Doughnut Scattering of 255 MeV Electrons at <100> Axial Channeling in Thin Si Crystal

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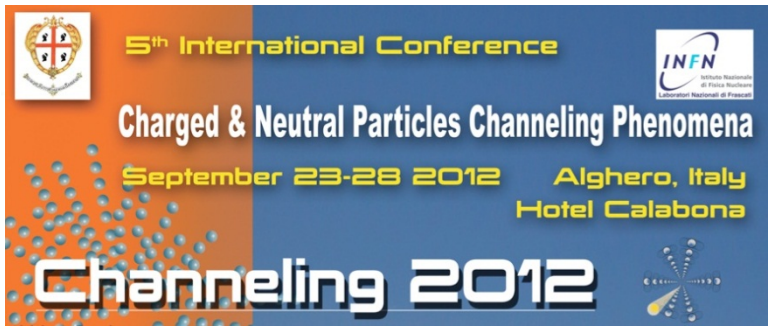

Channeling-2012

- **Motivation:** «doughnut scattering» was observed first in high-energy channeling experiments using the proton and meson beams at CERN (U.Uggerhoj, The interaction of relativistic particles with strong crystalline field, NIMB, 252, 2006, 16-19)
- Earlier theoretical consideration and Monte-Carlo calculations of similar effects for the case of electrons and positrons, was performed: Shul'ga N F, Truten' S P 1982 Sov. Phys. Techn. Phys. 27 1399, Artru X, Fomin S P, Shul'ga N F 2005 Nucl. Instr. and Meth. in Phys. Res. B 230 476
- **Relativistic electron beam - early experiment (150 MeV):**

ELSEVIER

Nuclear Instruments and Methods in Physics Research B 252 (2006) 16–19

Beam Interactions with Materials & Atoms

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Electron beam deflection with channeling in a silicon crystal at the REFER electron ring

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- A dependence of the deflection on the beam divergence, which indicated the possibility of using such a technique for beam diagnostics as well as beam handling was clearly observed
- **Our work:** more detailed investigation & more correct computer simulations of relativistic electrons «doughnut scattering»

SAGA Light Source (SAGA-LS)

Operated by Saga Prefecture in Japan

In 2004, the accelerators were completed.

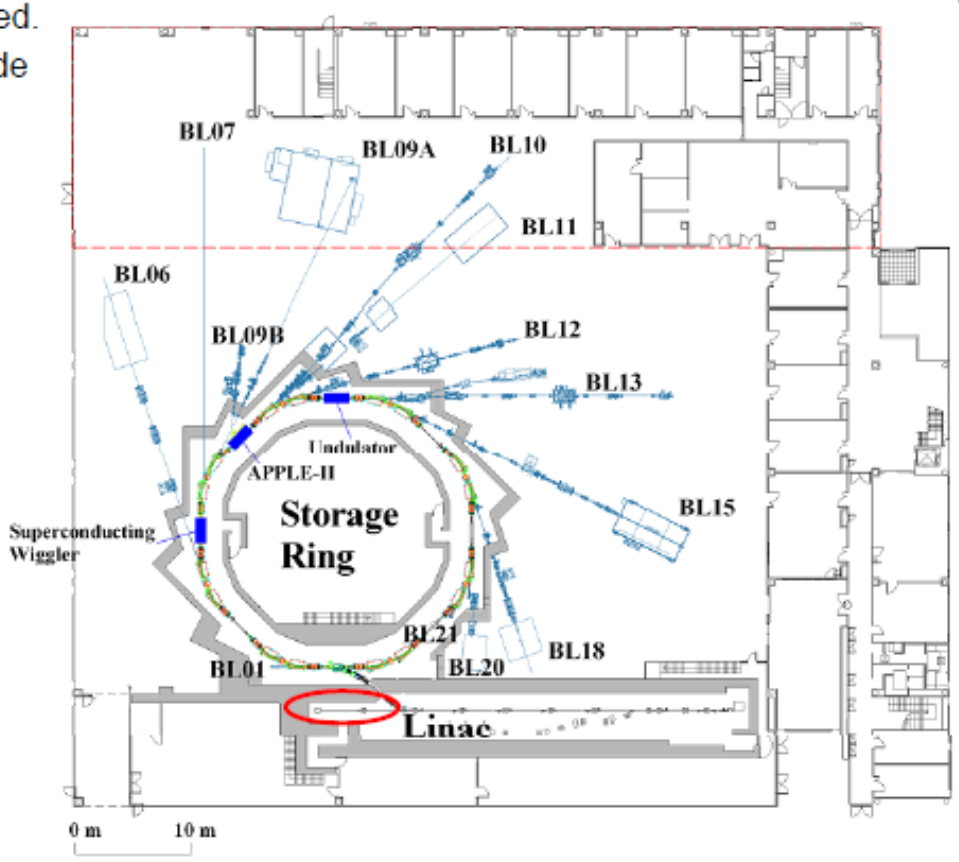
In 2006, the SAGA-LS started user-mode operation.

Storage Ring

Circumference	75.6 m
Energy	1.4 GeV
Stored Current	300 mA
Emittance	25 nm·rad
Lifetime	~7 hours @300 mA
Critical Energy	1.9 keV

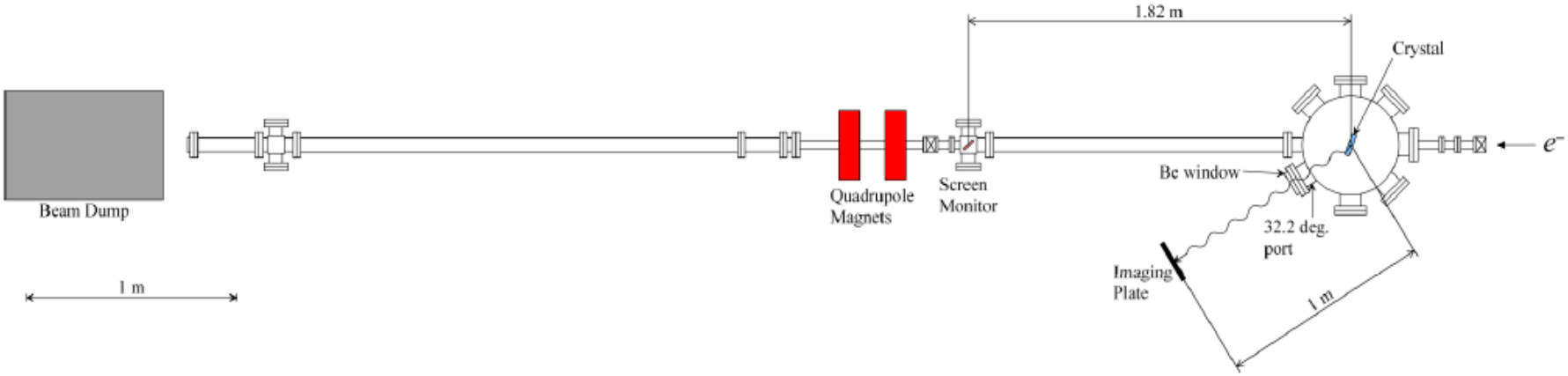
Injector Linac

Total Length	30 m
Energy	255 MeV
Average Current	12 nA
Repetition	1 pps



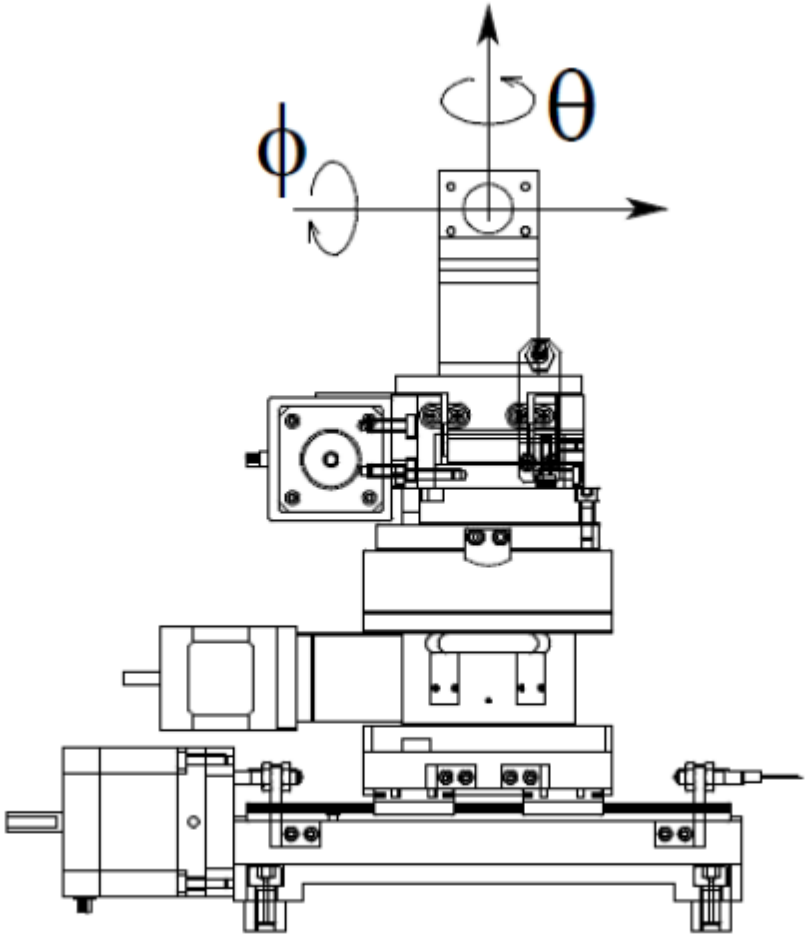
SAGA Light Source, 8-7 Yayoigaoka, Tosu, Saga 841-0005, Japan

The Experimental Setup SAGA LS



- <100> channeling in Si crystal
- The beam energy: **E = 255 MeV**
- Horizontal beam size: **0.2 mm**
- Vertical beam size: **0.7 mm**
- Horizontal angular divergence: **0.2 mrad**
- Vertical angular divergence: **0.3 mrad**
- Si crystal thickness: **l=20 µm**

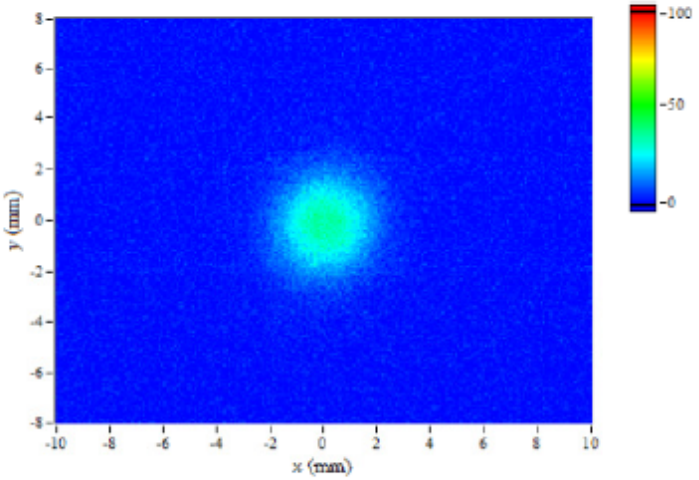
Goniometer



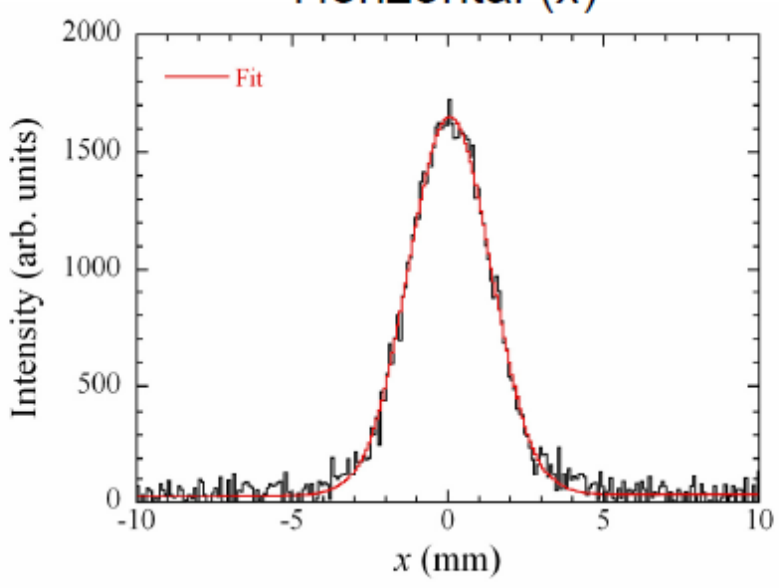
Angular step size **0.001°**

Data Analysis

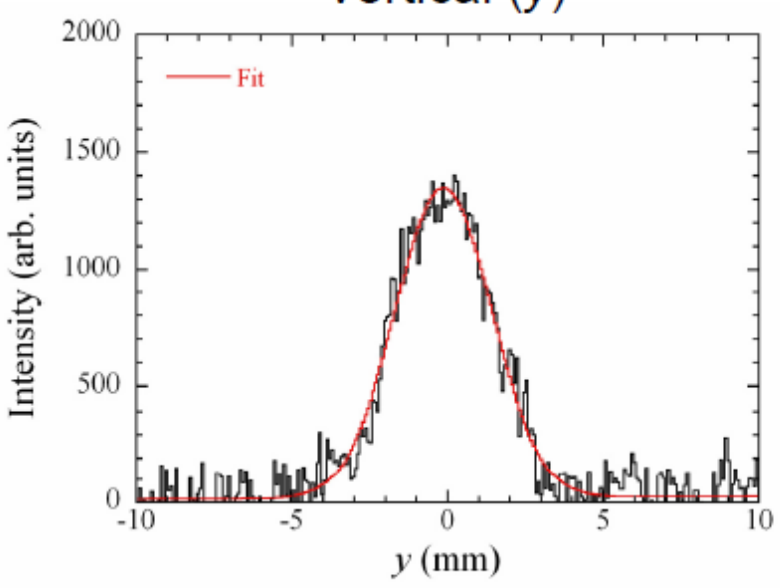
$(\theta, \phi) = (0°, 0°)$



Horizontal (x)



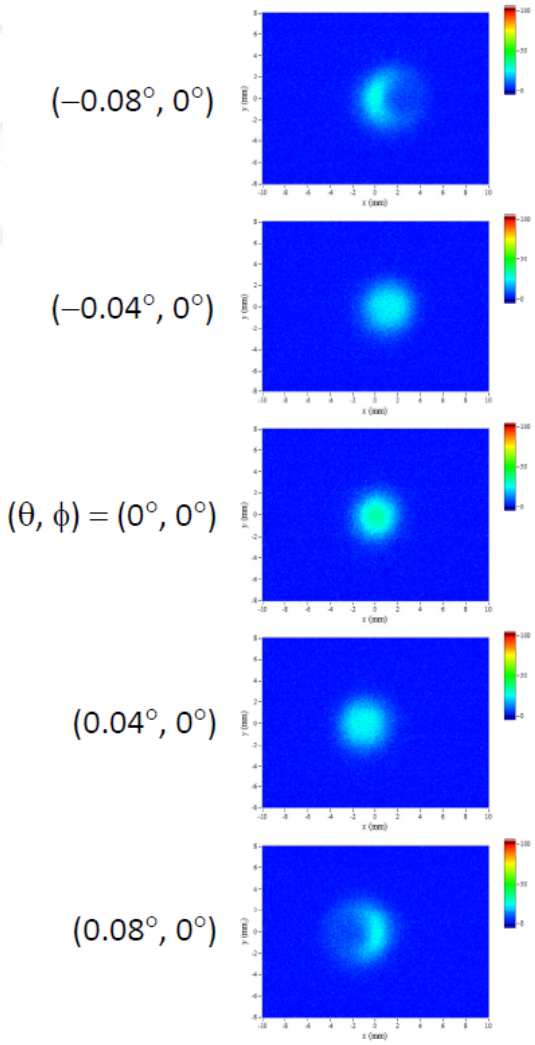
Vertical (y)

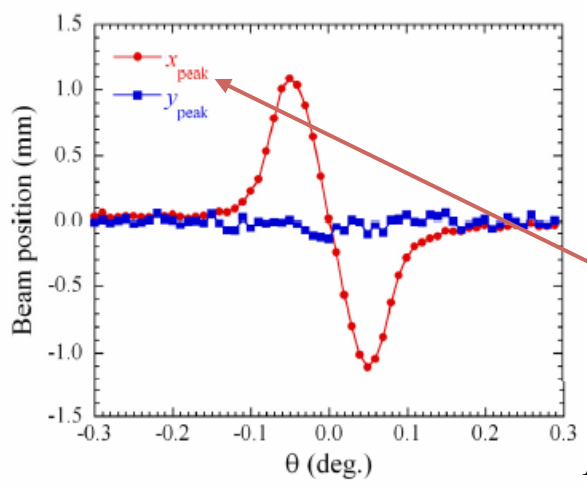


$$I_x = I_{0,x} \exp\left[-\frac{(x - x_{peak})^2}{2\sigma_x^2}\right] + a_x x + b_x$$

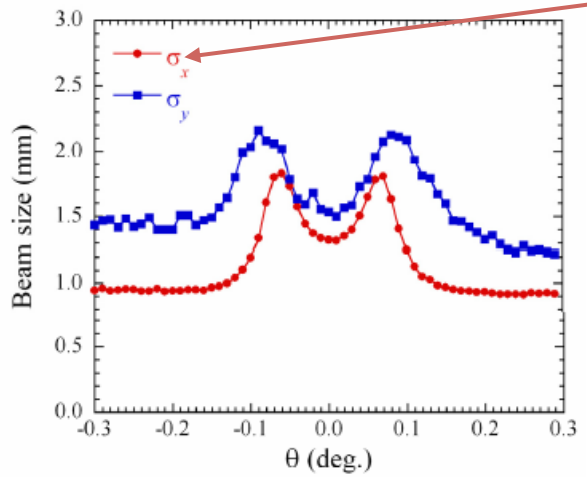
$$I_y = I_{0,y} \exp\left[-\frac{(y - y_{peak})^2}{2\sigma_y^2}\right] + a_y y + b_y$$

The experimental results for <100> channeling in Si





$$I_x = I_{ox} \exp\left[-\frac{(x - x_{peak})^2}{2\sigma_x}\right] + a_x x + b_x$$



Electron trajectories simulation

- System of equations

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

$$\gamma m\ddot{y} = F_y = -\frac{\partial U(x,y)}{\partial y}$$

- Initial conditions

$$x(0) \equiv x_0$$

$$y(0) \equiv y_0$$

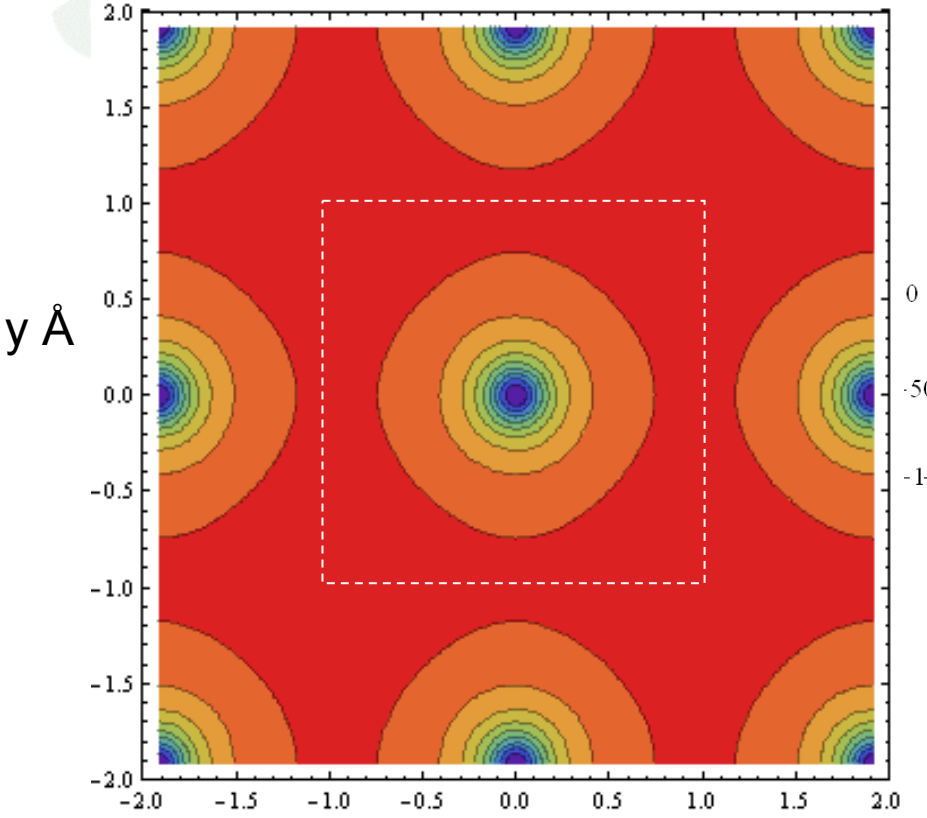
$$\upsilon_x(0) = c\sqrt{1-\frac{1}{\gamma^2}}\sin(\theta)\cos(\varphi)$$

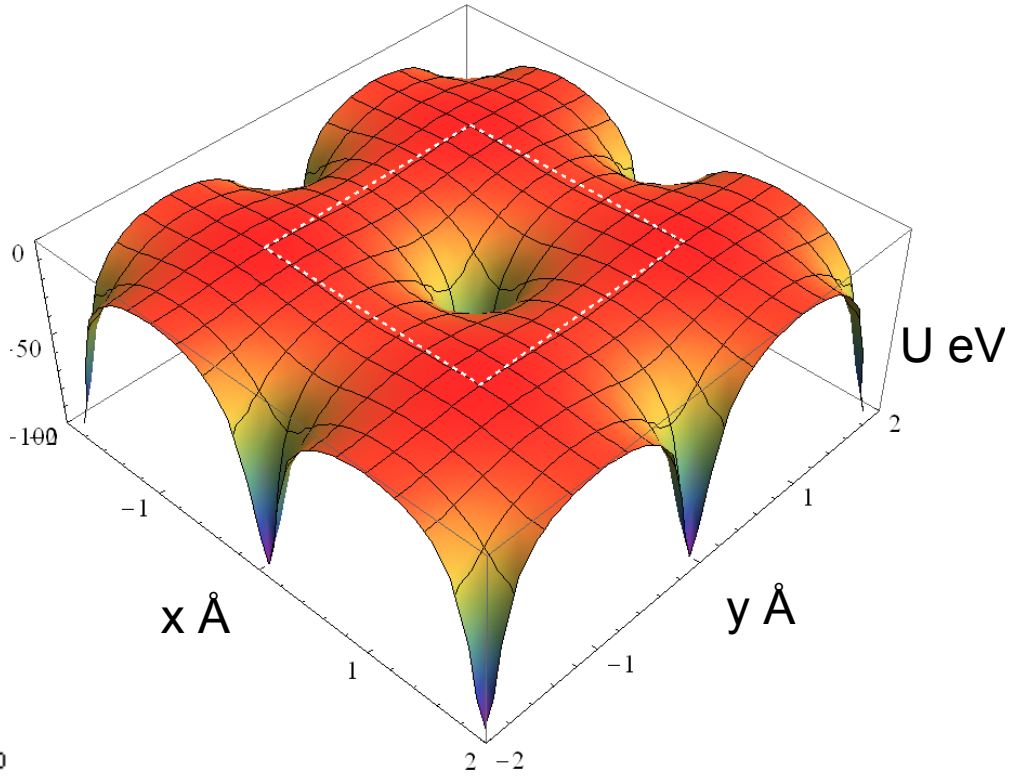
$$\upsilon_y(0) = c\sqrt{1-\frac{1}{\gamma^2}}\sin(\theta)\sin(\varphi)$$

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

Simulation results two-dimensional potential of the crystallographic axes

$$U(x,y) = eV(x,y) = e\sum_k V_{ax}(x - kd_{xp}, y - kd_{yp})$$

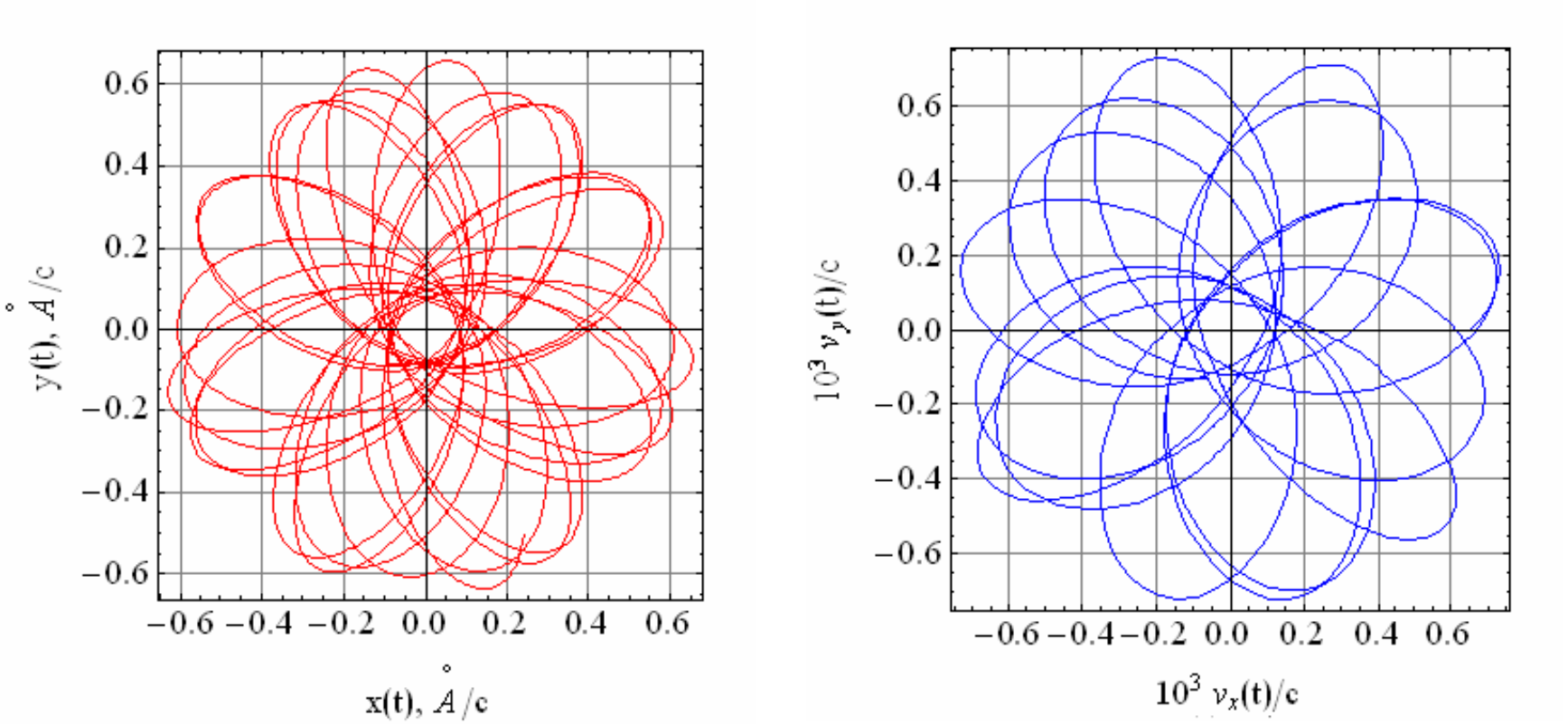




Doyle P.A. and Turner P. S.// Acta Cryst. 1967 A24, 390

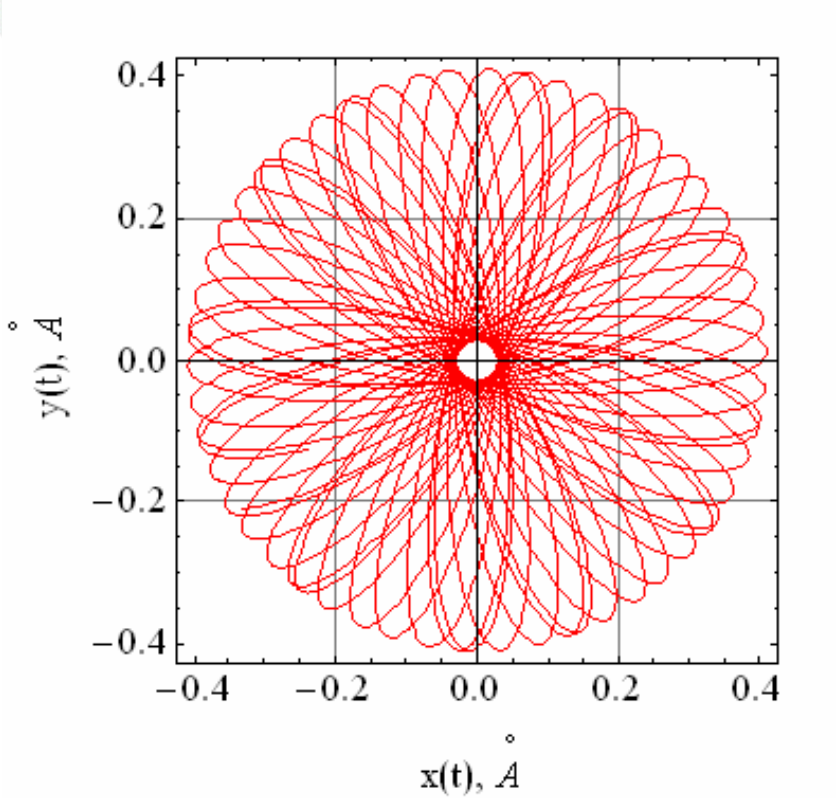
Simulation results
trajectories

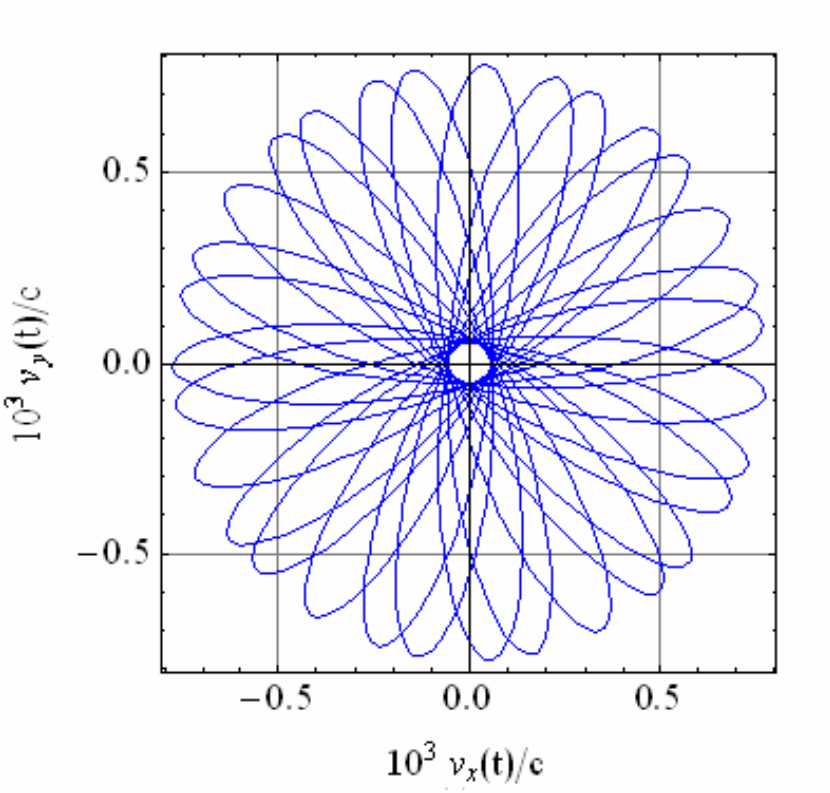
$\theta=0.037^{o}$, $\varphi=0.01^{o}$, E = 255 MeV, <100> Si, l=20 μm



Simulation results
trajectories

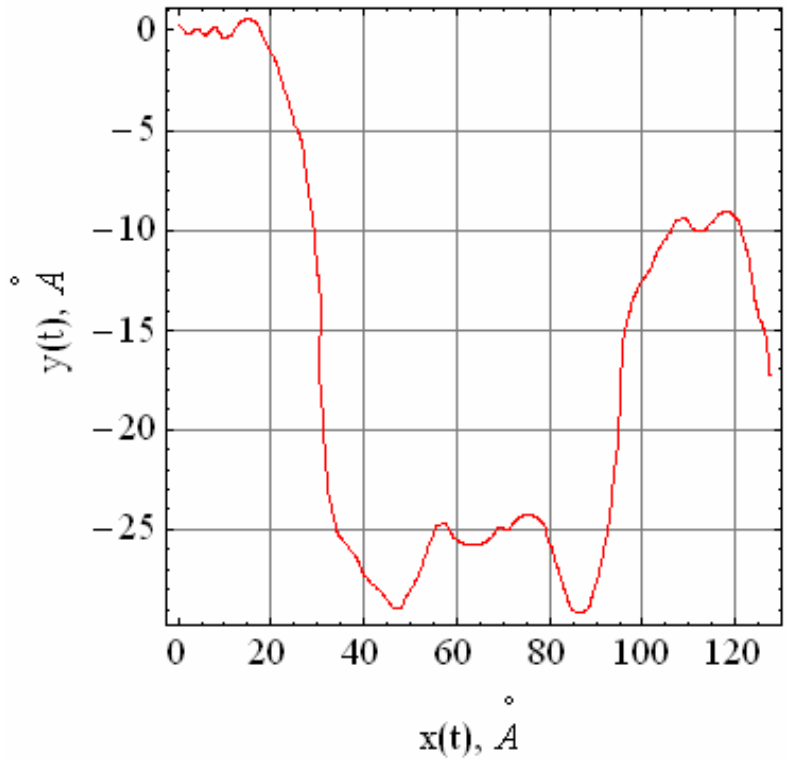
θ=0.062°, φ=-0.028°, E = 255 MeV, <100> Si, l=20 μm

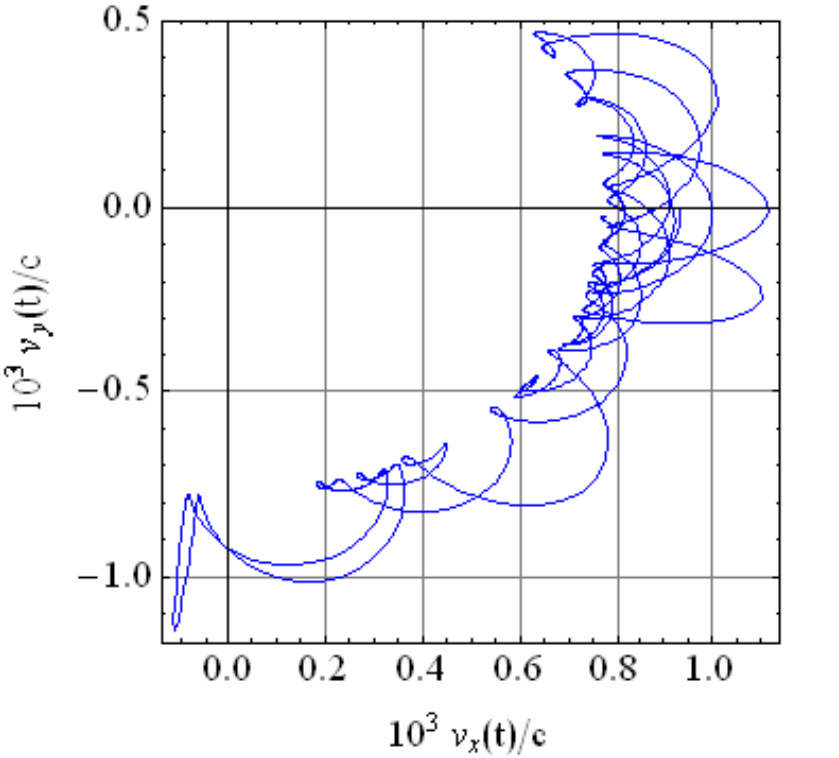




Simulation results
trajectories

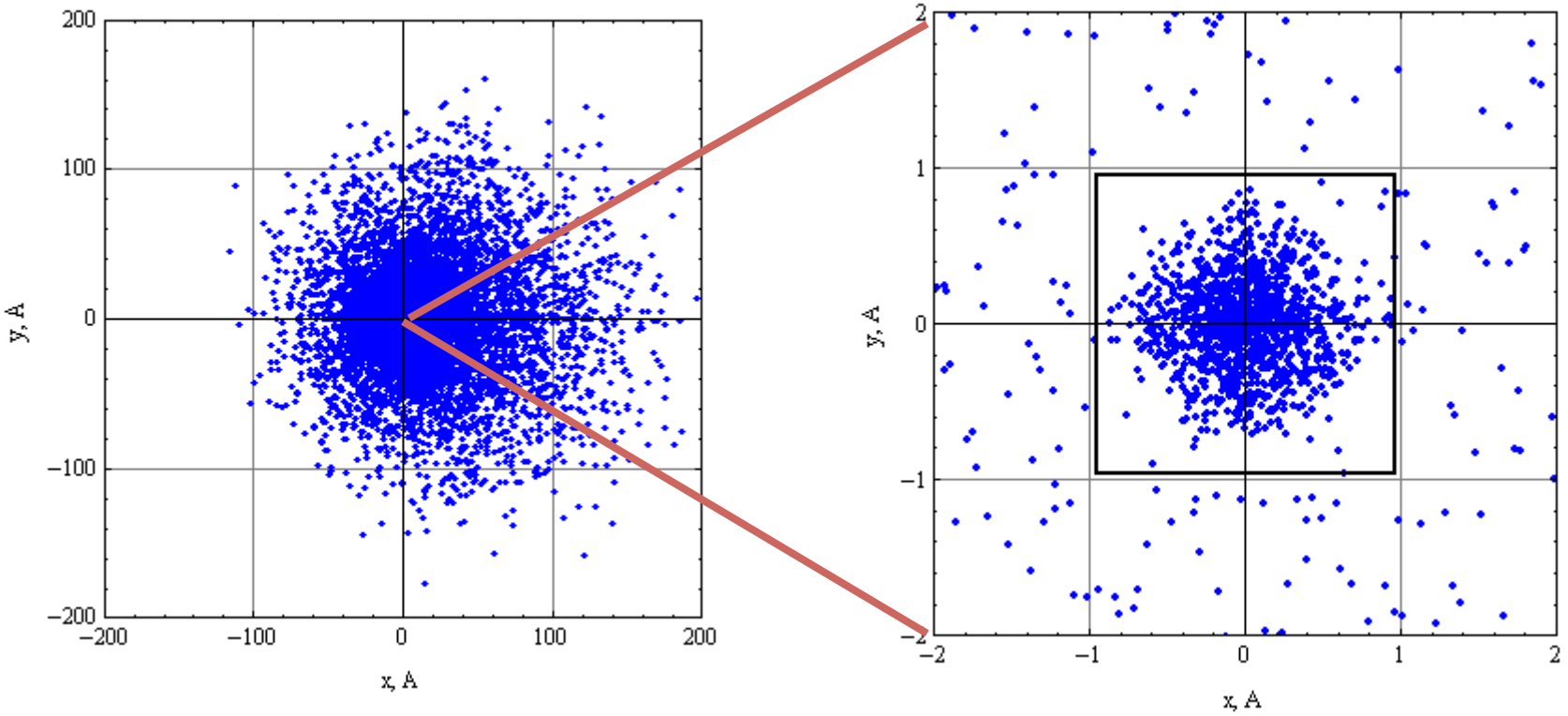
θ=0.053°, φ=-0.036°, E = 255 MeV, <100> Si, l=20 μm





Simulation results
exit points of the particles

θ=0.025°, φ=0.0°, E = 255 MeV, <100> Si, l=20 μm

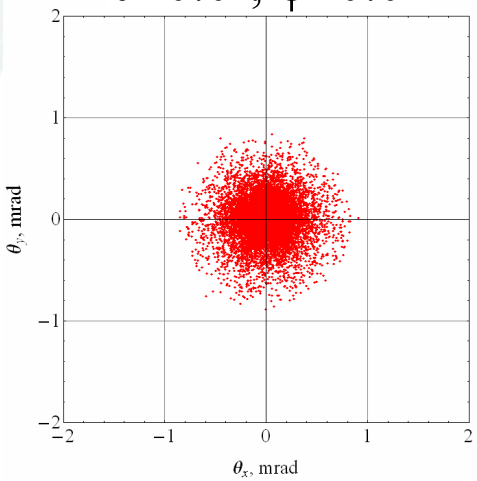


Simulation results
electrons angular distributions

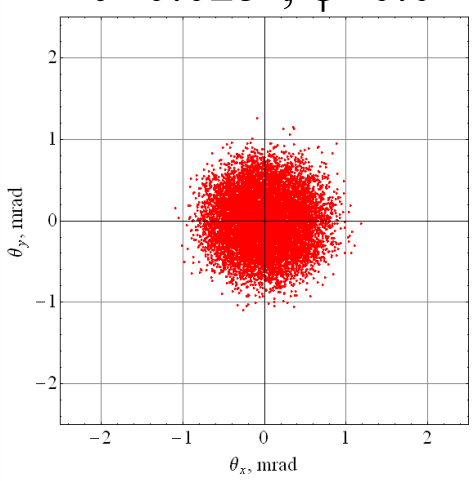
Critical angle

$$\theta_x = \upsilon_x(l)/c$$
$$\theta_y = \upsilon_y(l)/c$$

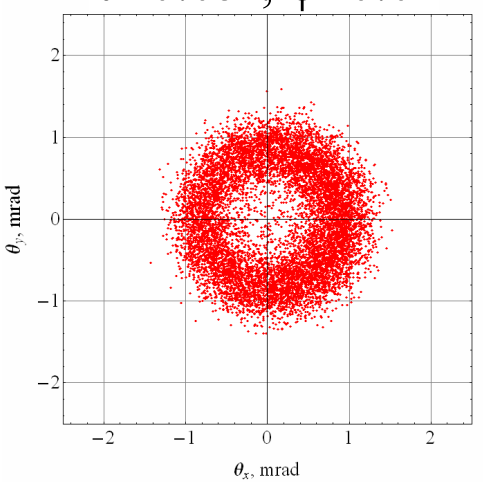
θ=0.0°, φ=0.0°



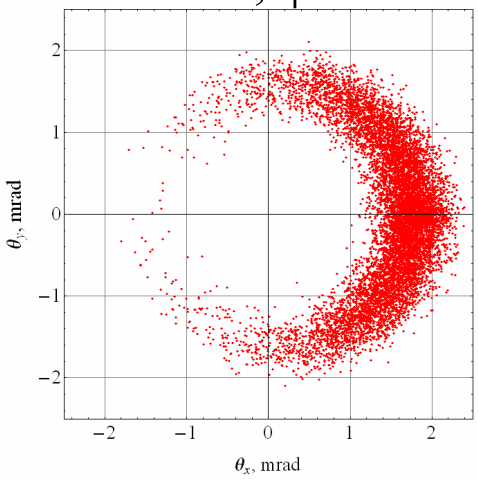
θ=0.025°, φ=0.0°



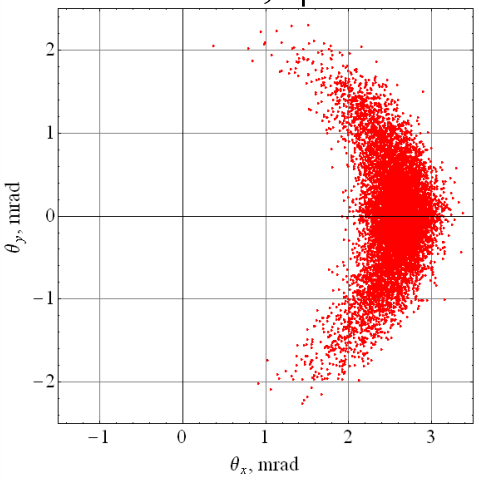
θ=0.05°, φ=0.0°



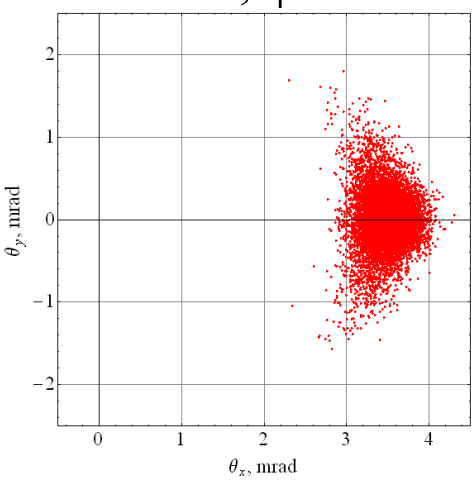
θ=0.1°, φ=0.0°



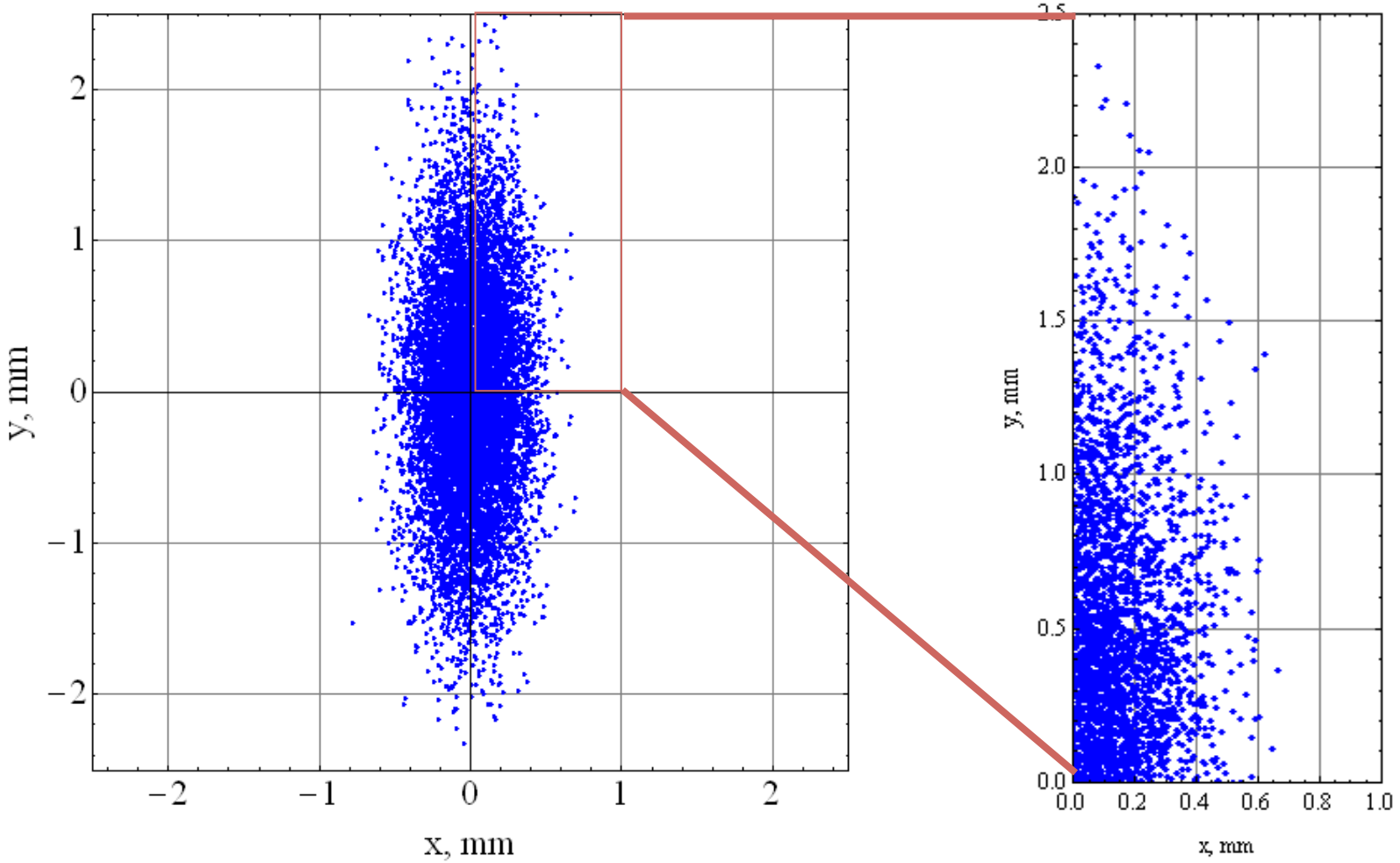
θ=0.15°, φ=0.0°



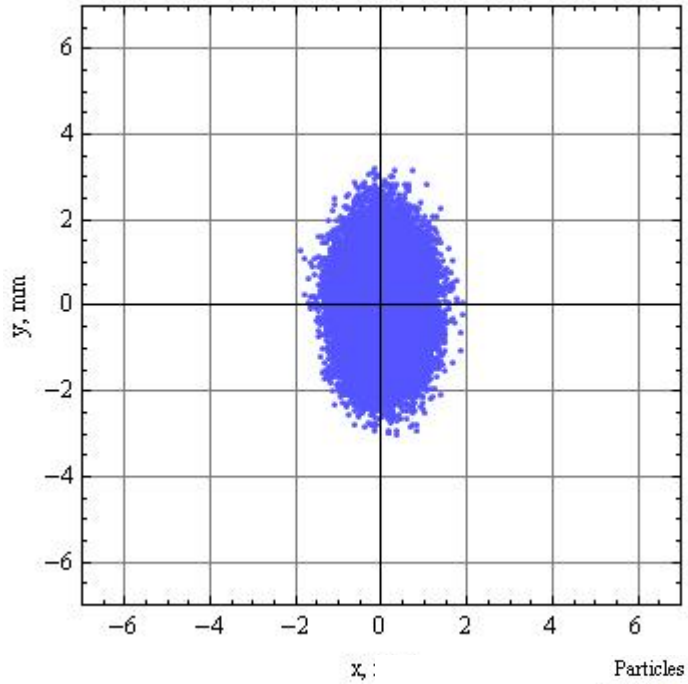
θ=0.2°, φ=0.0°



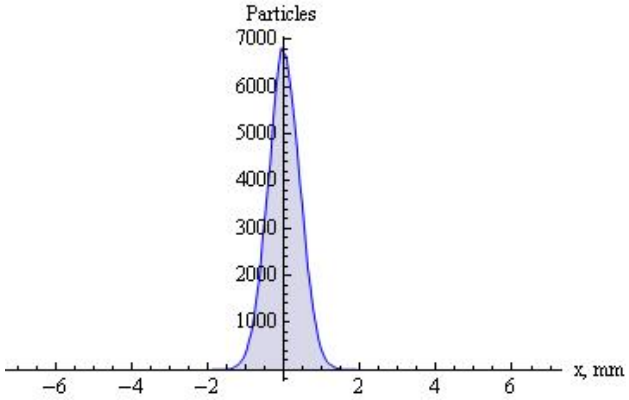
Simulation results
SAGA-LS incident beam profile

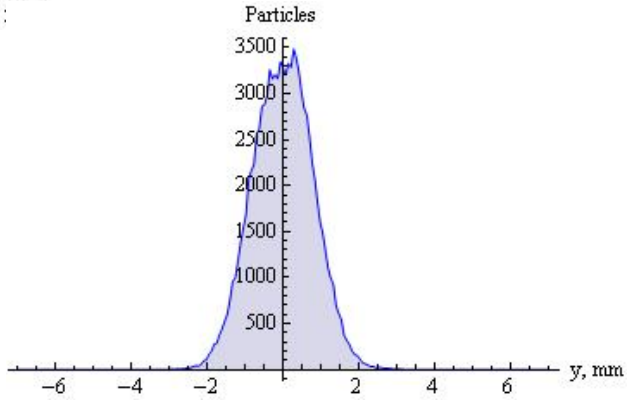


Simulation results
electrons spatial distribution on the screen monitor $\varphi=0$

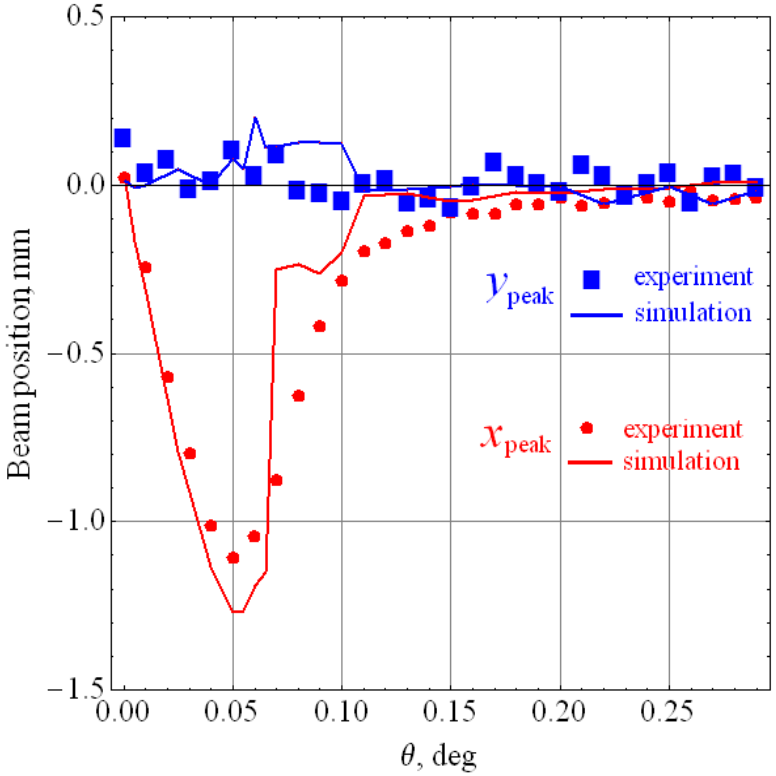


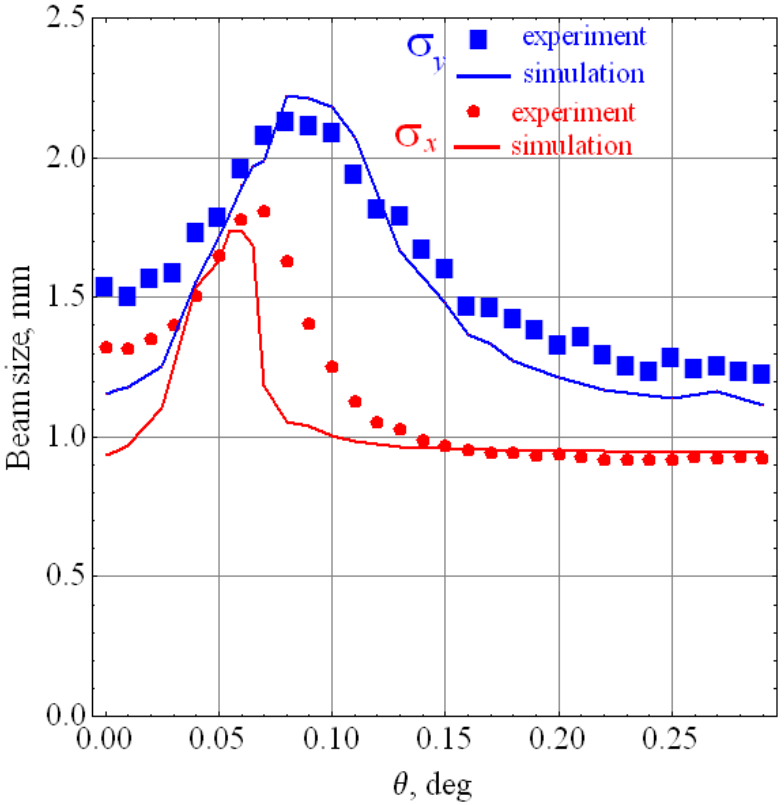
θ={0.0, 0.005, 0.01, 0.025, 0.04, 0.05, 0.055, 0.06, 0.065, 0.07, 0.08, 0.09, 0.1, 0.11, 0.13, 0.15, 0.16, 0.17, 0.18, 0.2, 0.22, 0.25, 0.27, 0.29};





Simulation results
beam position and beam size





$$\sigma = \sqrt{\sigma^2_{simulation} + \sigma^2_{ms}} \qquad \theta_{ms} = \mathbf{0.4\ mrad}$$

Review of Particle Physics. 2010.

Future plans for SAGA LS – TPU collaboration

- Scattering at planar channeling condition (silicon crystal, L=20 micrometers, electron energy 255 MeV) – the experiment has been recently performed, data processing and computer simulation are in progress
- Scattering in a thin silicon crystal (L=1 micrometer, electron energy 255 MeV)
- Scattering in a diamond crystal (L=50 micrometers, electron energy 255 MeV)
- Further studies of PXR, PXRC, DCR
- Further development of theory and simulation methods

Conclusions

- The first experiments on 255 MeV electrons channeling and scattering in thin aligned Si crystal were performed at SAGA-LS injector Linac
- The simulation of trajectories at the <100> axial channeling in Si, angular and spatial distributions of electrons on the screen monitor have been performed taking into account initial spatial and angular beam divergence of the electron beam
- Comparison of the experimental and theoretical results shows a quite good agreement
- Both experimental data and simulations show the brilliant effect of so-called «doughnut scattering»
- Application of electrons «doughnut scattering»: possibility to use for the beam diagnostics

Details of experiment and simulations:

O. V. Bogdanov, Yu. L. Pivovarov, Y. Takabayashi, T.A. Tukhfatullin
Journal of Physics: Conf. Ser. 357 (2012) 012030.

Thank you for attention

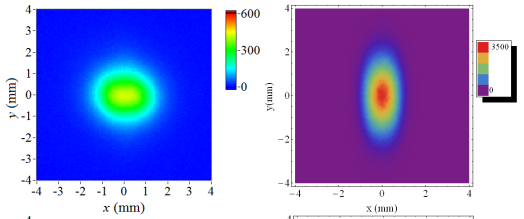
(220) PLANAR CHANNELING

Beam profile

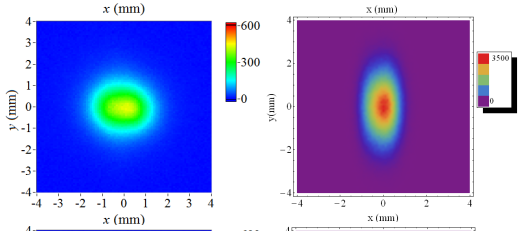
experiment simulation

(θ,φ)

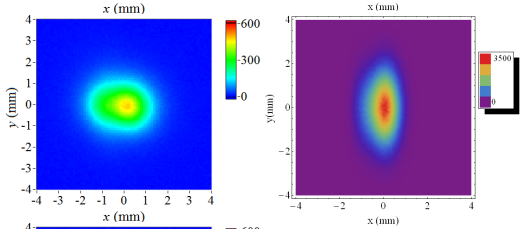
(0.00°,1°)



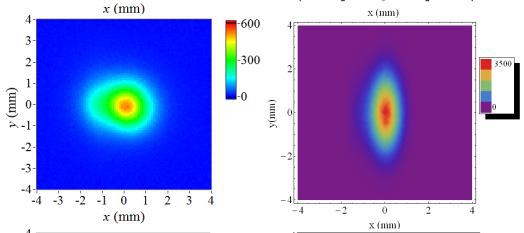
(0.01°,1°)



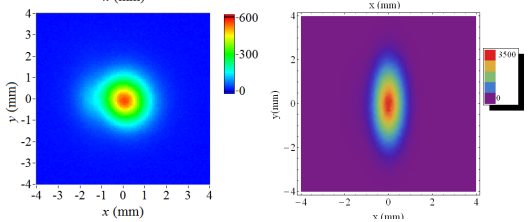
(0.02°,1°)



(0.03°,1°)



(0.04°,1°)



Beam position and size vs incident angle

Critical channeling angle 0.023°

initial vertical beam size - σ_x=0.2 mm, horizontal beam size - σ_y=0.9 mm

horizontal angular beam divergence -0.2 mrad

vertical angular beam divergence - 0.3 mrad