Experiments on deflection of charged particles in Japan for ILC and J-PARC.

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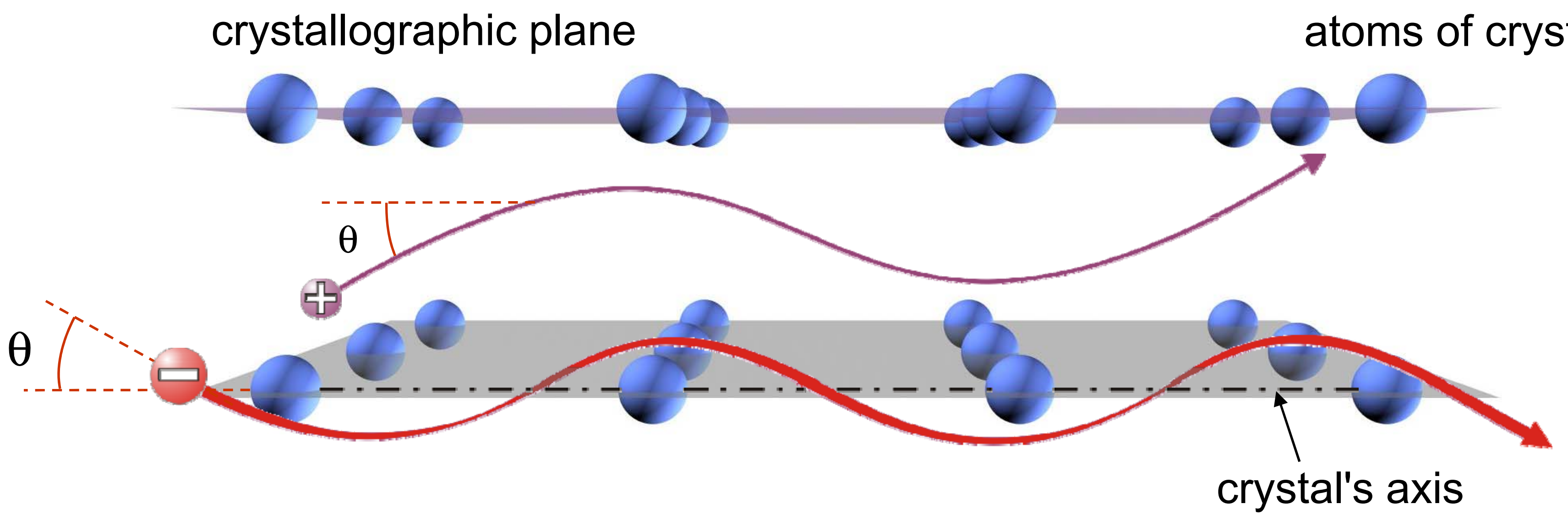
Introduction (channelling effect)



positive particles → planar channeling

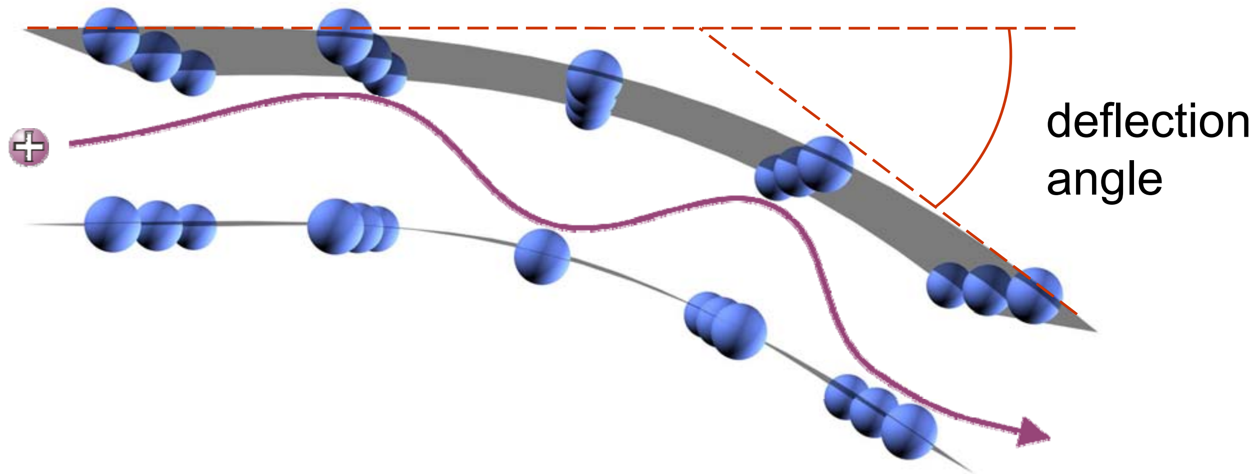
negative particles → axial channeling

θ < critical (Lindhard) angle → channeling effect

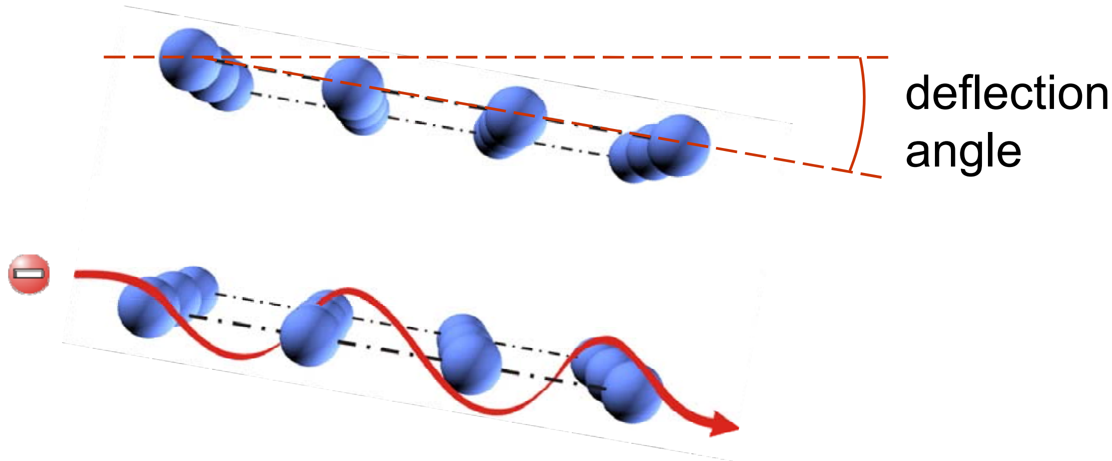
θ > critical (Lindhard) angle → no channeling effect

Introduction (beam steering)

- Deflection of POSITIVE particles by BENT crystal

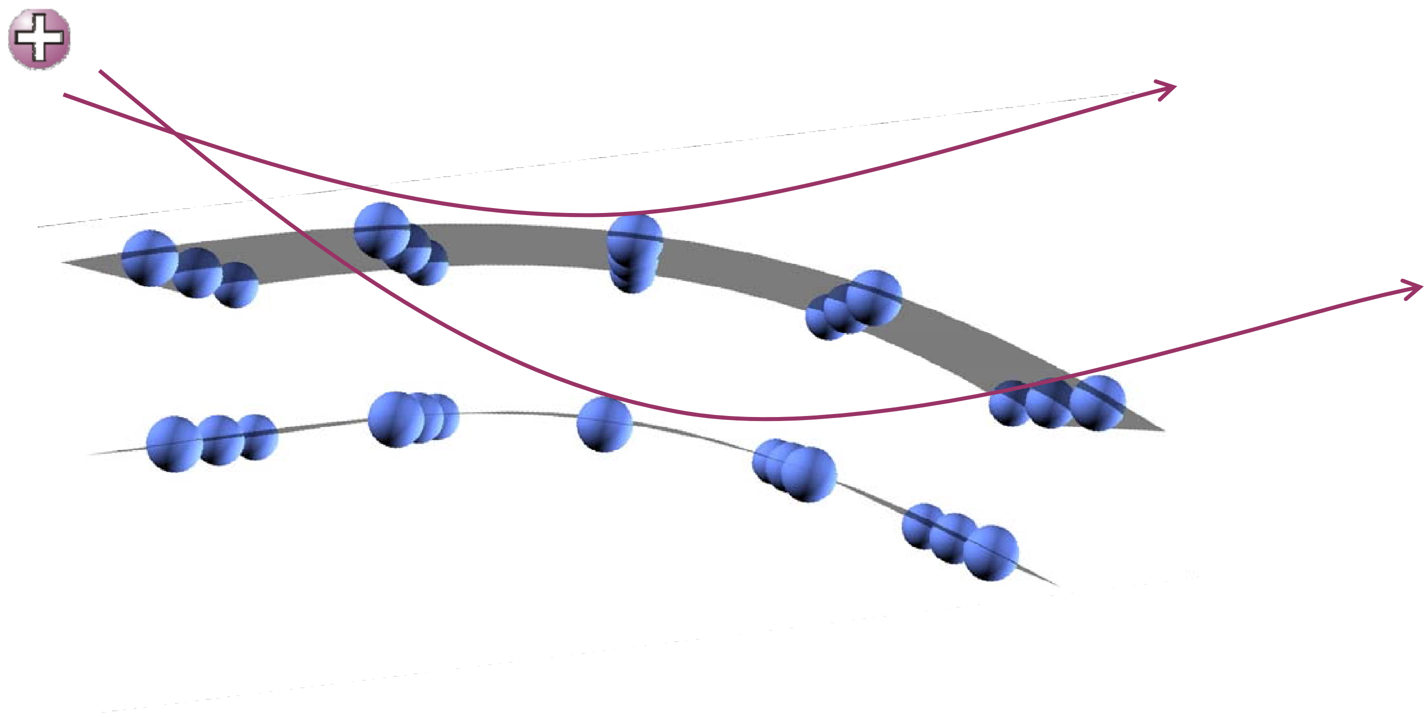


- Deflection of NEGATIVE particles by STRAIGHT crystal



Introduction (beam steering)

- Deflection of POSITIVE particles by BENT crystal using volume reflection



Motivation

To develop techniques of beam handling systems using crystals

- establishment of bent crystal systems for the proton beam separation
- getting basic understanding for the electron beams (not so well studied as in case of protons)

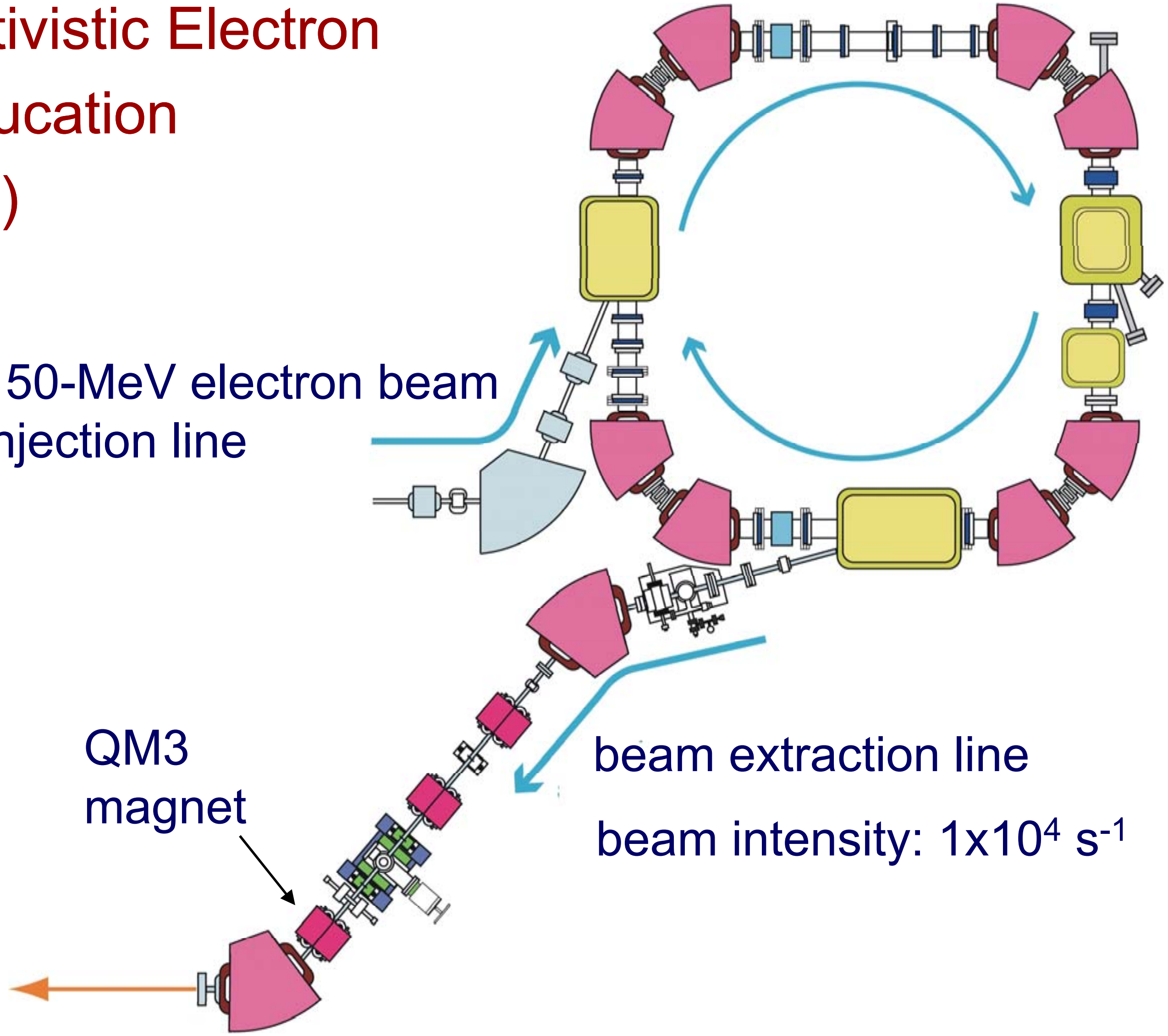
Future applications

- proton beam separation at J-PARC (Japan Proton Accelerator Research Complex)
- electron beam collimation at ILC (International Linear Collider)
- electron extraction system at the REFER ring (Relativistic Electron Facility for Education and Research) at HU

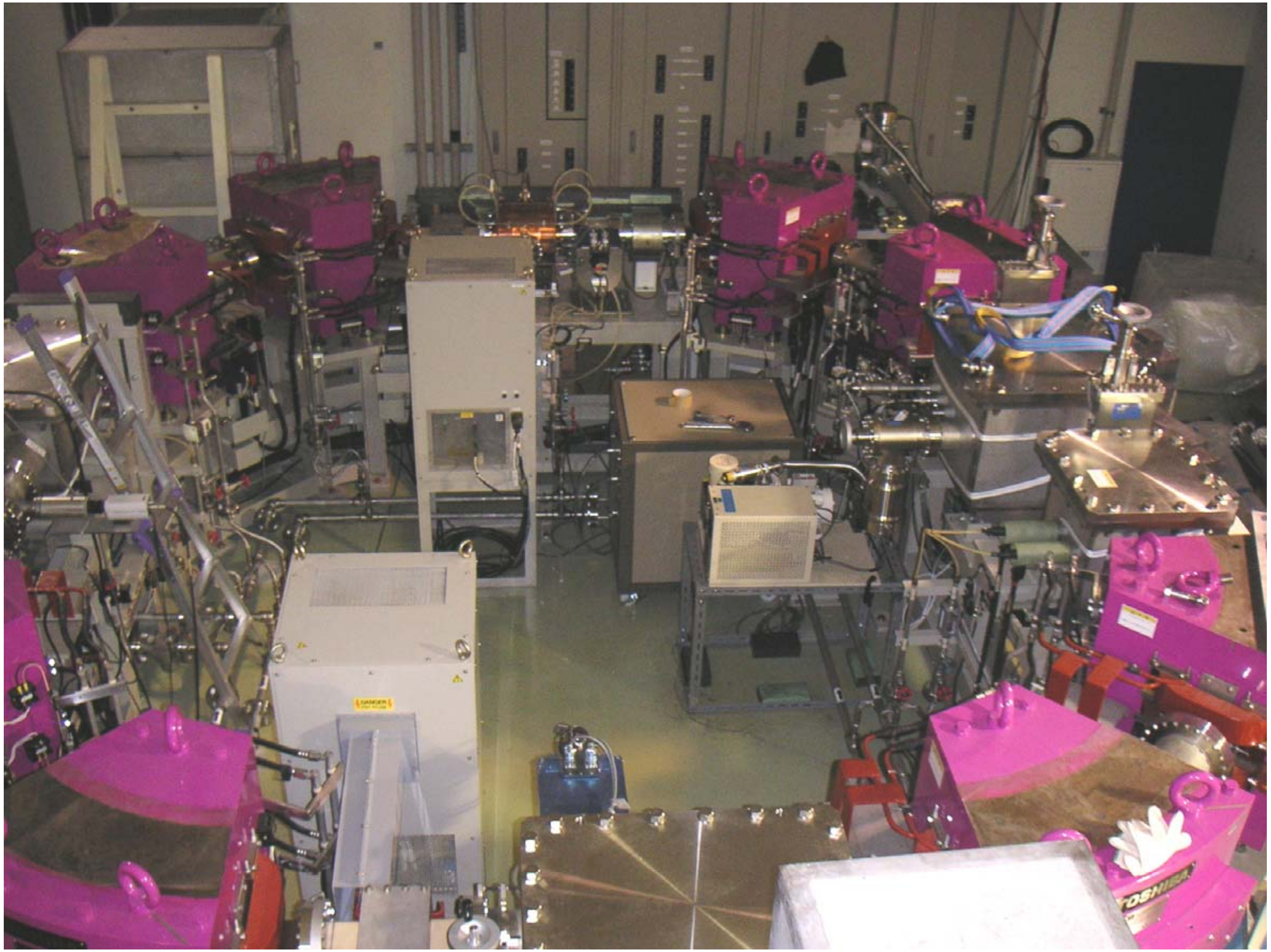
Experiment on electron beam deflection (REFER ring, Hiroshima University)

REFER ring @ Hiroshima University

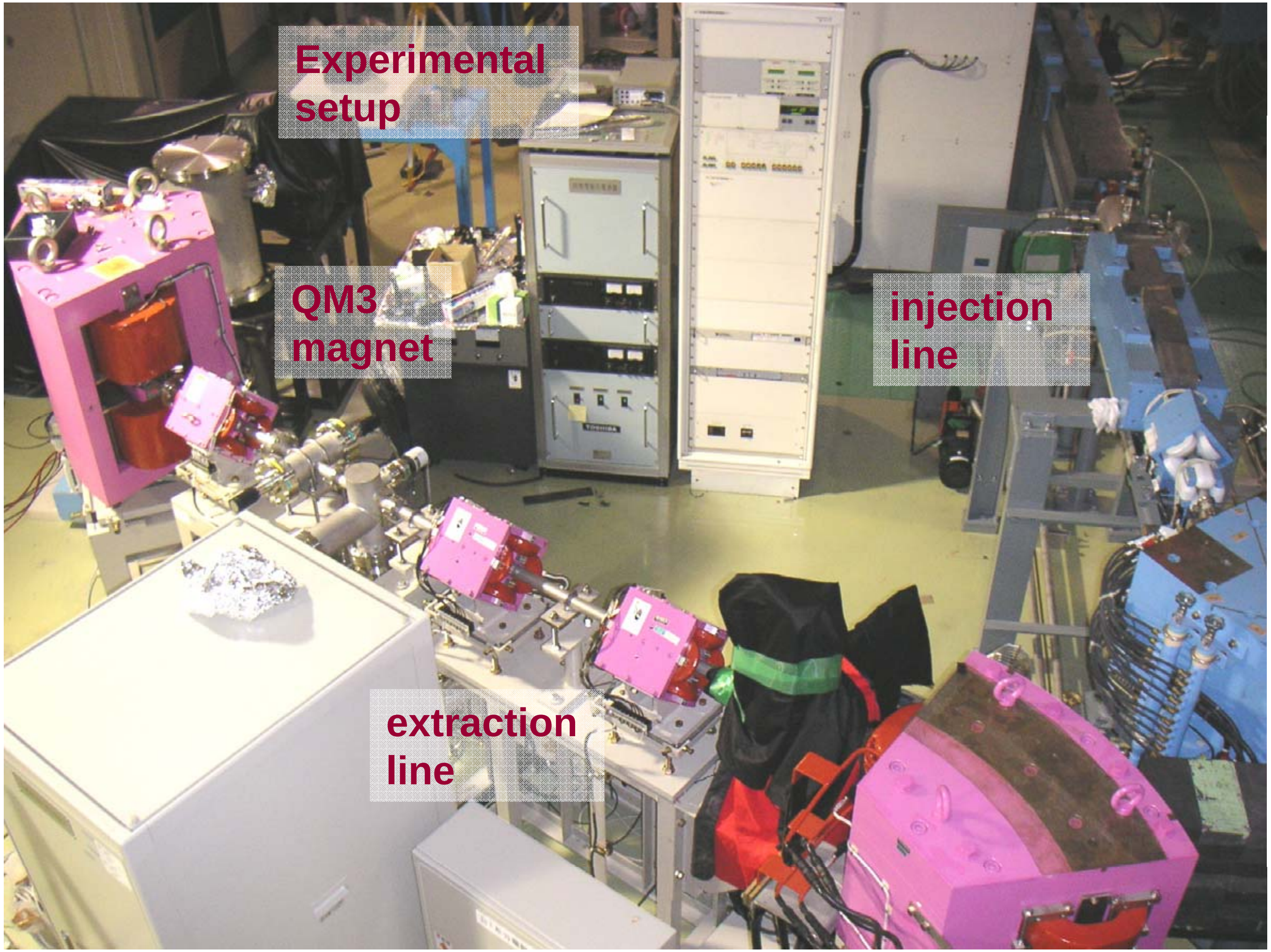
REFER (Relativistic Electron Facility for Education and Research)



REFER ring @ Hiroshima University

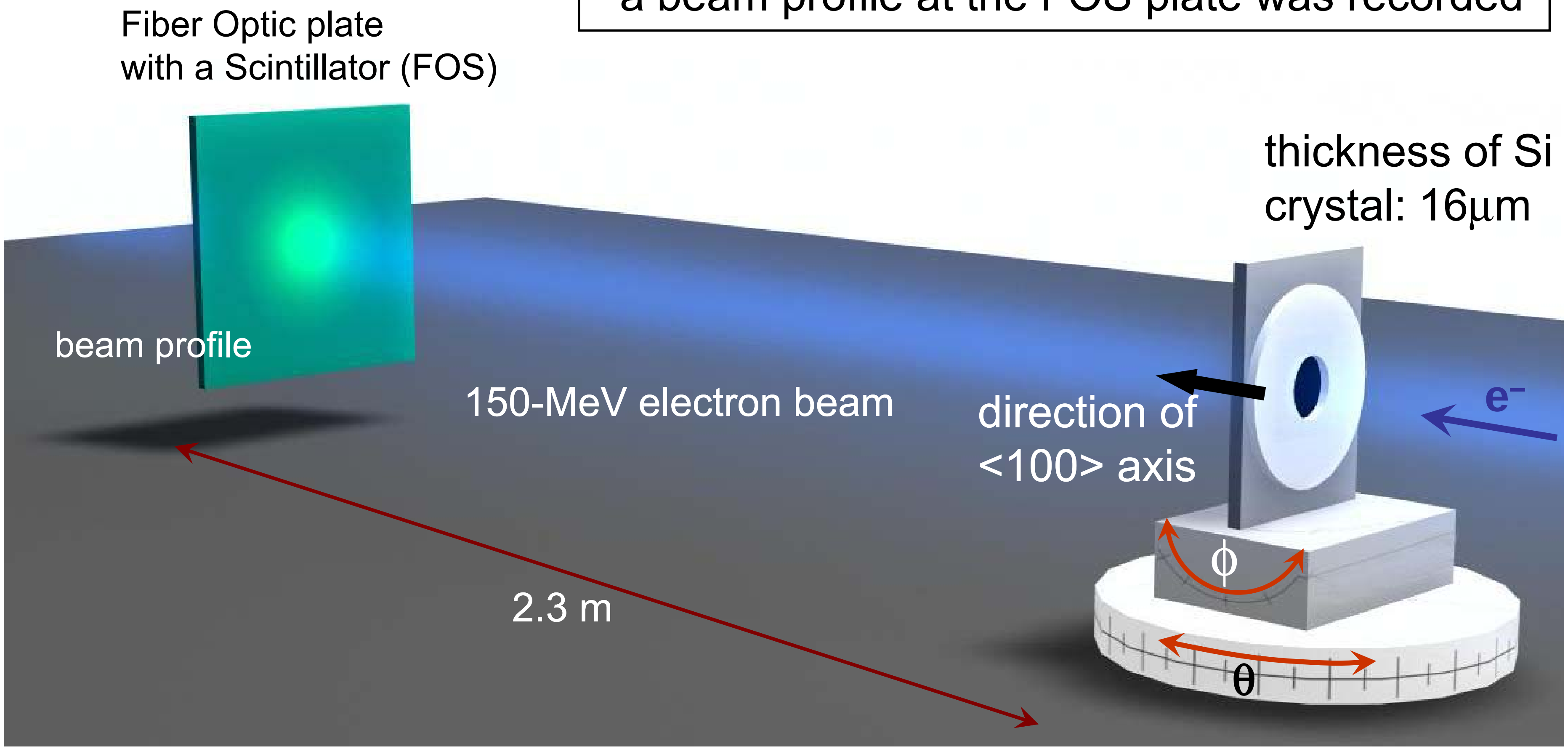


Extraction line

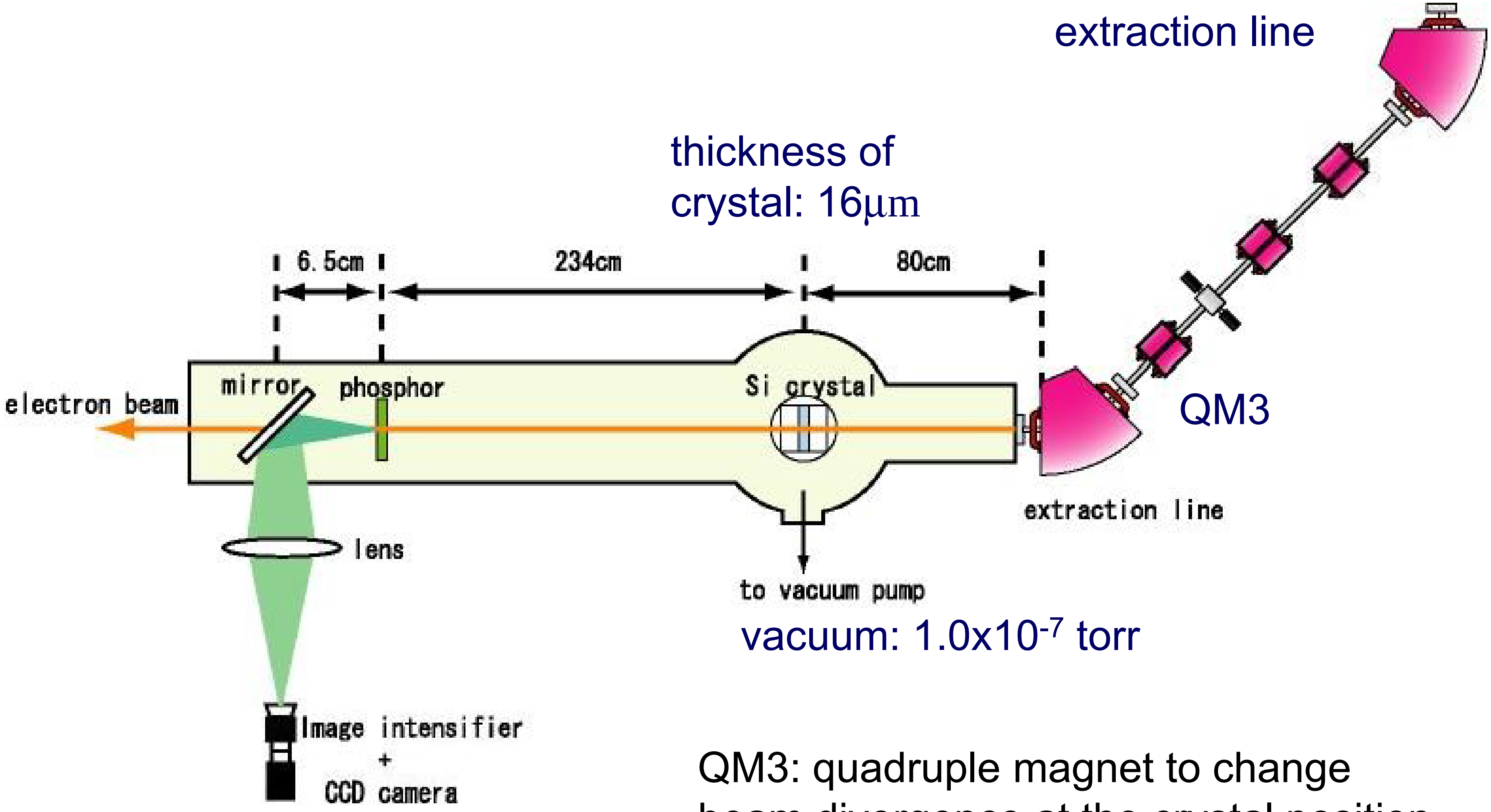


Schematic view of the setup

- the <100> axis was roughly aligned to the beam direction
- each combination of θ and ϕ angles and a beam profile at the FOS plate was recorded

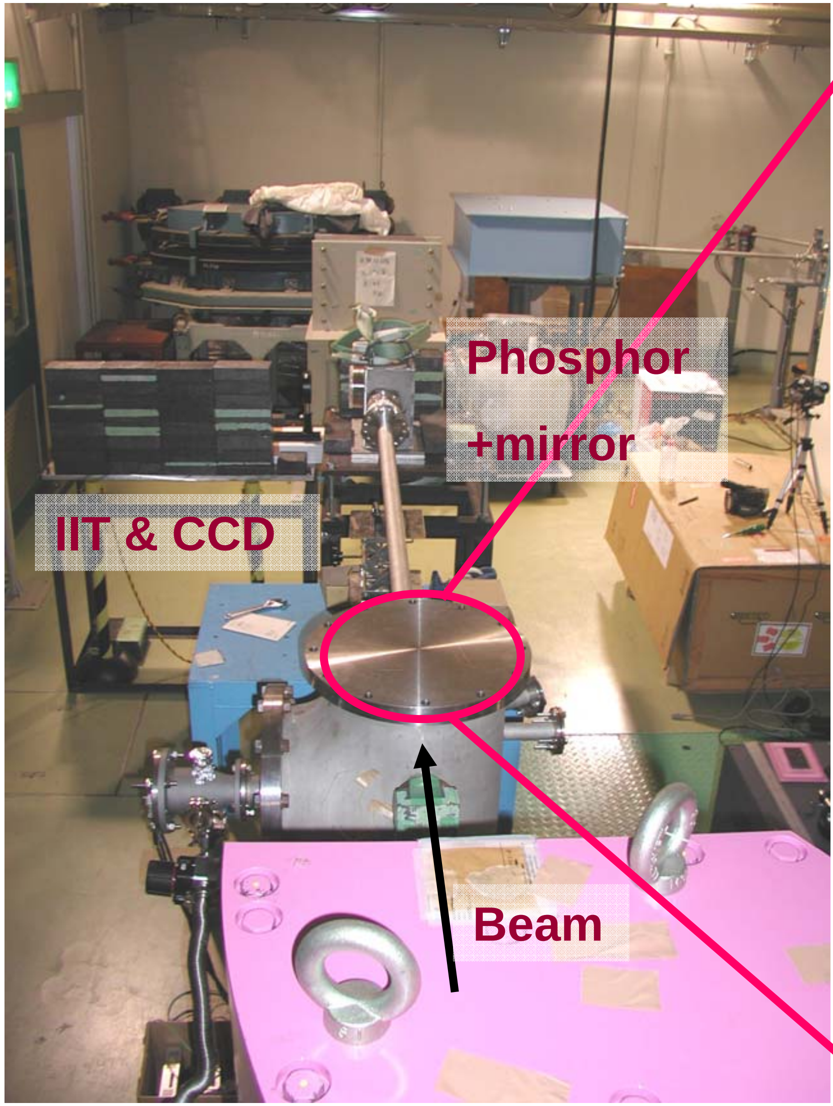


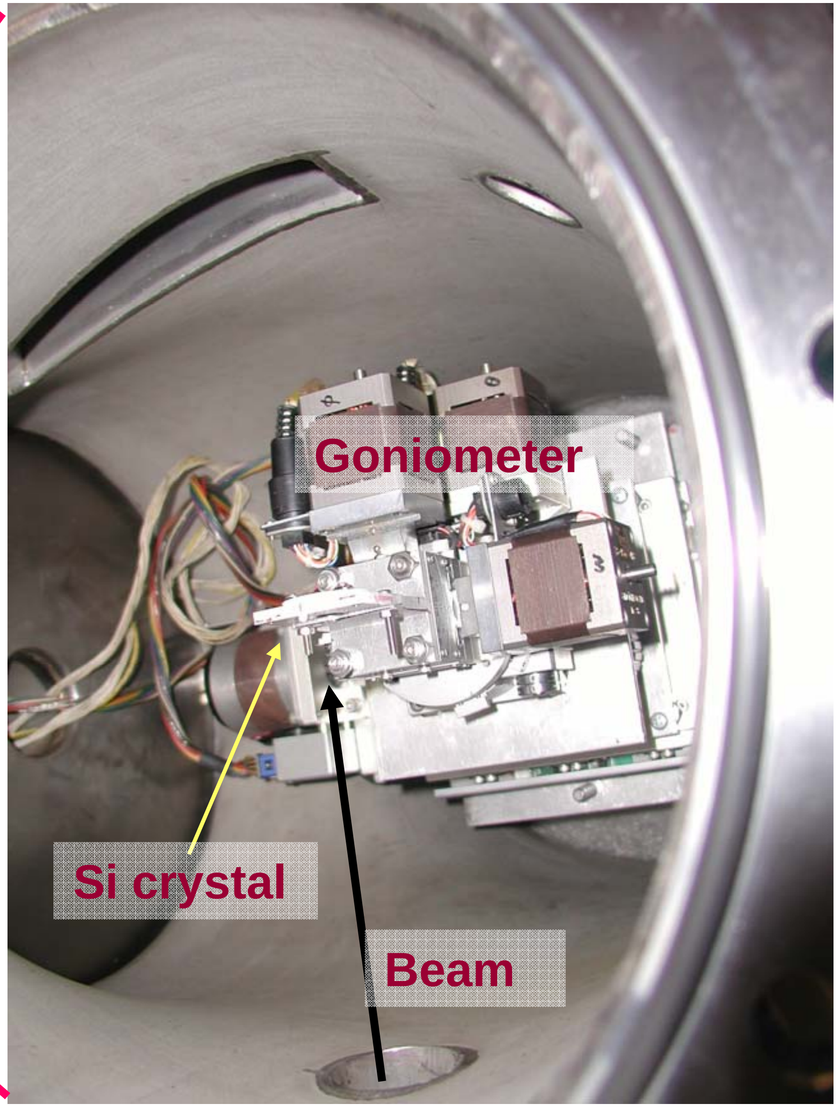
Experimental setup



QM3: quadruple magnet to change beam divergence at the crystal position

Setup

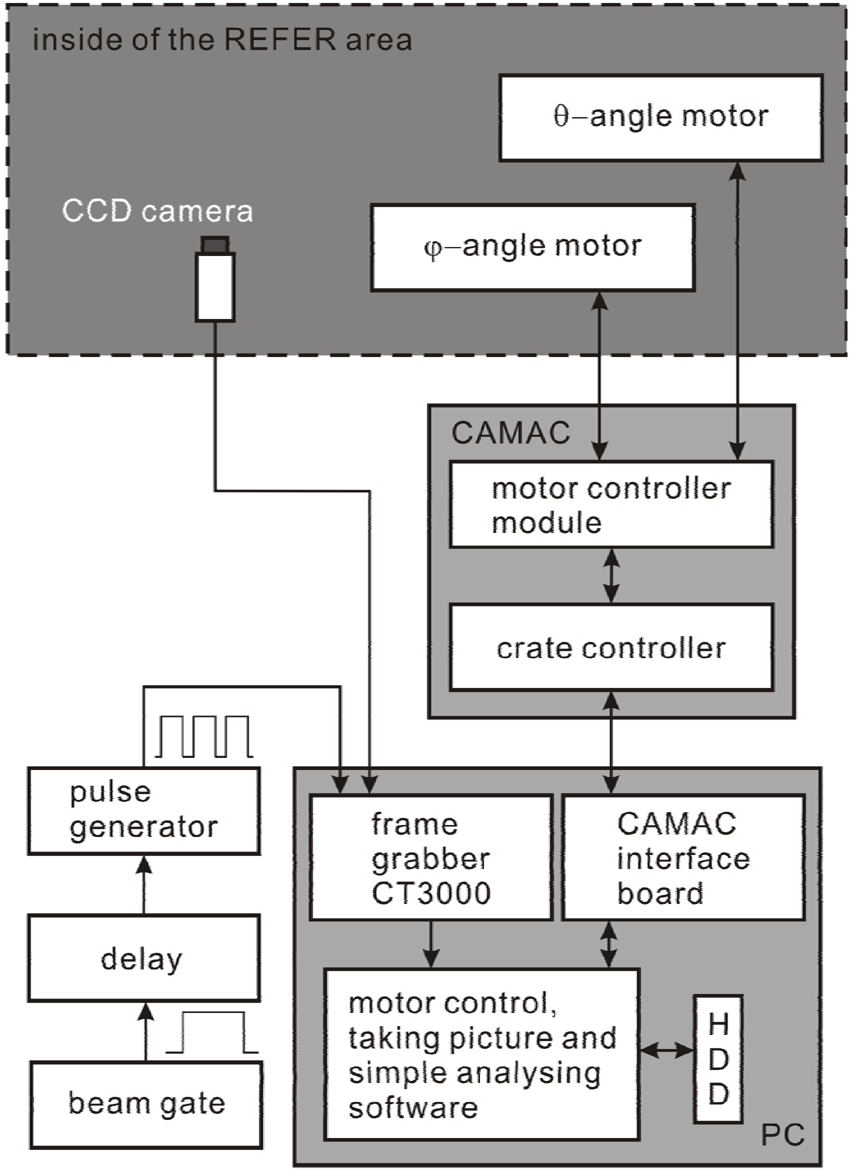




Data Acquisition system

The procedure of grabbing pictures and moving two goniometers was synchronized with the beam gate.

Pictures were taken only when electron beam hit the FOS plate.

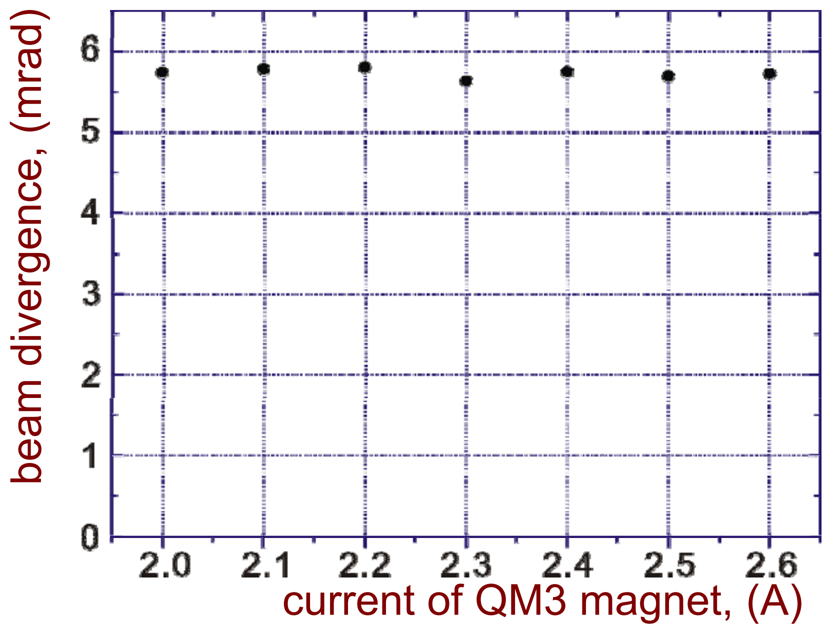


Experiment: beam divergence

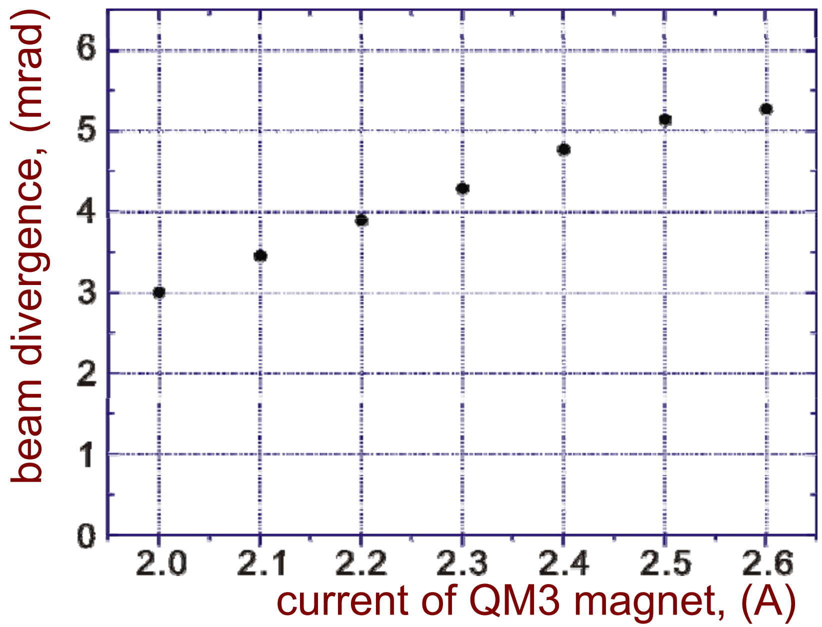
Beam divergence as a function of QM3 current

(it was estimated from the measurements and calculations of the optics of the beam line)

horizontal



vertical



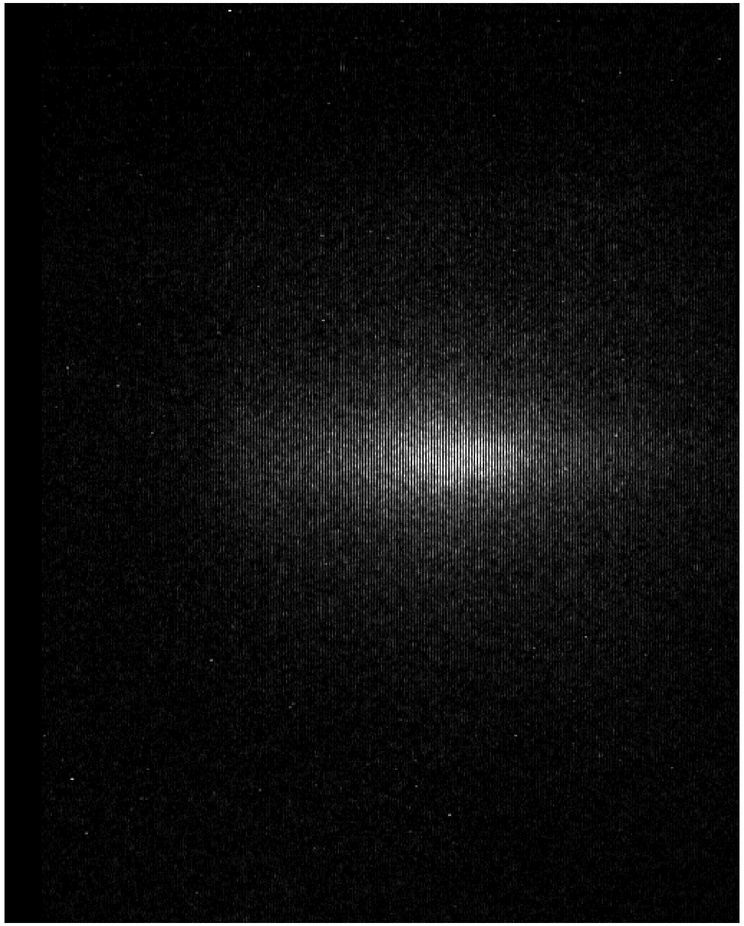
Vertical angle dependence of the profile is changing in a range from 2.0 A to 2.6 A

Lindhard angle for <100> axis of Si crystal: 0.7 mrad

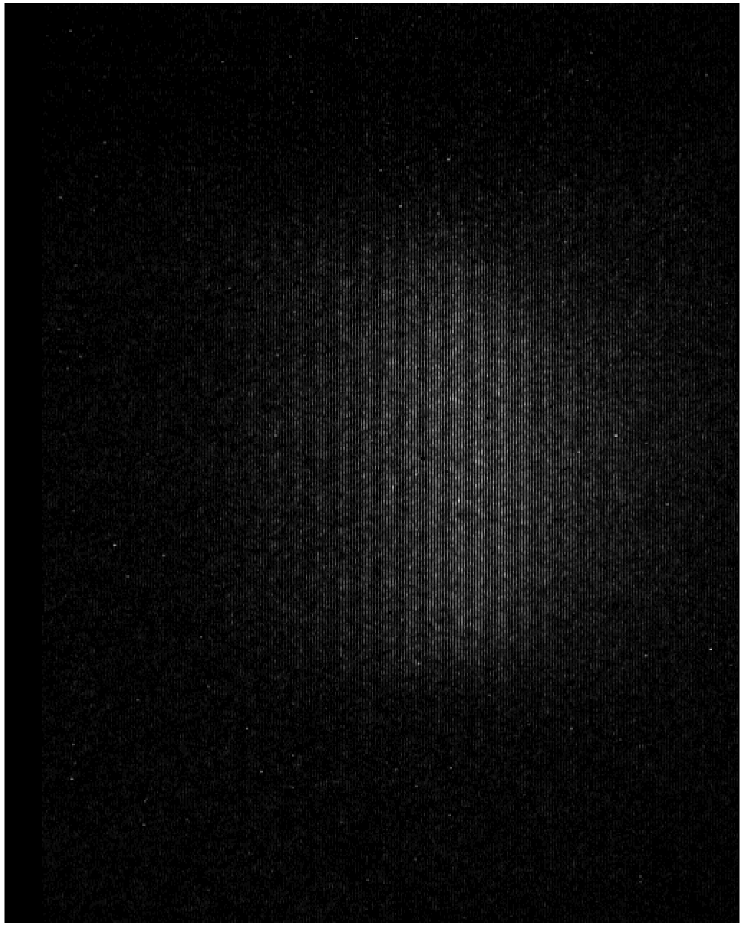
Beam divergence > Lindhard angle

Beam profiles

QM3: 2.0 A, θ = 0, ϕ = -1.5 mrad
Beam divergence: 3.0 mrad



QM3: 2.6 A, θ = 0, ϕ = -1.5 mrad
Beam divergence: 5.2 mrad

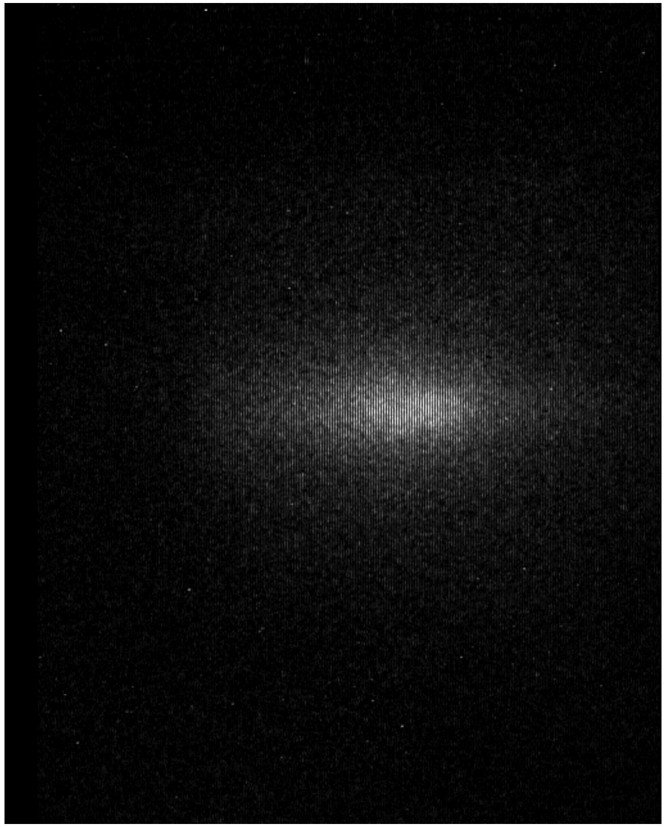


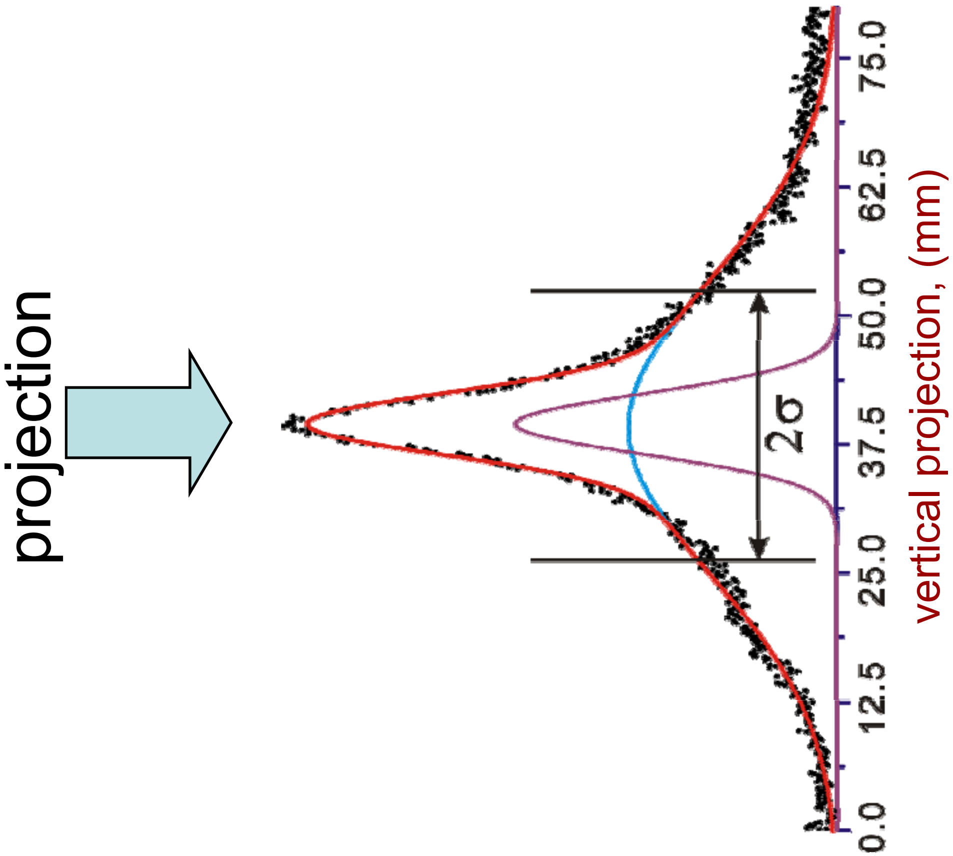
Analysis

Vertical beam divergence: 3.0 mrad

QM3: 2.0 A

Projected beam profile
was fitted with double Gaussian



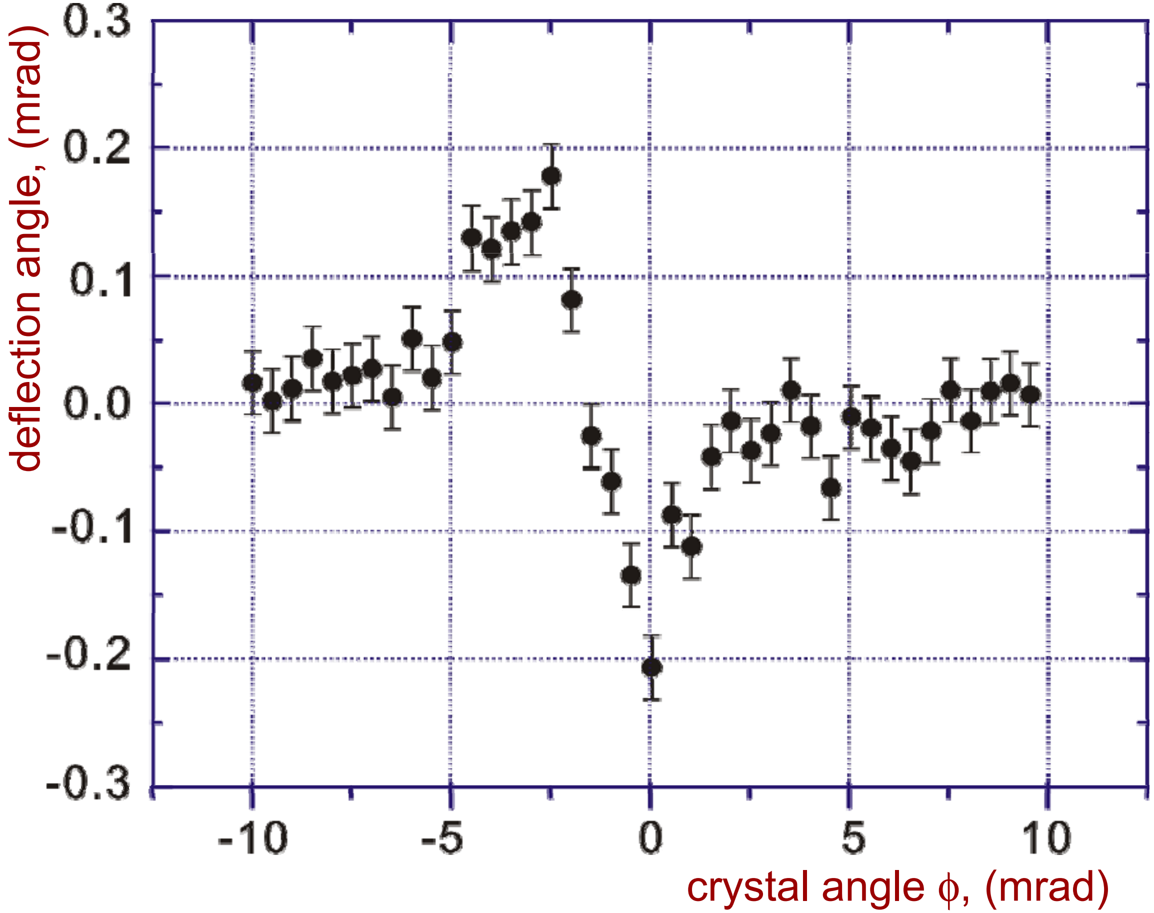


Beam center was determined as
the weighted average in 2σ region

Results (1)

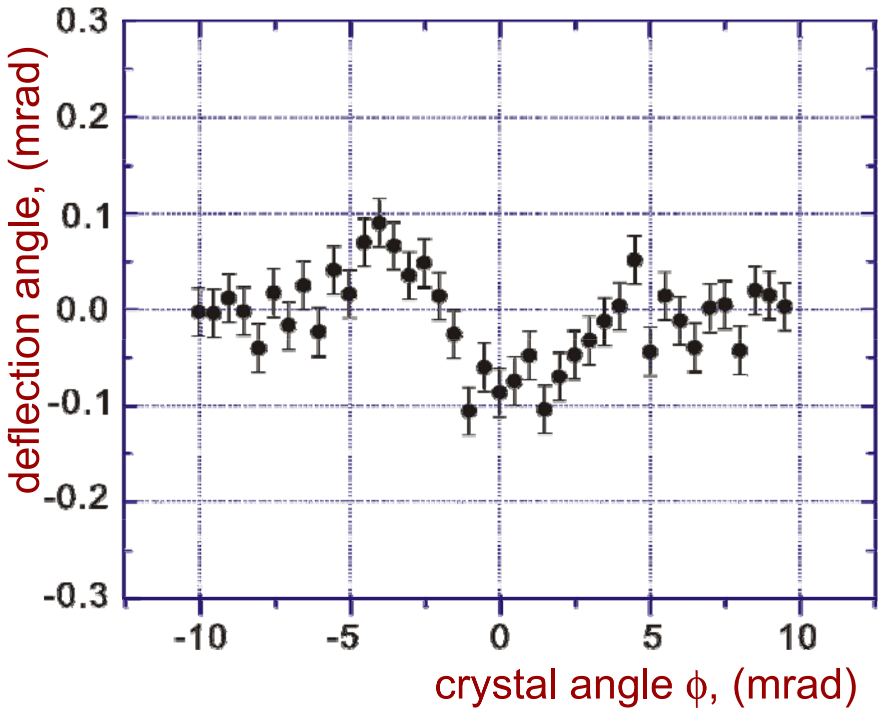
Deflection angle = change of the beam center + 2.34 m

Vertical beam divergence: 3.0 mrad θ=0 mrad (QM3: 2.0 A)

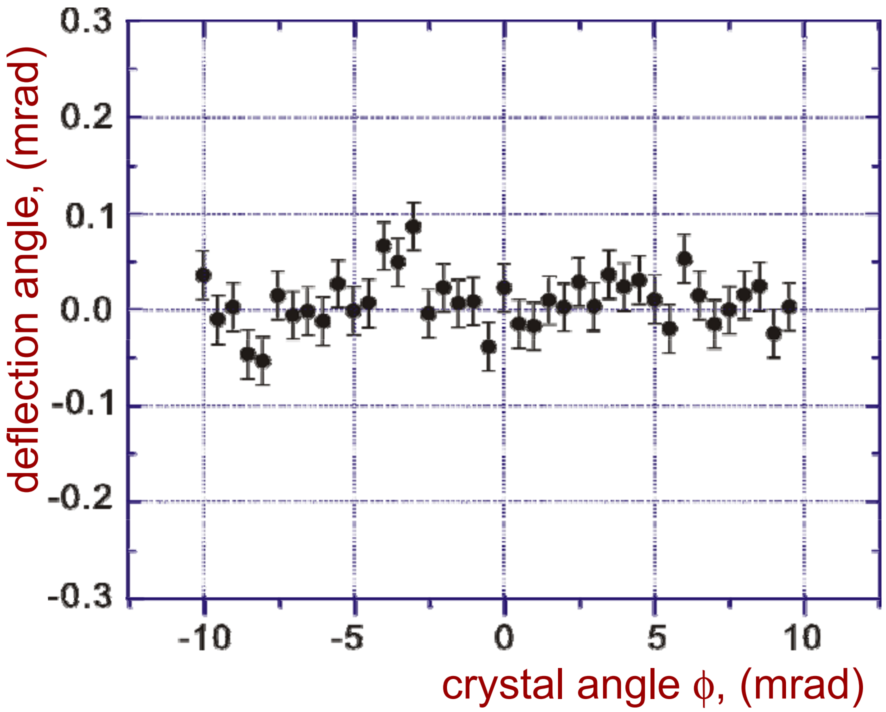


Results (2)

Vertical beam divergence:
3.8 mrad (QM3: 2.2 A).
θ = 0 mrad

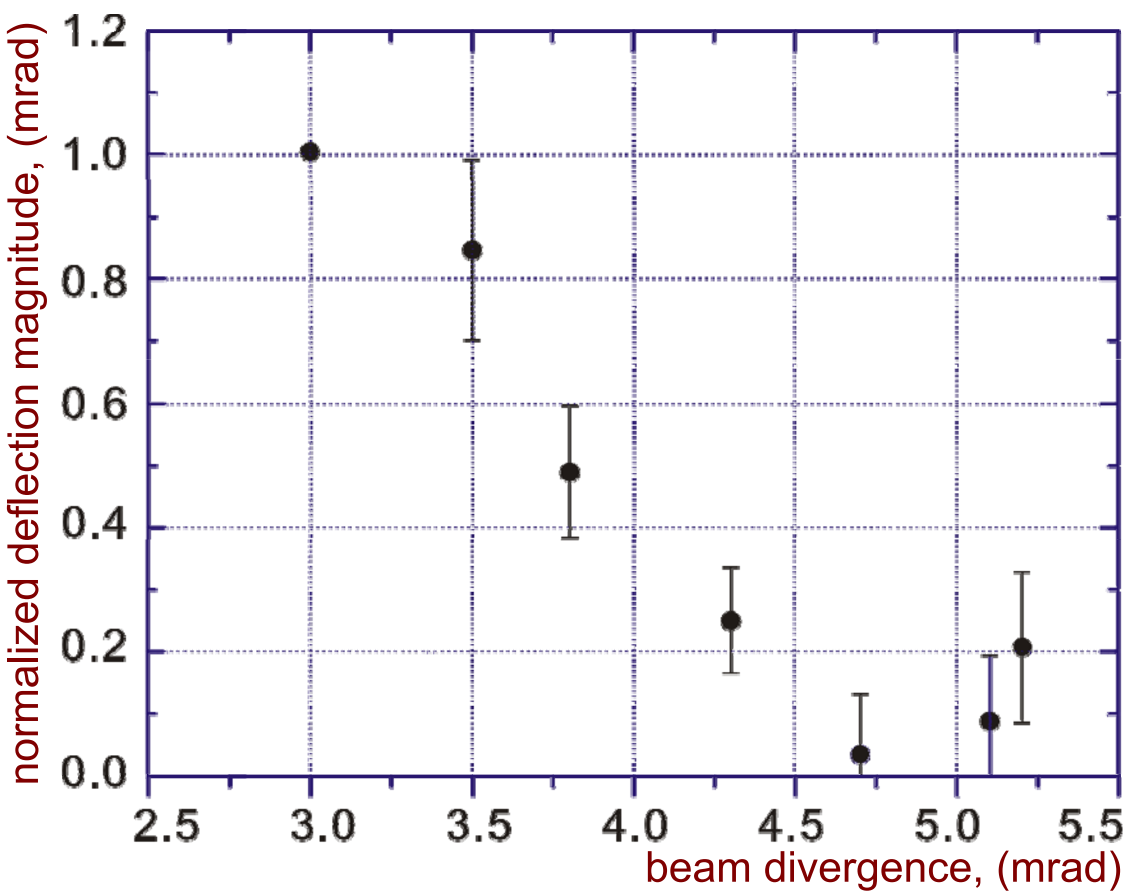


Vertical beam divergence:
5.2 mrad (QM3: 2.6 A).
θ = 0 mrad

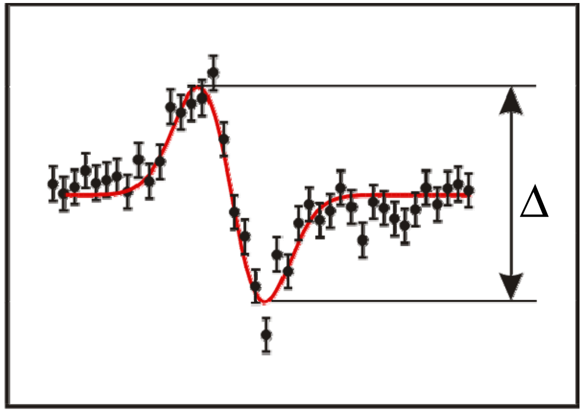


Results (3)

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

$$U_{ax}(\rho) = \frac{2Z_1 Z_2 e^2}{d} \ln\left[1 + \left(C\,\frac{a}{\rho}\right)^2\right]^{1/2}$$

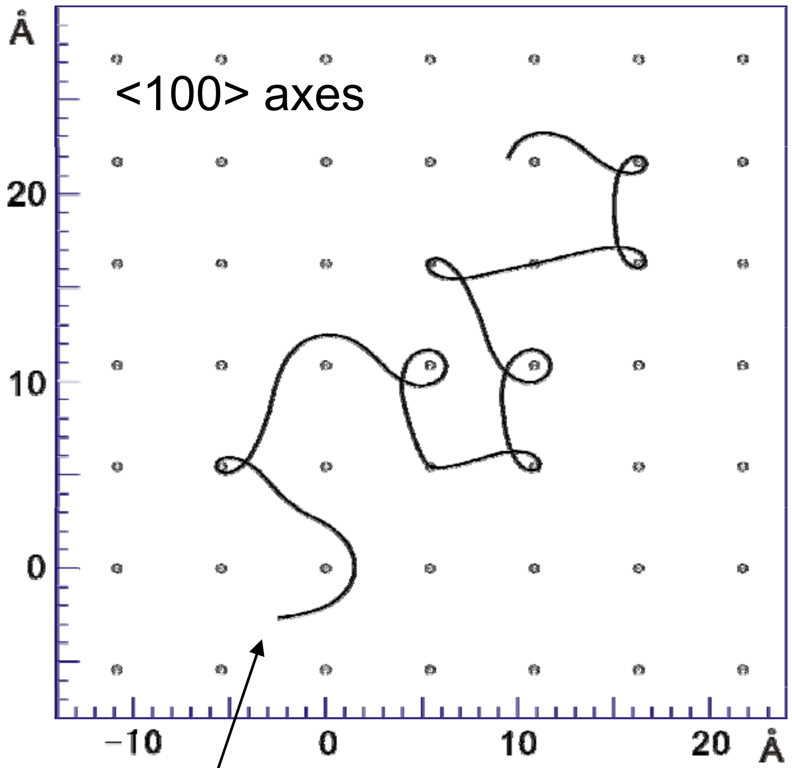
a – Thomas-Fermi radius
ρ – distance from <100> axis
d – lattice constant, it is 5.43 A for Si
$Z_1 e$ – charge of incident particle
Z_2 – atomic number, 14 for Si
C – Lindhard constant Sqrt[3]

Conditions for simulation

- 4th order of Runge-Kutta method
- Without consideration of single and multiple scattering, channeling radiation and crystal imperfection
- To save a computational time the incident angles of particles was limited to the twice of the Lindhard angle
- Energy of electrons: 150 MeV
- Thickness of the crystal: 16 μm

Simulation: trajectory

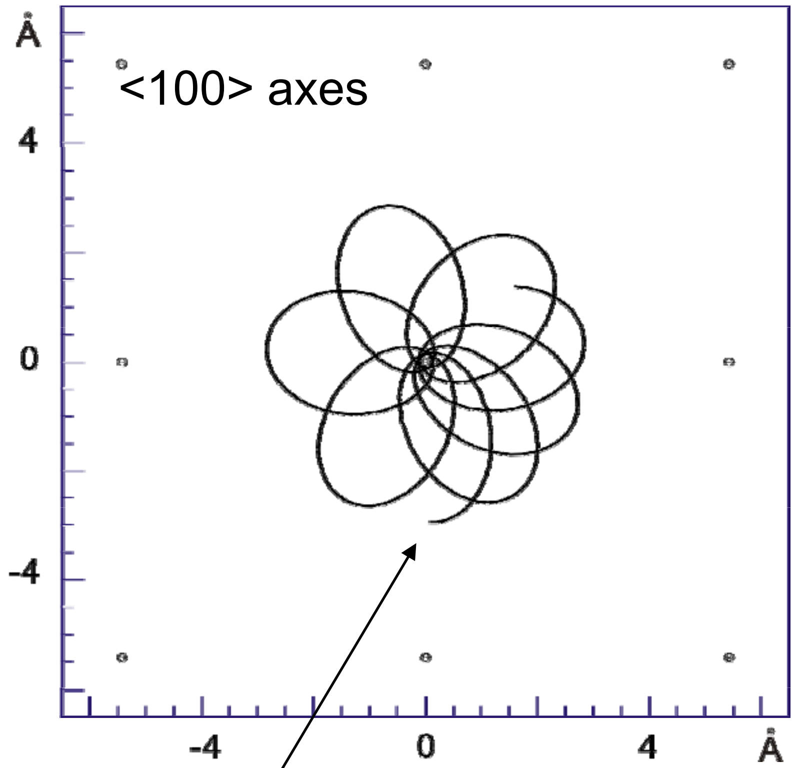
Trajectory of the 150-MeV electrons inside of the Si crystal



Initial position : X=-2.5Å,Y=-2.5Å

X direction = 0.1 mrad

Y direction = 0.01 mrad



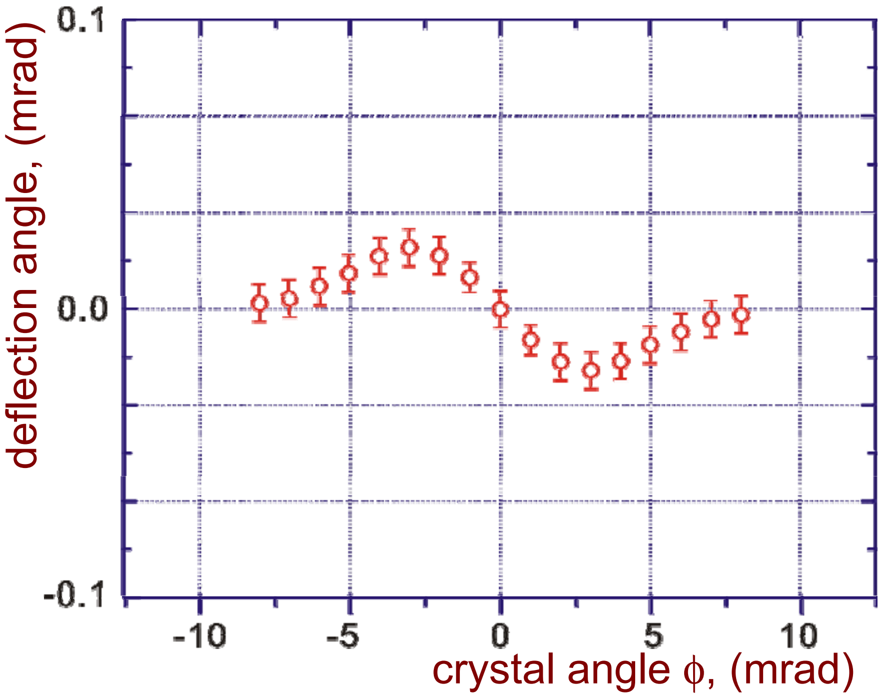
Initial position : X=0Å,Y=-2.5Å

X direction = 0.095 mrad

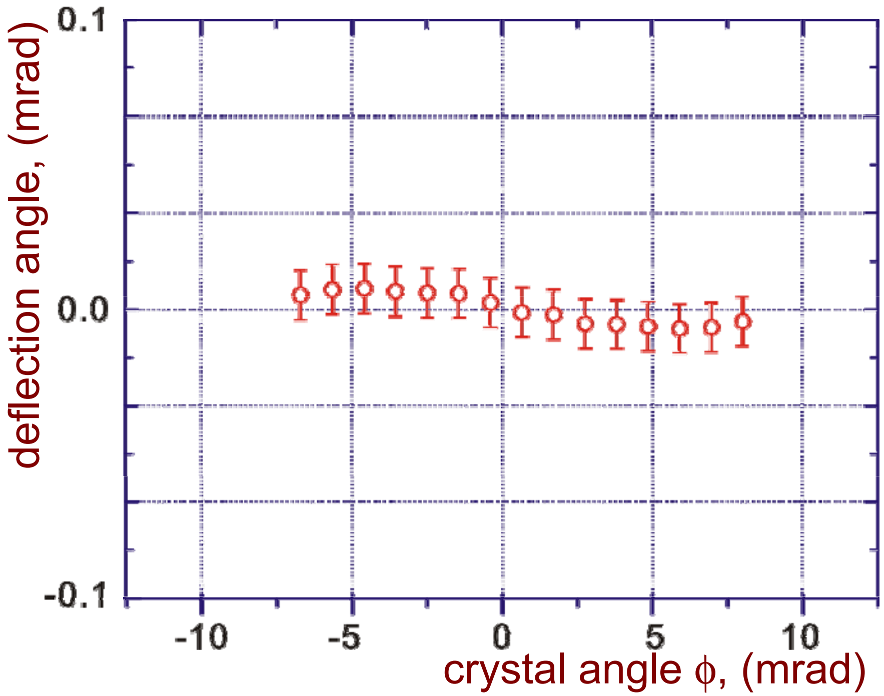
Y direction = 0.09 mrad

Simulation (1)

Beam divergence: 3.0 mrad



Beam divergence: 5.2 mrad

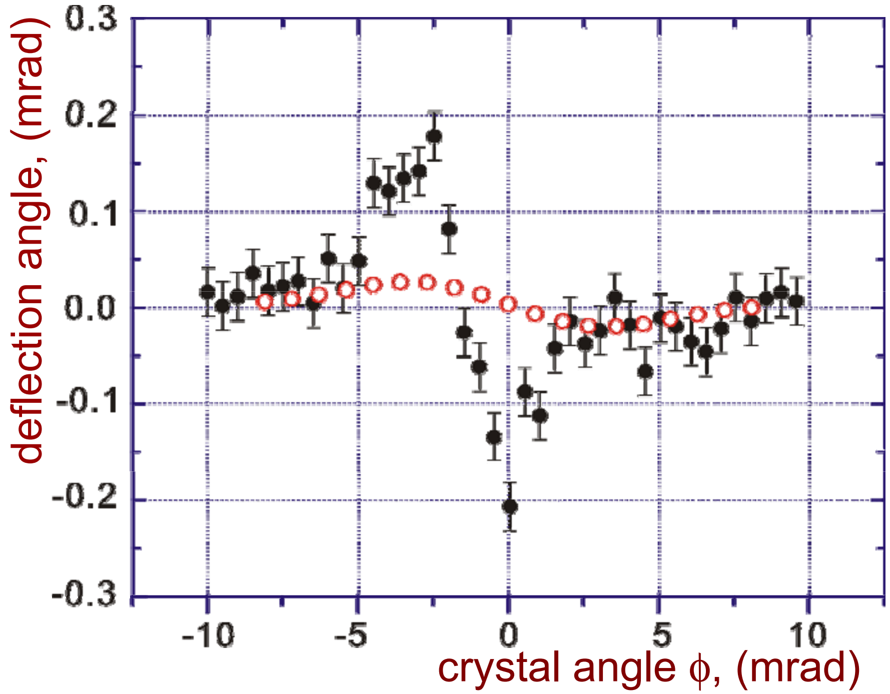


Larger beam divergence → Smaller deflection

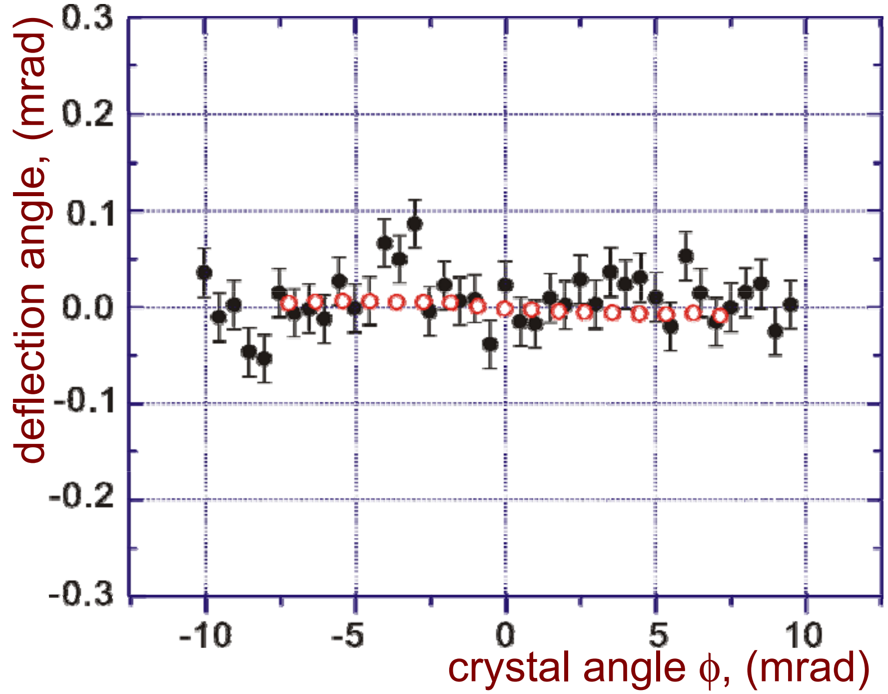
Simulation (2)

Comparison with experimental data

Beam divergence: 3.0 mrad



Beam divergence: 5.2 mrad



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 mrad, while it's around 0.04 mrad for the simulation.

Simulation (3)

The possible reason of quantitative difference is that in reality the electrons which travel in the crystal with angles more than Lindhard angle can also be trapped by the potential of the crystal, while the simulation cannot take into account the processes for particles with the large beam divergence.

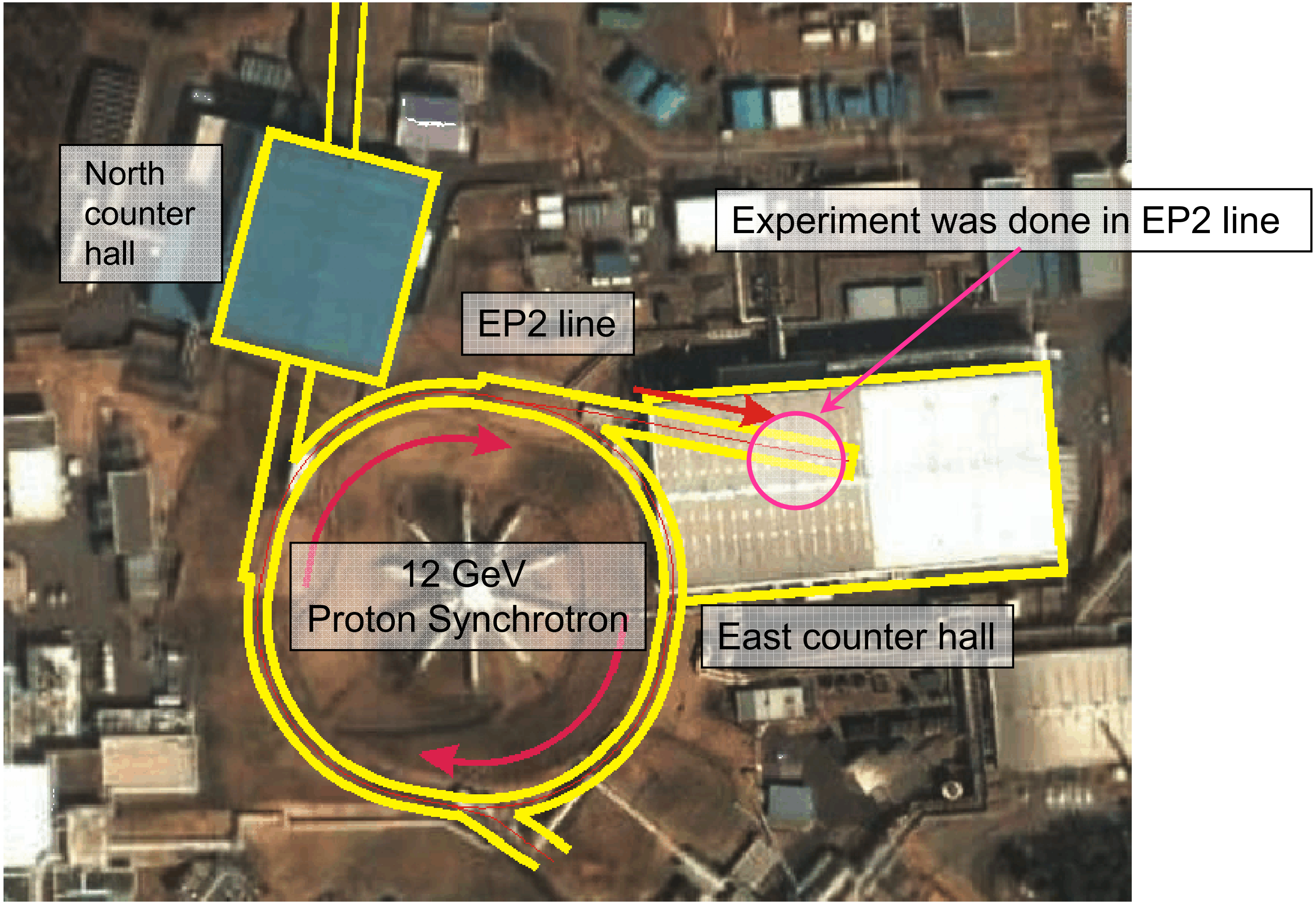
Simulation which includes all physical processes should be performed.

Summary on REFER experiment

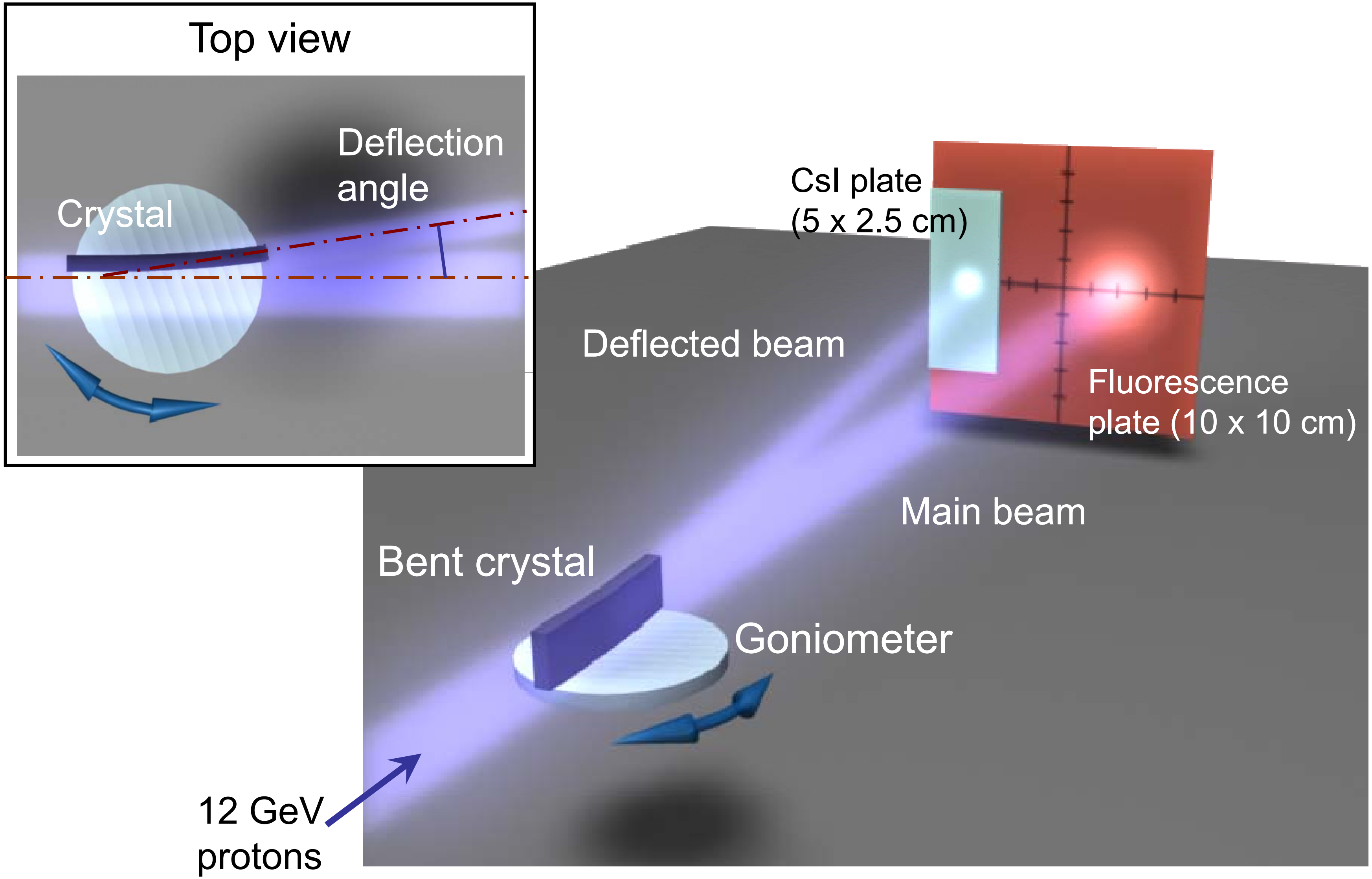
- Deflected 150-MeV electron beam by using <100> axis was clearly detected in this experiment.
- It showed clear evidence of ability to use crystals for handling negatively charged particles.
- The beam deflection as a function of the beam divergence was systematically investigated. Such technique can be used to determine the beam divergence.
- Simulation of this experiment was performed as well. Comparison of the experimental data with simulation showed:
  - qualitative agreements
  - quantitative comparison showed difference – additional simulation which includes all physical processes should be done.

Experiment on proton beam deflection
(Proton Synchrotron, KEK)

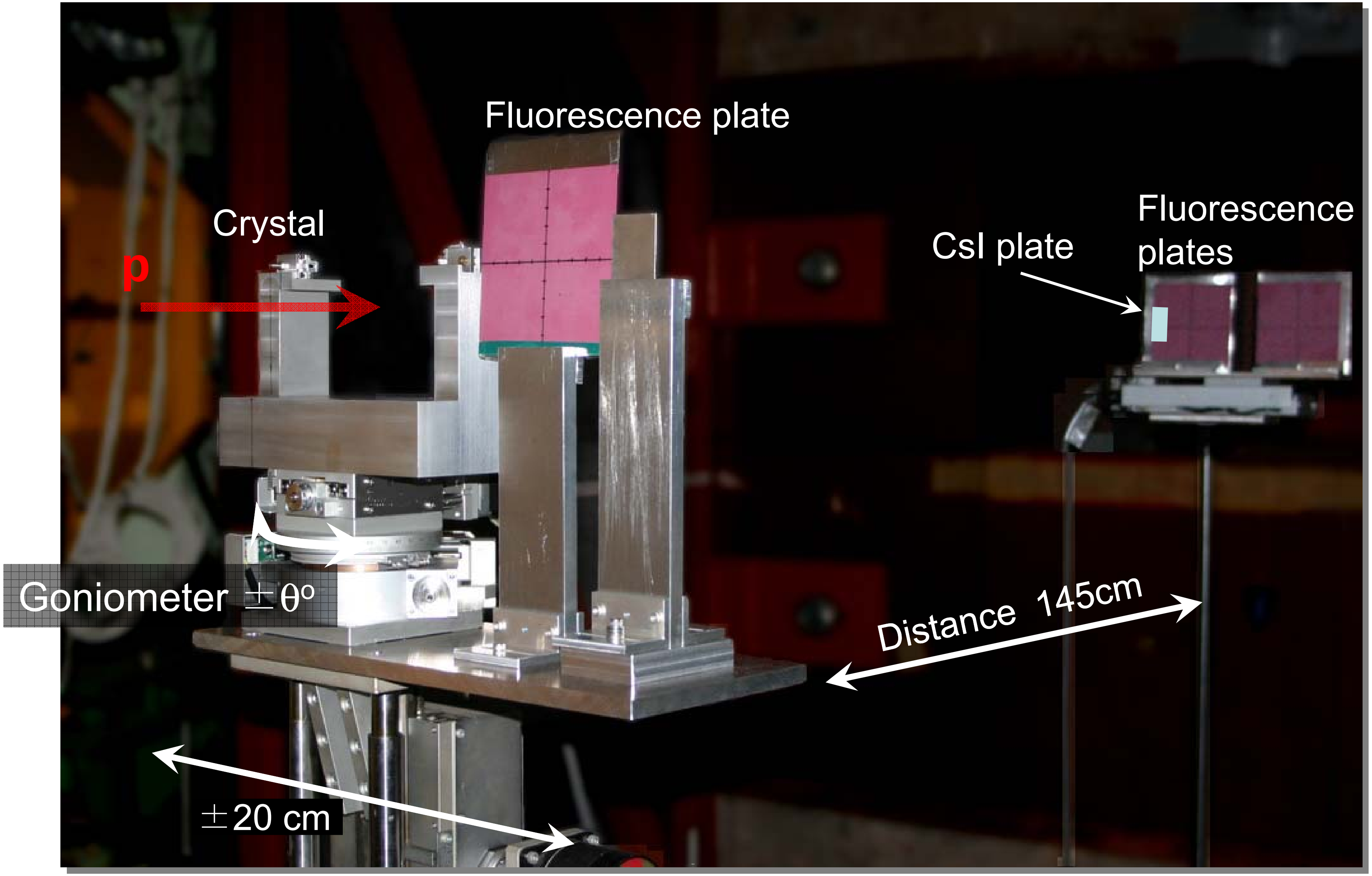
Experiment at KEK-PS



Schematic drawing of the experiment



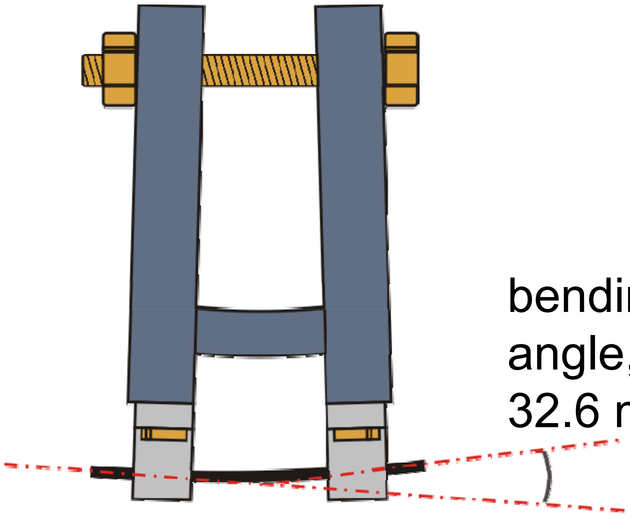
Experimental setup



Crystal, proton beam

Parameters of crystal

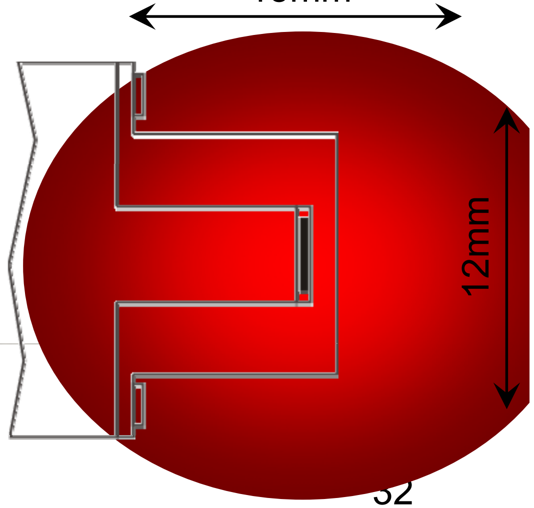
Material:	Silicon
Size:	3 x 0.3 x 10 mm
Bending angle:	~ 32.6 mrad
Plane:	(111)
Lindhard angle:	0.051 mrad



bending angle, 32.6 mrad

Parameters of the proton beam

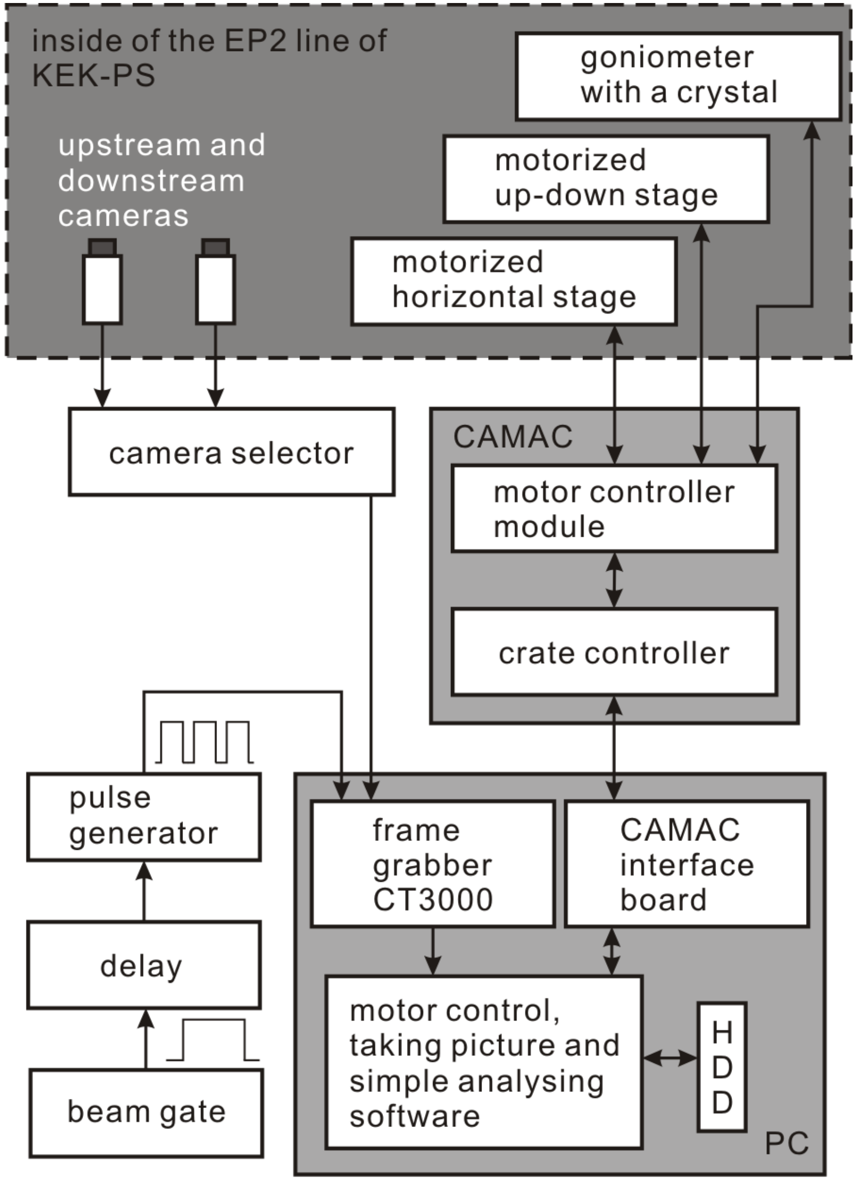
Energy:	12 GeV
Intensity:	10^{12} protons/spill
Size:	15 x 12 mm
Divergence:	< 5 mrad



Data Acquisition system

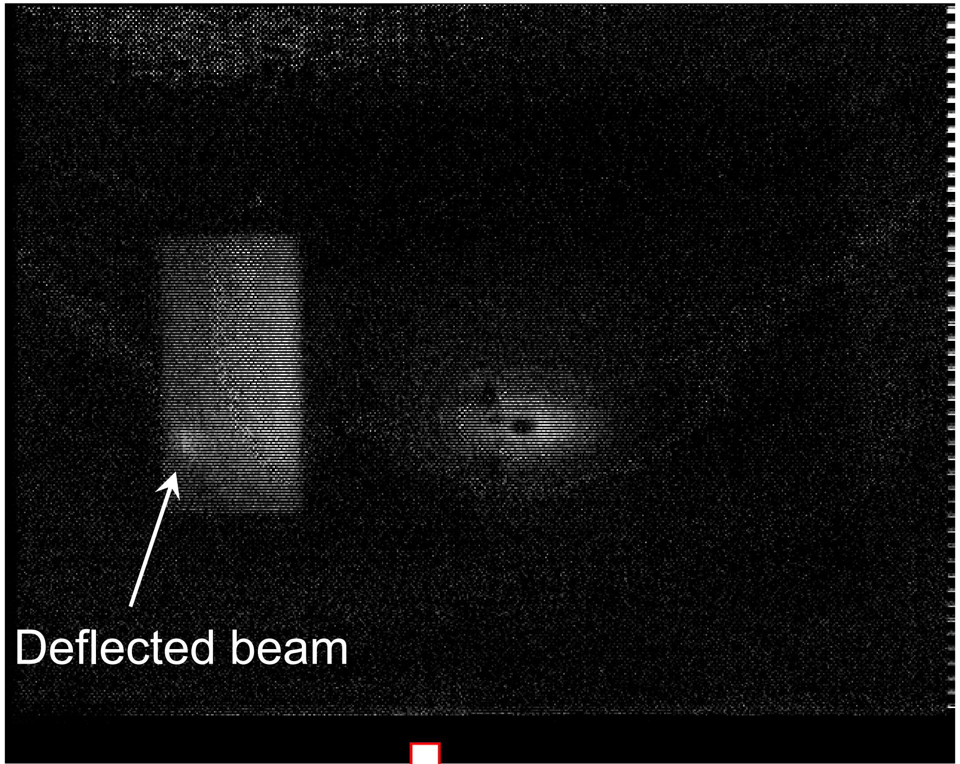
The procedure of grabbing pictures and movement of goniometers was synchronized with the beam gate.

Pictures were taken only when electron beam hit the Fluorescent plate.

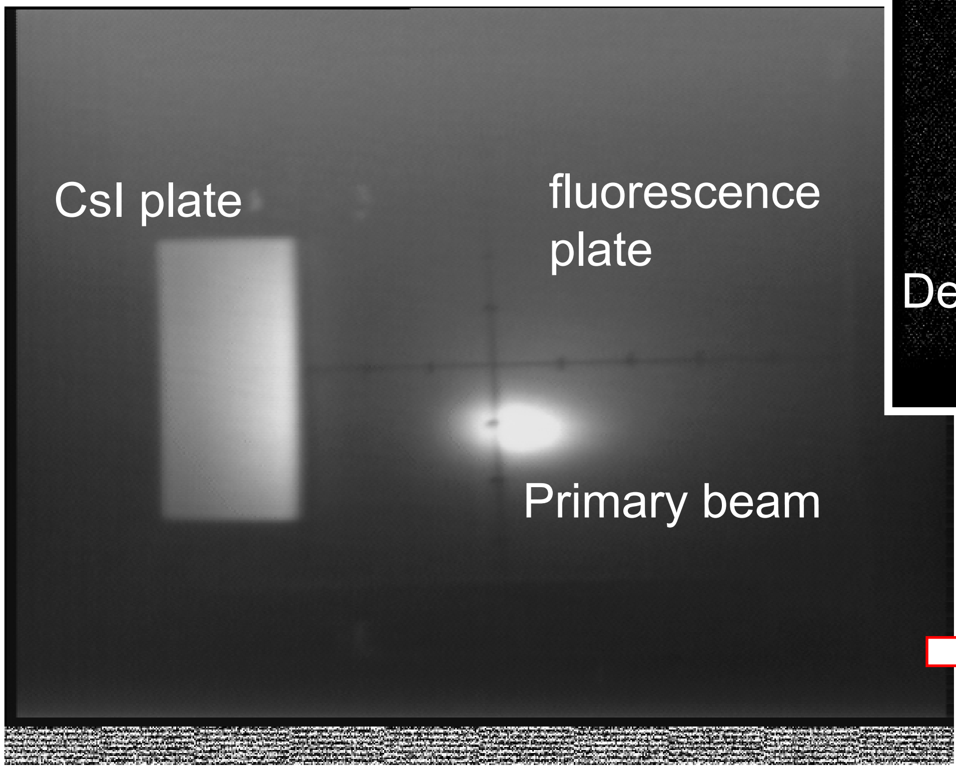


Typical pictures

image after
background subtraction

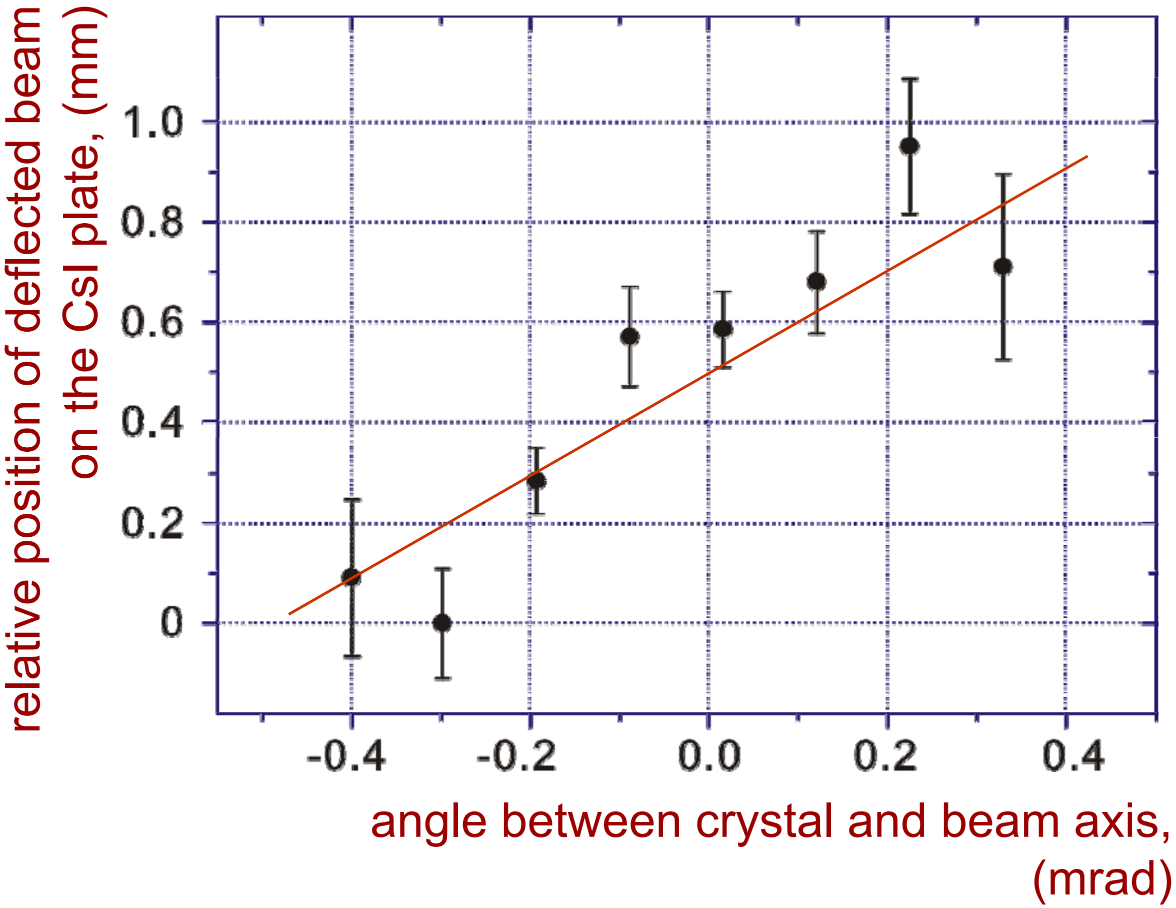


raw image



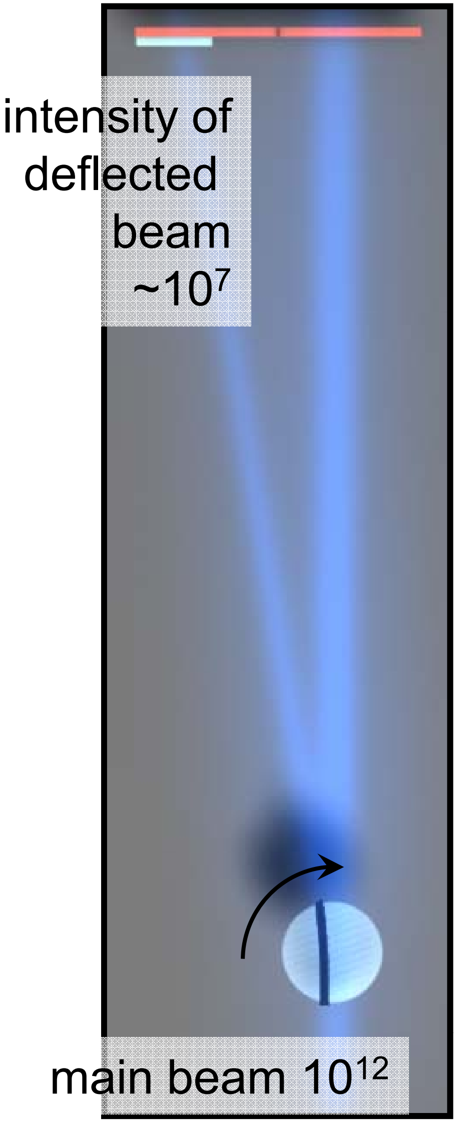
- intensity of deflected beam
- bending angle
- crystal efficiency

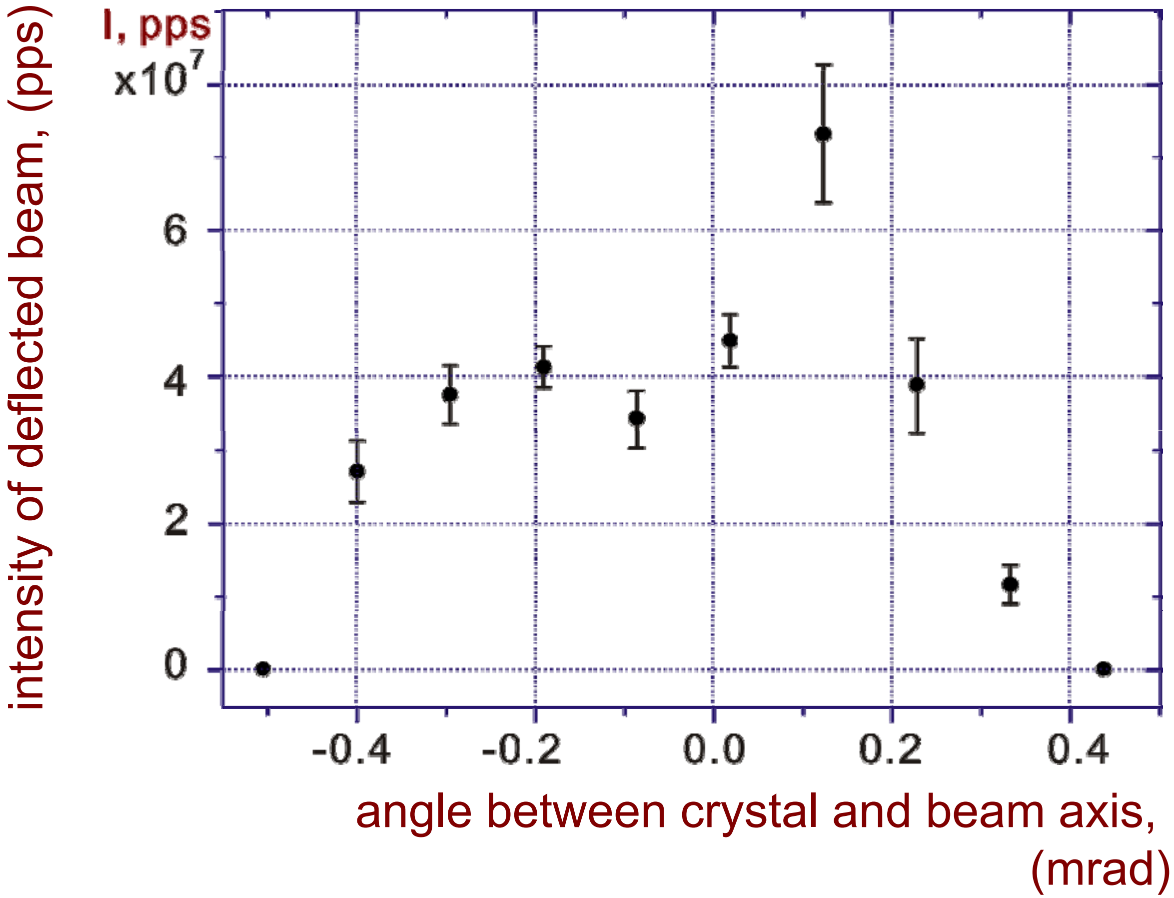
Results (1)



dependence agreed with the estimations

Results (2)





10^{12} pps → ~ 10^7 pps of deflected beam

Theoretical crystal efficiency

To understand the results of the experiment, the crystal efficiency was calculated

$$Crystal\ efficiency = A_S A_B \exp\left[-\frac{L_{crystal}}{L_d^{bent}}\right]$$

A_S – probability of the particle being captured into the channelling mode for the straight crystal

A_B – reduction factor in case of bent crystal

$L_{crystal}$ – length of the crystal

L_d^{bent} – dechanneling length for the bent crystal

$$L_d = \frac{256}{9\pi^2} \frac{E\beta^2}{\ln\left[2m_e c^2\gamma/I\right] - 1} \frac{a d_p}{Z_1 r_e m_e c^2},$$

$$L_d^{bent} = L_d \left(1 - \frac{R_c}{R}\right)^2,$$

I – ionization potential

γ – Lorentz factor

R_c – critical radius

R – radius of the bent crystal

β – velocity of the particle in terms of the speed of light

Theoretical crystal efficiency is 21%

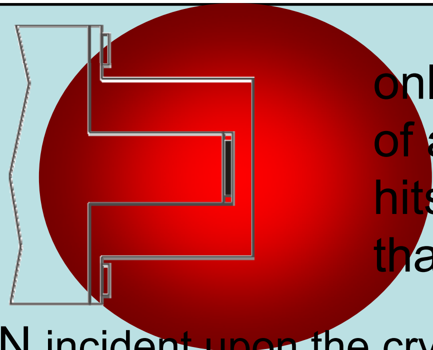
Experimental crystal efficiency

N deflected = <u>Crystal Efficiency</u> x

Angular Efficiency x

N incident upon the crystal.

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



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

N incident upon the crystal = $3x10^{9}$

N deflected includes unknown difference of response between the CsI and fluorescence plates = X $4x10^{7}$ pps (?)

Beam divergence and normalization factor are needed to be known to find Crystal Efficiency

Simulation: CATCH code

The CATCH code is widely used for the tracking of positive particles through the crystal.

Lindhard planar continuous potential

$$U_{pl}(\rho) = 2\pi N d_{pl} Z_1 Z_2 e^2 \left[\sqrt{\rho^2 + C^2 a^2} - \rho\right]$$

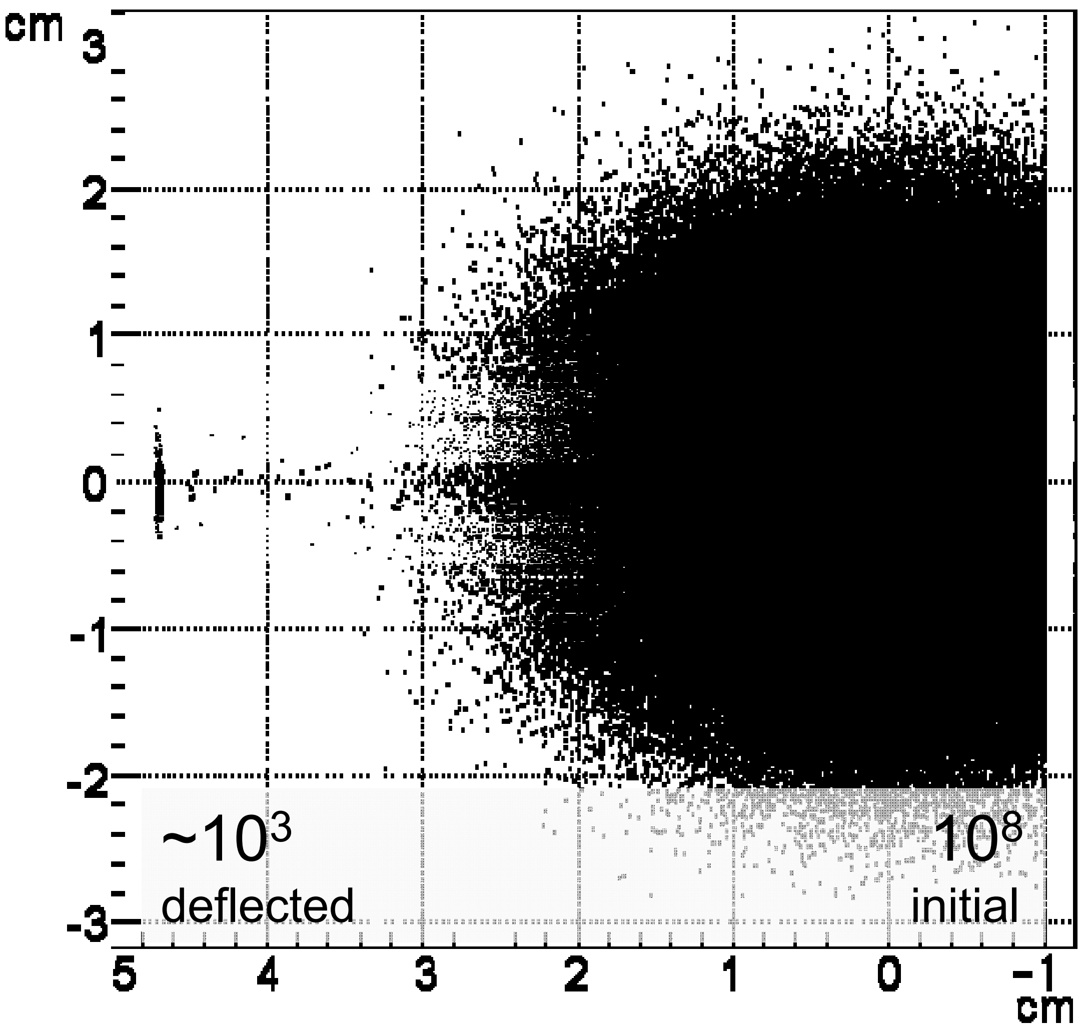
a – Thomas-Fermi radius
ρ – distance from (111) plane
d_{pl} – distance between the planes (2.35 A for (111) planes)
$Z_1 e$ – charge of incident particle
Z_2 – atomic number of crystal material (14 for Si)
C – Lindhard constant Sqrt[3]

Conditions for simulation

- single and multiple scattering of the protons on electrons and nuclei are included,
- such crystal imperfections as roughness of the surface and possible amorphous layer were taken into account.

Simulation

picture at the distance 145 cm from the crystal



Initial parameters

Beam

Energy: 12 GeV

Size: 15 x 12 mm

Divergence: 0.3 - 5 mrad

Crystal

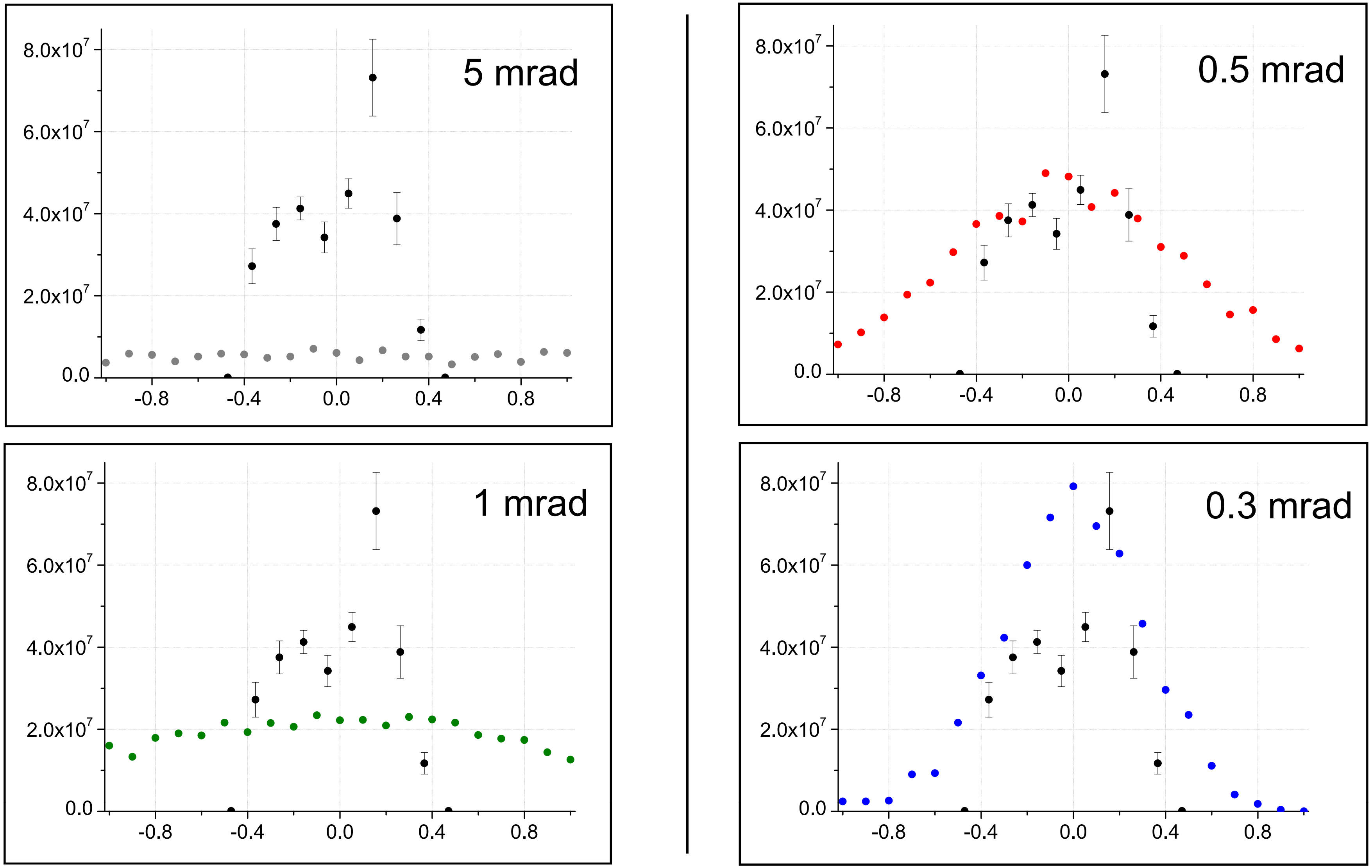
Size: 3 x 0.3 x 10 mm

Bending angle: ~ 32.6 mrad

Plane: (111)

10^8 pps → ~ 10^3 deflected pps

Simulation vs. Experimental data (1)

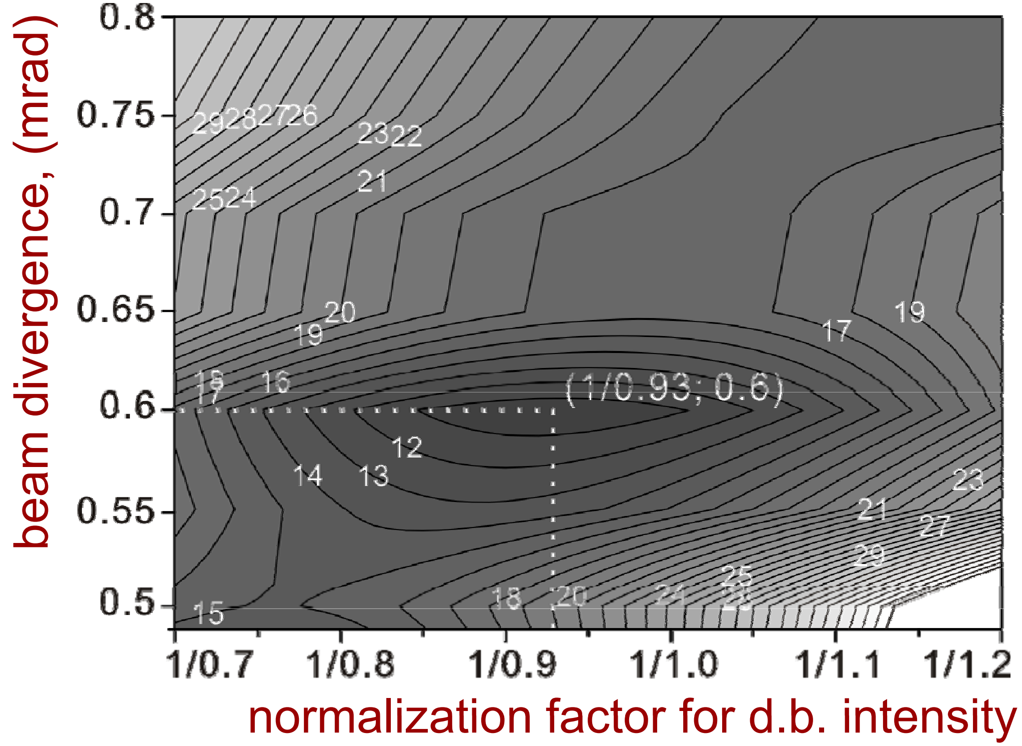


Simulation vs. Experimental data (2)

Searching of χ^2 minimum

$$\chi^2 = \frac{1}{n-p}\sum_{i}^{n} w_i (y_i^{exp} - y_i^{sim})^2$$

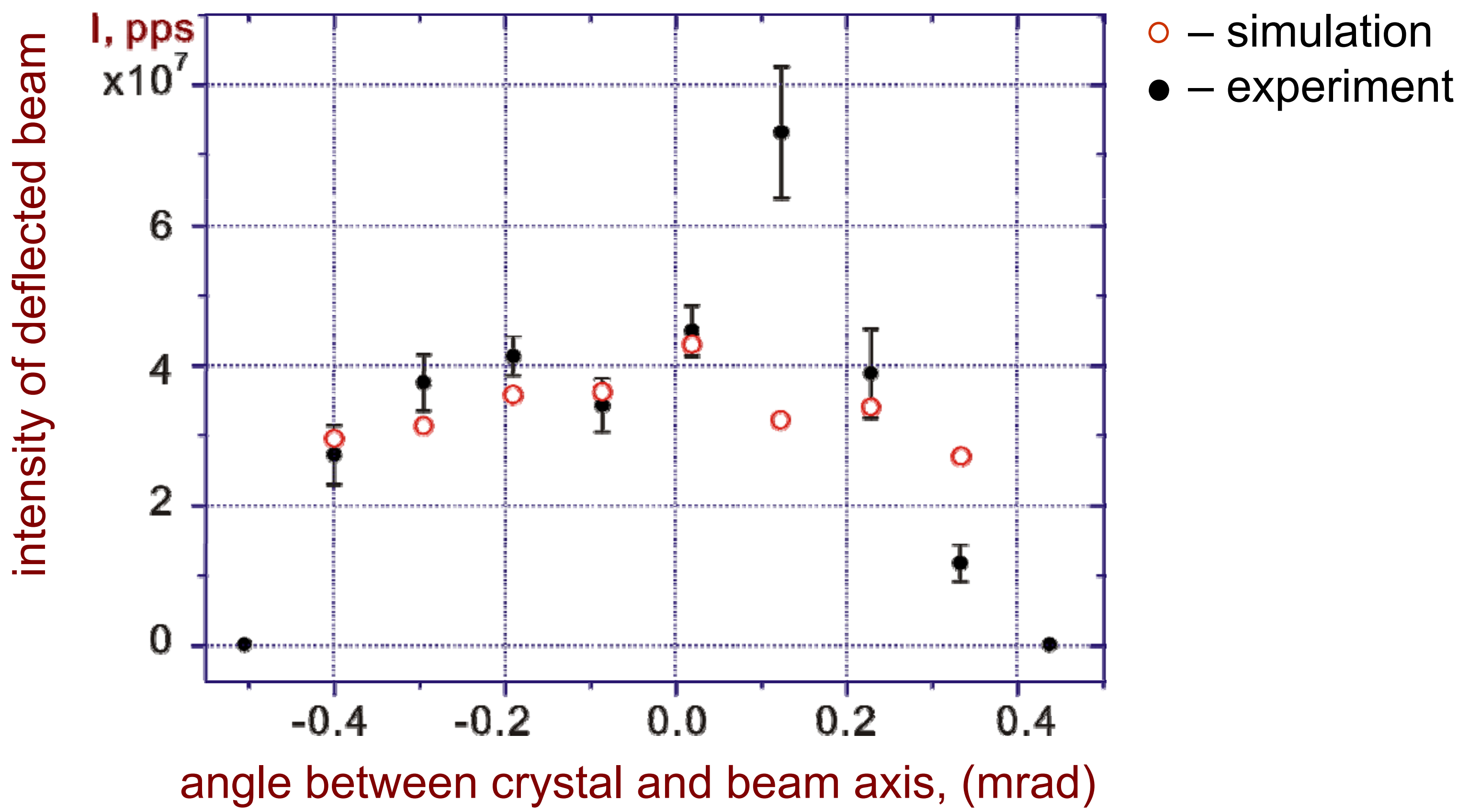
n – number of data
p – number of adjustable parameters (=2)
y_i^{exp} – i-th experimental vaue
y_i^{sim} – data from the simulation
$\omega_i = 1/\sigma_i^2$ – weight of each experimental point, where σ_i is a standard deviation



Beam divergence found to be <u>0.6 mrad</u>,
and the normalization for deflected beam intensity <u>1/0.93</u>

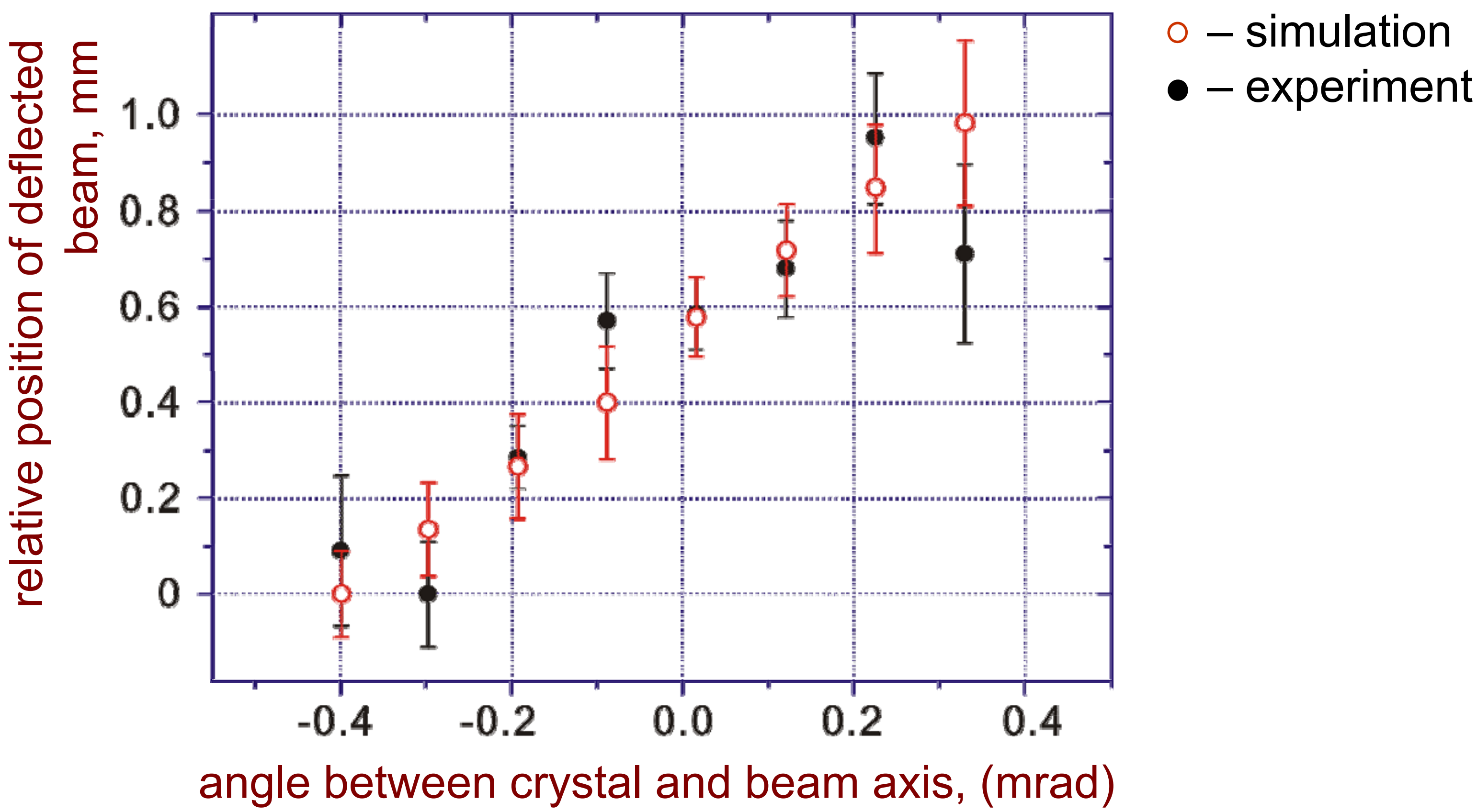
Simulation vs. Experimental data (3)

Experimental intensity of the deflected beam compared with the best fitted simulation for the beam divergence of **0.6 mrad** and normalization factor for the d. b. intensity of **1/0.93**.



Simulation vs. Experimental data (4)

Position of the deflected beam at the distance 145 cm from the crystal compared with the simulation.



Crystal efficiency

Using both experimental data and the results of simulation

N deflected = Crystal Efficiency x

Angular Efficiency x

N incident upon the crystal.

↓

Crystal Efficiency was 23%

Estimated theoretical value was 21%

Summary on KEK-PS experiment

- Experiment on the deflection of proton beam by the bent crystal was successfully done – we could clearly observe deflected beam.
- A Monte-Carlo simulation was used to find the beam divergence and normalization factor.
- Using results of simulation and experimental data a deflection efficiency was found to be 23% which is consistent with the theoretical estimation of 21%.

Possible applications for ILC, J-PARC, and REFER

ILC

Creation of system to remove beam tails

Spoiler – copper 8.6 mm thick ($0.6X_0$)

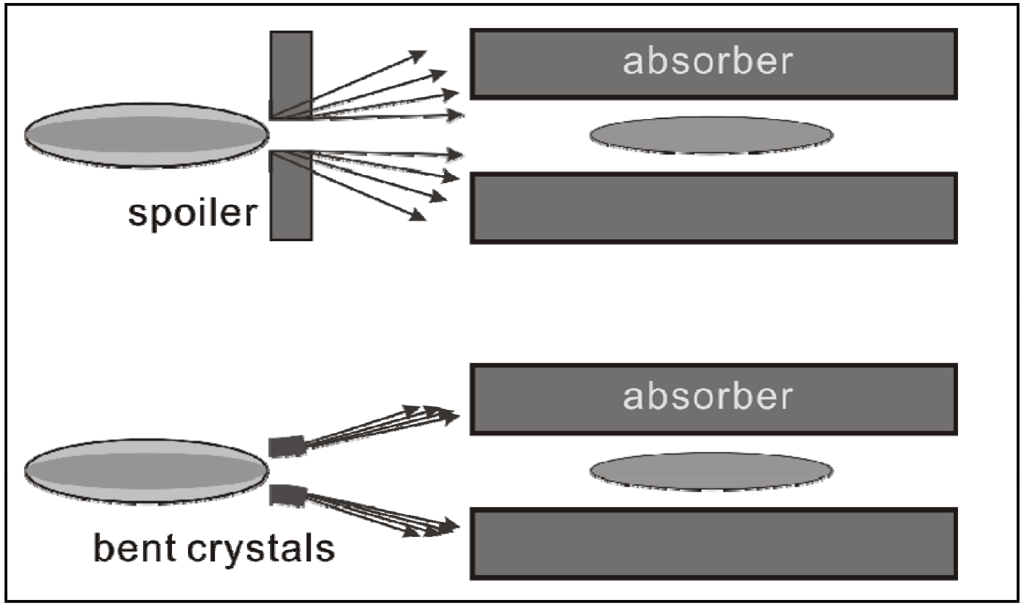
Absorber – copper 4.3 m thick ($30X_0$)

Bent crystal – silicon 2 mm thick ($0.02X_0$)

X_0 is the radiation length

Deflection efficiency for the 2 mm Si crystal which is bent at 0.1 mrad and 250-GeV positrons is 80%

deflected tails can be localized

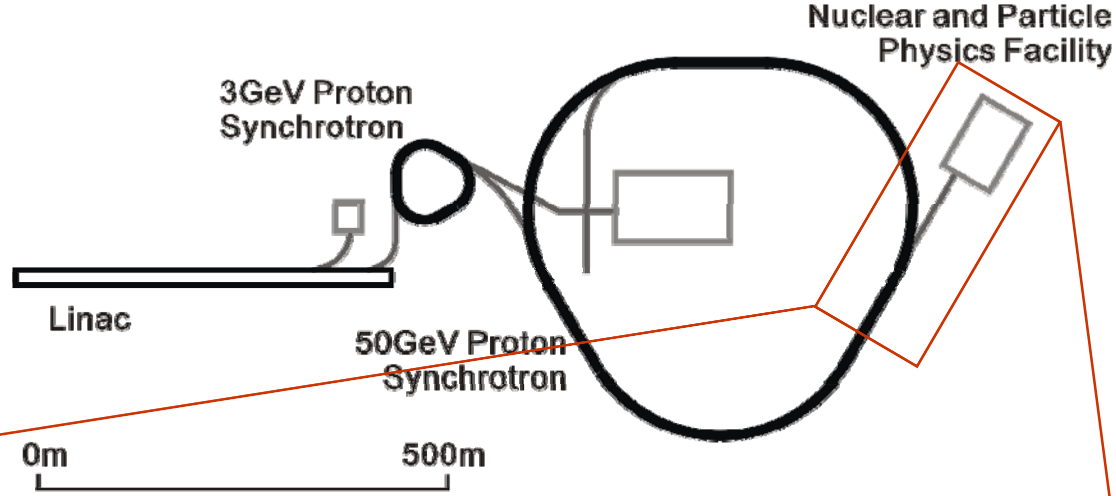


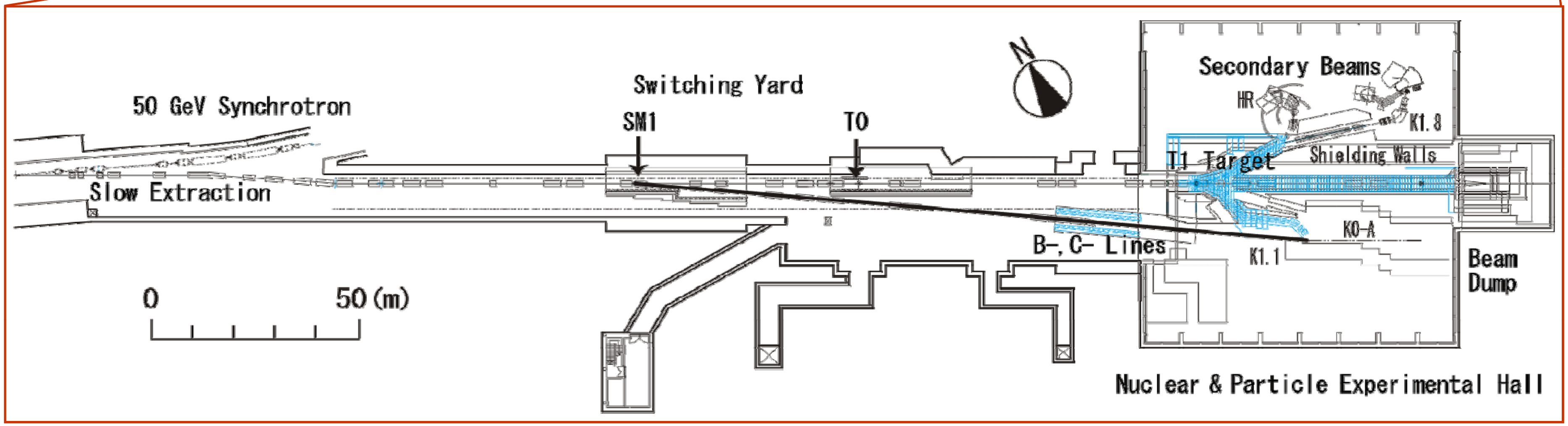
J-PARC (Japan Proton Accelerator Complex)

50 GeV proton beam with the intensity of 10^{14} protons per second

Benefits of using crystals in a deflection device for J-PARC

- smaller beam profile (few mm^2) and emittance compare with the conventional extraction systems,
- smaller beam losses.



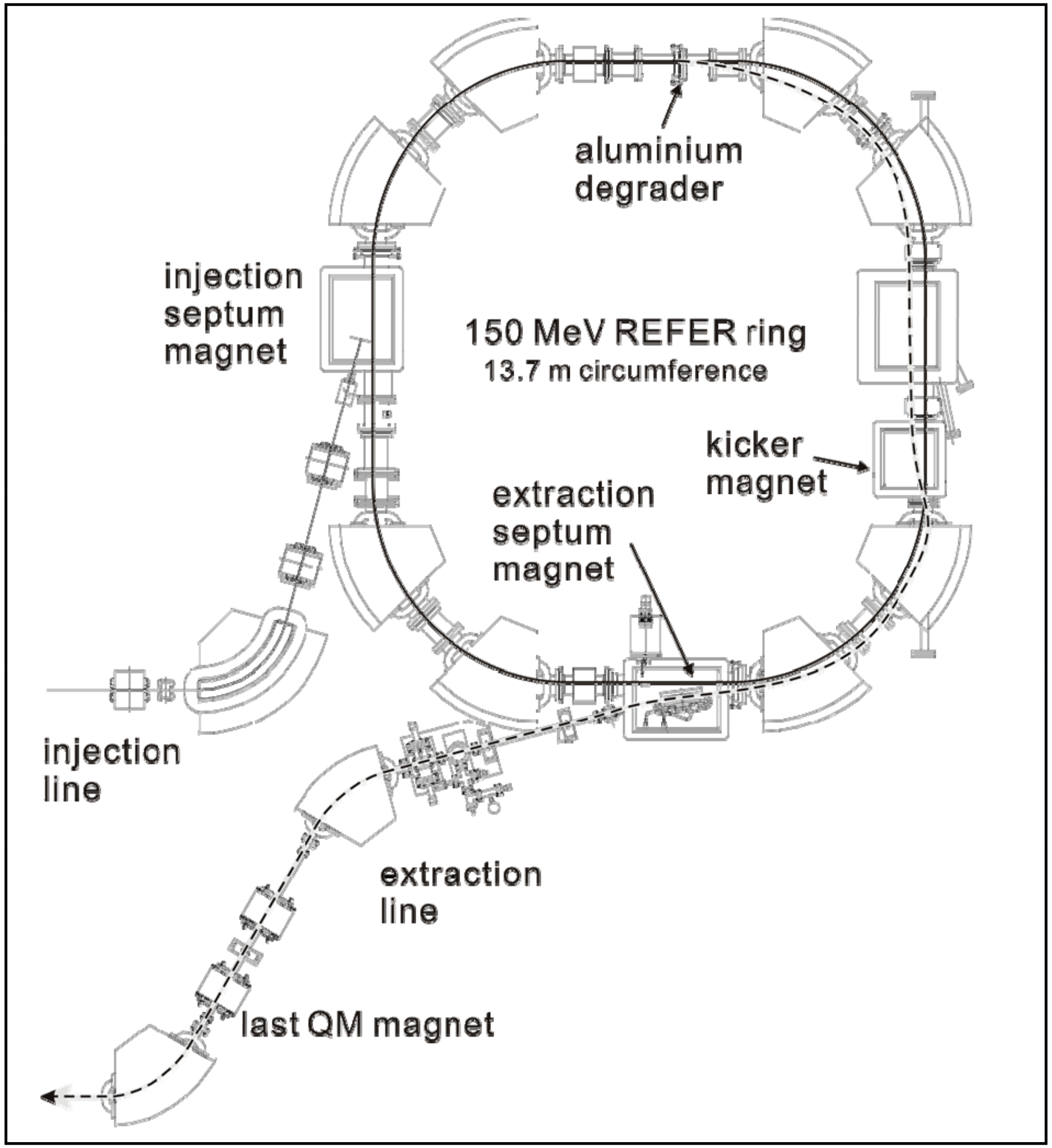


REFER ring

Creation of the system to extract 150-MeV electron beam

Replace aluminium energy degrader by the crystal will reduce energy losses and increase the intensity of extracted beam.

- - - -   extraction trajectory of the electron beam.



Future experiments

KEK-ATF

Basic studies for development of beam collimation system for ILC at KEK-ATF

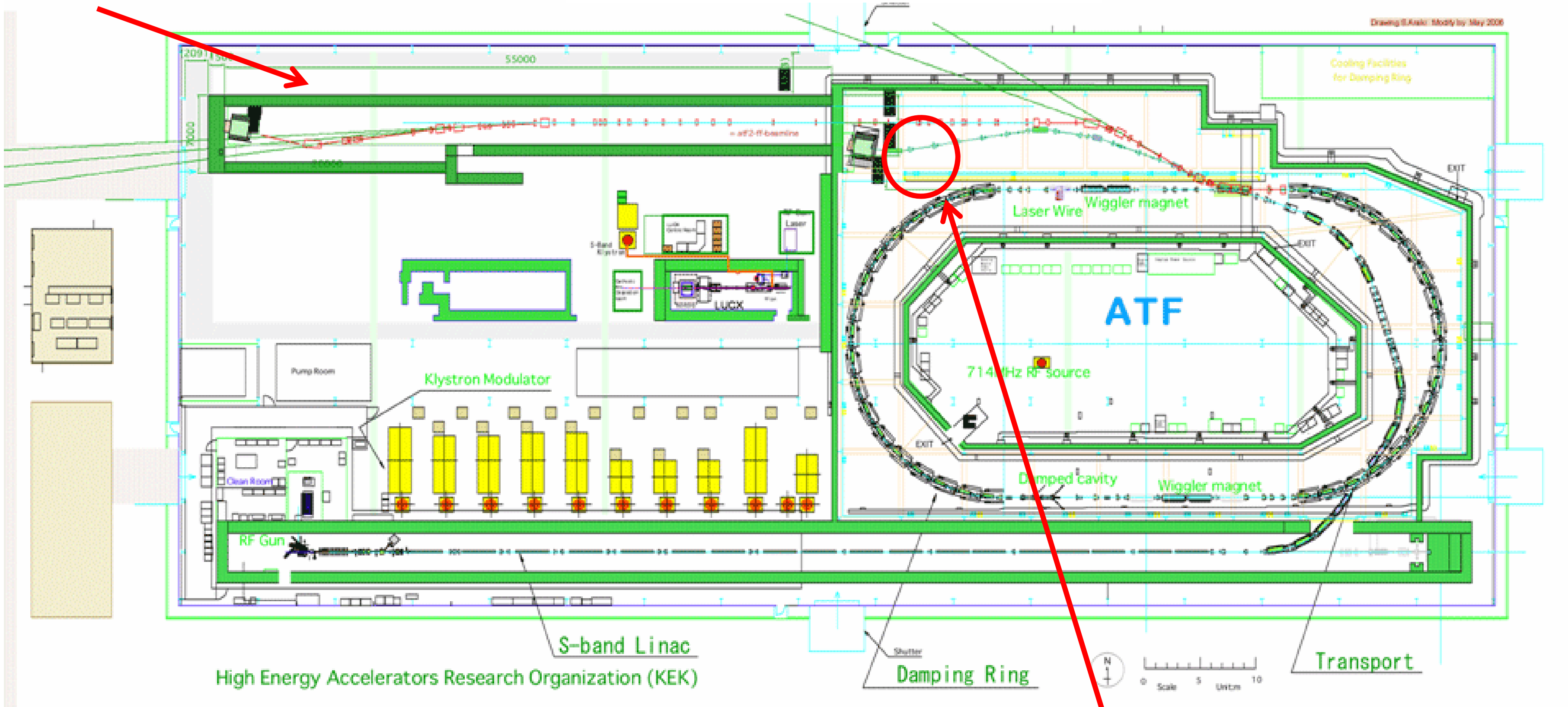
beam divergence angle < Lindhard angle (0.24 mrad)

Plan:

1. experiments on the electron beam deflection
   using straight crystal
2. experiments on the beam separation
   with a bent crystal
3. basic studies on the beam collimation
4. test at the ATF2 extraction line in future

KEK-ATF/ATF2 layout

ATF2 beam line



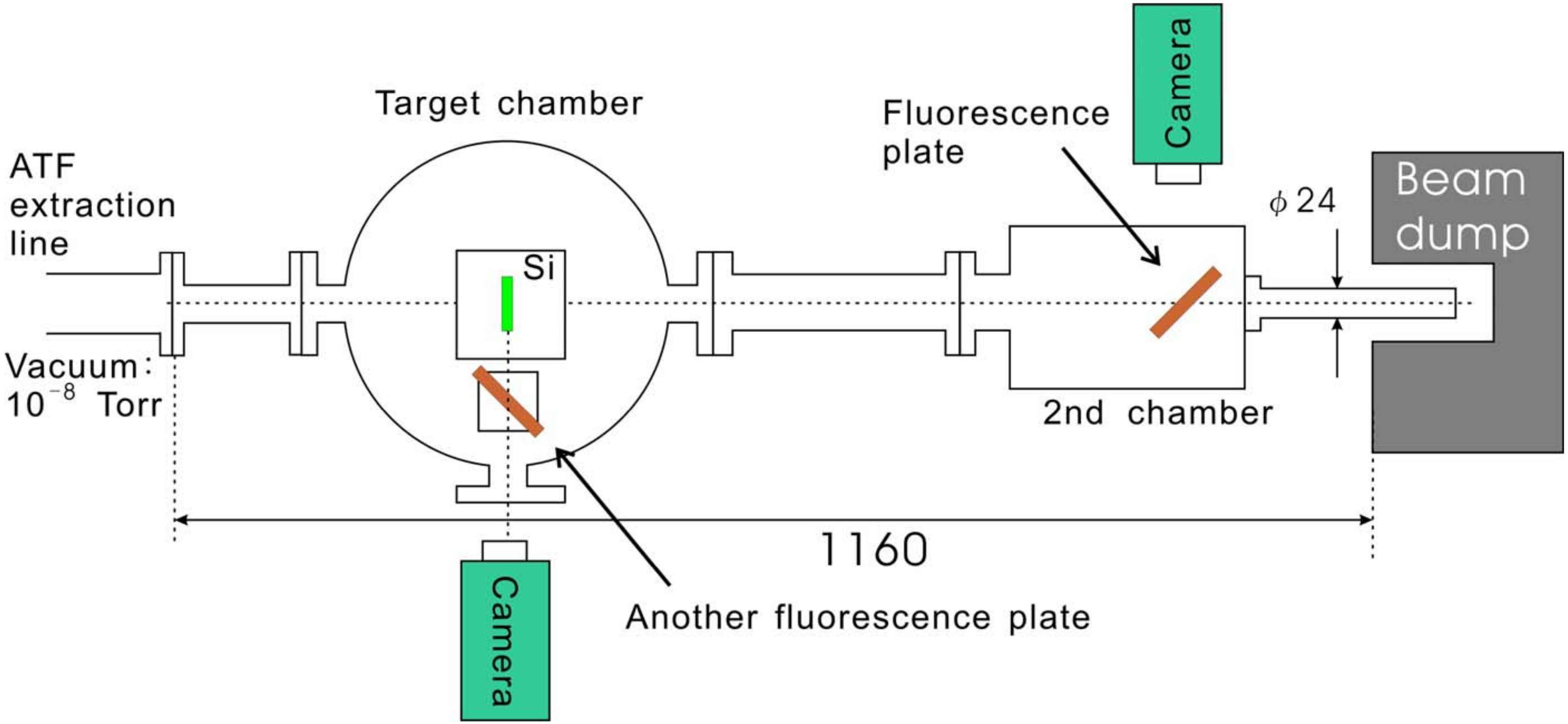
test for deflection and collimation

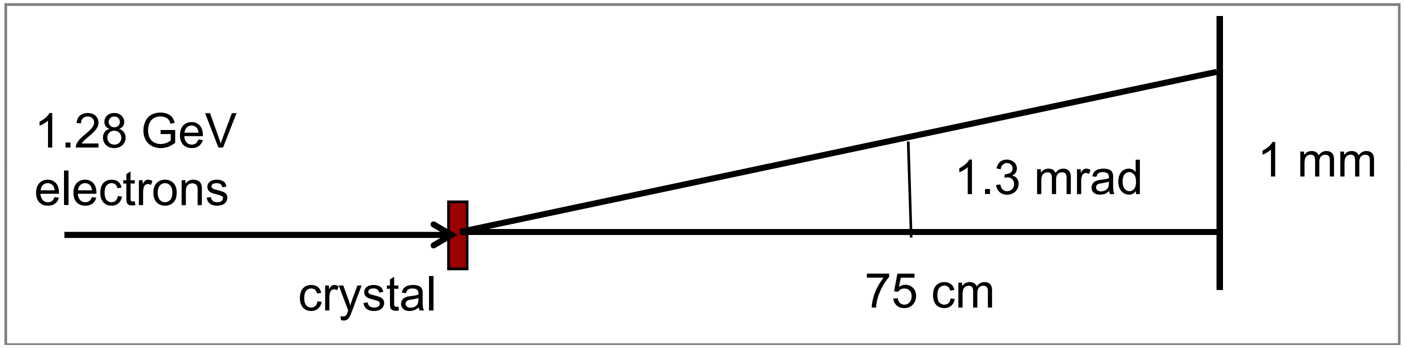
Beam energy : 1.28 GeV

Low Emittance X: $1\text{x}10^{-9}$ rad m

Y: $1\text{x}10^{-12}$ rad m

Proposed setup

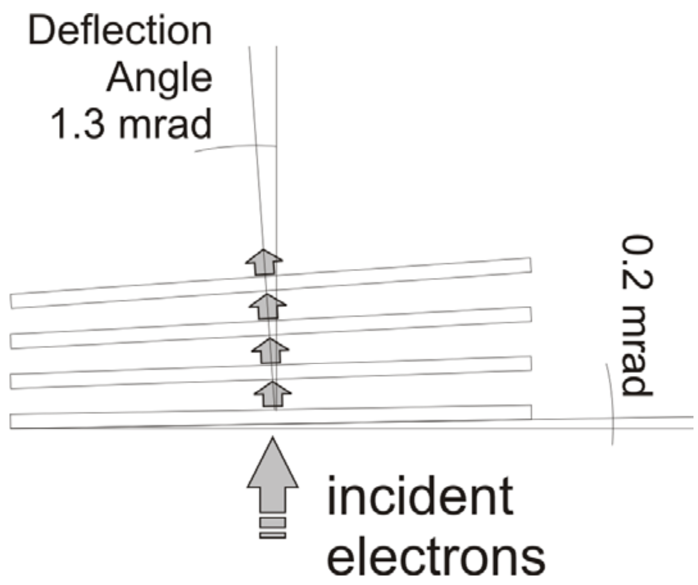




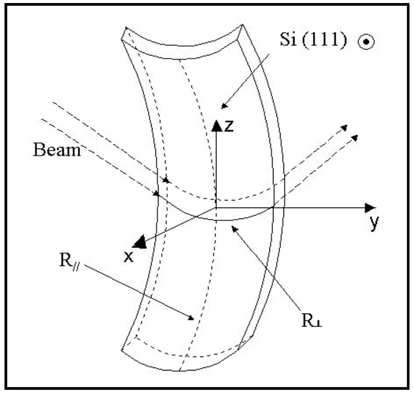
Crystals for KEK-ATF experiment

Dechanneling length 44 um

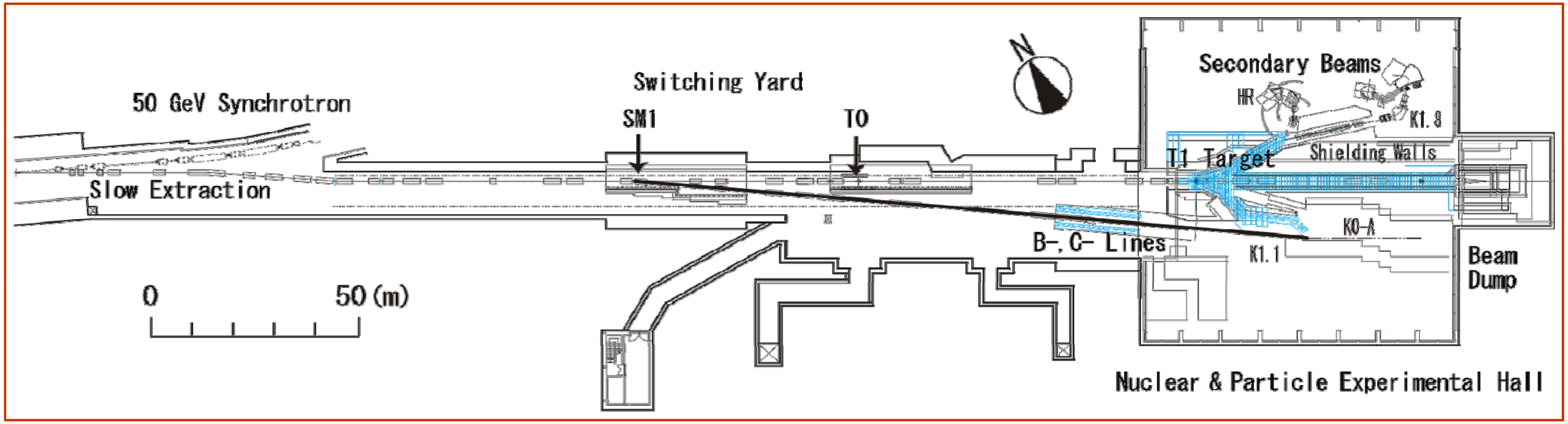
1. System of crystals



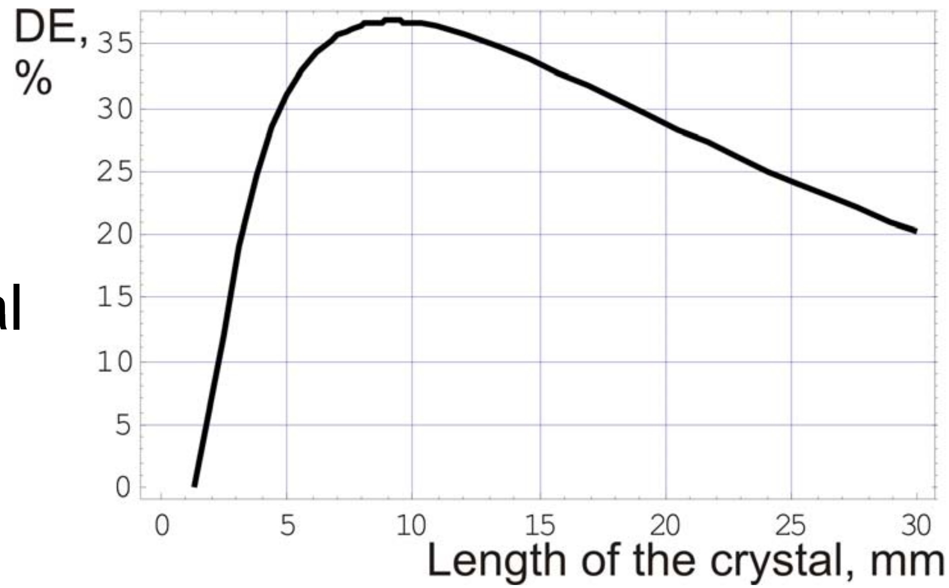
2. Anticlastic angle



J-PARC experiment

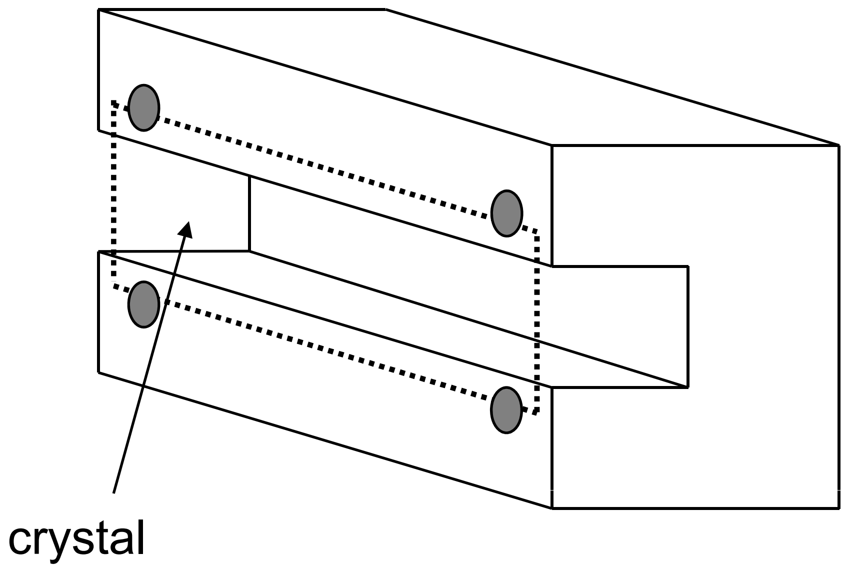


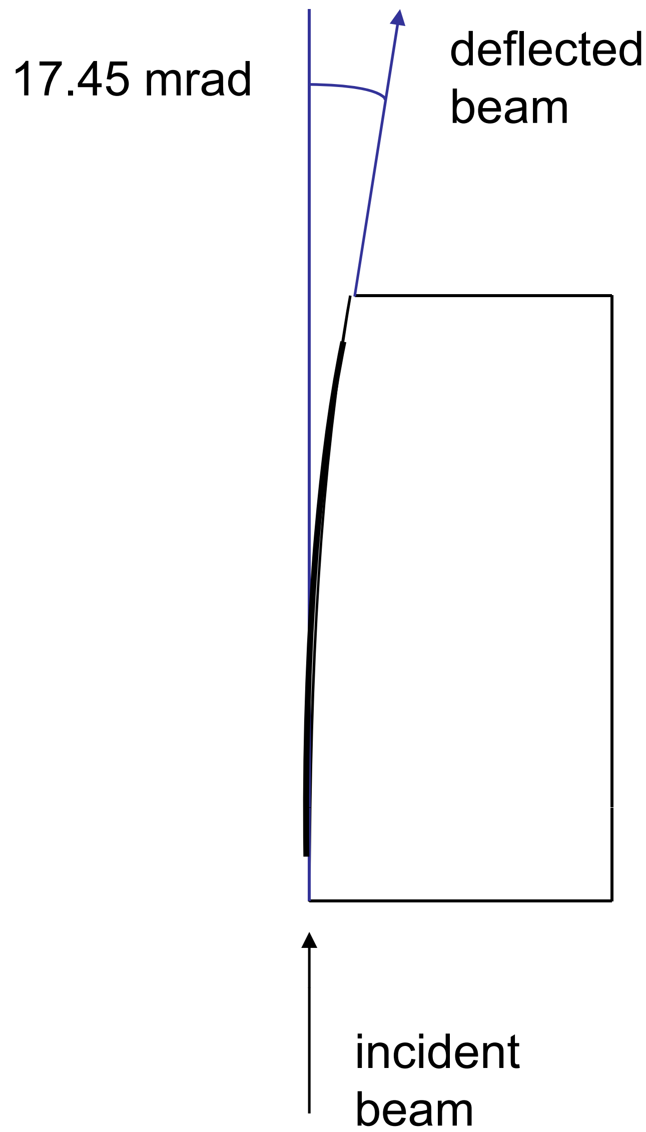
- 30 GeV proton beam
- Deflection angle 1°
- (111) plane of silicon crystal



Crystal for J-PARC experiment

Conventional bending device





Summary

In some cases the crystal can be good replacement for the conventional deflection systems. However possible radiation and heating damages of the crystal should be study beforehand.

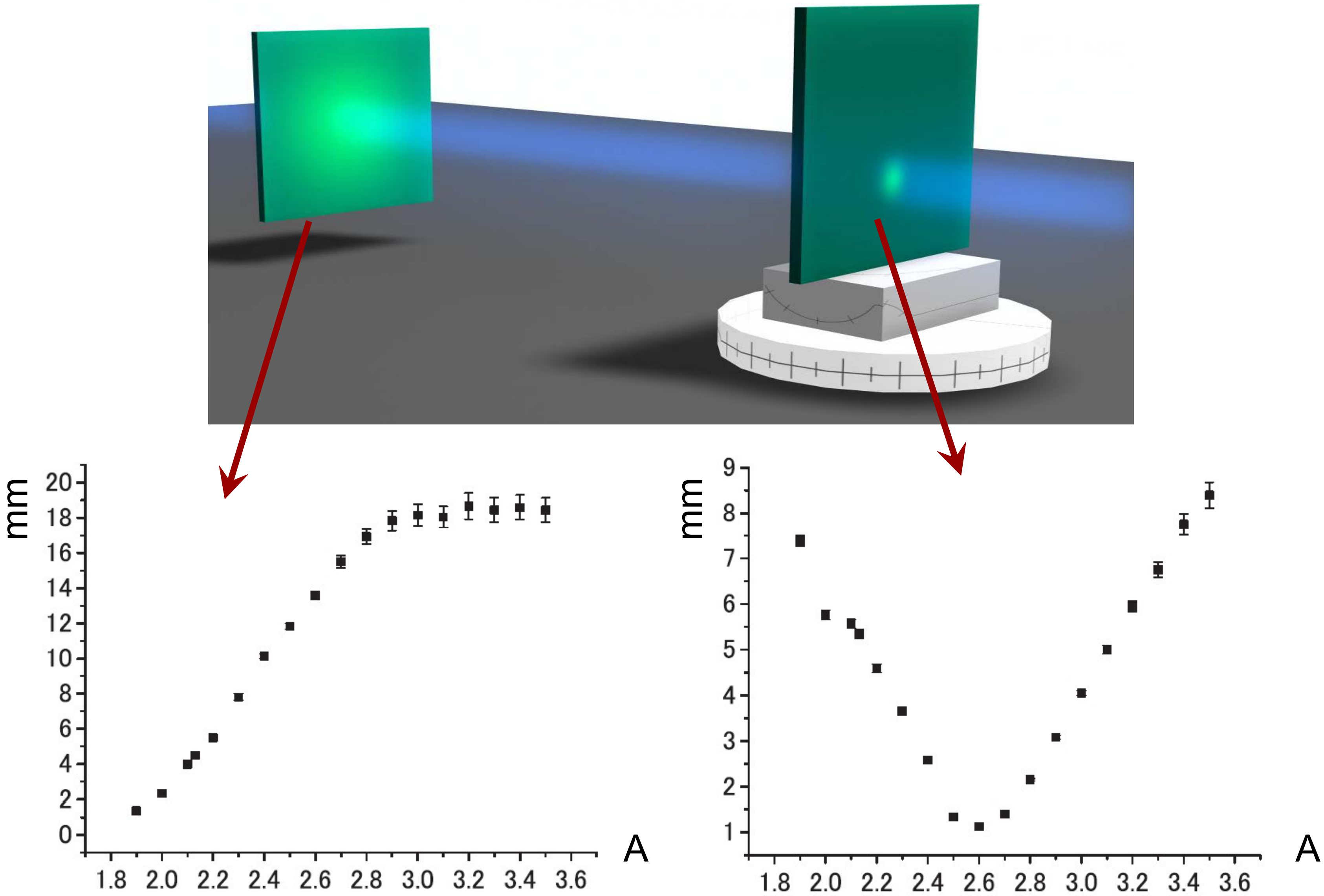
For the ILC and REFER ring applications, additional investigations are needed:

- an experiment on the channeling of ultra-low emittance electron beam will be performed at the KEK-ATF,
- if above experiment will be successful, an experiment at ATF2 will be proposed.

As for the proton beam:

- investigations of the possible thermal and radiation damages have to be done,
- collaboration with the Fermilab on the experiments with the proton beam,
- experiments with the low energy proton beam will be performed at the J-PARC.

Thank you!



mm
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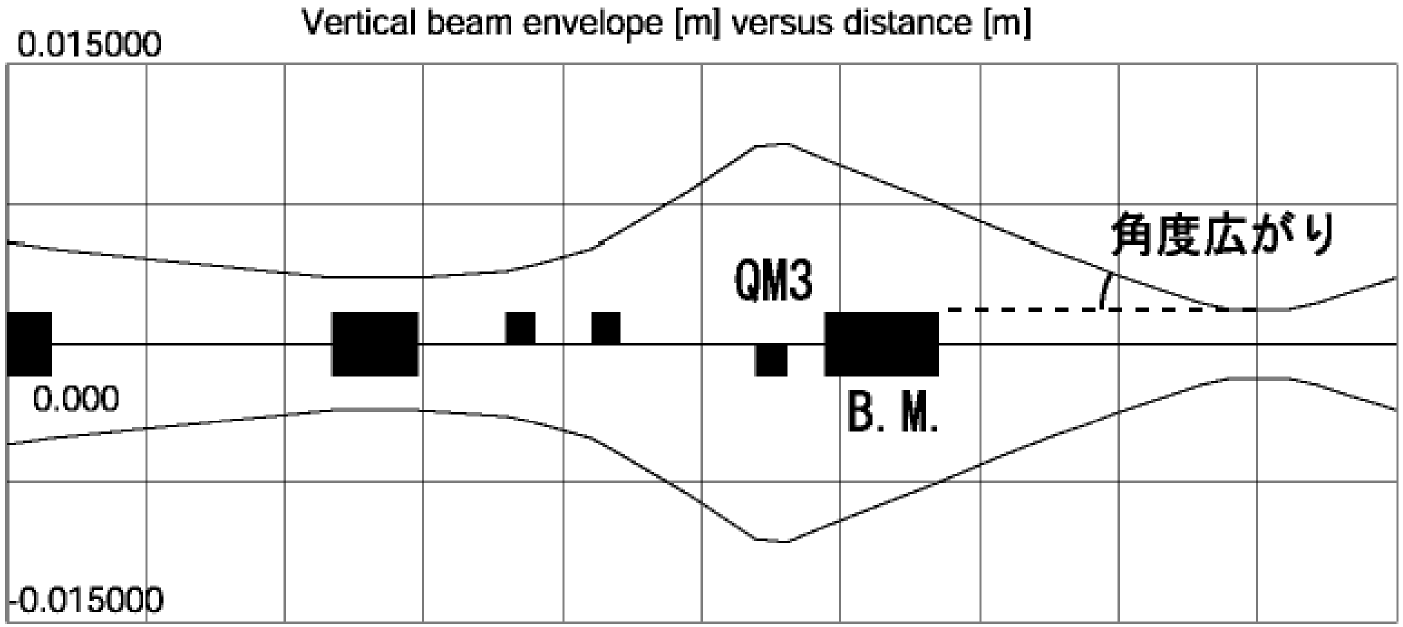
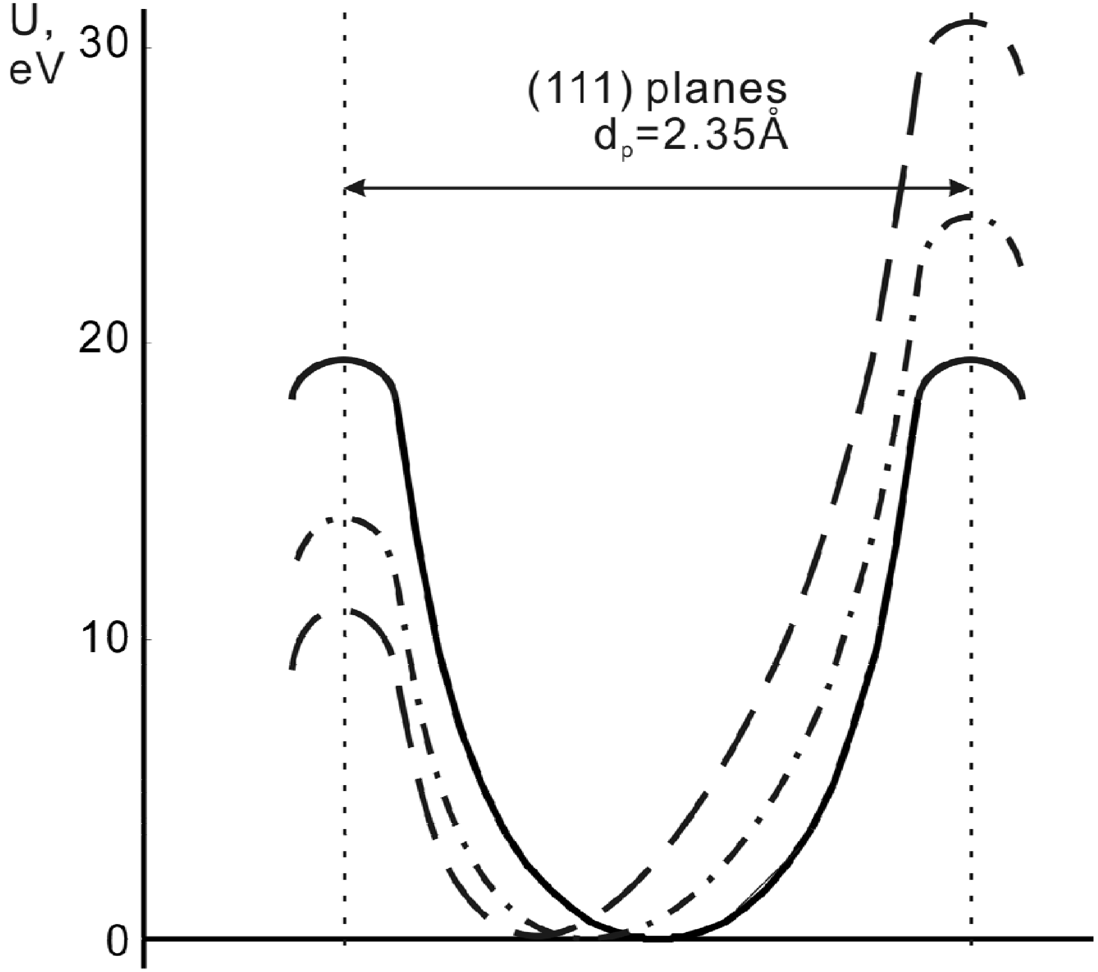
3.6


Vertical beam envelope [m] versus distance [m]
0.015000
0.000
-0.015000
角度広がり
QM3
B. M.


U,
eV
30
20
10
0
(111) planes
d_p=2.35Å