Specifications of silicon sensor for g-2/EDM

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20/02/2014 @LPNHE

Outline

- Muon g-2/EDM experiment at J-PARC (E34)
- Specification of silicon strip sensor
- Estimation of sensor alignment
- Producing and evaluate test sensors

Magnetic & electric dipole moment

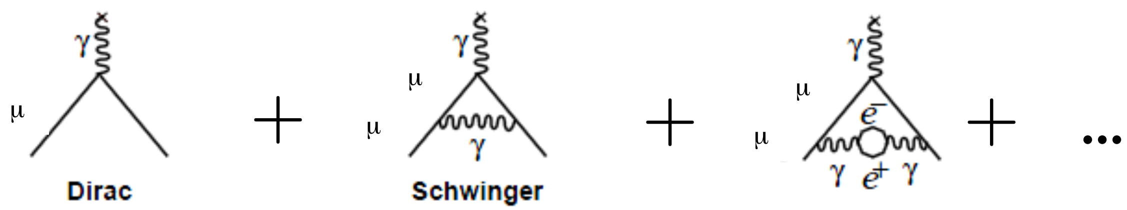
Anomalous magnetic moment (*g*-2)

$$\overrightarrow{\mu} = g\left(\frac{q}{2m}\right)\overrightarrow{s}$$

$$a_\mu = \frac{g-2}{2}$$

Dirac equation → g=2
Quantum effect → g≠2

g =



experiment ⟺ SM (theory)
3.3 σ discrepancy

$$\overrightarrow{d} = \eta\left(\frac{q}{2mc}\right)\overrightarrow{s}$$

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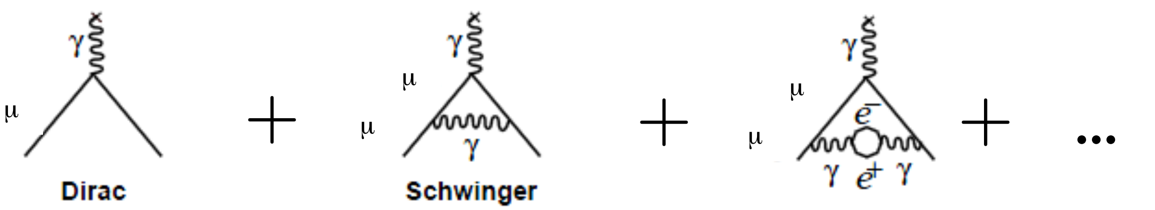

experiment ⟺ SM (theory)

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Electric dipole moment (EDM)

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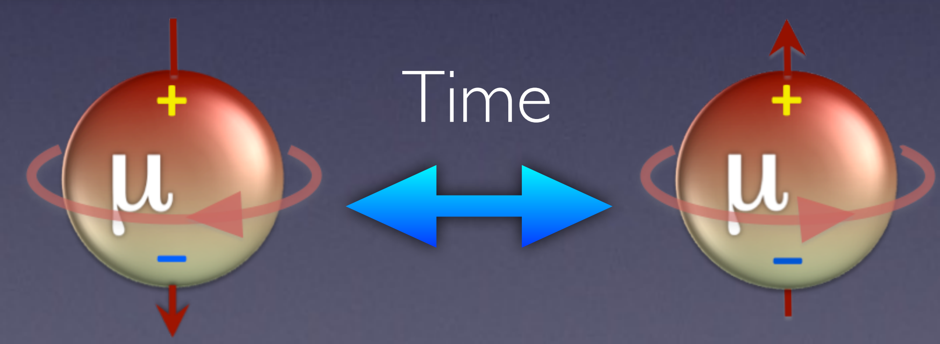

T is violated

→CP is violated because of CPT theory

Magnetic & electric dipole moment

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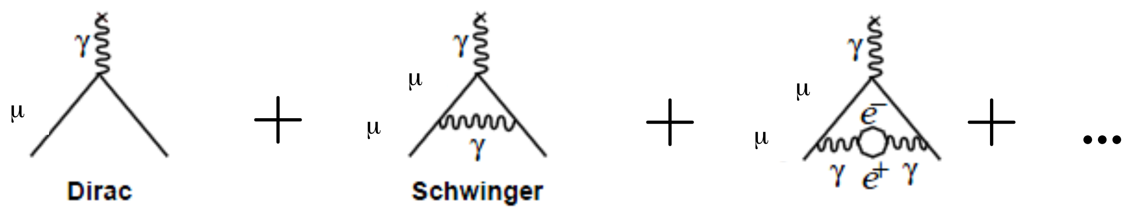

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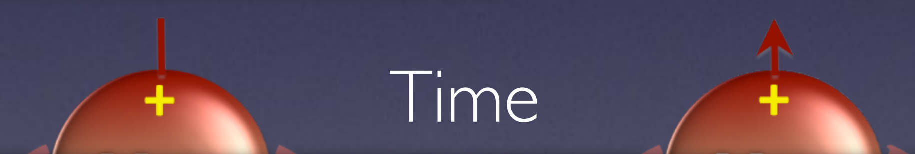
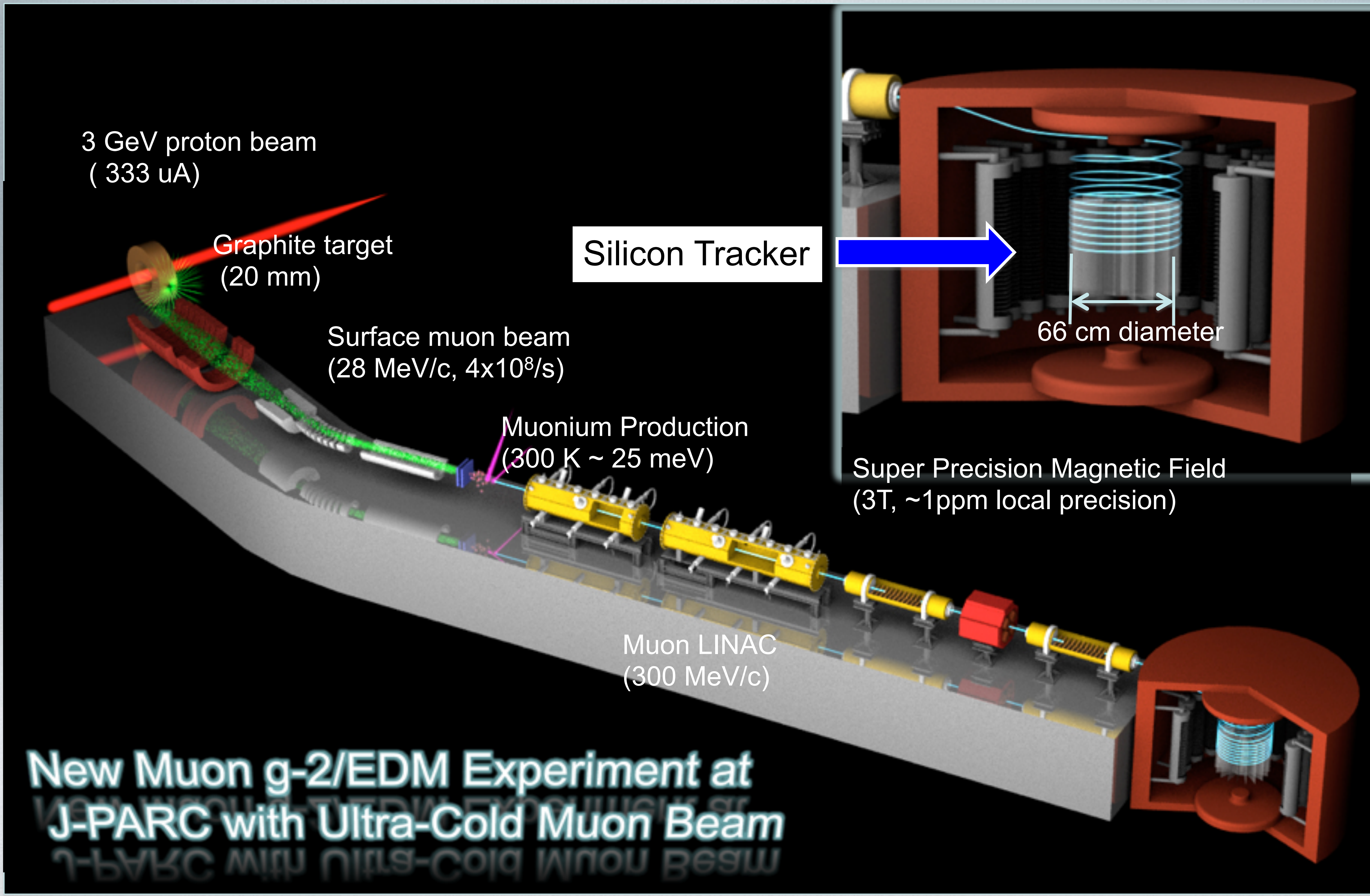


***g*−2 ： 0.54 ppm → 0.1 ppm**

EDM ： 1.8×10^{-19} e・cm → 10^{-21} e・cm

ry

J-PARC muon *g*-2/EDM experiment (E34)

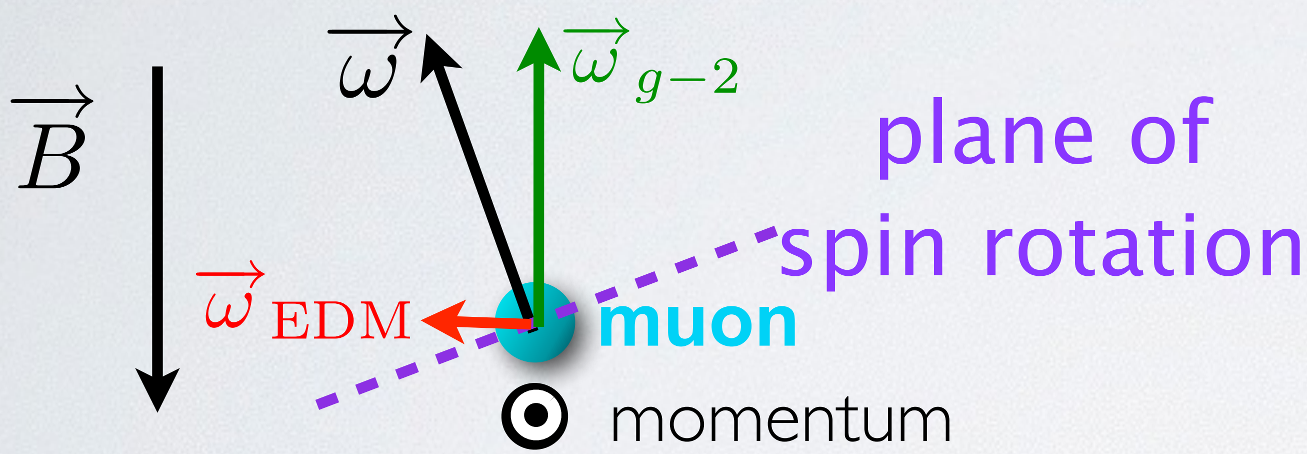


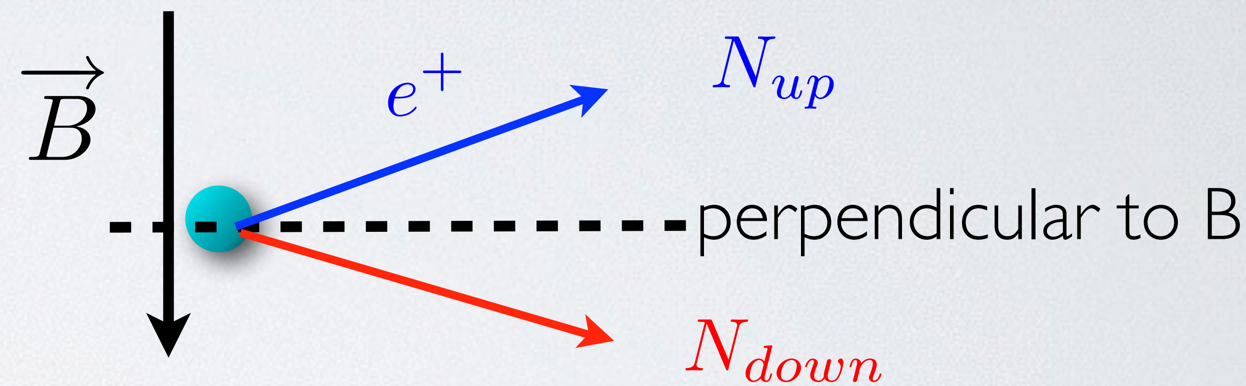
How to measure g-2/EDM

- spin precession w/ continuous B field and E field =0,

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right] \qquad a_\mu = \frac{g-2}{2} \qquad \vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s} \qquad \vec{d} = \eta\left(\frac{q}{2mc}\right)\vec{s}$$

g−2 EDM





ω tilt because of $\omega_{\rm EDM}$.

$\omega_{\rm EDM}$ is smaller than $\omega_{g\text{-}2}$.

If EDM $d_\mu = 10^{-21}$ e・cm, angle between $\vec{\omega}$ and $\vec{B}$ =10 μrad

measure ω and B precisely

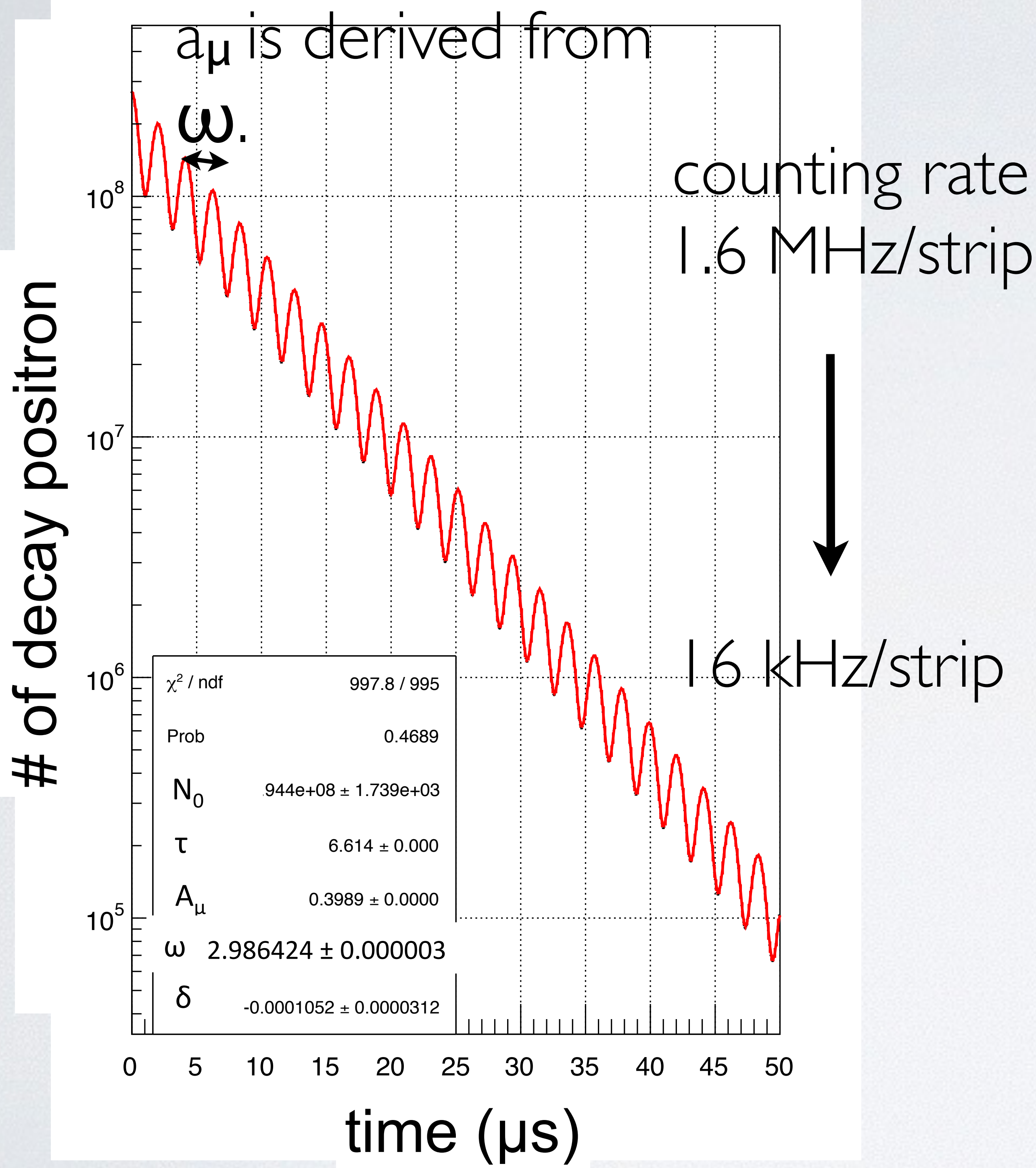
→ measure a_μ

- measure up down asymmetry $A_{UD} = \frac{N_{up} - N_{down}}{N_{up} + N_{down}}$

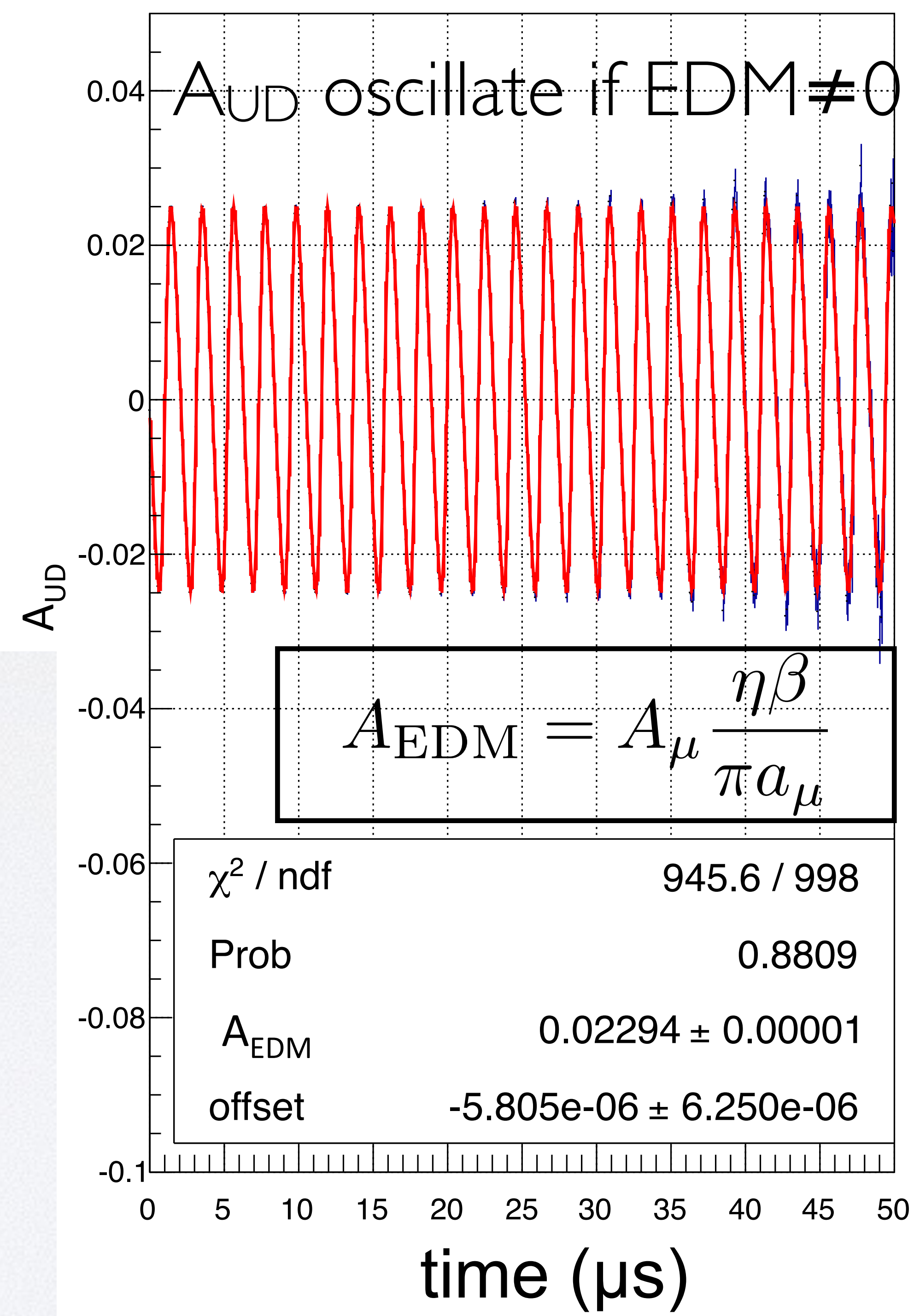
→ measure EDM

Time spectrum of decay positron and up down asymmetry

$$N_{total} = N_0 e^{-\frac{t}{\tau}} \left(1 + A_\mu \cos\left(\omega t + \delta\right)\right)$$



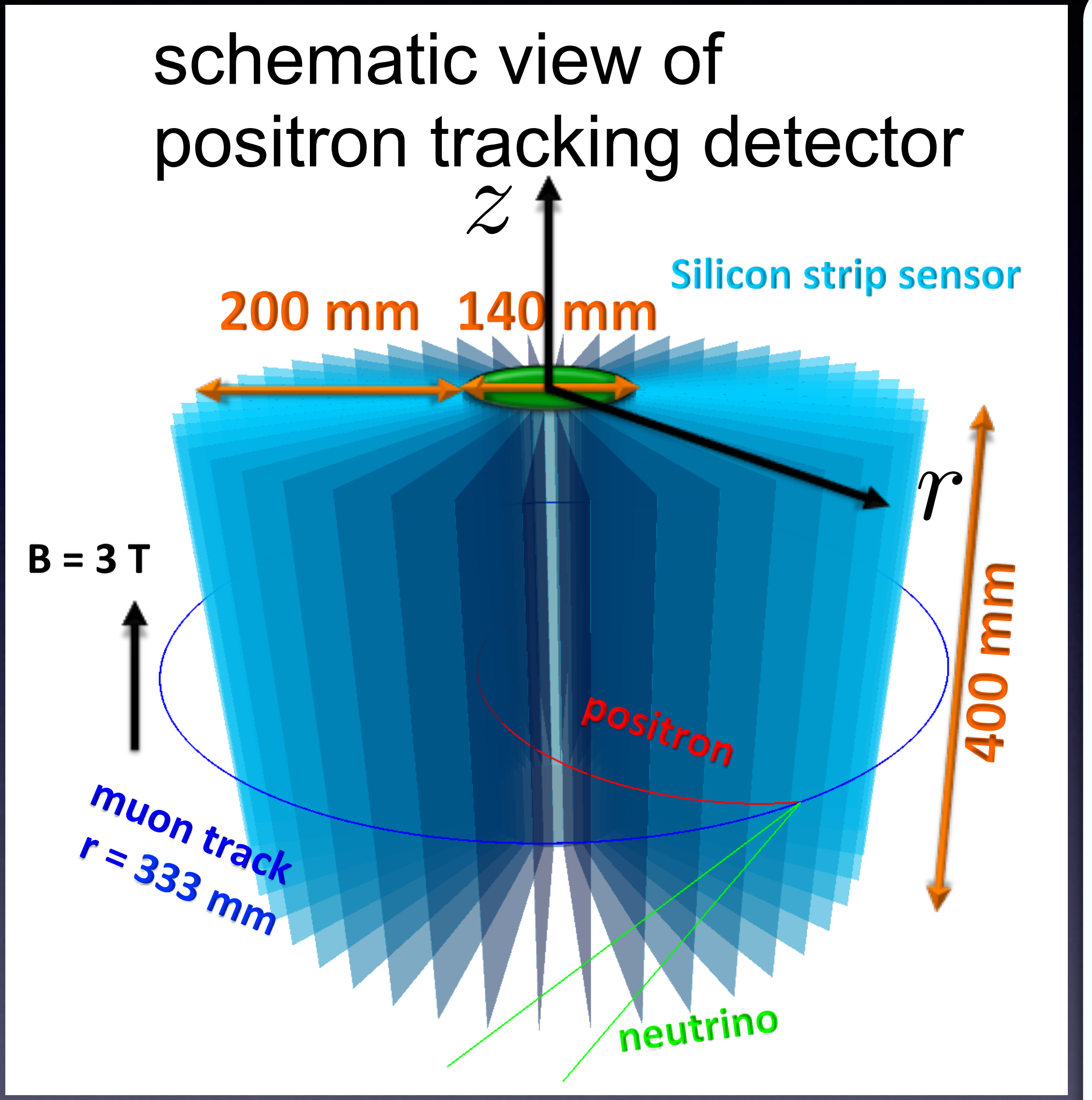
$$A_{UD} = \frac{-A_{\mathrm{EDM}} \sin(\omega t + \delta)}{1 + A_\mu \cos(\omega t + \delta)}$$

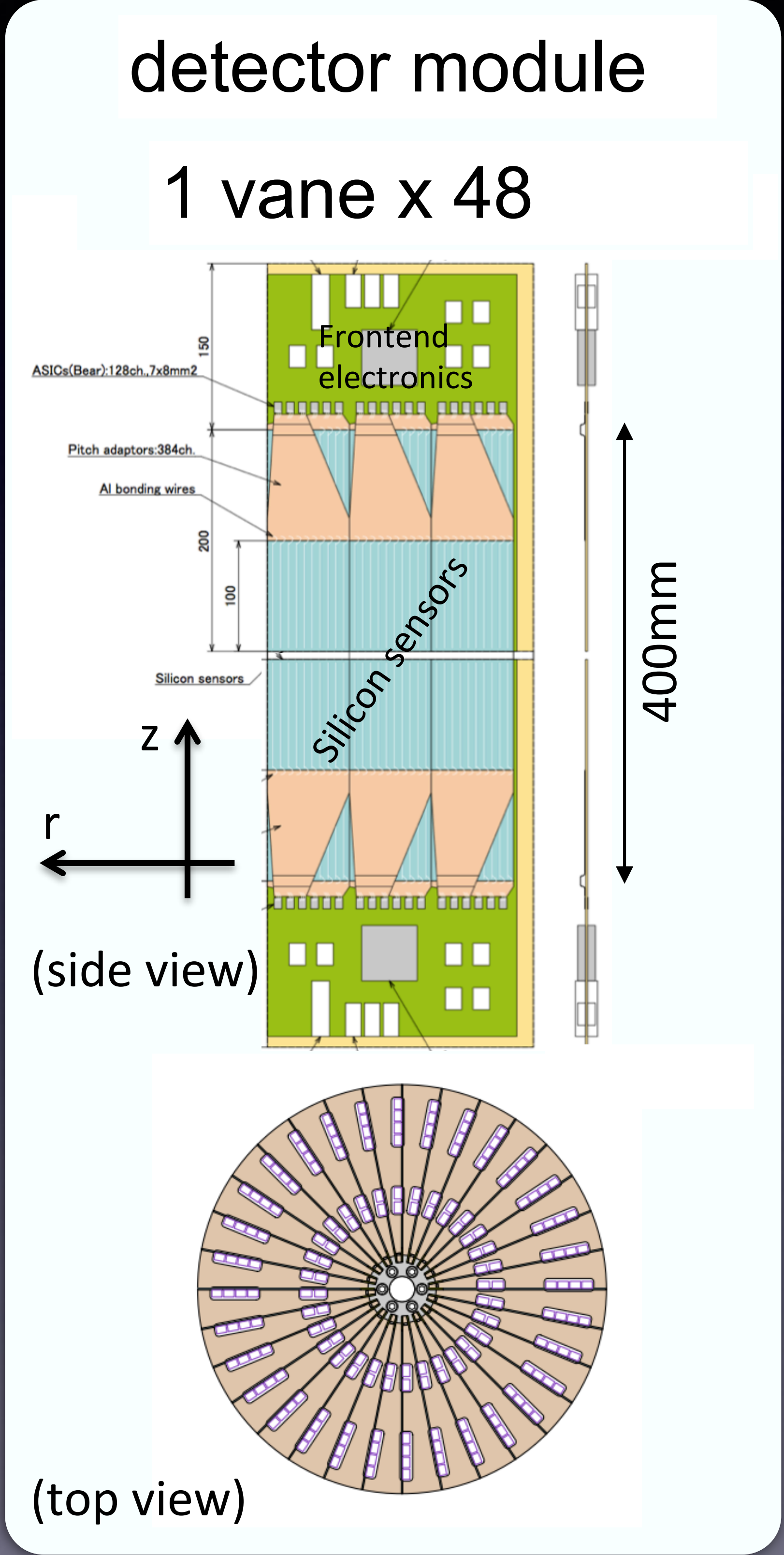


$$d_\mu = 1 \times 10^{-17}\ \mathrm{e \cdot cm}$$
$$1.5 \times 10^{11}\ \mathrm{muon}$$

Positron tracking detector

- positron momentum
  - p>200 MeV/c
- amplitude of spin oscillation
  - ~10 μrad





high rate beam

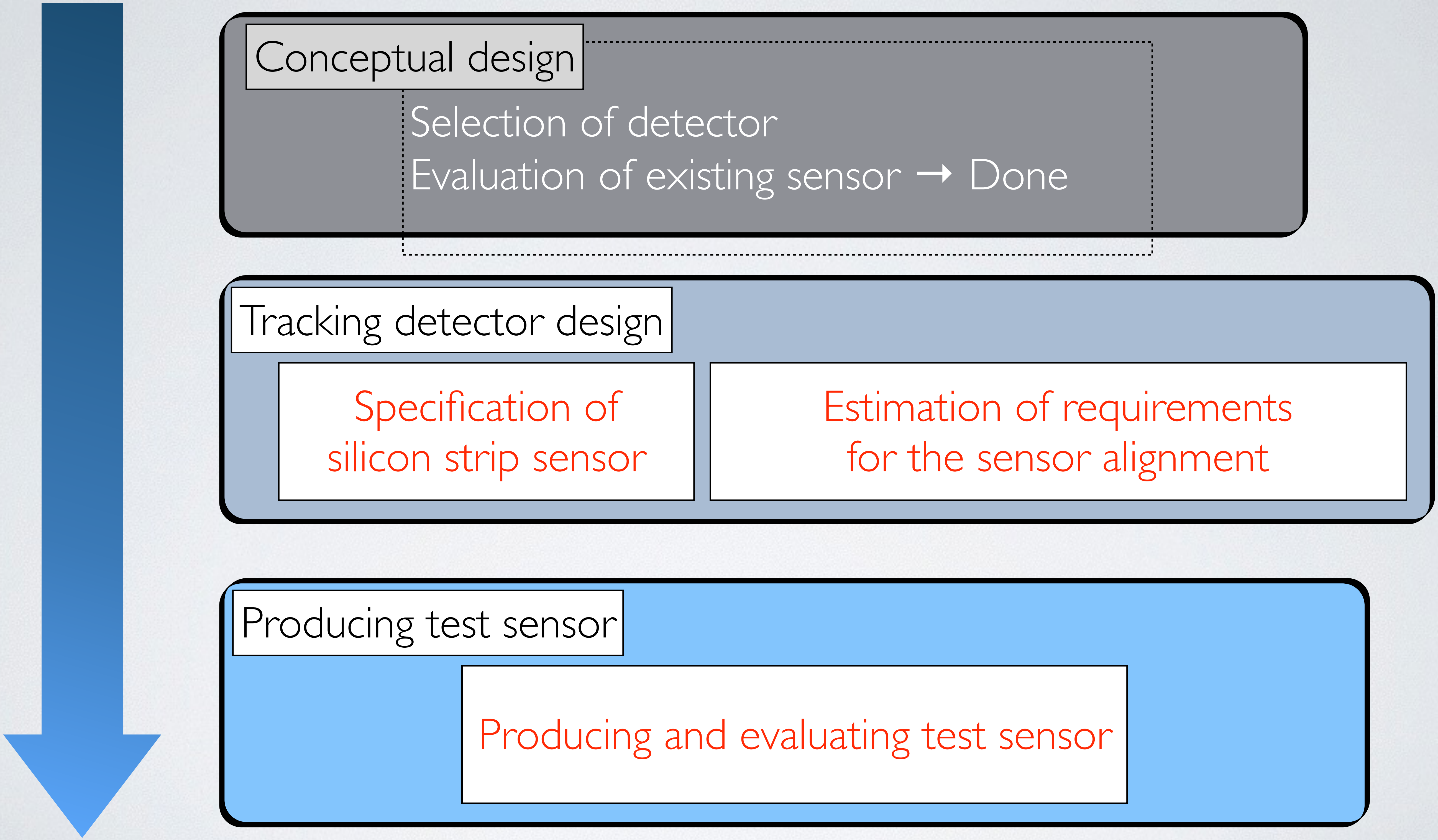
- high granularity
- fast response
- high stability

measure EDM highly sensitive

- high reliability

Silicon strip sensor is very useful.

Development of tracking detector



Development of tracking detector

Conceptual design

Selection of detector
Evaluation of existing sensor → Done

Tracking detector design

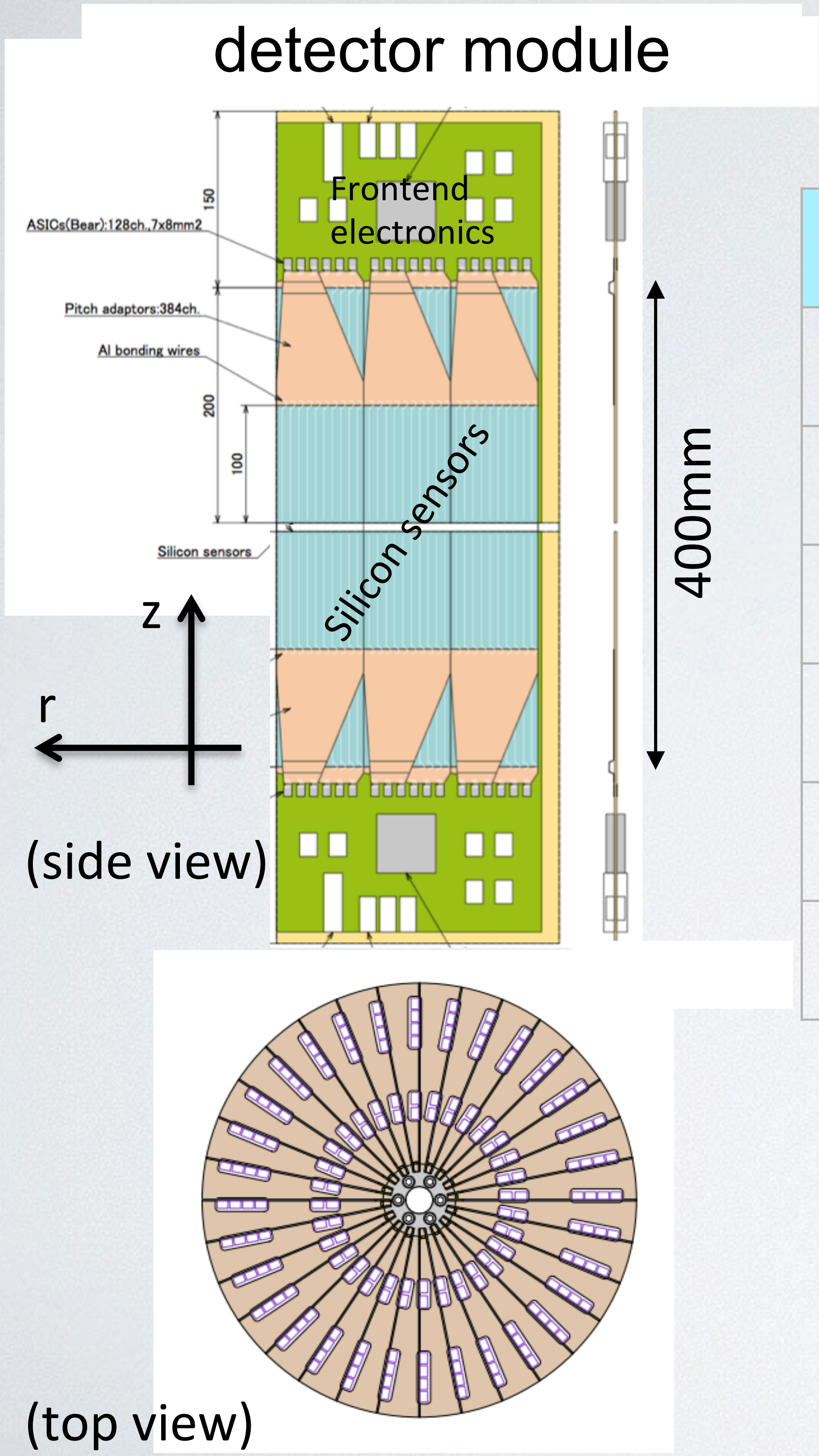
Specification of silicon strip sensor

Estimation of requirements for the sensor alignment

Producing test sensor

Producing and evaluating test sensor

Specifications of silicon strip sensor



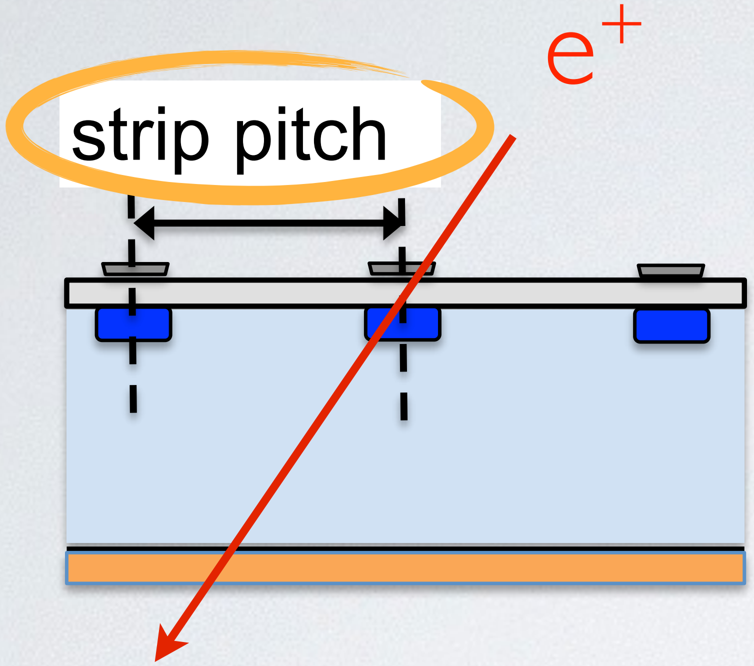
sensor spec
considering mean hit rate

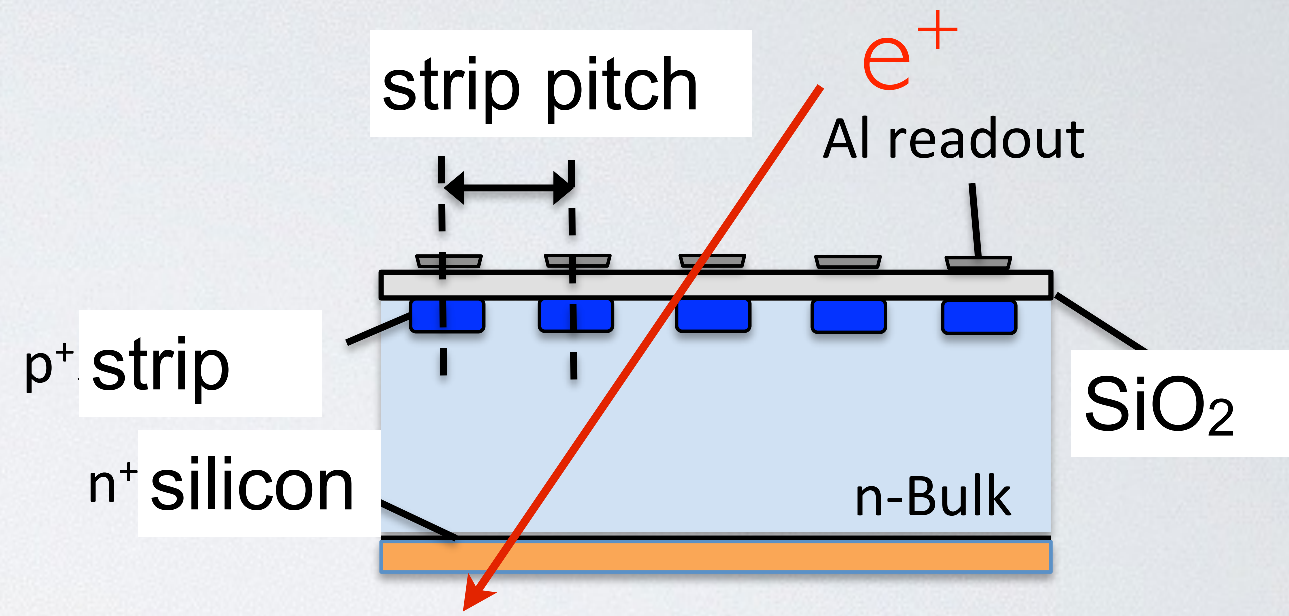
Item	Specifications
sensitive area	240 mm x 400 mm
# of vane	48
sensor size	74 mm x 98 mm x 0.32 mm
# of sensor	48 x 12 (12 sensors per vane)
radial strip (r)	0.188 mm pitch, 72 mm long
axial strip (z)	0.255 mm pitch, 98 mm long

We optimized strip spec
considering event structure

Specification of sensor strip pitch

If strip pitch becomes more narrow,





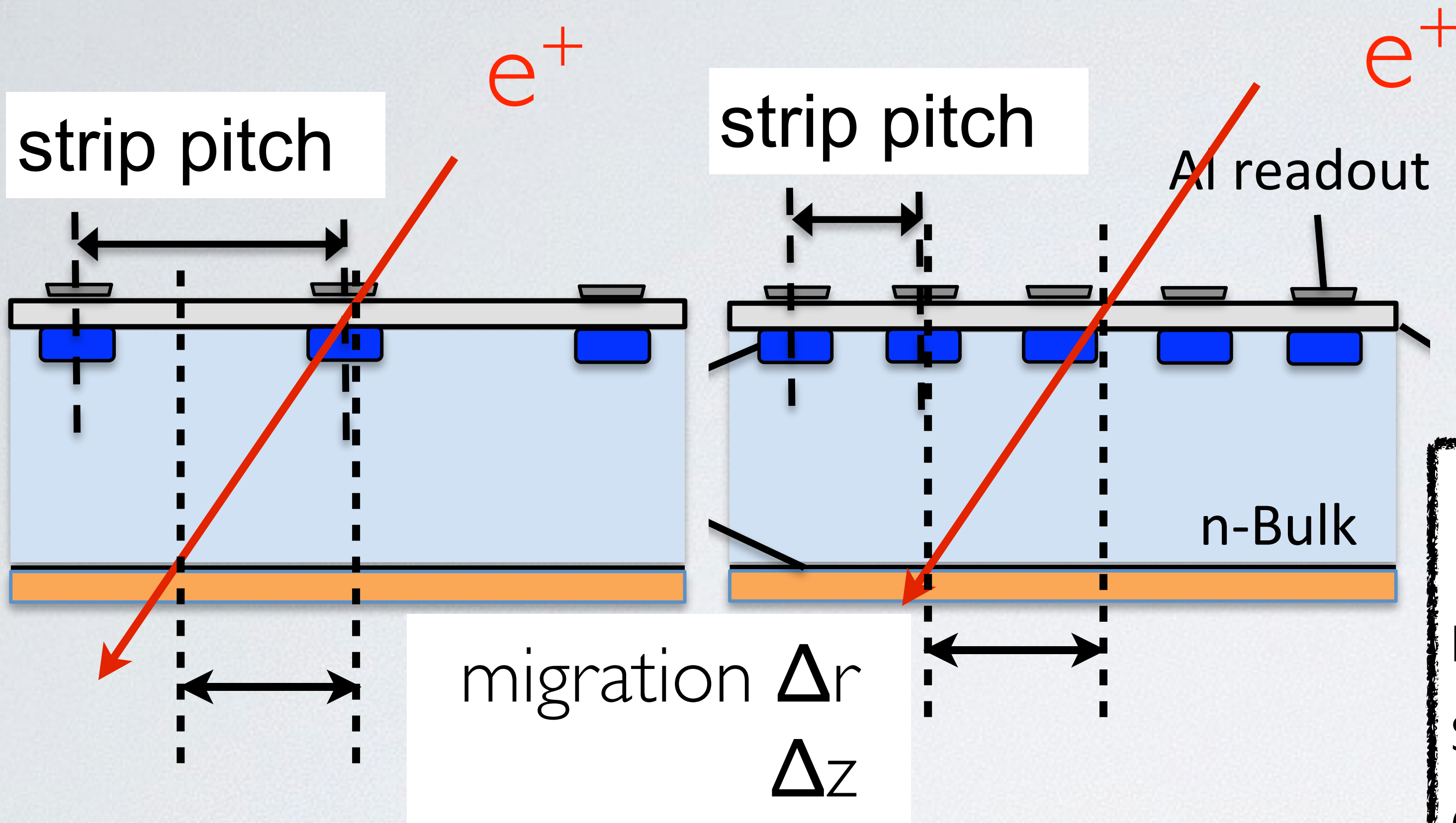
merit

- the sensor is more resistant to high rate
- position resolution become better

demerit

- handling become more difficult
- cost increase because of increasing readout channel

Relation between hit rate and strip pitch



positron migration in the sensor for

r direction :Δr

z direction :Δz

- Though strip pitch shorter than migration length of positron in the sensor, strip occupancy is not change.

Studying Δr, Δz distribution,
we specified strip pitch.

➡ Simulation study is important.

Δr, Δz is concerned about

- incident angle (0.5 rad @ 200 MeV)
- multiple scattering (0.003 rad @200 MeV)

Simulation set up

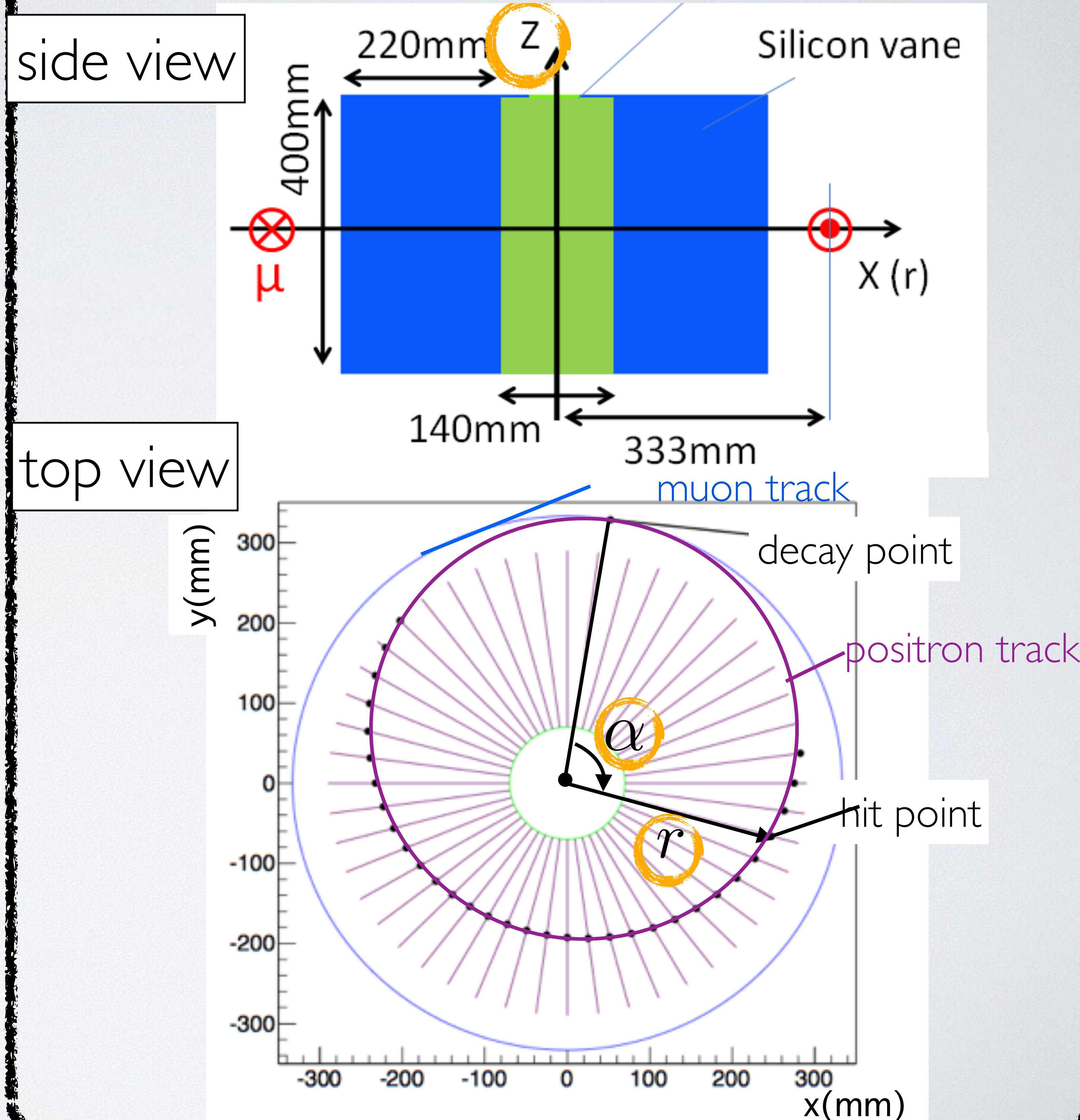
Using Geant4.9.6

✦tracking detector
- # of vane : 48
- thickness of sensor : 0.3 mm

✦Condition
- B field : 3 Tesla
- E field : 0 V/m
- γ_μ : 3 (300 MeV/c)
- in the vacuum

r : radial coordinate
z : axial coordinate
α : rotate angle from decay point

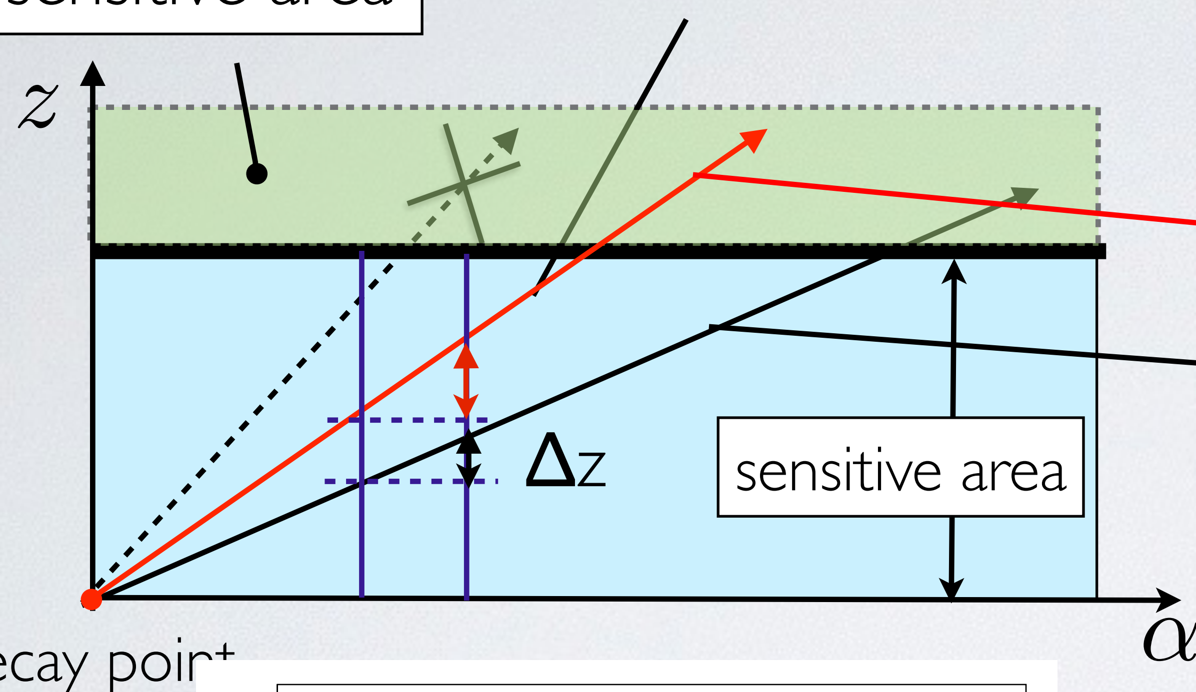
geometry and important variables

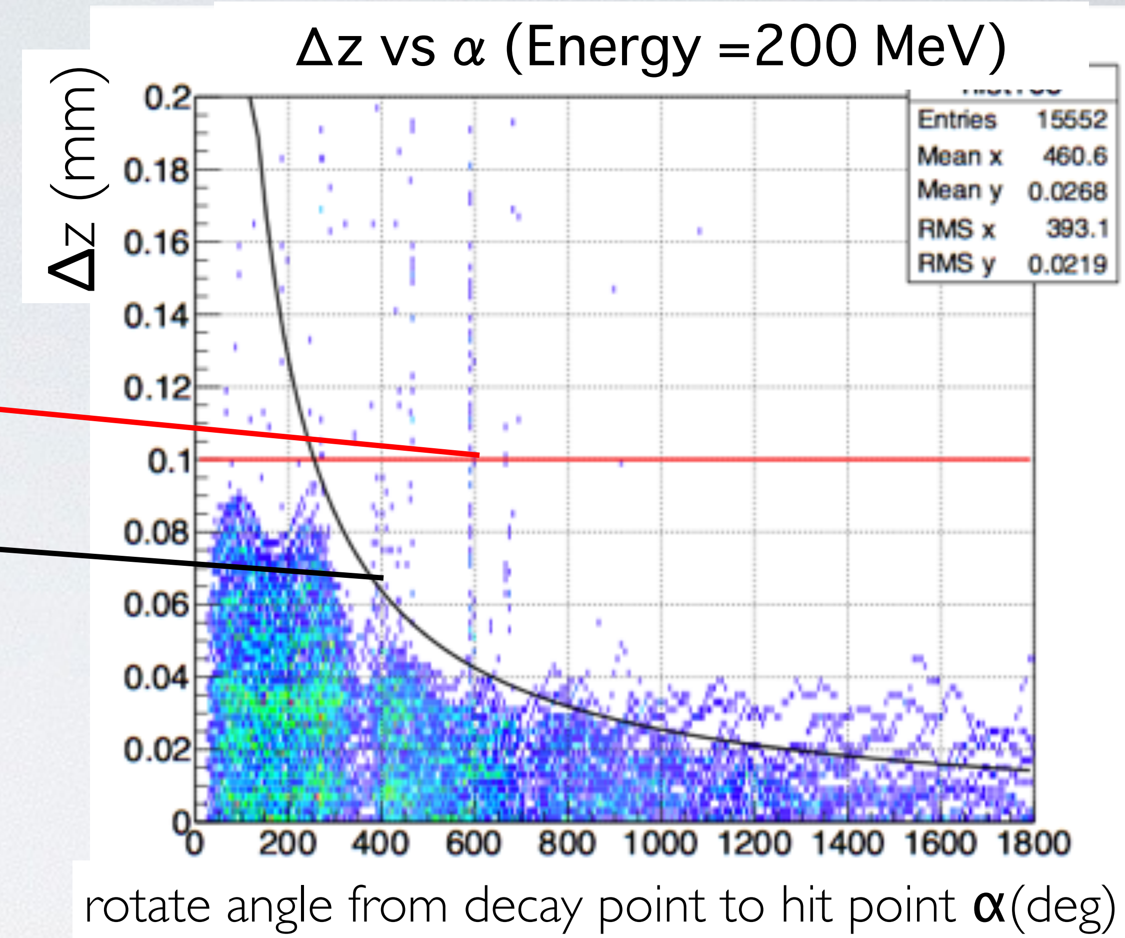


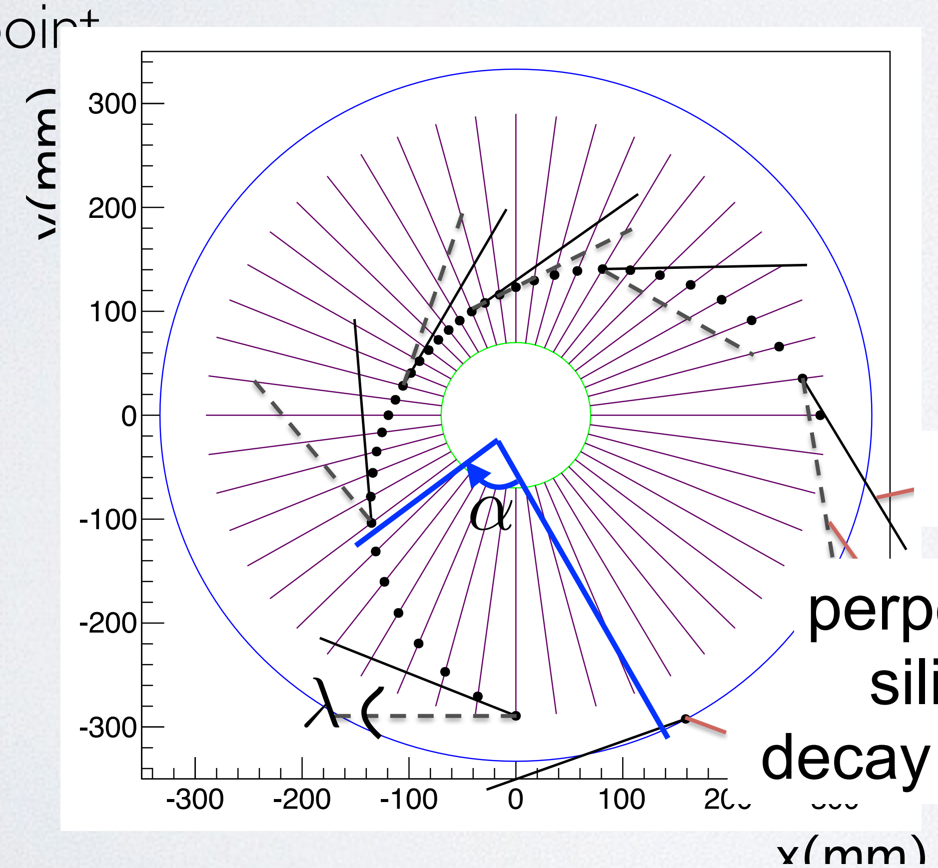
Positron migration in the sensor (Δr, Δz)

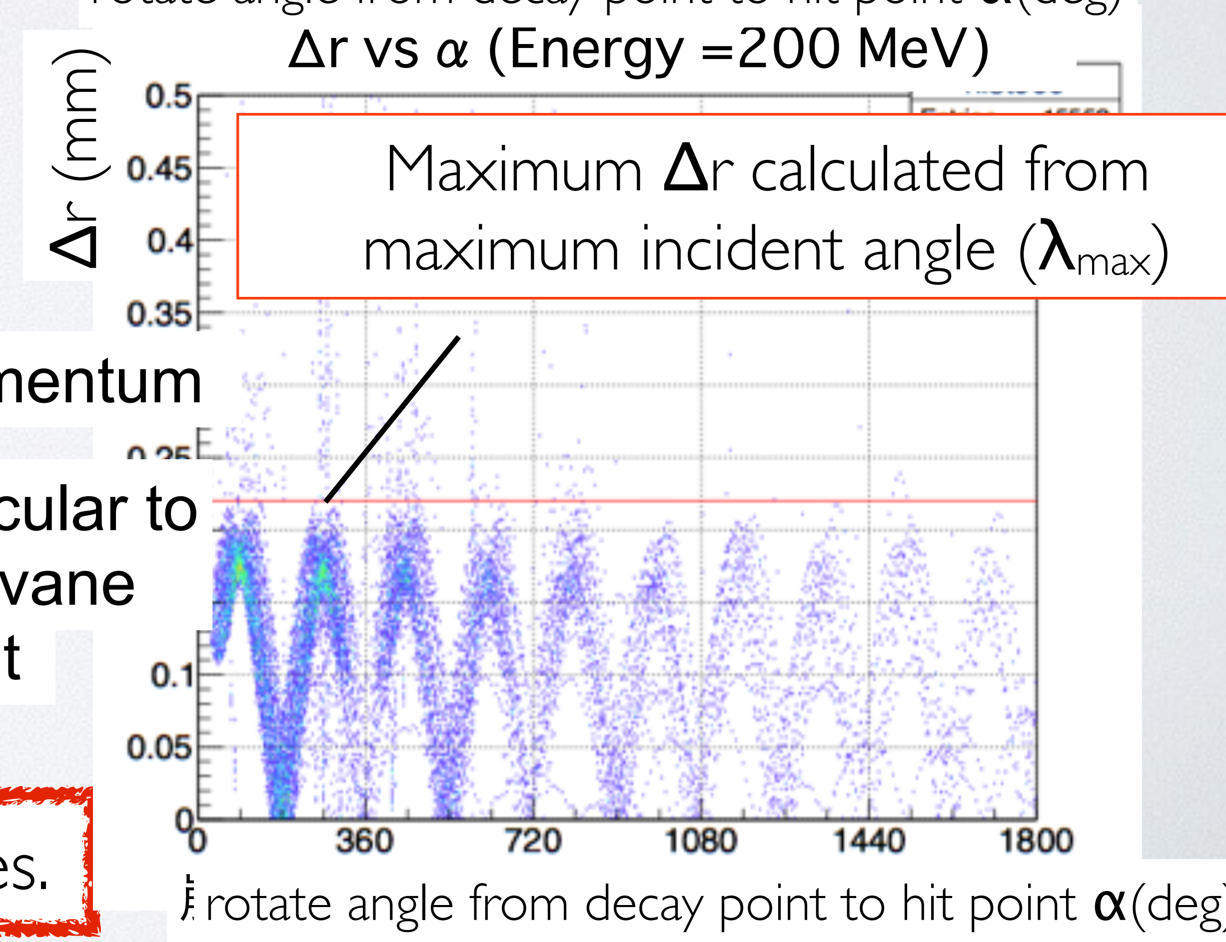
Positron goes out from sensitive area

maximum Δz



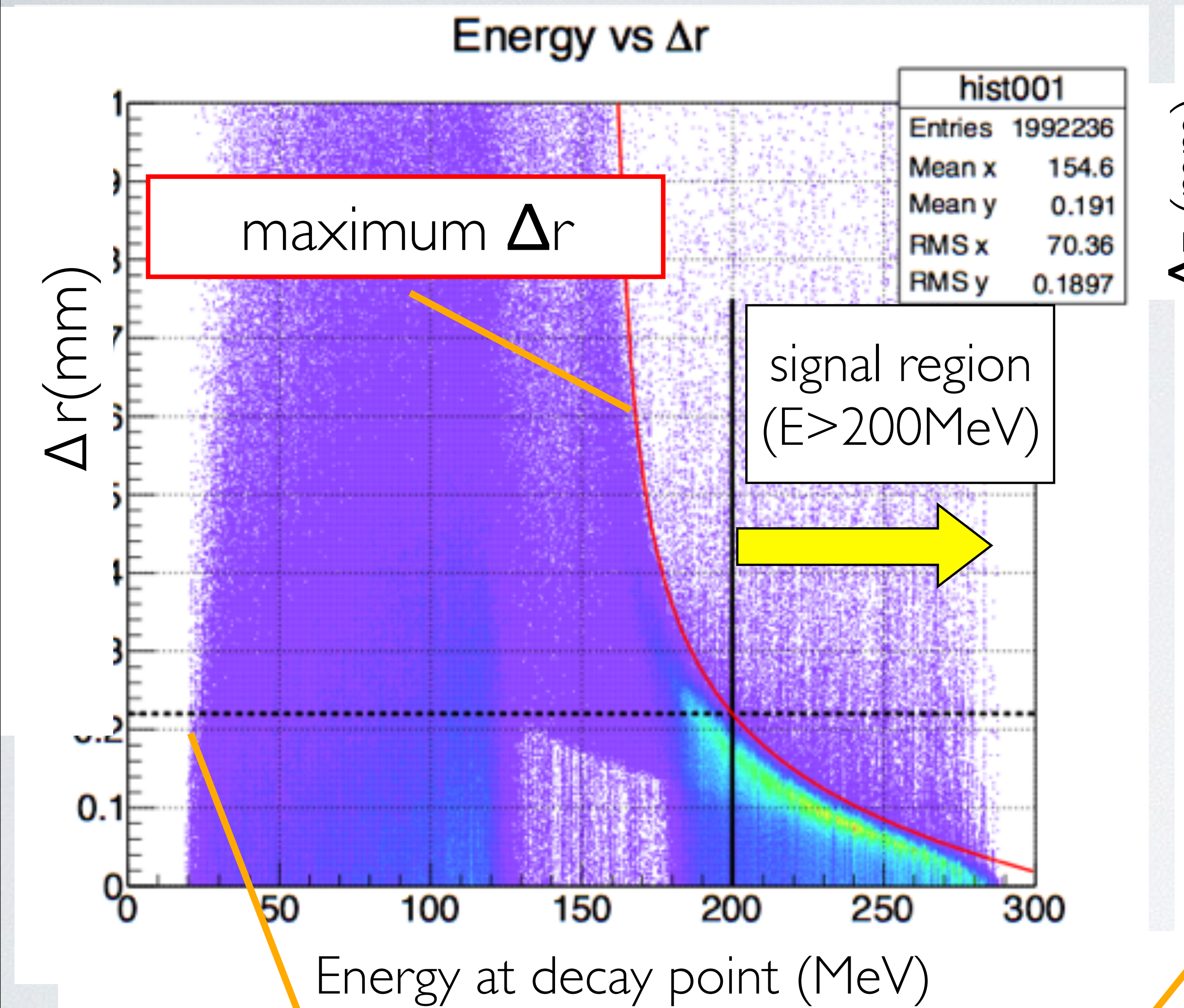


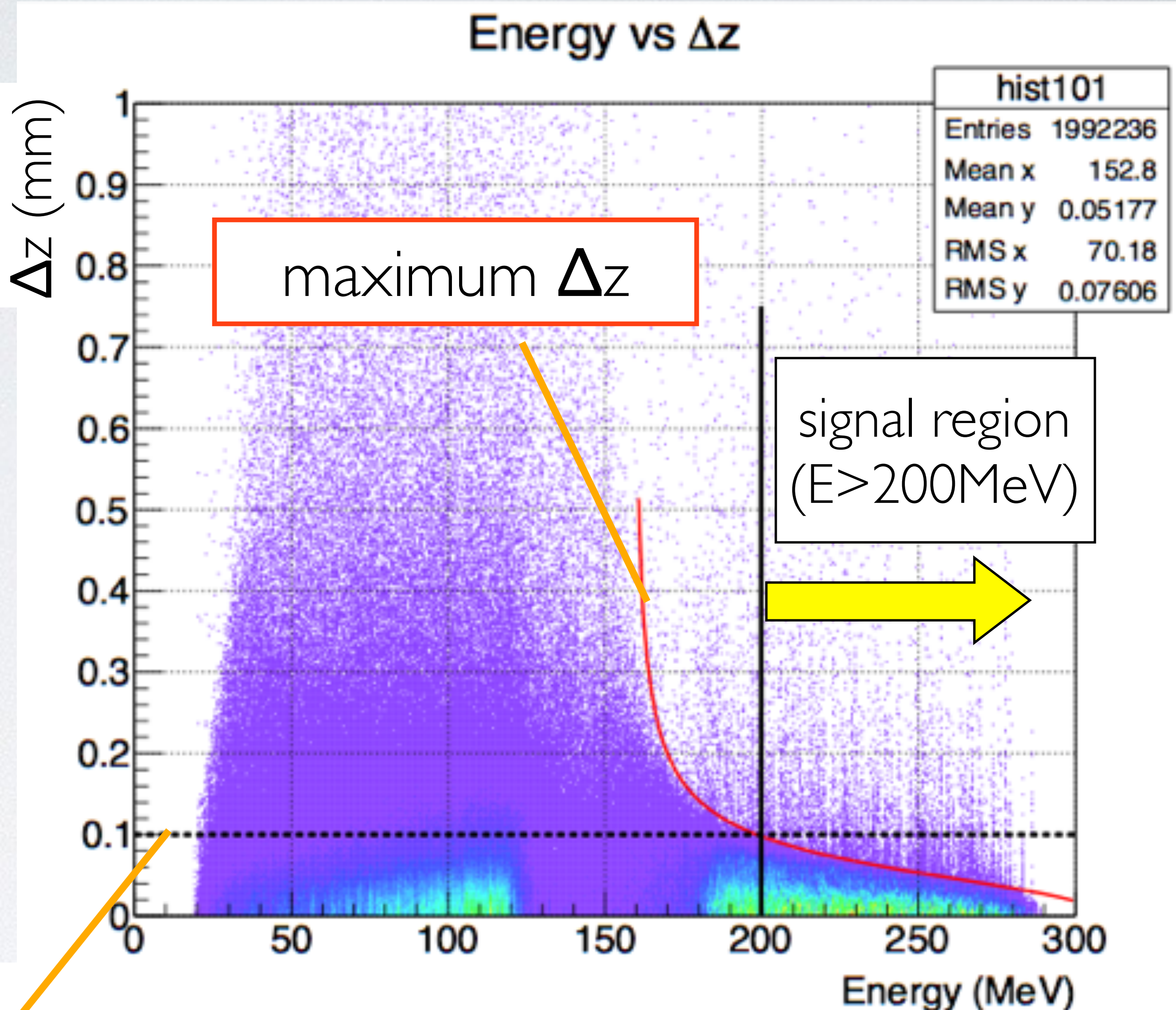




Maximum Δr & Δz are limited under red lines.

Δr ,Δz vs Energy at decay point





maximum Δr, Δz in the signal region

The limit in the signal region is

$\Delta r < 0.22$ mm

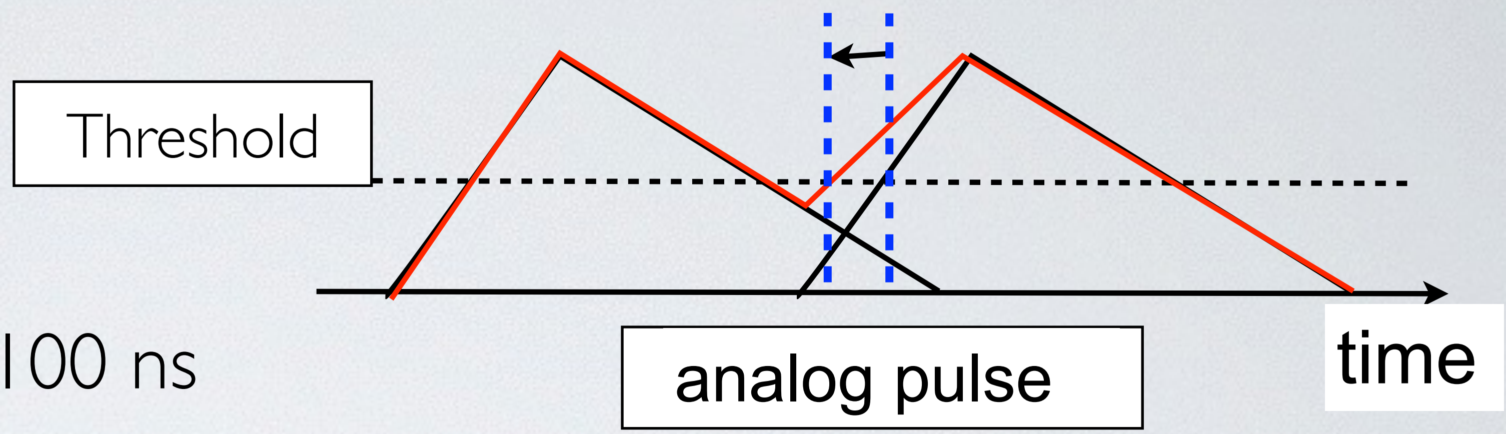
$\Delta z < 0.10$ mm

Sensor strip pitch should be
r : 0.188 mm→0.22 mm
z : 0.255 mm→0.10 mm

Requirement about hit rate

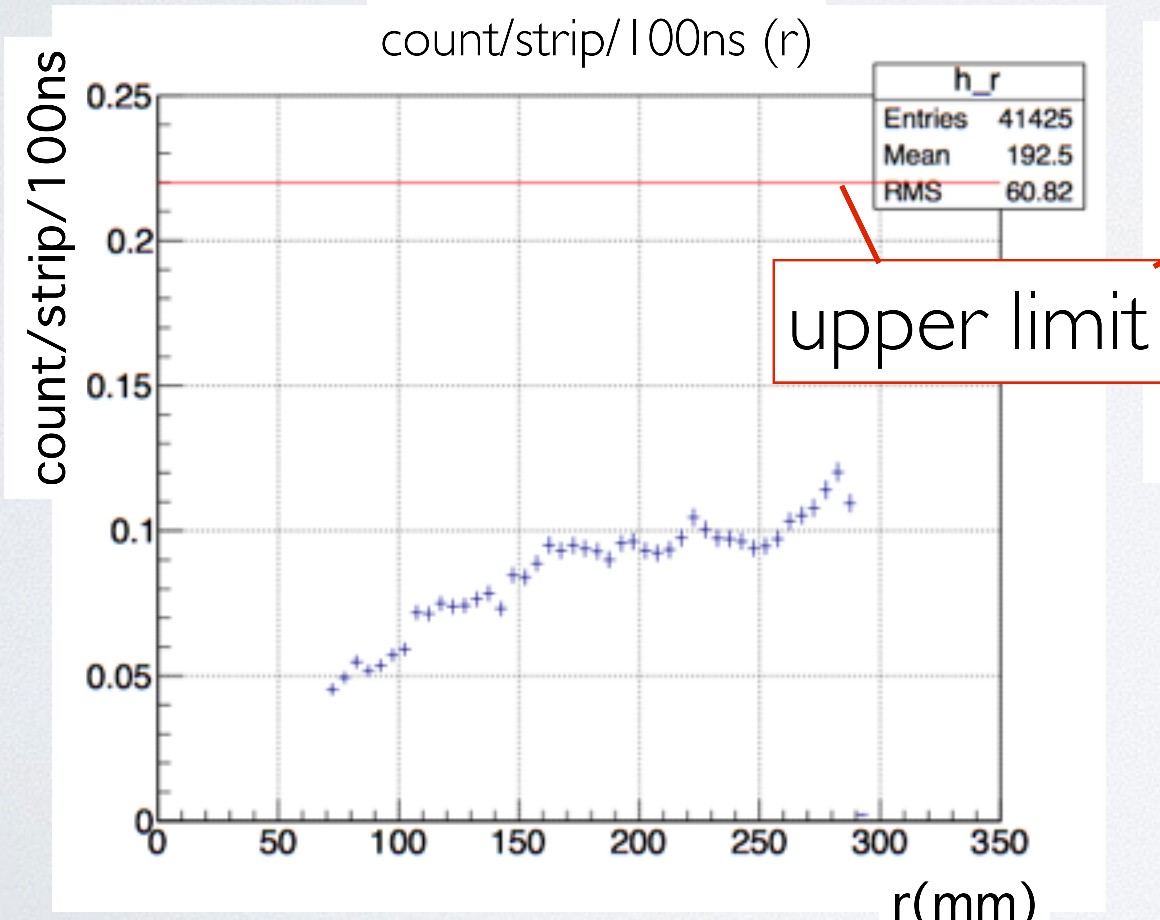
Pileup makes time spectrum of decay positron deformed.

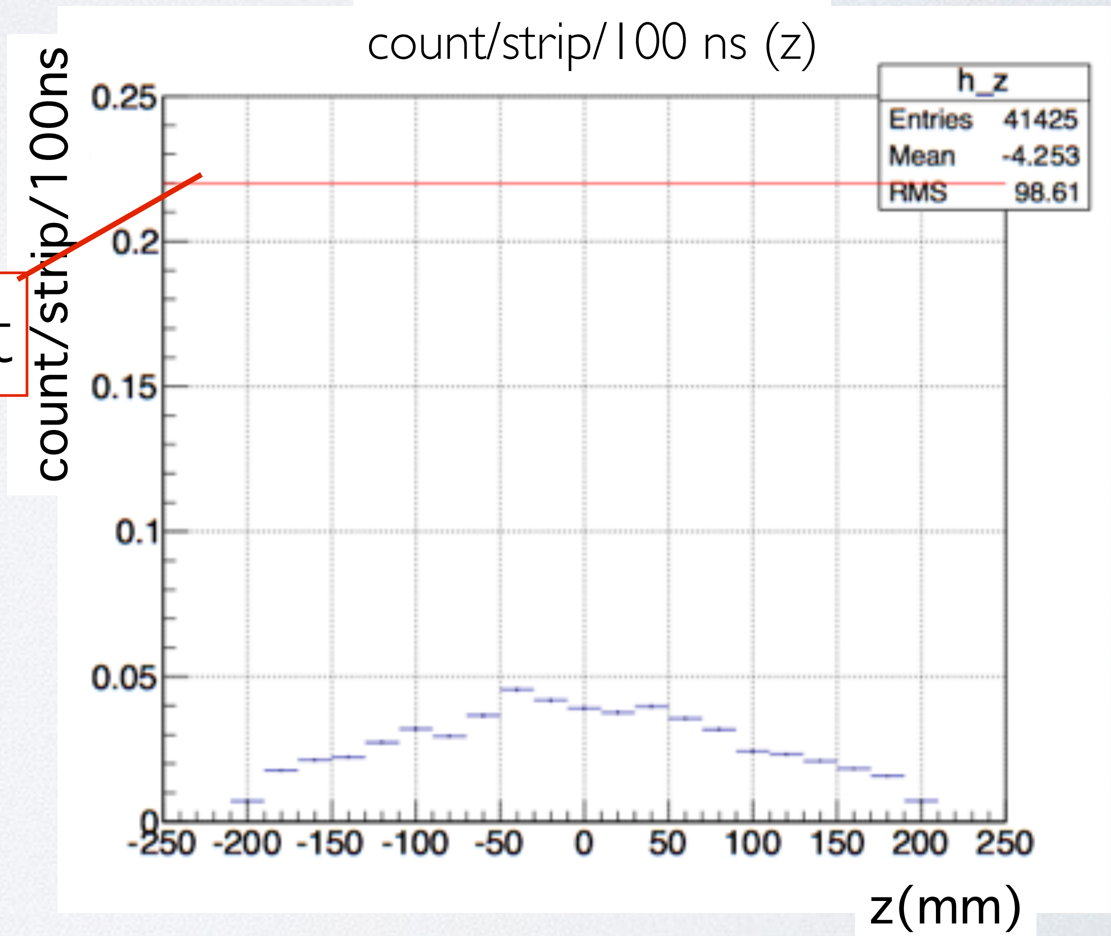
→ ω would be wrong…



Hit rate must be < 0.22 count/strip/100 ns

strip pitch	r : 0.22 mm	
	z : 0.10 mm	

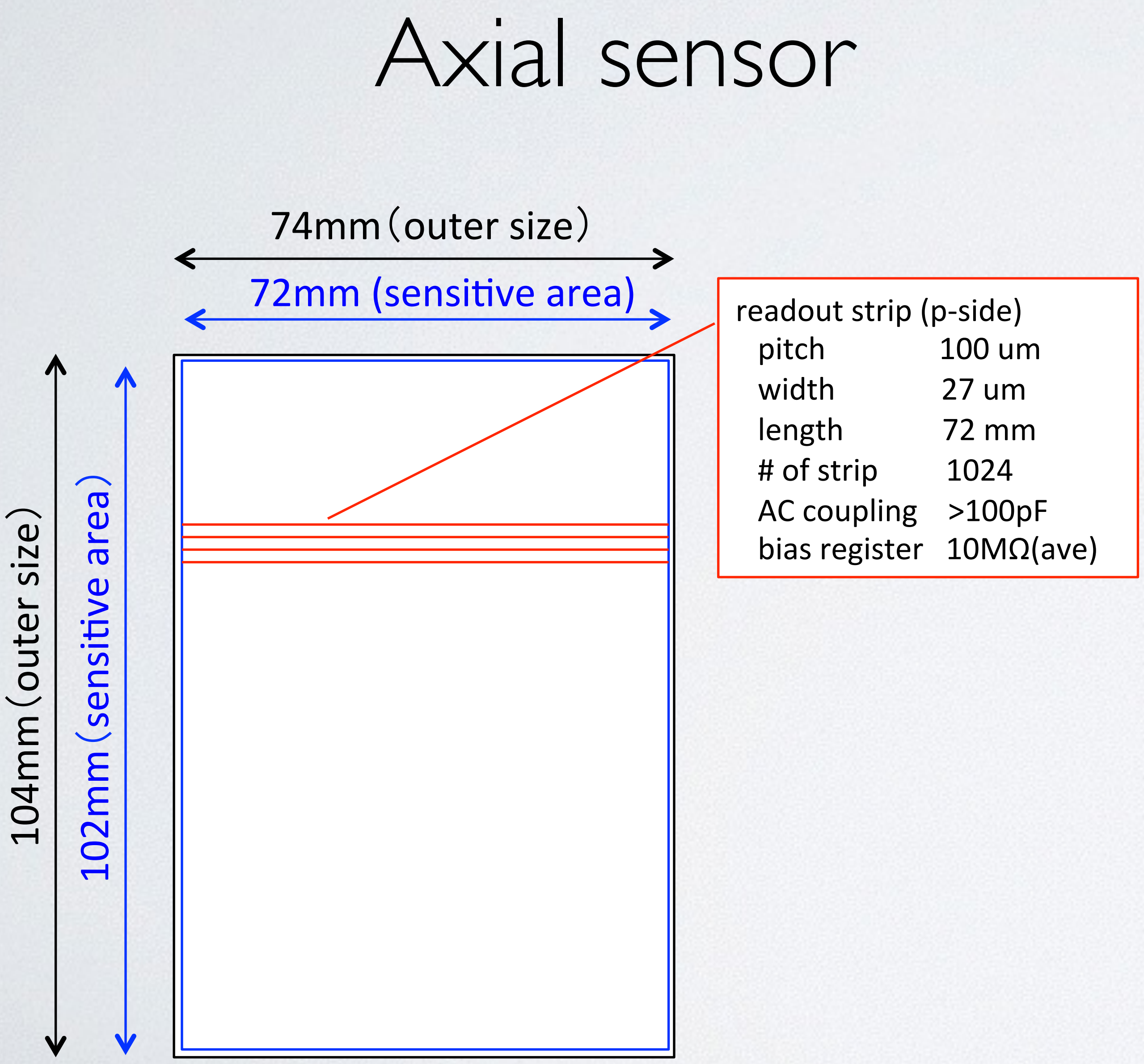


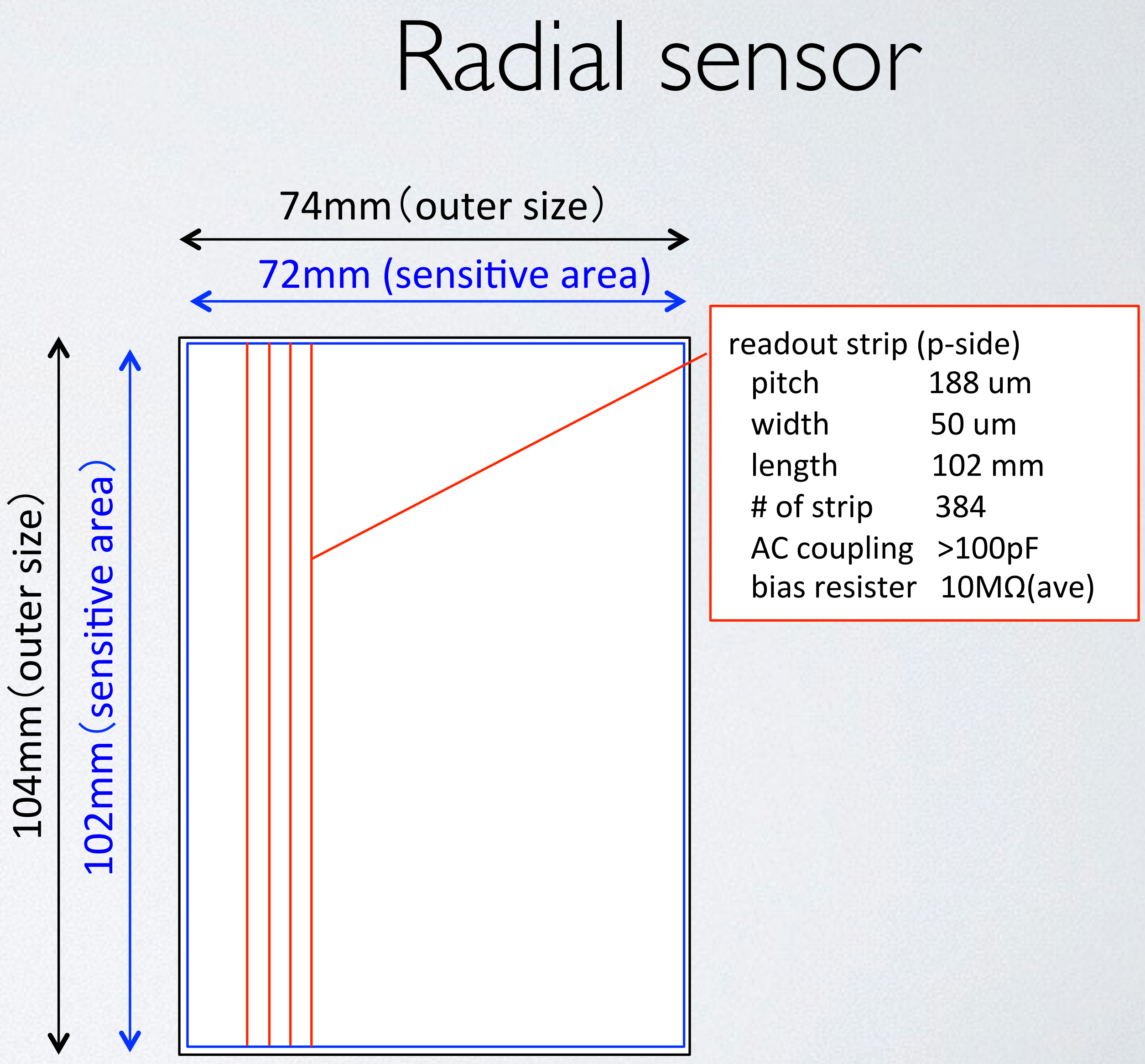


These new strip pitch satisfied the requirement.

Sensor specification

We determined the spec of silicon strip sensor.





Development of tracking detector

Conceptual design

Selection of detector
Evaluation of existing sensor → Done

Tracking detector design

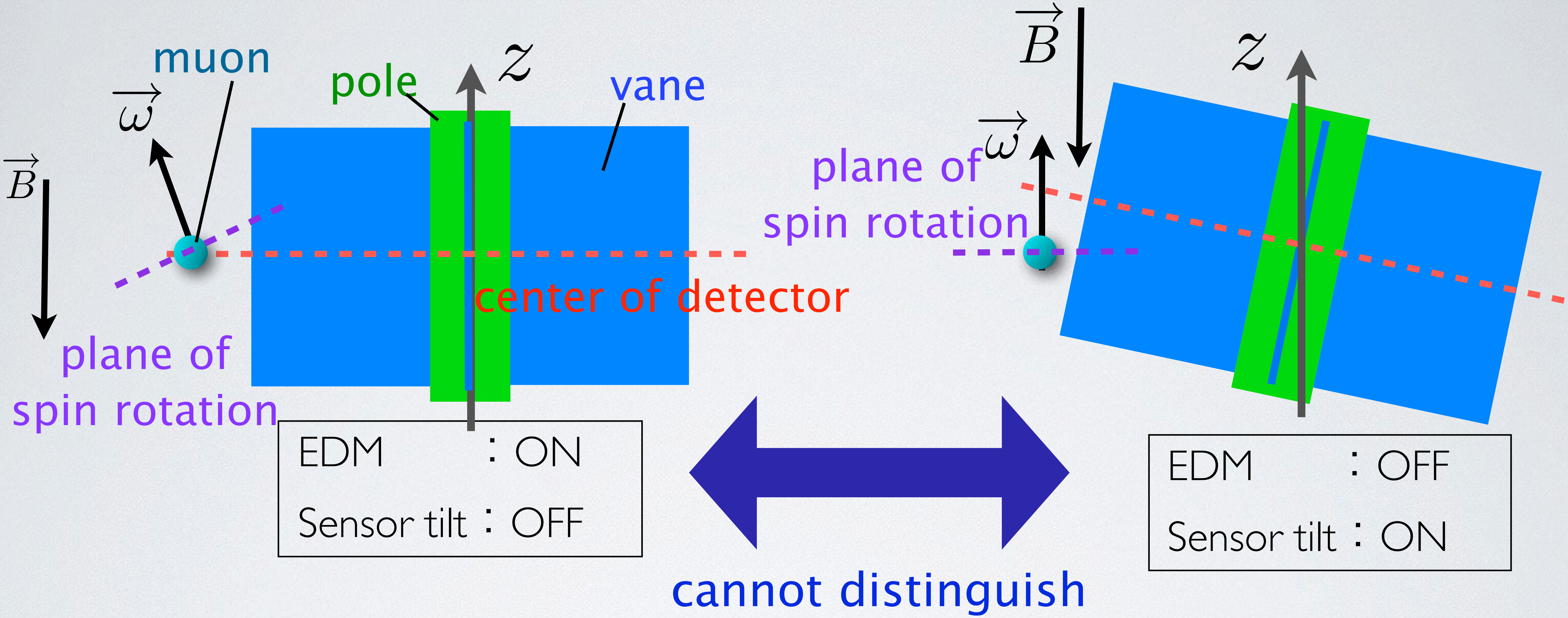
Specification of silicon strip sensor

Estimation of requirements for the sensor alignment

Producing test sensor

Producing and evaluating test sensor

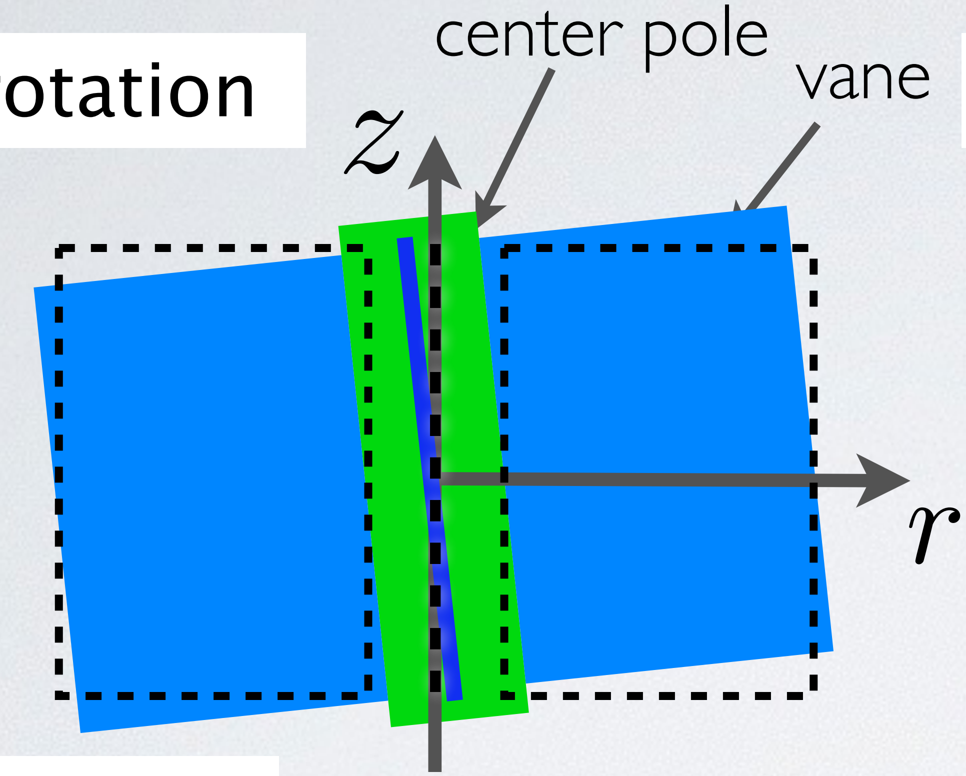
Sensor misalignment



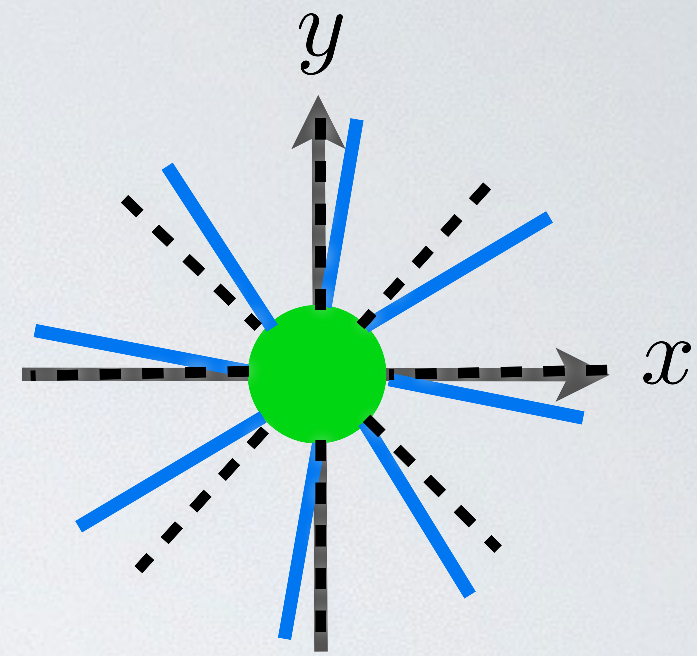
- Sensor tilt can lead fake EDM signal.
- We considered 4 types of detector tilt and checked whether fake EDM appears or not by simulation

4 types of detector tilt

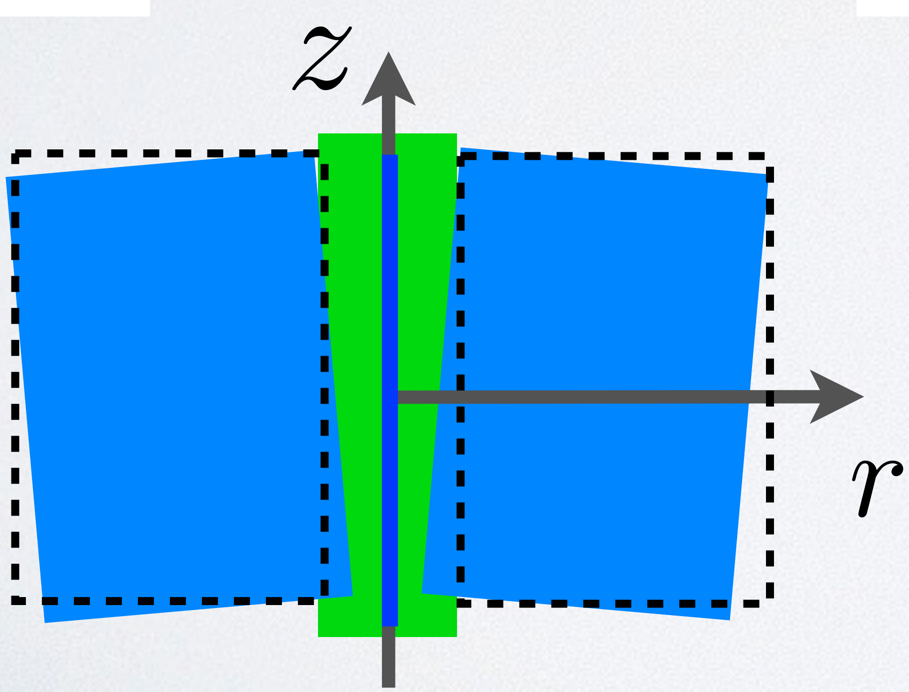
global rotation



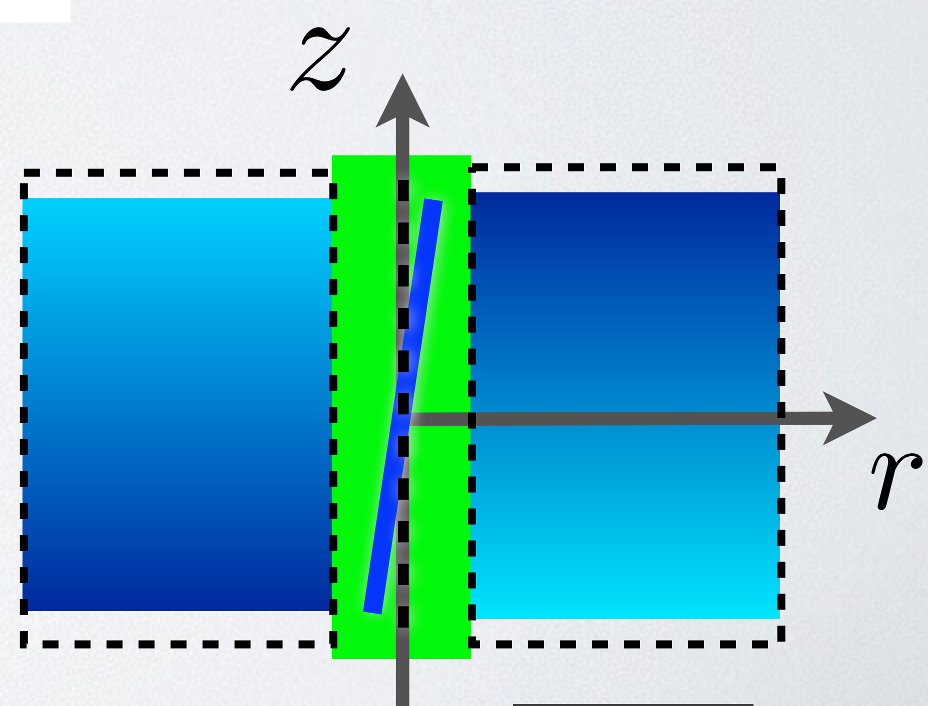
z axis rotation



φ axis rotation



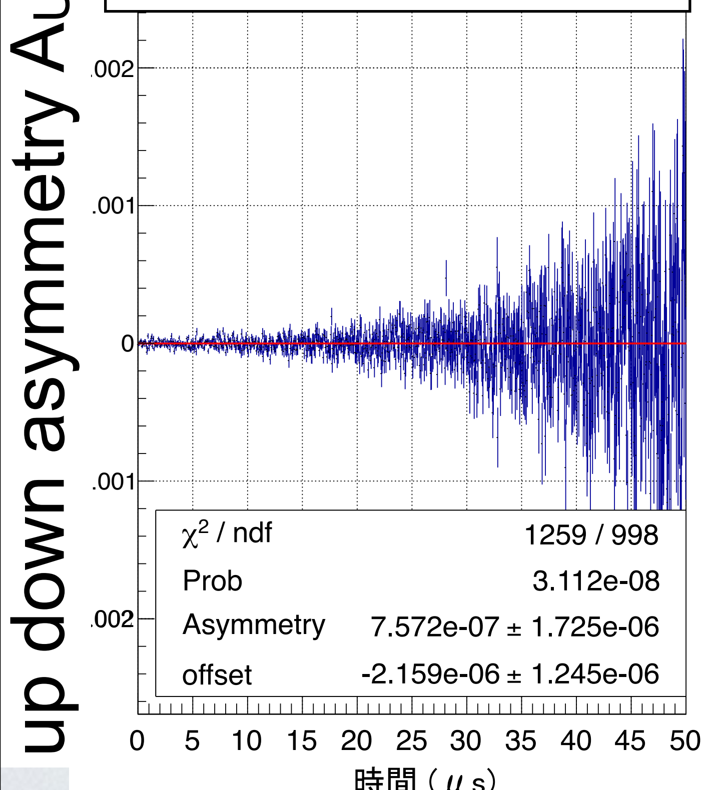
r axis rotation



Relation between the type of detector tilt and fake EDM

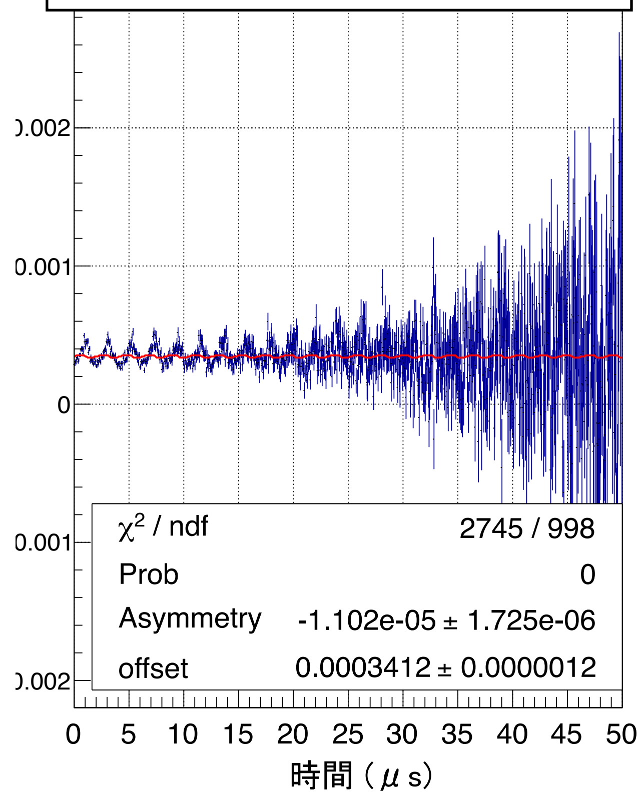
$$d_\mu = 0 \ \mathrm{e} \cdot \mathrm{cm}$$
$$3.4 \times 10^{12} \ \mathrm{muon}$$

global rotation
1 mrad



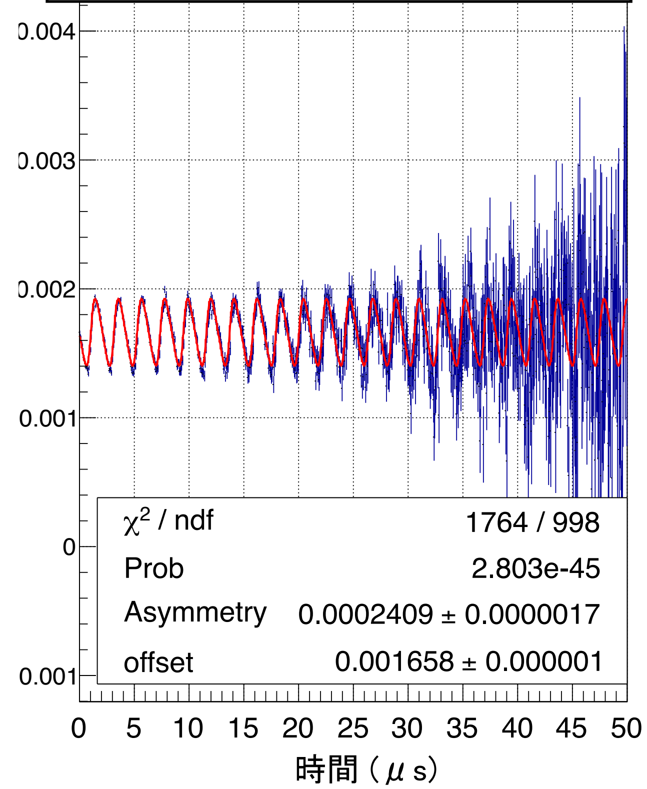
no signal

z axis rotation
1 mrad



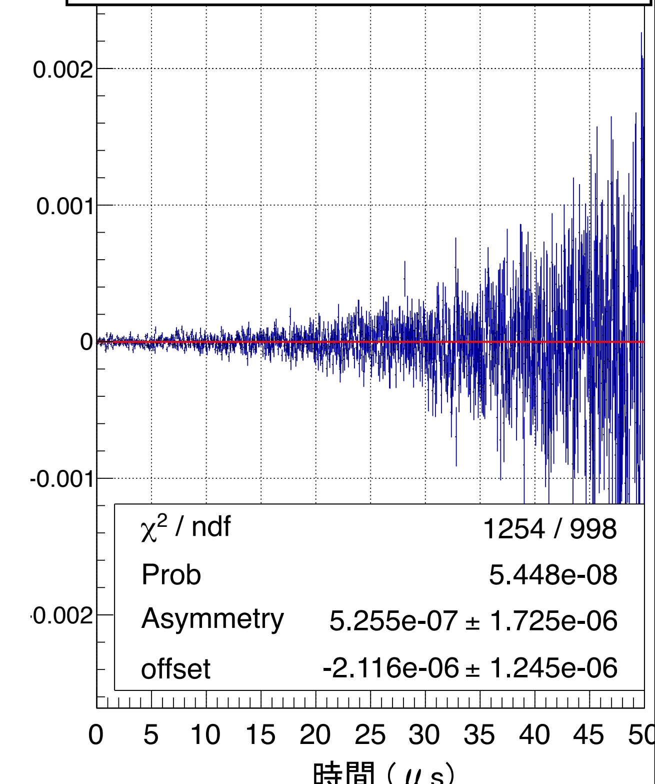
oscillate but
phase is different

φ axis rotation
1 mrad



fake EDM

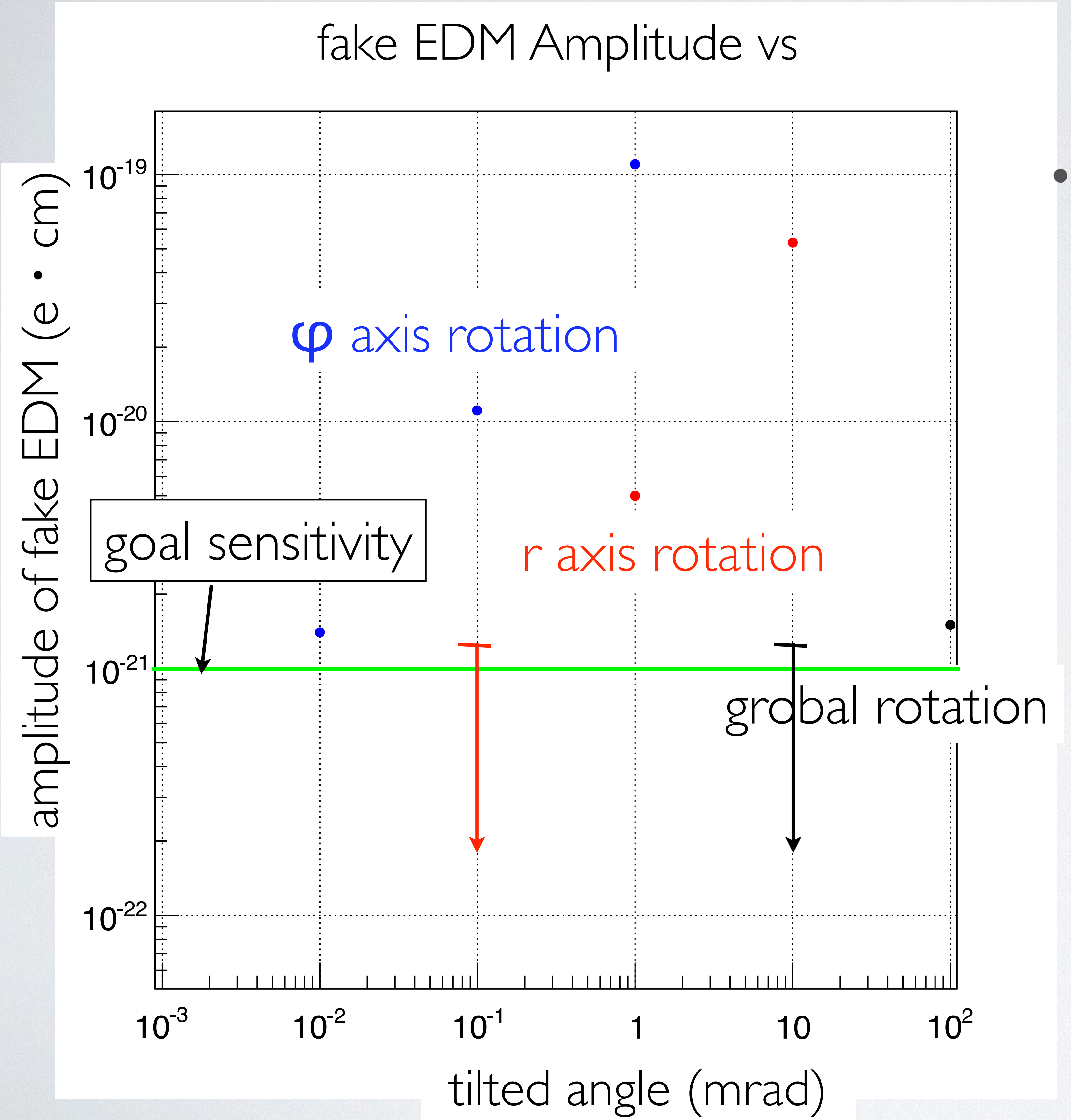
r axis rotation
1 mrad



no signal

r and φ axis rotation is important problem.

Results about misalignment and fake EDM



- To make fake EDM smaller than goal sensitivity,

  φ axis rotation :

  < 0.01 mrad

  r axis rotation :

  < 0.2 mrad

  z axis rotation :

  no change even if sensors tilt100 mrad

  global rotation :

  < 100 mrad

Development of tracking detector

Conceptual design

Selection of detector
Evaluation of existing sensor → Done

Tracking detector design

Specification of silicon strip sensor

Estimation of requirements for the sensor alignment

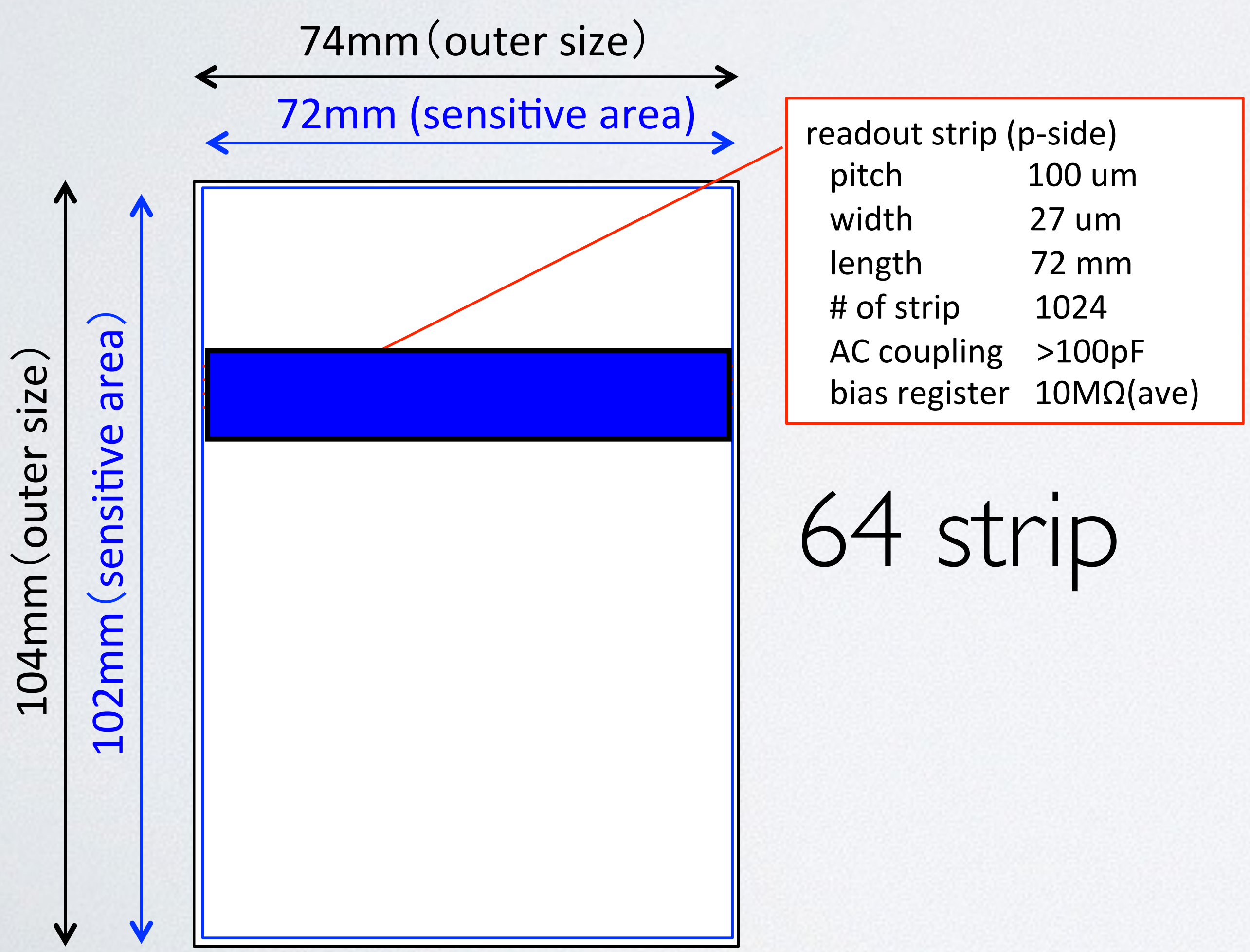
Producing test sensor

Producing and evaluating test sensor

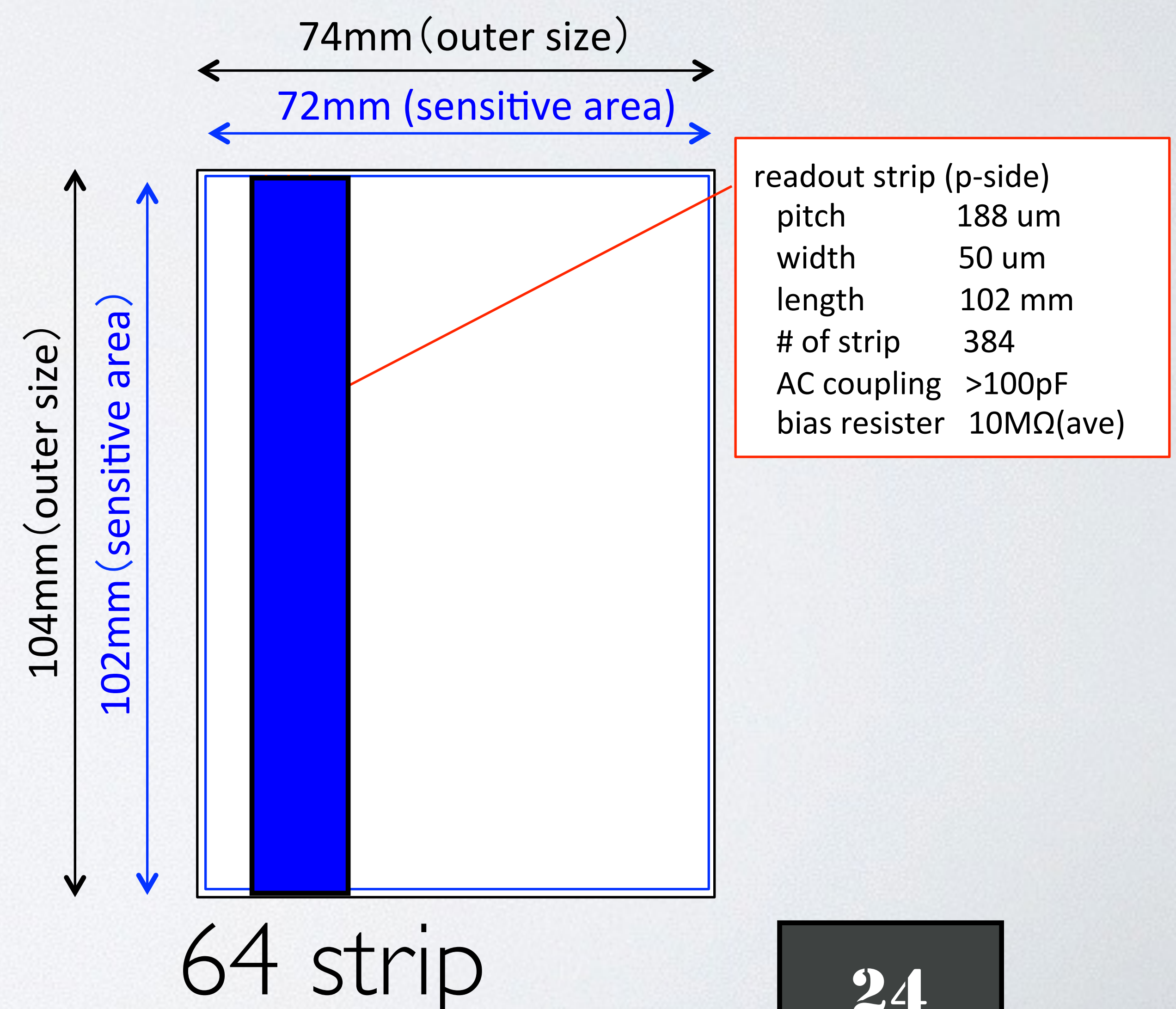
producing test sensors

- We produced test sensors with 64 strip.
- Test sensors equivalent to a part of whole sensors. (blue region in the figure)

Axial (A) sensor



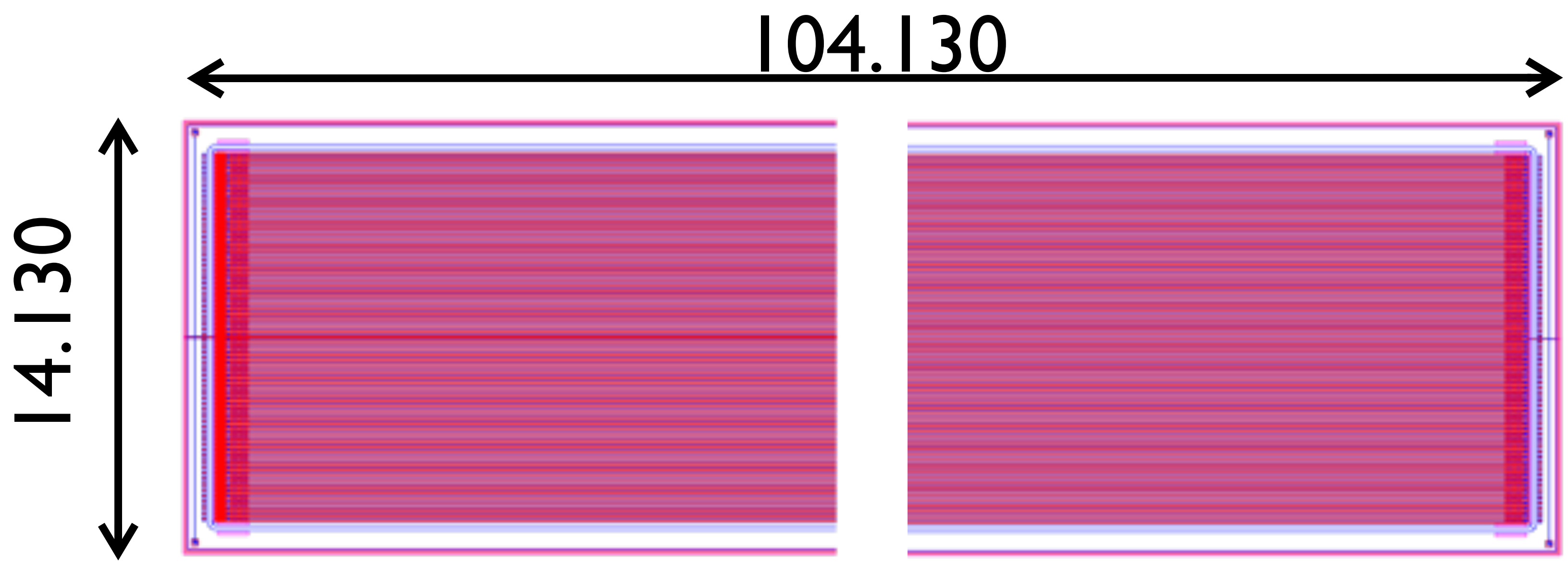
Radial (R) sensor



Test sensor specification

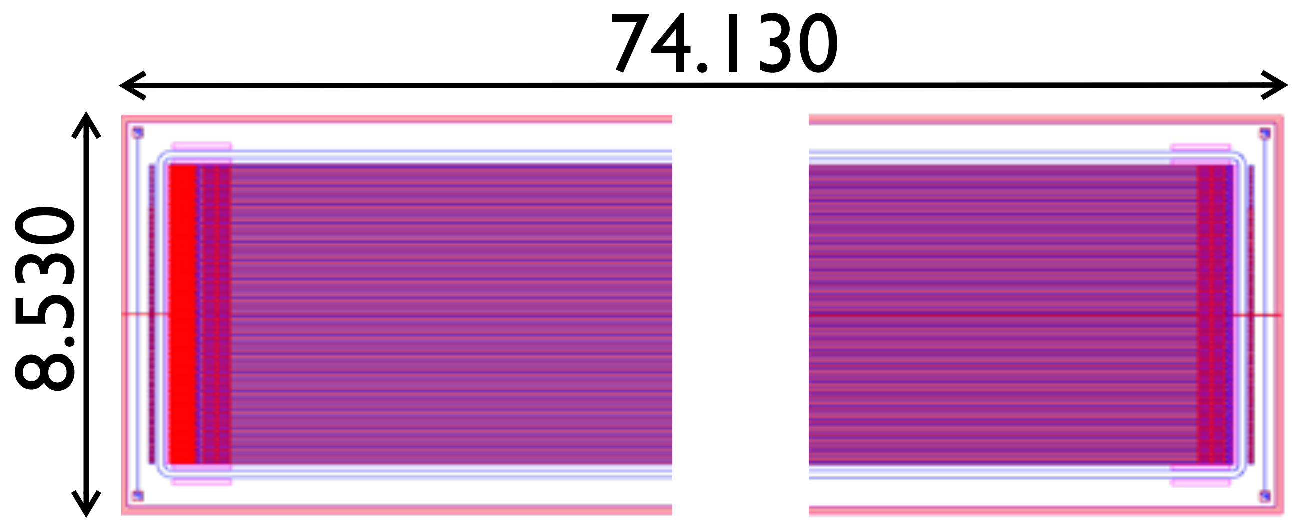
Radial (R) sensor

Thickness	:	0.320 mm
Strip pitch	:	0.188 mm
Strip width	:	0.050 mm
Strip length	:	102 mm
# of strip	:	64



Axial (A) sensor

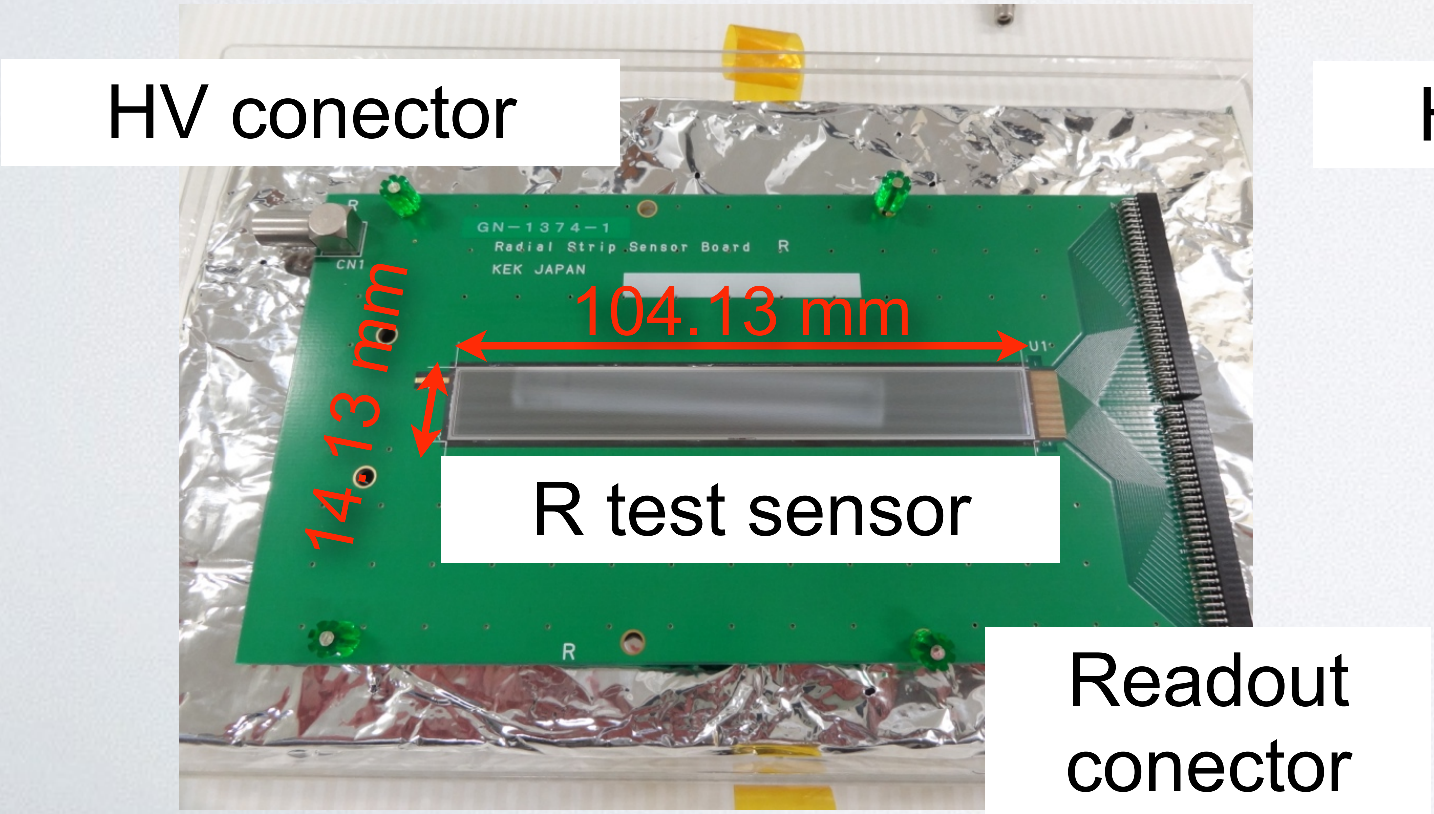
Thickness	:	0.320 mm
Strip pitch	:	0.100 mm
Strip width	:	0.027 mm
Strip length	:	72 mm
# of Strip	:	64



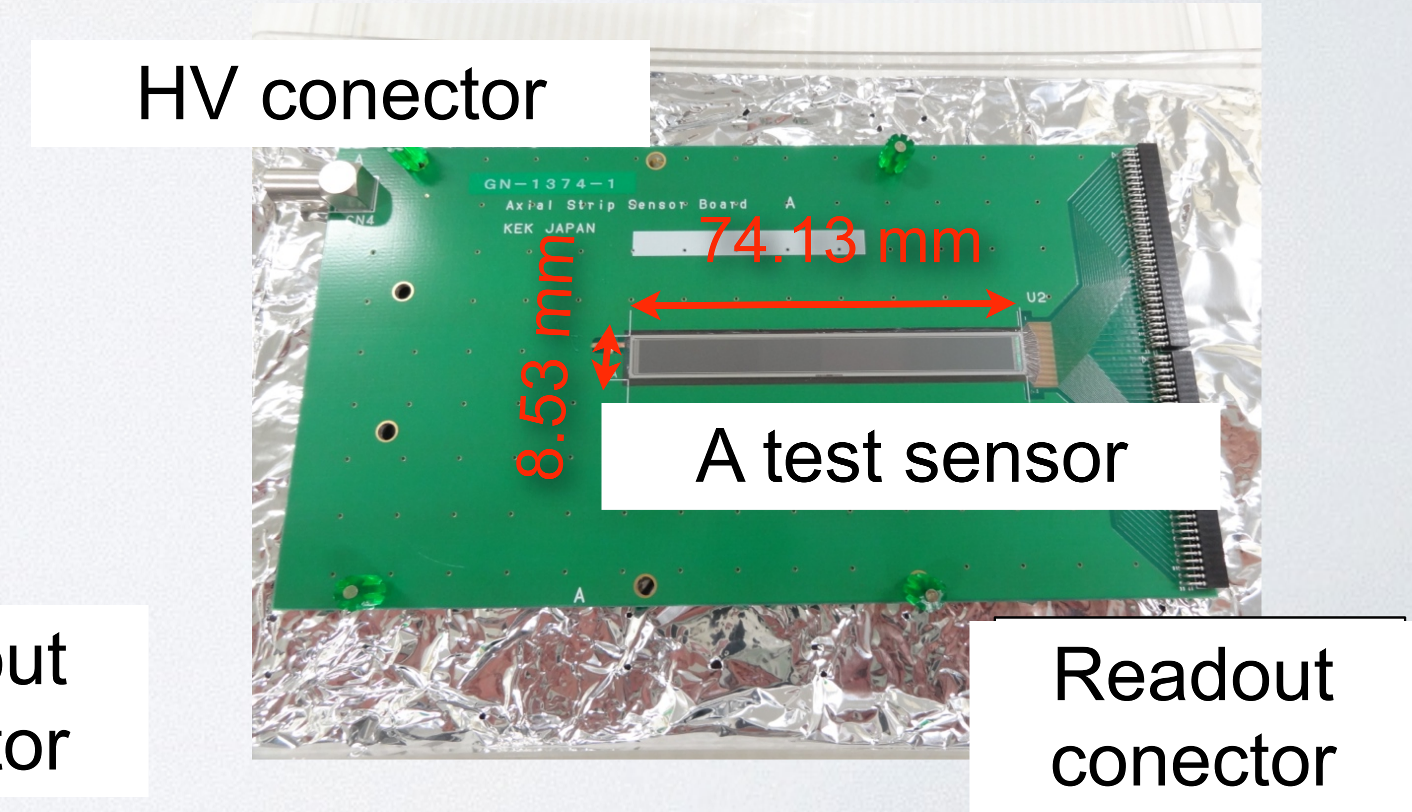
Test sensors and sensor boards for evaluation

- Producing test sensor
- Designing and producing sensor board
- Mount test sensors for the sensor boards

Radial sensor



Axial sensor



Flow chart of sensor evaluation

- **Sensor property**
  - Checking the surface of sensor with microscope
    → Checking mis-patterned sensor
  - I-V measurement
    → Measuring leak current
  - C-V measurement
    → Measuring Full depletion voltage and sensor capacitance
  - Inter strip capacitance measurement
    → Measuring sensor capacitance
- **Sensor Evaluation**
  - Noise measurement
  - Signal measurement with pulse laser

Results of sensor evaluation

	R sensor		A sensor	
	expectation	measured	expectation	measured
Sensor check		O.K.		O.K.
I-V		O.K.		O.K.
Full depletion voltage		93 V		73 V
Bulk capacitance	350 pF	360 pF	150 pF	170 pF
Inter strip capacitance	6 pF	7.4 pF	4 pF	6.2 pF
Detector capacitance		23.4 pF		15.9 pF
ENC	1500 e	1500 e	1300 e	-
Laser test	2.4x10	2.6x10	2.4x10	2.5x10
S/N	16	17	18	

Next step

Tracking detector design

Specification of silicon strip sensor → Done

Estimation of requirements for the sensor alignment → Done

Producing test sensor

Producing and evaluating test sensor → Done

beam test

sensor improvement & detector construction test

Improve the sensor based on evaluation

demonstration of detector construction

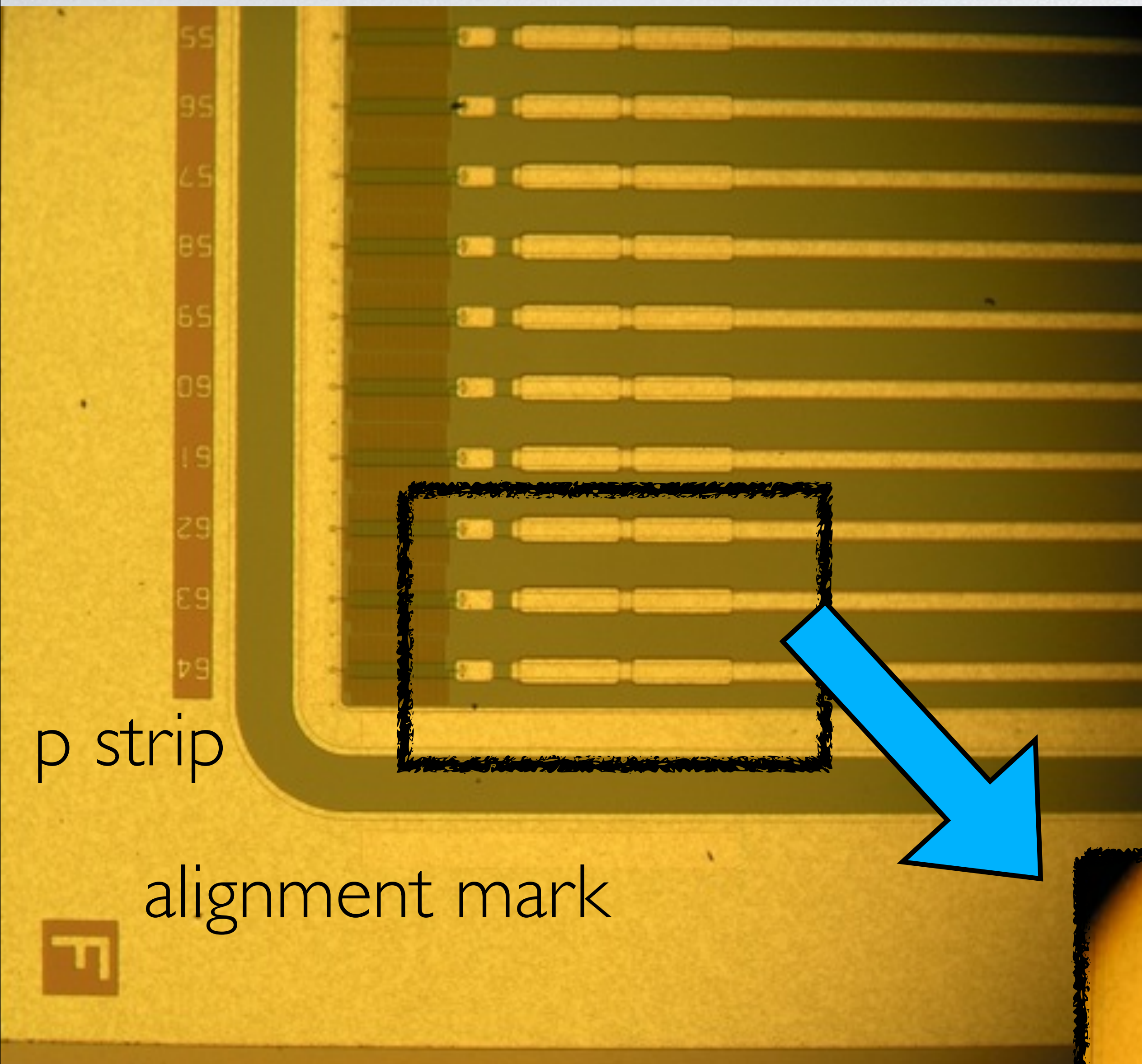
Tracking detector construction

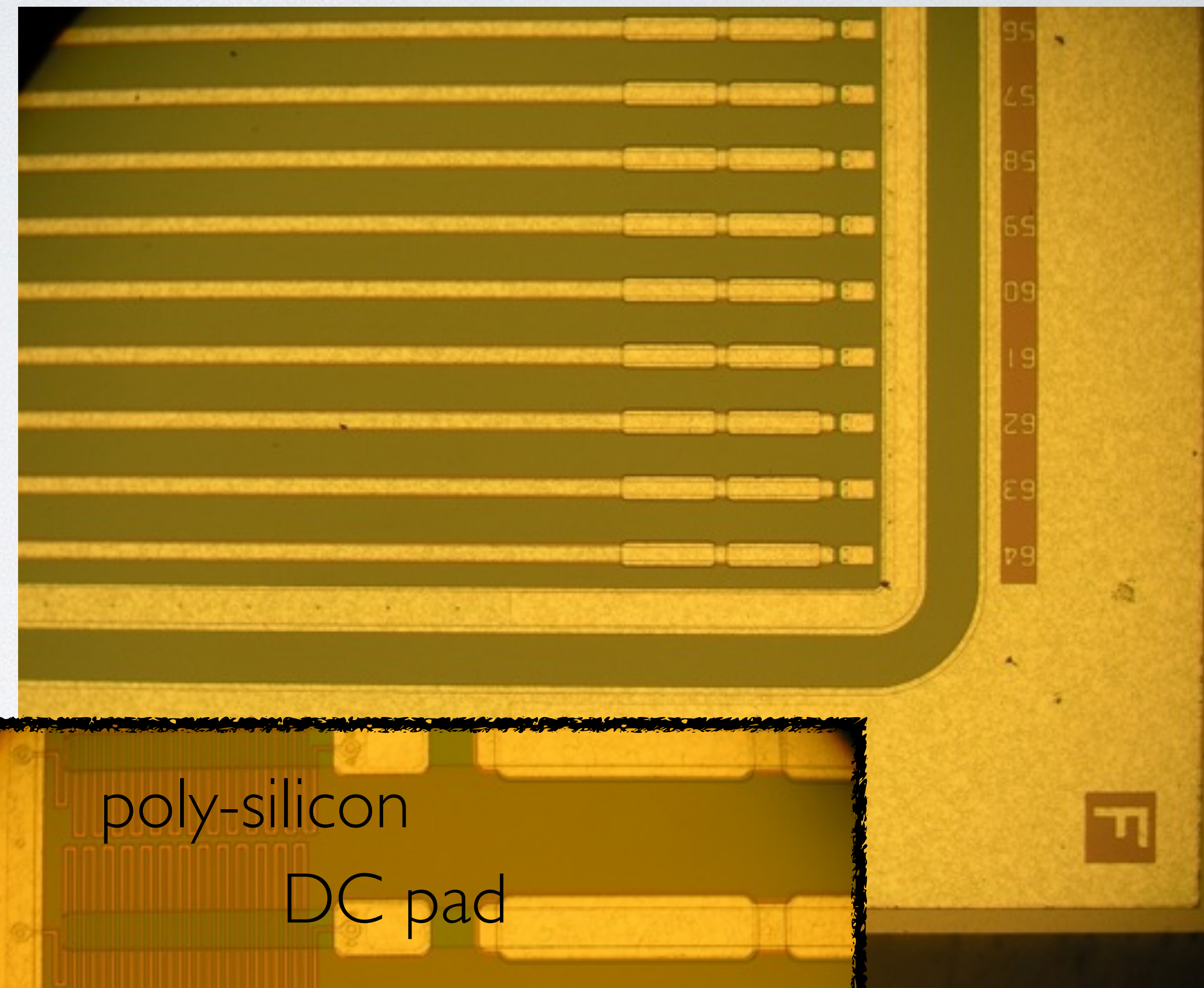
summary

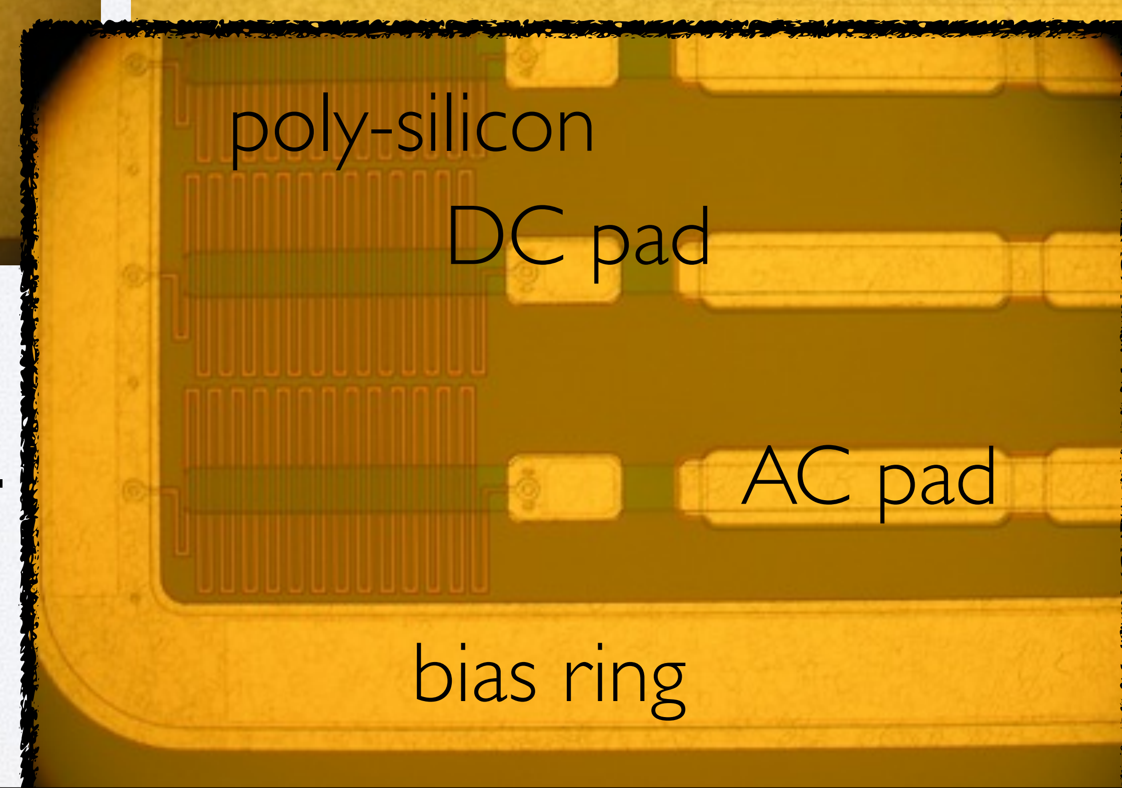
- **J-PARC muon g-2/EDM experiment**
  - g-2 ： 0.54 ppm → 0.1 ppm
    EDM ： 1.8×10^{-19} e · cm → 10^{-21} e · cm
- **Specification of silicon strip sensor**
  - We optimized strip pitch from positron migration in the sensor
  - We determined the sensor spec.
- **Estimation of requirement for sensor alignment**
  - Sensor tilt can lead fake EDM.
  - φ axis rotation is most important and must be limited 10 μrad.
- **Producing and evaluating test sensor**
  - We produced and evaluated two types test sensor.

back up

Sensor check with microscope





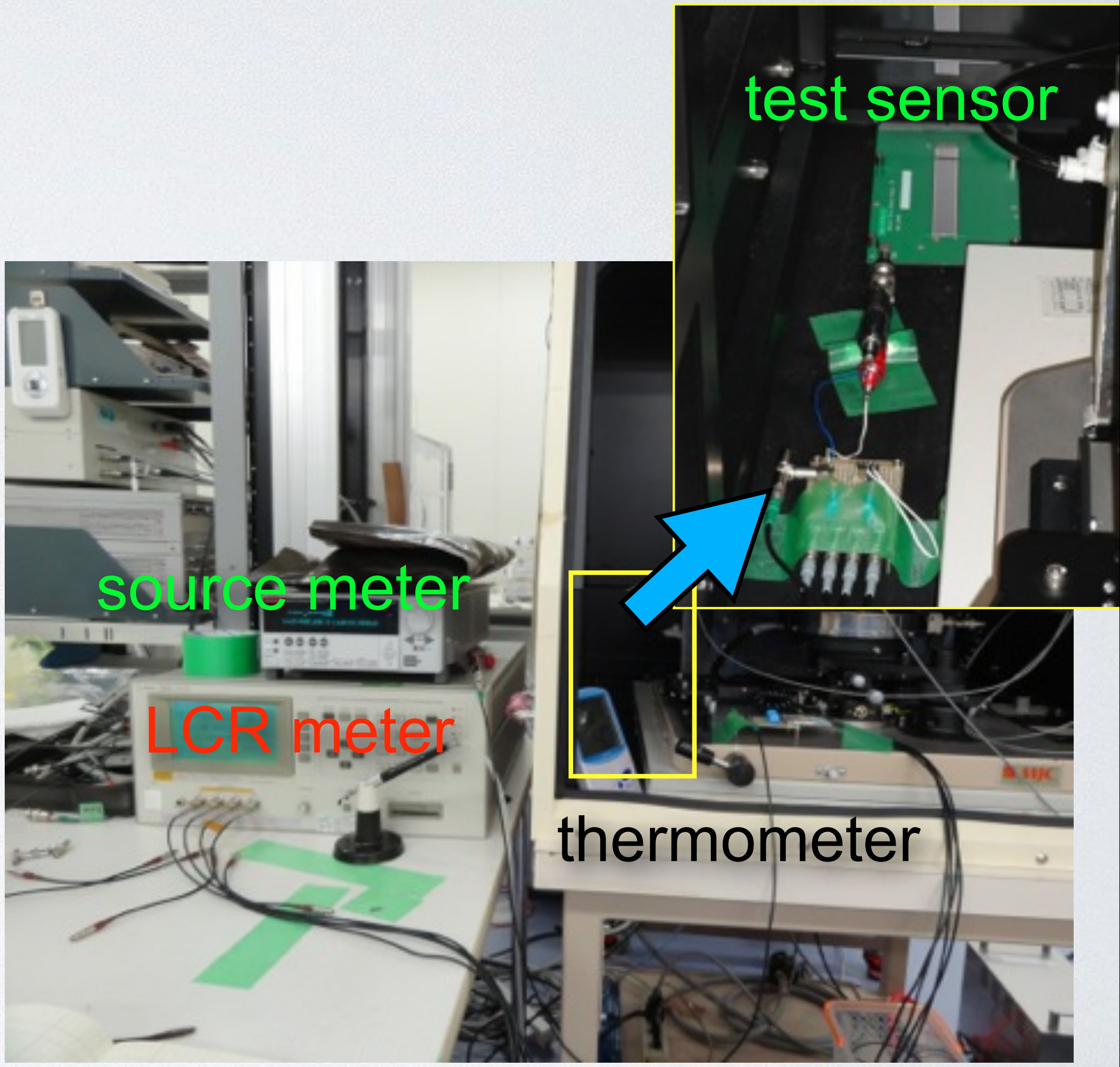


There is no remarkable damage.

Sensor characteristic (I-V, C-V measurement)

- We can check if the sensor is work well or not by I-V and C-V measurement.
- And we can also check the full depletion voltage of the silicon sensor.

setup of the measurement

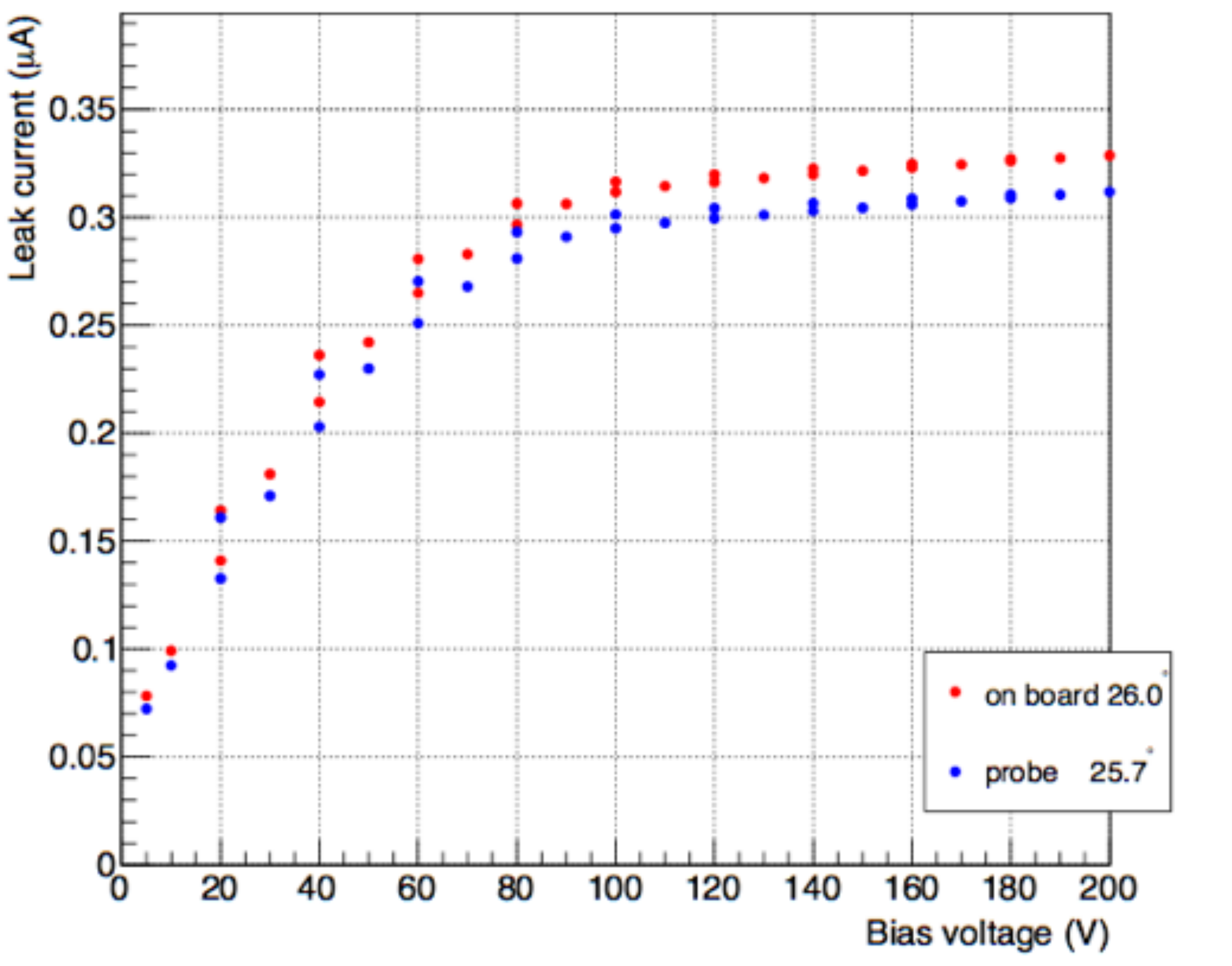


I-V measurement

- We can see plato region over 90 V

- Because of difference of temperature in these two measurement, leak current is different.

Radial strip sensor I-V



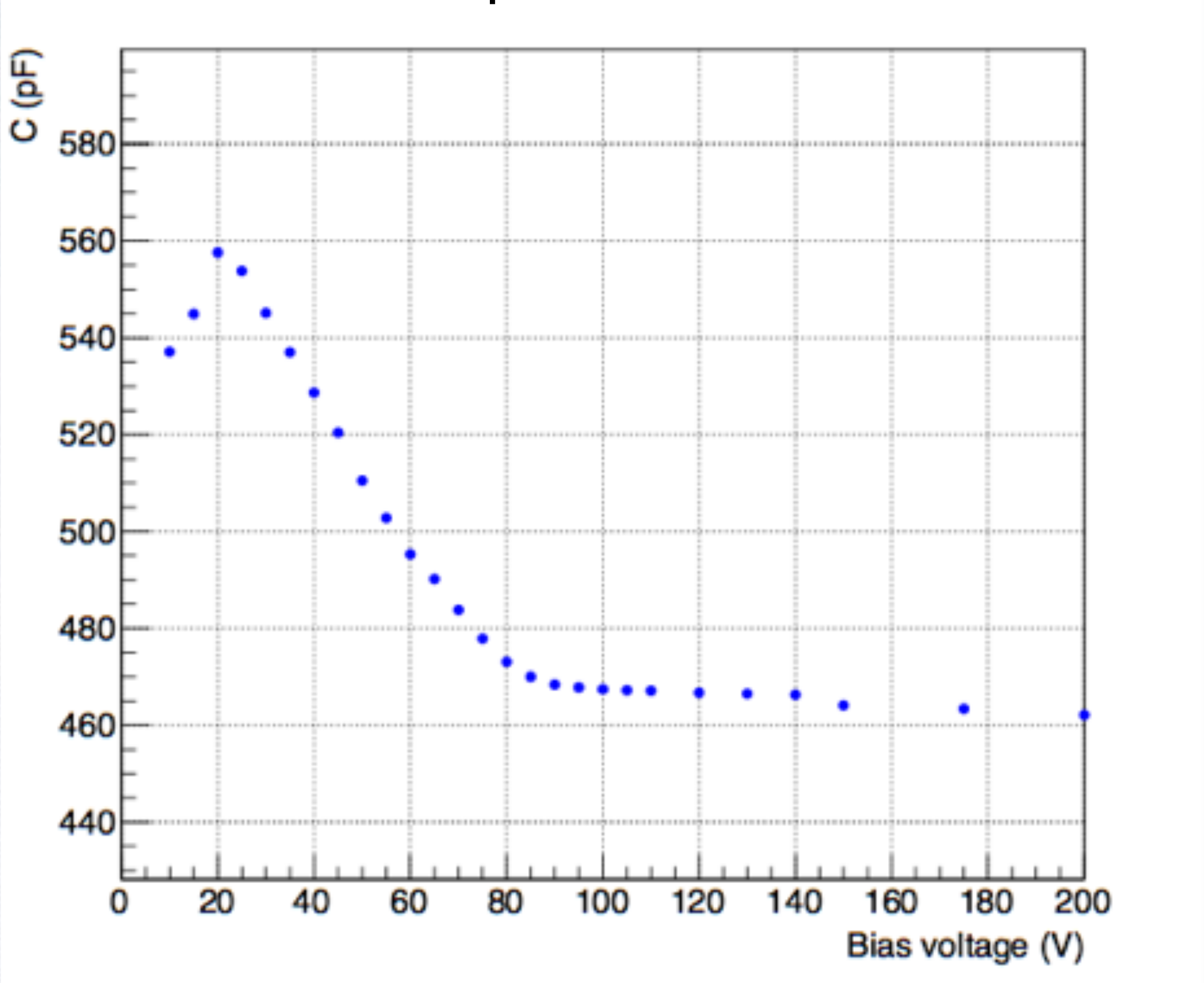
C-V measurement

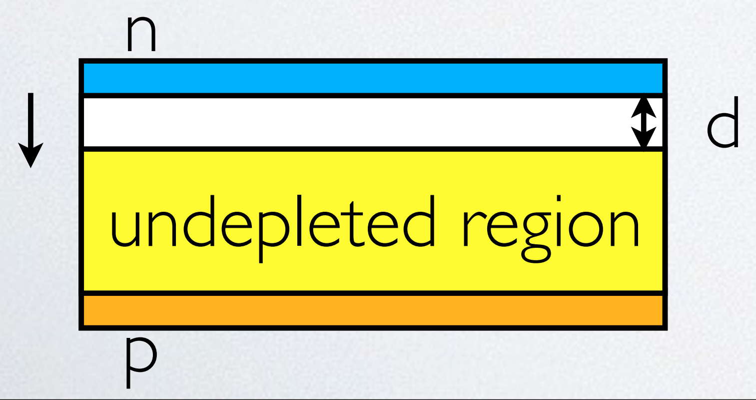
- Considered the sensor as a capacitance,

$$C = \epsilon \frac{S}{d}$$

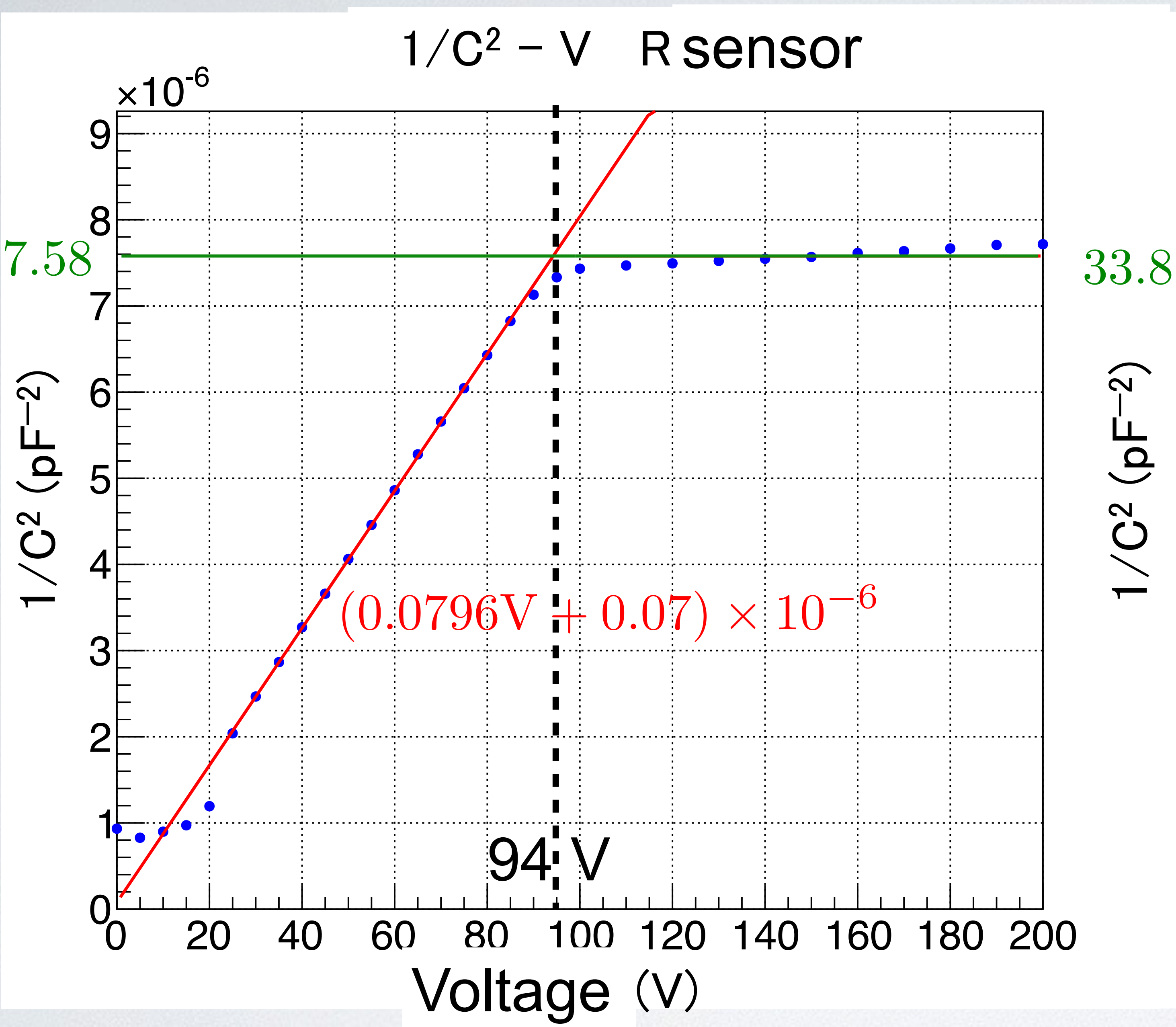
- d is thickness of depleted region, and proportional to square root of bias voltage $\sqrt{V}$.

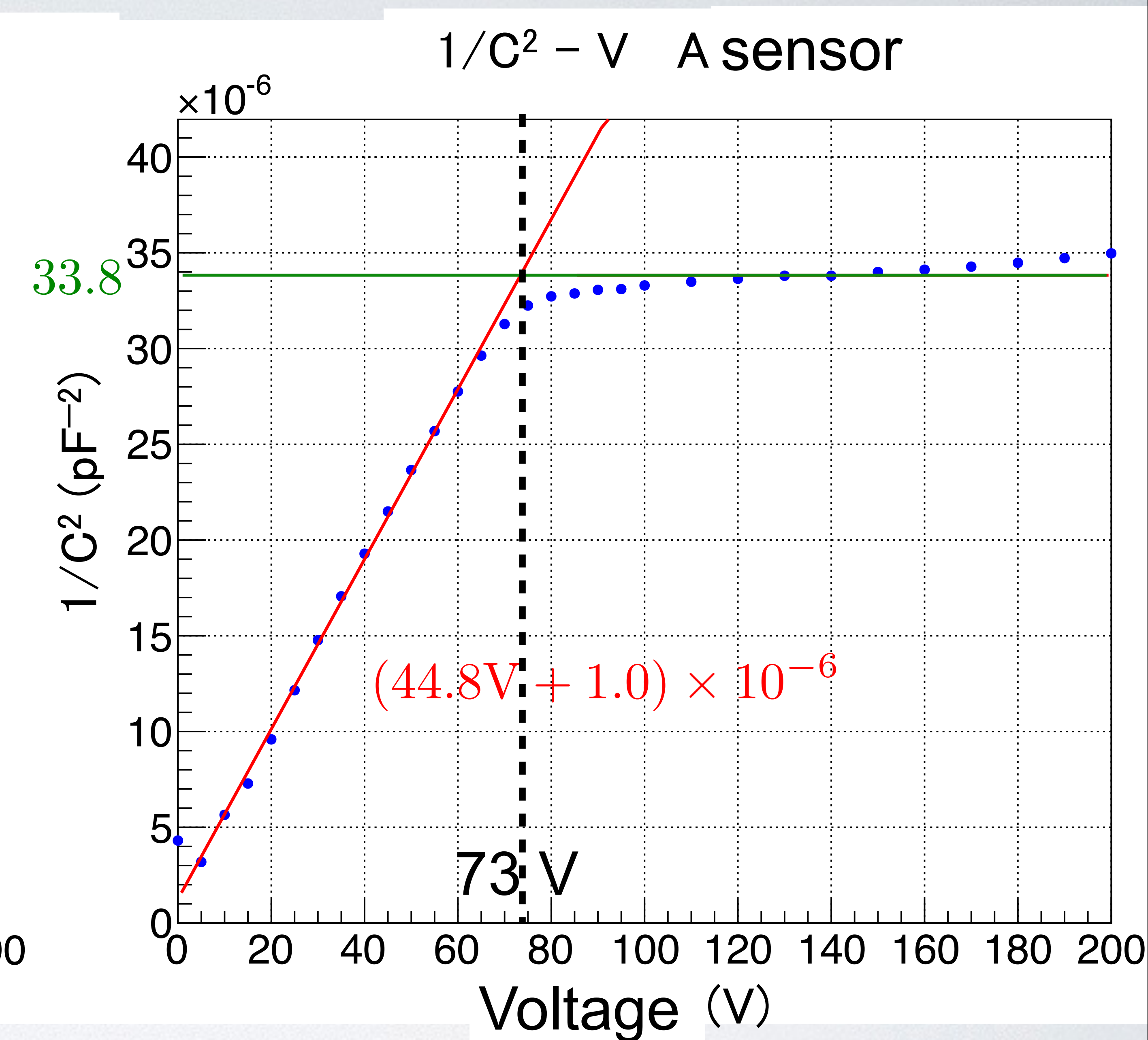
Radial strip sensor C-V





Full depletion voltage





- R sensor: 94 V
- A sensor: 73 V
- These results are consistent with I-V measurement

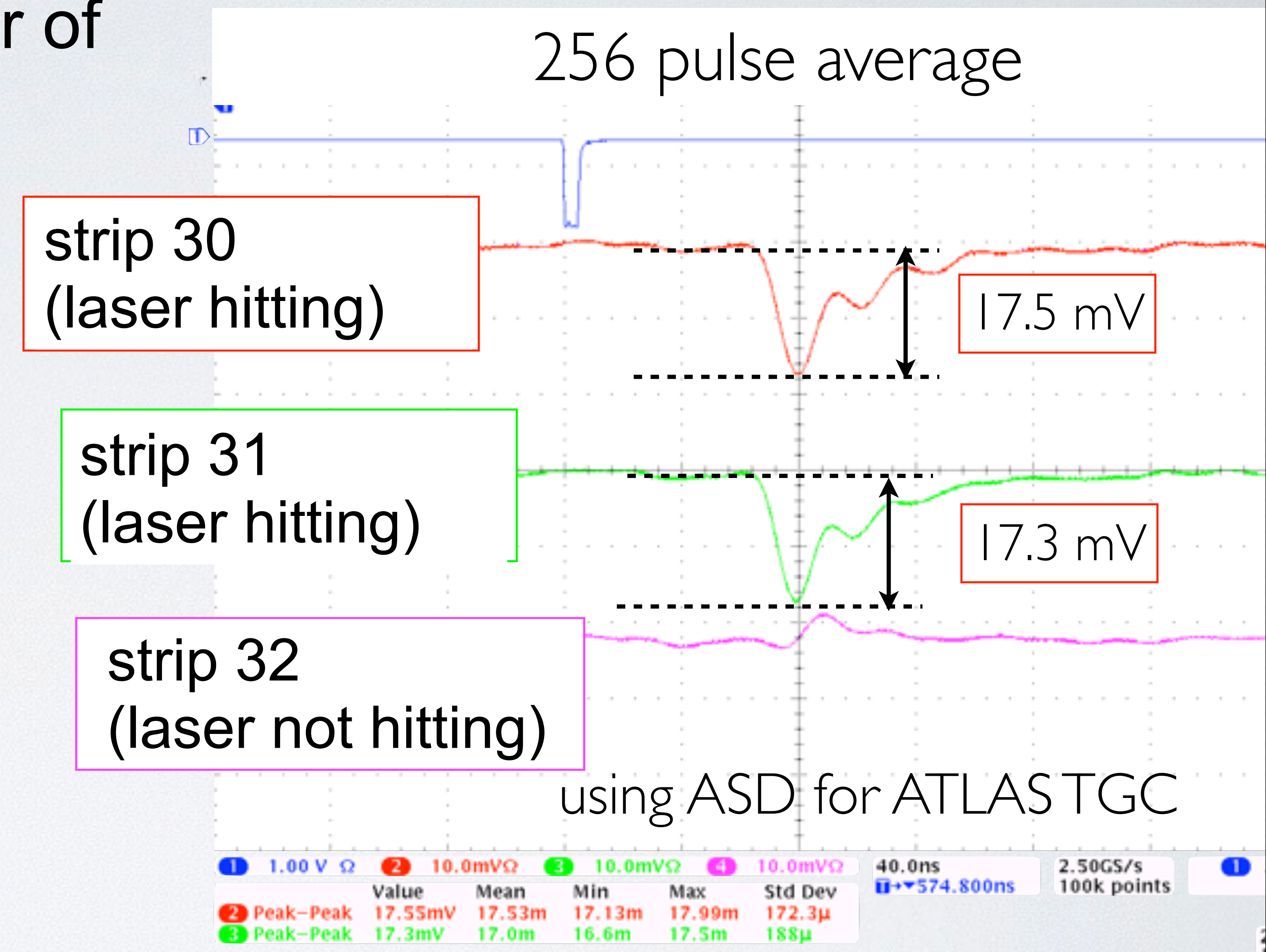
Pulse laser test

- Producing same number of e-h pair as MIP with an infrared laser pulse.

wave length =1060 nm
energy / pulse = 87 keV

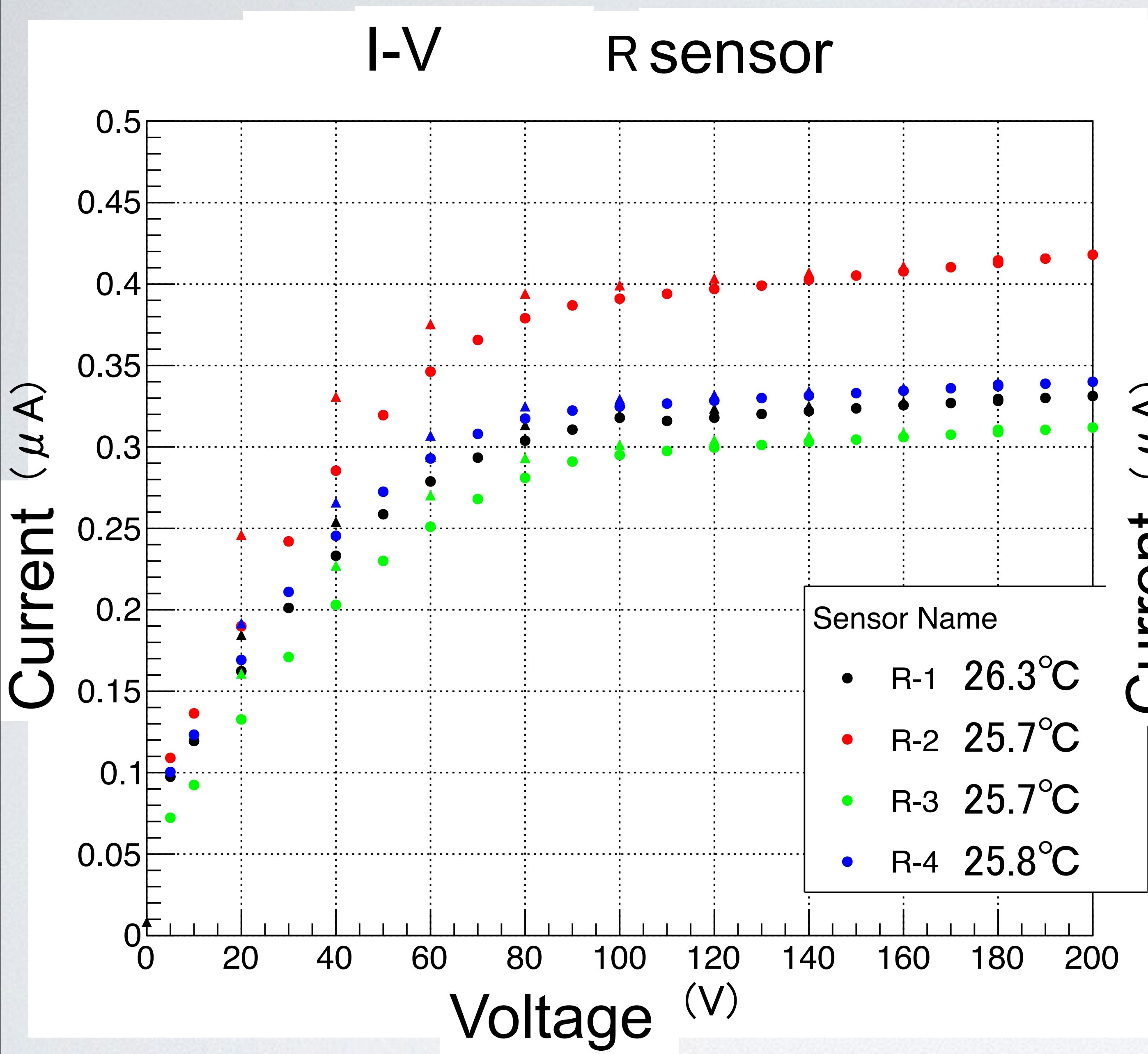
- Expectation : 2.4×10^4 e
- Measured : 2.6×10^4 e

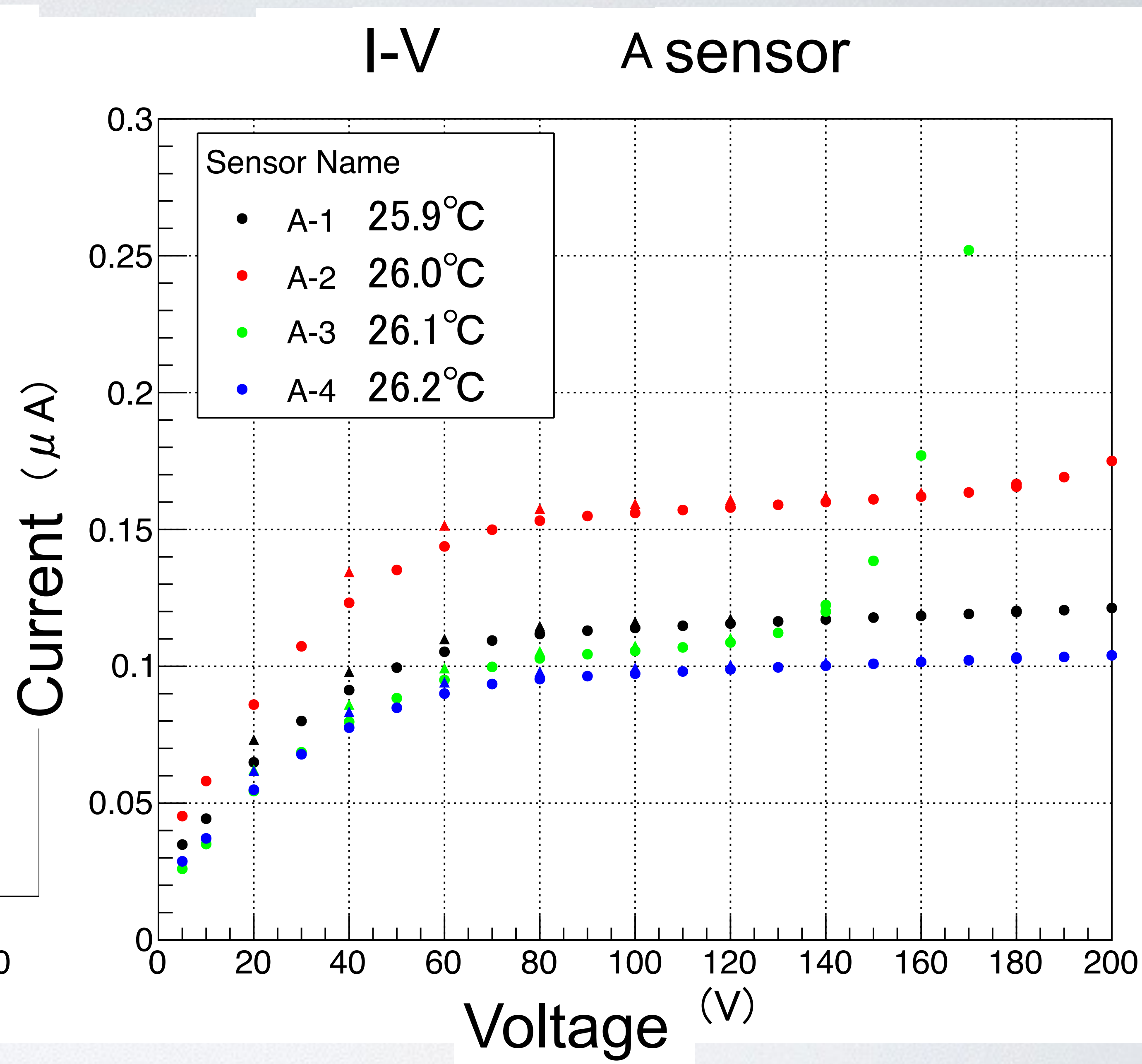
⟶ Consistent



Signal 2.4×10^4 / ENC1500 e → S/N=16
→It seems to be achieved S/N=15 (goal).

I-V measurement





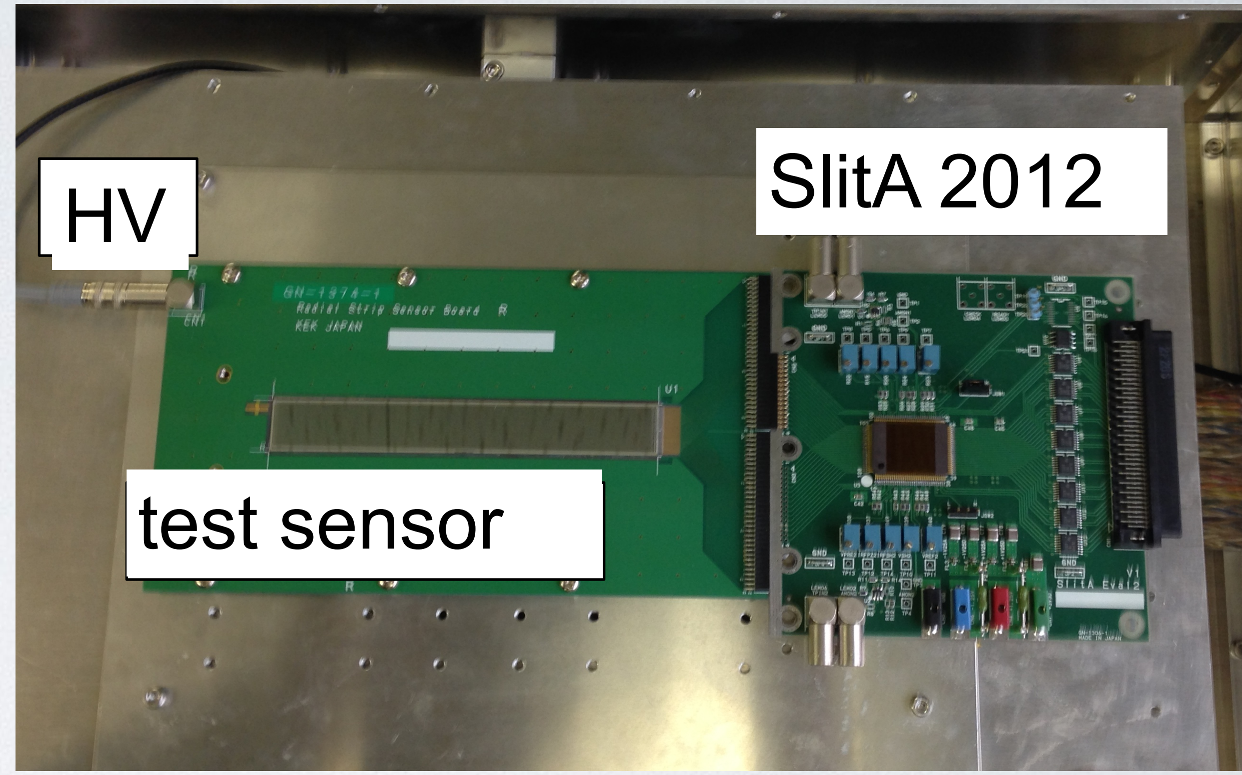
SlitA 2012

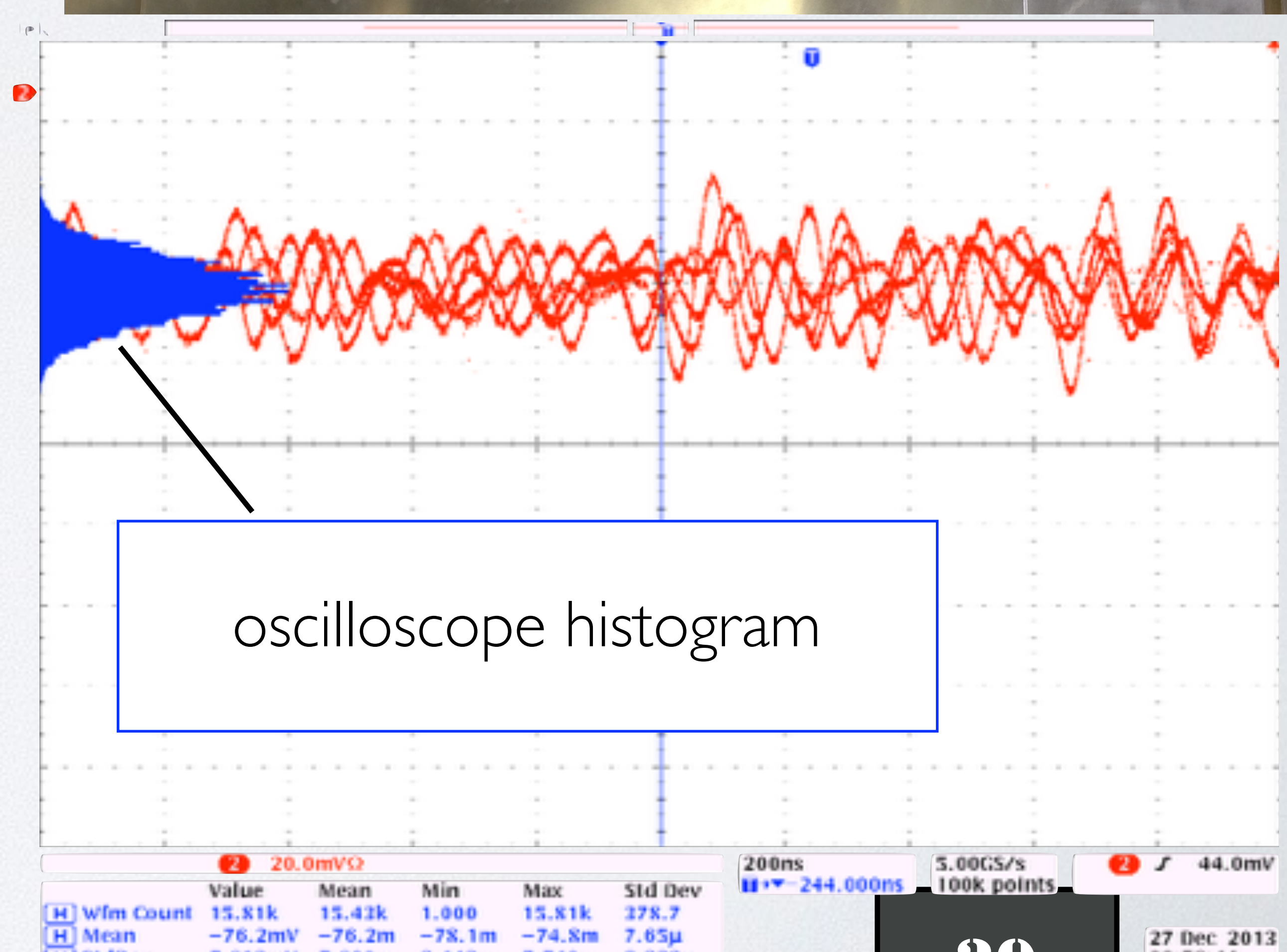
- ENC calculated from measured capacitance, ENC=860+29xC_{total} =1500 e

- Measured ENC

$$\mathrm{ENC} = \frac{7.6\ (mV)}{32\ (mV/fC)e} = 1500\ e$$

consistent





C-V measurement

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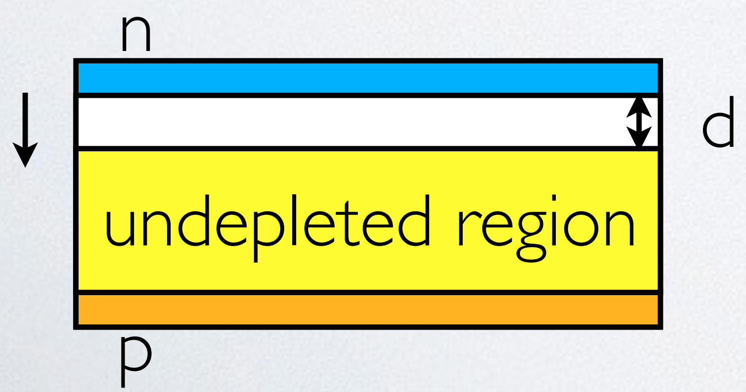


Radial strip sensor C-V

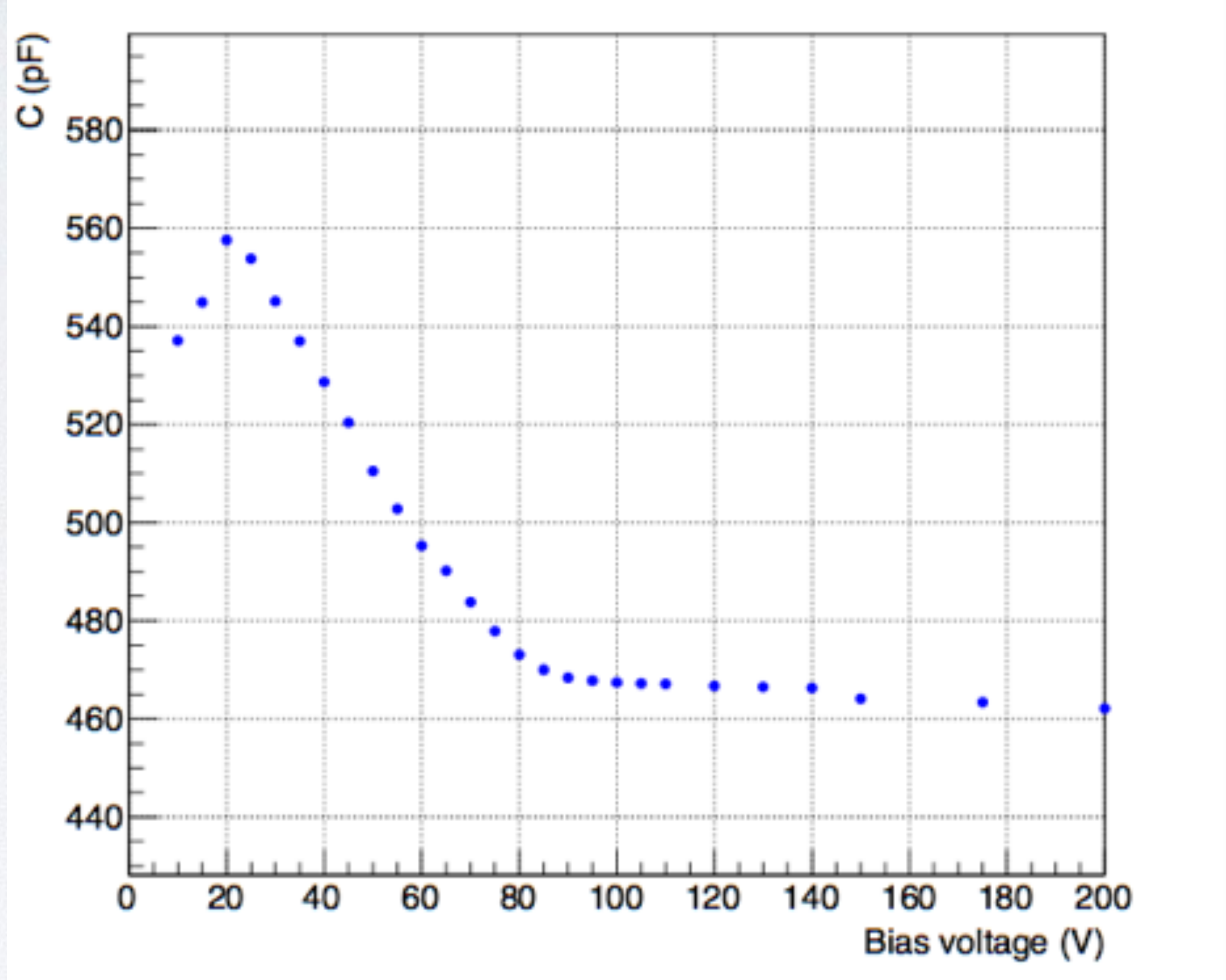
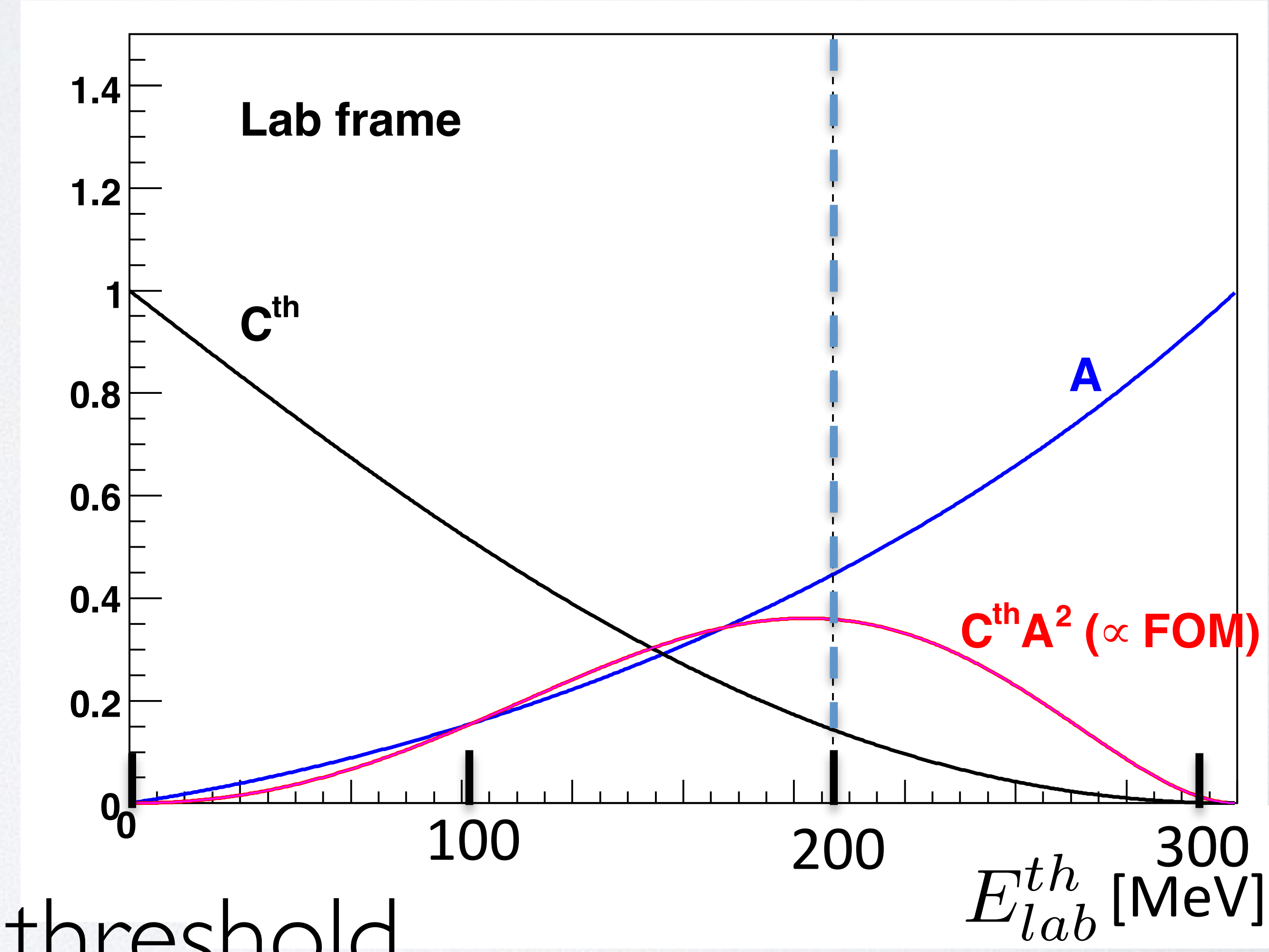


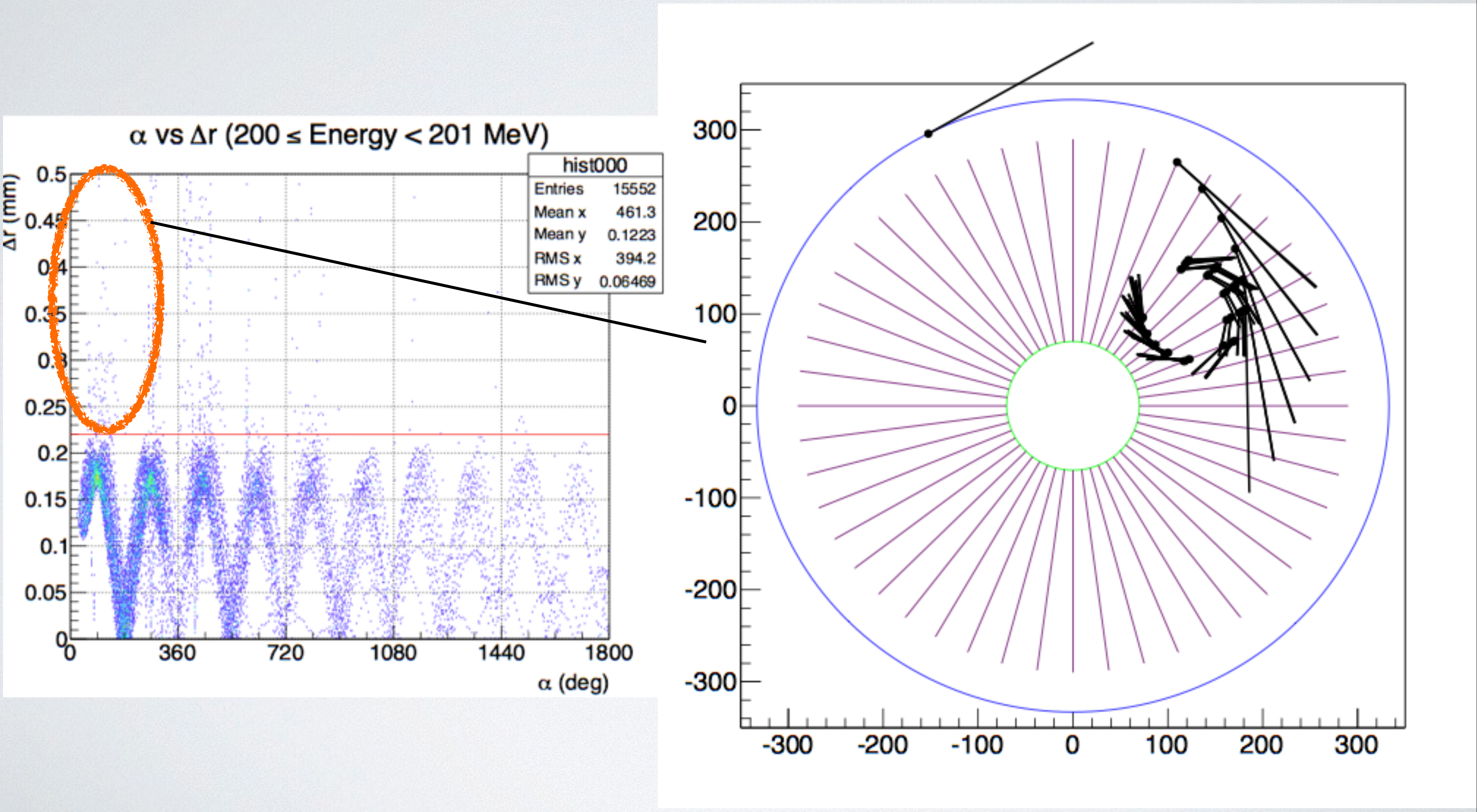
figure of merit

E ≧ 200 MeV　signal
E < 200 MeV background



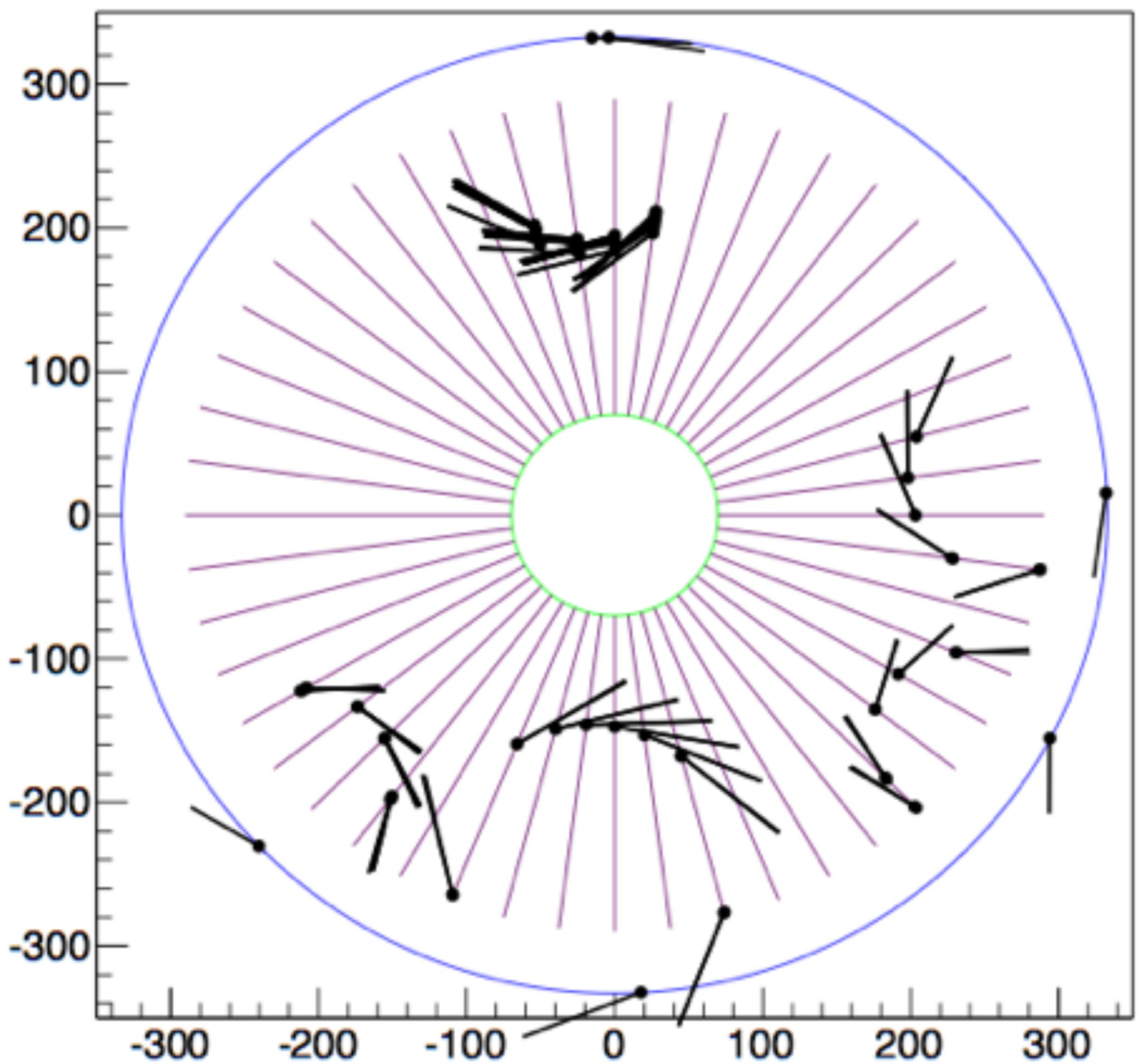
Cth : # of positron over threshold
A　: Asymmetry

Event display

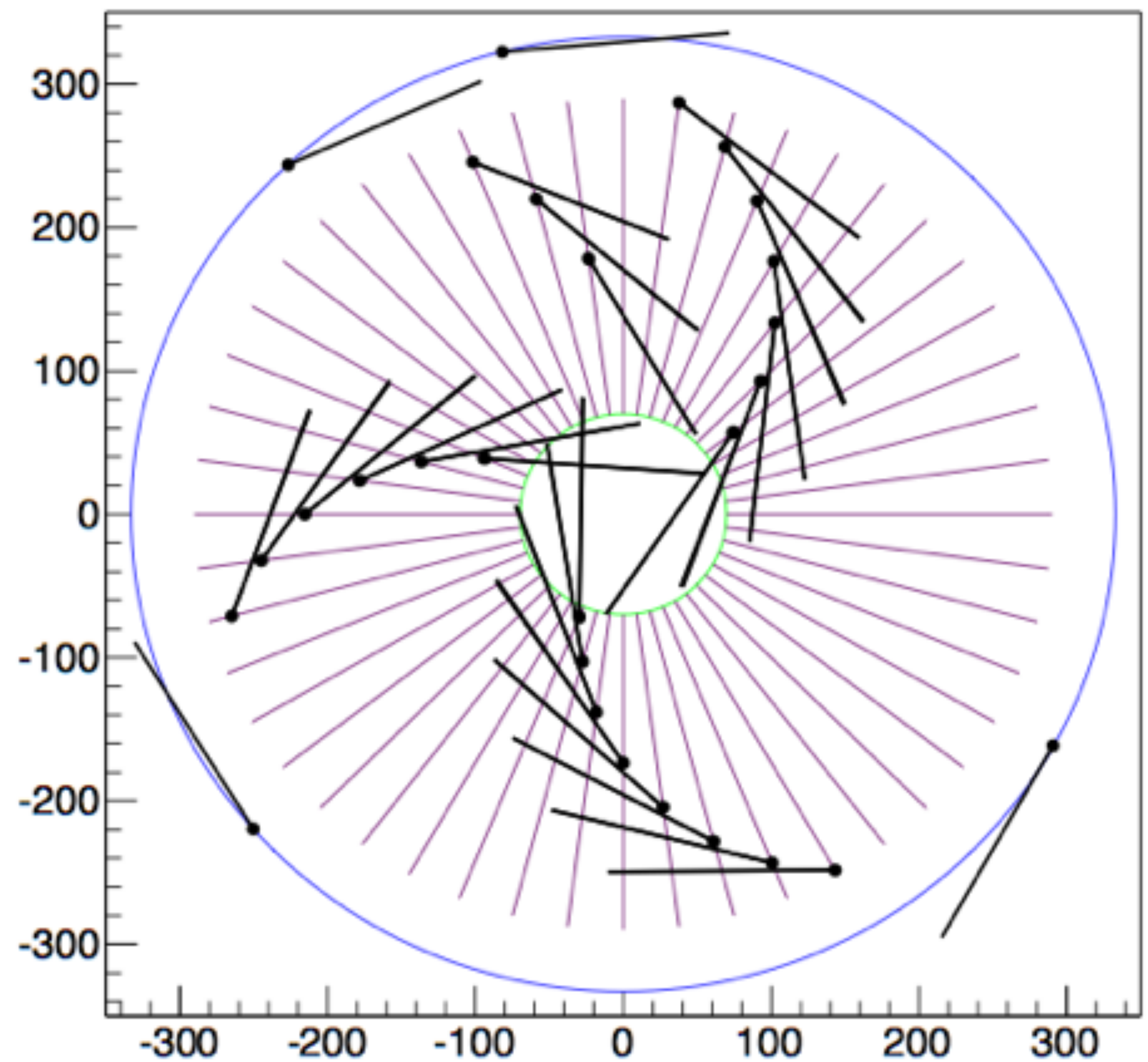


Event display

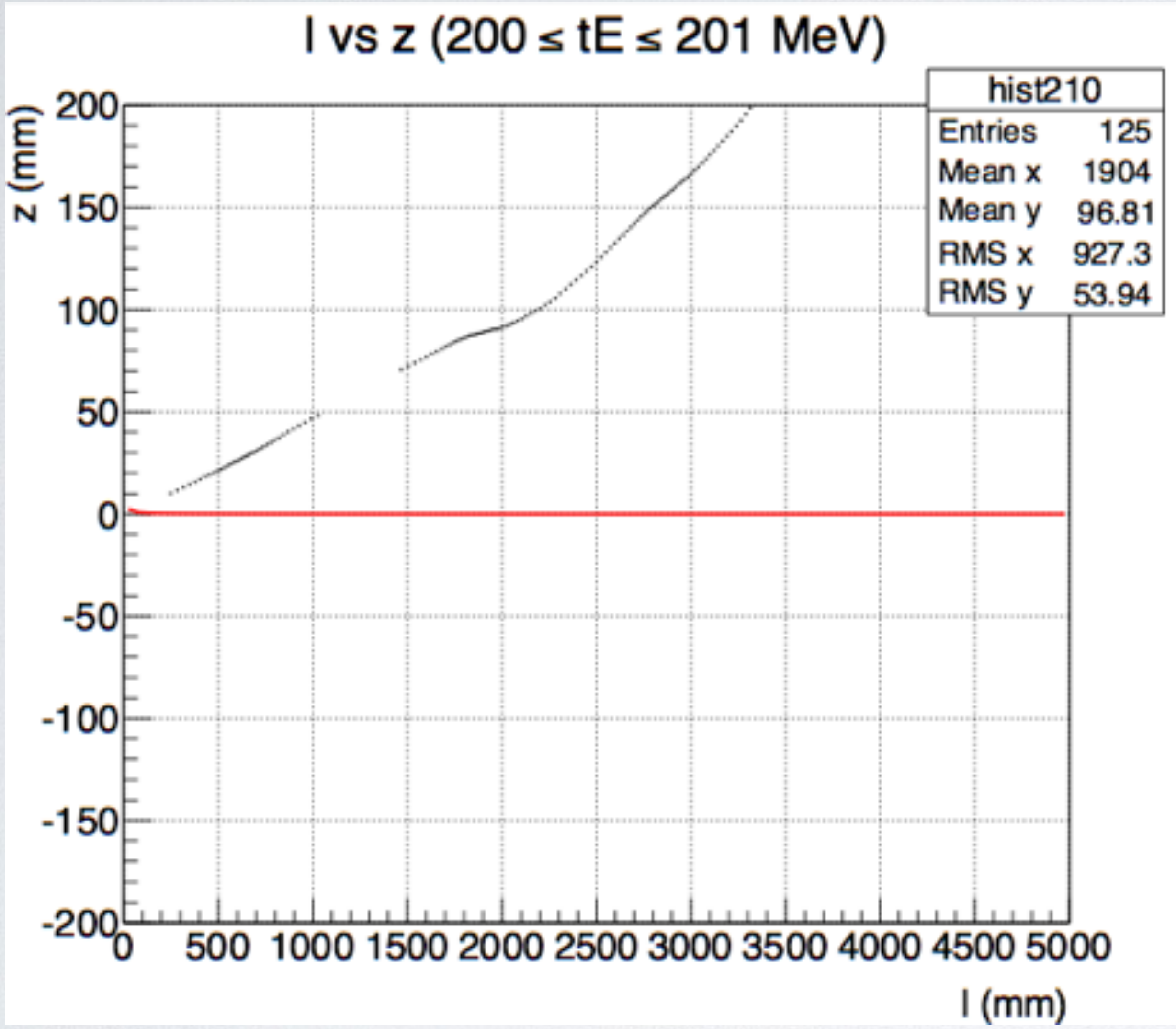
E < 100 MeV

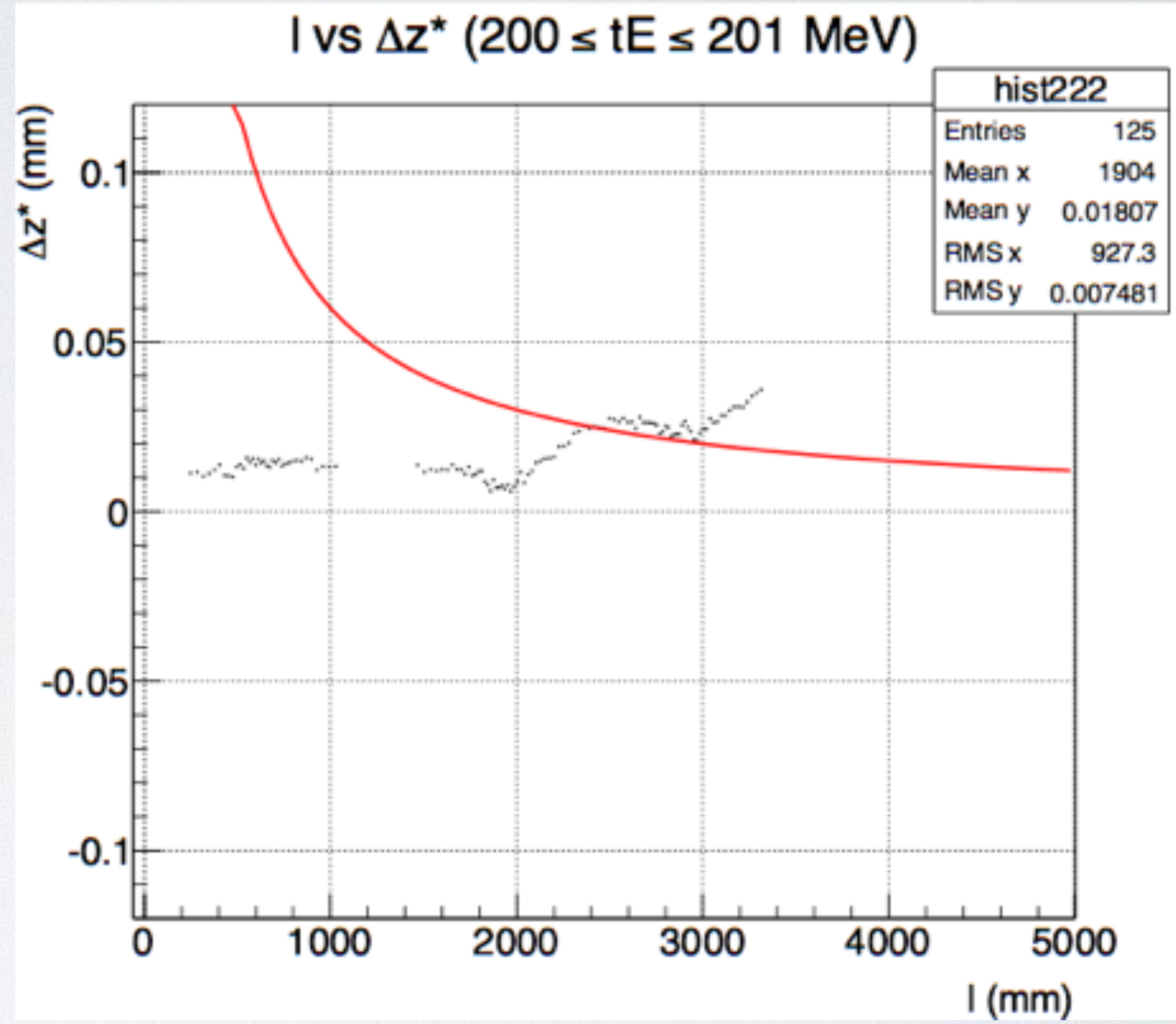


E = 120~170 MeV



Δz vs positron track length





distribution of momentum, and r and z of hotpoint