Full-body PET

based on Liquid Xe TPC

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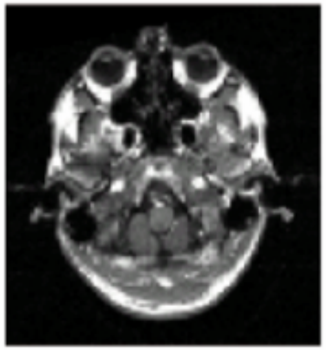
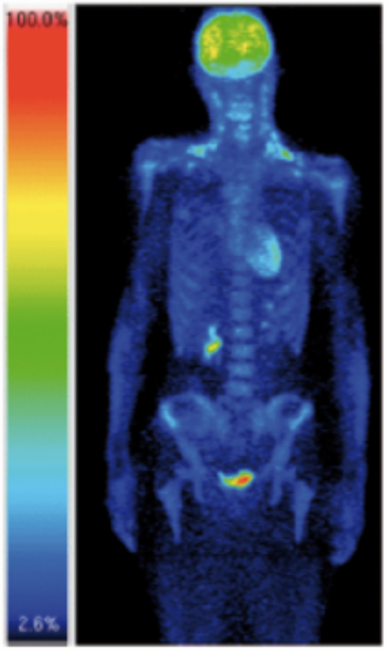
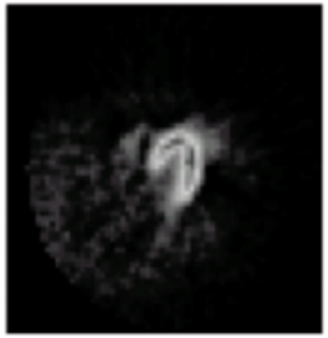
PET

(Positron Emission Tomography)

Various Medical Tomographys

CT	MRT	PET	SPECT
Computer-Tomography	Magneto-Resonance-Tomography	Positron Emission Tomography	Single-Photon-Emissions-Computed-Tomography



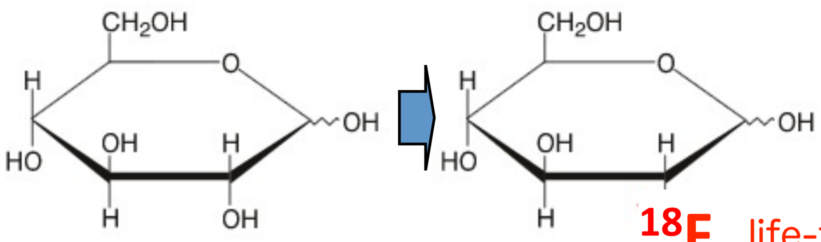
	CT	MRT		PET	SPECT
Resolution:	0,5 - 1 mm	1 mm	FWHM)	5 mm	5 mm
Radiation Dose: (flight ~0,05)	~10 mSv	0 mSv		~5 mSv	~3 mSv

(natural annual dose=2.4mSv)

Anatomy (Anatomical imaging) ← → Metabolism (Functional imaging)

PET Imaging principle

(1) Production of fluorodeoxyglucose (^{18}F-FDG)



Glucose FDG

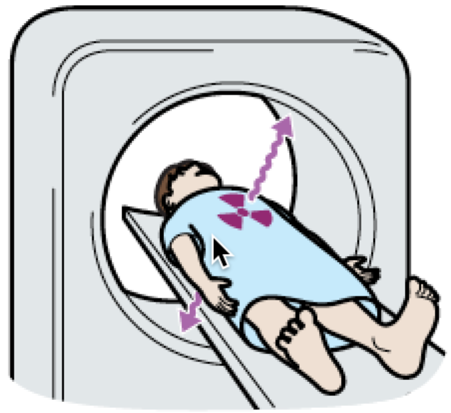
^{18}F life-time of 109.8 minutes with a positron emission

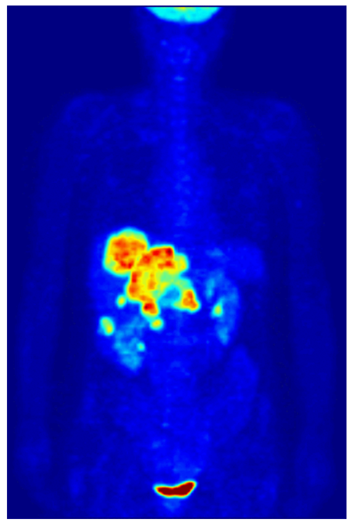
^{11}C-methionine(MET) for brain tumor (τ =20 minutes)

(2) Injection (a dose of 200- 400 MBq) and accumulation in tumors or diagnosis of glucose metabolism

who has been fasting for at least 6 hours

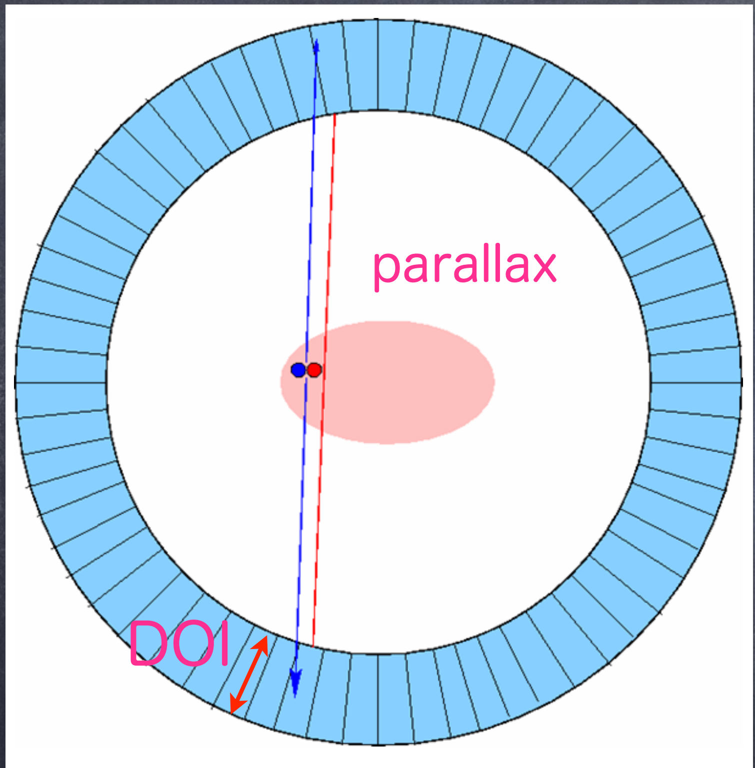
(3) Imaging the distribution of ^{18}F-FDG in the body by a PET scanner for 20 minutes





PET検査Q&Aより,日本核医学会、日本アイソトープ協会

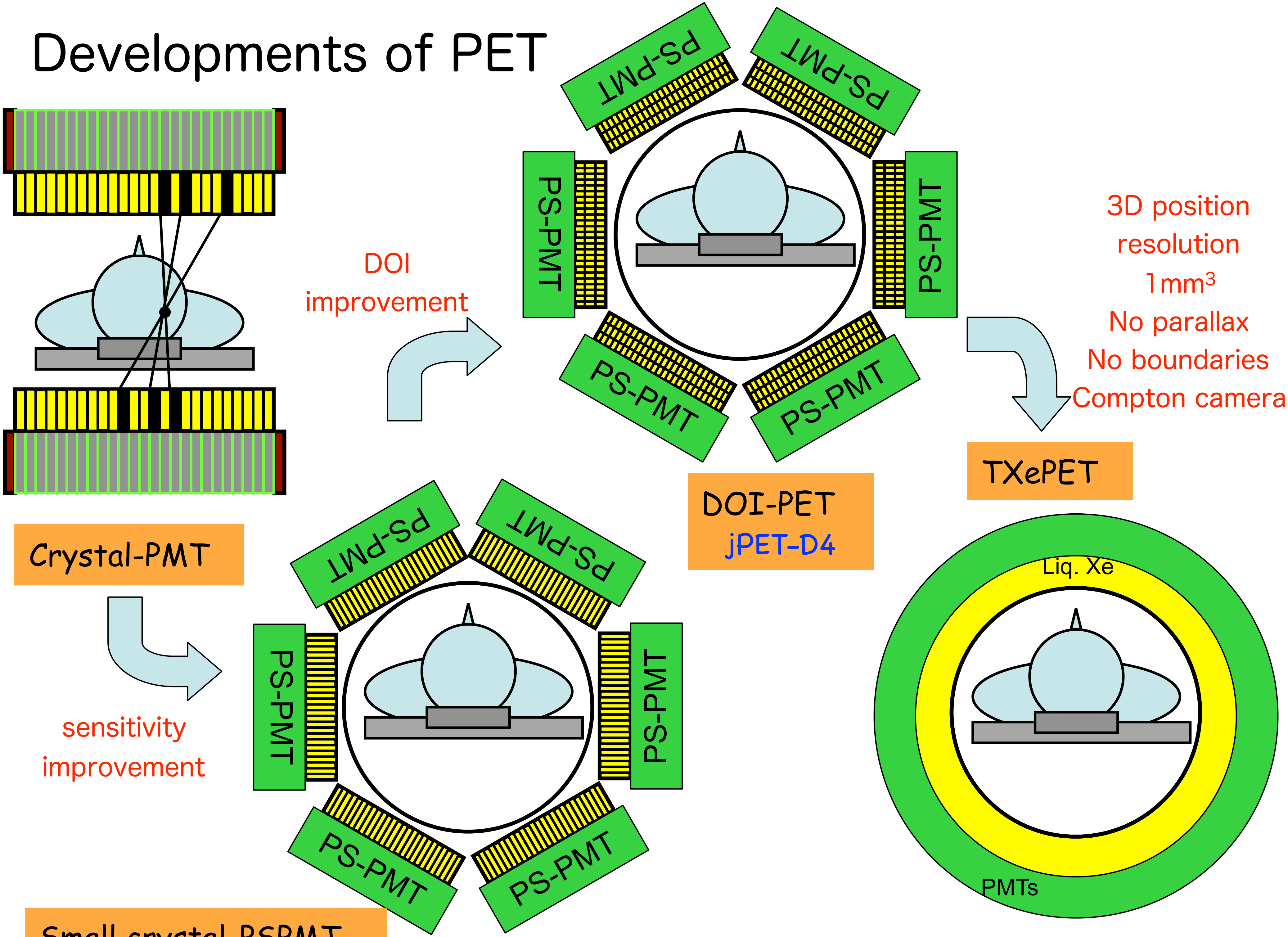
Major limitation of conventional PETs



Large parallax due to the Depth of Interaction (DOI) resolution, i.e. the size of scintillation crystals

➡ Lower resolution

Developments of PET



PSPMT = Position Sensitive PMT

Liquid Xenon

Characteristics of Liquid Xenon Deteoctor

Liquid Xenon is a Rich Detection Media

Scintillation signals	and	Ionization signals
fast timing/energy, ROI		3D positions, energy
Photomultipliers		Time Projection Chamber (TPC)
(APD, MPPC)		(Ionization chambers)
22,000 photons/511KeV		30,000 electron-ion pairs/511KeV
		electron drift at 2.3mm/us with 2kV/cm

At 511 keV, 22% photoelectric, 78% Compton in xenon

~0.5 mm of absorption length for 511 keV photoelectron

Scintillator	GSO Gd_2SiO_5	LSO $Lu_2SiO_5(Ce)$	Liquid Xe
Density(g/cm^3)	6.71	7.4	3.06
Rad. Len. (cm)	1.38	1.14	2.77
Scintillation light : wave len. (nm)	430	420	175
: decay time(ns)	30-60	40	2, 30
: relative yield (%)	20	40-75	100
: reflection index	1.85	1.82	1.6
Melting point (℃)	1950	2050	-111.75
a crystal size (mm^3)	2.45x5.1x30	4x4x20	monolithic
Drift vel.(mm/μs)	-	-	2.3 (E=2kV/cm)

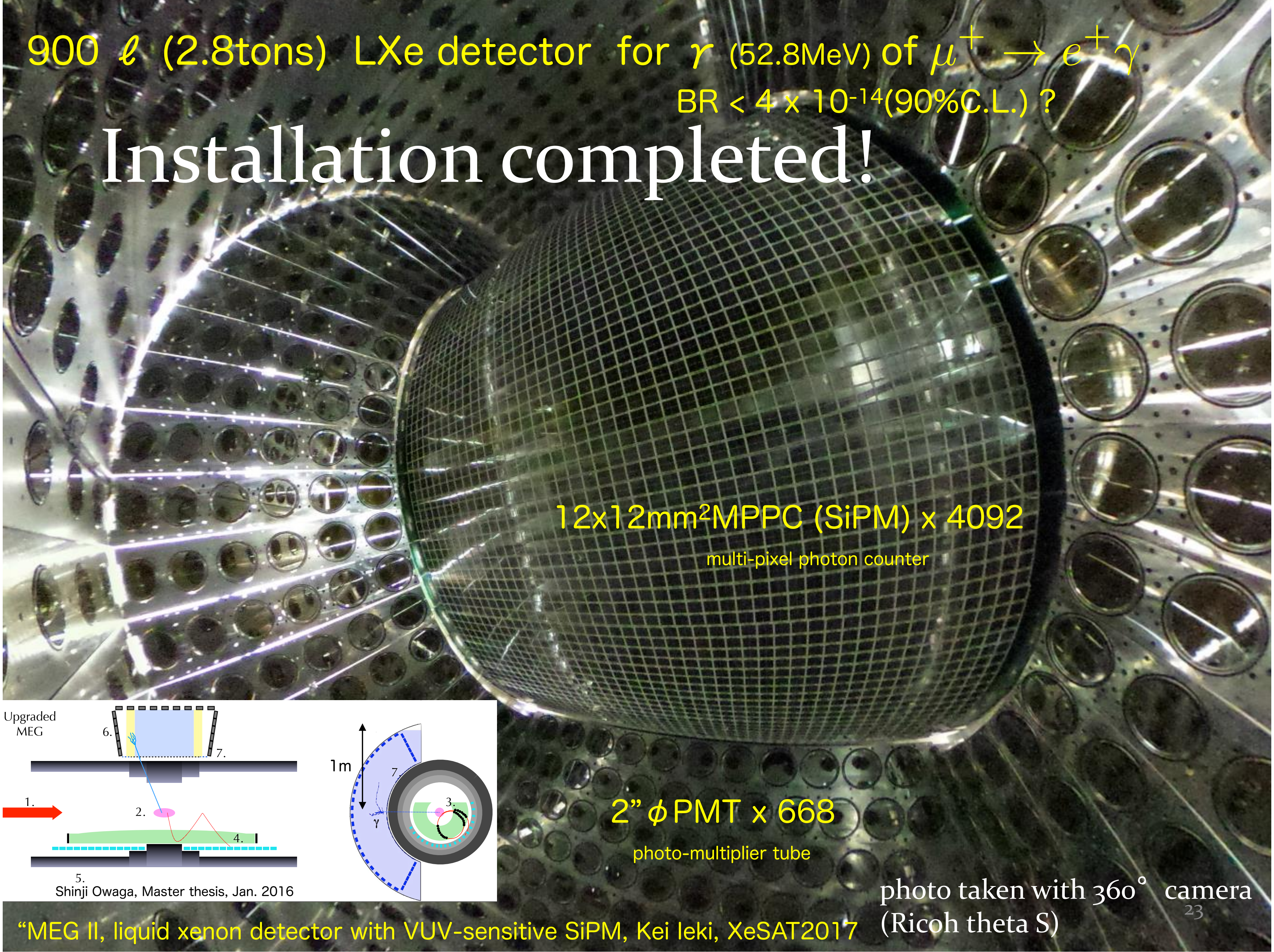
Liquid Xenon Detector

MEG II

900 ℓ (2.8tons) LXe detector for γ (52.8MeV) of $\mu^+ \to e^+\gamma$

BR < 4 x 10^{-14}(90%C.L.) ?

Installation completed!



12x12mm^{2}MPPC (SiPM) x 4092

multi-pixel photon counter

2"ϕ PMT x 668

photo-multiplier tube

Shinji Owaga, Master thesis, Jan. 2016

photo taken with 360° camera (Ricoh theta S)

"MEG II, liquid xenon detector with VUV-sensitive SiPM, Kei Ieki, XeSAT2017

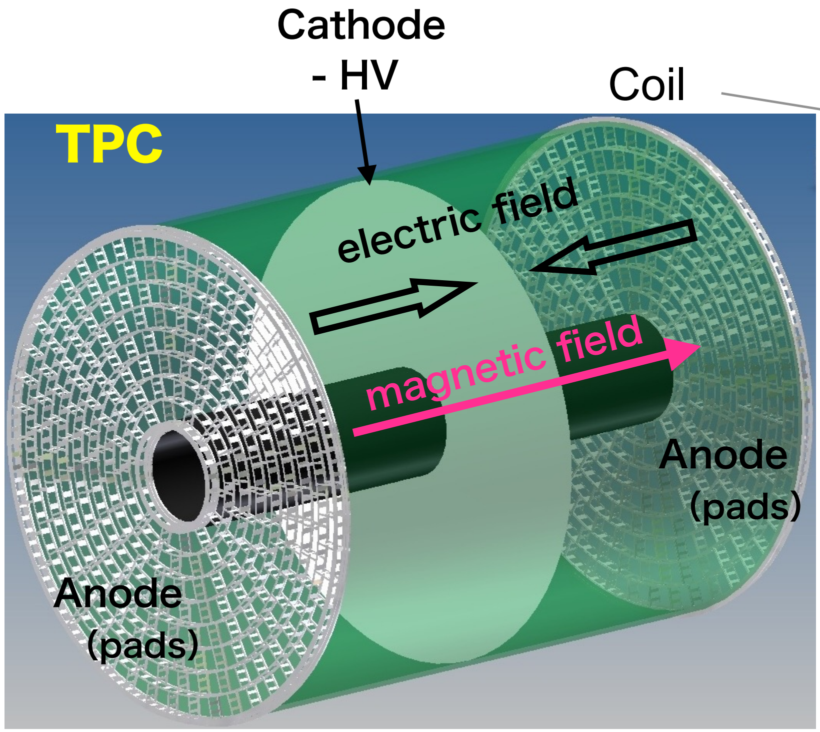
TPC

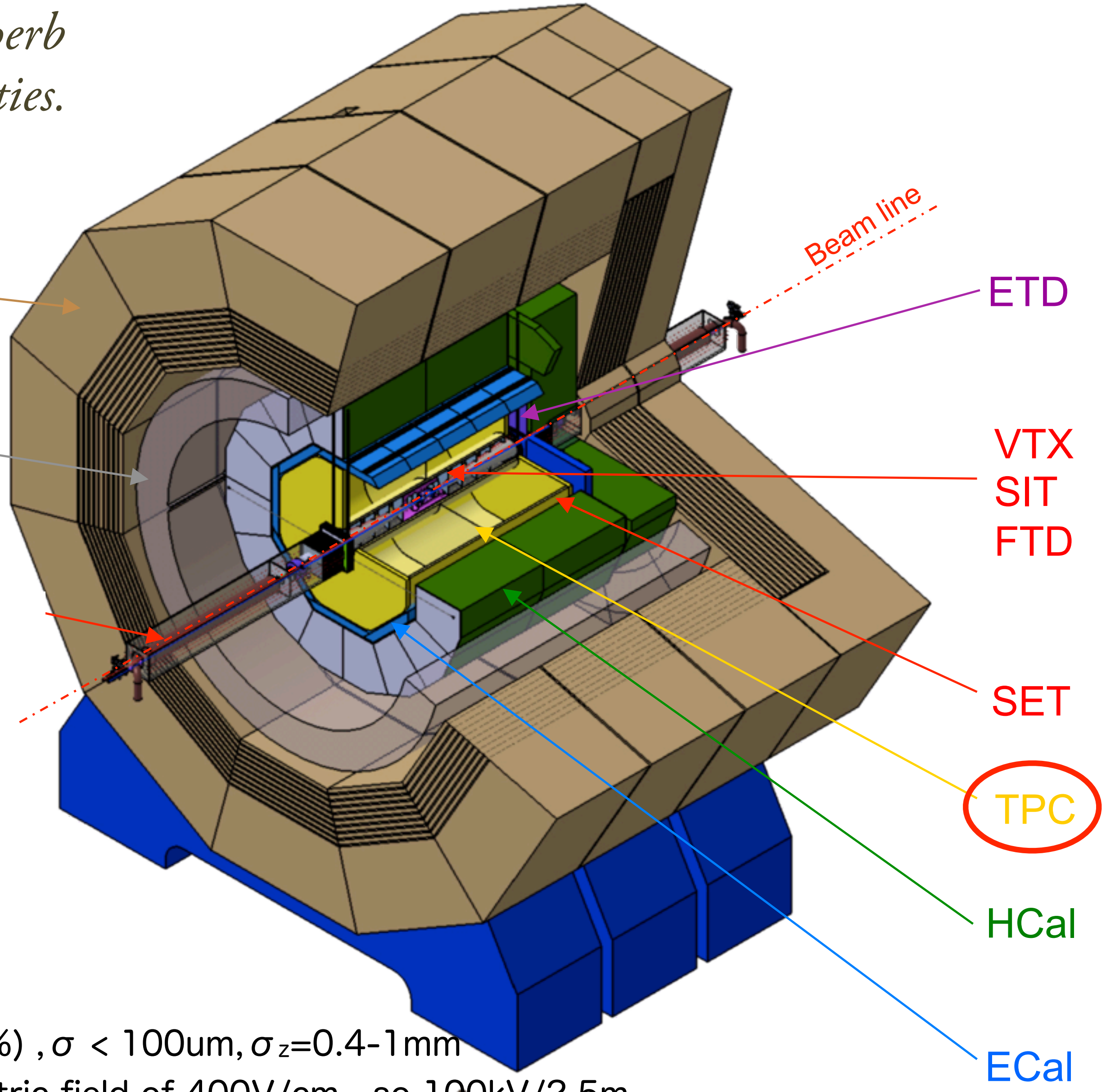
Time Projection Chamber (TPC) for the central tracking detector of charged particles at the high energy experiments

International Large Detector

at the International Linear Collider, ILC

Detector optimized for ***particle flow****, with highly granular calorimeters and superb tracking and vertex finding capabilities.*





so-called T2K gas (Ar-CF_4(3%)-isobutane(2%) , σ < 100um, σ_z=0.4-1mm

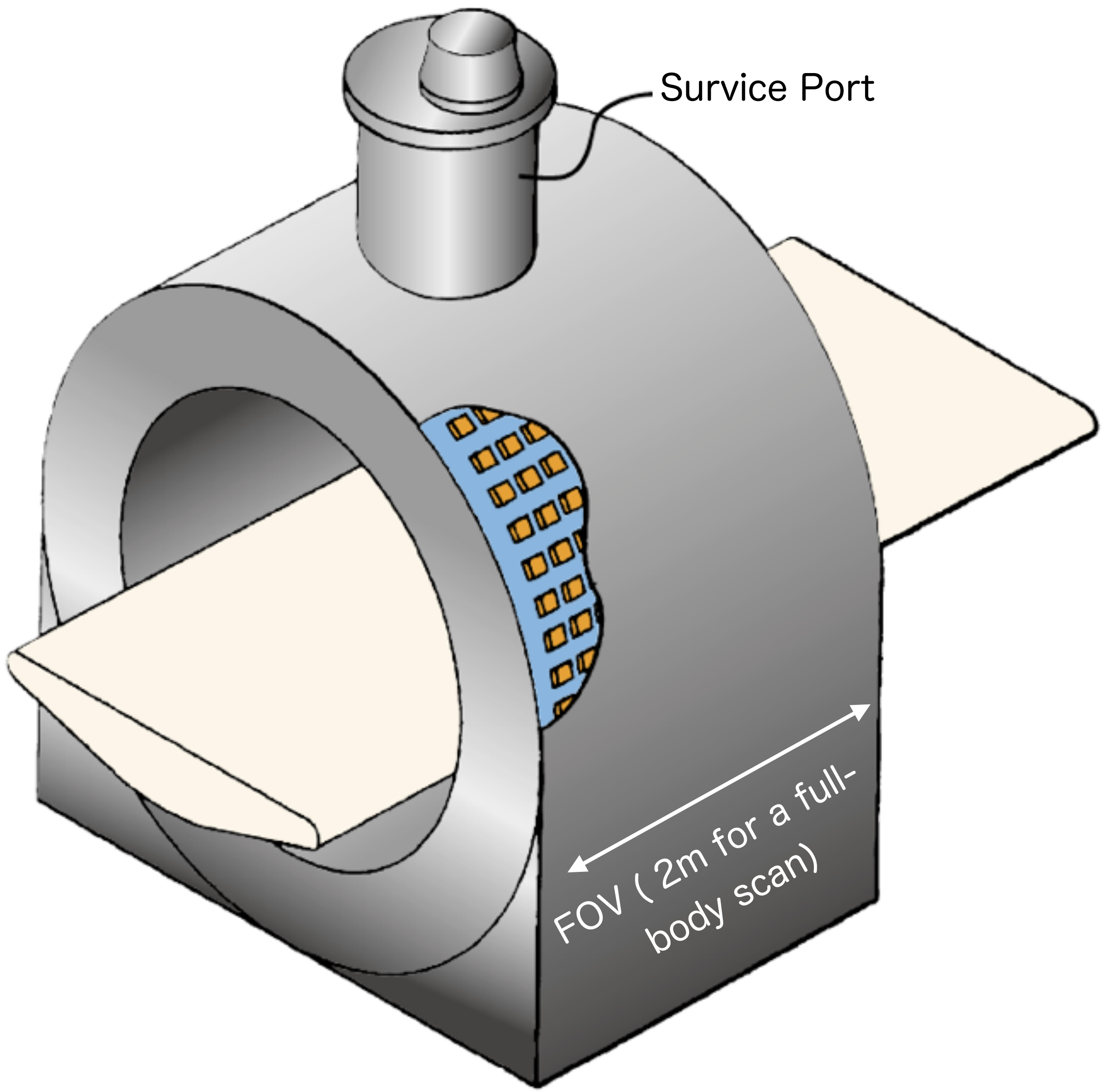
2.5m drift in 3.5T solenoid field and the electric field of 400V/cm so 100kV/2.5m

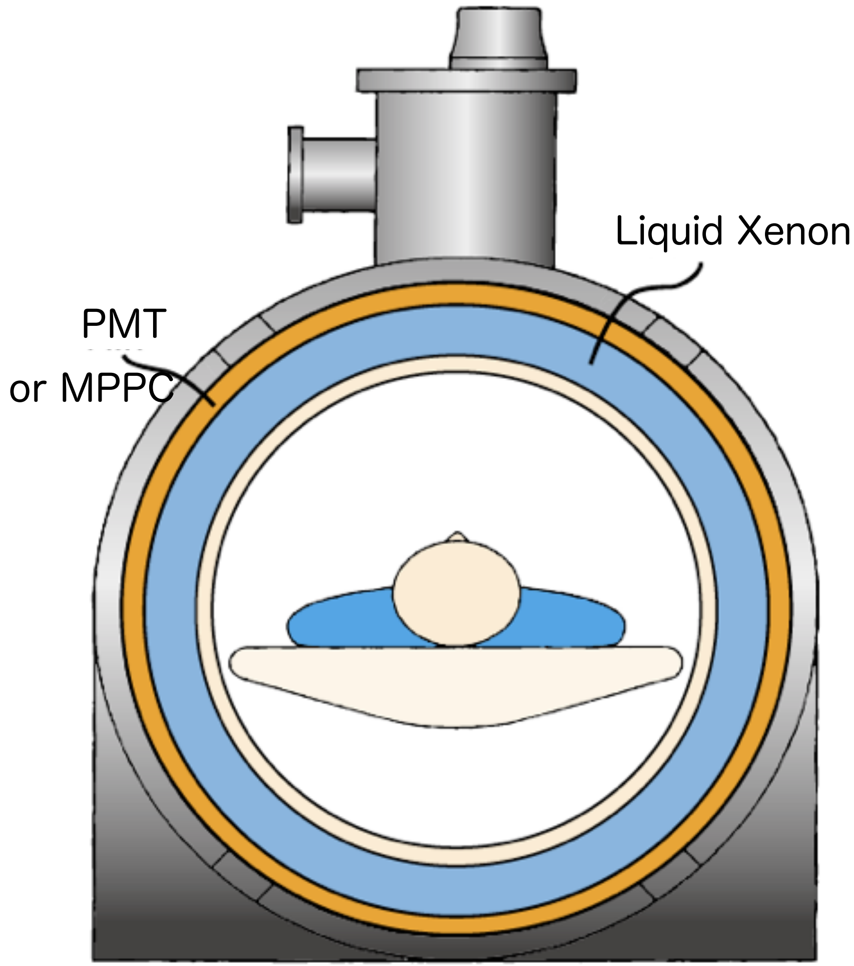
New Generation PET: TXePET

based on the liquid Xe TPC

TXePET

PET based on TPC in liquid xenon





TXePET (2m FOV for the full-body)

Liq.Xe : 140L, 88cm-dia,48cm FOV, 9cm DOI (93% γ eff.)

Resolutions(σ) : 1mm of the 3D positions, 5% of the energy

PMT(1"□): 8x112x2=1,792本

or MPPC(12x12mm^2):~7,100

spatial res.(FWHM) = 2cm

coincidence time = 10 nsec

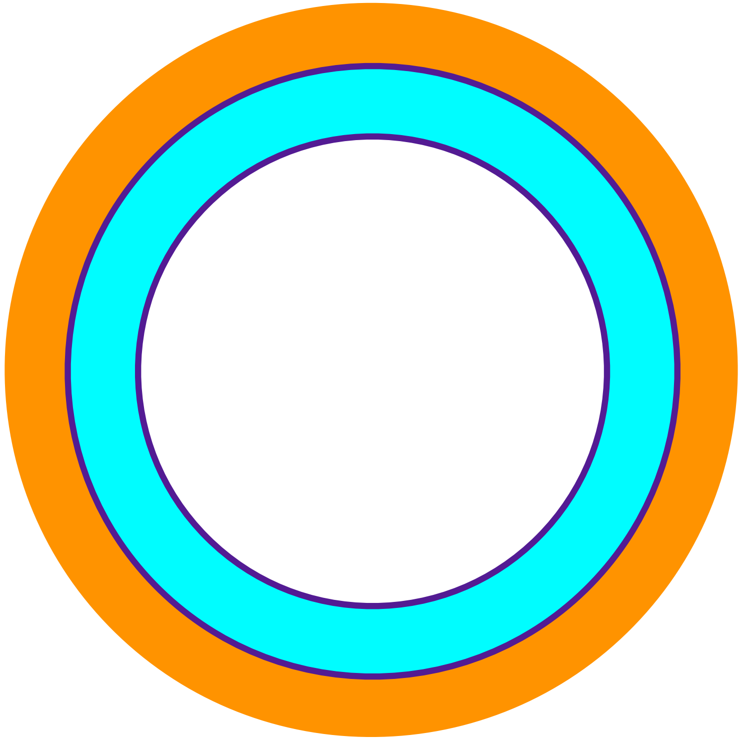
time stamp for TPC

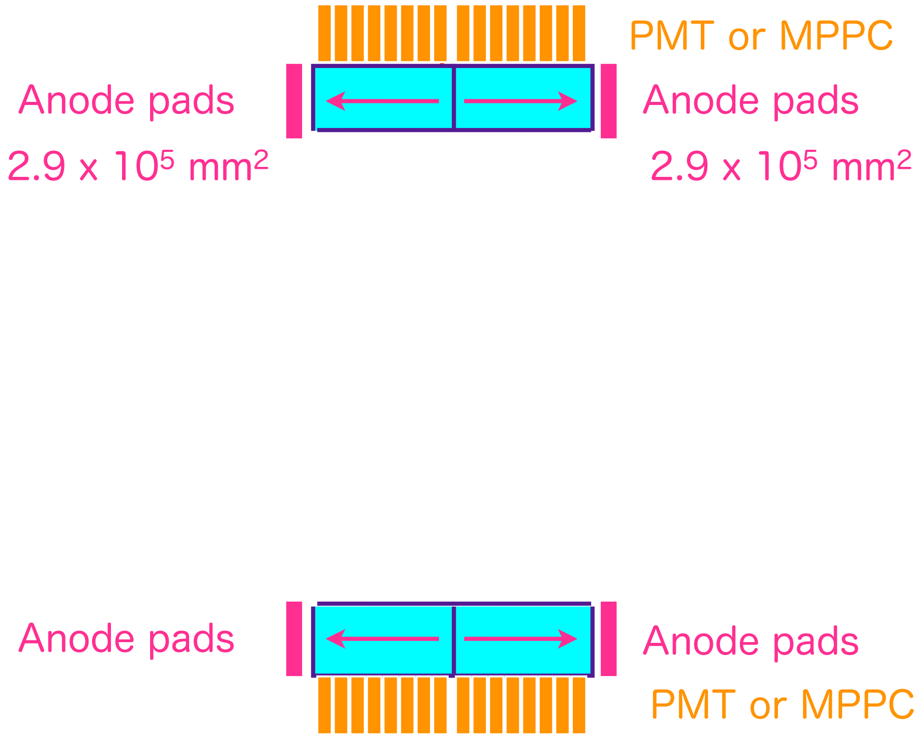
TPC : E=48kV/24cm

drift time : 104 μsec/±24cm

(velocity : 2.3mm/μsec)

pipeline readout, i.e. no deadtime





Prototype of TXePET

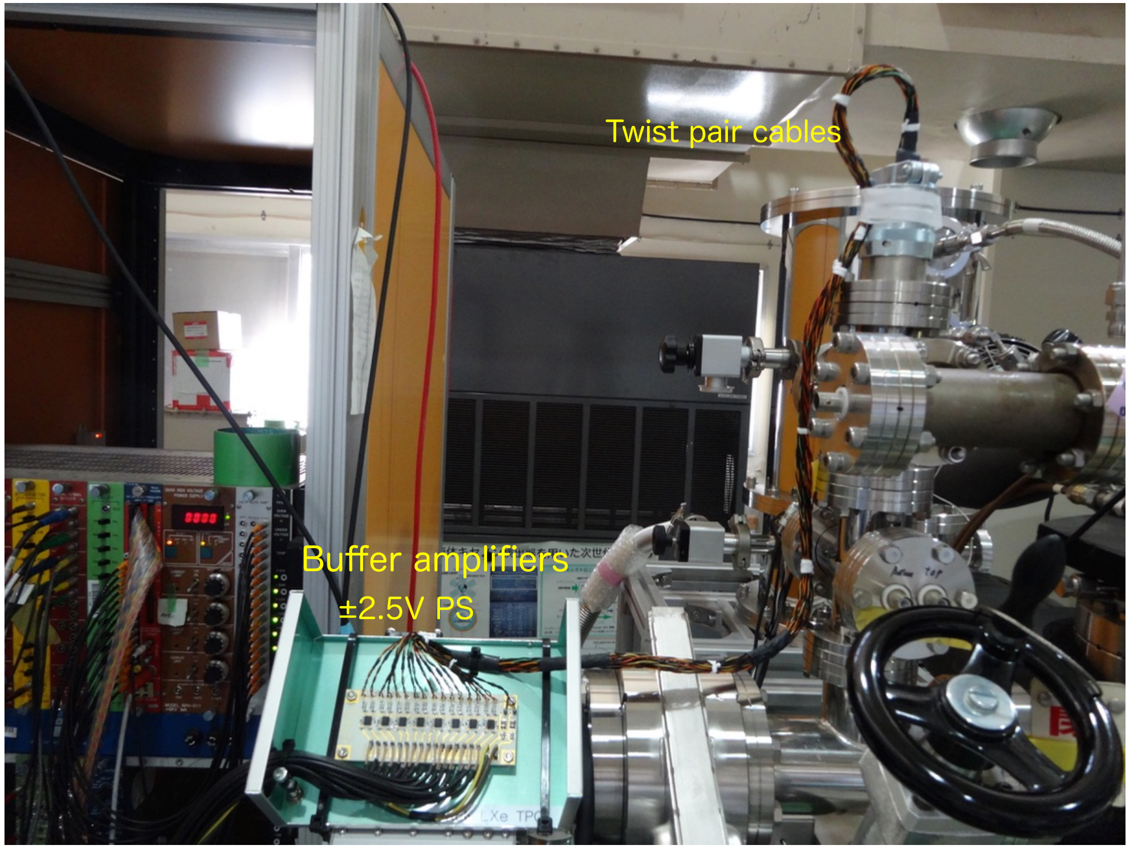
at KEK

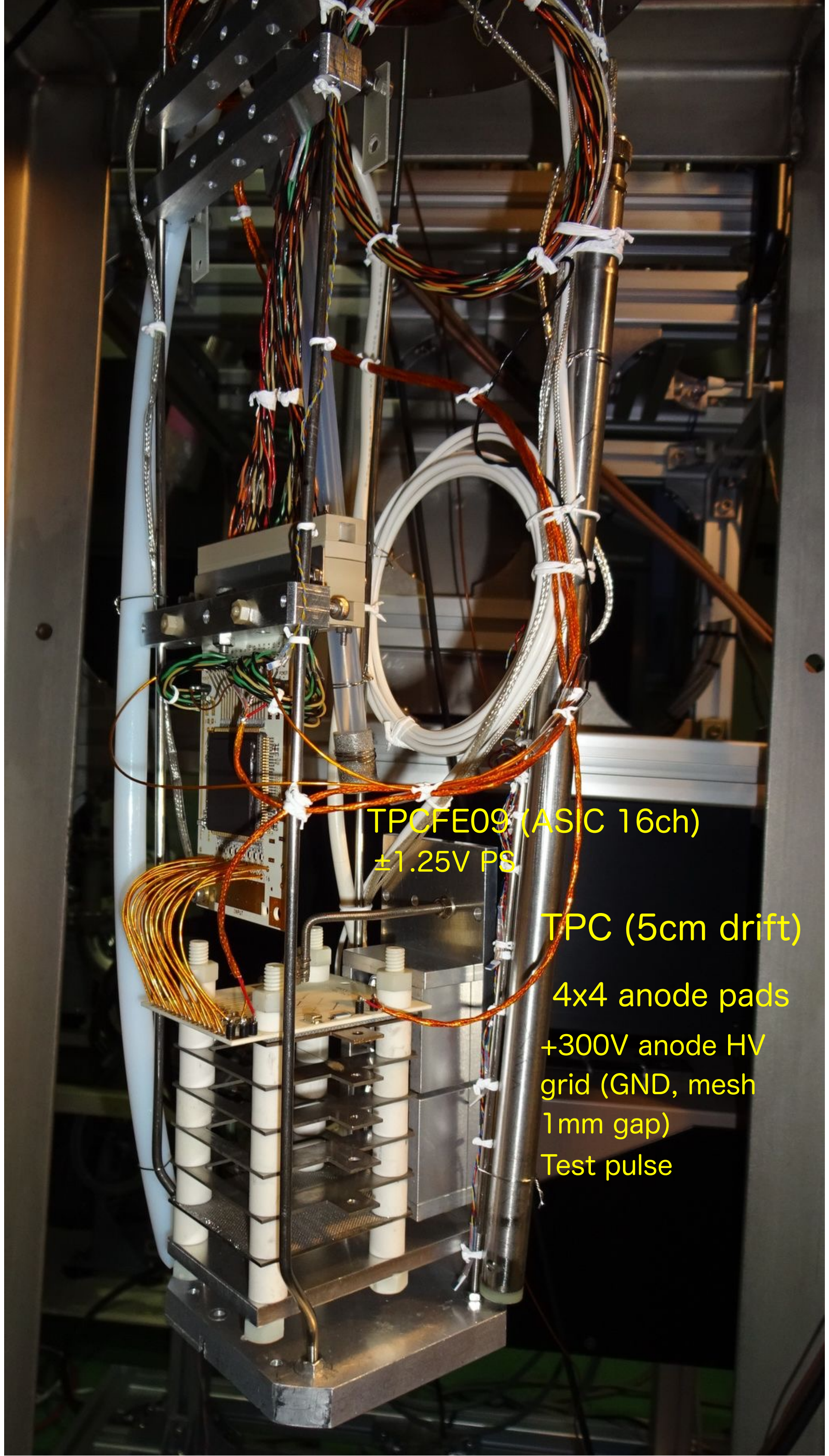
LXeTPC

prototype -2

ASIC Frontend Electronics(16ch/chip) with the pre-cooling sytem

Optimized setup, 22 October, 2015





3γ PET

as an innovative imaging modality

3 γ Imaging unique to a Liquid Xe PET

for better sensitivity and lower injected activity

L. Gallego Manzano et al., NIM A787(2015) 89-93

LOR and 3rd γ (Compton telescope) measurements at the same time

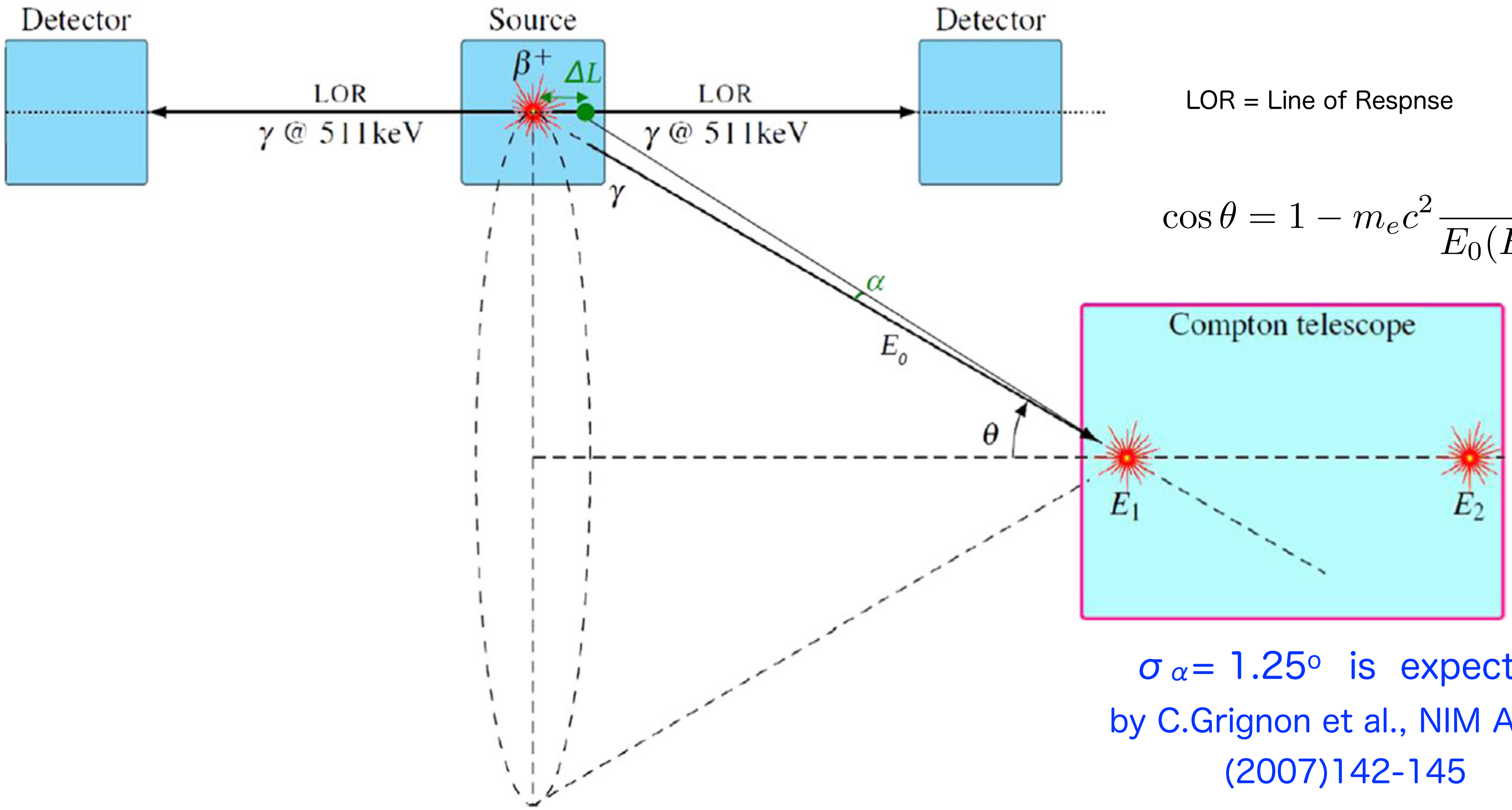
$$^{44}_{21}\mathrm{Sc} \rightarrow ^{44}_{20}\mathrm{Ca}^{*} + e^{+} + \nu_e \rightarrow ^{44}_{20}\mathrm{Ca} + \gamma + e^{+} + \nu_e$$

β^+ 94.3%

Emax=1.474MeV

τ =4h

~100% emission of a 1.157MeV γ ,which has 79% probability of Compton scattering in Liquid Xe



LOR = Line of Respnse

$$\cos\theta = 1 - m_e c^2 \frac{E_1}{E_0(E_0 - E_1)}$$

σ_α = 1.25° is expected by C.Grignon et al., NIM A571 (2007)142-145

Prototype of 3γ PET (XEMIS) at Subatech

XENON Group @ Subatech

XEMIS @ Subatech

- Jean-Pierre Cussonneau
- Eric Morteau
- Dominique Thers

Post-doc:

- Nicolas Beaupere
- Lucía Gallego

PhD students:

- Debora Giovagnoli
- Loïck Virone
- Yajing Xing
- Yuwëi Zhu

Mechanical Service:

- Patrick Le Ray
- Jean-Sébastien Stutzmann

Electronic Service

Collaborations

CHU / INSERM

- Thomas Carlier

IRCCyN

- Imaging

KEK Japon

- R&D photodetectors

Air Liquide Advanced Technologies

- R&D liquid xenon cryogenics

Pôle Micrhau

- R&D electronics

ARRONAX

- Radioisotope production

XEMIS: XEnon Medical Imaging System

Low activity Medical Imaging (~20 kBq)

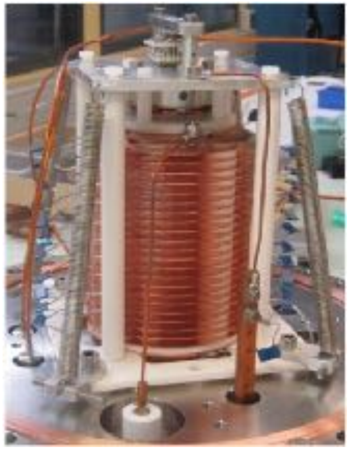
for 20 min.

↓

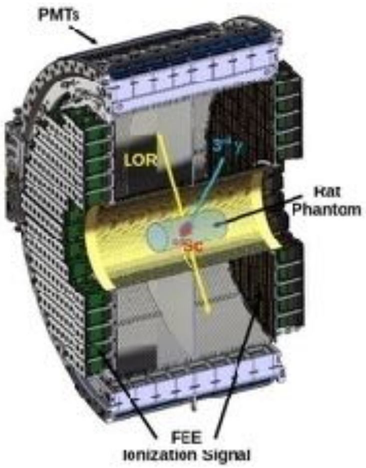
3γ imaging + Liquid xenon Compton camera

So the injected activity is about 1/1000 , the imaging time can be <1 sec !

XEMIS1	**XEMIS2**	**XEMIS3**
R&D	Small animal imaging	Whole body imaging



30 kg
12 cm drift TPC



200 kg
2 x 12 cm drift TPC

From 2020

LXe clinical camera

- Neurology: ~250 kg
- Paediatrics: ~700-800 kg
- Whole body: few tons

Prototype of the full-body PET and also in-beam imaging

Evolution of XEMIS2 (small animal imaging)

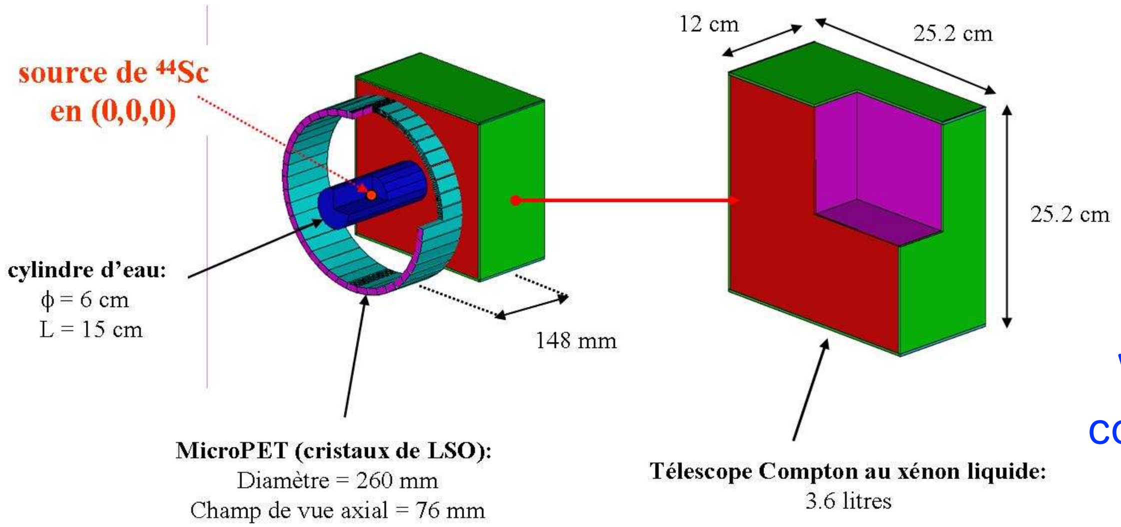
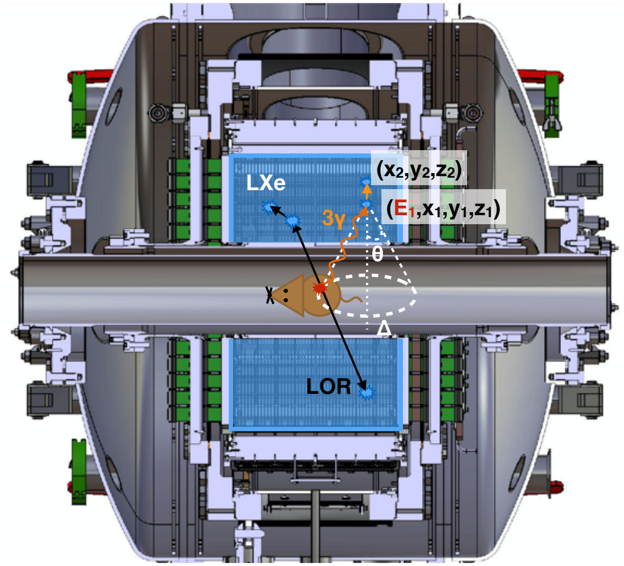


FIG. 6.4 – Représentation du télescope Compton au xénon liquide associé à une micro-TEP au LSO

with KEK collaboration



3γ sensitivity > 7 %

Expected resolution along the LOR < 1cm

Subatech group

Doctor thesis of C.Grignon, Nantes university, 2007, and

C.Grignon et al., NIM A571 (2007)142-145

L. Gallego Manzano et al., NIM A787(2015) 89-93

Establishment of XEMIS2 in CHU-Nantes

(Nantes university hospital)

ReStox XEMSI2
Patent in progress

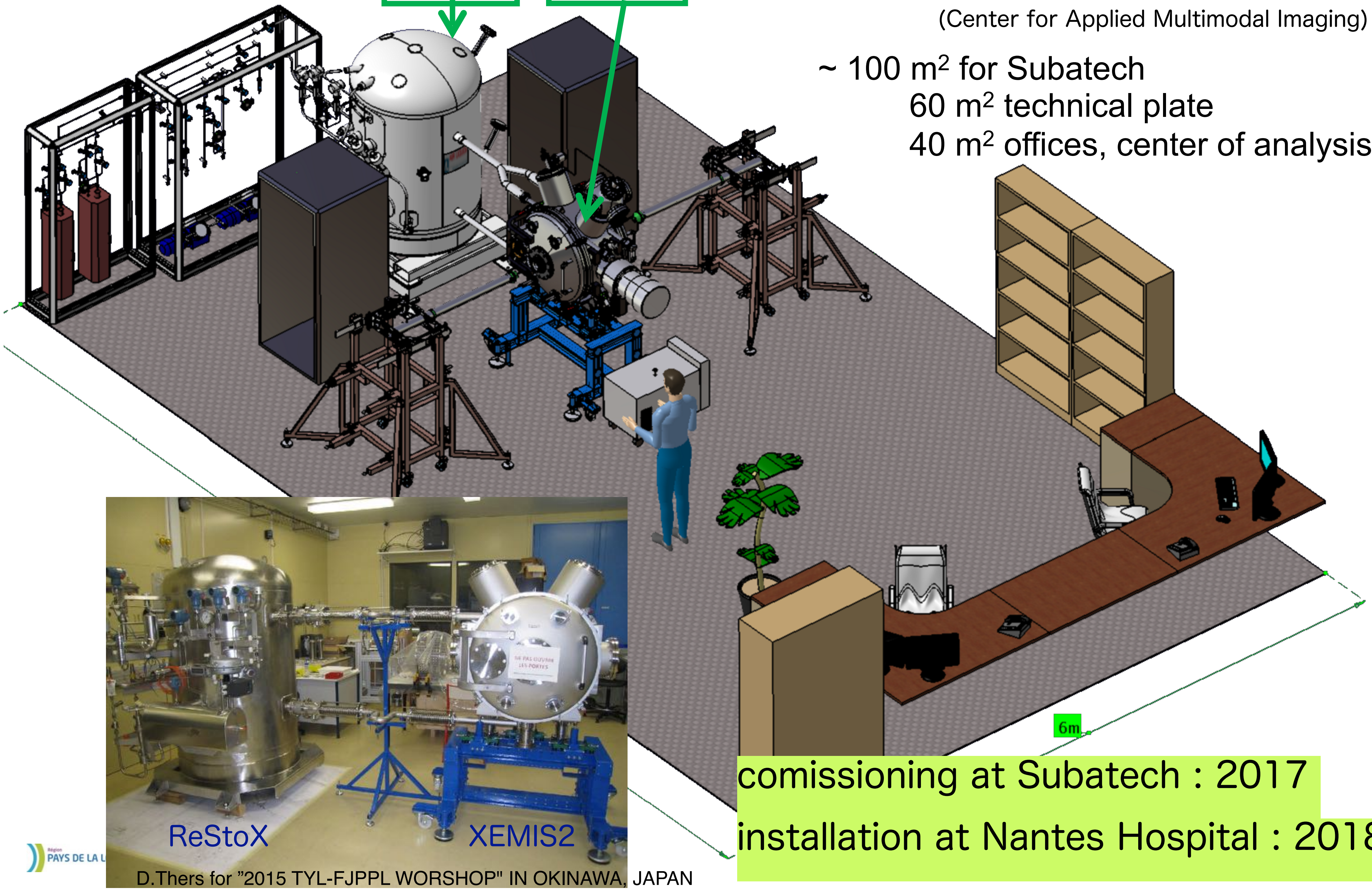
ReStoX

Caméra

New center of imagery CIMA

(Center for Applied Multimodal Imaging)

~ 100 m^2 for Subatech
60 m^2 technical plate
40 m^2 offices, center of analysis



comissioning at Subatech : 2017

installation at Nantes Hospital : 2018

In-beam Imaging

(Ion beam range monitoring at hadron therapy)

realtime or 4D imaging?

in-beam imaging

Physics Today **68**, 6, 24 (2015)

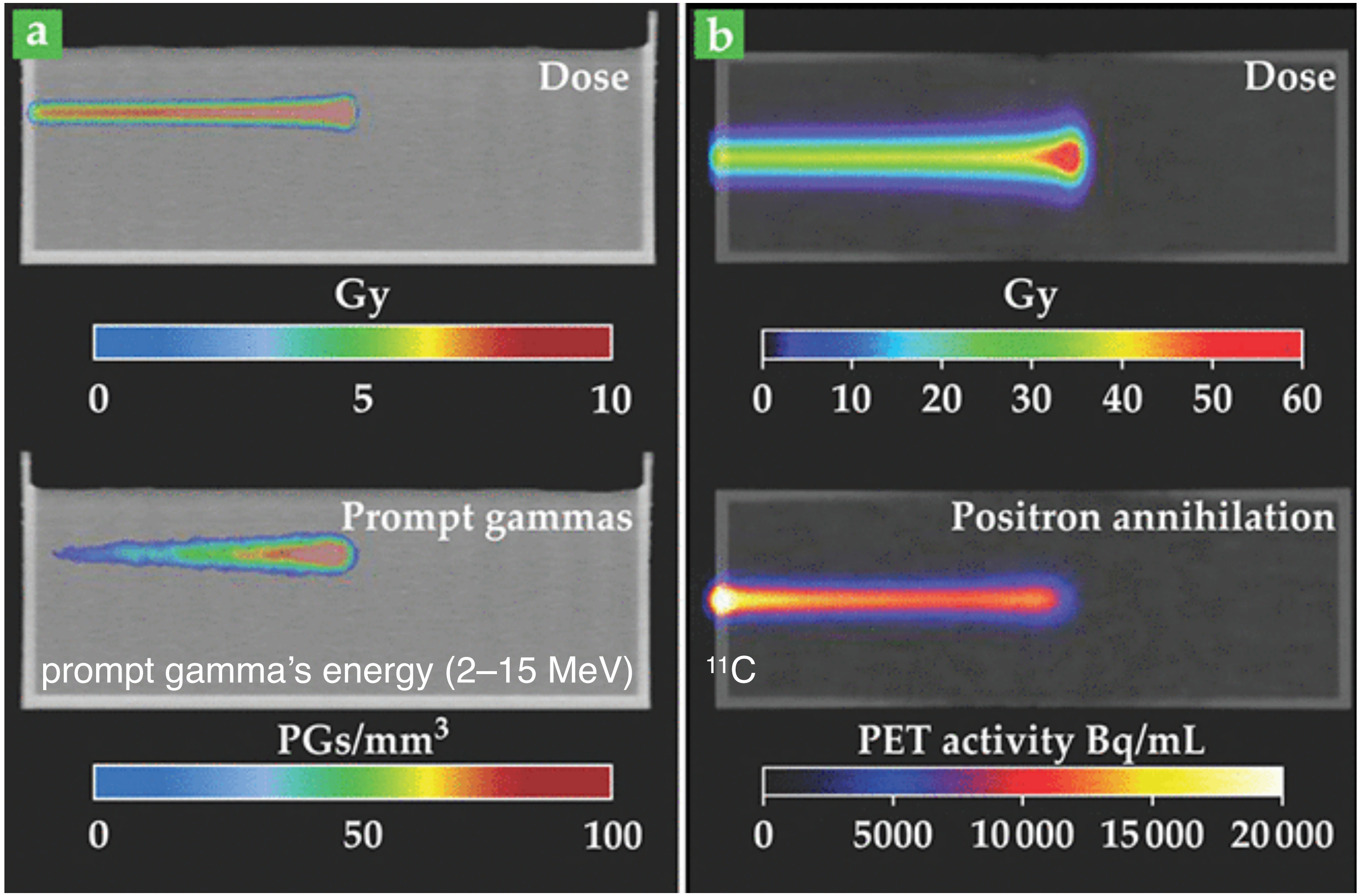


Figure 4. Simulated patients—tanks of water or gelatin—are irradiated with proton beams for proof-of-principle gamma imaging. In each case, the dose distribution in the upper panel is calculated, and the gamma distribution in the lower panel is measured. **(a)** A 150-MeV clinical proton pencil beam impinges on a water tank, and the prompt-gamma (PG) emission is imaged with an experimental Compton camera specially designed for the purpose. **(b)** Positron-annihilation gamma emission from a tank of tissue-like gelatin is imaged with a commercial diagnostic positron emission tomography instrument shortly after irradiation with a 177-MeV proton beam. The strong signal near the entrance region in the PET image is a result of carbon-11 activation in the carbon-rich walls of the tank. (Panel b courtesy of Julia Bauer, Heidelberg Ion-Beam Therapy Center.)

an experimental Compton camera

PET

The liquid xenon TPC can work both for the Compton camera and PET !

A beam structure can be optimized for this detector ?

Proton radiotherapy for the breast cancer very close to the heart and LAD

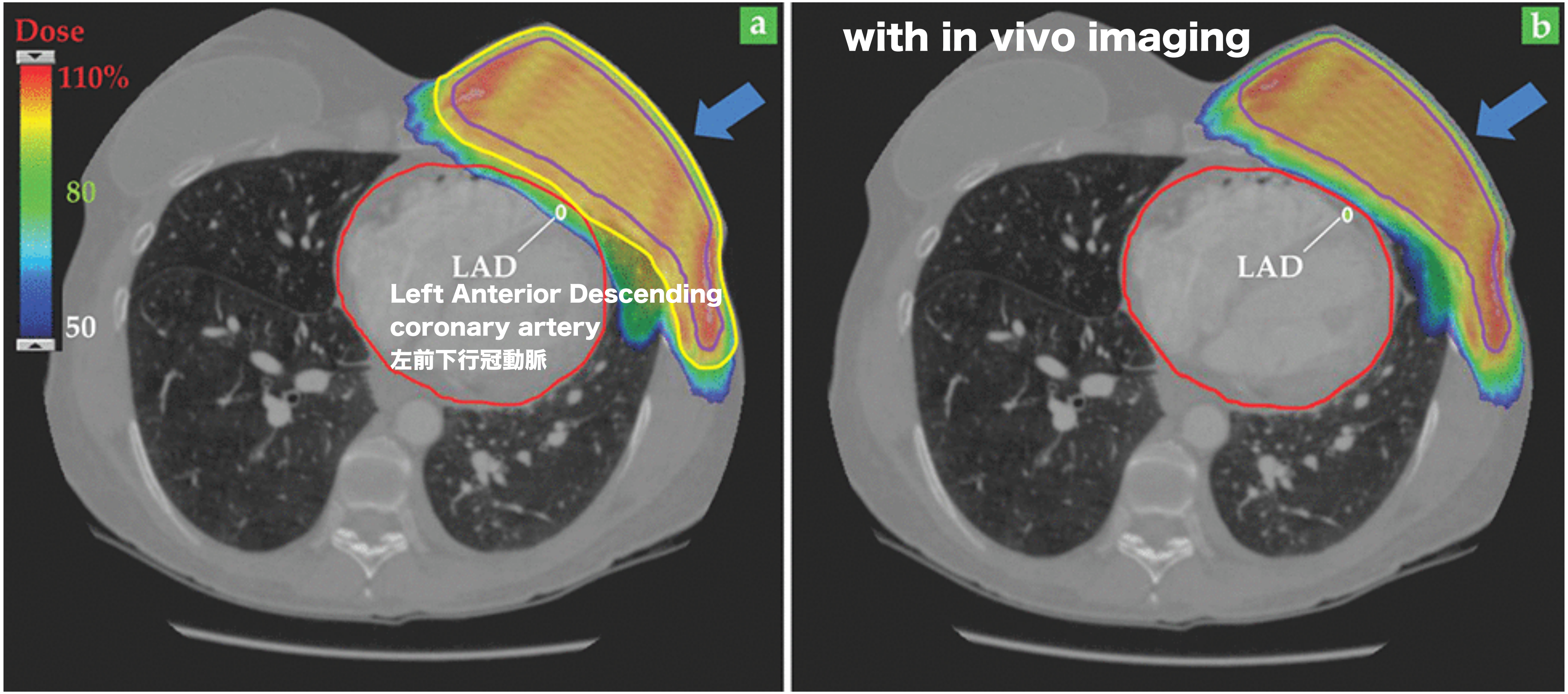


Figure 5. Patient outcomes can be greatly improved by in vivo imaging that reduces beam-range uncertainty by just a few millimeters. In this breast cancer patient, the intended treatment volume is indicated by the purple line, and the direction of the treatment beam is shown by the blue arrow. **(a)** To account for the beam-range uncertainty, the treatment volume must be expanded to the region enclosed in yellow. As a result, significant dose (shown here as a percentage of the prescribed dose) is delivered to the heart (red line) and the left anterior descending coronary artery (LAD; white line). **(b)** With range-verified proton radiotherapy, no expansion to the treatment volume would be needed. Dose delivered to the heart and the LAD is greatly reduced, as is the patient's risk of radiation-induced heart disease.

For this particular patient, the mean heart dose could be reduced from 3.0 Gy to 0.6 Gy, the LAD dose from 4.0 Gy to 0.6 Gy, and the lung dose from a mean value of 10.0 Gy to 6.5 Gy.

Summary

1. The liquid Xe TPC can be an ideal PET with a good DOI resolution, i.e. the 3 dimensional resolution of a few mm. Fine imaging is expected with smaller radiation dose. It is also a good Compton camera especially for prompt gammas, i.e. for the in vivo imaging.

2. A prototype, XEMIS2, was constructed for a small animal PET, which will demonstrate the basic characteristics of the 3 γ imaging.

3. For the real-time tracking, the imaging speed depends on algorithm of the deconvolution and the computer power with GPU (Graphics Processing Unit). The successive approximation method such as the ML-EM must be improved for the fast imaging of 10 frames/sec (*) .

(*) 2 frames/sec with an average delay time of 2.1 sec has been demostrated for a point source in the OpenPET based on jPET-D4 by T.Yamaya et al.
ref: Yamaya T., Tashima H. (2017) OpenPET Enabling PET Imaging During Radiotherapy. In: Inoue T., Yang D., Huang G. (eds) Personalized Pathway-Activated Systems Imaging in Oncology. Springer, Singapore