Introduction to "Synchrotron Radiation Workshop"

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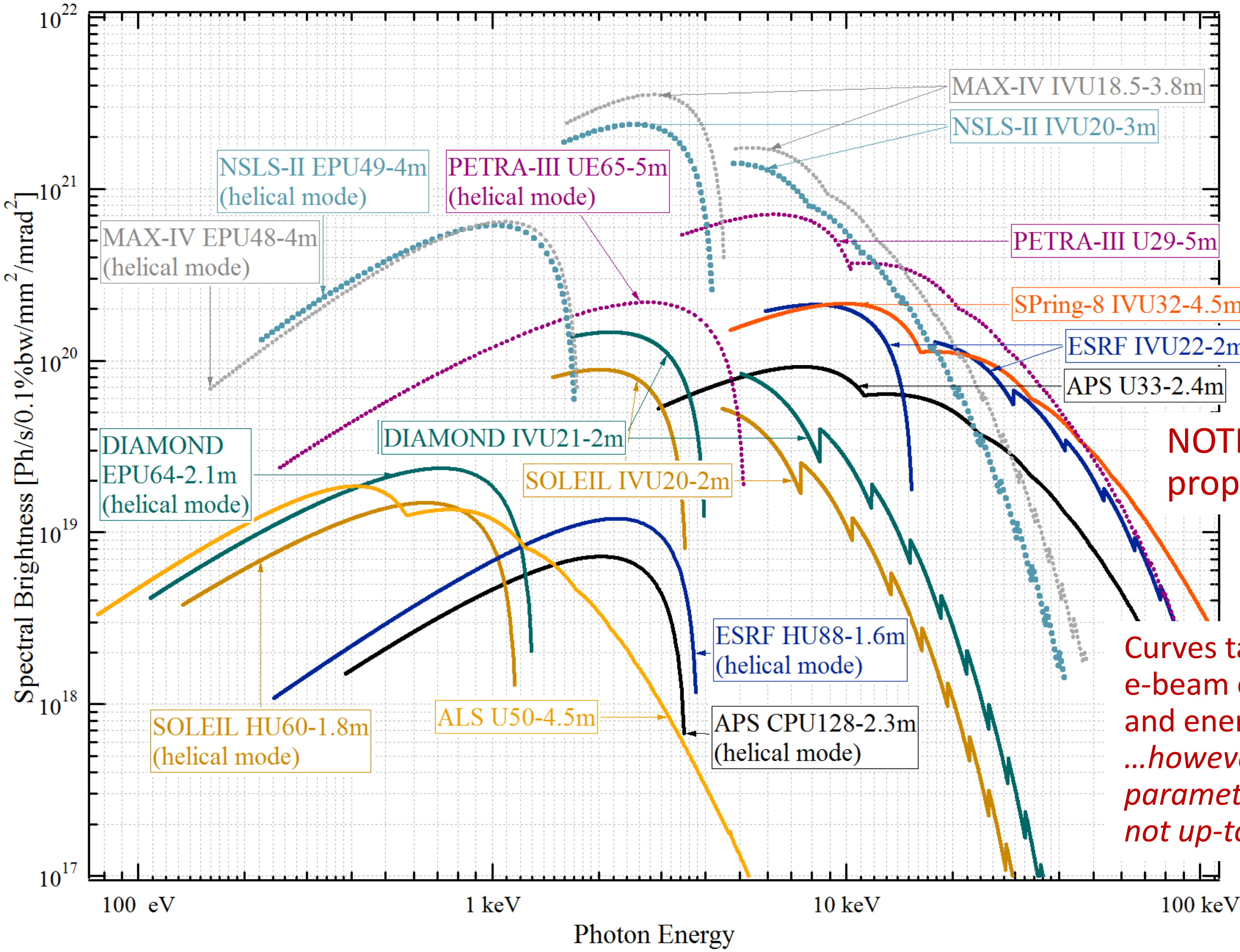
Synchrotron Optics Simulations: 3-Codes Tutorial
3 - 5 June 2013, ESRF, France

Outline

1. Light Source Developments Driving the Needed Improvements in X-Ray Optics Simulation and Modeling
2. Some Details of Single-Electron Undulator Radiation
3. Method for Simulation of Emission and Propagation of Partially-Coherent SR
4. Simulation Examples: Beamlines and Experiments
5. Current Status of SRW and Collaborations
6. Summary

Approximate Spectral Brightness of Undulator Sources in 3rd(+) Generation Storage Rings



ε_x = 0.26 nm

ε_x = 0.55 nm

ε_x = 1.0 nm

ε_x = 3.4 nm

ε_x = 2.8 nm

NOTE: the "Coherent Flux" is proportional to Brightness:

$$F_{coh} \approx (\lambda/2)^2 B$$

Curves take into account e-beam emittance and energy spread *…however some source parameters may be not up-to-date…*

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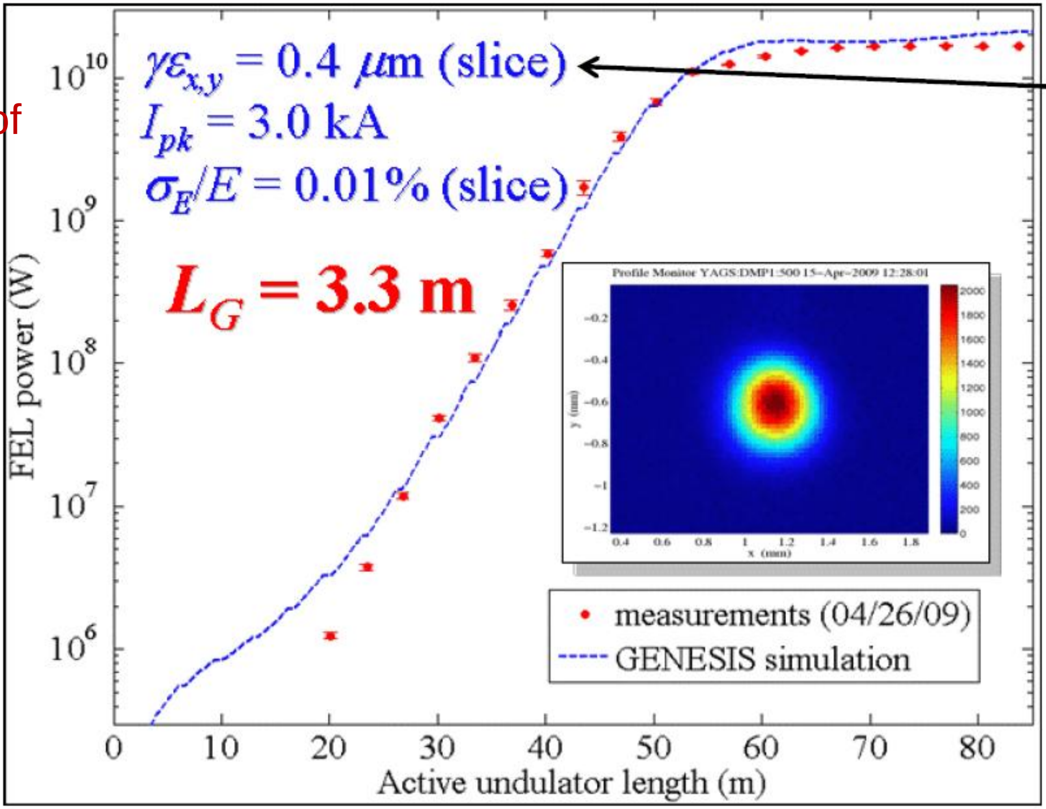
The Turn on of LCLS:
First Performance Exceeds Expectation

From presentations of
P. S. Drell (2009)
P. Emma, PAC-2009



Design: 1.2μm

- Typical x-ray beam energy **> 1 mJ** or **> 10^{12}** photons per pulse
- Typical x-ray pulse duration at 300pC charge **~ 100 fs** (FWHM).
- X-ray pulse duration at 20 pC charge < **10 fs**
- Saturation at 65 m (anticipated 87 m)

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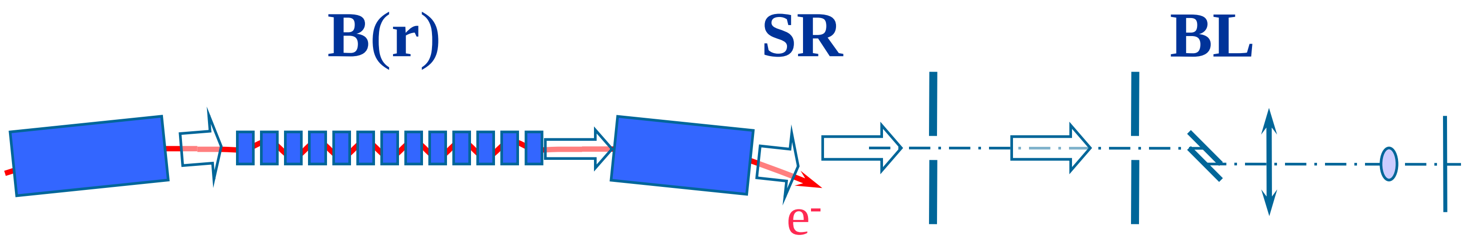
General Motivation: Start To End Simulation



- Computation of **Magnetic Fields** produced by Permanent Magnets, Coils and Iron Blocks and in 3D space, optimized for the design of **Accelerator Magnets**, **Undulators** and **Wigglers**
- Fast computation of **Synchrotron Radiation** emitted by relativistic electrons in Magnetic Field of arbitrary configuration
- **SR Wavefront Propagation** (Physical Optics)
- Simulation of some **Experiments** involving **SR**

RADIA

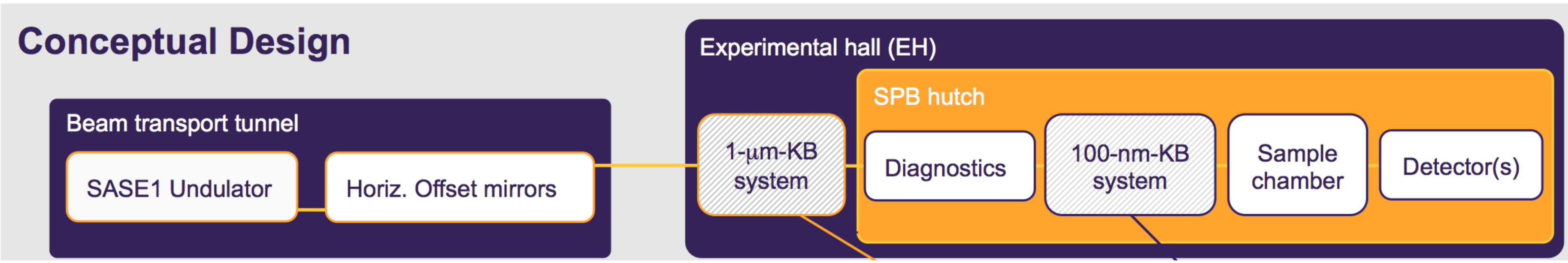
ESRF

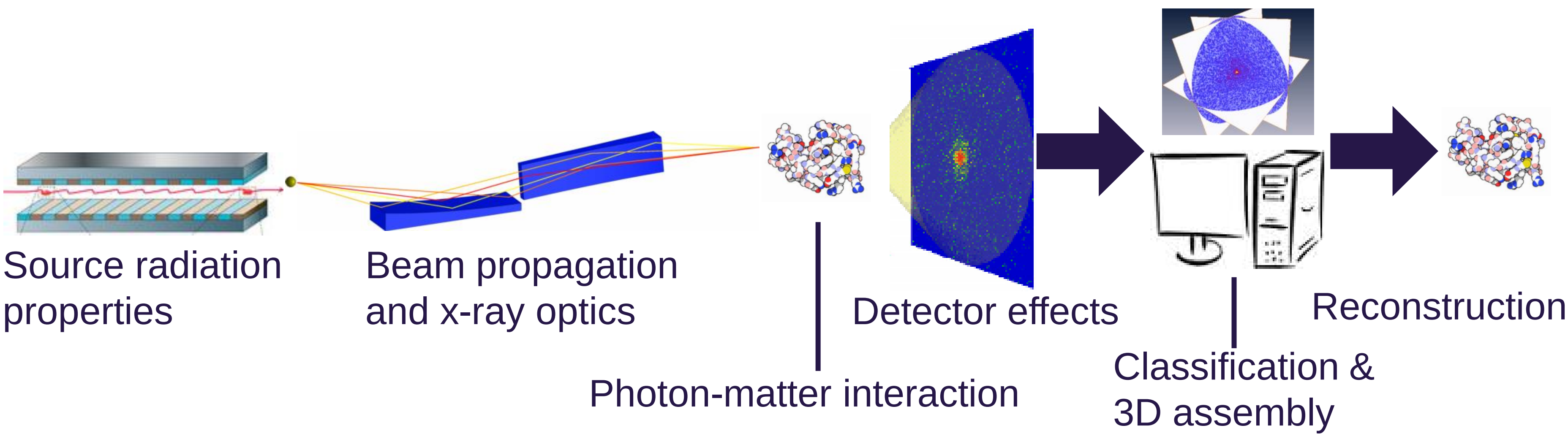
SRW

Started at ESRF thanks to Pascal Elleaume

Single particle imaging at the SPB instrument of the European XFEL–from start to end II

Courtesy of A. P. Mancuso and L. Samoylova





Images: *Nature Photonics* **4**, 814–821 (2010), x-ray-optics.de, pdb.org, J. Phys. B: At. Mol. Opt. Phys. 43 (2010) 194016, SPB CDR

Some Computer Codes for Synchrotron Radiation and X-Ray Optics Simulation

Spontaneous

- **Synchrotron Radiation**
  - URGENT (R .Walker, ELETTRA)
  - XOP (M.S. del Rio, ESRF, R. Dejus, APS)
  - SPECTRA (T. Tanaka, H. Kitamura, SPring-8)
  - WAVE (M. Scheer, BESSY)
  - B2E (P. Elleaume, ESRF, 1994)
  - SRW (O. Chubar, P. Elleaume, ESRF, 1997-…)
  - SRCalc (R. Reininger, 2000)
- **Geometrical Ray-Tracing**
  - SHADOW (F. Cerrina, M.S. del Rio)
  - RAY (F. Schäfers, BESSY)
  - McXtrace (E. Knudsen, A. Prodi, P. Willendrup, K. Lefmann, Univ. Copenhagen)
- **Wavefront Propagation**
  - PHASE (J. Bahrdt, BESSY)
  - SRW (O. Chubar, P. Elleaume, ESRF, 1997-…)
  - Code of J. Krzywinski et. al. (SLAC)
  - Code of L. Poyneer et. al. (LLNL)

Free

SASE (3D)

- GENESIS (S. Reiche, DESY/UCLA/PSI, ~1990-…)
- GINGER (W.M. Fawley, LBNL, ~1986-…)
- FAST (M. Yurkov, E. Schneidmiller, DESY, ~1990-…)

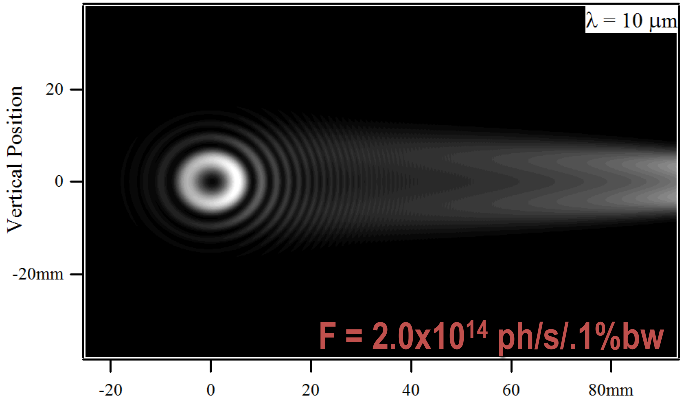
Commercial

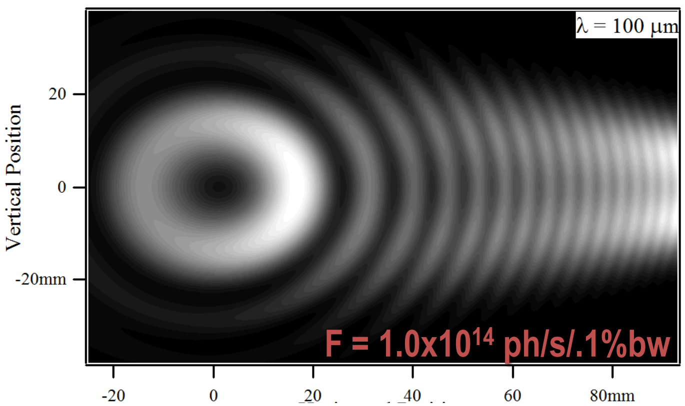
- ZEMAX (Radiant Zemax)
- GLAD (Applied Optics Research)
- VirtualLab (LightTrans)
- OSLO (Sinclair Optics)
- Microwave Studio (CST)

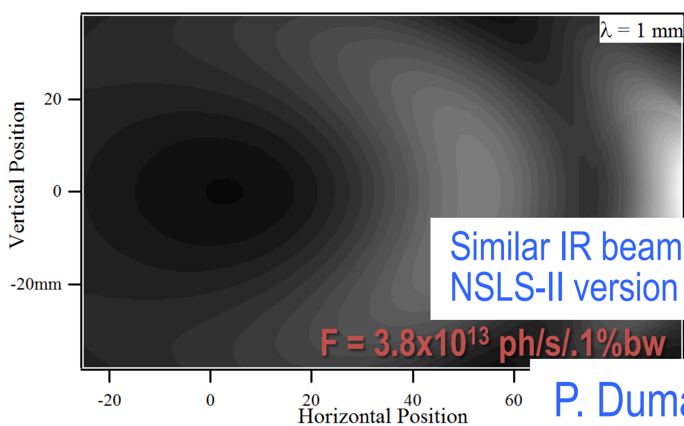
Commercial codes are expensive, and yet don't have all functions required for SR / X-ray Optics simulations

IR SR / ER Intensity Distributions in Transverse Plane at M1 of an Infrared Beamline of NSLS-II

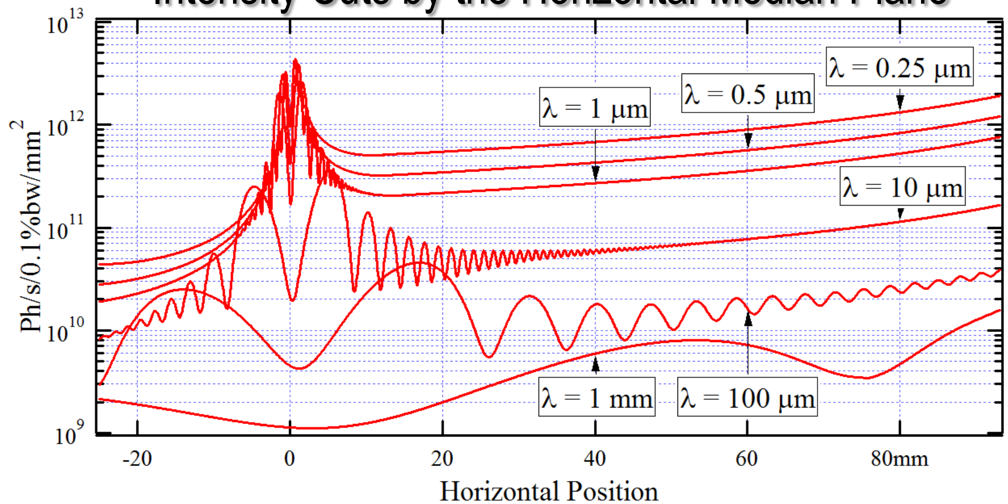
B = 0.4 T; Collection Aperture: ~50 mrad (h) x 35 mrad (v)



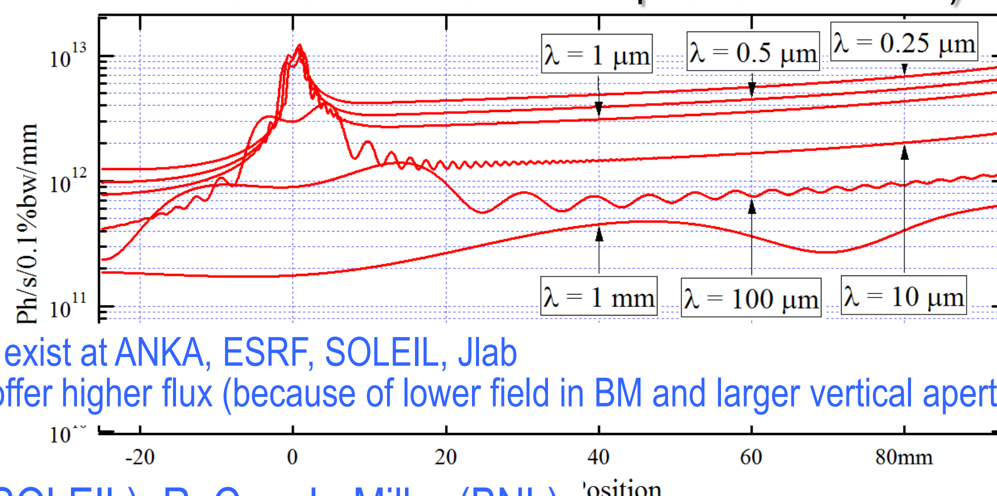




Intensity Cuts by the Horizontal Median Plane



Intensity Profiles (obtained by integration of 2D distributions over vertical position within M1)



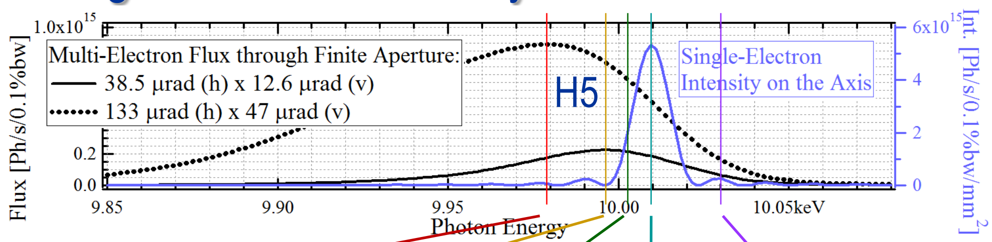
Similar IR beamlines exist at ANKA, ESRF, SOLEIL, Jlab
NSLS-II version will offer higher flux (because of lower field in BM and larger vertical aperture)

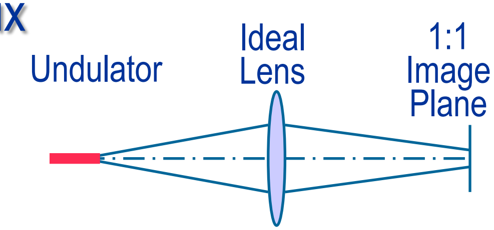
P. Dumas (SOLEIL), R. Carr, L. Miller (BNL)

Single-Electron (Fully Transversely-Coherent) UR Intensity Distributions “in Far Field” and “at Source”

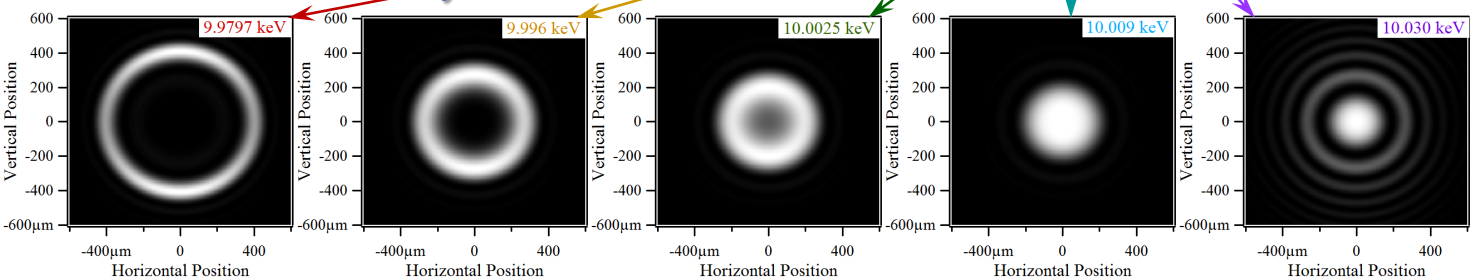
UR “Single-Electron” Intensity and “Multi-Electron” Flux

E-Beam Energy: 3 GeV
Current: 0.5 A
Undulator Period: 20 mm

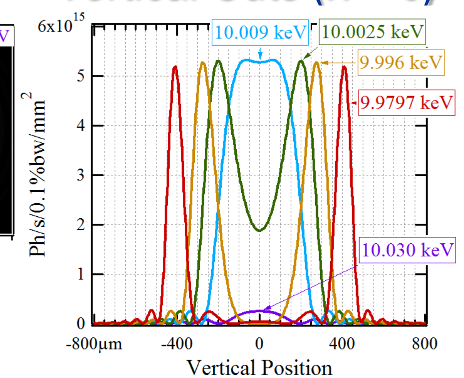




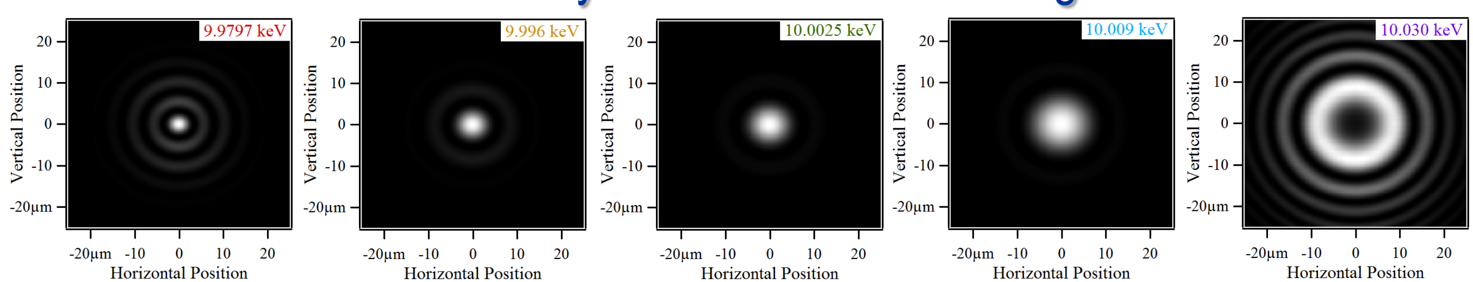
Intensity Distributions at 30 m from Undulator Center

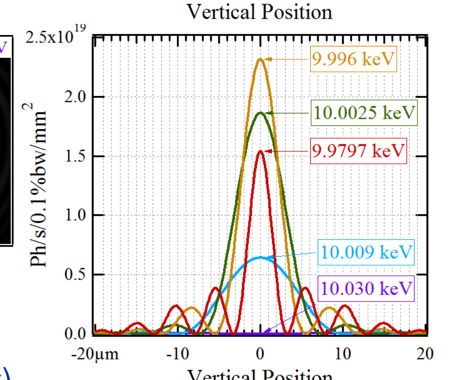


Vertical Cuts (x = 0)



Intensity Distributions in 1:1 Image Plane



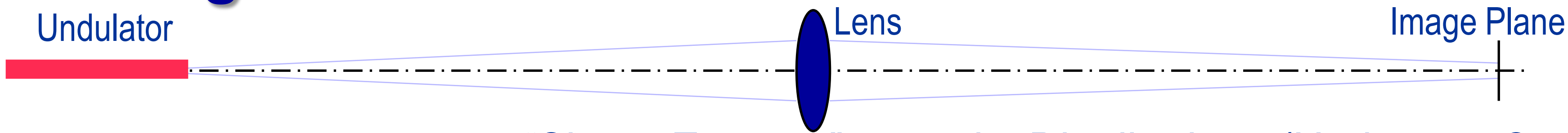


“Phase-Space Volume” Estimation for Vertical Plane

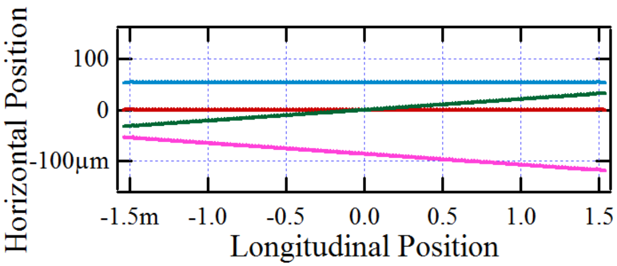
(RMS sizes/divergences calculated for the portions of intensity distributions containing 95% of flux)

$\sigma_y\sigma_y' \approx 7.7\frac{\lambda}{4\pi}$ $\quad 3.3\frac{\lambda}{4\pi}$ $\quad 1.9\frac{\lambda}{4\pi}$ $\quad 1.5\frac{\lambda}{4\pi}$ $\quad 9.2\frac{\lambda}{4\pi}$

Formation of Intensity Distribution of Partially-Coherent Spontaneous SR after Propagation through a Beamline in a 3rd Generation Source

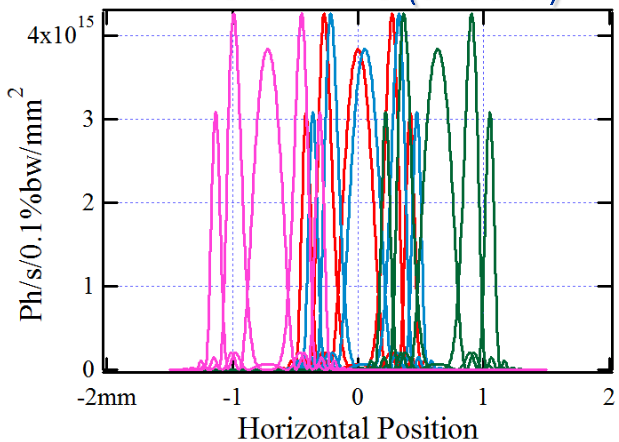


Electron Trajectories

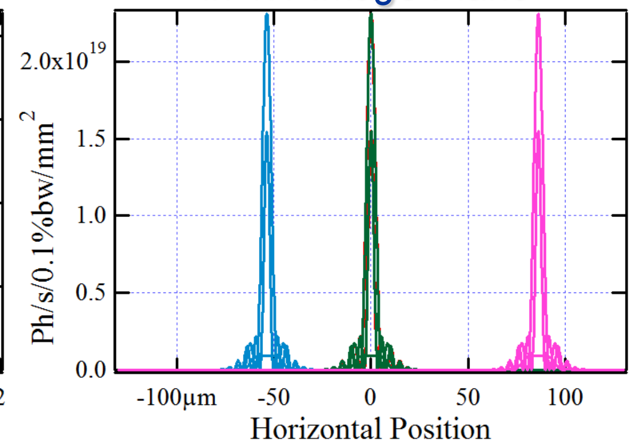


"Single-Electron" Intensity Distributions (Horizontal Cuts)

In Lens Plane (at 30 m)

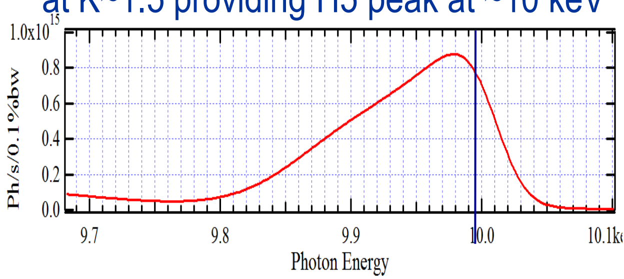


In 1:1 Image Plane

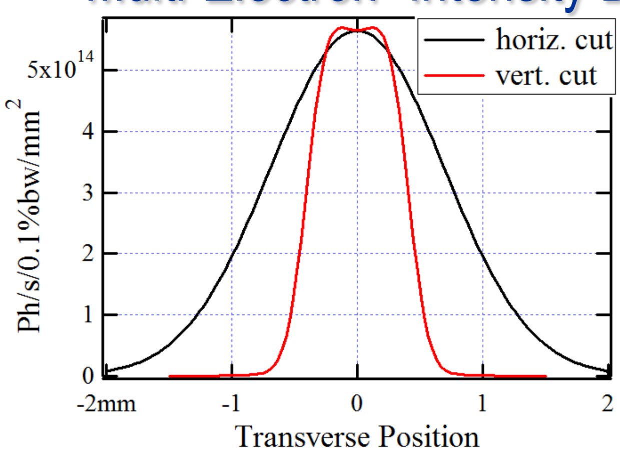


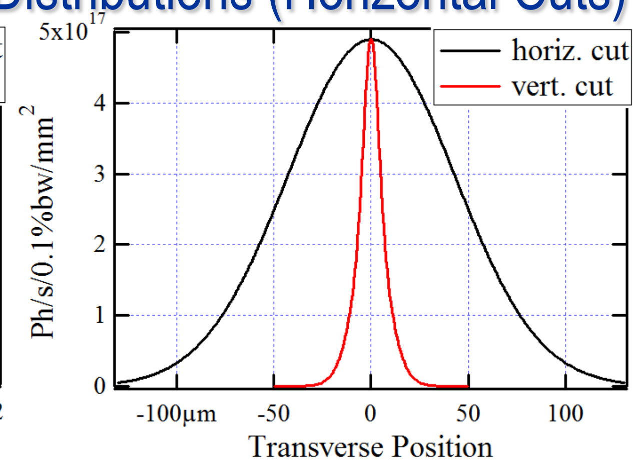
UR Spectrum

through 100 µrad (H) x 50 µrad (V) Ap.
at K~1.5 providing H5 peak at ~10 keV



"Multi-Electron" Intensity Distributions (Horizontal Cuts)

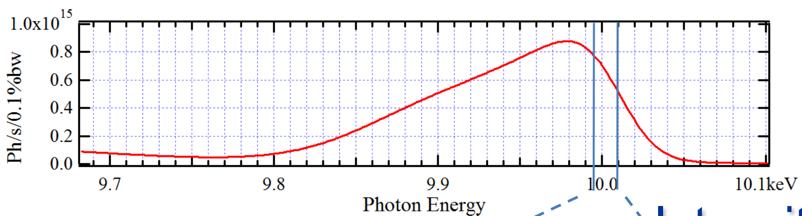




Estimation of X-Ray Beam Angular Divergence and Source Size by Wavefront Propagation

IVU20-3m Spectral Flux

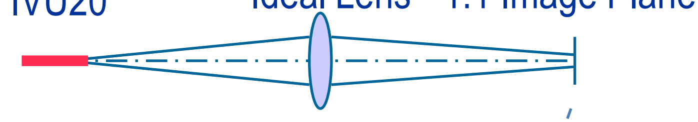
through 100 μrad (H) x 50 μrad (V) Aperture
at K~1.5 providing H5 peak at ~10 keV



Electron Beam:

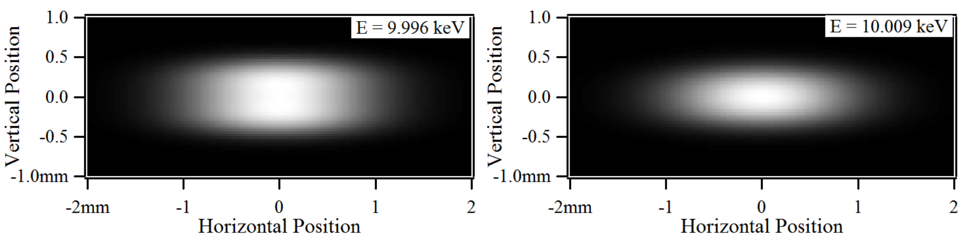
Hor. Emittance: 0.9 nm
Vert. Emittance: 8 pm
Energy Spread: 8.9x10^{-4}
Current: 0.5 A
Low-Beta Straight

Test Optical Scheme

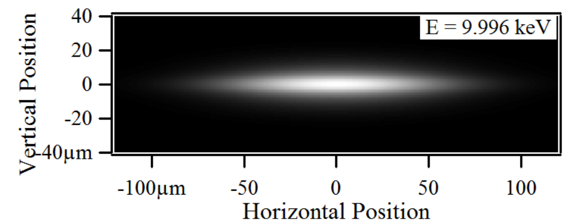


Intensity Distributions at ~10 keV

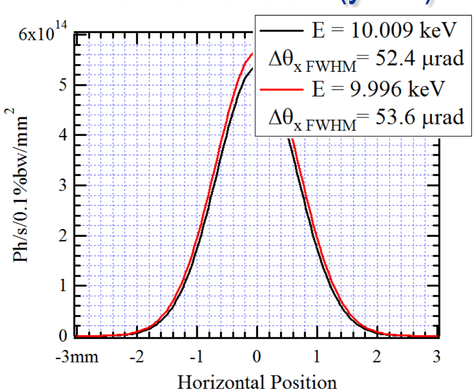
At 30 m from Undulator



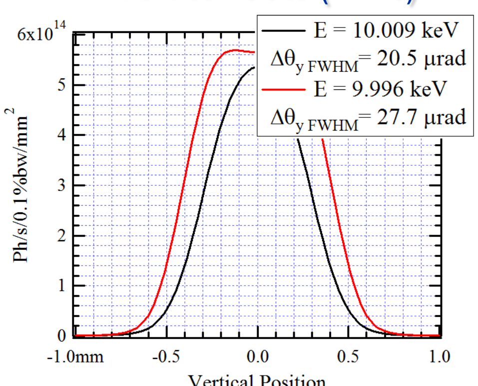
In 1:1 Image Plane



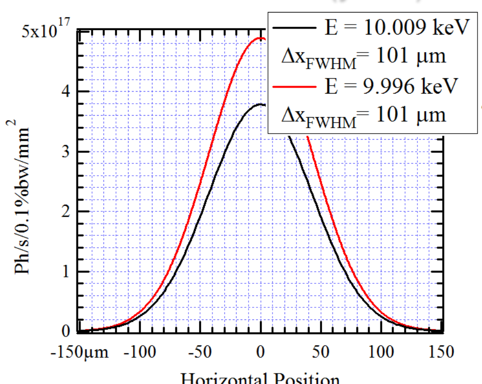
Horizontal Cuts (y = 0)



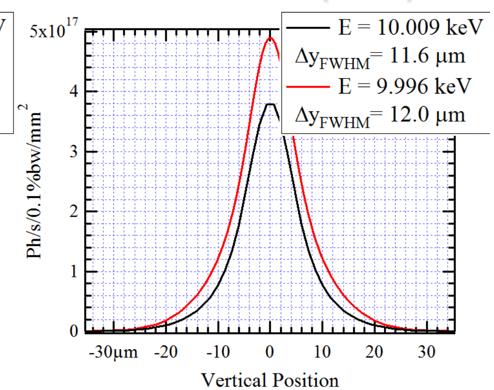
Vertical Cuts (x = 0)



Horizontal Cuts (y = 0)



Vertical Cuts (x = 0)



$$\sigma_x \sigma_x' \approx \mathbf{97}\frac{\lambda}{4\pi}; \quad \sigma_y \sigma_y' \approx \mathbf{5.7}\frac{\lambda}{4\pi}$$

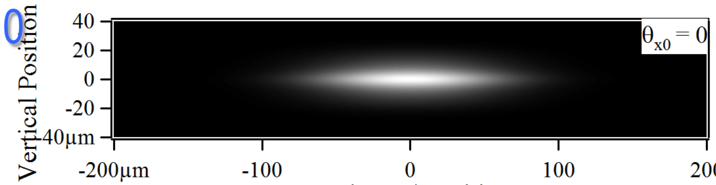
…very far from Coherent Gaussian Beam !

Intensity Distributions of Focused Wiggler Radiation from Partially-Coherent Wavefront Propagation Calculations

On-Axis Collection: $\theta_{x0} = 0$, $\theta_{y0} = 0$

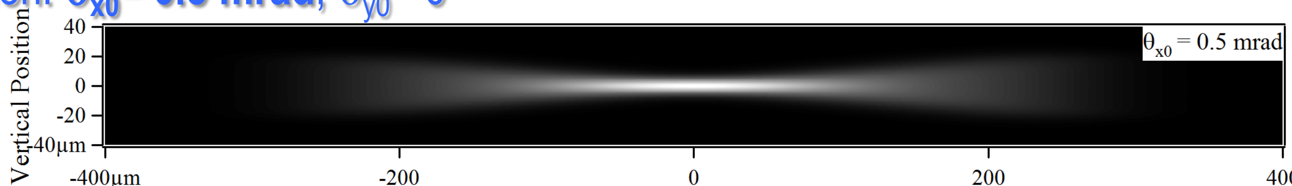
$|\theta_x - \theta_{x0}| < 0.1$ mrad

$|\theta_y - \theta_{y0}| < 0.1$ mrad

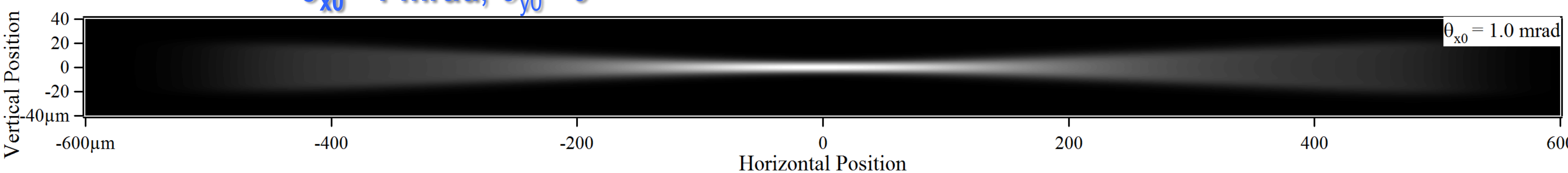


1 : 1 Imaging Scheme with "Ideal Lens"

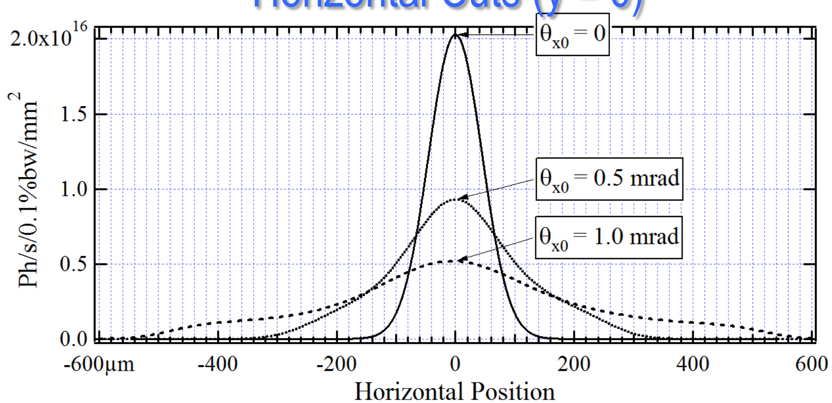
Off-Axis Collection: $\theta_{x0} = 0.5$ mrad, $\theta_{y0} = 0$



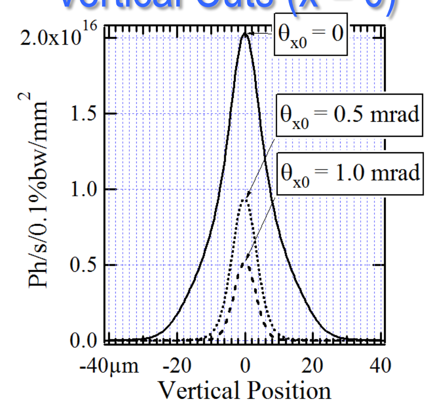
$\theta_{x0} = 1$ mrad, $\theta_{y0} = 0$



Horizontal Cuts (y = 0)



Vertical Cuts (x = 0)



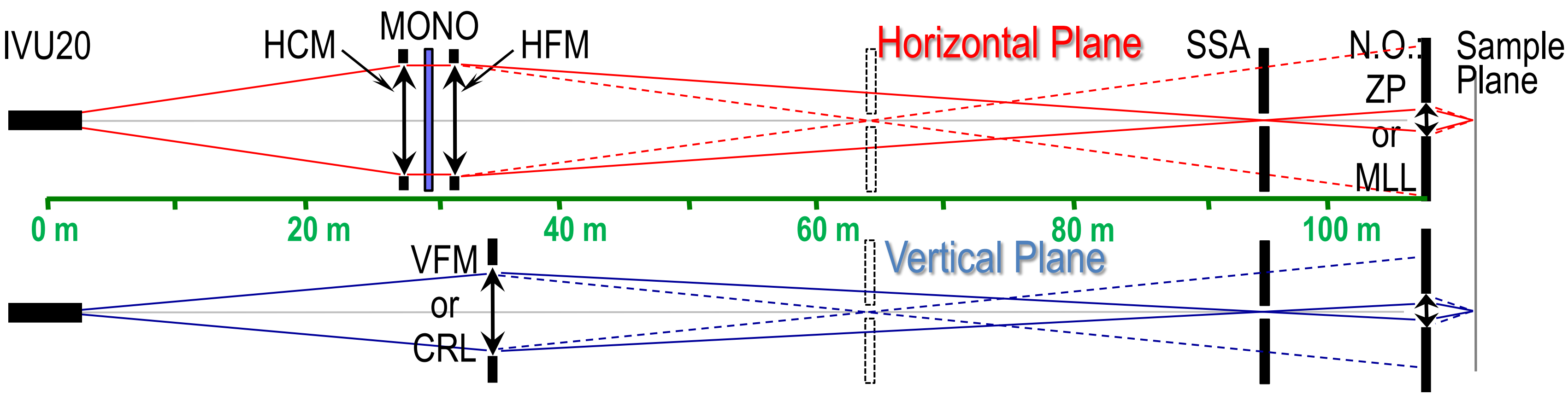
NSLS-II Low-Beta Straight Section

I = 0.5 A, $\varepsilon_x = 0.9$ nm, $\varepsilon_y = 8$ pm

SCW40: $\lambda_u = 40$ mm, $B_{max} = 3$ T, L = 1 m

Photon Energy: $E_{ph} = 10$ keV

NSLS-II Hard X-Ray Nanoprobe (HXN) Beamline Conceptual Optical Scheme



Y. Chu, H. Yan, K. Kaznatcheev

Approximations Used to Simulate Optical Elements:

Horizontal Collimating, Horizontal Focusing and Vertical Focusing **Mirrors** (HCM, HFM and VFM respectively), and **Nanofocusing Optics** (N.O.) simulated by **"Ideal" Lenses**.

Geometrical Apertures of all Mirrors, the Secondary Source Aperture (SSA), and the N.O. are **carefully respected**.

Monochromator (MONO) was assumed to be **"Ideal"**.

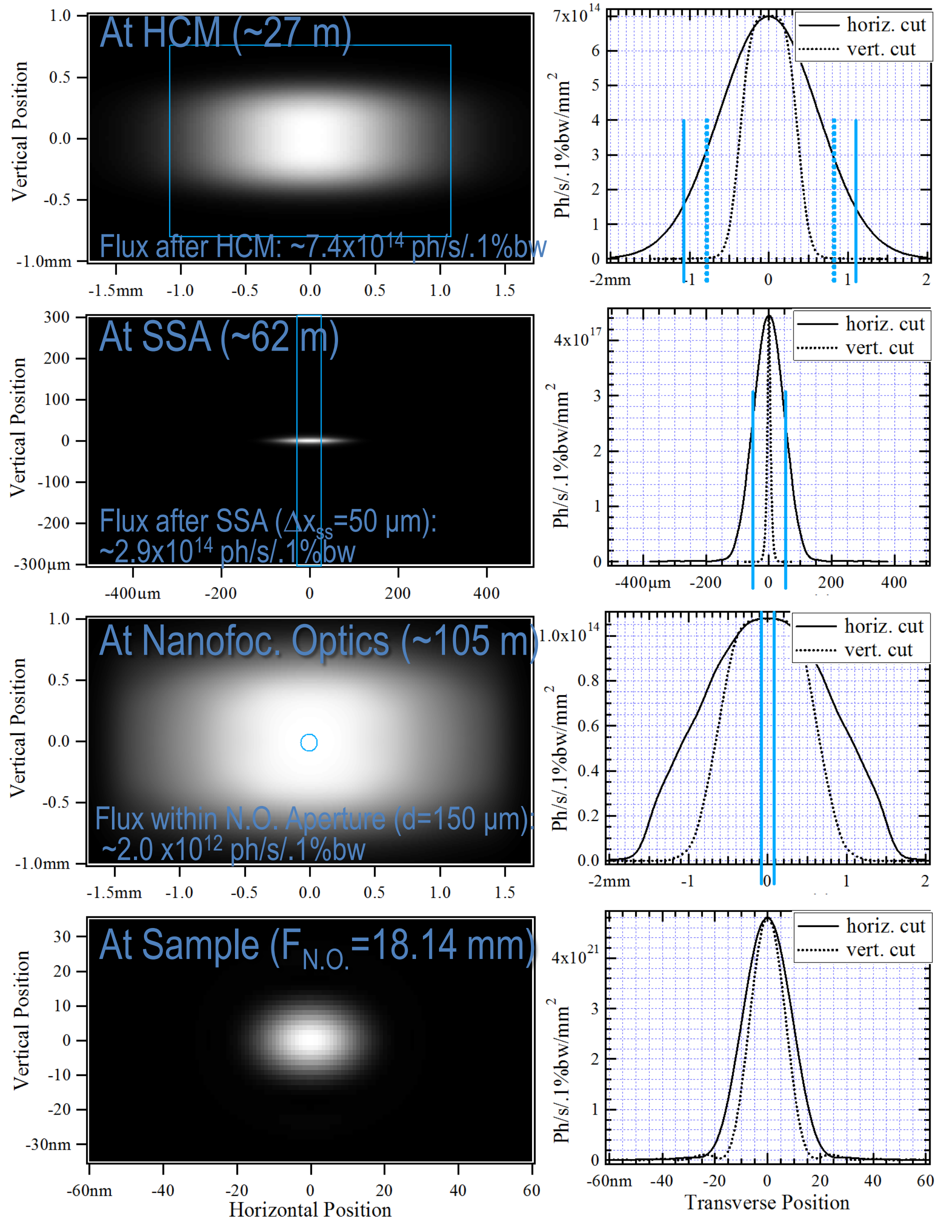
*Such approximations were used purposely, in order to "observe" pure effects related to **partial coherence** of the source, and to trace **losses on apertures**.*

Two possible SSA locations: at ~62 - 65 m and at ~92 - 94 m from undulator.

Two N.O. cases: F = 18.14 mm, D = 150 µm; and F = 42.33 mm, D = 350 µm (Δr ≈ 15 nm in both cases); E_{ph}≈ 10 keV

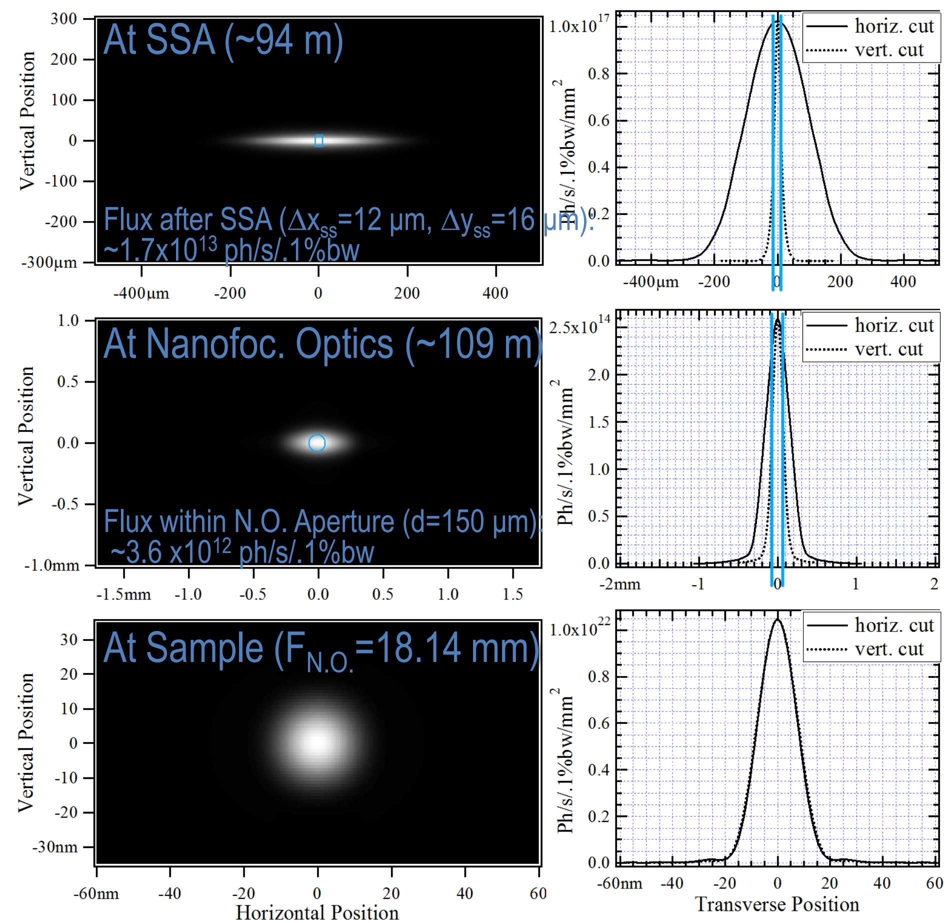
Intensity Distributions at Different Locations of HXN Beamline

Option with Secondary Source at 62 m



I_e = 0.5 A
E_{ph} ≈ 10 keV
5^{th} harmonic of IVU20 at K ≈ 1.5

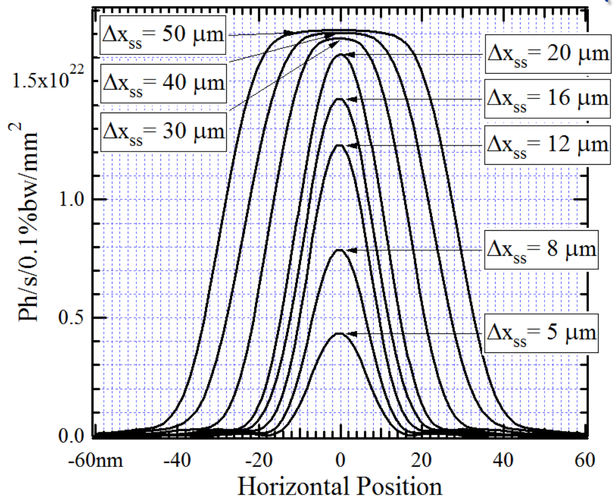
Option with Secondary Source at 94 m



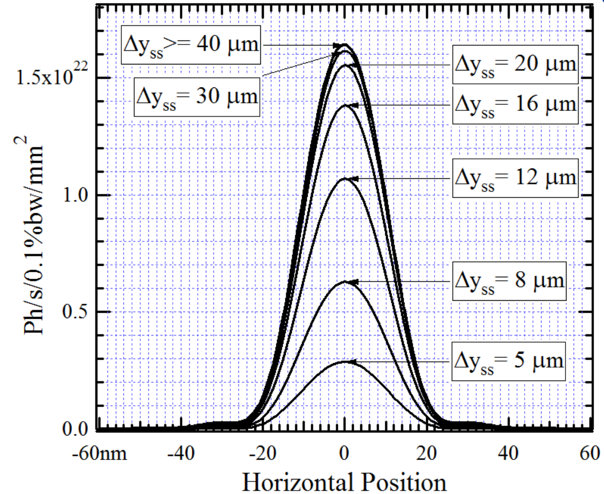
Intensity Distributions at Sample for Different Secondary Source Aperture Sizes at HXN (NSLS-II)

In Horizontal Median Plane (y = 0)

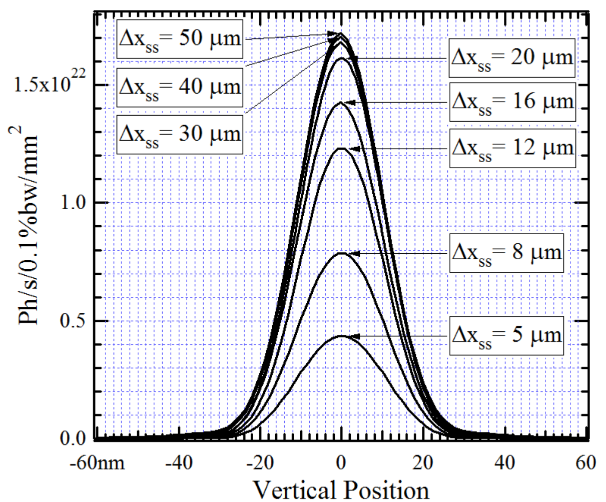
For Different Horizontal SSA Sizes (Δx_{ss})

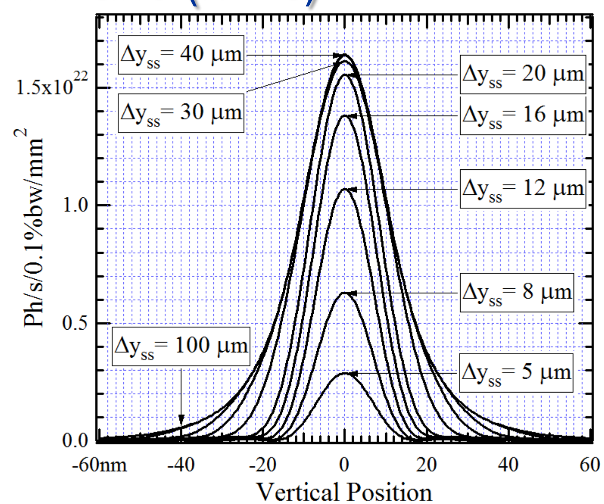


For Different Vertical SSA Sizes (Δy_{ss})



In Vertical Median Plane (x = 0)

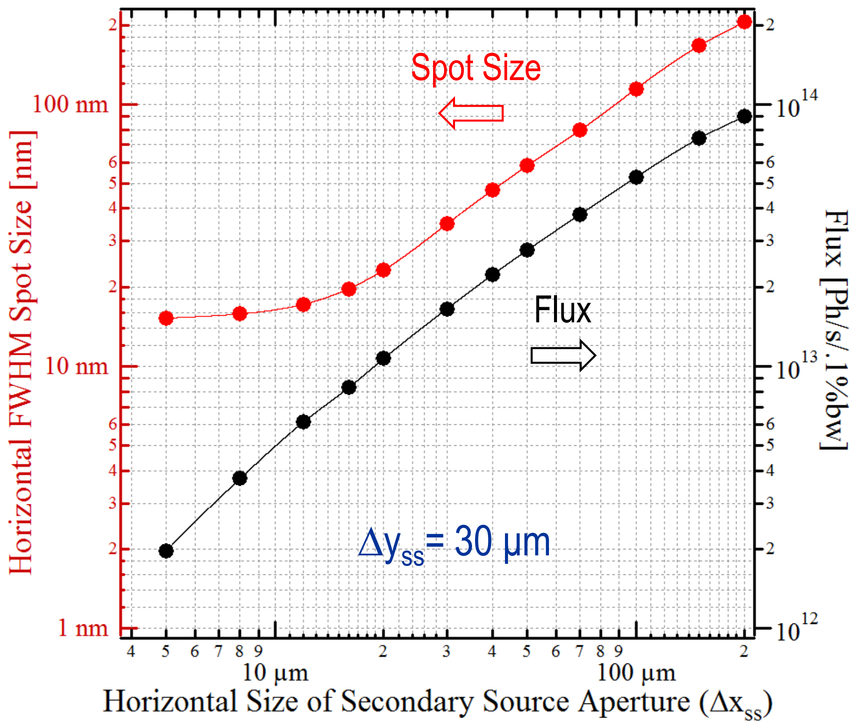




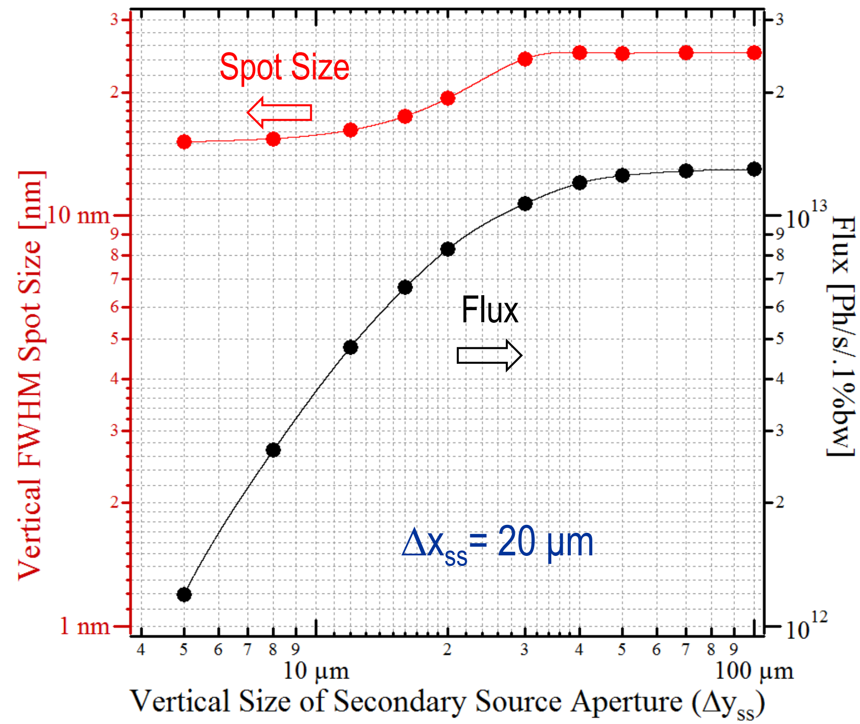
For Nanofocusing Optics with F = 18.14 mm, D = 150 μm ($\Delta r \approx 15$ nm; $E_{ph} \approx 10$ keV)
SSA located at 94 m, Nanofocusing Optics at 109 m from Undulator

Final Focal Spot Size and Flux vs Secondary Source Aperture Size (HXN, NSLS-II)

Horizontal Spot Size and Flux
vs Horizontal Secondary Source Aperture Size



Vertical Spot Size and Flux
vs Vertical Secondary Source Aperture Size



Secondary Source Aperture located at 94 m from Undulator
Spot Size and Flux calculated for Nanofocusing Optics simulated by Ideal Lens with F = 18.14 mm, D = 150 μm located at 15 m from Secondary Source (109 m from Undulator)

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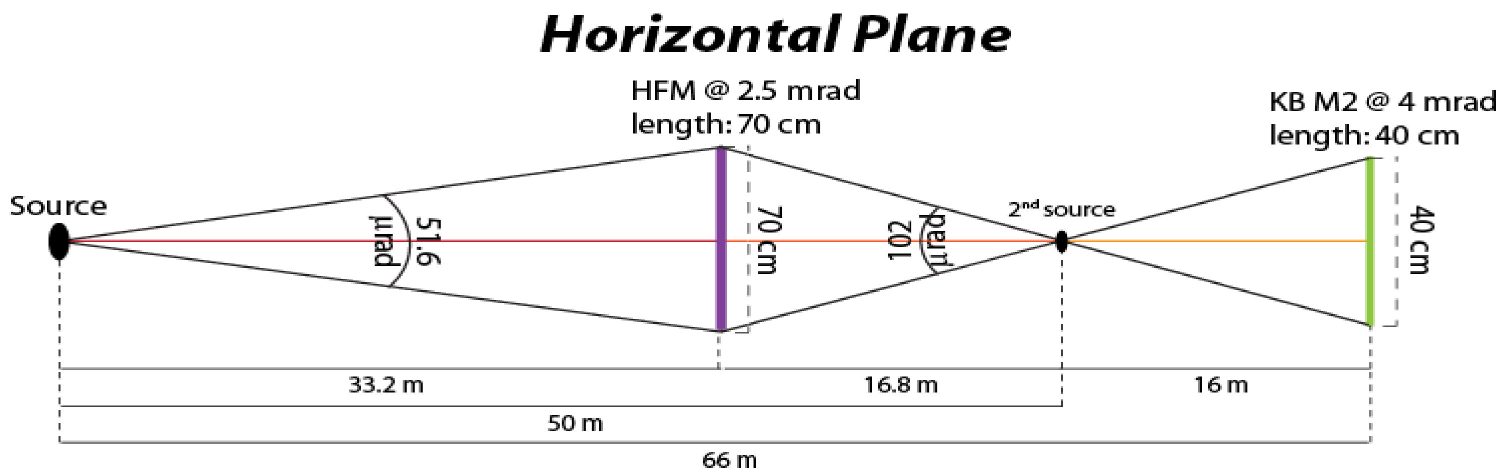
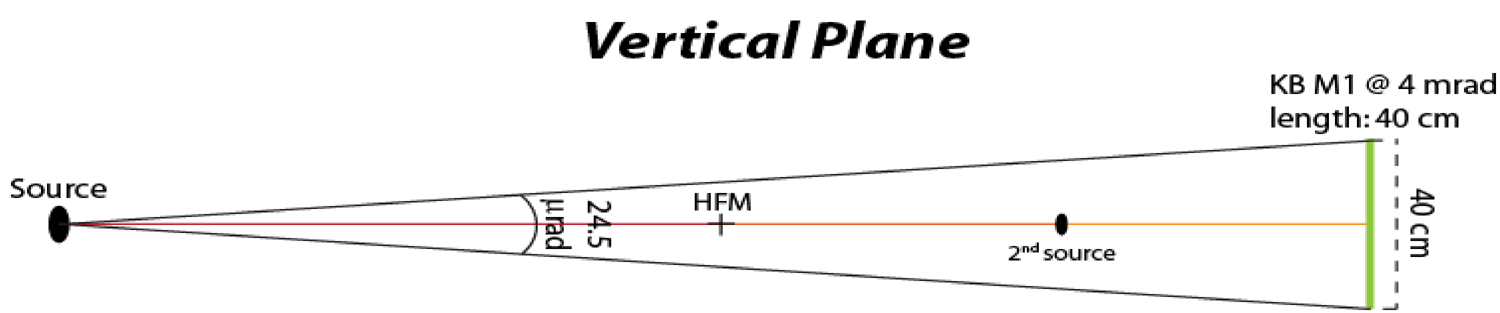
NSLS-II SRX Beamline
Conceptual Optical Scheme

2 operation modes with 2 sets of KB's:
- High flux mode (with large mirrors)
- High resolution mode (diffraction limited)

J. Thieme
V. DeAndrade

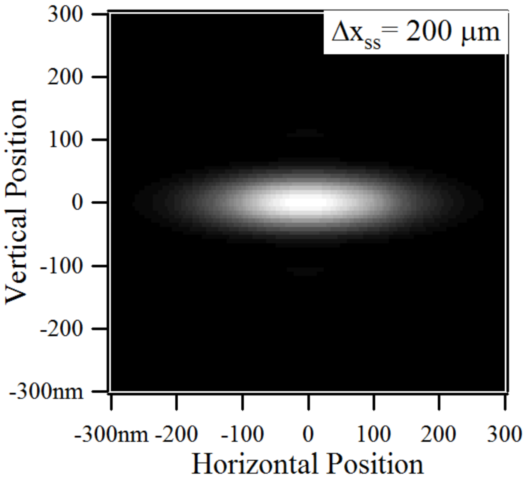




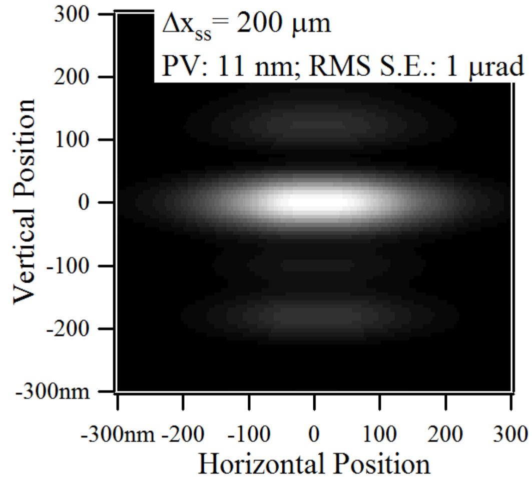
Preliminary Partially-Coherent Wavefront Propagation Simulation Results for SRX: **Imperfect K-B Mirrors (I)**

Intensity Distributions "at Sample" at **200 µm** Size of Secondary Source Aperture

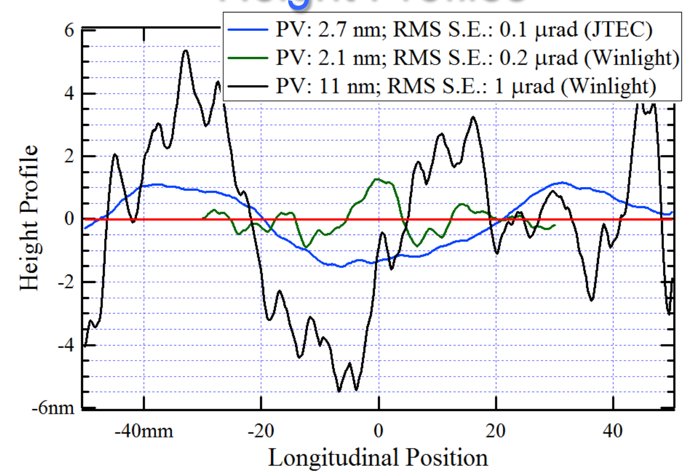
Perfect Optics (Ideal Lenses)



Imperfect Optics

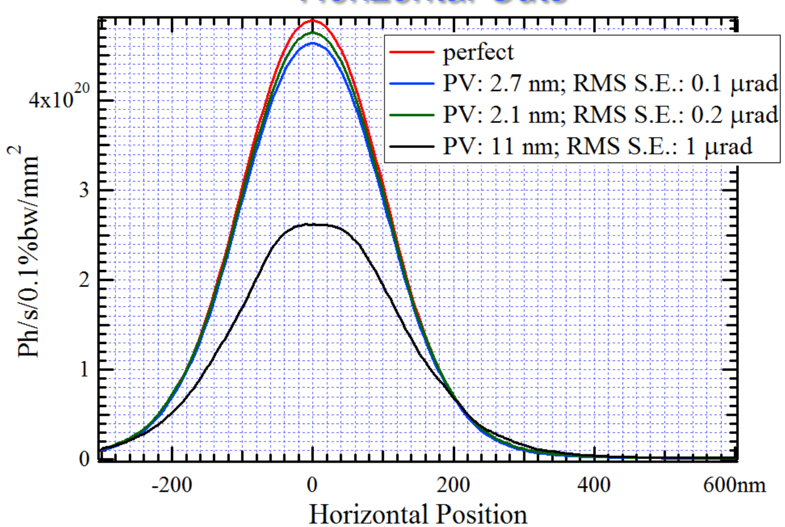


Imperfect Mirror Height Profiles

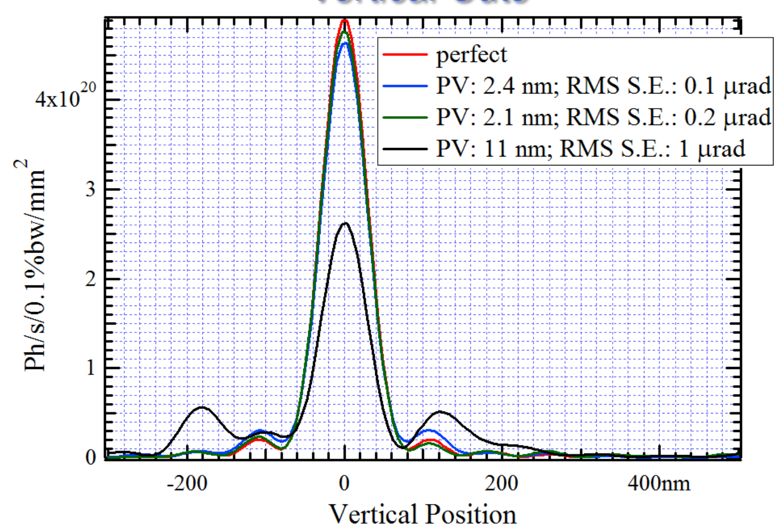


V. DeAndrade

Horizontal Cuts



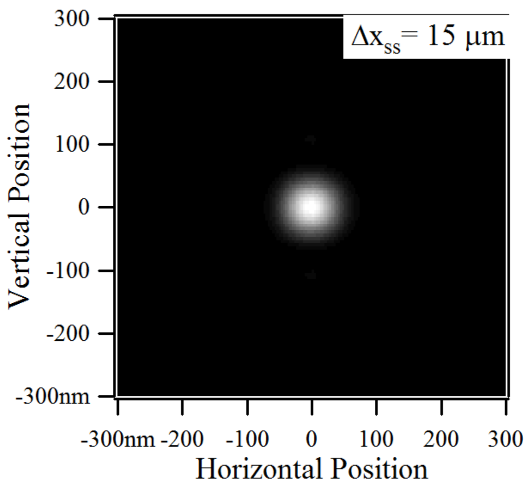
Vertical Cuts



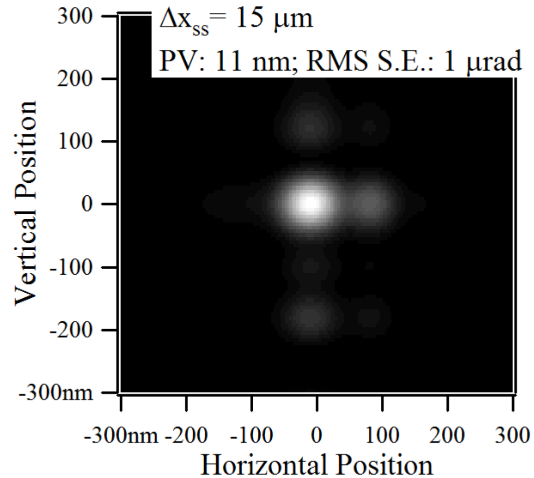
Preliminary Partially-Coherent Wavefront Propagation Simulation Results for SRX: **Imperfect K-B Mirrors (II)**

Intensity Distributions "at Sample" at **15 µm** Size of Secondary Source Aperture

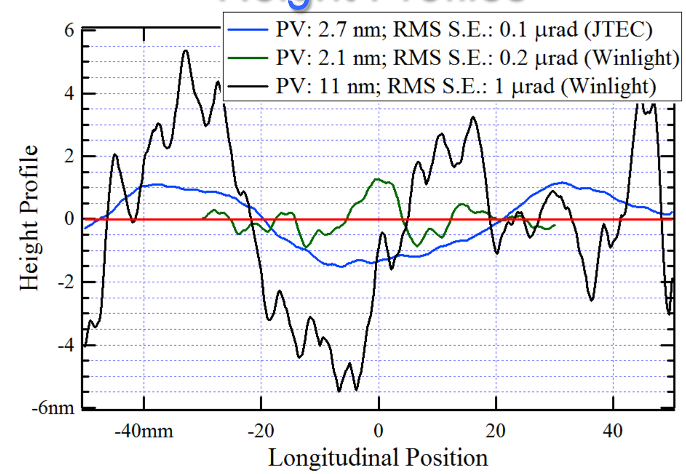
Perfect Optics (Ideal Lenses)



Imperfect Optics

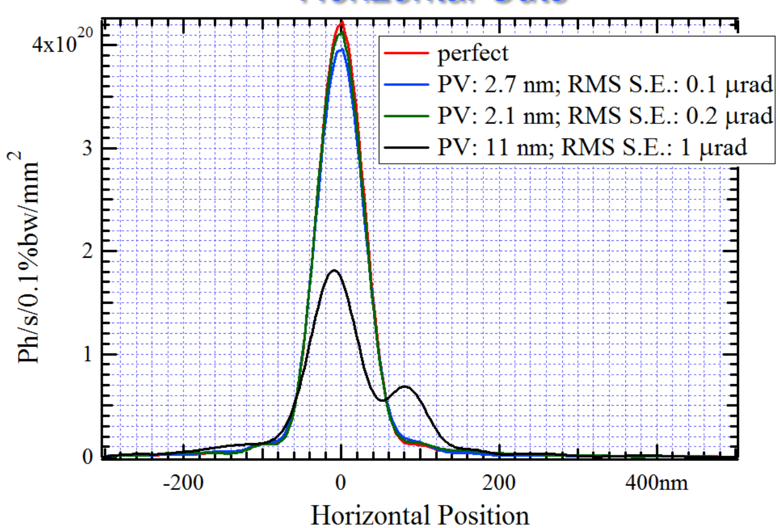


Imperfect Mirror Height Profiles

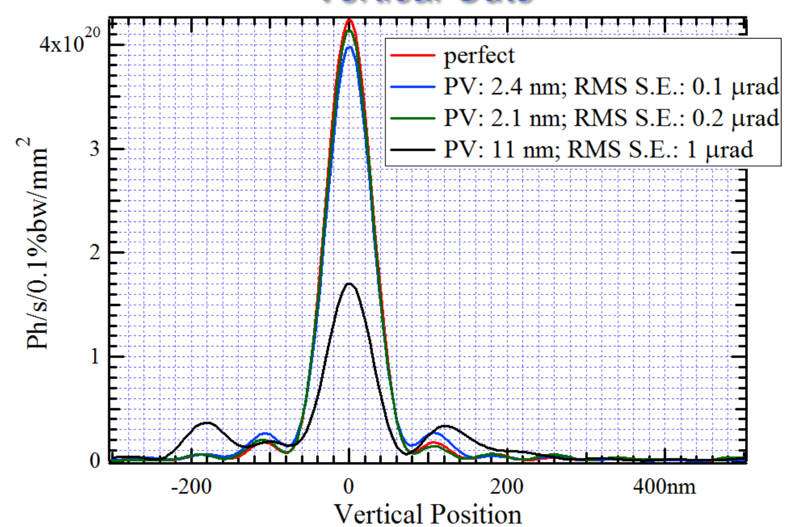


V. DeAndrade

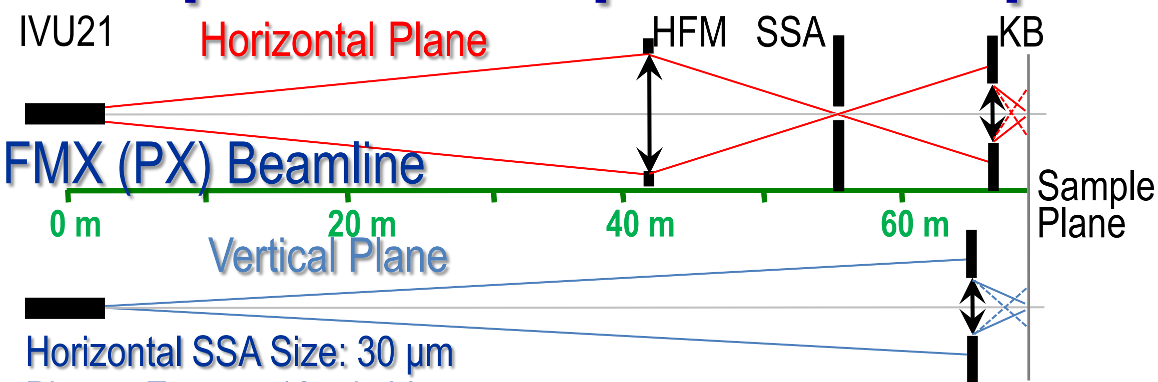
Horizontal Cuts



Vertical Cuts



Intensity Distributions at Sample Taking Into Account Ellipsoidal Shapes and Slope Errors of KB Mirrors



Horizontal SSA Size: 30 μm
Photon Energy: 12.7 keV
Flux at Sample: ~5.4x10^{13} ph/s/.1%bw

KB simulated using Grazing-Incidence "Thick Optical Element" Propagator based on Local Ray-Tracing.

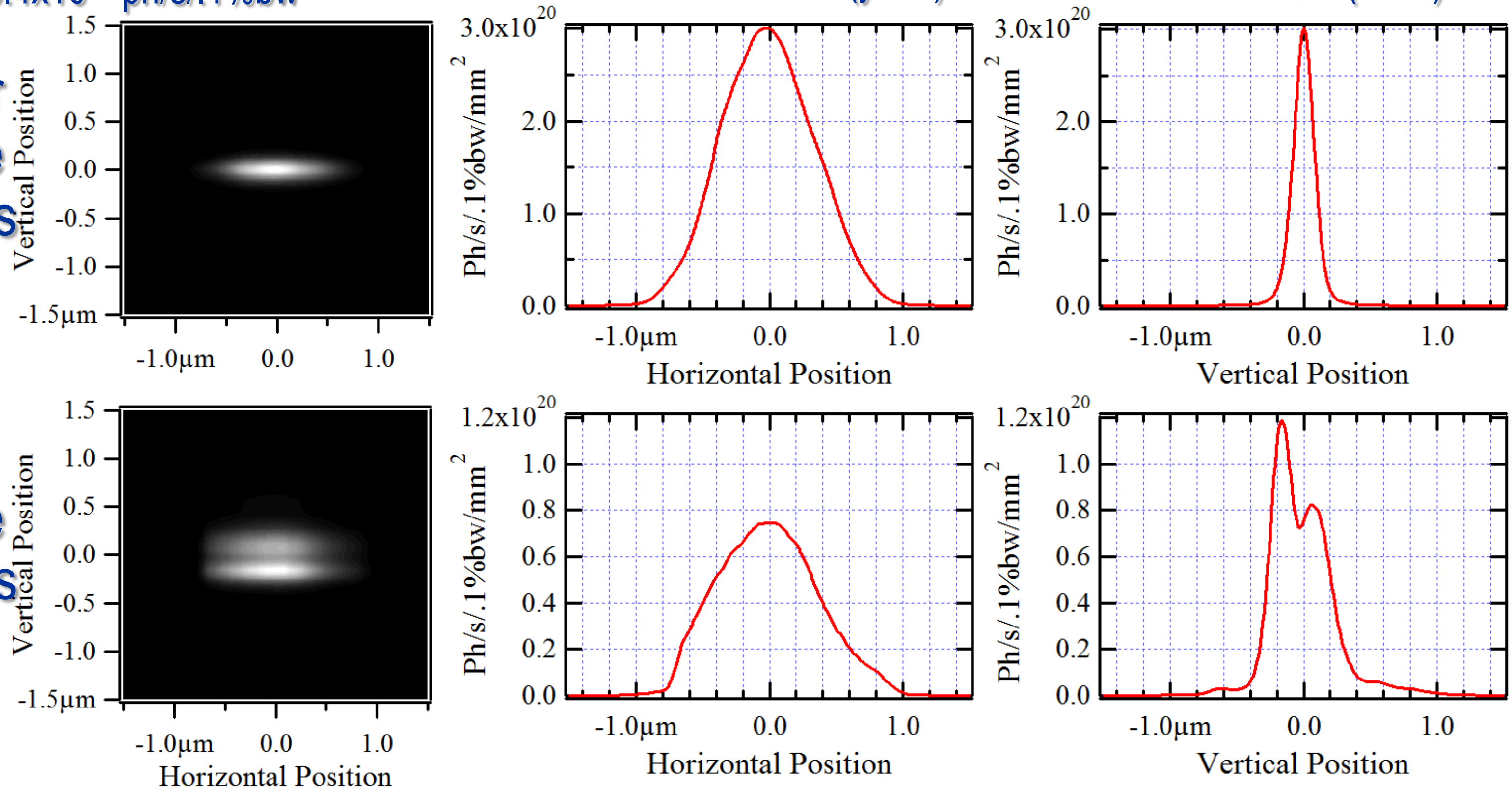
KB Surface Height Error simulated by corresponding Phase Shifts ("Masks") in Transverse Plane at Mirror Locations.

Horizontal Cuts (y = 0)

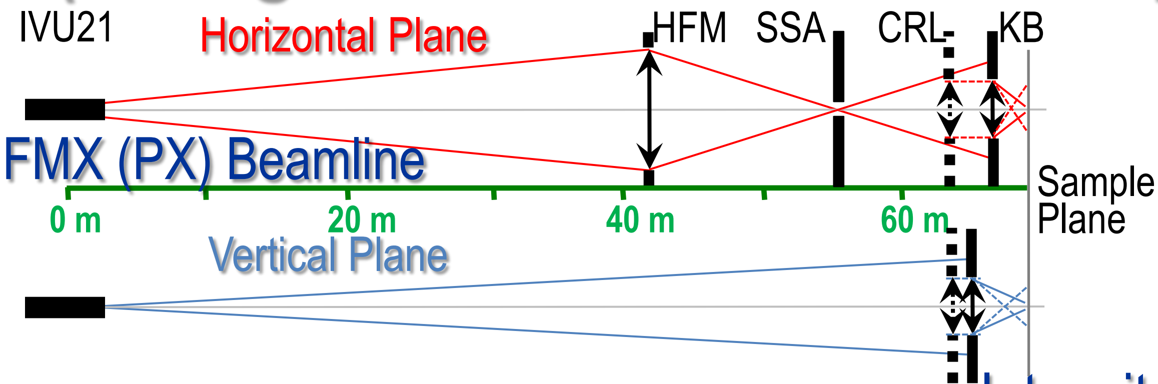
Vertical Cuts (x = 0)

Without Mirror Surface Slope (/Height) Errors

With Mirror Surface Slope (/Height) Errors



Using CRLs for Producing "Large Spot" at Sample (taking into account Mirror Shape and Slope Error)



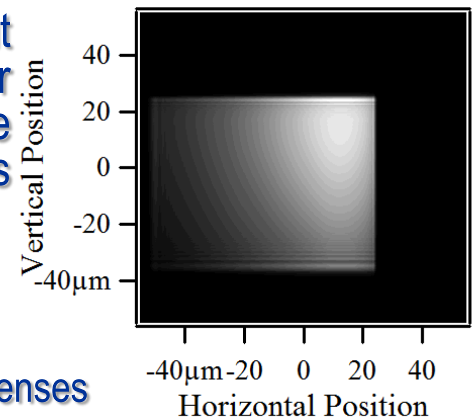
Source:

Electron Current: 0.5 A
Horizontal Emittance: 0.55 nm ("ultimate")
Vertical Emittance: 8 pm
Undulator: IVU21 – 1.5 m centered at +1.25 m from Low-Beta Straight Section Center

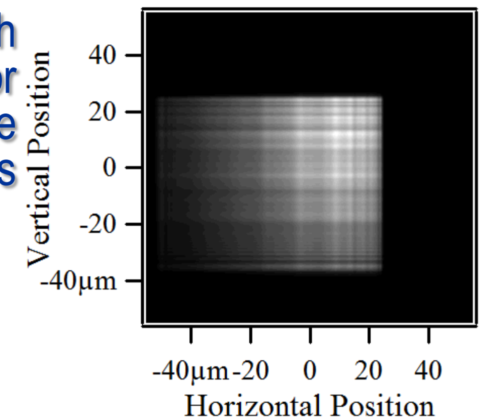
Horizontal SSA Size: 30 µm
Photon Energy: 12.7 keV

Intensity Distributions at Sample

Without Mirror Slope Errors



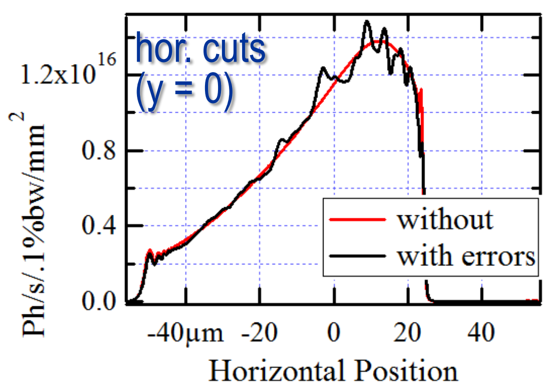
With Mirror Slope Errors

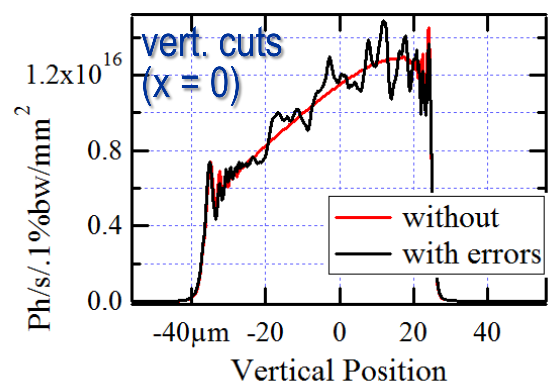


CRL "Transfocator":

8 Horizontally + 3 Vertically-Focusing Be Lenses
R_{min} = 200 µm
$F_h \approx$ 5.9 m, $F_v \approx$ 15.8 m
Geom. Ap.: 1 mm x 1 mm

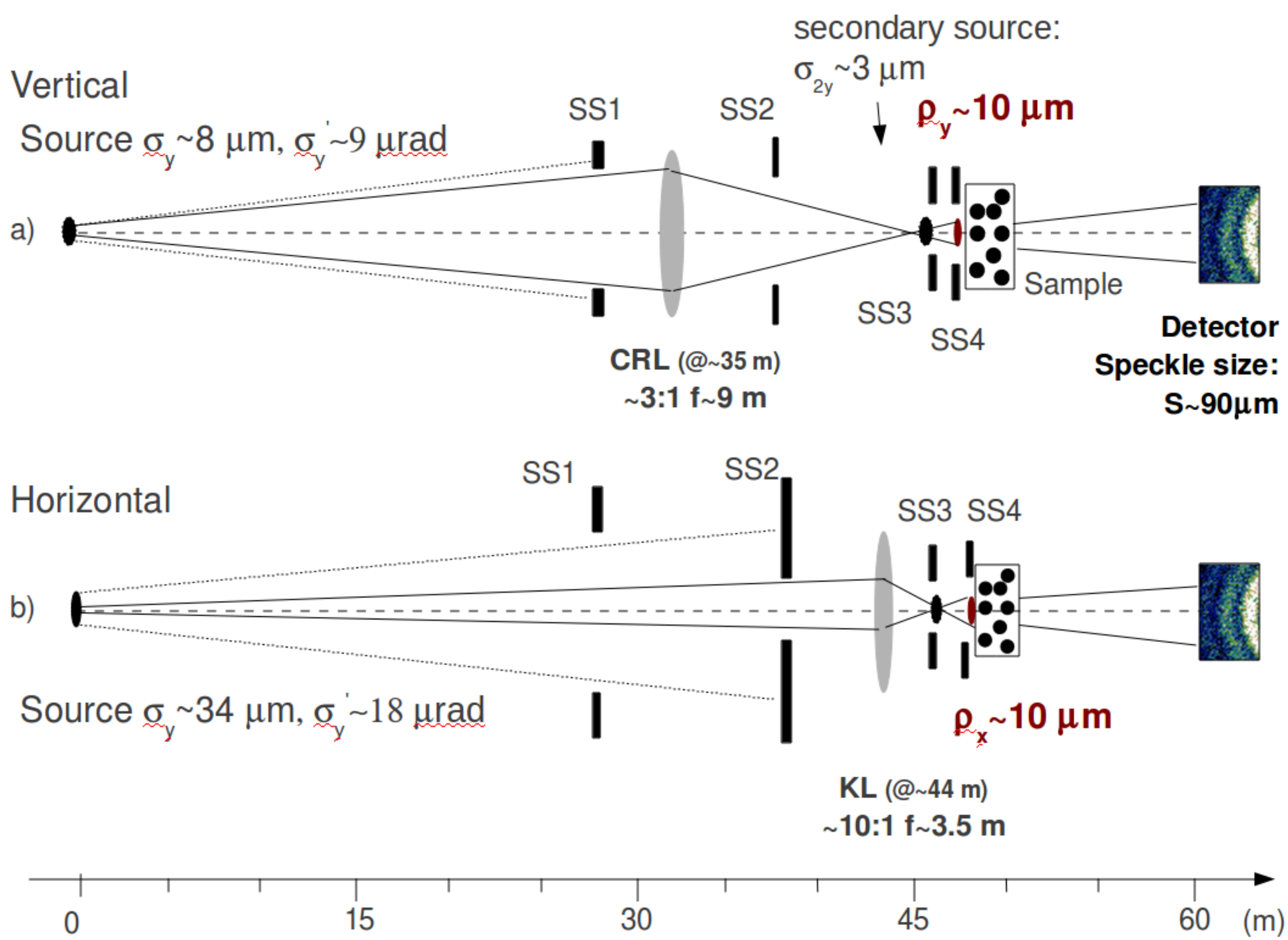
Located at 0.75 m before VKB edge
(10 m after SSA)
Flux Losses at CRL: ~1.6 times





NSLS-II Coherent Hard X-Ray (CHX) Beamline Conceptual Optical Scheme

A. Fluerasu, L. Wiegart, K. Kaznatcheev, L. Berman



U.S. DEPARTMENT OF ENERGY

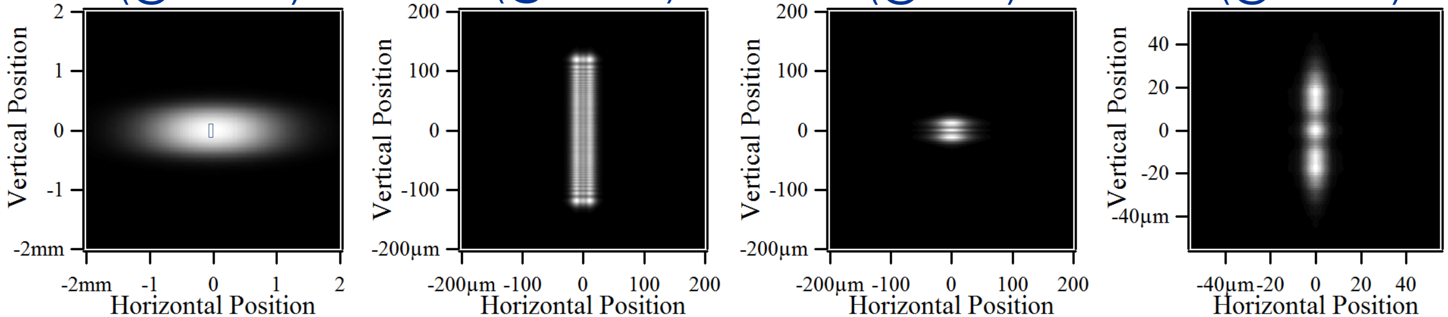
BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Partially-Coherent Wavefront Propagation Calculations for CHX

(I) Intensity Distributions in the Case of: ΔS_{1x}= 44 μm, ΔS_{1y}= 250 μm

Before SS1 (@33.5 m) | Before CRL (@35.3 m) | Before KL (@44 m) | At Sample (@48.5 m)

E=10 keV

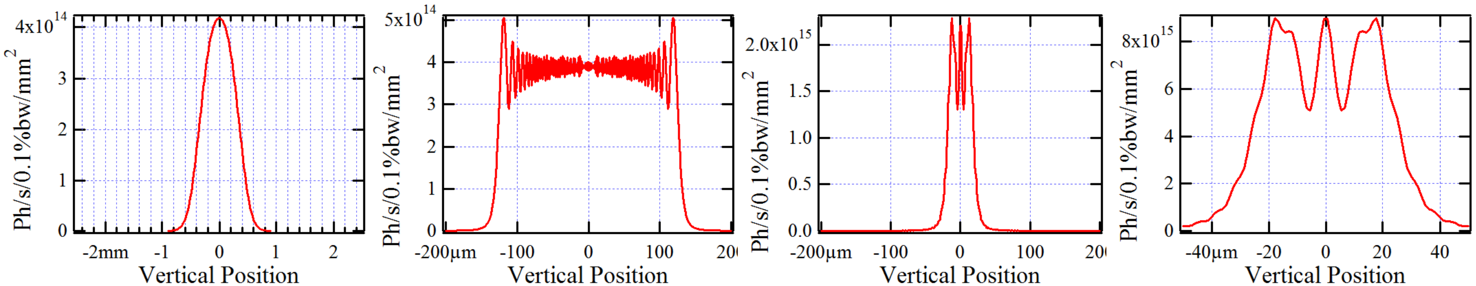


Be 1D CRL: N = 9, A_{geom}= 1 mm
R_{min}= 0.5 mm, F_y= 8.152 m

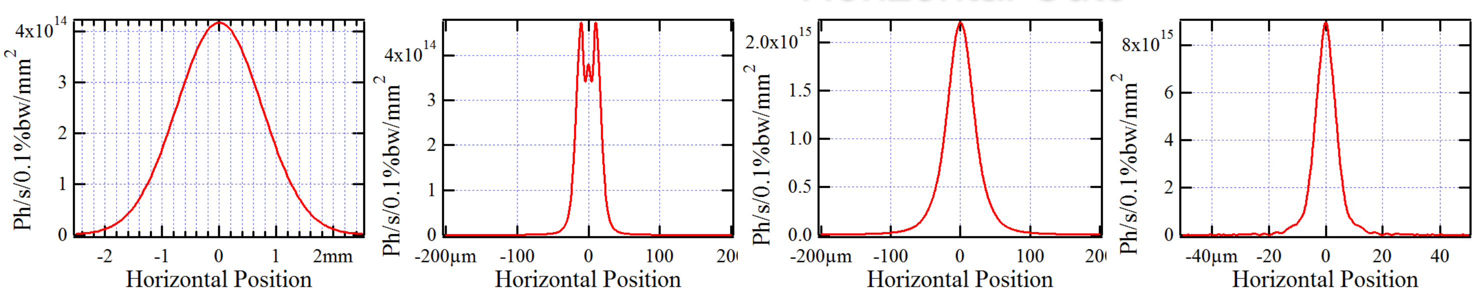
F_{KLx}≈ 3.5 m

Flux: 4x10[13] ph/s/.1%bw

Vertical Cuts



Horizontal Cuts

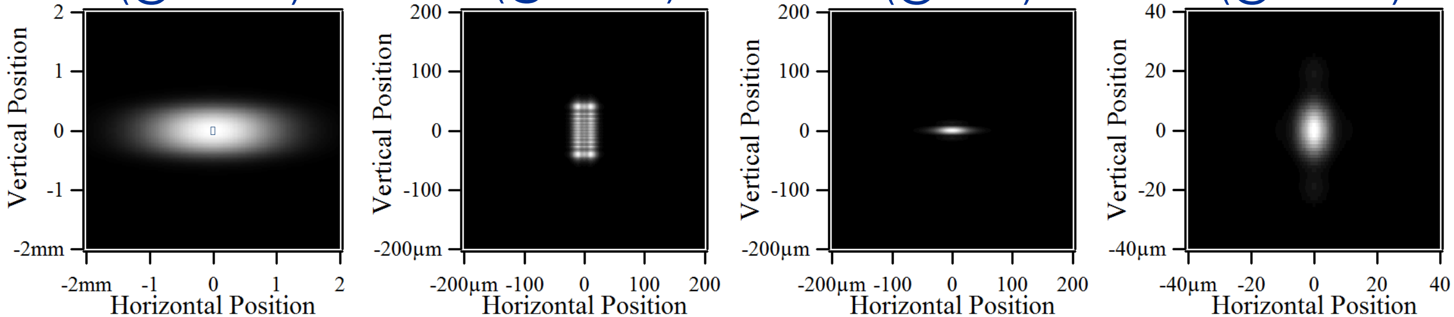


Partially-Coherent Wavefront Propagation Calculations for CHX

(II) Intensity Distributions in the Case of: ΔS_{1x}= 44 µm, ΔS_{1y}= 100 µm

Before SS1 (@33.5 m) | Before CRL (@35.3 m) | Before KL (@44 m) | At Sample (@48.5 m)

E=10 keV



After 2 Slits placed at Sample

Observation in Far Field

Slit Size: 1 µm

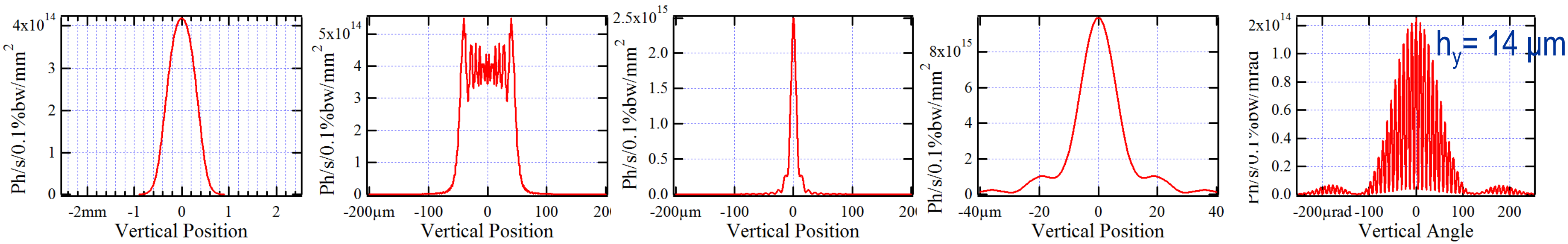
Be 1D CRL: N = 9, A_{geom}= 1 mm

R_{min}= 0.5 mm, F_y= 8.152 m

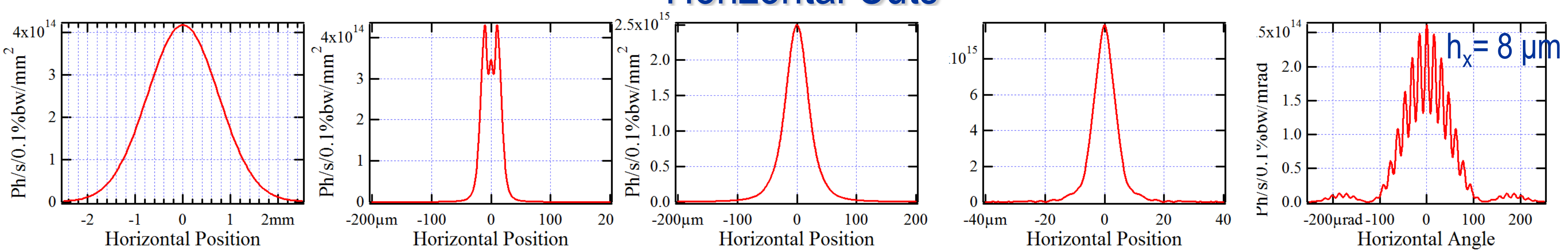
$F_{KLx}\approx$ 3.5 m

Flux: 1.6×10^{12} ph/s/.1%bw

Vertical Cuts



Horizontal Cuts



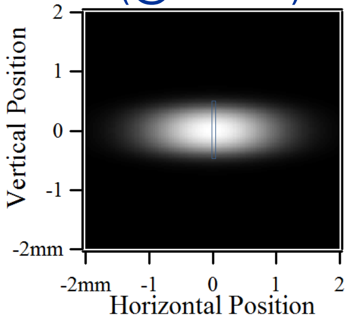
Partially-Coherent Wavefront Propagation Calculations for CHX

(III)

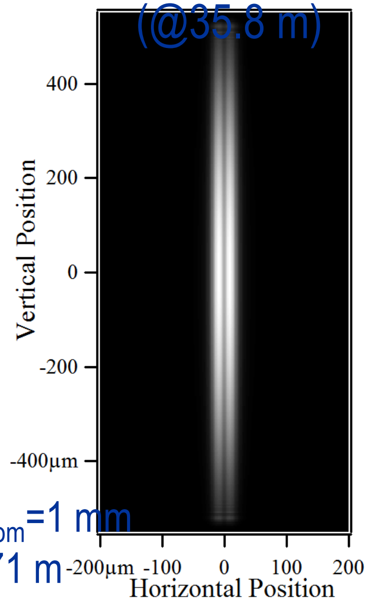
Intensity Distributions in the Case of: ΔS_{1x}= 44 μm, ΔS_{1y}= 1 mm

E=10 keV

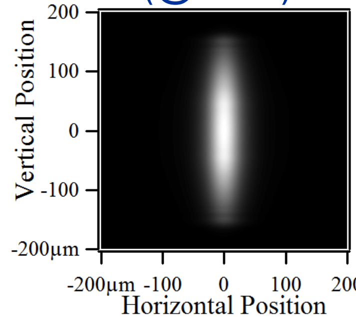
Before SS1 (@33.5 m)



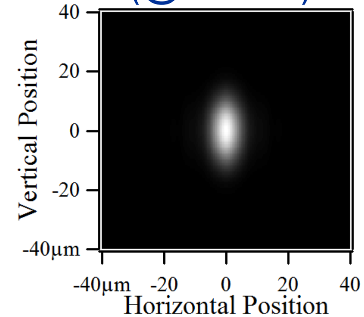
Before CRL (@35.8 m)



Before KL (@44 m)



At Sample (@48.5 m)



Be 1D CRL: N = 8, A_{geom}=1 mm

R_{min}= 0.5 mm, F_y= 9.171 m

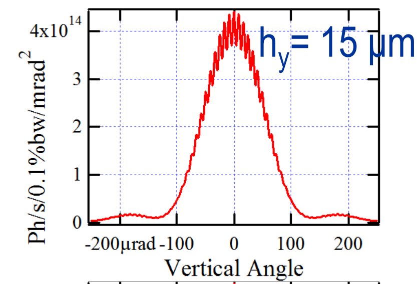
$F_{KLx} \approx$ 3.5 m

Flux: 10^{13} ph/s/.1%bw

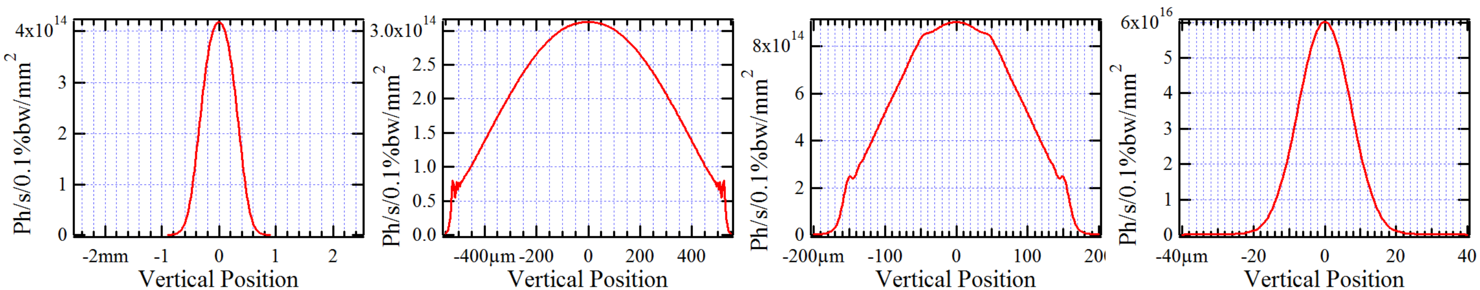
After 2 Slits placed at Sample

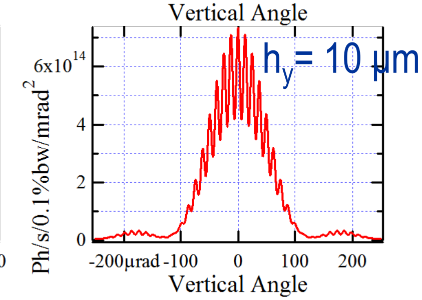
Observation in Far Field

Slit Size: 1 μm

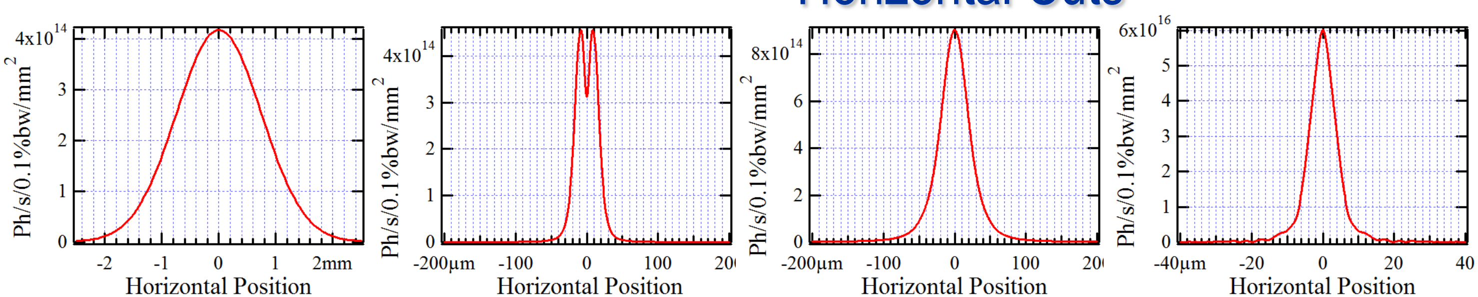


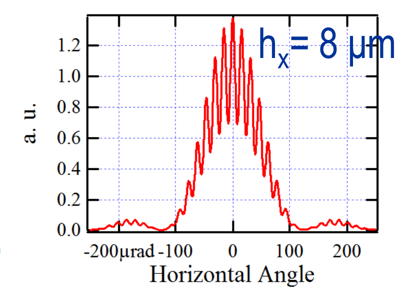
Vertical Cuts





Horizontal Cuts

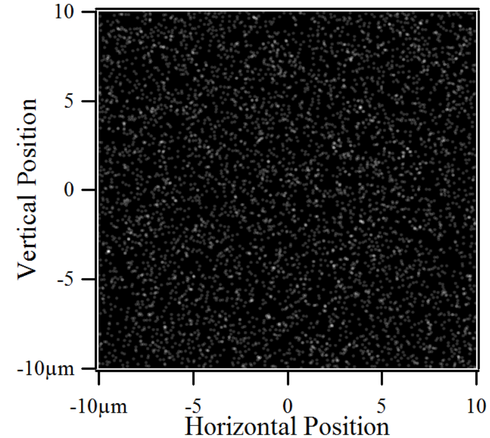




Partially-Coherent Wavefront Propagation Calculations for CHX

(IV) Diffraction / Scattering from Test Sample

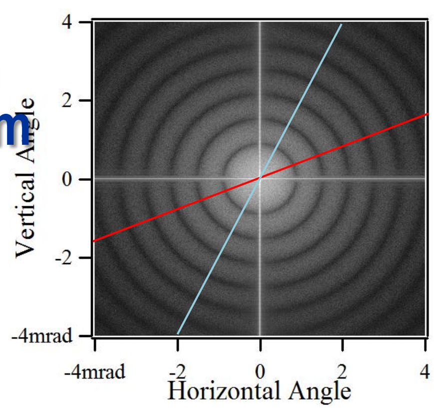
5000 “Silica Spheres”, d ≈ 200 nm

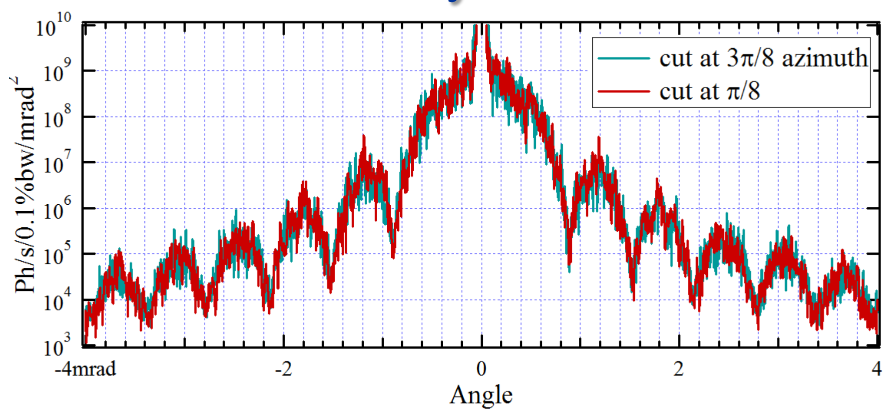


Sample data from Andrei Fluerasu

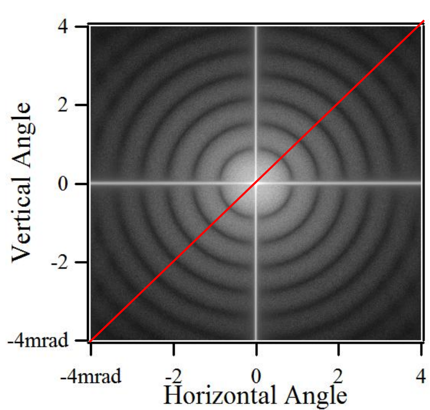
Angular Distribution of Scattered X-Rays at E=10 keV

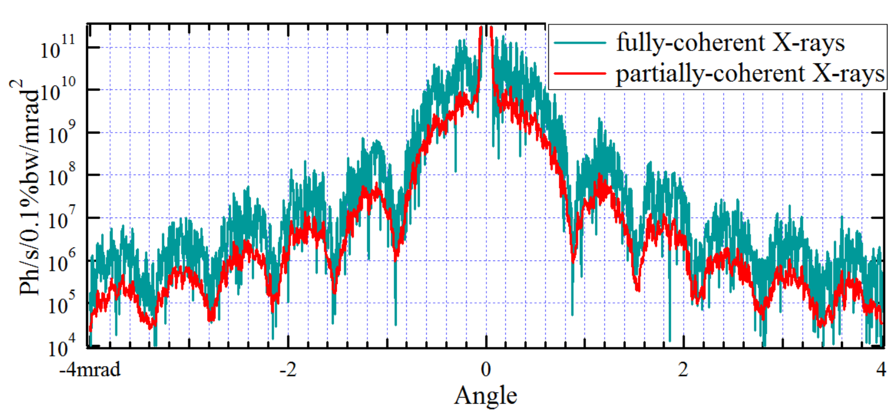
ΔS_{1x}= 44 µm
ΔS_{1y}= 100 µm





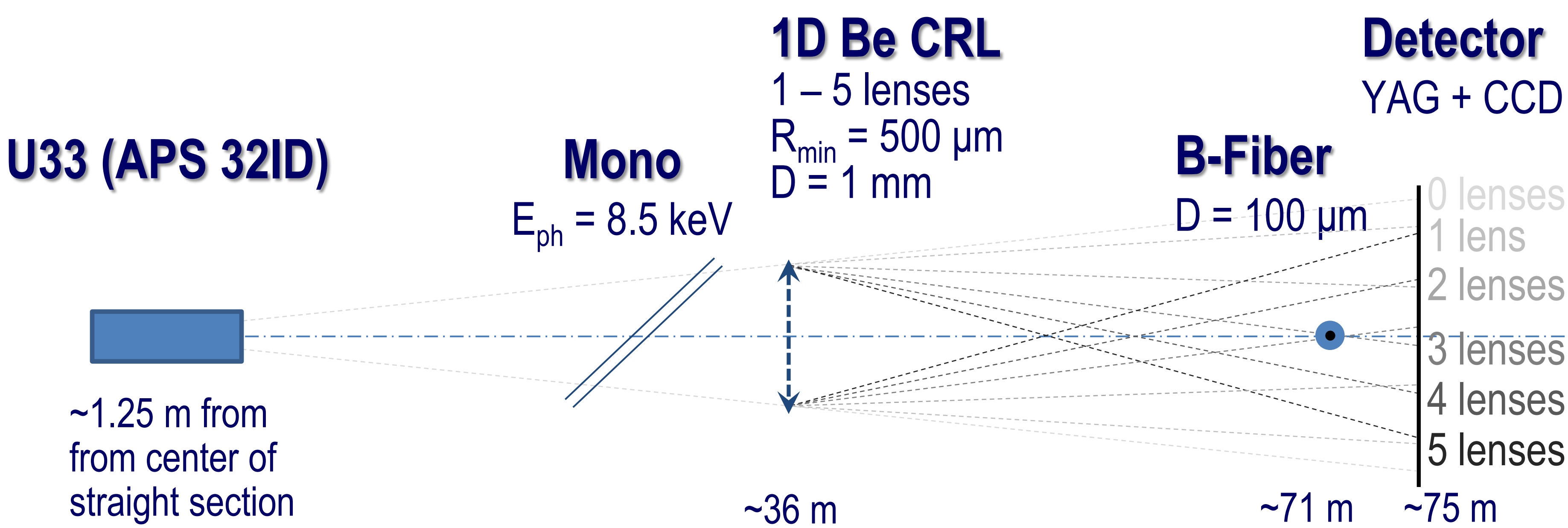
ΔS_{1x}= 44 µm
ΔS_{1y}= 1 mm





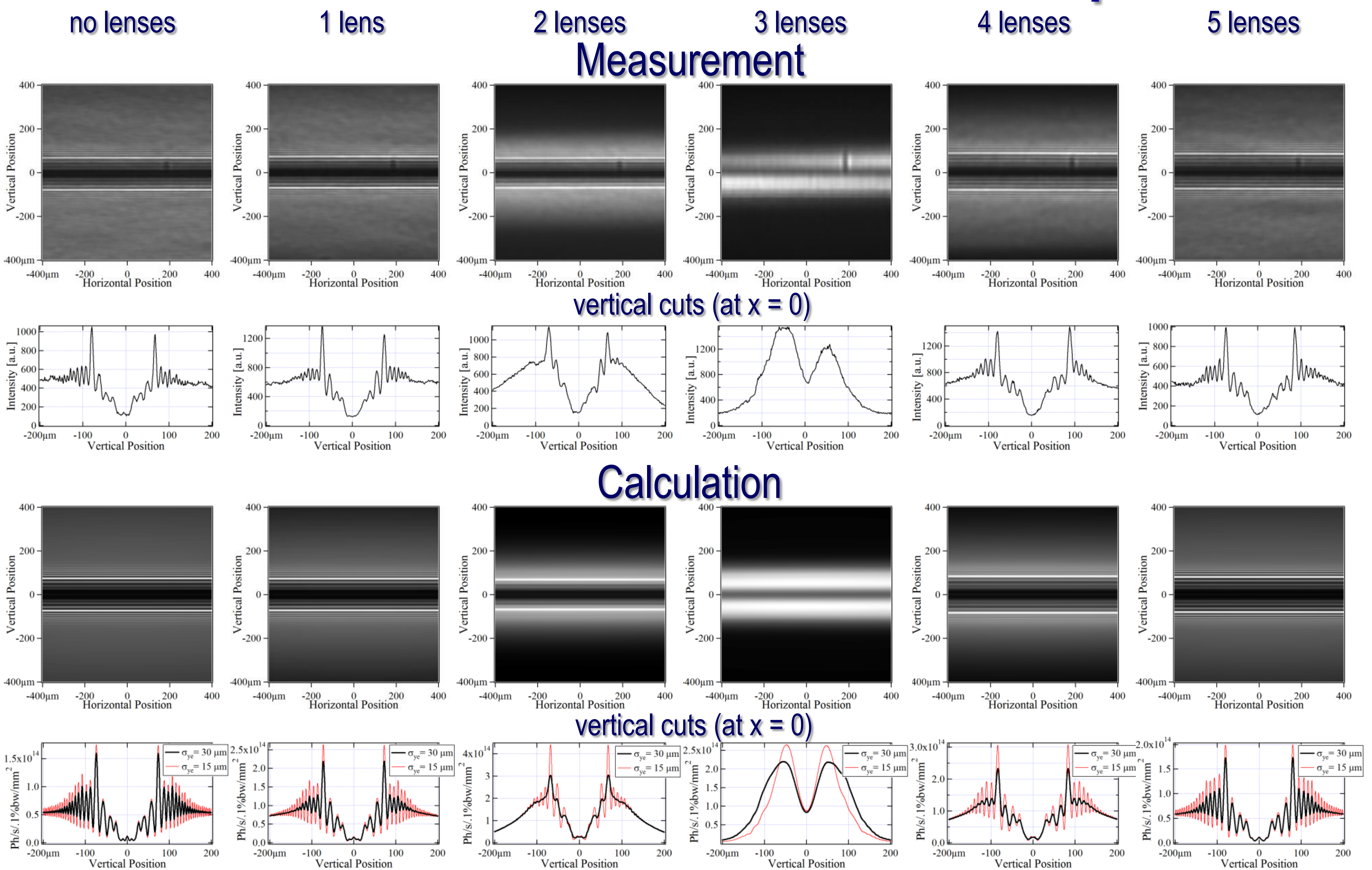
Optical Scheme of Wavefront Preservation Test Experiments with CRL and a Boron Fiber Probe

APS, Dec. 2011



- V. Kohn, I. Snigireva and A. Snigirev, "Direct measurement of transverse coherence length of hard X-rays from interference fringes", Phys. Rev. Lett., 2000, vol.85(13), p.2745.
- A. Snigirev, V. Kohn, I. Snigireva, B. Lengeler, "A compound refractive lens for focusing high-energy X-rays", Nature, 1996, vol.384, p.49.
- New generation CRL from B. Lengeler et al.

Intensity Distributions in B-Fiber Based Interference Scheme for Different Numbers of CRL in Optical Path



Simulations for FEL:
SASE Pulse Profiles and Spectra at FEL Exit

E-Beam: $E = 1$ GeV $\quad \sigma_{t\,e} \sim 200$ fs
$I_{peak} = 1.5$ kA $\quad \varepsilon_x = \varepsilon_y = 1.2\,\pi$ mm-mrad

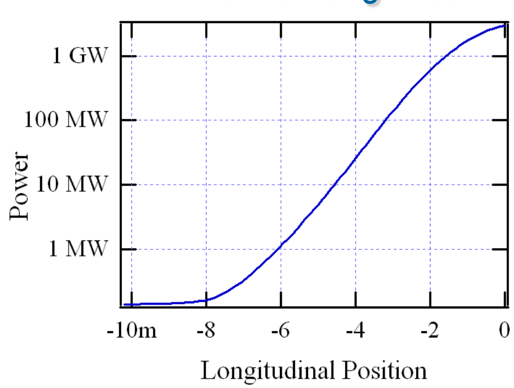
$P_{max\ ssed} \sim 50$ kW
$\sigma_{t\ seed} \sim 25$ fs

Undulator: $K \sim 2.06$
$\lambda_u = 30$ mm
$L_{tot} \sim 5 \times 2$ m
$\hbar\omega_0 = 100.15$ eV

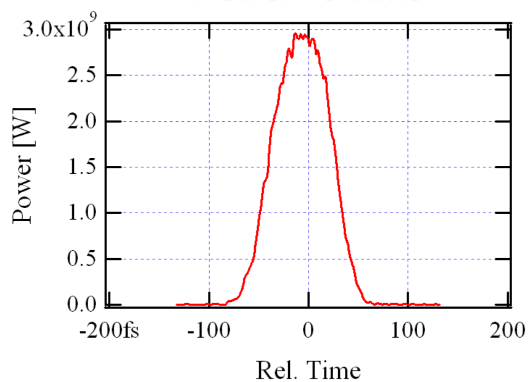
GENESIS
(integrated to SRW)

A: Seeded FEL operation

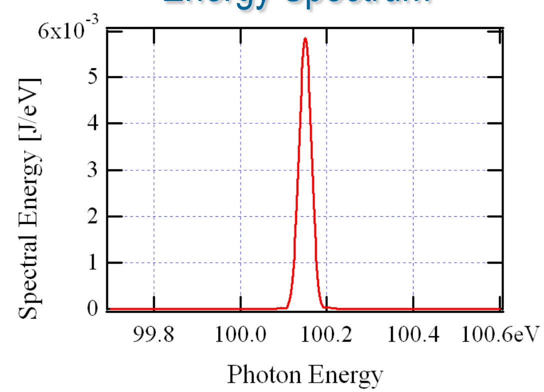
Peak Power vs Long. Position



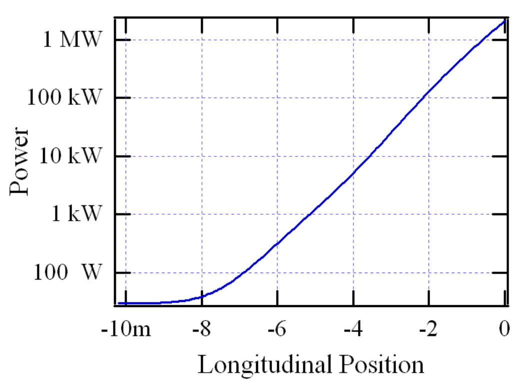
Power vs Time

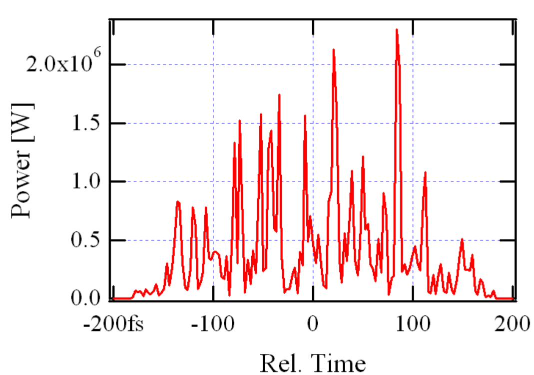


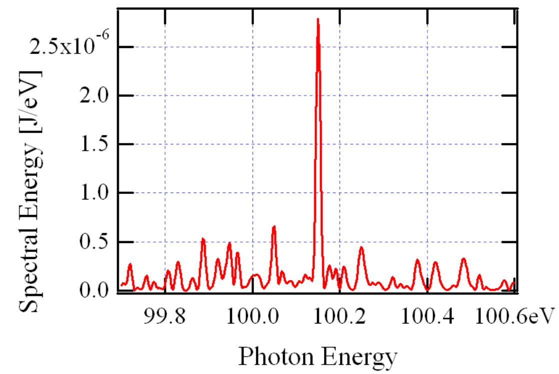
Energy Spectrum



B: SASE (not saturated)





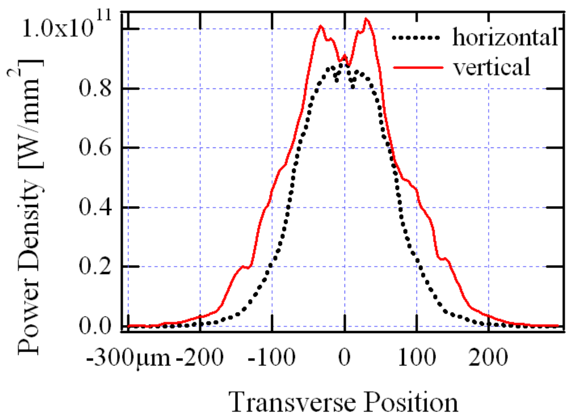


Simulations for FEL:
SASE Intensity Distributions at FEL Exit

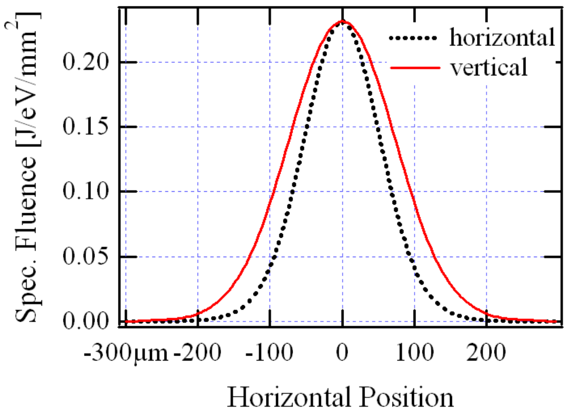
GENESIS
(integrated to SRW)

A: Seeded FEL operation

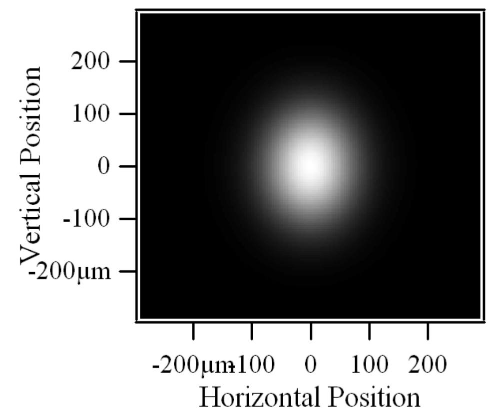
Power Density Cuts at Pulse Center



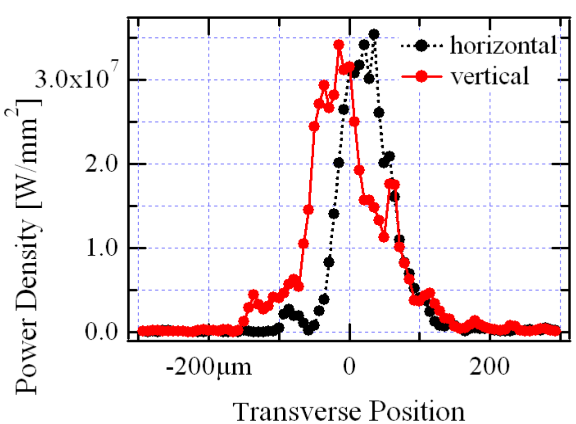
Peak Spectral Fluence Transverse Cuts

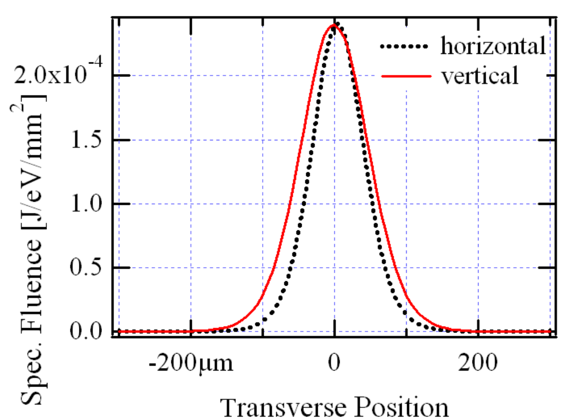


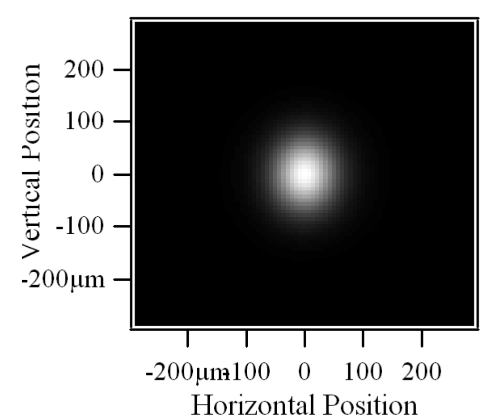
Fluence



B: SASE (not saturated)



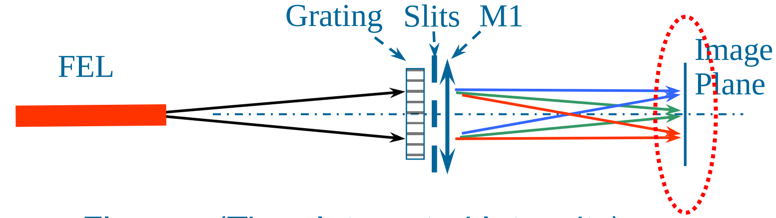




Time-Dependent FEL Wavefront Propagation Simulation:
Pulse Characteristics in Image Plane of a 2-Slit Interferometer with a Grating

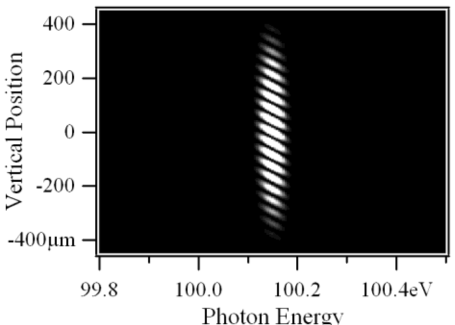
E-Beam: E = 1 GeV $\sigma_{t\,e}$ ~ 200 fs, $\varepsilon_x = \varepsilon_y$ = 1.2 π mm-mr
I_{peak} = 1.5 kA

Undulator: λ_u = 30 mm, L_{tot} ~ 5 x 2 m, K ~ 2.06

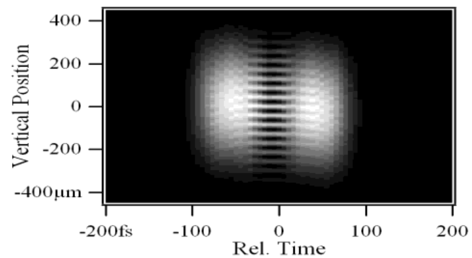


A: Seeded

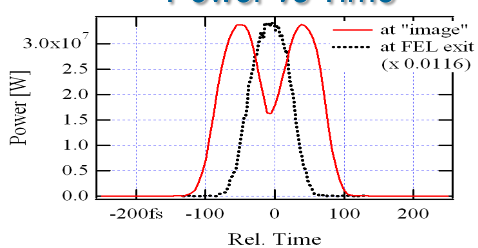
Spectral Fluence
vs Photon Energy
and Vertical Position (at x = 0)



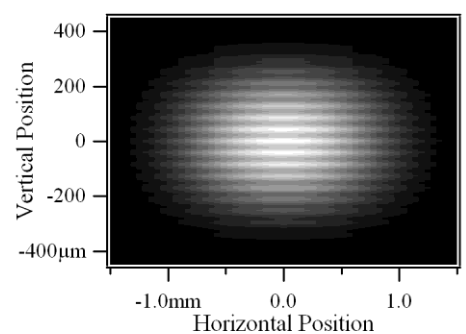
Power Density
vs Time and Vertical Position (at x = 0)

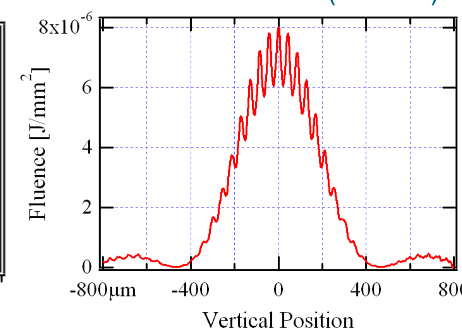


Power vs Time

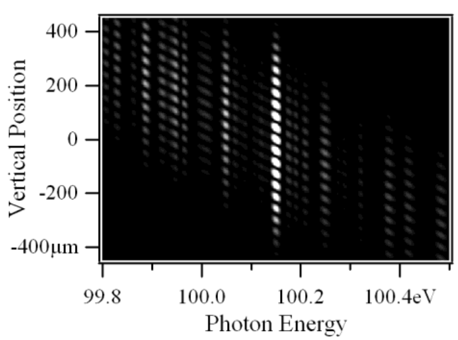


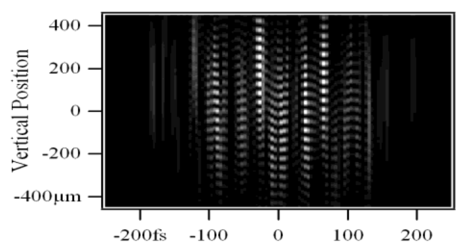
Fluence (Time-Integrated Intensity)
vs Horiz. and Vert. Positions vs Vert. Position (at x = 0)

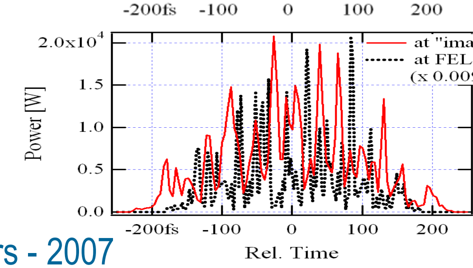


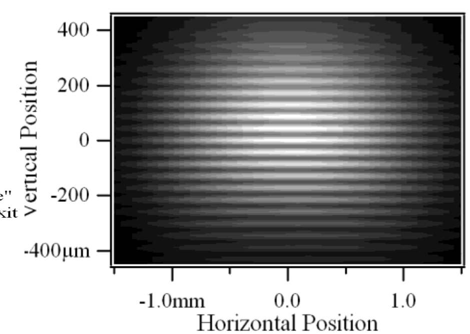


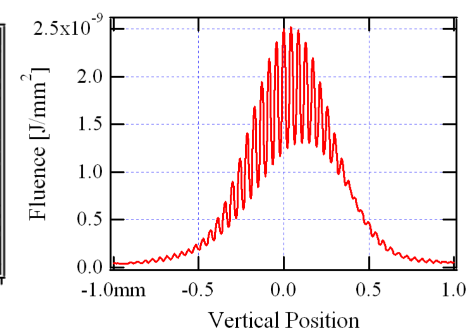
B: Started from noise











Reduction of processing time is possible by using In-Place FFTs on GPU systems with common memory.

GENESIS + SRW, FEL Frontiers - 2007

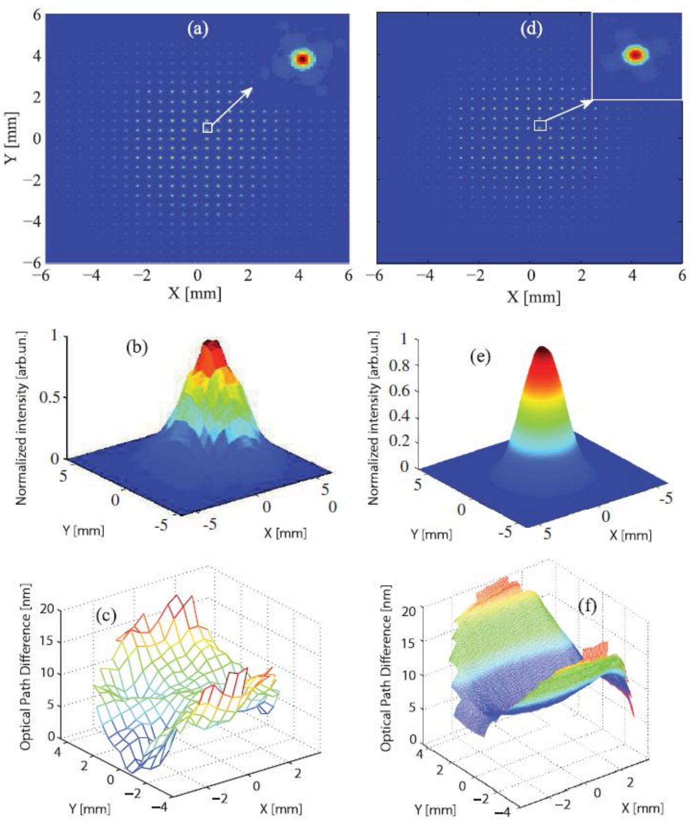
Extension of Hartmann Wavefront Sensor Method To Probe Transverse Coherence Over Wavefront

Measurements in Single-Shot Regime at SCSS Test Accelerator FEL

M.-E. Couprie
M. Idir
P. Mercier
R. Bachelard
M. Labat
T. Hara
et al.

At Fundamental Harmonic

Measured Simulated

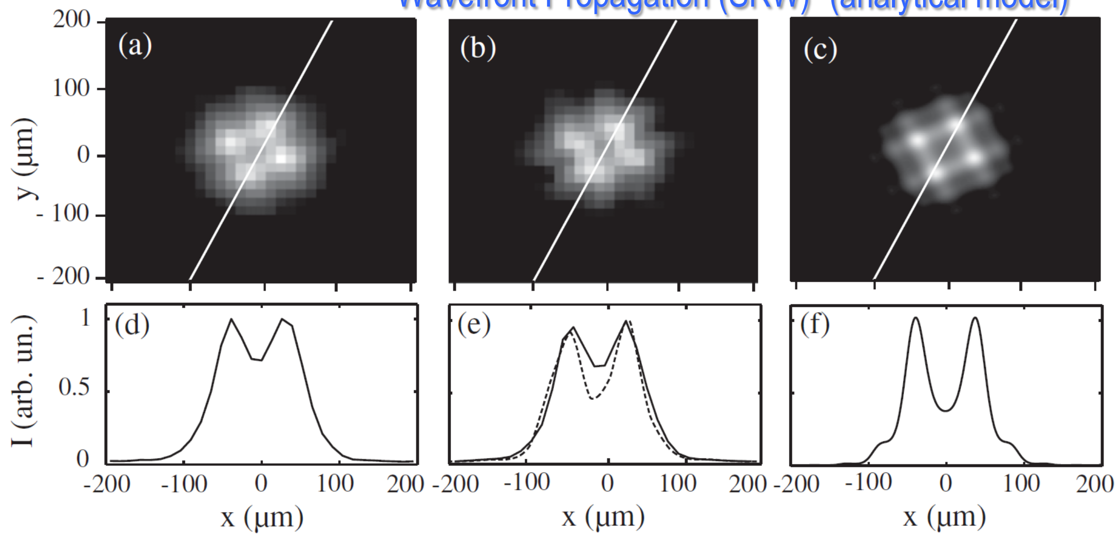


Diffraction Pattern from One Rectangular Tilted Hole at 3rd Nonlinear Harmonic

Measured

Simulated SASE (Genesis) + Wavefront Propagation (SRW)

Simulated Point Source (analytical model)



R. Bachelard et.al., PRL 106, 234801 (2011)

SRW Project Status (as of May 2013)

- "Synchrotron Radiation Workshop" (**SRW**) is electrodynamics / physical optics computer code for calculation of Synchrotron Radiation and simulation of Fully- and Partially-Coherent Radiation Wavefront Propagation
- SRW is written essentially in ANSI **C++**; **C API** is available (compiles as a 32- or 64-bit static or shared library for Windows, Linux, Mac OSX)
- Versions interfaced to **IGOR Pro** for Windows and Mac are available since **1997**: **http://www.esrf.eu/Accelerators/Groups/InsertionDevices/Software/SRW**
- SRW for **Python** (2.7 and 3.2, 32- and 64-bit) versions are available for Windows and Linux since 2012
- **Parallel** versions of SRW for **Python** are available for partially-coherent wavefront propagation simulations (two test implementations: based on MPI / mpi4py, and using data exchange via files)
- SRW has been recently released to the **Open Source** under **BSD**-type license (the release procedure has been completed at BNL; permissions for the release were obtained from all Contributed Institutions and from US DOE): **https://github.com/ochubar/SRW**
- Institutions and Individuals Contributed to SRW project:
  - **ESRF**: **P.Elleaume**, O.Chubar (O.C.), J.Chavanne, N.Canestrari (N.C.), M.S.del Rio
  - **SOLEIL**: O.C.
  - **BNL / PS**: O.C., N.C., R.Reininger (R.R.)
  - **E-XFEL** GmbH: L.Samoylova, G.Geloni, A.Buzmakov, I.Agapov
  - **DIAMOND** LS Ltd.: J.Sutter, D.Laundy, K.Sawhney
  - **ANL / APS**: R.R.
- On-going developments:
  - "thick" optical elements and library of mirror surfaces (under benchmarking);
  - X-ray diffraction by perfect crystals in Bragg and Laue geometries;
  - improving efficiency of 3D time (/frequency) dependent simulations for X-ray FEL and short-pulse THz–IR applications;
  - facilitating inter-operation with SHADOW ray-tracing code and other software

SRW Applications (Summary)

Accurate calculation of Electric Field and other characteristics of Synchrotron Radiation and simulation of Fully- and Partially-Coherent Wavefront Propagation within the framework of Physical Optics, implemented in SRW computer code, allows for a large variety of applications in such areas as:

✓Development of New and Improvement of Existing Synchrotron Radiation Sources

✓Optimization of SR Beamlines for most efficient use of the properties of Sources and Optical Elements

✓Development of New types of Optical Elements for 3rd and 4th Generation Synchrotron Sources

✓Electron Beam, Insertion Device and Optical Element Characterization and Diagnostics

✓Simulation of User Experiments for most efficient use of Beam Time

Potentially: use of SRW functions for Data Processing in Experiments in such areas as Imaging and Microscopy

Acknowledgements

- **J.-L. Laclare**, **P. Elleaume**
- A. Snigirev, I. Snigireva, J. Susini, M. Sanchez del Rio, J. Chavanne (ESRF)
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- G. P. Williams (JLab)
- Y.-L. Mathis, P. Rieger (ANKA)
- V. Yashchuk, N. Artemiev, D. Robin, D. Shapiro (LBNL)
- R. Reininger, A. Khounsary, A. Zholents, Y. Shvydko (ANL)
- N. Smolyakov, S. Tomin (Kurchatov Inst.)
- J. Bahrdt (BESSY)
- S. Dierker, Q. Shen, L. Berman, S. Krinsky, M. Idir, T. Shaftan, A. Fluerasu, L. Wiegart, K. Kaznatcheev, V. DeAndrade, Y. Chu, N. Canestrari, G. Bassi, A. Suvorov, P. Ilinski, V. Litvinenko (BNL)

SPARE SLIDES

Spontaneous Emission by Relativistic Electron in Free Space

Lienard-Wiechert Potentials for One Electron moving in Free Space:

$$\vec{A} = e\int_{-\infty}^{+\infty} \vec{\beta}_e R^{-1} \delta(\tau - t + R/c)\, d\tau, \quad \varphi = e\int_{-\infty}^{+\infty} R^{-1}\delta(\tau - t + R/c)\, d\tau$$

(Gaussian CGS)

$$\Downarrow$$

Electric Field in Frequency Domain (exact expressions!):

$$\vec{E}_\omega = \frac{ie\omega}{c}\int_{-\infty}^{+\infty} R^{-1}[\vec{\beta}_e - [1 + ic/(\omega R)]\,\vec{n}\,]\exp[i\omega(\tau + R/c)]d\tau$$

I.M.Ternov used this approach in Far Field

$$\vec{E}_\omega = \frac{e}{c}\int_{-\infty}^{+\infty} \frac{\vec{n}\times\left[\left(\vec{n}-\vec{\beta}_e\right)\times\dot{\vec{\beta}}_e\right] + cR^{-1}\gamma^{-2}\left(\vec{n}-\vec{\beta}_e\right)}{R\cdot\left(1-\vec{n}\cdot\vec{\beta}_e\right)^2}\cdot\exp\left[i\omega\left(\tau + R/c\right)\right]d\tau$$

J.D.Jackson

The equivalence of the two expressions can be shown by integration by parts

Phase Expansion (valid for the Near Field and in the Far Field Observation Conditions):

$$\omega\cdot(\tau + R/c) \approx \Phi_0 + \frac{\omega}{2}\left[\tau\gamma^{-2} + \int_0^\tau |\vec{\beta}_{e\perp}|^2\, d\tilde{\tau} \;+\; \frac{|\vec{r}_\perp - \vec{r}_{e\perp}|^2}{c(z - c\tau)}\right]$$

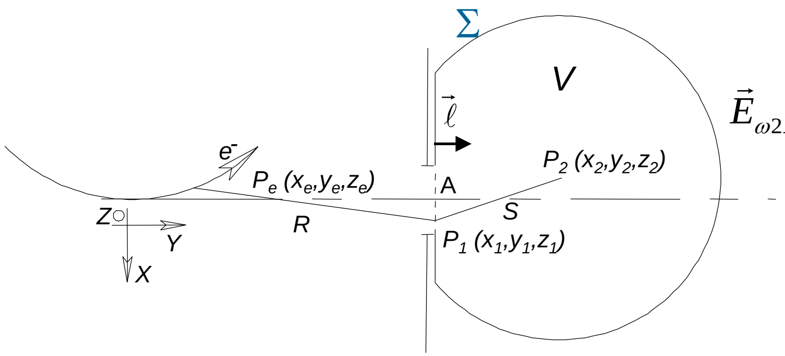
$\vec{r}_{e\perp}, \vec{\beta}_{e\perp}$ are 2D vectors defining transverse coordinates and angles of electron trajectory

$\vec{r}_\perp$ is a 2D vector defining transverse coordinates of observation point

z is longitudinal coordinate of observation point

Wavefront Propagation in the Case of Full Transverse Coherence

Kirchhoff Integral Theorem applied to Spontaneous Emission by One Electron



$$\vec{E}_{\omega 2\perp}(P_2) \approx \frac{k^2 e}{4\pi}\int_{-\infty}^{+\infty} d\tau \iint_A \frac{\vec{\beta}_{e\perp}-\vec{n}_\perp}{RS}\exp[ik(c\tau+R+S)]\cdot(\vec{\ell}\cdot\vec{n}_{p_e p_1}+\vec{\ell}\cdot\vec{n}_{p_1 p_2})d\Sigma$$

Valid at large observation angles;
Is applicable to complicated cases of diffraction inside vacuum chamber

Huygens-Fresnel Principle

$$\vec{E}_{\omega 2\perp}(P_2)\approx\frac{k}{4\pi i}\iint_A \vec{E}_{\omega 1\perp}(P_1)\frac{\exp(ikS)}{S}(\vec{\ell}\cdot\tilde{\vec{n}}+\vec{\ell}\cdot\vec{n}_{p_1 p_2})d\Sigma$$

Fourier Optics

Free Space:
(between parallel planes perpendicular to optical axis)

$$\vec{E}_{\omega 2\perp}(x_2,y_2)\approx\frac{k}{2\pi i L}\iint \vec{E}_{\omega 1\perp}(x_1,y_1)\exp[ik[L^2+(x_2-x_1)^2+(y_2-y_1)^2]^{1/2}]dx_1 dy_1$$

Assumption of small angles

"**Thin**" Optical Element:

$$\vec{E}_{\omega 2\perp}(x,y)\approx\mathbf{T}(x,y,\omega)\,\vec{E}_{\omega 1\perp}(x,y)$$

"**Thick**" Optical Element:
(from transverse plane before the element to a transverse plane immediately after it)

$$\vec{E}_{\omega 2\perp}(x_2,y_2)\approx\mathbf{G}(x_2,y_2,\omega)\exp[ik\Lambda(x_2,y_2,k)]\,\vec{E}_{\omega 1\perp}(x_1(x_2,y_2),y_1(x_2,y_2))$$

E.g. from Stationary Phase method

Incoherent and Coherent Spontaneous Emission by Many Electrons

Electron Dynamics:

$$\begin{pmatrix} x_e \\ y_e \\ z_e \\ \beta_{xe} \\ \beta_{ye} \\ \delta\gamma_e \end{pmatrix} = \mathbf{A}(\tau) \begin{pmatrix} x_{e0} \\ y_{e0} \\ z_{e0} \\ x'_{e0} \\ y'_{e0} \\ \delta\gamma_{e0} \end{pmatrix} + \mathbf{B}(\tau)$$

$\leftarrow$ Initial Conditions

Spectral **Photon Flux per unit Surface** emitted by the **whole Electron Beam**:

$$\frac{dN_{ph}}{dtdS(d\omega/\omega)} = \frac{c^2\alpha I}{4\pi^2 e^3}\left\langle\left|\vec{E}_\omega\right|^2\right\rangle$$

"Incoherent" SR

$\downarrow$

$$\left\langle\left|\vec{E}_\omega\right|^2\right\rangle = \int\left|\vec{E}_{\omega 0}(\vec{r};x_{e0},y_{e0},z_{e0},x'_{e0},y'_{e0},\delta\gamma_{e0})\right|^2 f(x_{e0},y_{e0},z_{e0},x'_{e0},y'_{e0},\delta\gamma_{e0})dx_{e0}dy_{e0}dz_{e0}dx'_{e0}dy'_{e0}d\delta\gamma_{e0} +$$

$$+(N_e-1)\left|\int\vec{E}_{\omega 0}(\vec{r};x_{e0},y_{e0},z_{e0},x'_{e0},y'_{e0},\delta\gamma_{e0}) f(x_{e0},y_{e0},z_{e0},x'_{e0},y'_{e0},\delta\gamma_{e0})dx_{e0}dy_{e0}dz_{e0}dx'_{e0}dy'_{e0}d\delta\gamma_{e0}\right|^2$$

$\uparrow$

Coherent SR

Common Approximation for CSR: **"Thin" Electron Beam**: $\left\langle\left|\vec{E}_\omega\right|^2\right\rangle_{CSR} \approx N_e\left|\int_{-\infty}^{\infty}\tilde{f}(z_{e0})\exp(ikz_{e0})dz_{e0}\right|^2\left|\vec{E}_{\omega 1}\right|^2$

For Gaussian Longitudinal Bunch Profile: $\left\langle\left|\vec{E}_\omega\right|^2\right\rangle_{CSR} \approx N_e\exp(-k^2\sigma_b^2)\left|\vec{E}_{\omega 1}\right|^2$

If $f(x_{e0},y_{e0},z_{e0},x'_{e0},y'_{e0},\delta\gamma_{e0})$ is Gaussian, 6-fold integration over electron phase space can be done analytically for the (Mutual) Intensity of Incoherent SR and for the Electric Field of CSR

Partially-Coherent SR Wavefront Propagation

Averaging of Propagated One-Electron Intensity
over Phase-Space Volume occupied by Electron Beam:

$$I_\omega(x,y) = \int I_{\omega 0}(x,y;x_{e0},y_{e0},z_{e0},x'_{e0},y'_{e0},\delta\gamma_{e0})\, f(x_{e0},y_{e0},z_{e0},x'_{e0},y'_{e0},\delta\gamma_{e0})\, dx_{e0}dy_{e0}dz_{e0}dx'_{e0}dy'_{e0}d\delta\gamma_{e0}$$

Convolution is valid in simple cases:
- projection geometry;
- focusing by a thin lens;
- diffraction on one slit (/pinhole);
- …

$$I_\omega(x,y) \approx \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \tilde{I}_{\omega 0}(x-\tilde{x}_e, y-\tilde{y}_e)\,\tilde{f}(\tilde{x}_e,\tilde{y}_e)\,d\tilde{x}_e d\tilde{y}_e$$

OR:

Propagation of **Mutual Intensity**

Initial Mutual Intensity:

$$M_\omega(x,y;\tilde{x},\tilde{y}) = \int \vec{E}_{\omega 0\perp}(x,y;\; x_{e0},y_{e0},z_{e0},x'_{e0},y'_{e0},\delta\gamma_{e0})\vec{E}^*_{\omega 0\perp}(\tilde{x},\tilde{y};\; x_{e0},y_{e0},z_{e0},x'_{e0},y'_{e0},\delta\gamma_{e0})$$
$$\times f(x_{e0},y_{e0},z_{e0},x'_{e0},y'_{e0},\delta\gamma_{e0})\, dx_{e0}dy_{e0}dz_{e0}dx'_{e0}dy'_{e0}d\delta\gamma_{e0}$$

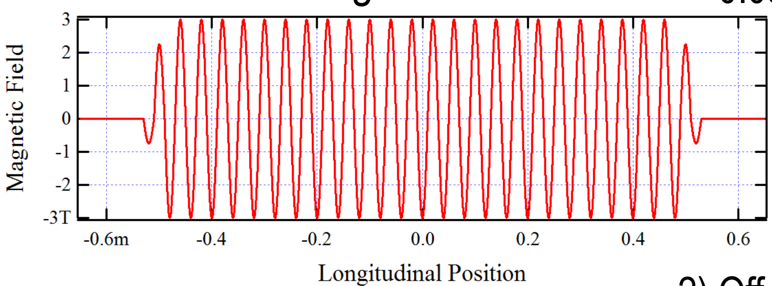
Wigner Distribution (or mathematical Brightness):

$$B_\omega(x,y;\theta_x,\theta_y) = \frac{1}{2\pi}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} M_\omega(x,y;\tilde{x},\tilde{y})\exp[ik(\theta_x\tilde{x}+\theta_y\tilde{y})]d\tilde{x}d\tilde{y}$$

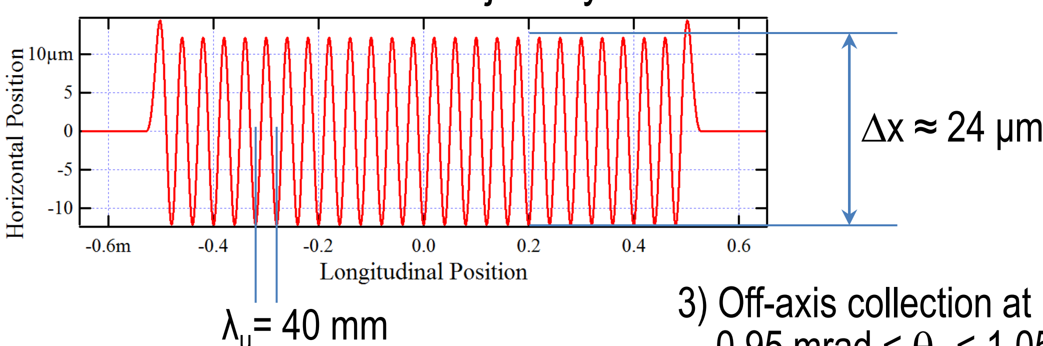
Intensity Distributions of Focused Wiggler Radiation (1 : 1)

Wavefront Propagation Calculations for “Filament” Electron Beam

Magnetic Field



Electron Trajectory



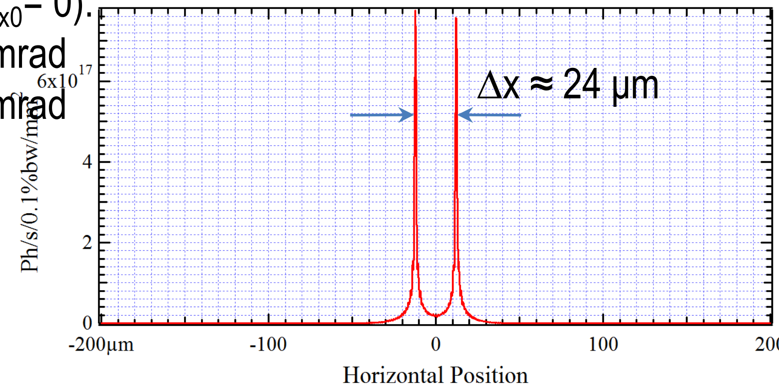
E-beam: E = 3 geV, I = 0.5 A

SCW40: λ_u= 40 mm, B_{max}= 3 T, L = 1 m

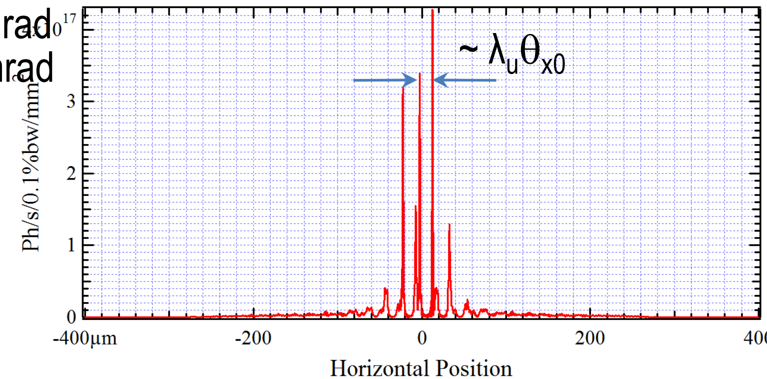
Photon Energy used in calc.: E_{ph}= 10 keV

Horizontal Cuts (y = 0)

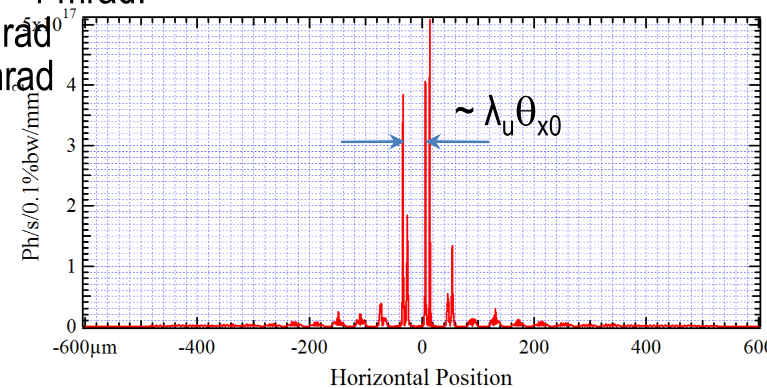
1) On-axis collection (at θ_{x0}= 0):
-0.05 mrad < θ_x < 0.05 mrad
-0.05 mrad < θ_y < 0.05 mrad



2) Off-axis collection at θ_{x0}= 0.5 mrad:
0.45 mrad < θ_x < 0.55 mrad
-0.05 mrad < θ_y < 0.05 mrad



3) Off-axis collection at θ_{x0}= 1 mrad:
0.95 mrad < θ_x < 1.05 mrad
-0.05 mrad < θ_y < 0.05 mrad



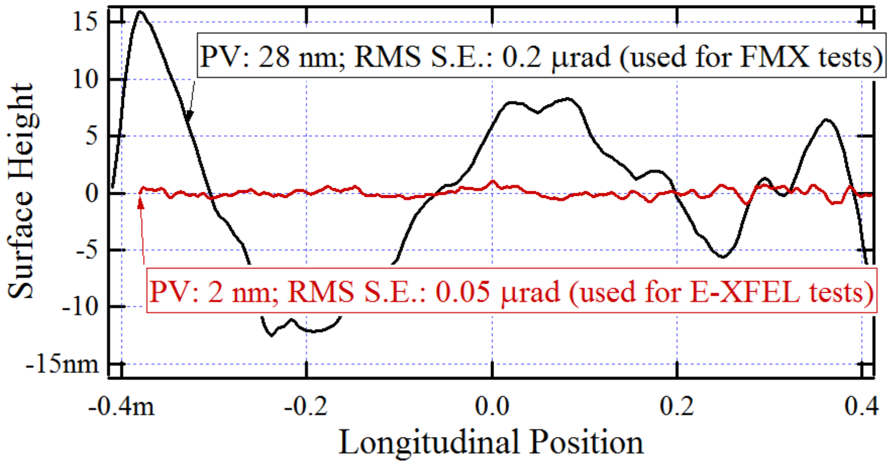
Features of Some Existing Free Computer Codes

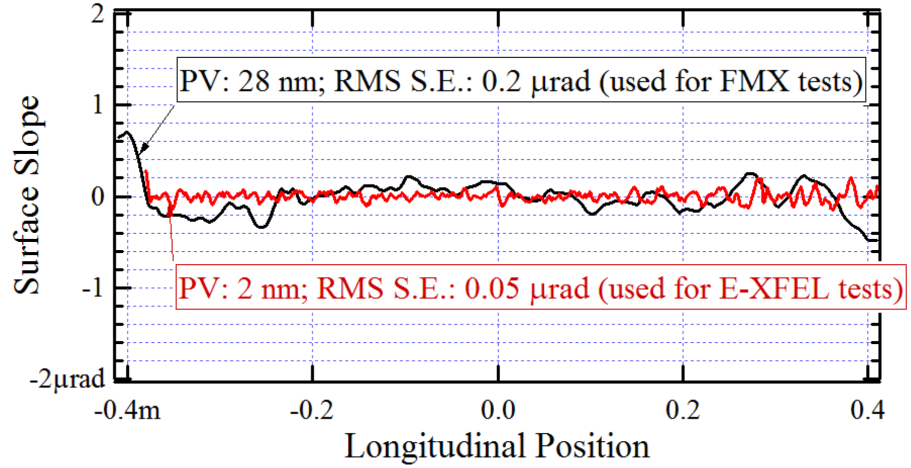
Features \ Codes	SPECTRA	WAVE	GENESIS	SHADOW	RAY	PHASE	SRW
Source Simulation	Y	Y	Y	Y(?)	N(?)	N(?)	Y
Gaussian Beams	Y	Y	Y	Y	Y	Y(?)	Y
Spontaneous SR	Y	Y	N(?)	Y (BM?)	N(?)	N	Y
Single-Electron	Y	Y	N(?)	N	N(?)	N	Y
Incoherent "Multi-Electron"	Y	Y(?)	N(?)	Y (BM?)	N(?)	N	Y
CSR	Y(?)	Y(?)	N(?)	N	N(?)	N	Y
SASE	N	N	Y	N	N(?)	N	N(?)
Geometrical Ray-Tracing	N	N	N	Y	Y	N	N
Wavefront Propagation	N(?)	N	N(?)	N	N(?)	Y	Y
Fully-Coherent Beams						Y	Y
Partially-Coherent Beams						N(?)	Y
Time-/Frequency-Dependent						Y(?)	Y
Optical Elements	N	N	N	Y	Y	Y	Y
Grazing-Incidence Mirrors				Y	Y	Y	Y(?)
Refractive Optics				Y	Y	Y	Y
Diffractive Optics				N	Y	Y(?)	Y
Gratings				Y(?)	Y	Y	N(?)
Crystals				Y	Y	N(?)	N(?)
Framework	Y	Y	Y	Y	Y	Y	Y
Scripting Environment	N(?)	N(?)	N(?)	Y(?)	N(?)	N(?)	Y
File Input-Output	Y	Y	Y	Y	Y	Y	Y(?)
GUI	Y(?)	Y	N(?)	Y(?)	Y	Y	Y(?)
API	N(?)	N(?)	N(?)	N	N(?)	N(?)	Y
Cross-Platform	Y(?)	Y(?)	Y	Y	Y	Y	Y
Open Source	N(?)	N(?)	Y	Y	N(?)	N	Y
Development Effort (man-years to date, full time)	?	?	~4(?)	~5(?)	?	~3(?)	~4

Height Profiles and Slope Errors of Some Mirror

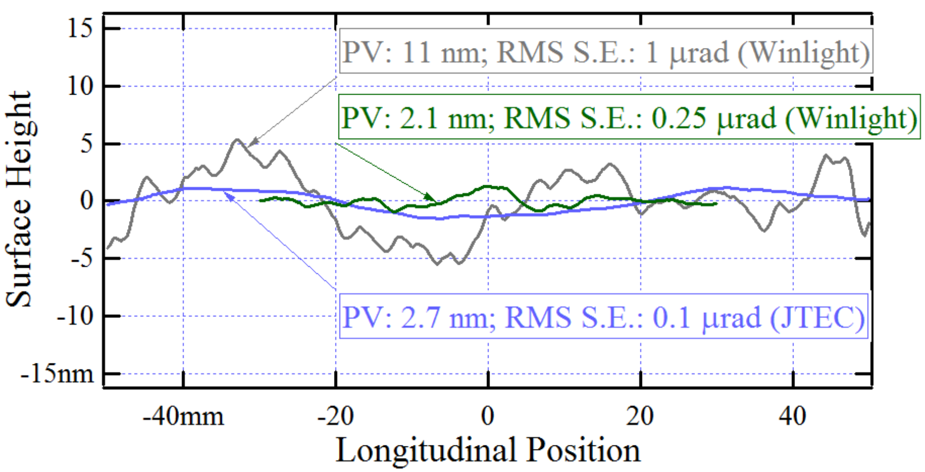
Height Profiles / Slope Errors

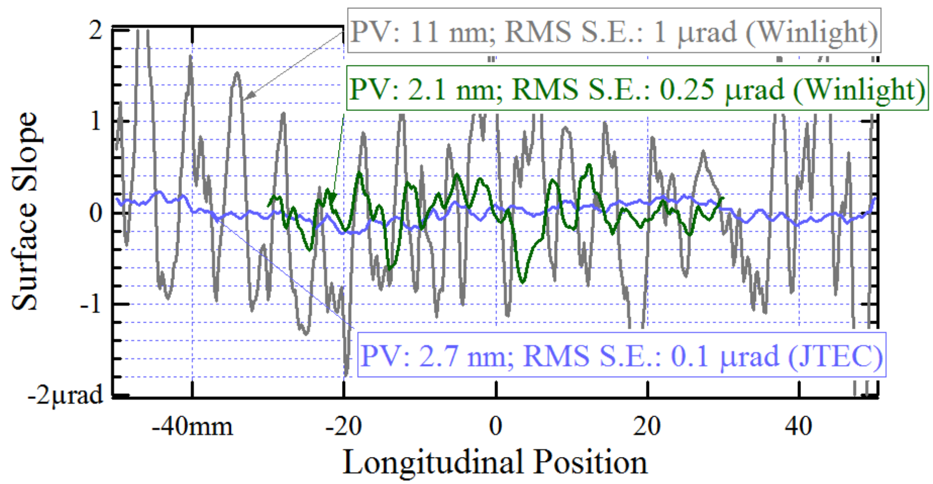
Long Mirror Considered for FMX BL Tests





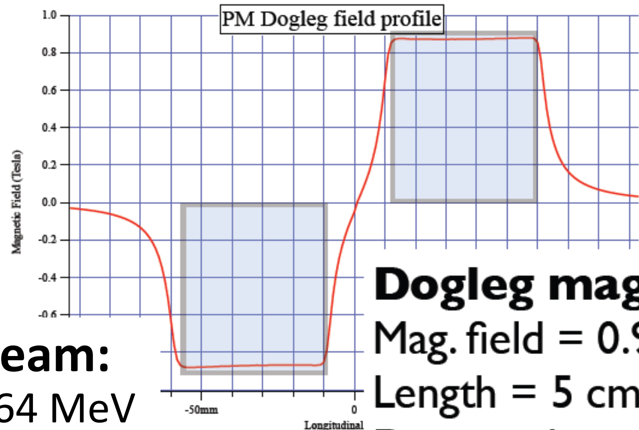
Short Mirrors Considered for SRX BL Tests





Data from M. Idir, R. Sweet, V. DeAndrade (BNL), L. Samoylova (E-XFEL)

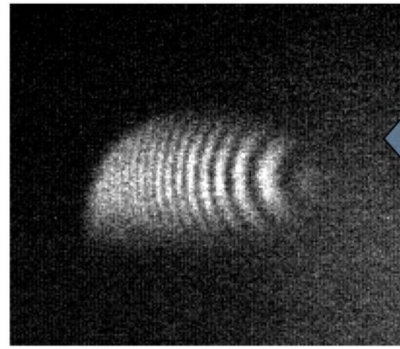
Non-Destructive Single-Shot E-Beam Emittance Measurement in ERL / FEL Injectors Using Interfering Edge Radiation



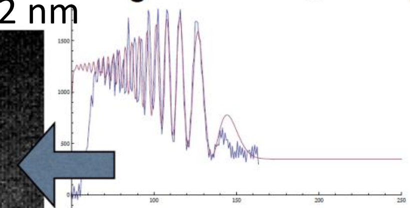
e-beam:
E = 64 MeV
dE/E = 2e-4
Q = 500 pC
$\varepsilon_N \approx 2\ \mu m$

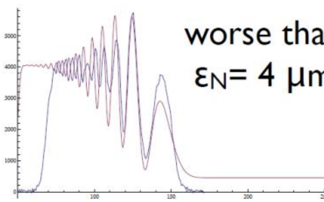
Dogleg magnets:
Mag. field = 0.9 T
Length = 5 cm
Distance between magnets = 2 cm

Image of PI camera,
filter: $d\lambda$ = 10 nm at λ = 532 nm

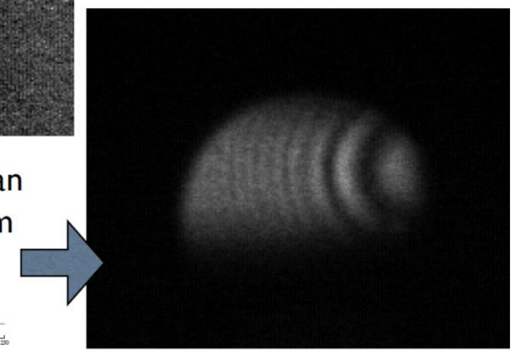


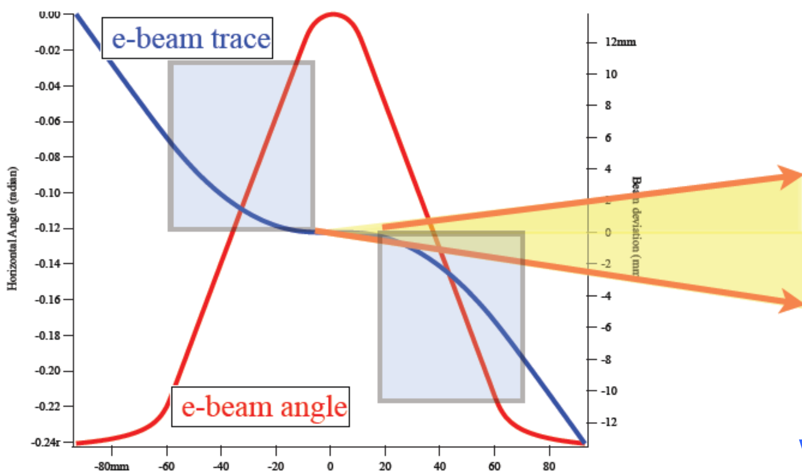
good fit to ε_N= 1.9 μm



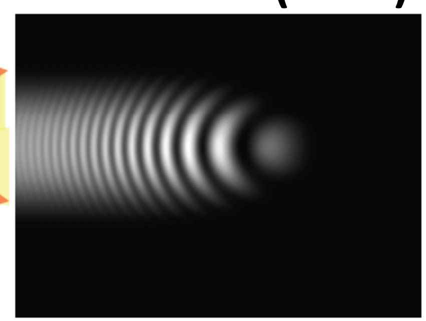


worse than ε_N= 4 μm

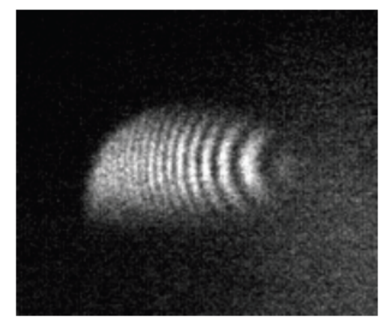




Simulation (SRW)



Measurement



V. Yakimenko, M. Fedurin (ATF, BNL, June 2012)

U.S. DEPARTMENT OF ENERGY

Method: O.C., Rev. Sci. Instrum., 1995, vol.66 (2), p.1872 (SRI-1994); "Siberia-1", Kurchatov Institute, Moscow

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