Conceptual raytracing for the X-FEL diagnostic monochromators-spectrometers

J. Rehanek, F. Schäfers, A. Erko

OUTLINE

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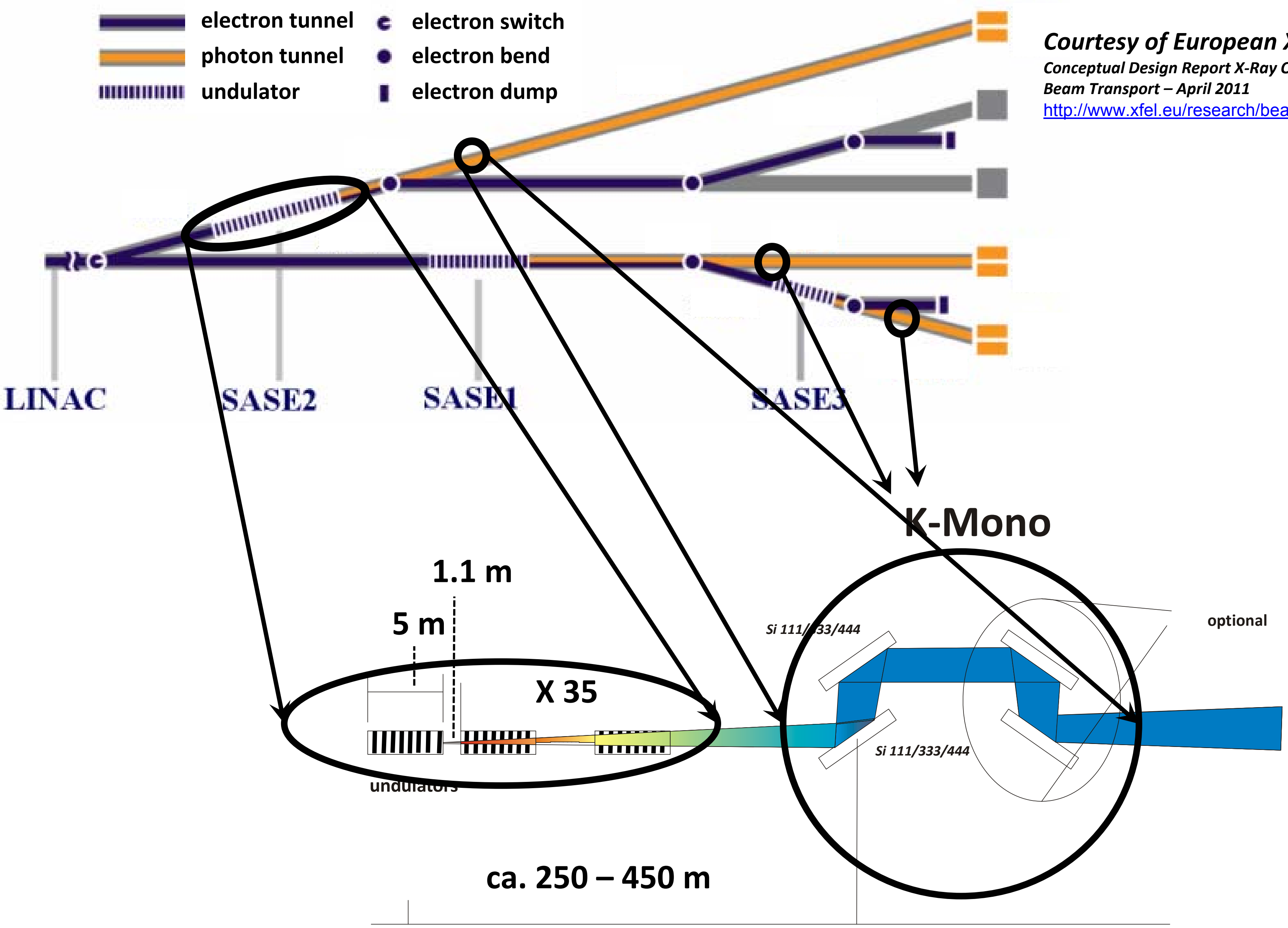
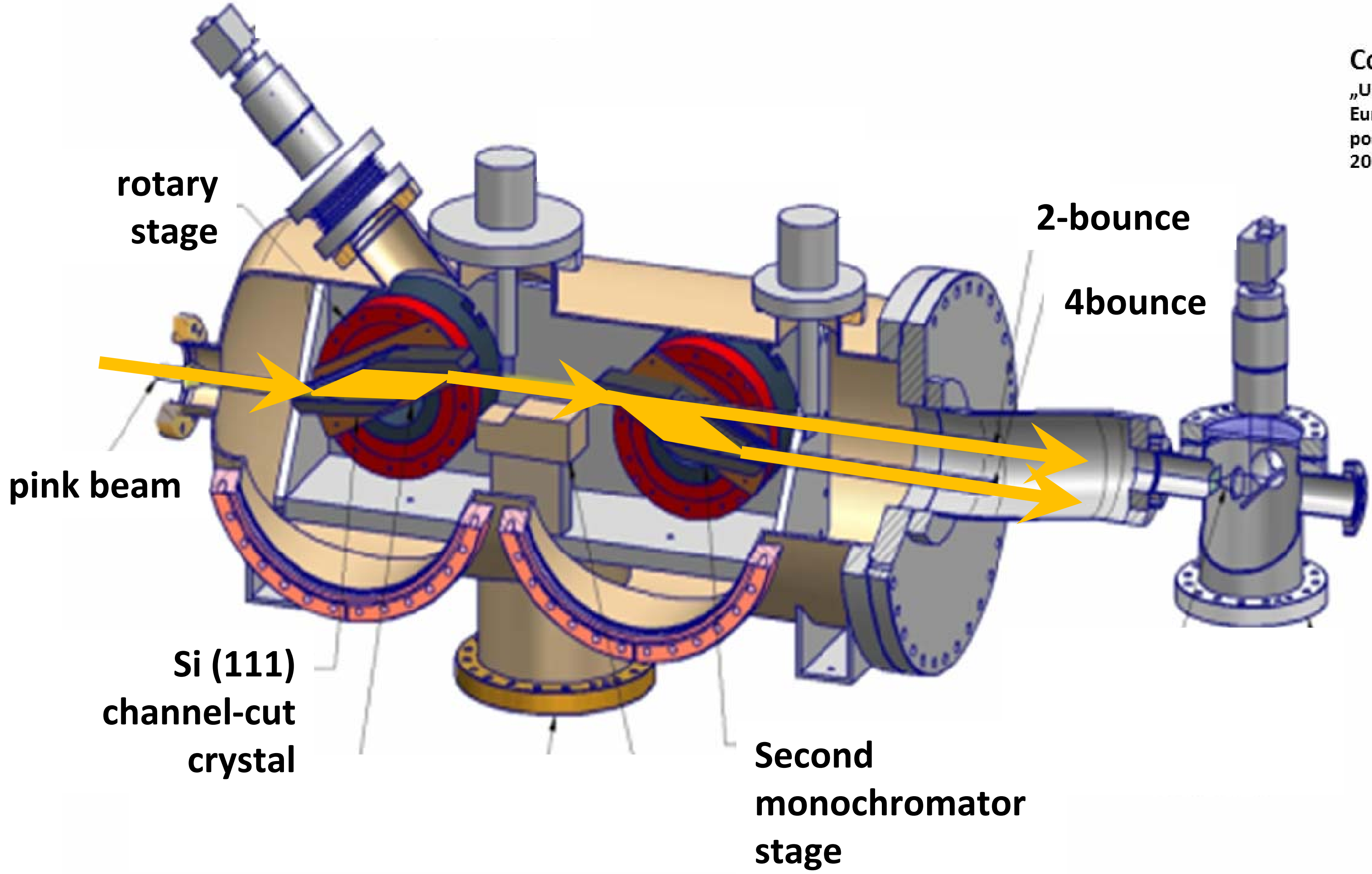
- Undulator commissioning
  - K-Monochromator (Jens Rehanek)
- Single-shot spectrometer (Alexei Erko)
  - dispersive crystal design
  - reflection zone plate (RZP) design

European XFEL – K-Monochromator

Courtesy of European XFEL
Conceptual Design Report X-Ray Optics and Beam Transport – April 2011
http://www.xfel.eu/research/beamlines/



K-Monochromator design concept



Courtesy of European XFEL
„Undulator comissioning spectrometer for the European XFEL",
poster W. Freund at XFEL-User's meeting January 2011

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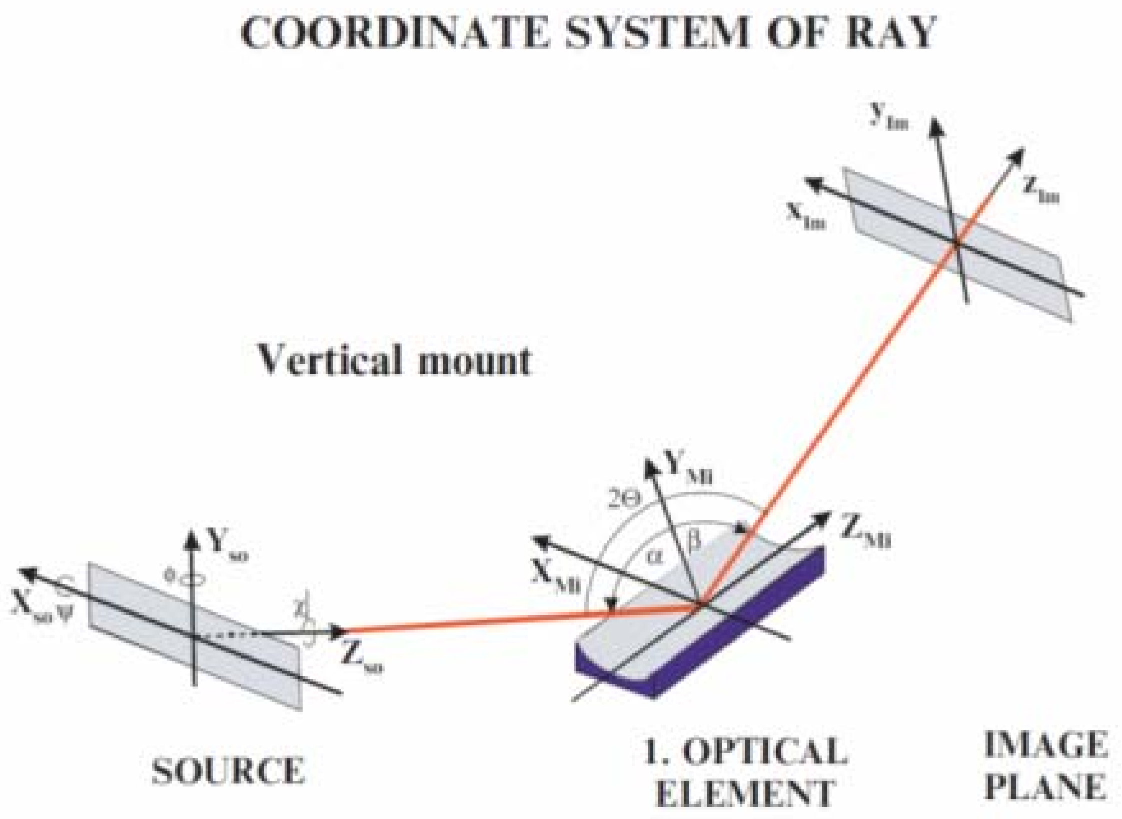
Simulate Optical systems up to 10 elements (F. Schäfers)
Beamline design tool
Geometric Optics

Sources

- Point
- Dipole
- Undulator
- External source file

Optical elements

- Reflection Mirrors
- Crystals (graded)
- Gratings (VLS)
- Transmission zone plates
- Reflection zone plates



EuroXFEL undulator parameters

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Electron source parameters

$\sigma_x = \sigma_z = 34\ \mu m$

$\sigma'_x = \sigma'_z = 1\ \mu rad$

Electron beam parameters:

Electron energy:	14 GeV
Emittance:	0.97 mm mrad
Beta function:	32 m
Period length:	40 mm
No. periods:	125
Gap-range:	10-28 mm

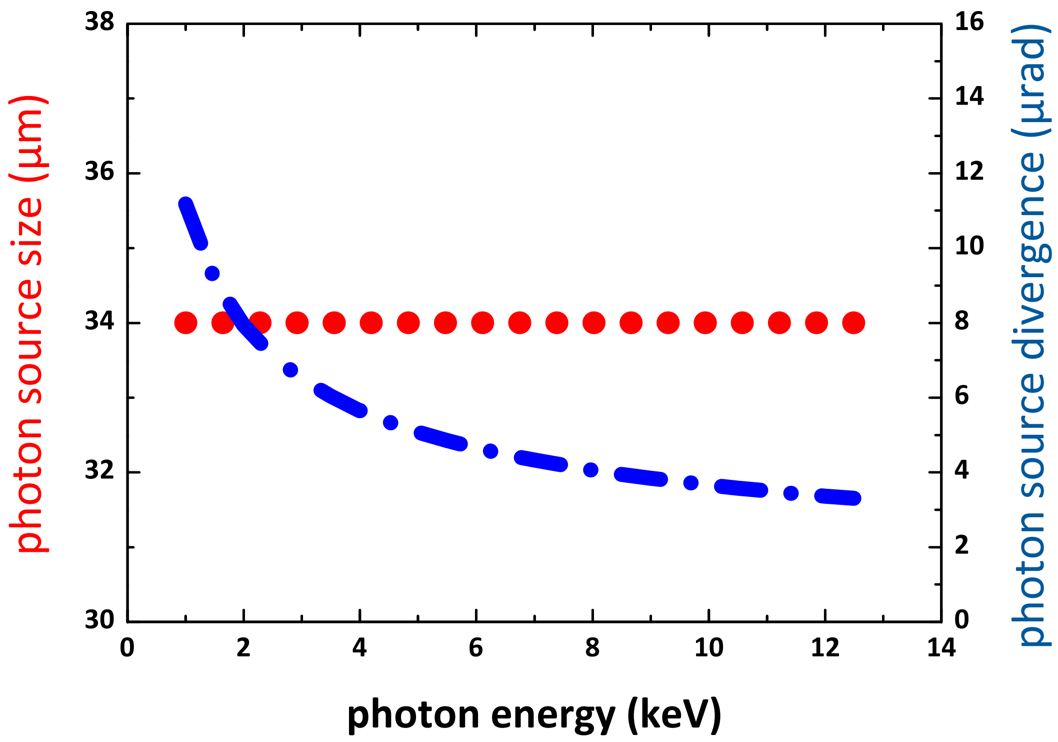
Photon Source Size = $\sqrt{\sigma^2_{X,Z} + \sigma^2_U}$

Source divergence = $\sqrt{\sigma'^2_{X,Z} + \sigma'^2_U}$

Undulator radiation*

$$\sigma_U = \frac{\sqrt{2\lambda L}}{2\pi}, \sigma'_U = \sqrt{\lambda / 2L}$$

1 undulator segment L= 5 m



* Onuki, Elleaume:Wigglers Undulators and their application, Tylor and Francis 2003, page 79

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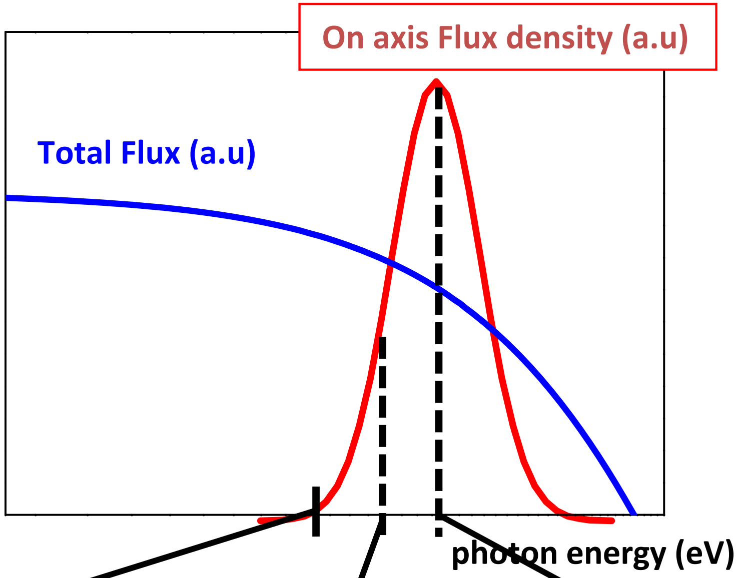
Radiation field (450 m after source point)

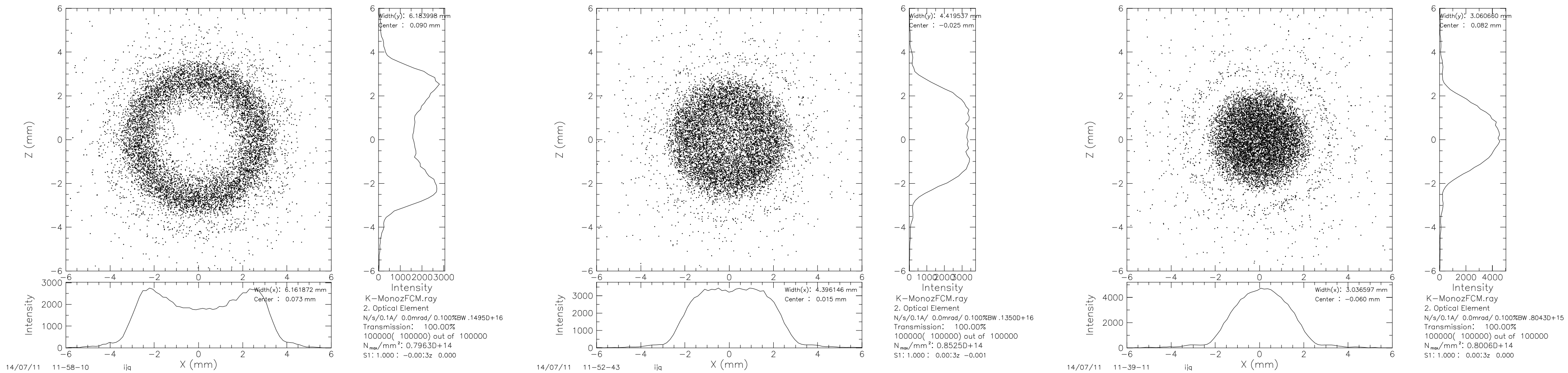
WAVE simulation

as input to RAY



- spontaneous radiation
- at K = 2.3

@12300eV **@12360eV** **@12400eV**



Energy variation (K-fixed)

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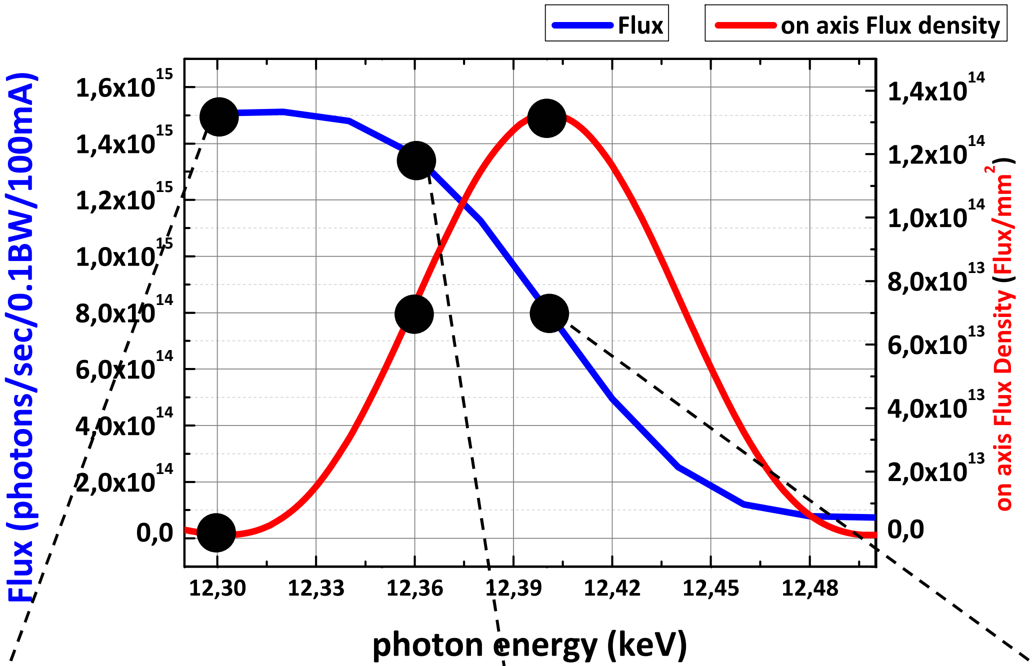
0.5 m after K-Mono

$\Delta E / E$ (K-Mono)$_{12.4keV}$

$\approx 1.2 \times 10^{-4}$

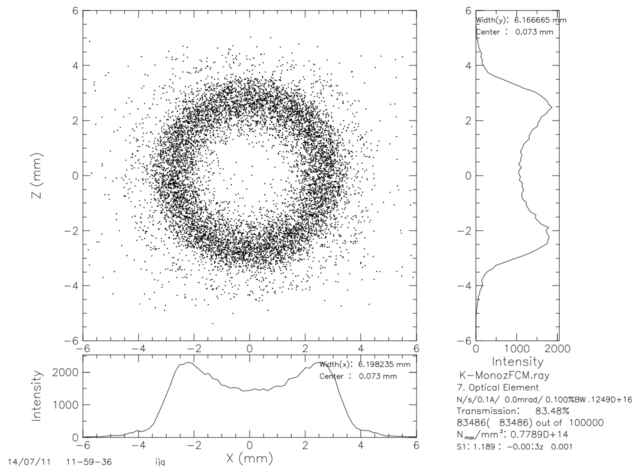


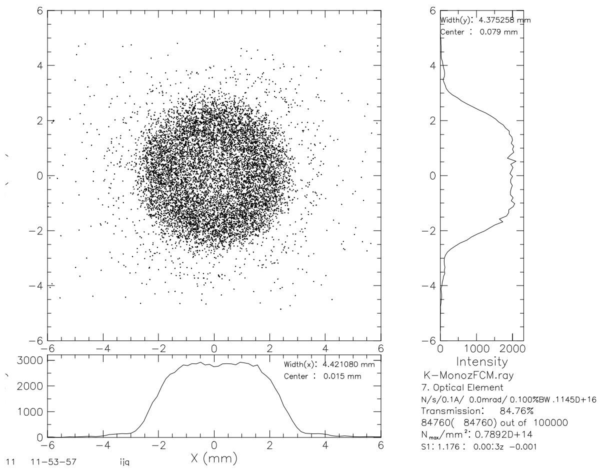
- spontaneous radiation of one undulator segment
- at K = 2.3
- change observation energy

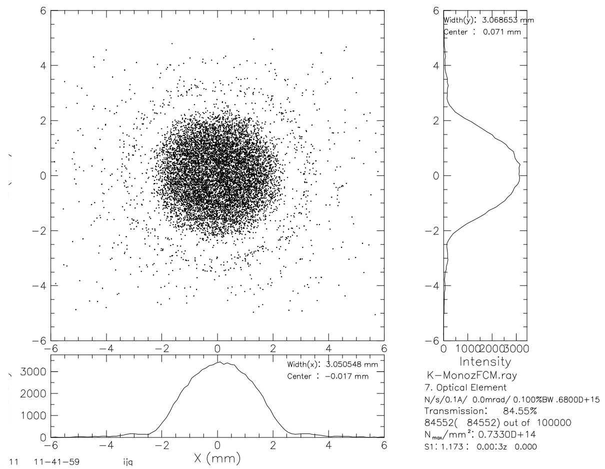
@12300eV

@12360eV

@12400eV







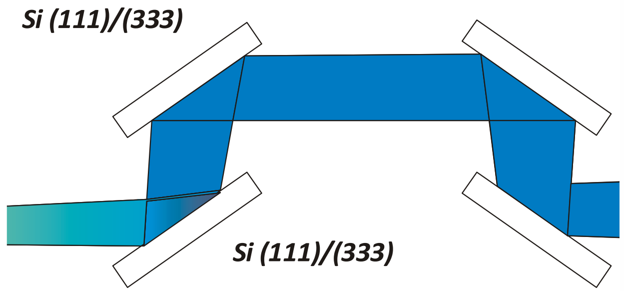
K-monochromator characteristics

Crystals: 2 x Si 111 *(333)* channel-cut monochromators

Energy range: 2 – 20 keV

Energy resolution:

photon energy (keV)	ΔE (eV)	ΔE / E
5	0.49	$1x10^{-4}$
10	1.2	$1x10^{-4}$
	0.065	$6.5x10^{-6}$
20	2.3	$1x10^{-4}$
	0.104	$5x10^{-6}$



K-parameter variation (E-fixed)

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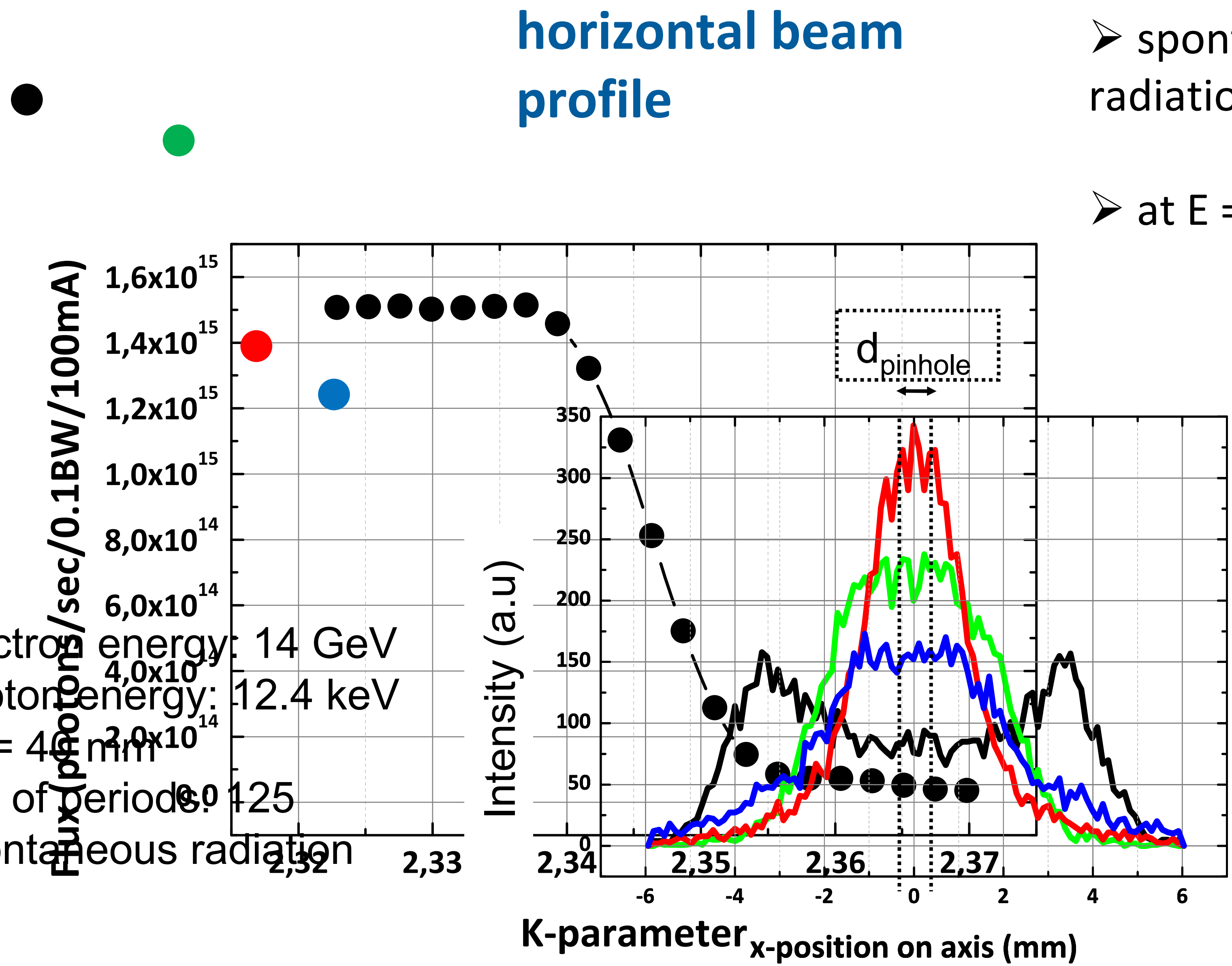
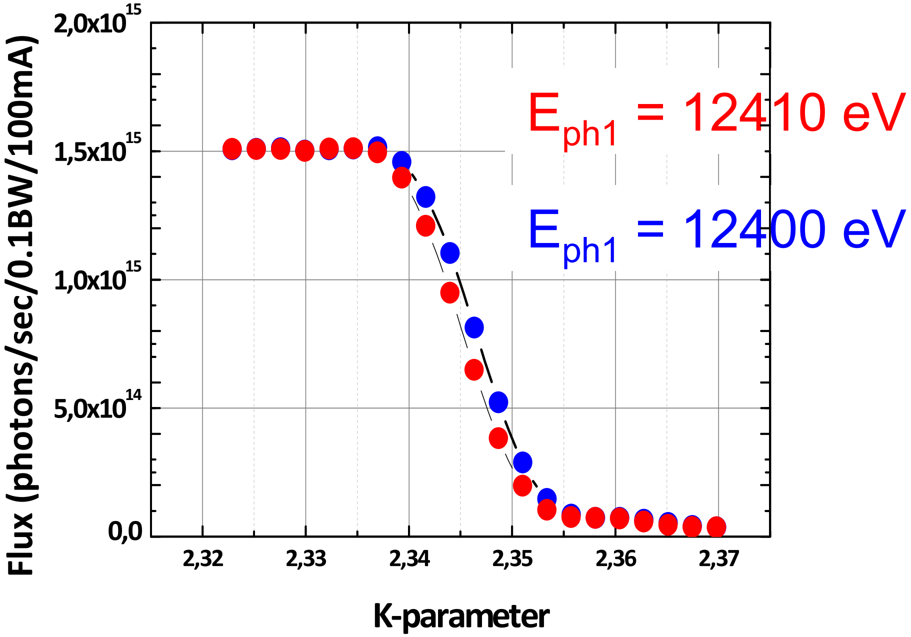


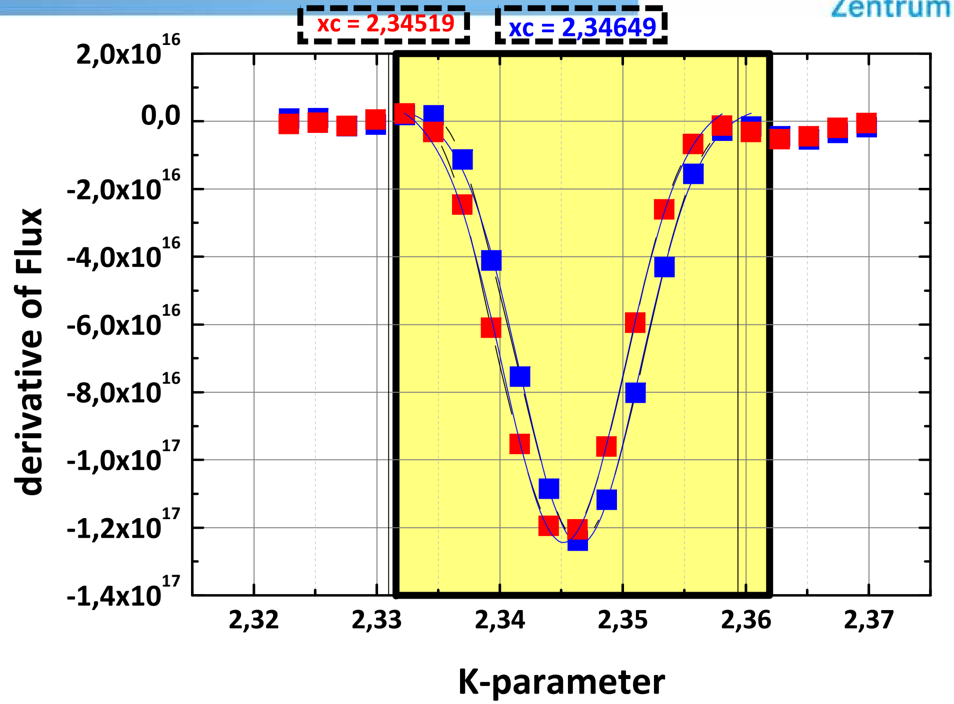
- spontaneous radiation
- at E = 12.4 keV

- electron energy: 14 GeV
- photon energy: 12.4 keV
- λ_U = 40 mm
- No. of periods: 125
- spontaneous radiation

Precise K-parameter measurements



Flux at full beam aperture



Flux differential

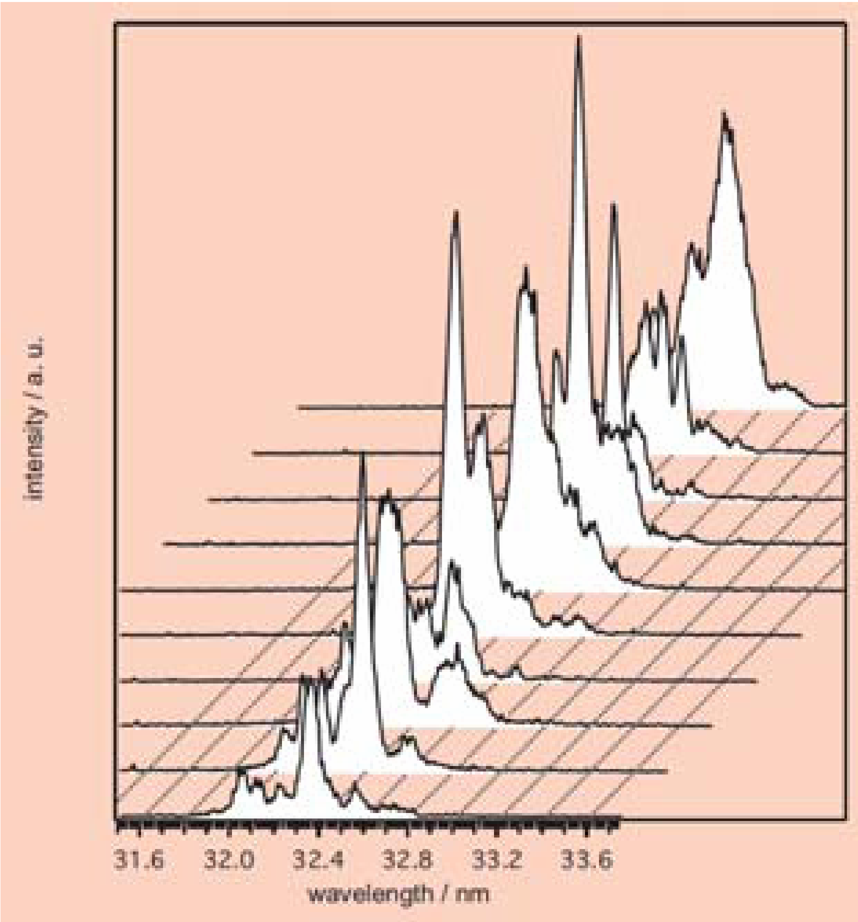
$$E_{ph}[keV] = 0.950 \frac{E_e^2[GeV]}{\left(1+\frac{K^2}{2}\right)\lambda_U[cm]}$$

$$\frac{\Delta E}{E} = \frac{K^2}{\left(1+\frac{K^2}{2}\right)} \frac{\Delta K}{K} \approx 1.46 \frac{\Delta K}{K} \Big/_{K=2.35}$$

„Gaussian fit method“

E_{ph1} = 12400 eV	Center @ K = 2.34649
E_{ph2} = 12410 eV	Center @ K = 2.34519
ΔE/E = 8x10^{-4}	**ΔK/K = 5x10^{-4}**

Motivation
- Typical SASE Single Shot Spectrum



- intensity at one wavelength varies from pulse to pulse significantly
- wavelength spectrum varies considerably

Dispersive crystal monochromator

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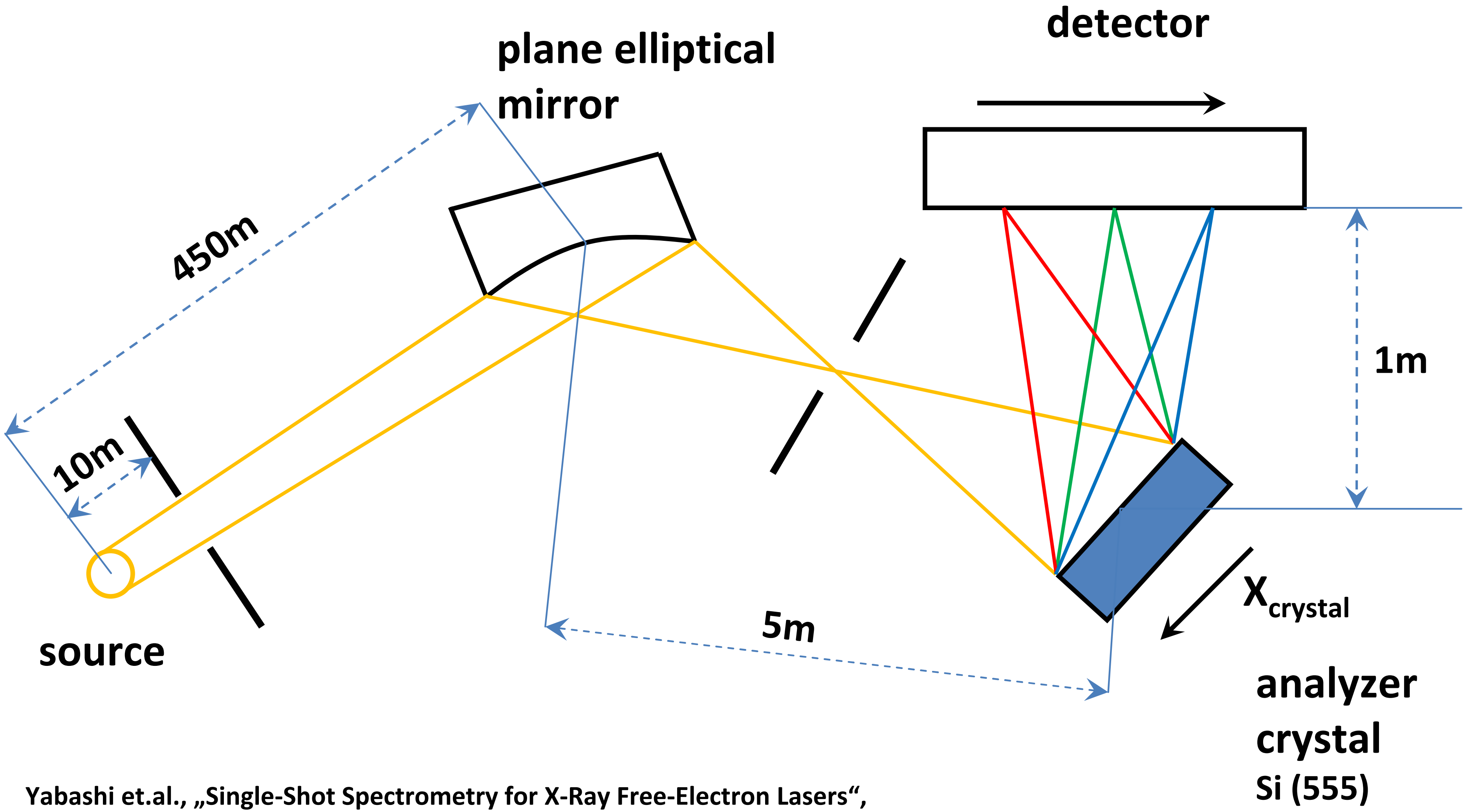
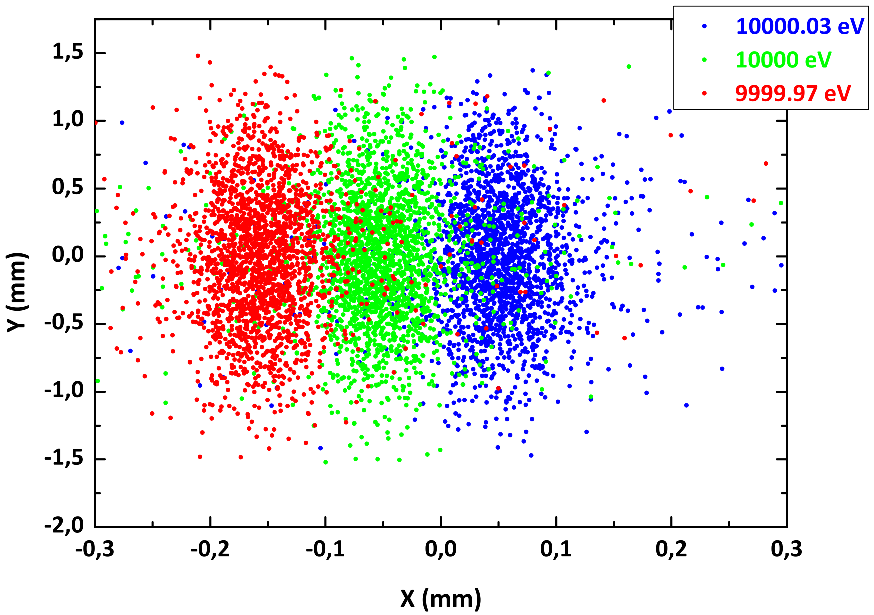
top view

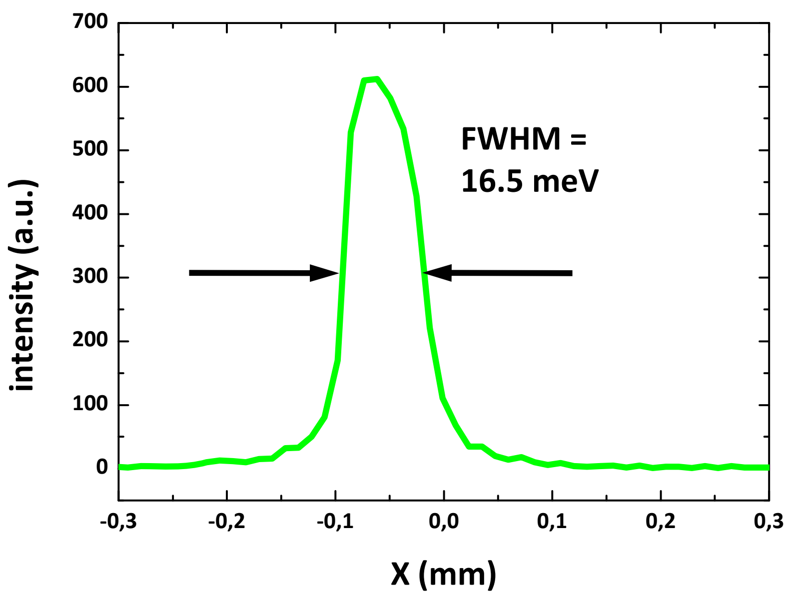


Yabashi et.al., „Single-Shot Spectrometry for X-Ray Free-Electron Lasers“, Phys.Rev.Lett. 97, 084802 (2006)

Summary Yabashi design



- resolution: ΔE = 30 meV / 0.1 mm
- dispersion: 300 meV / mm (0.5 eV/mrad)
- FWHM: 16.5 meV (55µm)
- slope errors: < 1.0 arcsec
  (state of the art: 0.3 arcsec)



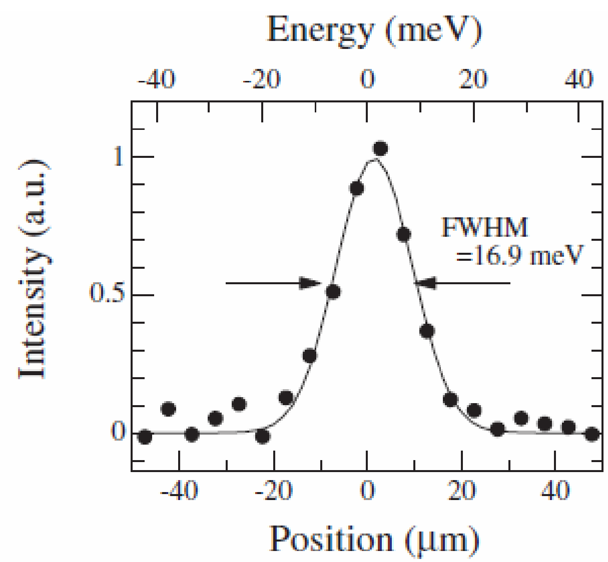


FIG. 3. Spatial profile of dispersed beam (lower axis). The corresponding energy scale is shown on the upper axis.

picture: Yabashi et.al., „Single-Shot Spectrometry for X-Ray Free-Electron Lasers“, Phys.Rev.Lett. 97, 084802 (2006)

Reflection Zone Plate
Single - Shot Monochromator

Motivation

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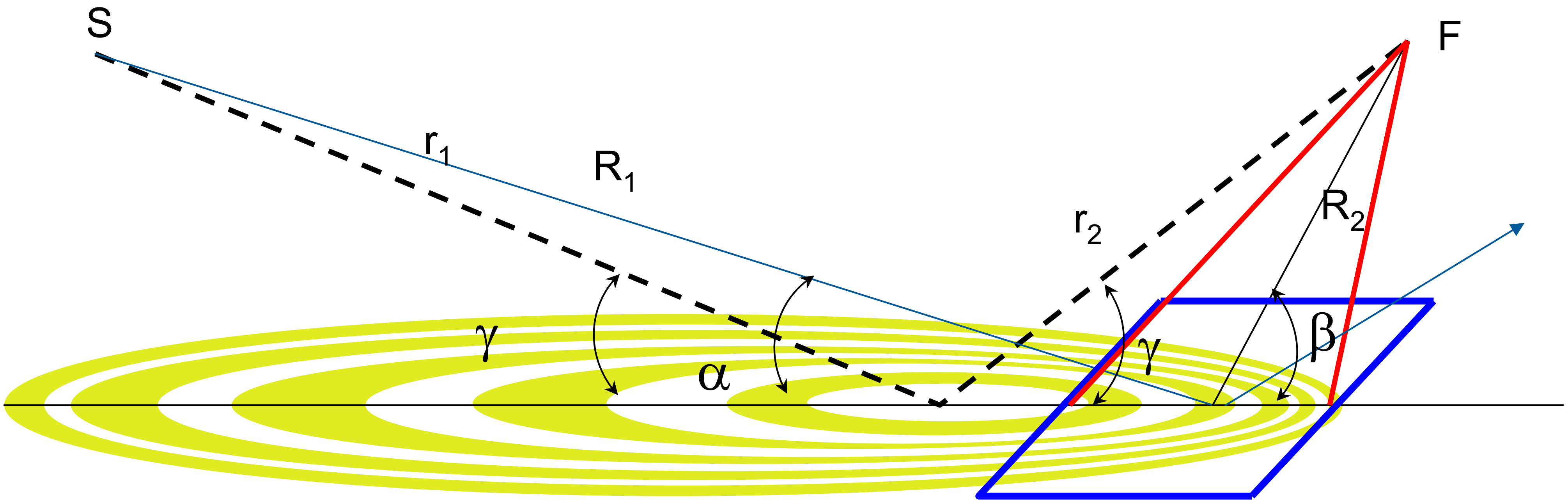
- X-ray laser is a source of coherent short-pulse radiation. Each optical element in the beam transport line will induce absorption, scattering, distortion etc. Normally, after interaction with 5 – 7 mirrors, the absorption reduces the flux by several orders of magnitude. Scattering and speckle formation processes will destroy all unique properties of the laser beam. Coherent experiments are very problematic.

- If a radiation of 1000 eV is reflected by 7 mirrors with Au coating, only 1.7 % of the radiation will go though the optics.

- X-ray lasers require new non-traditional solutions and non-conventional designs to ensure that their unique properties can be fully exploited.

Reflection zone plate (2D VLS)

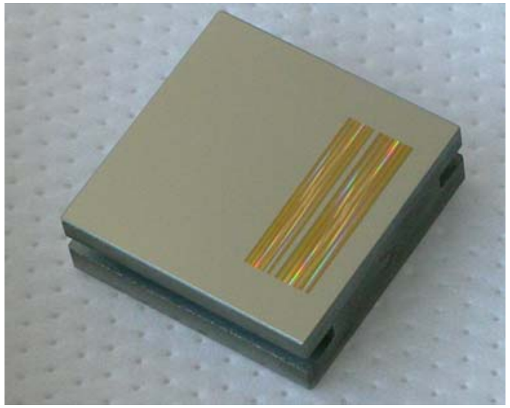


Wavelength range: 0.025 nm (50 keV) – 200 µm (0.062 eV)

Efficiency: 5% - 30 %

Energy resolution $\lambda/\Delta\lambda$: 100 – 50 000

RZP applications at BESSY II

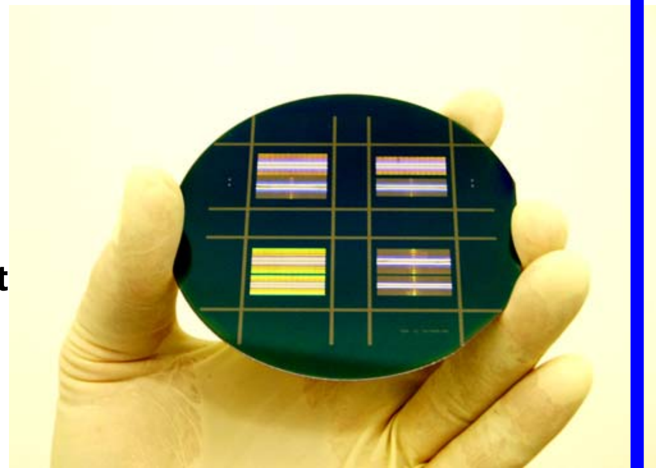


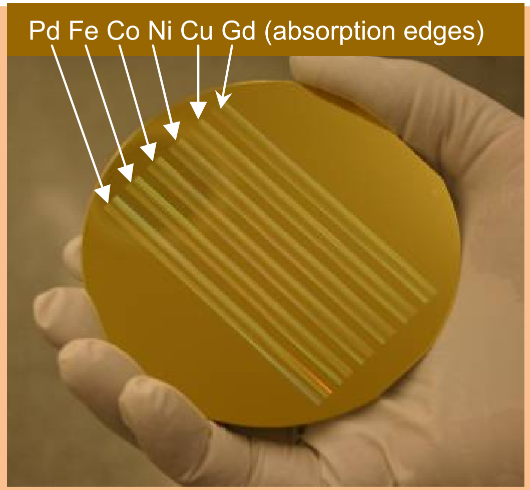
5 keV - 16 keV

Bragg-Fresnel Lens on the second monochromator crystal at MySpot beamline

10 eV – 60 eV

Total reflection zone plate as monocromator-spectrometer at HHG harmonic selector



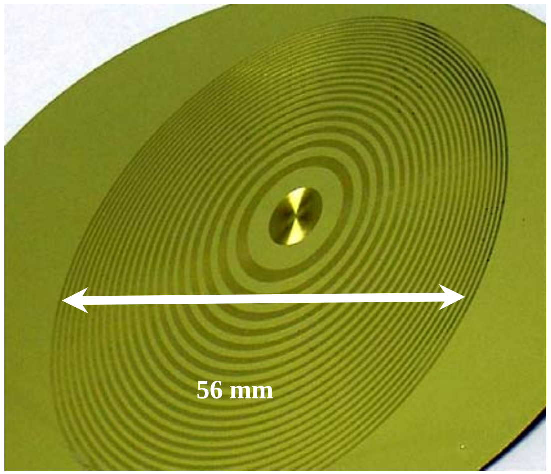


0.5 keV – 1.2 keV

Total reflection zone plate as monocromator-spectrometer at Slicing beamline

6.2 10^{-3} eV

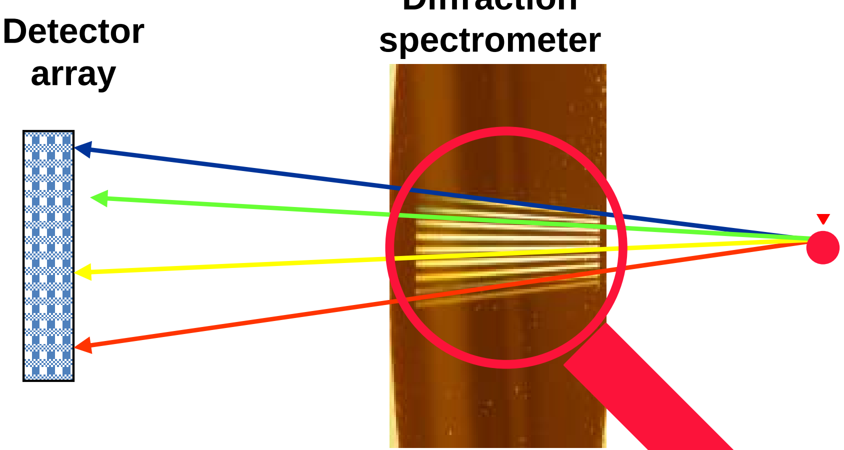
Total reflection zone plate as monocromator-spectrometer at THz beamline

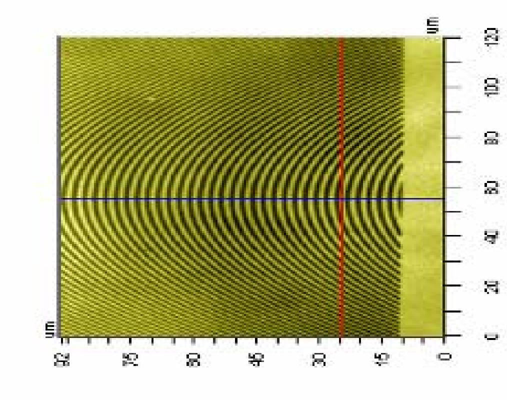


Parallel X-ray Fluorescence Spectrometer

One pulse, one spectrum:
Ultra-fast X-ray spectroscopy spectroscopy

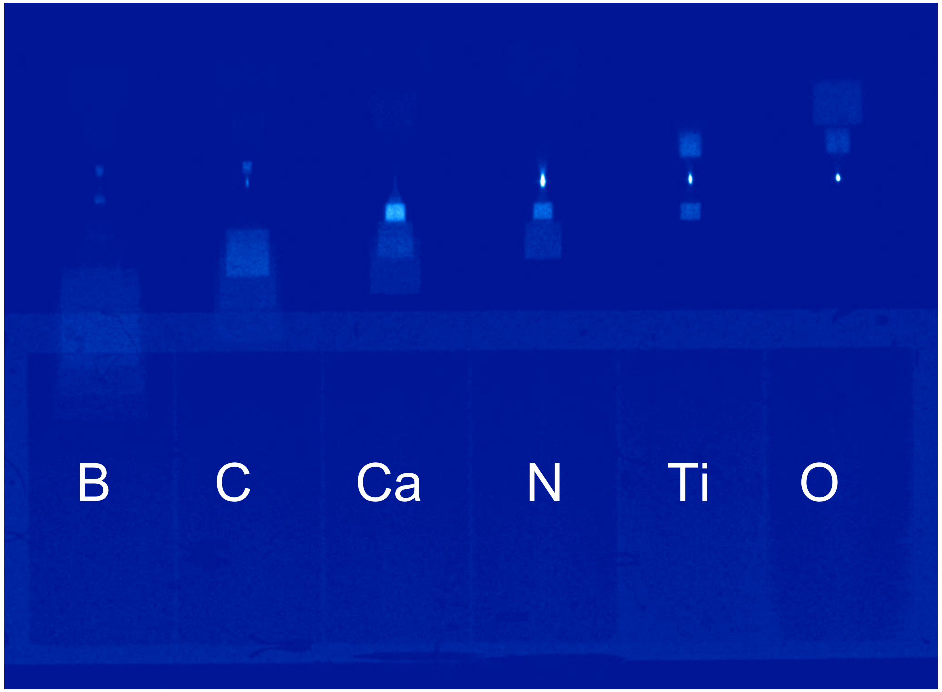
A. Erko, et al., Novel parallel vacuum ultra-violet/X-ray fluorescence spectrometer, Spectrochim. Acta Part B (2012), doi:10.1016/j.sab.2012.01.001

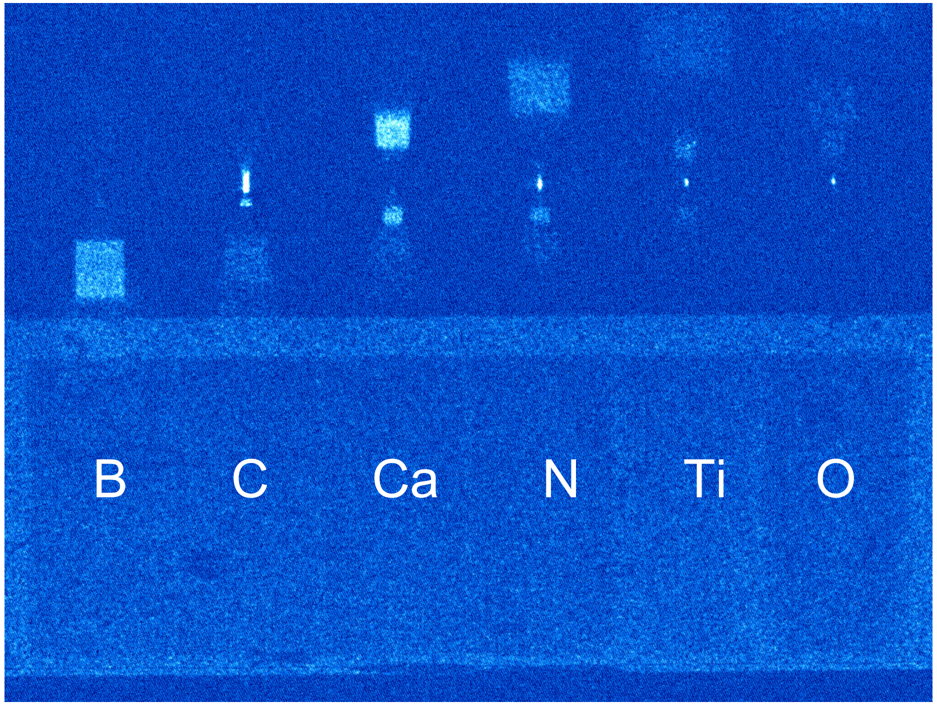


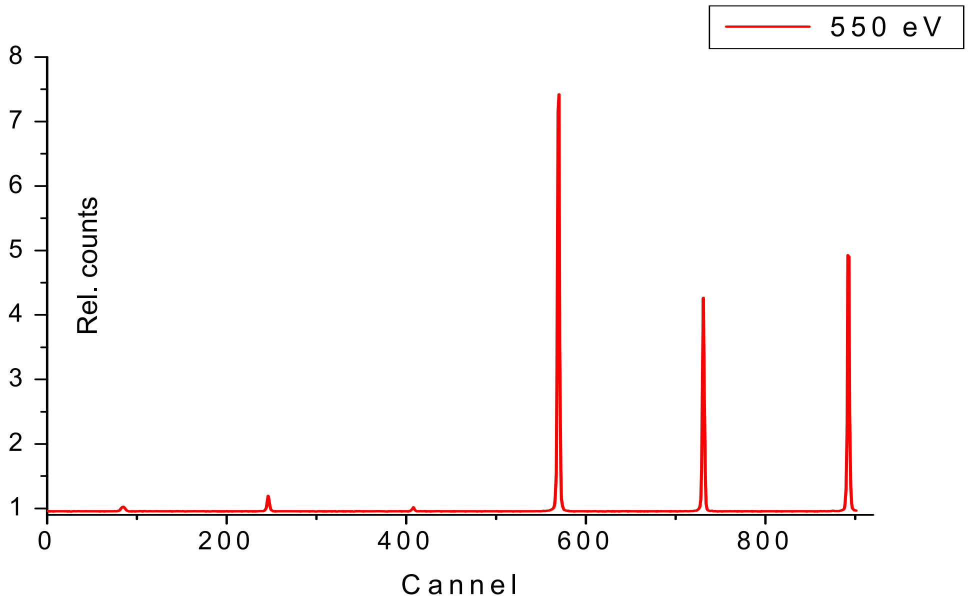


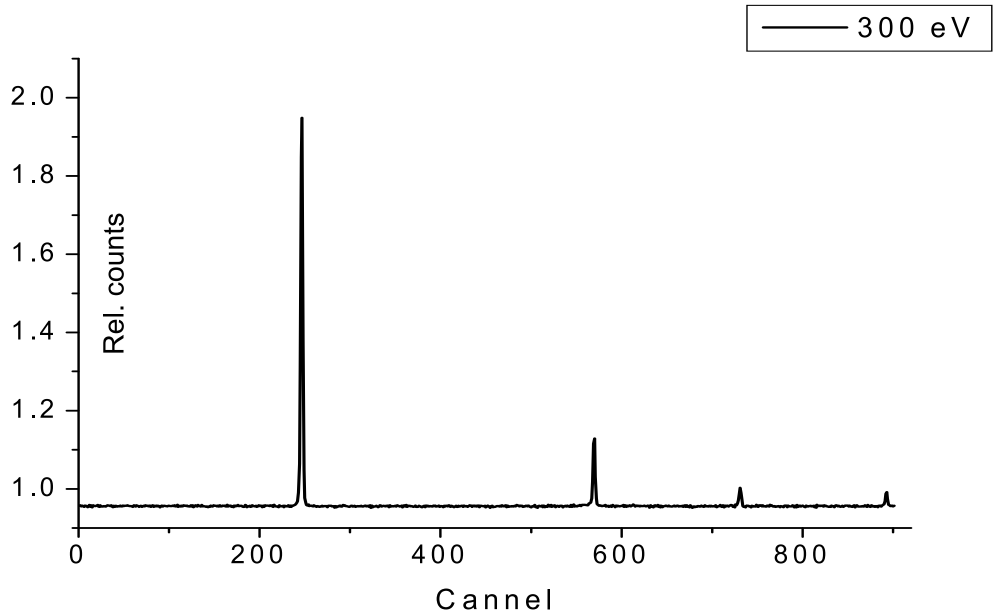
Multichanel Spectrometer

New generation: tests at RIXS beamline









Parallel detection scheme slicing beamline

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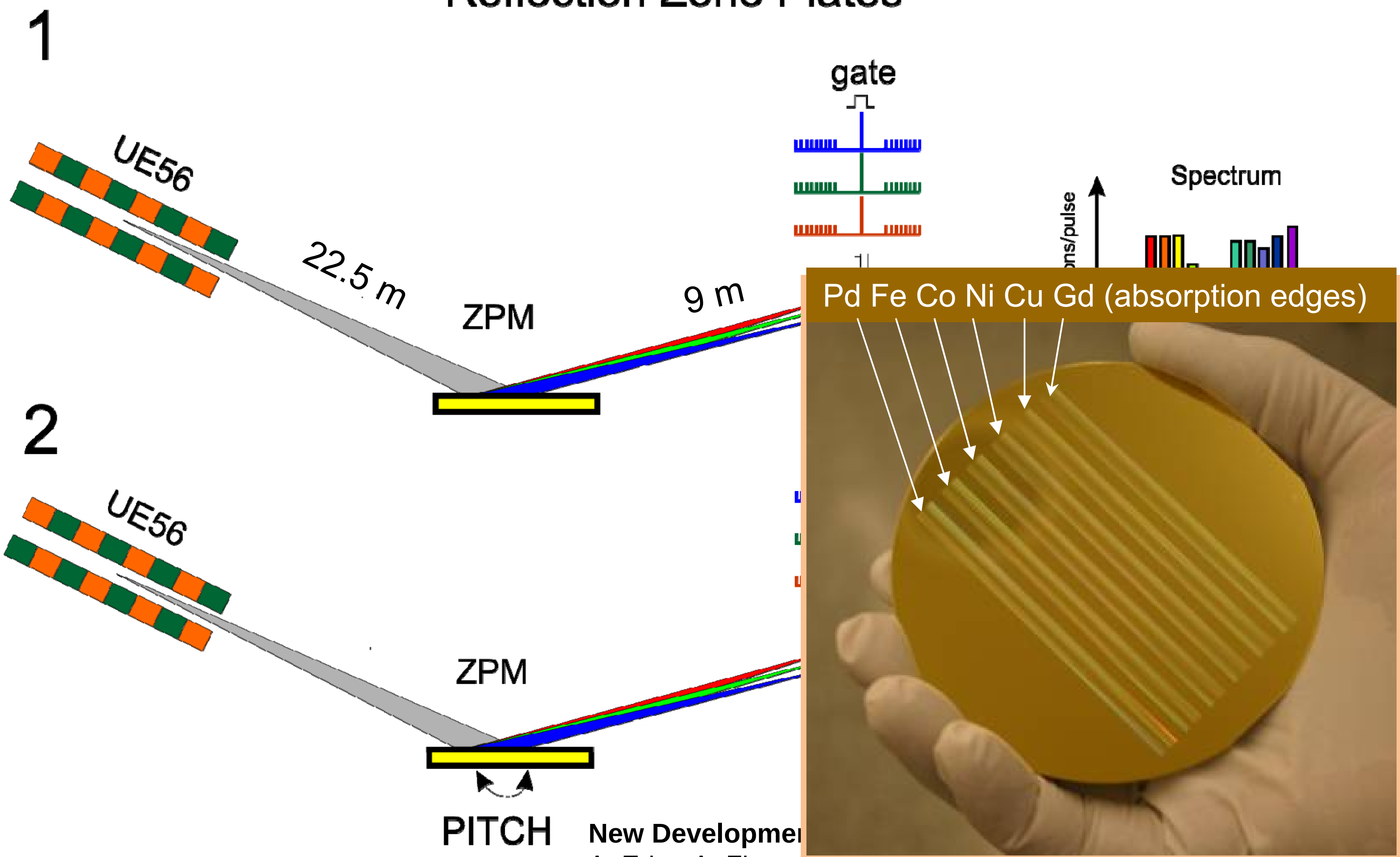
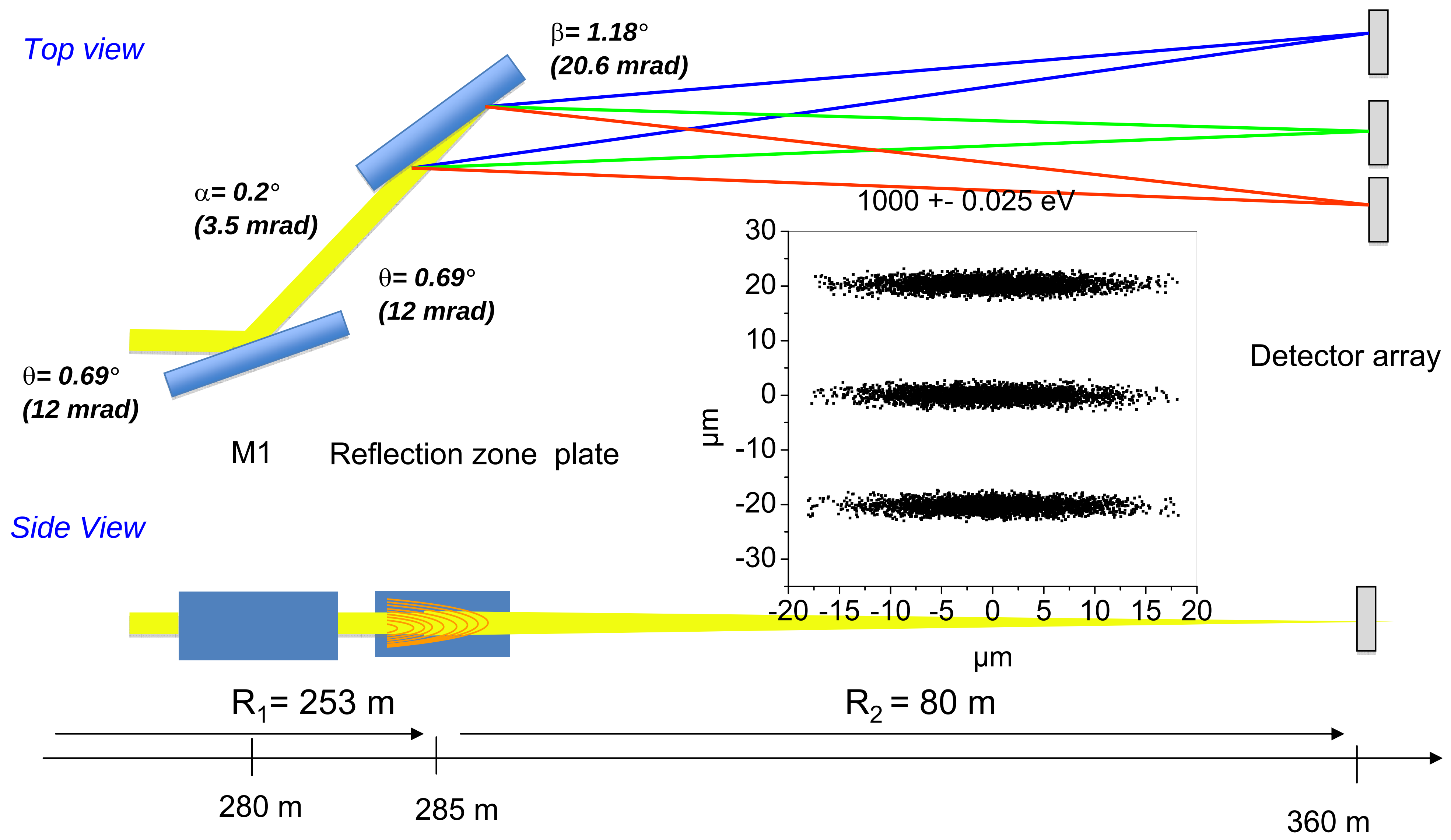
Time-Correlated Parallel detection with Reflection Zone Plates



New Developme
A. Erko, A. Firsov, K. Holldack, AIP Conf. Proc. 2010 1234, 177-180)

Concept Single-Shot monochromator

E = 1 keV, E/ΔE= 40 000 (25 meV at 1 keV), Detector pixel size = 20 µm



Example of RZP design, diagnostic version

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Beam parameters at 253 m

λ/E	Beam size D	Δt
1.24nm (1keV)	~7 mm	< 100 fs

$$\Delta t = \lambda / c \; N$$

Δt ~ 4.1 10^{-18} s, N = 25000

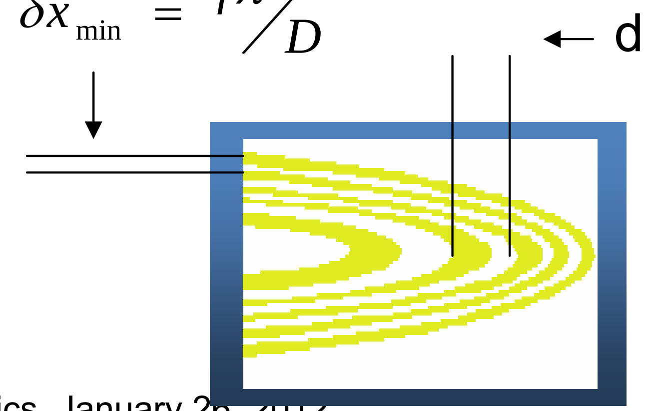
Diffraction structure parameters

L	α	β	d	Δx	λ/Δλ	2θ	R_1	R_2
155mm	0.2° (3.5 mrad)	1.18°	6.2 µm (160 l/mm)	20µm	25000	1.38°	253m	80m

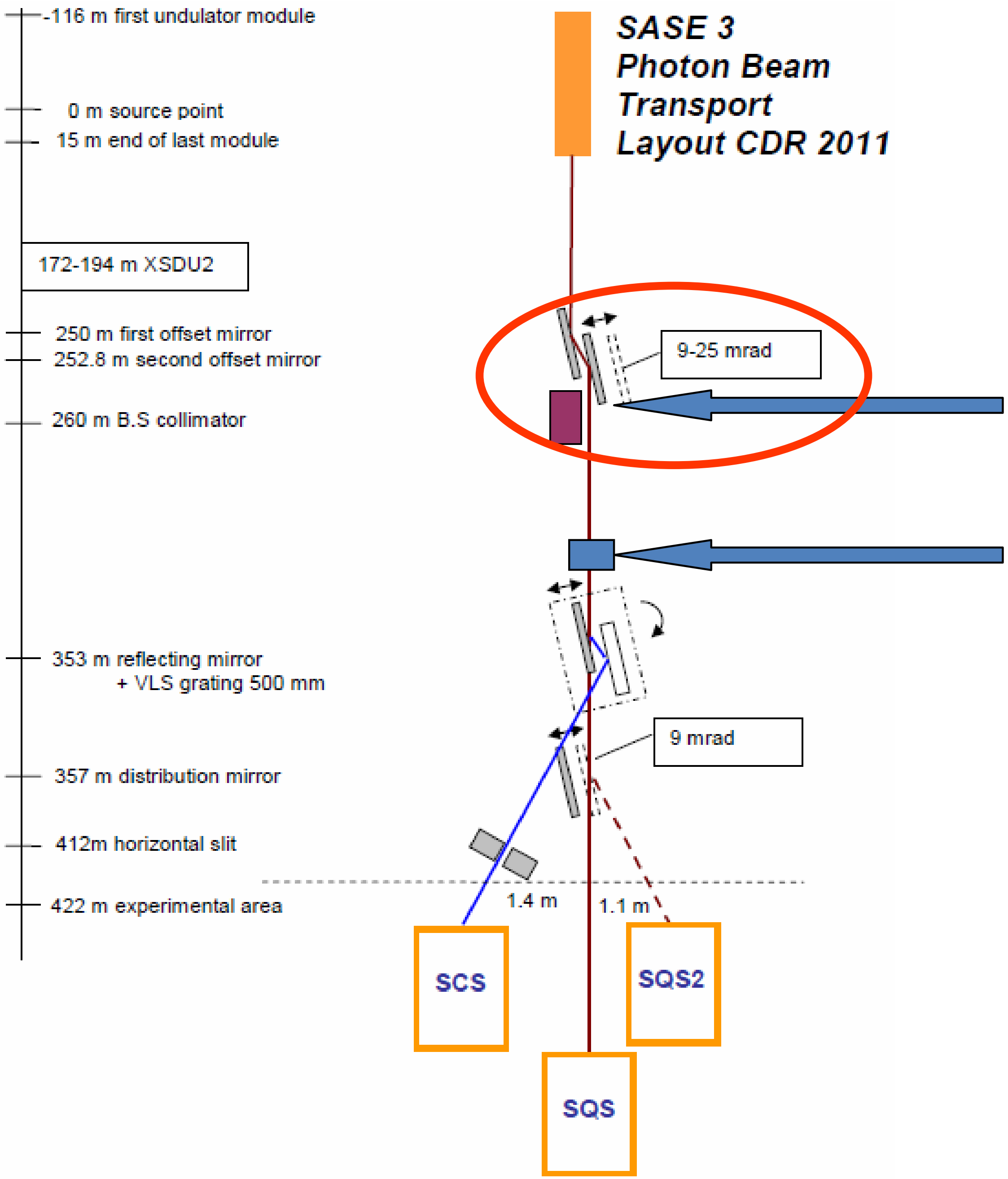
Reflection zone plate parameters

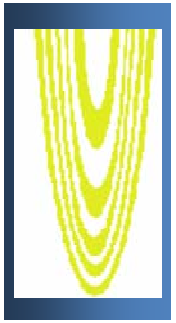
γ	r_1	r_2	δx_{min}
0.44°	116.2 m	216.8 m	10.8 µm

$$\delta x_{min} = f\lambda / D$$



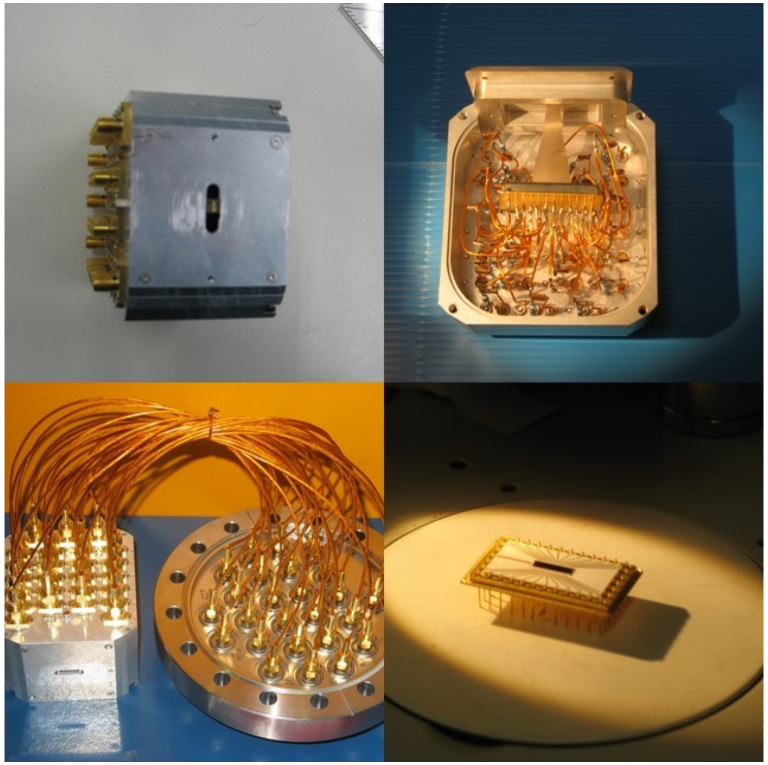
Single-Shot monochromator position SASE3





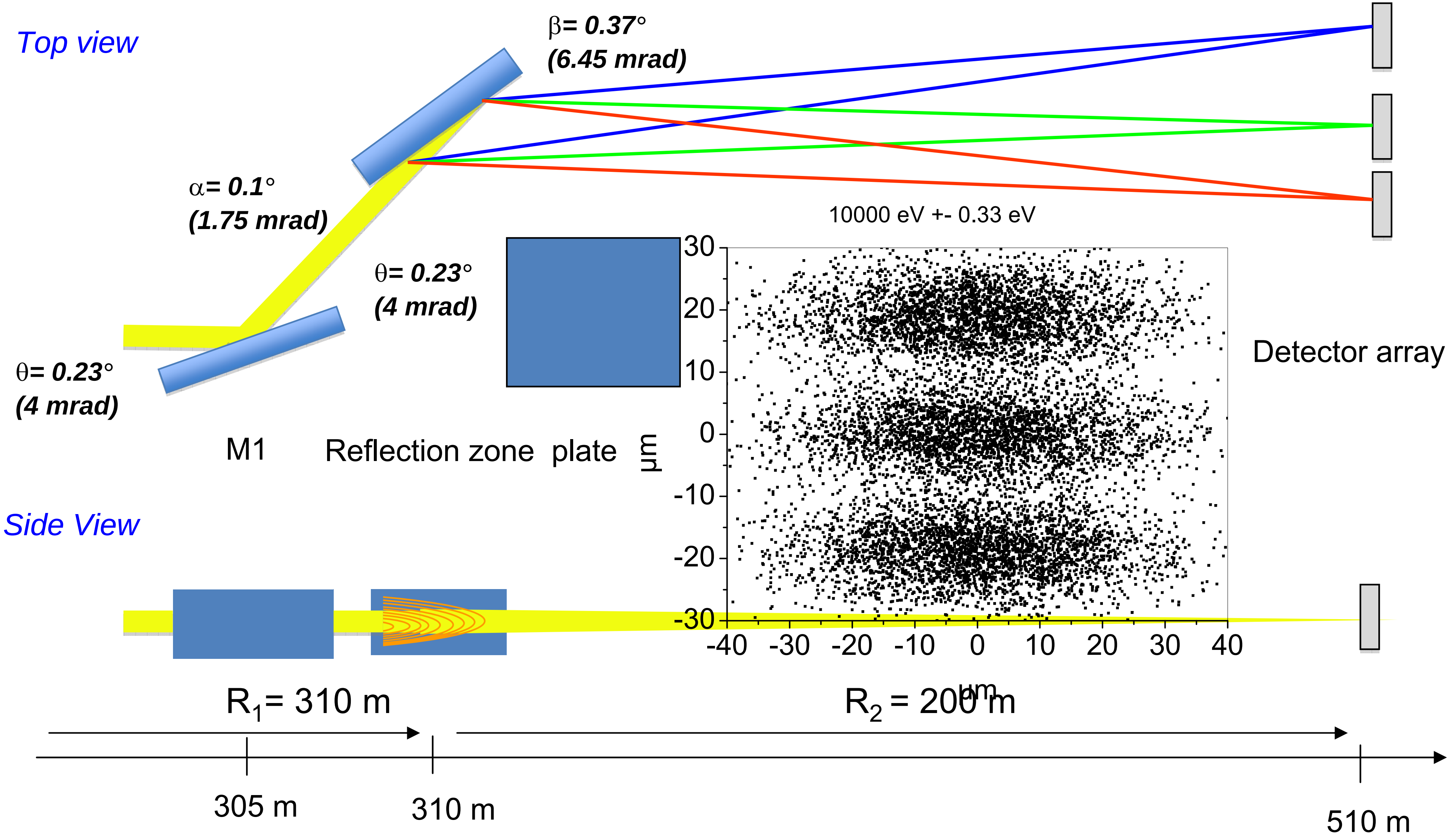
Reflection zone plate

Parallel detector array



Concept Single-Shot monochromator

E = 10 keV, E/ΔE= 30 000 (0.33 eV at 10 keV), Detector pixel size = 20 µm



Example of RZP design, 10 keV

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Beam parameters at 310 m

λ/E	Beam size
0.124nm (10 keV)	~ 1 mm

$\Delta t_N \sim 4.1\ 10^{-19}$ s, at 0.124 nm

N ~ 30000

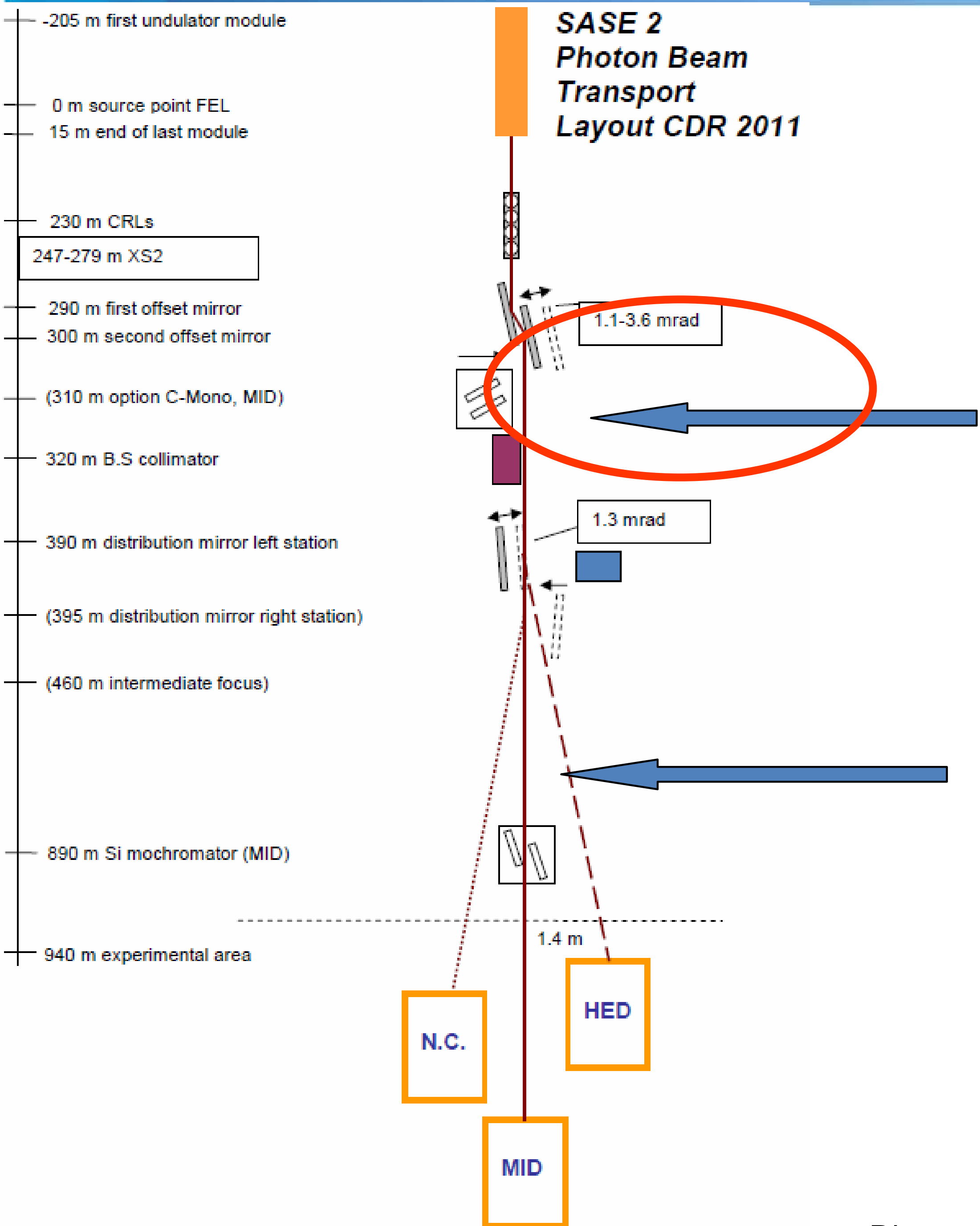
Diffraction structure parameters

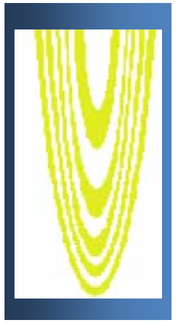
α	β	d	$\lambda/\Delta\lambda$	2θ	R_1	R_2
0.1° (1.75 mrad)	0.37°	6.4 µm (156 l/mm)	30000 0.33 eV	0.47°	310 m	200 m

Reflection zone plate parameters

L	γ	r_1	r_2	δx_{min}	Δt	Δx detector resolution
200 mm (400 mm)	0.2°	144 m	356 m	10.8 µm	~ 12 fs (25 fs)	20µm

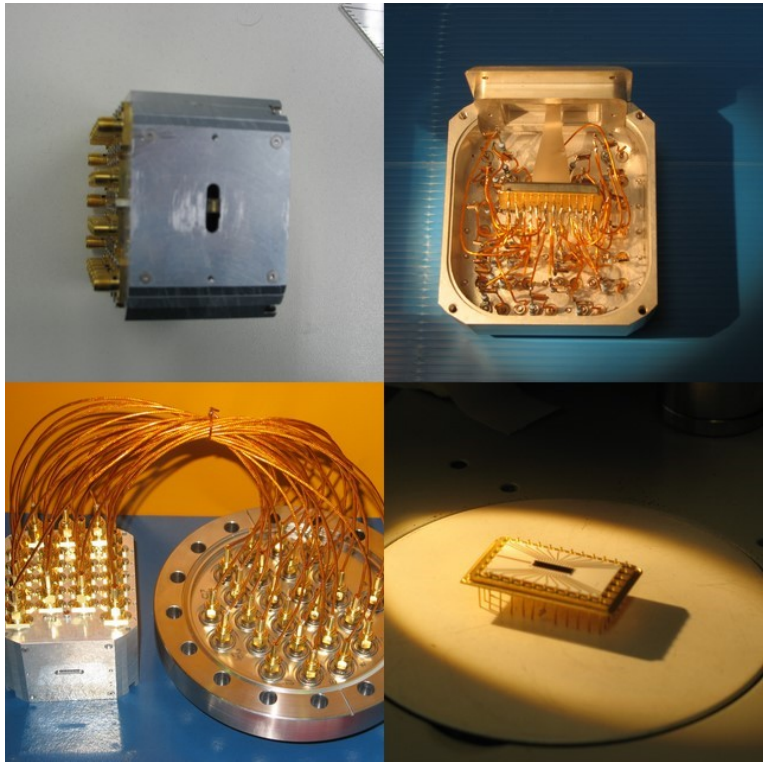
Single-Shot monochromator position SASE 2





Reflection zone plate

Parallel detector array



Conclusions

We propose minimizing the number of optical elements in the beamline by combining reflection, focusing and dispersion in one single element. We considerably increase efficiency (20 times in the example of the BESSY II Slicing beamline), reduce scattering and slope errors using flat substrates and PRESERVE COHERENCE.

Reflection zone plates have been experimentally tested in the energy range 0.062 eV to 20 keV at several BESSY II beamlines and show high stability, efficiency and energy resolution.

The radiation stability tests are necessary to confirm advantages of reflection zone plates in XFEL applications.

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Thank you!