Planar Channeling of 855 MeV Electrons in a Boron-doped (110) Diamond Undulator

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10th International Conference "Charged & Neutral Particles Channeling Phenomena“ , 8-13 Sept. 2024, Riccione (RN) (Italy)

Outline

1. Motivation
2. Experiments with a Strained Layer $Si_{1-x}Ge_x$ (110) Undulator - Revisited
3. Examination of a Boron Doped (110) Diamond Undulator at MAMI
4. Scatter Distribution at Oblique incidence
5. Conclusions

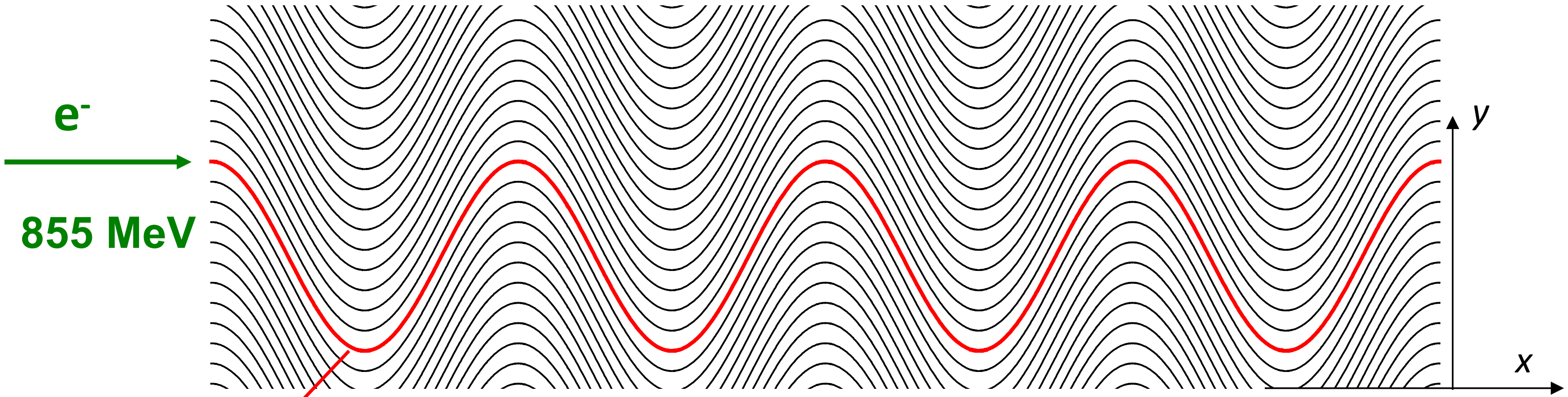
1. Motivation

Feasibility of a photon source with **micro-undulators** and medium energy **electron beams?**

W. Greiner, A.V. Solov'yov, and A.V. Korol et al.

Micro-Crystal Undulator

(110) $U_0 = 22$ eV $\lambda_U = 9.9\ \mu m$ $y \approx A \cdot \cos\left(\frac{2\pi}{\lambda_U} x\right)$ $A = 2.32$ Å $N_U = 4$



Coherent undulator radiation emission

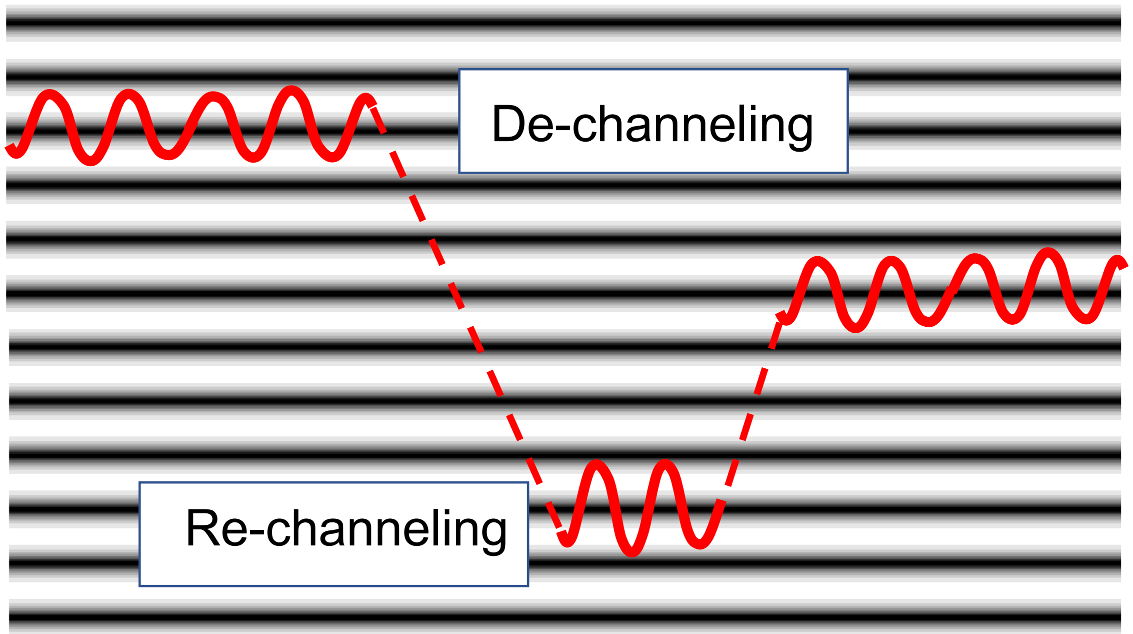
$R = 6.60$ mm $B_{equiv} = \frac{pv}{e\ R\ c} = 423$ Tesla $K = \gamma \cdot A \cdot \frac{2\pi}{\lambda_U} = 0.247$

Photon energy

$$\hbar\omega = k \frac{4\pi \cdot \gamma^2 \hbar c}{\lambda_U (1 + K^2/2 + \gamma^2(\theta_x^2 + \theta_y^2))} = 0.681\ \text{MeV}$$

at $\theta_x = \theta_y = 0,$ and first order $k = 1$

Obstacle



De-channeling rate λ_{de}

for straight and bent crystals

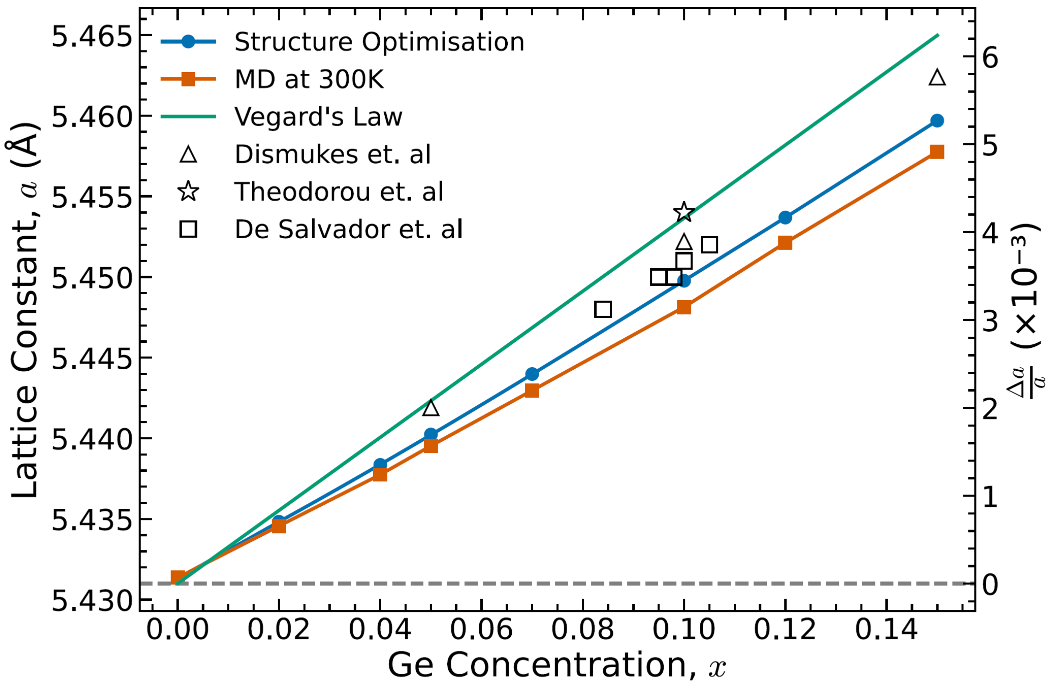
Re-channeling rate λ_{re}

2. Experiments with a Strained Layer $Si_{1-x}Ge_x$ (110) Undulator - Revisited

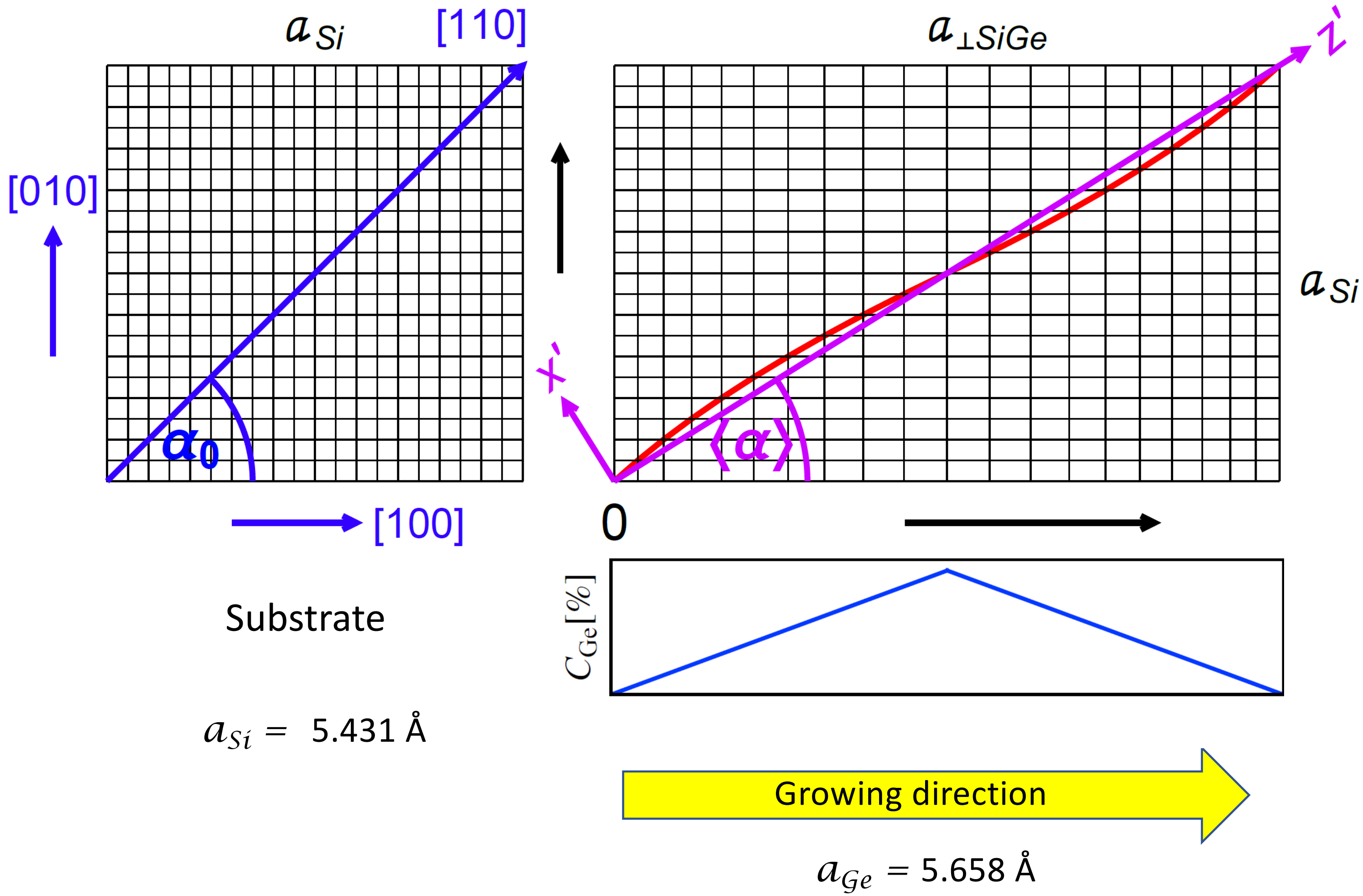
H. Backe et al.,
Nucl. Inst. Meth. in Phys. Res. B 309 (2013) 37 and
Journal of Physics: Conference Series **438** (2013) 012017

Dopant concentration effects on $Si_{1-x}Ge_x$ crystals

Matthew D. Dickers, et al., Eur. Phys. J. D (2024) 78 :77

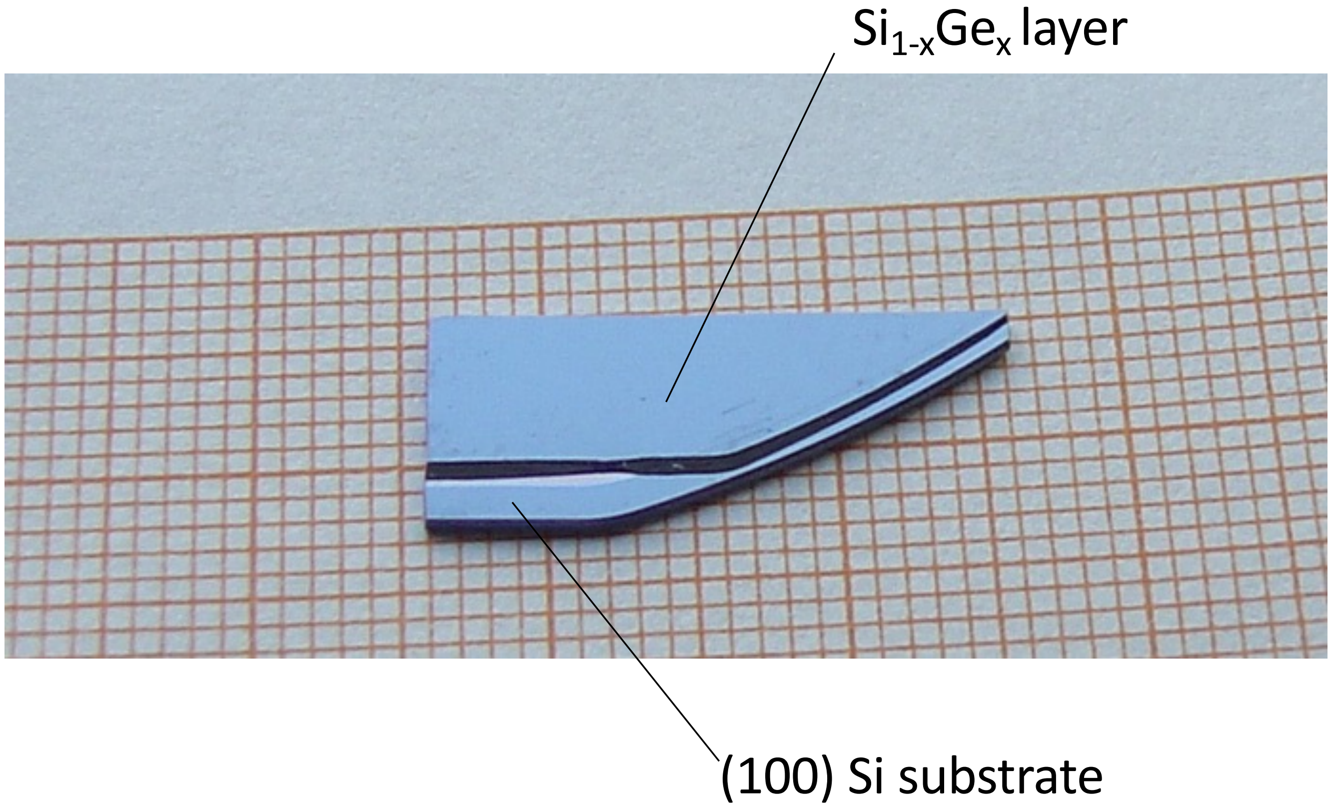


Periodic Graded Composition
Strained Layer $Si_{1-x}Ge_x$ Crystals



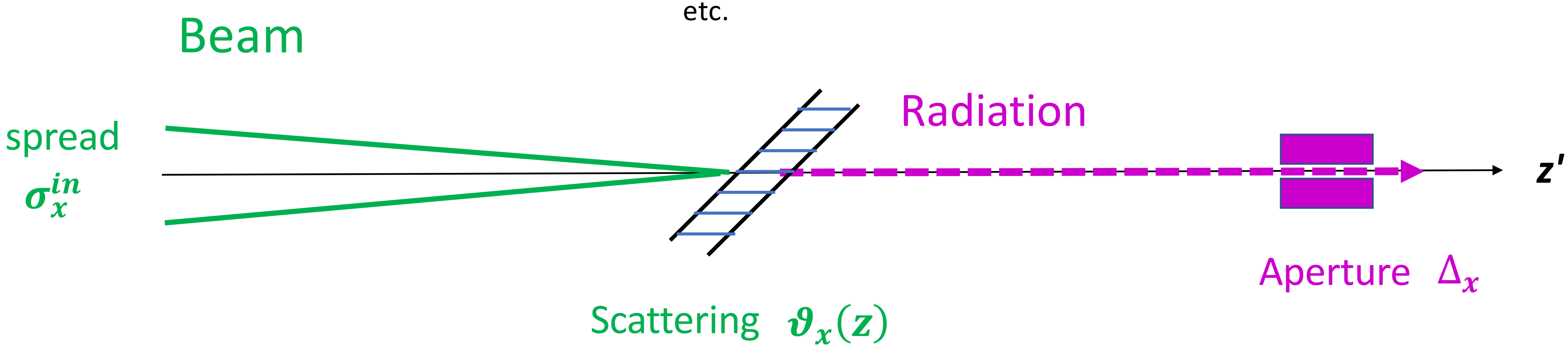
The Aarhus Undulator Crystal

John Lundsgaard Hansen, Arne Nylandsted, Ulrik I. Uggerhøj
MBE-Group
Department of Physics and Astronomy
University of Aarhus



Principle of the Experiment

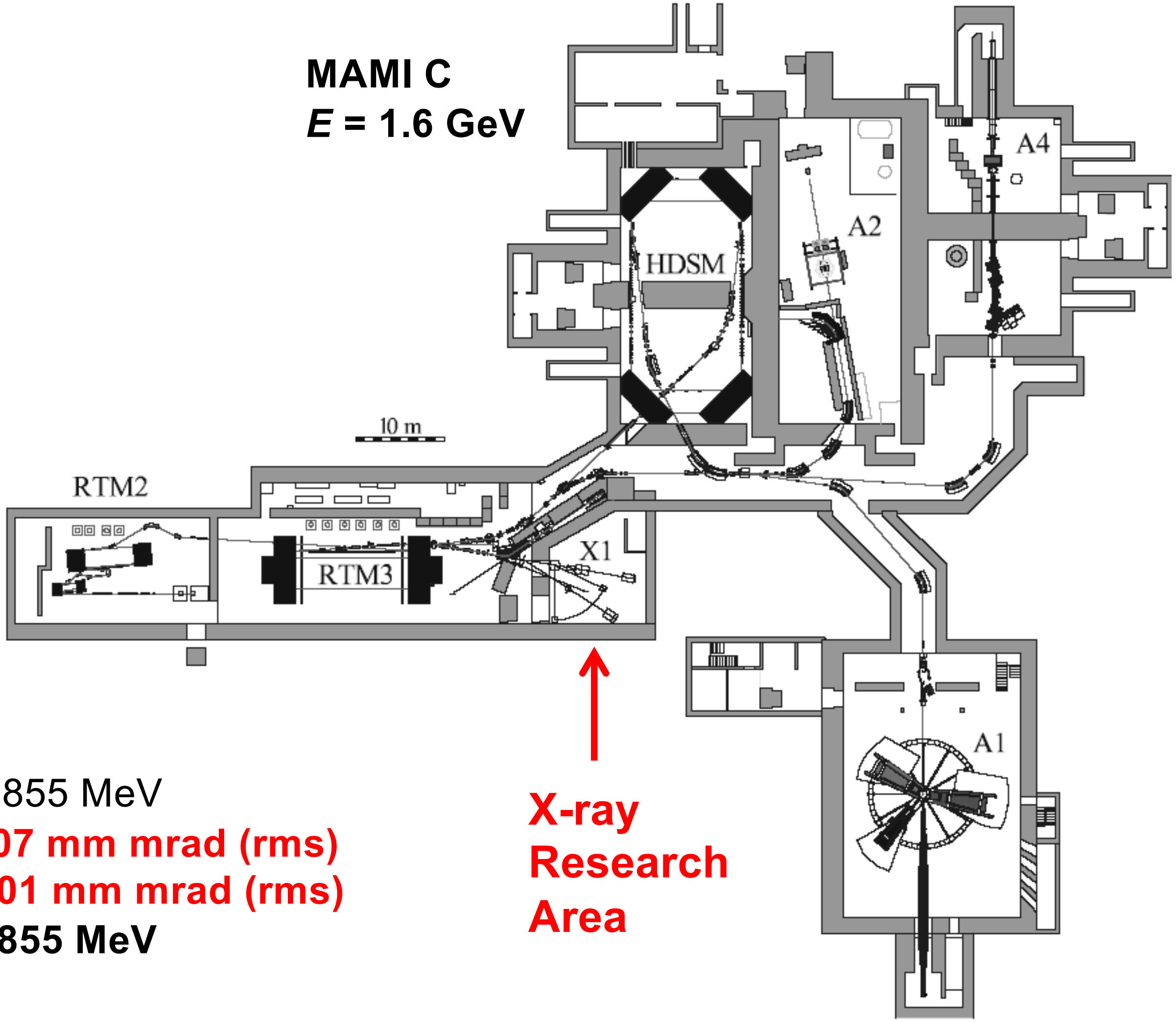
(110) undulator
bending radius R_{bent} ,
period λ_U,
number of periods N_U,
etc.



Rotation angle $\psi_x = 0$

Floor Plan of the Mainz Microtron MAMI Facility

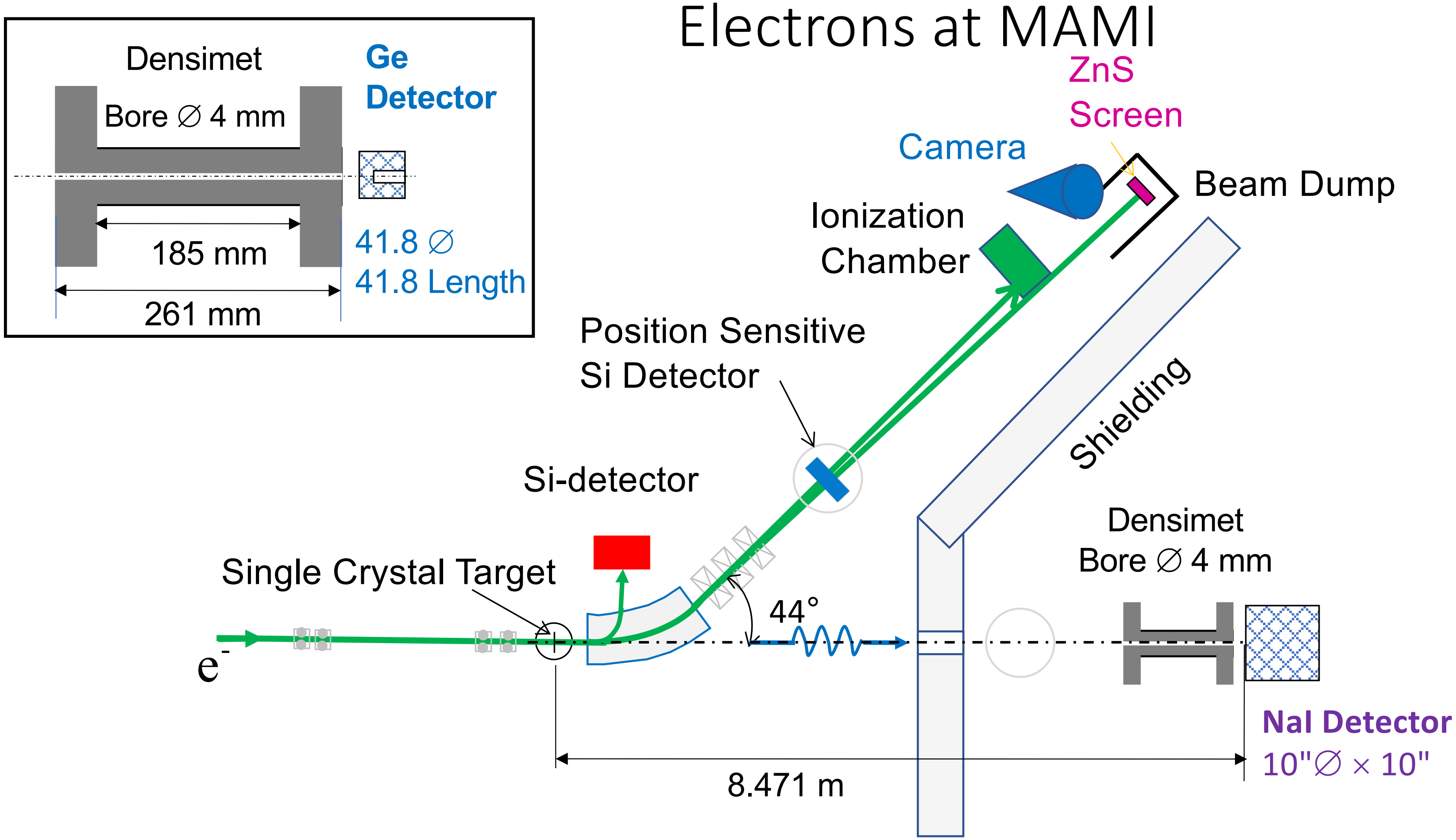
MAMI C
***E* = 1.6 GeV**



E = 180 - 855 MeV
$\varepsilon_{hor} \cong$ 0.007 mm mrad (rms)
$\varepsilon_{vert} \cong$ 0.001 mm mrad (rms)
at 855 MeV

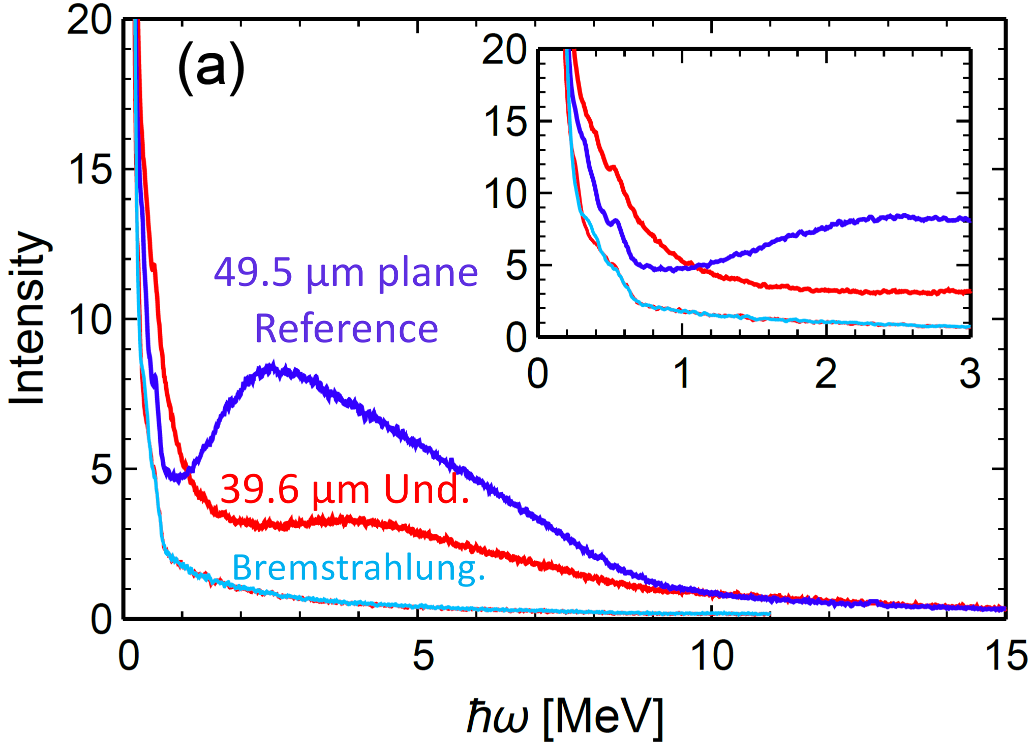
X-ray Research Area

Basic Setup for the Experiments with Electrons at MAMI

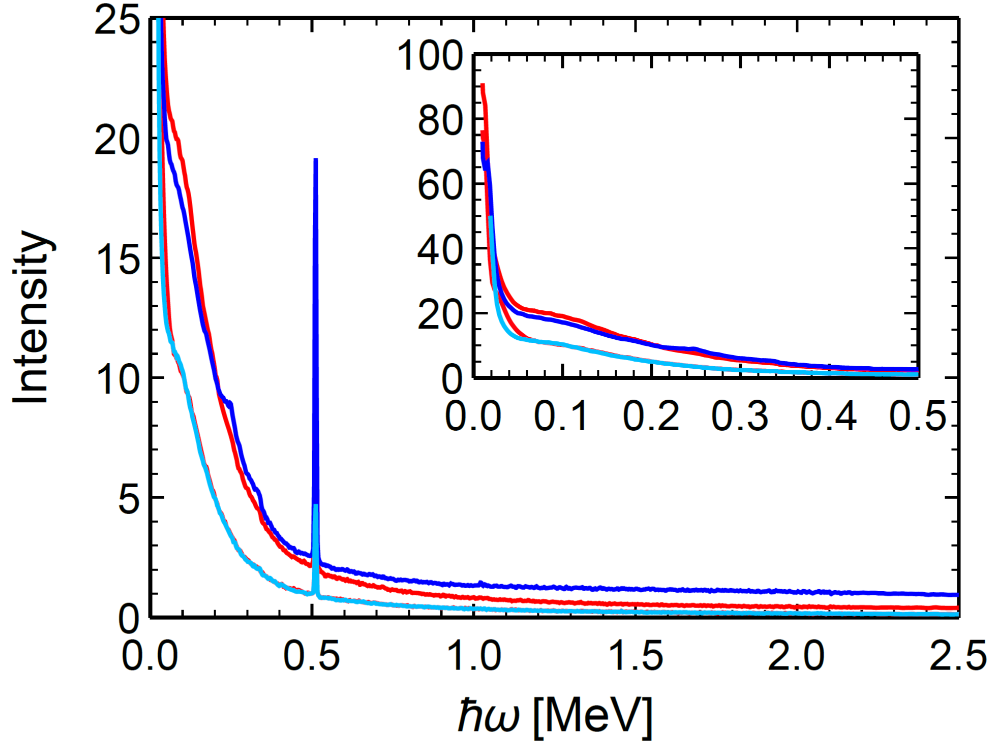


Measured Raw Spectra

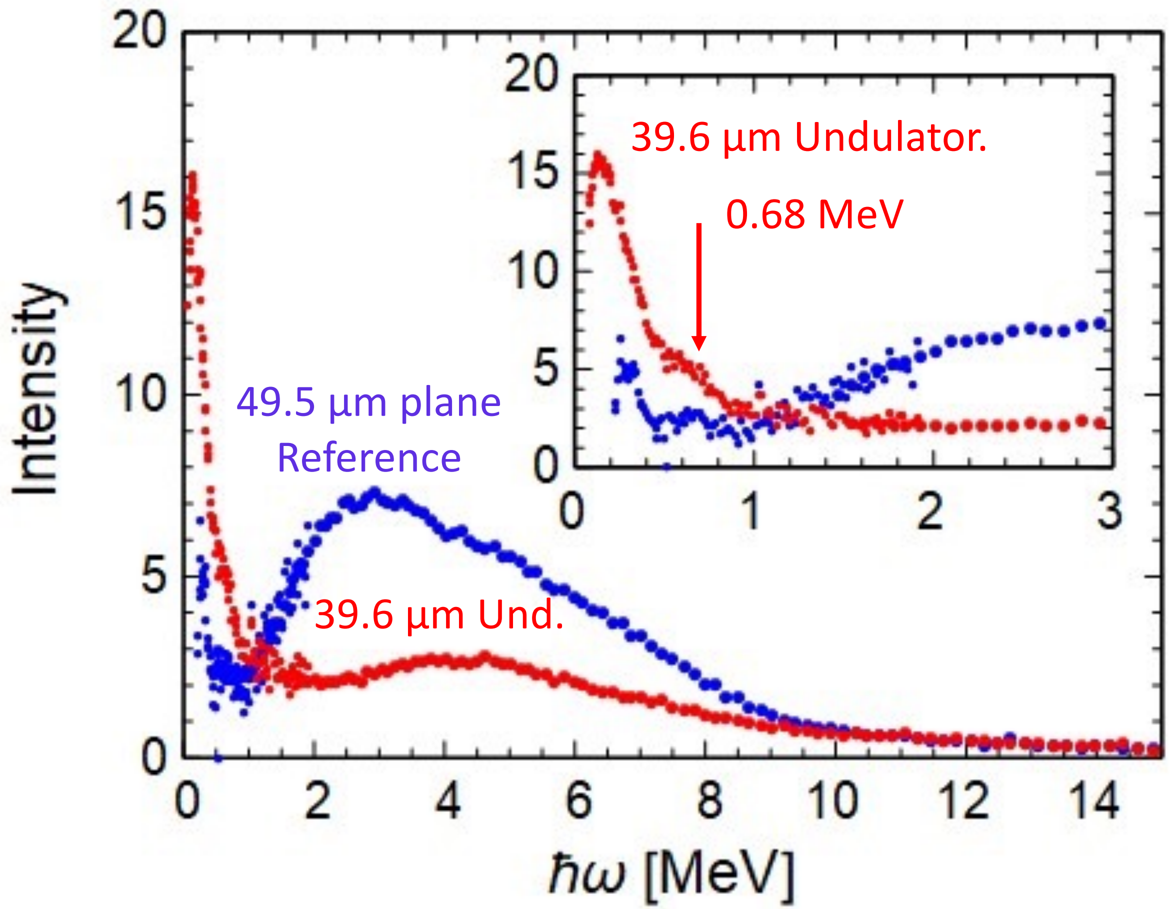
NaI Detector



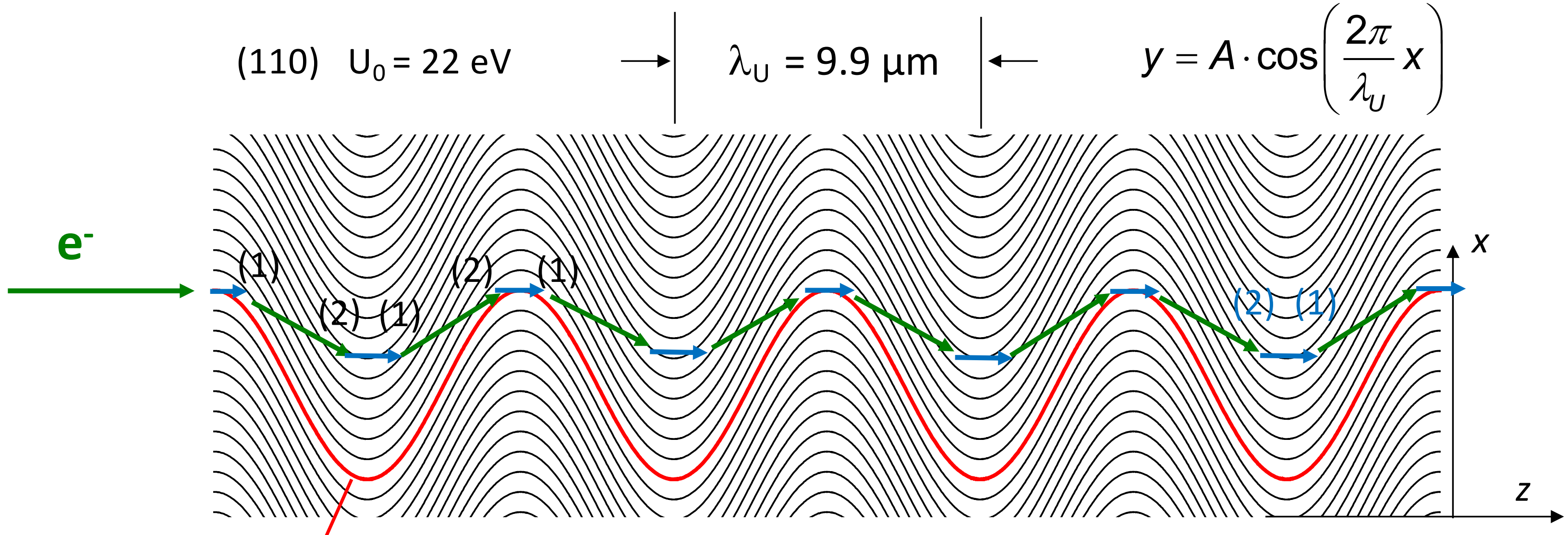
Ge Detector



De-convoluted Spectra



De- and Rechanneling for the 4-period Undulator Crystal



Coherent undulator radiation emission with coherence length L_{coh} = 4.0 to 6.0 µm

(1) Centrifugal force causes dechanneling

(2) Electron finds proper direction and re-channels

Synchrotron radiation emission from arc elements (2) $\rightarrow$ (1) with reduced length. Incoherent since between (1) $\rightarrow$ (2) electron loses phase information

Conclusion of the silicon undulator experiments

A successful prove-of-principle study was performed for a $Si_{1-x}Ge_x$ undulator with the 855 MeV electron beam of MAMI via observation of synchrotron radiation

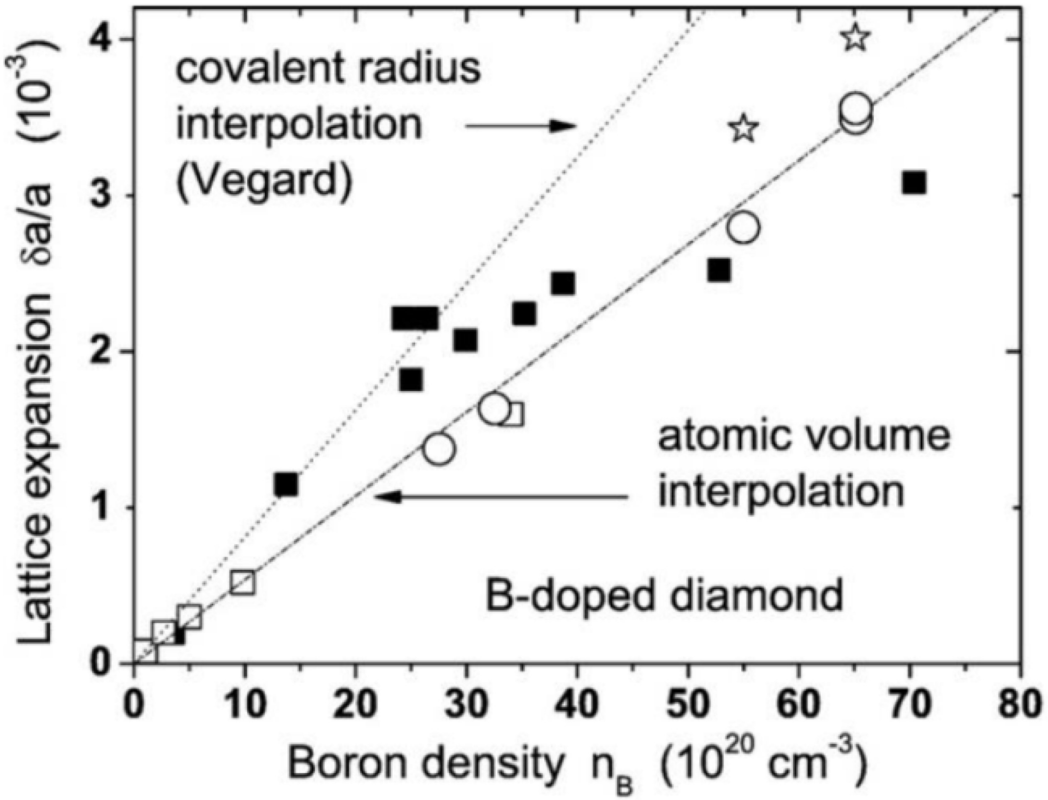
The undulator peak could not be observed because of the very short de-channeling length in the periodically bent crystal of 4-6 µm

The undulator was probably designed for experiments at BTF at Frascati with 500 MeV positrons for which the de-channeling length is with 460 µm much larger

Unfortunately, the Molecular Beam Epitaxy (MBE) laboratory at the University of Aarhus was closed.

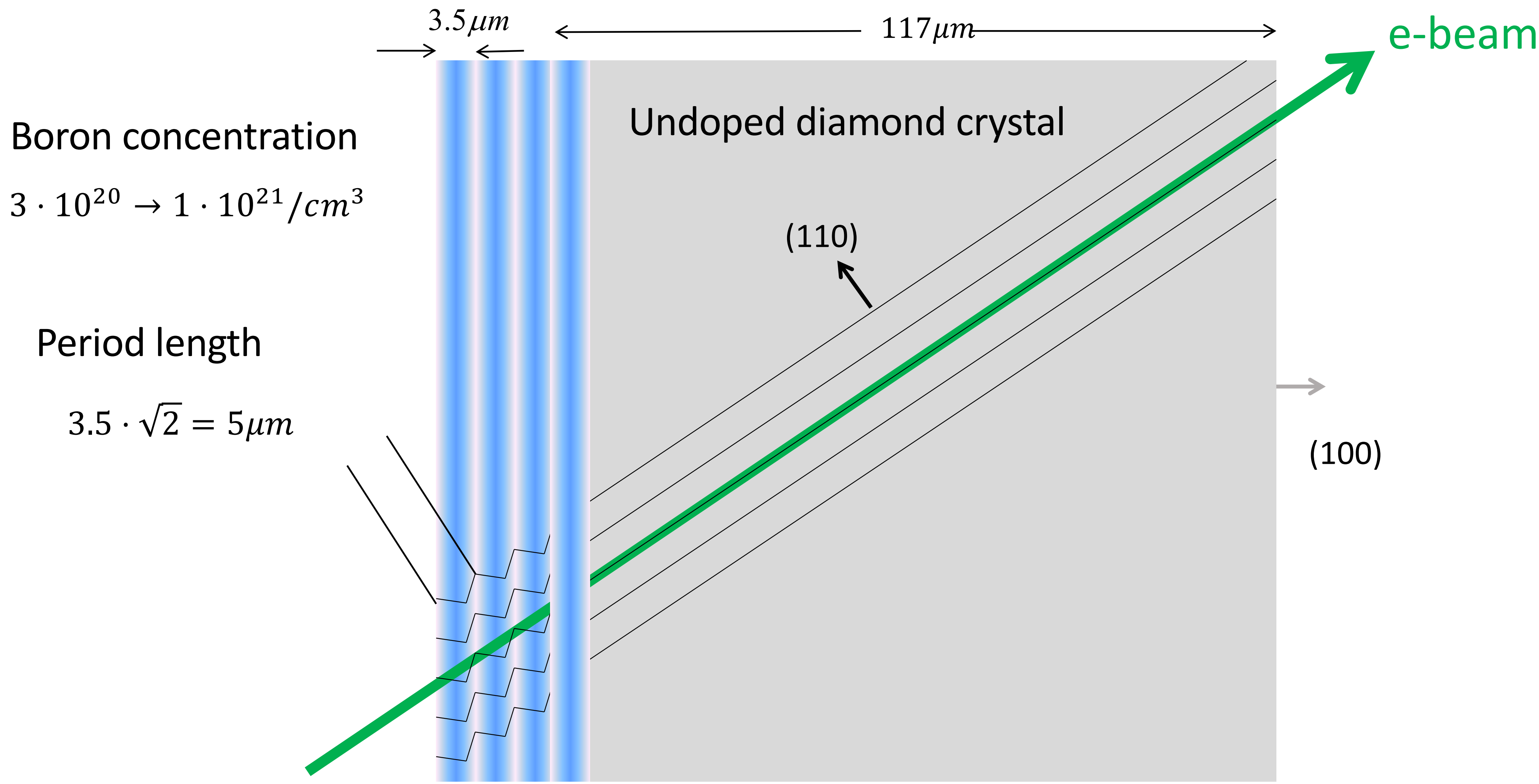
3.Examination of a Boron Doped (110) Diamond Undulator at MAMI

Lattice Expansion as Function of Boron Density

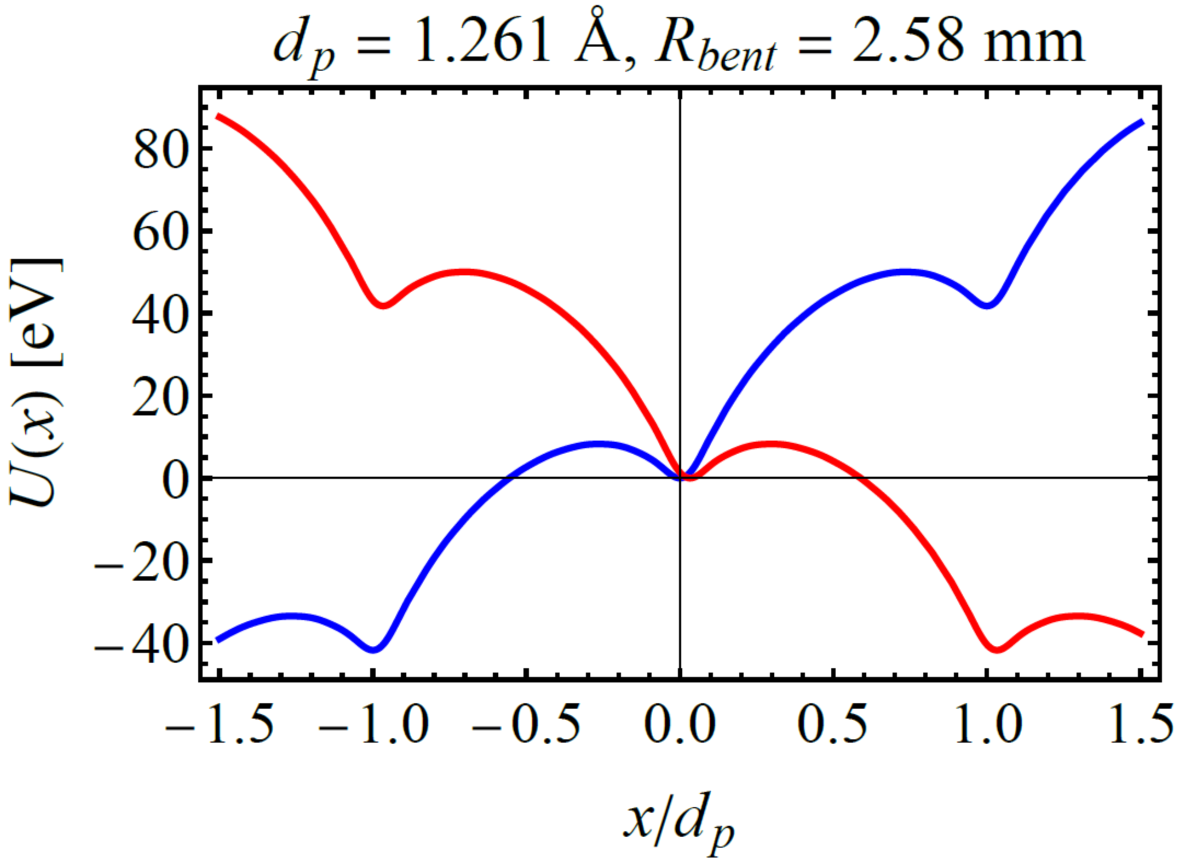


Collaboration with Thu Ni Tran Caliste, Rebecca Dowek, and Jose Baruchel from ESRF

4 Period Diamond Undulator grown by Chemical Vapor Deposition



Flip Configurations of the Potential



Simulated Photon Number Spectra from 400 Trajectories

Jackson textbook

$$\frac{d^2 I}{d\hbar\omega\ d\Omega} = \frac{e^2}{4\pi^2 c}\left|\int_{-\infty}^{\infty} \frac{\hat{n}\times\left[(\hat{n}-\vec{\beta})\times\dot{\vec{\beta}}\right]}{\left(1-\vec{\beta}\cdot\hat{n}\right)^2} e^{i\omega(t-\hat{n}\cdot\vec{r}(t)/c)}dt\right|^2$$

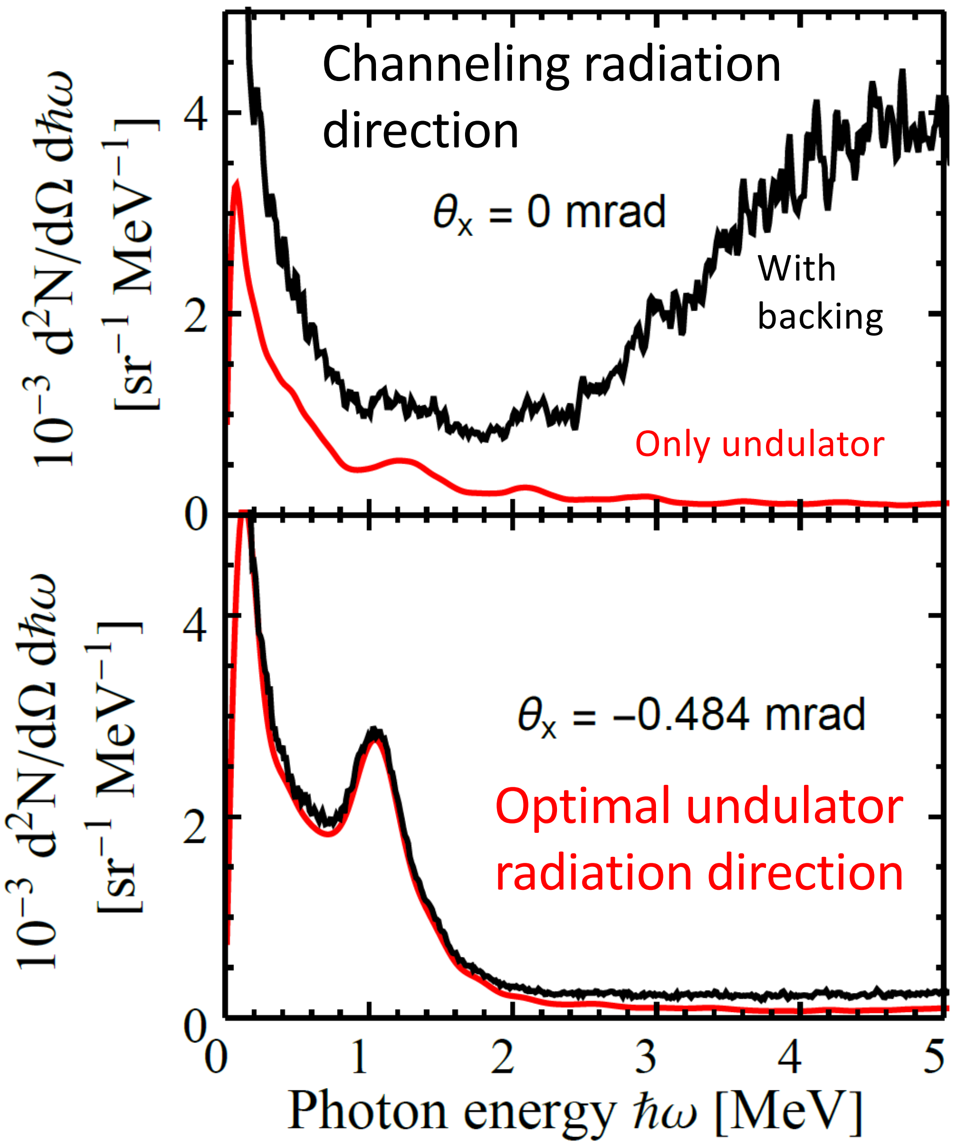
$$= \frac{d^2 N\ \hbar\omega}{d\hbar\omega\ d\Omega} = \frac{\alpha}{4\pi^2}\left|\int_0^{\varsigma_0} \frac{\{a_x(\zeta^{-1}), a_y(\zeta^{-1}), 0\}}{d\zeta/dz(\zeta^{-1})} e^{i\bar{\omega}\zeta} d\zeta\right|^2$$

$$\zeta = z + \gamma^2 \int_0^z dz' \left((\theta_x - \vartheta_x(z'))^2 + \left(\theta_y - \vartheta_y(z')\right)^2\right)$$

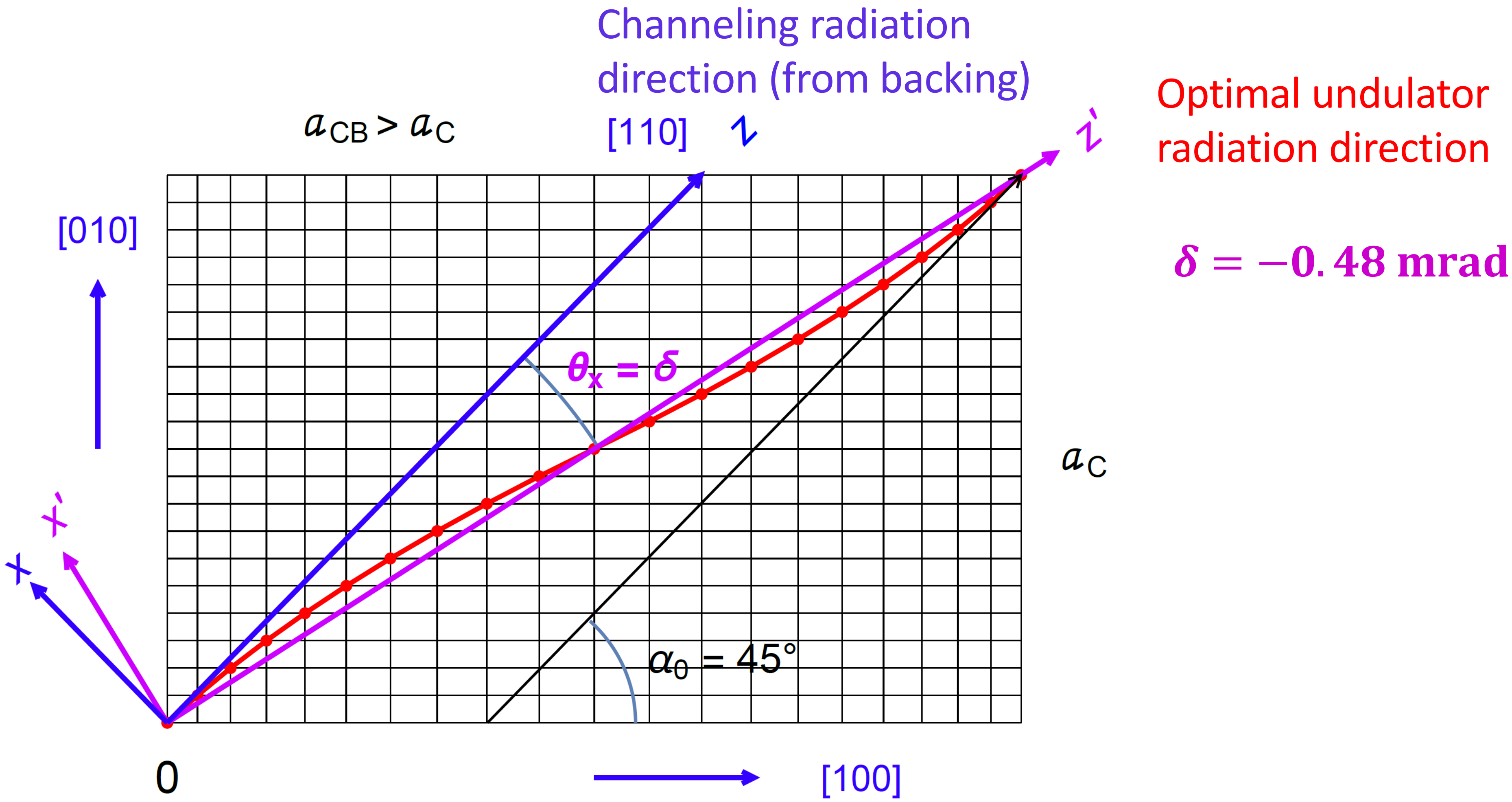
$$\mathrm{d}\zeta/dz = 1 + \gamma^2 \left((\theta_x - \vartheta_x(z))^2 + \left(\theta_y - \vartheta_y(z)\right)^2\right)$$

$$\bar{\omega} = \frac{\hbar\omega}{\gamma^2 \hbar c}$$

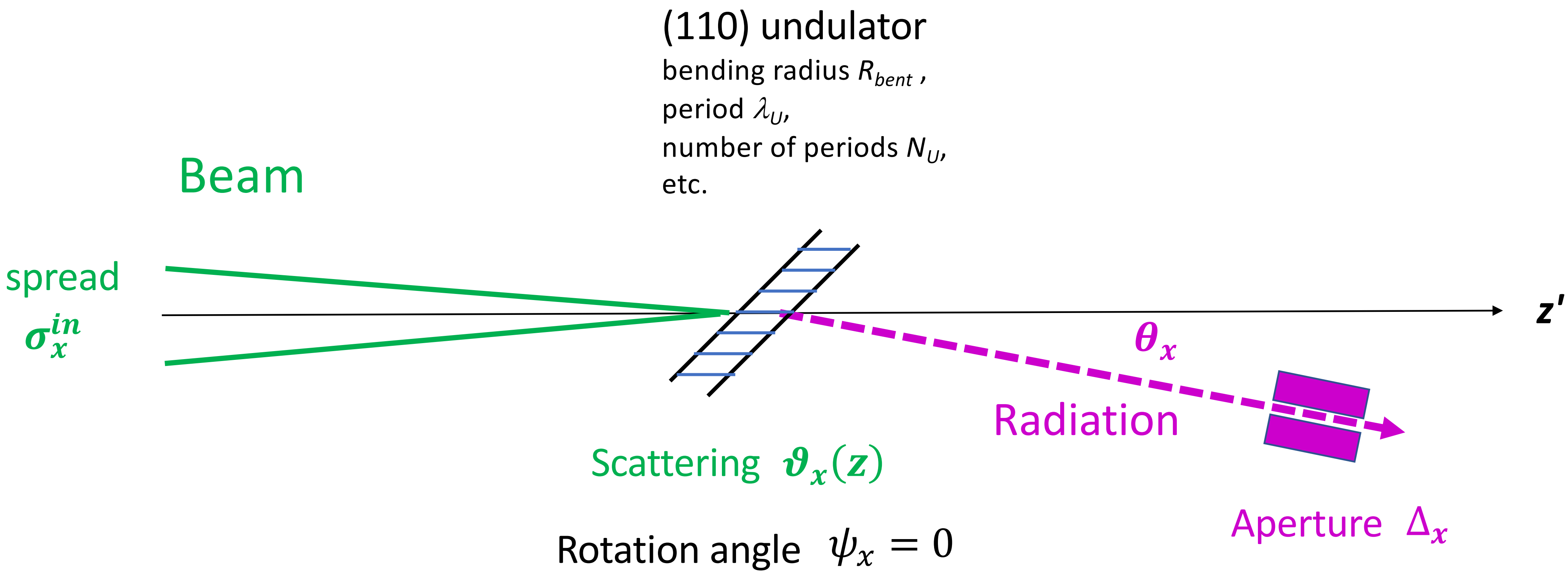
For details see arXiv:2404.15376v2



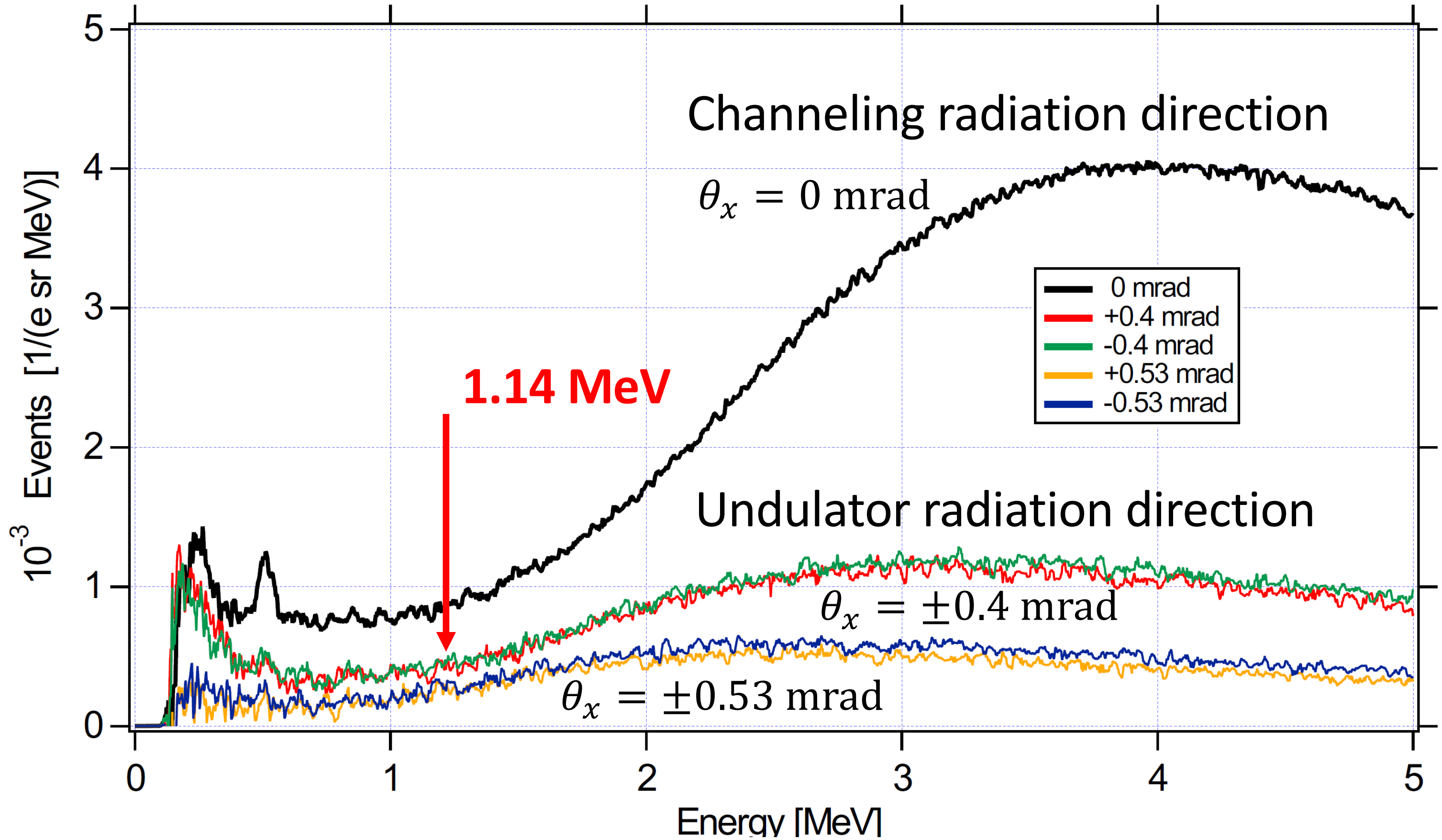
Definition of Observation Directions



Principle of Peak Search

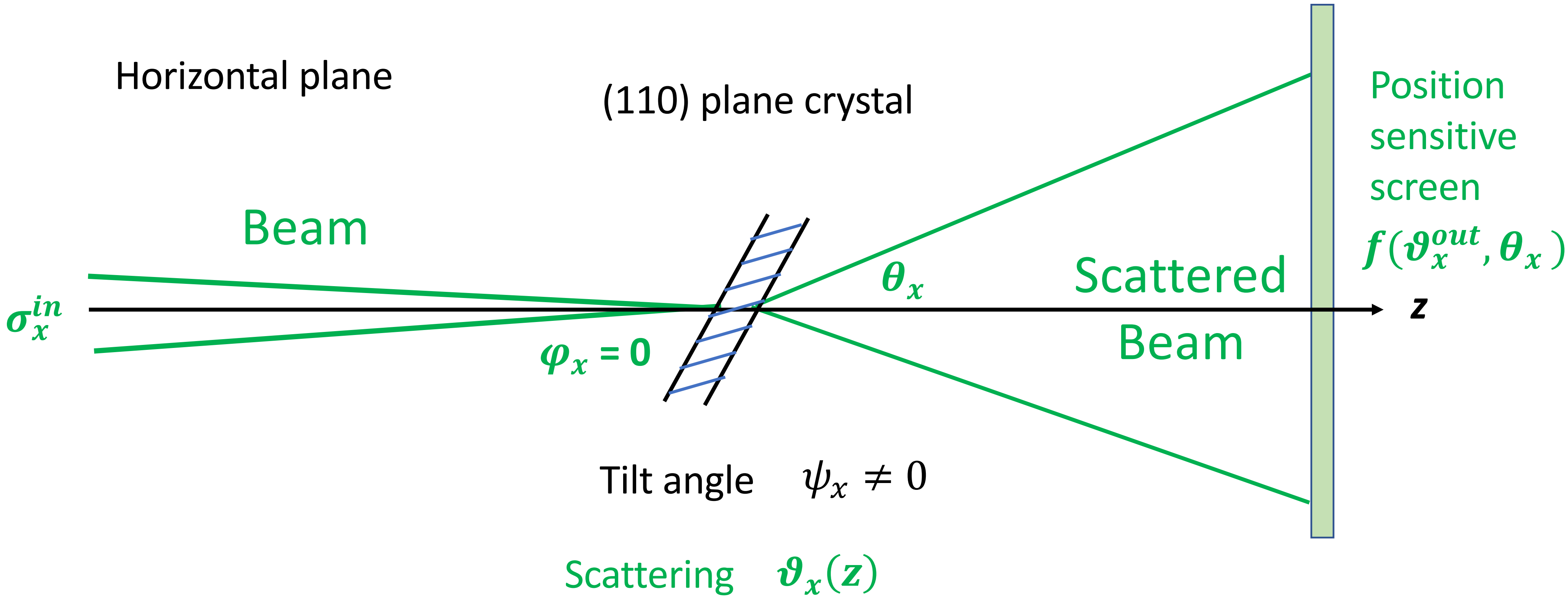


Experimental Results of Peak Search

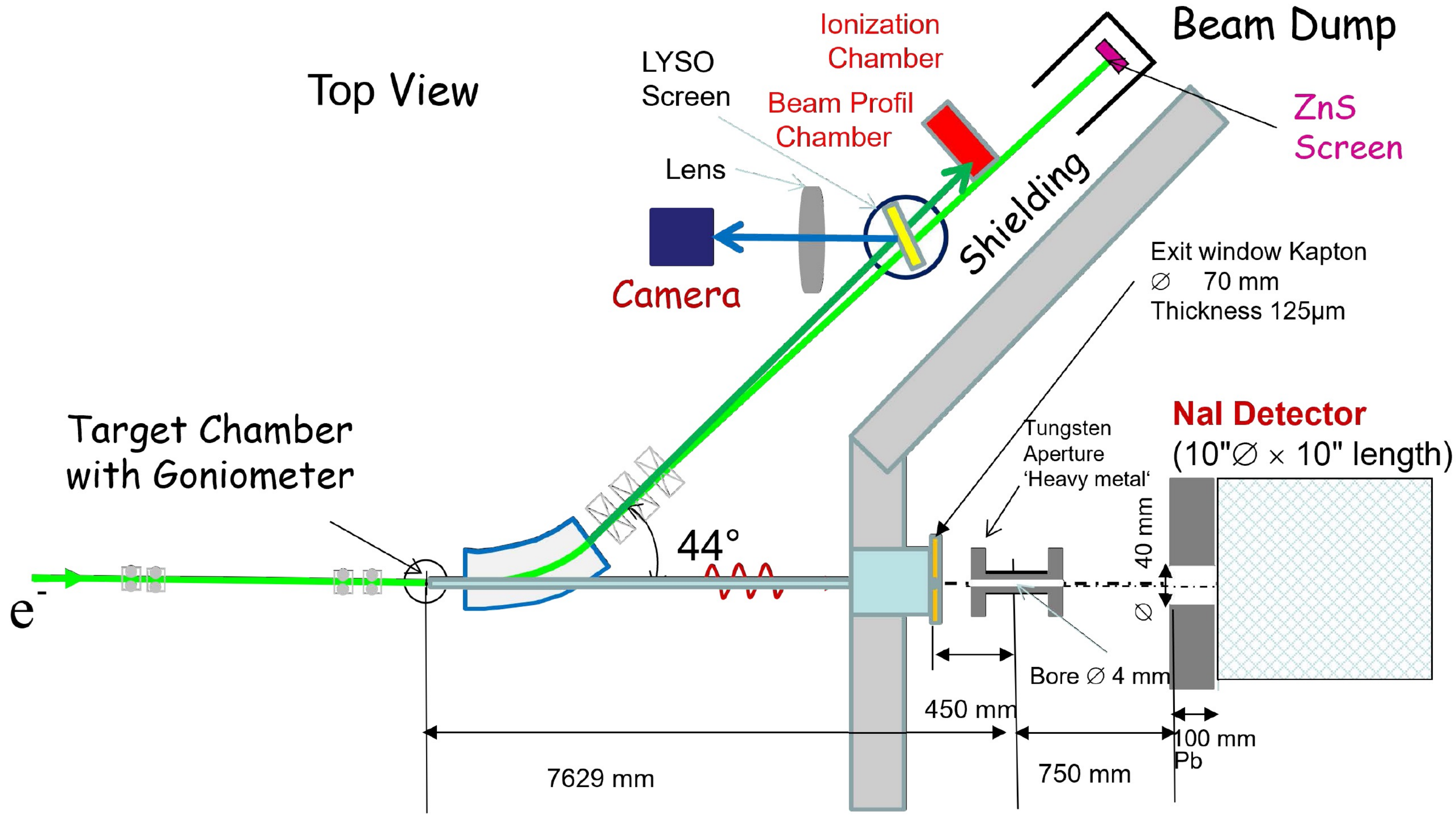


4. Scatter Distribution at Oblique Incidence on a Plane (110) Diamond Crystal of 76.4 µm thickness

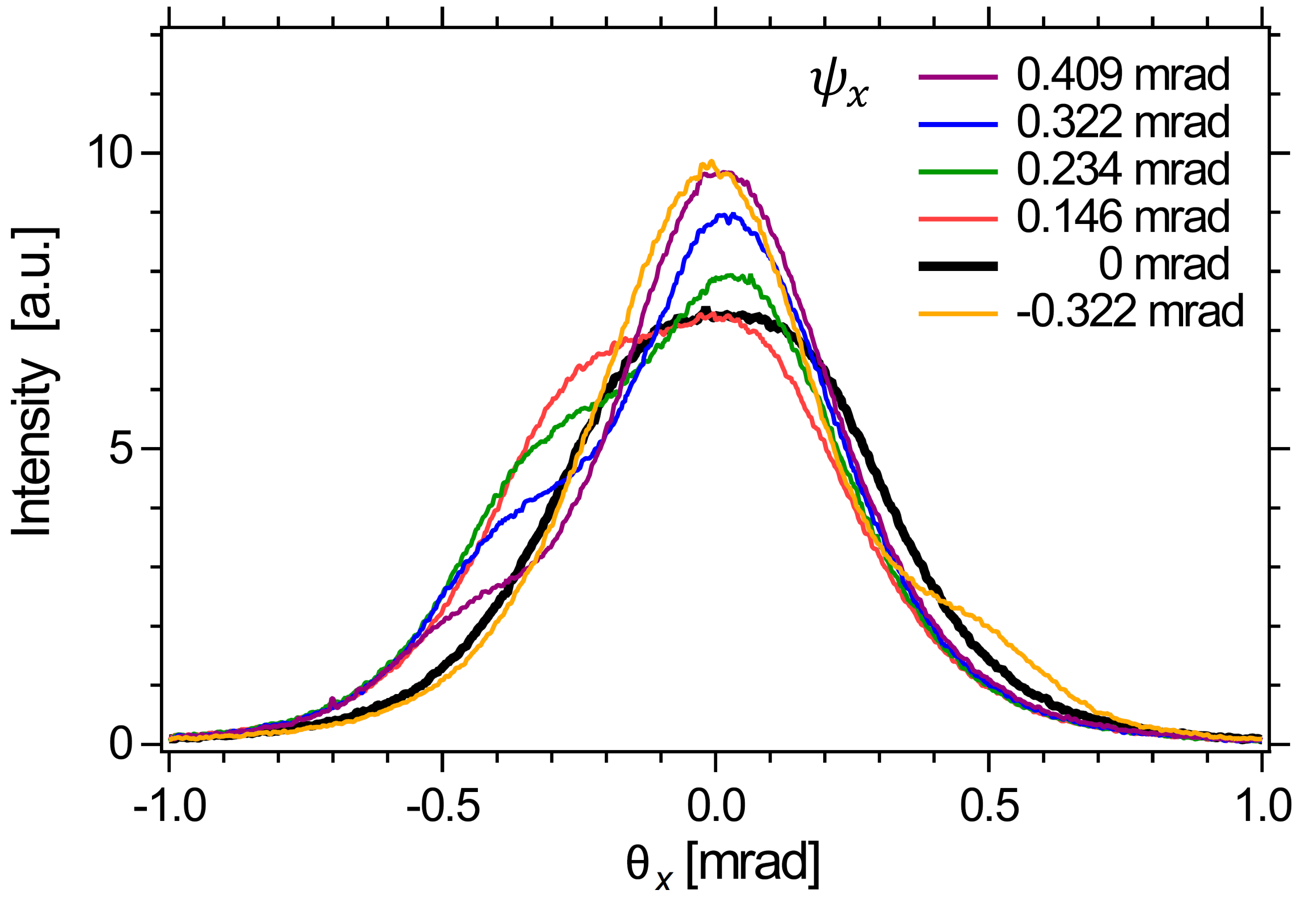
Principle of the Experiment

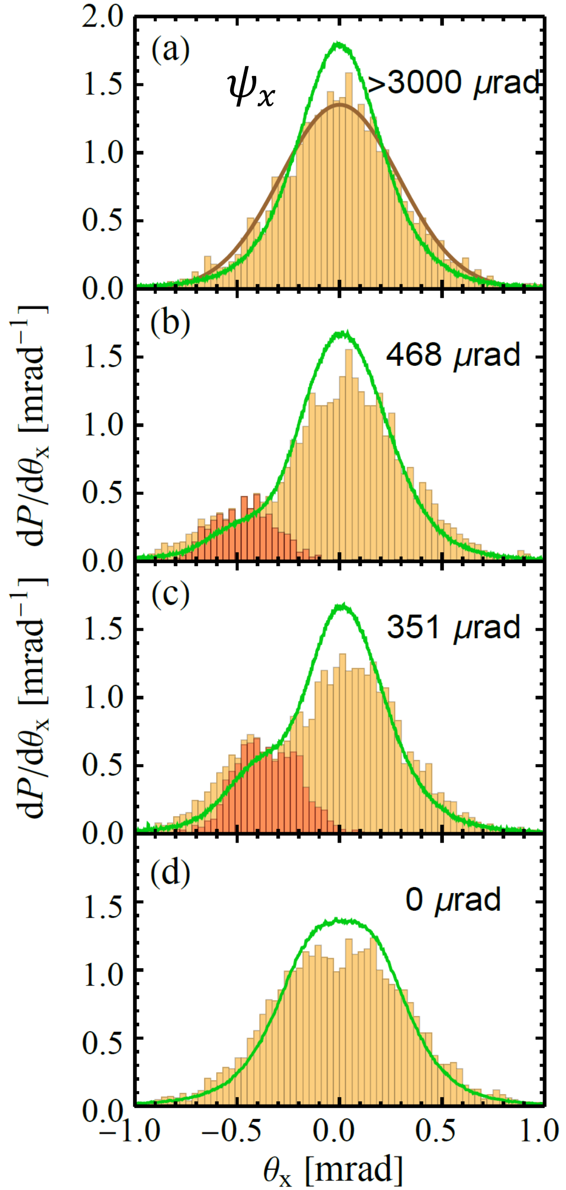


Experimental Setup



Experimental Scatter Distribution as Function of Target Tilt Angle ψ_x





Simulated scatter distributions at tilt angles ψ_x

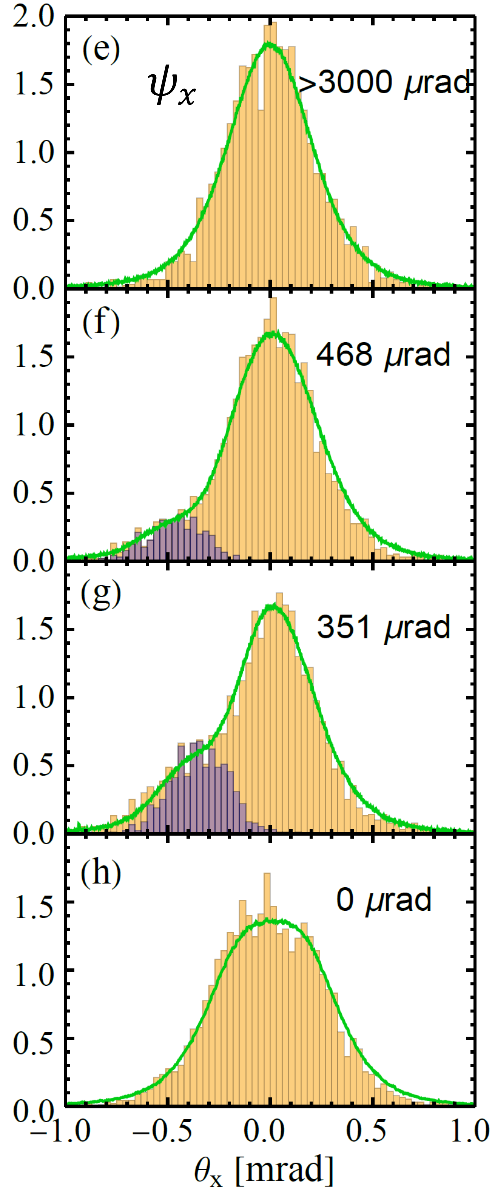
Experimental Scatter Distributions

Dark brown distributions are fractions which rechanneled and experienced channeling antil the crystal exit

Scattering distributions in (a) according to Particle Data Group

Preliminary Results

Increasing mean free path length by a factor of 2



Acknowledgments

Experiments:

Werner Lauth Institute for Nuclear Physics, Mainz

Pascal Klag Institute for Nuclear Physics, Mainz

Thu Ni Tran Caliste ESRF, Grenoble

Theory:

A.V. Solov'yov, and A.V. Korol et al.

within the

EU TECHNO-CLS — HORIZON-EIC-2021-PATHFINDER Project

See also

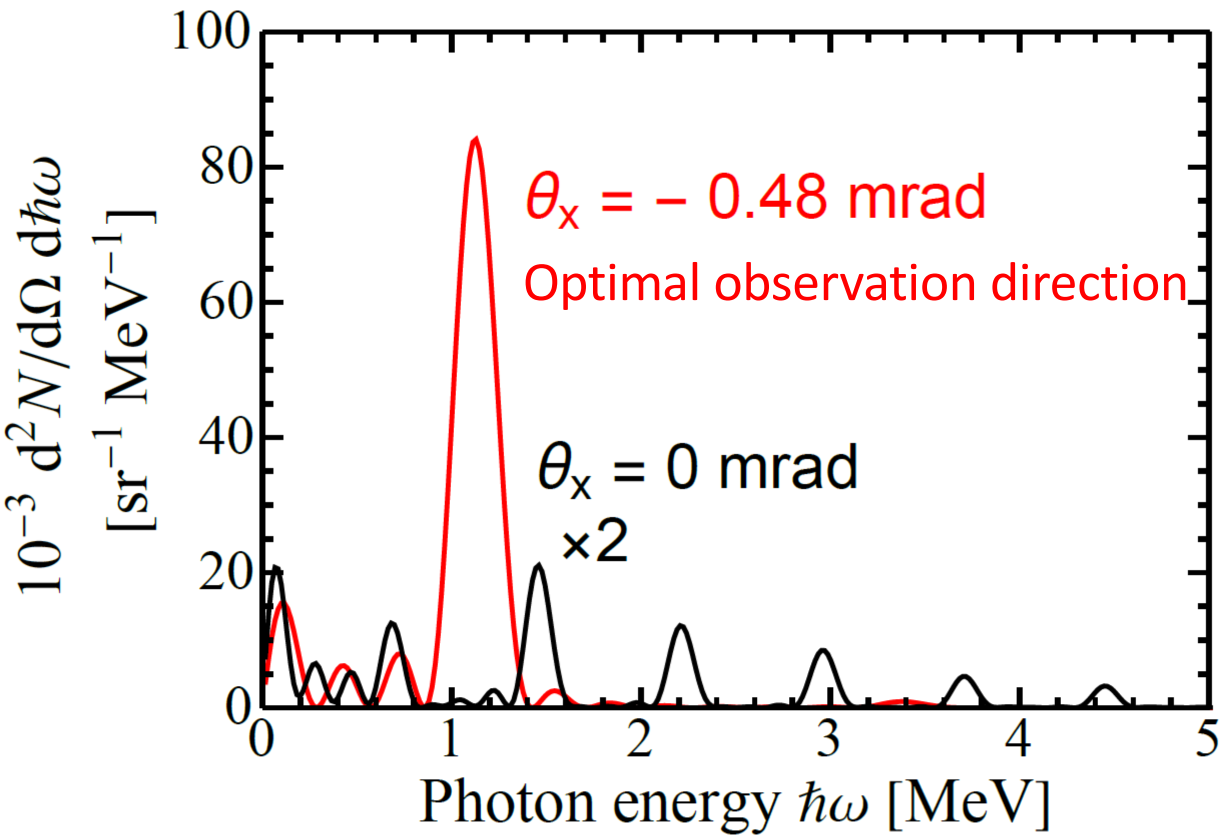
https://www.linkedin.com/company/techno-cls-project/

5. Conclusions

1. A prove-of-principle study with a $Si_{1-x}Ge_x$ undulator indicated that undulators can be studied with the MAMI electron beam via radiation emission – no peak but synchrotron radiation
2. For a boron doped diamond undulator no characteristic undulator radiation was observed at all
3. Production of $Si_{1-x}Ge_x$ undulators with Molecular Beam Epitaxy, and boron doped diamond undulators grown by Chemical Vapor Deposition is obviously a challenge
4. A quenching was observed of the width of the scattering distribution for a plane 76.4 μm thick (110) diamond crystal at oblique incidence (preliminary)
5. A much better diagnostic tool for undulators may be in the future the 530 MeV MAMI positron beam (Pascal Klag)

For details see arXiv:2404.15376v2

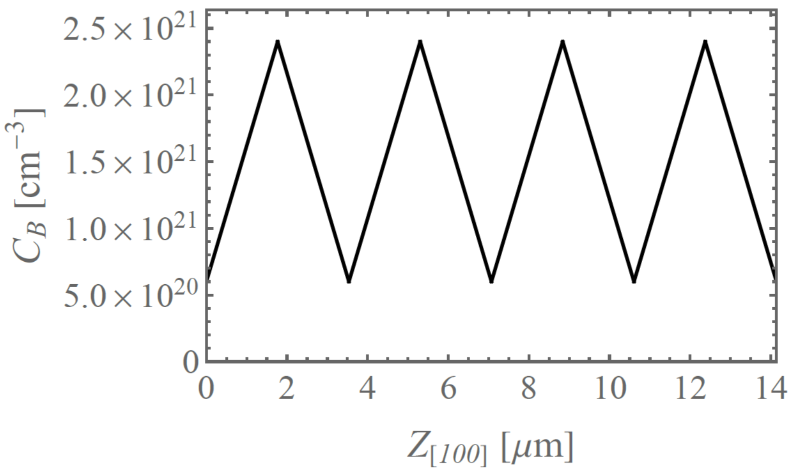
Spectra of Undulator for Model **Trajectory**



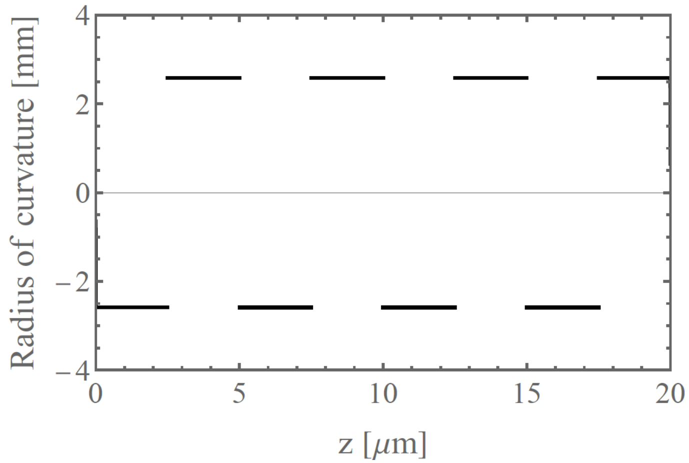
Observation angle θ_x with respect to [110] direction of backing

Construction of Model Trajectory

Boron doping profile



Radius of curvature



Angular acceleration

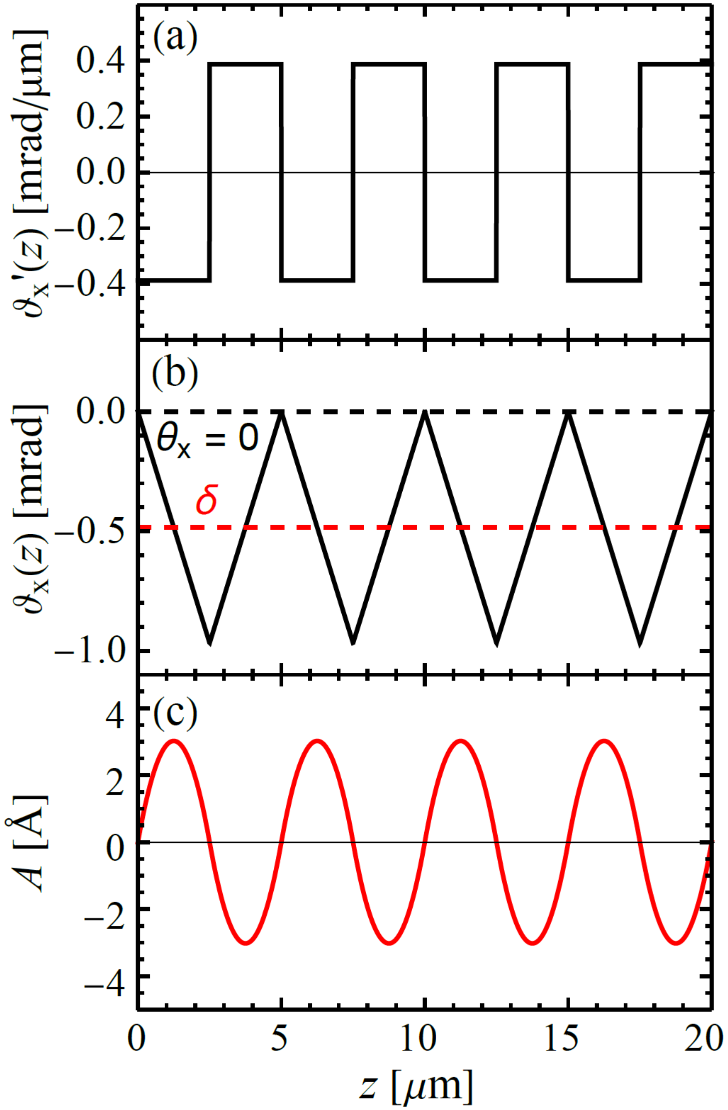
$\vartheta_x'(z)$

Angular slope

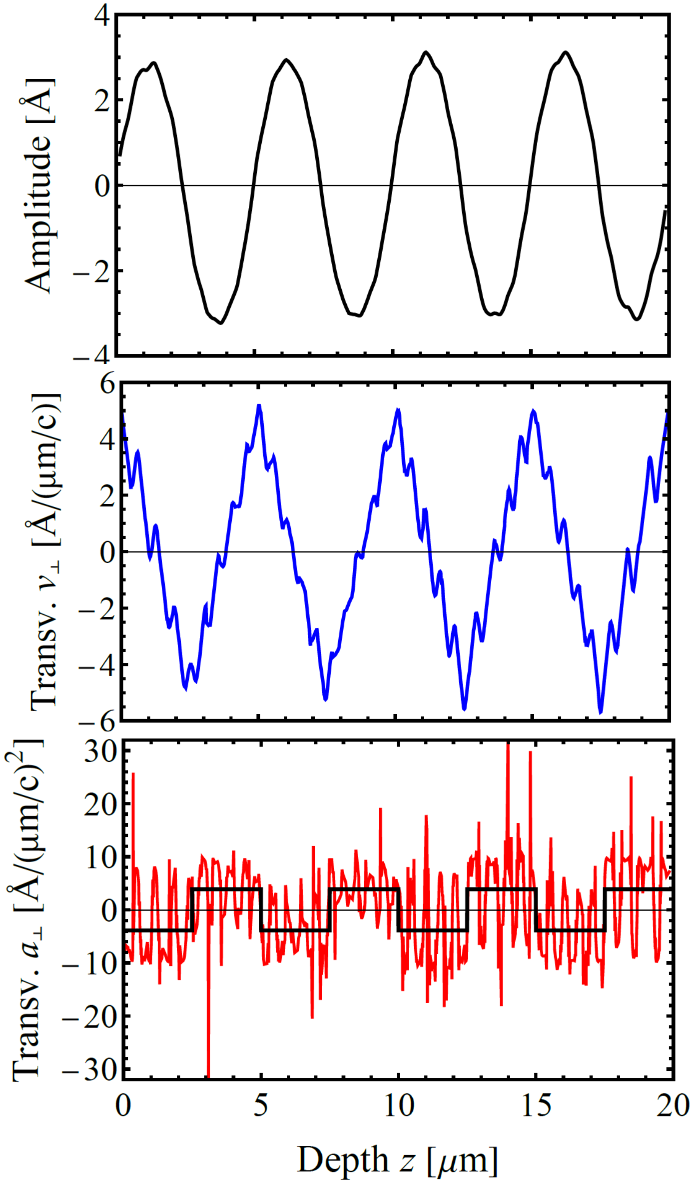
$\vartheta_x(z)$

Amplitude

A(z)



Trajectories



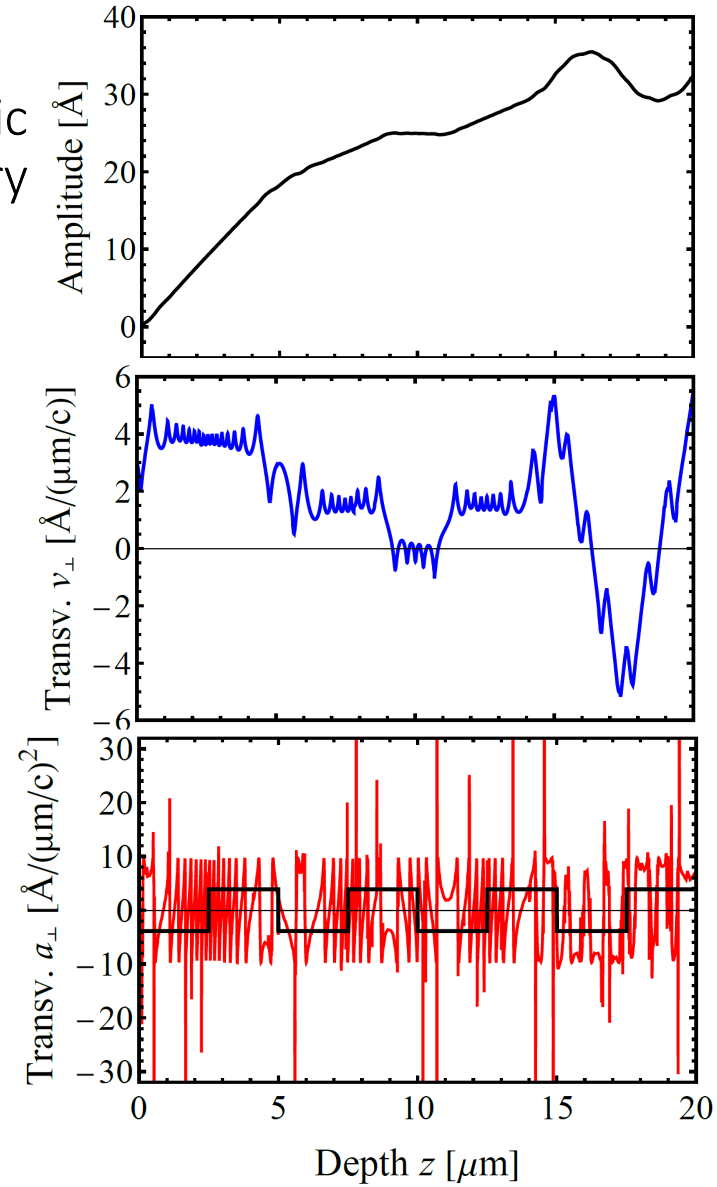
Full channeling Case ($<10^{-3}$)

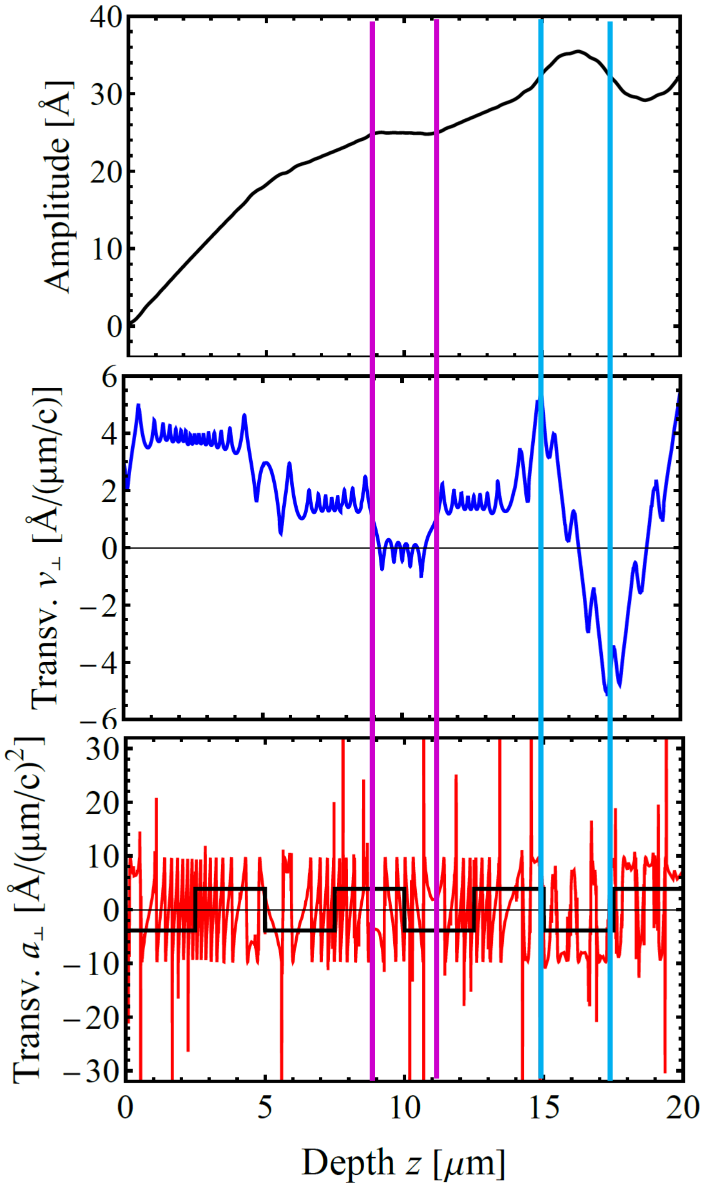
Realistic trajectory

Amplitude

Transverse velocity

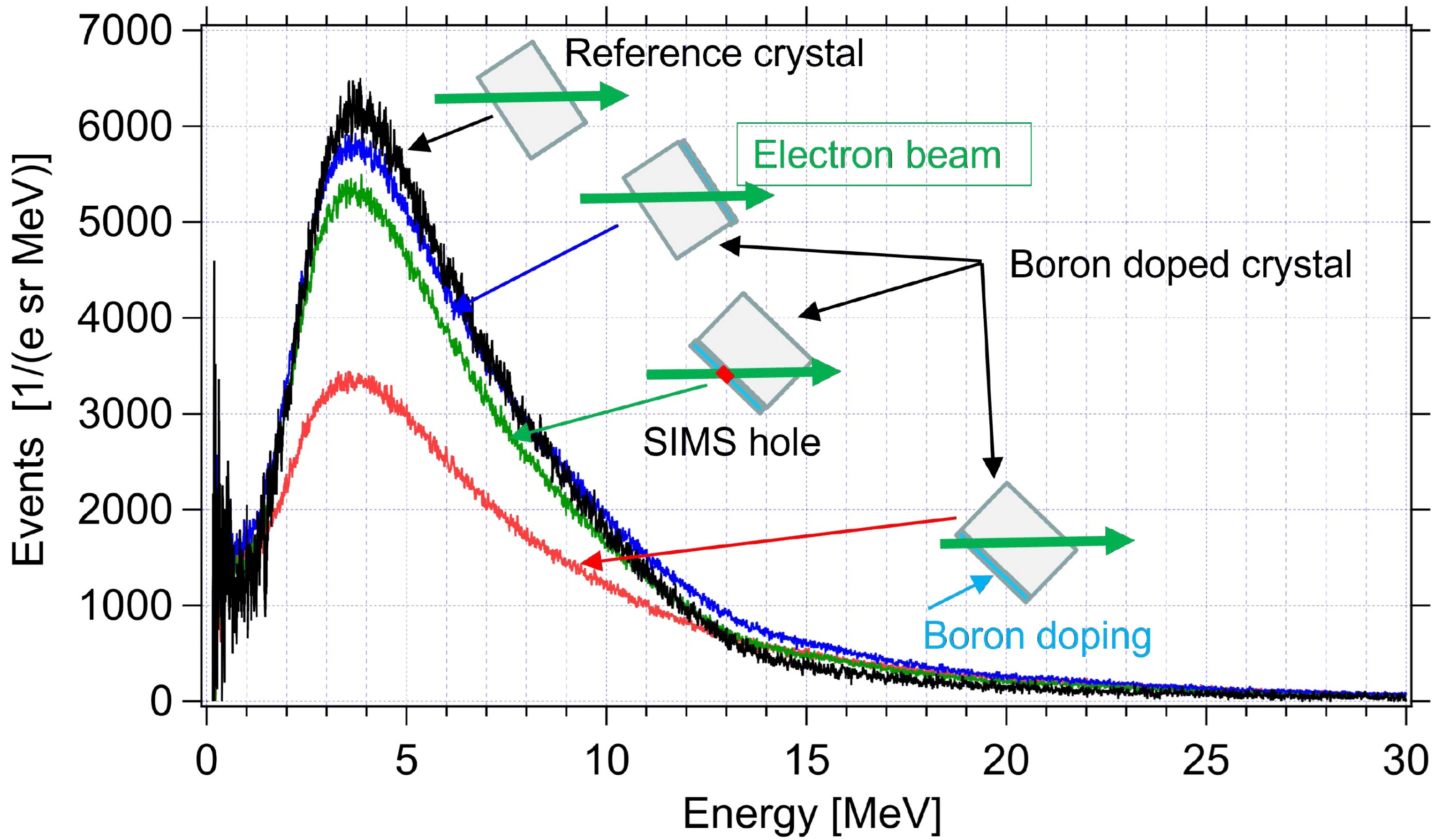
Transverse acceleration





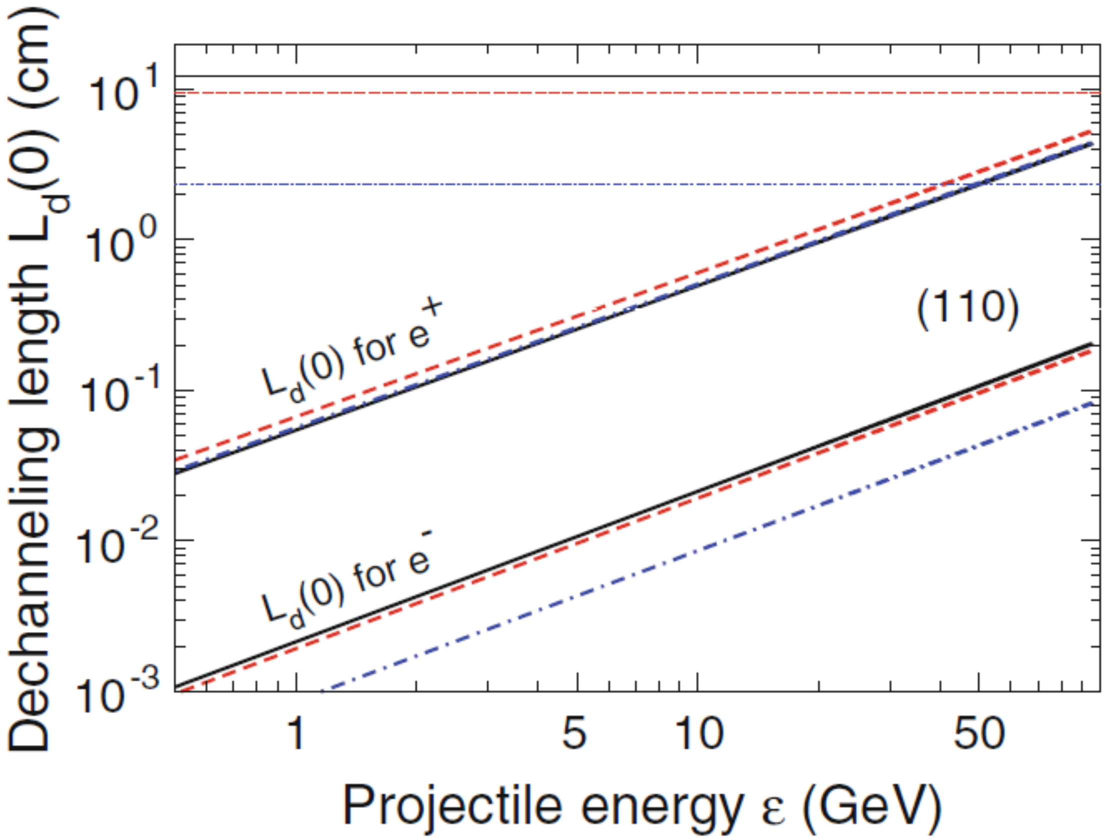
Amplitude [Å]
Transv. $v_\perp$ [Å/(μm/c)]
Transv. $a_\perp$ [Å/(μm/c)^2]
Depth z [μm]

Experimental Spectra taken with NaI Detector



De-channeling Lengths for Electrons and Positrons

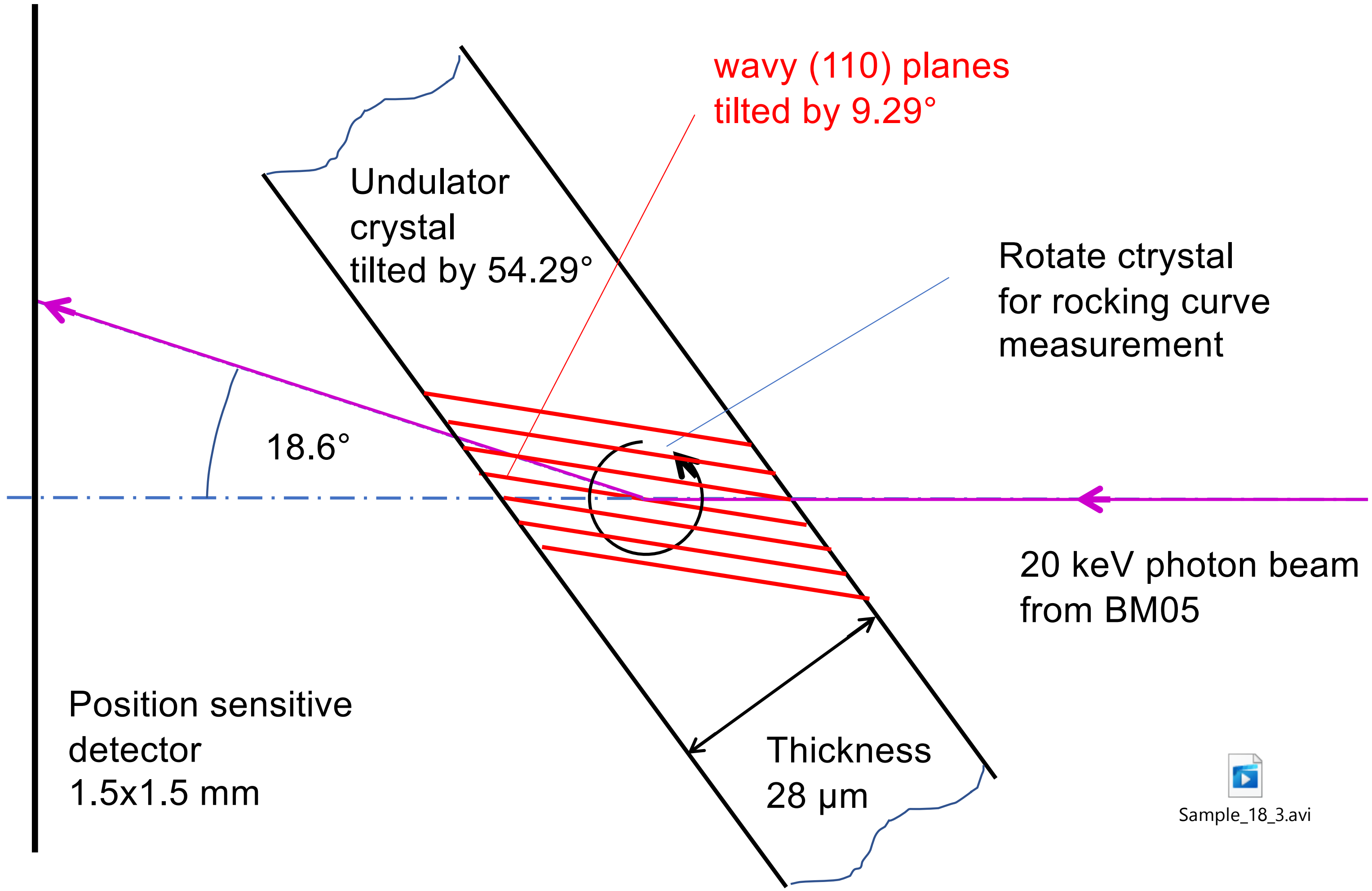
A.V. Korol, A.V. Solov'yov, W. Greiner, *Channeling and Radiation in Periodically Bent Crystals*, 2nd edn. (Springer Verlag, Berlin Heidelberg, 2014), Fig. 6.2



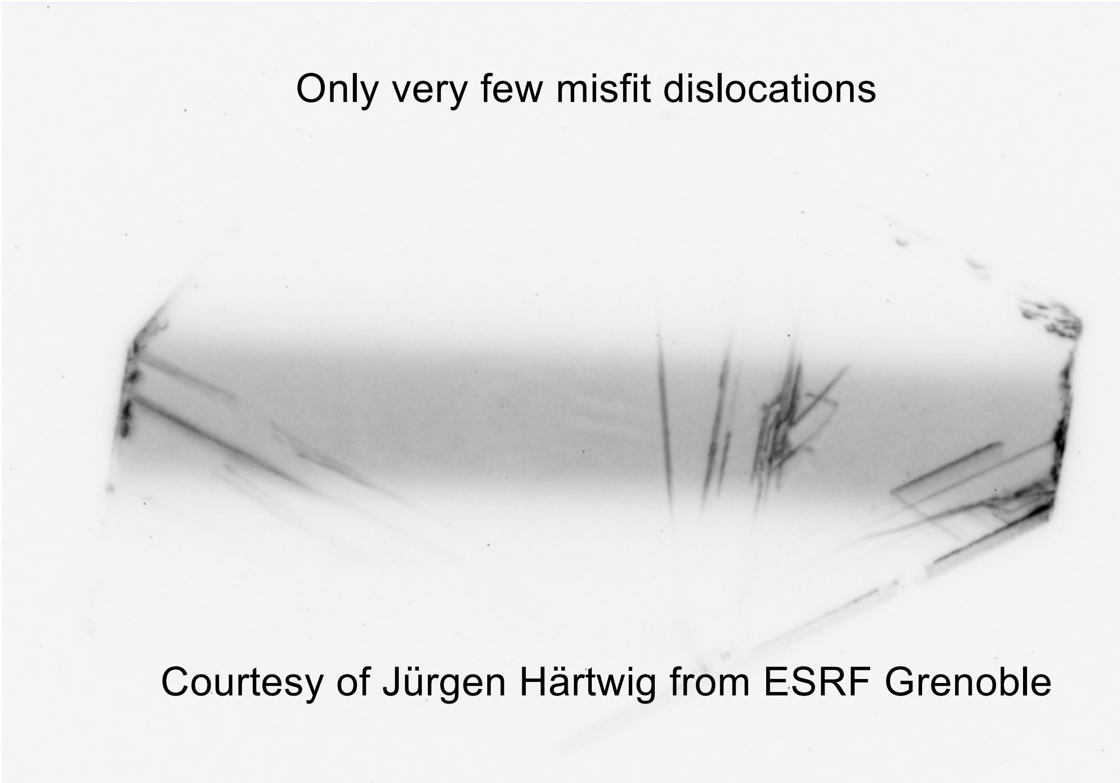
Electron de-channeling length at 0.855 GeV
$L_d(0)$= 18 µm

Positron de-channeling length at 0.530 GeV
$L_d(0)$= 390 µm

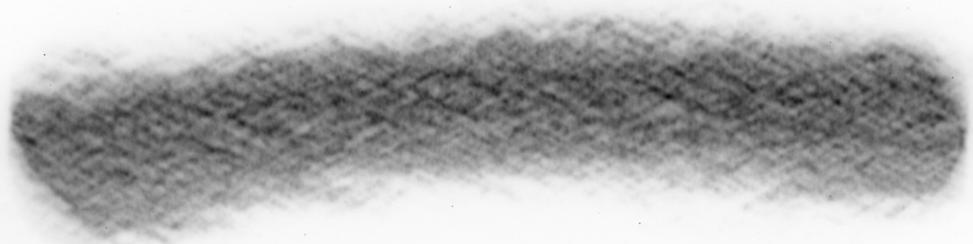
X-ray topography of the Si_xGe_{1-x} undulator with (220) reflection at ESRF (Grenoble)



Snap-shot at a fixed rocking position
Nearly perfect crystal



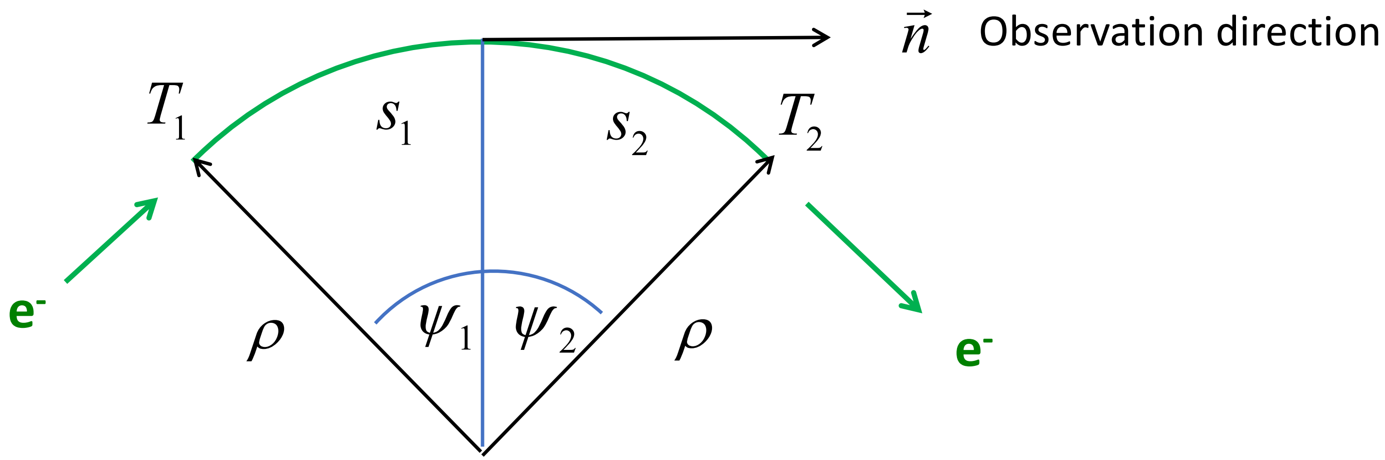
Snap-shot at a fixed rocking position
$Si_{1-x}Ge_x$ undulator crystal



Preliminary results of measurements at ESRF indicate a very dense networks of misfit dislocations

Courtesy of Jürgen Härtwig and Thu Nhi Tran Thi

Synchrotron-like Radiation Emission
from Finite Arc Element of Undulator



Schwinger's approach $T_1 \to -\infty, \quad T_2 \to \infty$

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5. Remark Addressing Theoreticians
6. Conclusions

In Honor of
Prof. Dr. Dr. h.c. mult. Walter Greiner

* October 29, 1935; † October 5, 2016

At FIAS with Andrey V. Solov'yov and Andrei V. Korol

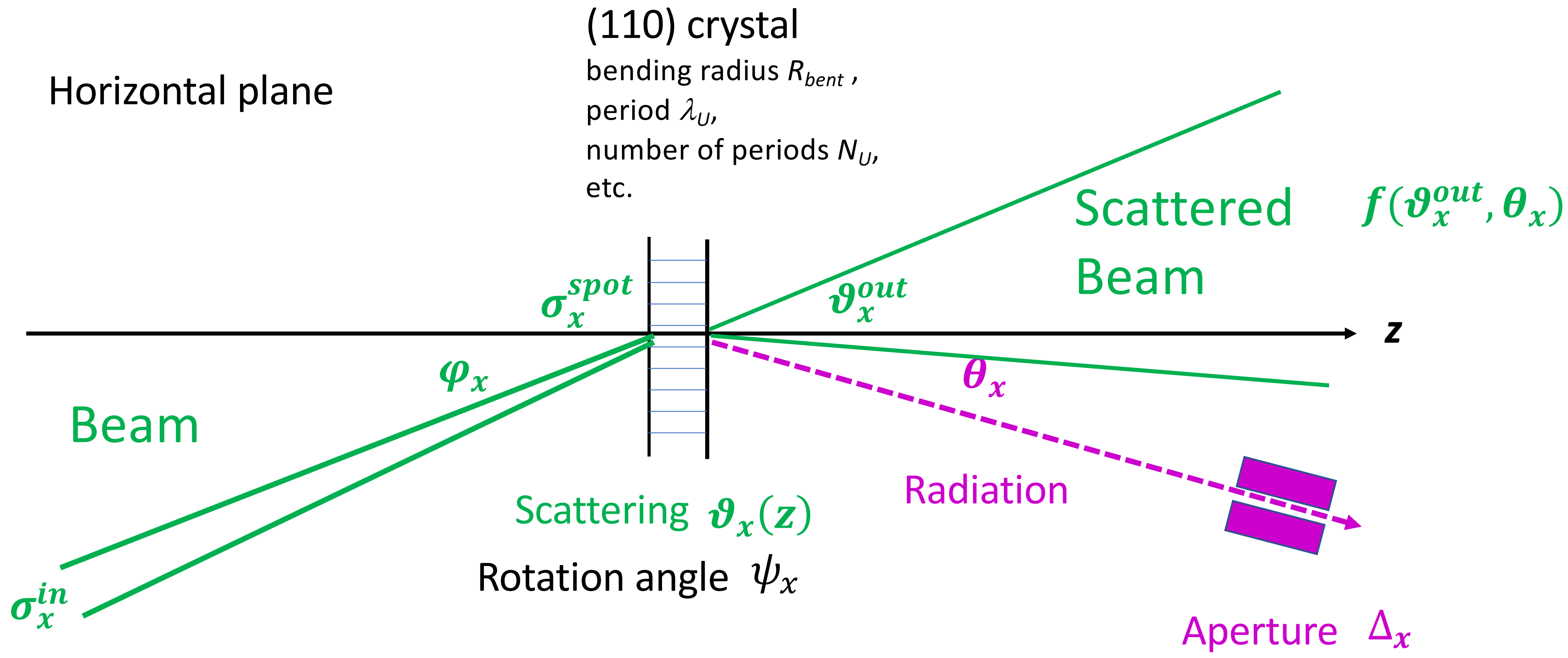
5. A Remark of an Experimentalist addressing Theoreticians: A Fast Simulation Explorer running on a PC would be most welcome

Why?

Not mainly for optimizing designs of undulators, however,

primarily for a fast feedback for decisions during the course of an experiment

The Experimental Multi Parameter Space



Totally 2×7 parameters