Experiments on deflection of charged particles using silicon crystals at REFER ring (Hiroshima University) and Proton Synchrotron (KEK)

S. Sawada

KEK – High Energy Accelerator Research Organization

T. Takahashi, I. Endo, M. Iinuma, H. Sato, S. Strokov, K. Ueda

Graduate School of Advanced Sciences of Matter, Hiroshima University

H. Kuroiwa, T. Ohnishi

Venture Business Laboratory, Hiroshima University

V. Biryukov, Yu. Chesnokov

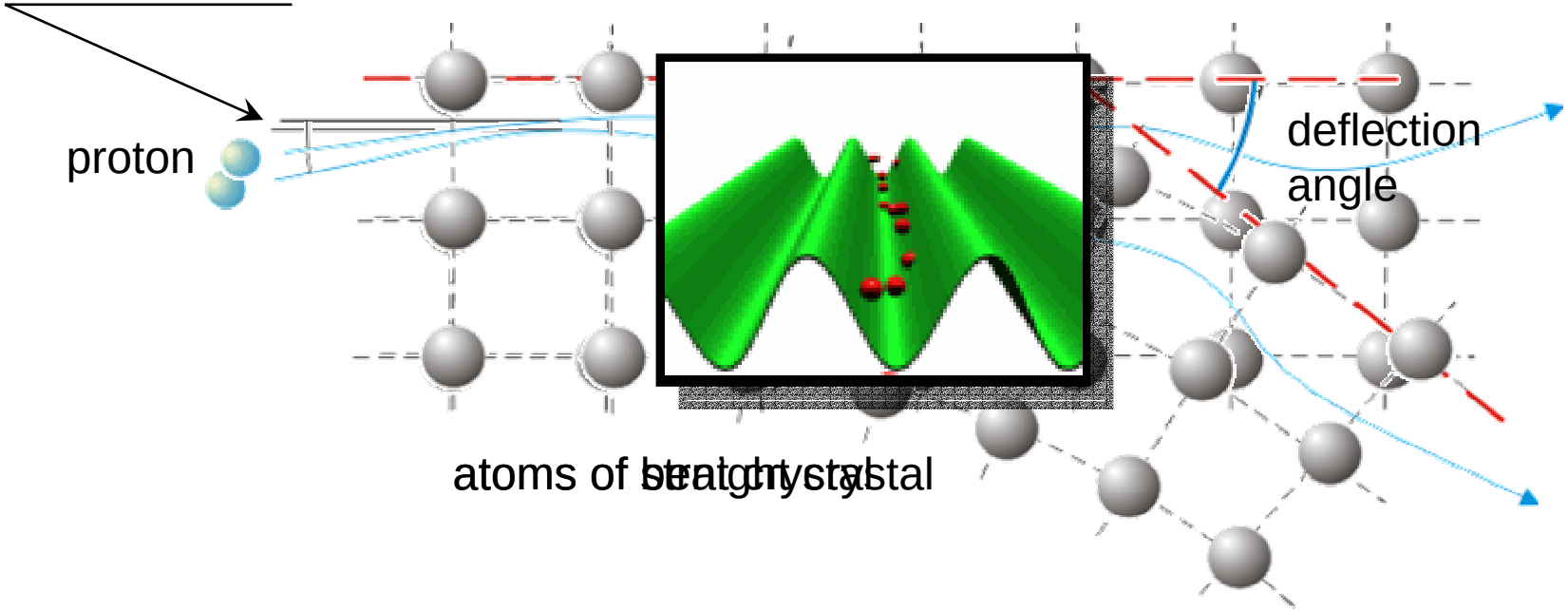
Institute for High Energy Physics, Russia

Contents

1. Introduction to the channeling effect
2. Motivation
3. Experiment on electron beam deflection (REFER, Hiroshima University)
4. Experiment on proton beam deflection (Proton Synchrotron, KEK)
5. Conclusion

Introduction (channeling effect)

θ – angle of incident particle
to the crystallographic plane



θ < Lindhard angle → channeling effect

θ > Lindhard angle → no channeling effect

Motivation

Application to deflection of high energy (50 GeV) and high intensity proton beam at J-PARC (Japan Proton Accelerator Research Complex):

- beam splitting in a slow-extraction beam,
- beam collimator,
- slow beam extraction from the synchrotron in the future.

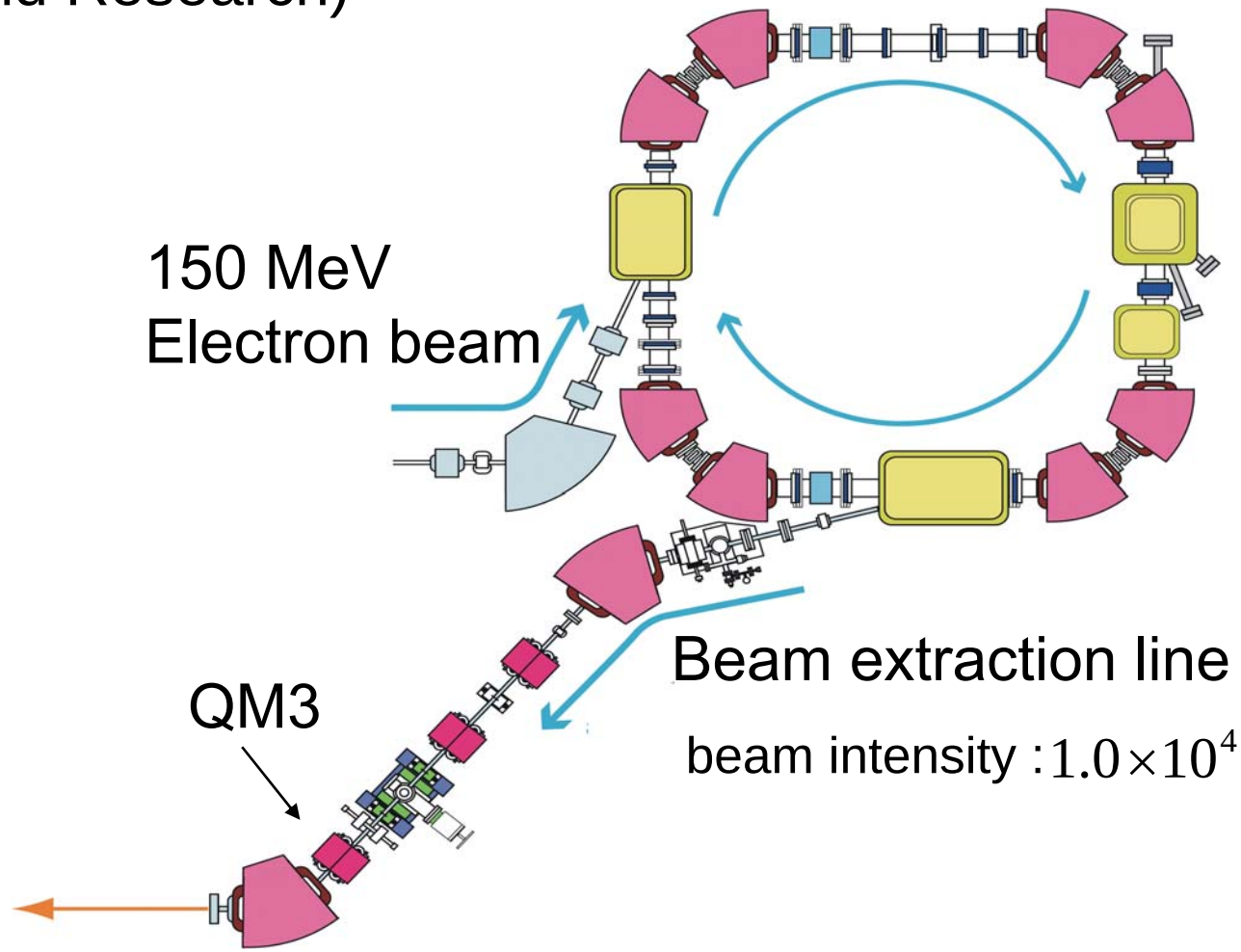
Collimation of the ultra-low emittance beam at ILC (International Linear Collider).

Beam extraction from the REFER ring is within the scope.

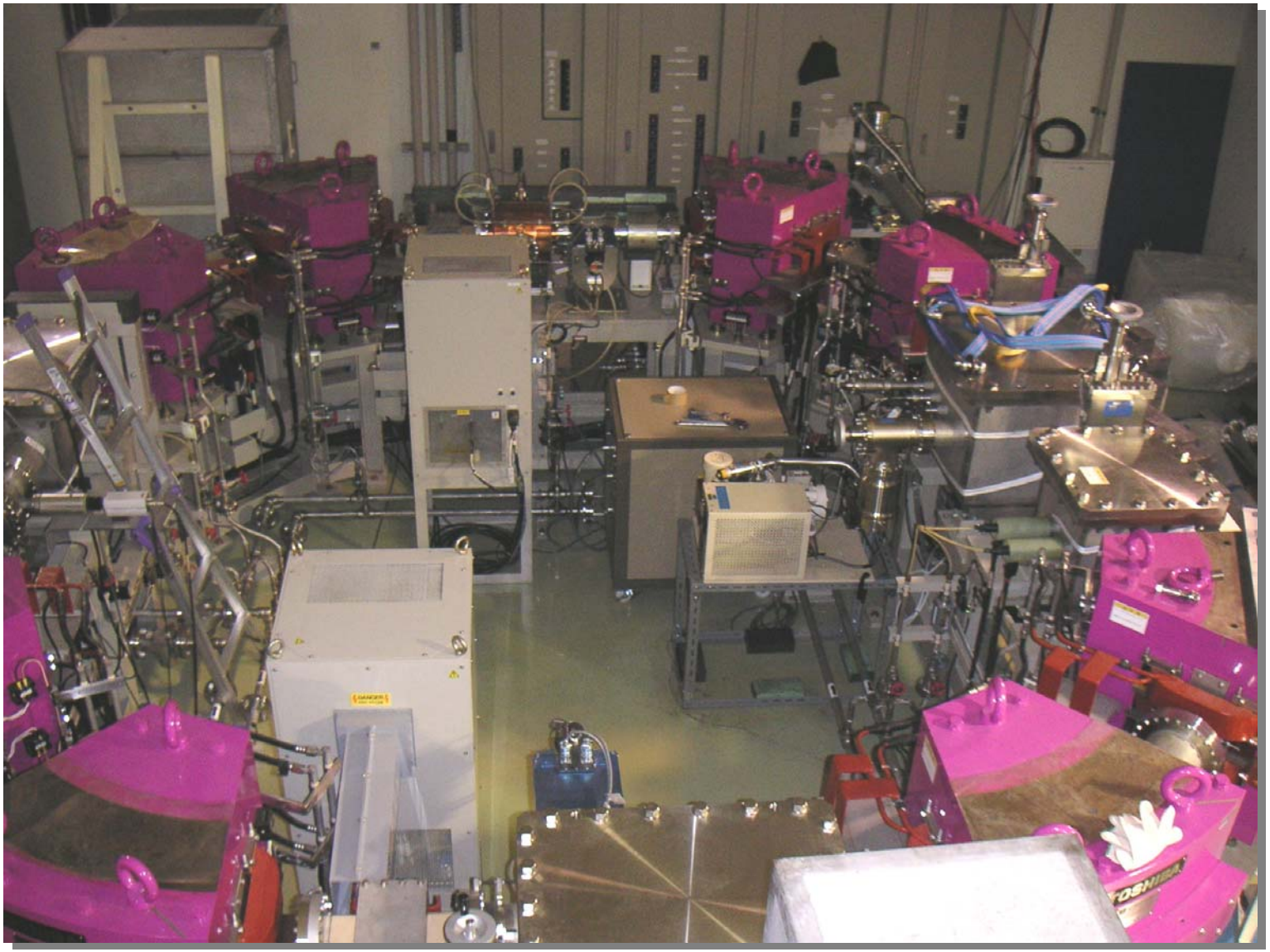
Beam diagnosis by channeling effect (beam divergence and profile).

REFER ring @ Hiroshima University

- REFER (Relativistic Electron Facility for Education and Research)

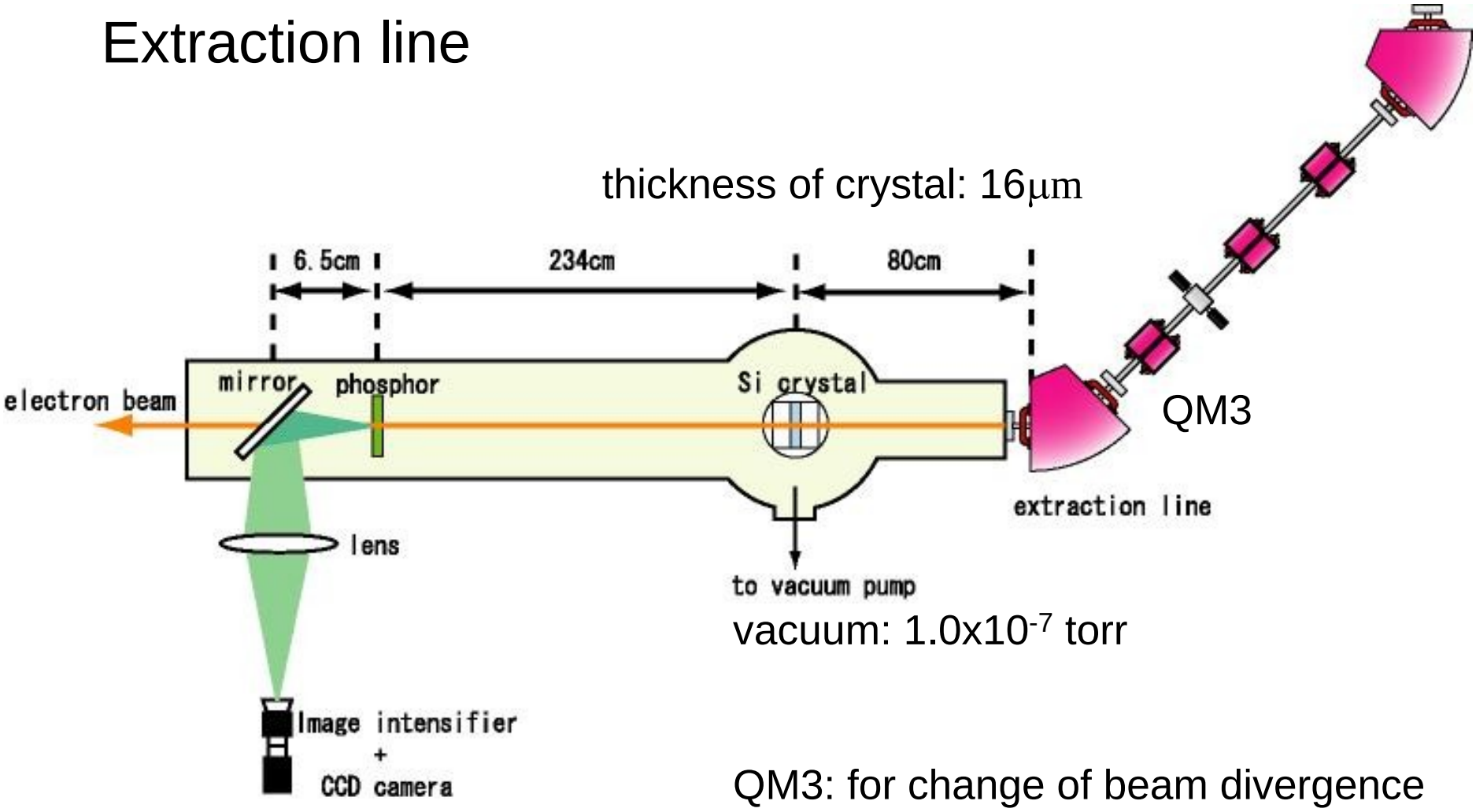


REFER ring @ Hiroshima University



Experimental setup

Extraction line

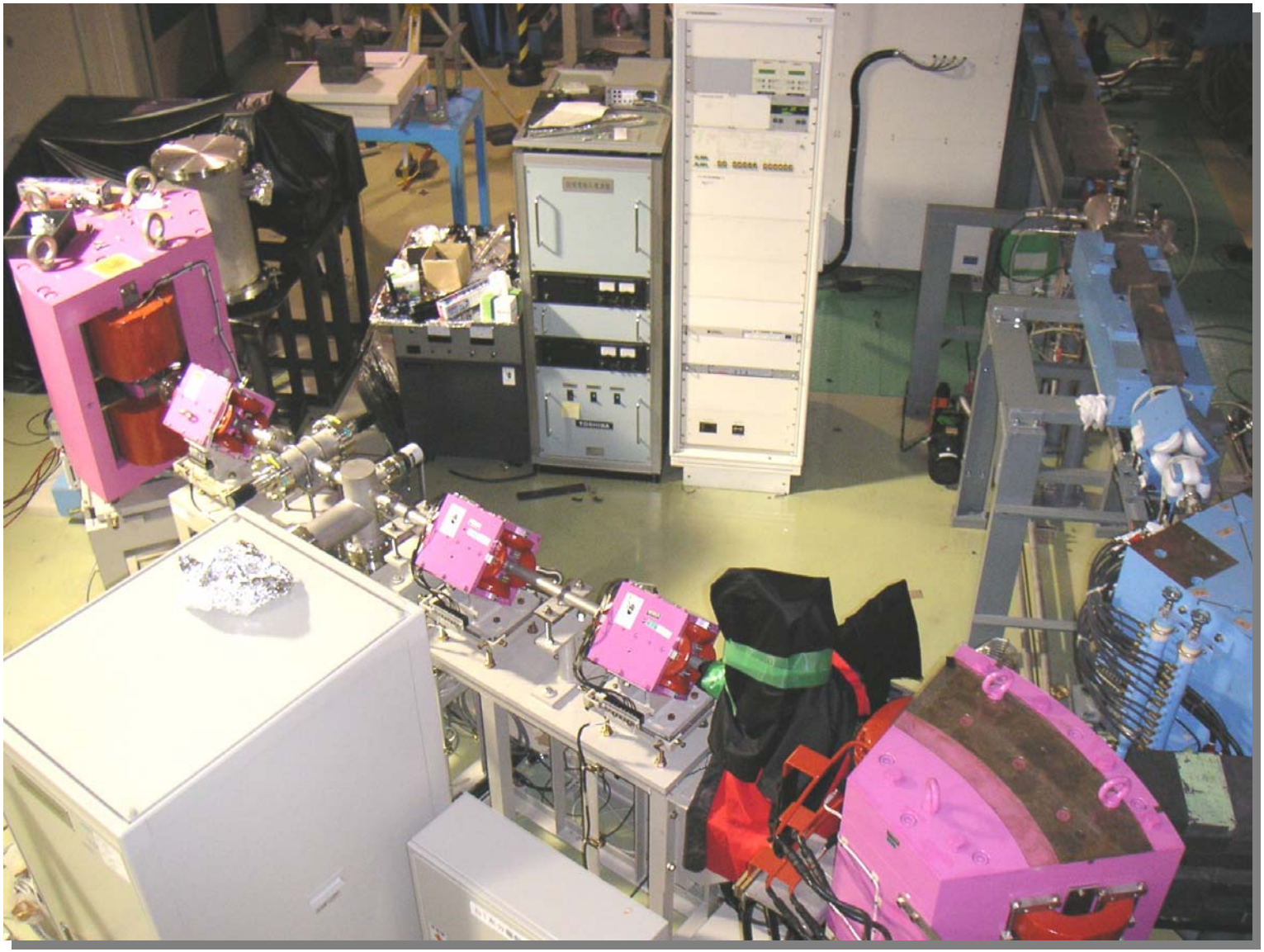


thickness of crystal: 16μm

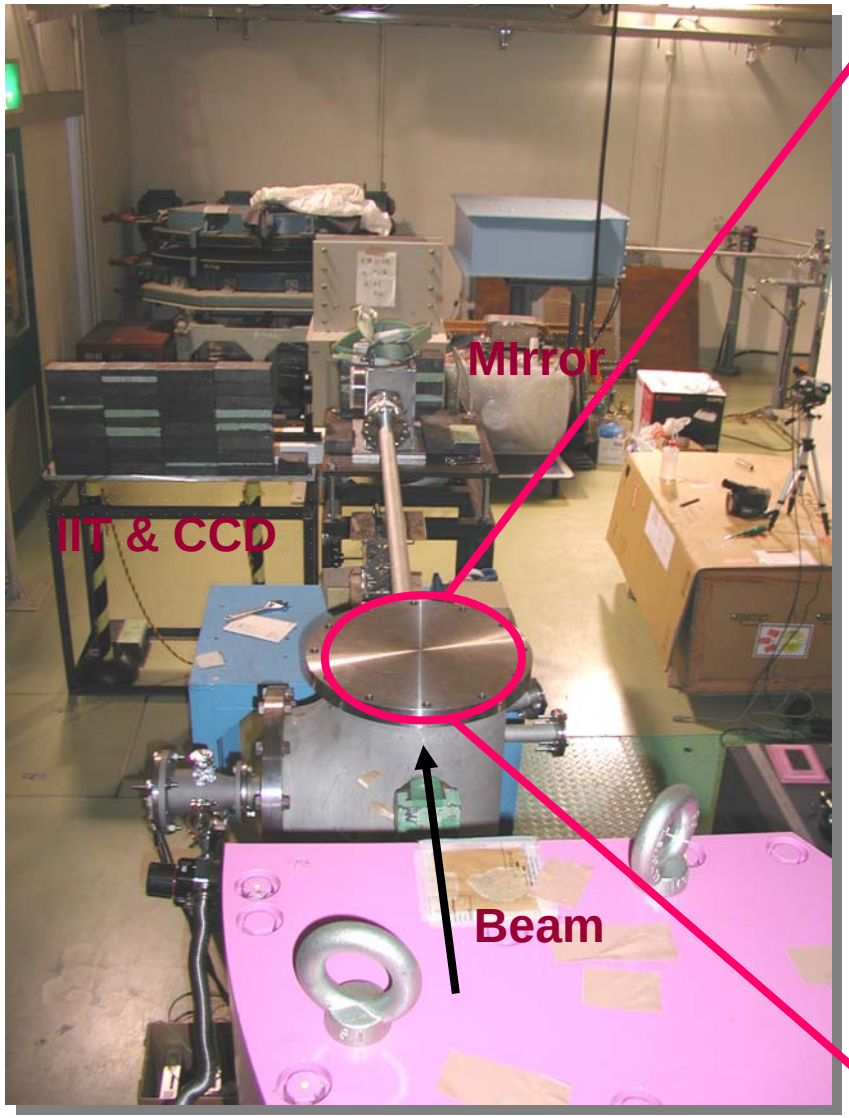
vacuum: 1.0×10^{-7} torr

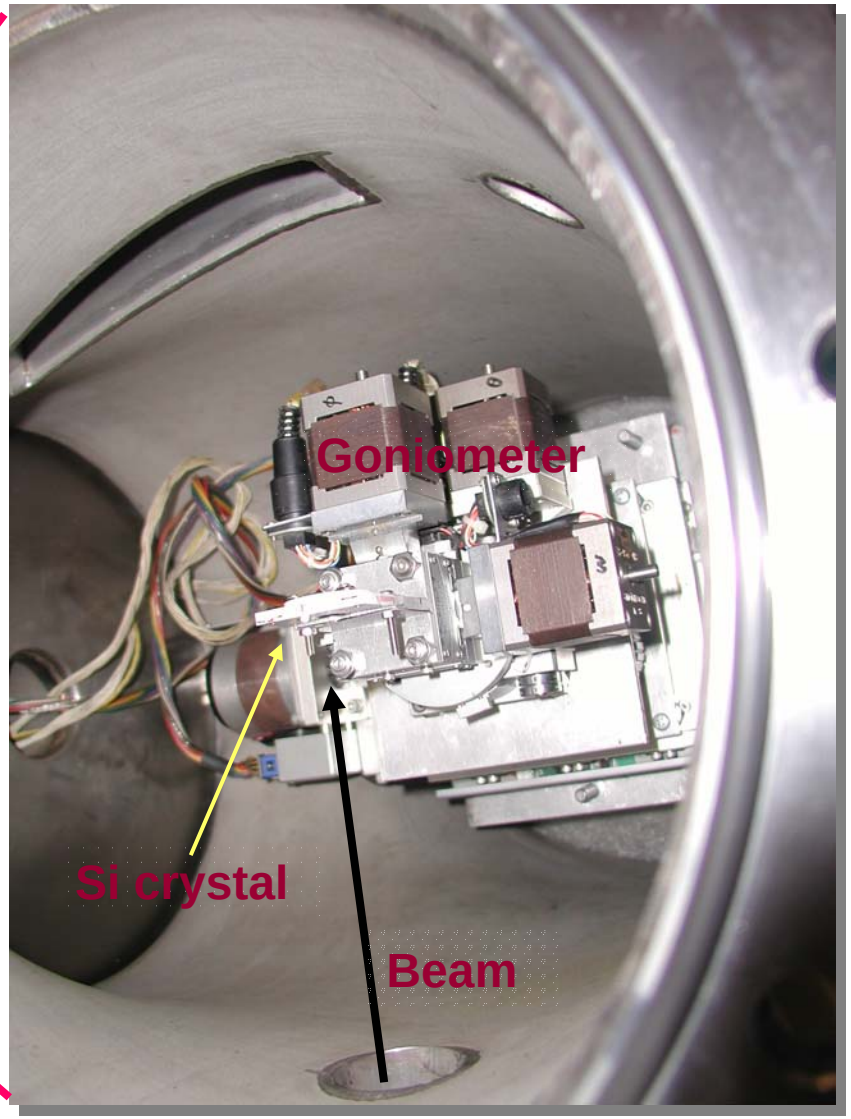
QM3: for change of beam divergence

Extraction line

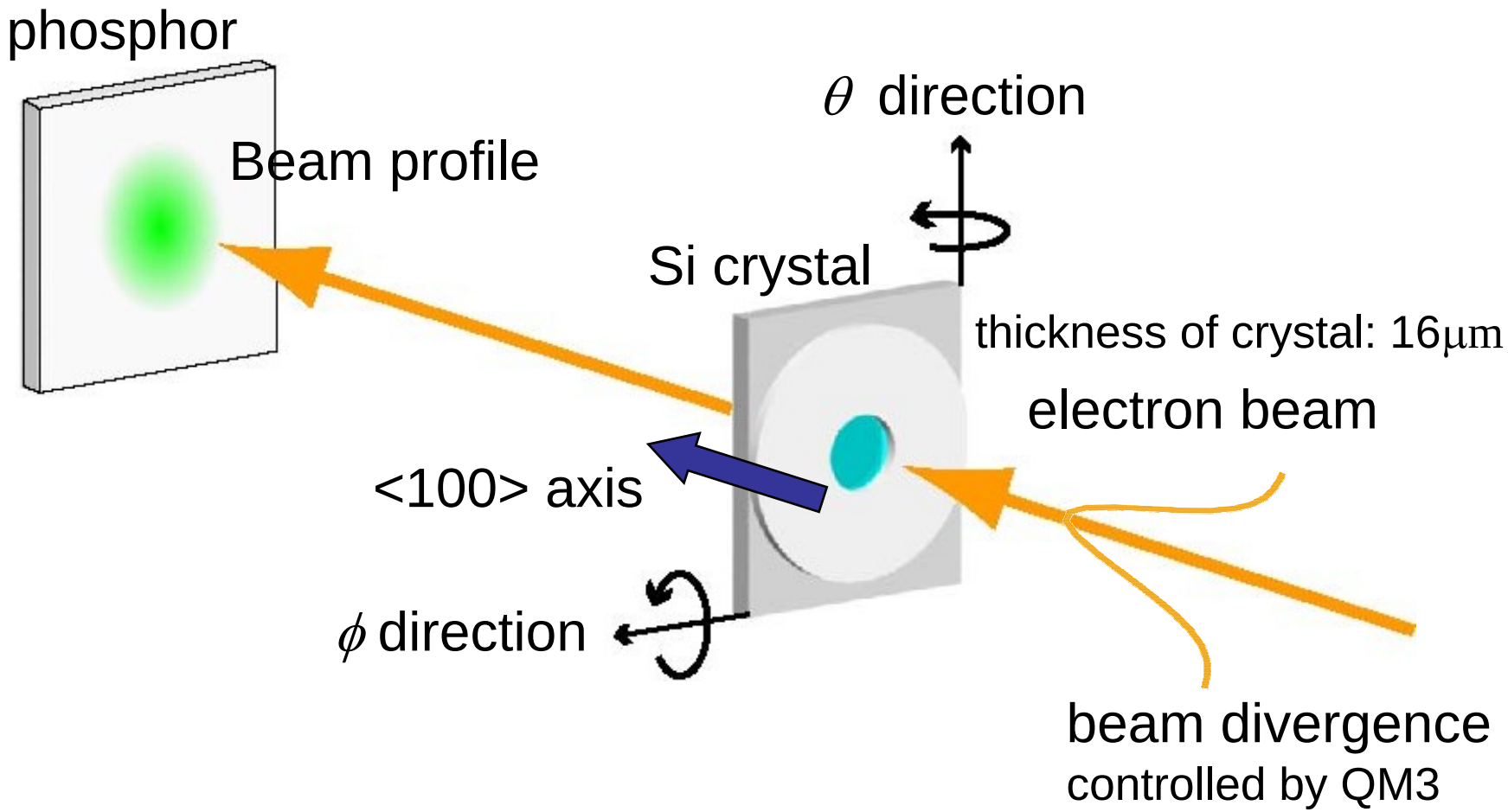


Setup



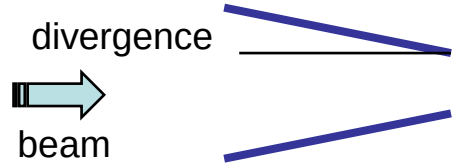


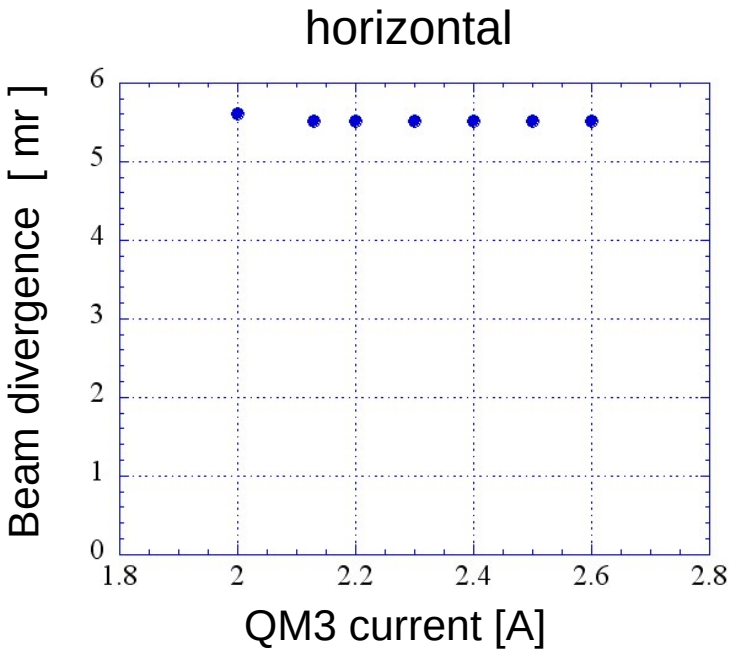
Schematic view of the setup

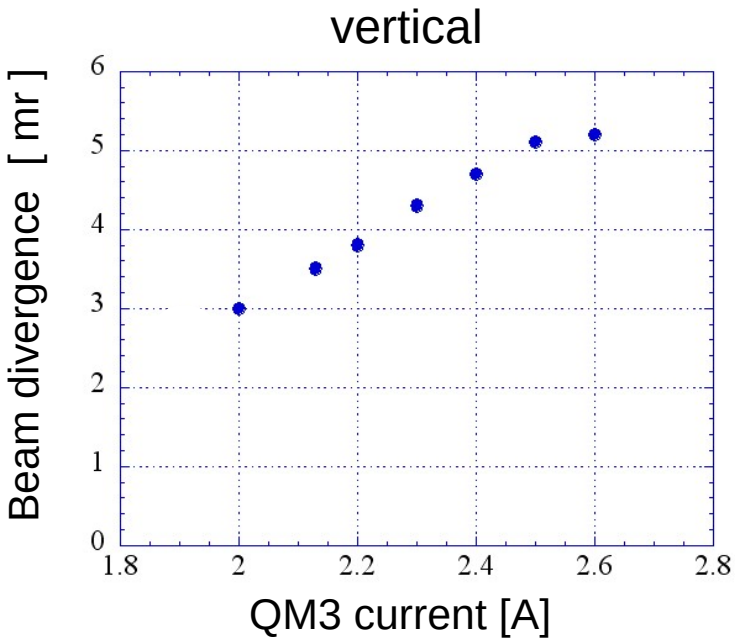


Experiment: beam divergence

- Beam divergence vs. QM3 current
  (🡸 measured beam profile and optics calculation)





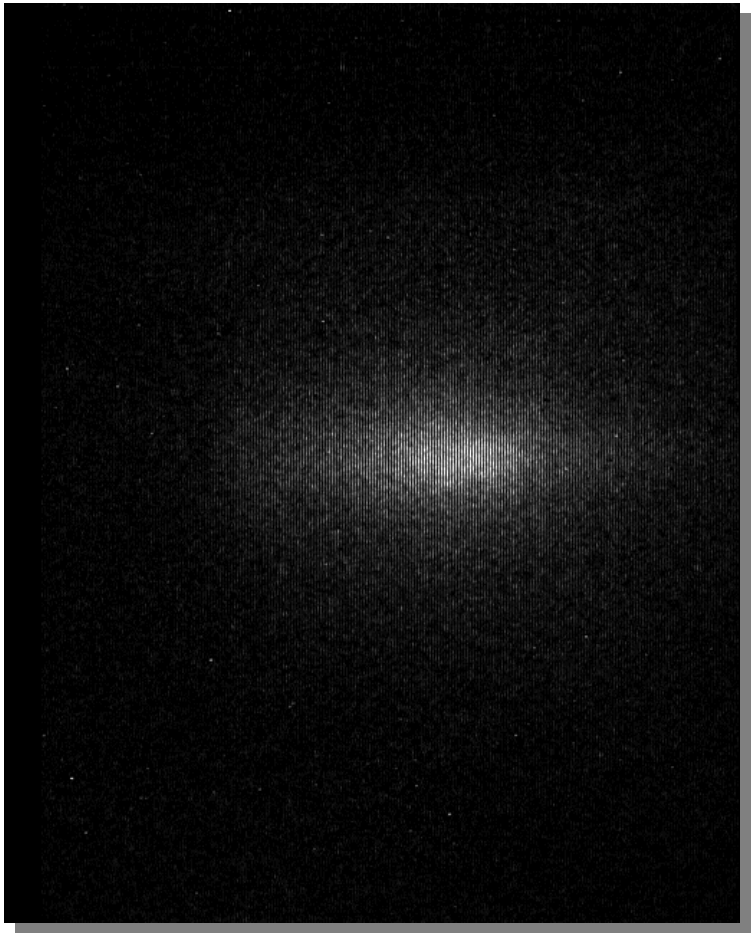


- Vertical angle dependence of the profile is the point.
- Lindhard angle for <100> axis of Si : 0.7 mr
  - Beam divergence > Lindhard angle

Results: Beam Profiles

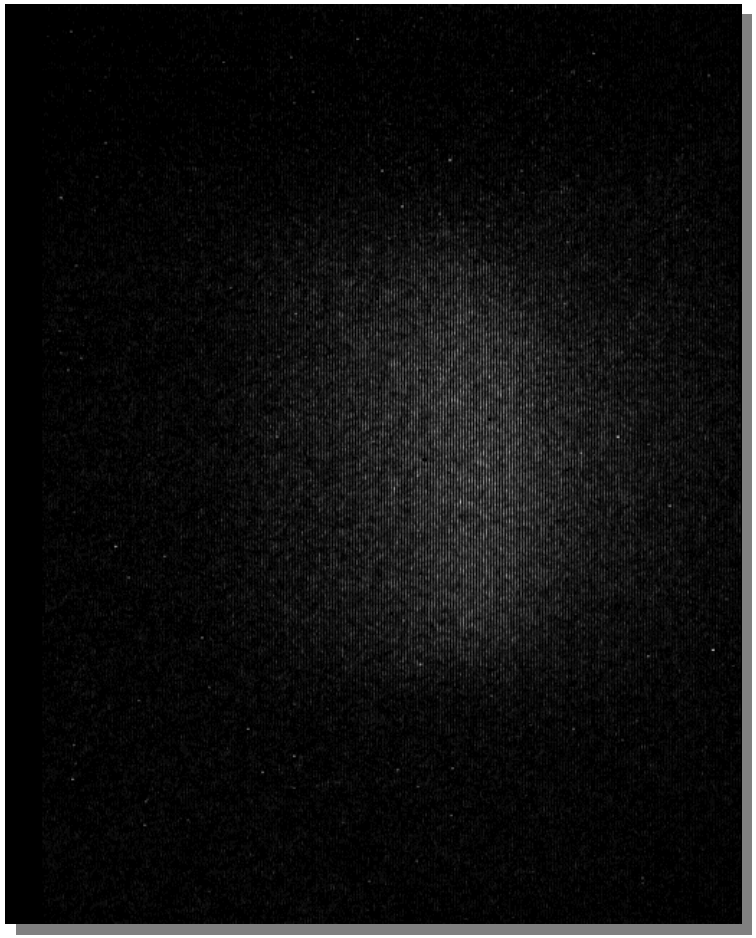
QM3: 2.0A $\theta = 0$, $\phi = -1.5$mr

Beam divergence: 3.0 mr



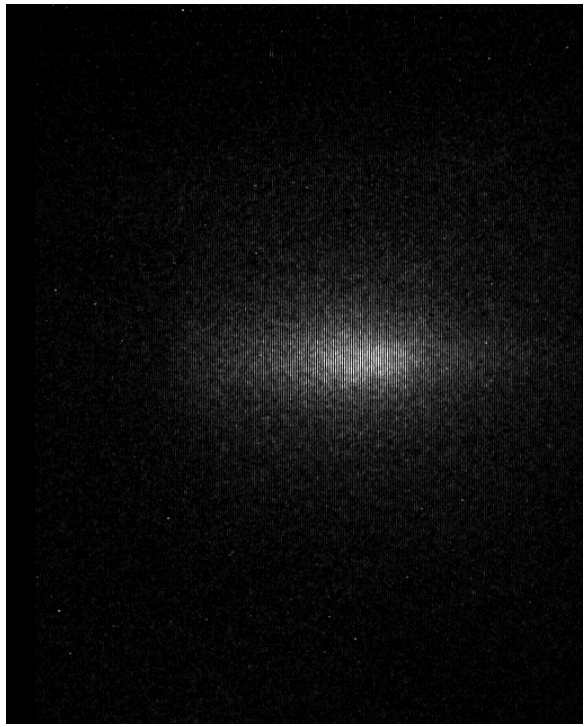
QM3: 2.6A $\theta = 0$, $\phi = -1.5$mr

Beam divergence: 5.2 mr



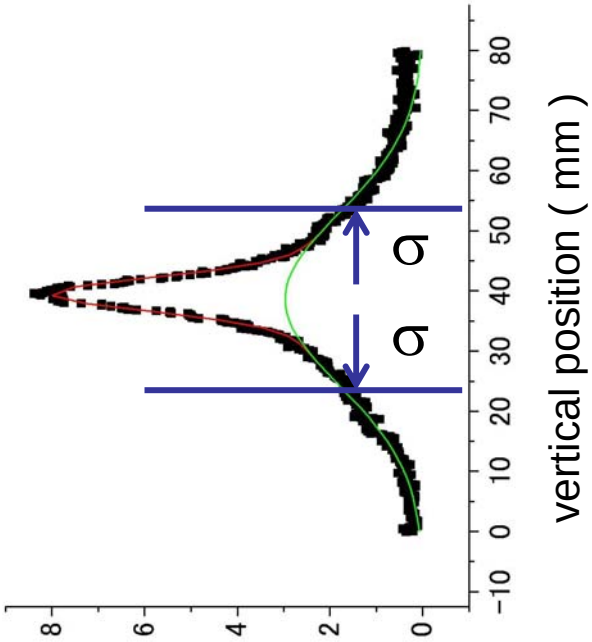
Analysis

- Beam divergence (vertical): 3.0 mr QM3: 2.0 A



projection

Fitting with double Gaussian

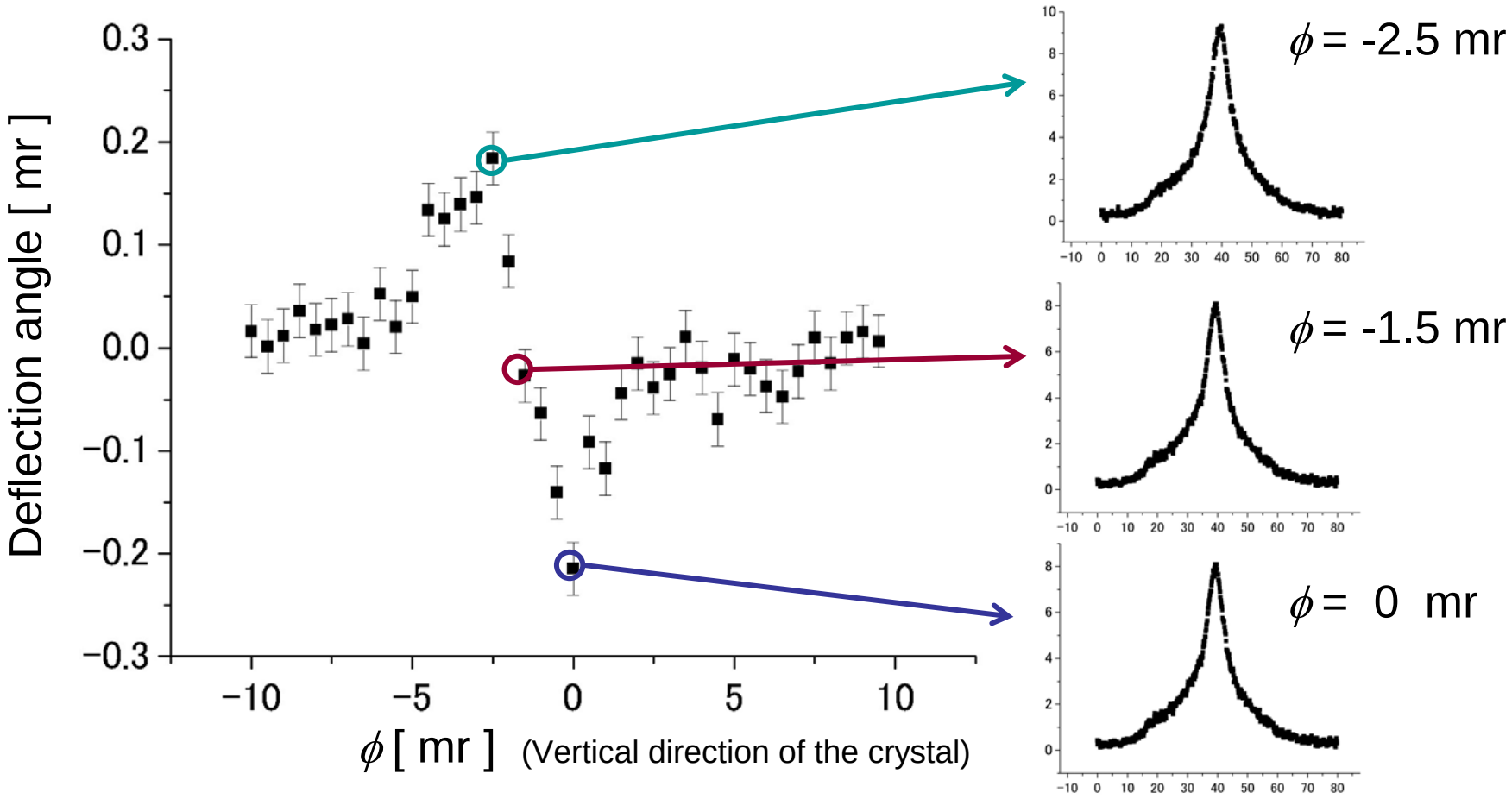


Beam center ≡ weighted average in 2σ region

Results (1)

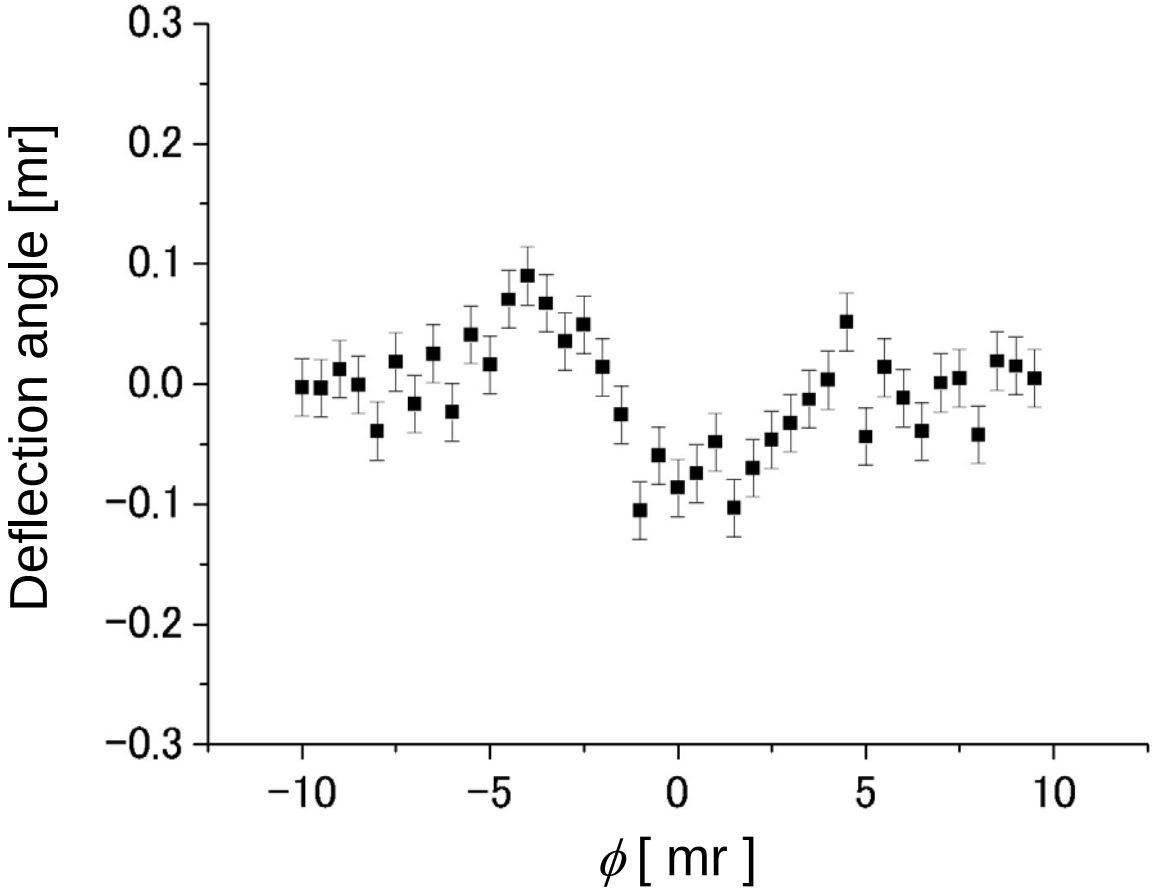
- Beam divergence (vertical) : 3.0 mr θ=0 mr (QM3: 2.0 A)

Deflection angle ← change of beam center + 2.34m



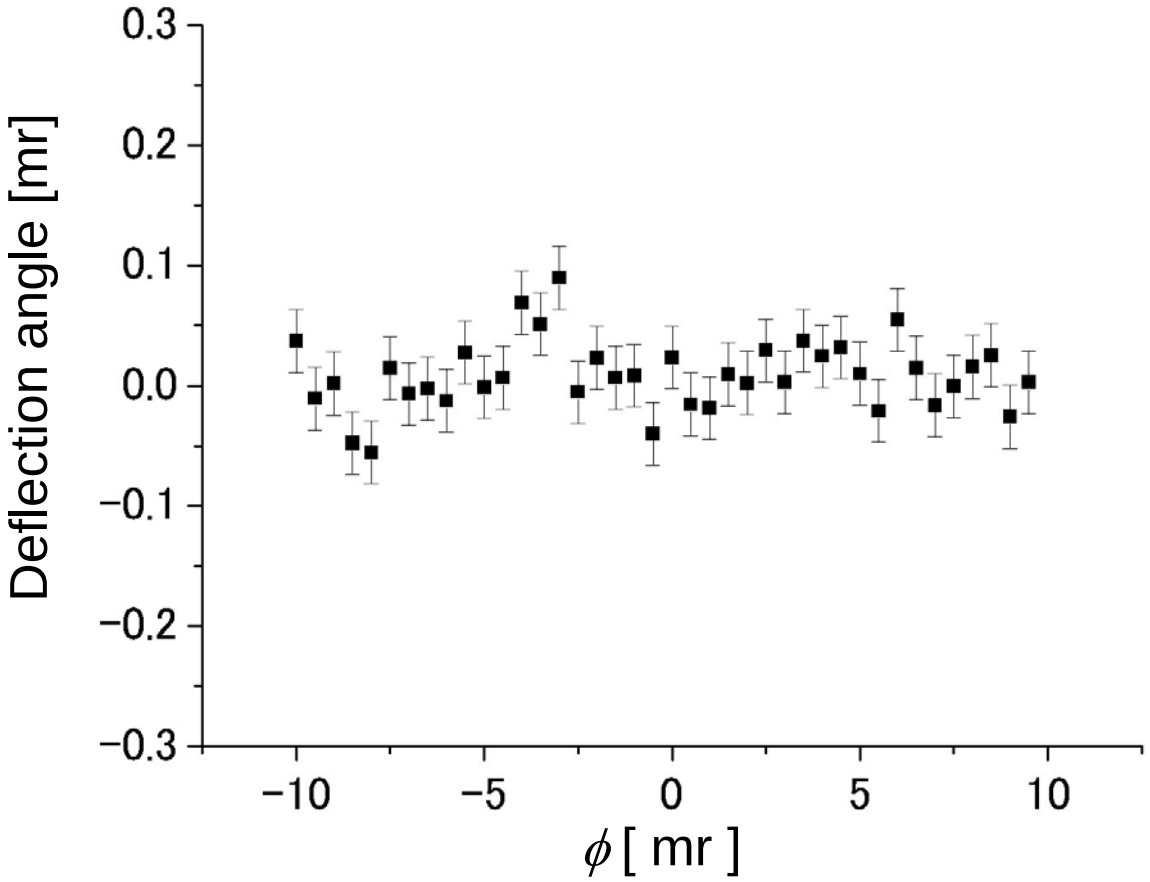
Results (2)

- Beam divergence = 3.8 mr θ = 0 mr (QM3 : 2.2 A)



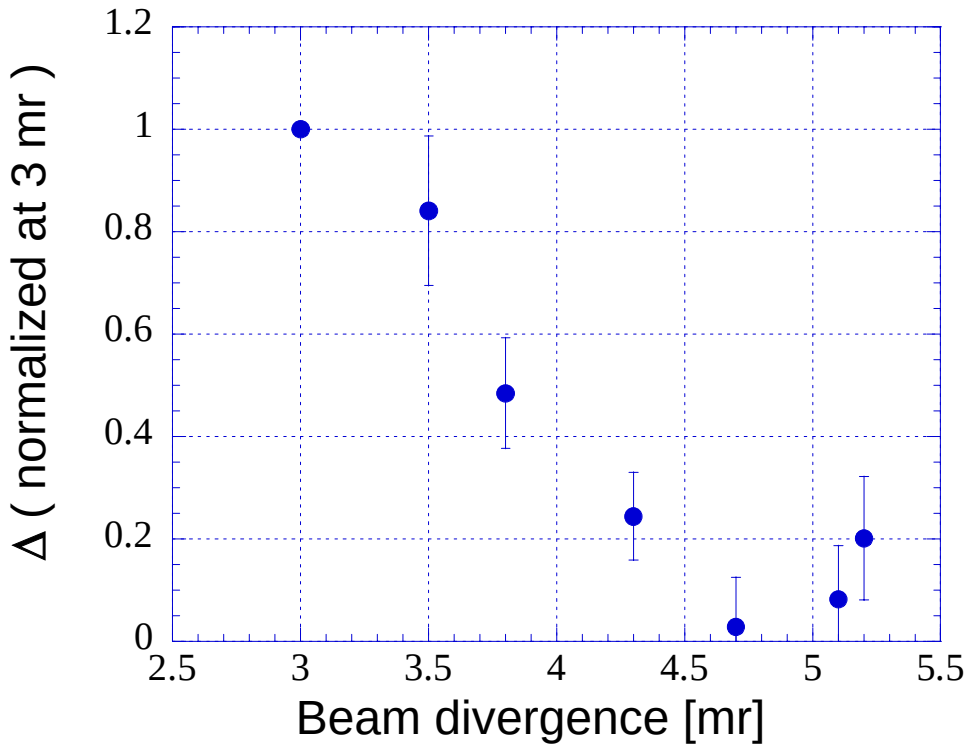
Results (3)

- Beam divergence : 5.2 mr θ = 0 mr (QM3 : 2.6 A)

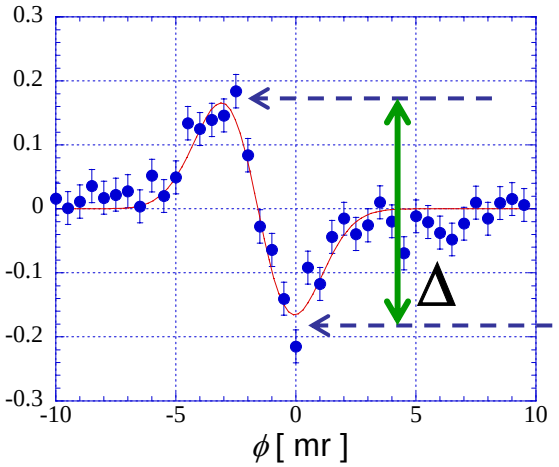


Results: deflection vs. beam divergence

- Deflection vs. beam divergence



The magnitude of the deflection, Δ, was determined by fitting the plot with 1st derivative of Gaussian function



Larger beam divergence → Smaller deflection

Simulation

Lindhard string continuous potential

$$U = \frac{2Ze^2}{d} \ln \sqrt{1 + \frac{3R^2}{\rho^2}}$$

R : Thomas-Fermi radius

ρ : Distance from <100> axis

d : lattice constant in <100> axis (5.43Å for Si)

Z : Atomic number (14 for Si)

Conditions for simulation

4^{th} order of Runge-Kutta method

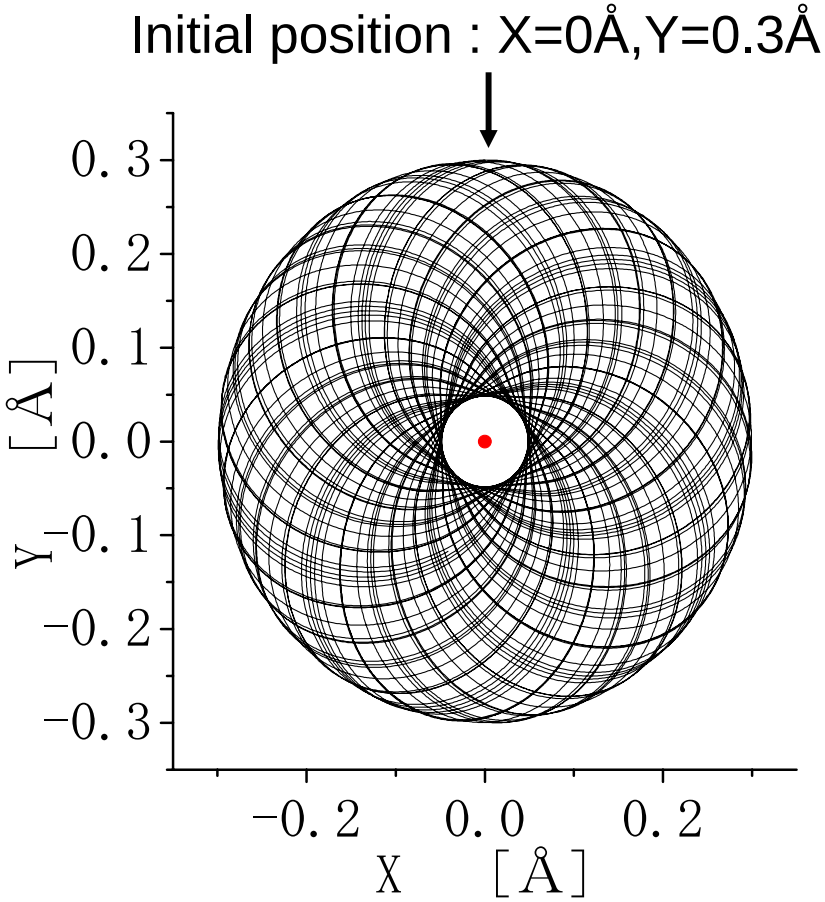
Without consideration of multiple scattering and channeling radiation

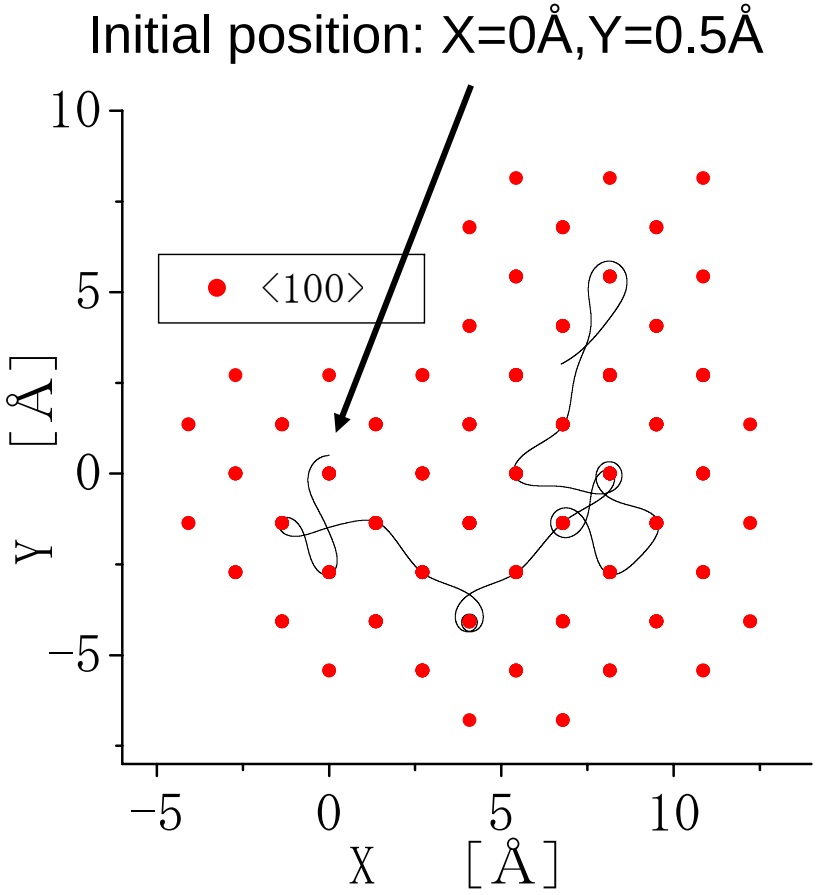
Energy of electrons : 150 MeV

Thickness of the crystal : 16 μm

Simulation: trajectory

- Trajectory of an electron

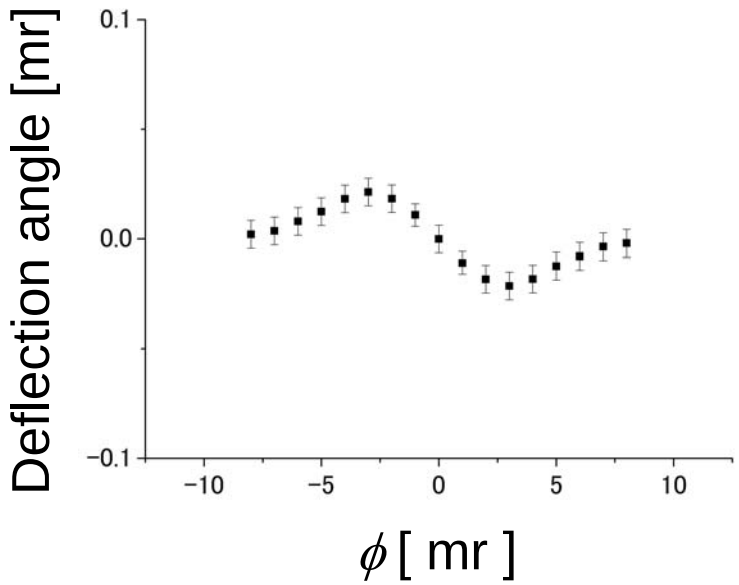




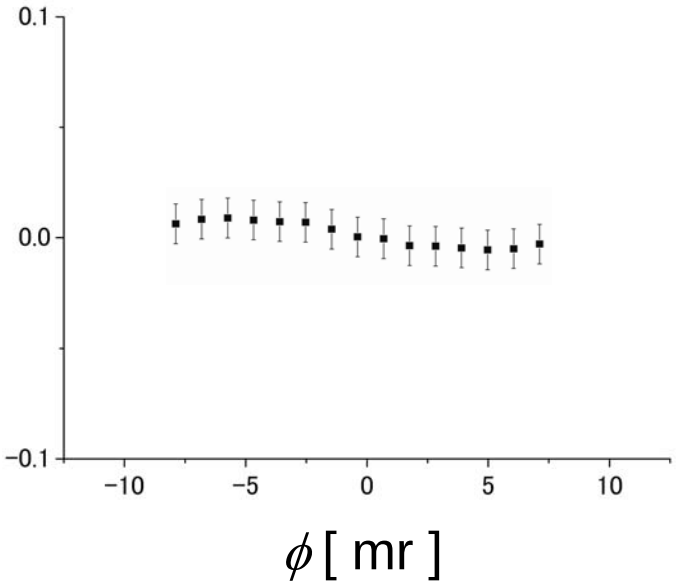
Simulation (1)

- Preliminary results

Beam divergence : 3.0 mr



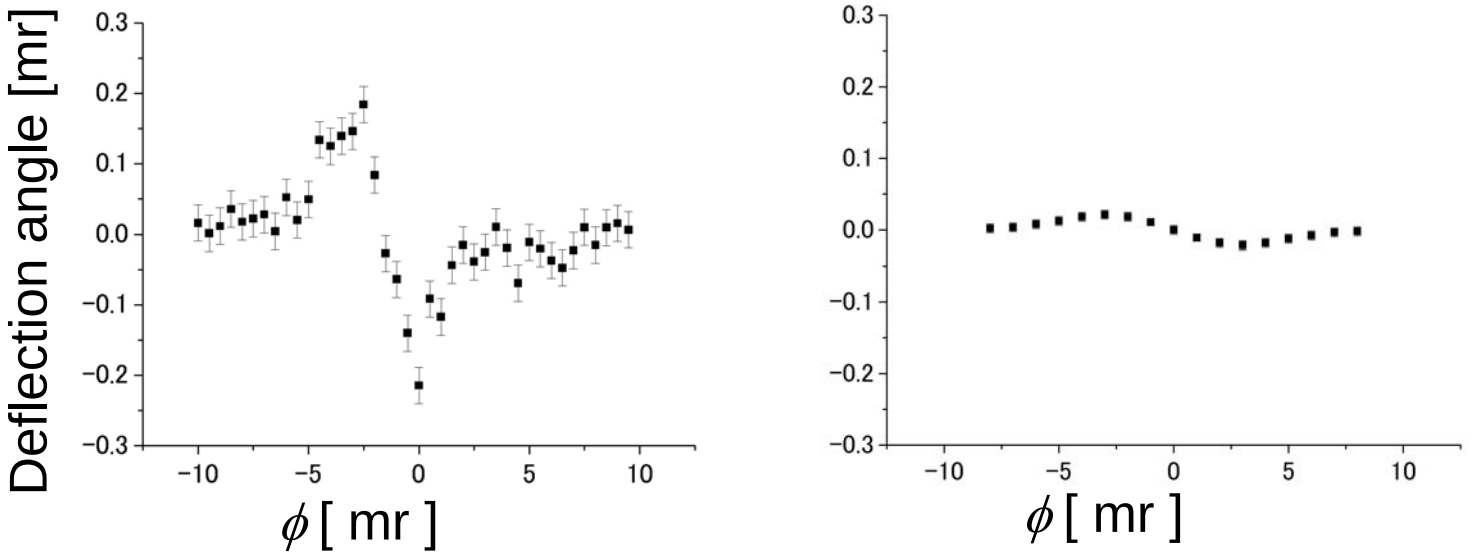
Beam divergence : 5.2 mr



Larger beam divergence → Smaller deflection

Simulation (2)

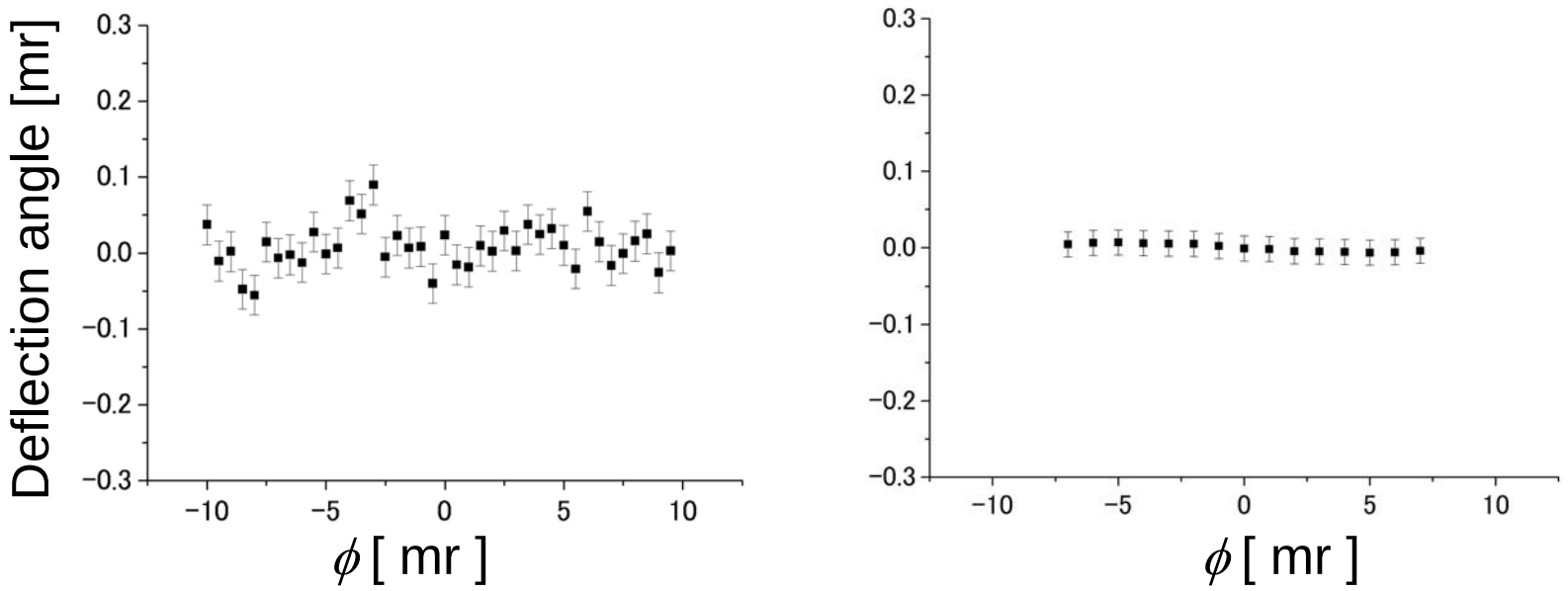
- Comparison with experimental data
  - Beam divergence : 3.0 mr (QM3 : 2.0 A)



The tendency of the deflection as a function of the vertical direction of the crystal (ϕ) is same. But, in quantitative comparison, the peak-to-peak difference of the deflection angle of the measurement is about 0.4 mr, while it's around 0.04 mr for the simulation.

Simulation (3)

- Comparison with experimental data
  - Beam divergence : 5.2 mr (QM3 : 2.6 A)



Experimental data agree with simulation qualitatively.

Study with more realistic beam profiles etc. is underway.

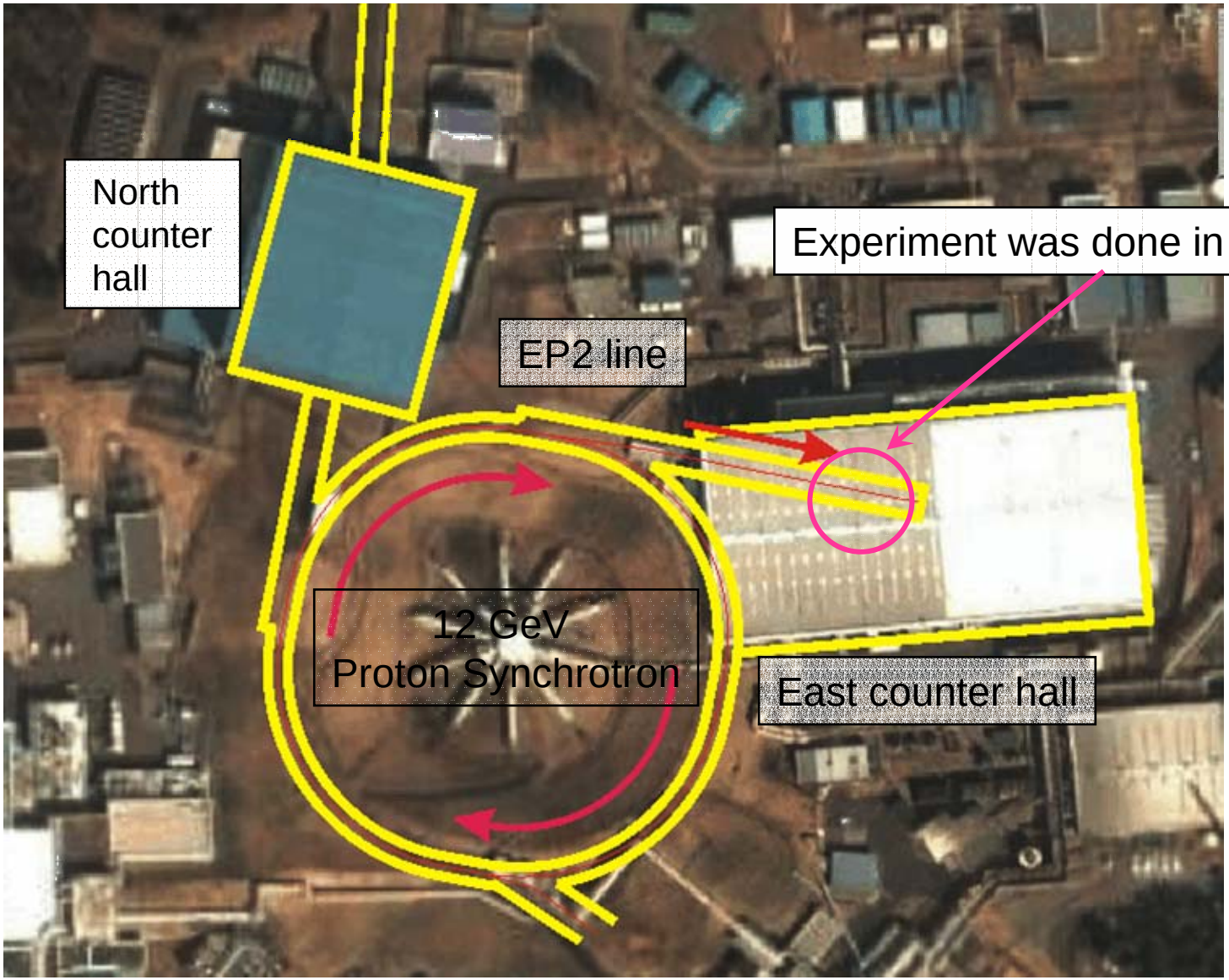
Summary

- Performed experiment on beam deflection at REFER with the150-MeV electron beam.
- Systematic investigation of the beam deflection as a function of the beam divergence.
- Preliminary comparison with simulation:
  - Qualitative agreements
  - Quantitative comparison … being studied

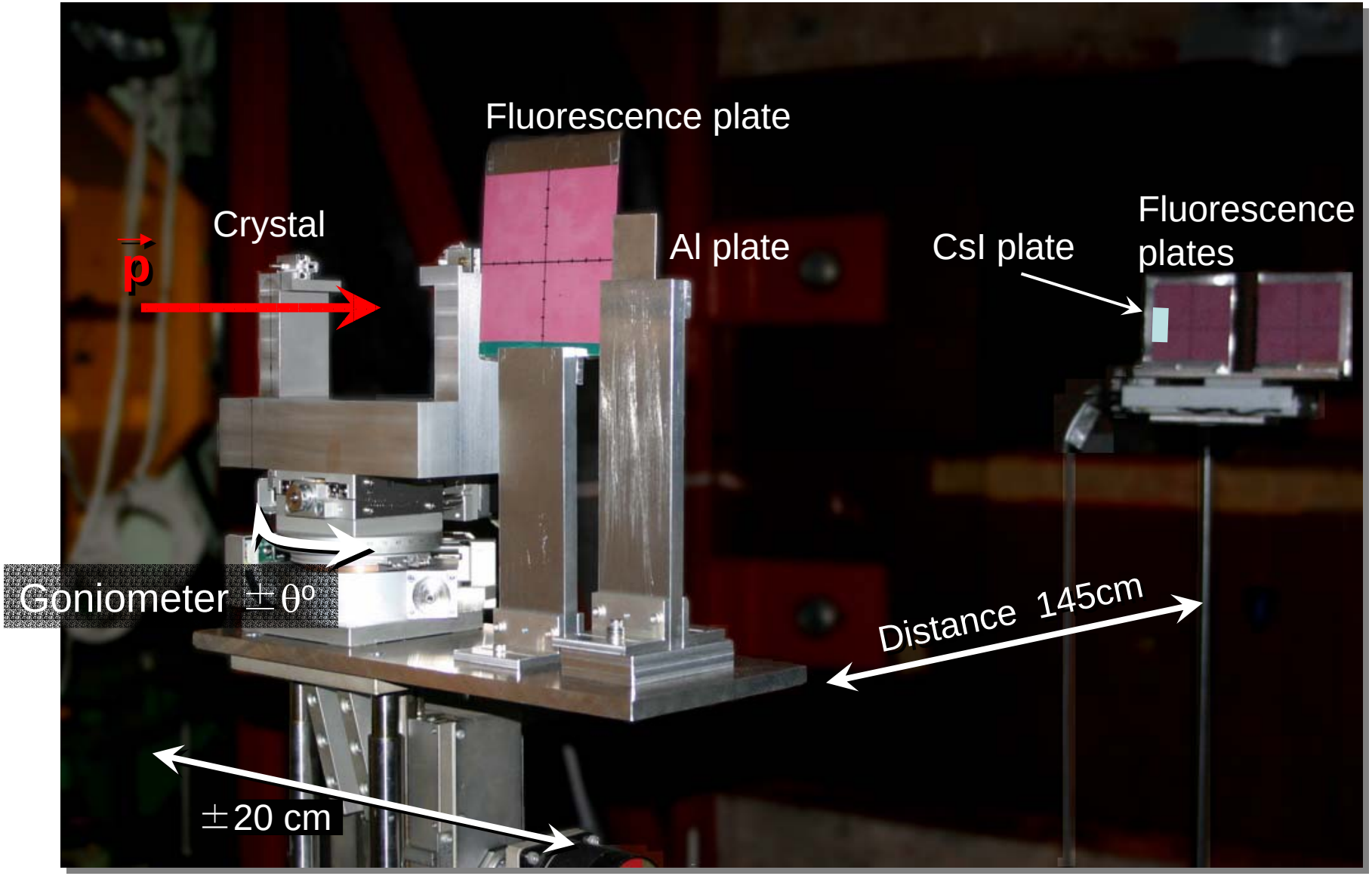
Prospect

- Experiment at KEK-ATF (Accelerator Test Facility)
  - E = 1.28 GeV
  - Normalized emittace: $\varepsilon_x = 3.4 \times 10^{-6}$m, $\varepsilon_y = 4.5 \times 10^{-8}$m
  - Just a similar experiment at ATF as the REFER experiment
  - See channeling effects with the super-low emittance beam.

Experiment at KEK-PS



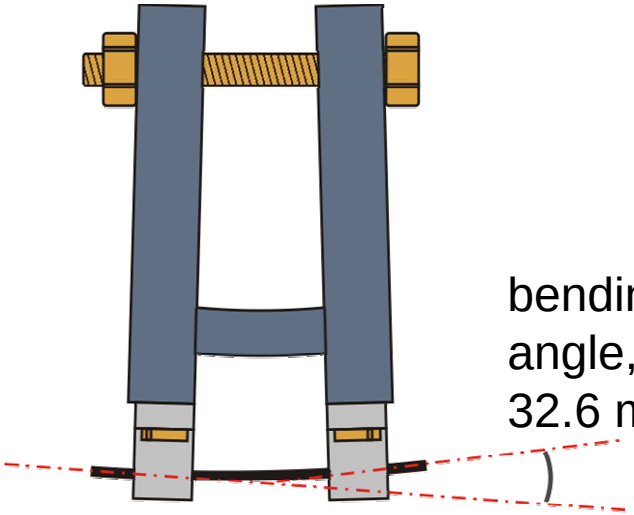
Experimental setup



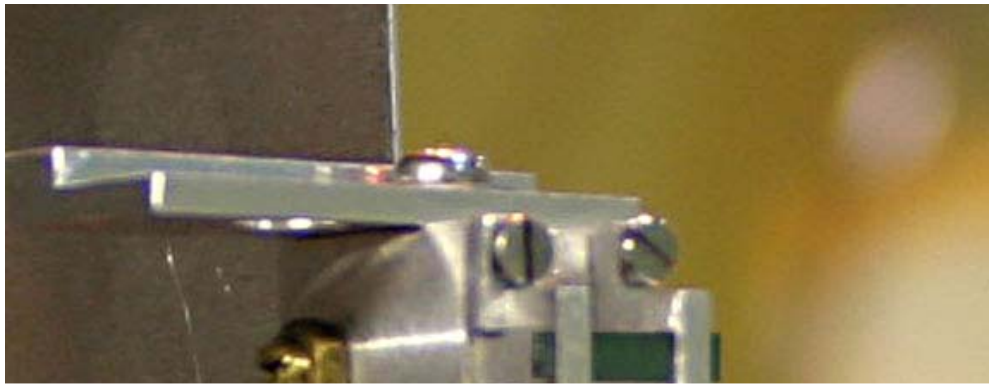
Crystal, proton beam

Parameters of crystal

Material:	Silicon
Size:	3 x 0.3 x 10 mm
Bending angle:	~ 32.6 mrad
Plane:	(111)
Lindhard angle:	0.066 mrad

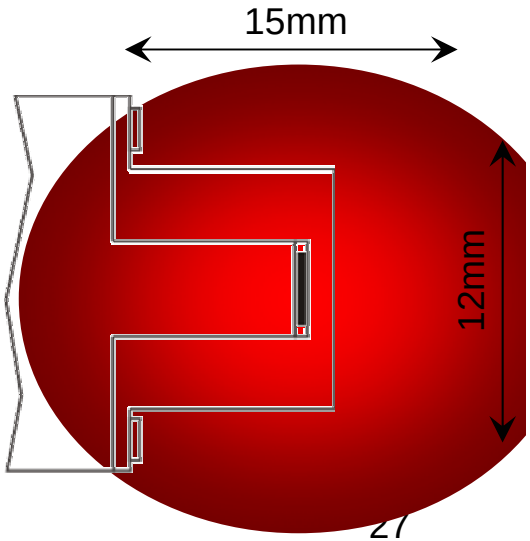


bending angle, 32.6 mrad

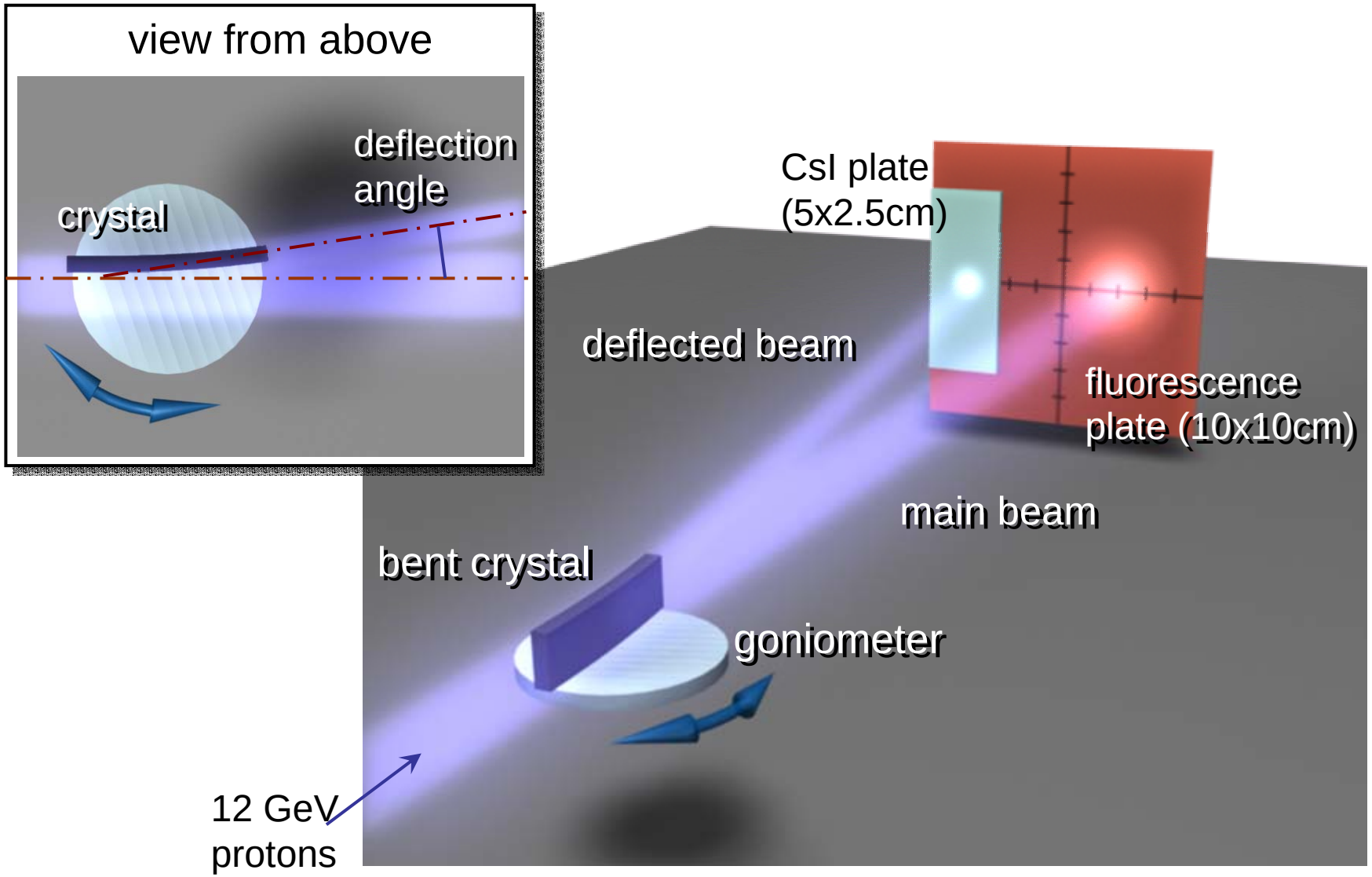


Parameters of the proton beam

Energy:	12 GeV
Intensity:	10^{12} protons/spill
Size:	15 x 12 mm
Divergence:	< 5 mrad

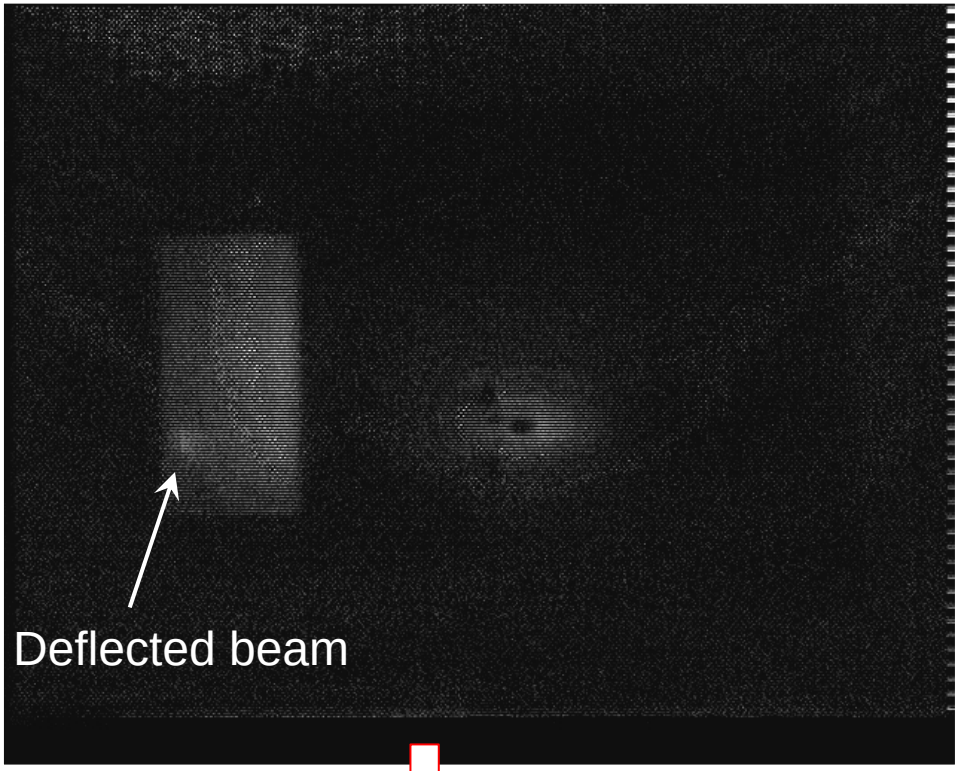


Schematic drawing of the experiment

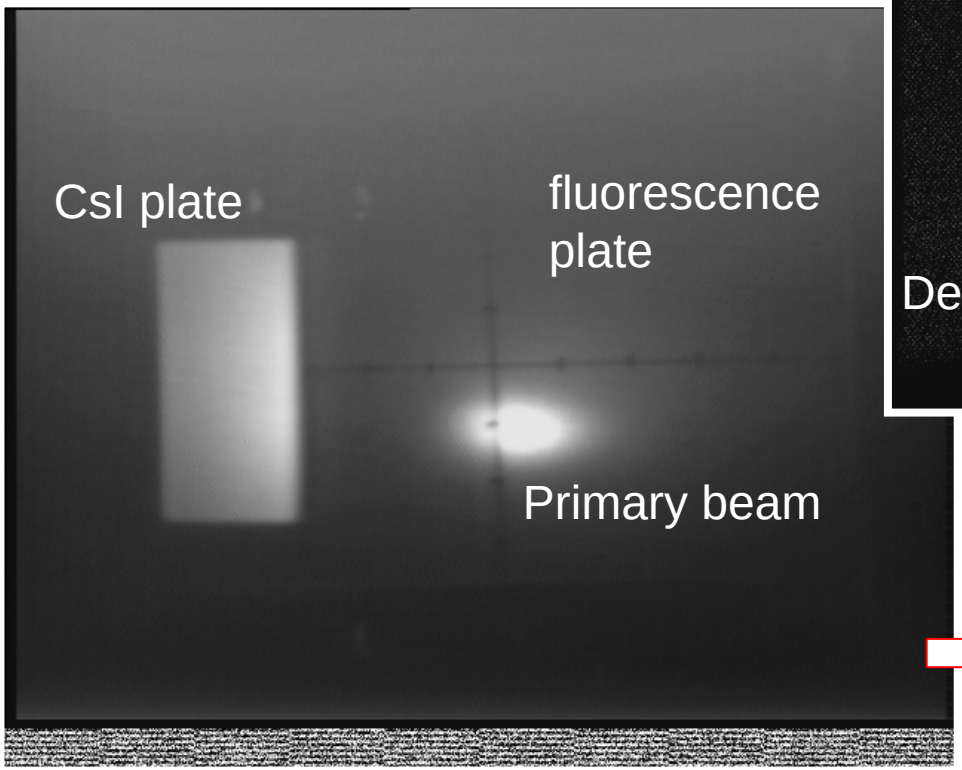


Typical pictures

image after
background subtraction

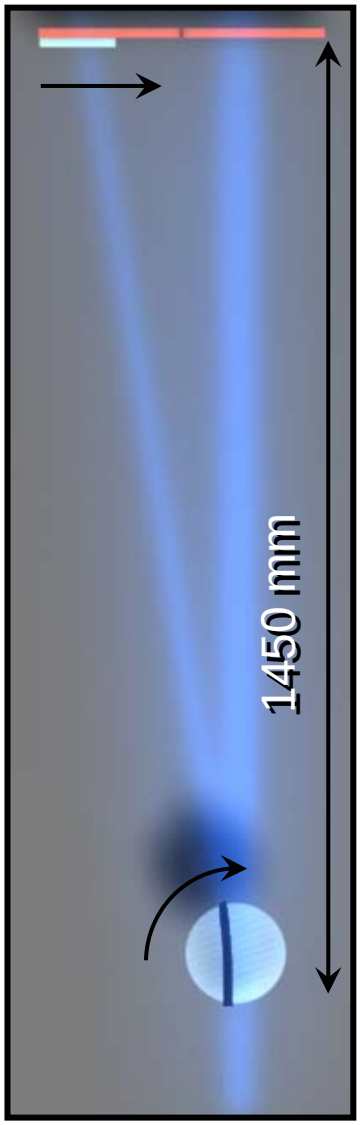


raw image

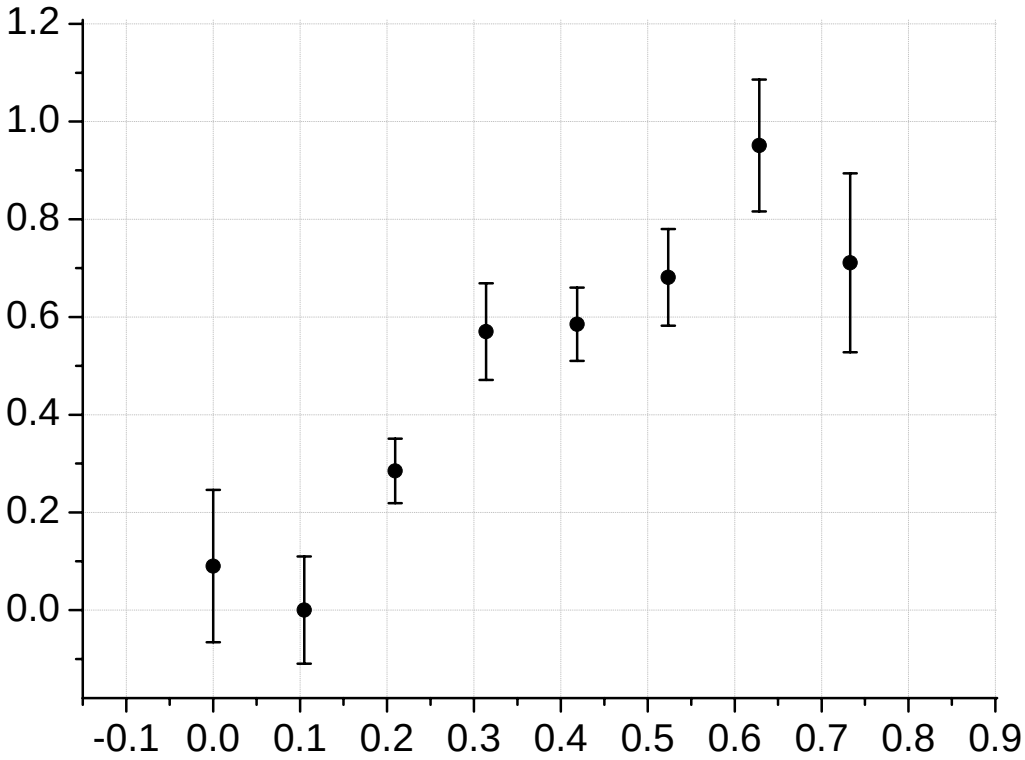


- intensity of deflected beam
- bending angle
- crystal efficiency

Results (1)



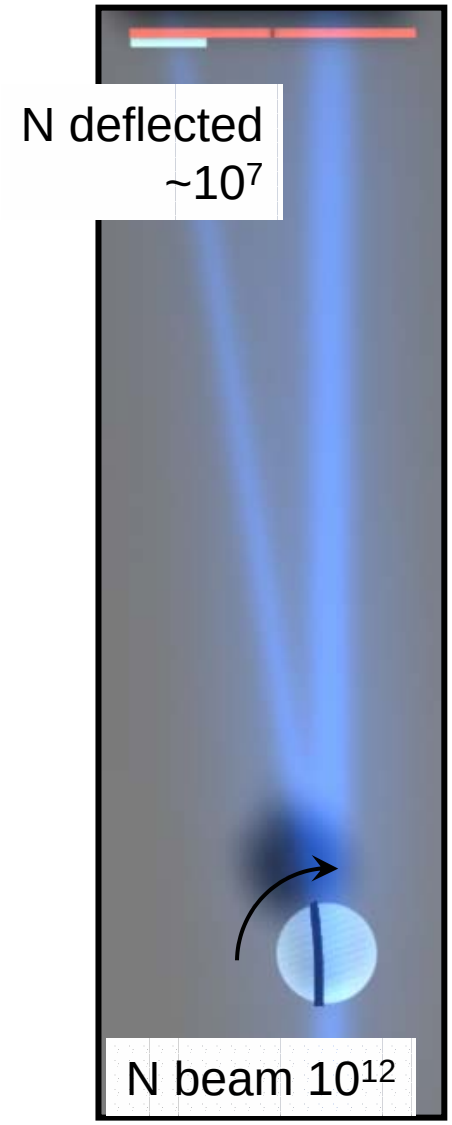
position of deflected beam on CsI plate, (mm)

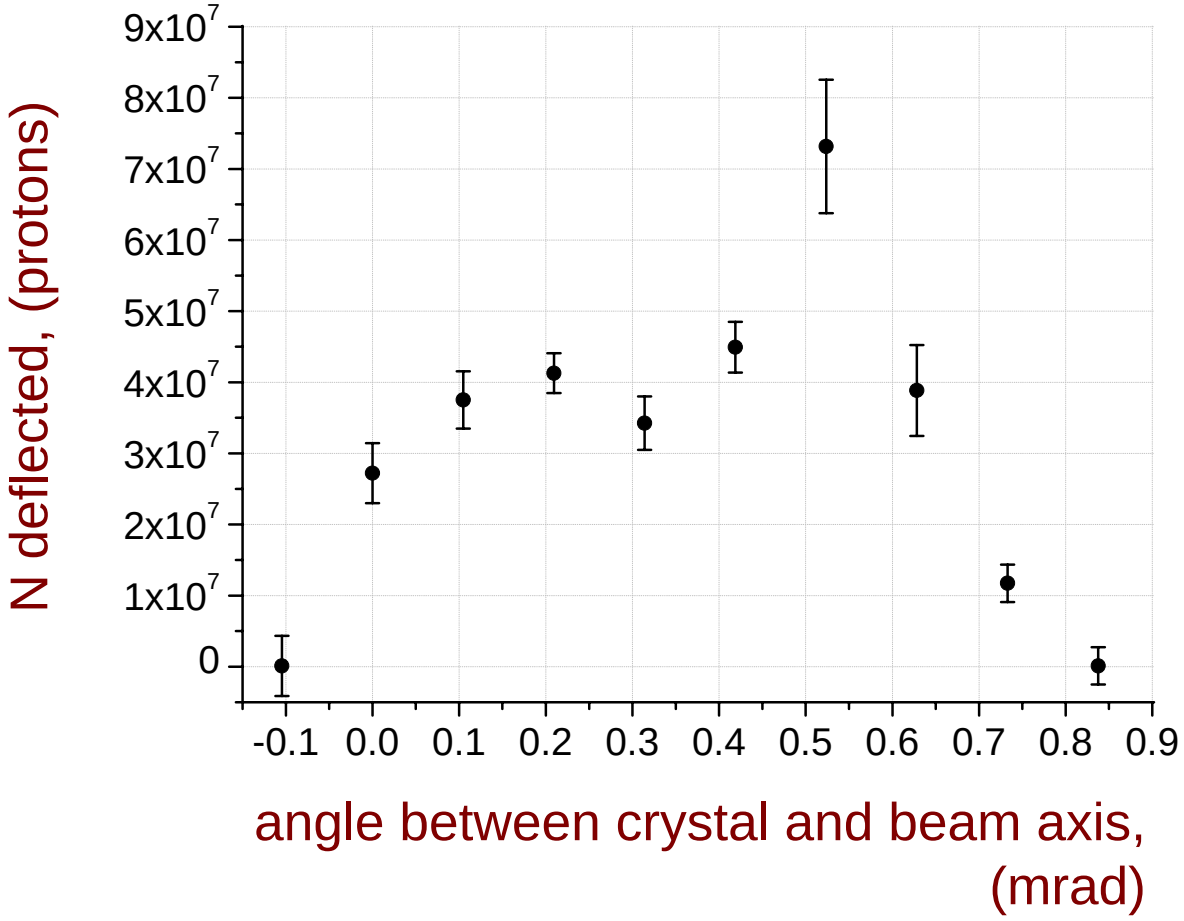


angle between crystal and beam axis, (mrad)

Such dependence agrees with estimations

Results (2)





10^{12} protons → ~ 10^7 deflected protons

Crystal efficiency

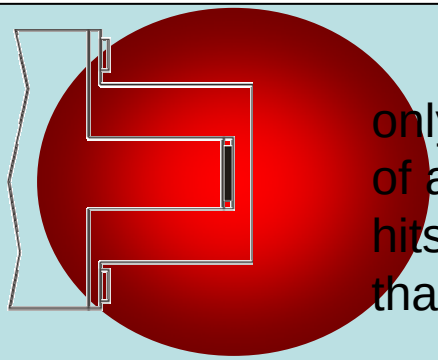
N deflected = Crystal Efficiency x

Angle Efficiency x

N incident upon the crystal.

Incident particles within critical (Lindhard) angle to the crystallographic plane.

At the beam divergence <5 mrad and Lindhard angle 0.066 mrad, angle efficiency is > 1%



only small part of all protons hits crystal, that is 0.3%

N incident upon the crystal = 3×10^9

Crystal Efficiency could be:

100% → at 5 mrad

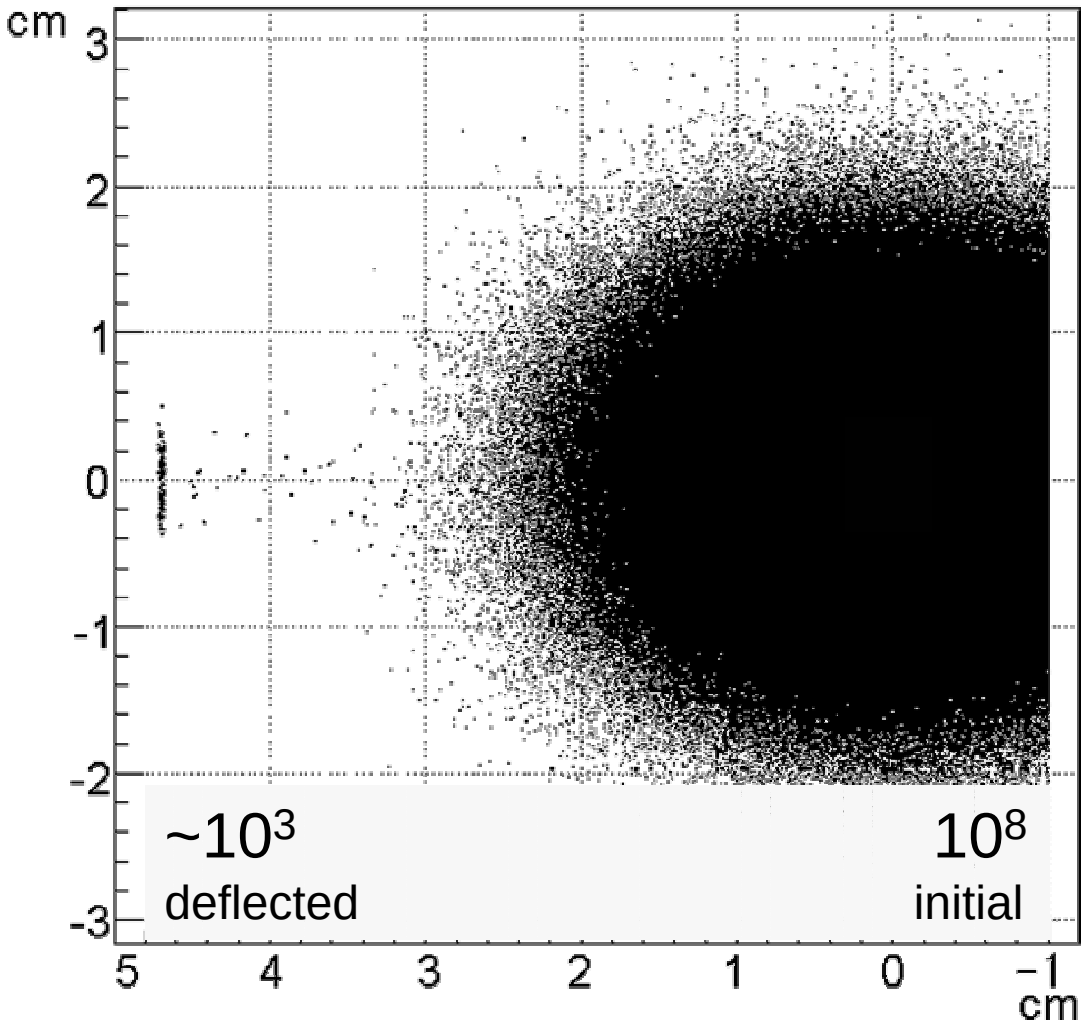
26% → at 1 mrad

13% → at 0.5 mrad

N deflected = 4×10^7 protons

Simulation

picture at the distance 145 cm from the crystal



"Catch" code

Initial parameters

Beam

Energy: 12 GeV

Size: 15 x 12 mm

Divergence: 0.3, 0.5, 1, 5 mrad

Crystal

Size: 3 x 0.3 x 10 mm

Bending angle: ~ 32.6 mrad

Plane: (111)

10^8 protons → ~ 10^3 deflected protons

Simulation

N deflected = Crystal Efficiency x

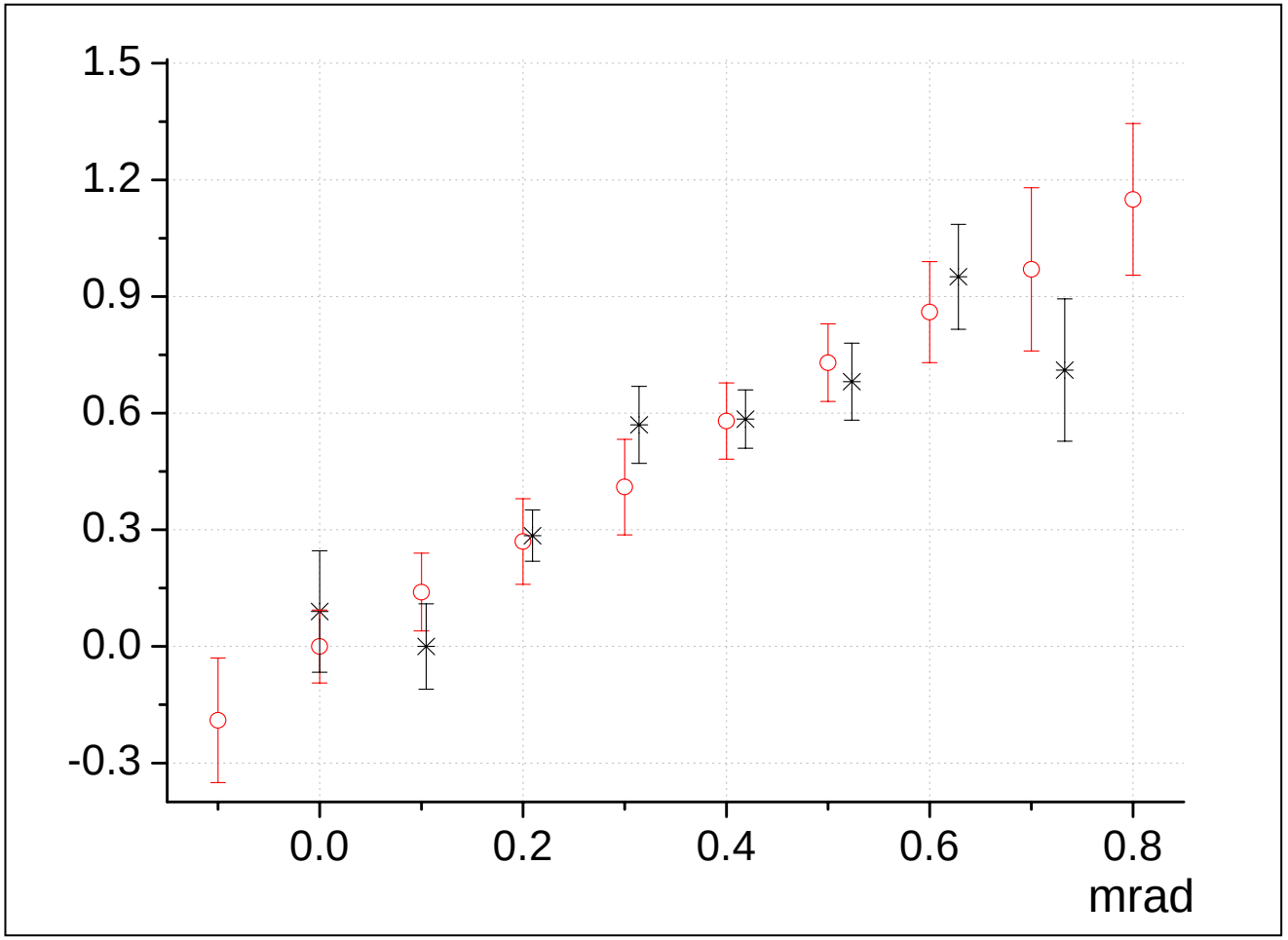
Angle Efficiency x

N incident upon the crystal.

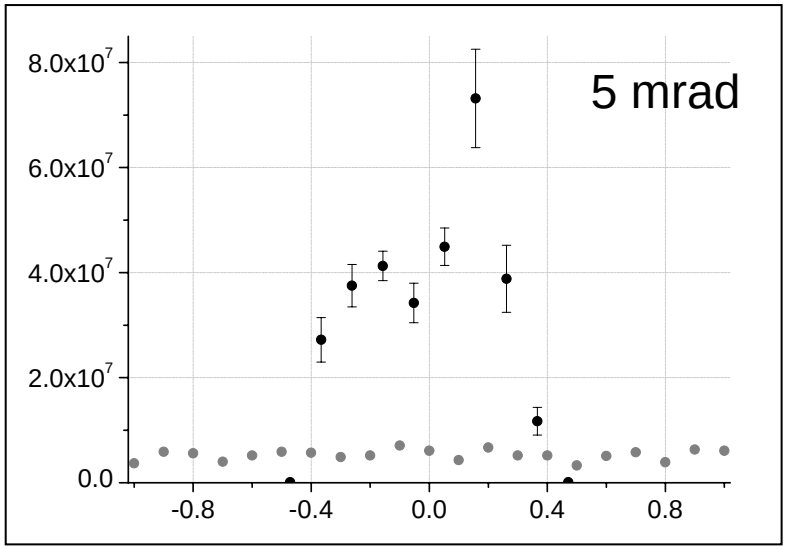
Crystal Efficiency is 15%

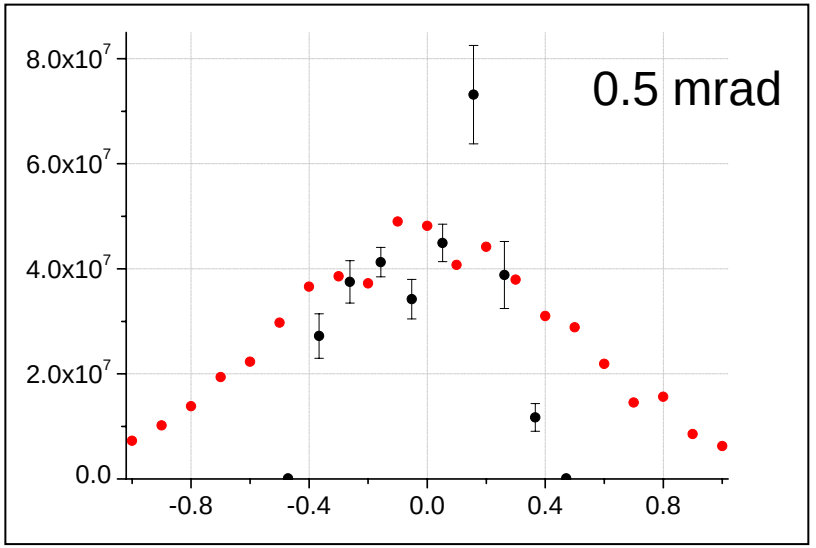
Simulation vs. Experimental data (1)

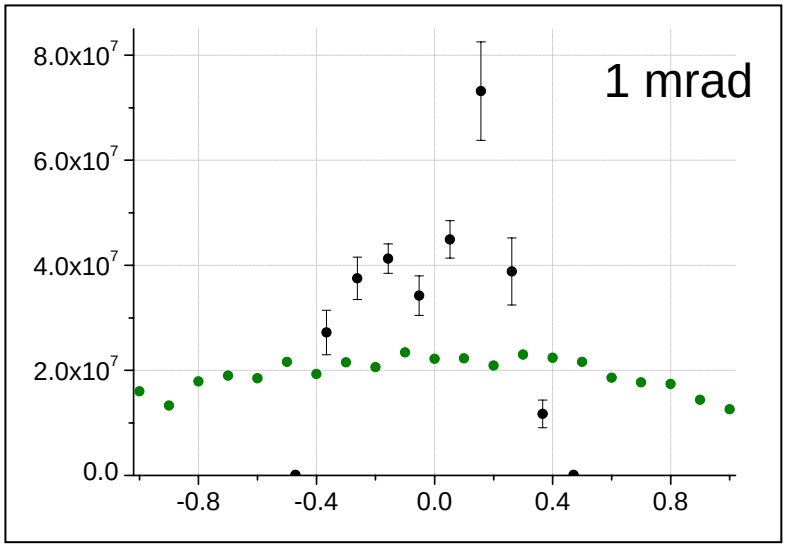
Position of the deflected beam
at the distance 145 cm from the crystal, (mm)

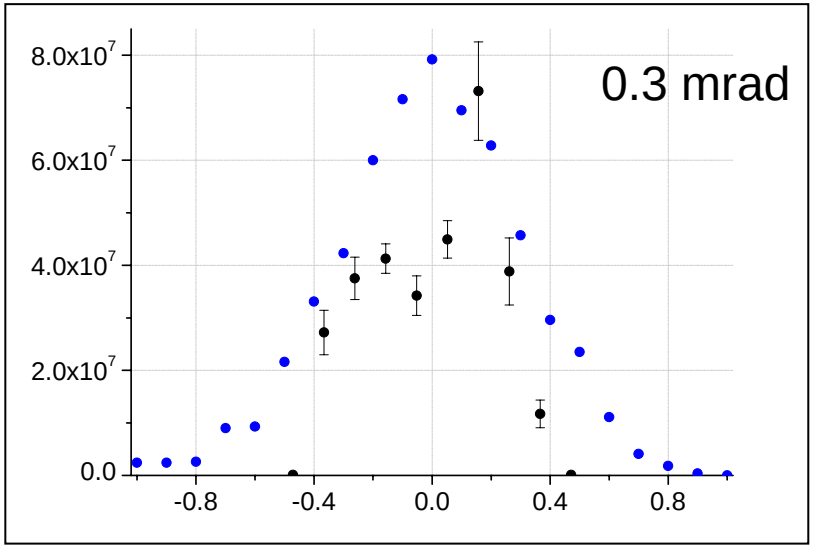


Simulation vs. Experimental data (2)









Crystal efficiency

At the beam divergence 0.3 - 0.5 mrad

crystal efficiency in experiment was 8 - 13%

From the simulation it is 15%

Summary

- Experiment on the deflection of proton beam by the bent crystal was successfully done.
- The crystal shows good deflection efficiency which is 8 -13%.
- Performed Monte-Carlo simulation proves the experimental data

Future projects

Next experiment on the channeling of ultra-low emittance electron beam will be performed at KEK-ATF (Autumn, 2006).

Participation at the experiment on proton collimation at the Fermilab.

Experiment at the REFER ring, Hiroshima University with the 150 MeV electron beam (channeling radiation)

Application for the J-PARC