The Background Control of PandaX-4T and A Low-background PMT for PandaX-xT

Youhui Yun, Shanghai JiaoTong University

On behalf of the PandaX Collaboration

(2461352794@sjtu.edu.cn)

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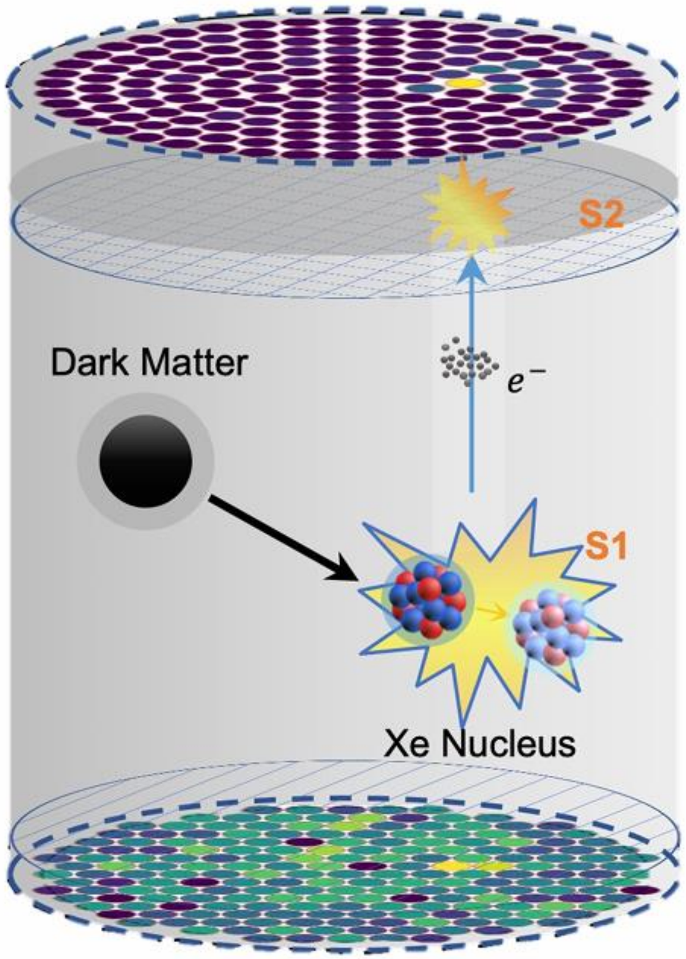
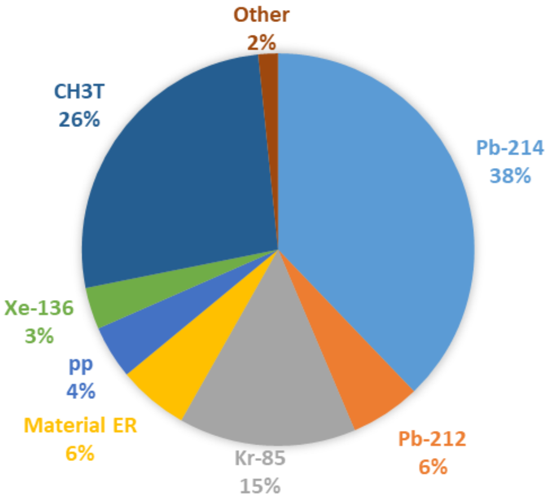
LRT2024

What is PandaX-4T?

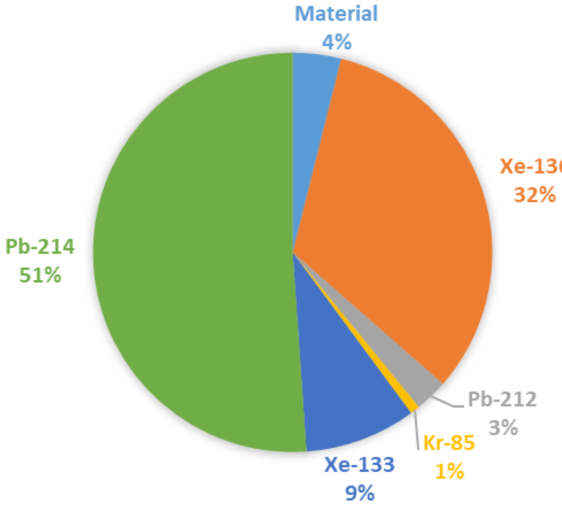
- PandaX-4T is a multi-ton Xenon TPC that searches for rare signals such as dark matter and neutrinoless double β decay.
- We are planning to construct PandaX-xT to boost the sensitivity.
- These backgrounds need be measured and controlled.



Schemetic diagram of xenon TPC



Background composition of WIMP ROI, arXiv:2408.00664v1



Background composition of ^{134}Xe 0νββ, Phys. Rev. Lett. 132, 152502

Background control for PandaX-4T

- **Background measurement program**
  - Internal: ^{222}Rn and ^{85}Kr in xenon
  - External: radioactive isotopes (^{238}U, ^{232}Th, ^{60}Co, etc) in detector components and environment

- **Background Control Method**
  - Low-background material screening
  - Distillation
  - Surface treatment

Background	Origin of the background	Measurement system	Control method
Internal	^{222}Rn in xenon	radon emanation system	distillation, screening
	^{85}Kr in xenon	krypton assay station	distillation
External	Isotopes in the bulk	HPGe counting station,ICPMS	screening
	surface contamination	alpha detector	surface treatment

Background measurements and control methods in PandaX-4T

Background measurement and control method

Measurement systems

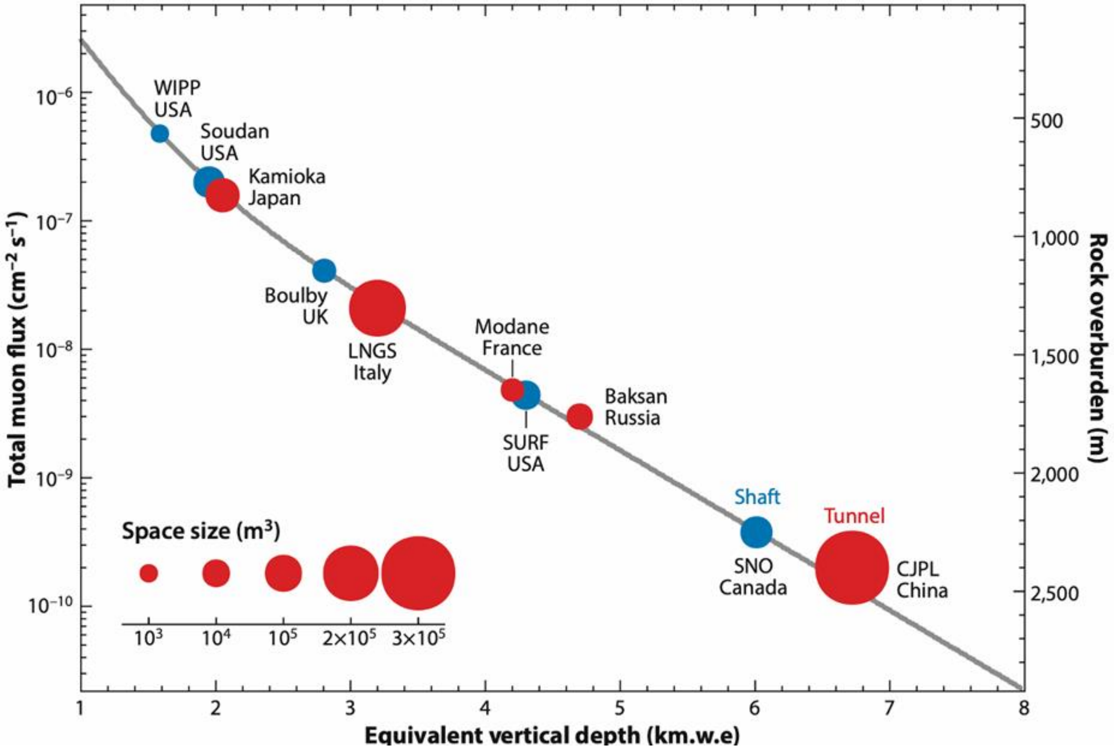
- HPGe counting stations
- ICPMS
- Radon emanation systems
- Krypton assay station
- Alpha detector

HPGe counting stations

- A type of semiconductor detector (excellent energy resolution, low detection threshold)
- Located in the China Jin-Ping Underground Laboratory (CJPL)

HPGe detector	JP1	JP2	JP3
Crystal mass [kg]	3.7	0.6	0.9
Relative detection efficiency	175%	35%	51%
FHWM@1332 keV [keV]	2.7	2.5	2.0
FHWM@662 keV [keV]	2.5	2.3	1.4
60-2700 keV Integral [counts/kgGe/day]	594	1039	1572

HPGe Detector Parameters,
Nuclear Techniques 008 (2022), 045

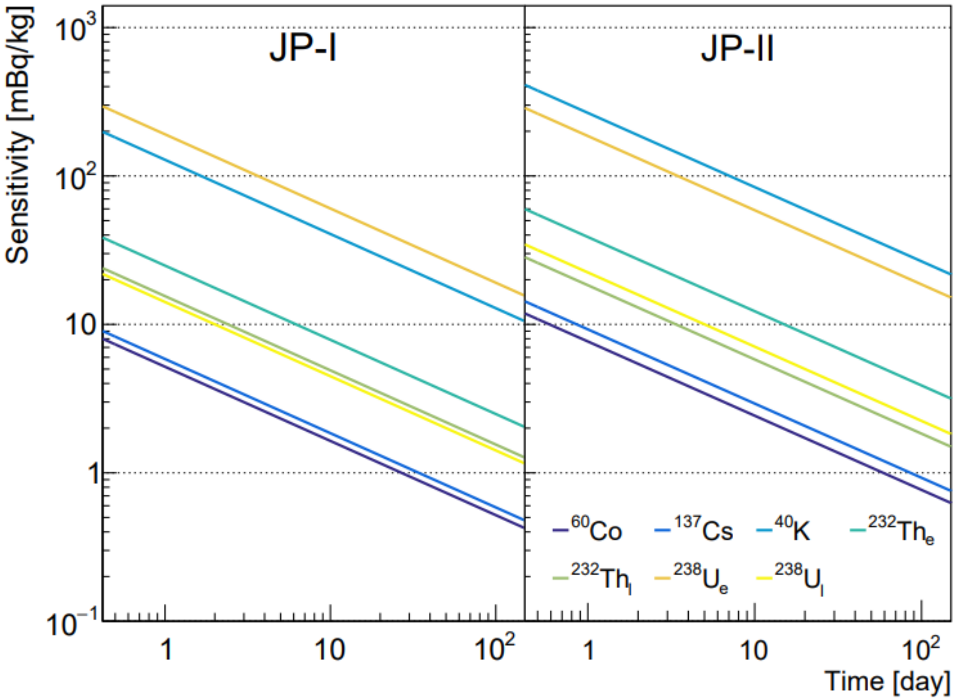


Muon flux of underground lab
Ann.Rev.Nucl.Part.Sci.,2017,67:231-251

HPGe counting stations

- 10 cm oxygen-free copper shield and 20 cm lead shield
- Stainless steel vacuum chamber to avoid air ^{222}Rn in the counting chamber
- Low MDA and ~1000 samples screening since 2017 for PandaX, JUNO, etc

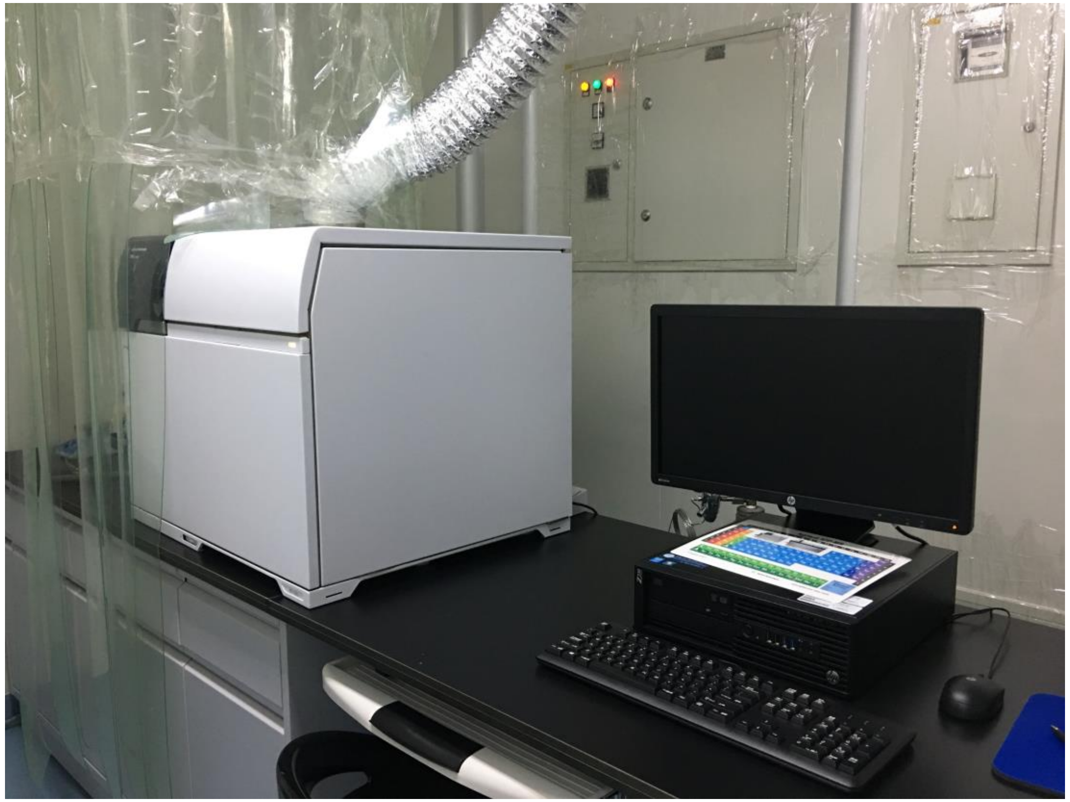
HPGe counting station photo



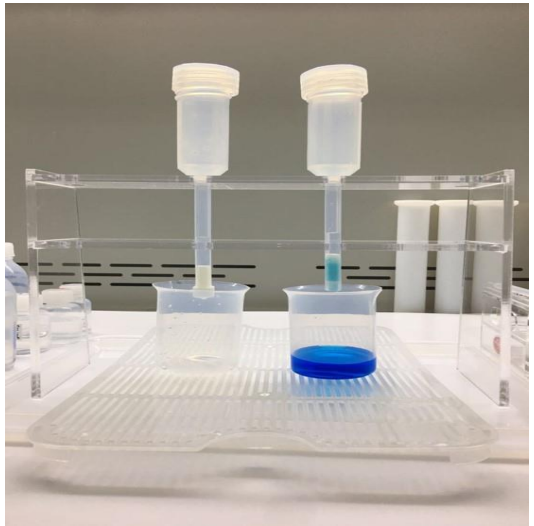
MDA for a cylinder teflon sample (D: 10 cm, H: 1 cm)
JHEP 06 (2022) 147

ICPMS

- ICPMS: Agilent 7900
- Class10 cleanroom for sample preparation
- Resin Extraction Method: TEVA/UTEVA resin



ICPMS



TEVA、UTEVA resins columns for
U/Th extraction from copper solution

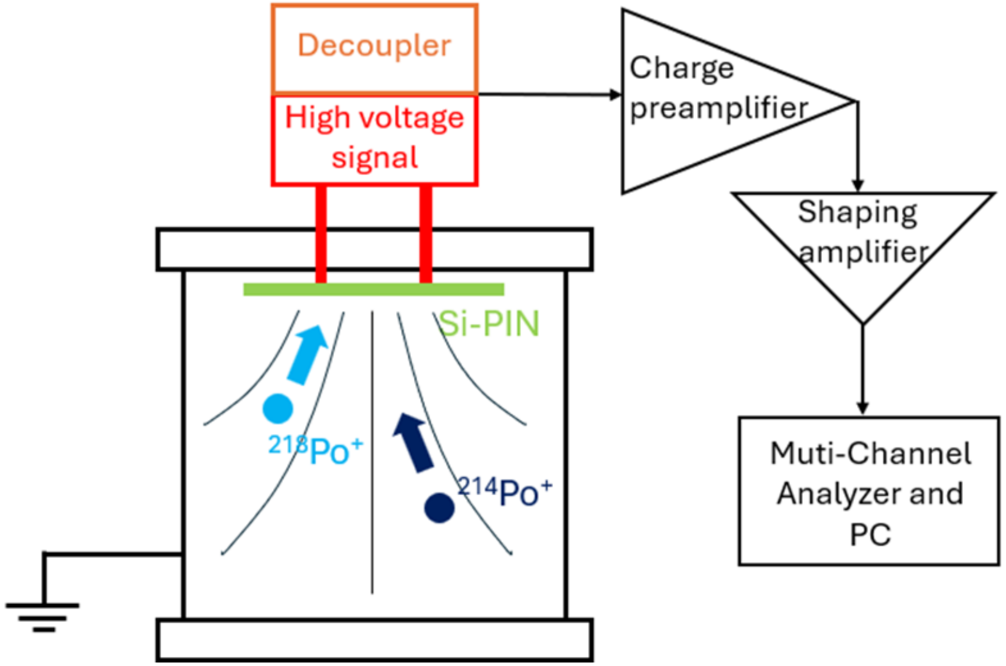
Detection limits	[pg/g]	[uBq/kg]
^{232}Th	0.04	0.14
^{238}U	0.07	0.90

Detection limits of ICPMS

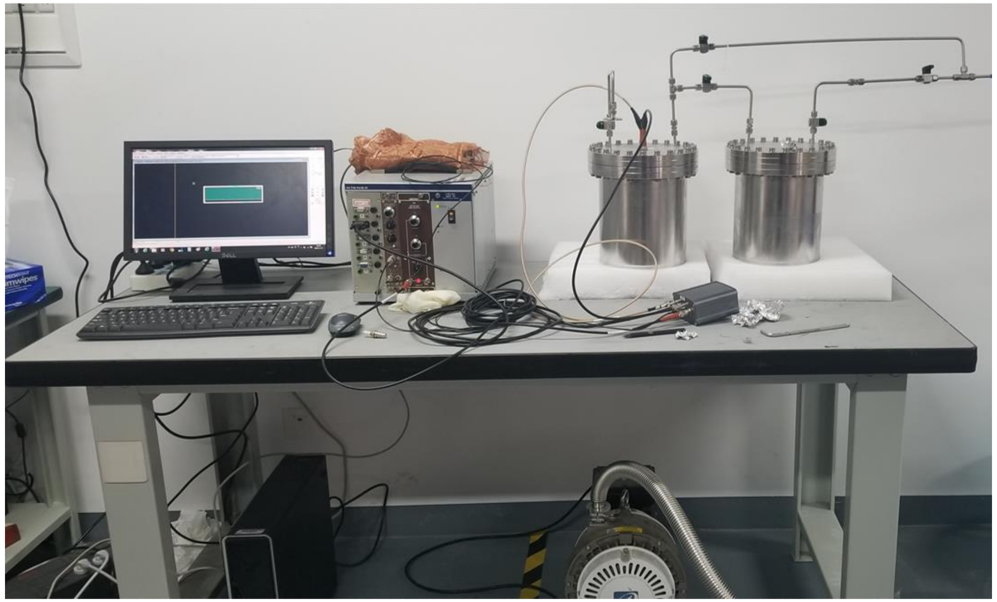
Radon emanation system

- Four radon emanation measurement systems with electrostatic collection technique was designed

- A radon trap system is introduced to boost the sensitivity (trap efficiency: 89.18 ± 4.15% @ 1 slpm 77 K)



Schematic diagram of radon emanation system

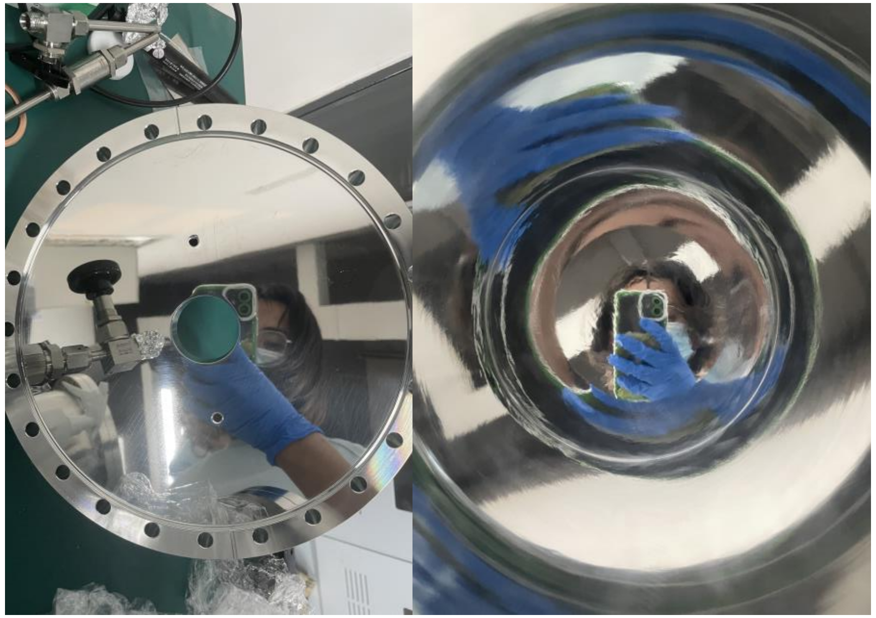


Actual picture of radon emanation system

Radon emanation system

- Use polishing (mirror, mechanical and electrochemical) and coating (epoxy, mylar etc) to reduce the background, more details see https://indico.fais.uj.edu.pl/event/1/contributions/119/

- The background can reach **0.03±0.01 mBq (@12.3 L)**



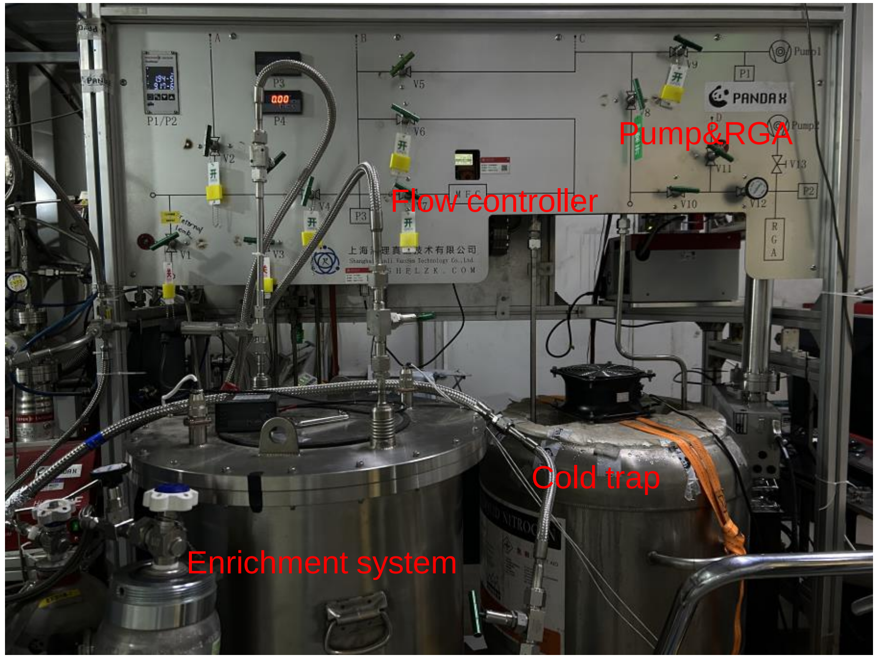
Internal surface after polishing

Internal surface after epoxy coating

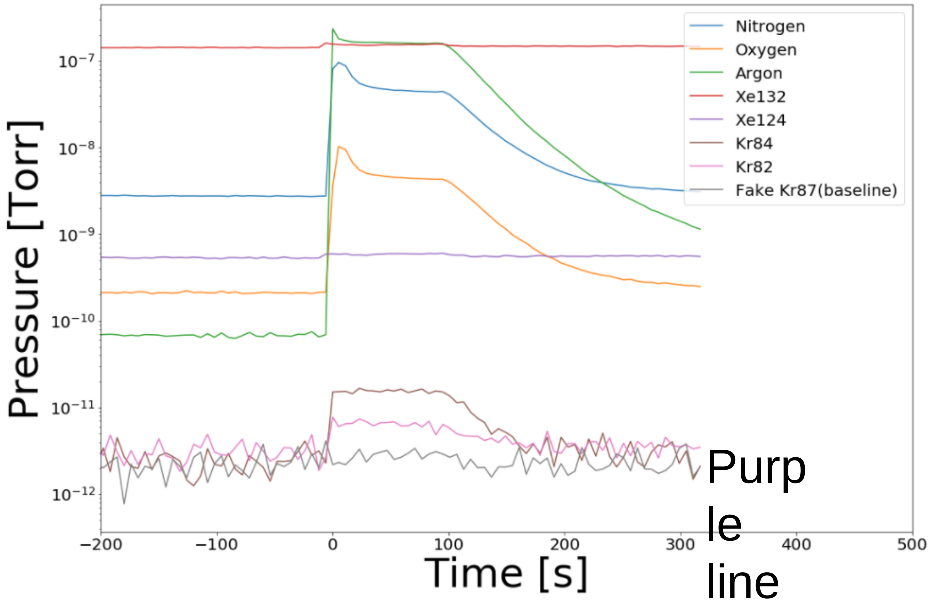
Krypton assay station

- Residual gas analyzer (RGA) and the cold trap combination are used to measure krypton concentration in xenon, the best sensitivity reaches **~10 ppt**

- The enrichment system (mainly made of vacuum chamber, cold head and heating rod) makes the sensitivity increase three times.



Krypton assay station



Krypton measurement

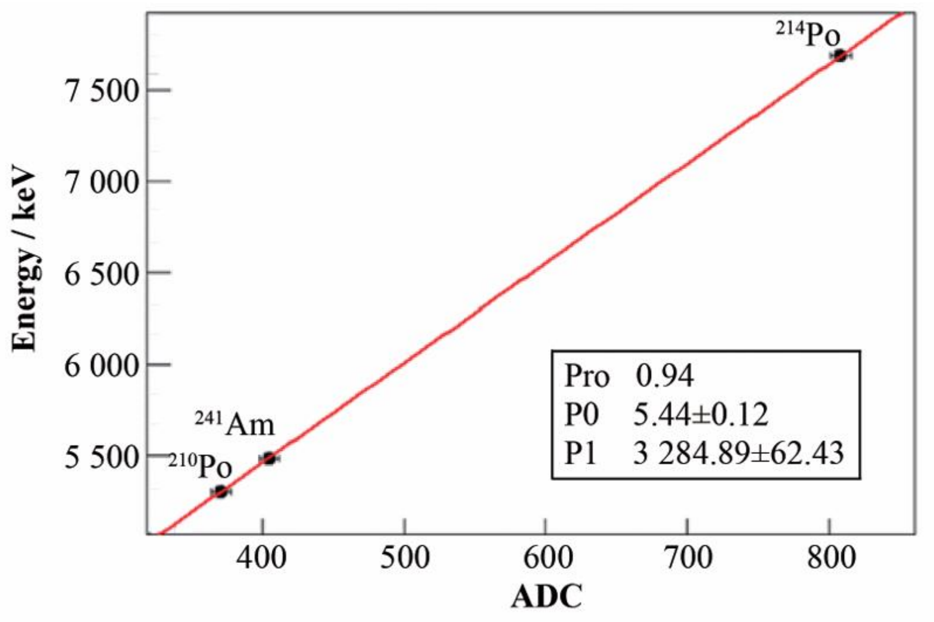
Cold head and the inner structure of enrichment system

Alpha detector

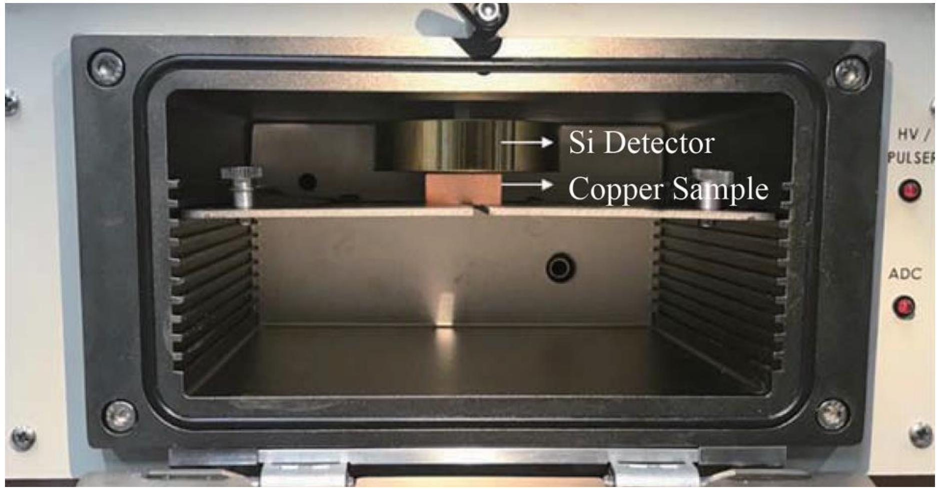
- ORTEC commercial alpha detector
- Provide surface measurements (e.g. ^{210}Po) for different materials

Performance	
Active area	1200 mm^2
Vacuum	<300 mTorr
^{210}Po Background	~0.02 mHz
Detection efficiency (for 200 mm^2 Copper Sample)	47.35±0.22 [%]

Alpha detector performance



Energy calibration of alpha detector



Sample screening in alpha detector

Control Methods

- Screening low-background materials
- Distillation
- Surface treatment

Distillation

- An online cryogenic distillation system was designed to remove krypton and radon in xenon

- Two modes
  - Krypton removal: a 7 orders of magnitude reduction @10 kg/h
  - Radon removal: a radon reduction factor of 190 @10 slpm (distillation tower only)

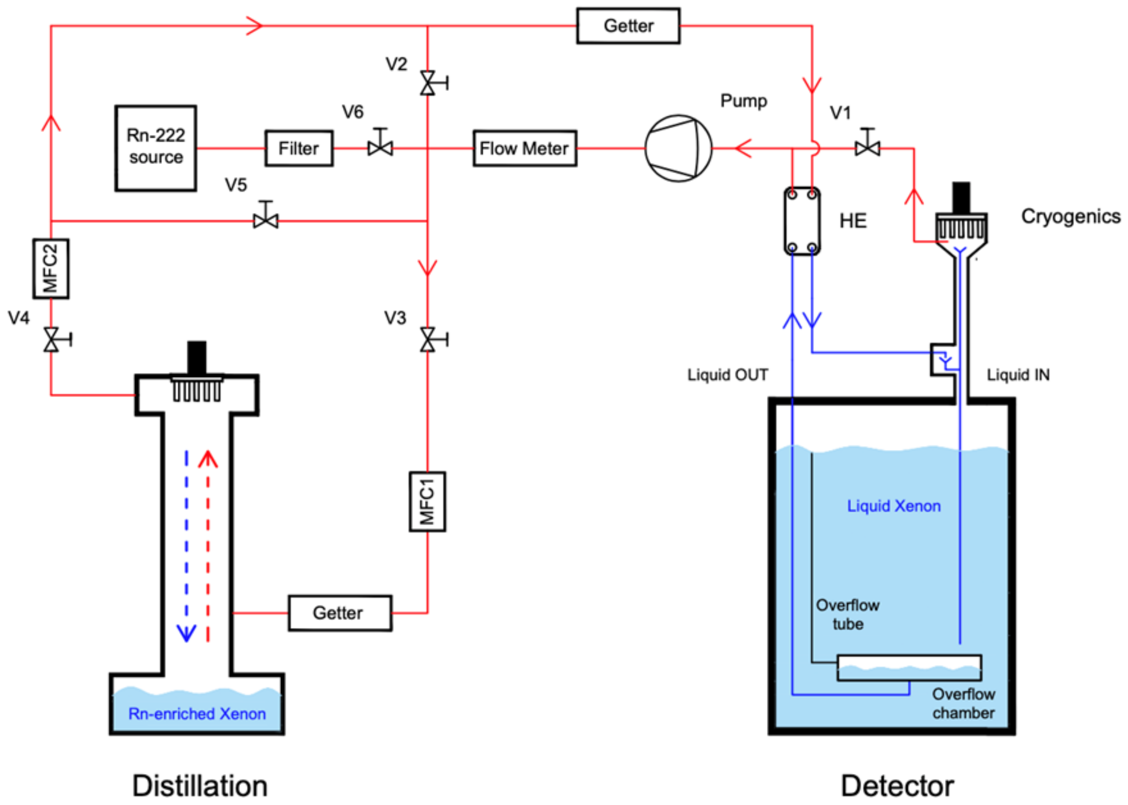


Diagram of the distillation tower and detector,
2024 JINST 19 P07010
2021 JINST 16 P07046

Surface treatment

- Mutiple methods are used to remove the surface radioactivities (^{210}Po, ^{210}Pb etc), dust, oils and oxides for different materials.

Material	Treatment	Reagent
copper	pickling and passivation	sulfuric acid+hydrogen peroxide, citric acid
	degrease	Alconox
stainless steel	ion gun blowing	-
	ultrasonic cleaning	Alconox, ultrapure water
teflon	ion gun blowing	-
	ultrasonic cleaning	alcohol, acetone, ultrapure water
	acid soaking	HNO_3
peek	ion gun blowing	
	ultrasonic cleaning	ultrapure water

PandaX-4T surface treatment methods

Before(left) and after(right) pickling and passivation copper

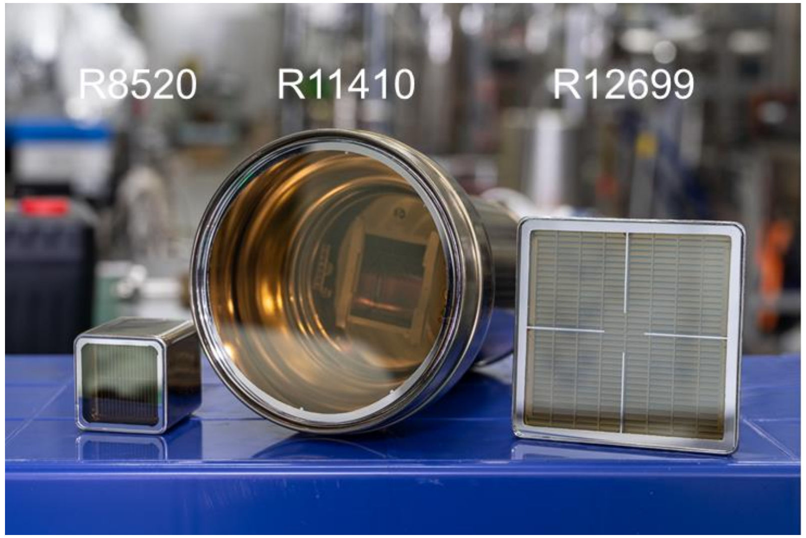
Measurement	1	2	3
Dissolved mass[%]	0.20	0.21	0.24
Removal efficiency[%]	80.80±4.06	73.56±6.24	83.78±3.08

Copper surface ^{210}Po removal efficiency through pickling and passivation JHEP 06 (2022) 147

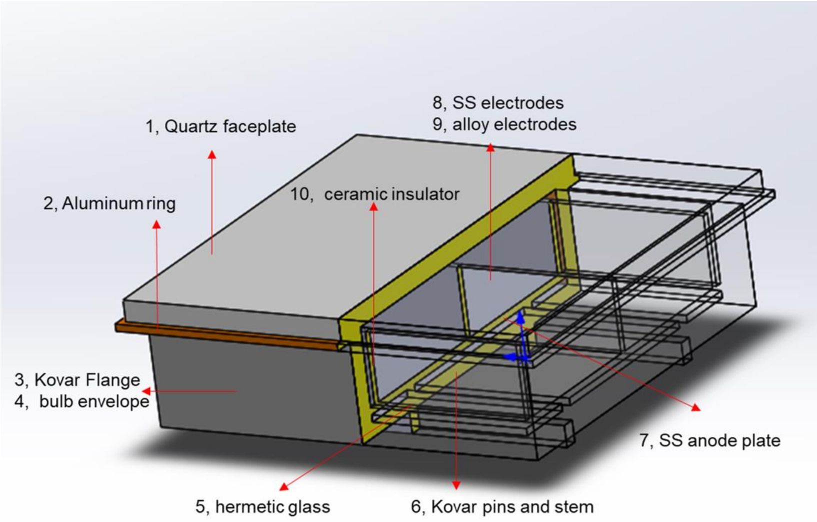
A low-background PMT for PandaX-xT

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

PMT characteristics



PMT used in three generations of PandaX

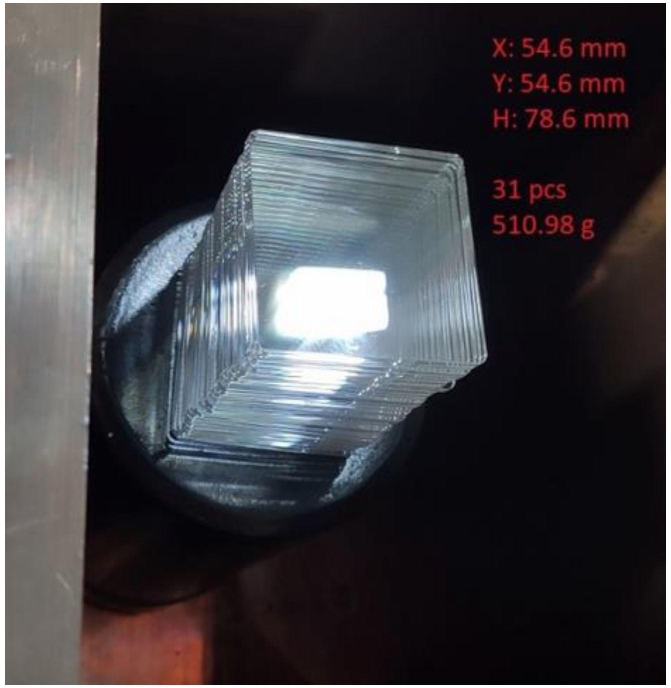


PMT R12699 Structure

- A new 2-inch low-background R12699 PMT for next generation LXe detectors: PandaX and Hamamatsu
  - 2x2 individual anodes
  - Operation at low temperatures down to -110°C
  - High quantum efficiency (>30 %) at 175 nm
  - Fast time response
  - Low background
  - ……

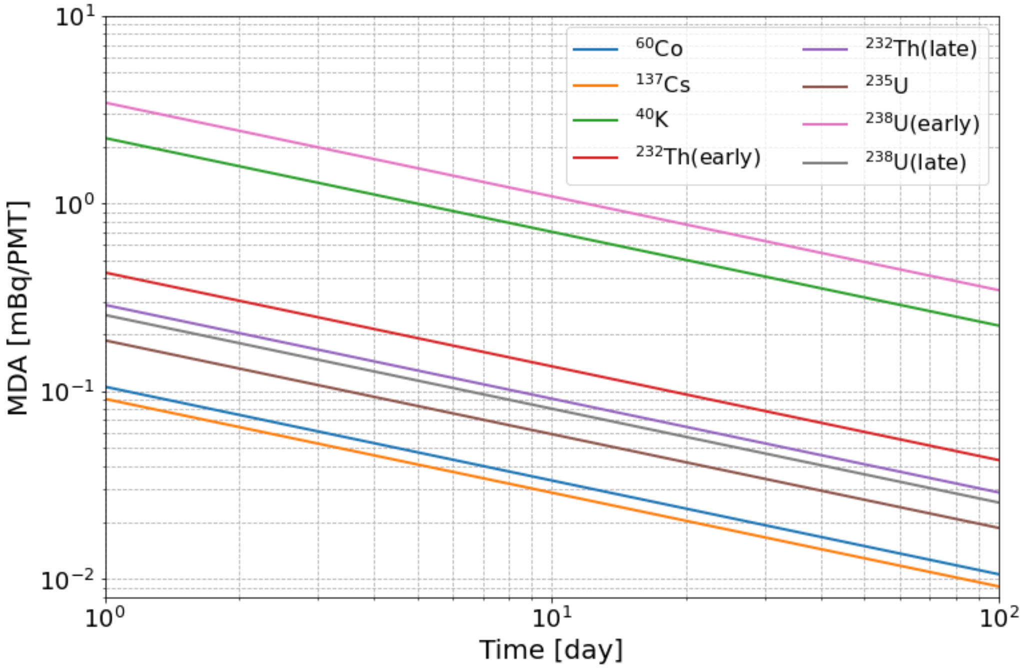
Radioactivity improvement

- The radioactivity of all material (aluminum, kovar, stainless steel, multiple glasses, alloy, ceramic, etc) are assayed with JP1 HPGe counting station.
- PMT radioactivities are measured to confirm batch by batch.



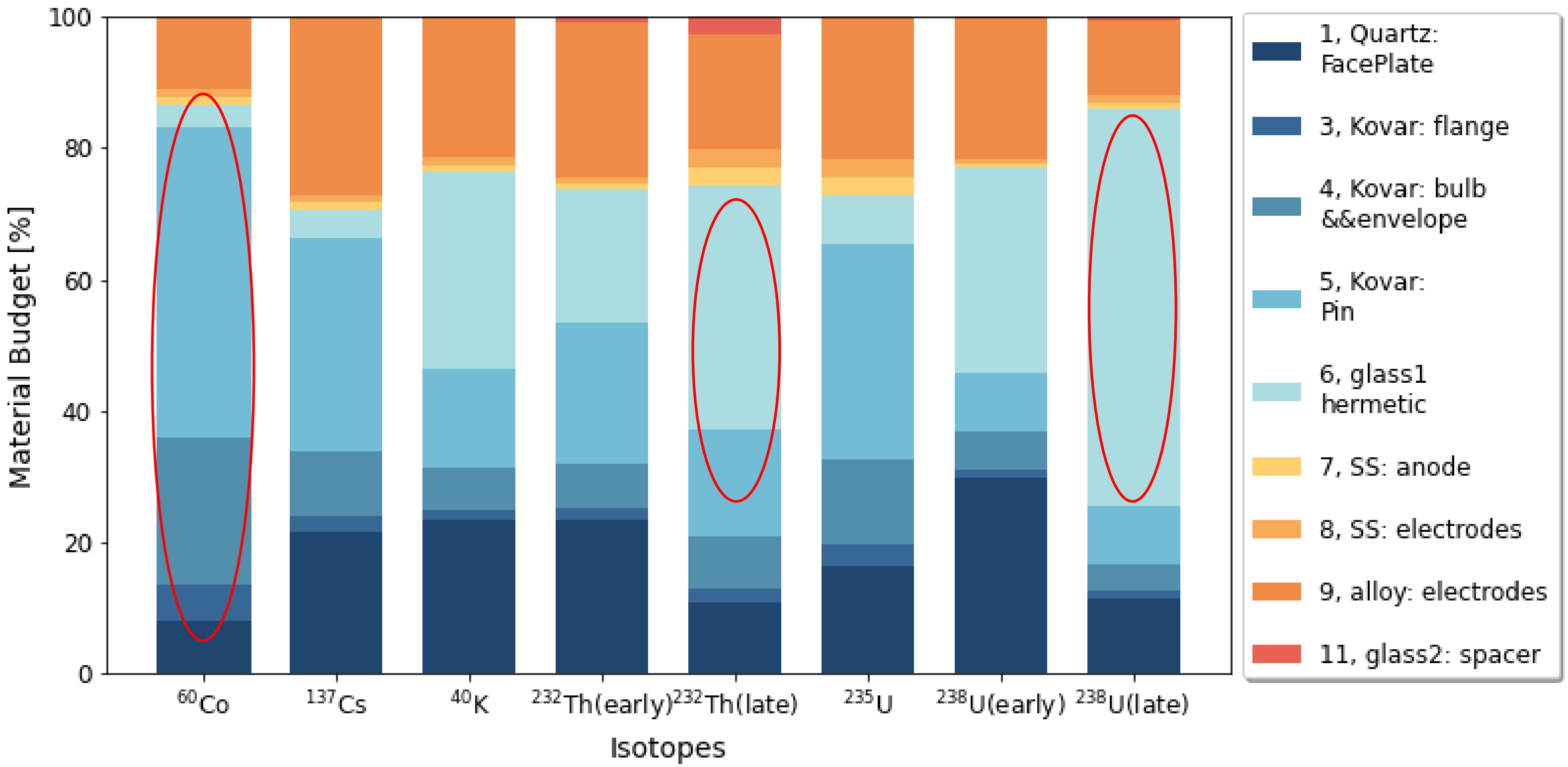
Quartz Screening


PMT Screening



MDA for PMT counting

Radioactivity improvement



v0 material measurement result

Material	^{60}Co[mBq/kg]
Kovar	11.3±1.45
Replaced alloy	<0.87

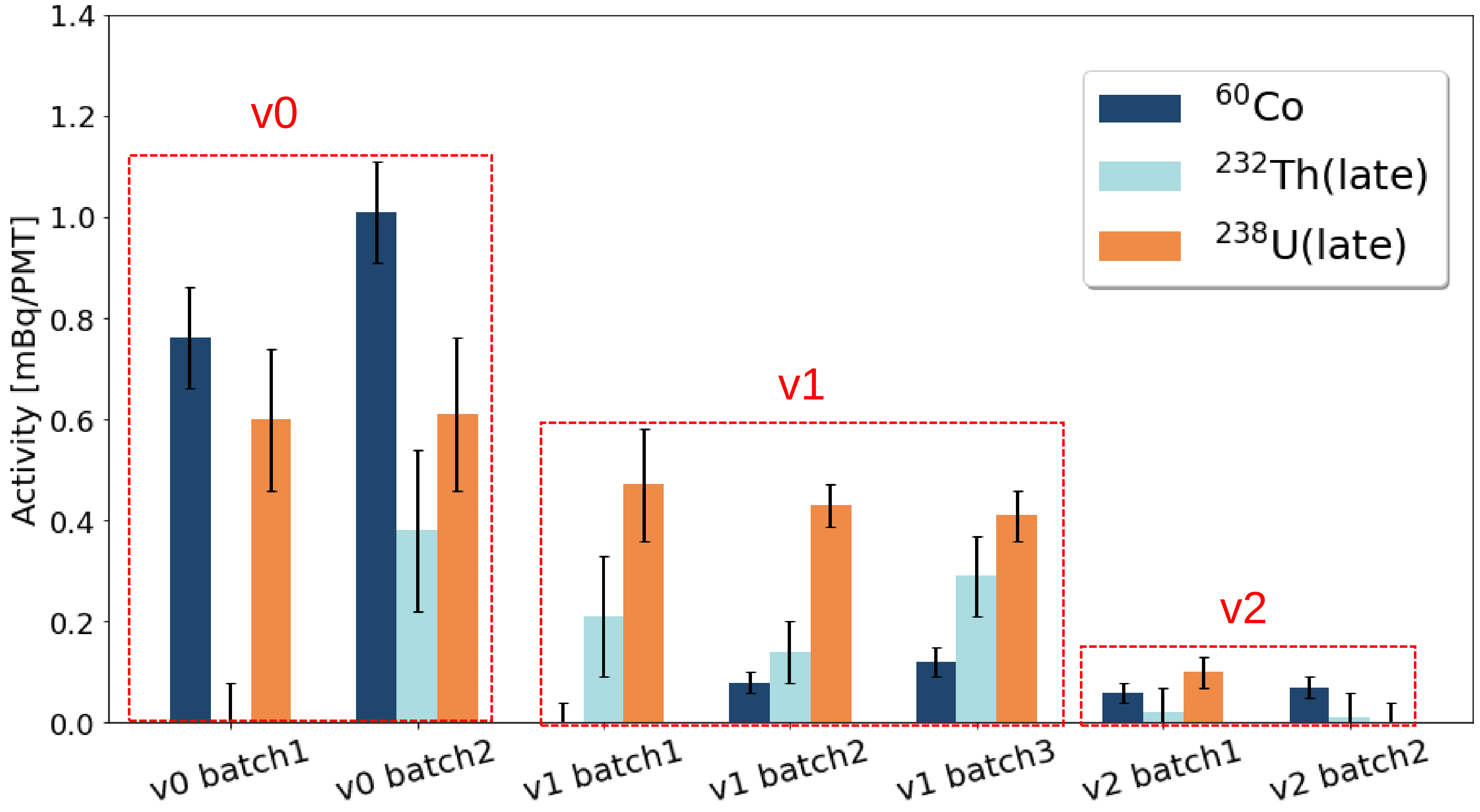
Material	^{232}Th(late) [mBq/kg]	^{238}U(late) [mBq/kg]
glass	1379±51	1518±48
Replaced glass	<78	95±21

Replaced materials

- ^{60}Co mainly from Kovar flange, pins etc and ^{238}U(late) mainly from hermetic glass.
- The kovar are replaced to get version 1 and both replaced to get version 2

Radioactivity improvement

- Mutiple batches of R12699s are measured to confirm the ^{60}Co radioactivity reduction from v0 to v1 and ^{238}U(late) reduction from v1 to v2.



PMT screening result

PMT&SiPM radioactivity comparsion

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

PMT&SiPM Comparsion

PMT (mBq/cm^2)	^{60}Co	^{137}Cs	^{40}K	^{232}Th(e)	^{232}Th(l)	^{235}U	^{238}U(e)	^{238}U(l)
R11410-10 (LZ)[1]	0.059(6)	-	0.38(3)	0.043(25)	0.025(6)	0.025(19)	0.15(7)	0.028(6)
R11410-20 (XENONnT)[2]	0.033(1)	<0.004	0.44(2)	0.015(2)	0.014(1)	0.012(3)	0.28(6)	0.015(2)
R11410-23 (PandaX-4T)[3]	<0.073	<0.057	<0.69	<0.24	<0.095	<0.88	<1.75	<0.12
R12699 (v2)	0.003(1)	<0.003	1.58(10)	<0.011	<0.003	<0.013	<0.054	0.004(1)
R13111 (XMASS)[4]	0.003(1)	-	0.052(13)	0.005(2)	-	-	<0.036	0.011(2)

SiPM (μBq/cm^2)	^{60}Co	^{137}Cs	^{40}K	^{232}Th(e)	^{232}Th(l)	^{235}U	^{238}U(e)	^{238}U(l)
S13371 Hamamatsu[5]	-	-	<26	<9.2	<6.6	-	<908	<7.5
FBK[6]	-	-	~3e-3	~6e-4	-	-	<4e-4	-
MPPC Hamamatsu[6]	-	-	<3	<3	-	-	<7	-
SiPM SensL[7]	<3.3	<3.6	<60	<33.3	<7.8	<6.9	<1139	<8.9

- R12699 PMT radioactivities
  - ^{60}Co: 1 order of magnitude better than LZ/XENON, comparable to XMASS
  - ^{238}U(late): 3-7 times better than LZ/XENON/XMASS
  - ^{60}Co and ^{238}U levels similar to SiPM

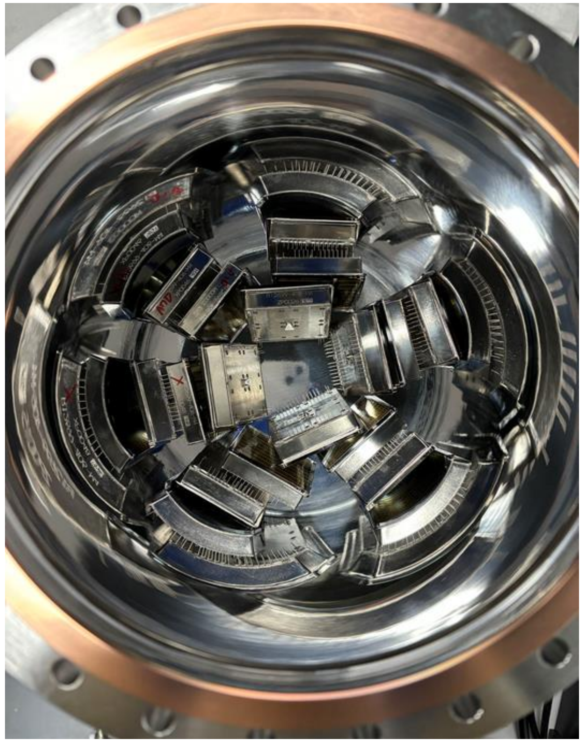
[1]: Eur. Phys. J. C 80 (11) (2020) 1044.
[2]: Eur.Phys.J.C 82 (2022) 7, 599
[3]: JHEP06(2022)147
[4]: J. Phys. Conf. Ser. 1468 (2020) 012231.196
[5]: Journal of Instrumentation 13 (2018) P10022
[6]: SiPM R&D for NEXO, 2019.
[7]: Journal of Instrumentation 10 (2014) .201

Radon Emanation Rate

- The radon emanation rate of multiple batches of R12699 was screened.

Type	Radon Emanationm
R11410 (LZ)[1]	$1.9^{+1.7}_{-1.9}$ mBq/pc
R11410 (XENON-nT)[2]	2 ± 1 μBq/pc
R12699 v2 batch1	<3.0 μBq/pc
R12699 v2 batch2	<3.3 μBq/pc
R12699 v2 batch3	<2.1 μBq/pc

PMT radon emanation rate



R12699 measurement

[1] Eur. Phys. J. C 80 (11) (2020) 1044
[2] Eur.Phys.J.C 82 (2022) 7, 599

Summary

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

- **Background screening and control for PandaX-4T**
  - Mutiple radioassay programs support the measurements
  - Remove radon and krypton using distillation
  - Control surface contamination by the surface treatment
- **A new 2-inch low-background PMT has been developed to the community**
  - After replacement of materials, its ^{60}Co ~ 0.06 mBq/PMT and ^{238}U(late) ~ 0.1 mBq/PMT
  - A promising option for the next generation rare event search experiment

Thanks!

PANDA X

PARTICLE AND ASTROPHYSICAL XENON TPC

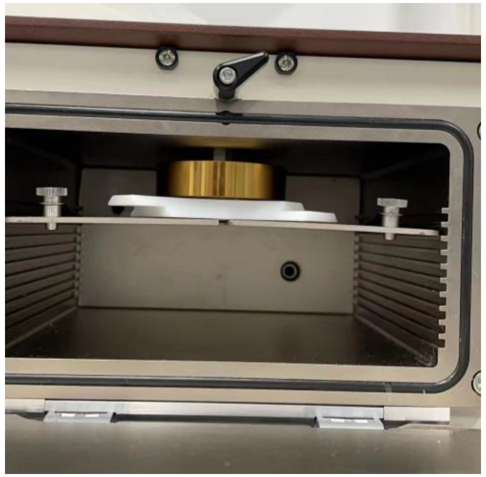
Back Up

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

Radon emanation system

Serial Number	Chamber Type	Polishing	Volume[L]	Location	Blank [mBq]
0	counting	Mechanical+ mirror+electr ochemical	7.4	SJTU	0.07±0.03
1	counting	Mechanical+ mirror	12.9	SJTU	0.28±0.02
2	emanation	Mechanical+ mirror	12.9	SJTU	2.05±0.37
3	emanation	Mechanical+ mirror	12.9	SJTU	0.99±0.24
4	emanation	Mechanical+ mirror	12.9	SJTU	1.49±0.29
5	emanation	Mechanical+ mirror	12.9	JP	1.62±0.29
6	counting	Mechanical+ mirror	12.9	JP	0.034±0.009

Alpha Measurement



- Quartz sample
- Cleaning procedure: wipe with alcohol 3 times

	Before pollution	After pollution	Clean 1st	Clean 2nd
Rate [mHz]	0.40±0.16	8.53±1.00	1.00±0.29	**0.51± 0.18**

- PTFE sample

Cleaning procedure	None	35% HNO_3 for 3 days	35% HNO_3 for 8 days
Rate [mHz/mm2]	<7.22e-04	<1.57e-05	< 2.45e-05
Supposed Po-210 rate in TPC [mHz]	< 3266	< 71	< 111

Consistent with data

- Assume ROI [1,10] keV

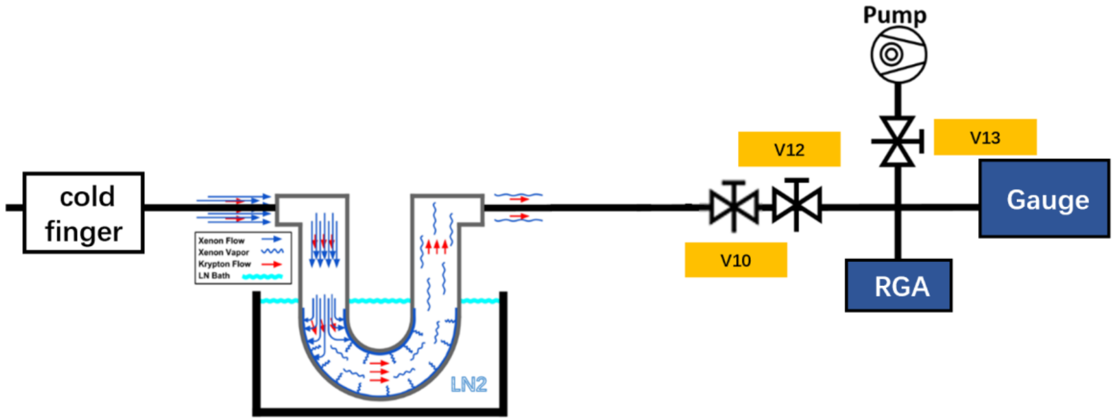
	Surface neutron	Total neutron
MC Rate [mDRU]	6e-5	2.8e-4

Surface treatment for copper

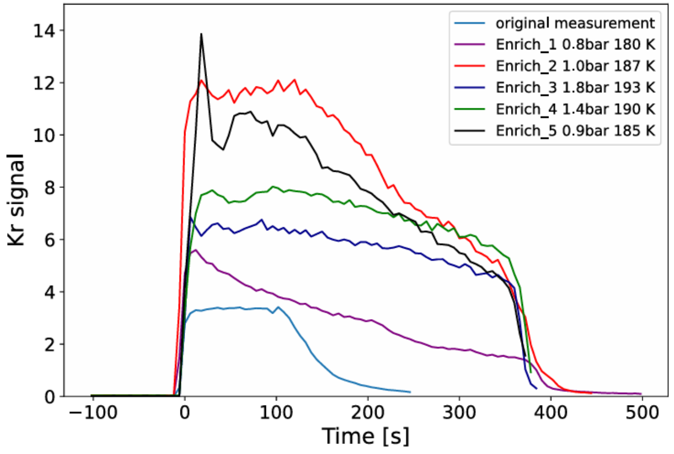
➢ Investigate radon daughter Po-210 removal method from copper surface

Pickling solution	Dissolved mass [%]	Count rate pre cleaning [mHz]	Count rate post cleaning [mHz]	Removal efficiency [%]
$1\%H_2SO_4+3\%H_2O_2$	0.20	13.5±0.4	2.6±0.2	80.8±4.1
	0.21	5.4±0.3	1.4±0.1	73.6±6.2
	0.24	22.7±0.5	3.8±0.2	83.7±3.1
$15\%HNO_3+2\%H_2O_2$	0.16	20.4±0.5	17.5±0.5	14.2±3.3
	0.21	11.4±0.4	9.9±0.3	13.5±4.2
	0.22	11.6±0.4	9.5±0.3	18.0±4.3
$5\%C_6H_8O_7+8\%H_2O_2$	0.19	13.0±0.4	0.03±0.03	99.8±4.3
	0.19	12.9±0.4	0.00±0.02	100.0±3.9
	0.20	15.5±0.4	0.00±0.02	100.0±3.9

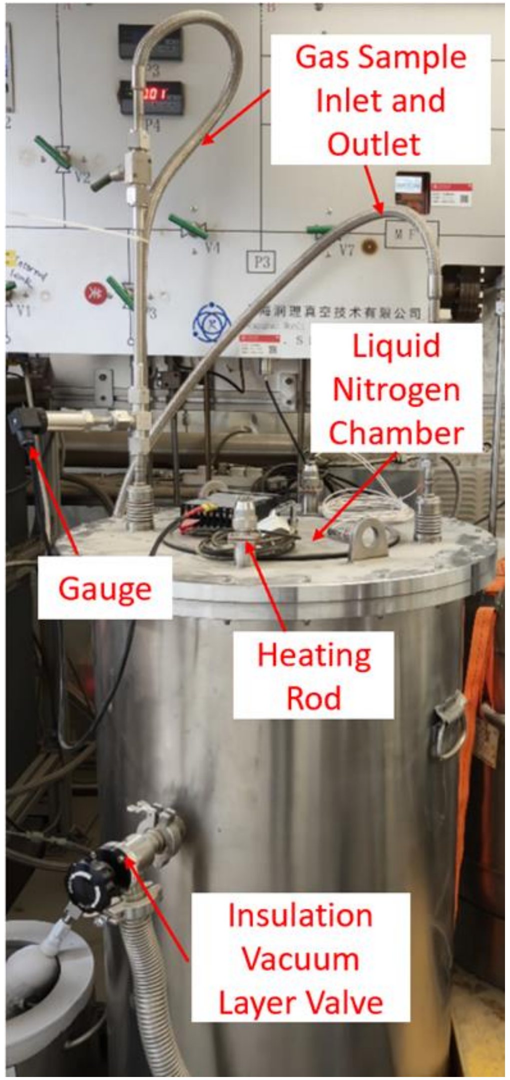
Krypton assay station



Schematics of krypton assay station



Enrich signal

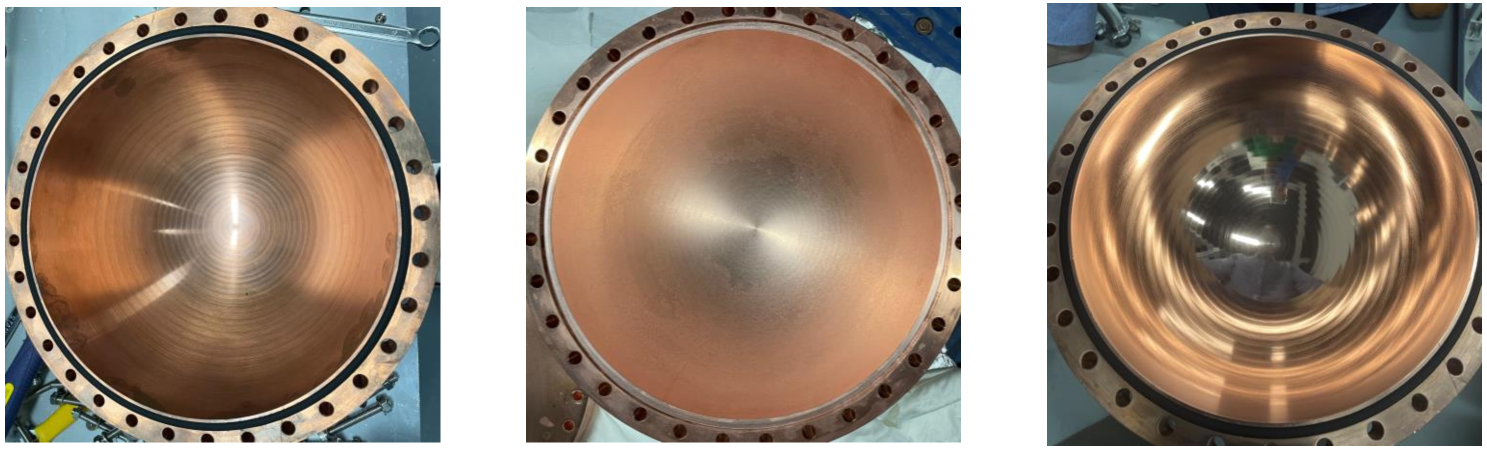


Enrichment structure

Radon emanation systems

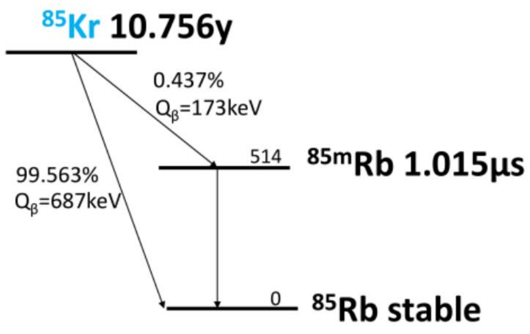
- Hemisphere copper chamber with 4.93 L volume

Polishing method	Mechanical polishing	Pickling and passivation	Mirror polishing
Roughness [um]	-	0.12	0.087±0.058
Efficiency [%]		27.8±0.5	
^{238}U Intrinsic [mBq/kg]		<0.0019	
Blank [mBq]	0.54±0.09	0.68±0.06	0.32±0.04
Blank [uBq/cm^2]	0.35±0.06	0.44±0.04	0.21±0.02



Surface of emanation chambers using different polishing method
(left: mechanical, middle: pickling and passivation, right: mirror)

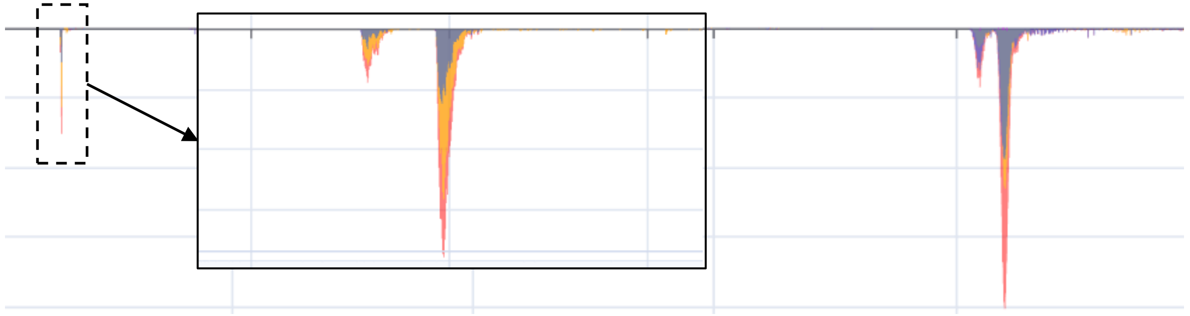
^{85}Kr estimation



Energy level of ^{85}Kr decay

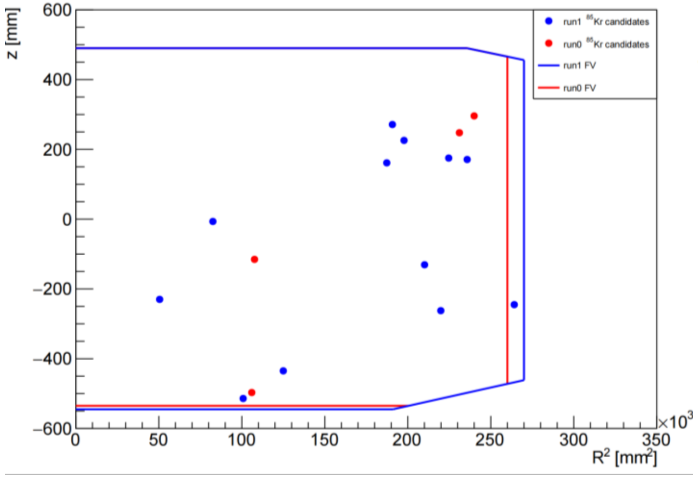
β energy cut	[20, 200] keV
γ energy cut	[314, 714] keV
Coincidence time cut	[0.3, 3] us

Selection cuts of β-γ coincidence

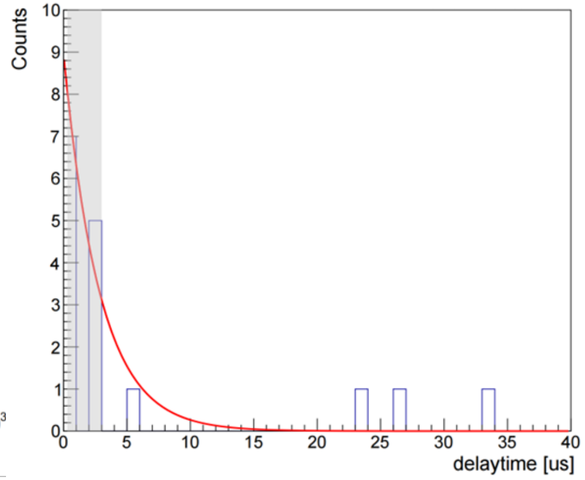


Waveform of ^{85}Kr's β-γ coincidence

- Estimate based on a correlated emission of β-γ coincidence
- Kr/Xe
  0.51±0.26 ppt for run0
  0.92±0.27 ppt for run1



Vertex distribution of β-γ candidates

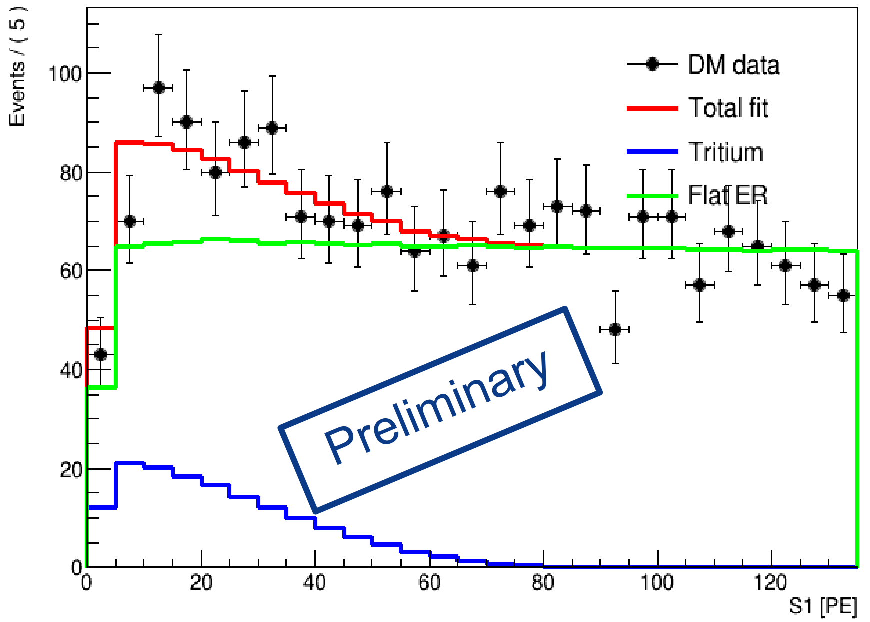


Time separation between β-γ

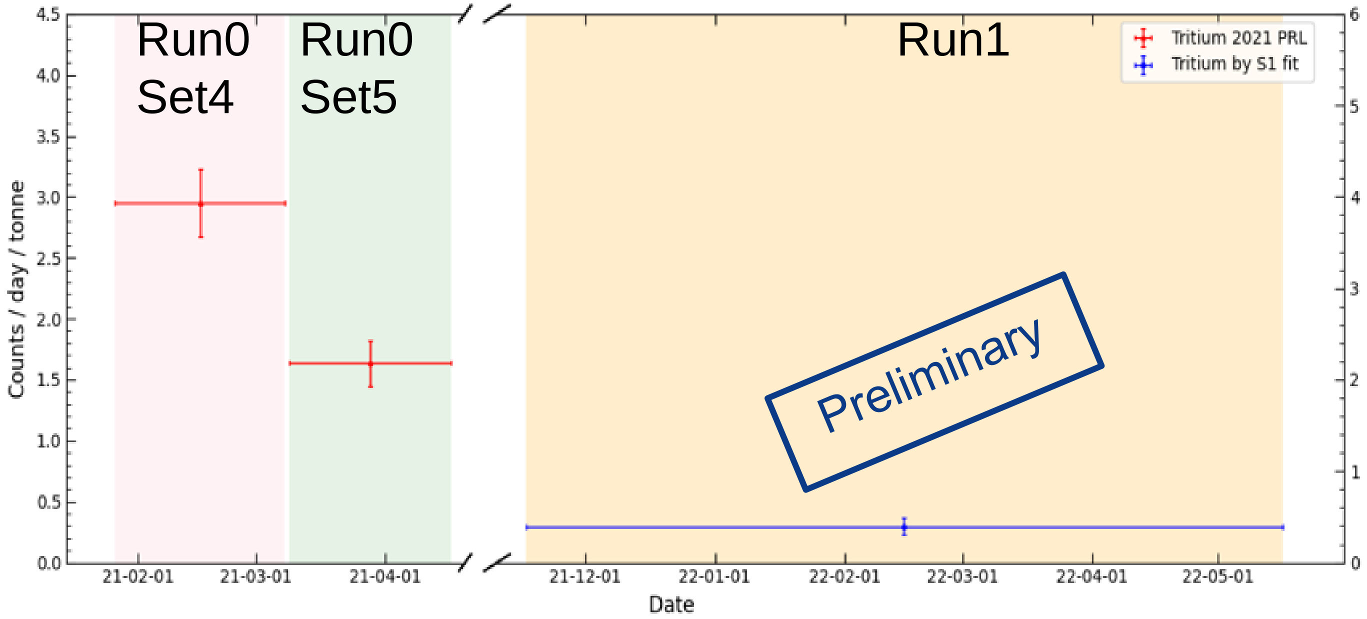
Tritium

- Fitting on S1, keep S2 blinded (getter+flush+pump+ distillation)

Data set	Run0 Set 4	Run0 Set 5	Run1
Tritium (event/day/tonne)	3.0 ± 0.3	1.6 ± 0.2	0.4 ± 0.1



Fitting of energy spectrum

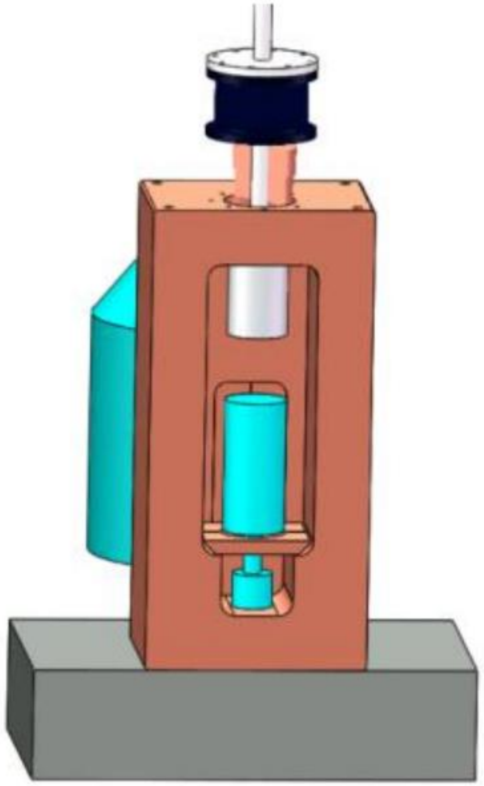


Evolution of tritium concentration

HPGe upgrade: further improving the MDA

- Gamma spectroscopy system with dual HPGe detectors for improved detecting efficiency and coincidence analysis
- Expected MDA of the GS-DHPGe for the plastic sample (diameter: 5 cm, height: 1 cm) with 10 days counting time

Isotope	JP1 MDA / $mBq \cdot kg^{-1}$	Expect MDA / $mBq \cdot kg^{-1}$	Improved factor
^{60}Co	11.93	6.50	1.84
^{137}Cs	11.84	4.81	2.46
^{40}K	267.11	92.99	2.87
^{232}Th-early	55.54	27.51	2.02
^{232}Th-late	32.24	14.02	2.30
^{235}U	38.11	11.57	3.30
^{238}U-early	291.38	123.31	2.36
^{238}U-late	28.94	11.51	2.51

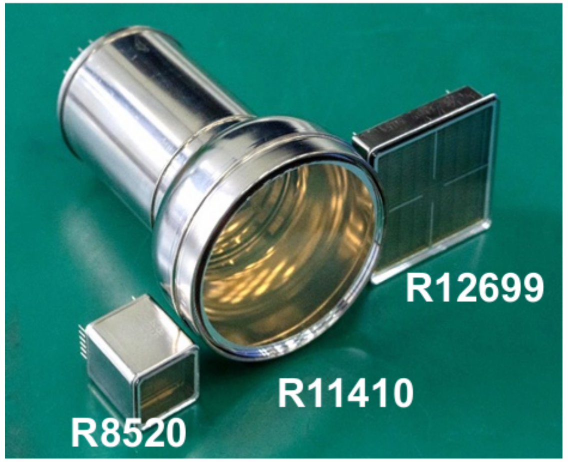


Dual High-Purity Germanium Detectors

- MDA for coincidence setup for the GS-DHPGe [mBq] for the sample (diameter: 1 mm, height: 1mm) with 10 days counting time

Isotope	Single HPGe	non $\gamma-\gamma$ coincidence of GS-DHPGe	$\gamma-\gamma$ coincidence of GS-DHPGe
^{60}Co	0.18	0.10	0.03
^{208}Tl	0.44	0.19	0.08
^{214}Bi	0.73	0.29	0.28

PMT Characteristics



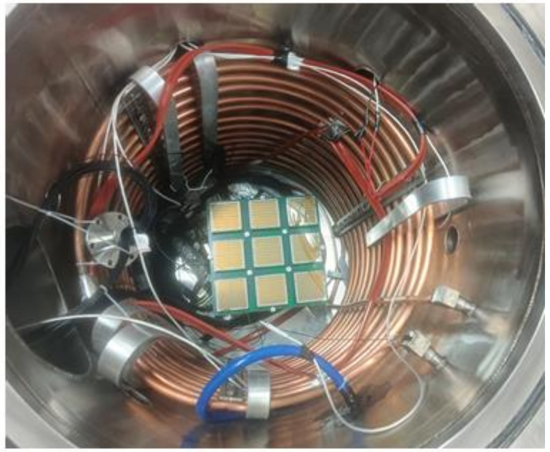
Characteristics at 25 deg C

Parameter		R12699-406-M4	R11410-20	Unit
Cathode Sensitivity	Luminous (2856K)	**95**	**90**	uA/lm
	Blue Sensitivity Index	**10.0**	**10**	-
Anode Sensitivity	Luminous (2856K)	**140**	**315**	A/lm
Gain		**1.5×10^6**	**3.5×10^6**	-
Anode Dark Current (Each anode) (after 30min. storage in darkness)		**1.5**	**10**	nA
Time Response	Rise Time	**1.2**	**5.5**	ns
	Transit Time	**5.9**	**46**	ns
	Transit Time Spread (FWHM)	**0.41**	**9**	ns
Uniformity Between Each Anode		**1:1.5**	**-**	-
Pulse Linearity (Each Anode)	at ±2% Deviation	**8**	**20**	mA
	at ±5% Deviation	**20**	**-**	mA

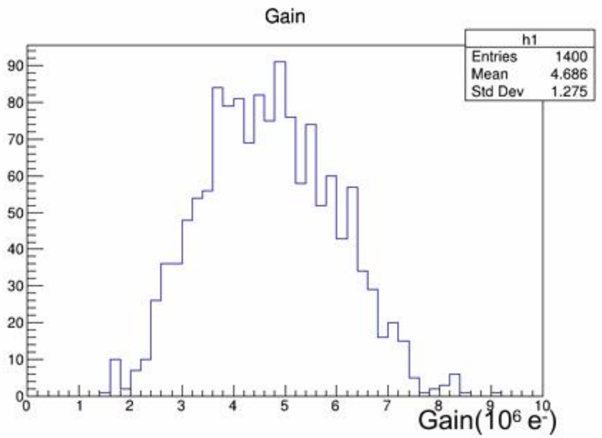
PMT Characteristics

Warm and cold temperature test:

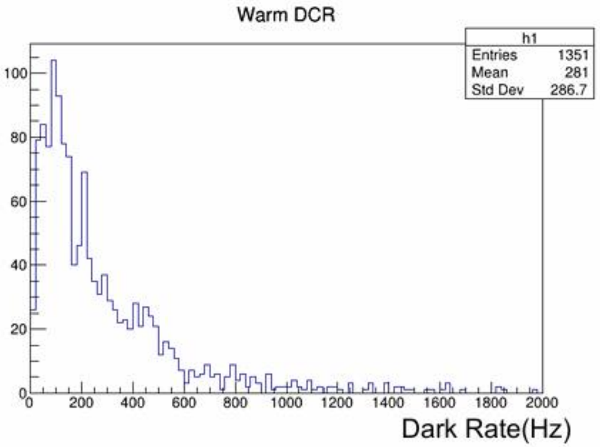
- Temperature: 25 deg C and -100 deg C
- Gain of each channel is about 5×10^{6} e^{-} with 1000 V
- Dark rate at -100℃ is about 10 Hz per channel
- After-pulse: <1%



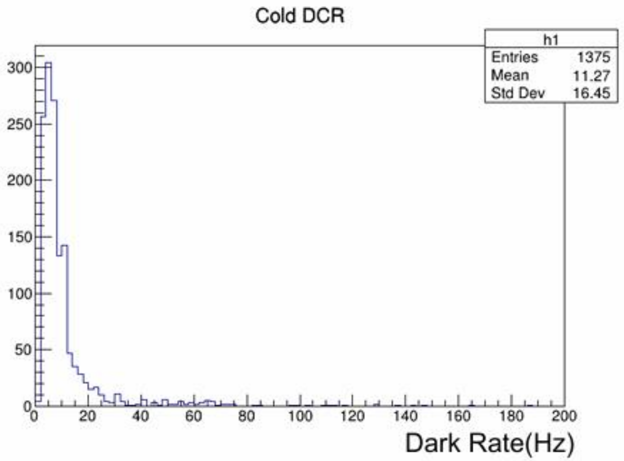
Setup for the cold test



Gain



Dark rate at room temperature



Dark rate at cold temperature