ALETHEIA: Hunting for low-mass dark matter with liquid helium TPCs

The XIX International Conference on Topics in Astroparticle and Underground Physics (TAUP 2025)

Junhui LIAO
China Institute of Atomic Energy

Outline

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- ALETHEIA: A Liquid hElium Time projection cHambEr In dArk matter.

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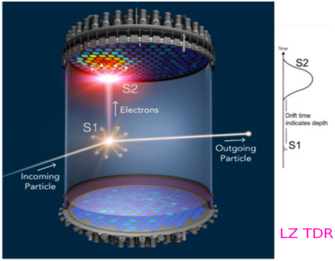

LZ TDR

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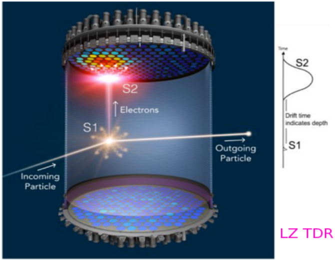

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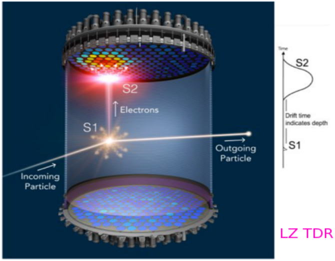
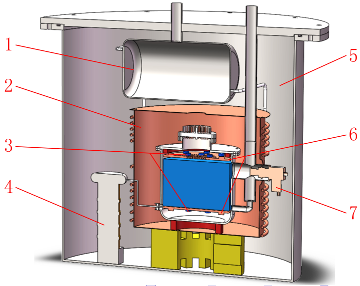


LZ TDR



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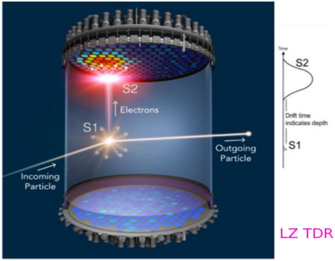
- For details: Eur. Phys. J. Plus (2023) 138:128.



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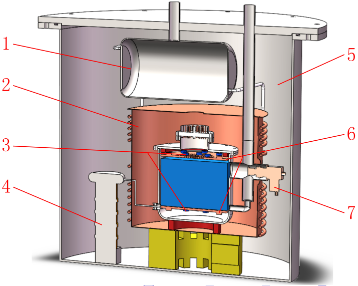
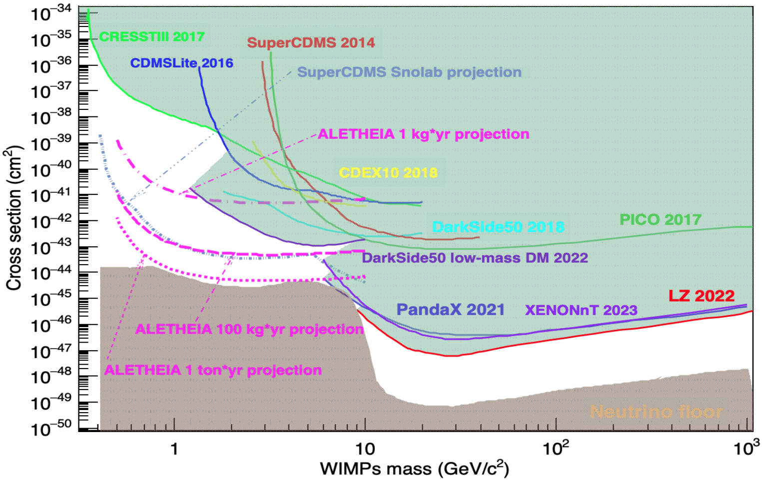


ALETHEIA NR channel: Projected sensitivities

- 1 ton*yr ALETHEIA can "touch down" the ^{8}B solar ν fog (Assuming IBF, 50% Eff.).



ALETHEIA review, Oct 2019.

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- *"It is possible that liquid helium could enable especially low backgrounds because of its powerful combination of intrinsically low radioactivity, ease of purification, and charge/light discrimination capability."*

ALETHEIA collaborators so far

5 institutions (at present), ~ 20 members

- CIAE (China Institute of Atomic Energy), ~ 10 researchers.
- FBK (not officially, but already cooperated in SiPMs related researches for 3+ years).
- Peking University, 1 + 2 (?) researchers.
- SCRI (Shanghai Cable Research Institute), 3 researchers.
- University of South China, 1 + N (?) researchers.

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   - ALETHEIA prototype detector R&D on the 30g-V1 LHe
   - TPB coating on a PTFE chamber
   - SiPMs tests near LHe temperature.
   - A novel NR calibration on LHe detectors
   - Ongoing tests at CIAE
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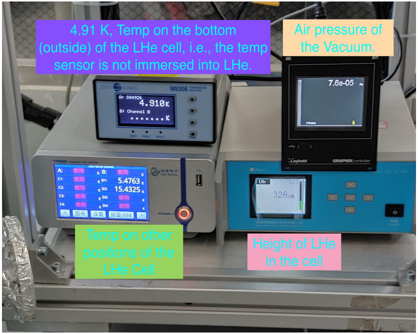
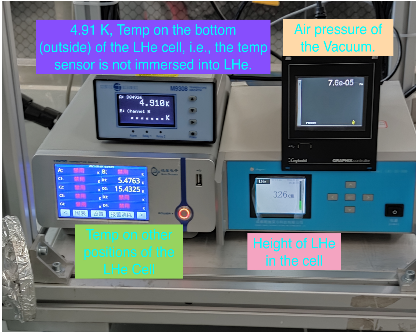
The R&D of the 30g-V1 LHe prototype.

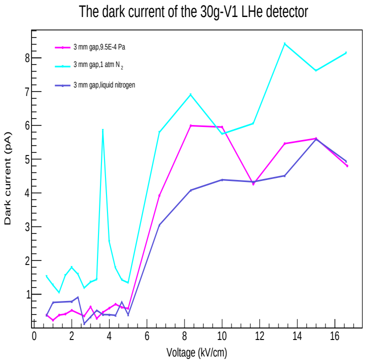
- Left picture: the detector successfully cooled to 4 K.



The R&D of the 30g-V1 LHe prototype.

- Left picture: the detector successfully cooled to 4 K.
- Right plot: dark current is less than 10 pA under several circumstances.





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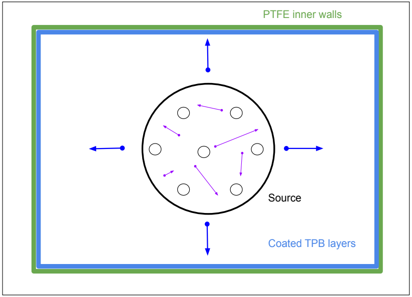
LHe light peaked 80 nm, TPB to convert into visible light.

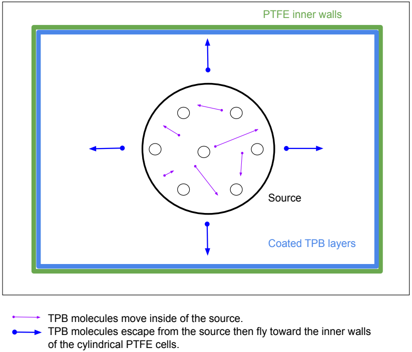
- Left picture: the principle of TPB coating.

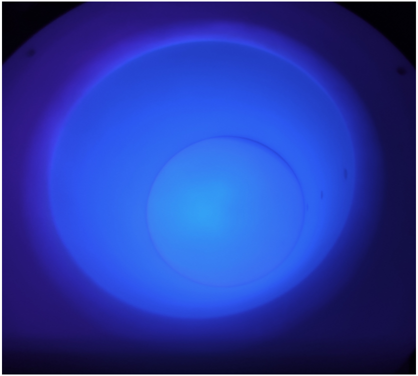


TPB molecules move inside of the source.
TPB molecules escape from the source then fly toward the inner walls of the cylindrical PTFE cells.

LHe light peaked 80 nm, TPB to convert into visible light.

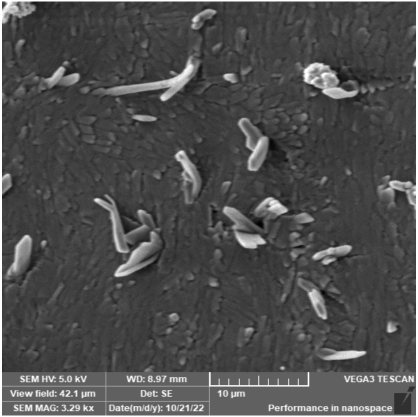
- Left picture: the principle of TPB coating.
- Right plot: top view of the coated 10-cm size PTFE chamber.
- Published: Acta Phys. Sin. Vol. 71, No. 22 (2022) 229501





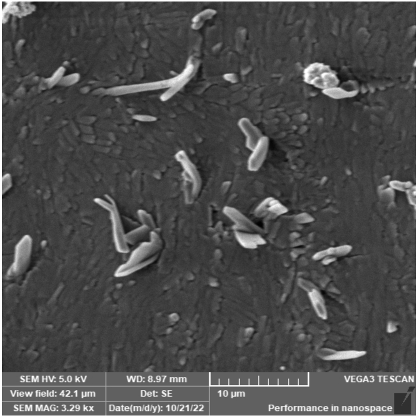
TPB coating film, exposed at 4 K.

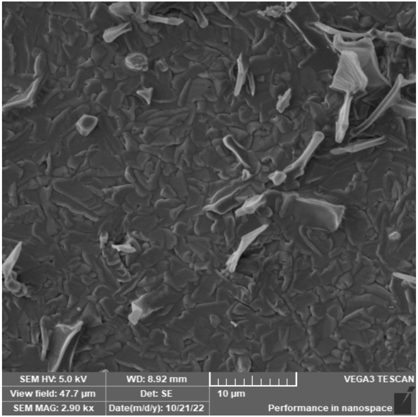
- Left picture: SEM scanning imagine on TPB coated film experienced at 4 K.



TPB coating film, exposed at 4 K.

- Left picture: SEM scanning imagine on TPB coated film experienced at 4 K.
- Right plot: SEM scanning imagine on TPB coated film W/O cryogenic experience.
- Published in JINST, 2022 JINST 17 P12001.





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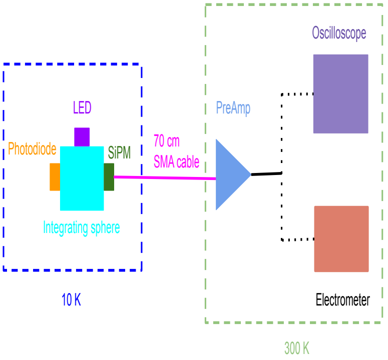
PDE test setup.

- Left picture: Schematic drawing.



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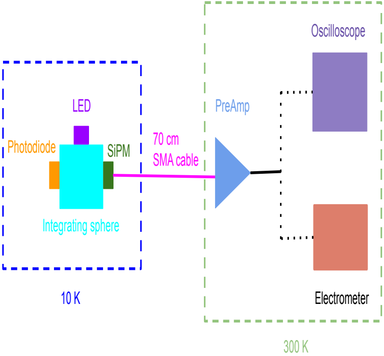

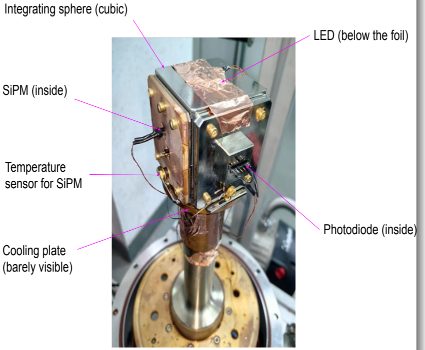

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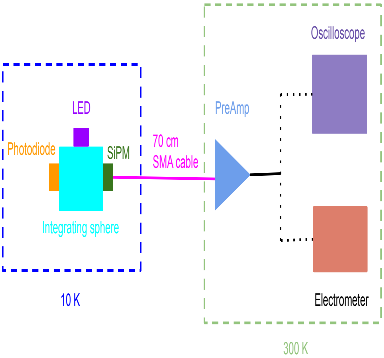
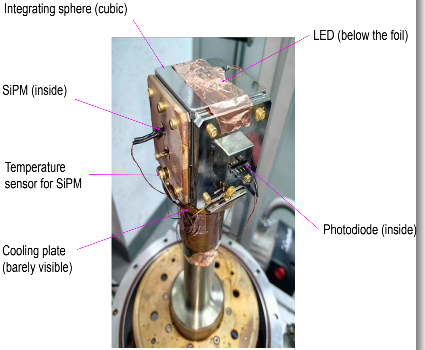
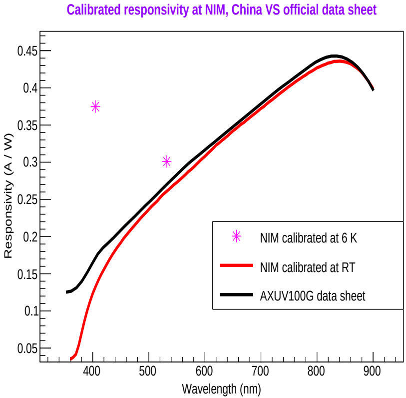
- Paper submitted to NIM(A), arXiv: 2311.10497 (not synchronized to the submission)





Photodiode calibration at 6 K and SiPMs' DCR at 10 K.

- Left picture: Photodiode responsivity calibration at 6 K at the National Institute of Metrology (NIM).



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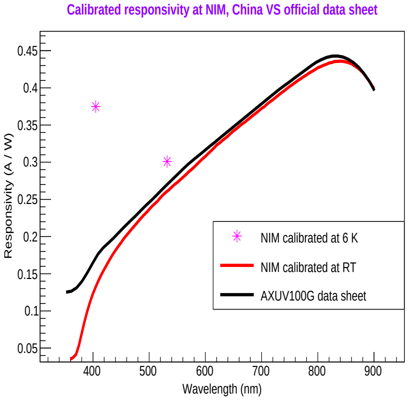
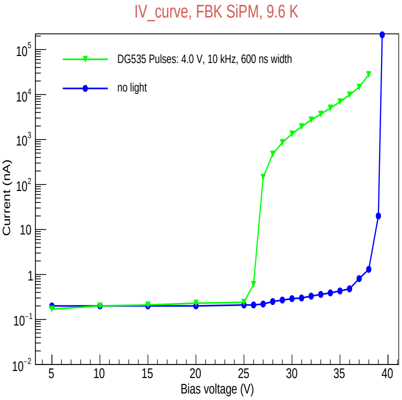
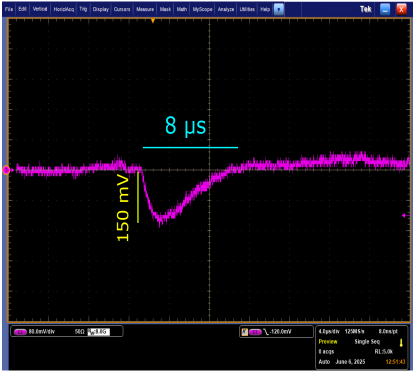
- Right plot: SiPMs I-V curve at 10 K, W and W/O weak light.





SiPMs' raw signals and charge spectrum and its fit at 10 K.

- Left picture: a typical SiPMs raw signal measured at 7 K at CIAE.



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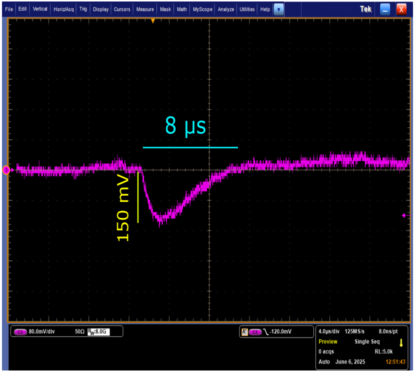
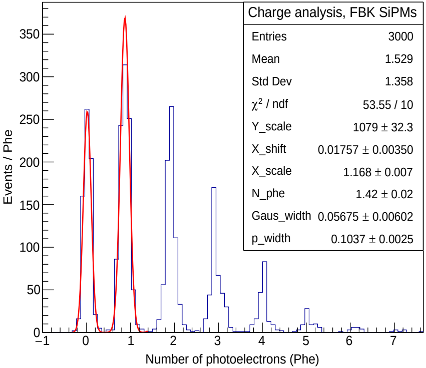
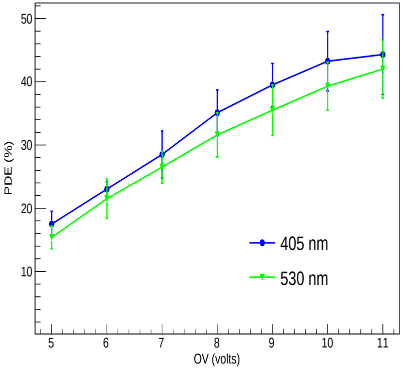
- Right plot: Charge histogram (T = 10 K, OV = 6 V), and Gaussian convoluted Poisson fit.





FBK SiPMs PDE @ 10 K and 7 K, 405 and 530 nm; and AP.

- FBK NUV-HD-Cryo SiPMs, ~ 100 mm^2; Lowest temperature measured.
- Left plot: PDE ≥ 40% at OV 10+ V.



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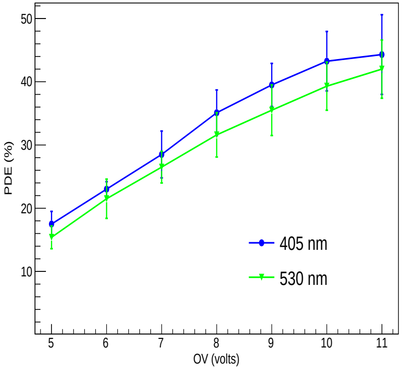
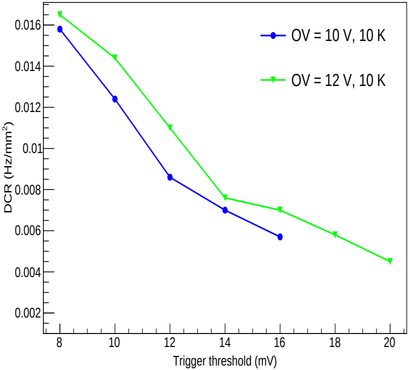
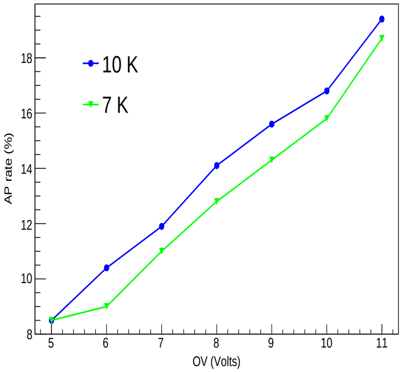
- Right plot: DCR, 0.01 Hz/mm^2 ≊ DCR of Hamamatsu R11410 PMTs in LZ TPC.





AP and CT tests 10 K and 7 K.

- Left picture: AP results.



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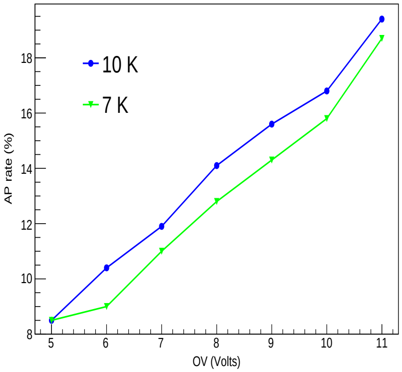
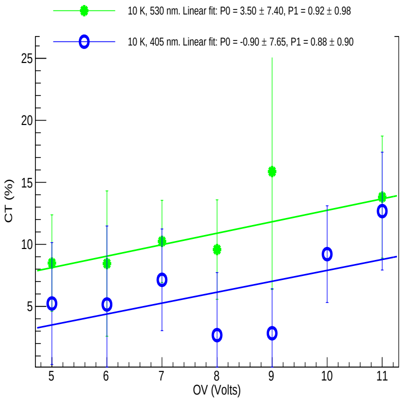
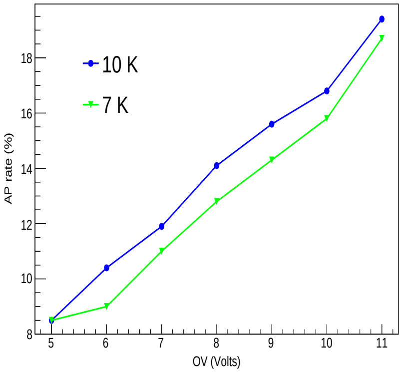
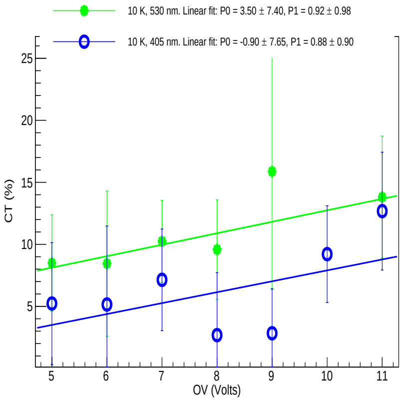




AP and CT tests 10 K and 7 K.

- Left picture: AP results.
- Right plot: CT results
- Both AP and CT consistent with similar version SiPMs tested at 40 K by DS-20k





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Traditional NR calibration: implementing fast neutrons

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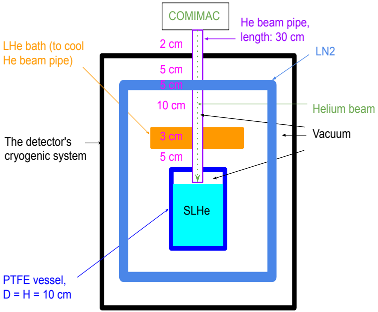

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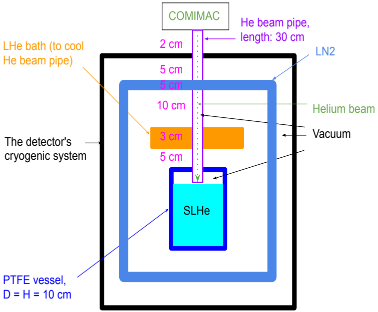
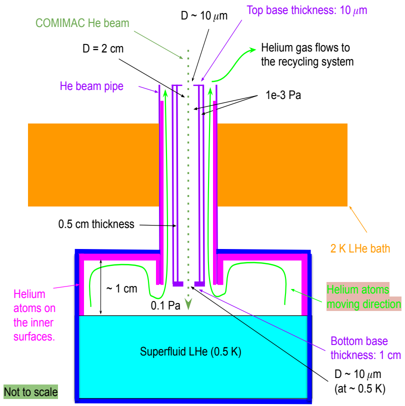
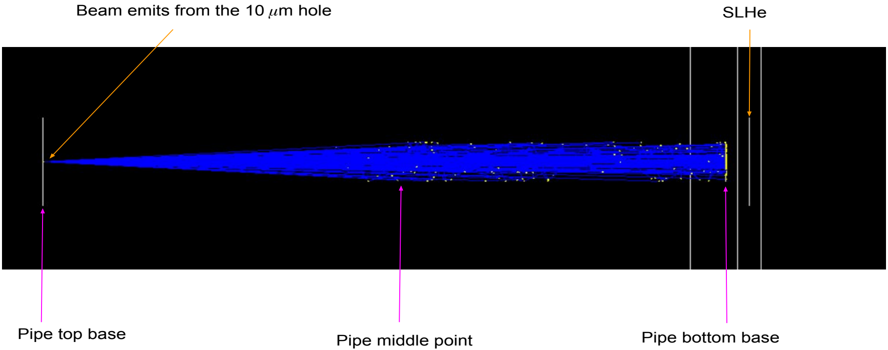




Beam introduction

- G4 simulation shows a typical beam trajectory



Beam energy deposition in the journey before hitting SLHe

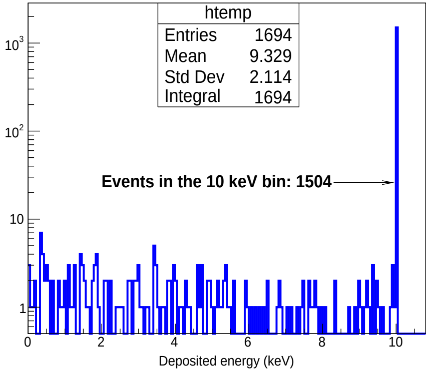
G4 simulation shows beam energy deposition in the journey is ignorable

- ~ 1 / 1000 of beam energy

Medium	**2 keV** α			**10 keV** α			**50 keV** α		
length (cm)	**G4** (keV)	**NIST** (keV)	**SRIM** (keV)	**G4** (keV)	**NIST** (keV)	**SRIM** (keV)	**G4** (keV)	**NIST** (keV)	**SRIM** (keV)
30.0 (1e-3 Pa air)	5.0e-5		9.6e-5	1.2e-4		1.4e-4	2.8e-4		2.6e-4
0.5 (0.1 Pa He_2)	1.7e-3	2.2e-3	2.3e-3	2.5e-3	2.6e-3	2.6e-3	5.2e-5	5.4e-3	5.4e-3
1.0 (0.1 Pa He_2)	3.2e-3	4.3e-3	4.7e-3	5.0e-3	5.2e-3	5.3e-3	1.0e-2	1.1e-2	1.1e-2
2.0 (0.1 Pa He_2)	6.2e-3	8.7e-3	9.3e-3	9.9e-3	1.0e-2	1.1e-2	2.1e-2	2.2e-2	2.2e-2
SLHe	1.6			9.2			50		

The events rate

- Events rate = (α particles in the beam) / (recorded meaningful events) ≅1.5 E-4
- The beam rate can go up to 100 kHz $\Rightarrow$ ~ 10 Hz events rate.
- Paper published, Eur. Phys. J. Plus (2024) 139:437.



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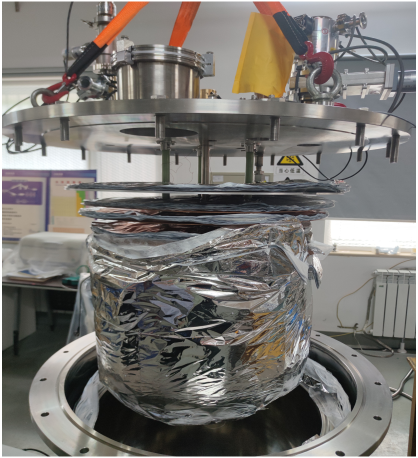
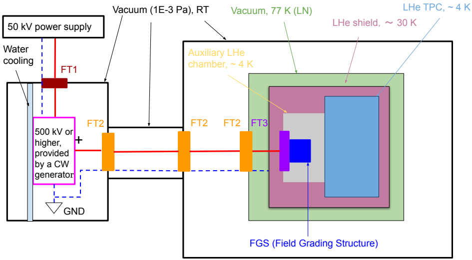


Transmitting ~ MV (Million Volts) into an LHe TPC, 2310.12504

- 10 kV/cm drift field is trade-off to get reasonable drift speed (2 m/s) and fraction of ion-e separation (~50%); 1m size TPC (~ 100 kg LHe) requires 1 MV.



FT1: 50 kV, RT, one side is air, another is vacuum.

FT2: 500 kV or higher, both sides are RT or 77K and vacuum, no need to seal.

FT3: 500 kV or higher, one side is vacuum and ~ 30 K, another is LHe and 4 K, seal vacuum from LHe.

FGS: Immersed in 4 K LHe.

—— : Thin wall tubing (304 SS); - - - - : Grounding cable or cathode.

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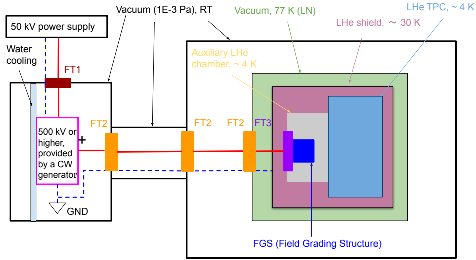
- Left plot: the preliminary scheme. Right plot: an electrode capable of delivering 100 kV is house-made at CIAE. Testing underway.



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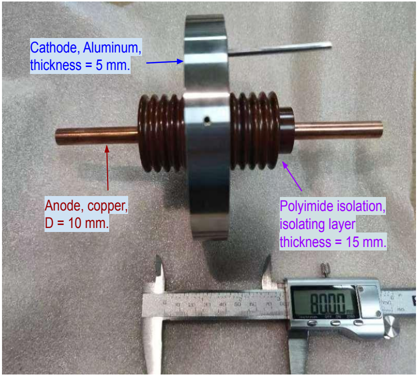

Summary

We demonstrated the viability of a single-phase LHe TPC

- (a) detector assembly,
- (b) wavelength-shifter TPB coating,
- (c) FBK NUV-HD-Cryo SiPMs' performance lines up well with ALETHEIA's requirements near LHe temperature.

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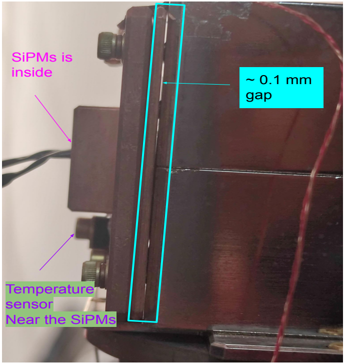
The R&D on a dual-phase LHe TPC is currently underway.

Back up slides

Why we tested two temperatures: 10 K and 7 K

- Invisible 0.1 mm gap existed due to warming-up and cooling-down cycles.



Why we tested two temperatures: 10 K and 7 K

- Invisible 0.1 mm gap existed due to warming-up and cooling-down cycles.
- After filling the gap with an indium film, the temperature decreased from 10 K to 7 K, consistent with COMSOL simulations.