KB focusing optics for the SQS Scientific Instrument

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Instrument Scientist

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Hamburg, January 24th 2017

Outline

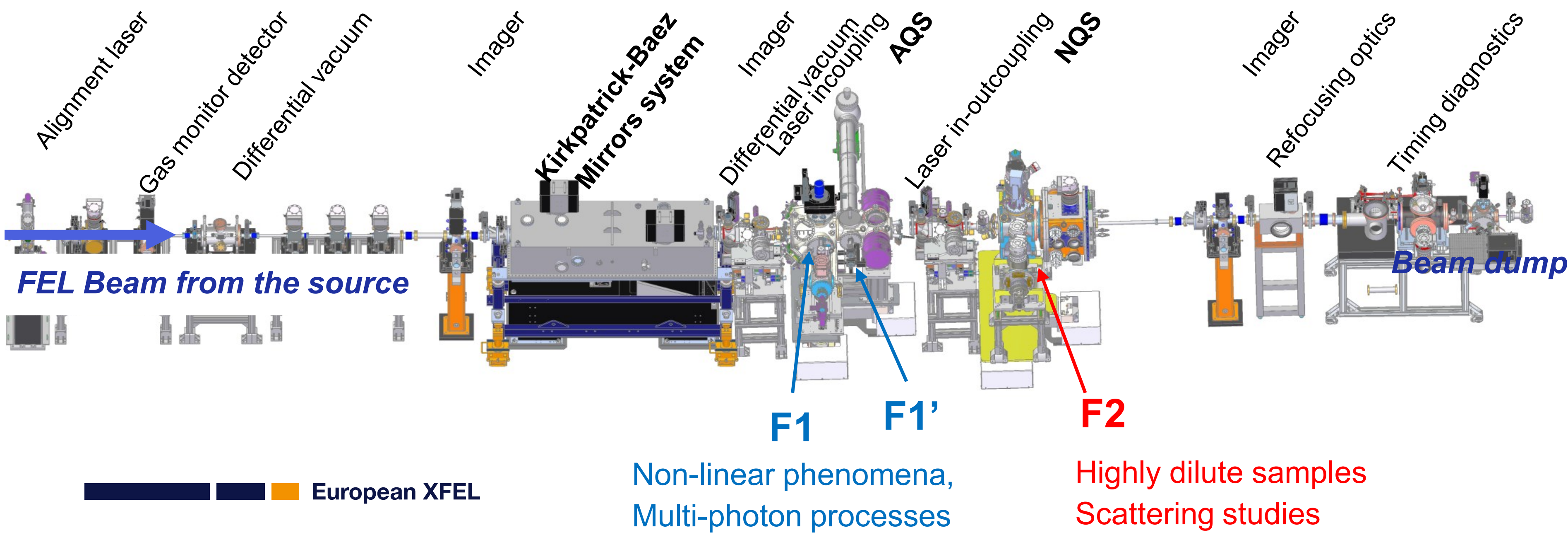
- Focusing system functional specifications coping with
  - Science case
  - Source, beamline, instrument characteristics
- Conceptual and technical solution for the SQS KB system
- Expected performances: results from simulations
  - ray tracing
  - wavefront propagation
- The solution for day one
- Characterization tools

Functional specifications

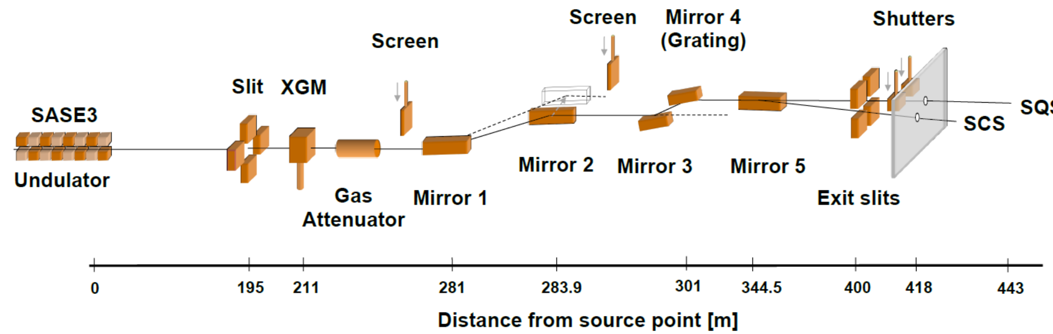
- Focus high power FEL radiation over a broad photon energy range (0.25 – 3 keV)
- Focus it very tightly to obtain conditions for non-linear phenomena
- Focus it very tightly into three (!!) different interaction regions
- In addition: allow for operation of both mono and pink beam operation

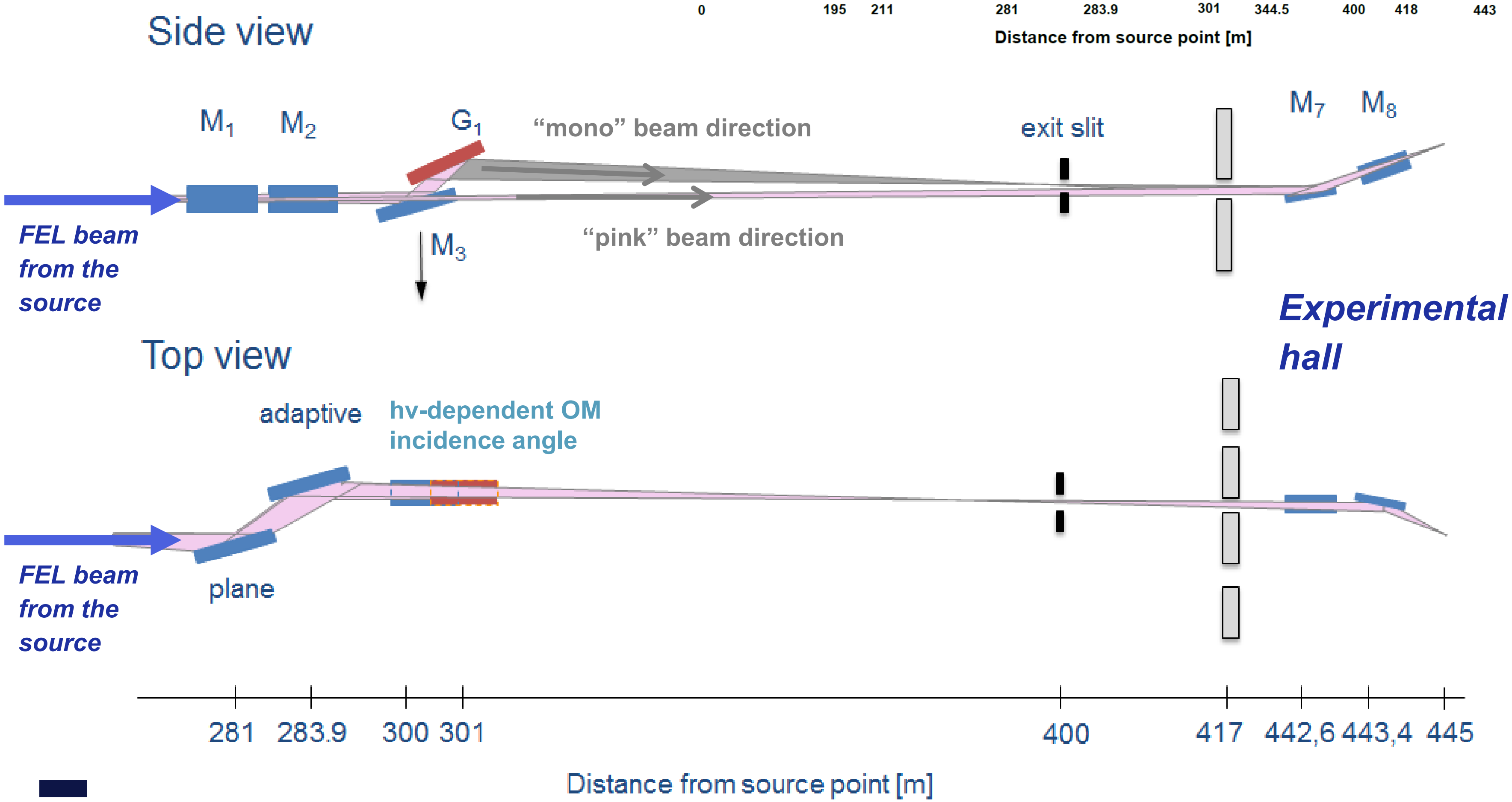
SQS Scientific Instrument science cases:

- Non-linear phenomena, multi-photon processes
- Ultra-fast dynamics
- Extremely dilute targets processes with small cross section



SASE3 Optical Layout

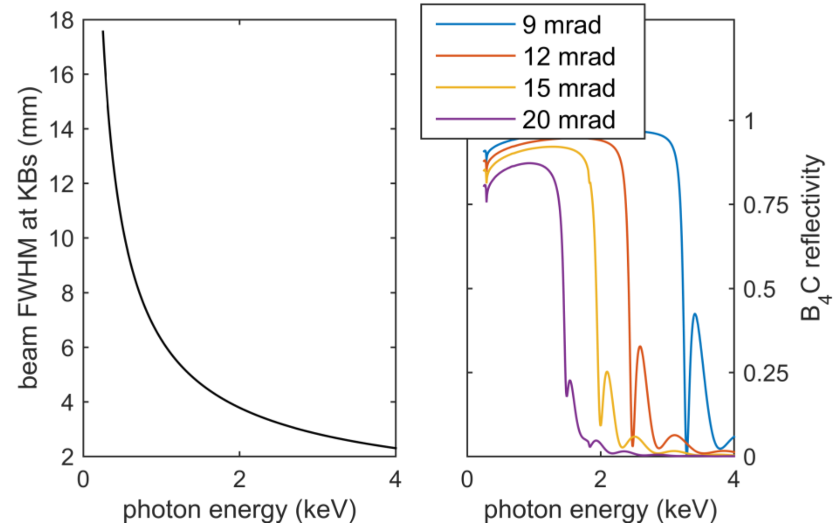




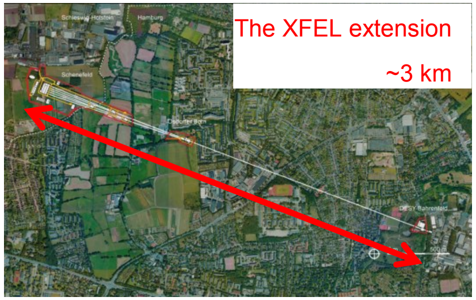
The solution, conceptually:
KB optical system made of two elliptical mirrors that are:

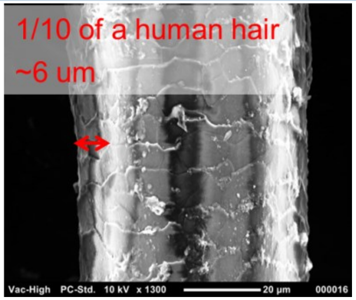
1. Very long
2. With very high surface quality
3. Actively cooled
4. Equipped with mechanical benders to be adaptive

*Why should the mirrors be **that** long?*



*What does our surface quality requirement **(2nm / 1m)** mean:*



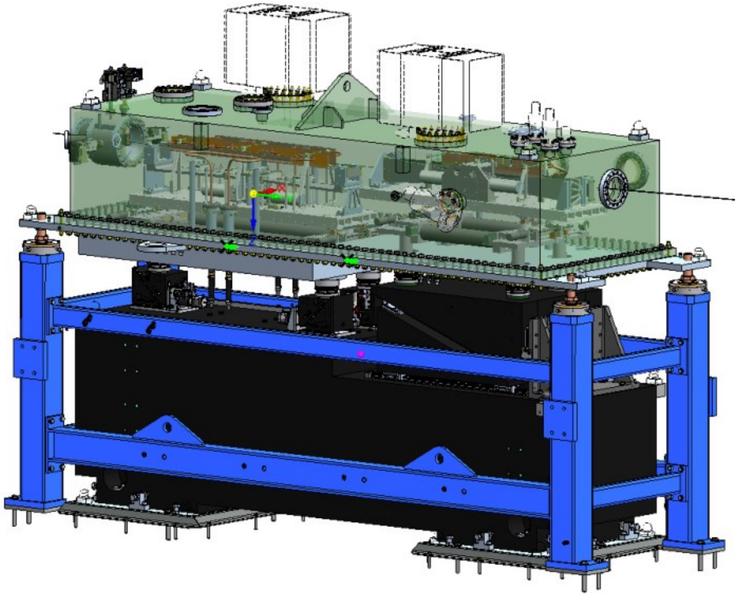


The solution, technically

- Contract awarded to FMB Oxford
  - Super-polished substrates (subcontractor: JTEC)
  - Vacuum vessel + mechanics
  - installation
- Current status:
  - Final design released (Dec 2015)
  - Vessel and mechanics under production (ready soon)
  - Grouting plates installed in the experimental hutch (Jan 2017)

FMB Oxford

JTEC



The solution, technically

- Contract awarded to FMB Oxford
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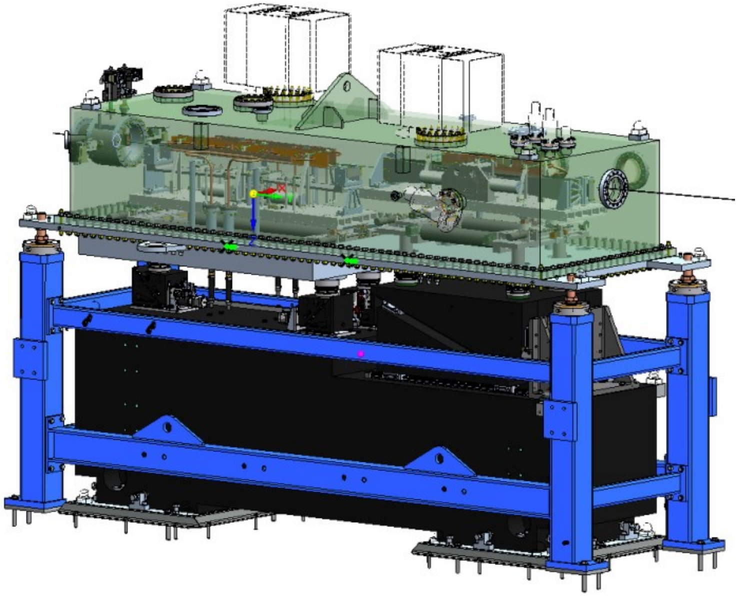
  - Vacuum vessel + mechanics
  - installation
- Current status:
  - Final design released (Dec 2015)
  - Vessel and mechanics under production (ready soon)
  - Grouting plates installed in the experimental hutch (Jan 2017)
  - Substrates being processed by the subcontractor
    - ► Expected delivery Dec 2017
    - ► Plan B with spare mirrors for day one under consideration

FMB Oxford

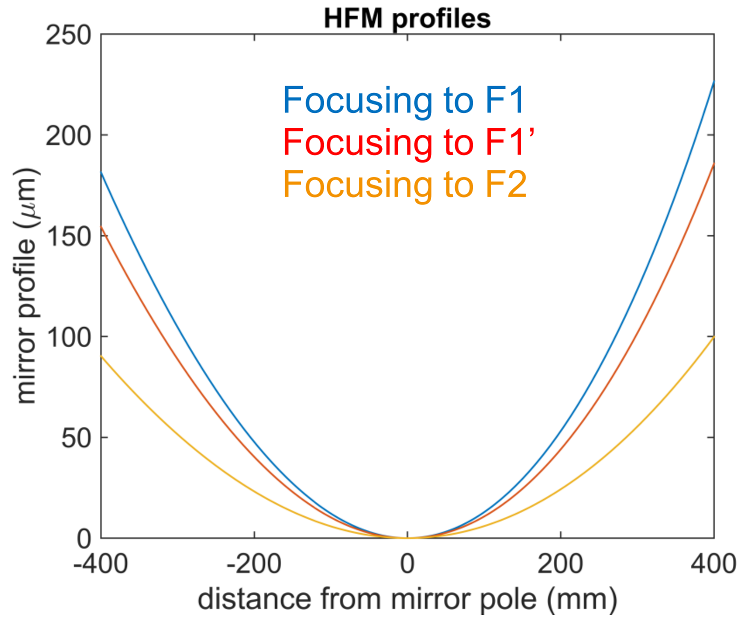
TEC



The solution, technically: polishing profiles

- Very steep elliptical profiles!
- Adaptive mirrors with mechanical benders: two end couples induce a curvature in the mirror beam according to the Bernoulli-Euler equation
- **Idea**: polish to profile F1 and bend to the difference between F1 and F1'
- **Problem**: the action of two end couples can only provide a cubic approximation to an ellipse.
- ***Solution***: the width of the mirror is modified such that the inertia I(x) is position dependent; for each coordinate it gives the wanted radius of curvature
- Chosen approach:

" polish to F1, lateral shape to F1' "



Bernoulli-Euler equation

$$EI_0 \frac{d^2 y}{dx^2} = \frac{C_1 + C_2}{2} - \frac{C_1 - C_2}{L} x,$$

Ellipse curvature

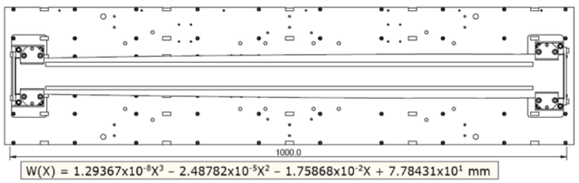
Position-dependent mirror width

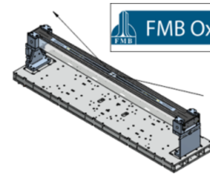
$$b(x) \sim I(x) \sim \frac{(C_1 + C_2)/2 - (C_1 - C_2) \cdot x/L}{\text{"exact ellipse curvature"}}$$

Howells et al., Theory and practice of elliptically bend x-ray mirrors, Opt. Eng. 39(10) 2748-2762 (2000)

Bending-induced surface error: results from FEA analysis

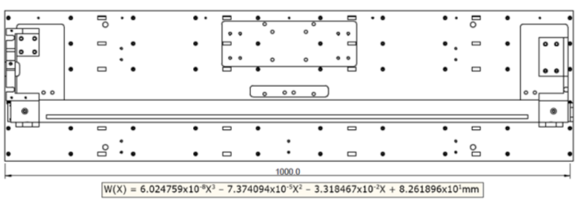
VFM

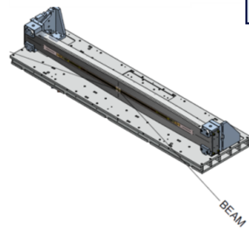




FMB Oxford

HFM





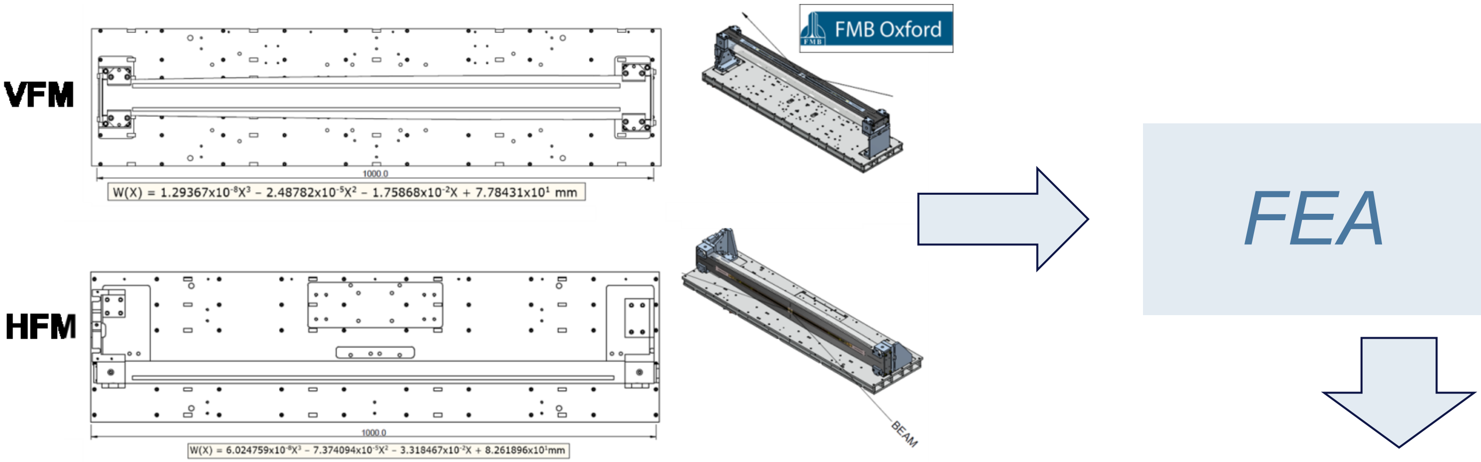
FEA

FEA analysis performed by FMB Oxford using ANSYS, estimating:

- optimal clamping force
- optimal end couples for bending to F1' and F2
- Residual error respect to the ideal ellipse (quantified in RMS slope)
- The effect of the thermal load to optimize the design of the bending grooves (see later)

KB	focus	p [m]	q [mm]	Clear aperture [mm]	Error [nrad RMS]
HFM	F1	433,9	1800	800	0
VFM	F1	432,7	3000	800	0
HFM	F1'	433,9	2150	800	15
VFM	F1'	432,7	3350	800	9

Bending-induced surface error: results from FEA analysis



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HFM	F1’	433,9	2150	800	15
VFM	F1’	432,7	3350	800	9
HFM	F2	433,9	3832	800	1652
VFM	F2	432,7	5032	800	280

“high residual error for F2, but we have a solution for it”

Expected performances: ray tracing simulations

Source size and divergence (calculated by Yurkov et al.)

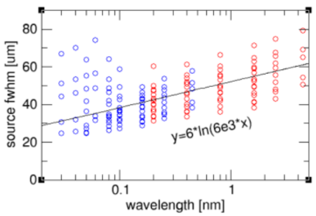


Figure 10: Size of the photon source in the undulator. Red and

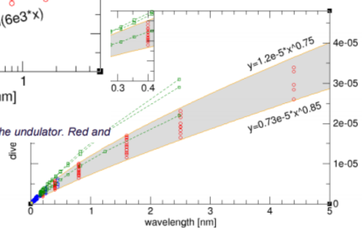


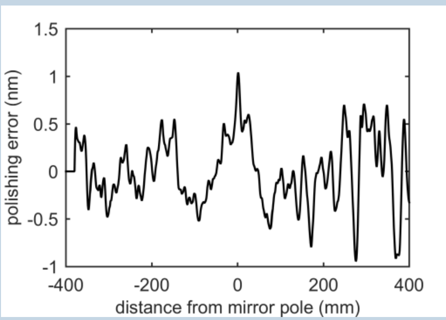
Figure 8: Calculated divergences (FWHM) for 10.5–17.5 GeV and 20pC–1nC. Blue circles are calculations for SASE1 and SASE2, red circles for SASE3. The green dots are calculations for the LCLS (from the LCLS website) for 20, 40, and 250 pC bunch charge.

H. Sinn et al., CDR X-Ray Optics and Beam Transport April 2011

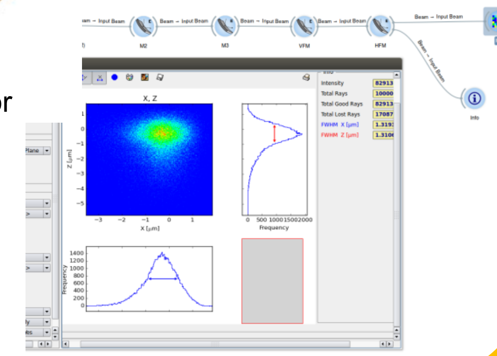
Beamline 3D geometry

Mirrors reflecting surface profiles

- Polishing error (example from BT mirror prototype, courtesy L. Samoylova)
- Bending error from finite element analysis



https://www.elettra.trieste.it/oasys.html



Including ShadowOui, user interface for Shadow3 (new release of the widely used x-ray optics simulation package)

Credits:
M. Sanchez del Rio (ESRF)
L. Rebuffi (Elettra)

+

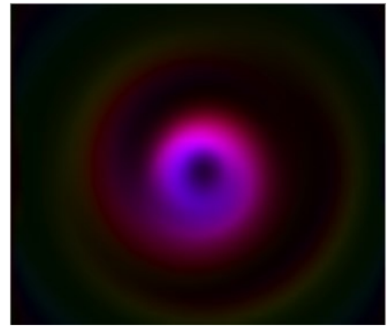
- ✓ Mirrors reflectivity from the CXRO database
- ✓ Diffraction simulated by a randsinc2 contribution

Output:
- ✓ *Focal spot profile*
- ✓ *Rayleigh length*
- ✓ *Transmission*

Expected performances: wavefront simulations

Gaussian beam

Beamline 3D geometry (simplified)



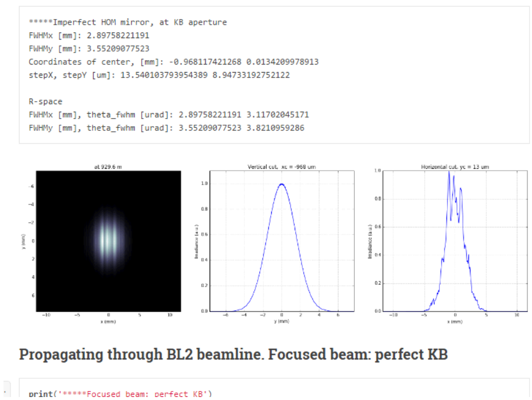
WPG

WaveProperGator

with SRW/C++ library

Credits:
Alexey Buzmakov (Russian Academy of Science),
Liubov Samoylova (XFEL.eu),
Oleg Chubar (BNL)

http://wpg.readthedocs.io/en/latest/index.html



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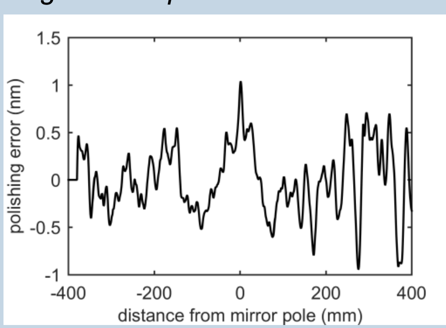
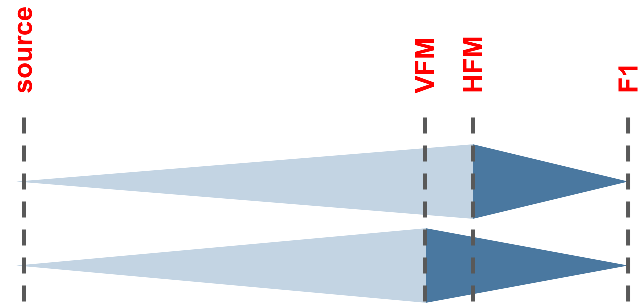


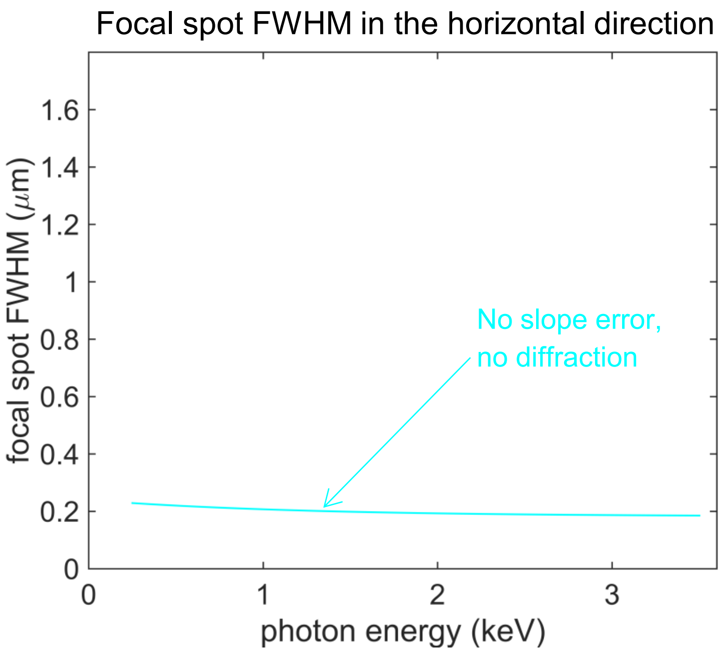
Output:

✓ *focal spot profile (relative estimate)*

✓ *Wavefront*

Ray tracing:
Focusing performances in F1





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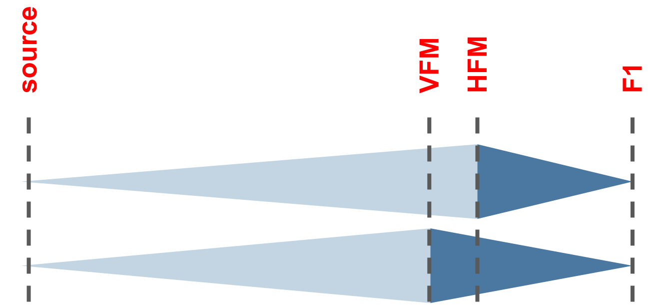

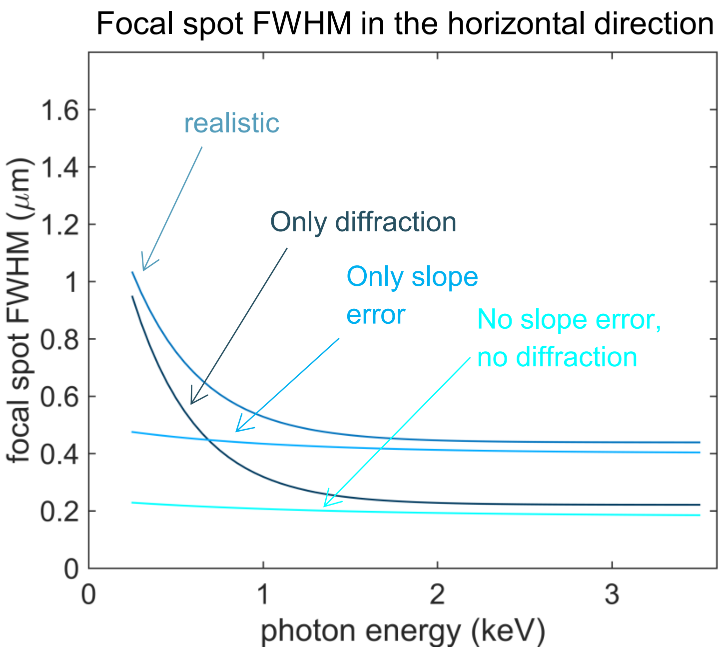

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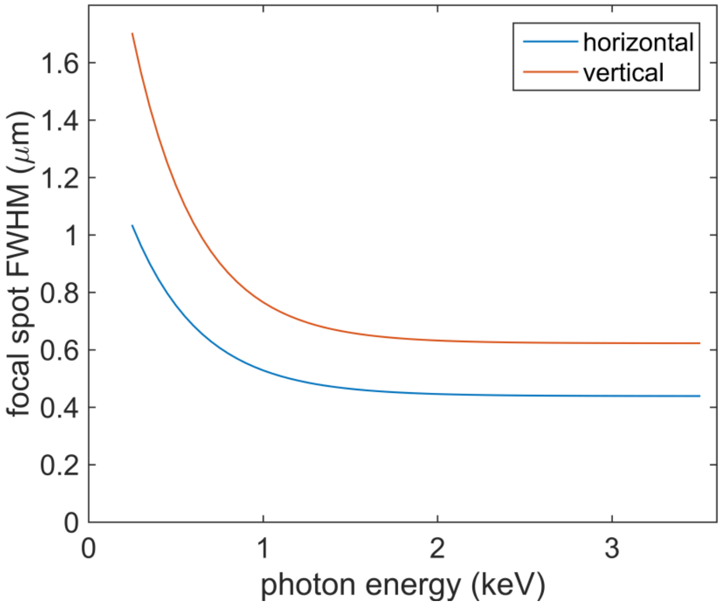

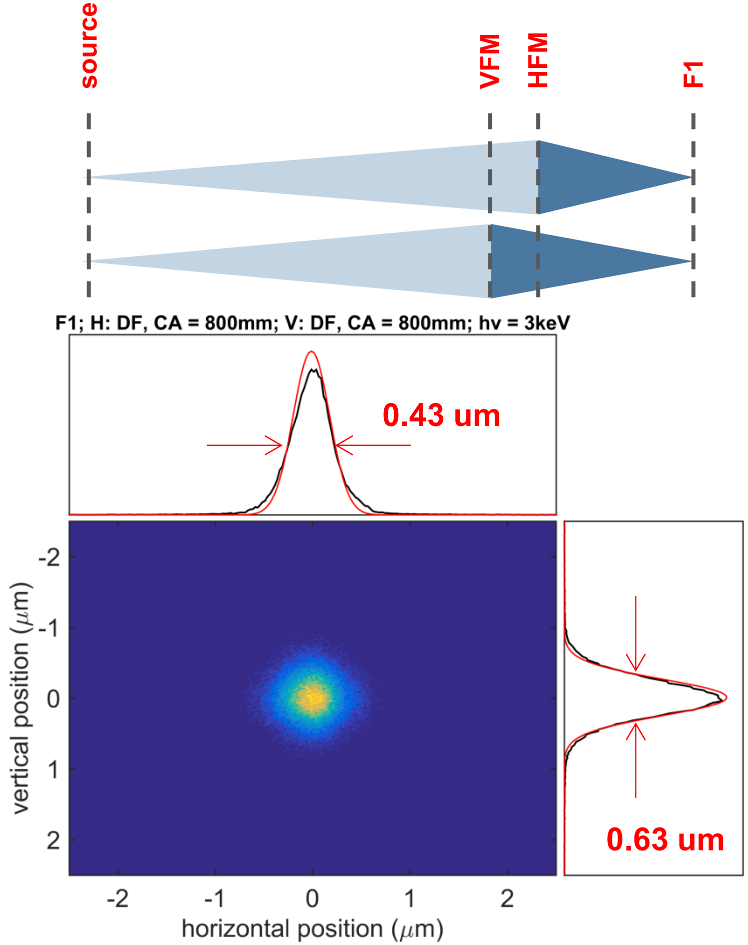

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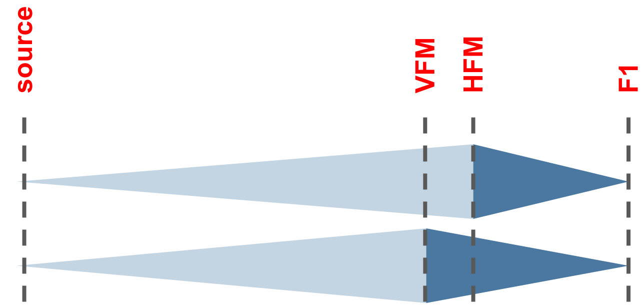
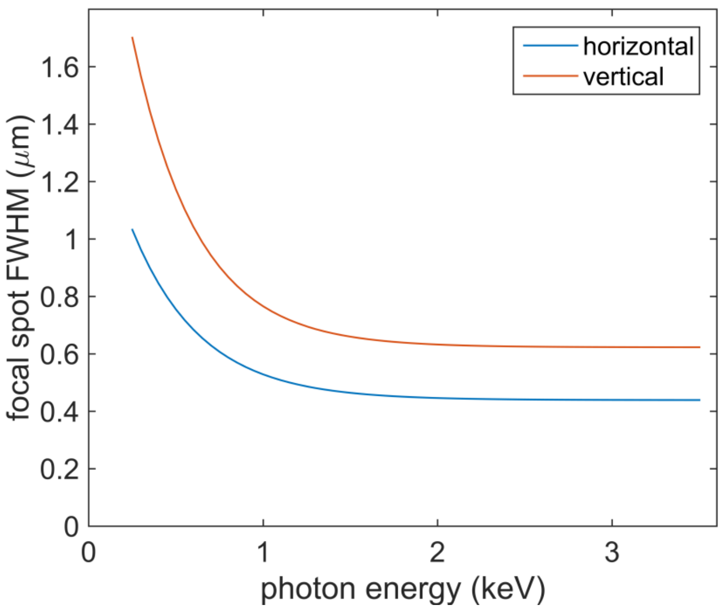
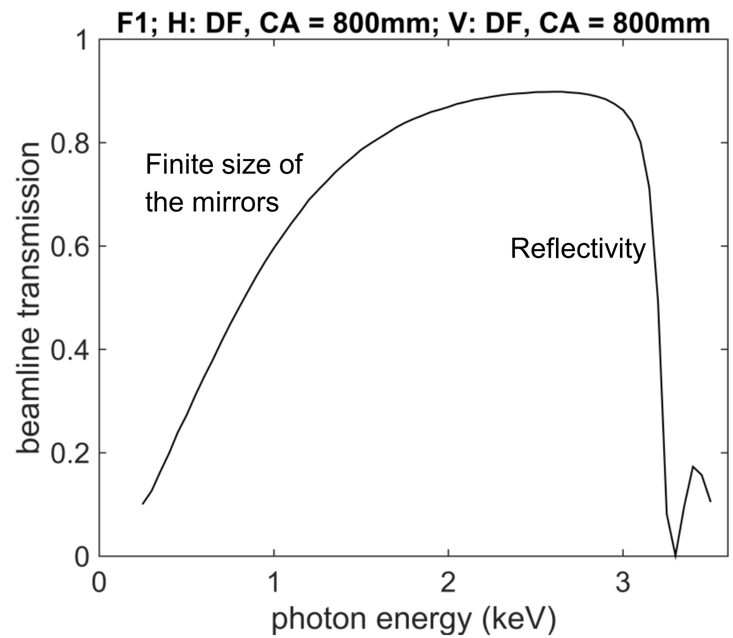
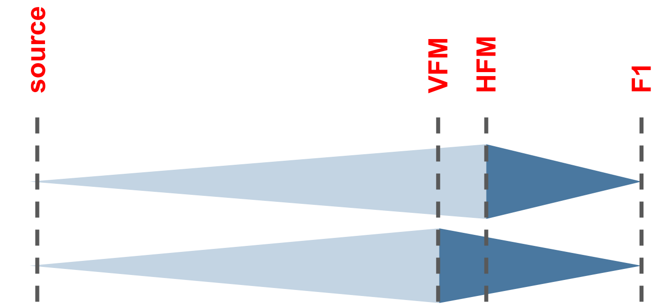


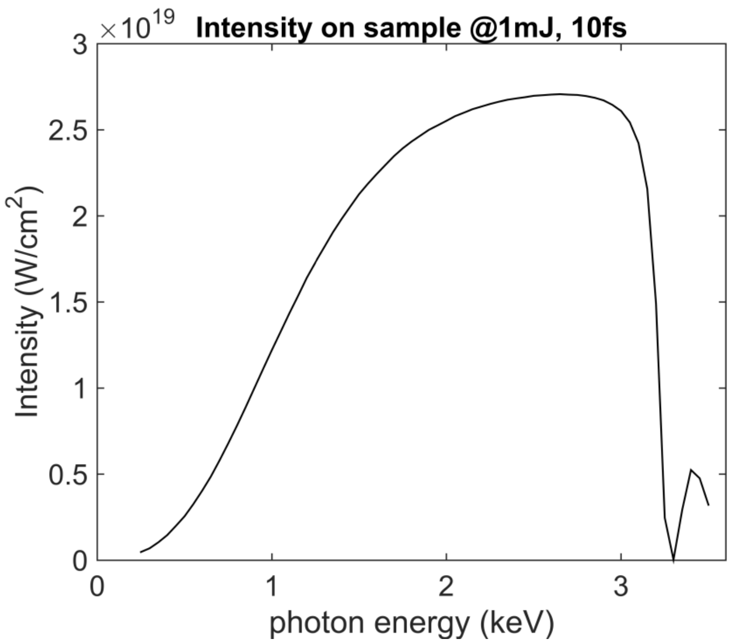


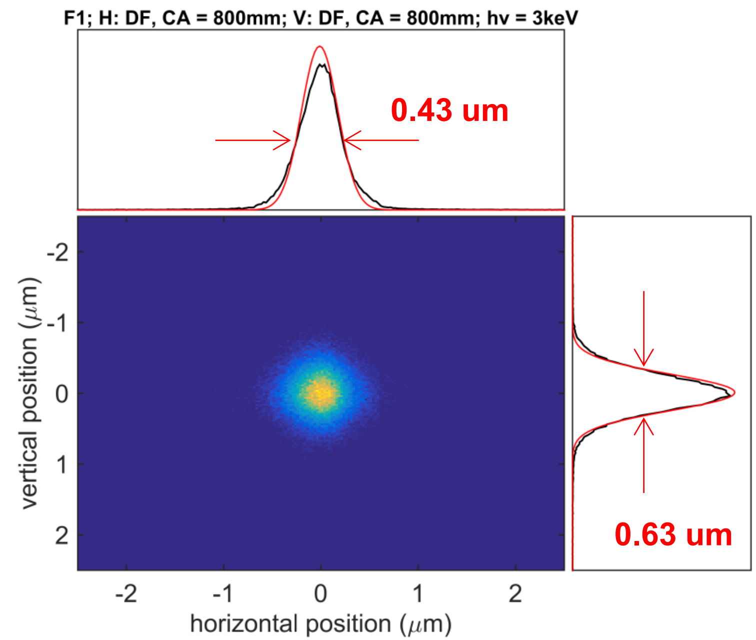


hv [keV]	Spot size FWHM [um]	Transmission [%]
0,3	1,25	12
1	0,65	60
3	0,53	87

Ray tracing:
Focusing performances in F1



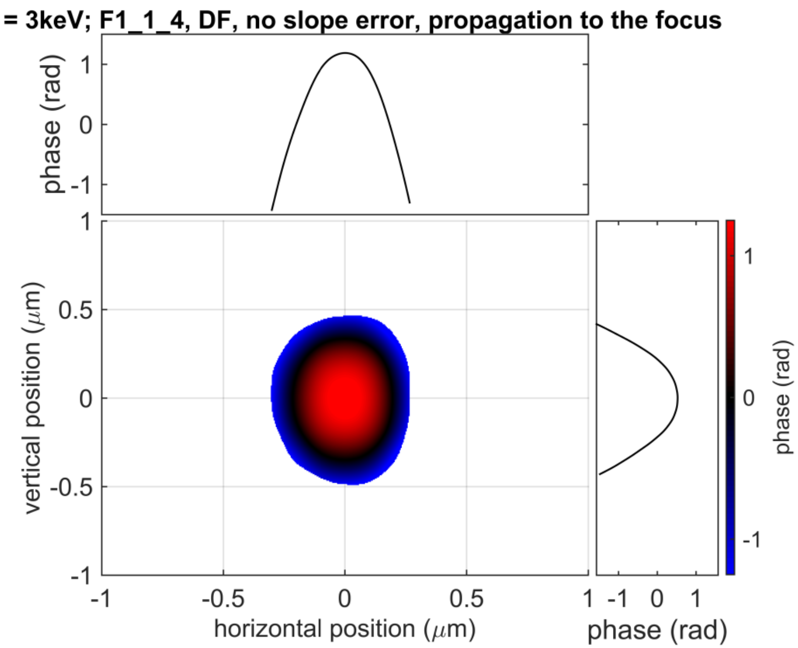




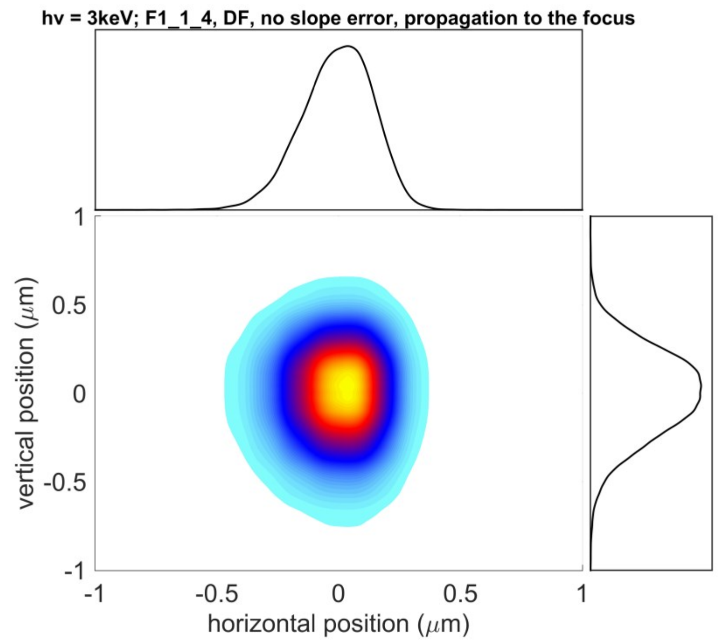
$$I = 8\left(\frac{log2}{\pi}\right)^{3/2} E_p \cdot T_{beamline} \cdot \frac{1}{\tau \cdot FWHM^2}$$

hv [keV]	Spot size FWHM [um]	Transmission [%]	Intensity [W/cm²]
0,3	1,25	12	$7{,}0\ 10^{17}$
1	0,65	60	$1{,}2\ 10^{19}$
3	0,53	87	$2{,}6\ 10^{19}$

Wavefront propagation:
Wavefront in F1, hv = 3 keV, without slope error

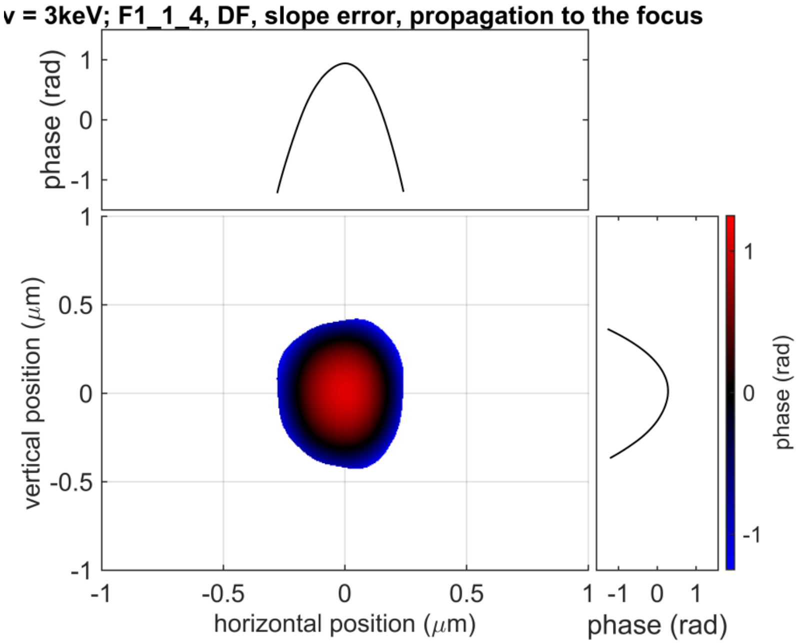


Wavefront phase

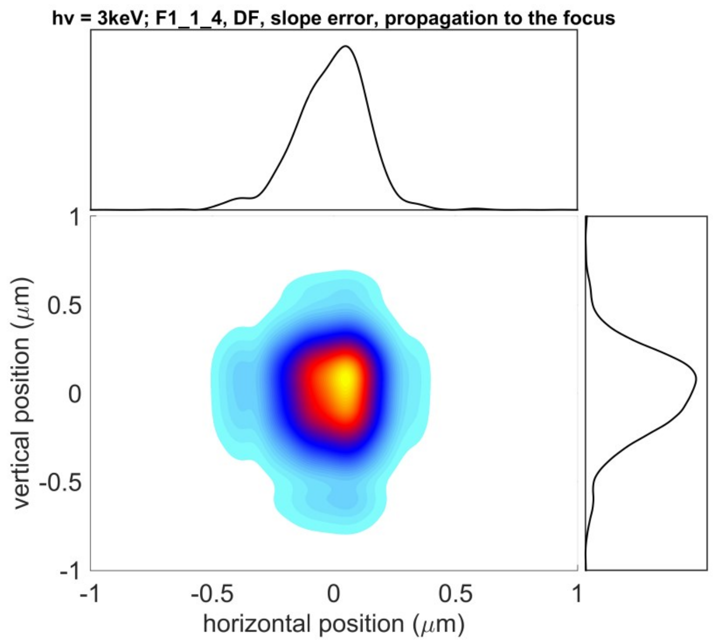


Wavefront intensity

Wavefront propagation:
Wavefront in F1, hv = 3 keV, with slope error



Wavefront phase



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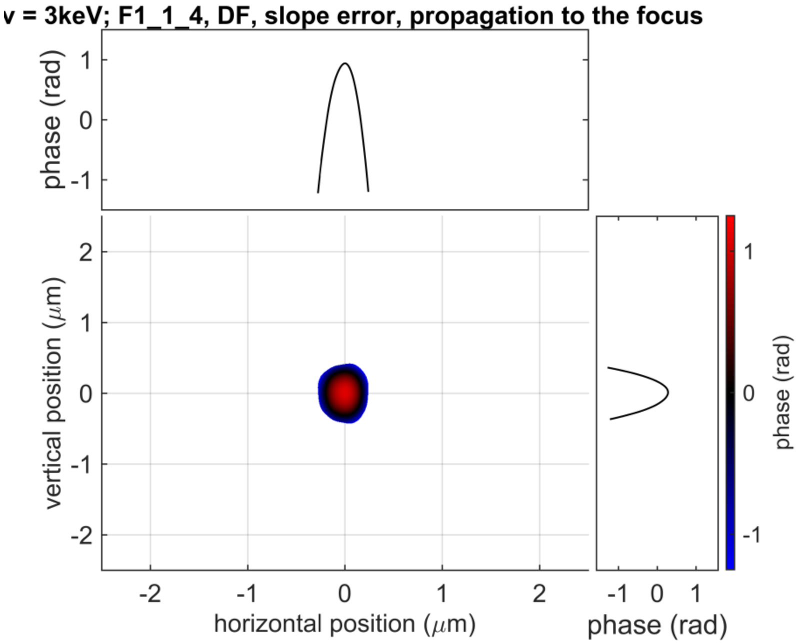
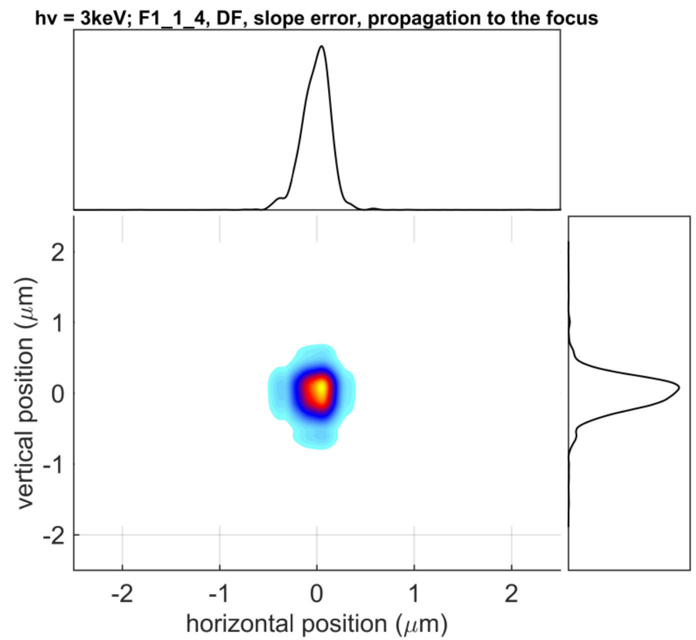
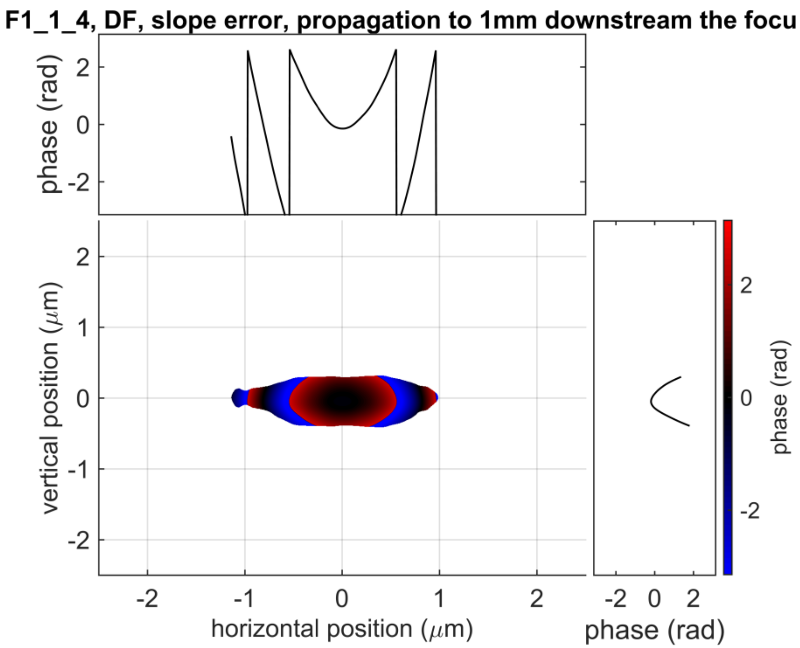


Wavefront phase

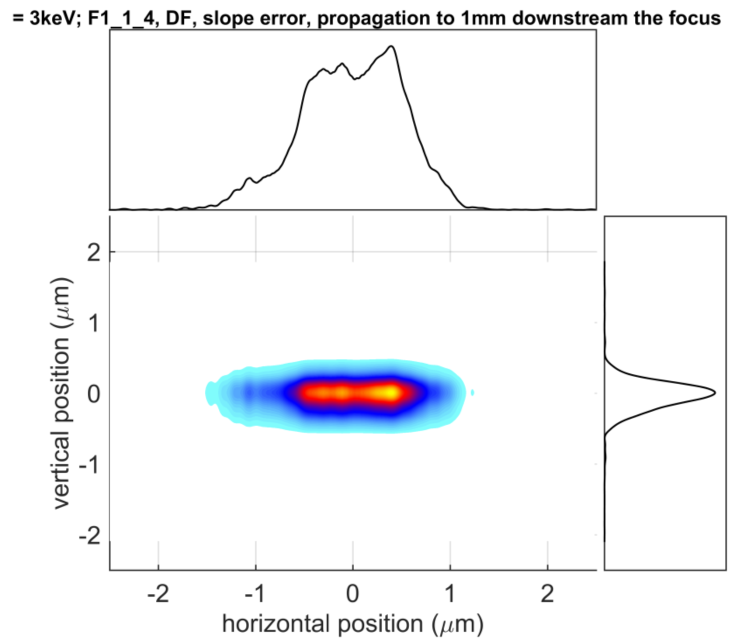


Wavefront intensity

Wavefront in F1, hv = 3 keV, with slope error, 1mm out of focus

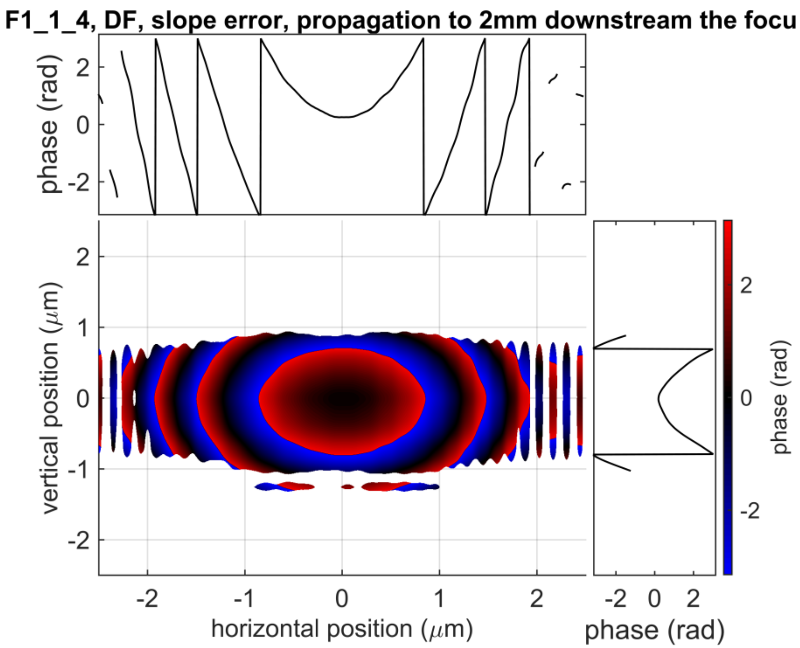


Wavefront phase

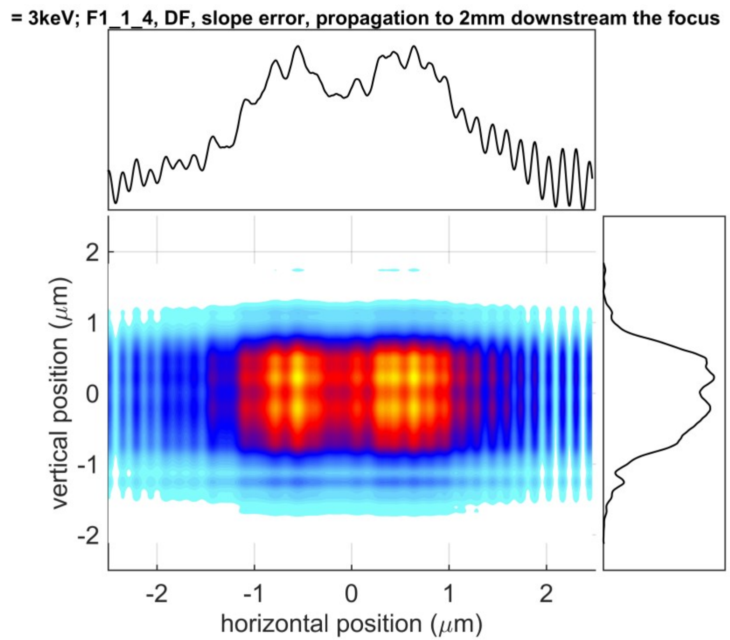


Wavefront intensity

Wavefront in F1, hv = 3 keV, with slope error, 2mm out of focus

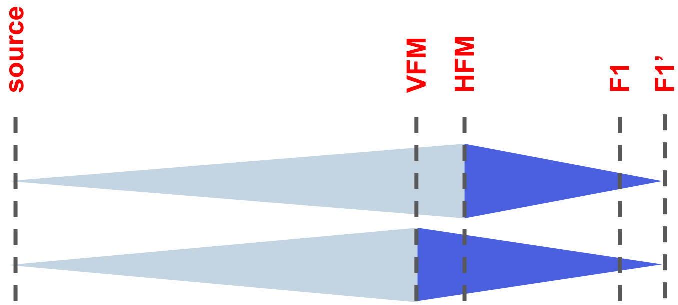


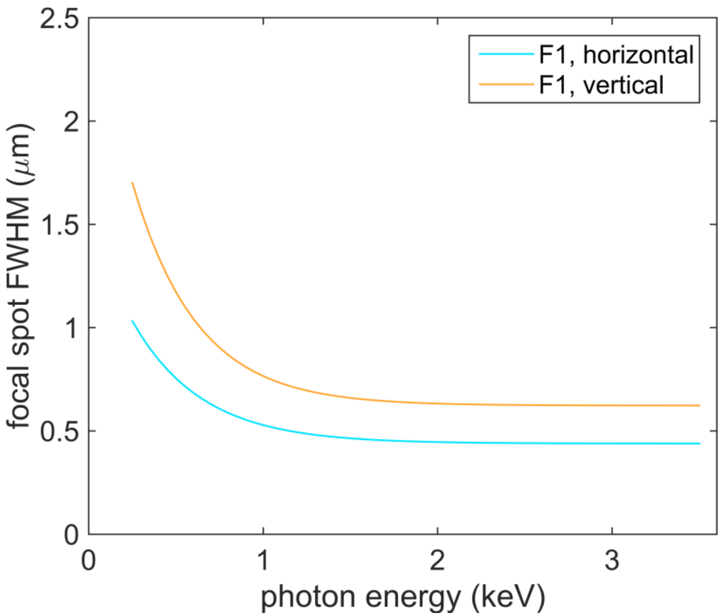
Wavefront phase



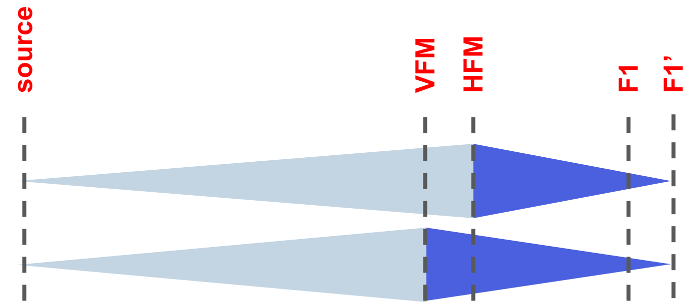
Wavefront intensity

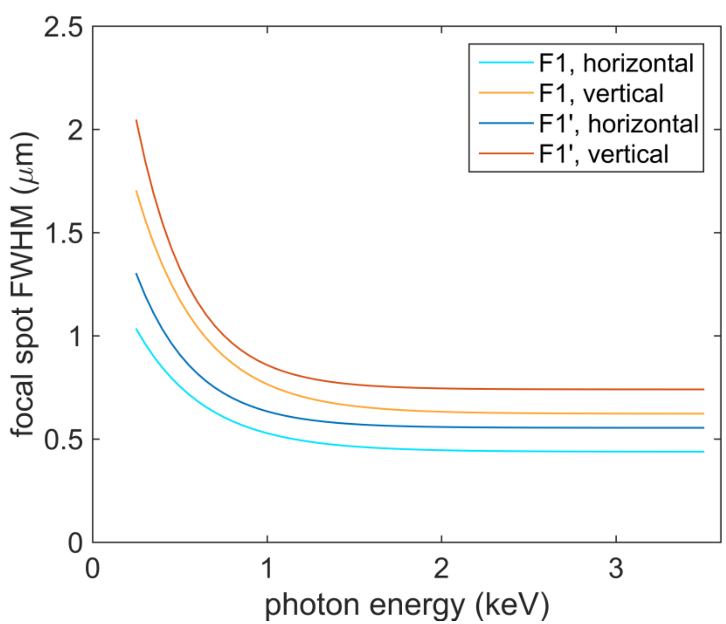
Ray tracing:
Focusing performances in F1’

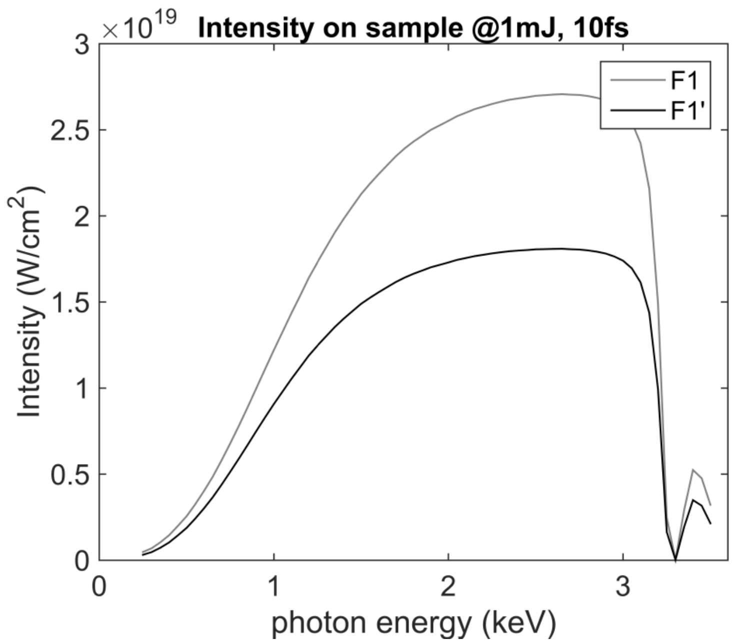




Ray tracing:
Focusing performances in F1’



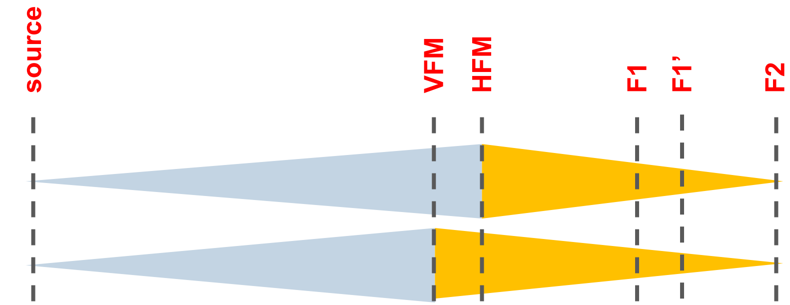


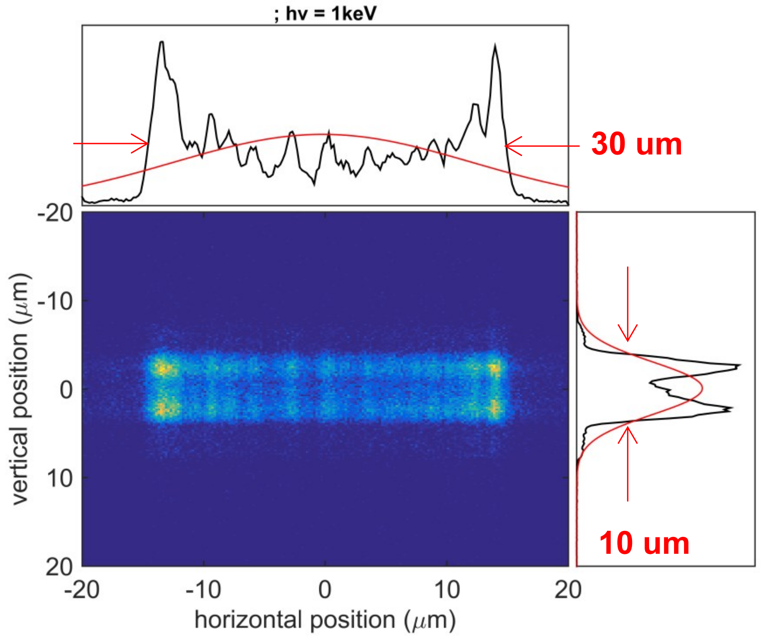


hv [keV]	Spot size FWHM [um]	Transmission [%]	Intensity [W/cm²]
0,3	1,52	12	4,7 10^{17}
1	0,75	60	9,0 10^{18}
3	0,65	87	1,7 10^{19}

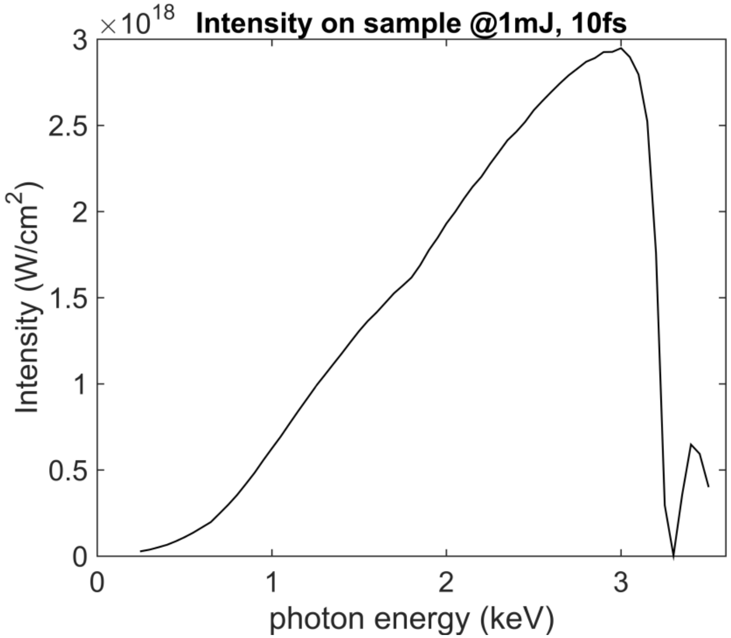
Ray tracing:
Focusing performances in F2

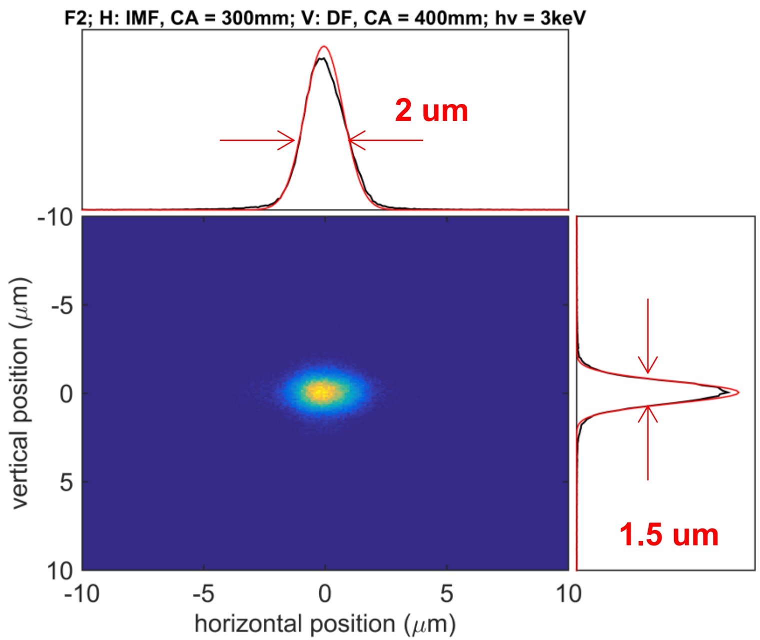
KB	focus	p [m]	q [mm]	Clear aperture [mm]	Error [nrad RMS]
HFM	F1	433,9	1800	800	0
VFM	F1	432,7	3000	800	0
HFM	F1’	433,9	2150	800	15
VFM	F1’	432,7	3350	800	9
HFM	F2	433,9	3832	800	**1652**
VFM	F2	432,7	5032	800	**280**





Focusing performances in F2 – what is in fact possible
(in the way described in the next slides)





hv [keV]	Spot size FWHM* [um]	Intensity* [W/cm²]
0,3	5,1	3,8 10^{16}
1	2,1	6,3 10^{17}
3	1,7	2,9 10^{18}

(*): not matching each other

Ray tracing:
Focusing performances in F2

KB	focus	p [m]	q [mm]	Clear aperture [mm]	Error [nrad RMS]
HFM	F1	433,9	1800	800	0
VFM	F1	432,7	3000	800	0
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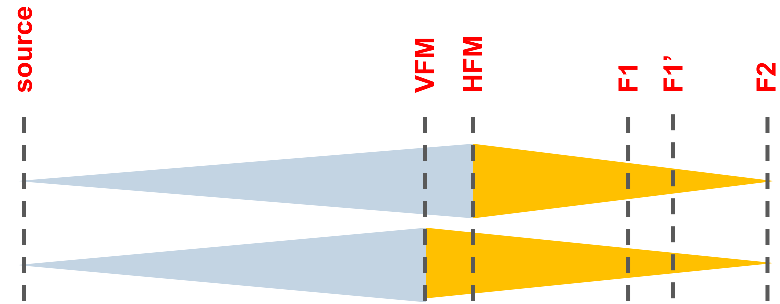
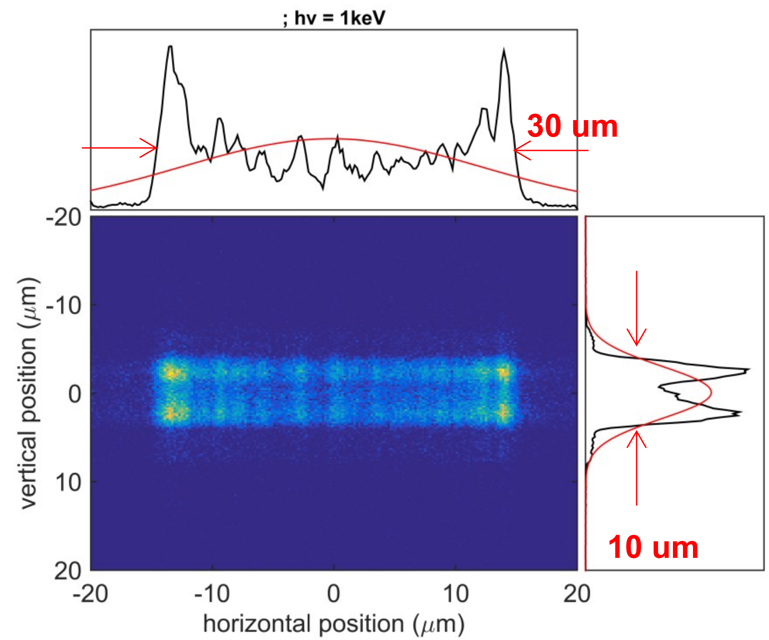
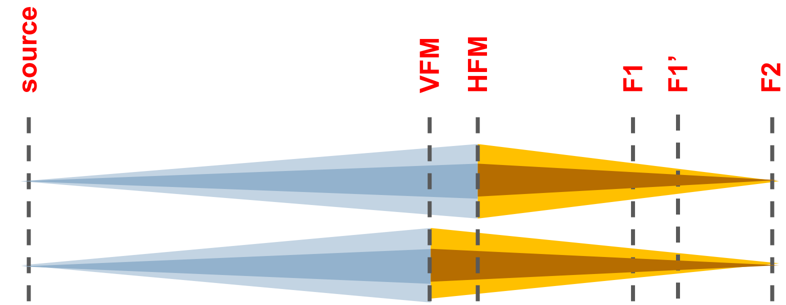
HFM	F2	433,9	3832	800	**1652**
VFM	F2	432,7	5032	800	**280**

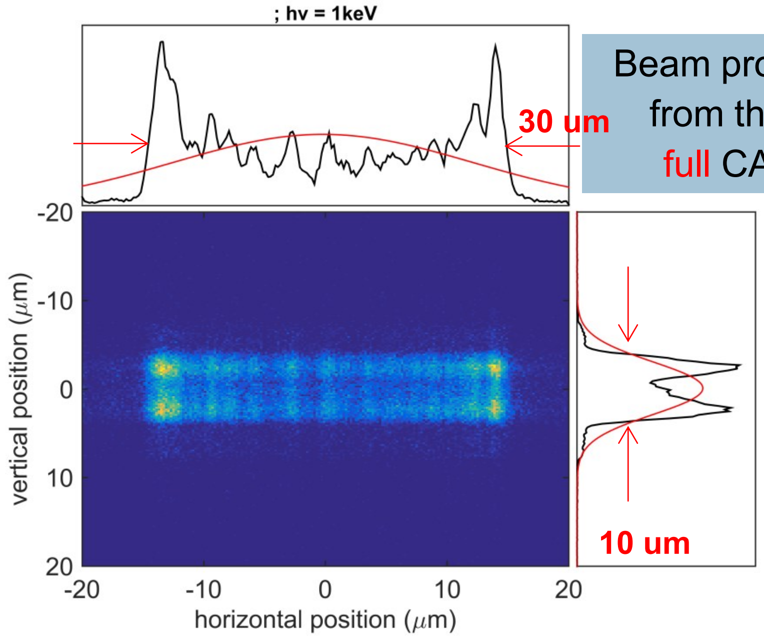




Ray tracing:
Focusing performances in F2

KB	focus	p [m]	q [mm]	Clear aperture [mm]	Error [nrad RMS]
HFM	F1	433,9	1800	800	0
VFM	F1	432,7	3000	800	0
HFM	F1'	433,9	2150	800	15
VFM	F1'	432,7	3350	800	9
HFM	F2	433,9	3832	800	**1652**
VFM	F2	432,7	5032	800	**280**
HFM	F2	433,9	3832	400	**264**
VFM	F2	432,7	5032	600	**118**





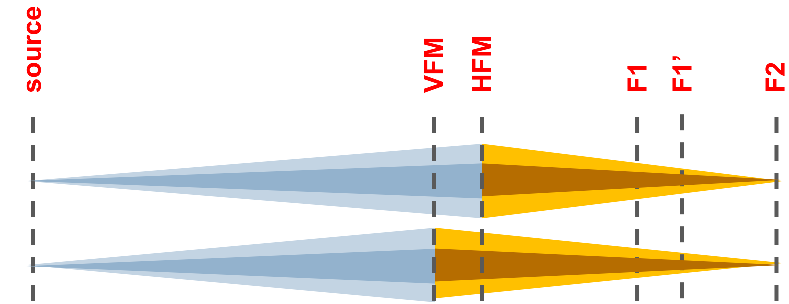
Beam profile from the full CA

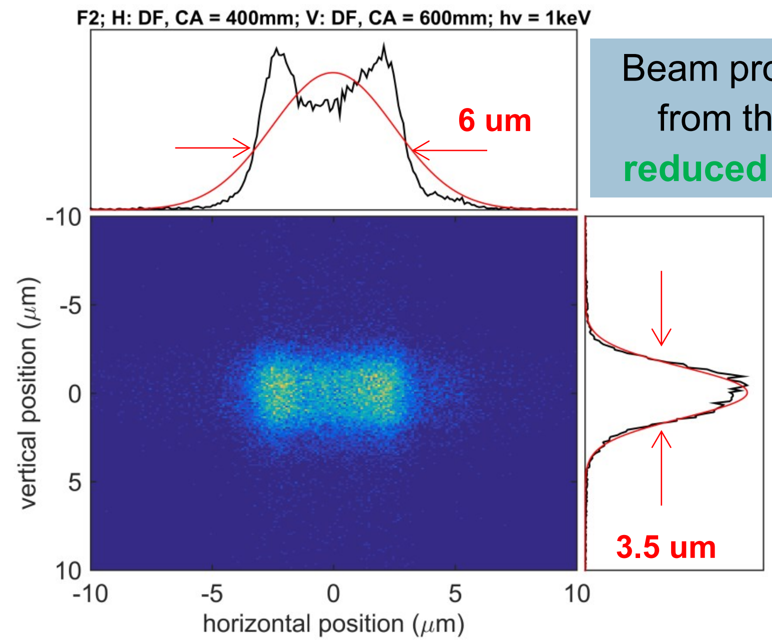
Handles:
- *Slit down the beam*

The bending couples are optimized on the reduced clear aperture

Ray tracing:
Focusing performances in F2

KB	focus	p [m]	q [mm]	Clear aperture [mm]	Error [nrad RMS]
HFM	F1	433,9	1800	800	0
VFM	F1	432,7	3000	800	0
HFM	F1’	433,9	2150	800	15
VFM	F1’	432,7	3350	800	9
HFM	F2	433,9	3832	800	**1652**
VFM	F2	432,7	5032	800	**280**
HFM	F2	433,9	3832	400	**264**
VFM	F2	432,7	5032	600	**118**





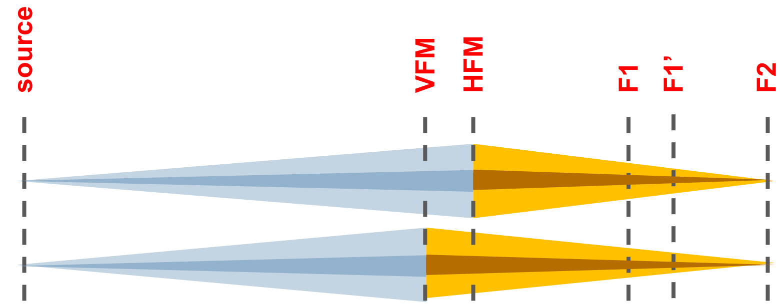
Beam profile from the **reduced** CA

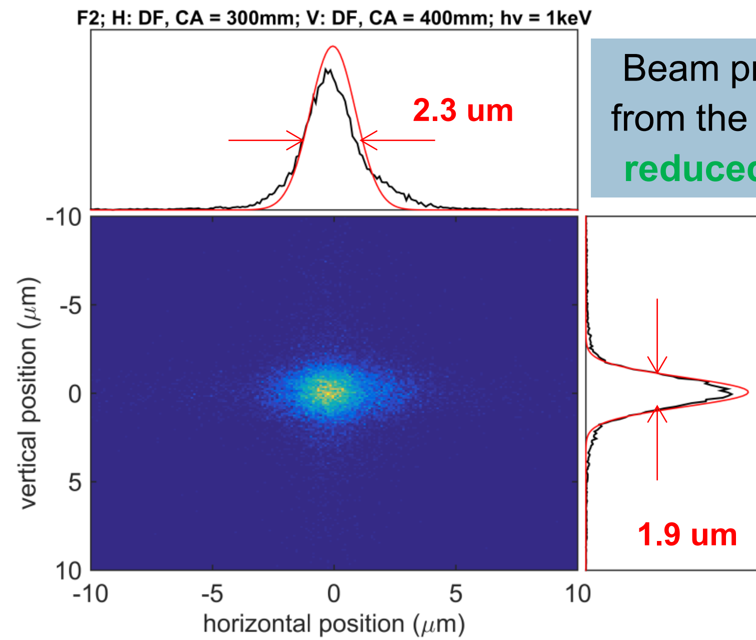
Handles:
- *Slit down the beam*

The bending couples are optimized on the reduced clear aperture

Ray tracing:
Focusing performances in F2

KB	focus	p [m]	q [mm]	Clear aperture [mm]	Error [nrad RMS]
HFM	F1	433,9	1800	800	0
VFM	F1	432,7	3000	800	0
HFM	F1’	433,9	2150	800	15
VFM	F1’	432,7	3350	800	9
HFM	F2	433,9	3832	800	**1652**
VFM	F2	432,7	5032	800	**280**
HFM	F2	433,9	3832	300	**130**
VFM	F2	432,7	5032	400	**40**





Beam profile from the more **reduced** CA

Handles:
- ➢ *Slit down the beam*

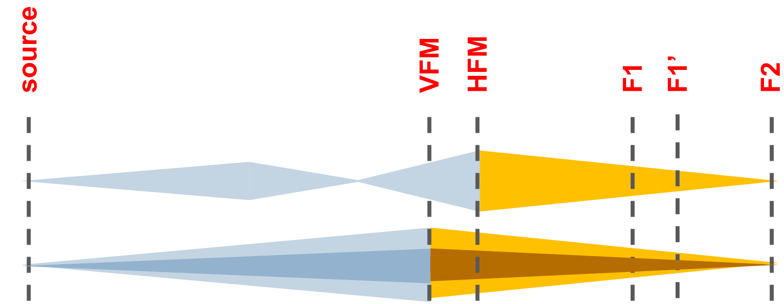
The bending couples are optimized on the reduced clear aperture

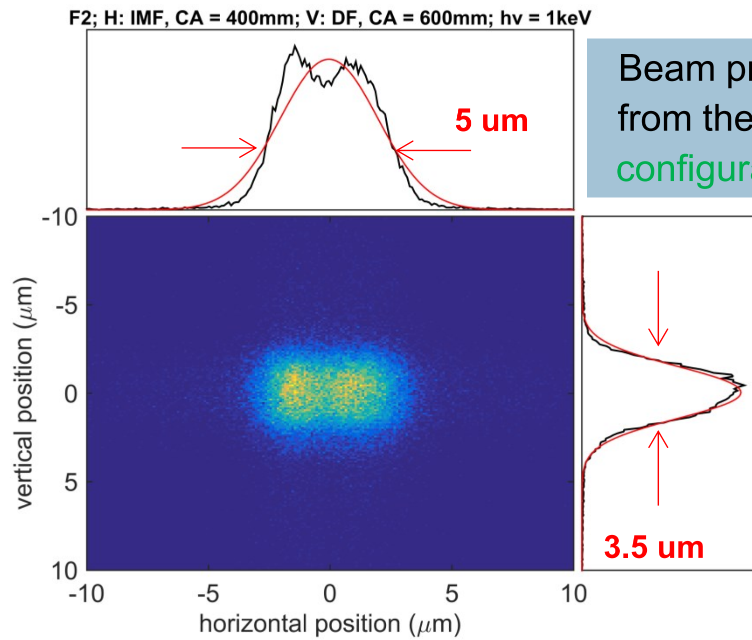
Ray tracing: Focusing performances in F2

KB	focus	p [m]	q [mm]	Clear aperture [mm]	Error [nrad RMS]
HFM	F1	433,9	1800	800	0
VFM	F1	432,7	3000	800	0
HFM	F1’	433,9	2150	800	15
VFM	F1’	432,7	3350	800	9
HFM	F2	433,9	3832	800	**1652**
VFM	F2	432,7	5032	800	**280**
HFM	F2	72	3832	400	**185**
VFM	F2	432,7	5032	600	**118**

Handles:

- *Slit down the beam*
- *Use the H intermediate focus*





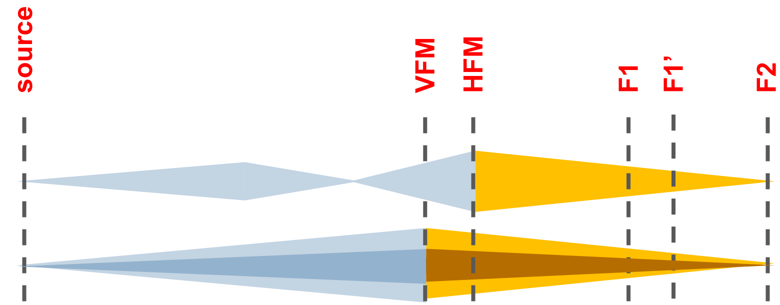
Beam profile from the IMF configuration

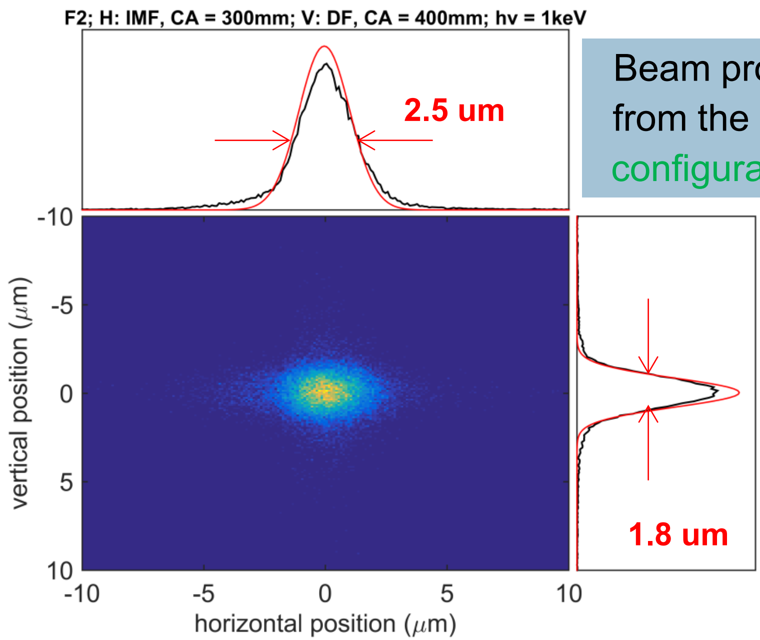
Ray tracing:
Focusing performances in F2

KB	focus	p [m]	q [mm]	Clear aperture [mm]	Error [nrad RMS]
HFM	F1	433,9	1800	800	0
VFM	F1	432,7	3000	800	0
HFM	F1’	433,9	2150	800	15
VFM	F1’	432,7	3350	800	9
HFM	F2	433,9	3832	800	**1652**
VFM	F2	432,7	5032	800	**280**
HFM	F2	72	3832	300	**131**
VFM	F2	432,7	5032	400	**40**

Handles:

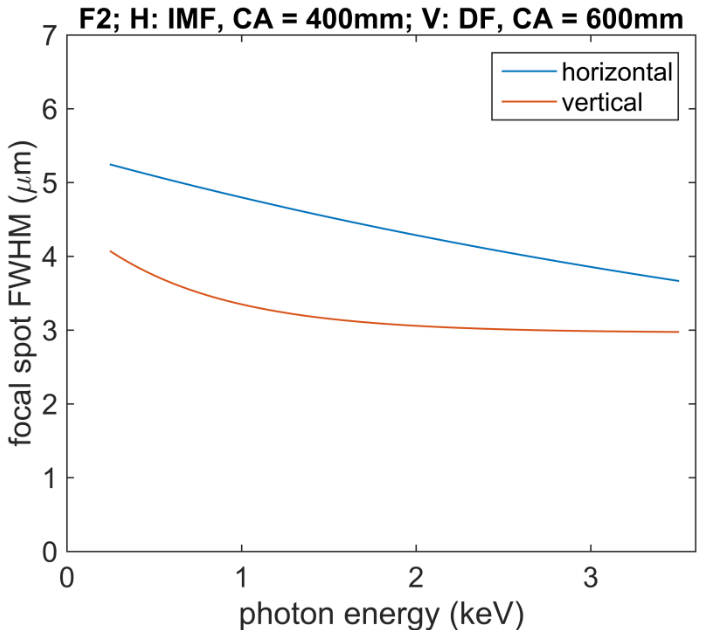
- *Slit down the beam*
- *Use the H intermediate focus*

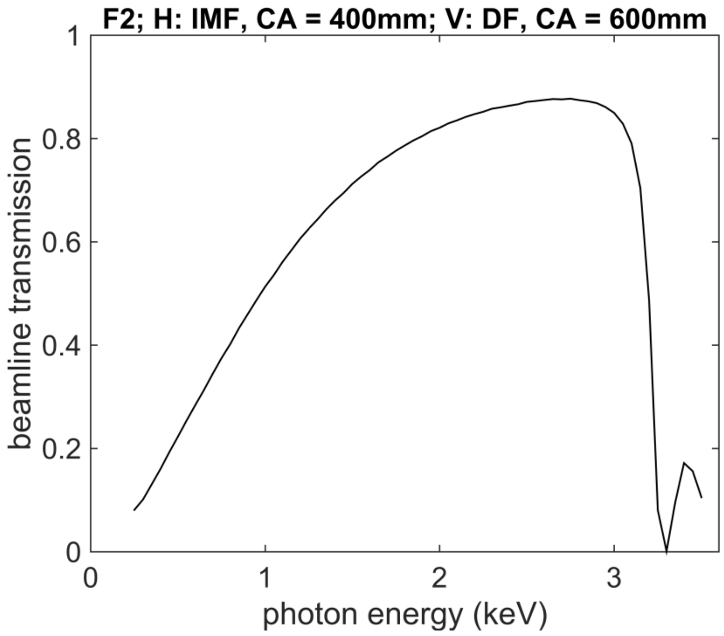




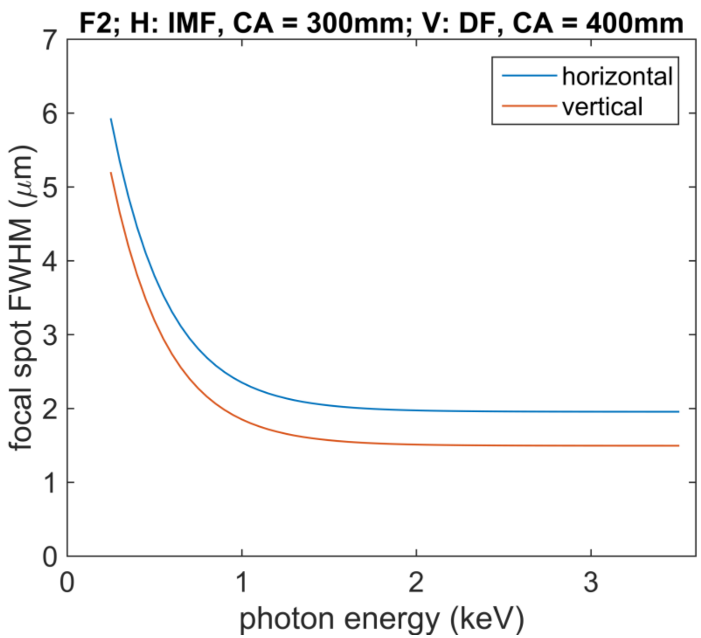
Beam profile from the IMF configuration

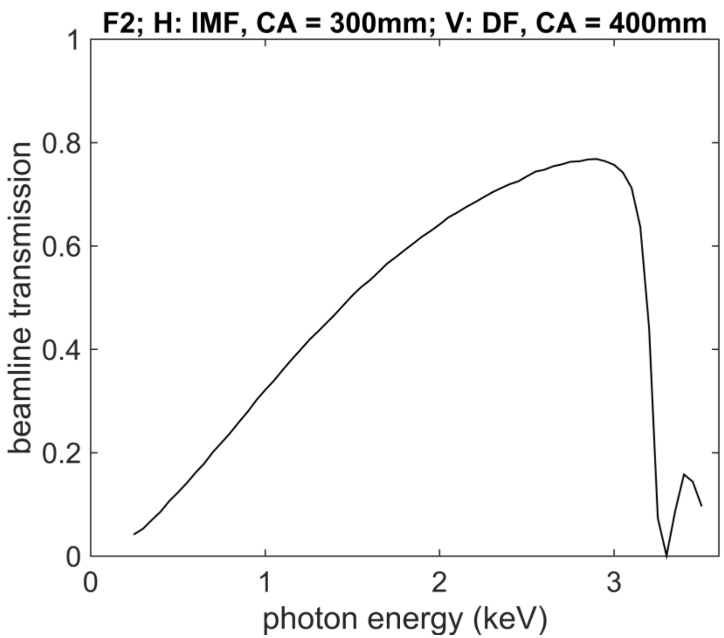
Ray tracing:
Focusing performances in F2: H IMF,CA=400; V DF,CA=600



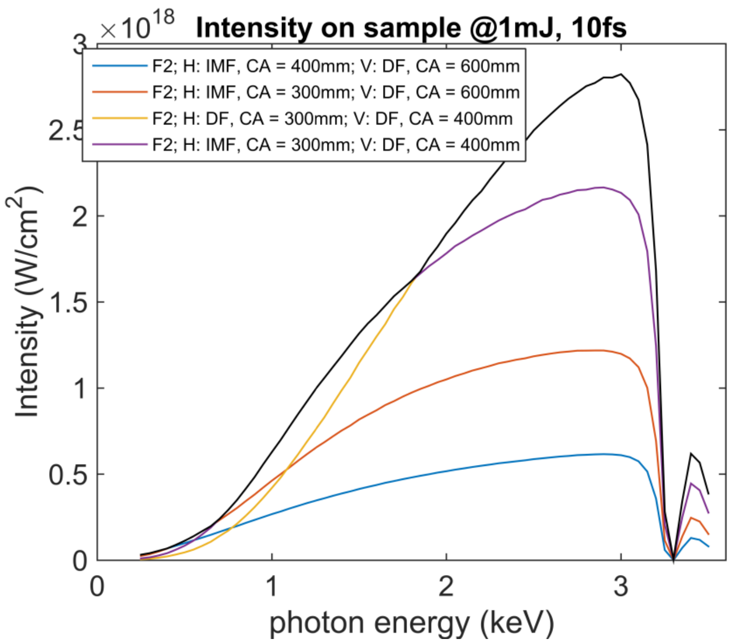


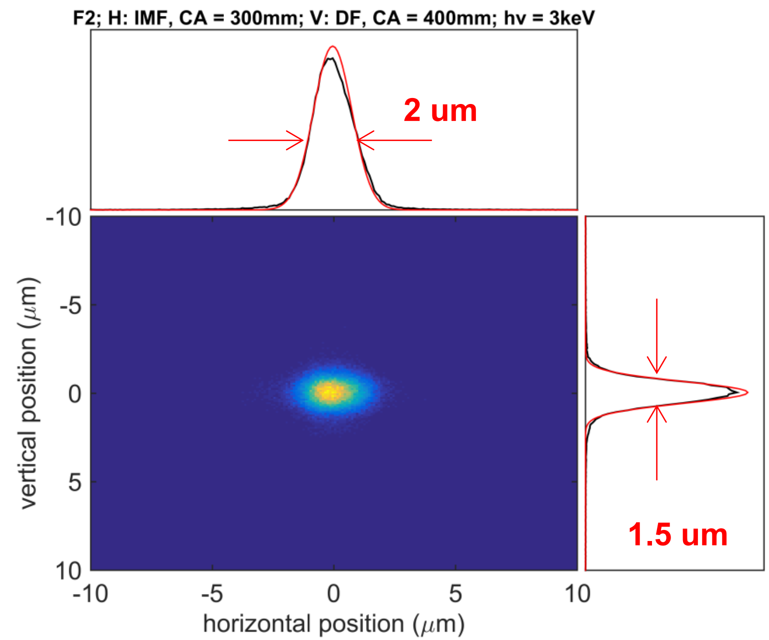
Ray tracing:
Focusing performances in F2: H IMF,CA=300; V DF,CA=400





Ray tracing:
Focusing performances in F2

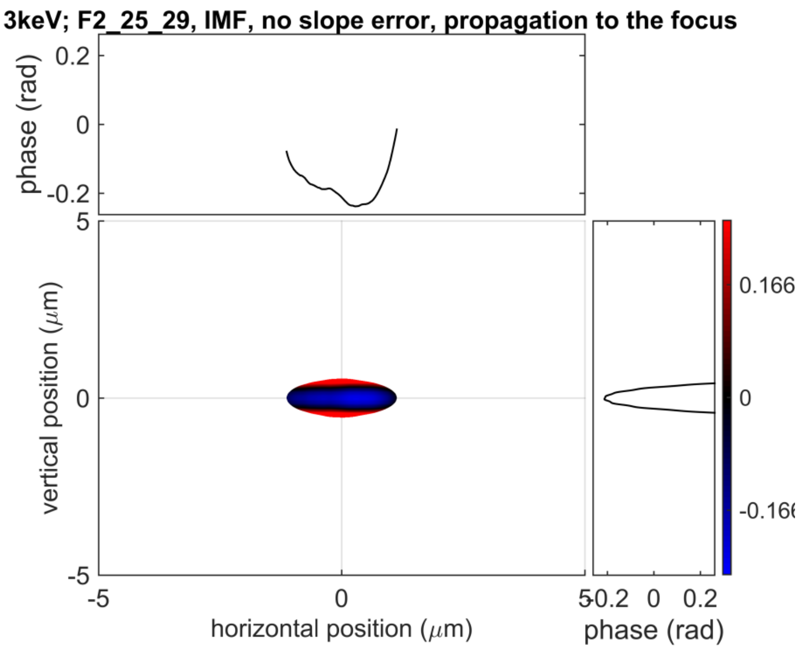




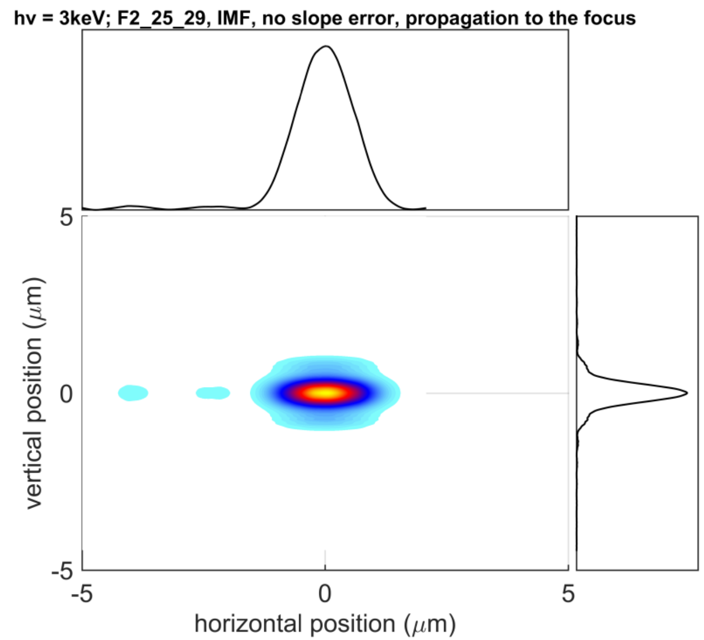
hv [keV]	Spot size FWHM* [um]	Intensity* [W/cm²]
0,3	5,1	$3{,}8\ 10^{16}$
1	2,1	$6{,}3\ 10^{17}$
3	1,7	$2{,}9\ 10^{18}$

(*): not matching each other

Wavefront in F2 – H IMF,CA=300; V DF,CA=400, w/o sl. err hv = 3keV, in focus

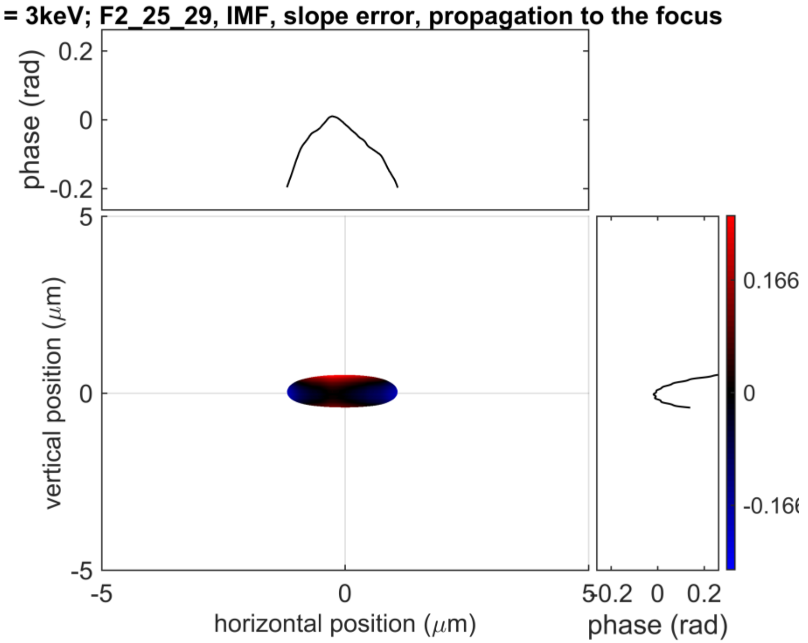


Wavefront phase

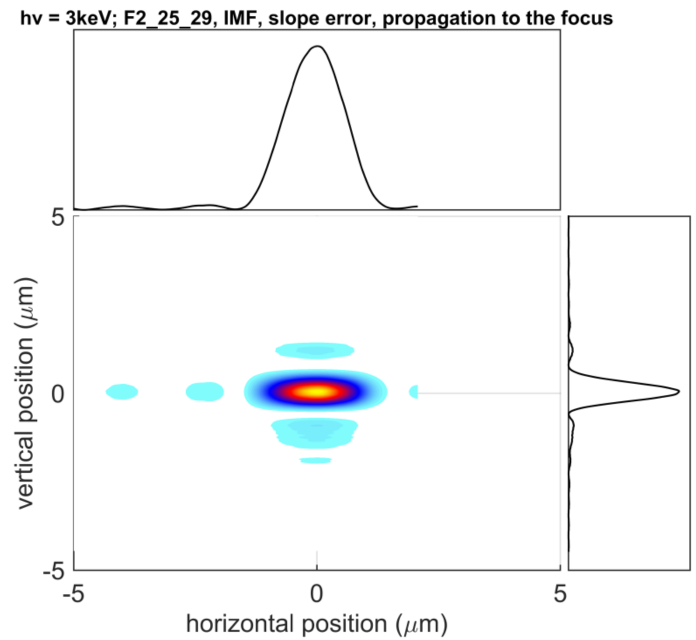


Wavefront intensity

Wavefront in F2 – H IMF,CA=300; V DF,CA=400, with sl. err hv = 3keV, in focus

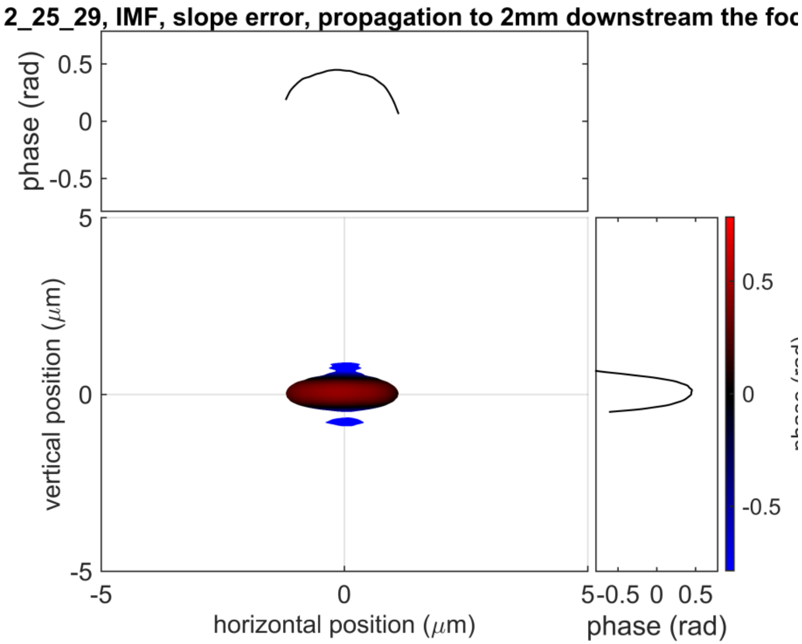


Wavefront phase

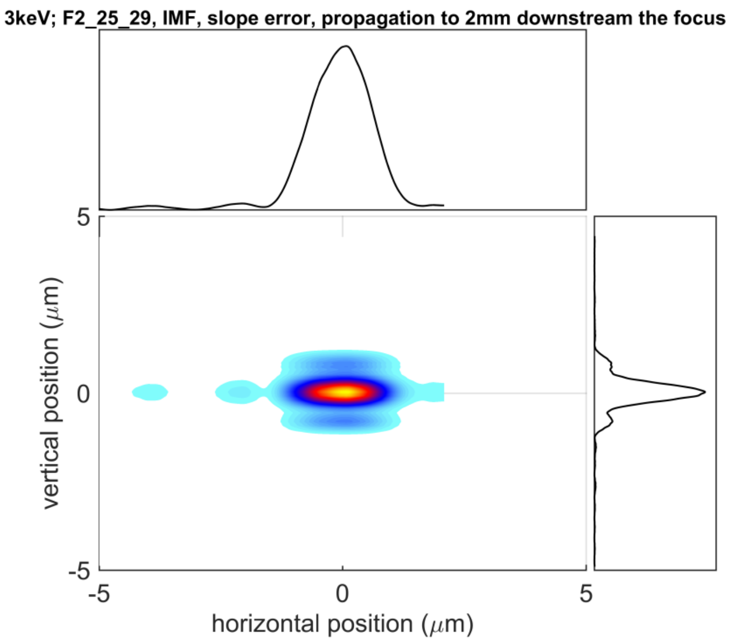


Wavefront intensity

Wavefront in F2 – H IMF,CA=300; V DF,CA=400, with sl. err hv = 3keV, 2mm out of focus



Wavefront phase

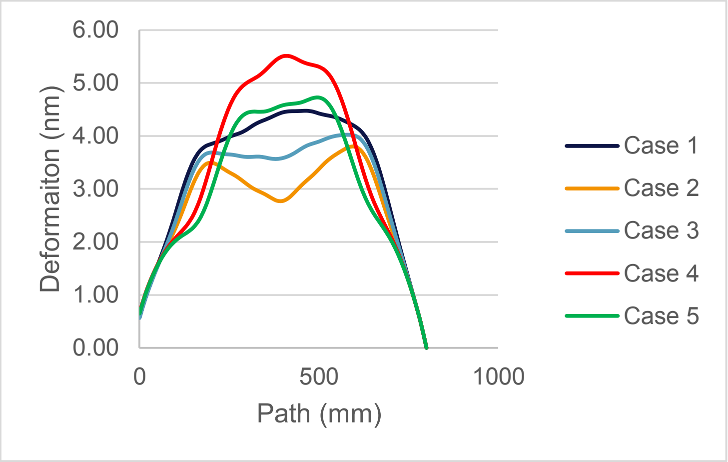


Wavefront intensity

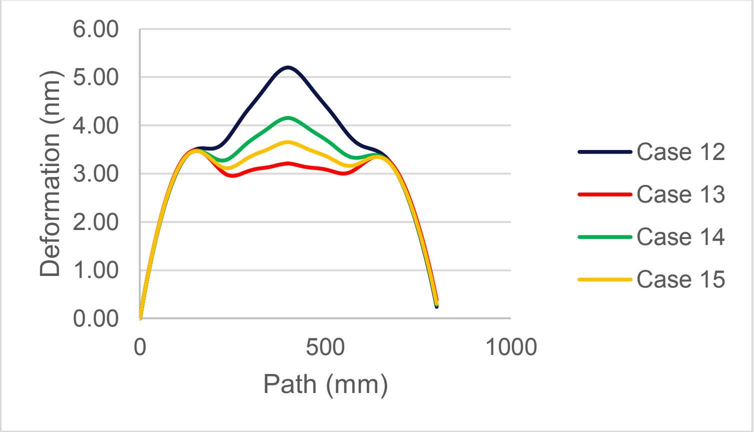
The effect of the thermal load

- Thermal load from FEL radiation induces surface modification on the nanometer level
- The effect can be quantified by finite element analysis; FEA can be used to optimize the cooling grooves geometry
- The deformation corresponding to the optimal cooling arrangement can be fed to the ray tracing simulations to obtain expected performances

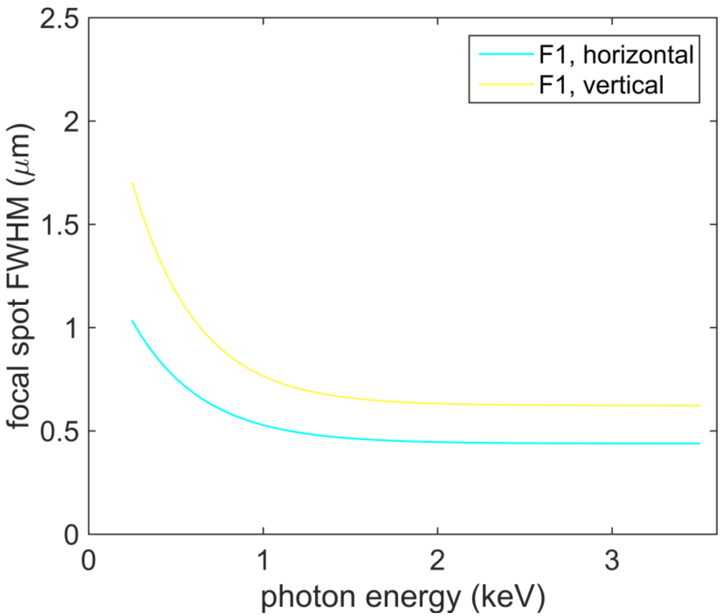
VFM Thermal deformation under “standard” conditions

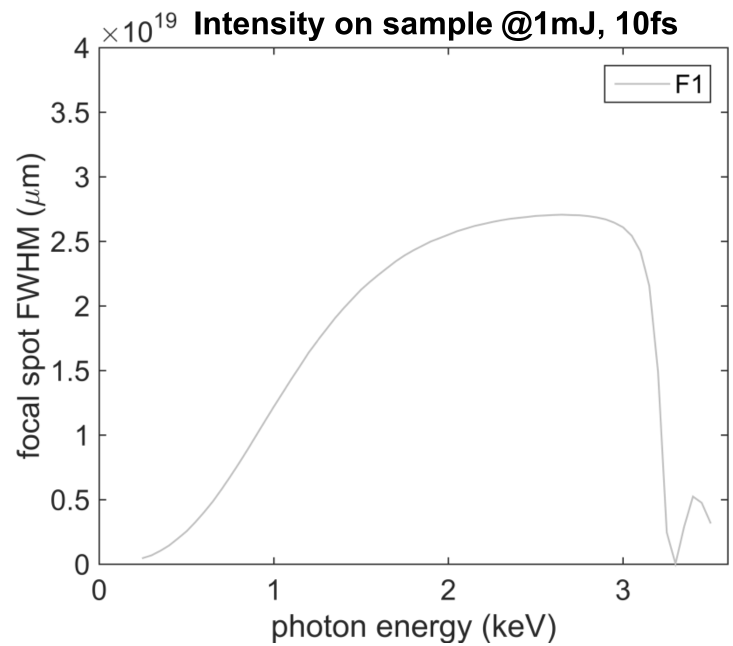


HFM Thermal deformation under “standard” conditions

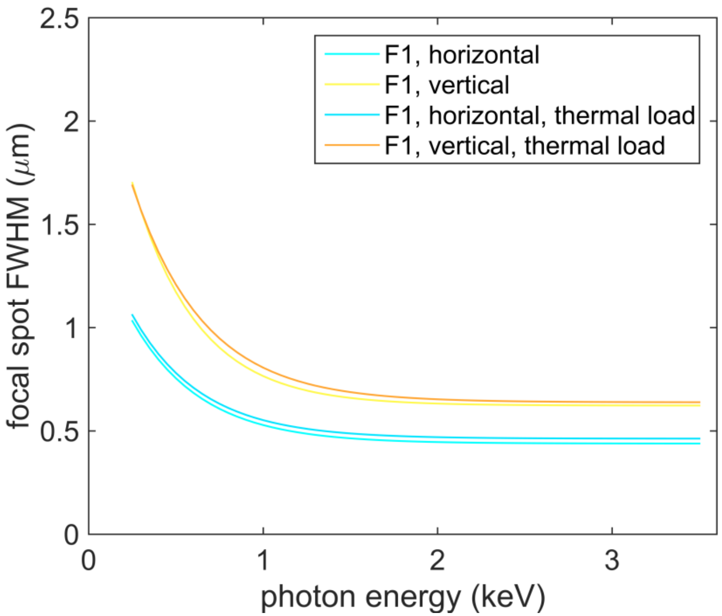


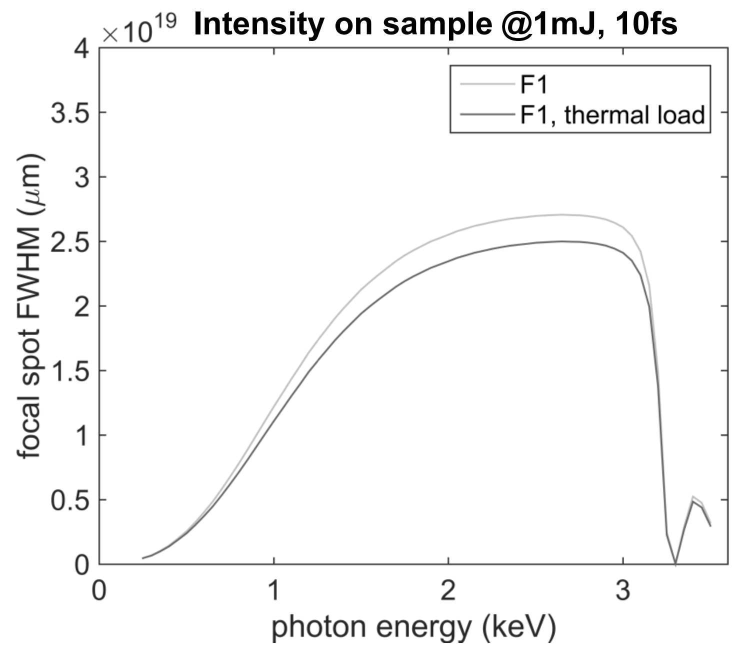
Ray tracing:
Focusing performances in F1 including thermal load





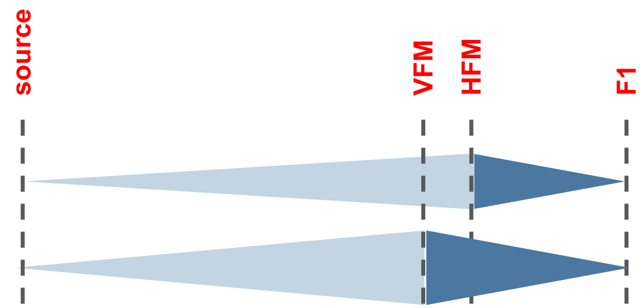
Ray tracing:
Focusing performances in F1 including thermal load





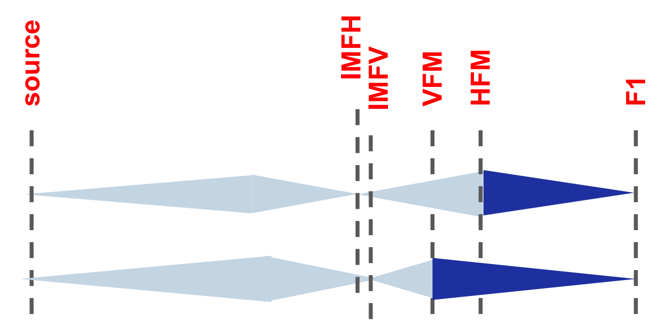
Possible interim solution for instrument commissioning and 1st experiment

- Expected delivery of the SQS mirrors:
  December 2017 (+ metrology + coating + …)
- Plan to be ready from commissioning activities:
  End of 2017

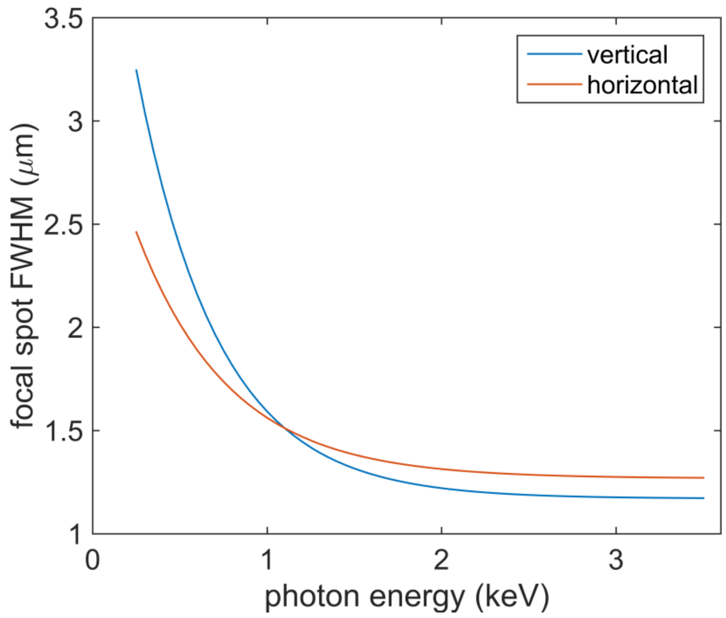


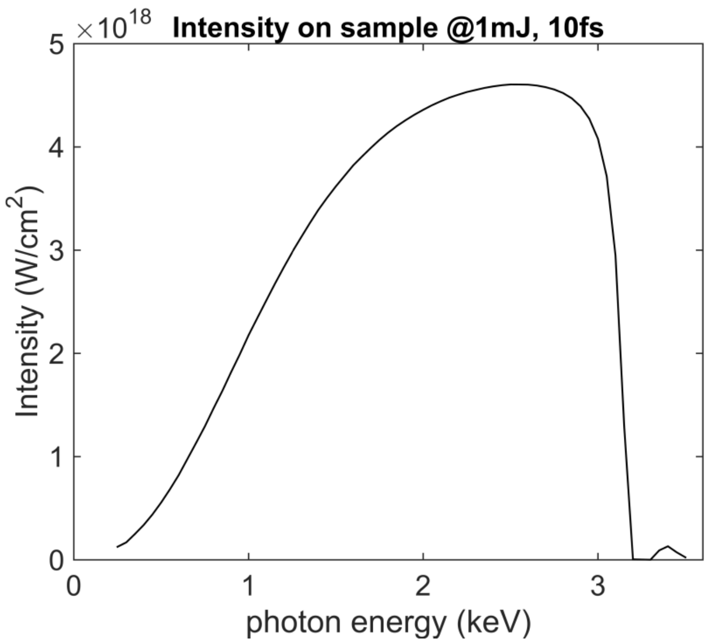
- Possible interim solution:

  Miscut SCS/SQS non-bendable mirrors, to be adapted to the SQS beamline layout by incidence angle detuning
  - Parameters (H): p = 52m; q = 3.3m; θ=9mrad
    ► p = 71m; q=3.3m → θ=9.14mrad
  - Parameters (V): p = 28m; q = 2.0m; θ=9mrad
    ► p = 43m; q = 2.0m → θ=9.24mrad



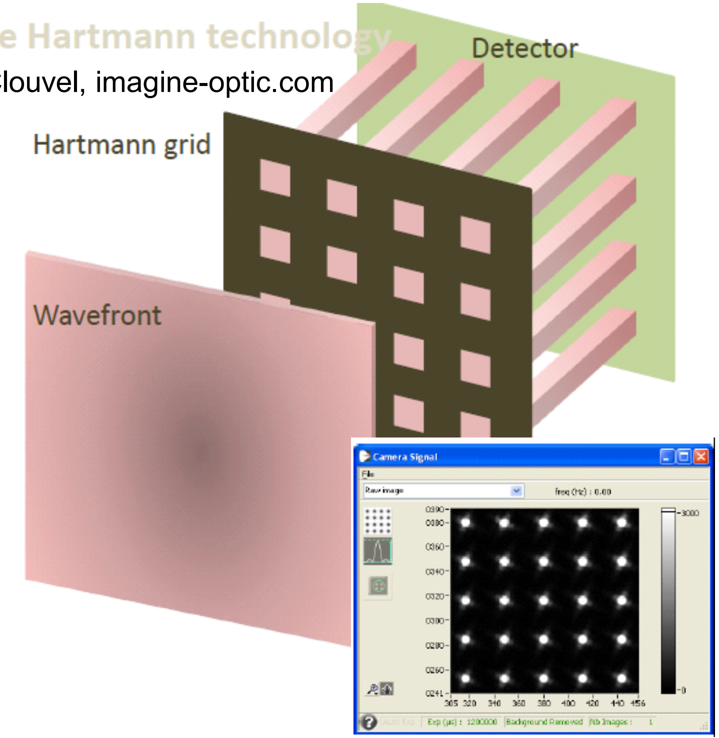
Ray tracing:
Interim solution expected performances





hv [keV]	Spot size FWHM [um]	Transmission [%]	Intensity [W/cm^2]
0,3	2,7	15	1,8 10^{17}
1	1,6	65	2,1 10^{18}
3	1,22	75	4,1 10^{18}

Courtesy of G. Clouvel, imagine-optic.com



Characterization methods

- wavefront sensor
  - Imagine optic
  - E. Ploenies, K. Tiedtke
- Knife edge characterization
- Pmma imprinting method

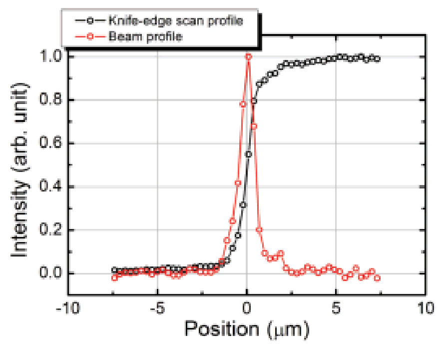


Figure 1. Typical beam profile measured with knife-edge scanning method in the horizontal direction.

Ishikawa et al., Journal of Physics: Conference Series 463 (2013) 012043

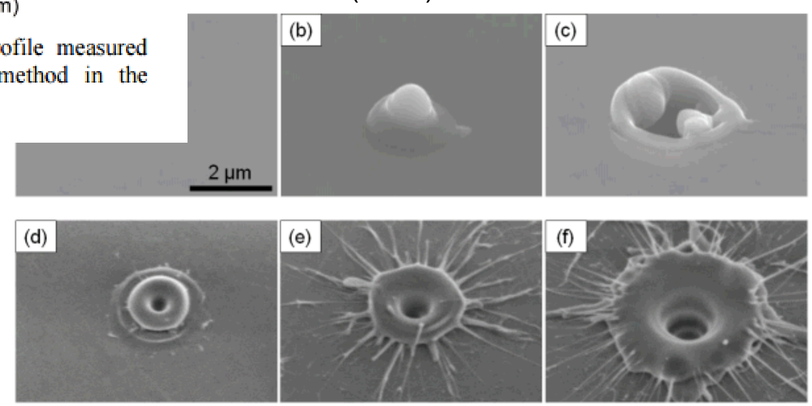


Figure 2. (a–c) Imprint SEM images of silicon under angle of 45° at fluence of 2.7 μJ/μm^2, 4.3 μJ/μm^2, and 6.7 μJ/μm^2. Imprint diameters were 1.1 μm, 2.4 μm, and 3.1 μm. (d–e) Imprint SEM images of synthetic fused silica under angle of 30° at fluence of 6.7 μJ/μm^2, 8.3 μJ/μm^2, and 12 μJ/μm^2. Imprint diameters were 1.7 μm, 2.4 μm, and 3.8 μm.

Summary

- Focusing system functional specifications coping with
  - Science case
  - Source, beamline, instrument characteristics
- Conceptual and technical solution for the SQS KB system
- Expected performances: results from simulations
  - ray tracing
  - wavefront propagation
- The solution for day one
- Characterization tools

- **Adaptive elliptical pre-polished** mirrors with mechanical benders and *cooling system*
- CDR specifications are met:
  - ray tracing:
    - Beam is nicely shaped in the focal spot; <1um (F1,F1'); <2um (F2) (hv>1keV)
    - Intensity: $10^{17} – 10^{19}$ W/cm2 (F1,F1'); $10^{16} – 10^{18}$ W/cm^2 (F2)
    - Thermal load effects are well compensated by the optimized cooling design
    - Acceptable focusing conditions from the day one solution
  - Wavefront propagation:
    - curved wavefront in F1 (and F1'), more flat in F2
    - Wavefront is not affected significantly by residual polishing and bending surface error
- **Elliptical** mirrors with **fixed profile**, angle-detuned to adapt to the SQS beamline geometry
- Different solutions envisaged

People

SQS Scientific Instrument

- Michael Meyer
- Thomas Baumann
- Alberto De Fanis
- Patrik Grychtol
- Markus Ilchen
- Tommaso Mazza
- Yevheniy Ovcharenko
- Haiou Zhang
- Pawel Ziolkowski

X-Ray Opics Group @XFEL

- Harald Sinn
- Daniele La Civita
- Maurizio Vannoni
- Liubov Samoloyova

FMB Oxford

- Richard Green, Kevin Mayo, Scott Mowat, Lucy Stock, Adam Young

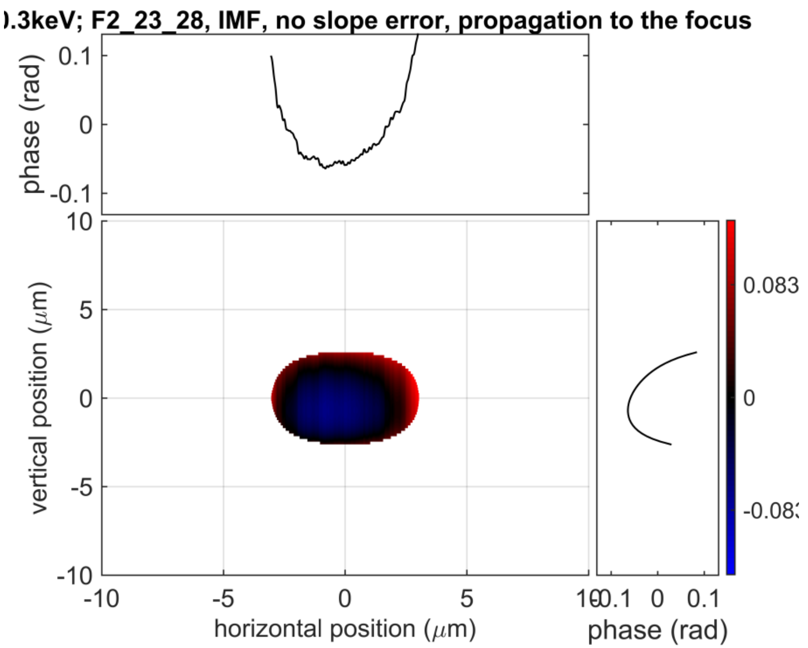
Elettra

- Luca Rebuffi

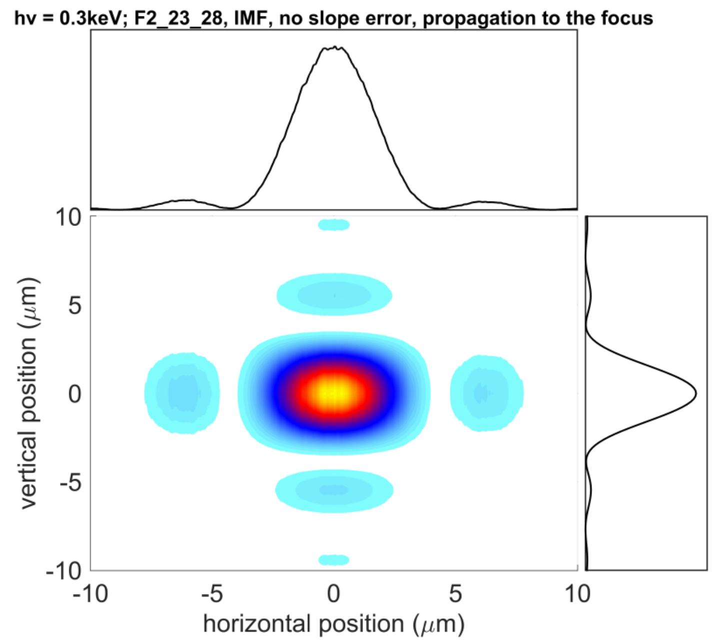
Additional information / topic

- Detuning dependence
- Rayleigh lengths
- Wavefront simulation for all scenarios
- Radiation dose
- Handling the gravitational sag
- Effect of thermal bump under extreme conditions
- Move also image for interim solution – how does it work

Wavefront in F2 – H IMF,CA=400; V DF,CA=600, w/o sl. err hv = 300eV, in focus

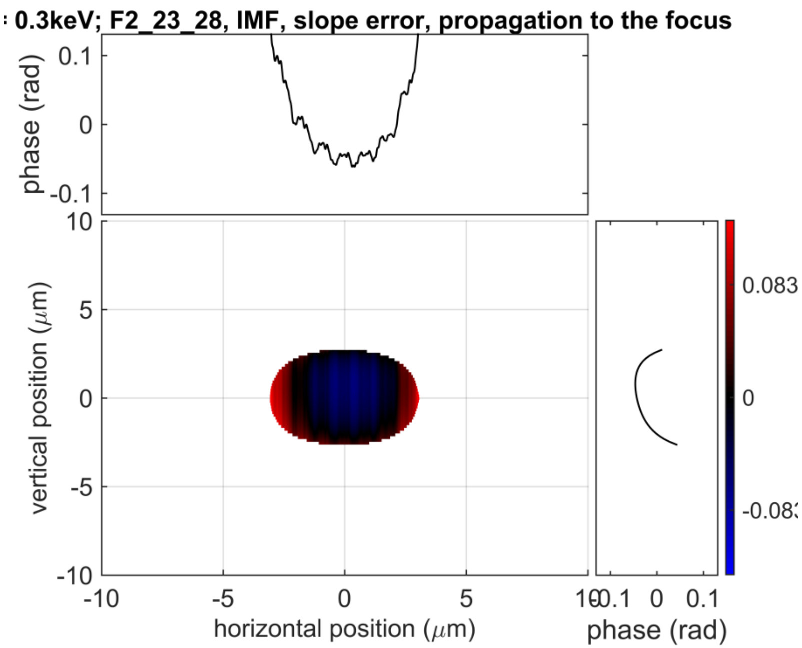


Wavefront phase

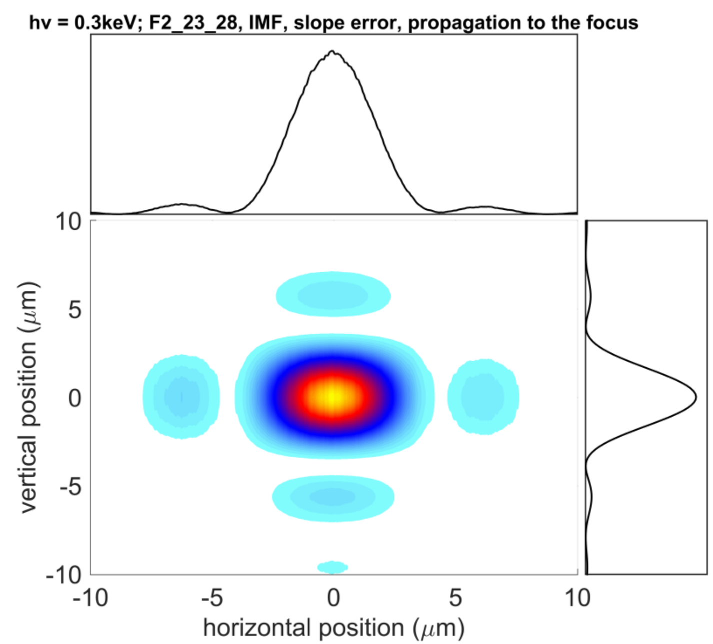


Wavefront intensity

Wavefront in F2 – H IMF,CA=400; V DF,CA=600, with sl. err hv = 300eV, in focus

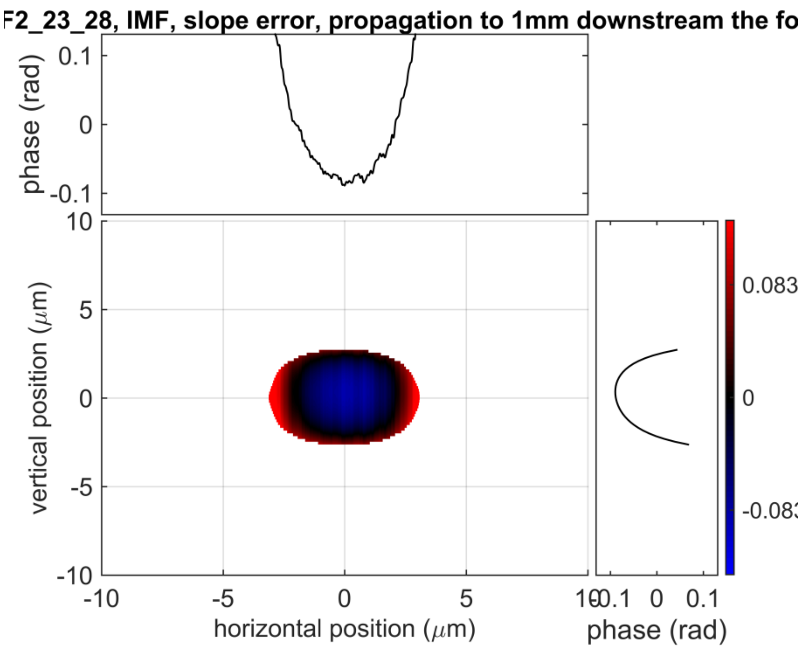


Wavefront phase

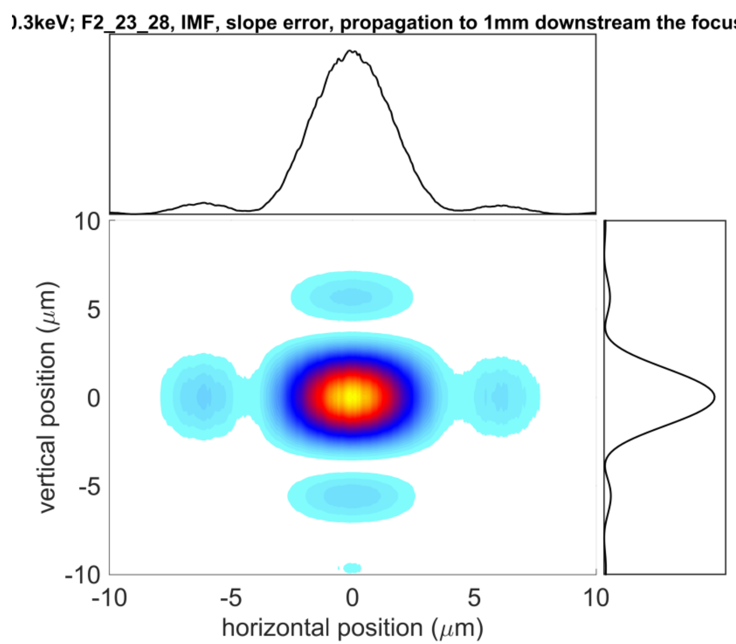


Wavefront intensity

Wavefront in F2 – H IMF,CA=400; V DF,CA=600, with sl. err hv = 300eV, 1mm out of focus

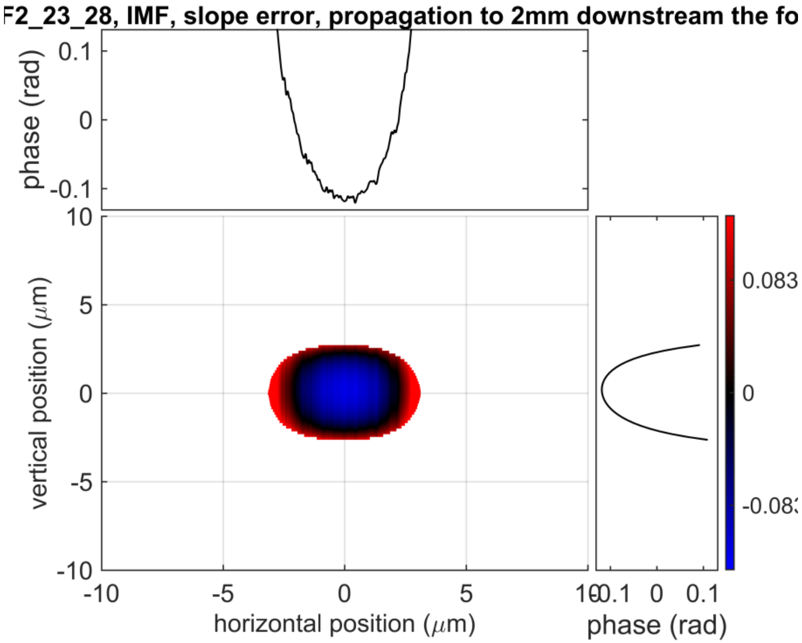


Wavefront phase

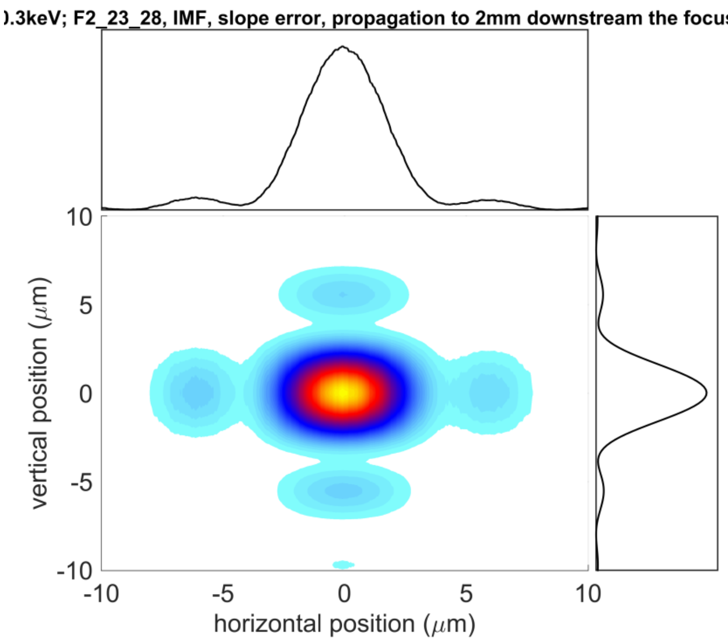


Wavefront intensity

Wavefront in F2 – H IMF,CA=400; V DF,CA=600, with sl. err hv = 300eV, 2mm out of focus

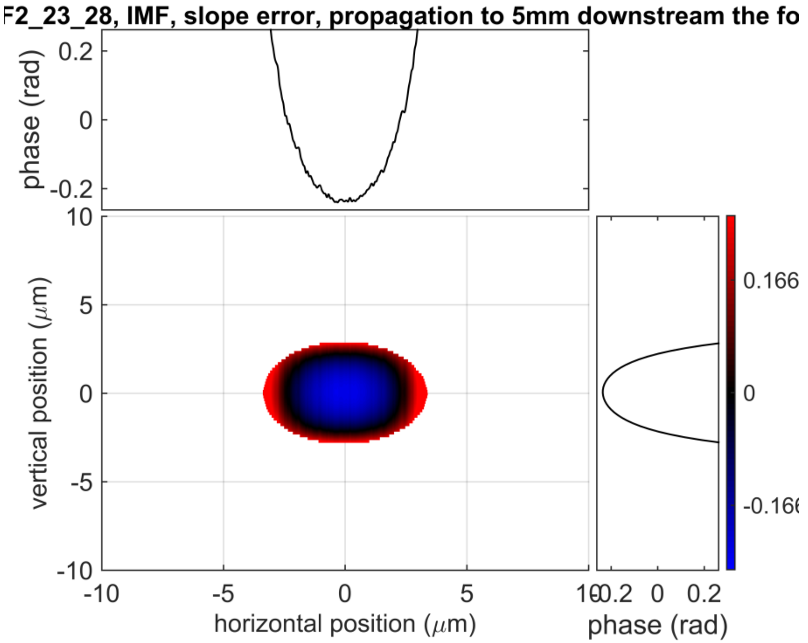


Wavefront phase

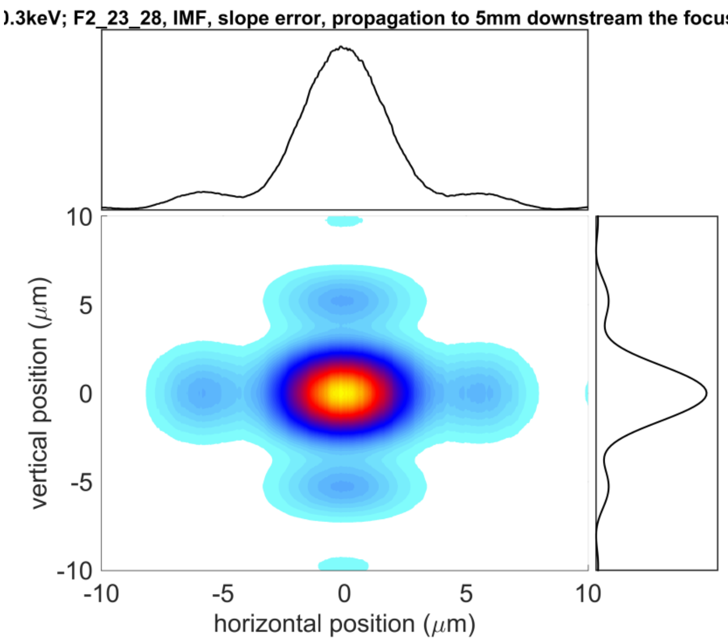


Wavefront intensity

Wavefront in F2 – H IMF,CA=400; V DF,CA=600, with sl. err hv = 300eV, 5mm out of focus

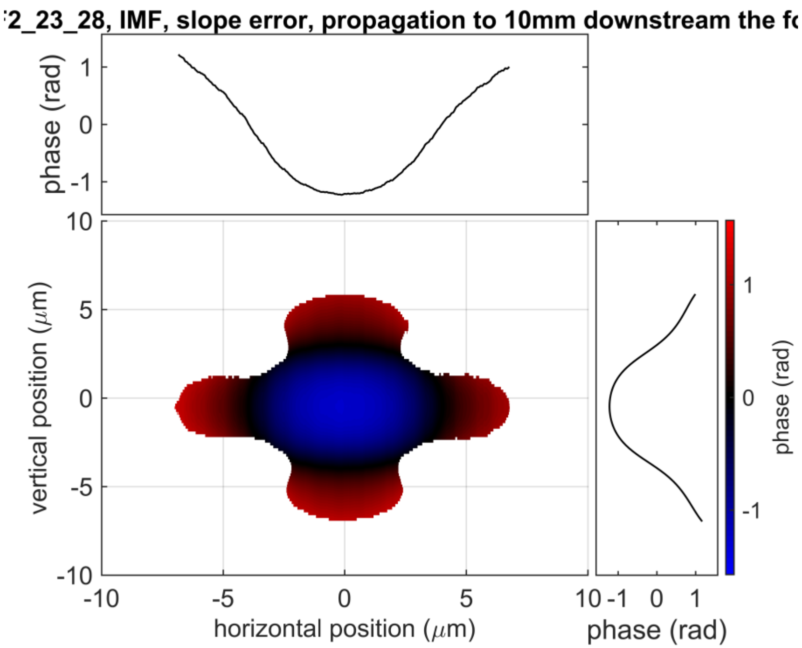


Wavefront phase

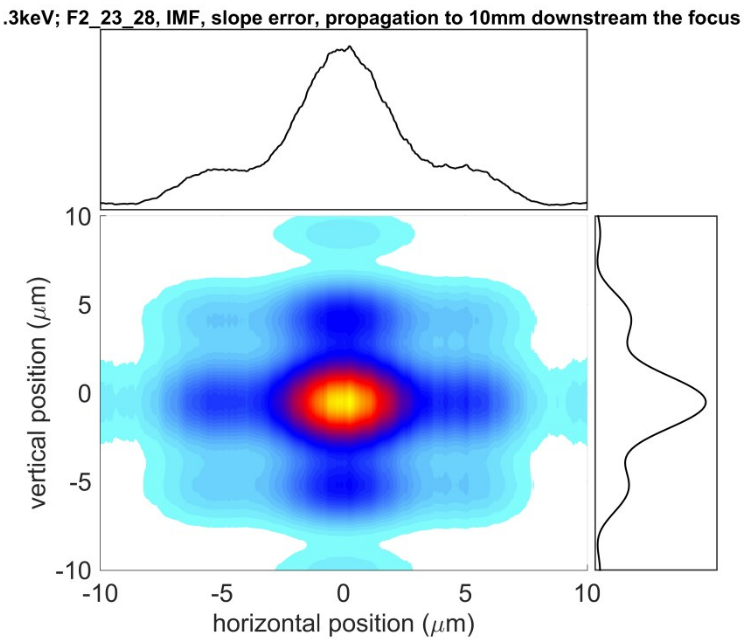


Wavefront intensity

Wavefront in F2 – H IMF,CA=400; V DF,CA=600, with sl. err hv = 300eV, 10mm out of focus



Wavefront phase



Wavefront intensity

Ray tracing:
Focusing performances in F1 including thermal load