Application of Geant4 to Double Beta Decay Experiment DCBA

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(1) Introduction to DBD
(2) DCBA experiment
(3) Application of Geant-4 to DCBA
(4) Future prospect
(5) Summary

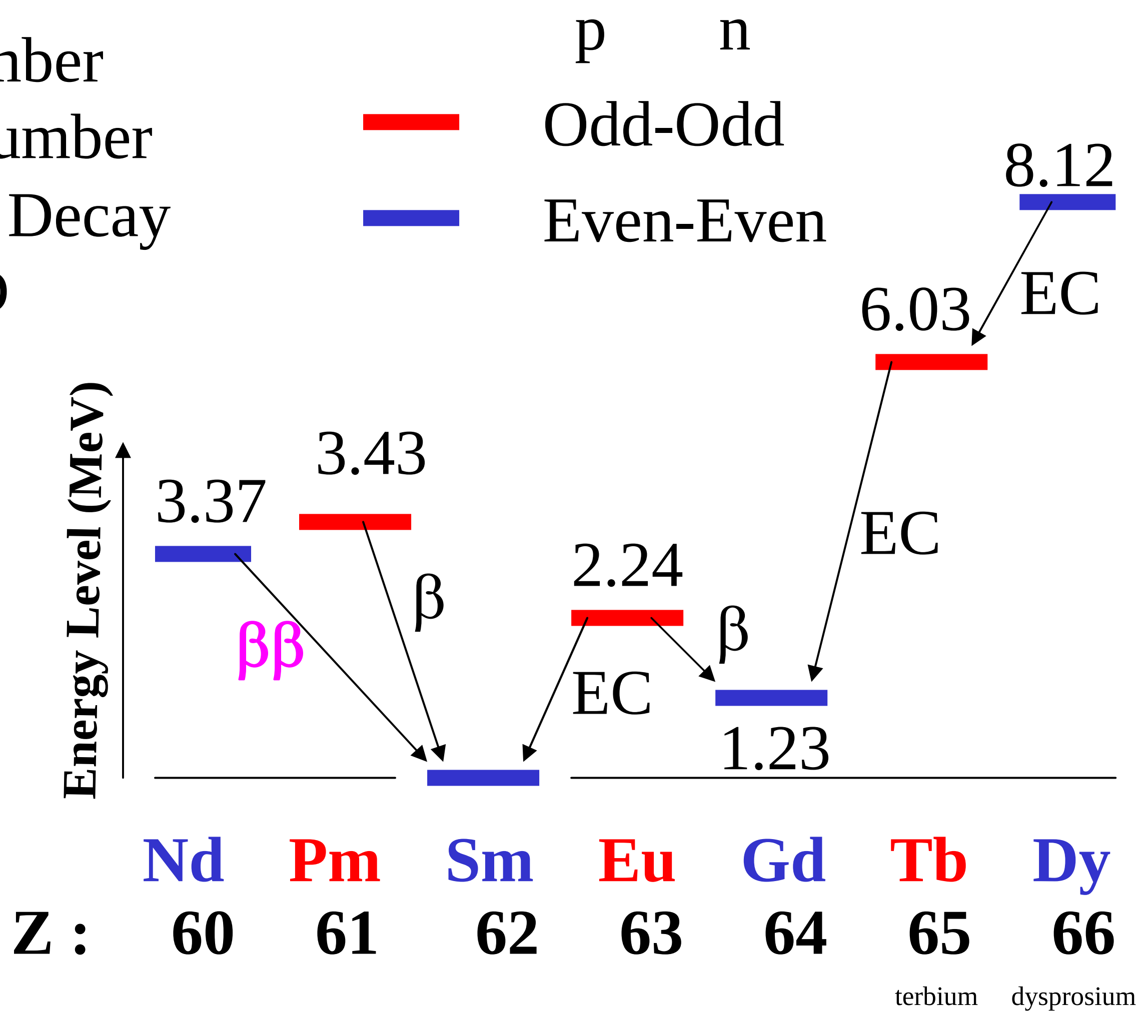
(1) Introduction to DBD

Neutrino oscillation experiments showed the existence of neutrino mass.
But the absolute mass scale and the neutrino Majorana nature are not known yet.
DBD experiments will give the information of the absolute mass scale and Majorana nature.

Beta Decay and Double Beta Decay

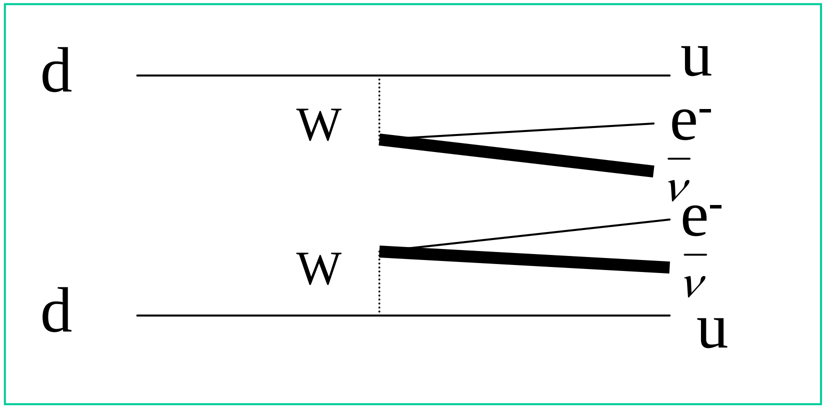
A: Mass Number
Z: Atomic Number
ΔZ = 1: Beta Decay
ΔZ = 2: DBD

Example
A=150



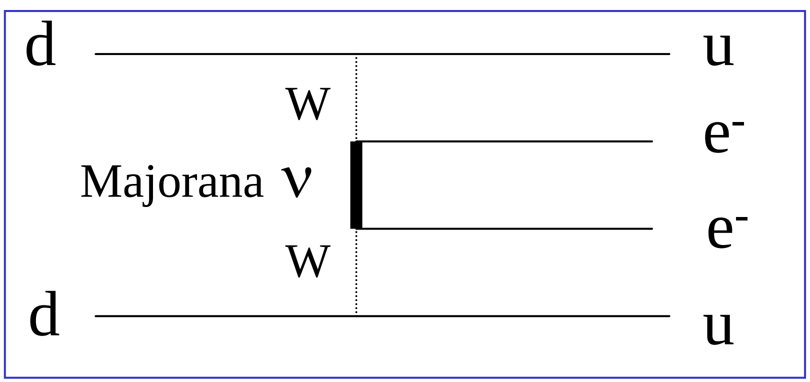
2ν- and 0ν-modes in DBD

2νββ: $(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\bar{\nu}$



0νββ: $(Z, A) \rightarrow (Z+2, A) + 2e^-$

Lepton number violation process



Seesaw mechanism

T. Yanagida, (1979)

M. Gell-Mann et al. (1979)

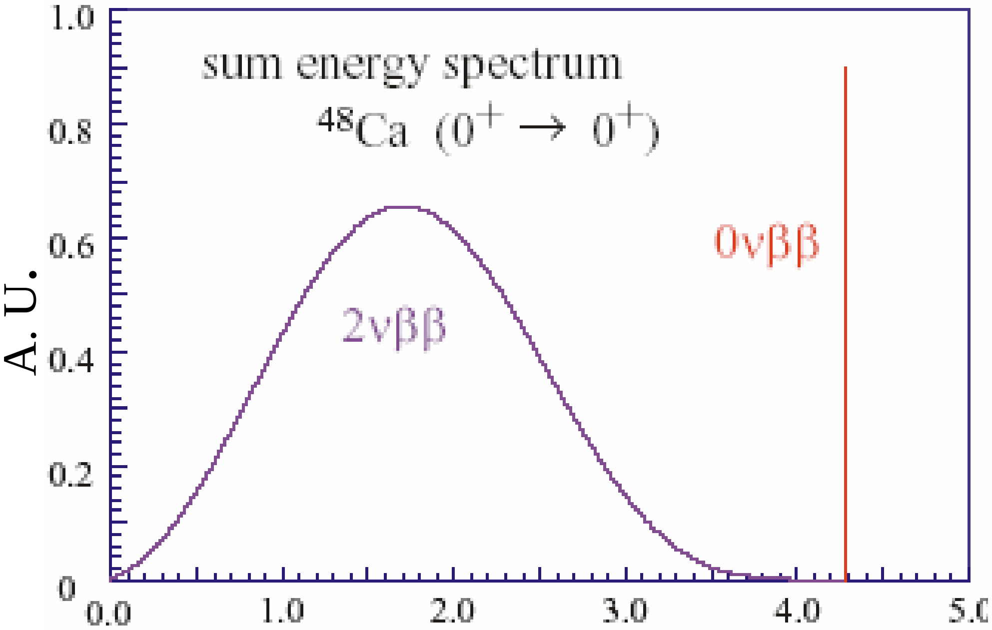
$$m_\nu \approx \frac{m_D^2}{M_R}$$

m_ν: Neutrino mass

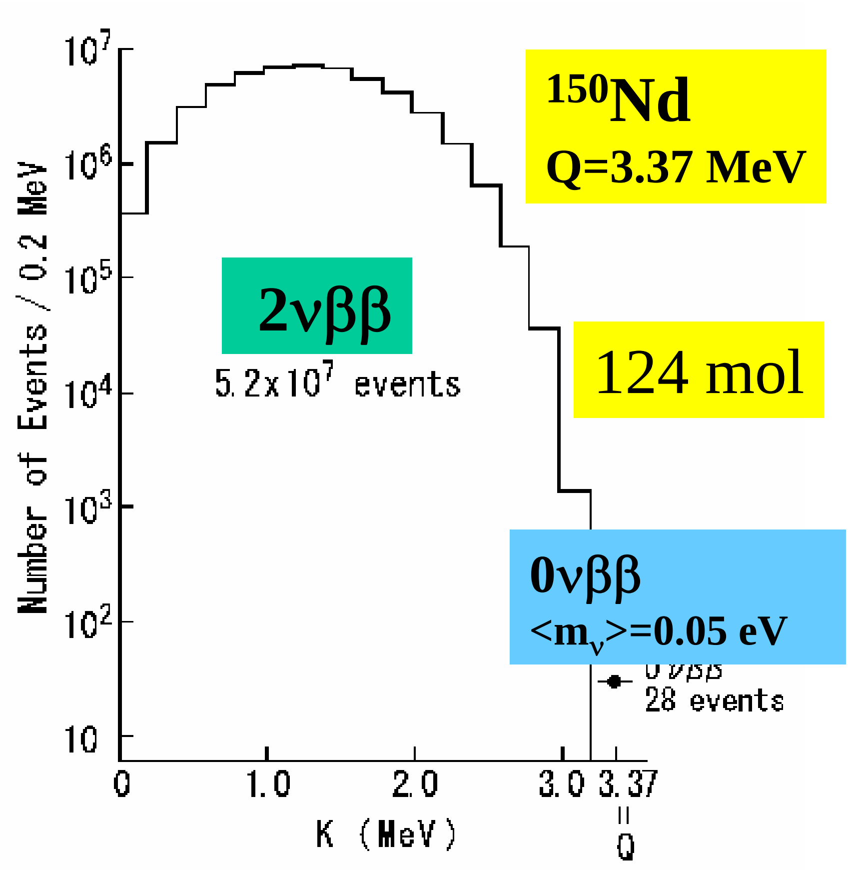
m_D : Dirac mass

M_R : Right handed neutrino mass (Majorana mass)

Sum-energy spectra of 2 electrons



T1+T2 (MeV)



T1+T2 (MeV)

Neutrino Mass and Double Beta Decay

Number of events and half-life

$$n = (\ln 2) k N_0 t \,/\, T_{1/2}$$

n : Number of events, N_0 : Number of nuclei

k : detection efficiency (to be obtained by Geant4)

t : Measuring time

Theoretical half-life (in the case of mass term dominance)

$$T_{1/2}^{0\nu} = (G^{0\nu} |M^{0\nu}|^2 <m_\nu>^2)^{-1}$$

$G^{0\nu}$: Phase space volume, $M^{0\nu}$: Nuclear matrix element

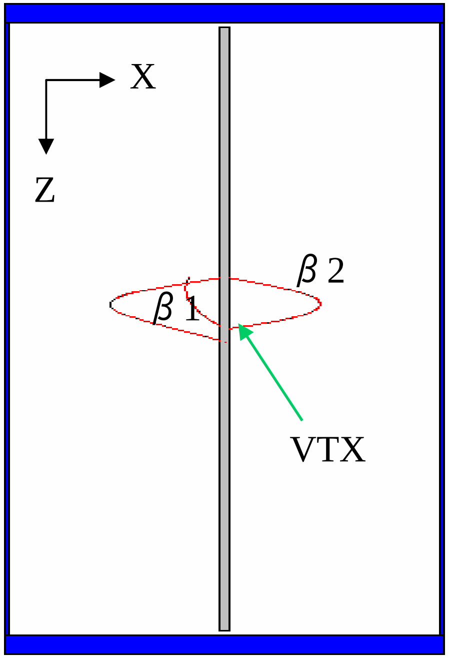
$<m_\nu>$: Effective mass

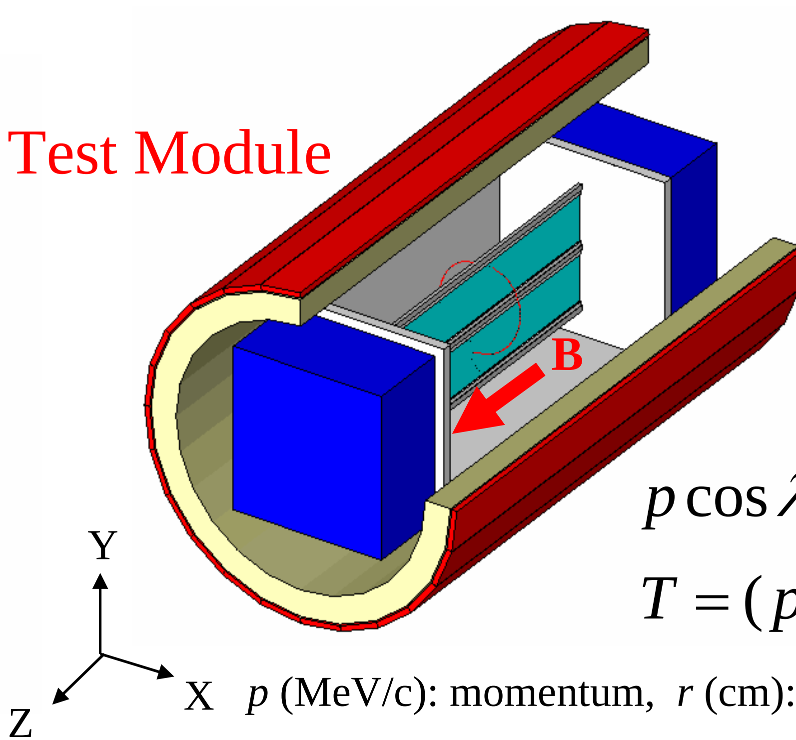
$$<m_\nu> = (n \,/\, (\ln 2) k N_0 t \, G^{0\nu} |M^{0\nu}|^2)^{1/2}$$

(3) DCBA experiment

DCBA (Drift Chamber Beta-ray Analyzer) is a momentum analyzer using a tracking detector in a uniform magnetic field.

Capabilities of the particle identification and the decay vertex identification can reduce background events caused by environmental gamma rays.





DCBA

Drift **C**hamber **B**eta-ray **A**nalyzer

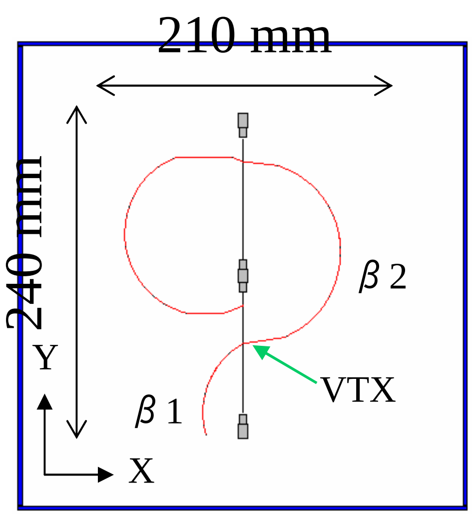
$^{150}Nd \rightarrow {}^{150}Sm + 2e^-$

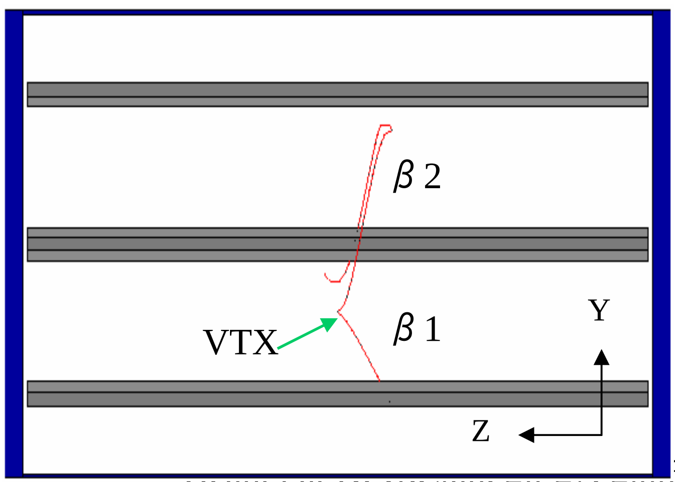
$$p\cos\lambda = 0.3rB,$$

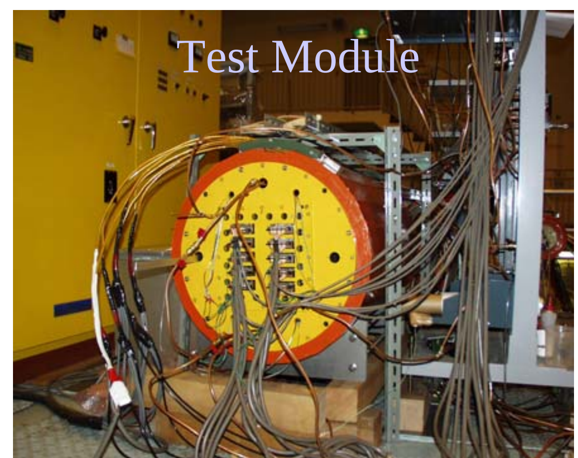
$$T = (p^2 + m_e^2)^{1/2} - m_e$$

p (MeV/c): momentum, *r* (cm): radius, λ: pitch angle

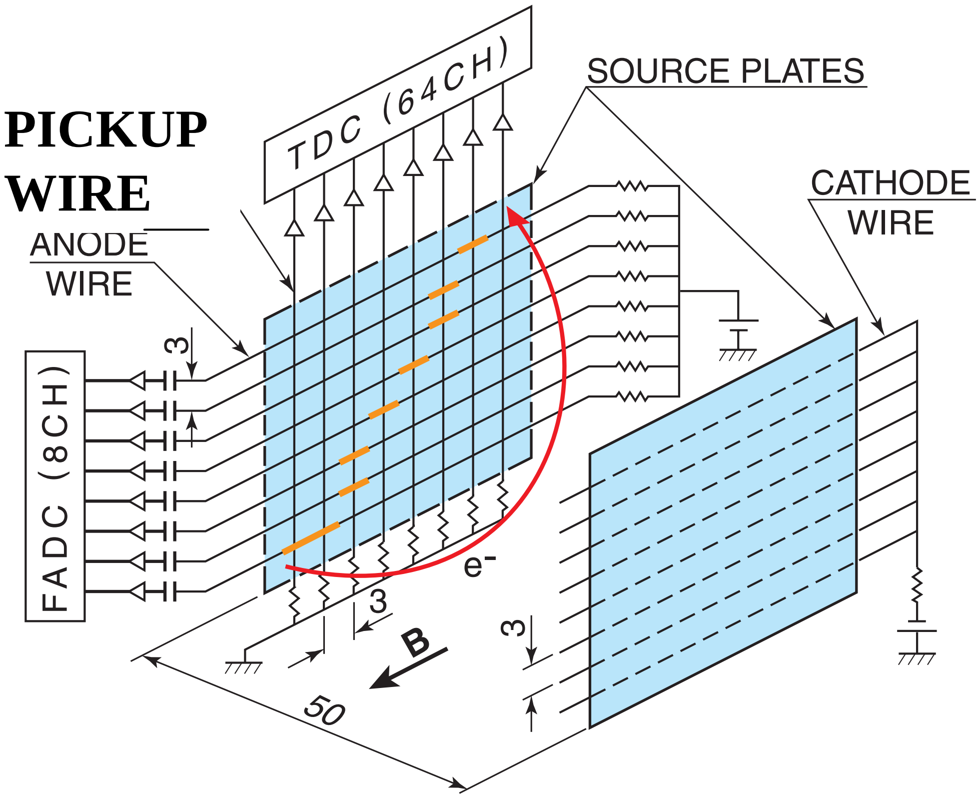
B (kG): mag. field, m_e (MeV/c^2): electron mass

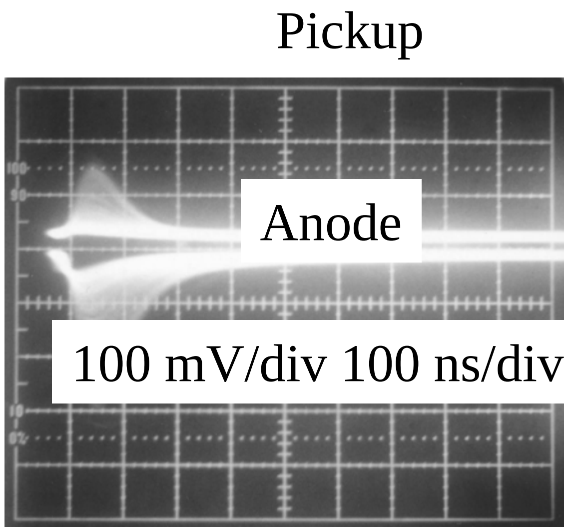




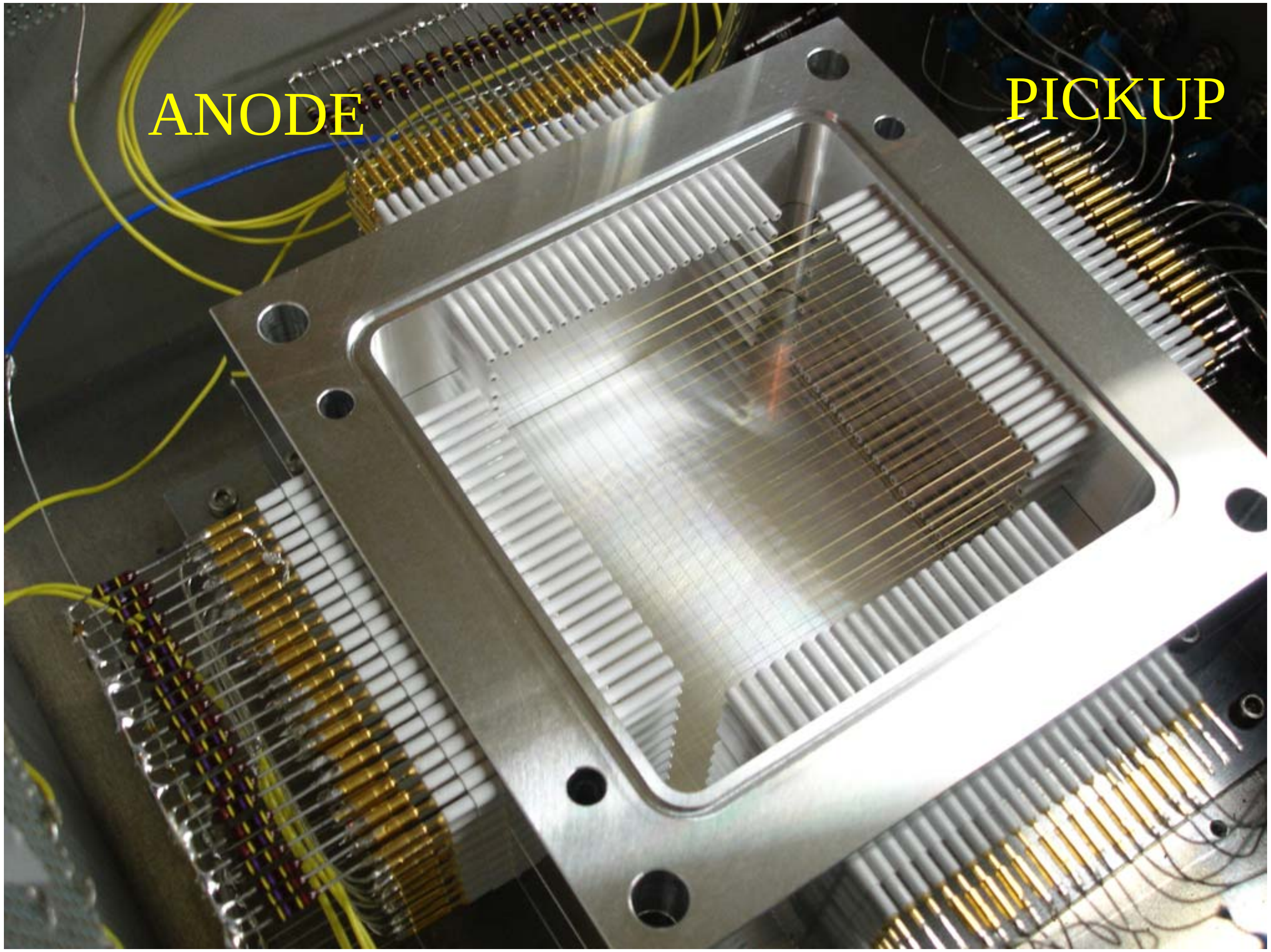


R&D of pickup wire reading out for Z-position



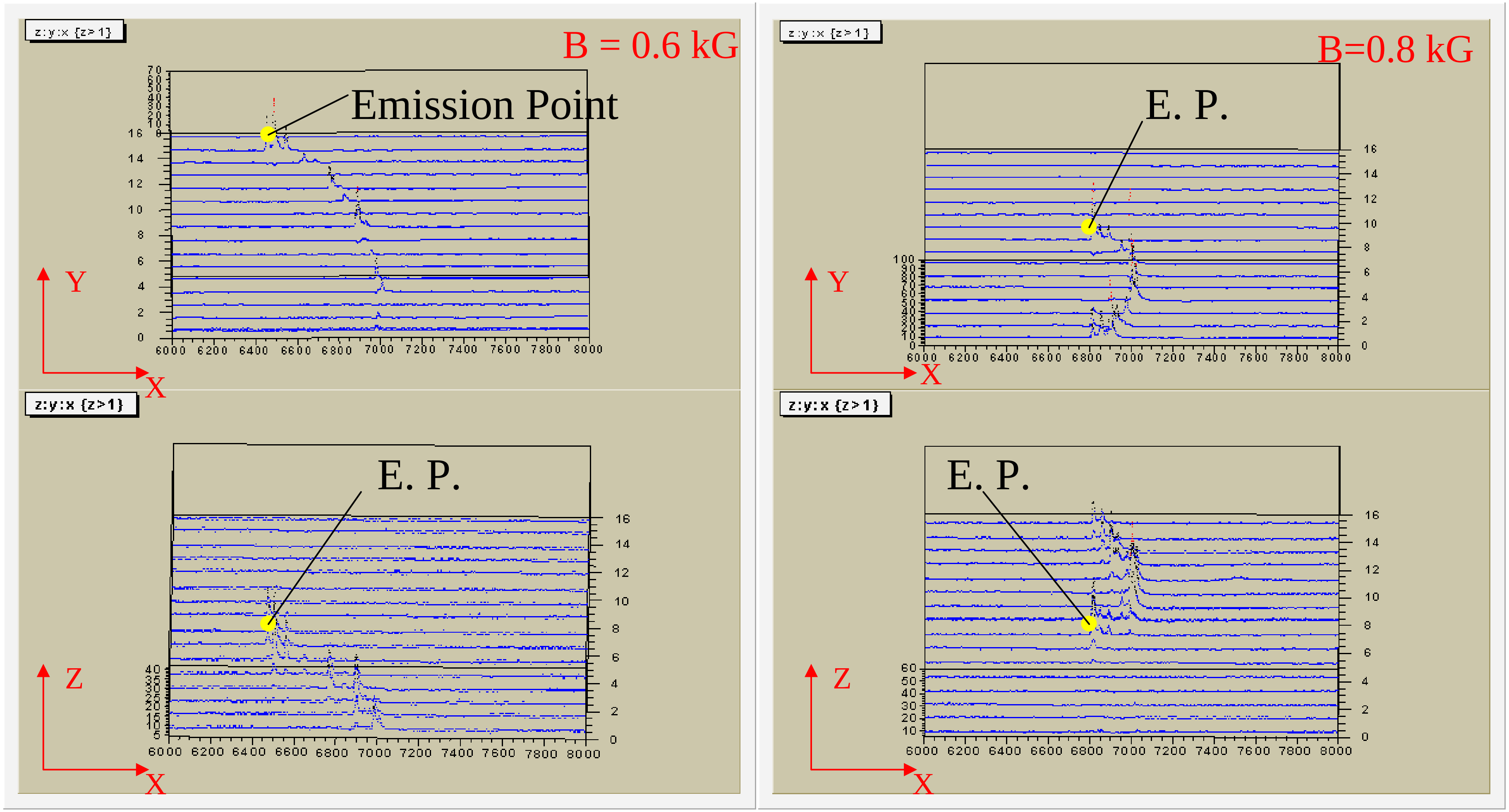


Test Chamber for Pickup-signal



Sensitive Volume $45 \times 45 \times 45$ mm^3

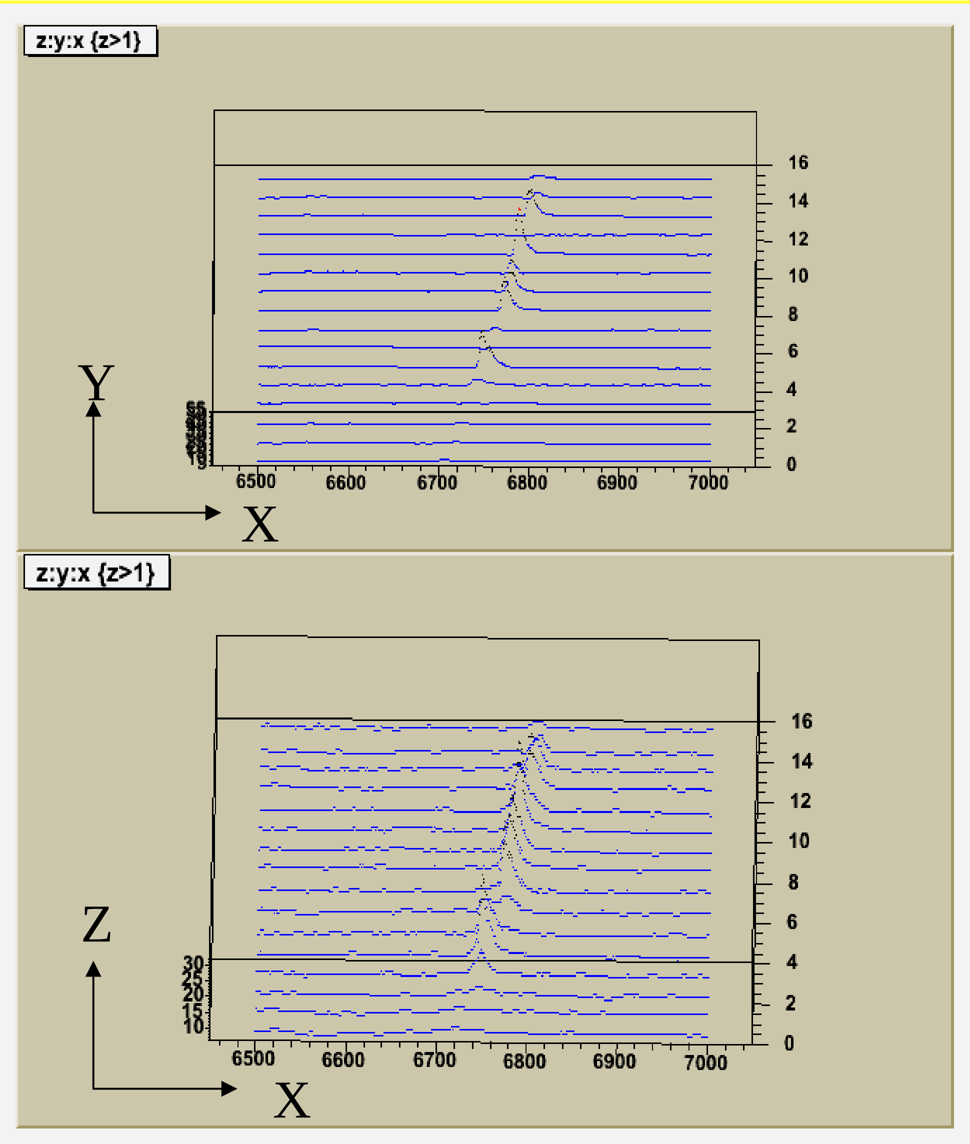
Electron Tracks in the Test Chamber

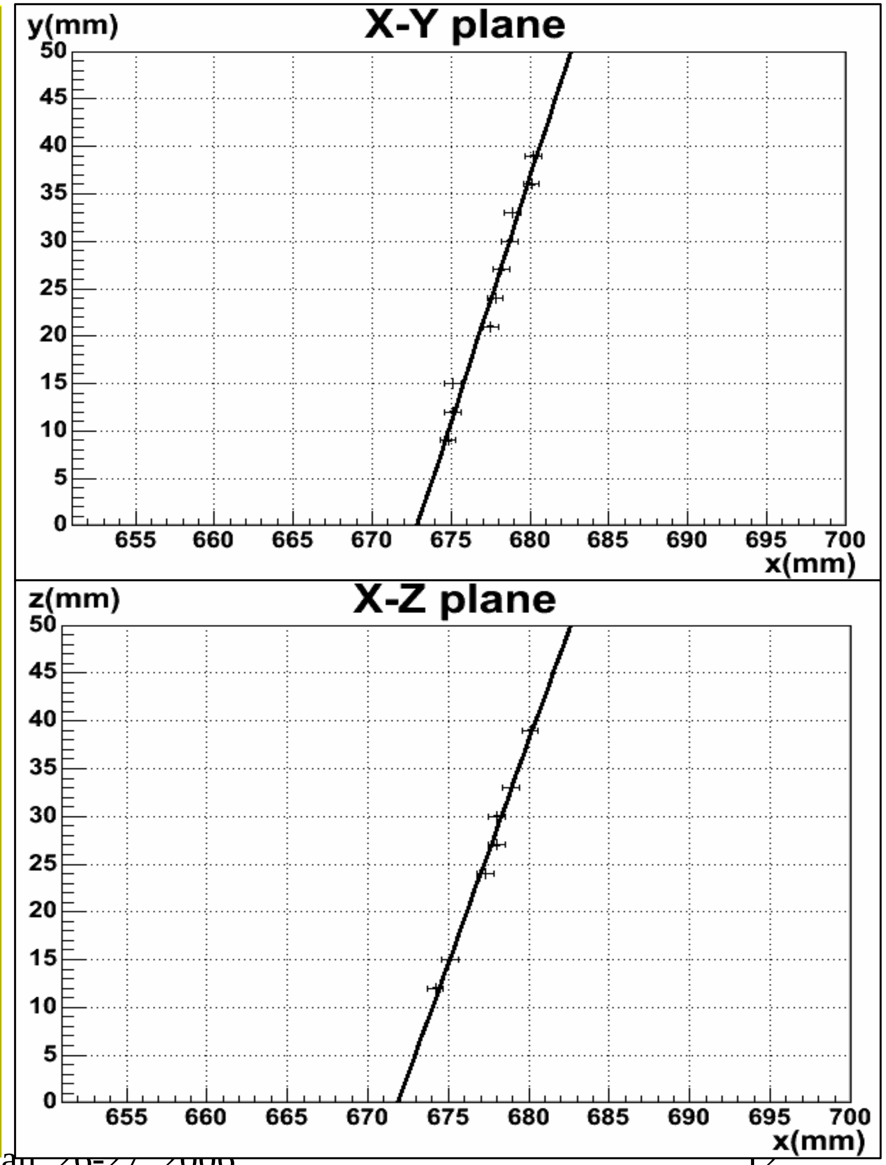


Internal Conversion Electron from ^{207}Bi (0.5 MeV)

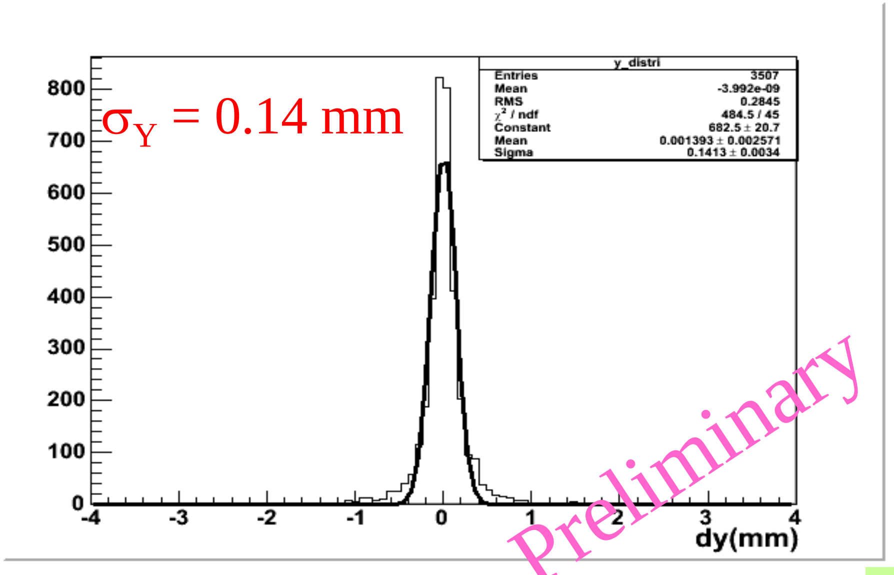
Electron Track (0.1 MeV)

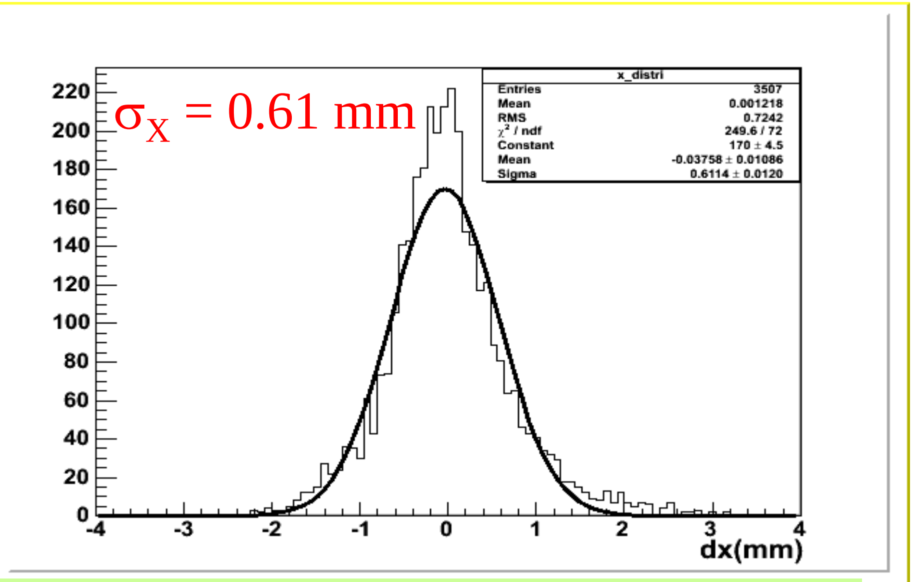
Cosmic-ray (Straight track)

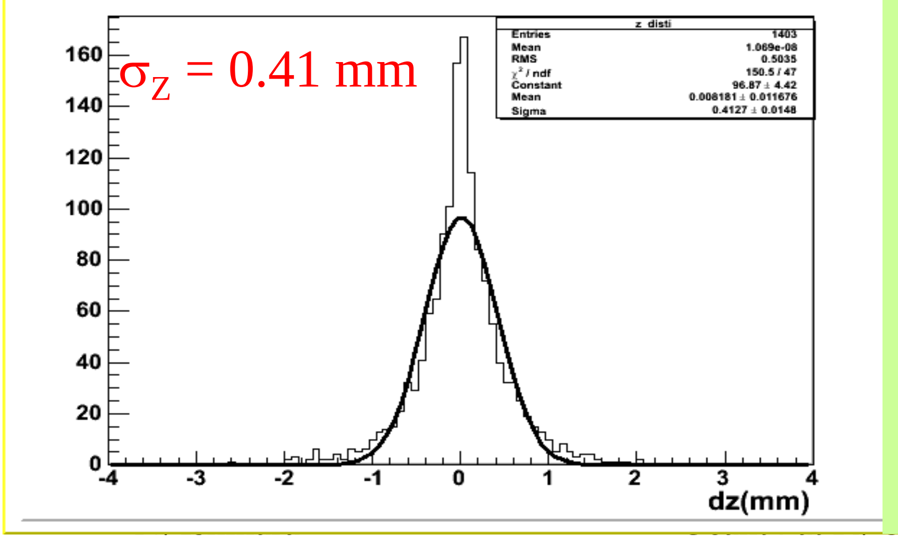




Position Resolutions Obtained From Cosmic-ray Events







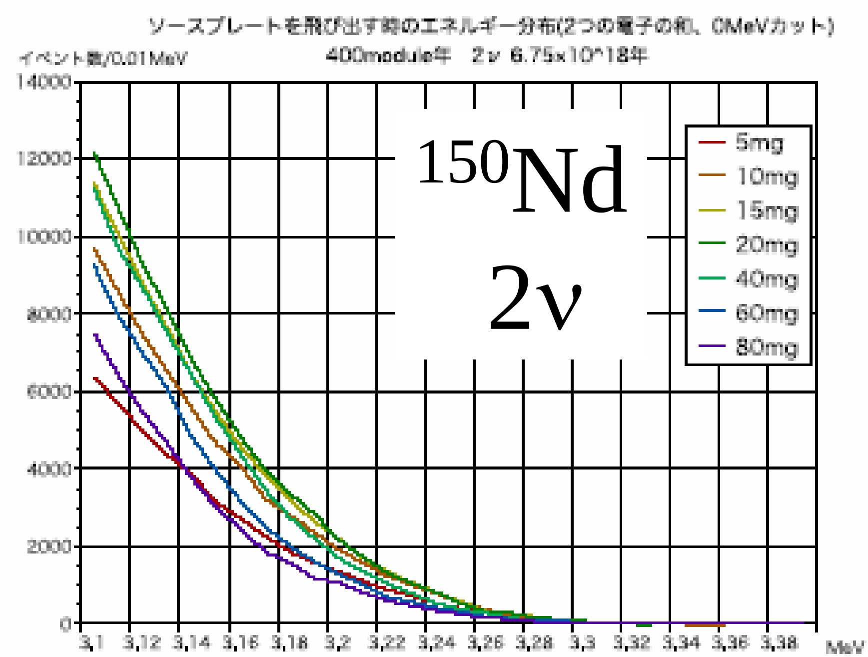
Required position resolution has been almost achieved.

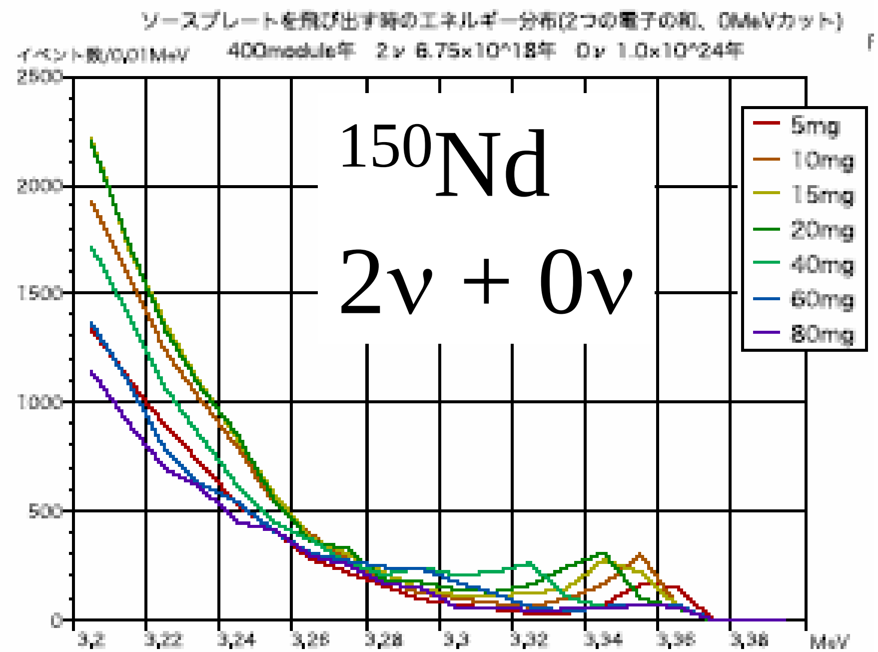
Energy resolution is under study using conversion electrons from ^{207}Bi.

(4) Application of Geant4 to DCBA

- Energy spectra of DBD events
- Energy resolution at Q-value (3.37 MeV)
- Track reconstruction
  by H. Hirai (Niigata Univ., 2005)
- Background studies
  by R. Ito (Tokyo Univ. of A & T, 2002)

Energy Spectra of 2ν and (2ν + 0ν)-events



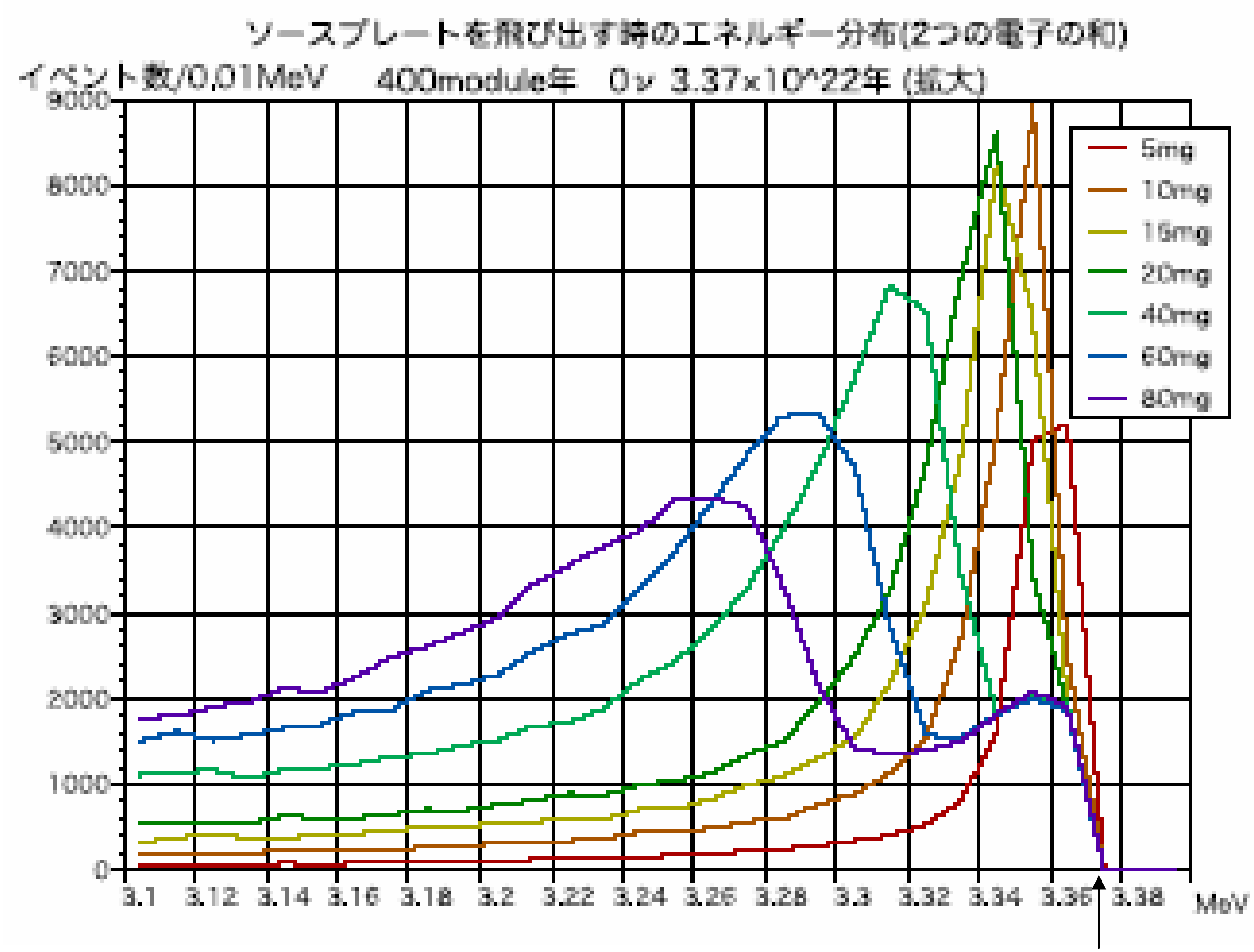


$$T_{1/2}^{2\nu} = 6.75\times 10^{18}\ \text{y}$$

$$T_{1/2}^{0\nu} = 1.0\times 10^{24}\ \text{y}$$

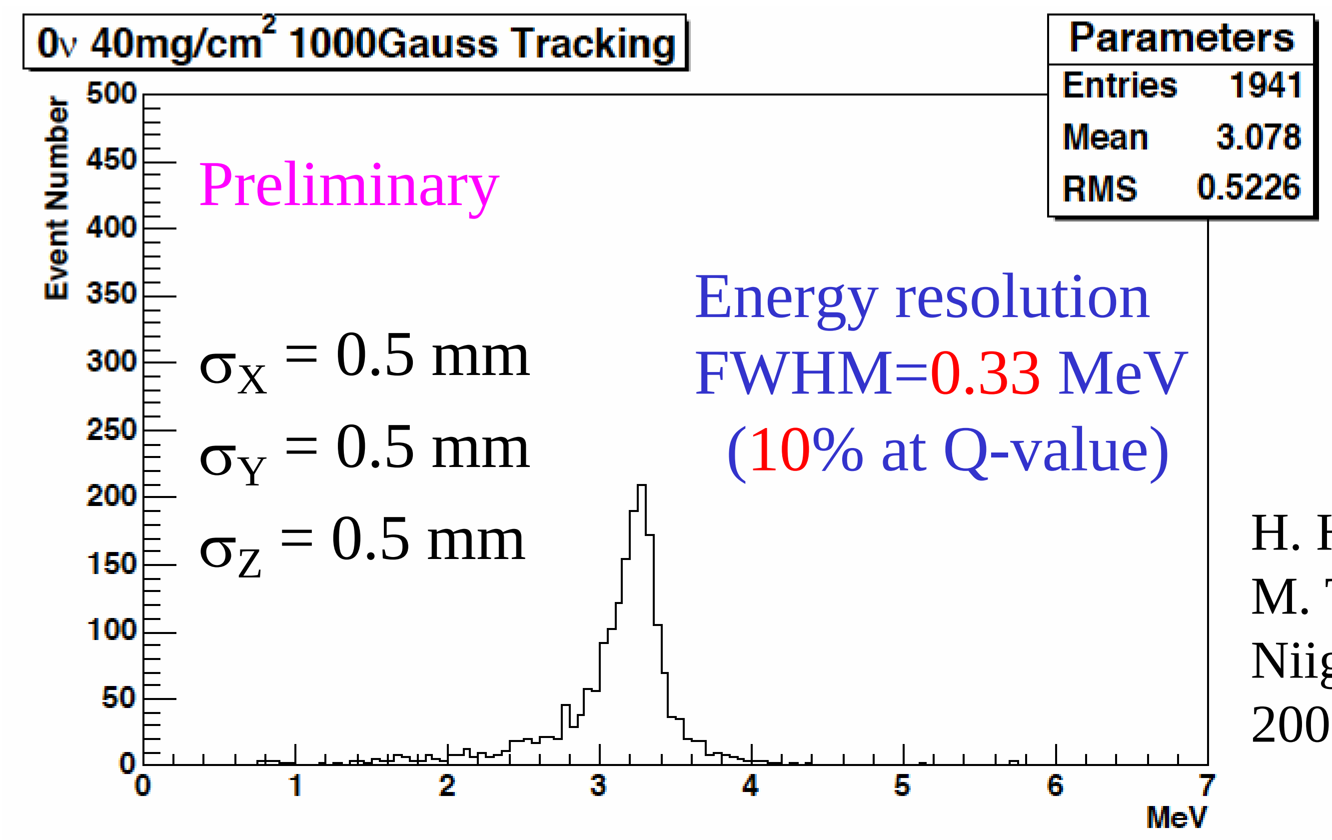
(<mν> ≈ 0.2 eV)

Energy spectra for various source thickness



Q

Geant4 study on energy resolution for ^{150}Nd (Q=3.37 MeV)



σ_X = 0.5 mm

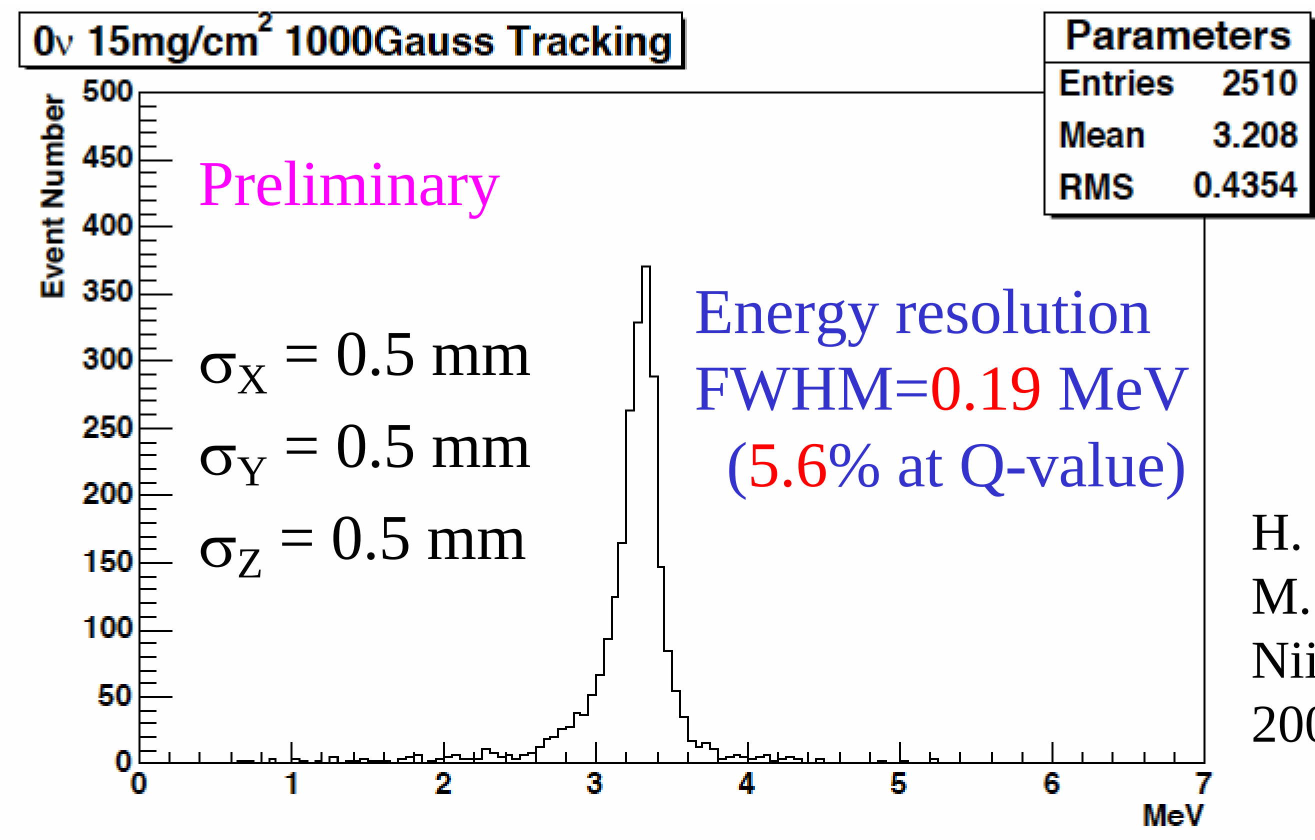
σ_Y = 0.5 mm

σ_Z = 0.5 mm

Energy resolution
FWHM=0.33 MeV
(10% at Q-value)

H. Hirai
M. T.
Niigata unv.
2005

Geant4 study on energy resolution for ^{150}Nd (Q=3.37 MeV)



H. Hirai
M. T.
Niigata unv.
2005

Sum Kinetic Energy Spectra of $0\nu\beta\beta$ and ^{214}Bi events

$$^{214}_{83}\mathrm{Bi} \rightarrow {}^{214}_{84}\mathrm{Po} + \underline{\underline{\beta^-}} + \bar{\nu}$$

(Q=3.28MeV)

$$\downarrow \rightarrow \underline{\underline{\text{conv. } e^-}}$$

$$\downarrow \rightarrow {}^{210}_{82}\mathrm{Pb} + \alpha$$

$$(T_{1/2} = 164\,\mu\,\mathrm{sec})$$

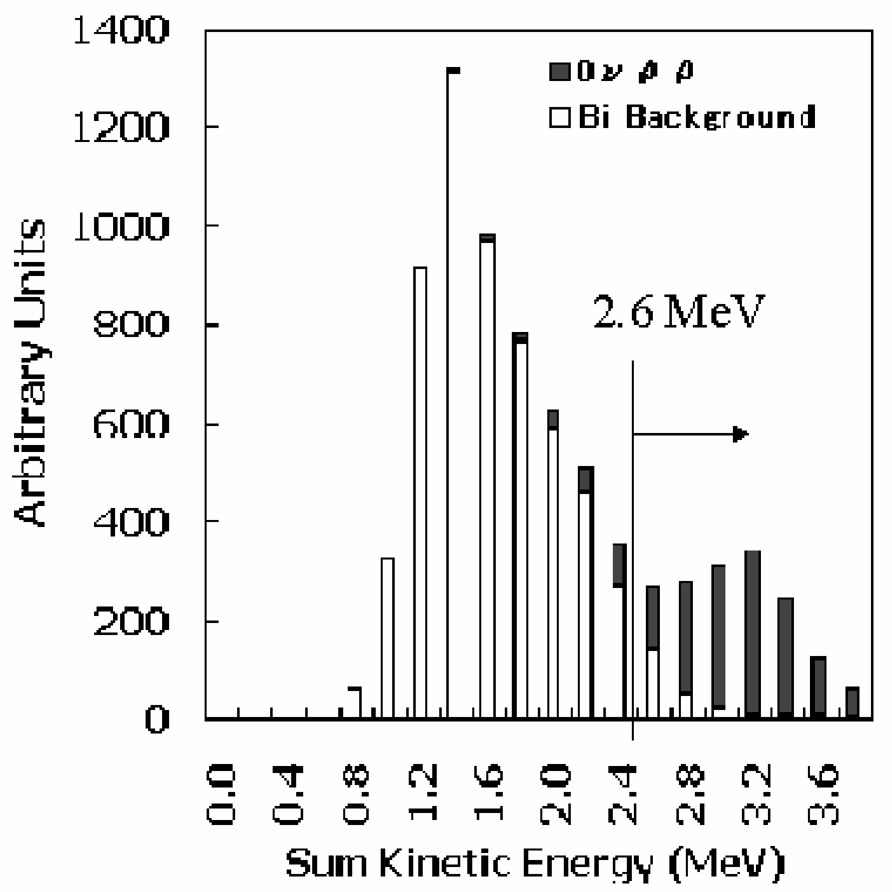
$0\nu\beta\beta$: 0.28

^{214}Bi : 2.3 x 10^{-3}

for $e^- e^-$ event

→ 1.2 x 10^{-6}

for whole ^{214}Bi



Sum Kinetic Energy Spectra of 0ν β β and ^{208}Tl events

$$^{208}_{81}\mathrm{Tl} \rightarrow {}^{208}_{82}\mathrm{Pb} + \underline{\underline{\beta^-}} + \bar{\nu}$$

$$(Q = 4.99\mathrm{MeV}) \downarrow$$

$$\underline{\underline{\text{conv. } e^- (2.6\mathrm{MeV})}}$$

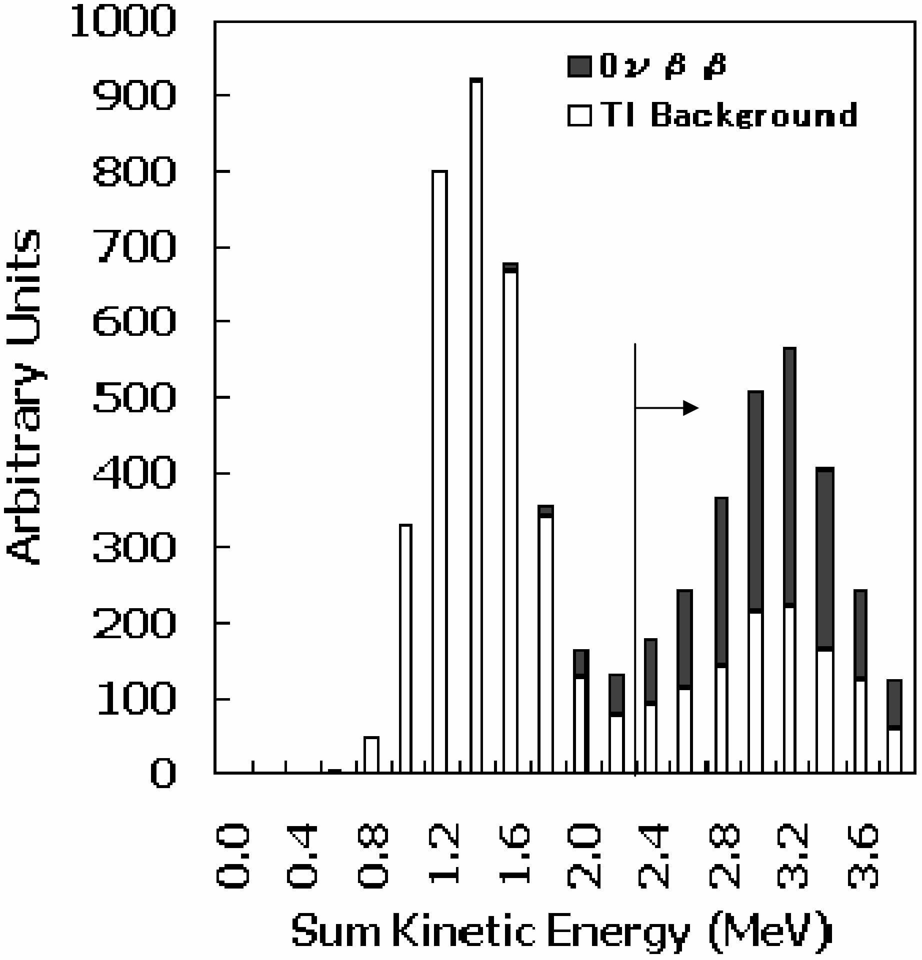
0ν β β : 0.28

^{208}Tl : 1.04 x 10^{-2}

for e$^-$ e$^-$ event

→ 1.5 x 10^{-4}

for whole ^{208}Tl



Sum Energy of 208Tl

Single Energy Spectra of 0νββ and ^{208}Tl events

$$^{208}_{81}\mathrm{Tl} \rightarrow {}^{208}_{82}\mathrm{Pb} + \underline{\underline{\beta^-}} + \bar{\nu}$$

$$(Q = 4.99\mathrm{MeV})\downarrow$$

$$\underline{\underline{\text{conv. } e^-(2.6\mathrm{MeV})}}$$

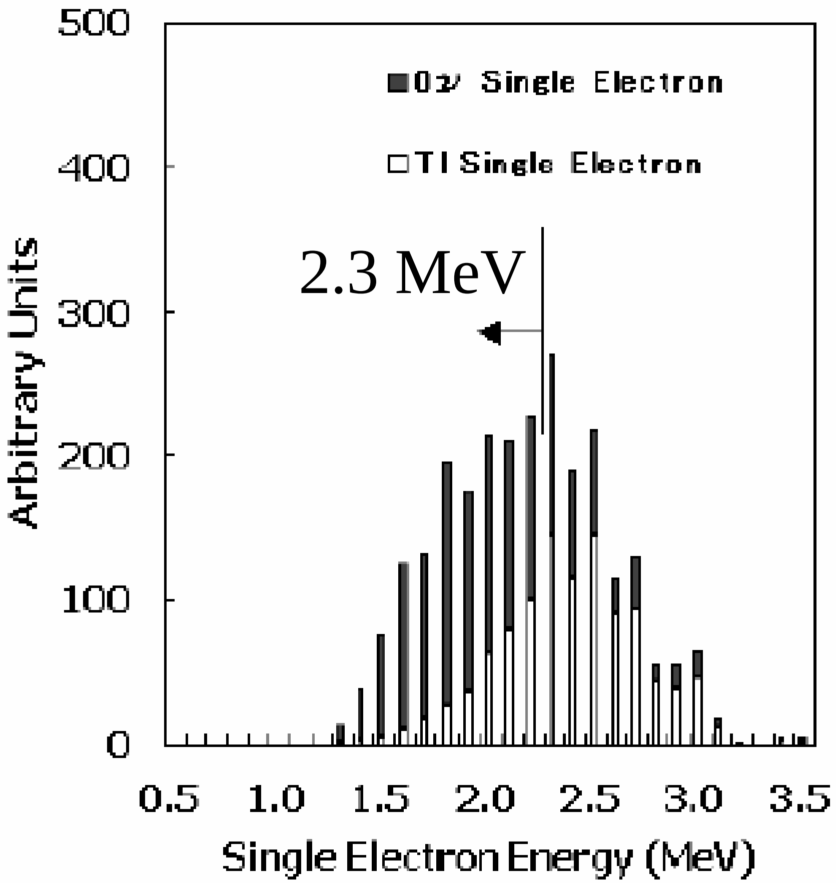
0νββ : 0.21

^{208}Tl : 3.3 x 10^{-3}

for e$^-$ e$^-$ event

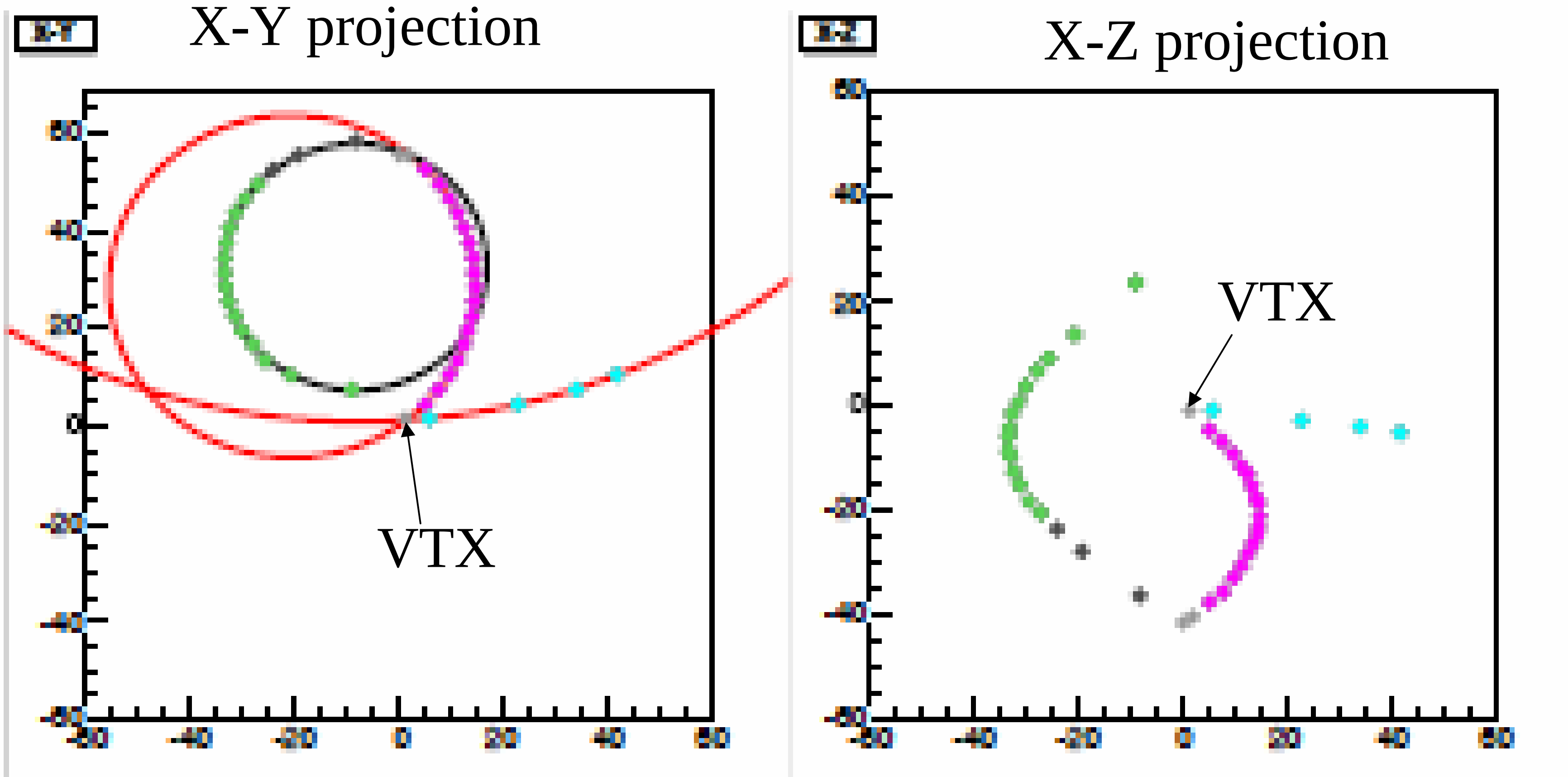
→ 4.7 x 10^{-5}

for whole ^{208}Tl



Lower energy out of 2 electrons

Tracking Simulated with Geant4



(5) Future prospect

Near future

- Study of energy resolution using internal conversion electron from ^{207}Bi.
- Half-life Measurement for 2νDBD.
  Calculation of k requires Geant4.

Future

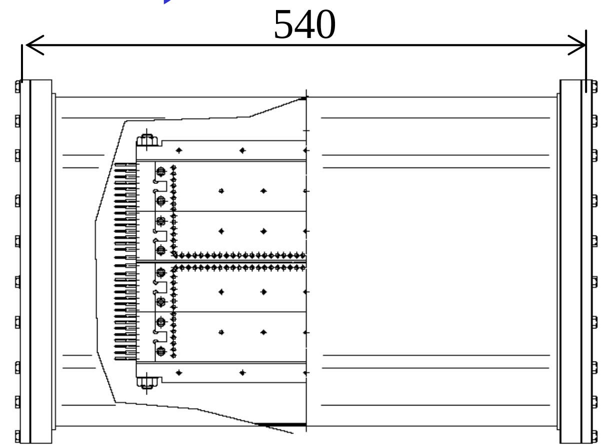
- Half-life Measurement for 0νDBD.
  Calculation of k requires Geant4.

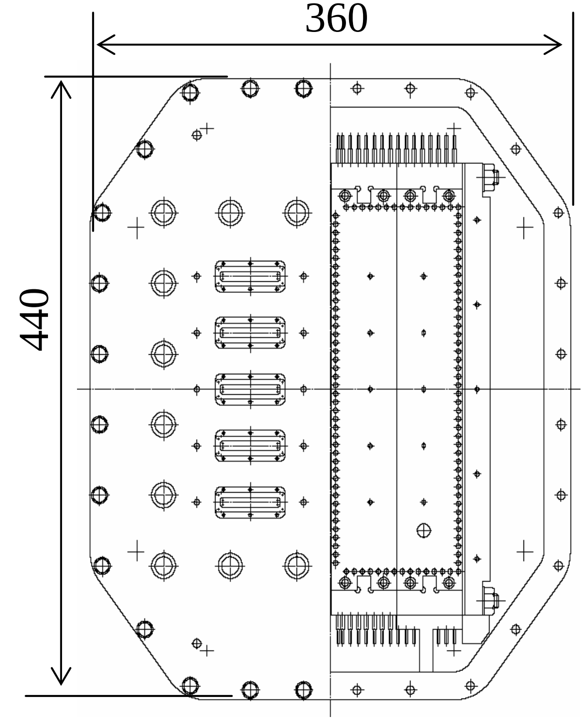
DCBA-T (under construction)

- Drift chamber — Multi-track capability
  - Source — Nd_2O_3 (40 mg/cm^2) (^{150}Nd =0.008 mol)
  - Sensitive vol. — 18(X) × 26(Y) × 26(Z) cm^3
  - Signal readout — Flash ADC
  - X-position — Drift velocity × Drift time ($\sigma_X \sim 0.5$ mm)
  - Y-position — Anode wire position ($\sigma_Y \sim 0.5$ mm)
  - Z-position — Pickup wire position ($\sigma_Z \sim 0.5$ mm)

- Magnet — Solenoid coil + Flux return yoke
  - Magnetic field — 0.8 kG (Max.)
  - Uniform Vol. — 40 dia. x 70 cm^3 ($\delta B/B_0 < 1\%$)

- Veto-counters — Scintillation counters

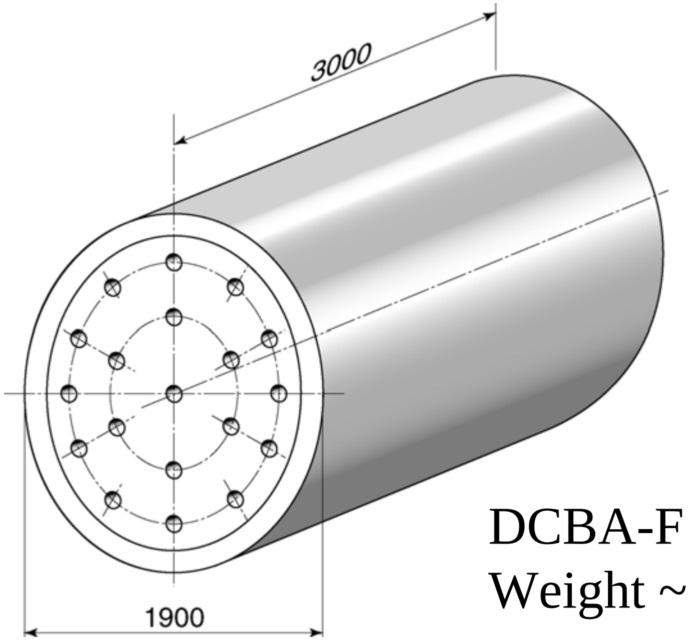




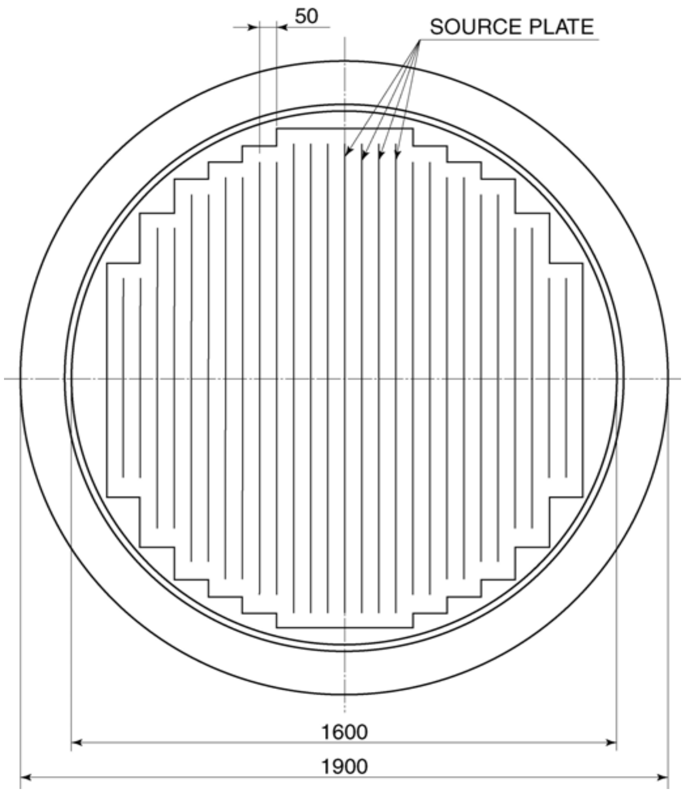
DCBA-Future

Source plate: 84 m^2/module
Thickness: 15 (40) mg/cm^2
Weight: 12.6 (33) kg/module
10 module → 126 (330) kg

Anode wire: 10720/module
Pickup wire: 13160/module



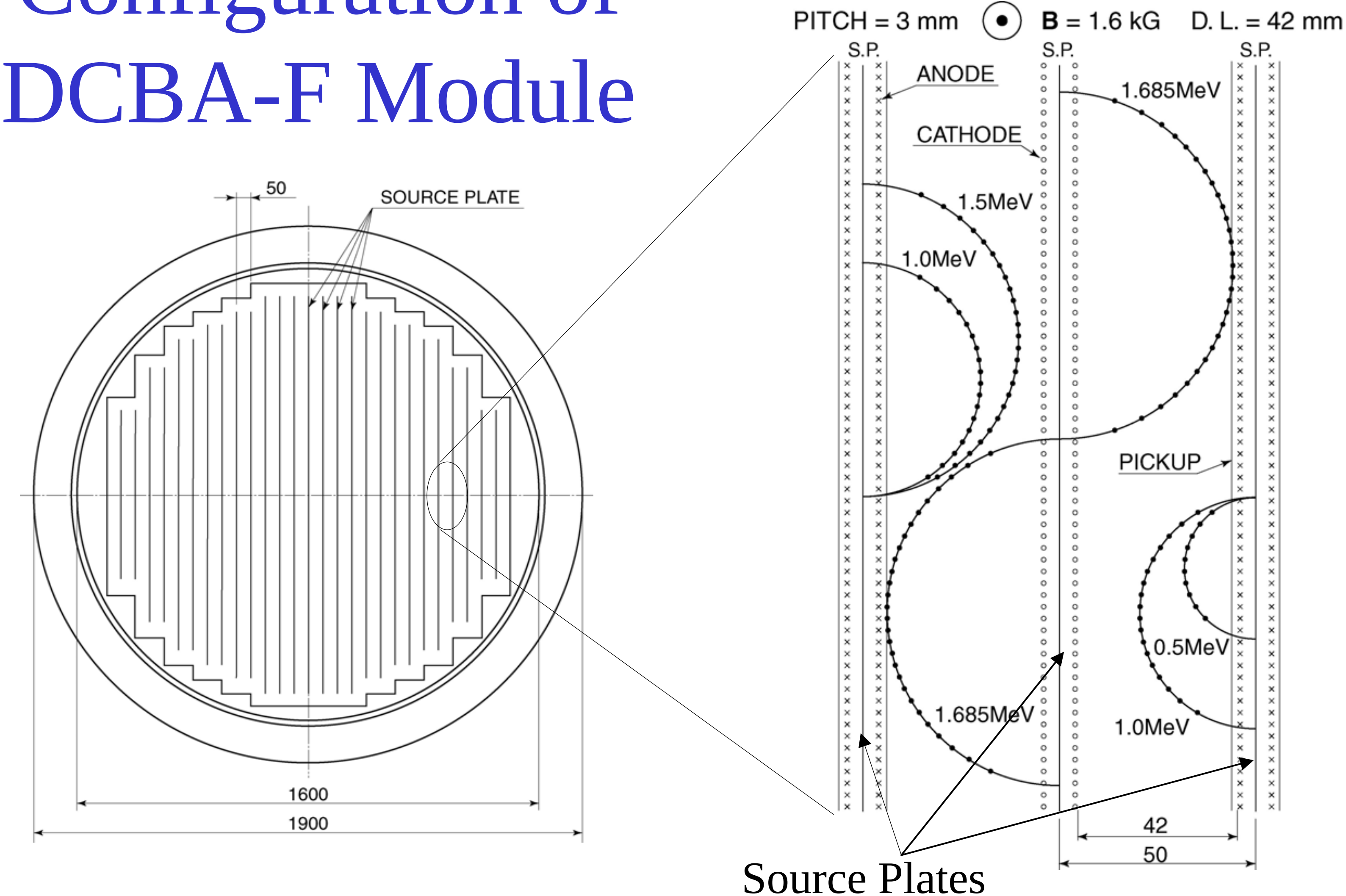
DCBA-F module
Weight ~ 10 t



$< m_\nu > \approx 0.3\,\text{eV}$ for natural Nd/module.year

$< m_\nu > \approx 0.1\,\text{eV}$ for 90% ^{150}Nd/module.year

Configuration of DCBA-F Module



Calculated $(\sigma_T/T) \approx 3\%$ for 1 MeV electron of $\lambda=0$

Half-life and Effective Mass Sensitivities of DCBA for ^{150}Nd, ^{100}Mo and ^{82}Se (Tentative)

	Natural Nd (5.6% ^{150}Nd)	^{150}Nd (80% enr.)	^{100}Mo (90% enr.)	^{82}Se (90% enr.)
DCBA Amount (mol) (600 kg ~ 50 modules)	190	2700	5400	6600
$T^{1/2}_{0\nu}$ sens. (yr)	9×10^{24}	1×10^{26}	2×10^{26}	3×10^{26}
$<m_\nu>$sens. (eV)	0.06	0.02	0.07	0.04

Nucl. Matrix Element: A. Staudt et al. Europhys. Lett. 13 (1) (1990) 31

Summary

1. 0νDBD can investigate the Majorana nature of neutrinos. Half-life measurement of 0νDBD can determine the absolute neutrino mass scale.
2. DCBA experiment uses a momentum analyzer with magnetic tracker. Spatial resolution of around 0.5 mm has been obtained in position coordinates, X, Y and Z. Now, we are studying for energy resolution.
3. Studies with Geant4 have shown that the energy resolution of DCBA is about 6% (FWHM) at the Q-value of ^{150}Nd, depending on the thickness of source plate. The serious backgrounds from ^{214}Bi and ^{208}Tl are effectively reduced.
4. Future DCBA will have the sensitivity of around 0.05 eV for the effective neutrino mass.