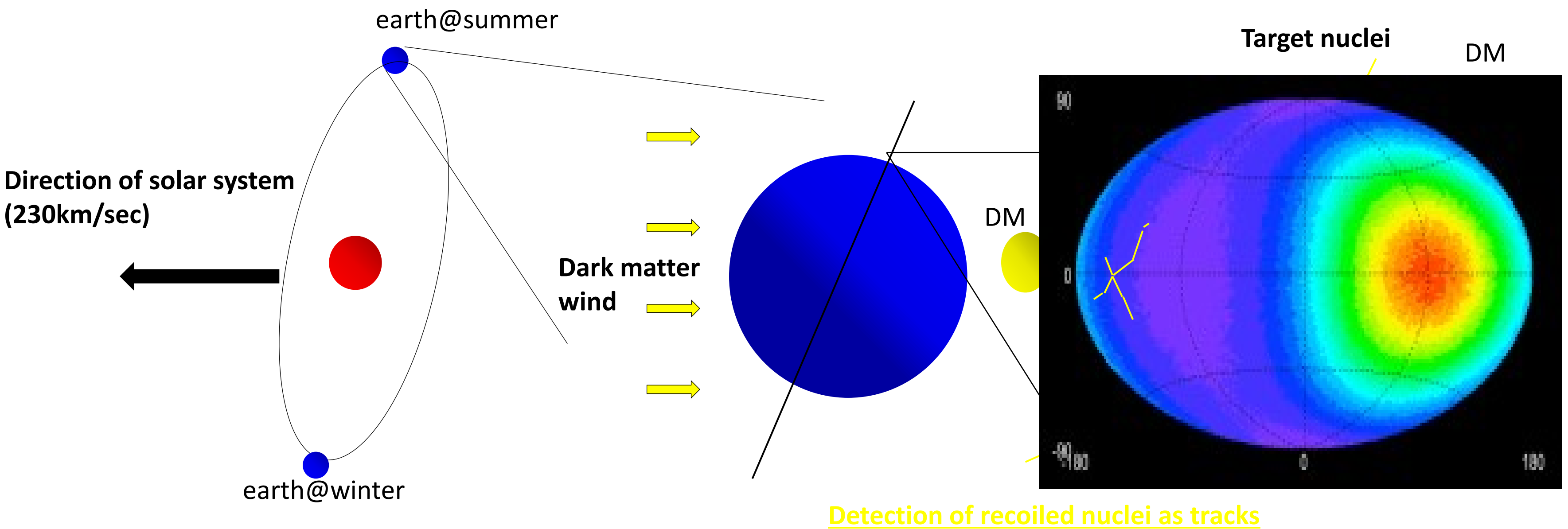
Directional Dark Matter Search Project with Super-High Resolution Nuclear Emulsions

Tatsuhiro Naka

KMI/IAR, Nagoya University, Japan

DBD'14, Oct. 6, 2014 @ Hawaii, USA

Directional Dark Matter Search



Annual Modulation ⟺ **Asymmetry of angular distribution**

✓ different information to identify the dark matter

✓ Identification with lower statistics (several 10 events) is possible from the asymmetry observation

What is the direction sensitive detector with scalability?

Challenge !!

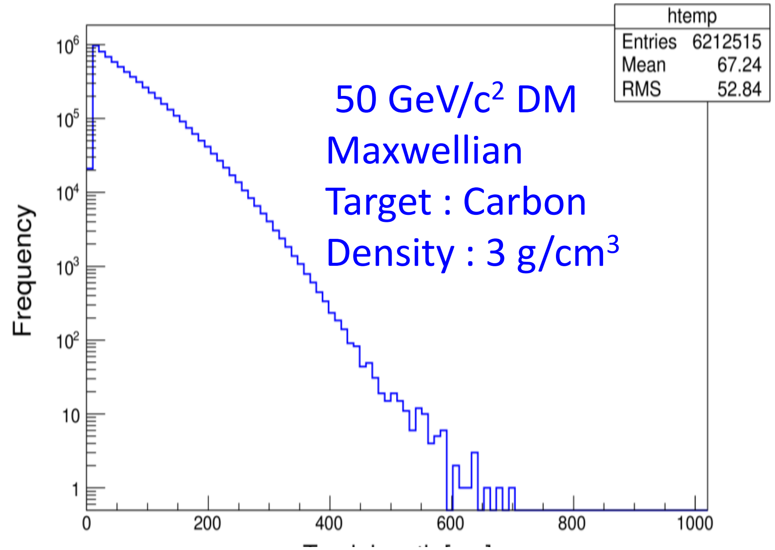
✓ Spin-dependent search is done by gaseous Detector ⇔spin-independent search ?

✓ Large mass detector with solid or liquid detector

⇒ very high spatial resolution (< 1 μm)

✓ Direction sensitive detector for nuclear recoil energy regions

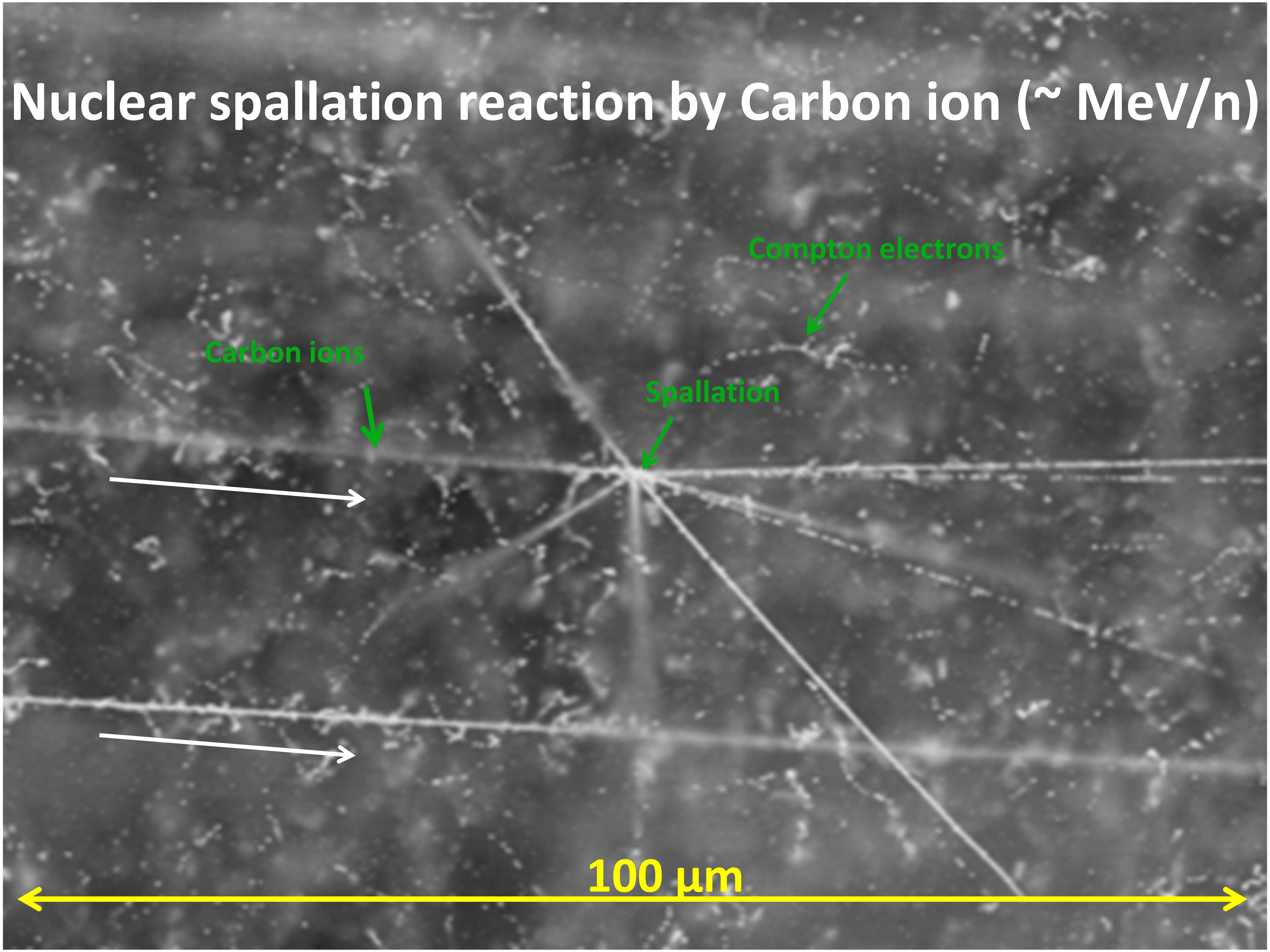
⇒ enough angular resolution (< ~ 45 deg.) for very short length tracks



Track length [nm]

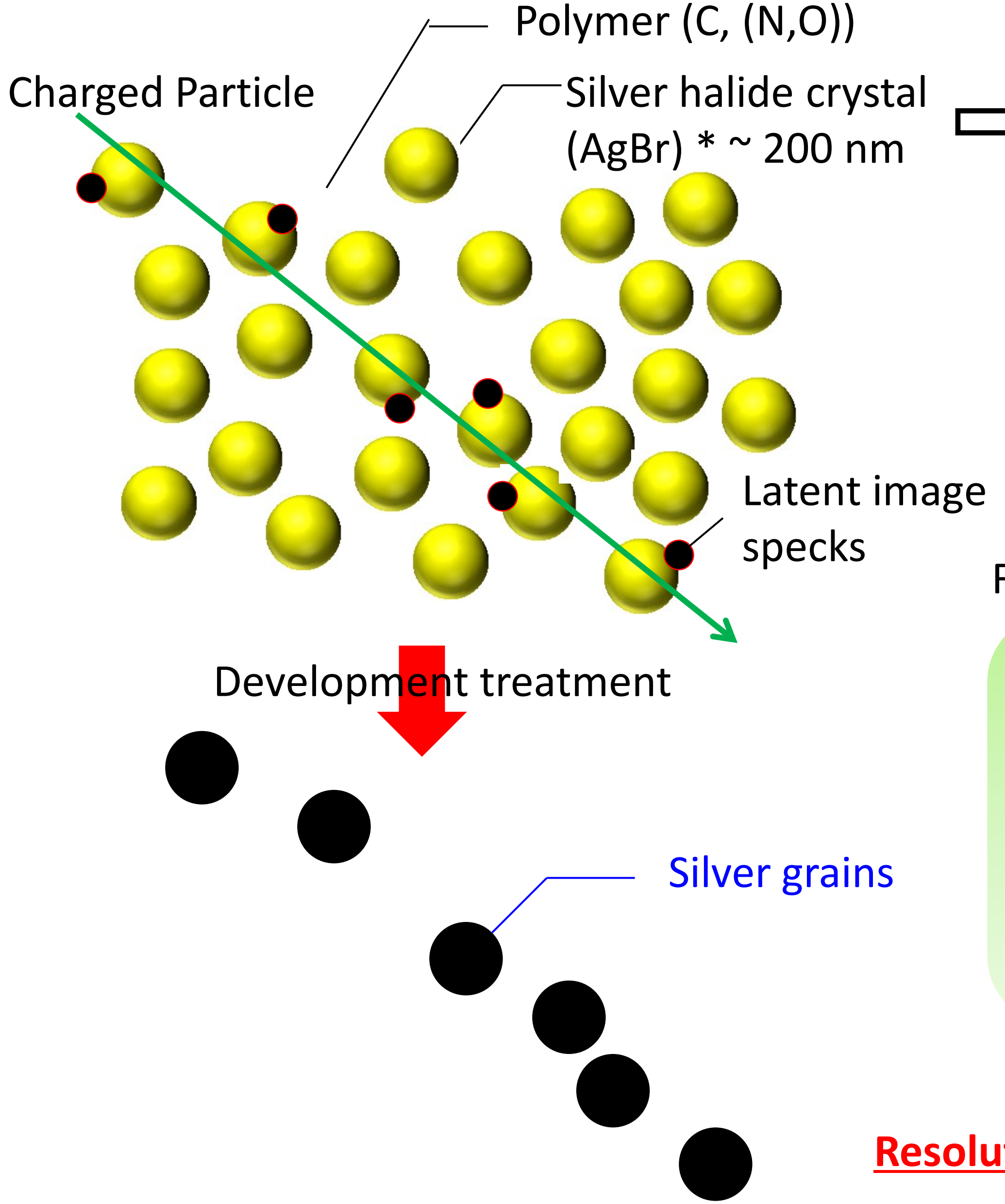
Can we make the direction sensitive detector with solid state ?

Special detector based on the nuclear emulsion



Nuclear spallation reaction by Carbon ion (~ MeV/n)
Compton electrons
Carbon ions
Spallation
100 µm

Detection Principle of emulsions detector



⇨ Semiconductor (VG ~ 2.7 eV)

☐ **Spatial resolution**
⇒ **Crystal size and density**

☐ **Angular Resolution**
⇒ **crystal size**

For example, in the case of usual type,

Crystal size : 200 nm (σ ~ 10 nm)
Density : 2.8 g/cm^3
(Vol. occupancy of crystal : 30 %)

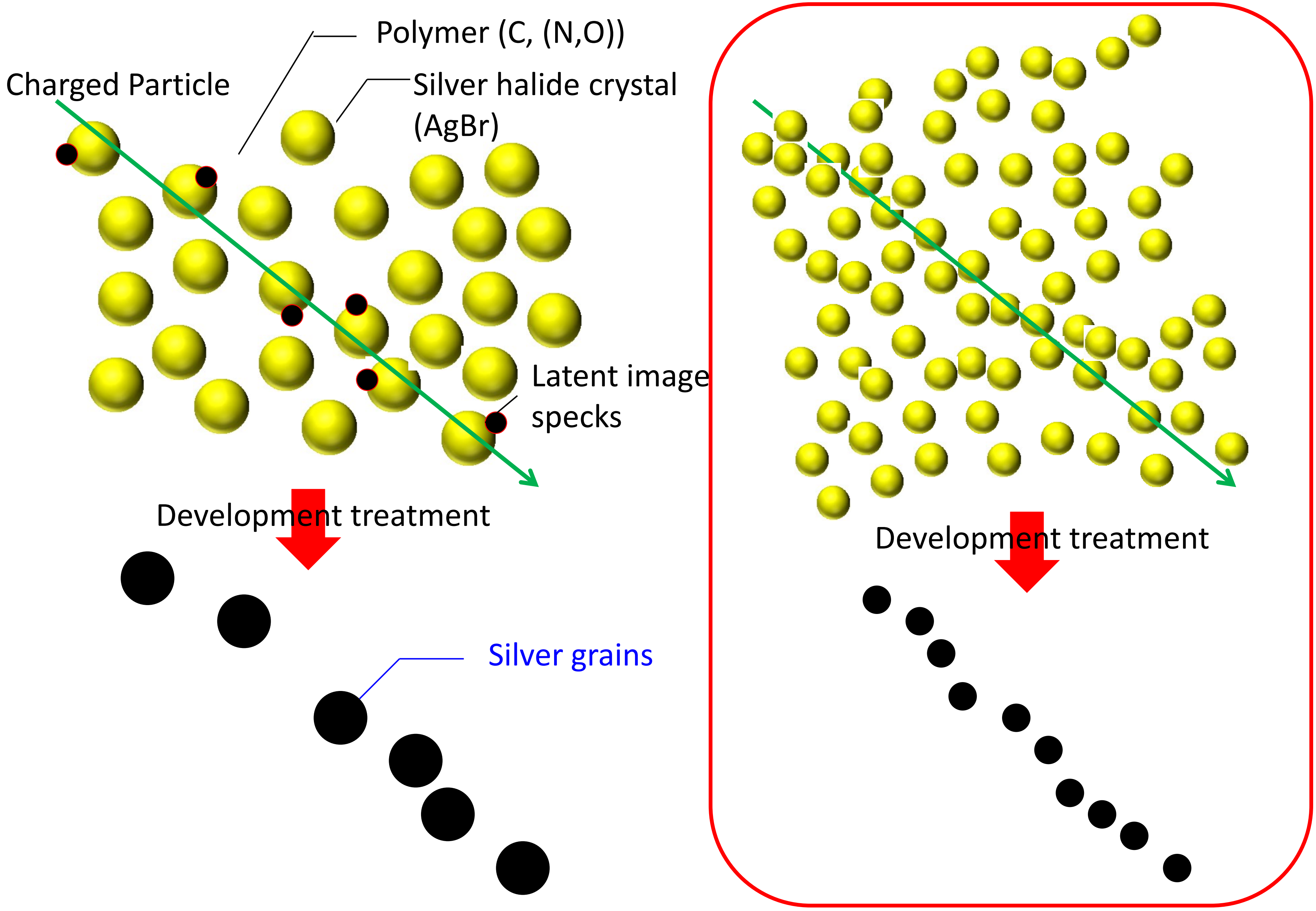
⇩

2.4 crystals / μm

Detectable more than μm order!!

Resolution is poor yet for directional DM search.

Higher resolution



Device Self-Production

1st Machine installed from 2010

Production scale : 1 kg detector / week

Very low-cost device : 1.5K $ /kg

- ☐ crystal size control
- ☐ control of Q.E. for the crystal
- ☐ R&D for low-background

Weight occupancy

AgBr・I : 74 %

Ag (42 %), Br (31 %), I (1 %)

Binder (gelatin + PVA) : 25 %

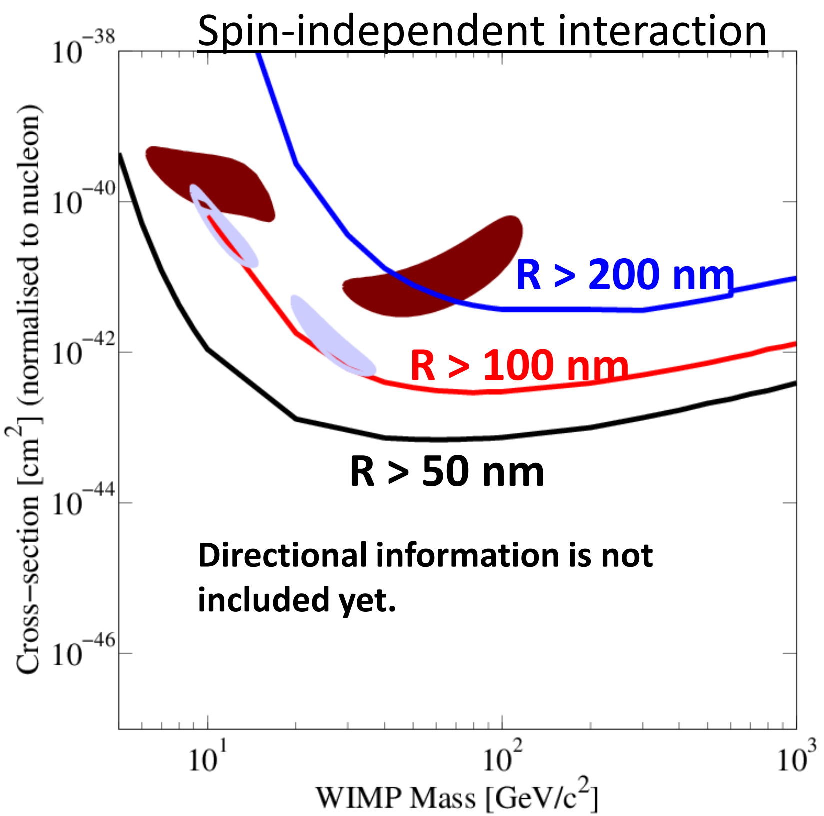
C (10 %), N (4%), O (10 %), others (2%)

□ Good scalability
⇒ no limitation for several kg scale
⇒ > 10 kg may be needed the production machine

□ No time resolution (disadvantage)
⇒ CYGNUS tracking by the mount of the equatorial telescope

□ Underground production and chemical development

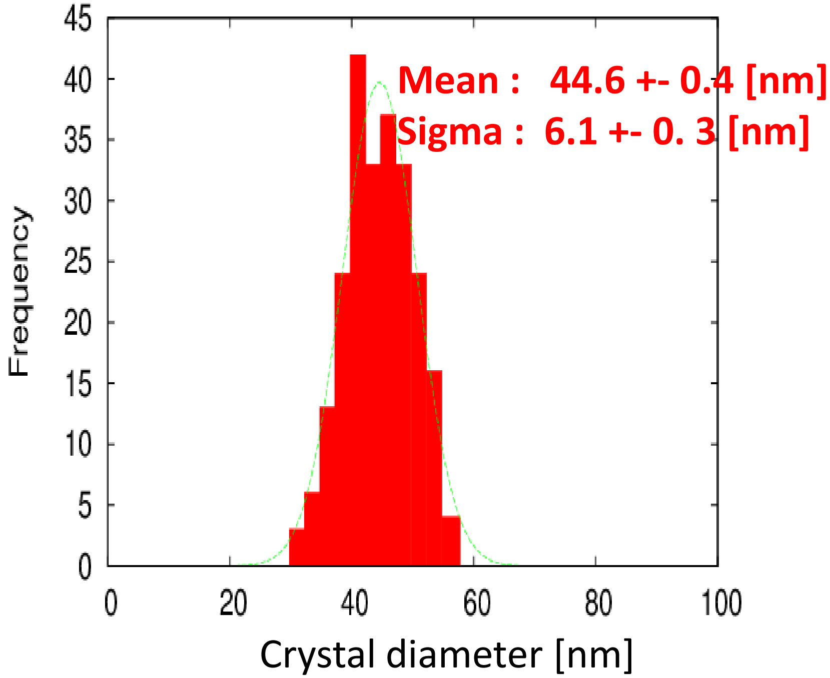
25 kg・y, 90 % C.L. , ideal predicted sensitivity

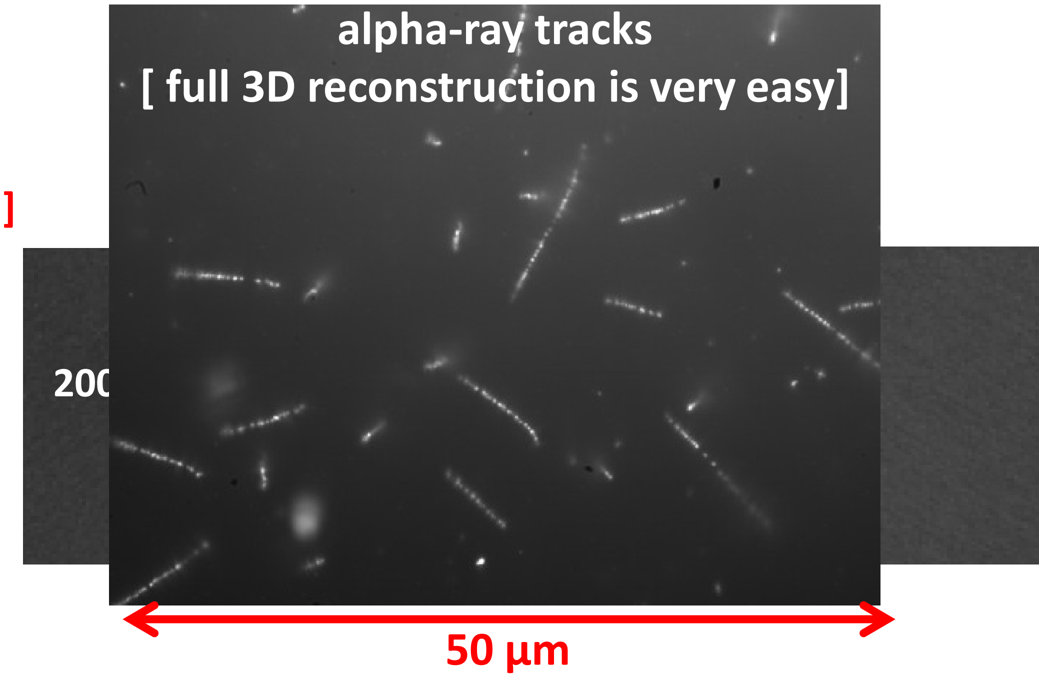


Super-High Resolution Device

Nano Imaging Tracker : NIT

Current R&D emulsion





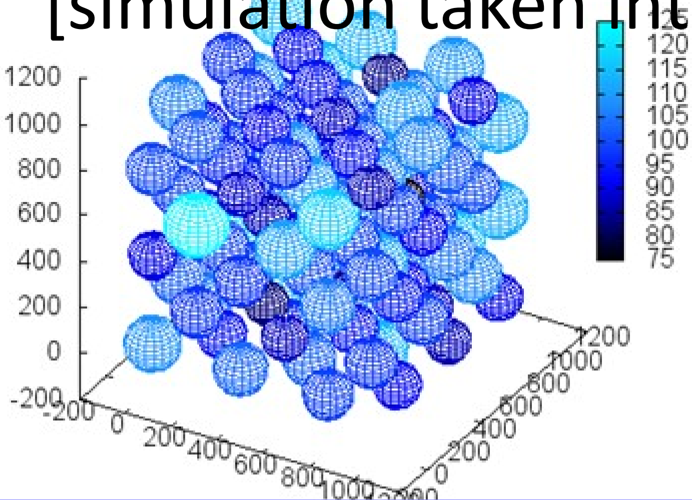
Detector density : 3.2 +- 0.1 g/cm3

Mean # of crystal per length : 13 crystals/µm

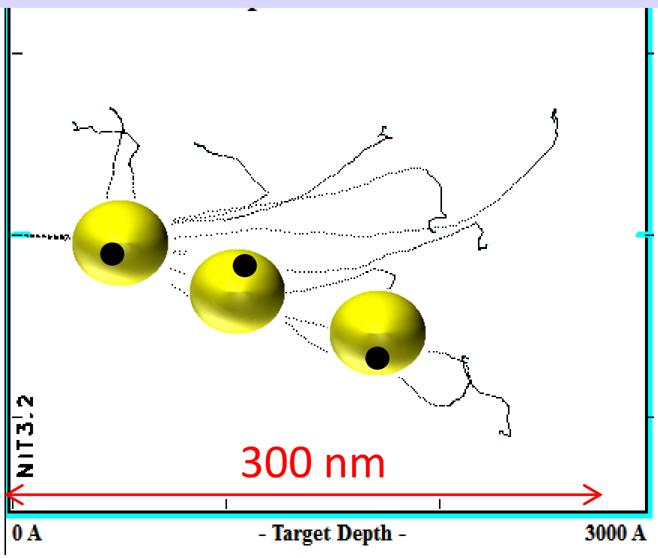
Research subject

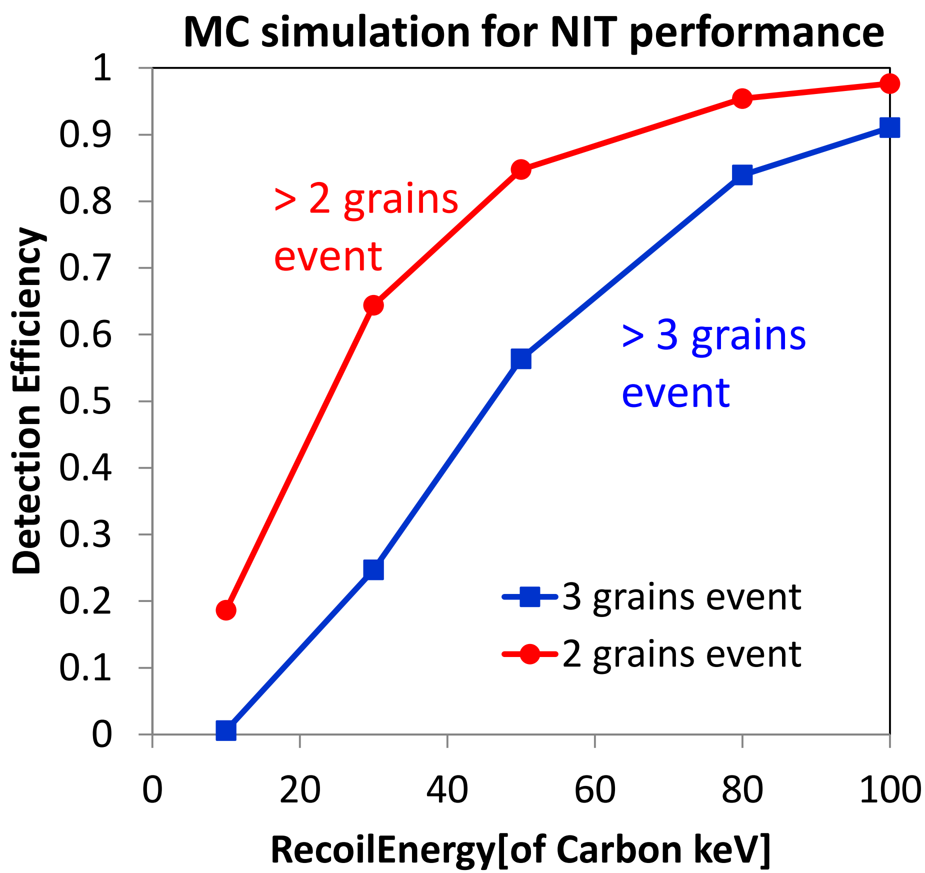
- ☐ Estimation of detector performance
- ☐ New readout technology for very short length tracks
- ☐ Lower background device and background rejection technologies

Performance Potential of the Detector [simulation taken into account the local structure]



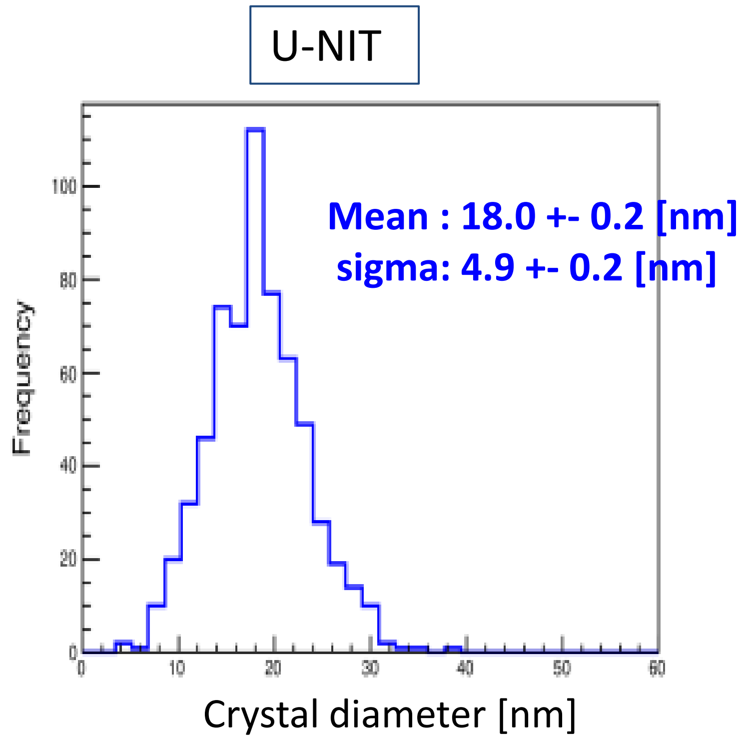
Mean crystal size : 43 nm
(σ of size dispersion 5.8 nm)
Volume occupancy of crystal : 39.6 %

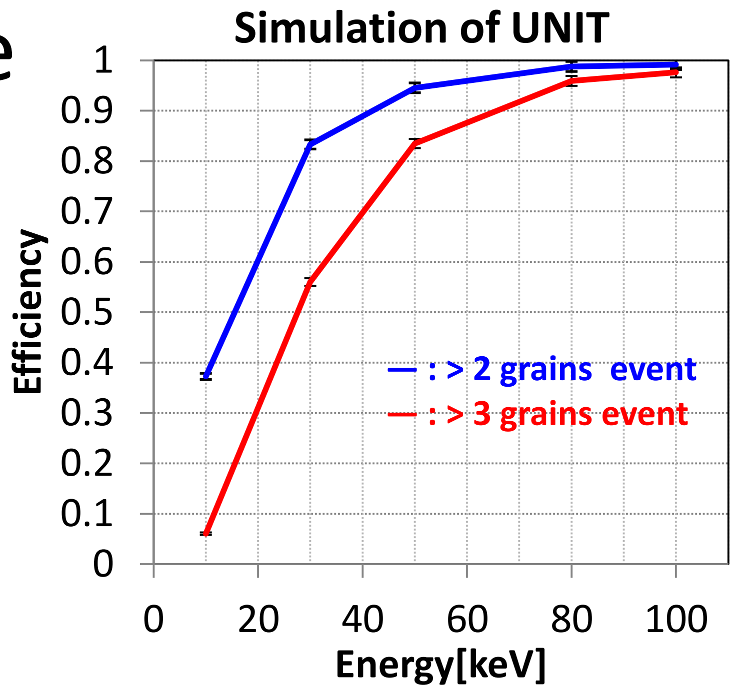


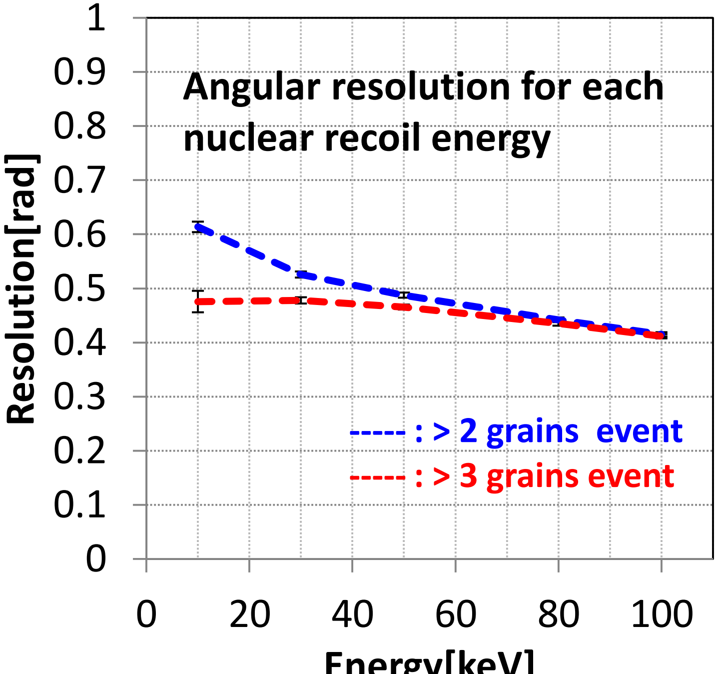


> 2 grain tracks : 25 keV @ 50% eff.
> 3 grains tracks : 50 keV @ 50 % eff.
※ 40 nm AgBr crystal

Potential of further device







Further detector for physics run

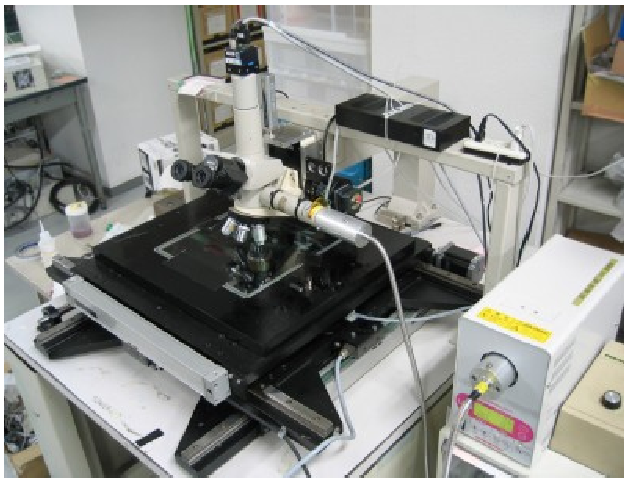
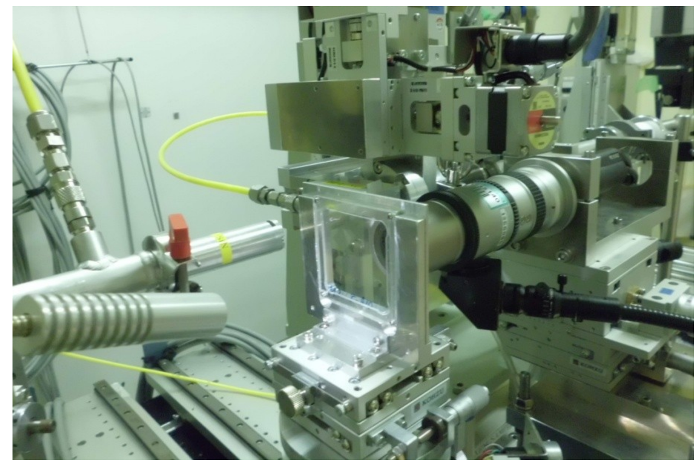
Crystal control have already been confirmed!!

> 2 grains event : 15 keV Eth @ 50 % eff.
then ⊿θ~ 33 °

> 3 grains event : 30 keV Eth @ 50 % eff.
then ⊿θ~ 27 °

Detector Analysis
[Readout technology]

Combined system between high-speed selection and high-precision system

Large volume scanning		High-resolution analysis
	⇔	
Optical microscope system		**X-ray microscope system**
✓ **High-speed scanning**		**@ SPring-8 (Syncrotron radiation ring)**
✓ **roughly candidate selection**		

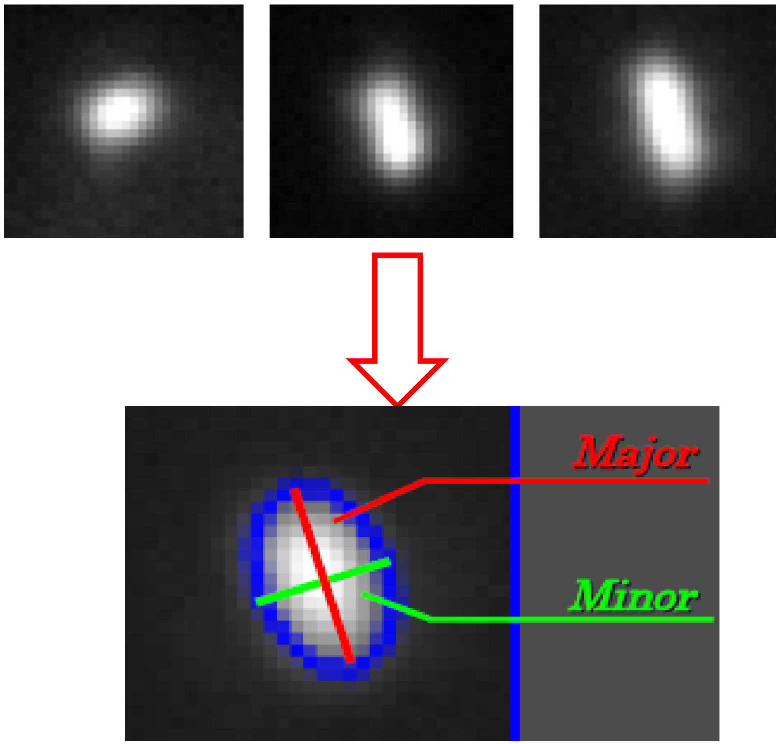
Finally, ton scale readout !
But, pour resolution.
Spatial : ~ 195 nm (limited by Reyleigh criterion)

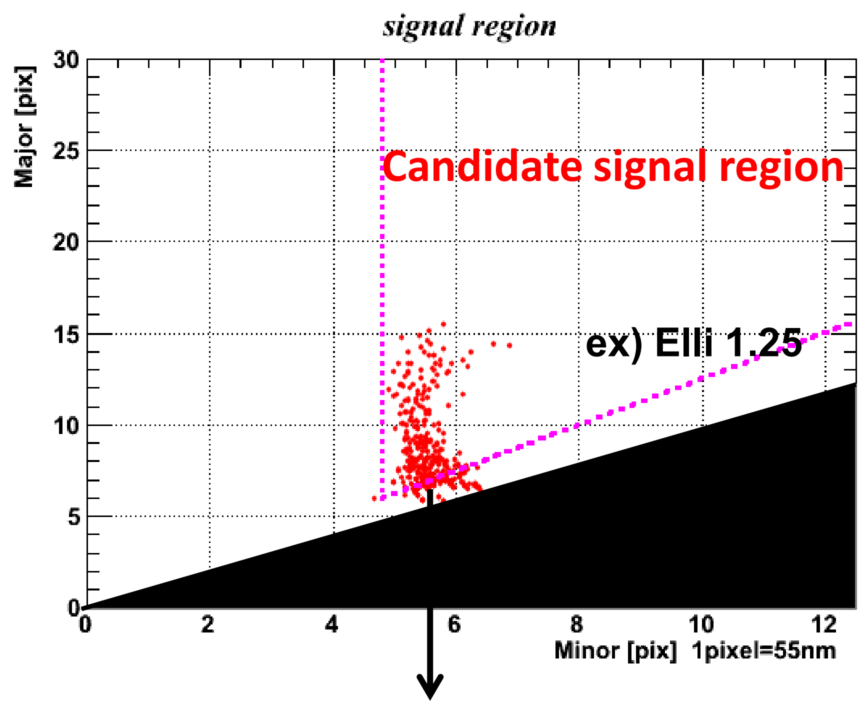
Spatial Resolution : 60 nm
scanning speed is pour, but 1000 events /days observation is possible.

Candidate selection for optical microscope system

Example of nuclear recoil signal

2D_Track length vs. Ellipticity





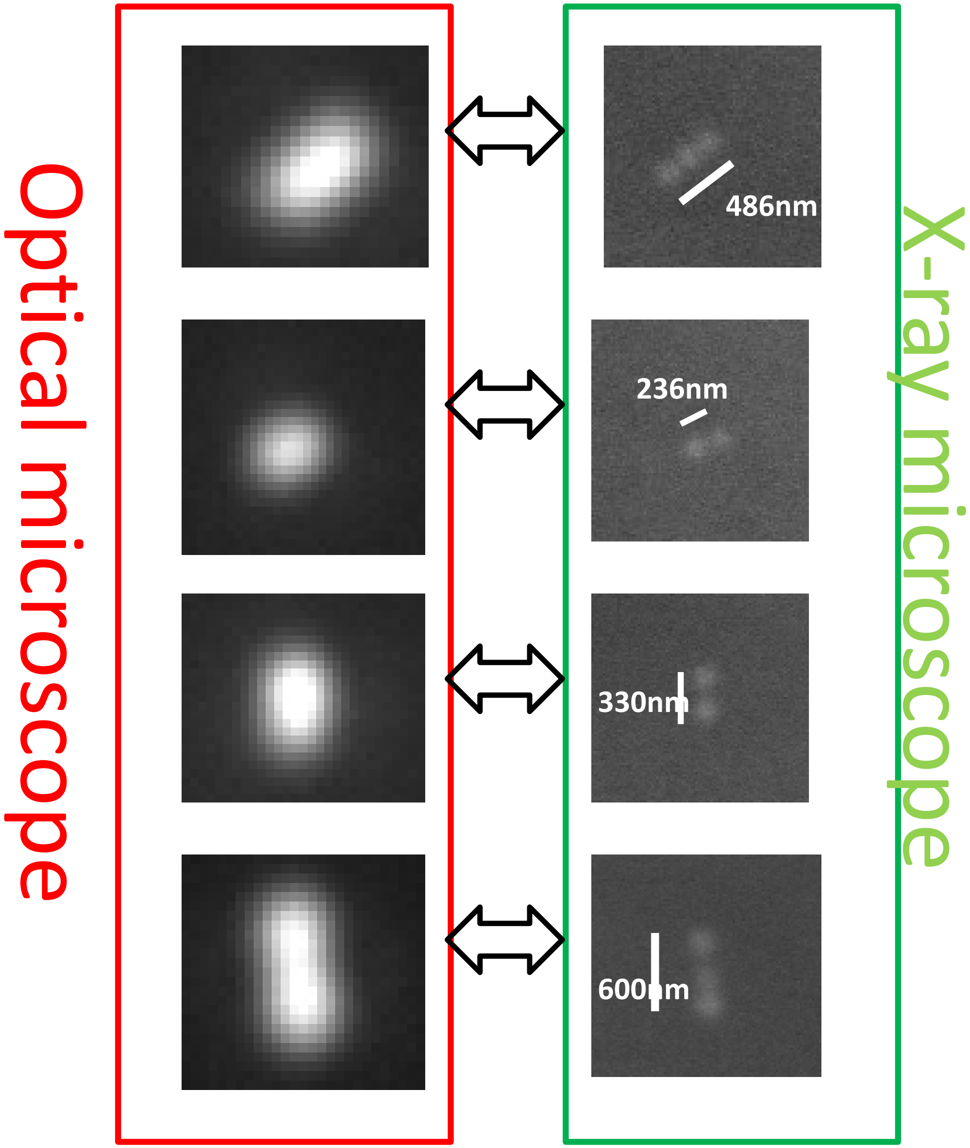
Current selection is used the simple elliptical shape

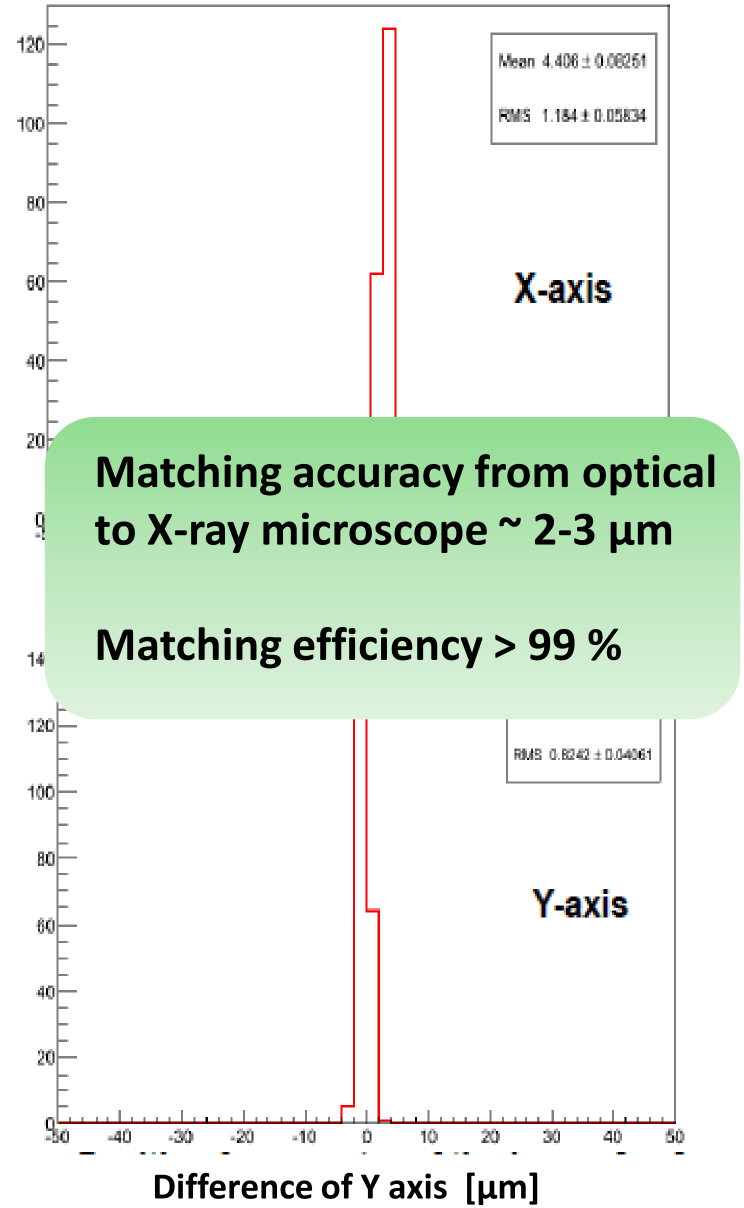
Another out put parameter
- **position information**
- **brightness**
- **area of signals**

γ/β events are expected to be distributed around Ellipticity of one.

Preliminary rejection power of electrons is better than 1E-3 by using other parameter, but it is under study.

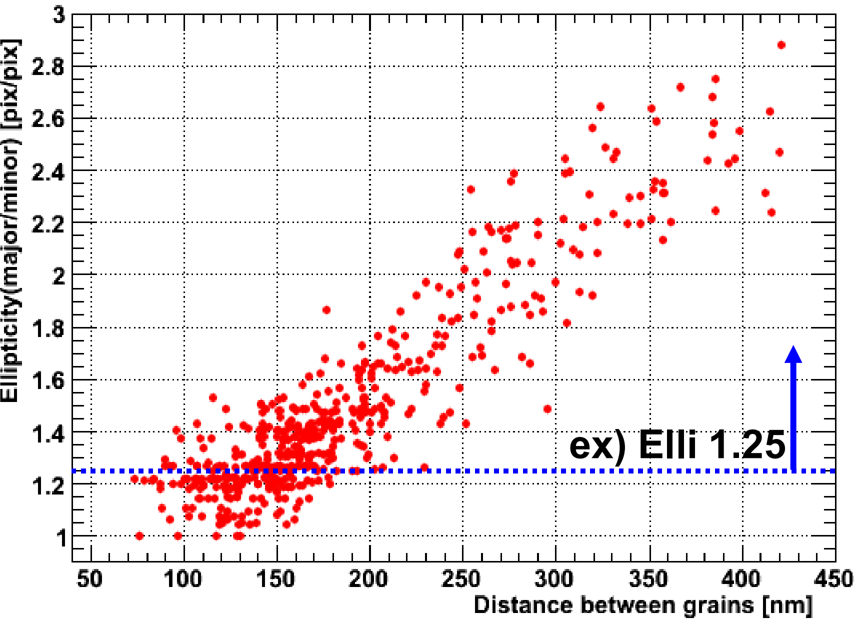
Confirmation of selected candidate events by the X-ray microscope system





Matching accuracy from optical to X-ray microscope ~ 2-3 μm

Matching efficiency > 99 %



Readout condition

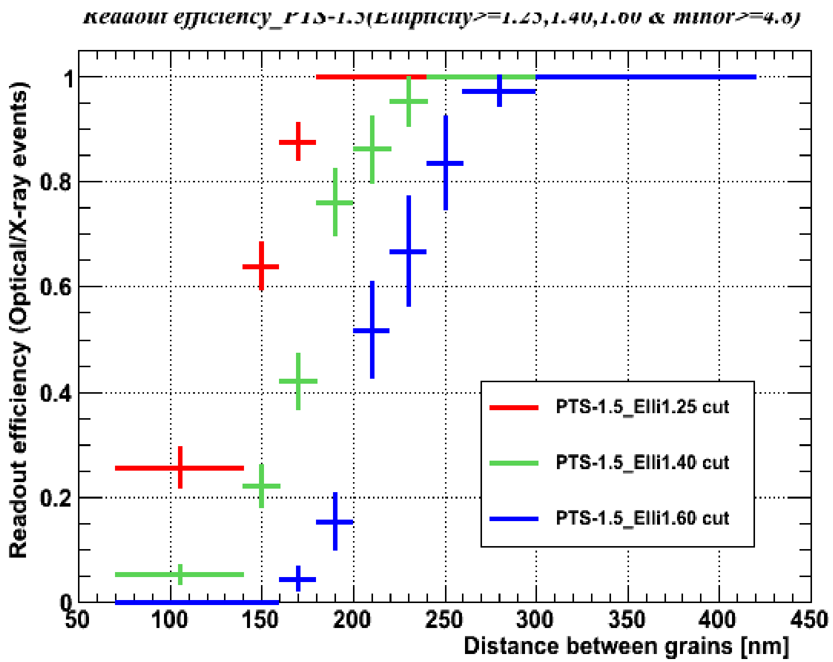
Wavelength : 450 nm (blue light)

N.A. (numerical apperture) of obj. lens : 1.4

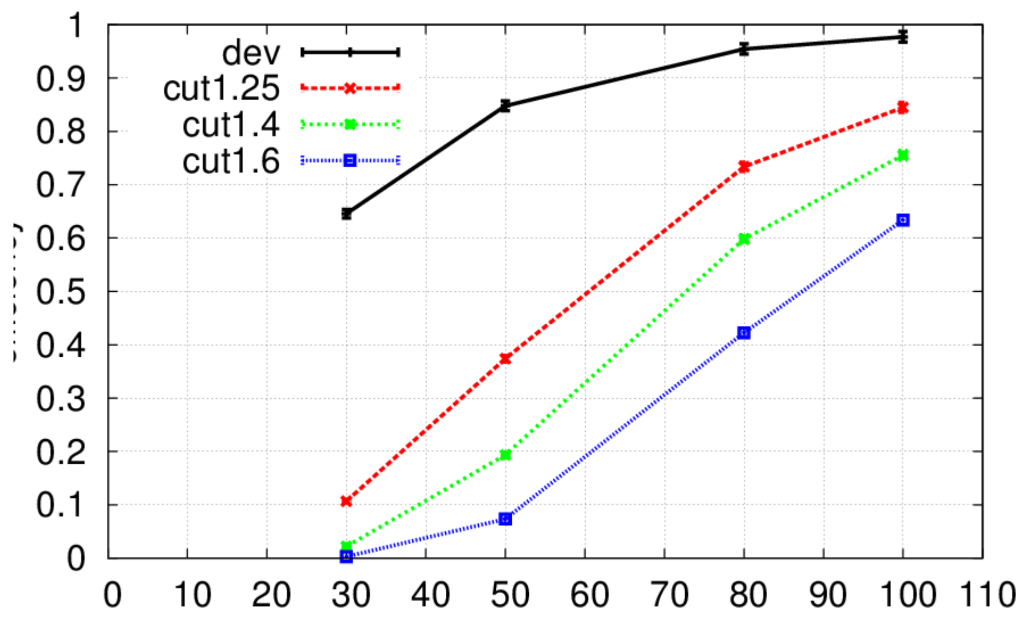
✓ > 170 nm tracks have 100 % readout efficiency.

✓ short length tracks(~ 100 nm) can be read out by mechanical expansion technique.

(M. Kimura and T. Naka, NIMA, Vol. 680,11 (2012))

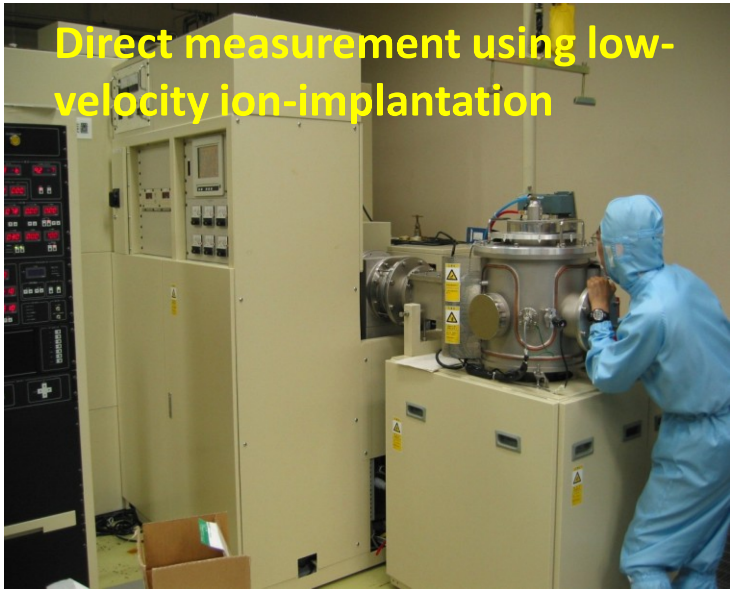


Simulation of detector performance taken into account the readout efficiency



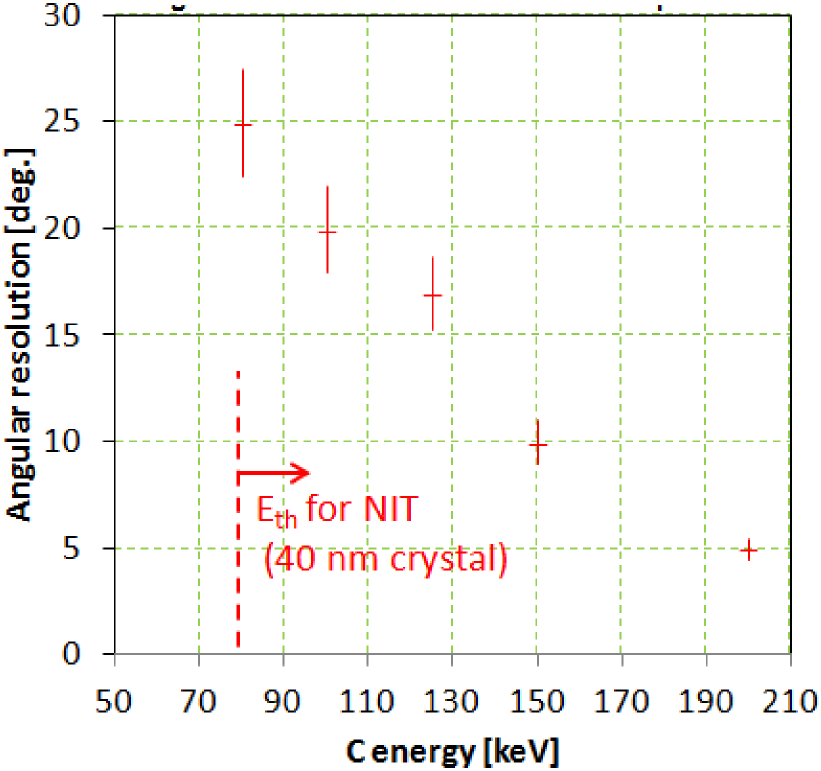
Carbon nuclear recoil energy [keV]

Angular resolution for 40 nm crystal NIT



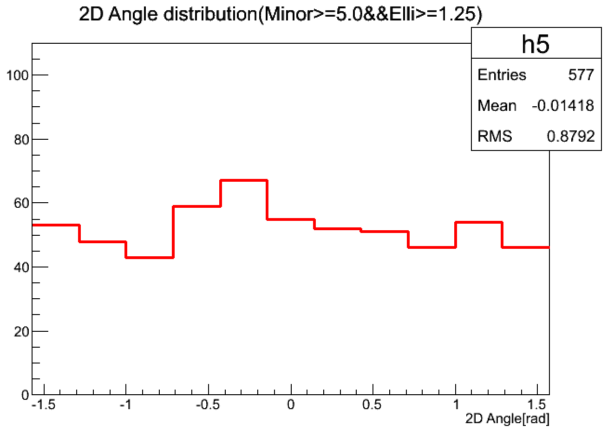
Accelerate voltage : > 10 keV (Max.200 kV)
Type of ions : C, O, Ar (from CO_2/Ar gas)
Kr (from Kr gas), F, B (from BF_3 gas)
IT is good calibration for sirect detection of nuclear recoil because of uniform direction and energy.

Angular resolution of detector



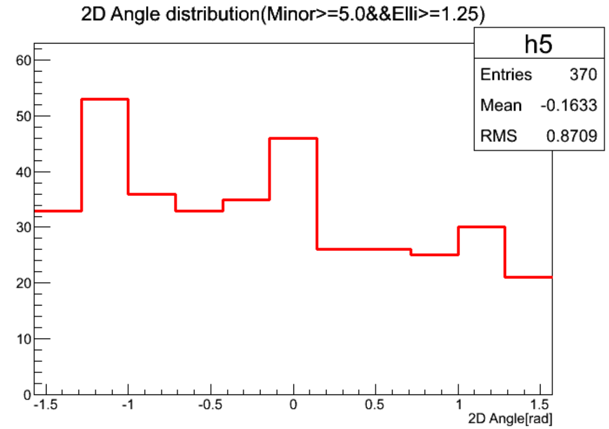
Demonstration of Angular Distribution Measurement

Mean range : 240 nm



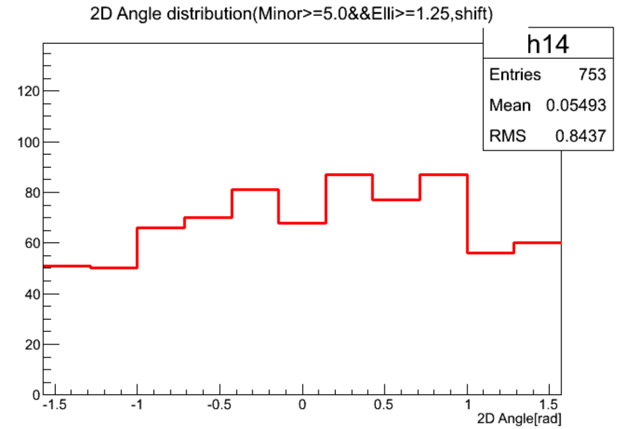
2D angle [rad.]

Mean range : 180 nm



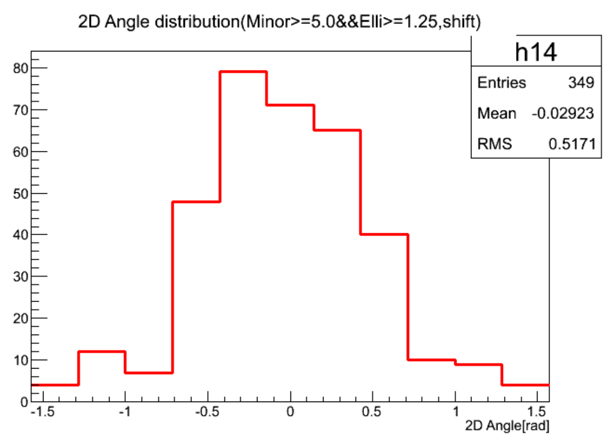
2D angle [rad.]

Mean range : 120 nm

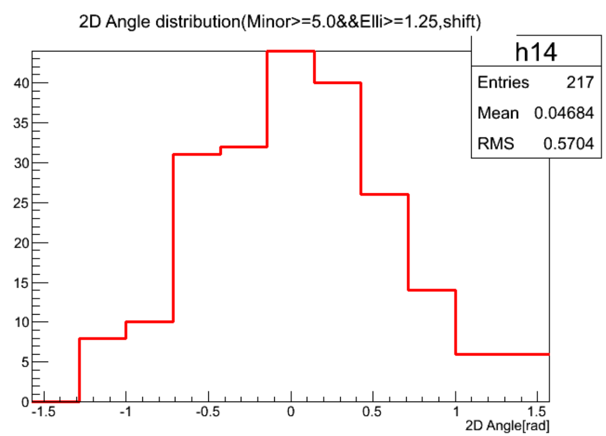


2D angle [rad.]

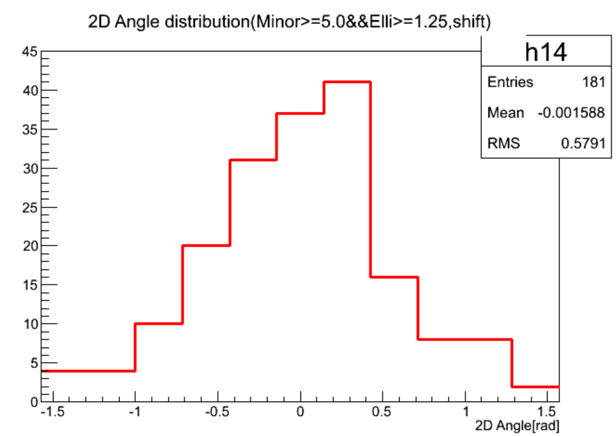
Vertically Ion Exposure



2D angle [rad.]



2D angle [rad.]



2D angle [rad.]

Horizontally ion exposure

Summary and Prospect

- **Self-production of the super high resolution was achieved.**

NIT : 40 nm crystal ⇒ideal Eth > 25 keV (2 grains) and > 50 keV (3 grains) @ 50 % eff.

U-NIT: 20 nm crystal ⇒ ideal Eth > 15 keV (2 grains) and > 30 keV (3 grains) @ 50 % eff.

- **Prototype Readout system started to run.**

1. combined system with optical microscope ⇔ X-ray microscope
2. 100 % readout efficiency for > 170 nm tracks
3. Angular resolution for NIT ⇒ better than 30 deg. at 80 keV C recoil.

Future technology

Super-resolution readout method using Plasmon effect

⇒ 50 nm resolution will be achieved in the optical microscope.

Background rejection

we started the background measurement to understand the serious backgrounds

Now, we are developing the new device with threshold for dE/dx .