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SAGA Light Source

First Observation of Scattering of Sub-GeV Electrons in Ultrathin Si Crystal at Planar Alignment and Relevance to Crystal-assisted Rainbow Scattering

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Motivation

- Continuation of experimental and theoretical studies of the scattering of 255 MeV electrons by aligned crystals at SAGA-LS accelerator facility and TPU.
- In the previous series of experiments we studied the
  - doughnut scattering (DS) (O. V. Bogdanov , Y. L. Pivovarov, Y. Takabayashi, T. A. Tukhfatullin, J. Phys.: Conf. Ser. 357 (2010) Article number 012030.)
  - scattering at planar alignment (SPA) (Y. Takabayashi, Yu.L. Pivovarov, T.A. Tukhfatullin, Phys. Lett. A 378 (2014) 1520)
  - and mirroring (Y. Takabayashi, Yu.L. Pivovarov, T.A. Tukhfatullin, Phys. Lett. B 751 (2015) 453.)
- The goal of the present work is experimental and theoretical search for another type of scattering named rainbow scattering (RS).
- We perform experimental studies and computer simulations of 255 MeV electrons scattering in an ultrathin 0.58 micrometer (111) Si crystal.

Motivation

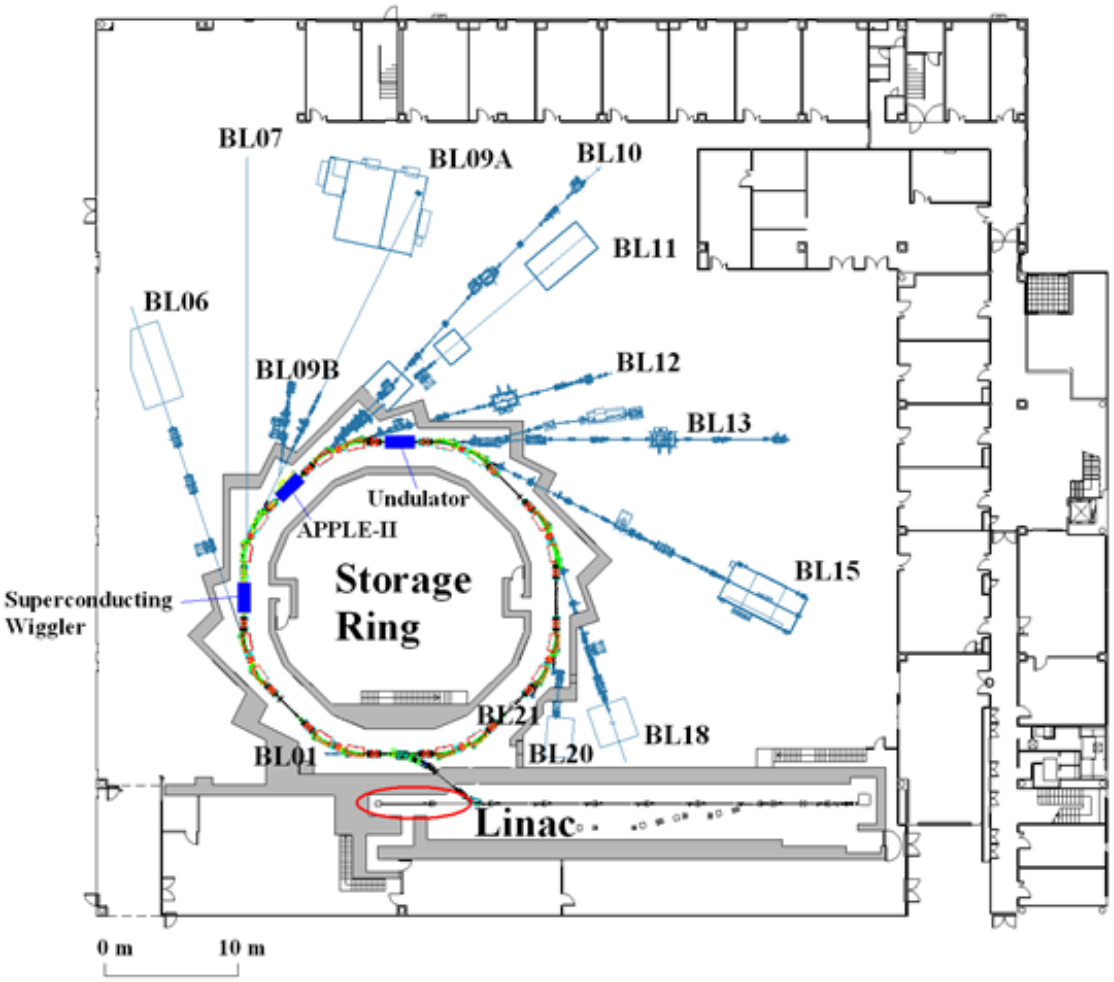
- **The RS is very specific type of scattering which in general appears in the scattering of the waves and particles (both classical and quantum)** (N.F. Mott, H.S. Massey. The Theory of Atomic Collisions. London, 1965., R. Newton. Theory of the waves and particles scattering. McGraw-Hill Book Company, 1969).
- **The earlier works on appearance of RS at ions channeling are reviewed (axially channeled 7-MeV and 2-MeV protons) in** (D.S.Gemmel. Rev. Mod. Phys. 46 (1974) 129).
- **The very precise studies of crystal-assisted RS in the case of non-relativistic ions were performed by N. Neškovi´c** (L. Živkovi´c, S. Petrovi´c, S. Kossionides, N. Neškovi´c, Phys. Lett. A 286 (2001) 292).

Features of Rainbow Scattering

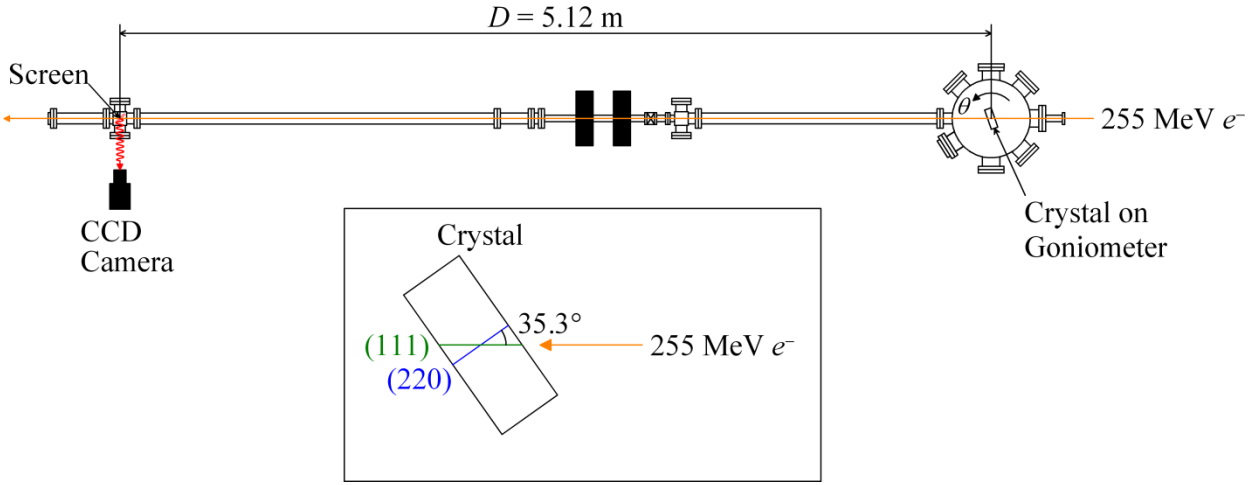
- **The key aspect of the crystal rainbows is an unusual dependence of the deflection angle on the impact parameter with a crystal axis.**
- **The RS for high-energy electrons (100 and 500 MeV) at axial alignment was theoretically considered in (L. Živkovi´c, S. Petrovi´c, S. Kossionides, N. Neškovi´c, Phys. Lett. A 286 (2001) 292) using both classical and quantum approaches and Lindhard's string potential.**
- **The theory predicted some contradictions between classical and quantum approaches.**
- **Similar contradictions between classical and quantum theories of RS in the case of planar alignment and 4 – 50 MeV electrons were discussed in (S.N. Shul'ga, N.F. Shul'ga, S. Barsuk, I. Chaikovska, R. Chehab, arXiv: 1512.04601v1 [physics.acc-ph] 14 Dec 2015.)**

SAGA Light Source (SAGA-LS), Tosu, Saga, Japan

Storage ring	
Circumference	75.6 m
Energy	1.4 GeV
Stored current	300 mA
Emittance	25 nm?rad
Lifetime	6 hours @300 mA
Critical energy	1.9 keV
Injector linac	
Total length	30 m
Energy	255 MeV
Average current	7 nA
Repetition	1 Hz
Normalized emittance	25 mm?mrad



Rainbow Scattering Experiment



- 255 MeV e[?] [?] 0.47-[?]m-thick Si crystal
- (111) planar alignment
- The effective thickness of the crystal 0.47 [?]m[?]cos(35.3[?]) [?] 0.58 [?]m
- Collimator with an inner diameter of 100 [?]m upstream of the crystal
- The beam intensity at the crystal is considered to be constant within a diameter of 100 [?]m.
- The angular divergences of the incident beam: [?][?]$_x$ [?] 0.09 mrad and [?][?]$_y$ [?] 0.05 mrad

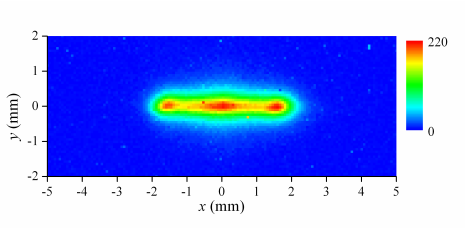
Results of Rainbow Scattering Experiment

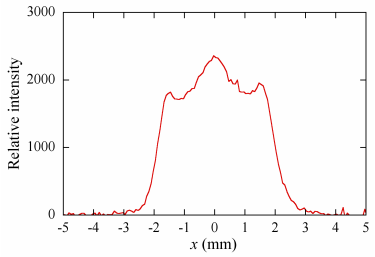
2D profile:

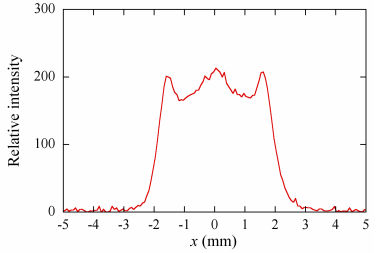
Horizontal projected profile: $I(x) = \int dy I(x, y)$

Horizontal cross-sectional profile: $I(x) = I(x,0)$

?=0°







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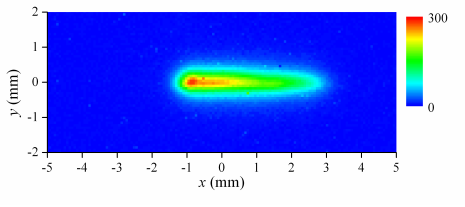

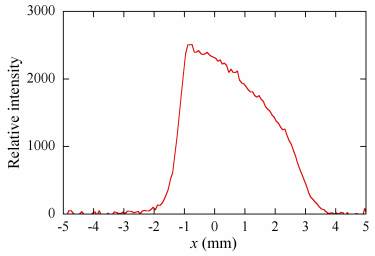

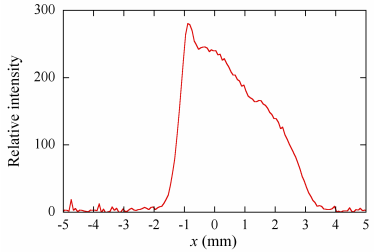

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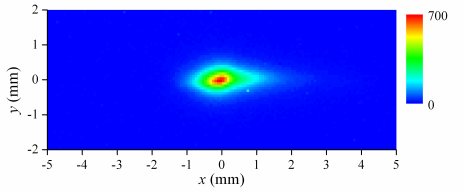

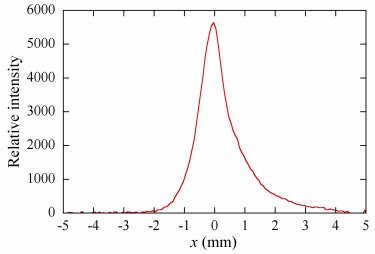

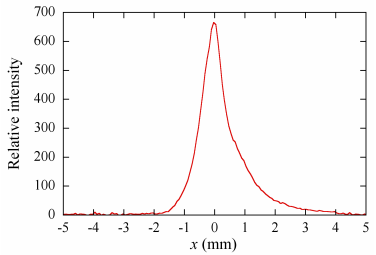

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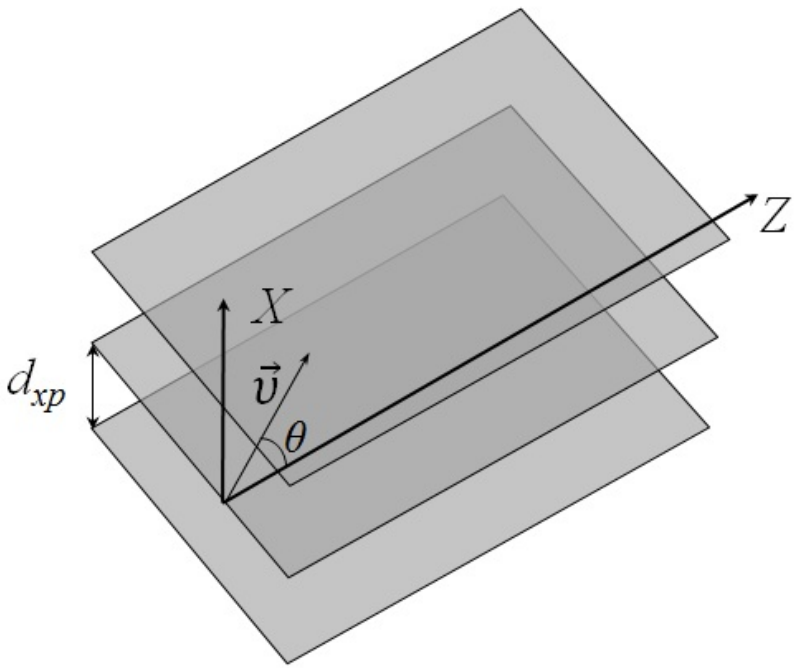
Angular Distribution Simulation



- **Equation of motion**

$$\gamma m\ddot{x} = F_x = -\frac{\partial U(x)}{\partial x},\ \gamma m\ddot{z} = 0$$

- **Initial conditions**

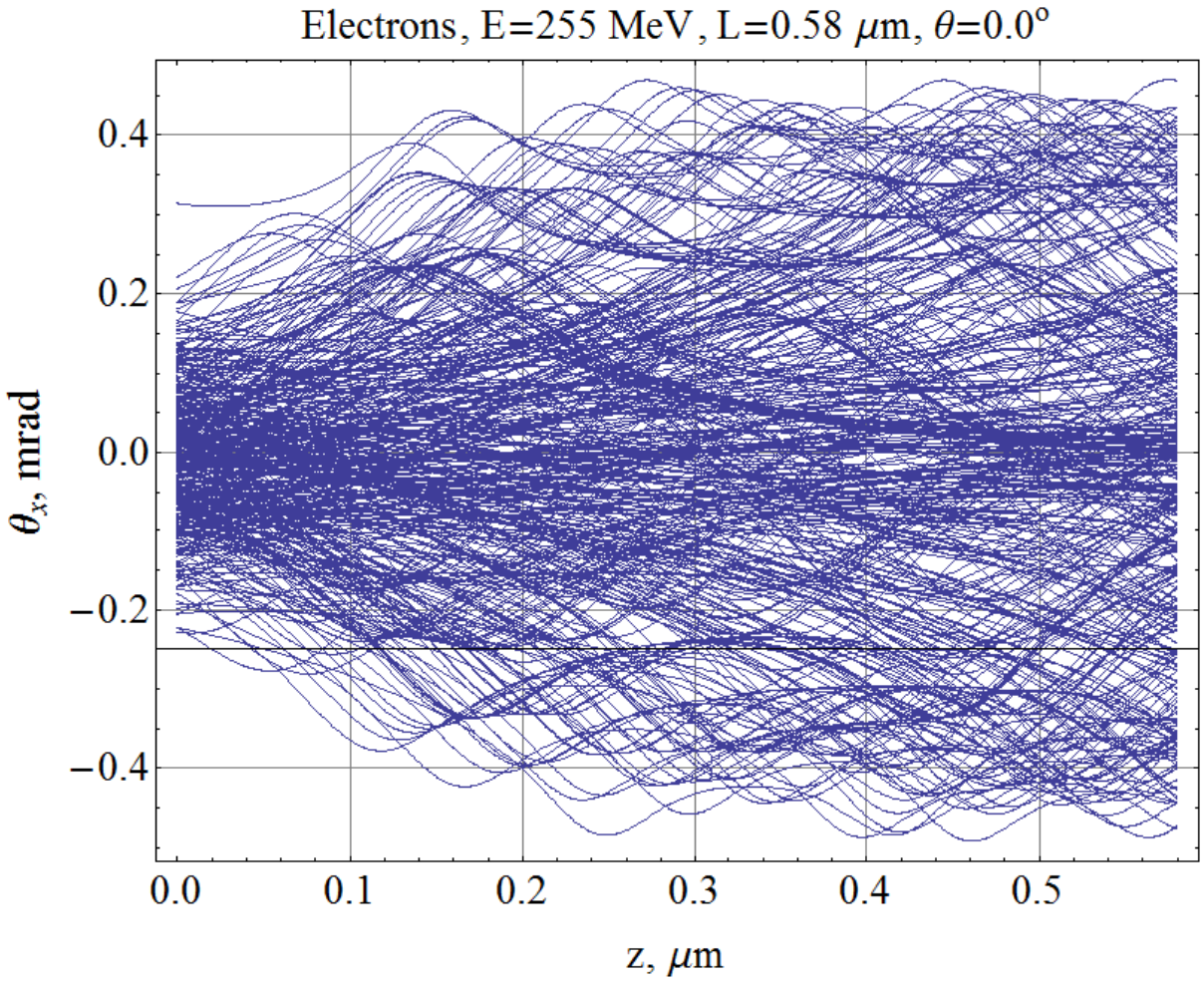
$$x(0) \equiv x_0$$

$$v_x(0) = c\sqrt{1-\frac{1}{\gamma^2}}\sin(\theta)$$

Bogdanov O. V., Fiks E. I., Korotchenko K. B., Pivovarov Yu. L. and Tukhfatullin T. A. Basic channeling with Mathematica©: A new computer code// J. Phys.: Conf. Ser. V. 236, 1, 2010, 012029

Angular Distribution Simulation

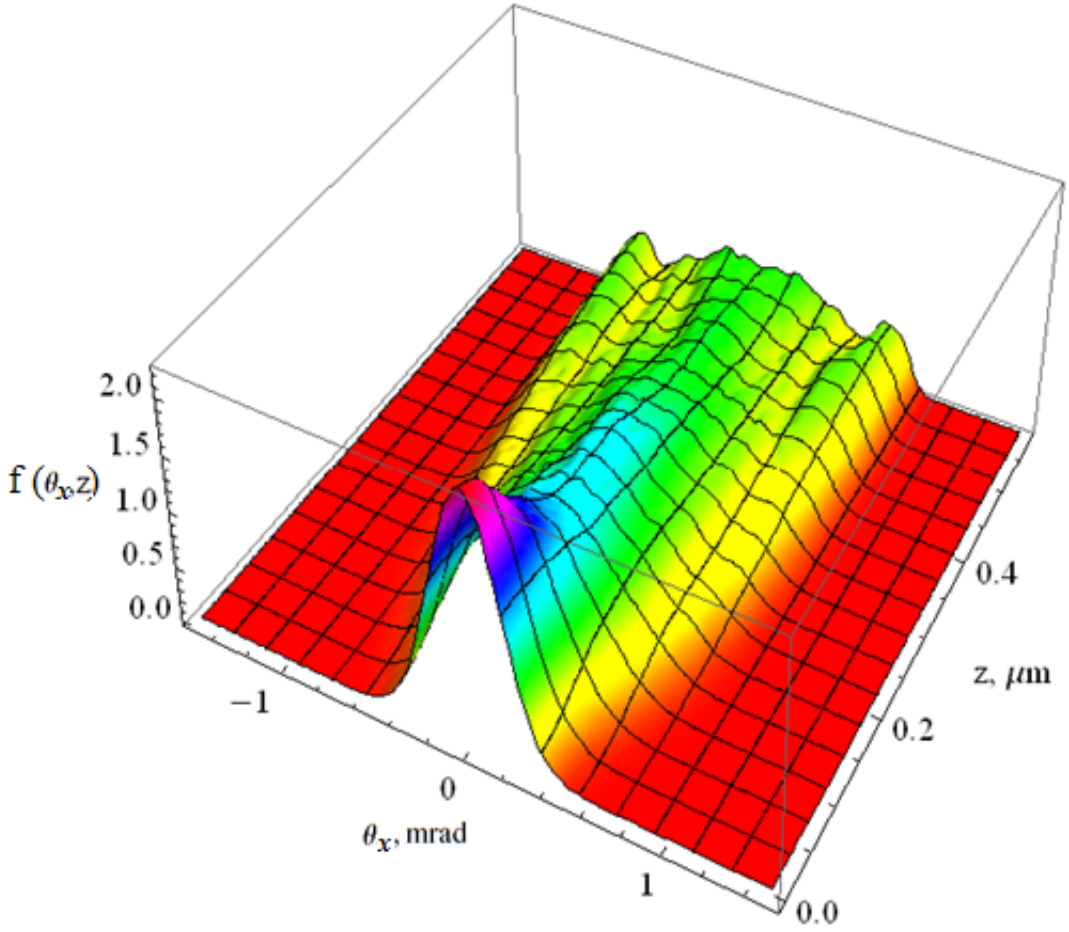
Scattering angle vs longitudinal coordinate



$$\theta_x = v_x / c$$

Angular Distribution Simulation

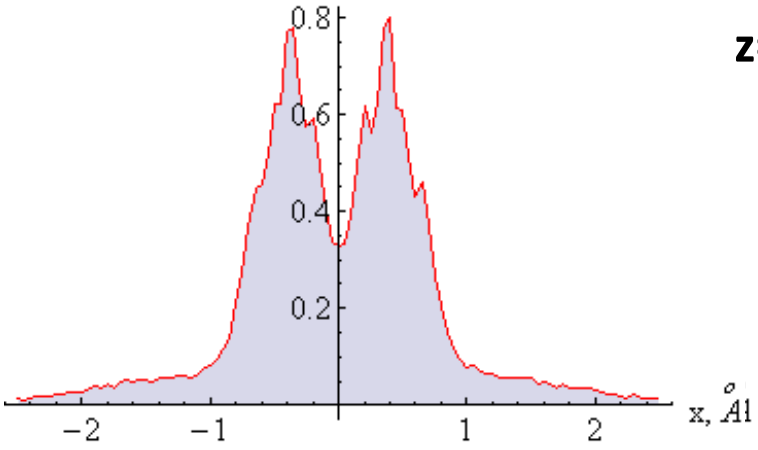
Electrons, E=255 MeV, L=0.58 μm, θ=0.0°



Angular Distribution Simulation

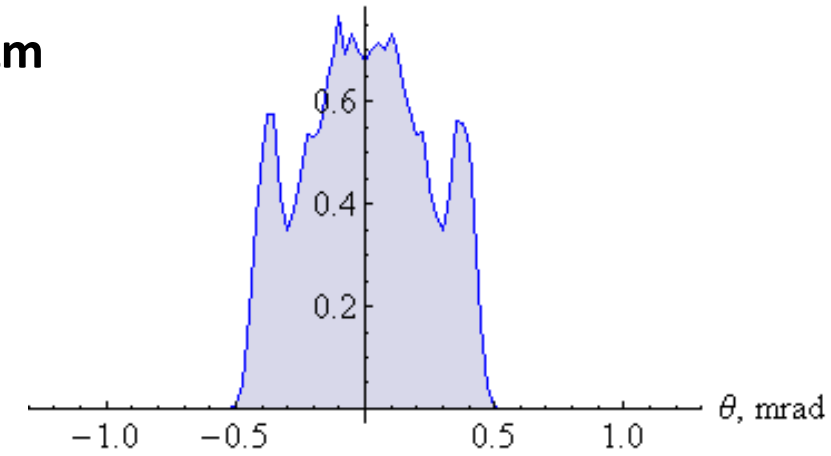
Electrons, E=255 MeV, L=0.58 μm, θ=0.0°

Spatial distribution



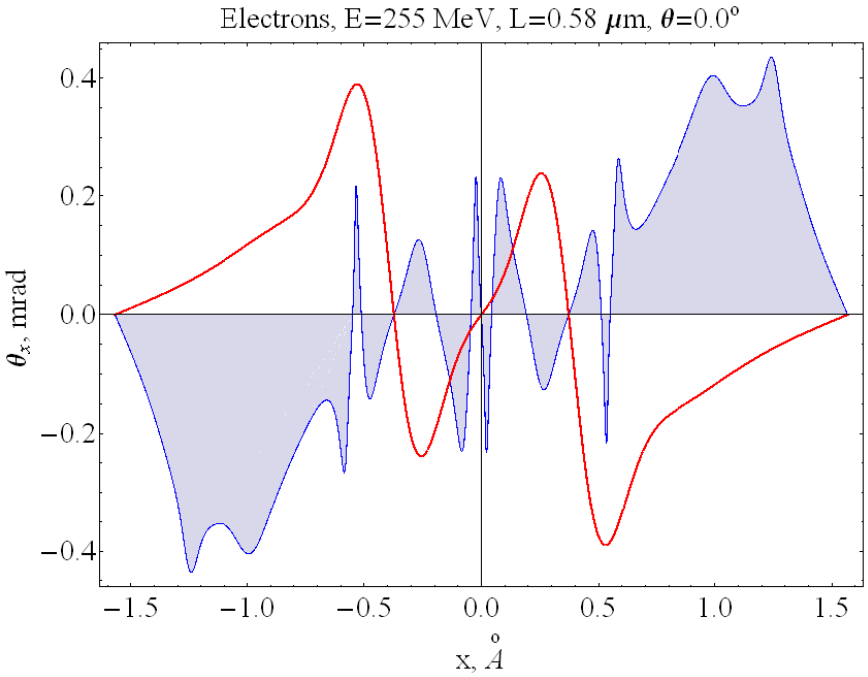
z=0.58 μm

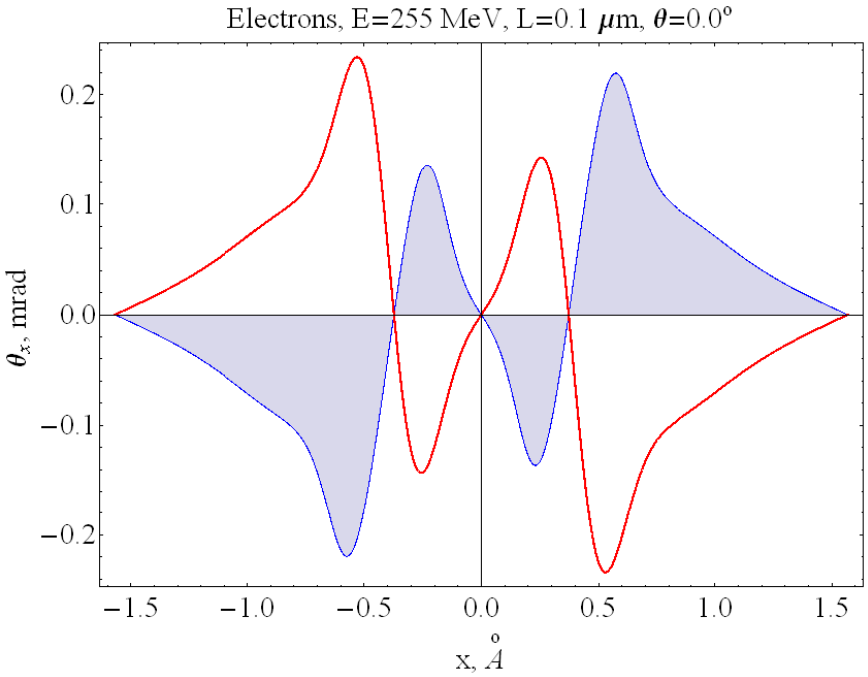
Angular distribution



Angular Distribution Simulation

The exit angles of the electrons vs the point of entry





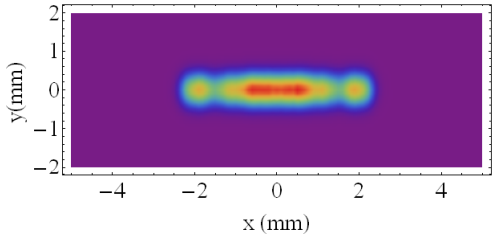
Red line is the gradient of potential in arbitrary unit

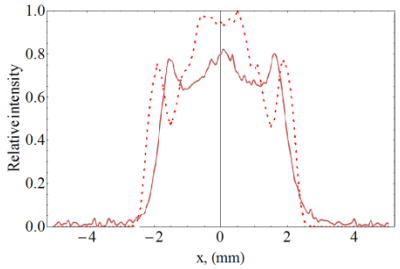
Results of Rainbow Scattering Experiment

2D profile:
Simulation

Horizontal cross-sectional $I(x) = I(x,0)$
Simulation (dashed line), experiment (solid line)

?=0°





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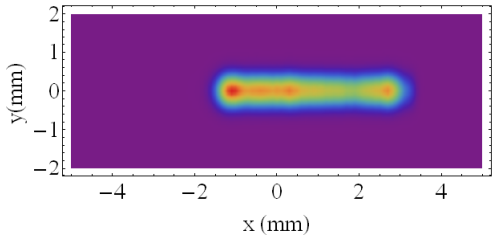

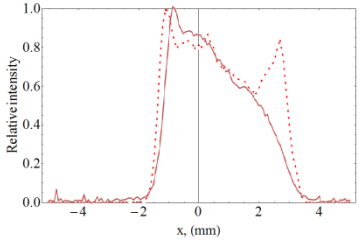

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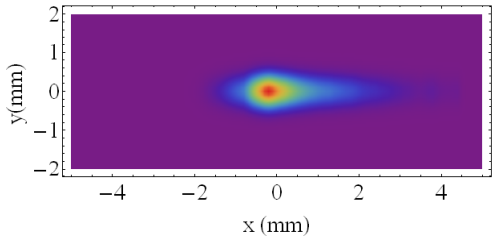

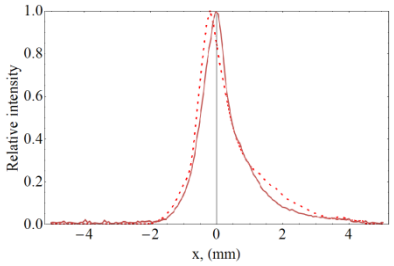

Conclusions

- The new experiments on channeling of 255 MeV electrons in an ultrathin Si crystal were performed at SAGA LS facilities
- Rainbow scattering for relativistic electrons in an ultra-thin Si crystal for (111) planar alignment were observed
- The simulations of trajectories at (111) planar channeling in Si, angular, spatial distributions of electrons have been performed taking into account initial spatial and angular divergence of the electron beam
- Comparison of the experimental and theoretical results shows a good agreement

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THANK FOR YOUR ATTENTION!

Comparison with experiment

Electrons, E=255 MeV, L=0.58 μm, θ=0.0°