中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

Gd-PMMA

a novel neutron tagging technology for low background detectors

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On behalf of the Gd-PMMA working gourp

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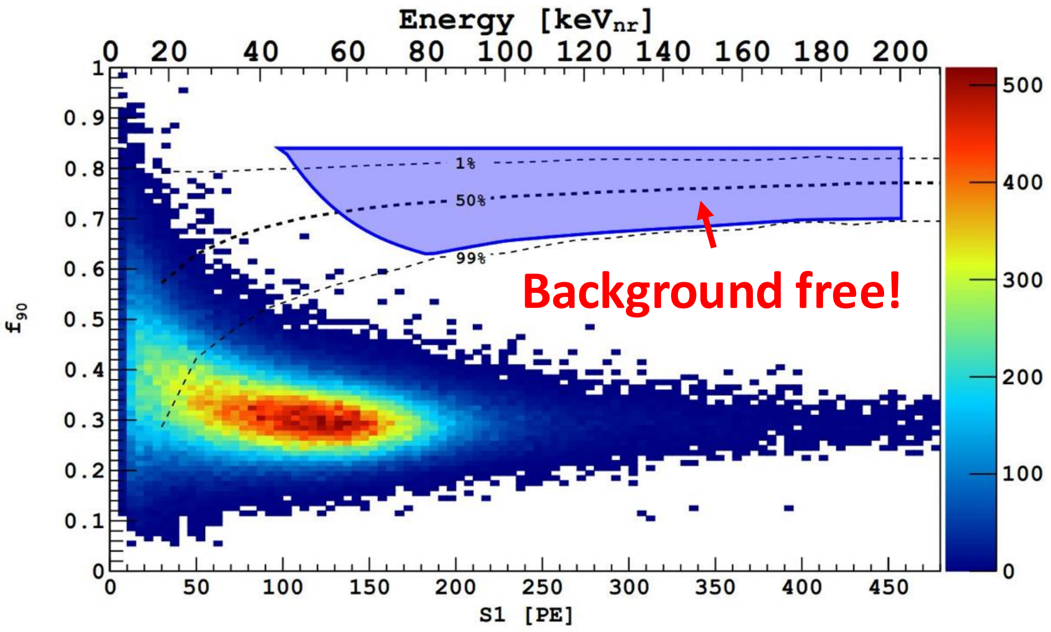
DarkSide-50

- DarkSide-50 has achieved background-free results in the search for WIMPs :
  - S1 Pulse Shape Discrimination (PSD);
  - Water Cherenkov Detector (WCD);
  - Liquid Scintillator Veto (LSV).



532 live-days data Phys. Rev. D 98, 102006 (2018)

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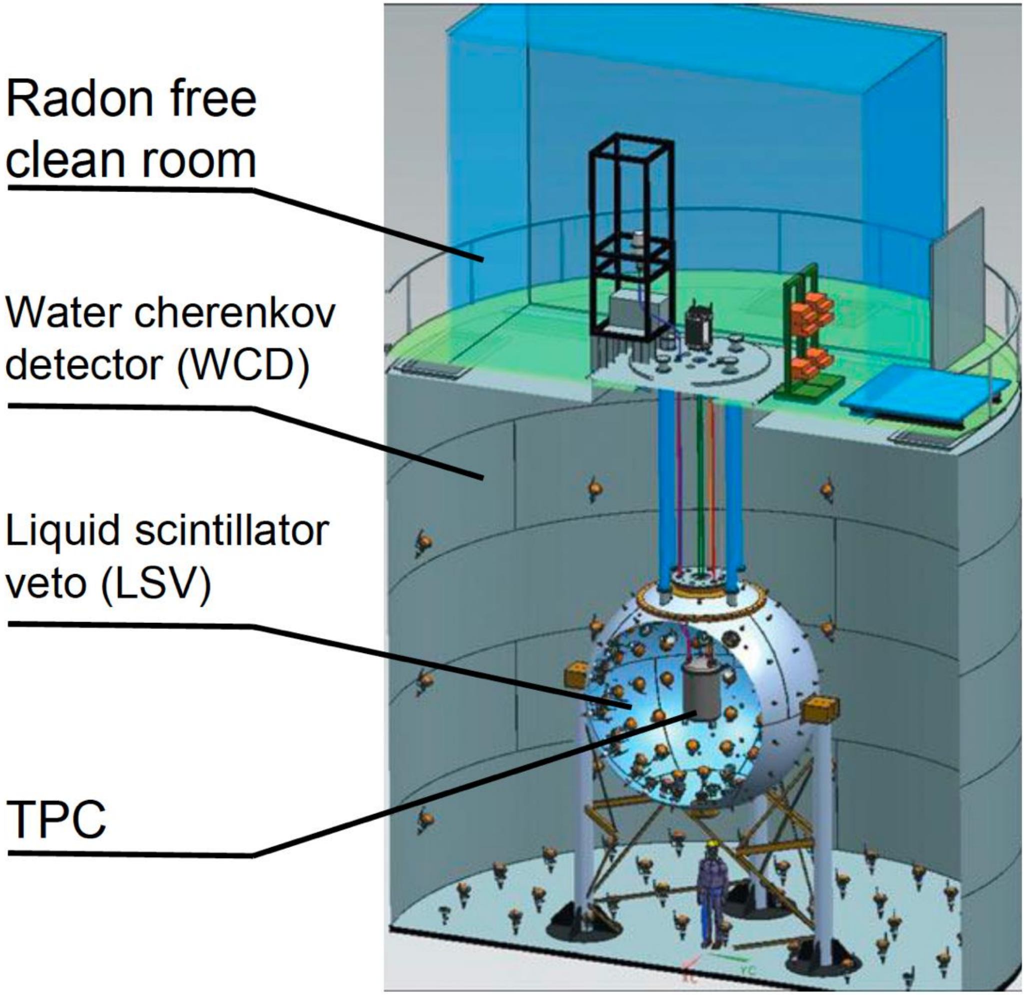


Background Mitigation

Source	Strategies & Tools
β/γ	UAr, PSD, material selection…
Radon progeny	Surface cleaning, Rn suppressed air…
Radiogenic neutron, mostly (α, n)	Neutron veto, fiducialization, material selection…
Cosmogenic neutron	Muon veto…
Neutrino induced NRs	irreducible

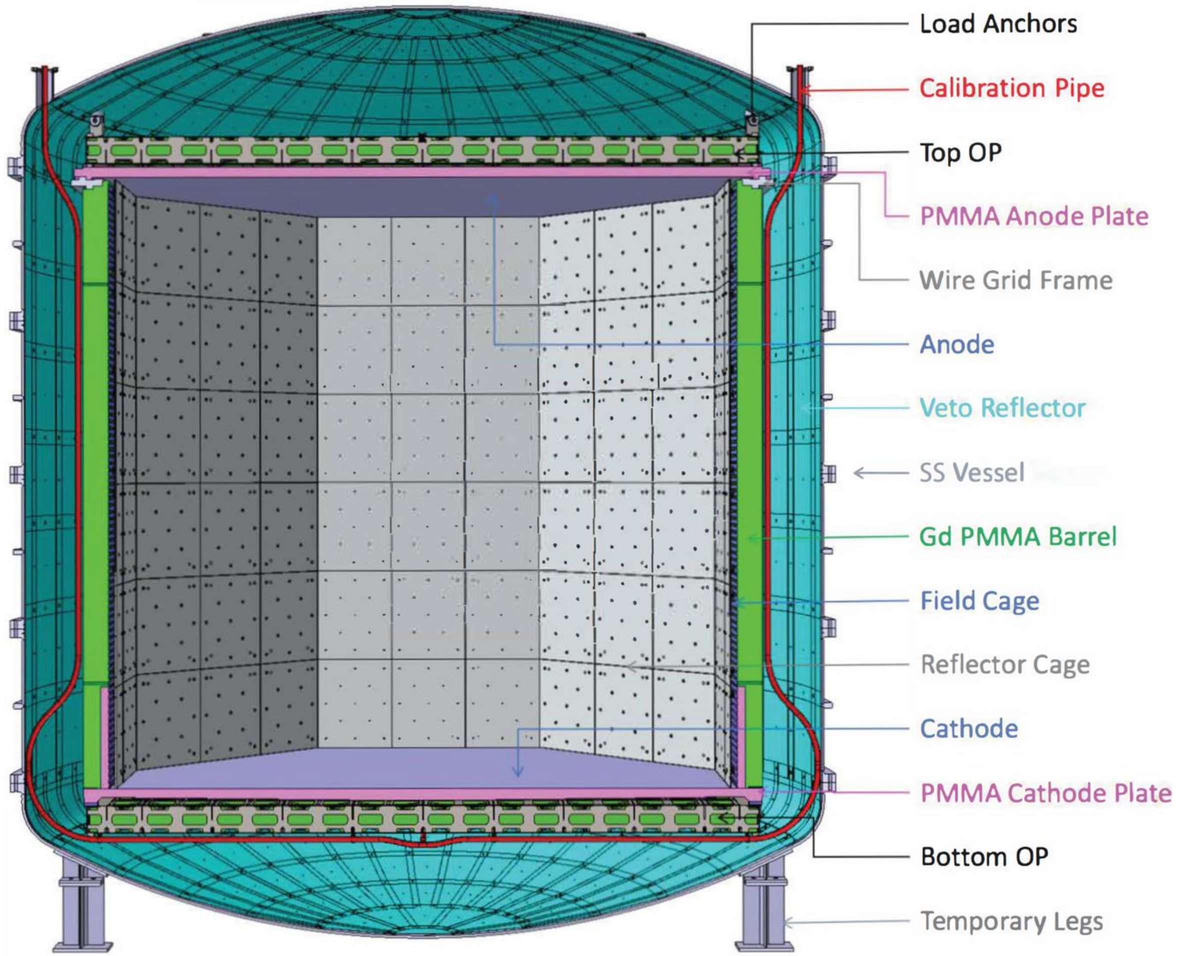
- For future large-scale time projection chambers, an efficient neutron veto is needed.
- Gd-PMMA is proposed as a structural neutron tagging material.

Dual-phase Ar TPC with Neutron Veto

- Proposed design of a dual-phase Ar TPC integrated with a neutron veto.
- SiPM as the photosensor.

See Maria Cecilia Queiroga Bazetto's talk for SiPM !!

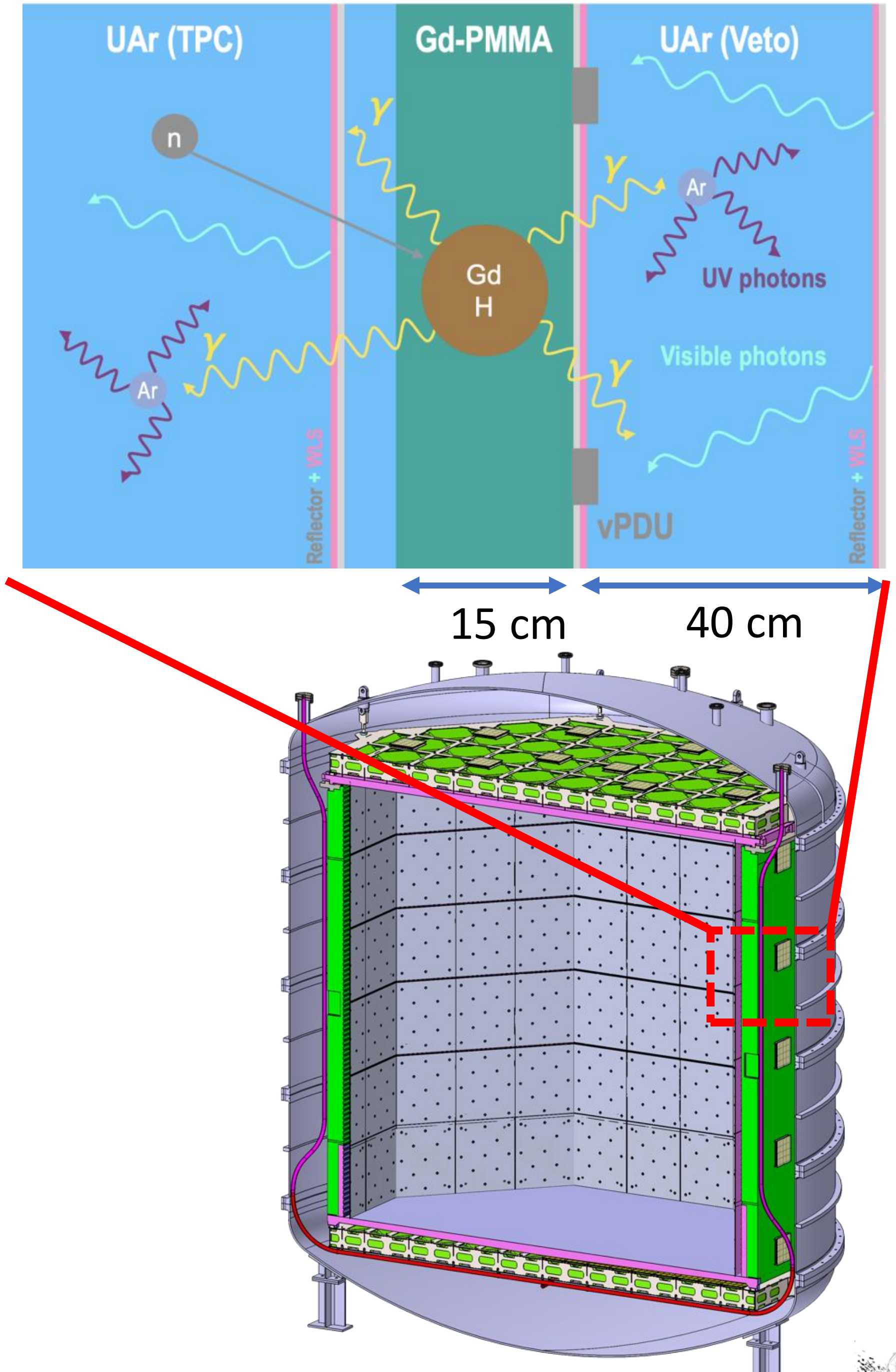
- Neutron Veto:
  - ➢Gd-PMMA for TPC main structure, top and bottom endcaps;
  - ➢TPC active volume 4π covered by Gd-PMMA;
  - ➢Ar buffer in the veto volume;
  - ➢Ar in the TPC.



Active Neutron Veto

- Gd-PMMA -> Hydrogen + Gadolinium:
  - ➢Hydrogen -> single γ ~2.2 MeV;
  - ➢Gadolinium -> multiple γ upto 8 MeV.
- Produced γ rays interact in Ar in both veto buffer (40 cm thick) and TPC;
- Scintillation lights detected by SiPMs in both veto buffer and TPC;
- ESR as reflector and PEN as wavelength shifter.

See Sarthak Choudhary's talk for more details about PEN !!



Neutron Tagging Inefficiency

- Optimizing the gadolinium concentration and the thickness of Gd-PMMA for enhanced neutron efficiency.

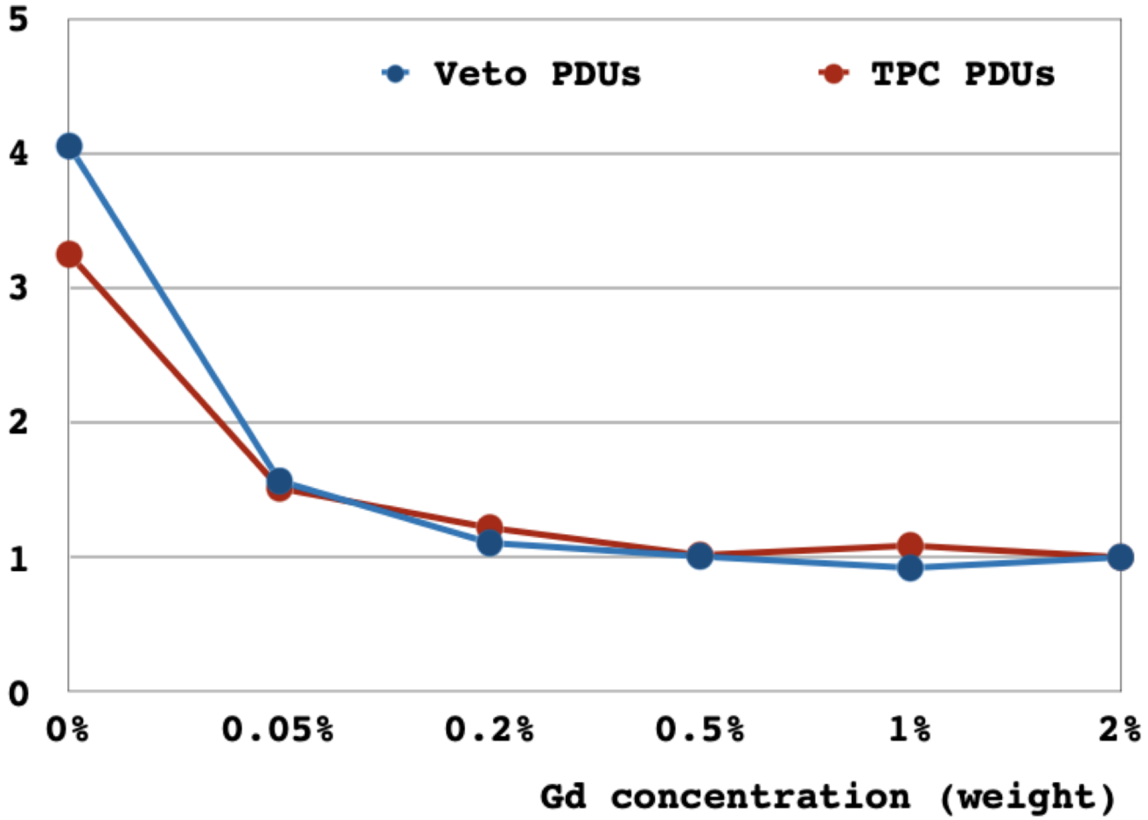
- Light yield assumptions:

➢TPC: 10 p.e./keVee;

➢Veto: 2 p.e./keVee.

- Gd concentration: 1 wt%;
- Thickness of Gd-PMMA: ≥ 15 cm;

➢Neutron tagging inefficiency ~5%.



The Development of Gd-PMMA

- Recipe development;
- Radiopurity;
- Industrialization;
- Residual stress & Annealing.

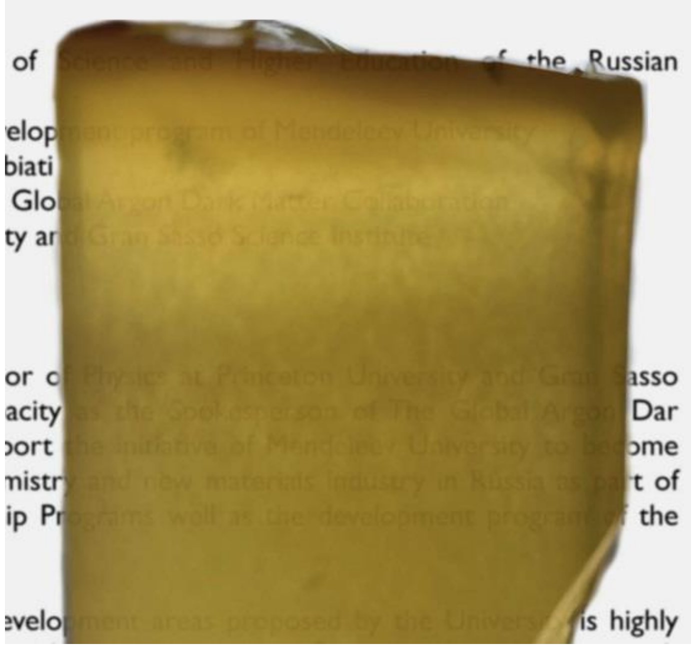
Development of Recipe

- Three approaches have been developed for Gd-PMMA:
  - Gd_2O_3 recipe: mechanically mix Gd_2O_3 nano grain with MMA for polymerization;
  - $Gd(acac)_3$ recipe: "directly" dissolve $Gd(acac)_3$ into MMA for polymerization;
  - $Gd(MAA)_3$ recipe: "indirectly" dissolve $Gd(MAA)_3$ into MMA for polymerization.

Gd_2O_3 recipe

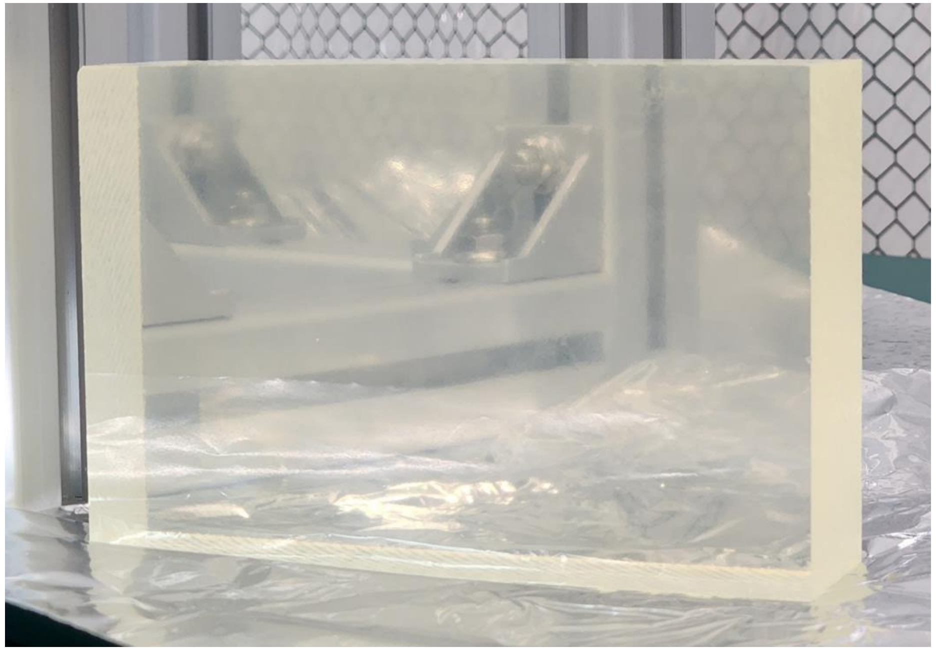
arXiv:2404.18492

$Gd(acac)_3$ recipe



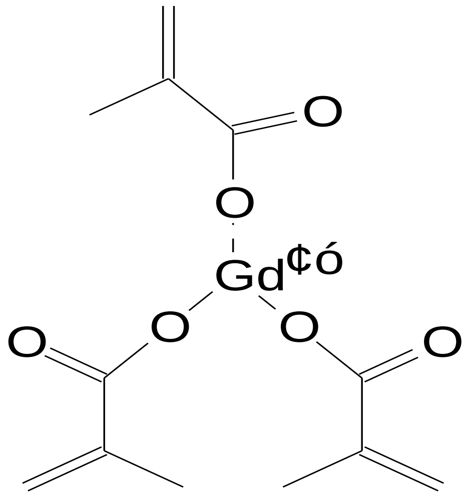
Materials 2021, 14, 3757

$Gd(MAA)_3$ recipe

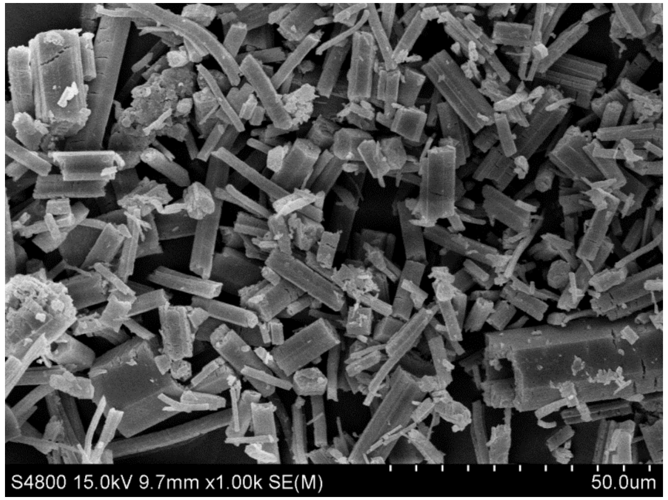


Rare metals 2010 34(4):568-573

Gd(MAA)$_3$



- Gadolinium methacrylate;
- It can be dissolved in liquid MMA monomer using a dedicated dissolving recipe;
- Good chemical stability due to the molecular connection between Gd(MAA)$_3$ and MMA;
- Max. ~30% Gd(MAA)$_3$ can be dissolved in liquid MAA (~10% Gd by mass fraction).



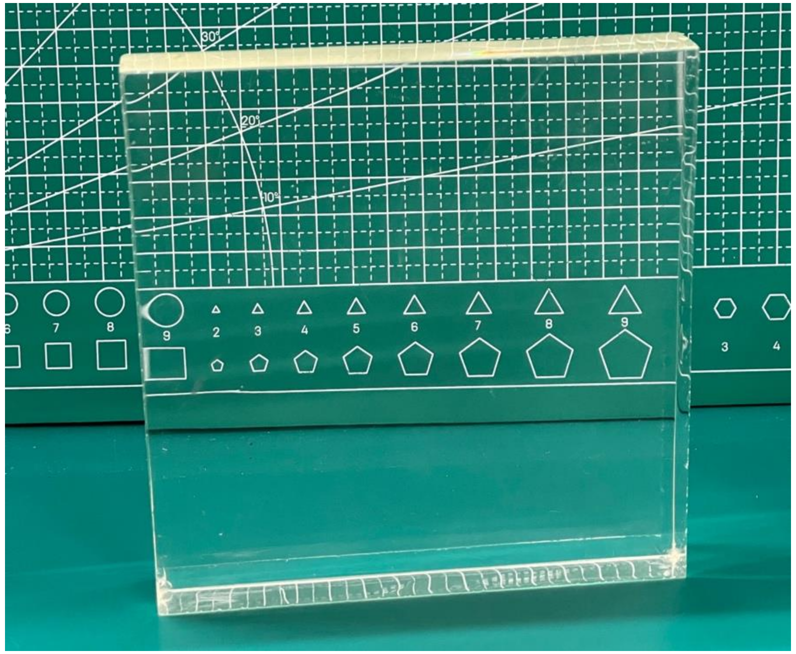
The dissolving recipe was developed by Yangzhou University & IHEP:

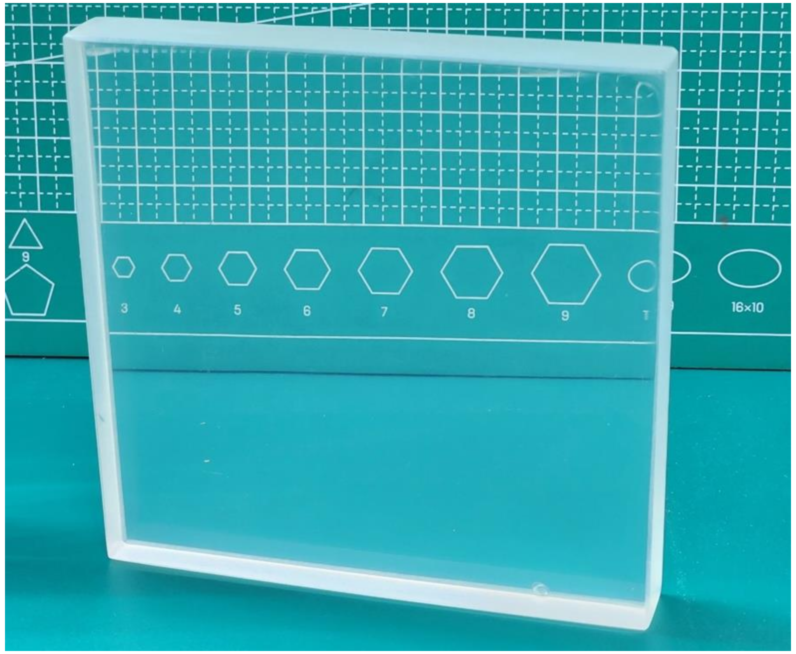
揚州大學 YANGZHOU UNIVERSITY

中國科學院高能物理研究所 Institute of High Energy Physics Chinese Academy of Sciences

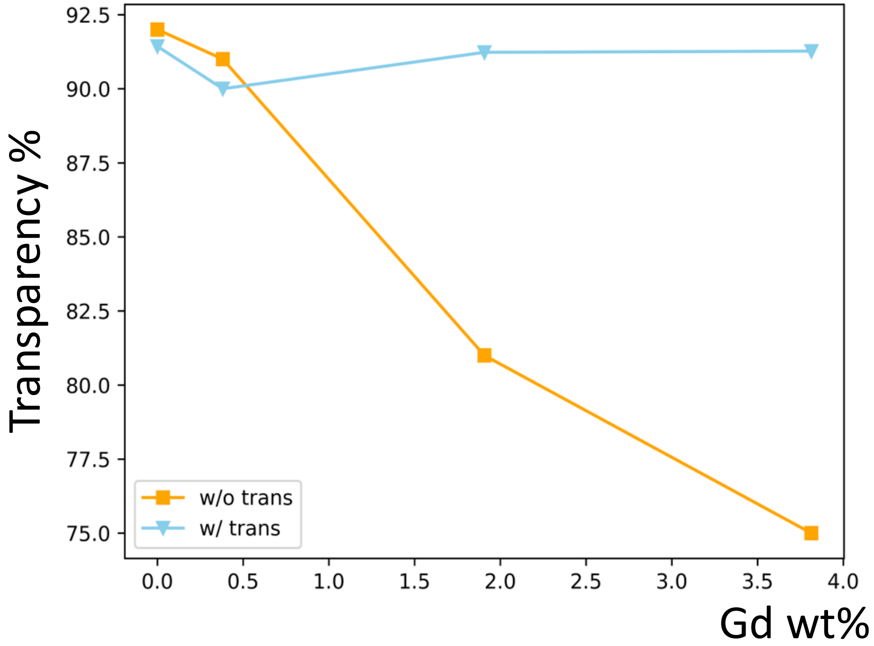
Gd-PMMA

- Polymerization of $Gd(MAA)_3$ doped liquid MMA;
- A dedicated initiator recipe was developed to prevent self-inhibition and implosion during polymerization;
- High optical transparency is achievable within limited dimensions.





with 420 nm light



Radiopurity Control

- PMMA is essentially pure, thanks to the radiopure PMMA production line developed by Donchamp for the JUNO experiment;
- 5N Gd_2O_3 from ShinEtsu is selected for Gd-PMMA production for low background.

JUNO PMMA

Isotopes	mBq/kg
Th232_Ra228	< 0.14
Th232_Th228	< 0.078
U238_Ra226	0.05±0.02
U238_Th234	< 2.1
U238_Pa234m	< 1.8
U235	< 0.07
K40	< 0.41
Cs137	< 0.025

ShinEtsu 5N Gd_2O_3

Isotopes	mBq/kg
Th232_Ra228	< 0.5
Th232_Th228	0.4±0.1
U238_Ra226	0.5±0.1
U238_Th234	< 33
U238_Pa234m	< 7.4
U235	< 0.31
K40	4±1
Cs137	< 0.079

Gd-PMMA (under validation)

Isotopes	mBq/kg
Th232_Ra228	< 0.33
Th232_Th228	< 1
U238_Ra226	< 1.3
U238_Th234	< 8.3
U238_Pa234m	< 49
U235	< 0.54
K40	< 11
Cs137	< 0.12

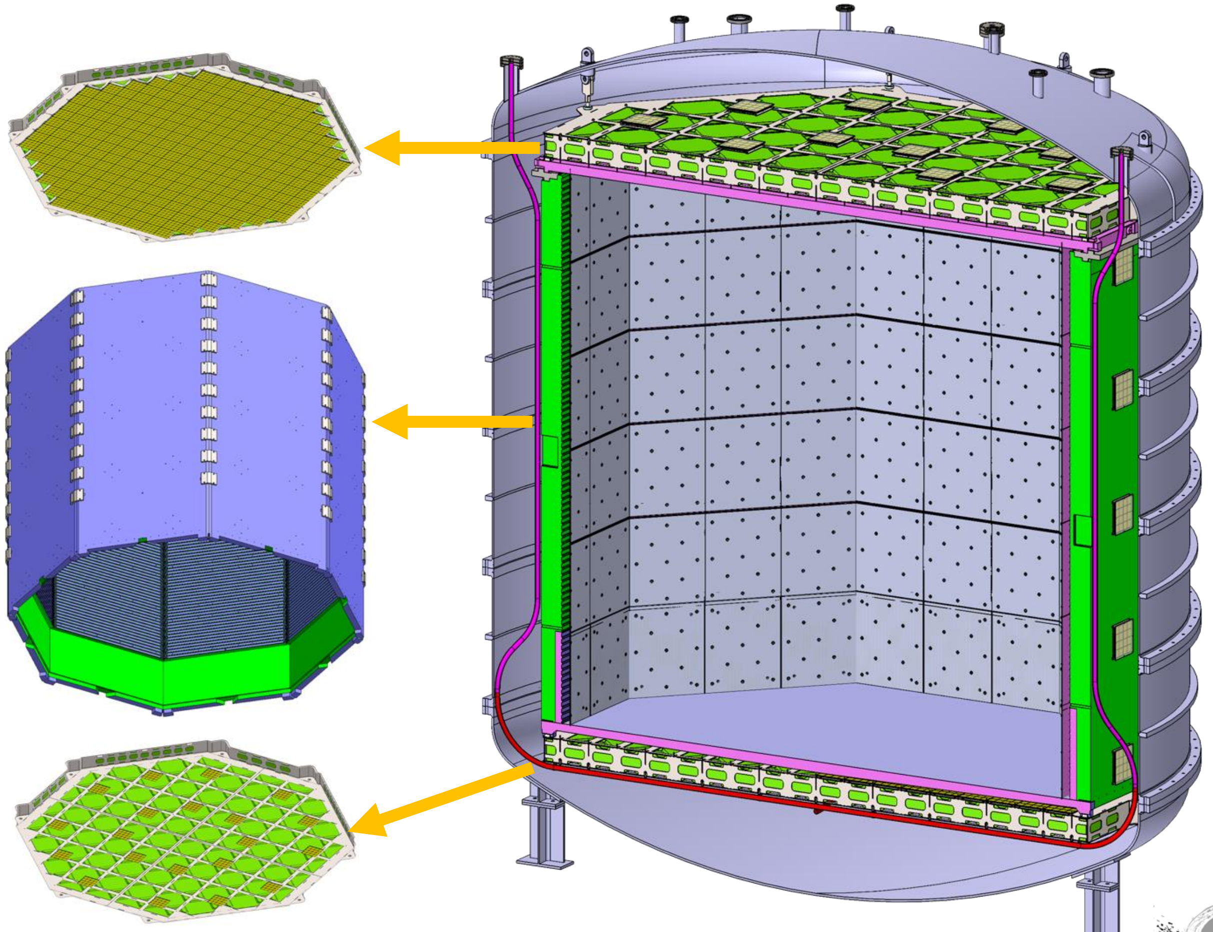
Preliminary

Radiopurity assay is still ongoing at LNGS.

From Lab to Production Line

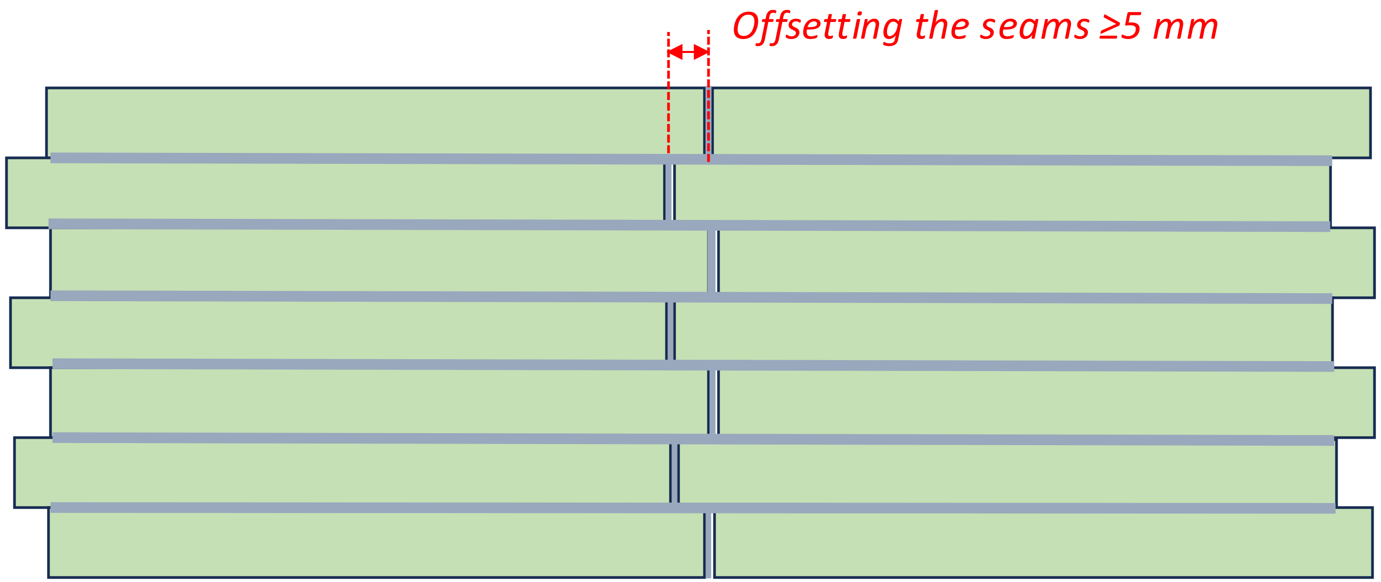
- Implementing a new recipe in a mature production line is not trivial.
- Production yield and material properties often need to be compromised.

- Dimension requirement if DarkSide-20k used Gd-PMMA everywhere:
- For the TPC barrel:
  - ➢ ~3.65 m x ~1.65 m x 15 cm.
- For the top and bottom endcaps:
  - ➢ ~40 cm x 40 cm x 15 cm.



Large Dimension Panels

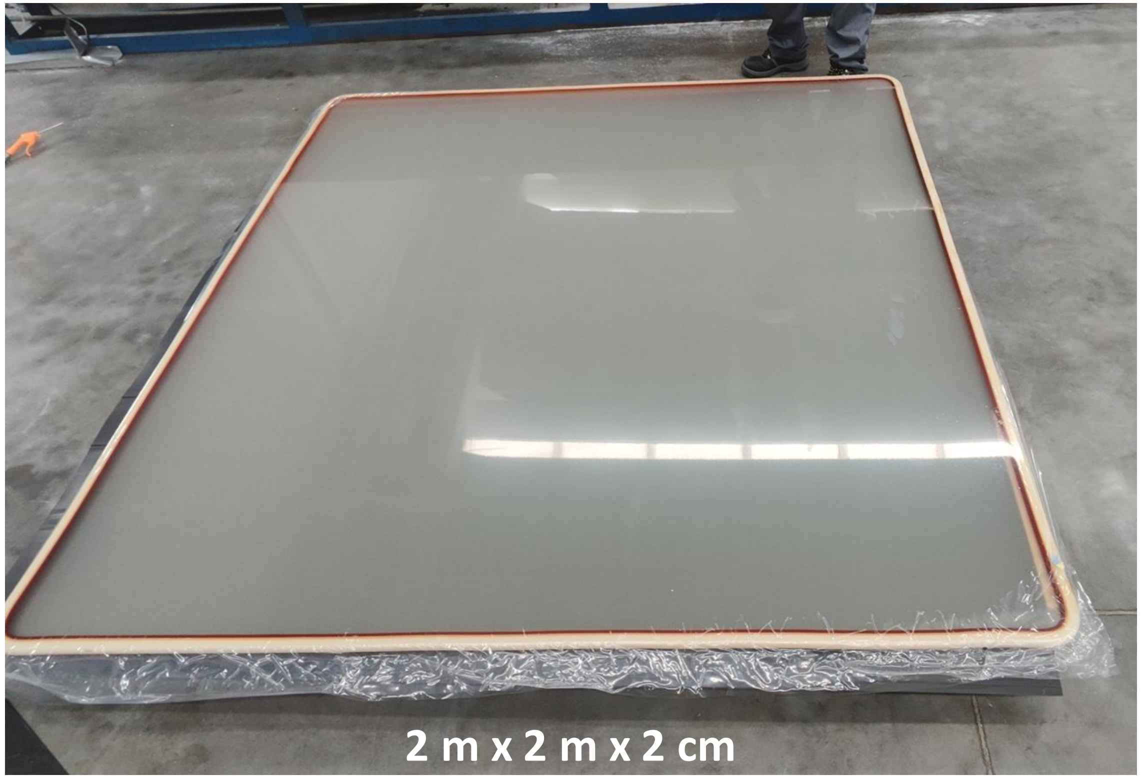
- Optimized dimension for a single Gd-PMMA sheet with a production yield > 90%: 2 m x 2 m x 2 cm.
- How do we achieve larger dimensions ?
- A bonding and lamination procedure has been developed. The adhesive uses the same ingredients as Gd-PMMA, specifically $Gd(MAA)_3$ dissolved in MMA.



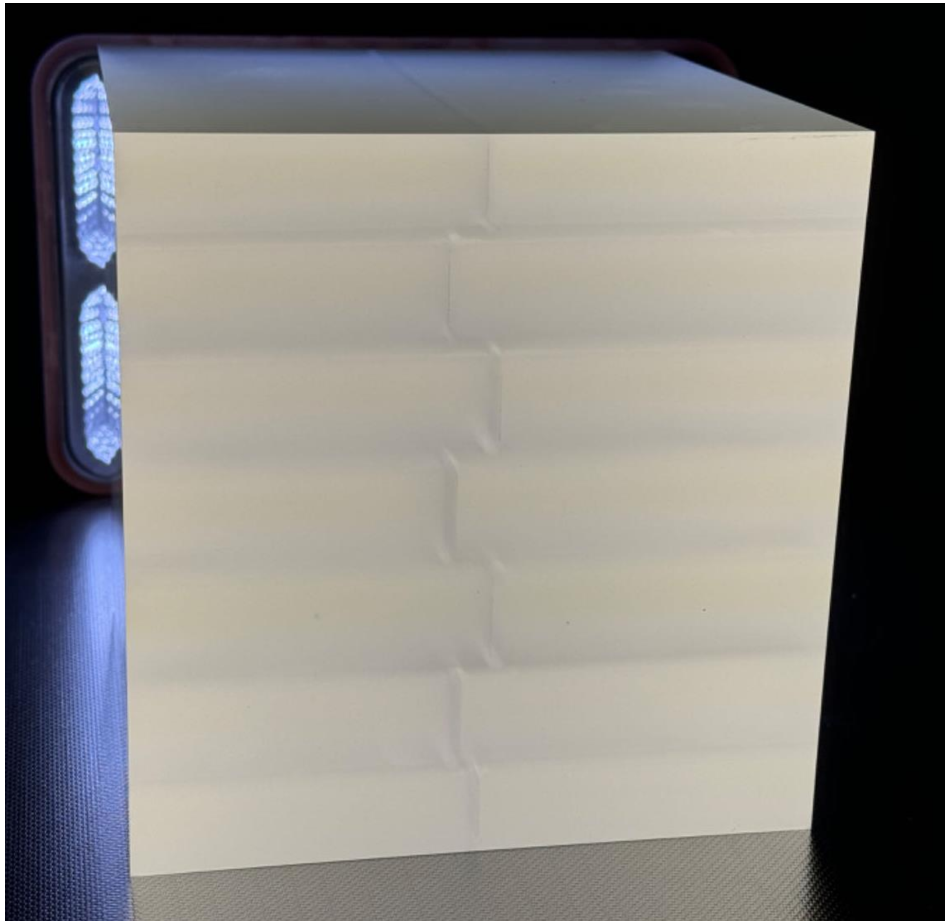
- ✓ Single sheet: 2 m x 2 m x 2 cm
- ✓ 14 sheets will be bonded and laminated as a barrel panel: 3.8 m x 1.8 m x 16.4 cm
- ✓ Then machine to the barrel, which the external dimension is 3.65 m x ~1.65 m x 15 cm.

Validation of the Final Procedure

- The first full-size Gd-PMMA panel, produced according to the final production procedure, was manufactured at Donchamp in China.



- Several 15 cm^3 bonded & laminated cubes are at IHEP for annealing and cooling tests.

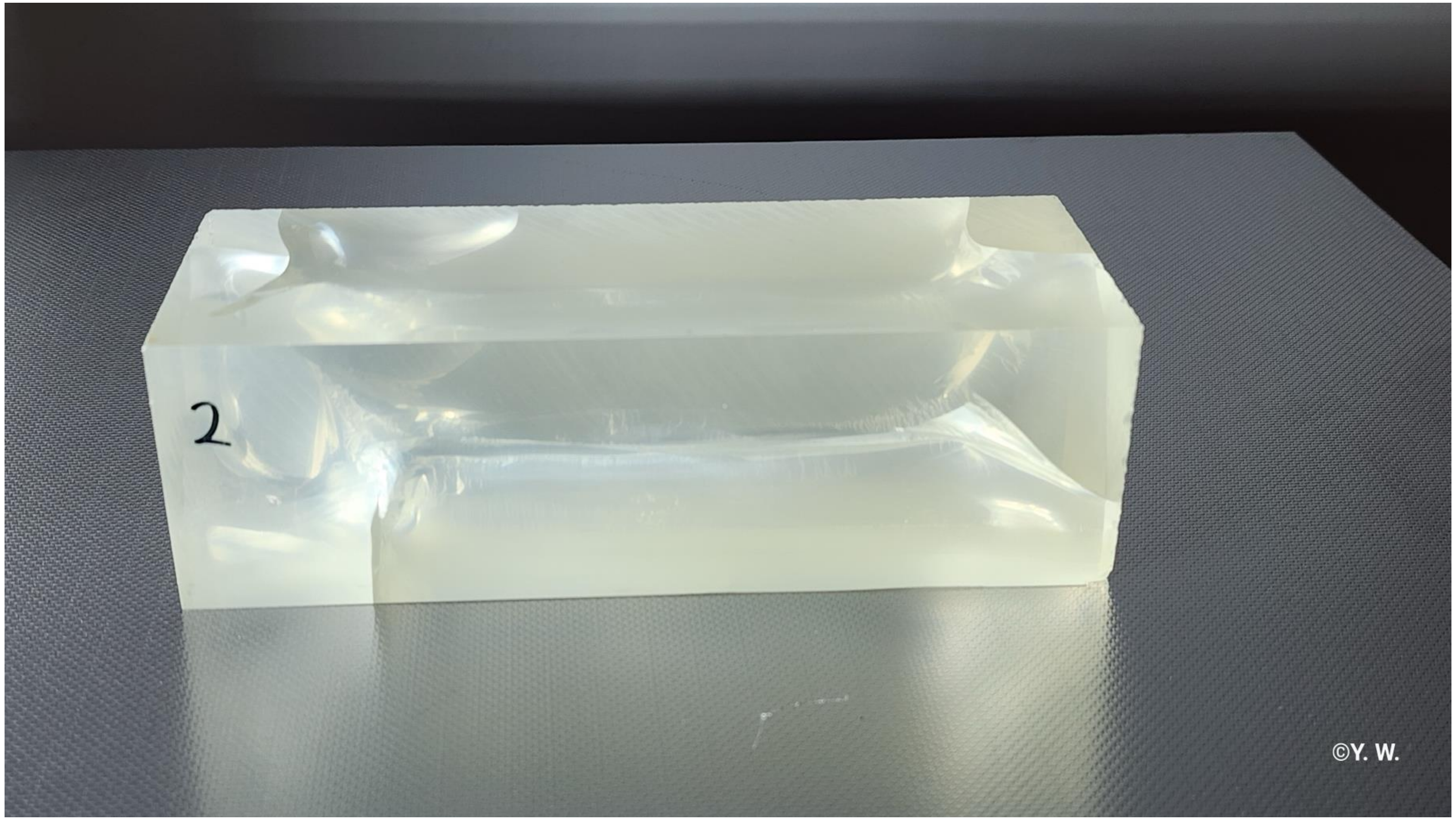


- A relatively large bonded & laminated sample, measuring 80 cm x 80 cm x 16.4 cm, has been produced. This sample will be used to study the annealing procedure at the University of Alberta.

- Annealing is the most important step to mitigate residual stress for applications at low temperatures.

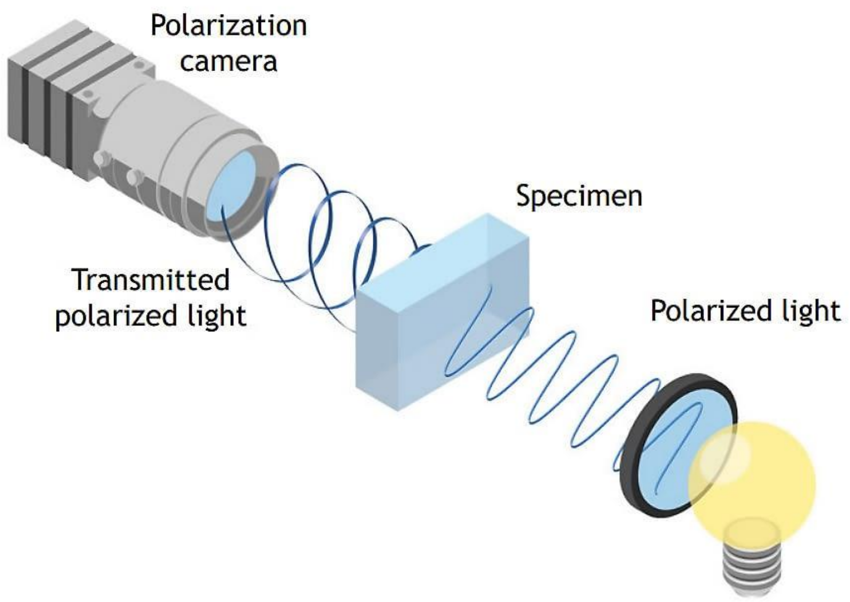
What if there are stresses ?

- Acrylic will crack if we do not carefully manage the stresses.

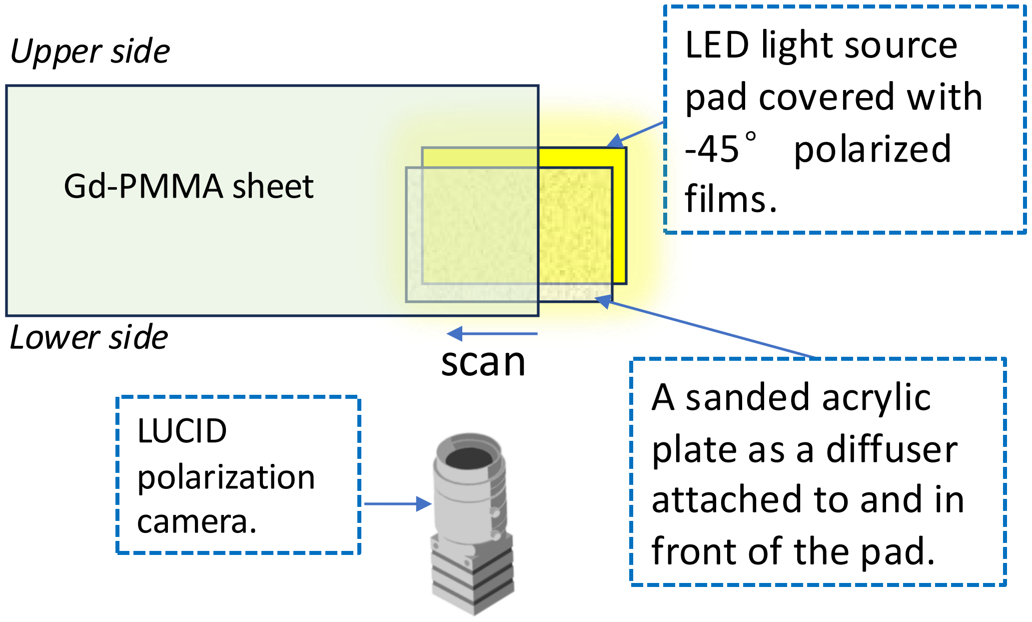


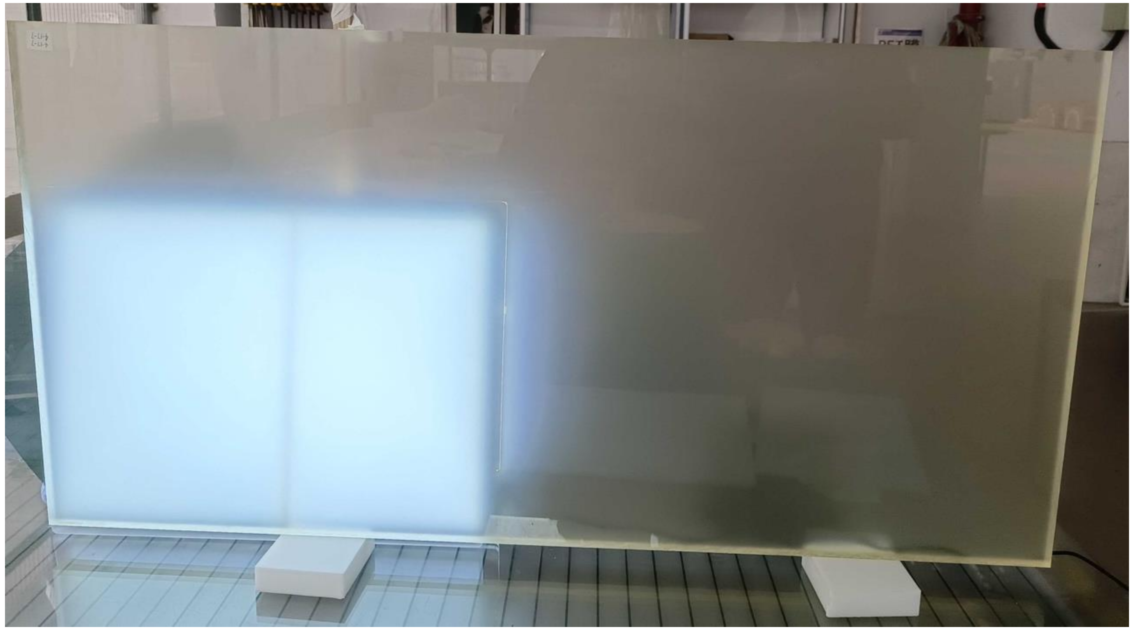
- ➢ Understand the stress.
- ➢ Mitigate the stress.

Stress Measurement



- Use a polarimeter to measure the stress.
- A polarization camera is not capable of scanning large areas.
- A segmented setup is used for scanning large Gd-PMMA sheets.



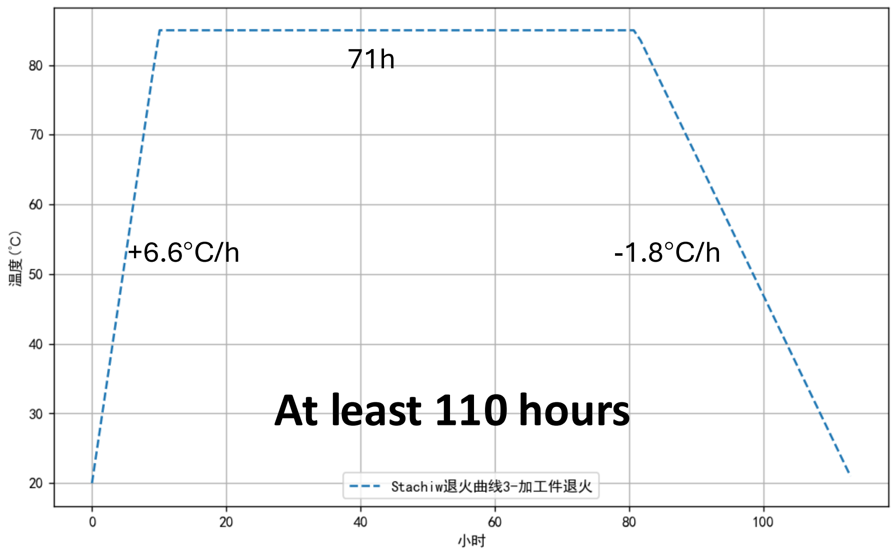


Annealing

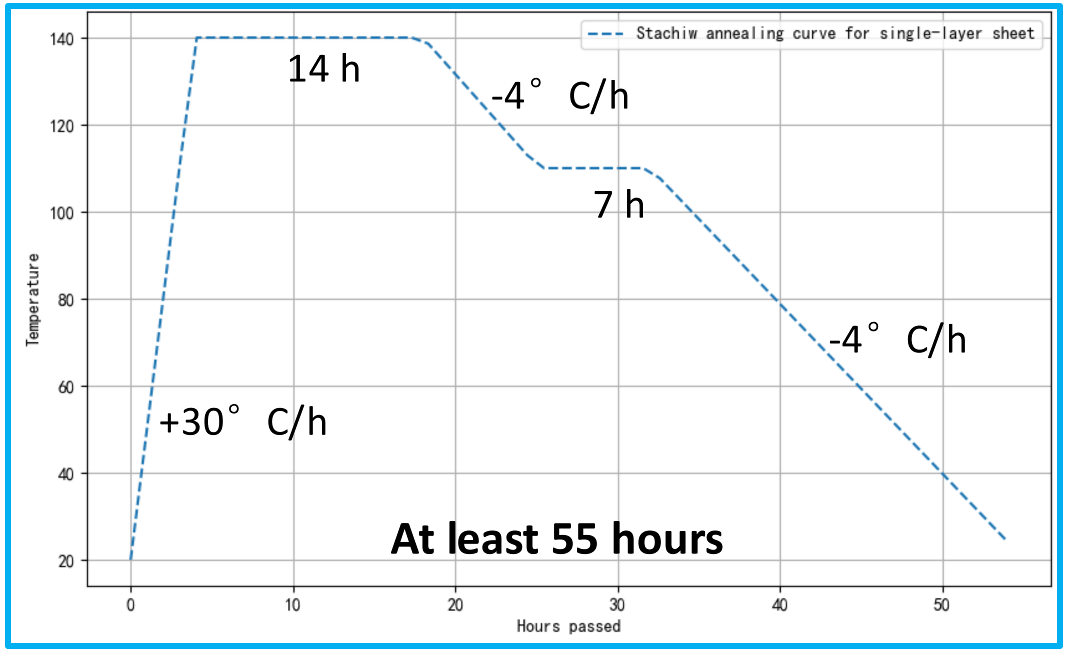
- 1st annealing for single sheet;
- 2nd annealing for bonded & laminated panel;
- 3rd annealing after machining.

ISBN number of Stachiw's book. 1-930536-15-1

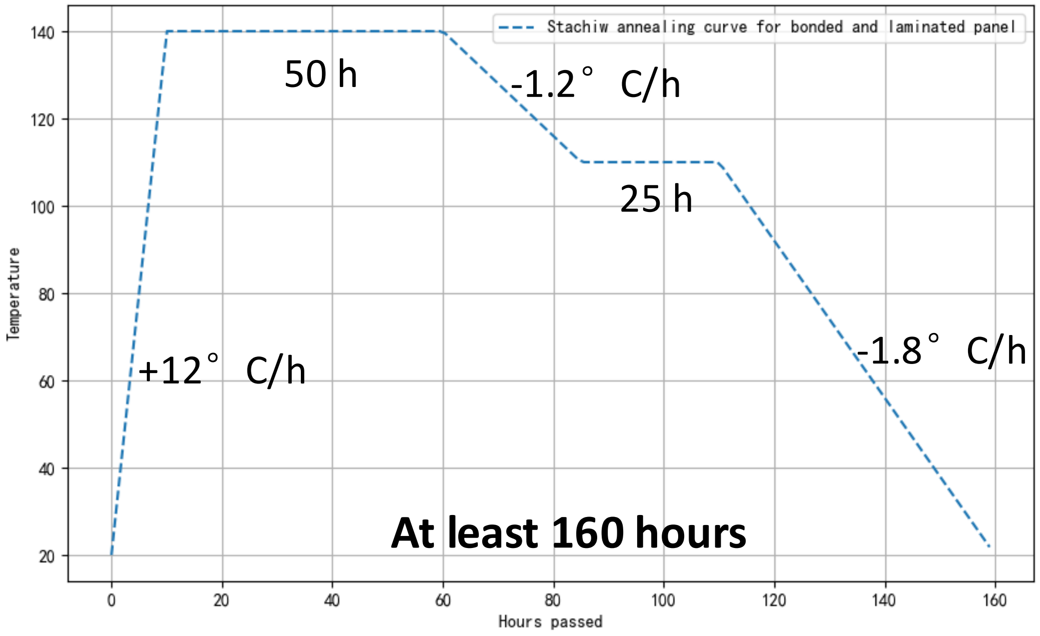
Stachiw annealing curve machined panel



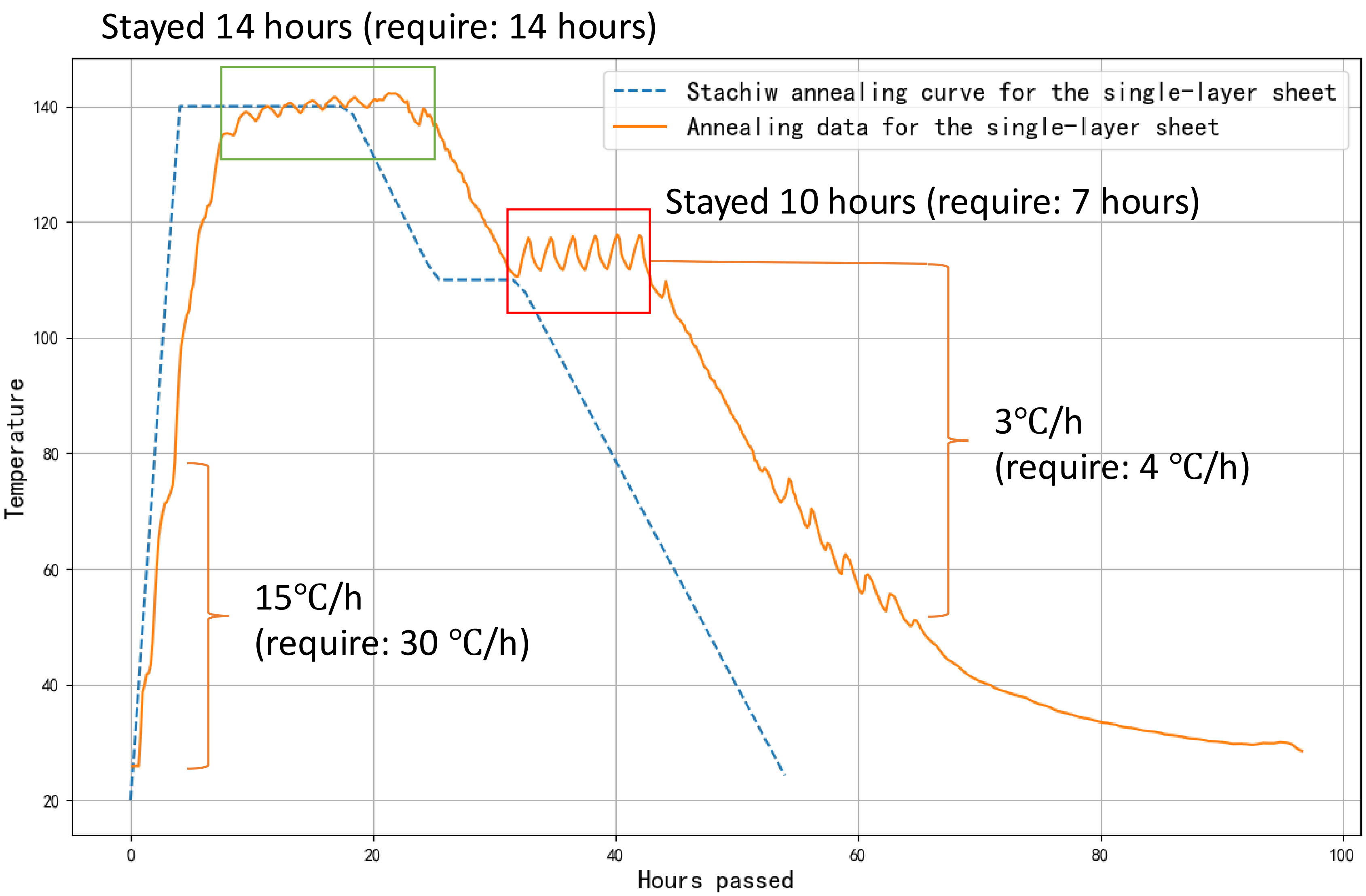
Stachiw annealing curve for single-layer sheet



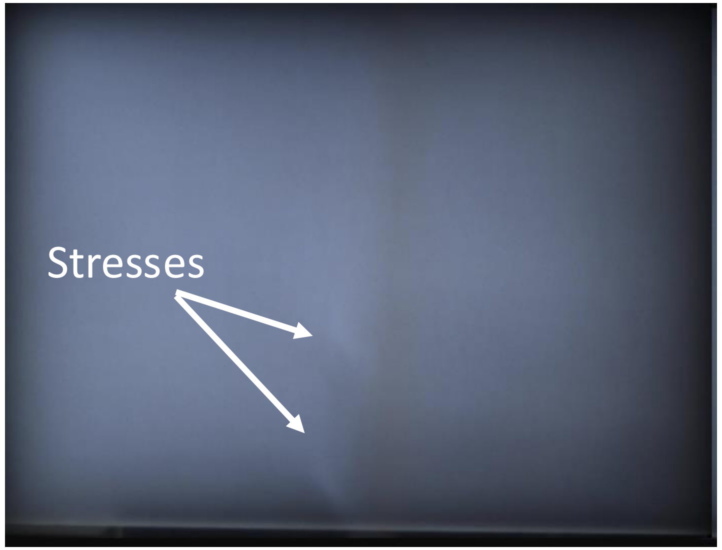
Stachiw annealing curve for bonded & laminated panel



Annealing for Single Sheet



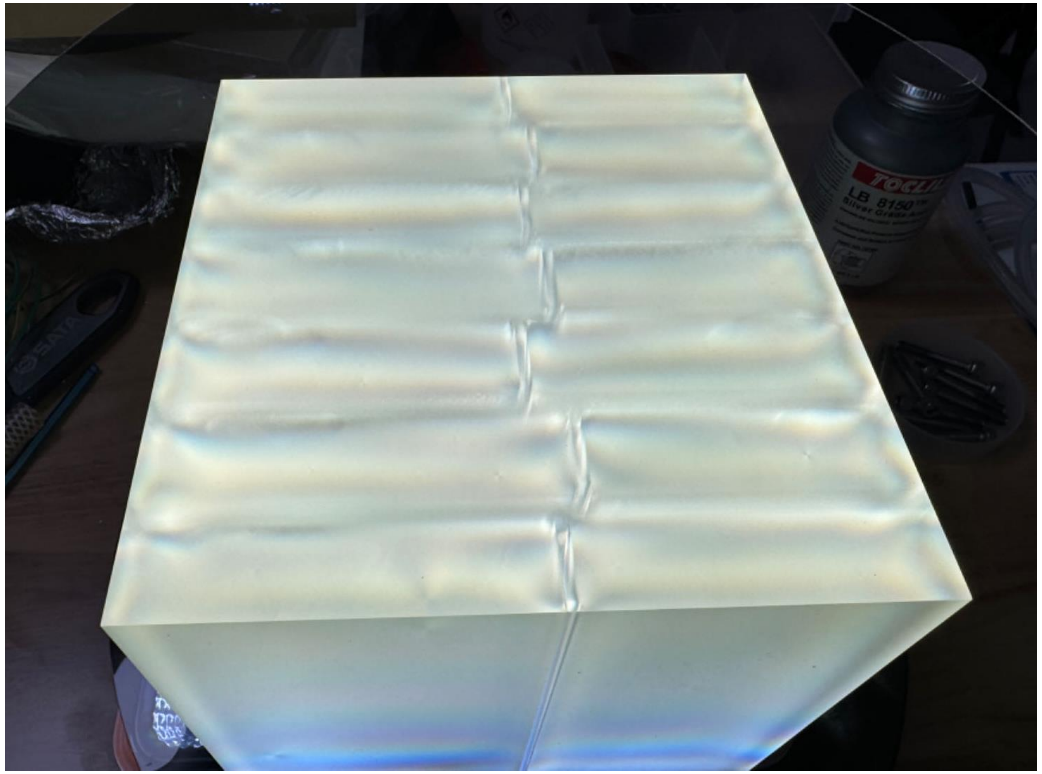
Before annealing



After annealing

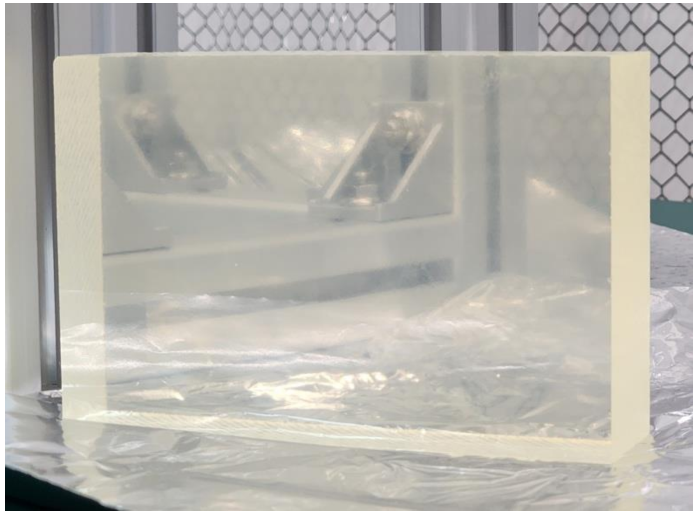
Annealing for Full Thickness Piece

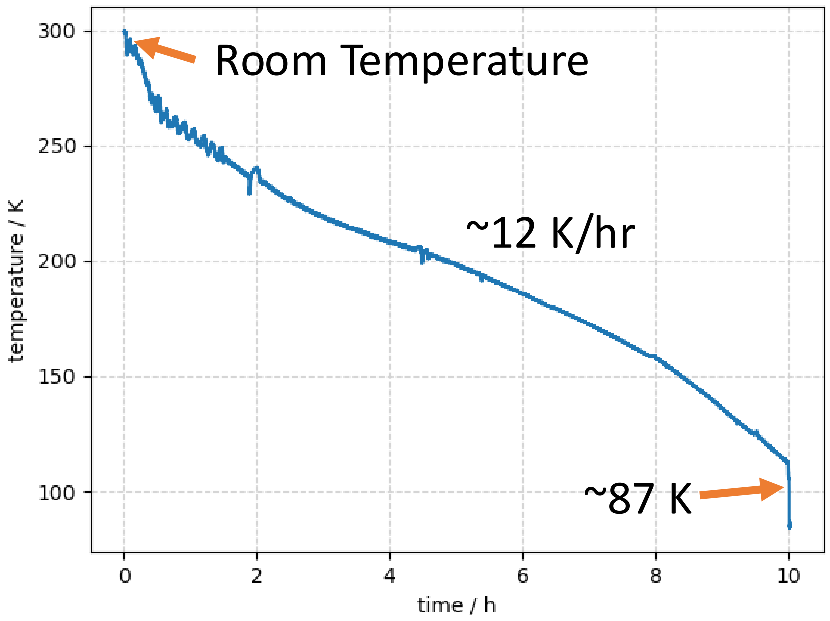
- The annealing study of the bonded & laminated sample is scheduled.
- Following this, a cooling test will be conducted by immersing the sample in liquid argon.

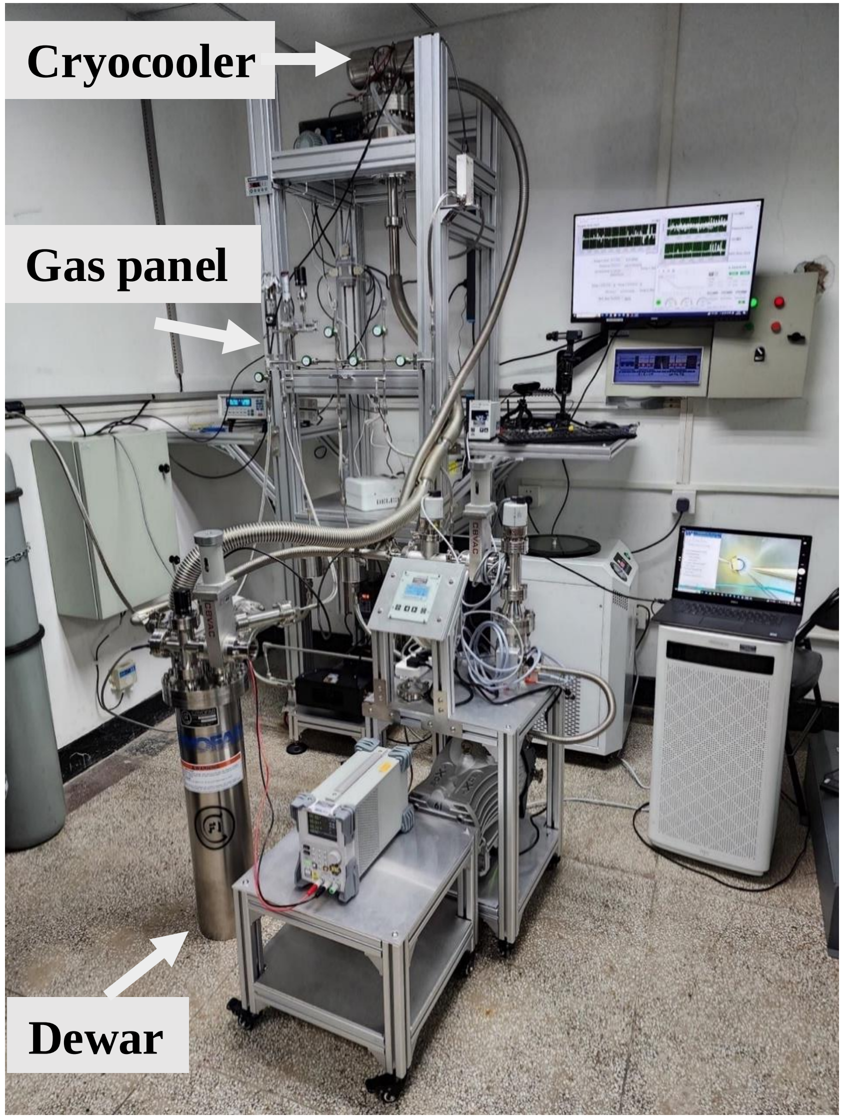


Cooling Test

- A test cooling procedure has been performed with a two-layer laminated Gd-PMMA sample.
- The average cooling rate was ~12 K/hr, while the slowest cooling rate of the cryogenic system is ~5 K/hr.
- No defects have been observed after the test.

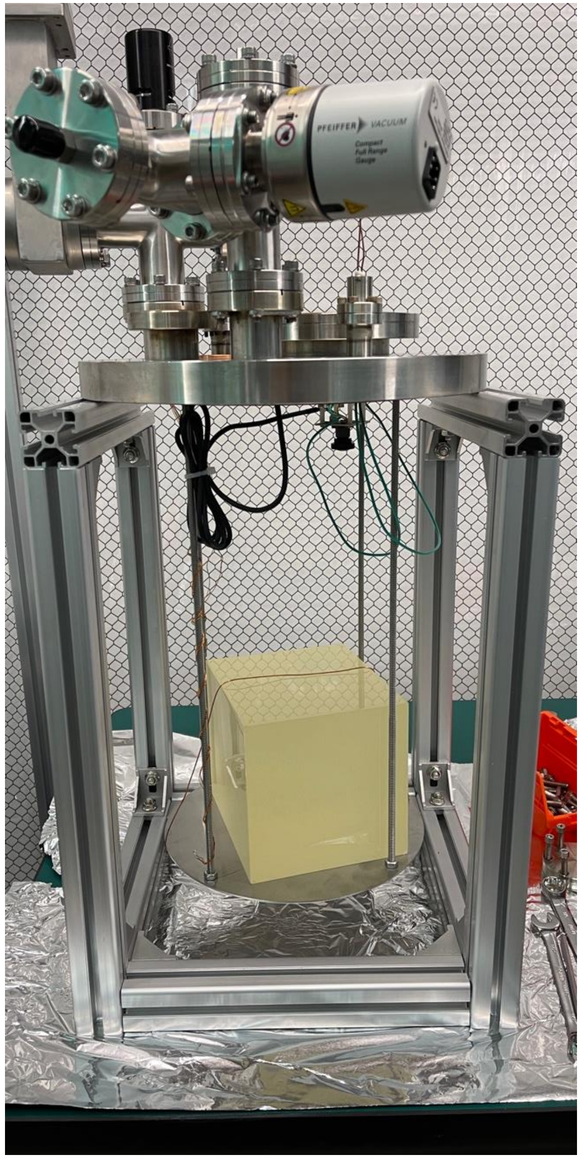


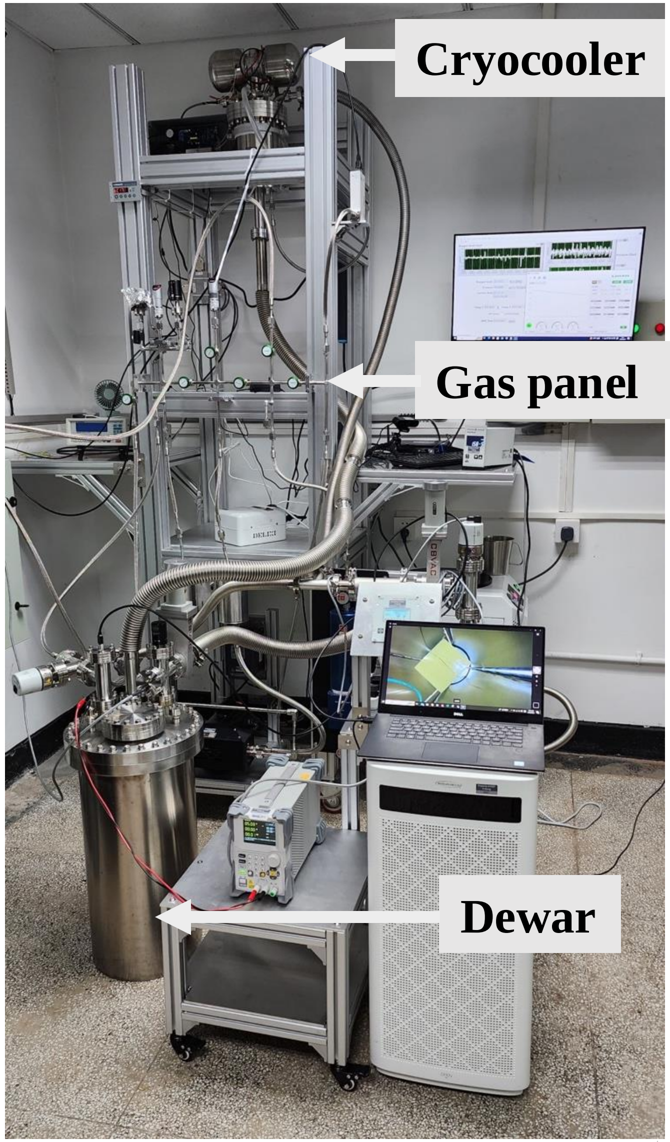




Cooling Test for the Full Thickness Sample

- A full thickness sample:
  a 15 cm^3 cube
- This test is scheduled to begin soon.





Summary & Discussion

- Dual-phase Ar TPC is a promising technique for background-free WIMP searches.
- A novel active neutron veto detector with Gd-PMMA has been designed.
- Gd-PMMA, based on the $Gd(MAA)_3$ recipe, has been successfully developed.
- Industrial-scale production of Gd-PMMA sheets has been validated.
- Extensive studies on stress management and the relevant annealing procedures are being conducted to ensure material reliability.

Beyond Gd-PMMA:

Lead-doped acrylic: successfully developed!
Boron-doped acrylic: development in progress…
Boron-doped plastic scintillator: development in progress…

For more information, please contact wangyi90@ihep.ac.cn.