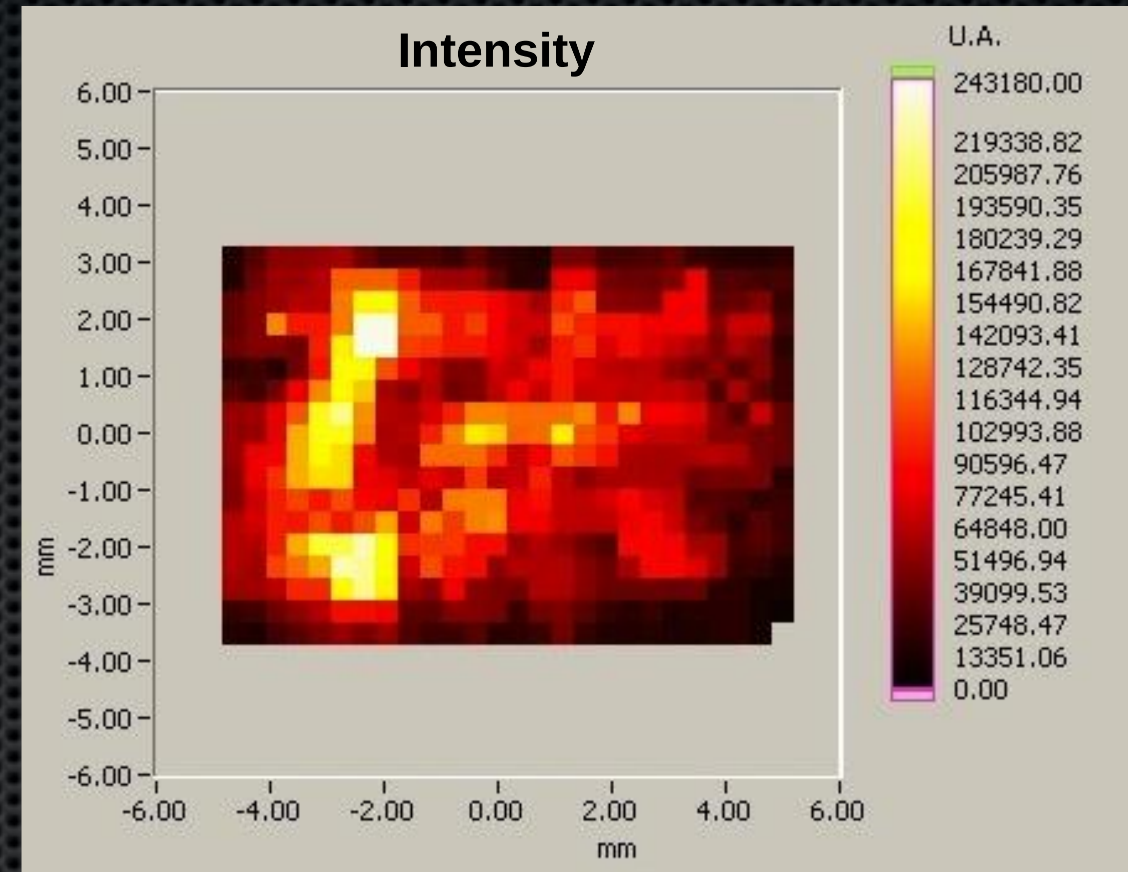
Work still in progress

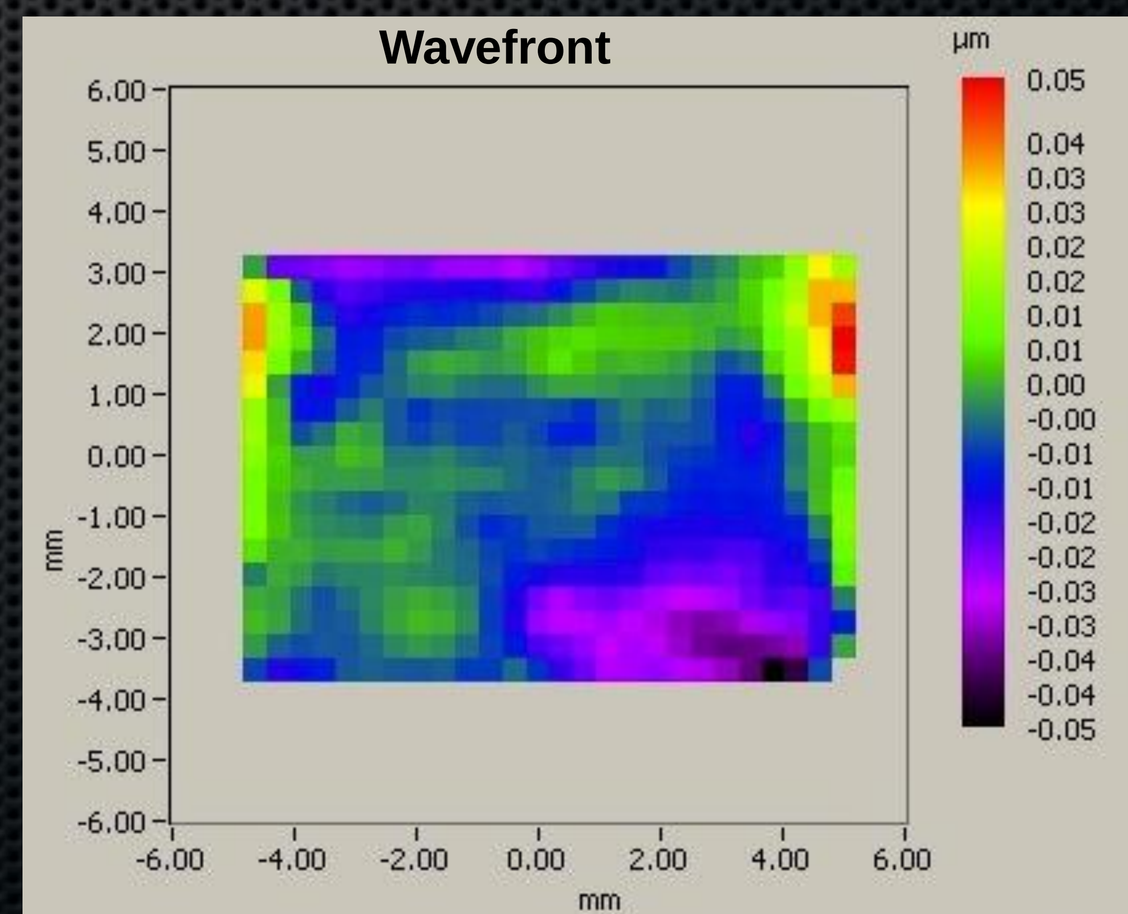
Focal spot measurements at DiProI end-station

Wavefront sensor measurements



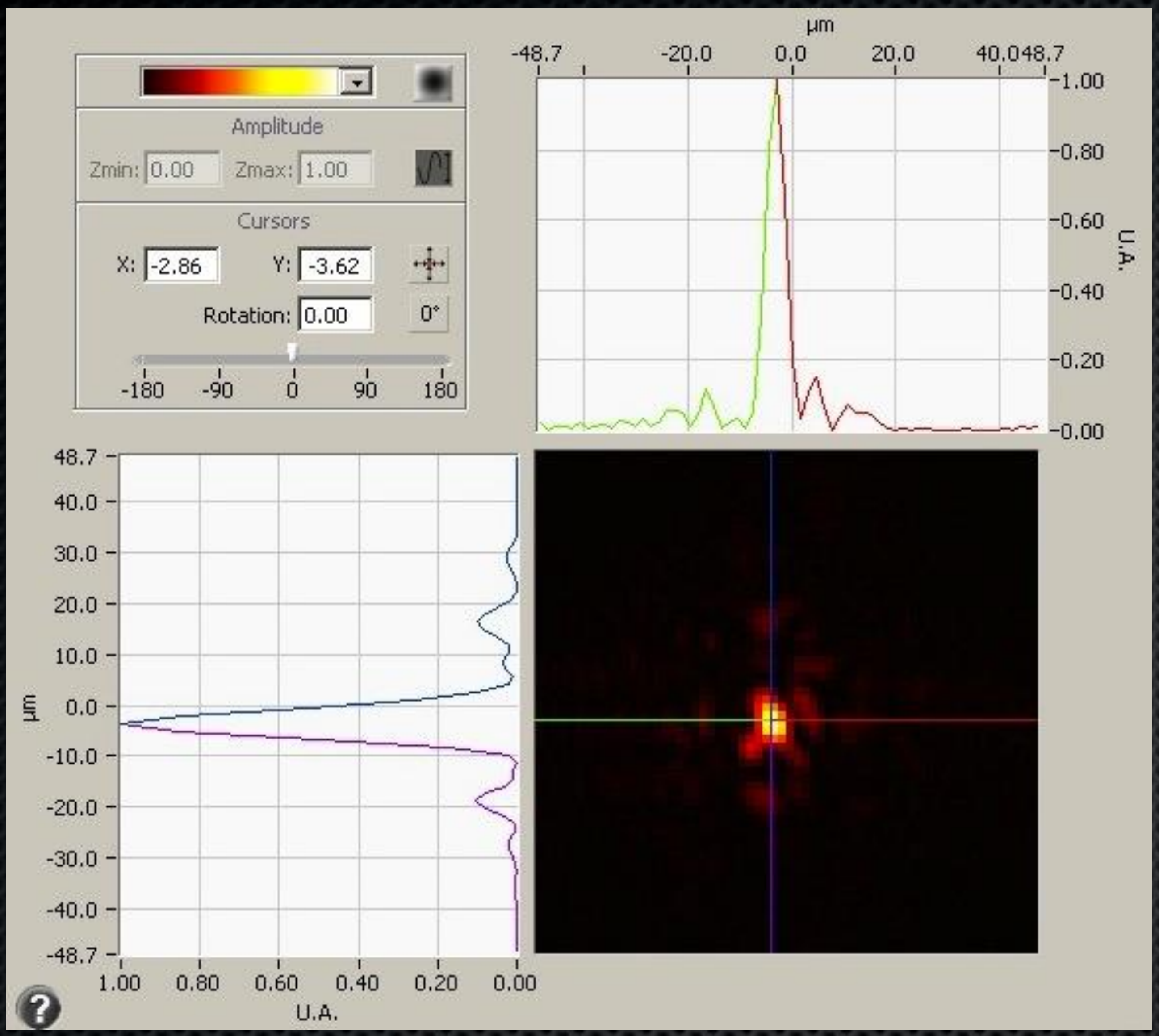
- FEL 1
- wavelength - 32 nm
- measuring of Intensity and Wavefront at 1m out of nominal focus
- reconstruction of the spot in focal plane
- **rms wavefront of best spot 12 nm**



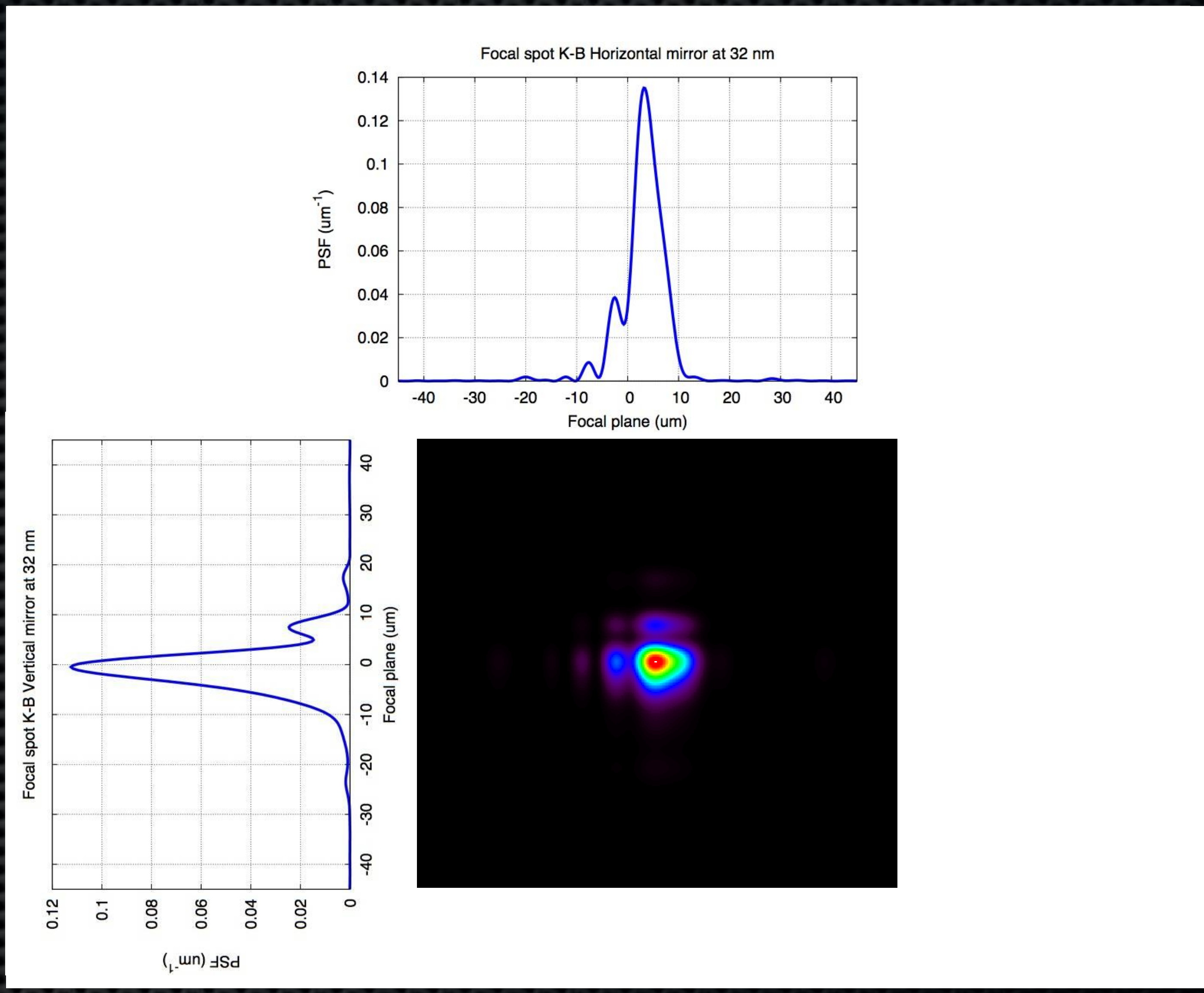


Focal spot measurements at DiProI end-station

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 $\boxed{\text{FWHM = 5x8 µm}}$

- 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) $\boxed{\text{FWHM = 5.2x7.7 µm}}$

CONCLUSIONS

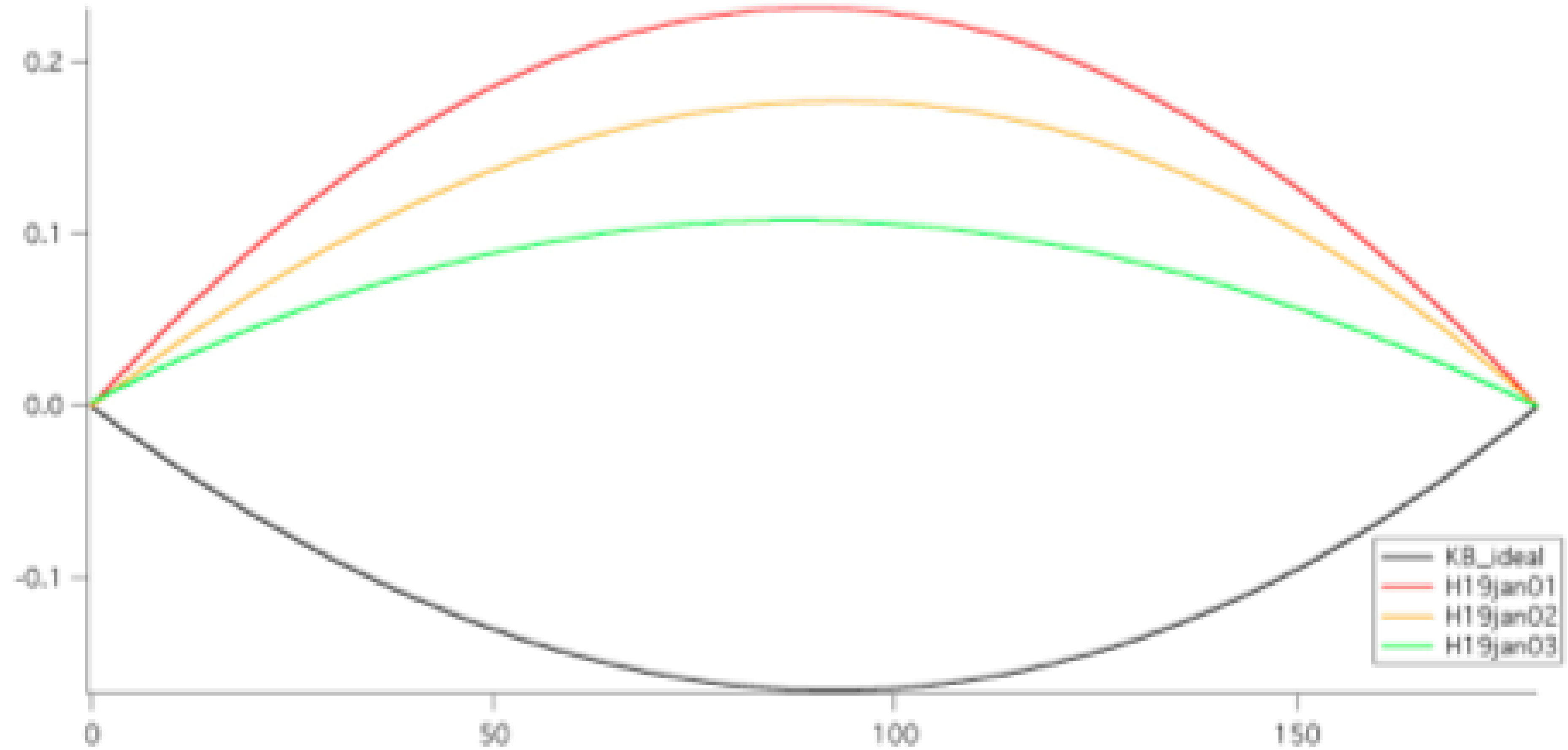
- We performed surface profile characterization of the K-B bendable system mounted in the DiProI chamber with Long Trace Profilometer.
- We extended the Fresnel diffraction method to FEL applications - non isotropic sources - focal spot given the best measured profile at LTP - FWHM = 4.4x7.7 µm
- We 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
- P. Zeitoun, G. Lambert, W.Boutu, H. Merdji, A. I. Gonzalez, G. Dovillaire, D.Gauthier – CEA + LOA + IMAGINE OPTIC

THANKS FOR YOUR ATTENTION

Adaptive correction tool software



Adaptive Correction Tool

CH.	Voltage Correction
00	+2600.2 V
01	+1861.7 V

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PSF WITH FRESNEL DIFFRACTION

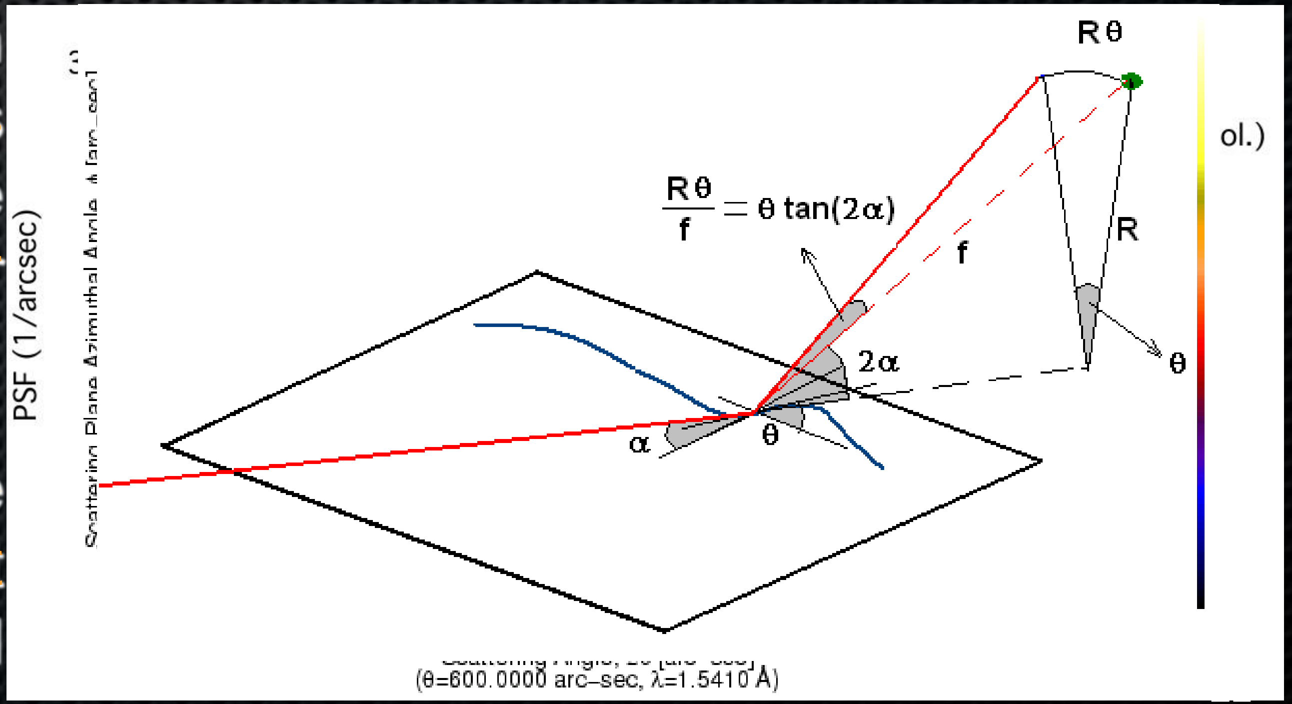
Approximations:

- 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 tan2α
  - 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)

In order to prevent mirror under sampling:

$$\Delta l \approx \frac{\lambda f^2}{2\pi R_0 r}$$

$$\Delta x \approx \frac{\lambda f^2}{\pi R_0 L}$$



PSF WITH FRESNEL DIFFRACTION

L. Raimondi, D. Spiga, SPIE Proc., 8147 (2010)

INTENSITY DISTRIBUTION ON THE FOCAL PLANE
OBTAINED BY SUPERPOSING THE LINEAR DIFFRACTION
FROM EVERY SLICE IN ITS MERIDIONAL PLANE

Kirchoff-Fresnel diffraction equation

$$U(P) = \frac{Ae^{ikr_0}}{r_0} \int\int_S \frac{e^{iks'}}{s'} K(\chi) dS'$$

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

$$E(x,y) = \frac{E_0}{f\lambda} \int_L e^{-i\frac{2\pi}{\lambda}(L+f-z_p+\sqrt{(x-x_p)^2+z_p^2})}\,\mathrm{d}l \int_{-\Delta y/2}^{+\Delta y/2} e^{-i\frac{2\pi y}{\lambda f} y_p}\,\mathrm{d}y_p$$

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

Integration over y and normalizing with flux intensity

$$\boxed{PSF(x) = \frac{\Delta R}{f\lambda L^2} \left| \int_L e^{-i\frac{2\pi}{\lambda}(\sqrt{(x-x_\mathrm{p})^2+z_\mathrm{p}^2}-z_\mathrm{p})}\,\mathrm{d}l \right|^2}$$

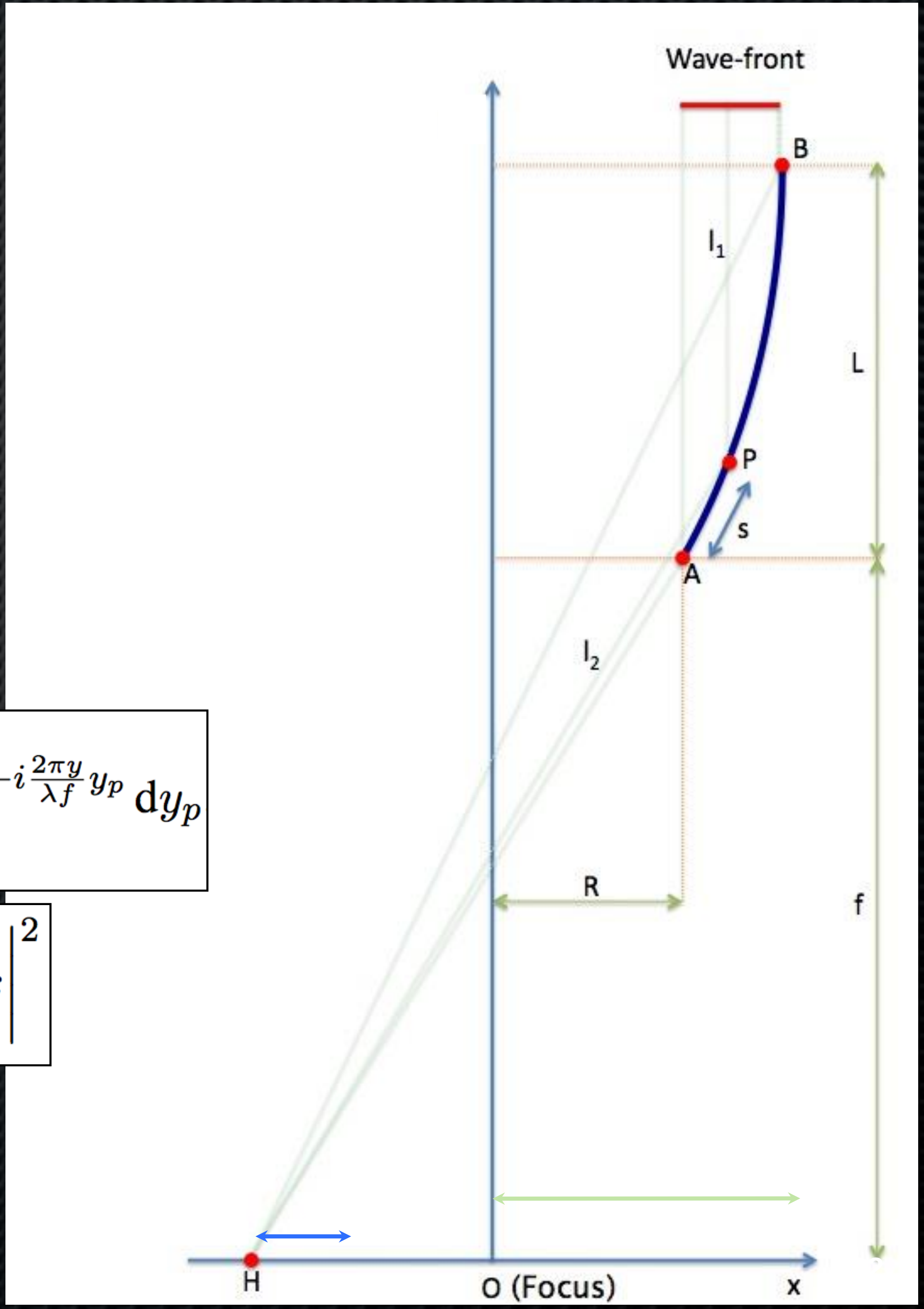
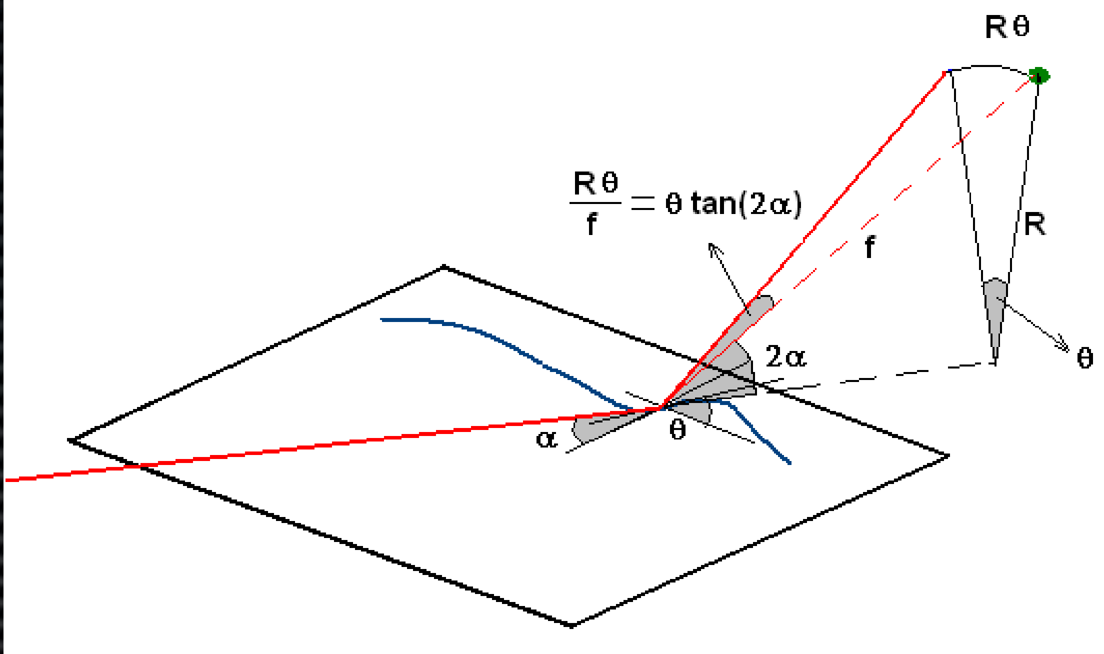


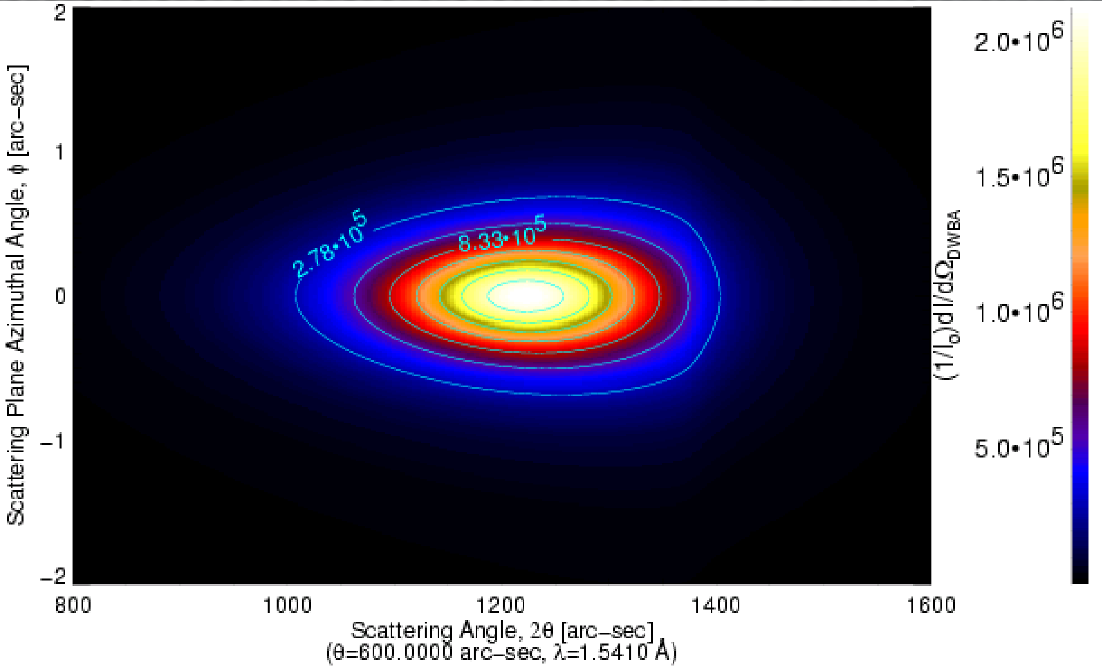
FIGURE ERRORS

$$2\theta \longleftrightarrow \theta(tg2\alpha)$$



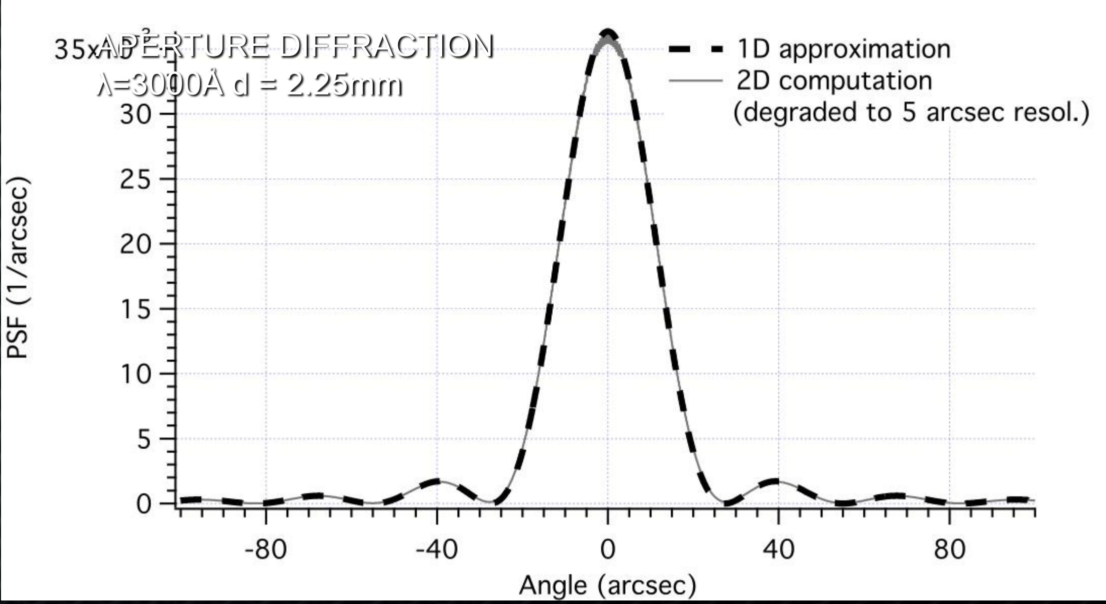
SCATTERING

$$\frac{(\vartheta_s - \vartheta_i)^2}{\frac{1}{2}} + \frac{\varphi_s^2}{\tan\vartheta_i} \approx \frac{f^2\lambda^2}{\cos\vartheta_i \sin\vartheta_i}$$

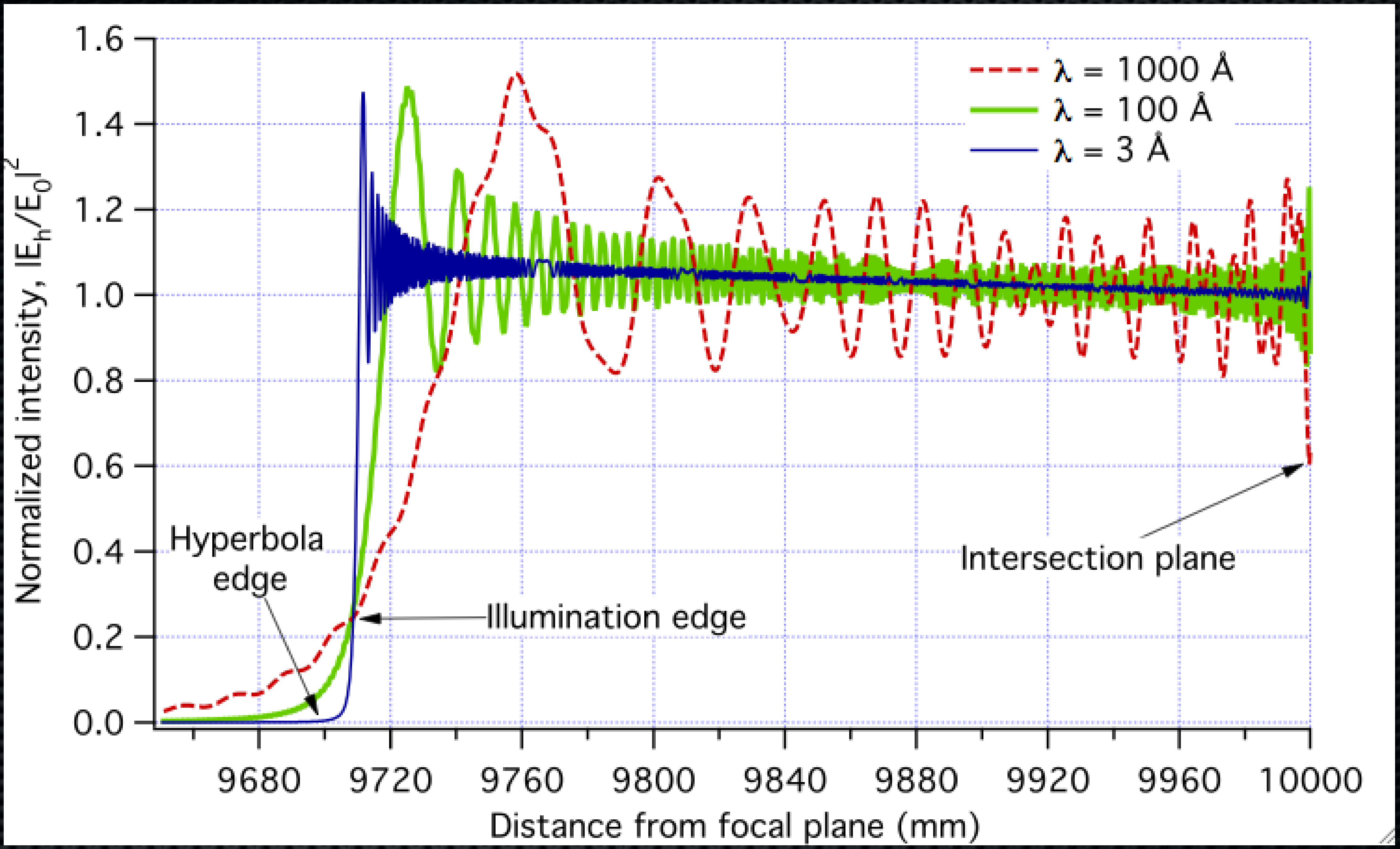


APERTURE DIFFRACTION

$$I(\vartheta) \propto \frac{\sin^2\left(\frac{\pi d}{\lambda}\sin\vartheta\right)}{\left(\frac{\pi d}{\lambda}\sin\vartheta\right)^2}$$



ELECTRIC FIELD DIFFRACTED ON THE HYPERBOLA



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

L. Raimondi, D. Spiga, SPIE Proc., 8147 (2011)

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)

$$dI_s/d\theta_s \propto PSD$$

$$\sigma^2 = \int PSD\, df$$

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

$$4\pi\sigma\sin\alpha < \lambda$$

e.g. λ=1Å α=0.5° σ<9Å