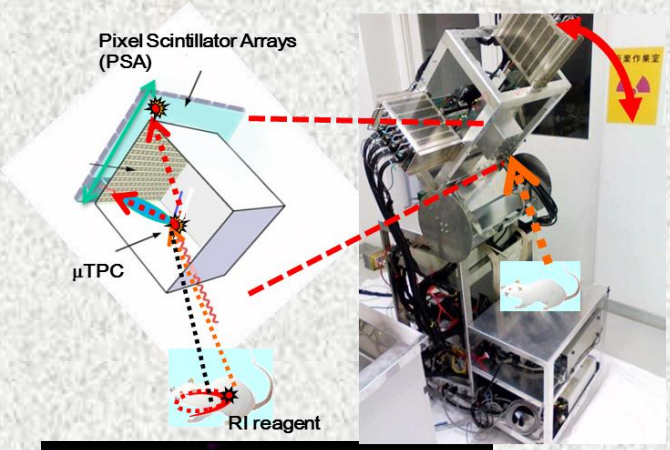
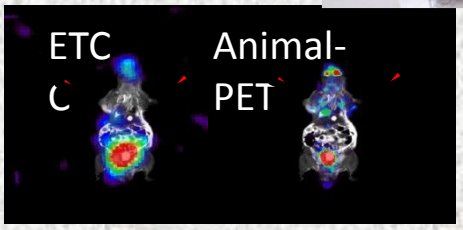
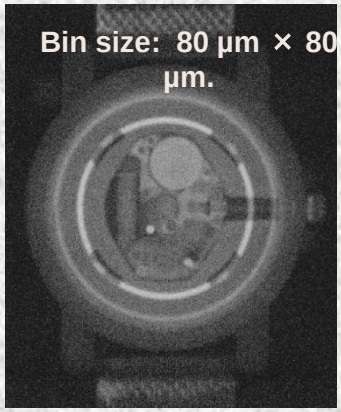
Development of Imaging Science using Quantum Beam (Neutron and Gamma Imaging)







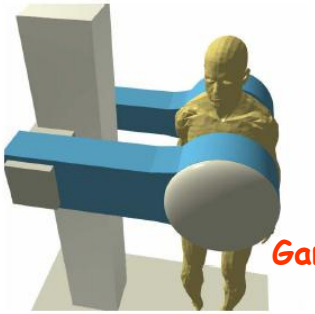
Interdisciplinary Research Programs
(f) The science of quantum beam imaging

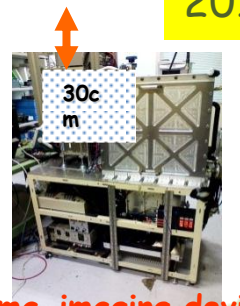
- Introduction
- 3D particle tracing and Tracking Compton Camera (ETCC)
- Application to nuclear Medicine
- TOF neutron Imaging detector
- TOF neutron science in J-PARC
- Summary

T. Tanimori (Gamma sub-group in Cosmic-ray group)
Dept. of Physics, Kyoto University

Science of quantum beam imaging (using the technology of elementary particle experiments to probe matter and living systems)

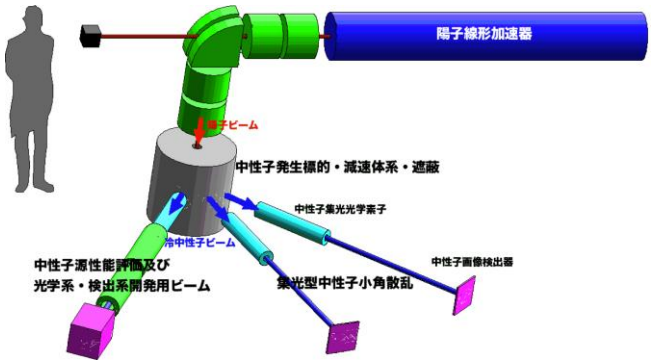
Introduction of Small pulsed Neutron Source in Dept. of Physics 2010 by supplementary budget



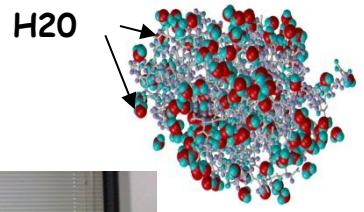


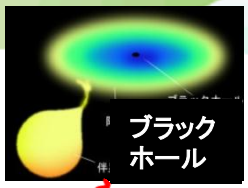
Gamma-imaging device

Gamma Imaging diagnosis

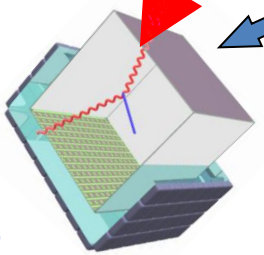


Cystography by neutron for protein

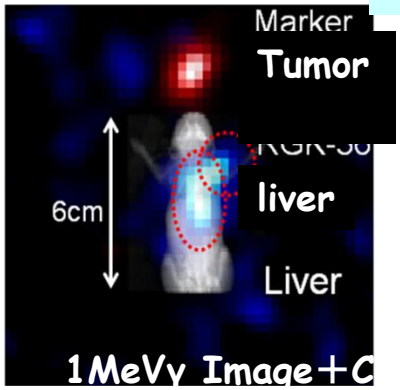




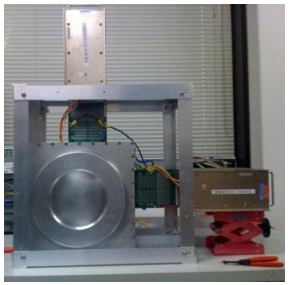
Gamma Neutron



Molecular Imaging by RI
Bio-marker

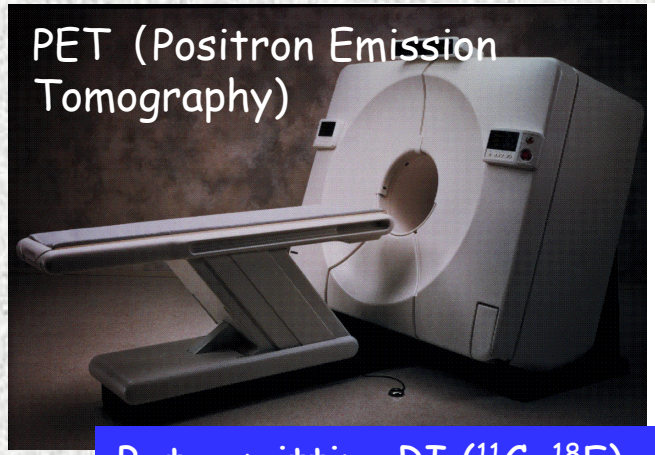


Gamma Imaging detector for Astrophysics using elementary particle physics



Neutron Imaging device using Gamma imaging

Gamma Ray Medical Imaging



Beta emitting RI (^{11}C, ^{18}F)

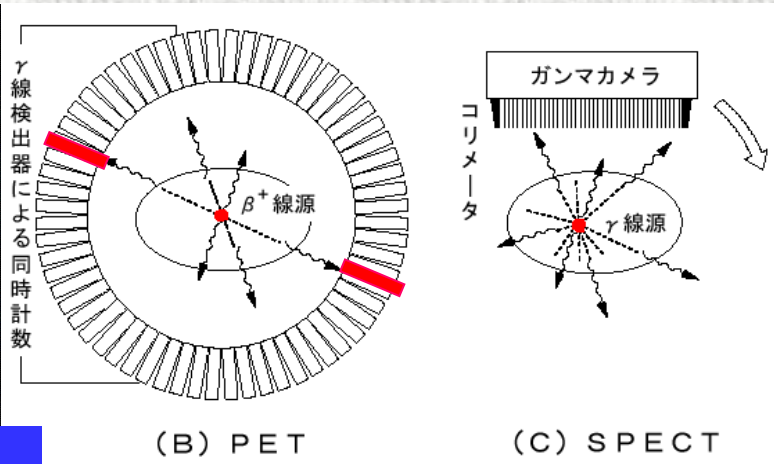
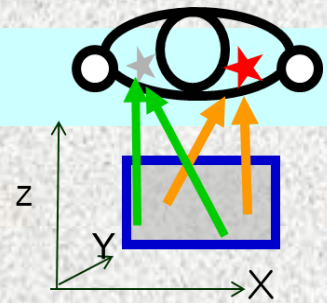


図1 X線イメージングと核医学イメージングの比較

[資料提供]放射線医学総合研究所

1. Many RIs
2. Large Fielld of View
3. 3D

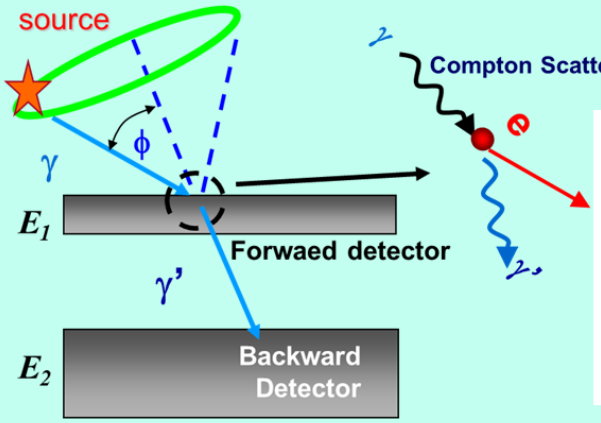


Collimator +Position Detect（SPECT)

Single Photon Emission CT

Low energy gamma RI (<300keV,^{99m}Tc:143keV):

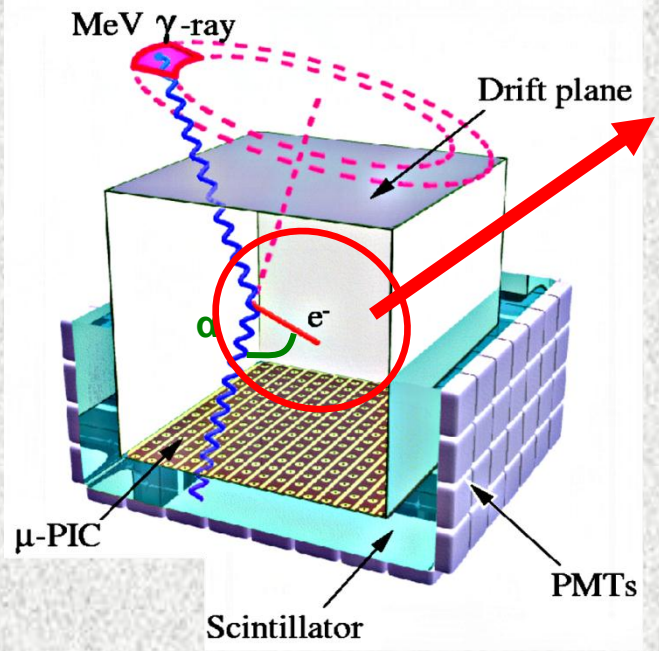
Compton Camera



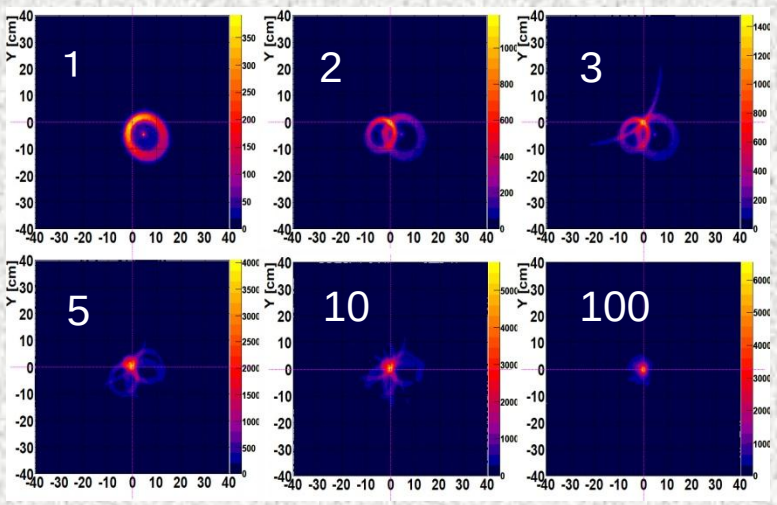
$$\cos\phi = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)$$

$\Delta\phi \propto \Delta E/E$ $(E=E_1+E_2)$

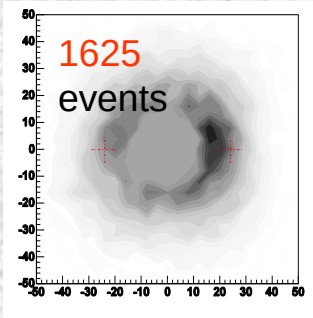
Electron Tracking Compton Camera (ETCC)
電子飛跡検出方コンプトンカメラ



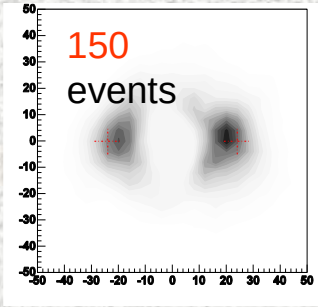
- Determination of each gamma direction ; useful for Noise red. & Clear Imaging
- Noise Reduction by Kinematics(a)+dE/dx
- Large FoV ~3str(good for monitoring)
- low dose
- Modular structure

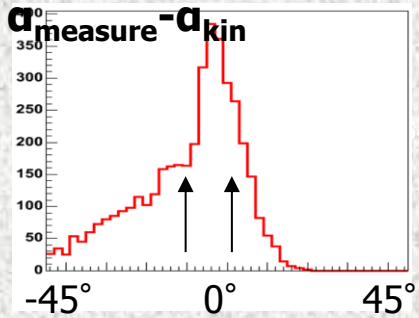


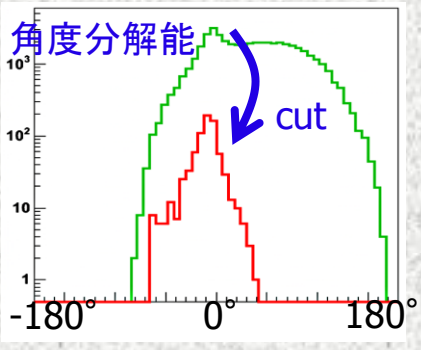
no use of electron track



In use of electron track





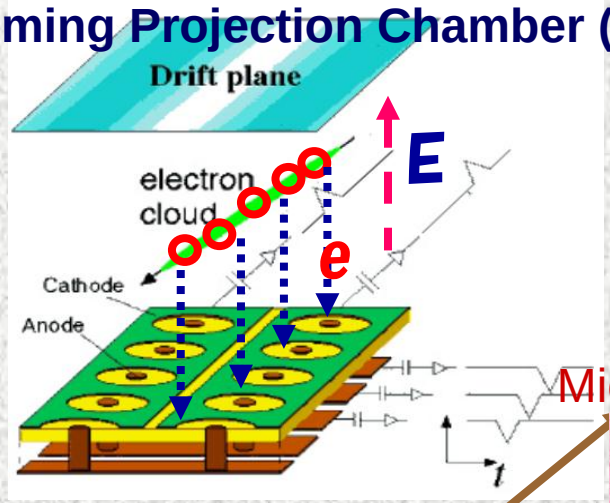


10cm-cube μ-TPC & ETCC

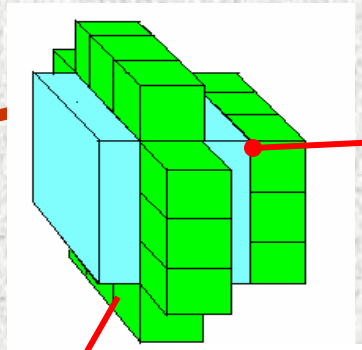
GSO Pixel

11%@ 662 keV (FWHM)

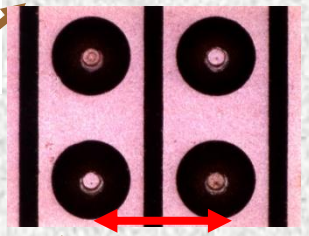
Timing Projection Chamber (TPC)



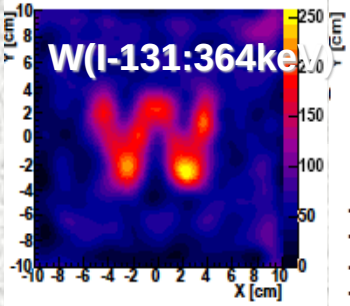
TPC

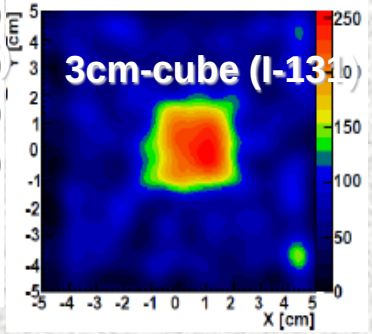


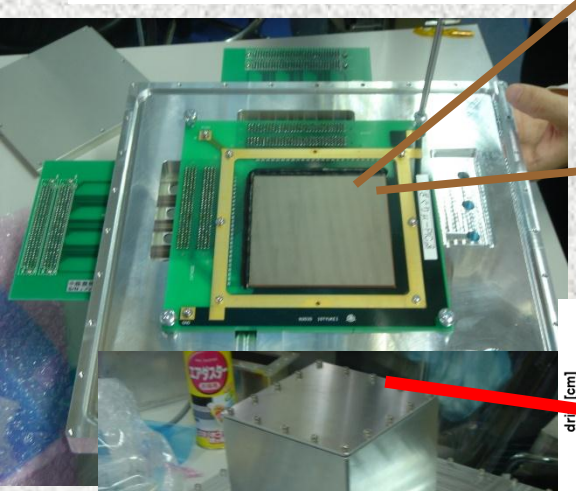
μ-PIC
Micro Pixel Chamber

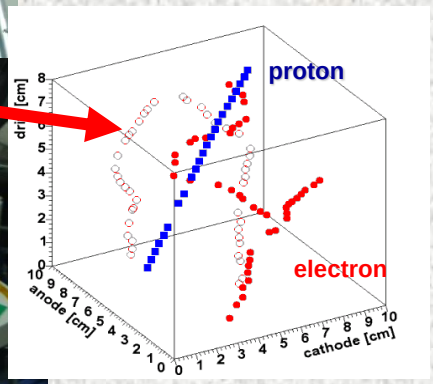


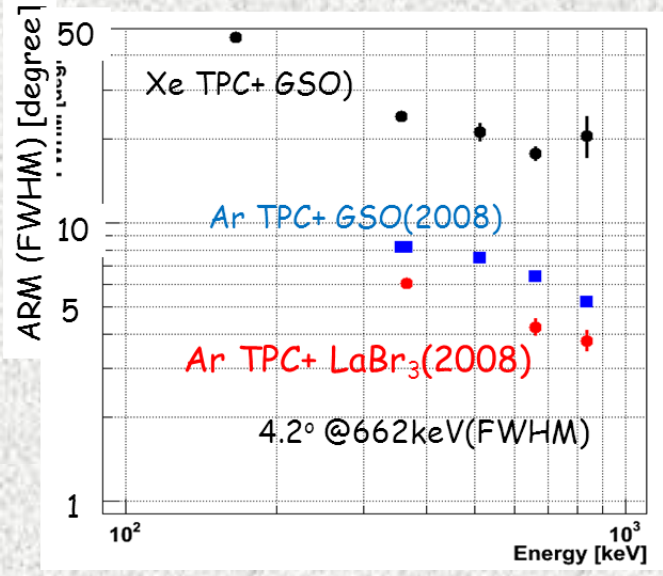
400μm

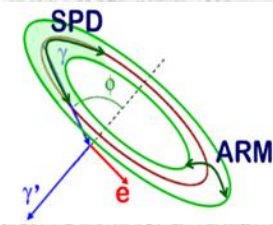








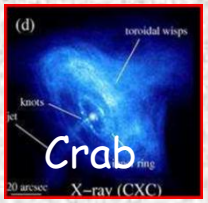


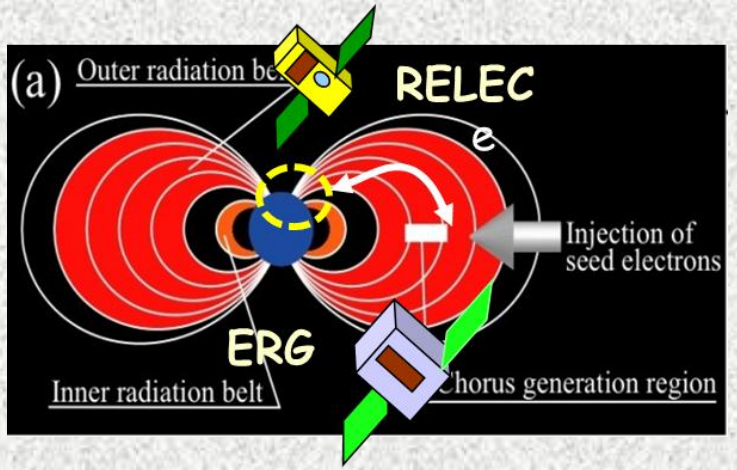


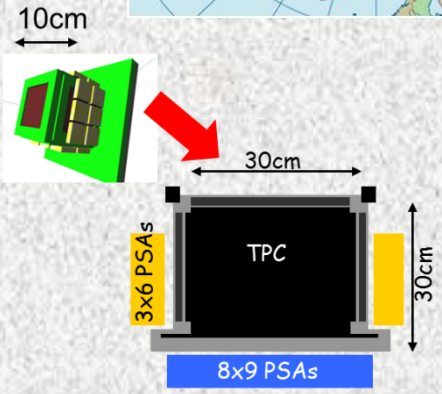
SMILE-II in the North Pole (2013~)

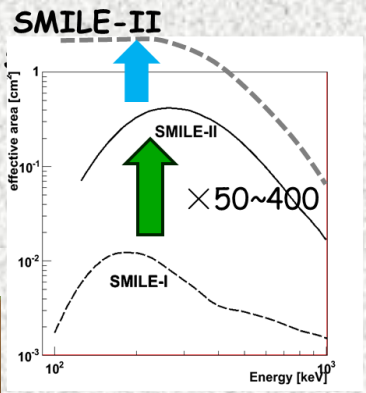
Terrestrial γ-ray bursts due to Relativistic Electron Precipitation (REP)

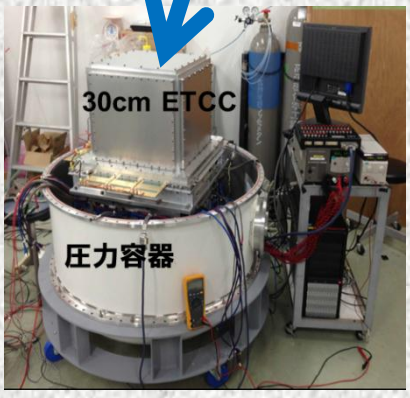
MeV γ from Compact stars, AGN & GRB

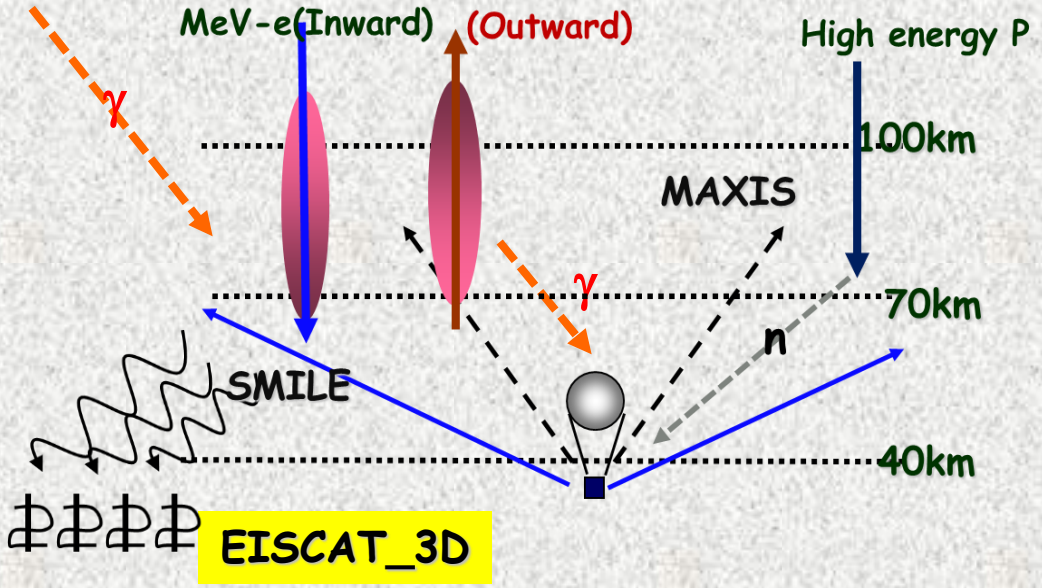






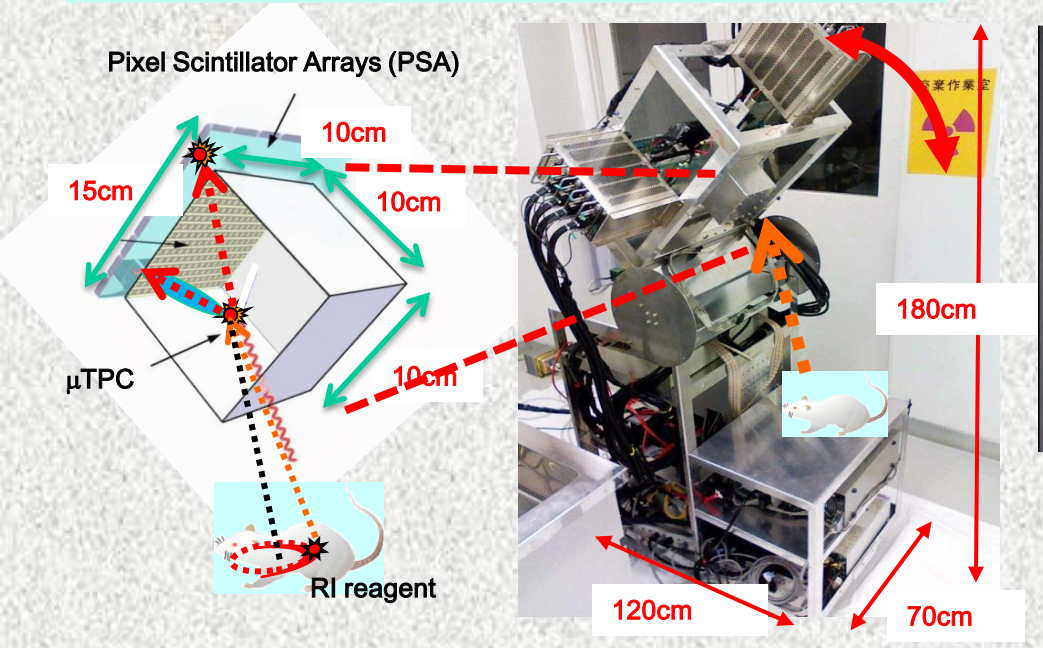


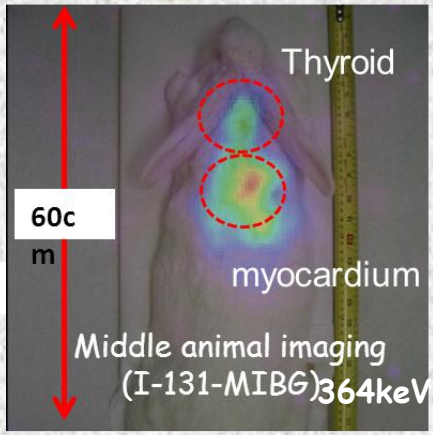


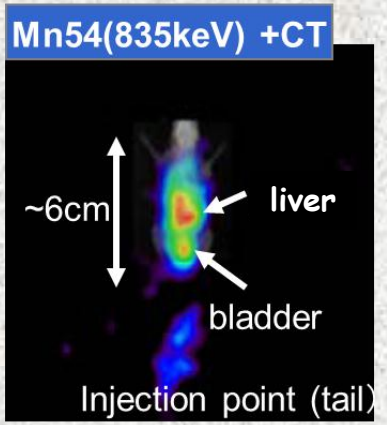


ETCC for Molecular Imaging
based on first balloon detector technology

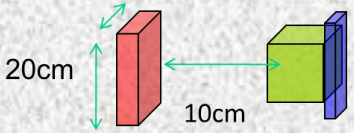
Mobile ETCC for small and middle animals



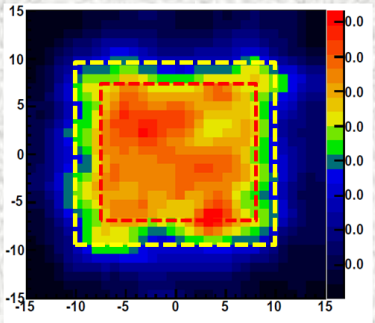




364keV panel phantom



Observation Time: a few MBq tumor of mouse -> ~2hrs
Pos. Res.: 8-5mm(FWHM:10cm -5cm front of ETCC)
Energy range: 150keV-2000keV
Field of View: 20x20cm@10cm front of ETCC
Uniformity Re-productivity ~10%

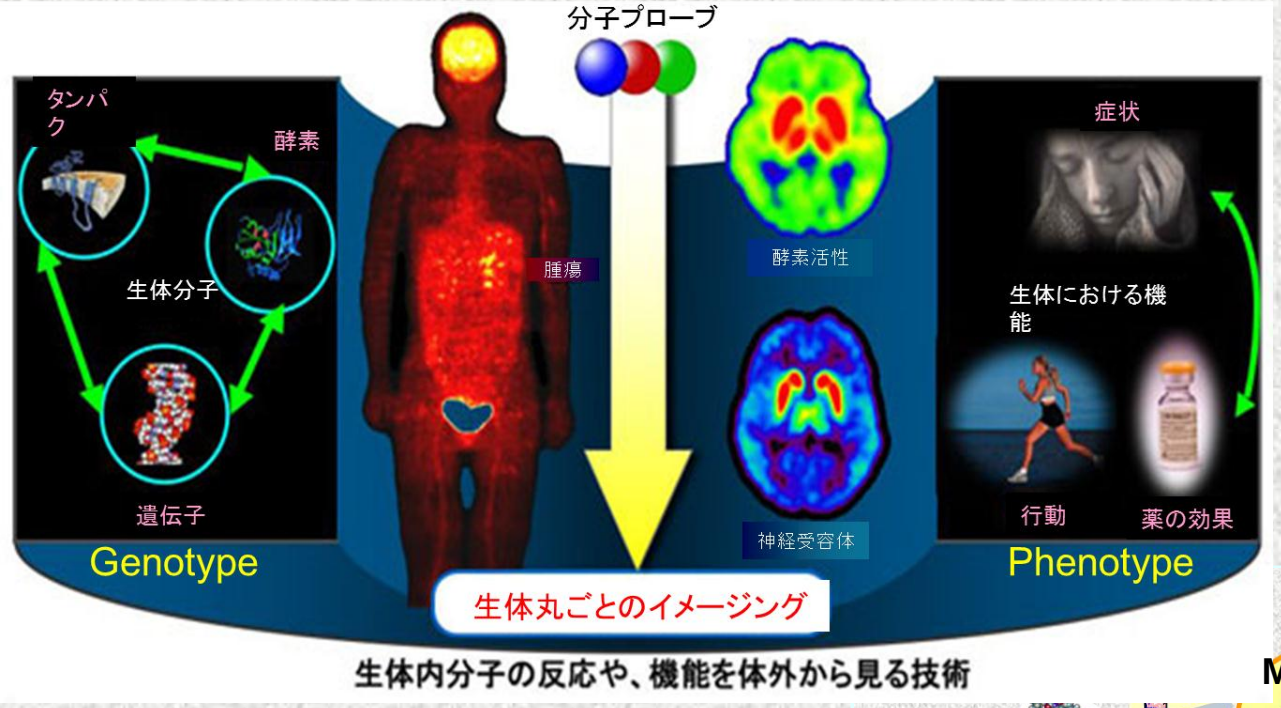


Uniformity : 11% (1σ)

分子イメージングMolecular Imaging

『生体で起こっている生理的、病的な生命現象を体外から分子レベルで捉えて画像化』 (Radiology, 219 (2001).)

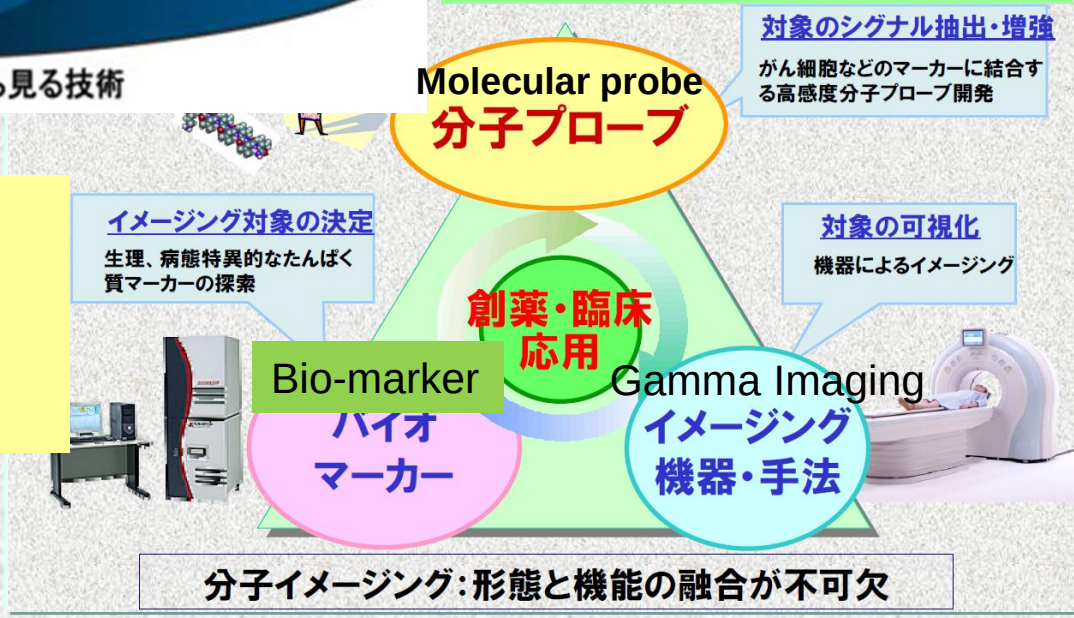
京大薬　佐治教授の資料より



生体内分子の反応や、機能を体外から見る技術

Drug Design
in next generation

Bio-marker labeling by RI
Visualization of vital functions such as metabolism 体内代謝
(^{18}F-FDG: saccharide糖類)



Features of ETCC to Molecular Imaging & Nuclear Medicine

1. Wide Energy Band　200keV ~ 2000 keV
2. New type of Tracers using RI with its decay time similar to biological decay time;
   visualizations of immunity（免疫）and enzyme（酵素）
   (FDG for visualization of metabolism)
3. Multi RI Tracer Image $^{99m}Tc + ^{18}F$ −> New Modality
4. Visualization of beam Therapy, Neutron Therapy, & Therapy using β-emitter biomarker
5. 3D imaging from one directional observation for operation supporting

Variety of RI applications in ETCC

	Ce-139	Cr-51	Ba-133	I-131	Au-198	Na-22	F-18	Cu-64	Cs-137	Mn-54	Fe-59	Zn-65	Co-60
Energy [keV]	167	320	354	364	410	511, 1275	511	511	662	835	1095, 1292	1116	1173, 1333
Life	137.6 day	27.7 day	10.52y ear	8.01 day	2.6 day	2.609 Year	109.8 min	12.70 hour	30.04 year	312.1 day	44.5 day	244 day	5.271 year

SPECT

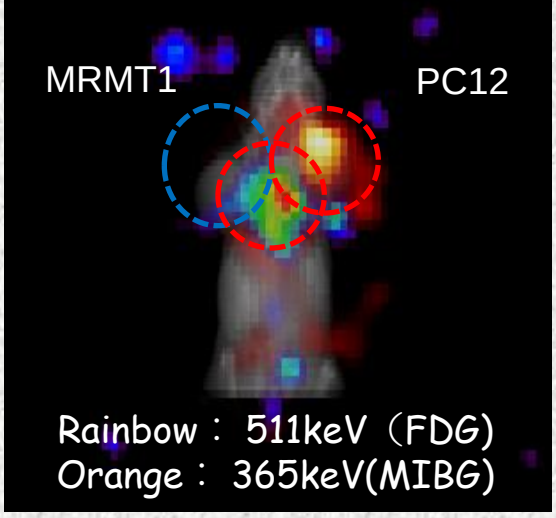
PET

Energy dynamic range : 167 – 1333 keV.

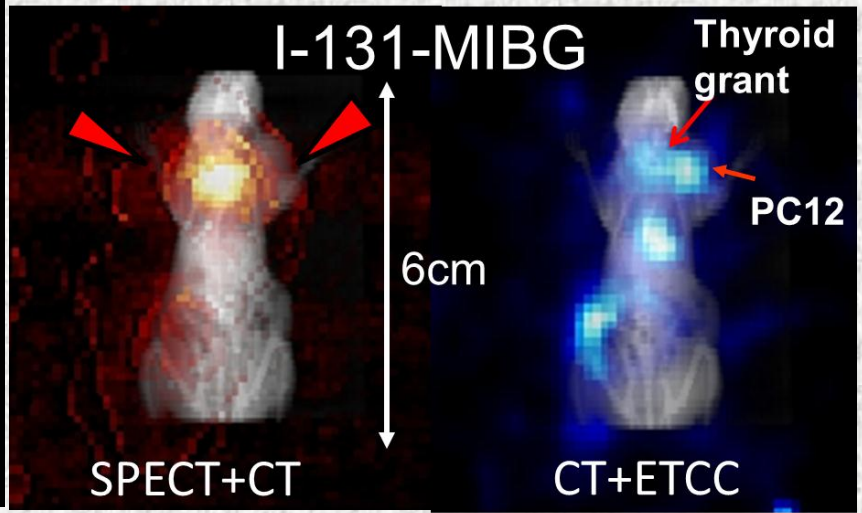
F18-FDG

ETCC

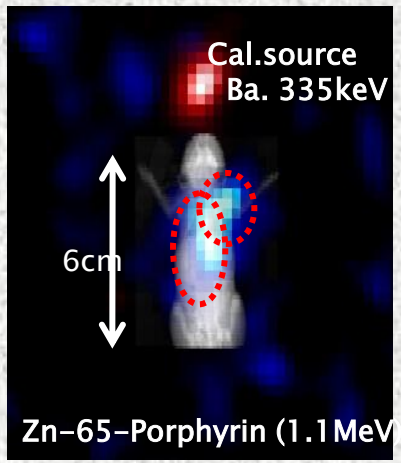
ETCC/CT (Duble Tracer)



B 線治療薬イメージング I

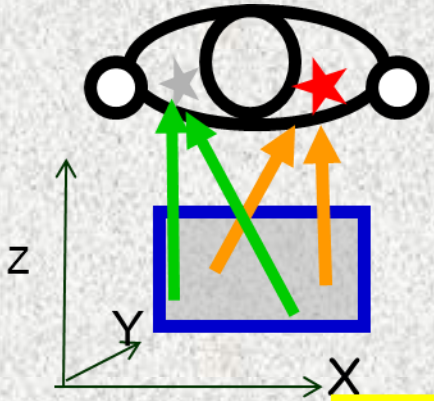


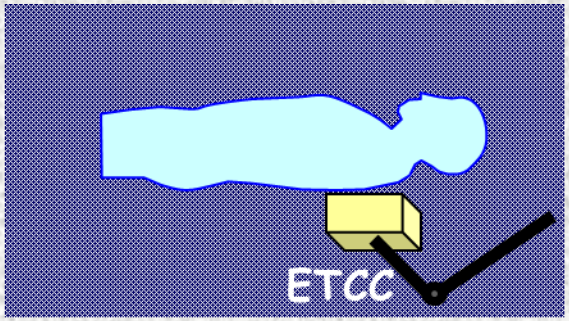
Zn-65-Porphyrin

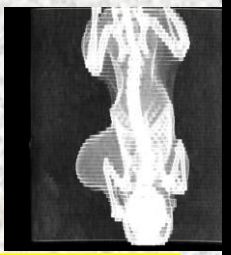


3D image from fixed directional observation

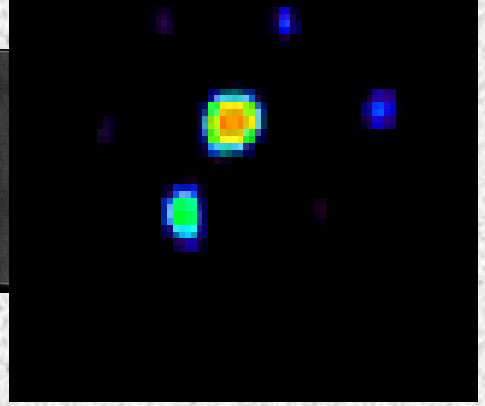
ETCC only can obtain 3D image by fixed Directional observation



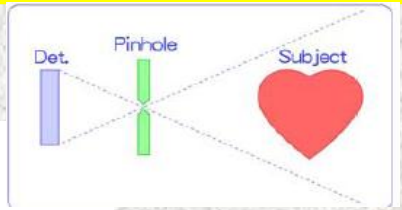




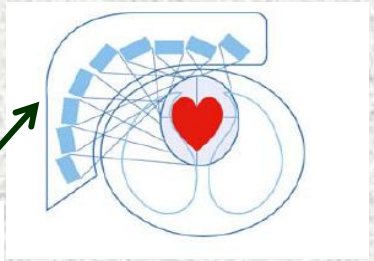
F18-FDGi in mouse tumor

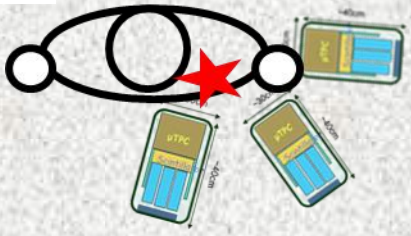


手術時のその場での3D-RI診断を可能に

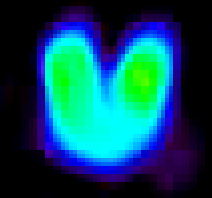


GE new-SPECT for heart



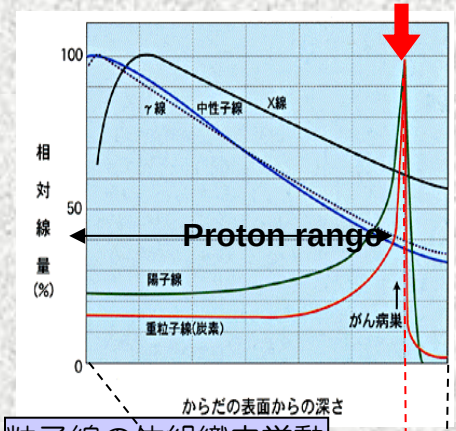


Thyroid grant of human

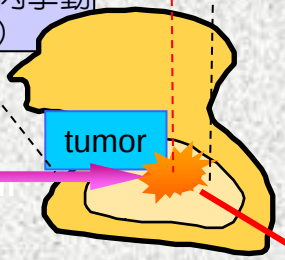


^{99m}Tc +^{18}F-FGD New Modality

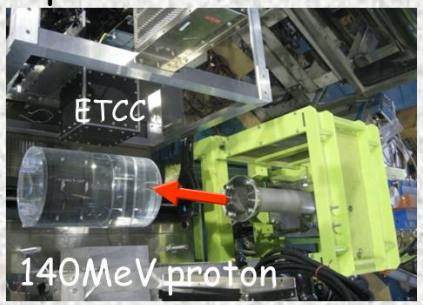
On-time imaging approach for beam therapy



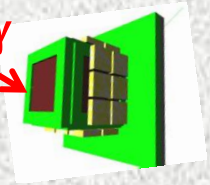
粒子線の体組織内挙動
（放医研HPより）

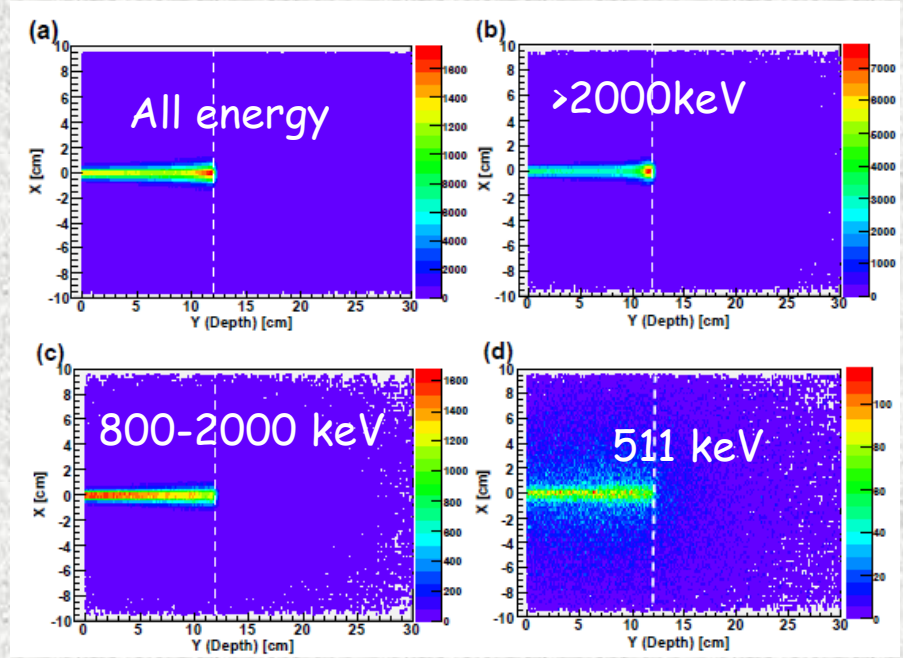


Experiment ` RCNP

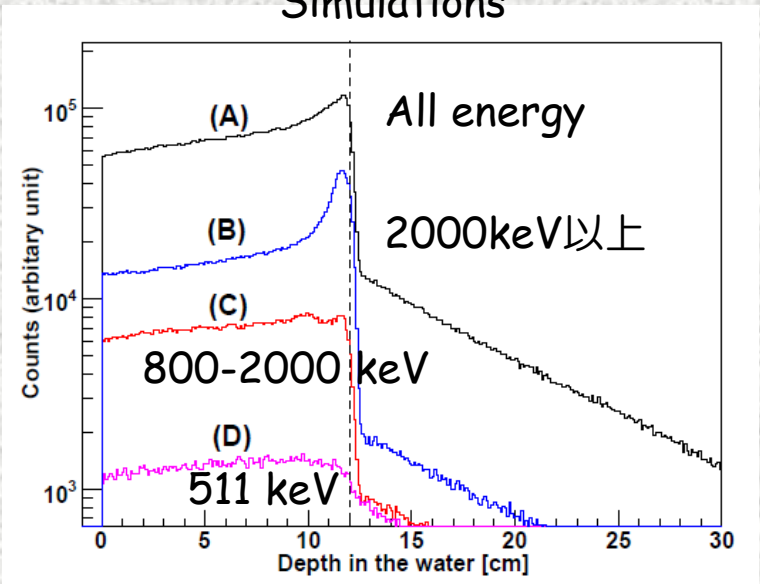


ETCC





Simulations

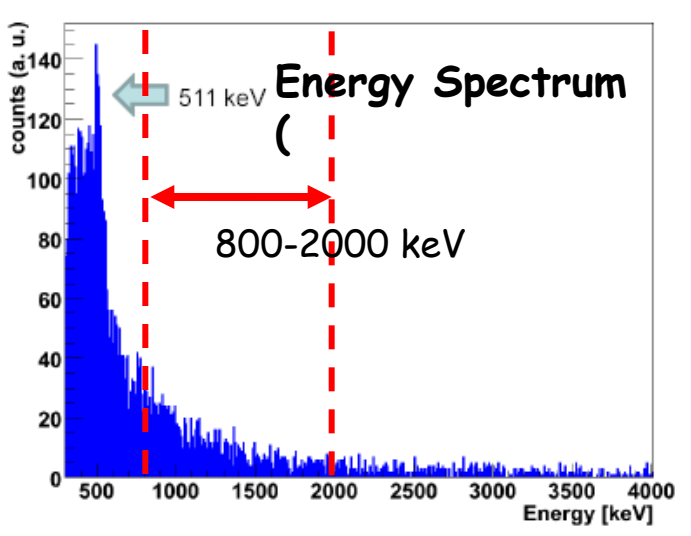


Gamma rays in Proton therapy

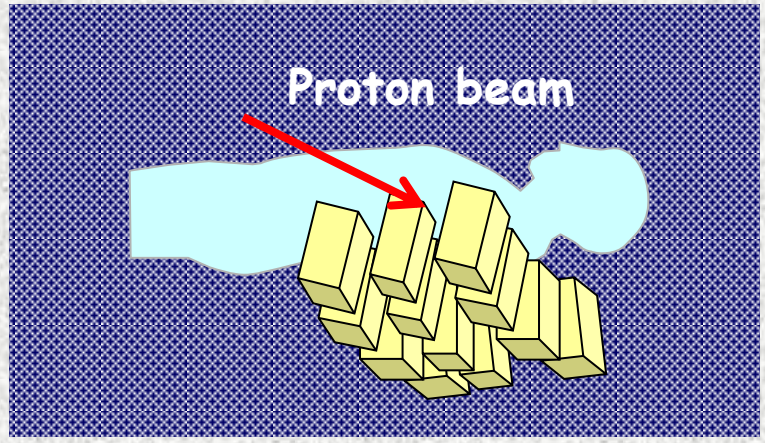
1. $^{16}O(p,2p2n)^{13}N$ $^{16}O(p,pn)^{15}O \rightarrow \beta^+$
   → 511keV (Proton >10MeV)
2. Prompt gamma(Proton <a few MeV)

Proton Therapy Beam-on Imaging @RCNP

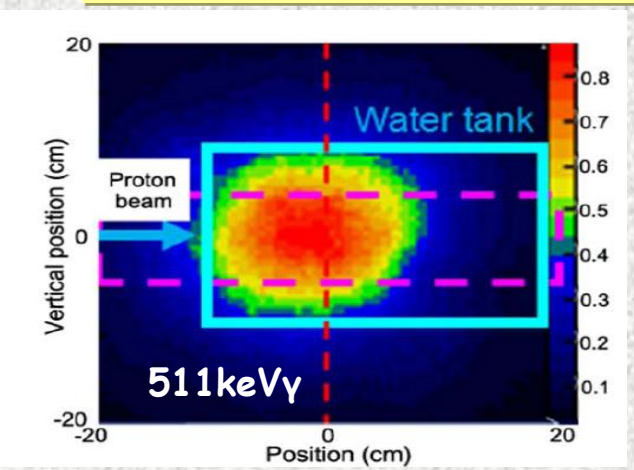
Kurosawa et al. (2012)

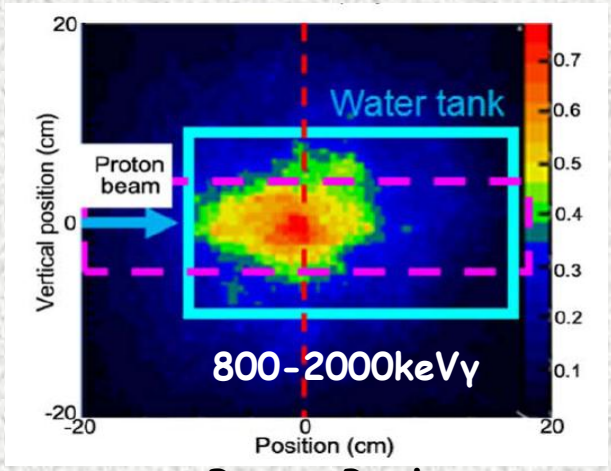


Collaboration with Japan National Cancer Center from 2012

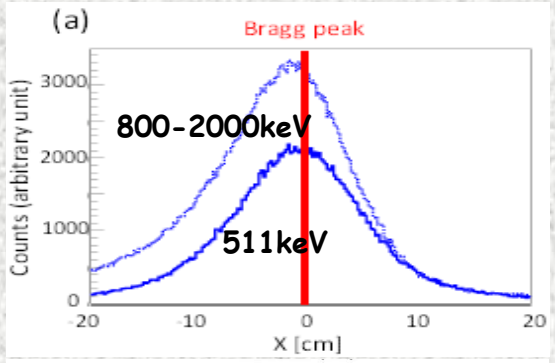


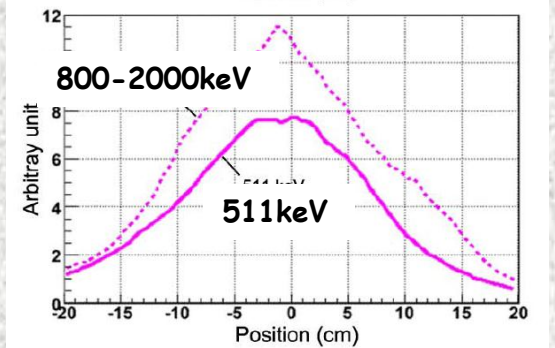
First Imaging at Beam-on !





Bragg Peak



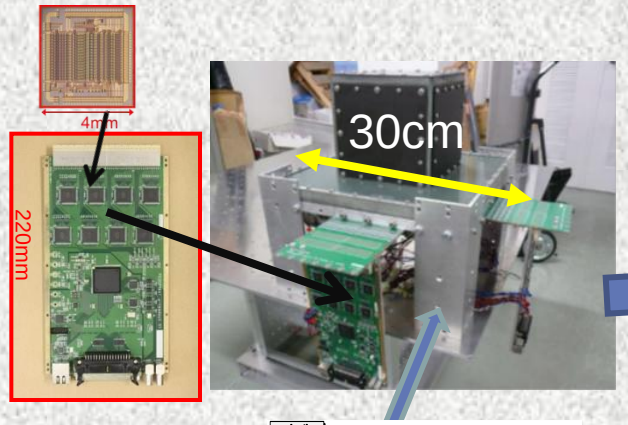


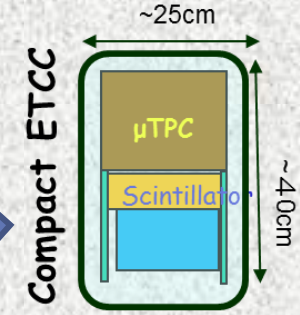
Improvement for practical use in 2013

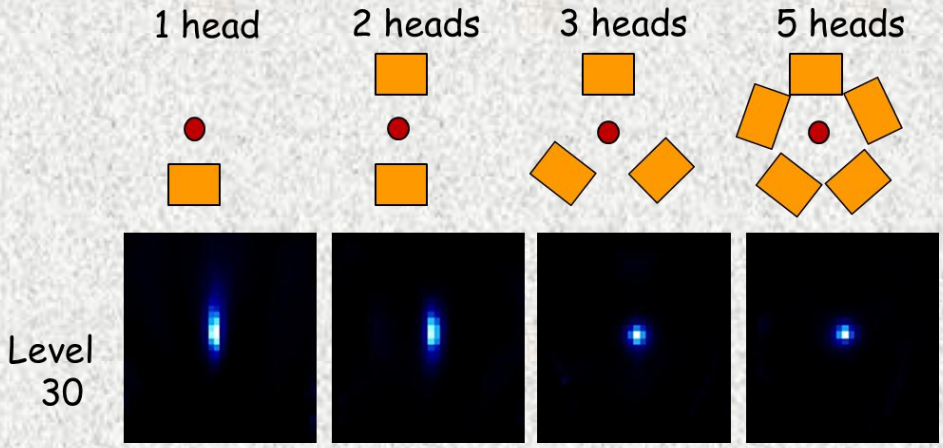
Observation time for mouse
2 hours-> 10-20min.

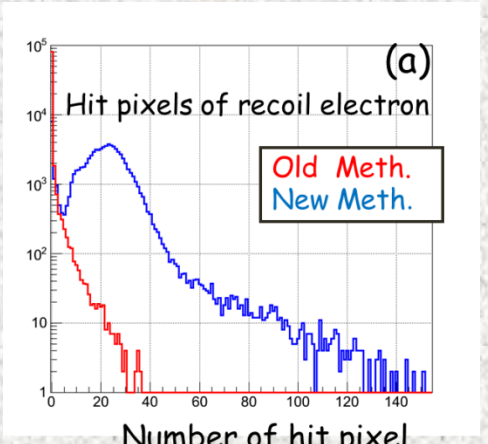
Improvement points
1. Efficient e-tracking (x10)
2. Mew readout of Sci. Pixel (x 3)
3. High Pressure and new gas
(3atm, CF_4) (x>20)

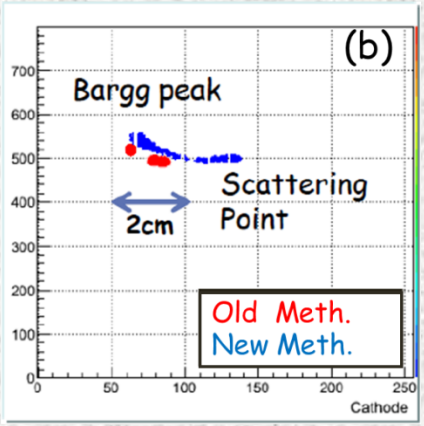
Total ~ >100 times faster
& Multi-head (3-6 heads)











Pulsed Neutron

- Thermal Neutron (~meV)
  Transparent for heavy material,
- Pulsed -> Time of Flight (TOF)
  -> Energy resolved

Material Analysis
(Structure, strain etc.)

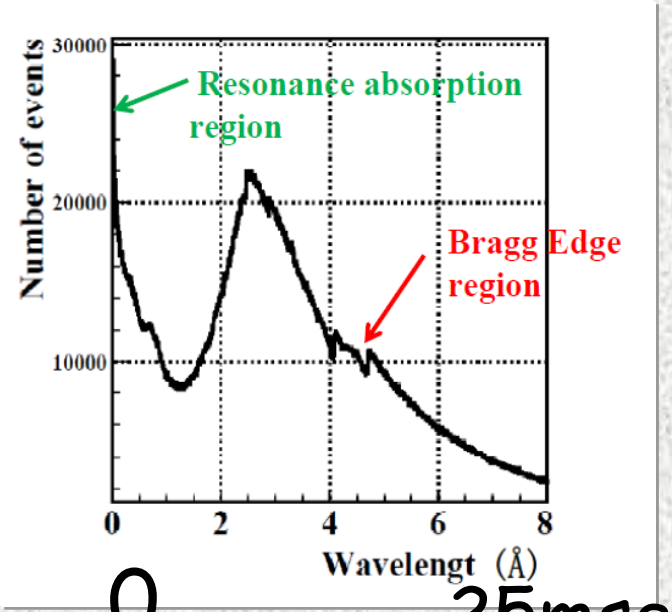
1 nuclear resonance->Identification of chemical element

2. Bragg edge

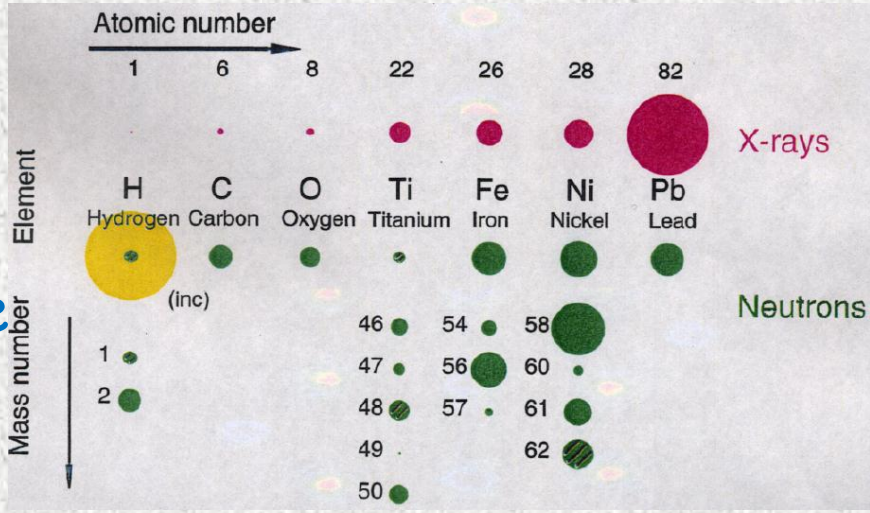
3. Small Angle Scattering

4. Spin analysis (Magnetic feature)

J-Parc Pulsed neutron



0 25msec

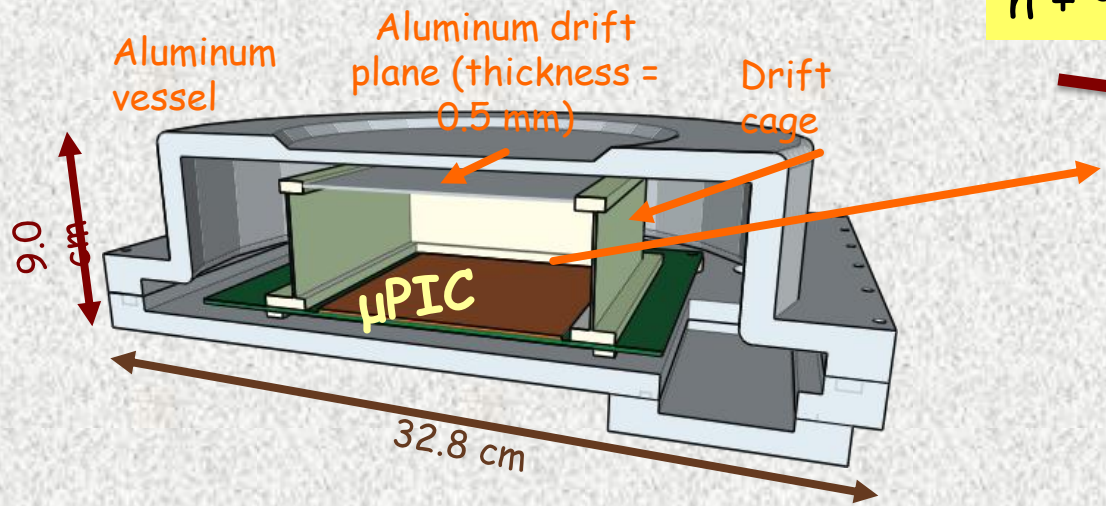


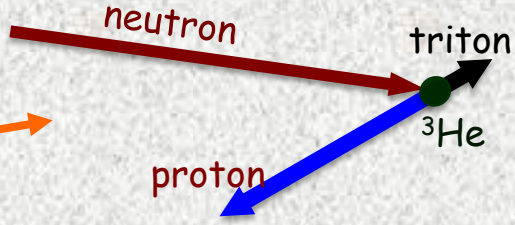
TOF Thermal Neutron imaging detector

TPC measures 3D track of proton-triton pair.

$n + {}^3He \rightarrow p + {}^3H$

764 keV energy release.

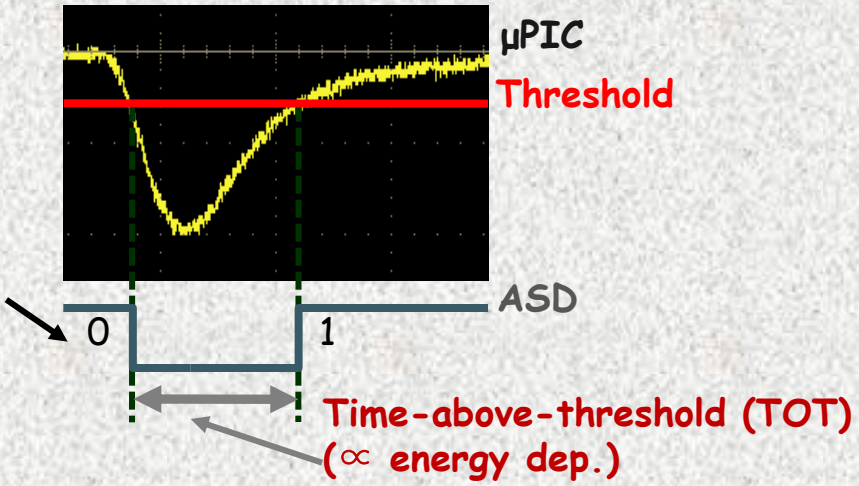


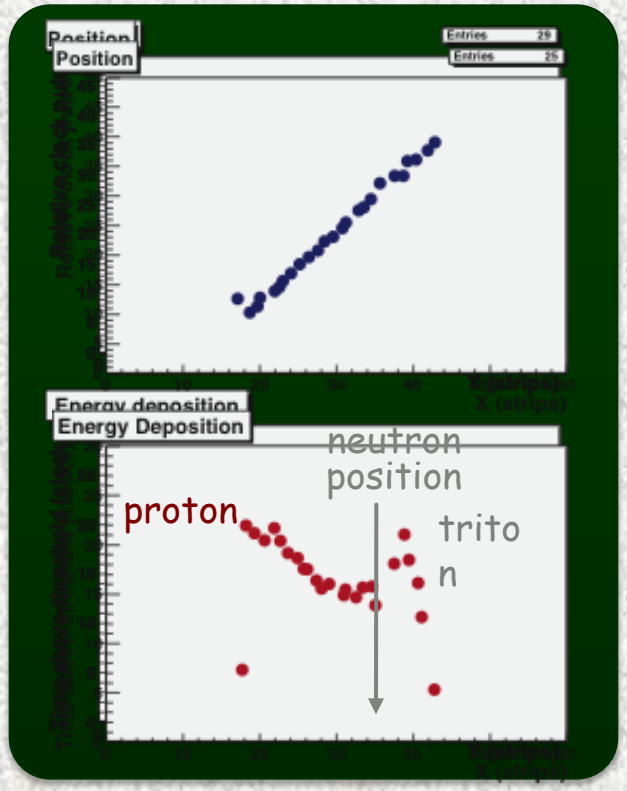


Track length ~1 cm.

Gas gain ~500: Ar-C_2H_6-^{3}He (up to 2 atm)

Timing Resolution of ~1μsec. (drift height 5cm)

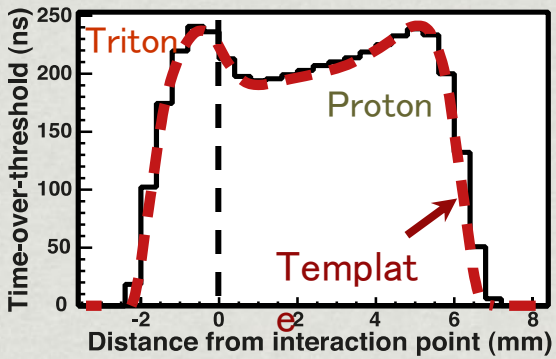


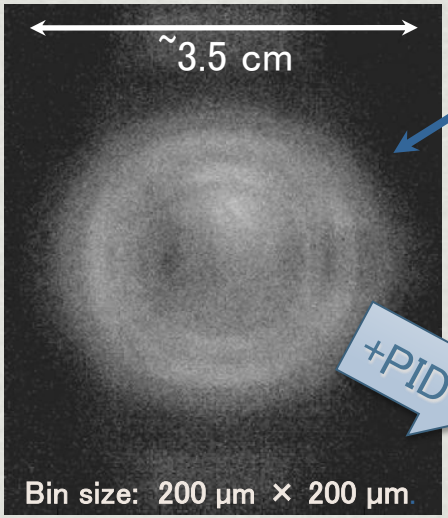


Simultaneous measurement of position and energy deposition at high rates.

Spatial resolution & Gamma Rejection

Measured TOT distribution

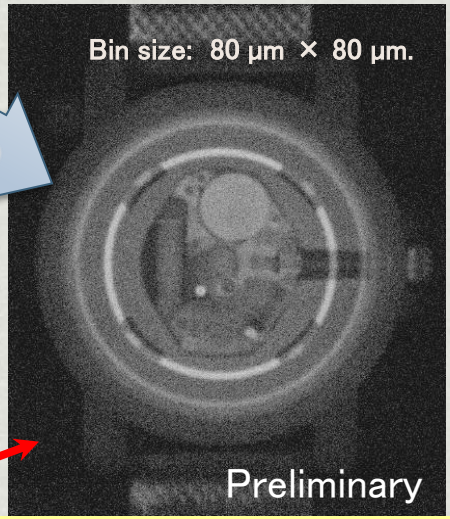




Position from mid-point of track.

Resolution: ~1mm(σ)

+PID

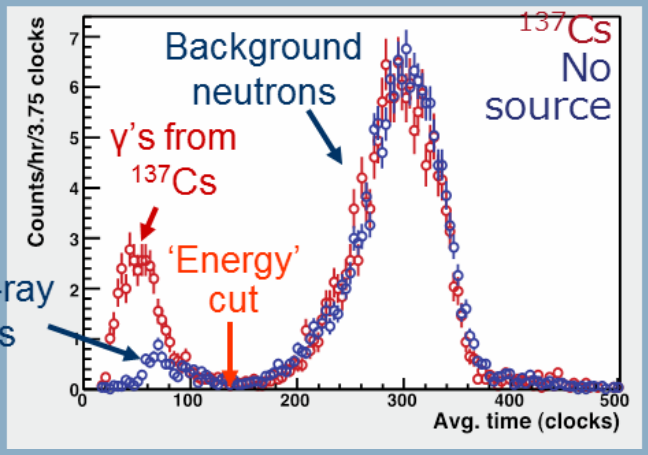


Resolution with PID:

Preliminary!

104 to 124μm(σ)

Gamma Rejection



Sensitivity of order 10^{-12} or less can be achieved at reduced gain without loss of neutron efficiency.

Improvements of Spatial res. (Simulation)

- Reducing gain variation (5~10%) and
- Reducing uniformity by 15~30%.
- pixel pitch reduced to ~200μm

Resolution after diffusion and gain variation improvements: 80~90μm.

Preliminary!

Plus increased pixel pitch: < 70μm.

Resonance absorption: Ag-In-Cd alloy

- Plate thickness: 3 mm.
- Exposure: 2 hrs.
- TOF gate: 0 – 3 ms.
- Neutron rate: ~10 kcps.
- DAQ live time: 70%.

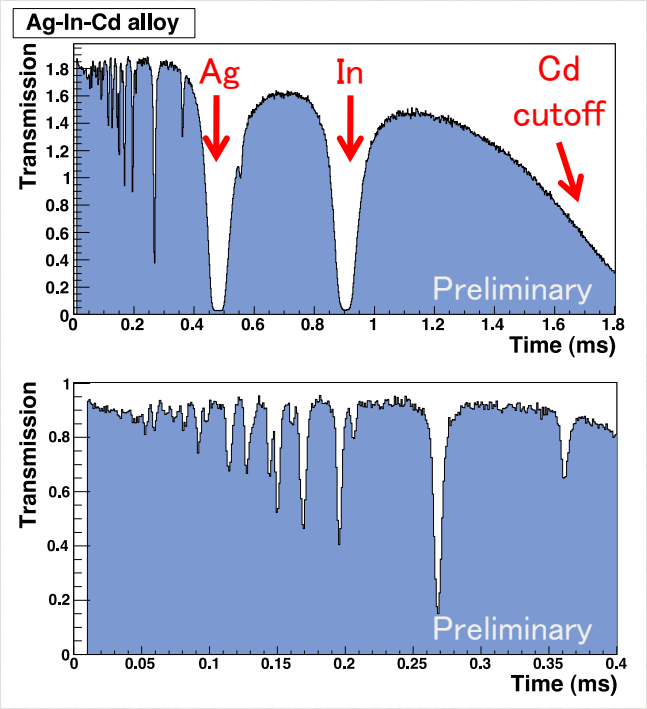
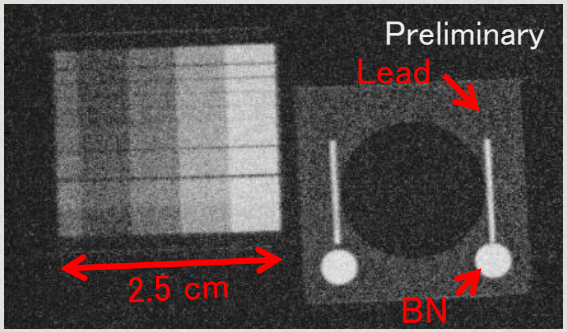


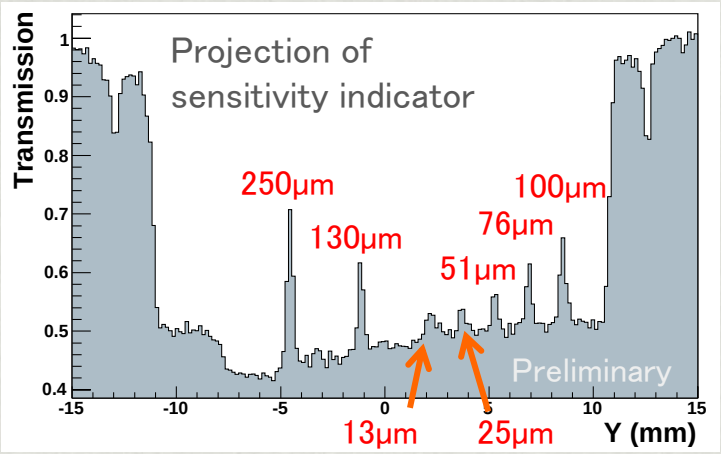
Image of ASTM indicator

Image taken with μPIC (100 μm bins)



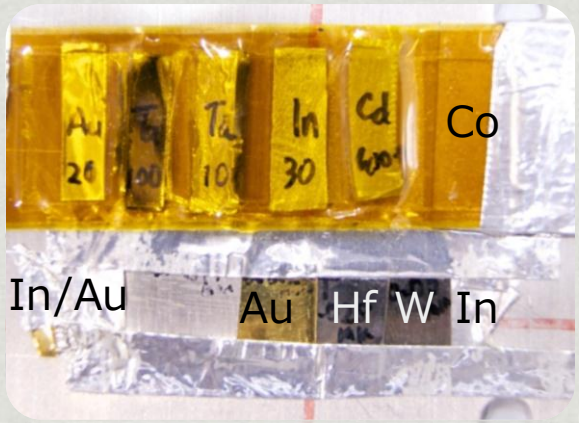
- Exposure: 3 hrs.
- No TOF gate.
- ~120 kcps.
- Live time: 14%.

X-ray imaging plate provided with sample



Data taken at NOBORU in March 2012.

Neutron resonance absorption



Exposure: 5 hrs
Rate: ~10 kcps
Live time:

External TOF gate applied (0 – 2.2ms)

- Measurement of neutron TOF allows selective imaging of nuclides via resonance absorption.
- Good time resolution is essential.

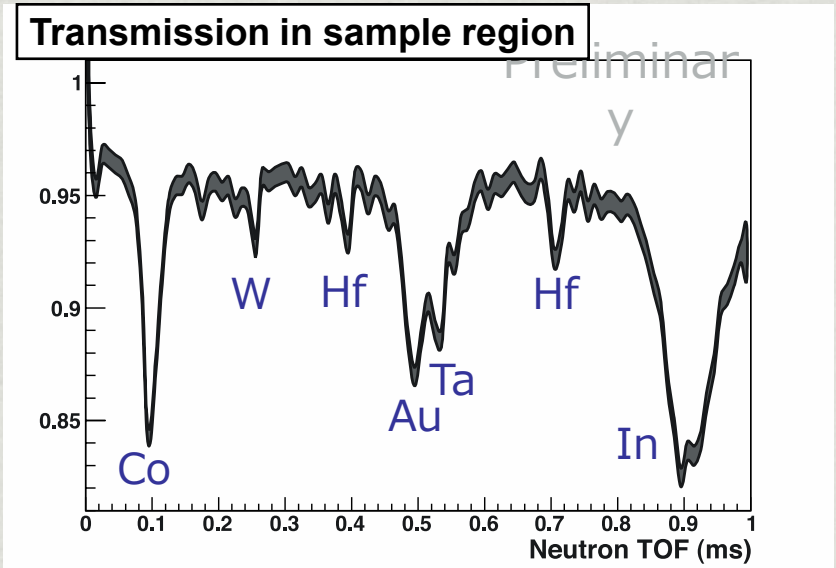
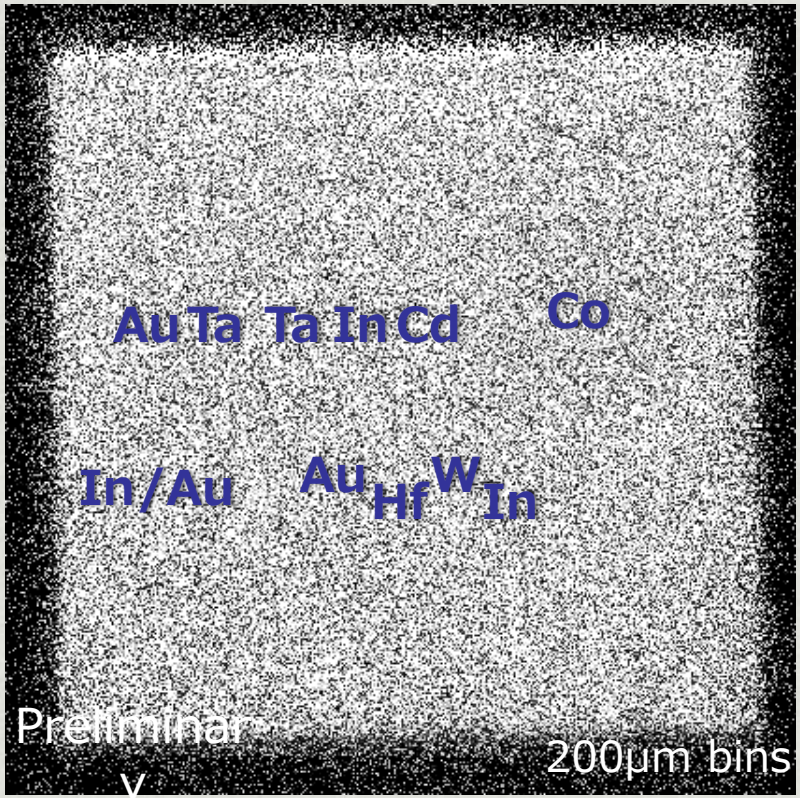


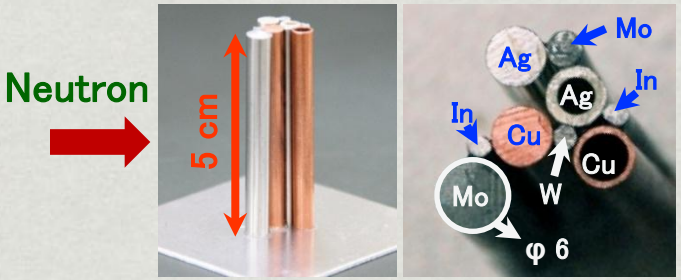
Image vs. TOF (0 ~ 1 ms)



Data taken at NOBORU in March 2012.

Resonance absorption with CT

Resonance CT sample

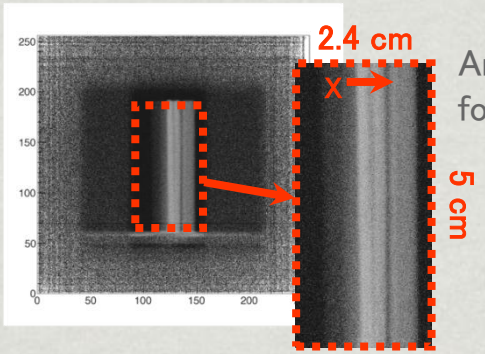


Exposure: 20 hrs
Rate: ~350 kcps
Live time: 50%

External TOF gate (0 – 2ms)

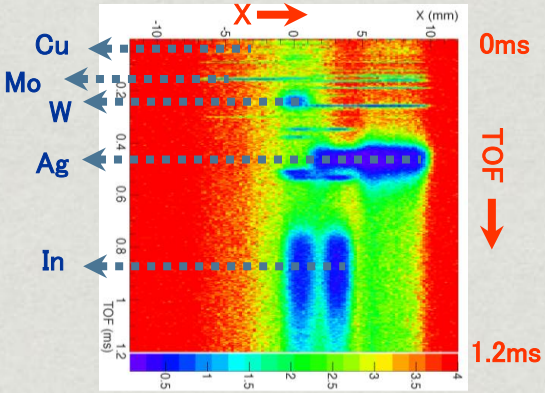
- 16 angles: 0° to 90° by 10° steps, 0° to −90° by 15° steps.
- 45~70 min/angle (11~17 × 10^6 neutrons/angle).
- No sample 2.5 hours (38 × 10^6 neutrons).

2D image at 90°



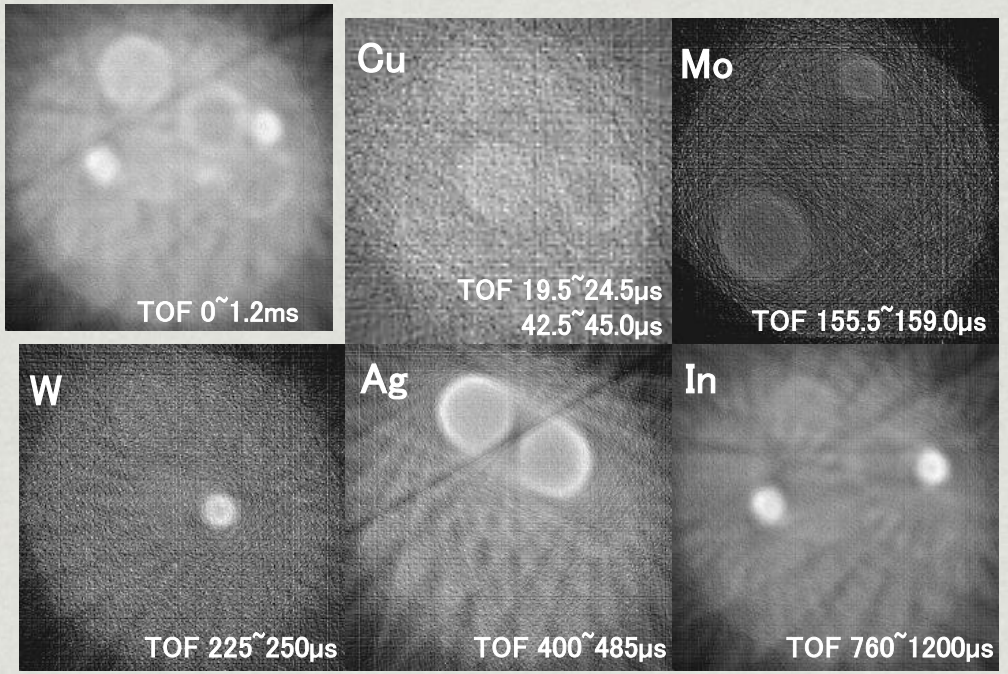
Area used for CT.

TOF for 0.2mm X slices



Reconstructed CT images

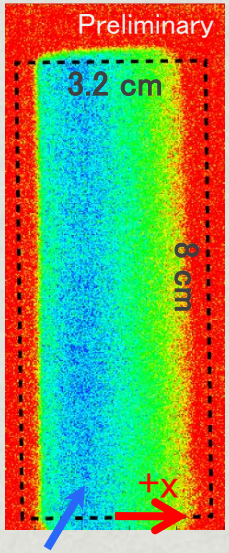
— Filtered back-projection method
— Neutron TOF cuts for selective imaging



Data taken at NOBORU in December 2012.

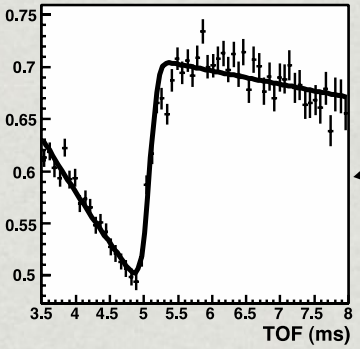
Bragg-edge transmission

Katana fragment
(15th or 16th century)



Region used for Bragg-edge study

TOF projection for one slice

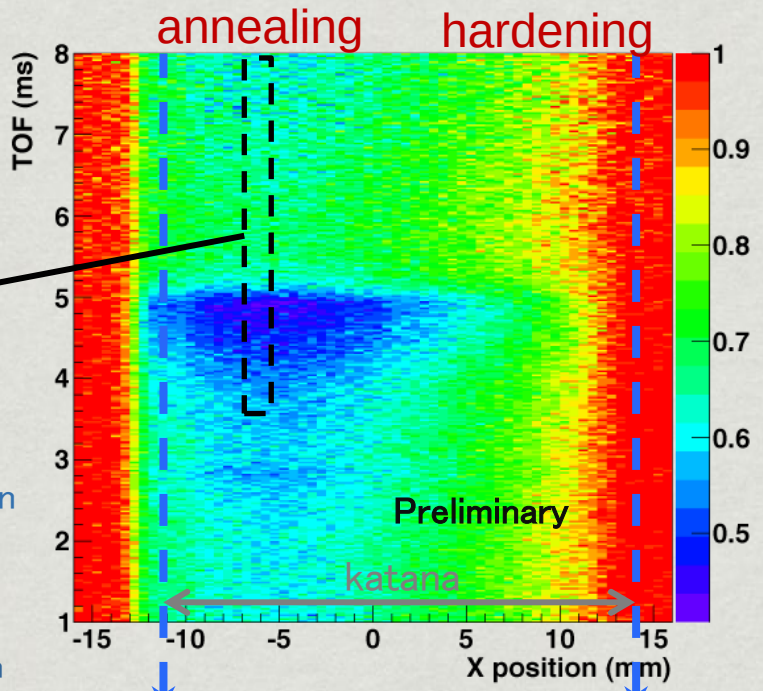


Edges (jumps) occur when Bragg condition can no longer be satisfied:

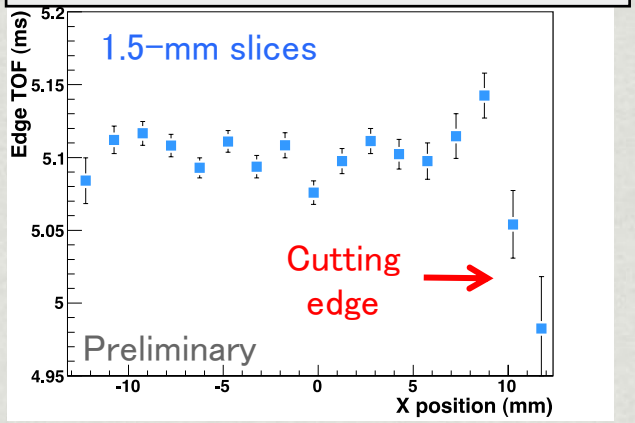
$$d = \frac{\lambda}{2}$$

d-spacing from wavelength

Neutron TOF vs. X position



TOF at largest Bragg-edge vs. X position



- Bragg-edge positions related to crystal spacing perpendicular to beam.
- Measured edge positions show some difference between crystal structure of cutting edge and spine.

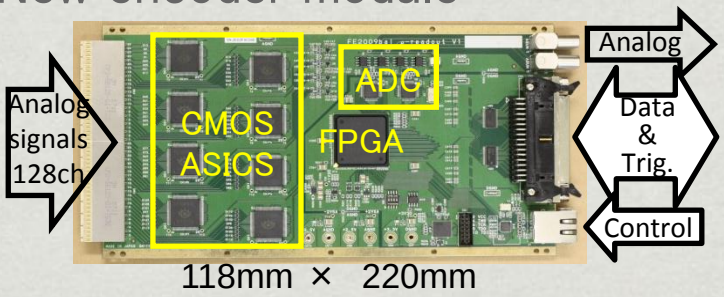
Data taken at Hokkaido University in February 2012.

System upgrade

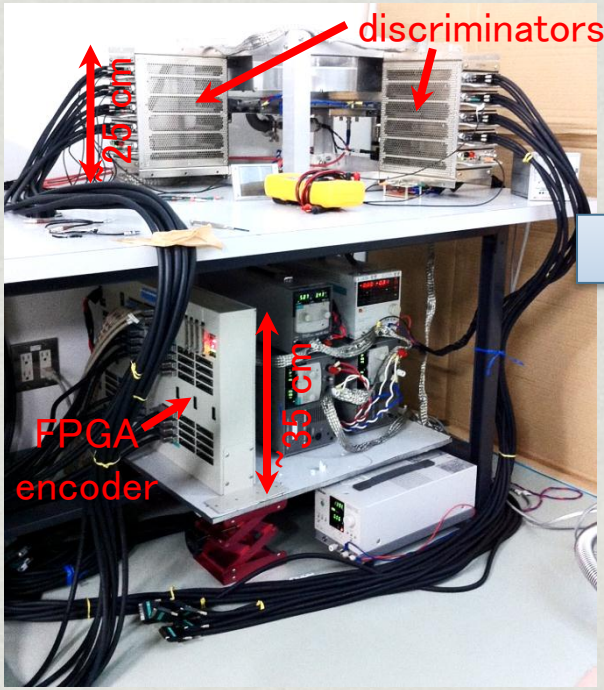
Requirements for practical use in J-PARC

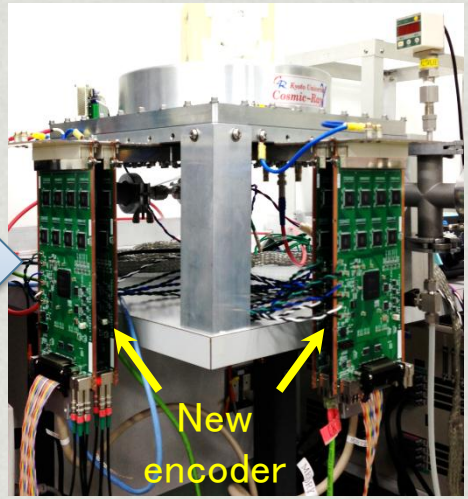
- **Increased data rate: x4 or more expected.**
- **Compact system–> new Electronics system**

New encoder module



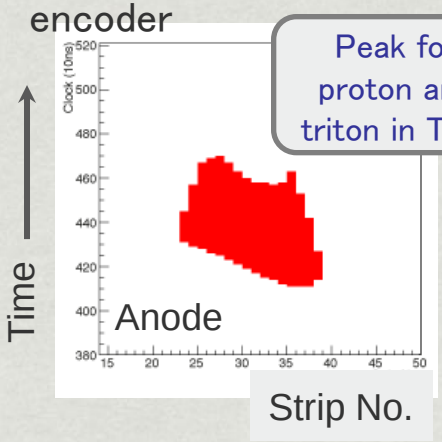
Current DAQ





Output through single FPGA limits DAQ rate to 10~12MHz (~200kcps)

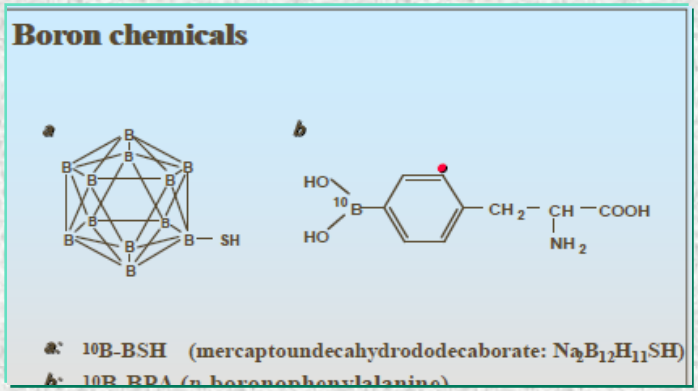
Neutron event measured with new encoder



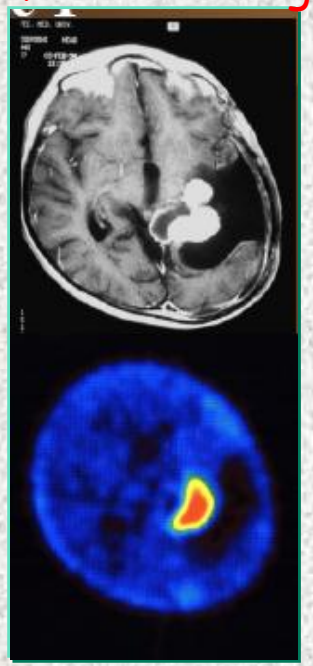
- **New system 30x30x40cm detector box + VME at least 4times DAQ rate (2012)**
- **VME–> Ethernet ~10times DAQ rate (2013)**

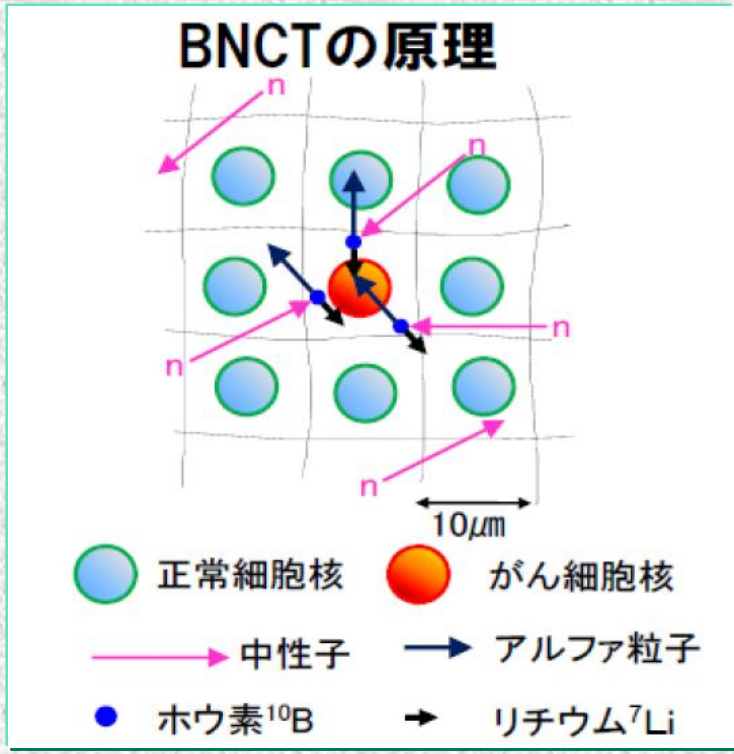
Neutron Therapy with Boron-10

Bio-markers including ^{10}B



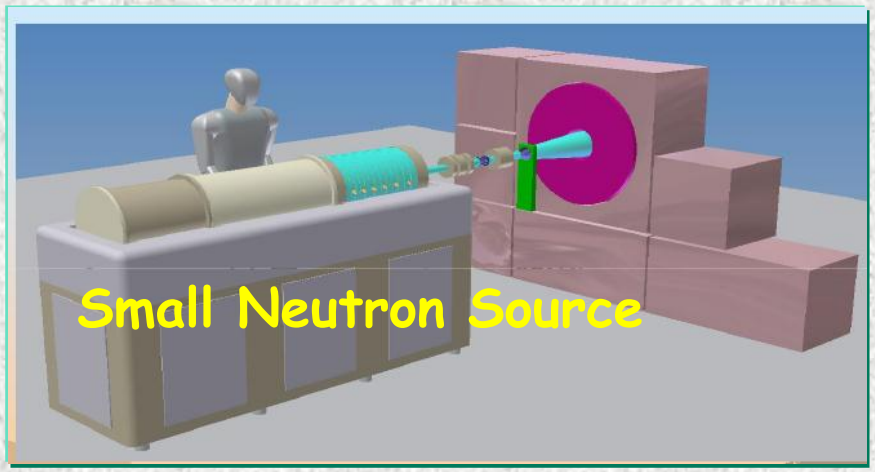
PET Image of Marker adding 18F

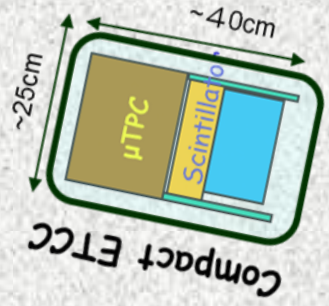




$^{10}B + n \rightarrow {}^{7}Li^{*} + \alpha + (2.31MeV)$

$^{7}Li^{*} \rightarrow {}^{7}Li + \gamma\ (0.478MeV)$





ETCC imagines ^{10}B distribution in body.by weak neutron beam before treatment

Summary

1. ETCC provides unique approaches in medical science; Multi Tracer , micro dosing with new RI, 3D imaging diagnosis, and on time imaging of beam therapy
2. High through-put modular ETCC will be operated under the collaboration with CANON in 2013

3. ETCC also is soon introduced into the field monitoring in Fukushima-accident by HORIBA (JST program)
4. TOF neutron imaging detector has both a good timing and spatial resolution of 1μs and 100μm, and provides a new imaging approach to material and life science.
5. TOF neutron imaging detectors will be available in J-PARC soon.

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