Gd-PMMA

a novel neutron tagging technology for low background detectors

Yi Wang

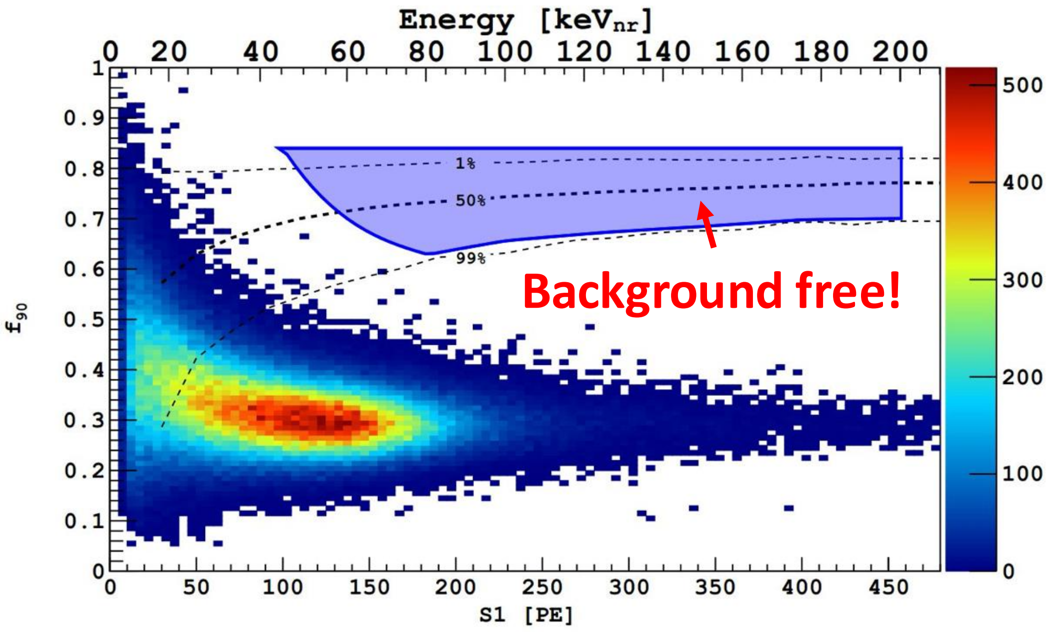
Institute of High Energy Physics, CAS

On behalf of the Gd-PMMA working group

LRT 2024, Kraków, Poland, 10/04/2024

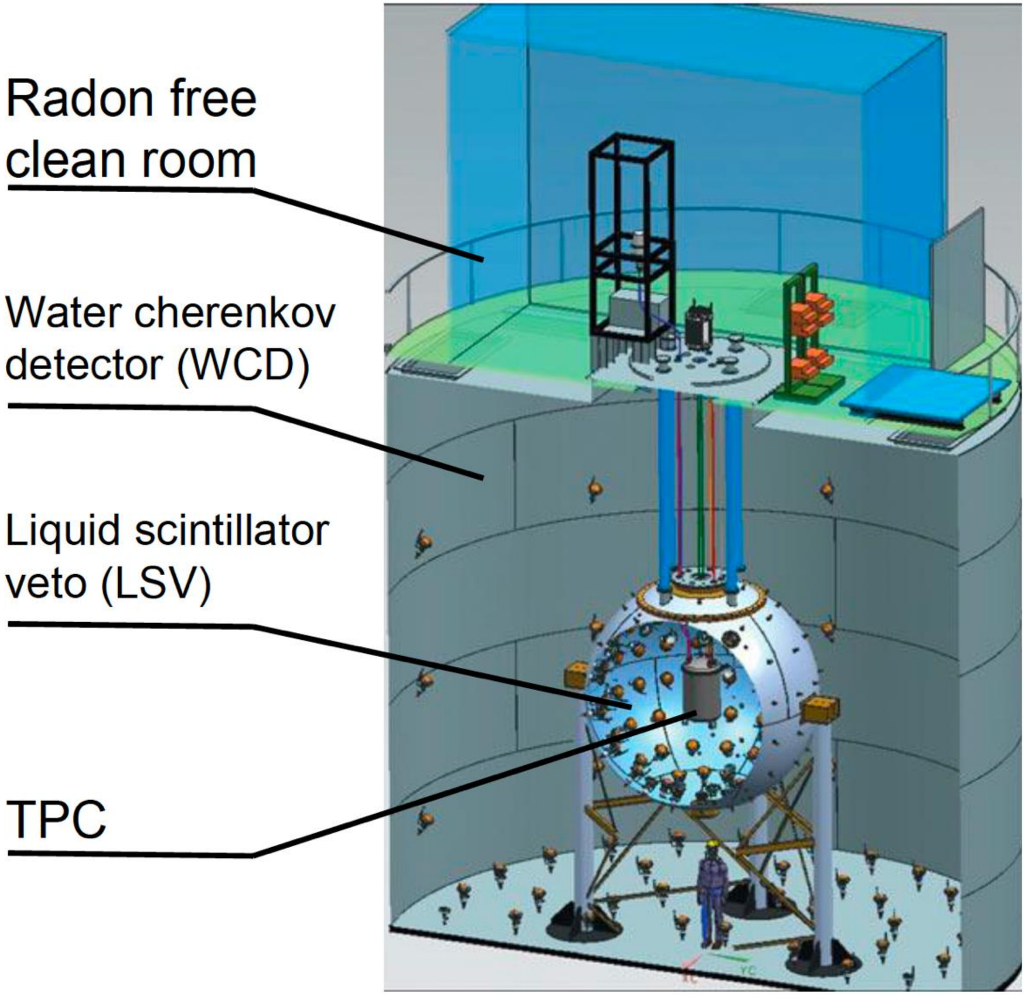
Motivation

- 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)

@LNGS Hall C



A strategy for rejecting neutrons is needed for the next generation of experiments.

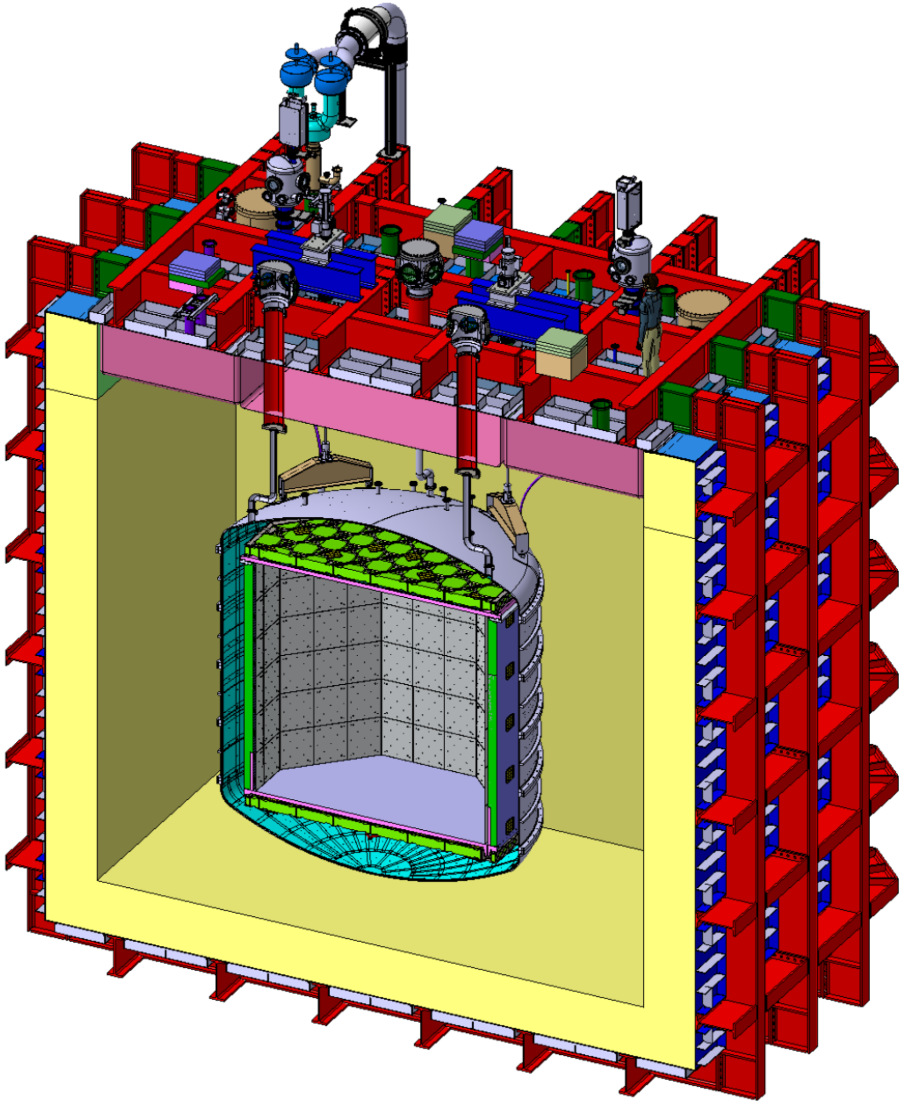
Neutron Veto Strategies Considered

- Several neutron veto strategies has been considered for the next generation WIMP search experiment with argon (DarkSide-20k):

➢Load CH_4 in argon (atmospheric);

➢Gadolinium-doped acrylic in atmospheric argon;

➢Gadolinium-doped acrylic in underground argon.



Dual-phase Ar TPC with Neutron Veto

- Gadolinium-doped acrylic is considered a solid material suitable for building the detector.
- Proposed design of a O (50) tonnes dual-phase Ar TPC integrated with a neutron veto.
- SiPM as the photosensor.

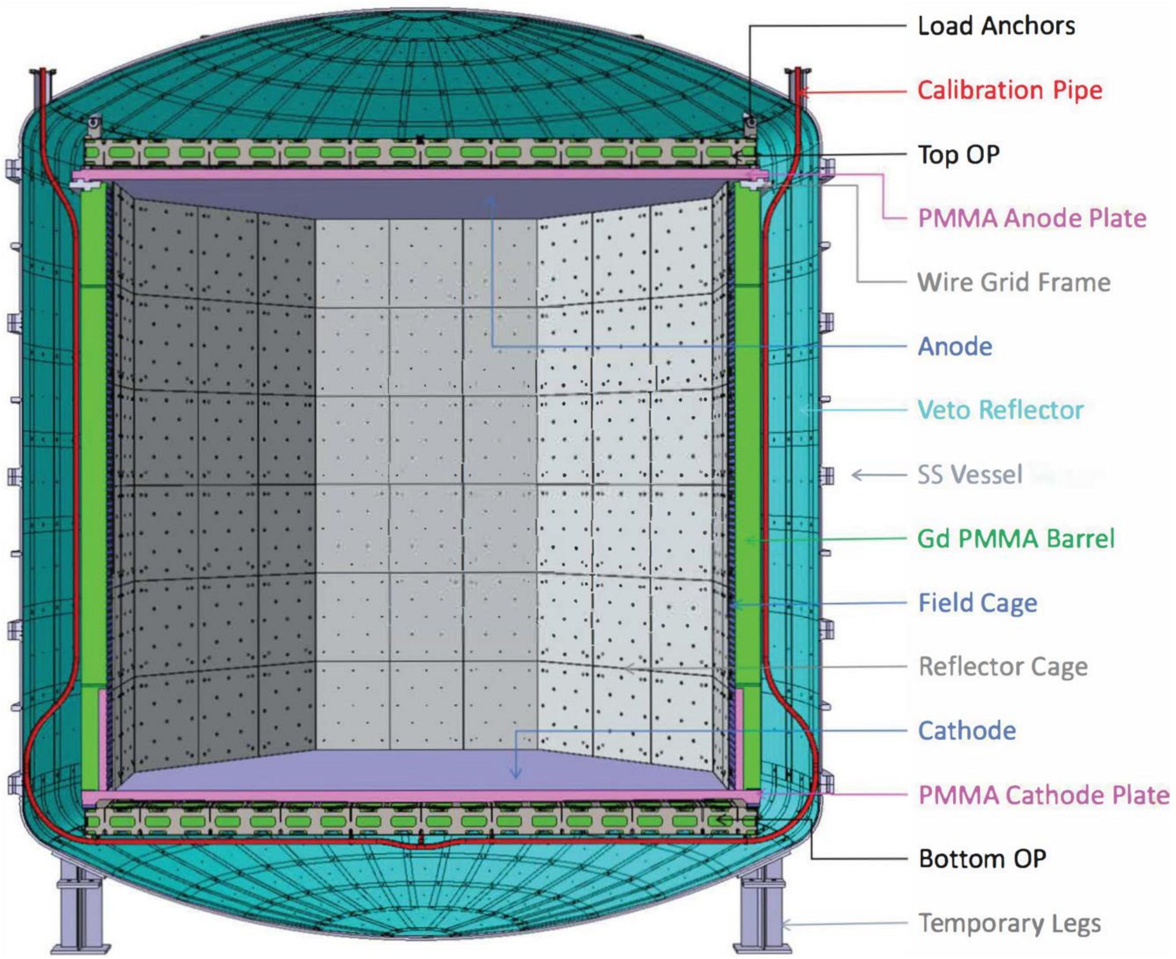
- Neutron Veto:

➢ Gd-PMMA for TPC main structure, top and bottom endcaps;

➢ TPC active volume 4π covered by Gd-PMMA;

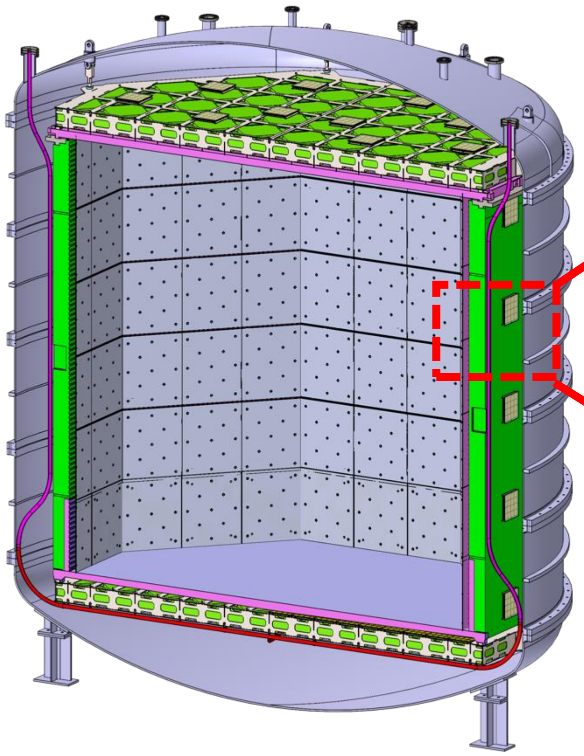
➢ Ar buffer in the veto volume;

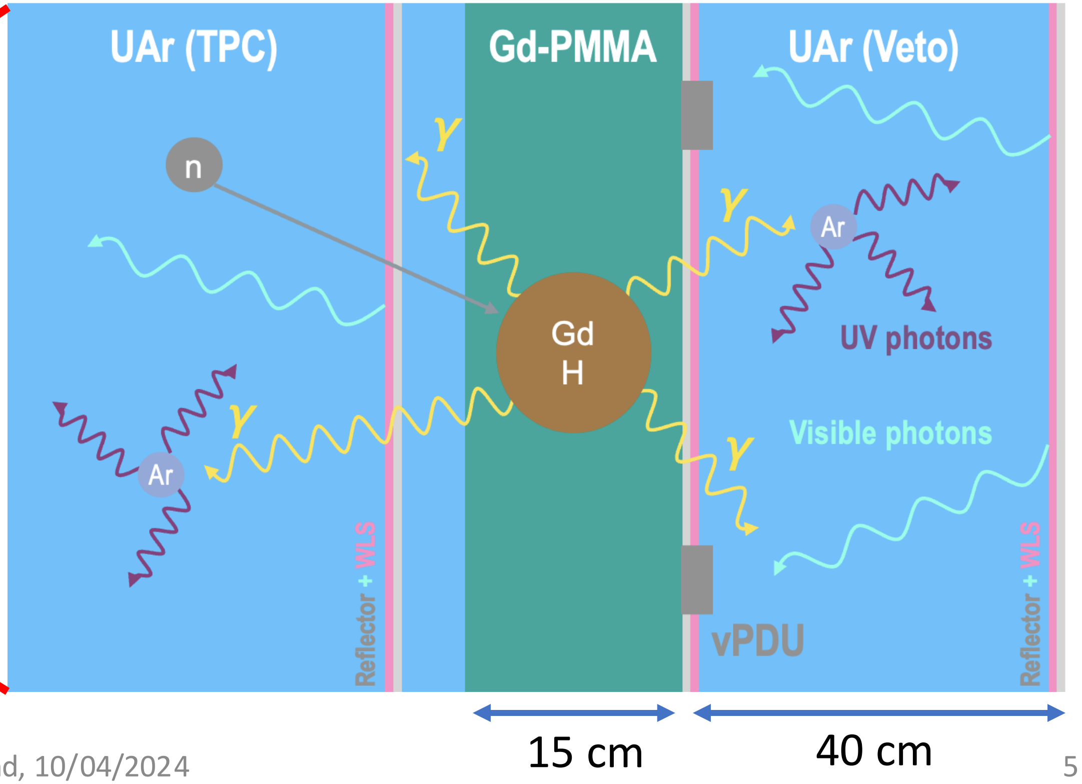
➢ Ar in the TPC.



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;

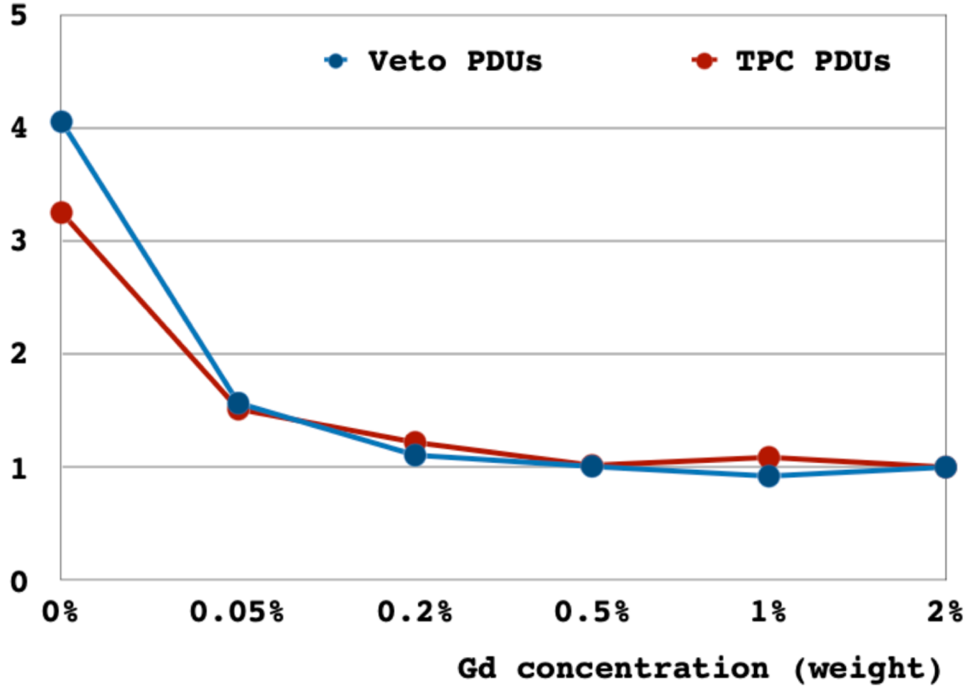




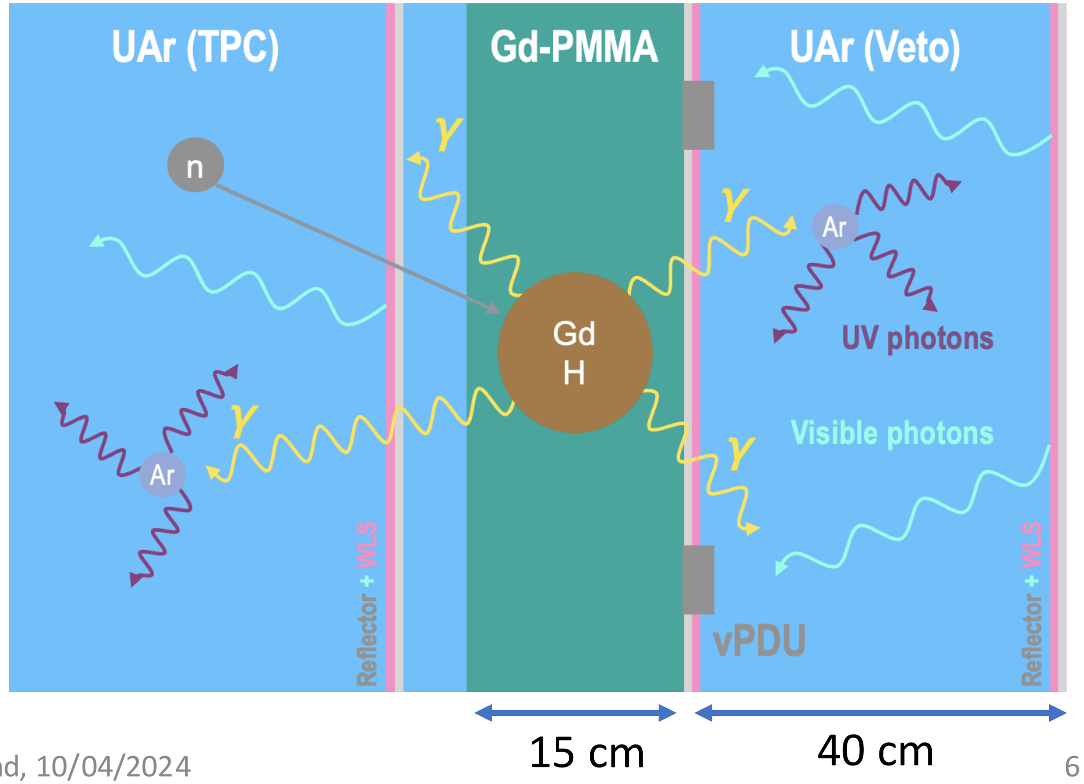
wangyi90@ihep.ac.cn

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:



- 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%.

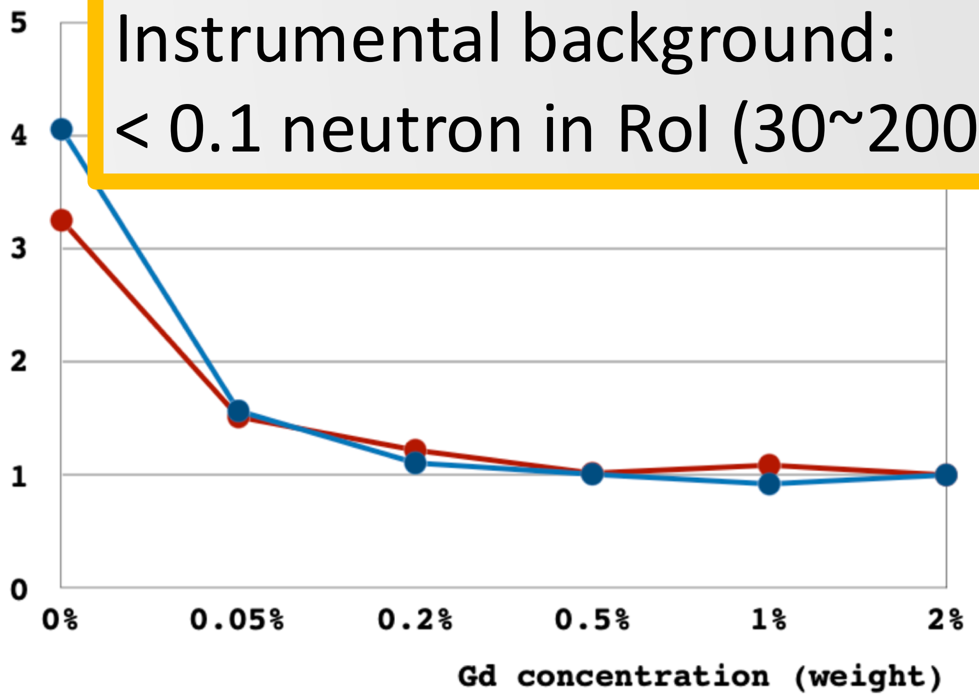


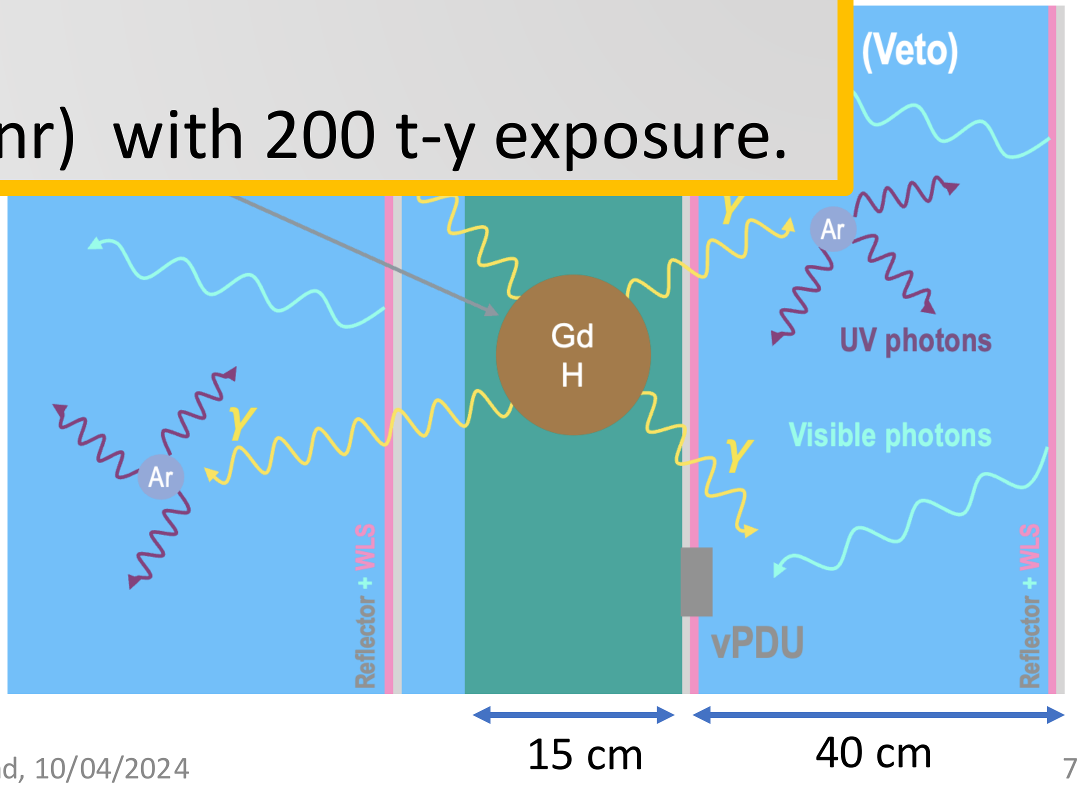
Active Neutron Veto

- Gd-PMMA -> Hydrogen + Gadolinium:
  - Hydrogen -> single γ ~2.2 MeV;
  - Gadolinium -> multiple γ upto 8 MeV.
- Produc
  (40 cm

- Light yield assumptions:
  - TPC: 10 p.e./keVee;
  - Veto: 2 p.e./keVee.
- Gd concentration: 1 wt%;
- Thickness of Gd-PMMA: ≥ 15 cm;
  ency ~5%.

For the case of DarkSide-20k, with Gd-PMMA 4-pi covered.
Instrumental background:
< 0.1 neutron in RoI (30~200 keVnr) with 200 t-y exposure.





The Development of Gd-PMMA

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

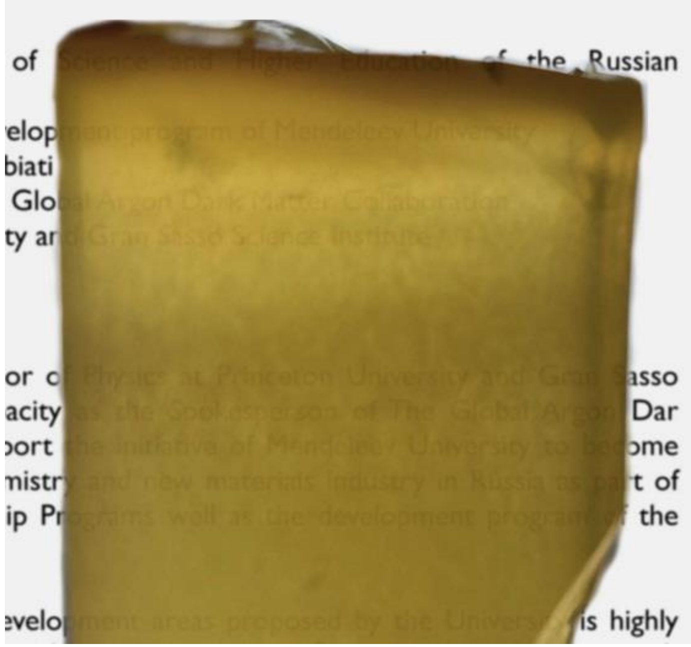
Development of Recipe

- 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

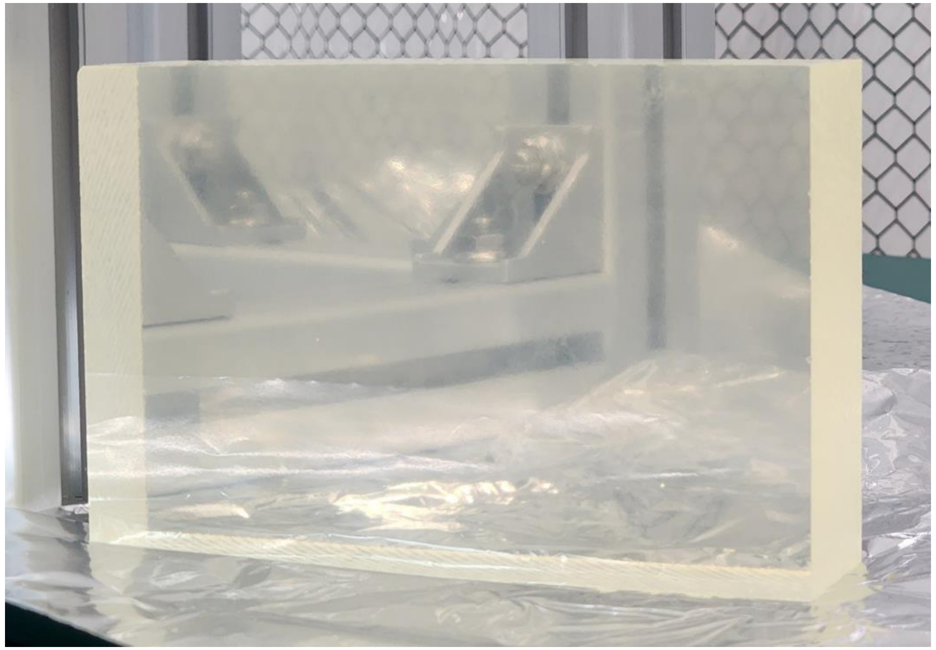
2024 JINST 19 P09021

$Gd(acac)_3$ recipe



Materials 2021, 14, 3757

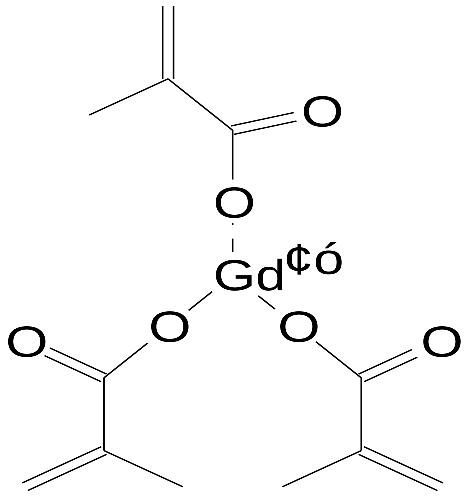
$Gd(MAA)_3$ recipe

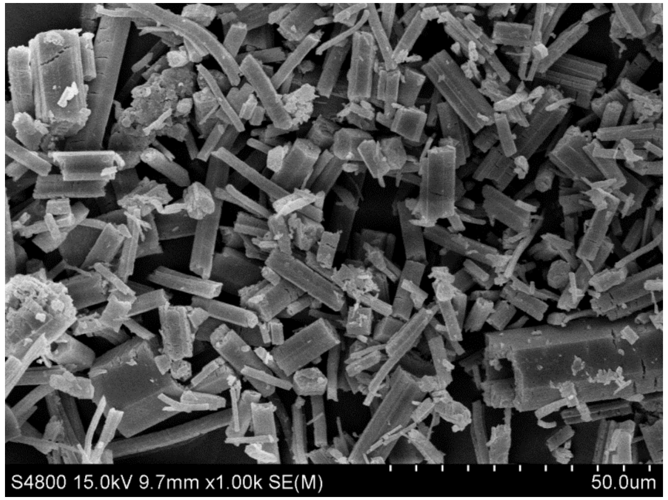


Rare metals 2010 34(4):568-573

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).





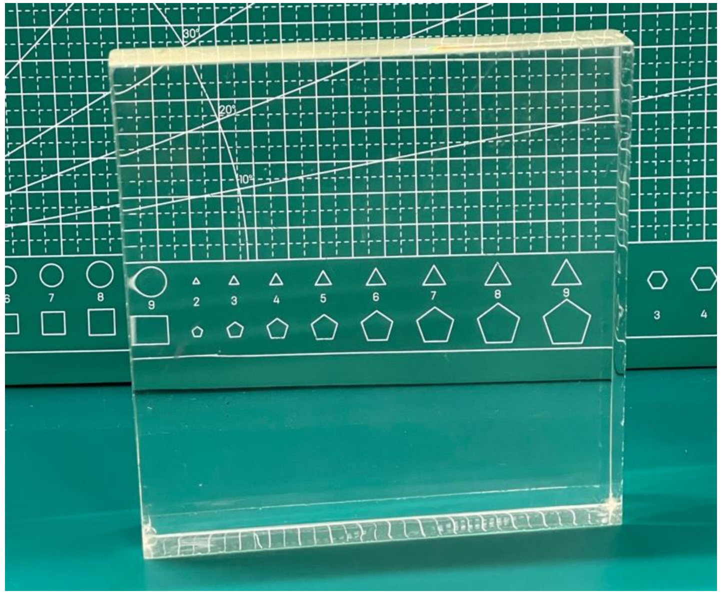
The dissolving recipe was developed by Yangzhou University & IHEP:

揚州大學 YANGZHOU UNIVERSITY

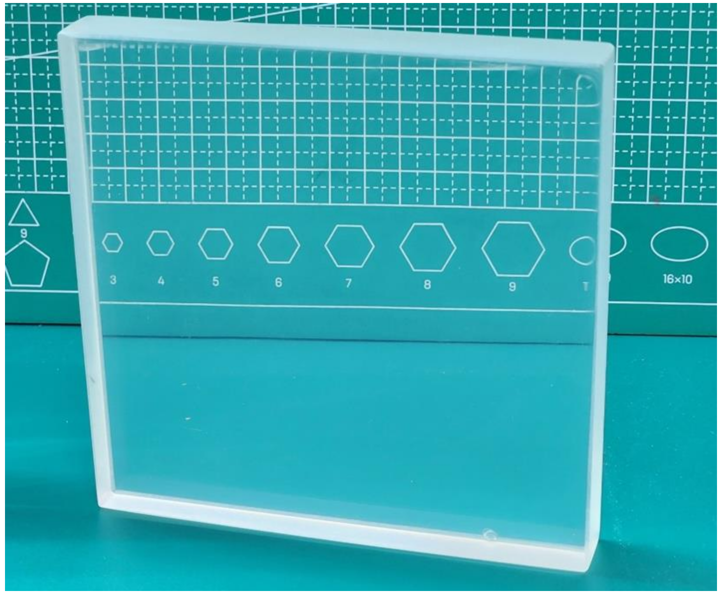
中國科學院高能物理研究所 Institute of High Energy Physics Chinese Academy of Sciences

Gd-PMMA

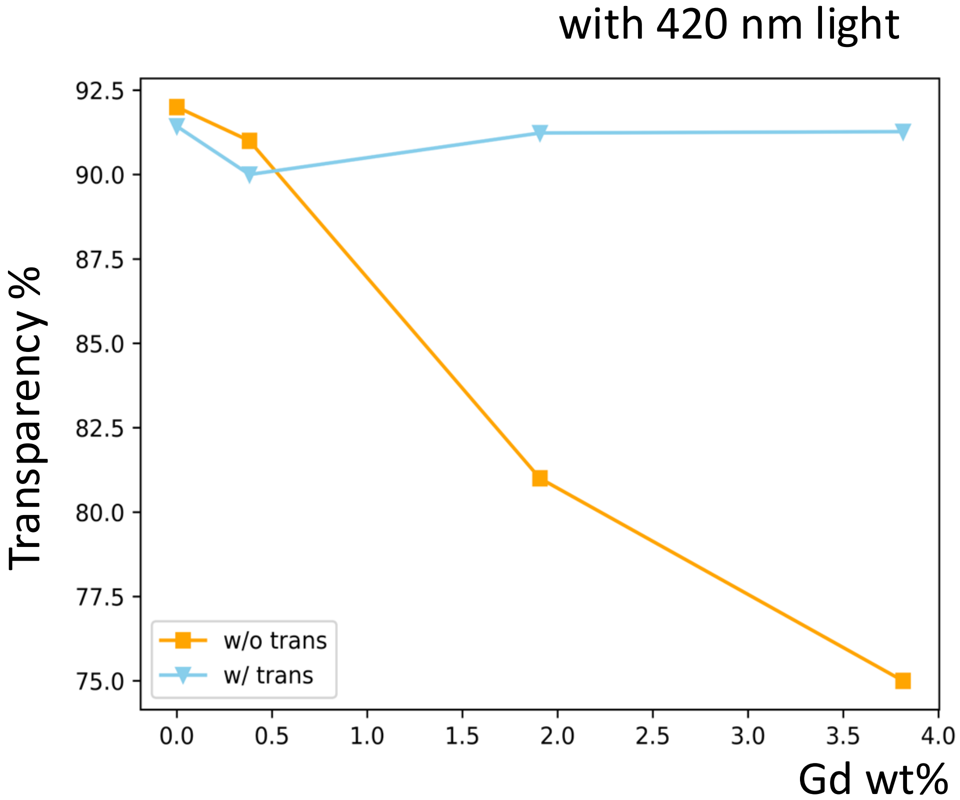
- Polymerization of $Gd(MAA)_3$ doped liquid MMA;
- A dedicated initiator recipe was developed to prevent self-inhibition and implosion during polymerization;
- High optical transparency is achievable.



High optical transparency



Normal optical transparency



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)

Preliminary

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

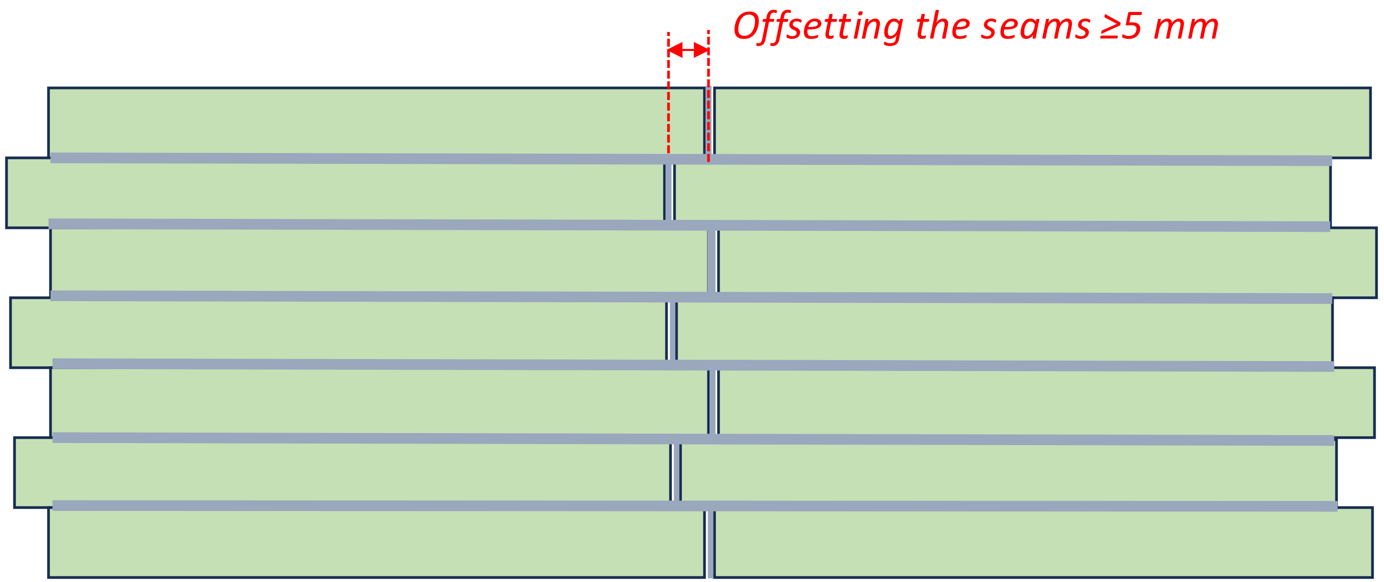
Radiopurity assay is still ongoing at LNGS.

Production of Large Dimension Panels

- Developed recipe has been implemented to an industrial scale production line.
- Dimension options for single-cast sheet (largest so far):
  - ➢For high optical transparency: 100 cm x 70 cm x 4 cm;
  - ➢For normal optical transparency: 200 cm x 200 cm x 2 cm.

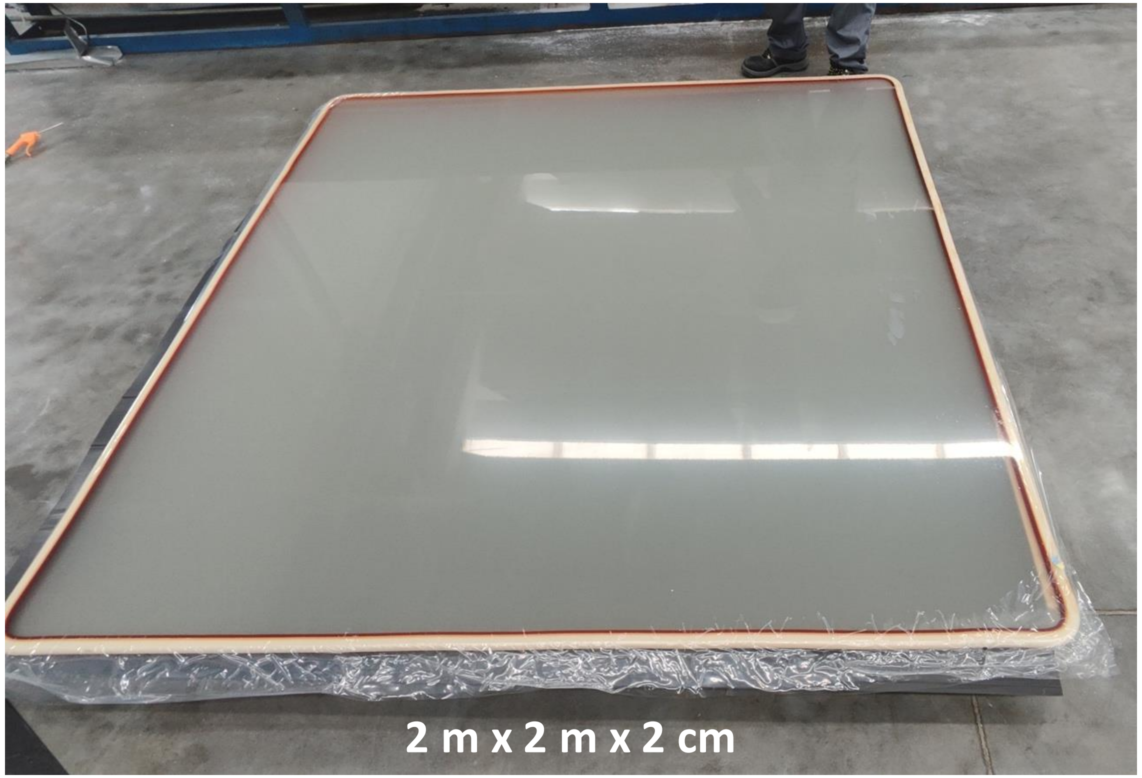
Production of Large Dimension Panels

- Developed recipe has been implemented to an industrial scale production line.
- Dimension options for single-cast sheet (largest so far):
  - ➢For high optical transparency: 100 cm x 70 cm x 4 cm;
  - ➢For normal optical transparency: 200 cm x 200 cm x 2 cm.
- A bonding and lamination procedure has been developed. The adhesive uses the same ingredients as Gd-PMMA, specifically $Gd(MAA)_3$ dissolved in MMA.

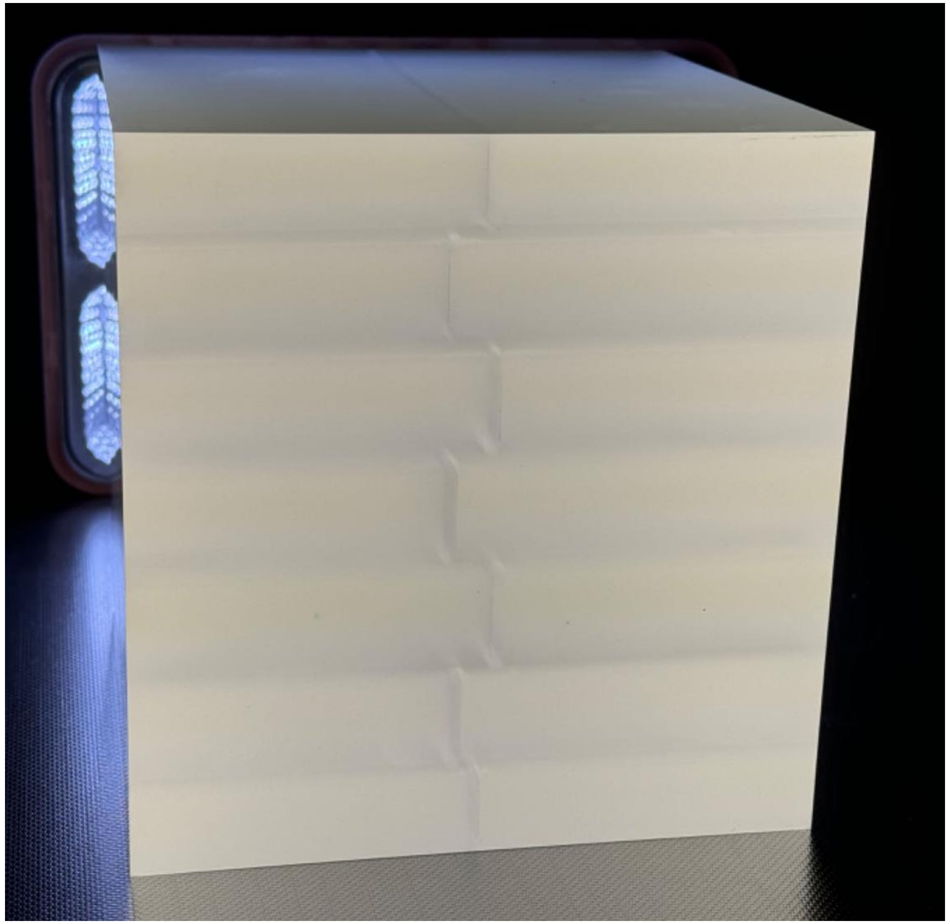


Production of Large Dimension Panels

- The first full-dimension Gd-PMMA single-cast panel, was manufactured at Donchamp in China in spring 2024.



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

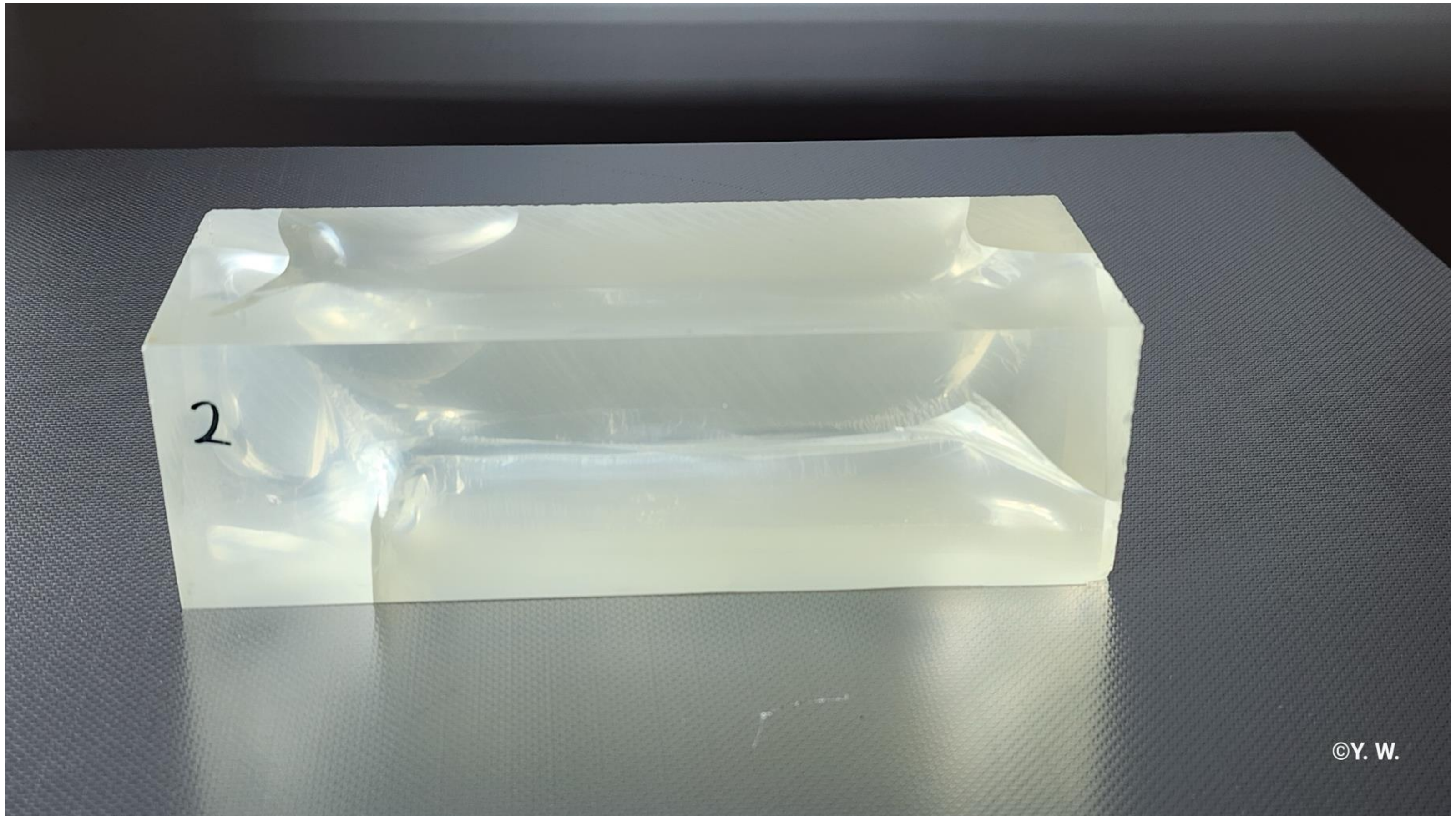


- A relatively large bonded & laminated sample, measuring 80 cm x 80 cm x 16.4 cm, has been produced. This sample will be used to study the large piece anneal at the University of Alberta.

- The next step is finalizing the annealing procedure, which is the most important step for mitigating residual stress in applications at low temperatures.

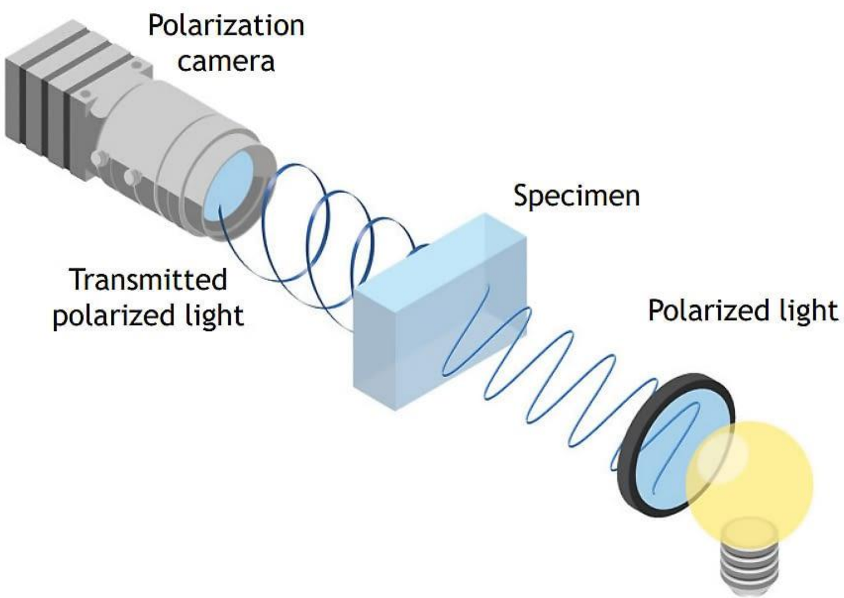
What if there are stresses ?

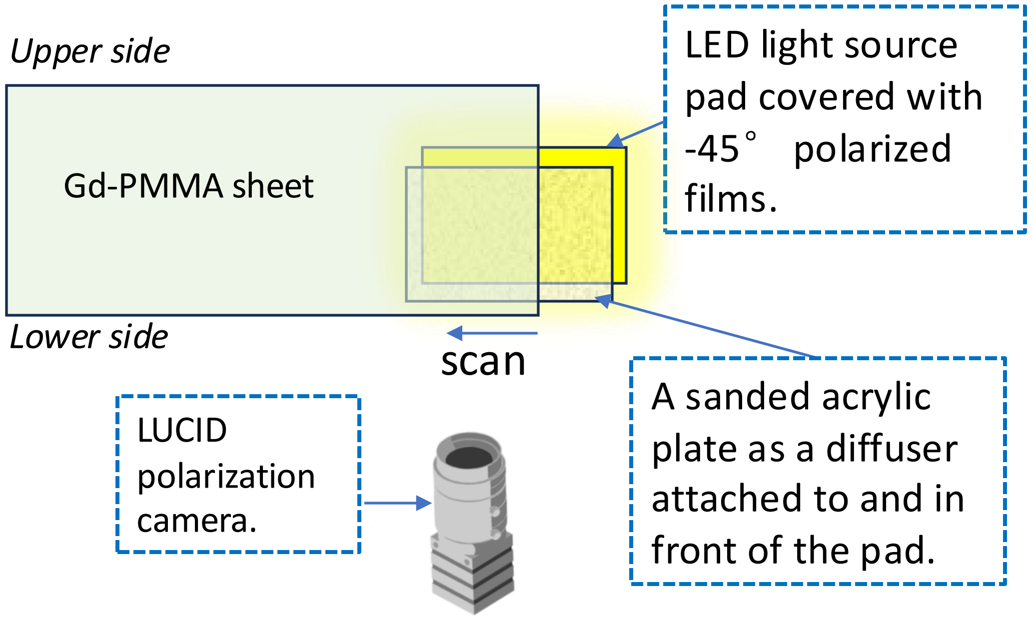
- Acrylic will crack if we do not carefully manage the stresses.

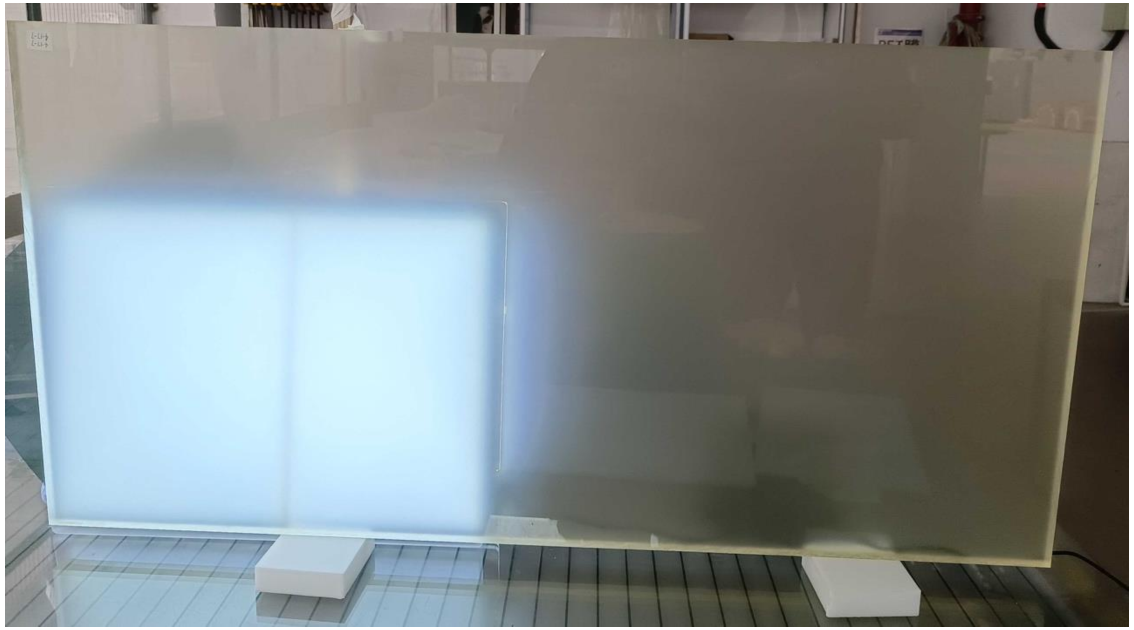


Stress Measurement

- 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.





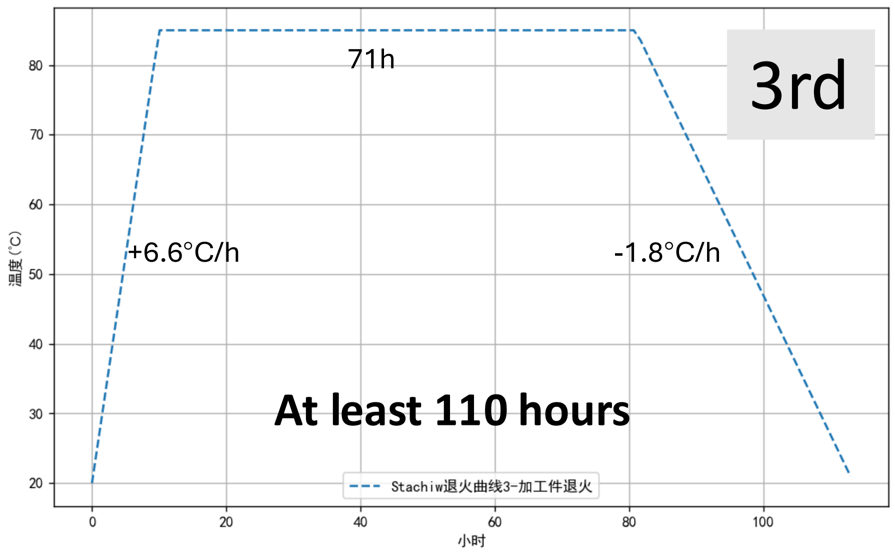


Annealing

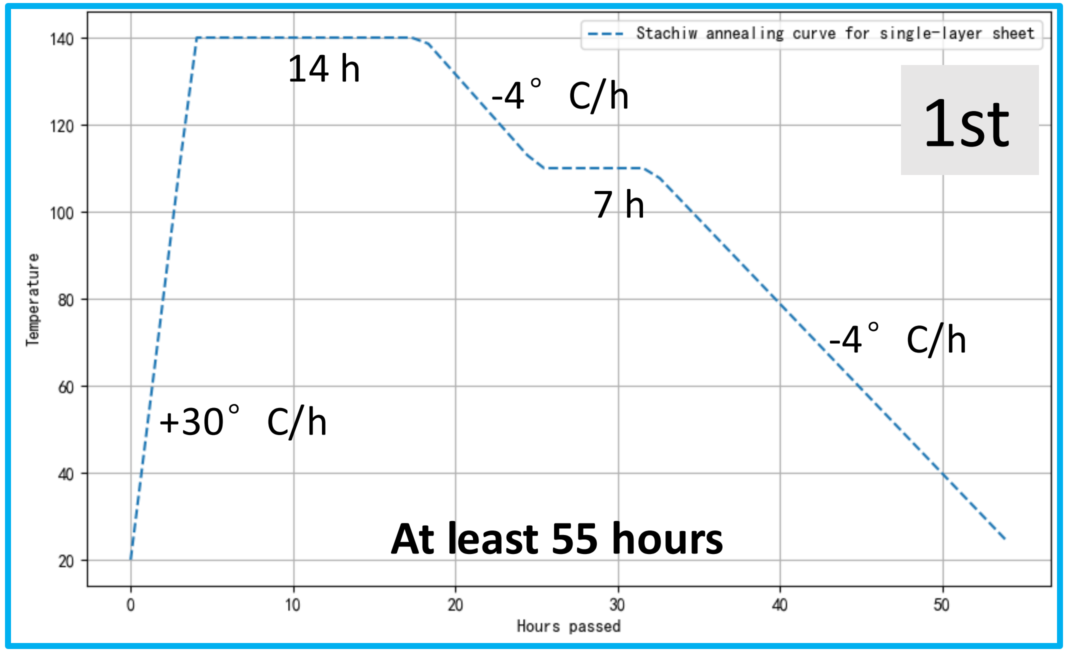
- 1st annealing for single-cast sheet;
- 2nd annealing for bonded & laminated panel;
- 3rd annealing after machining.

Stachiw's handbook ISBN 1-930536-15-1

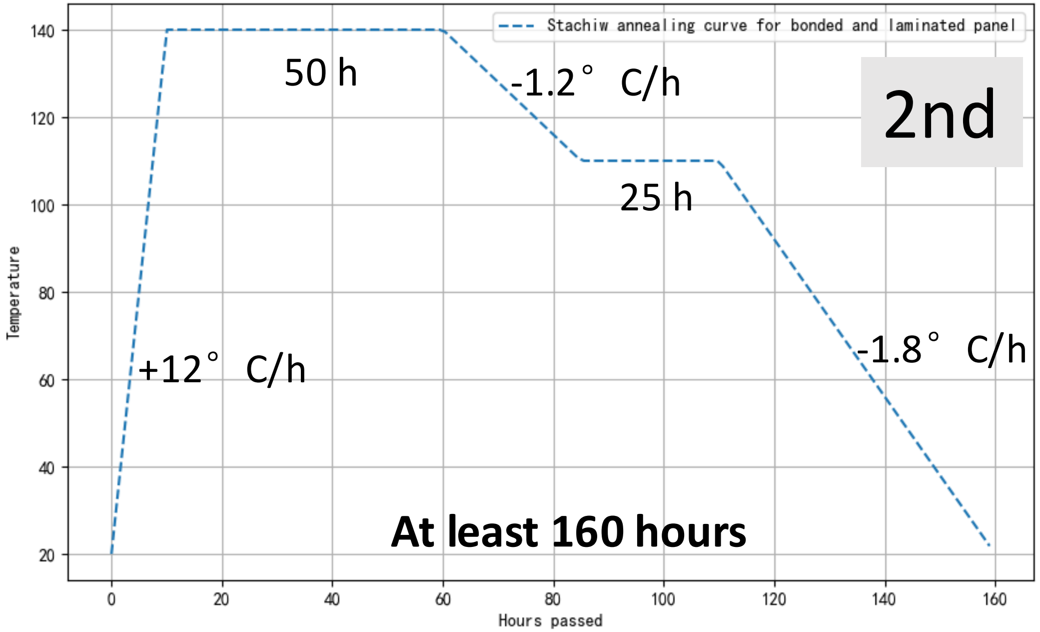
Stachiw annealing curve machined panel



Stachiw annealing curve for single-layer sheet

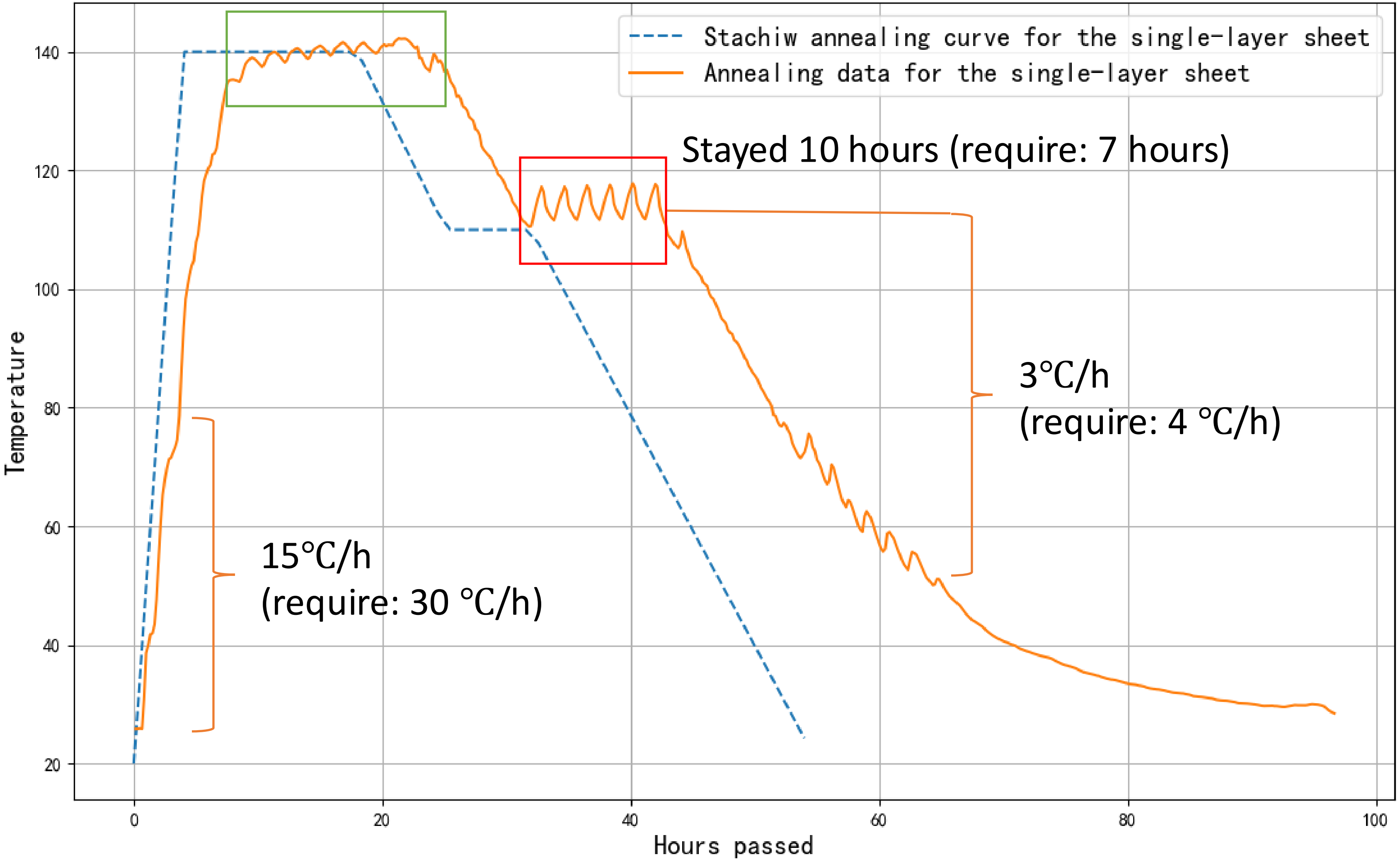


Stachiw annealing curve for bonded & laminated panel

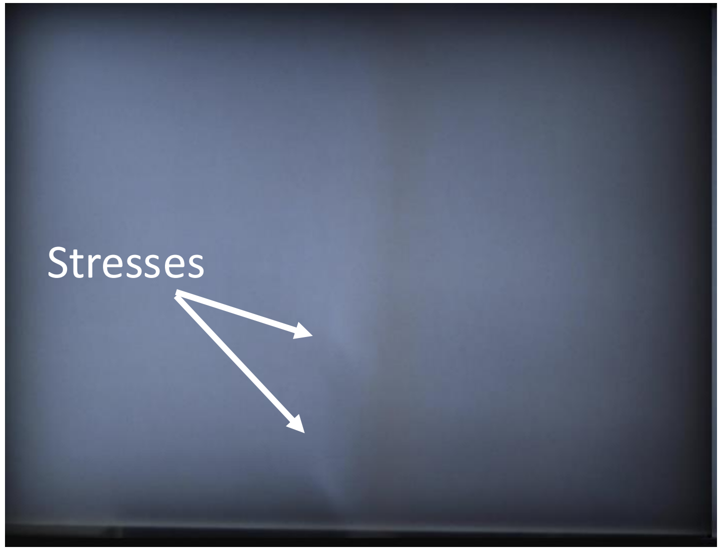


Annealing for Single Sheet

Stayed 14 hours (require: 14 hours)

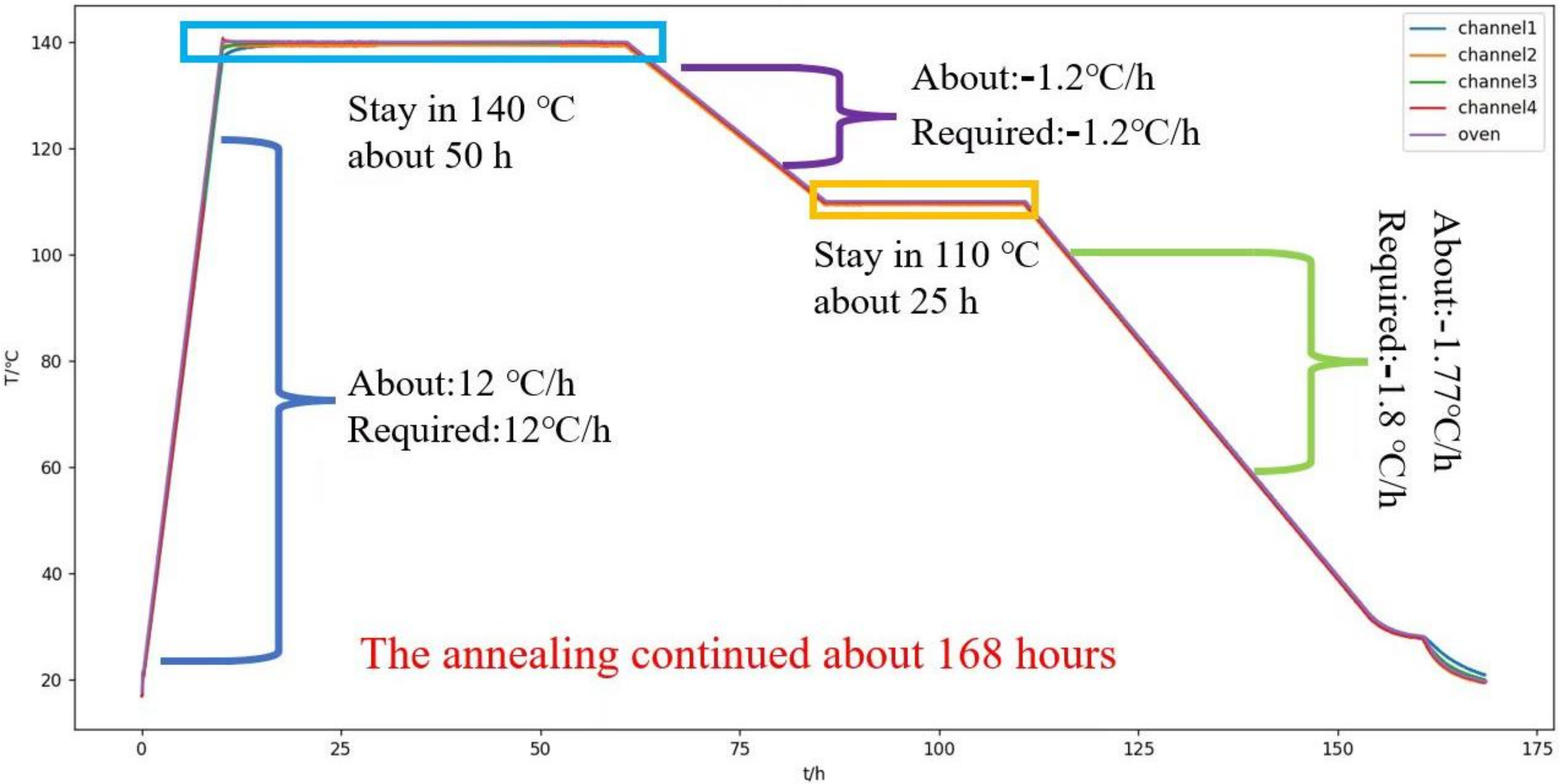


Before annealing



After annealing

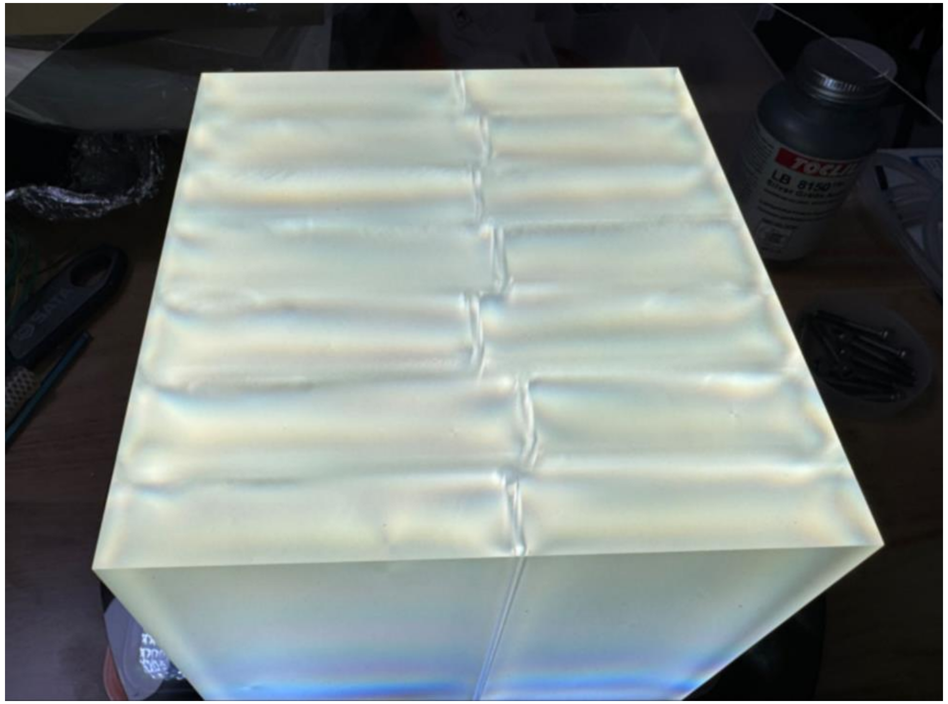
Annealing for 15 cm Thick Piece



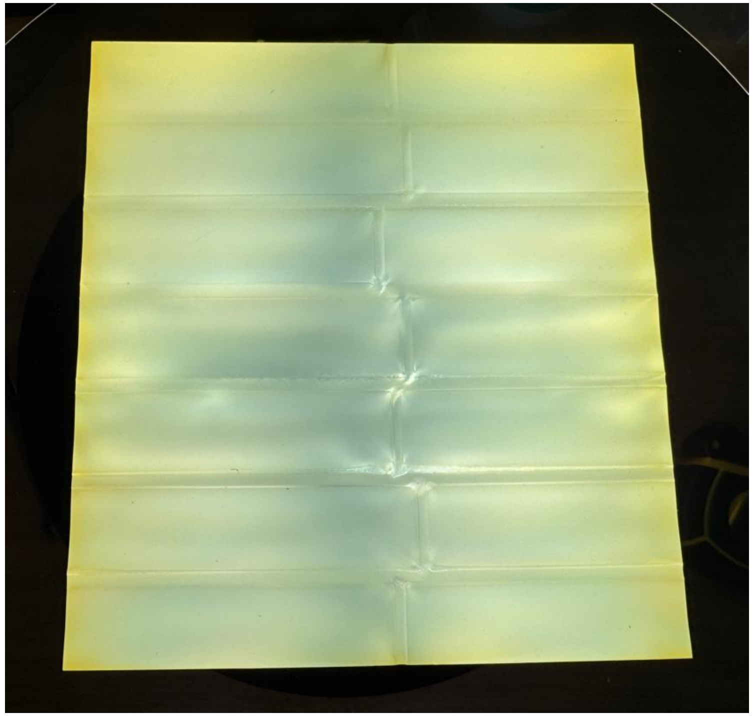
Annealing for 15 cm Thick Piece

- The residual stresses are significantly mitigated after the annealing process.

Before annealing

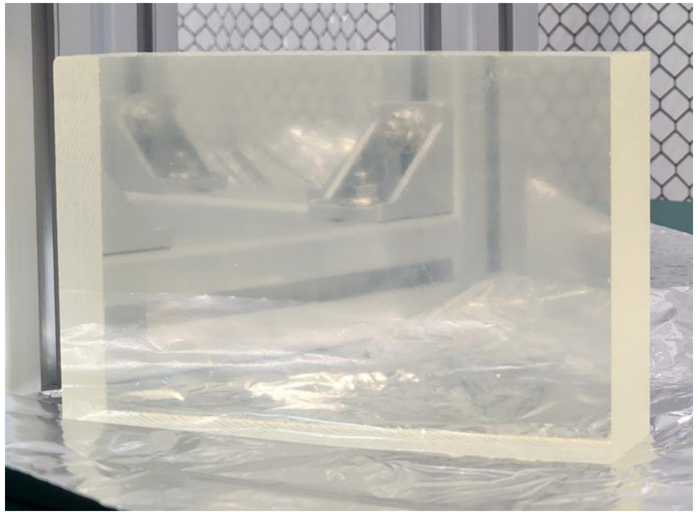


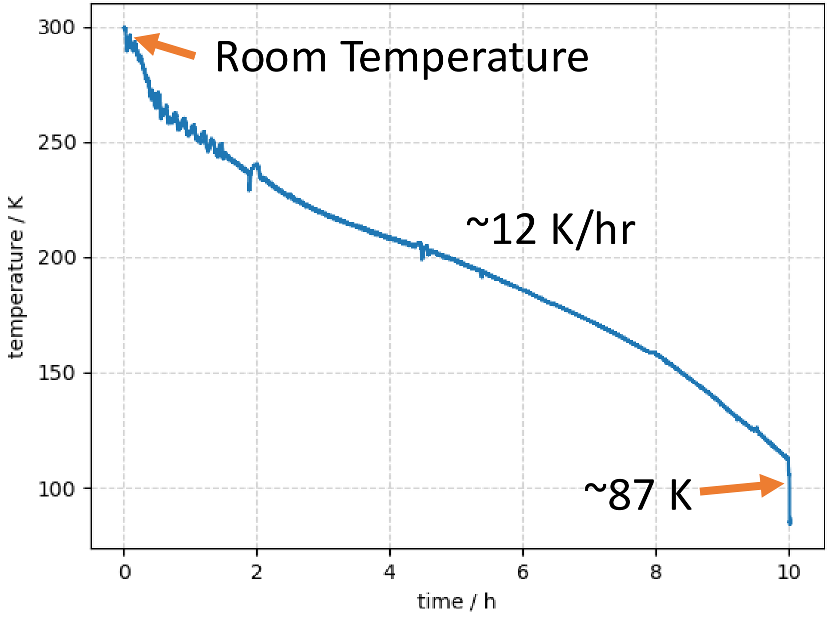
After annealing

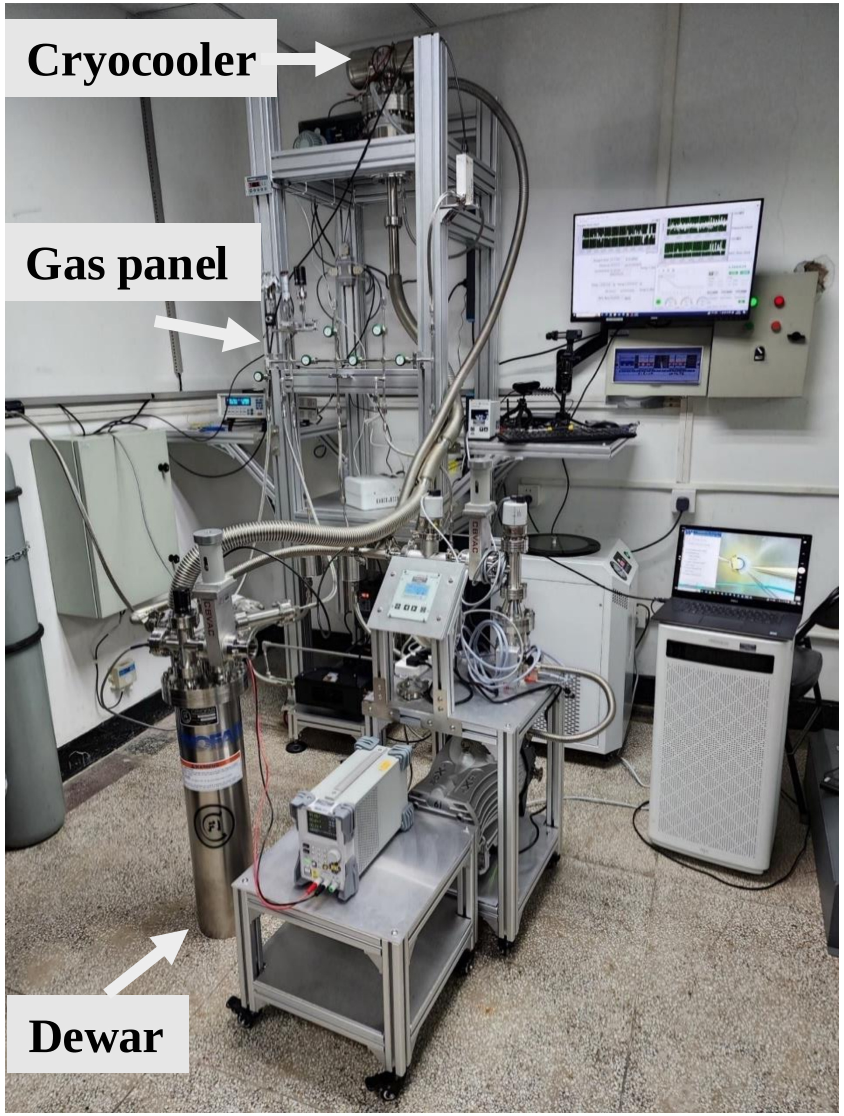


Cooling Test

- Study the cooling speed that can safely put Gd-PMMA in LAr;
- A test cooling procedure has been performed with a two-layer laminated Gd-PMMA sample (not annealed).
- 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.

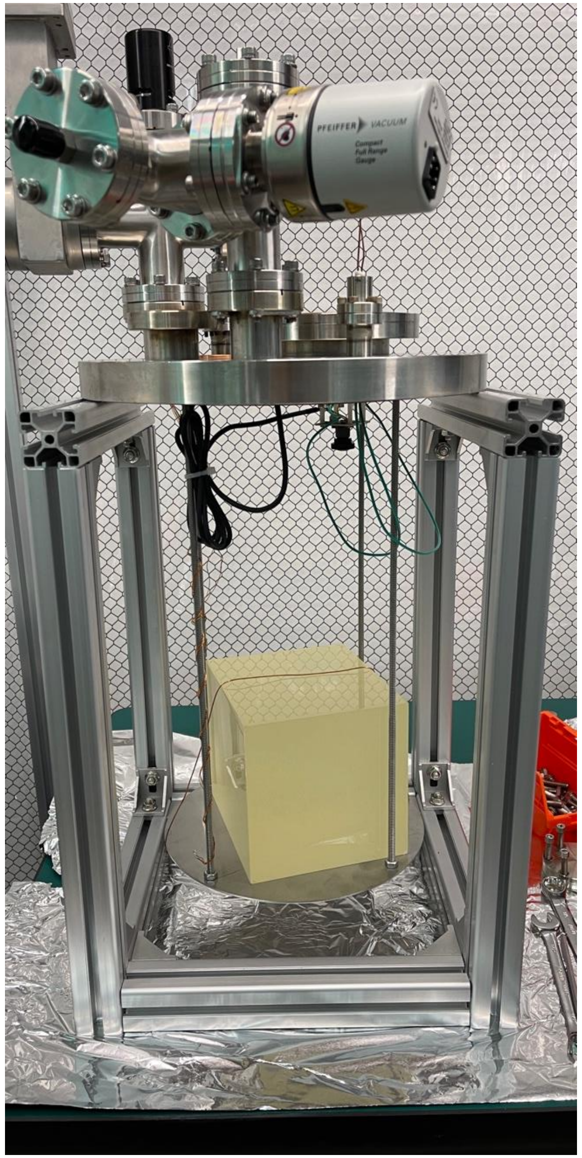


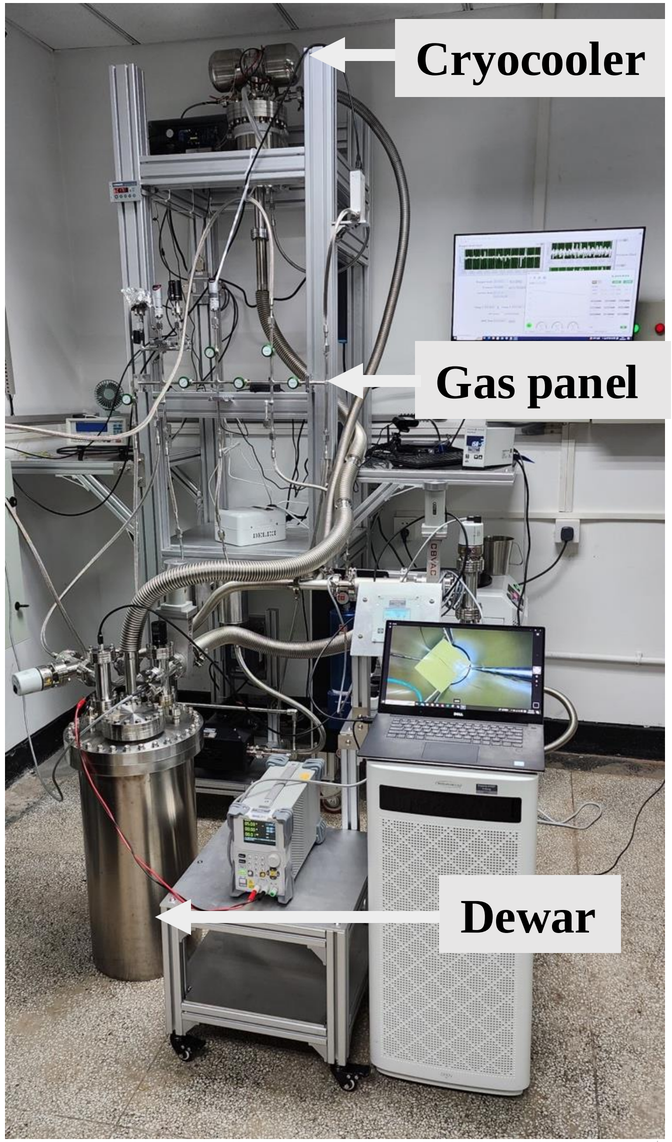




Cooling Test for the 15 cm Thick Sample

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





Summary & Discussion

- Dual-phase Ar TPC is a promising technique for background-free DM searches.
- A novel active neutron veto detector with Gd-PMMA was proposed.
- 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.