Development of a New ^{3}He Cryogenic Target within the ATRACT Project

M.Assié, M. Pierens, A. Barrière, M. Le Bihan, P. Duthil, H. Saugnac, S. Blivet, P. Sebaoun, L. Velasquillo, E. Picchi, D. Beaumel, Y. Blumenfeld, F. Hammache, N. De Séréville, V. Girard-Alcindor

presented by Antoine Barrière

Colloque GANIL 2026

Laboratoire de Physique des 2 infinis Irène Joliot-Curie

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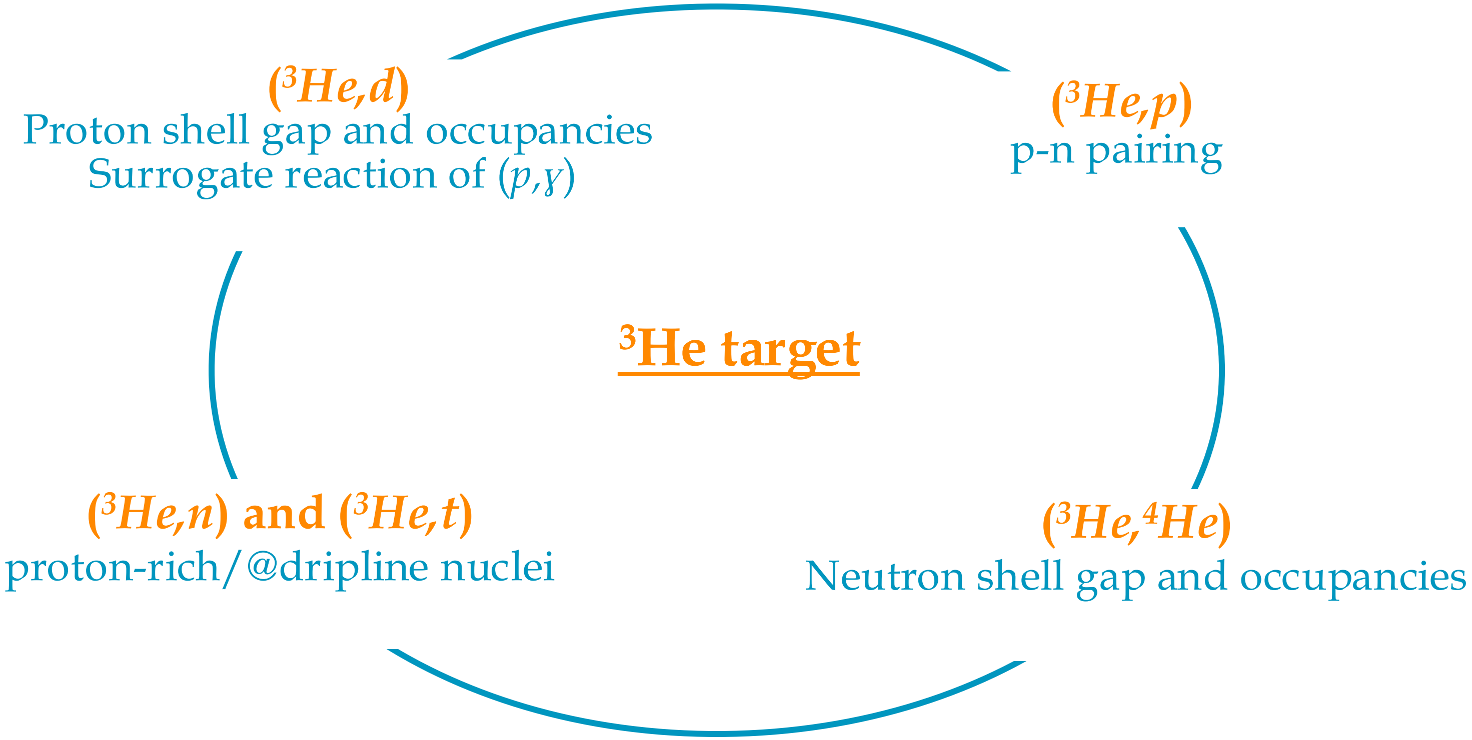
Motivations : transfert reactions in inverse kinematics with an ^{3}He target

Direct reactions (and especially **transfer reactions**) are unique tools for probing **single-particle** and **collective properties**, and their evolution across the nuclear chart.

For inverse kinematics reactions, **many H_2 and D_2 targets** were developed, whereas **only a few ^{3}He targets** are available.

There are, however, strong interests in using such targets:



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There are, however, strong interests in using such targets:

(^{3}*He*,*d*)
Proton shell gap and occupancies
Surrogate reaction of (p,γ)

(^{3}*He*,*p*)
p-n pairing

<u>^{3}He target</u>

(^{3}*He*,*n*) and (^{3}*He*,*t*)
proton-rich/@dripline nuclei

(^{3}*He*,^{4}*He*)
Neutron shell gap and occupancies

ATRACT stands for New <u>A</u>venue of <u>T</u>ransfer <u>R</u>eactions with <u>A</u>ctive and <u>C</u>ryogenic ^{3}He <u>T</u>argets
This project aims at developing thick ^{3}He targets > 10^{20} atoms/cm^{2}

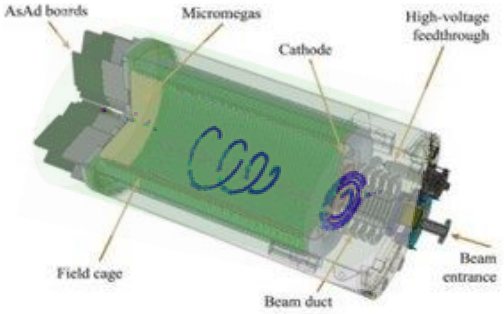
Available (or close to) thick ^{3}He targets

Active targets

AT-TPC @FRIB

^{3}He areal density > **10^{20} at/cm^{2}**

- Limited range of particles
- Not compatible with gamma sphere/array (e.g. AGATA)
- Well adapted for low E_c(ejectile)



ATRACT TPC

Expected ^{3}He areal density : **$3 . 10^{20}$ at/cm^{2}**

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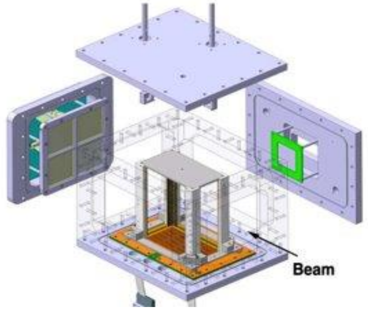

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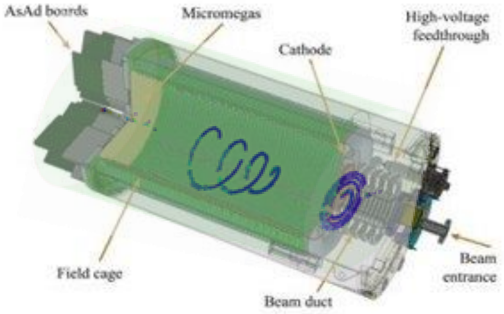

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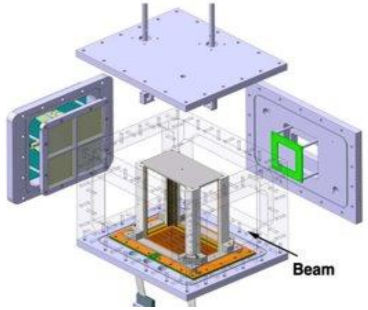

^{3}He implanted targets on W and Al

^{3}He areal density : **$5\text{-}7 \cdot 10^{18}$ at/cm^2**

- Background from the thick backing, more favorable to the ($^3He,n$) reaction

- Non-negligible ^{3}He leak during beam time

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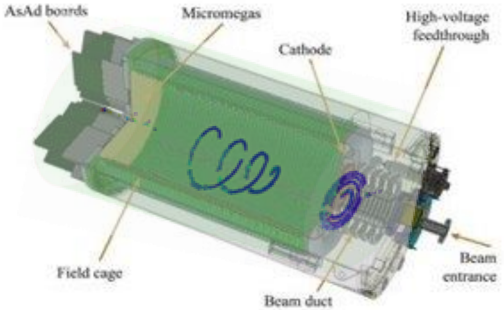

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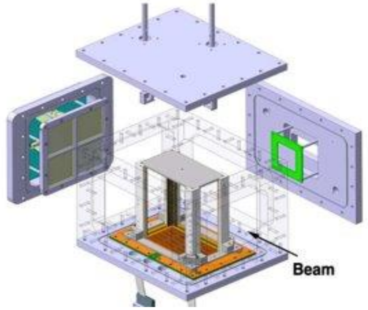

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Cryogenic targets

HeCTOr (first attempt)

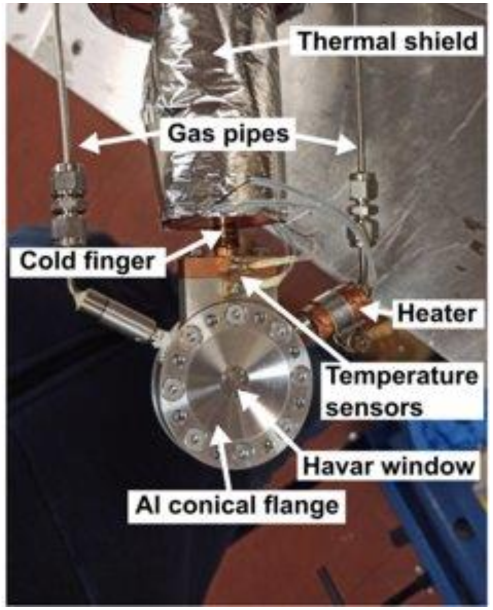
^{3}He areal density : ~ **10^{20} at/cm^2**

=> see next slides

CTADIR

^{3}He areal density : ~ **10^{20-21} at/cm^2**

- Target body in Al
- New cryocooler (without LHe)
- Thick Havar window , with a small radius



ATRACT Cryogenic target

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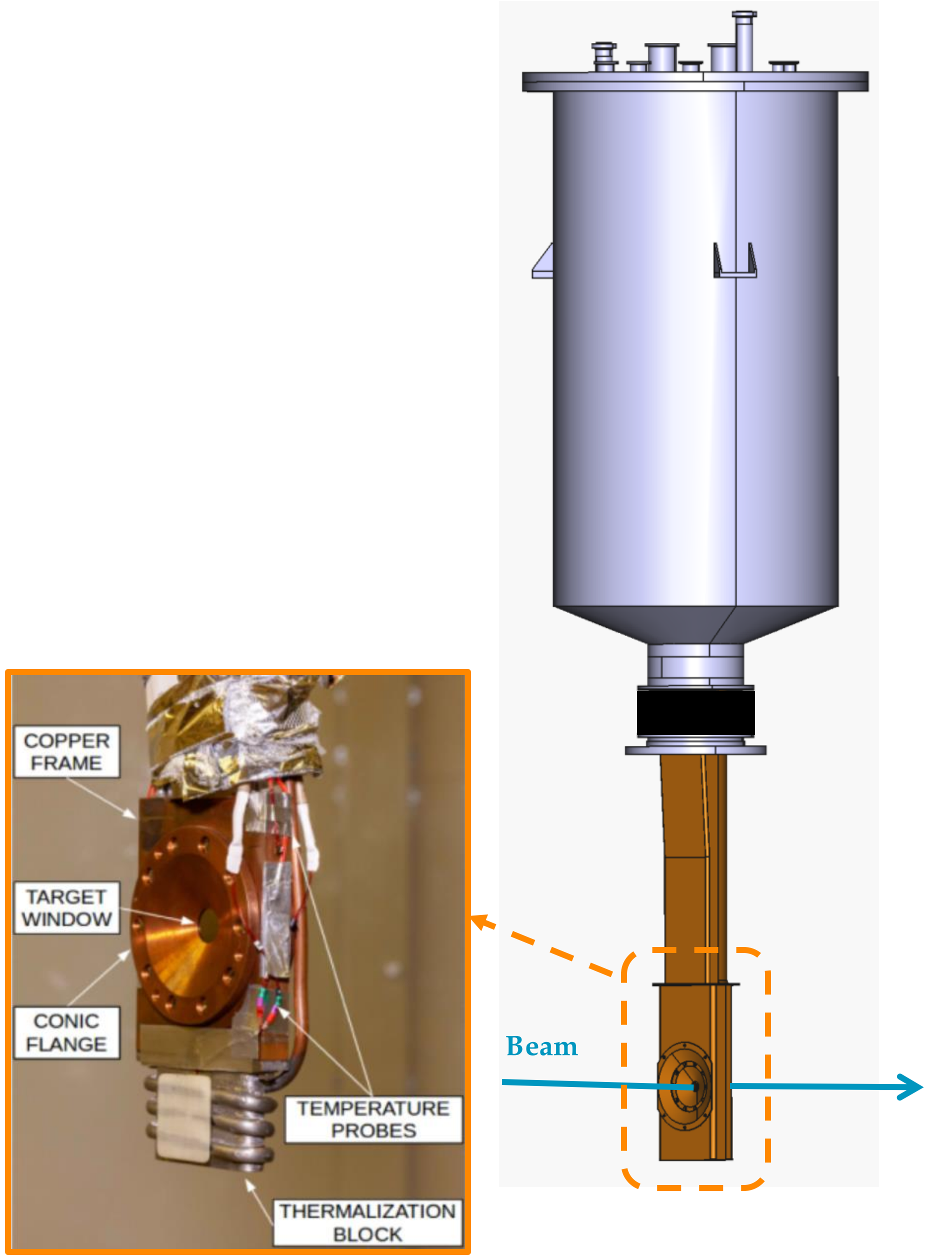
Example of the HeCTOr cryogenic target

Target used during a **MUGAST-AGATA-VAMOS** campaign

^{46}Ar(^{3}*He,d*)^{47}K@10MeV/u *(submitted to PRL)*

F. Galtarossa et al, NIMA (2022)

- Ø 16 mm
- Opening angle: 130 deg.
- Havar windows: 3.8um
- T ~ 6-7 K. / P up to 1 bar
- Equivalent thickness 2 mg/cm^2
- ^{3}He recycling 3.5 10^{20}at/cm^2
- LHe open circuit



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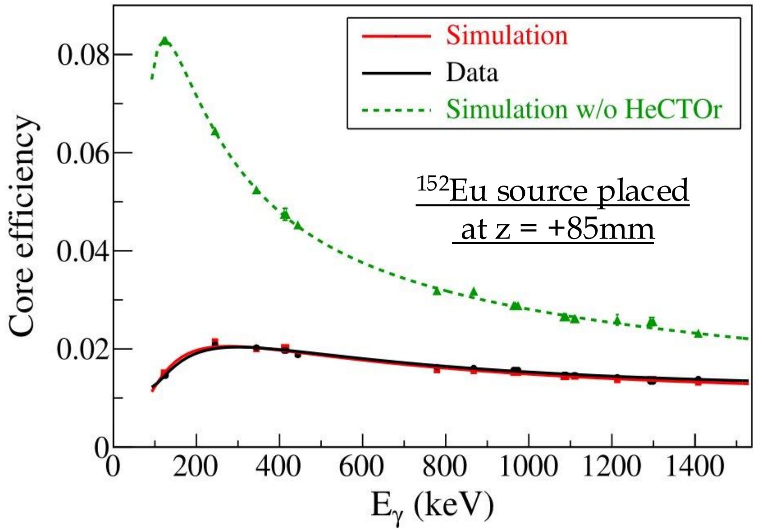
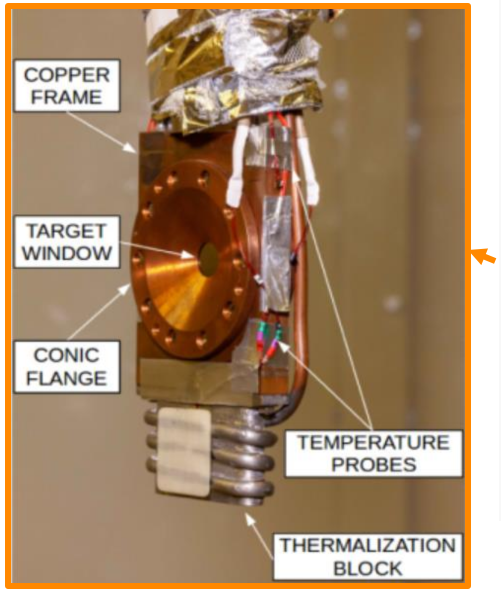
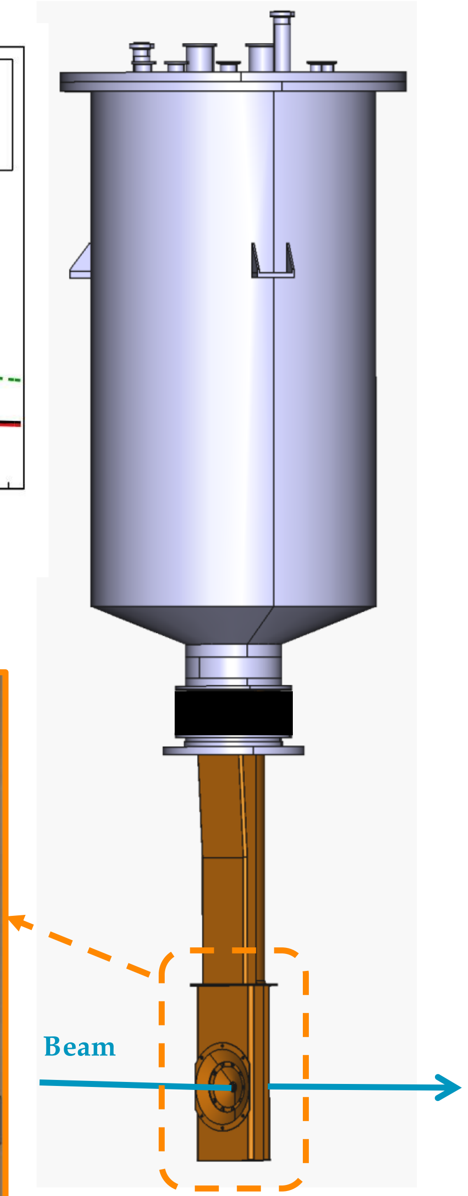
<u>Identified limitations:</u>

- Thick target cell (3.0 mm)
- Havar windows => strong contribution to the background
- Target body and heat shield were in copper => gamma absorption







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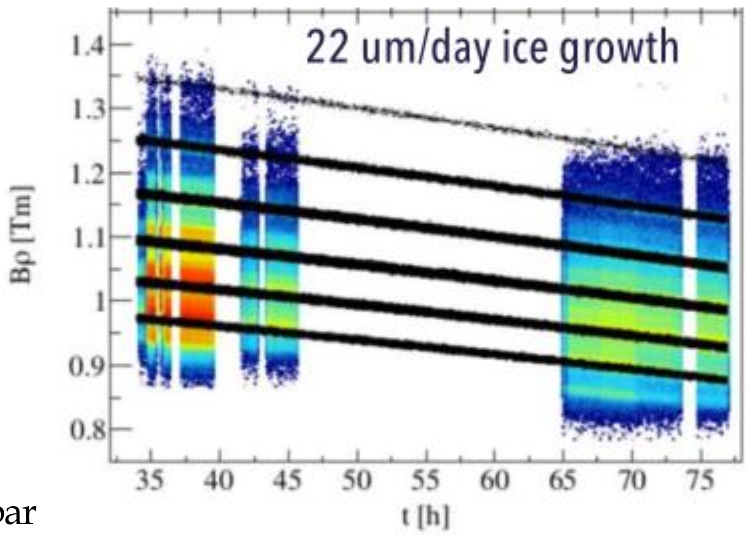

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- Havar windows => strong contribution to the background
- Target body and heat shield were in copper => gamma absorption
- Ice layer with a growth rate of 11µm/day/window with P ~ 10^{-6} mbar

=> deuteron with E_c < 1.5 MeV do not get out of the target (*)

=>No target-cold mass decoupling was allowed (LHe consomption)

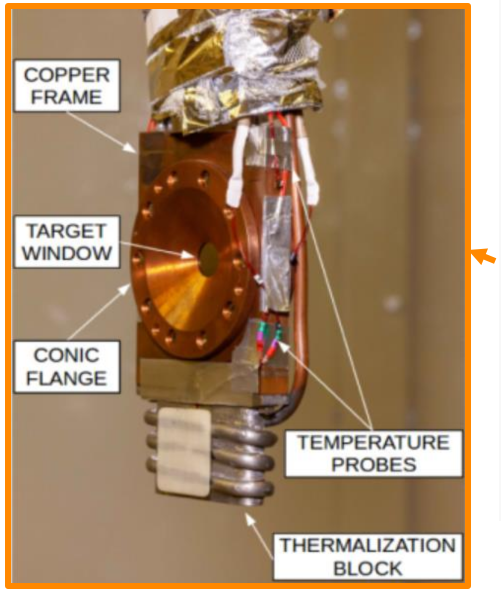
Contributions to the total excited energy resolution:

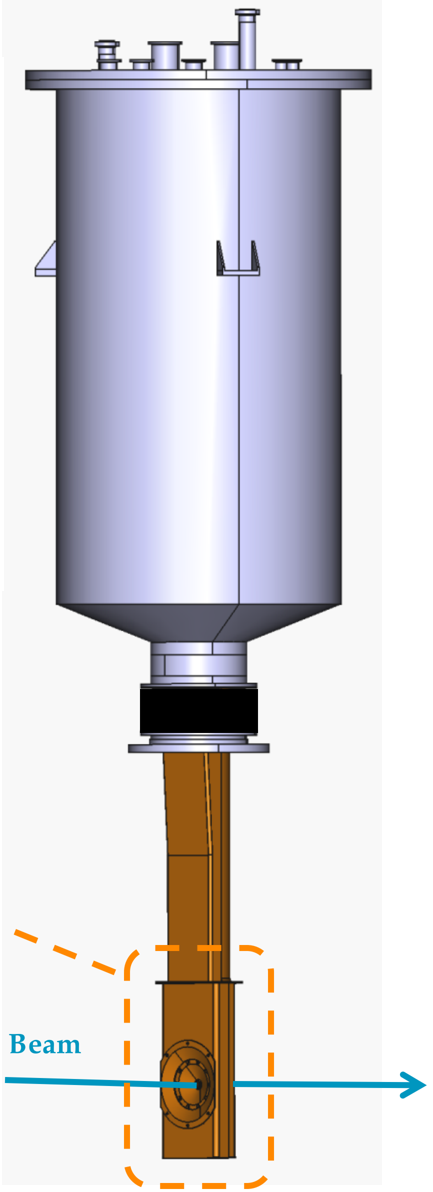
Total E* resolution (FWHM)	**1.3 MeV**
- Target (cell) thickness	**0.8 MeV**
- Havar windows	**0.6 MeV**
- Windows deformation	**0.4 MeV**
- Ice layer	**0.6 MeV**
- Intrinsic resolution (MUGAST)	**<0.1 MeV**

(*)Deuterons @3MeV lose:

270keV in half of the target gas

360keV in the Havar window





Requirements for the ATRACT cryogenic target

The ATRACT cryogenic target will be designed to significantly improve upon the limitations of HeCTOr.

- New window material/thickness : - to reduce **energy losses** ($E_{c,min}$ to go out of the target)
  - to reduce **straggling** (improve E* resolution)
  - with a well-known **profile** when $\Delta P>0$ (improve E* resolution)
  - still **compatible** with the **operational conditions** (ΔP,T,use of He)

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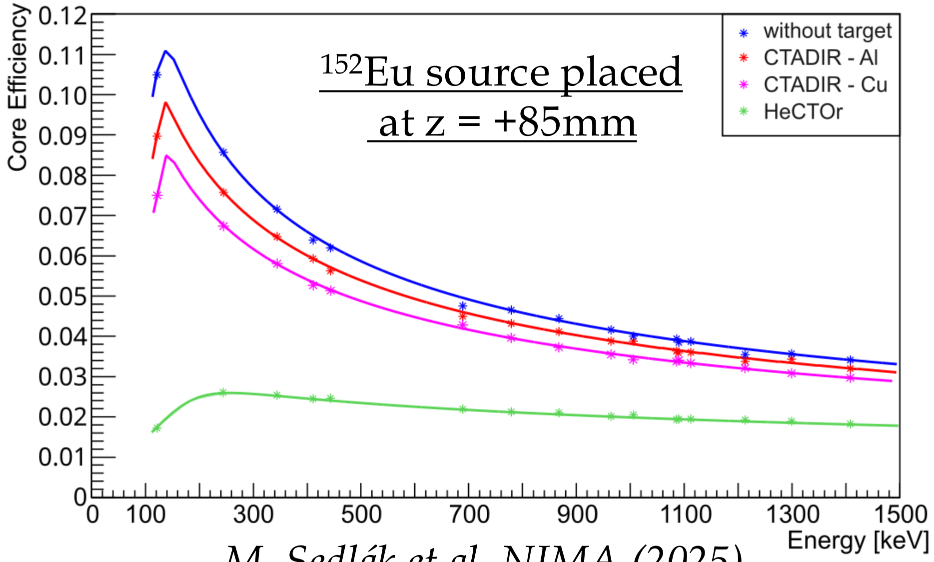

M. Sedlák et al, NIMA (2025)

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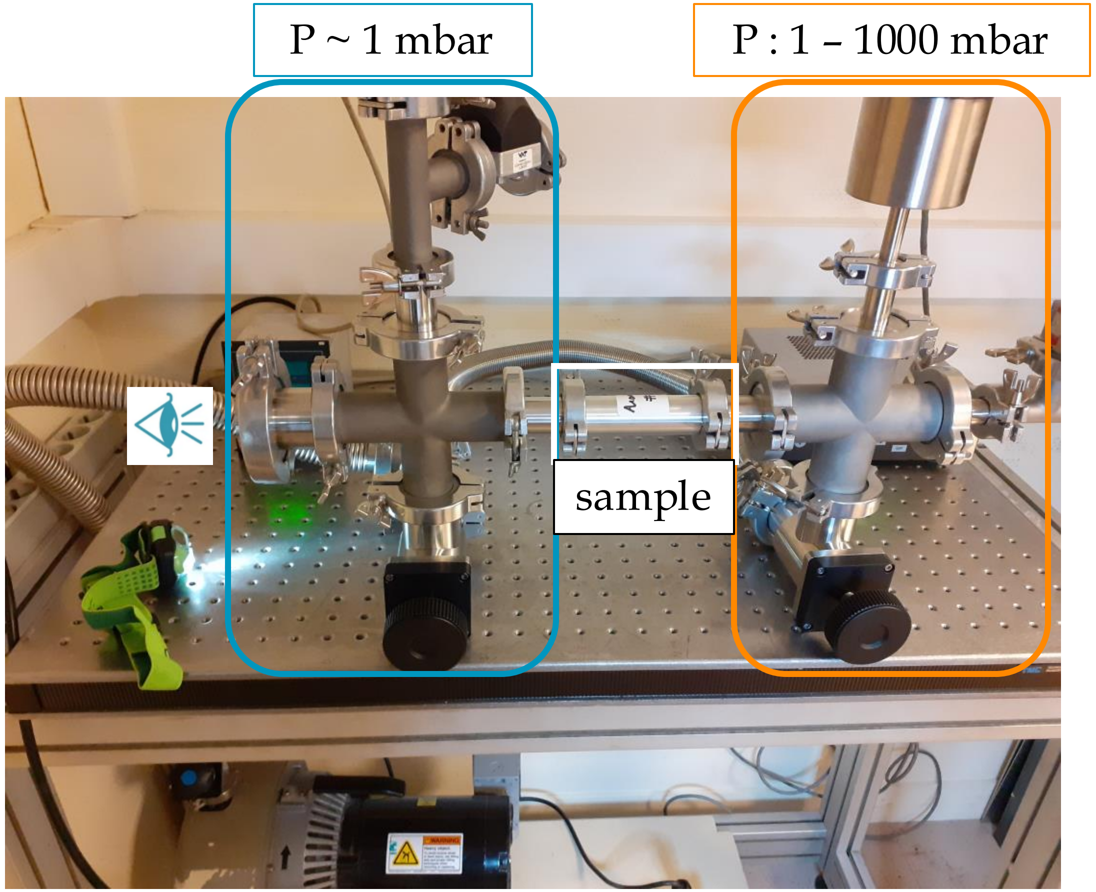
- De-icing protocol : remove ice layer using **continuous** or **sequential** methods

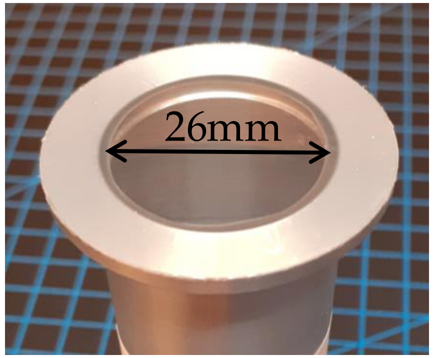
- Cryocooler not using LHe => Pulse Tube : allow for T increases during de-icing phases

Testbench at T_{std} : deformation of the windows



Testbench used to test polymers and technical ceramics at room temperature.

<u>Before this test:</u>



Flat surface

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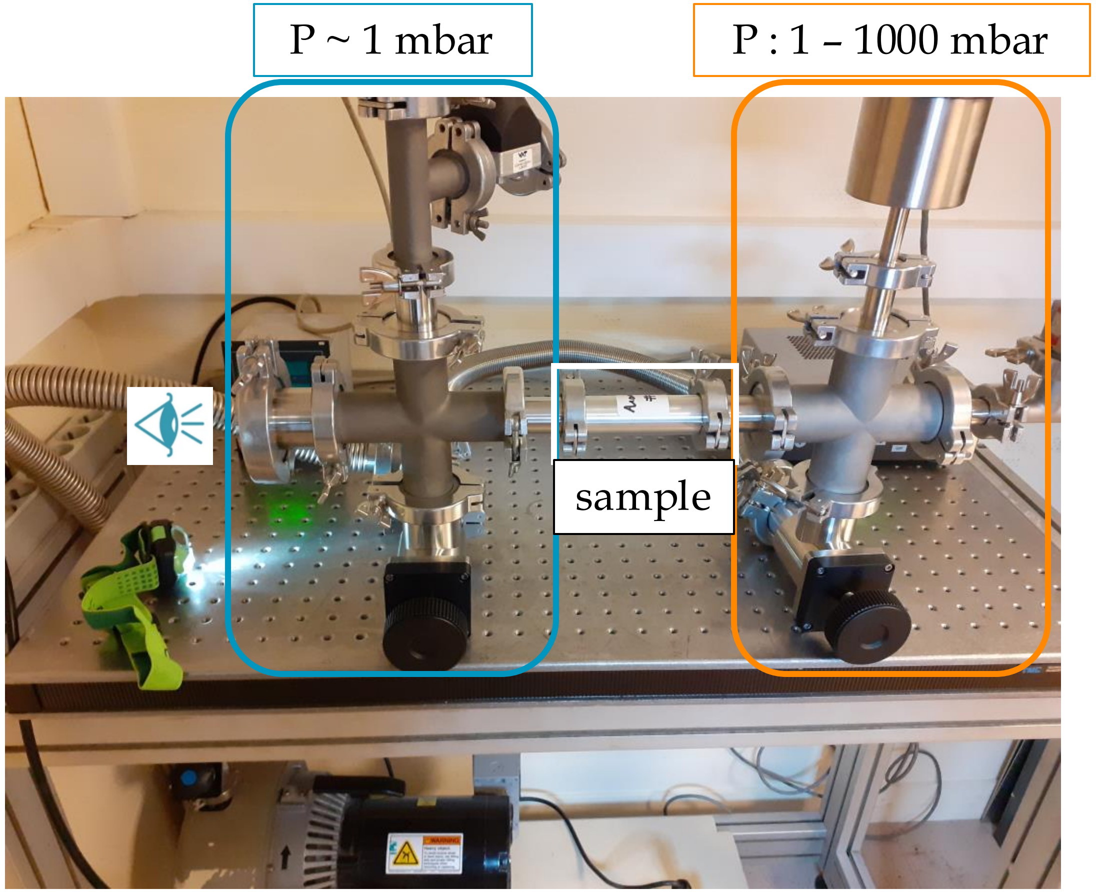

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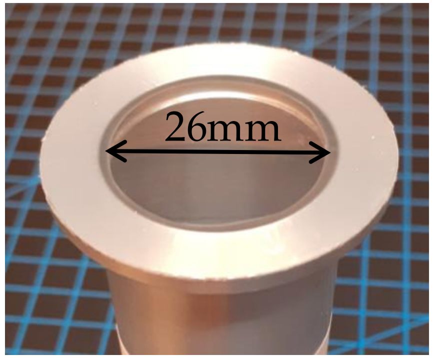

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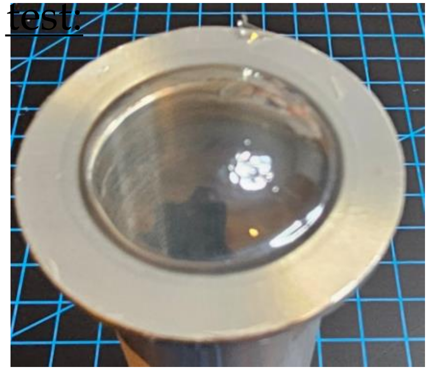

Permanent deformations (*plastification*) are observed for ΔP > 200 mbar.

=> Central deflection of few mm
Kapton(8µm), Mylar(12µm), Toray Aramid(4.4µm)

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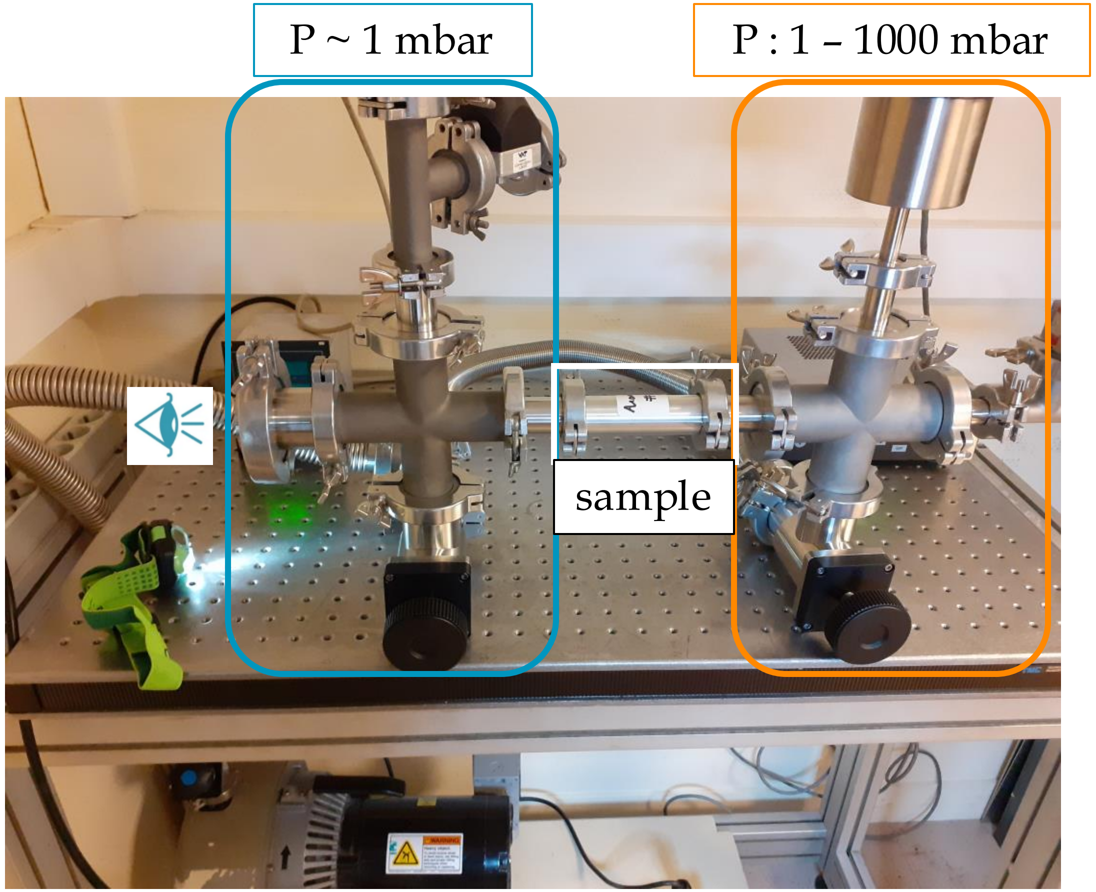

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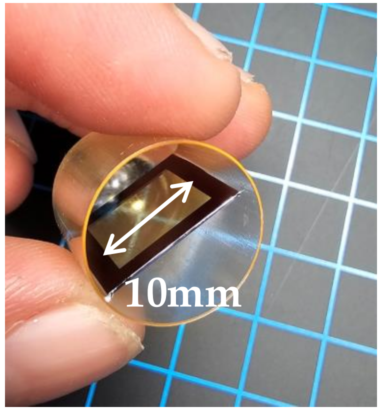
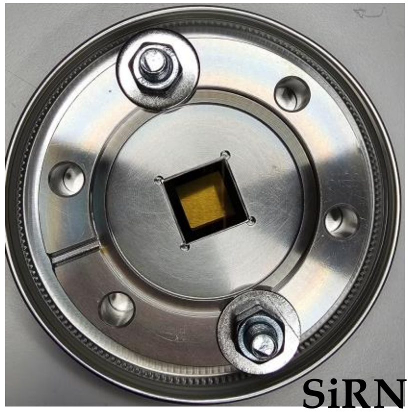
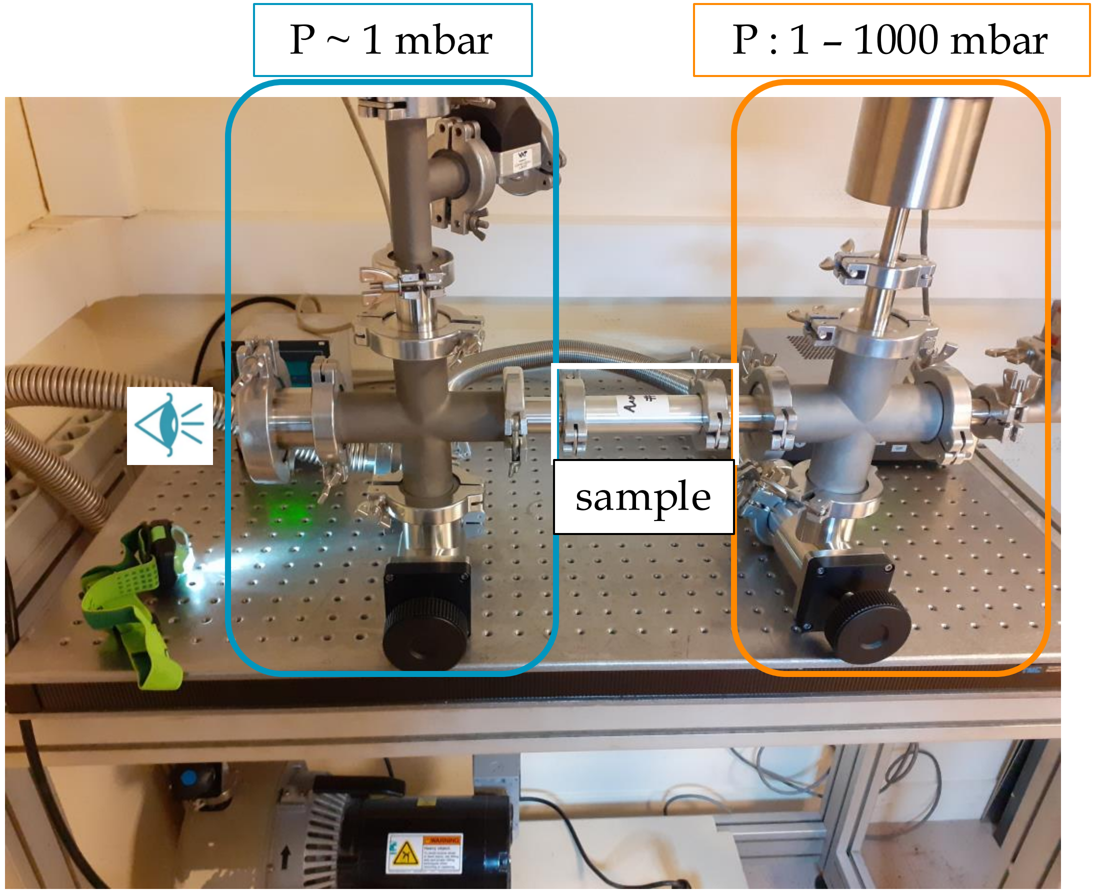




Technical ceramics (2µm) were tested under the same conditions.
When the pressures equalize, the surface remains flat.

Testbench at T_{std} : deformation of the windows



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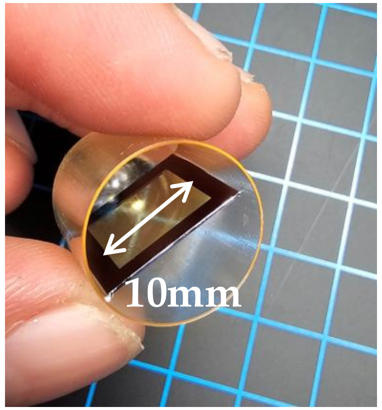

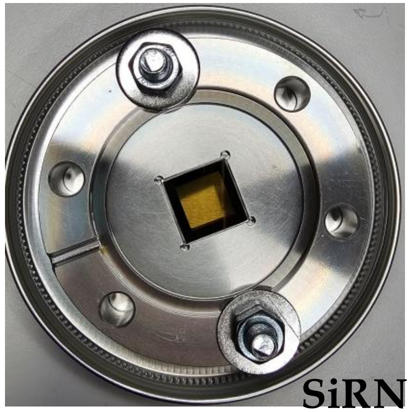

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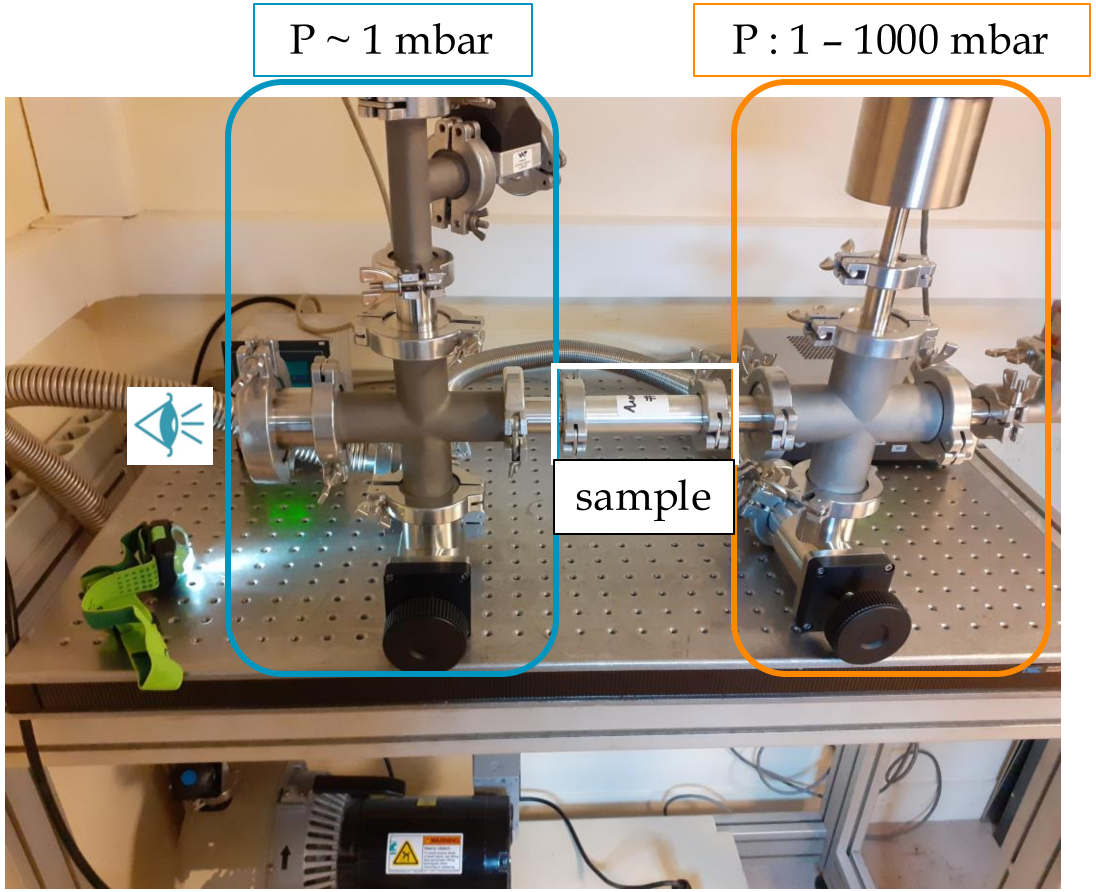

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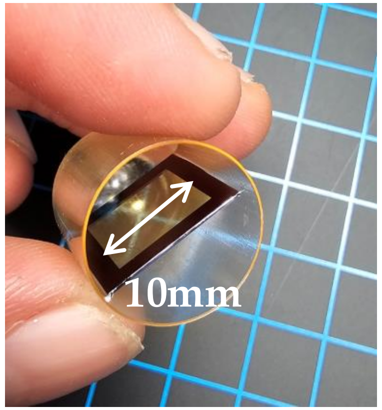

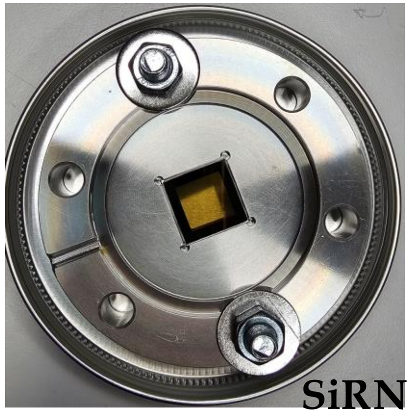

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+ Equivalent thickness ~ 1/4 x HeCTOr window (Havar 3.8 μm)

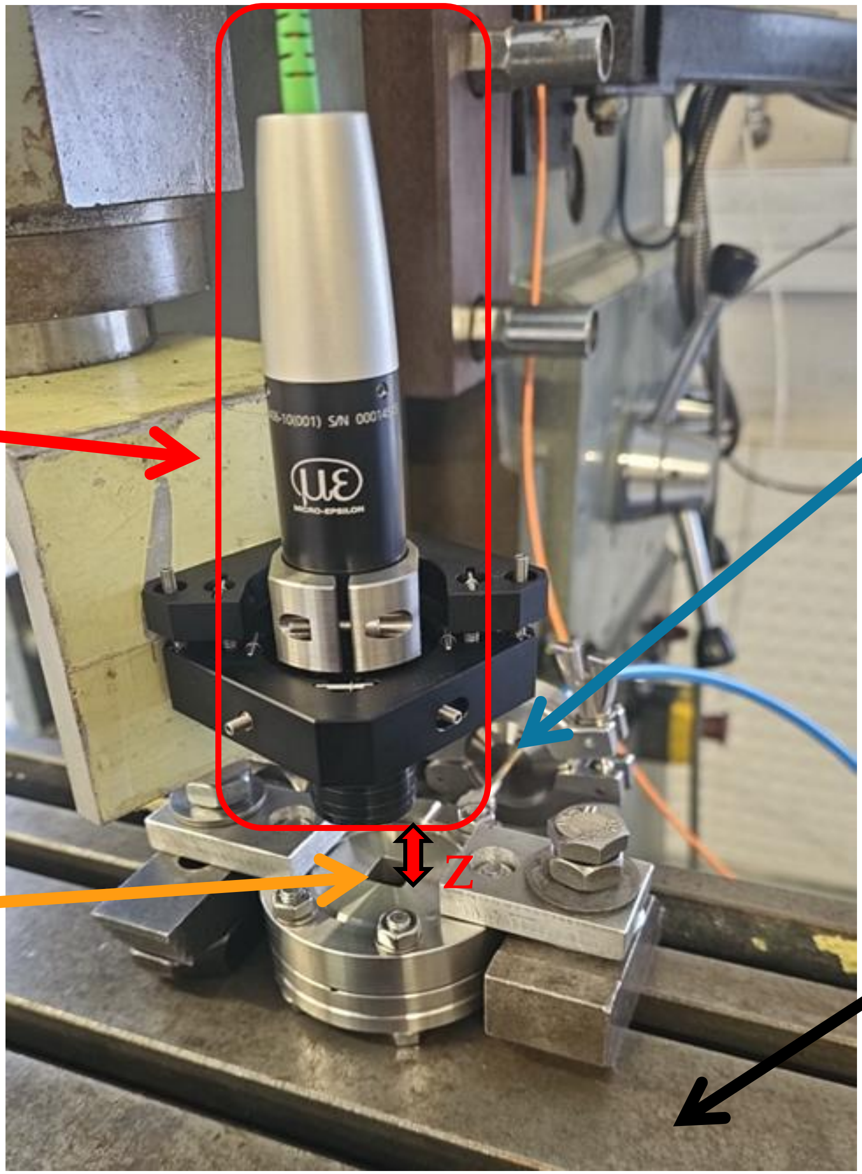
+ The He leak rate of the **SiRN samples** remains at the background level (regardless of the ΔP), while other tested materials perform worse than the **HeCTOr target body at T=5K**.

Determination of the window profile

How much does this material deform under pressure ?

Confocal microscope :
Measure the relative distance
to the membrane surface (Z)
(resolution < 1µm)

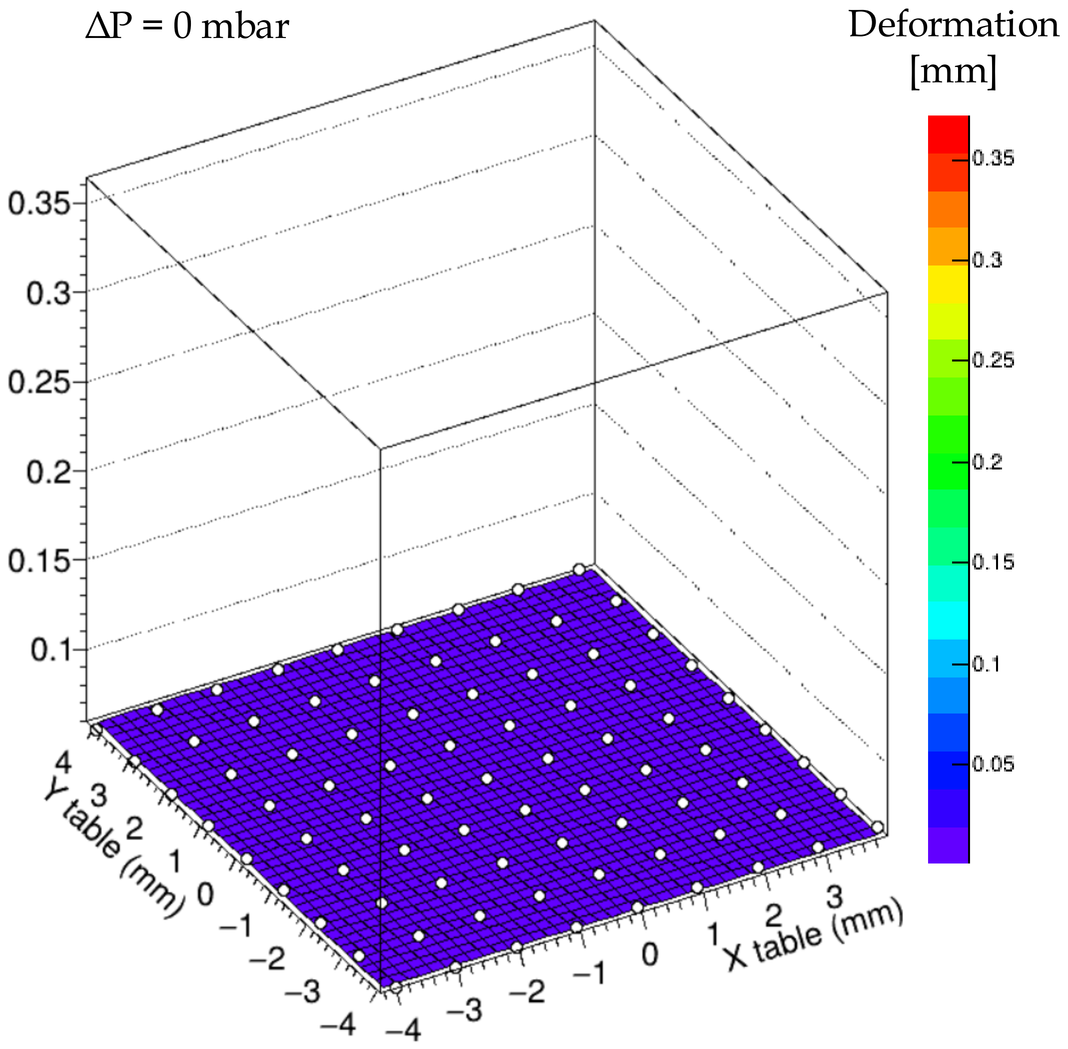
Flange-mounted membrane
(size : 10x10 mm²)



Compressed air supply
P = 1 – 2 bars

Manual milling table :
(X,Y) mapping with 1 mm sampling
(accuracy: 0.01mm)

Results of the mapping with respect to ΔP



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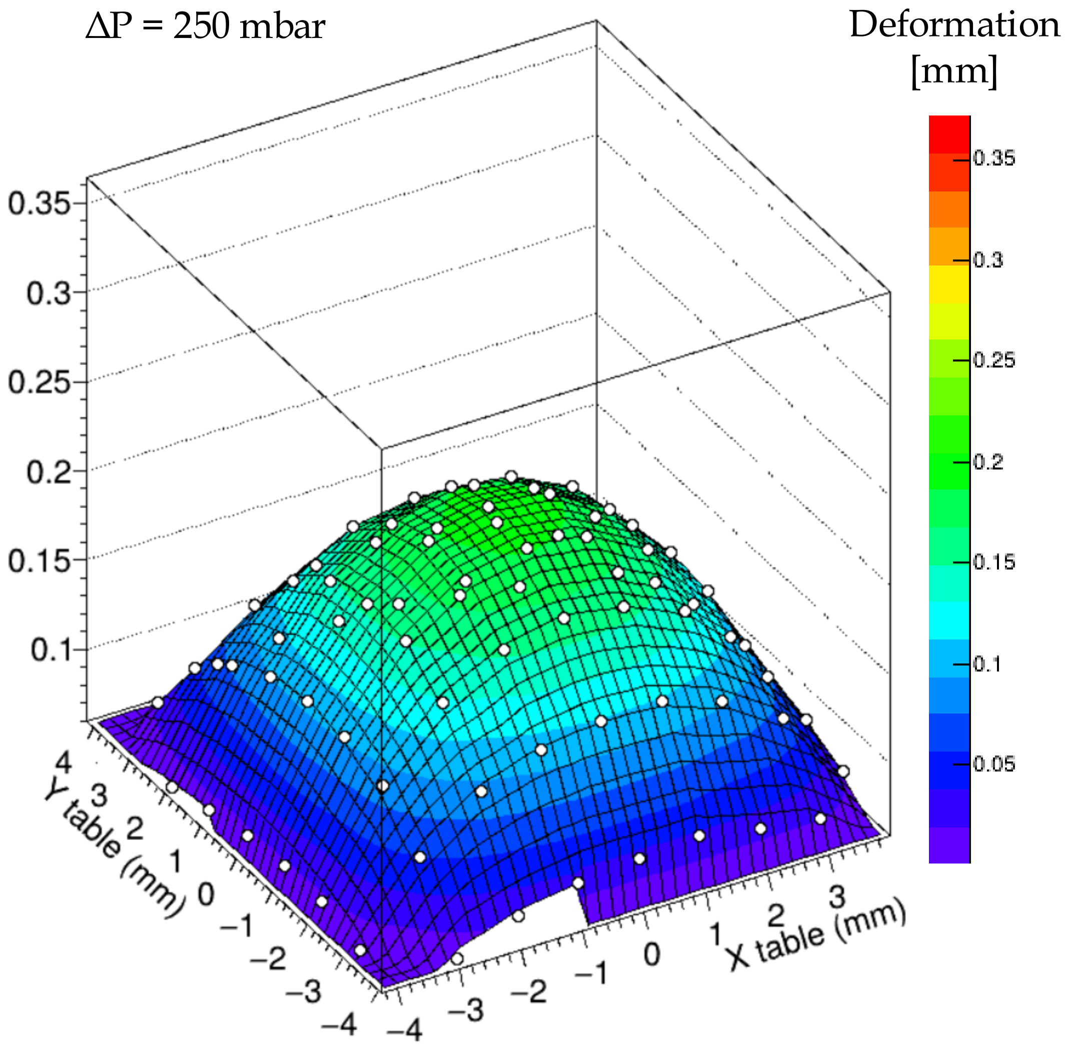
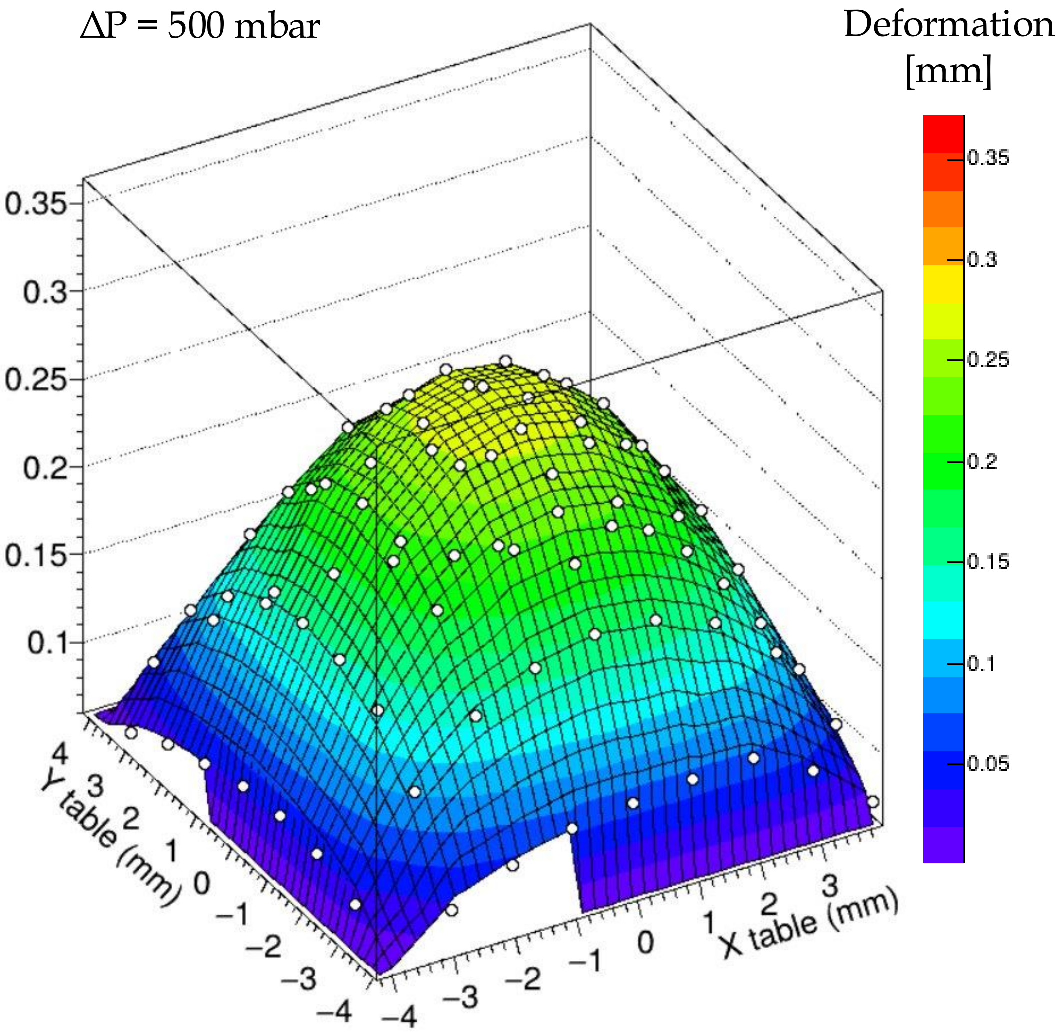


Results of the mapping with respect to ΔP

ΔP = 500 mbar



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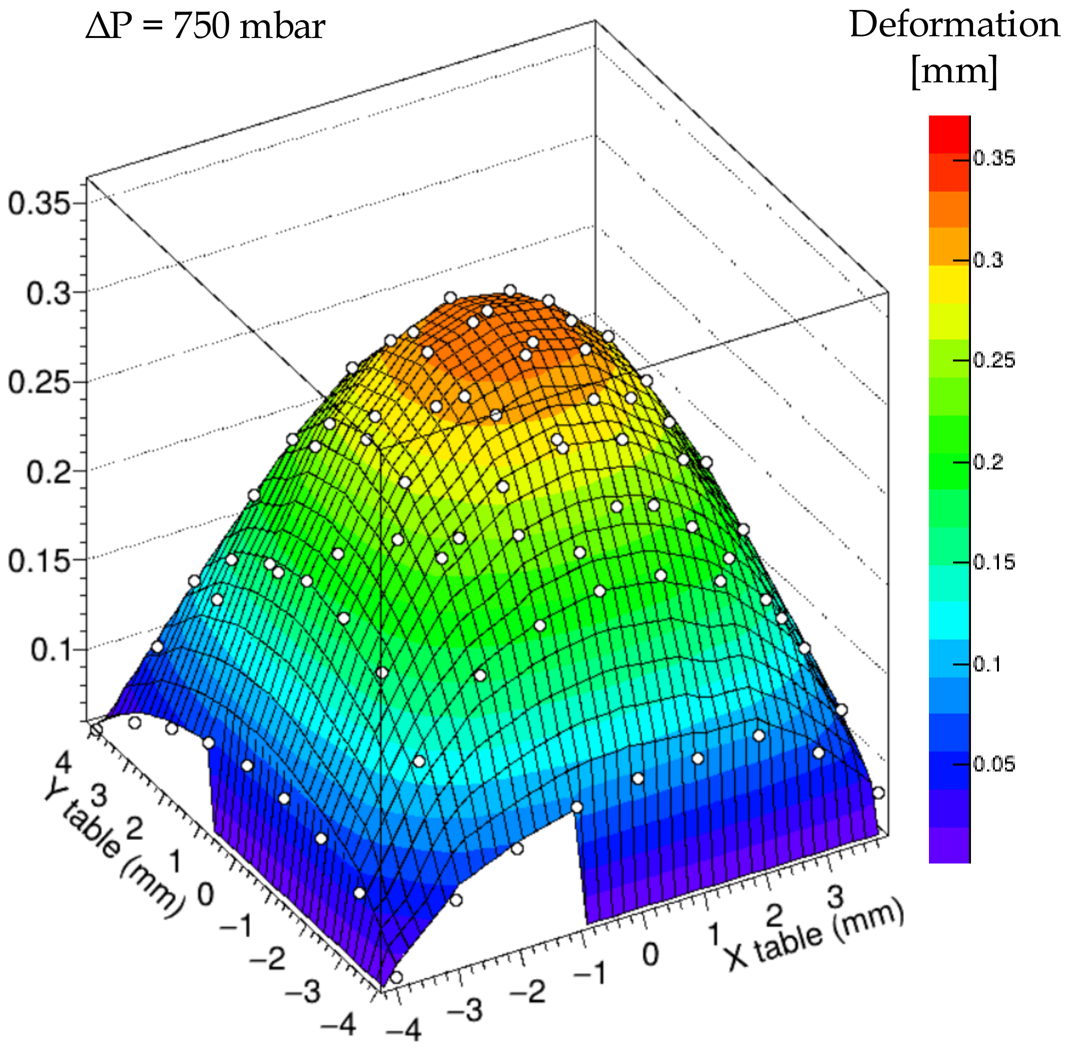

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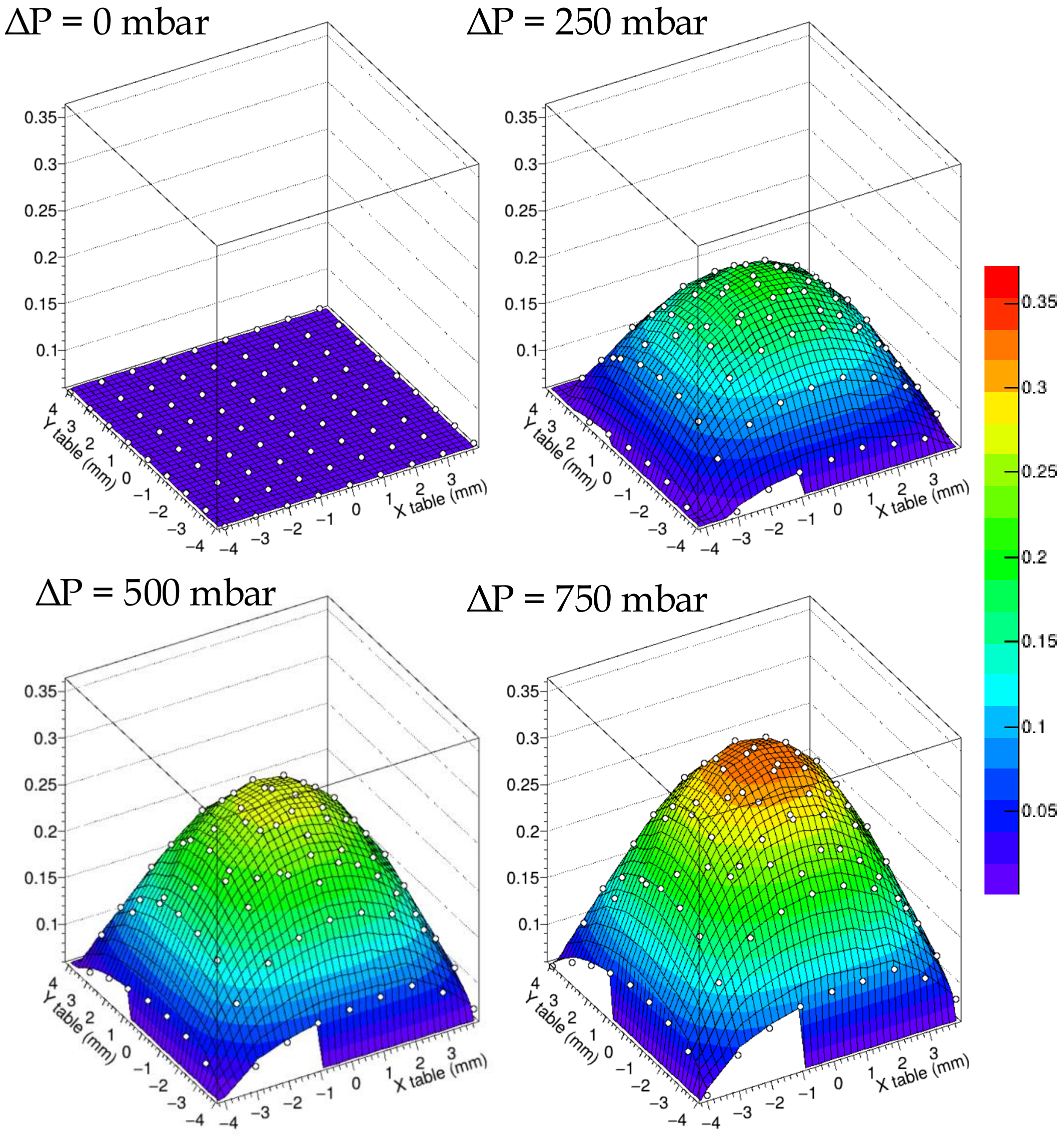
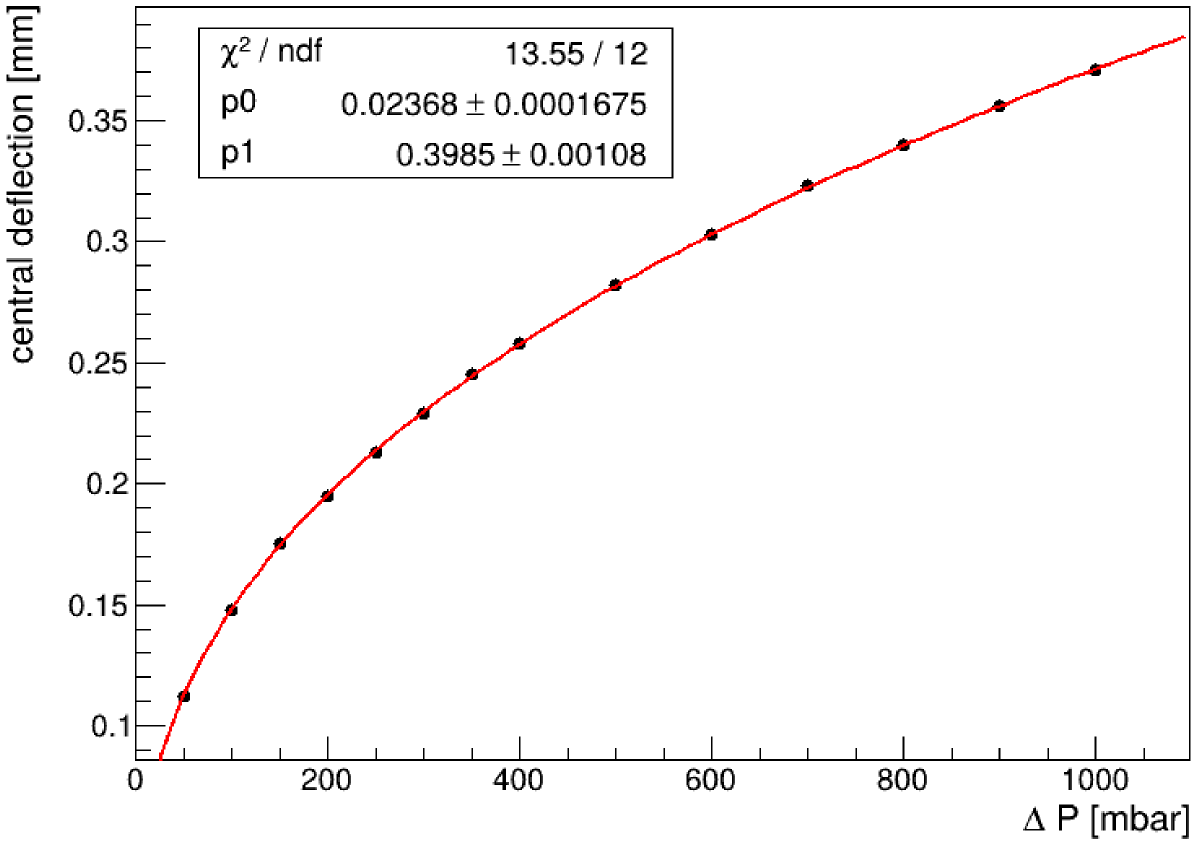


Evolution of the central deflection with the applied pressure
(also useful for material data : Young's modulus and residual stress)



(consistent with the analytic calculations)

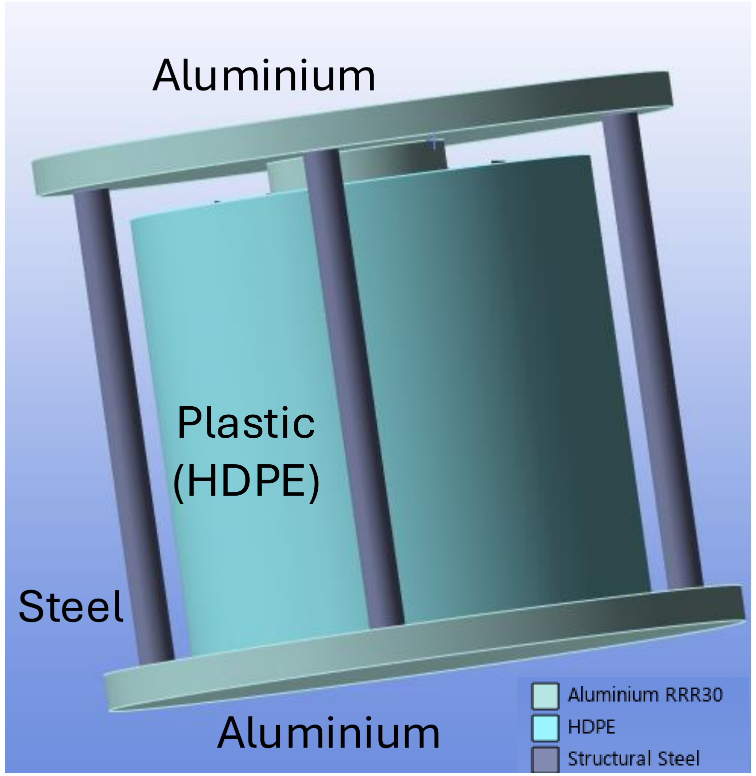
Estimation for 14×14 mm² membranes :
~0.6 mm (to be measured)

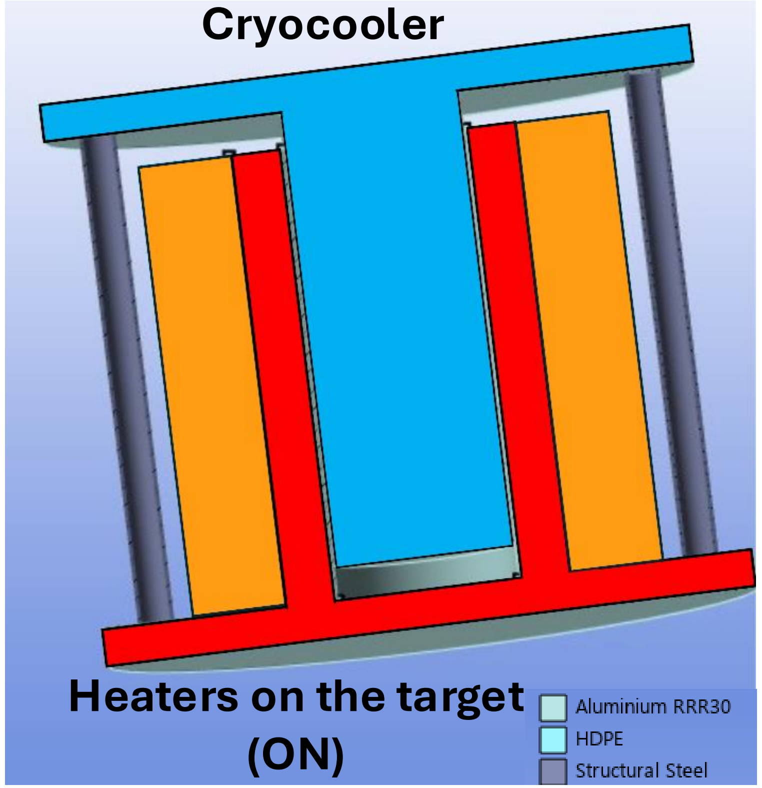
Thermal Switch Development

To decrease the cooling duration after de-icing steps, the target should be thermally decoupled from the cryocooler.

Solution to be tested : thermal switch based on differential thermal contractions ➡ α(Al) < α(HDPE)

- M. Dietrich, A. Euler, G. Thummes, Cryogenics **59**, (2014) 70-75
- M. Dietrich, A. Euler, G. Thummes, Cryogenics **83**, (2017) 31-34





Courtesy of M. Lebihan: ANSYS simulations

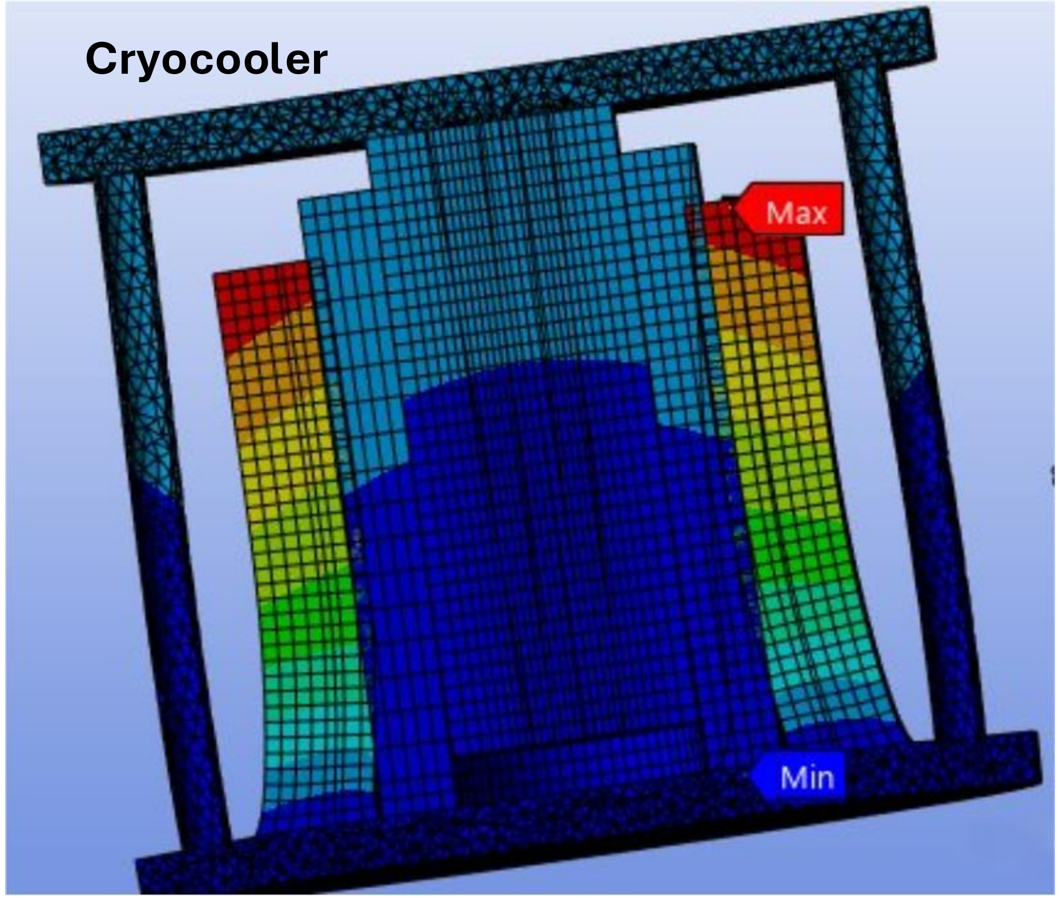
<u>De-icing step ongoing</u>

Heaters warm up the target

Tiny gap ~ 80 microns between the Al jaws and the central shaft

Switch state : OFF (no heat transfer)

Thermal Switch Development



Heaters on the target (OFF)

Courtesy of M. Lebihan

Default state

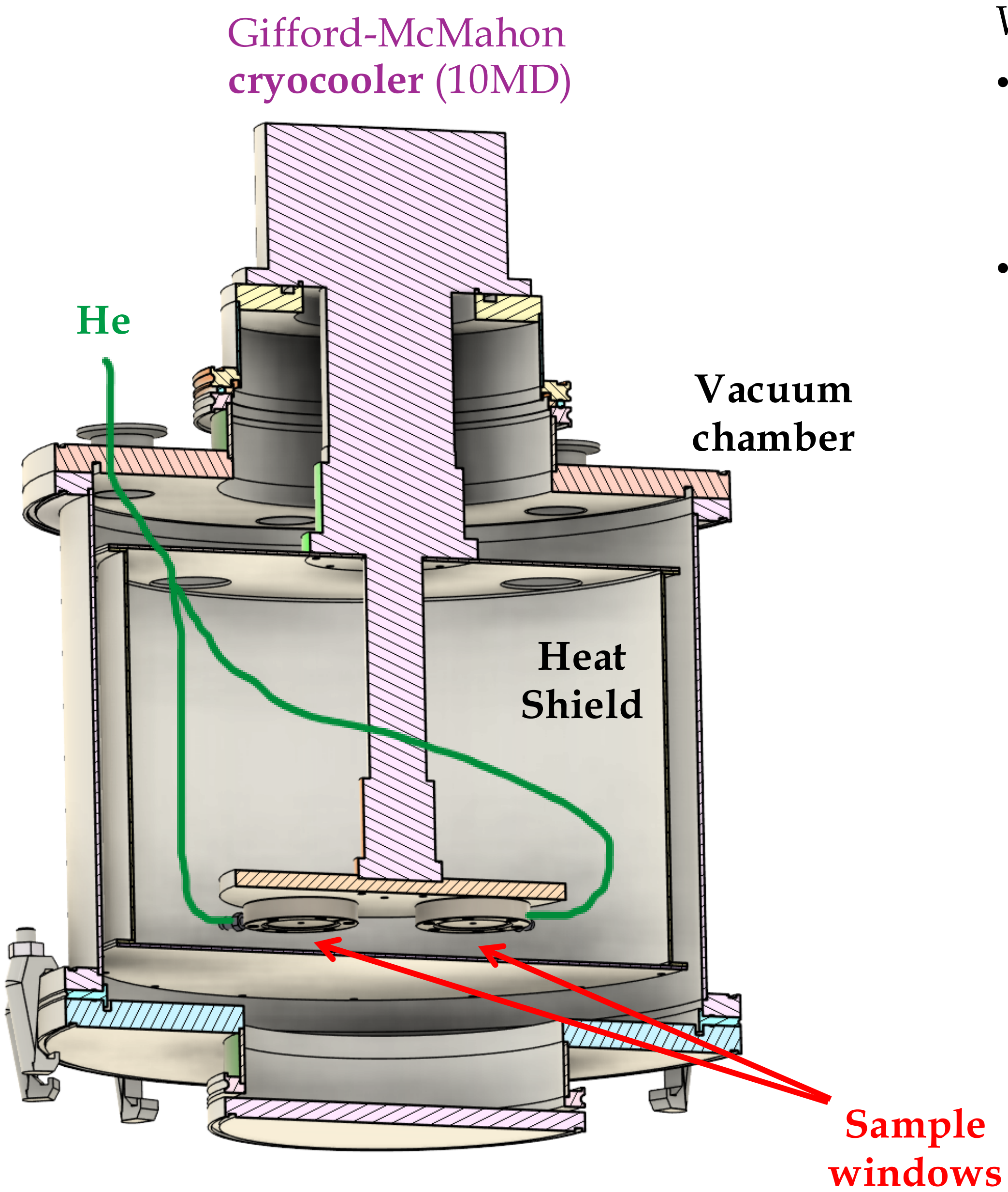
The plastic shrinks over the jaws : no gap + stresses from the jaws on the central shaft

Switch state : ON (enable heat transfer)

The cryocooler cools down the target

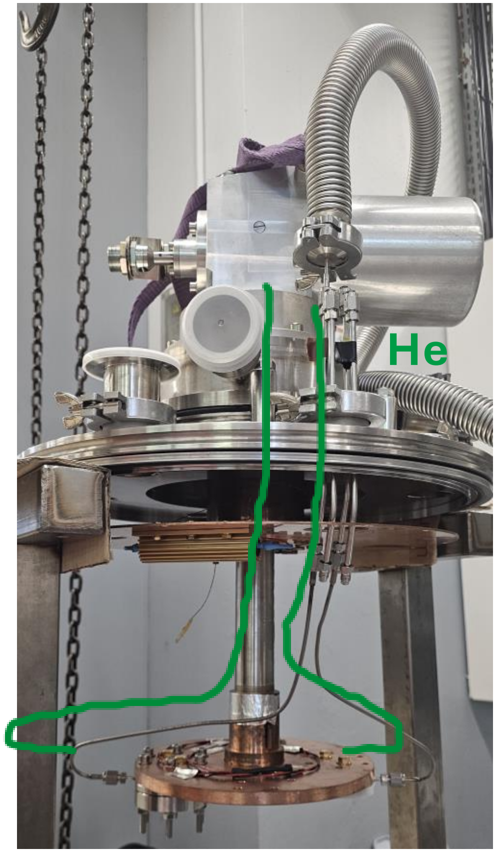
ANSYS simulations are ongoing to evaluate an initial gap size leading to the operating conditions of the target : expected thermal conductivity and $T_{critical}$(ON/OFF)

Testbench at T_{cryo} : objectives and features

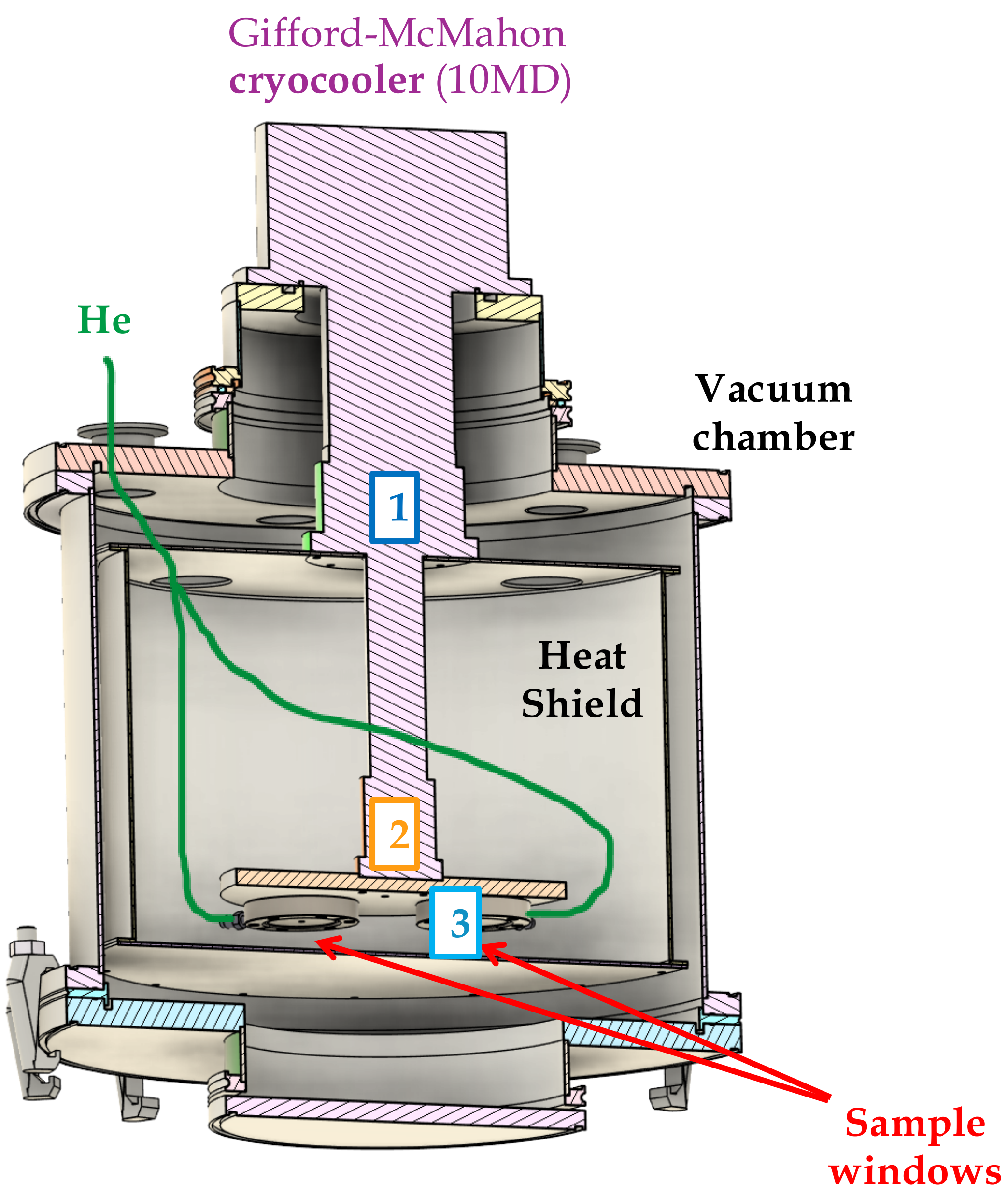


What are the purposes of this test bench ?

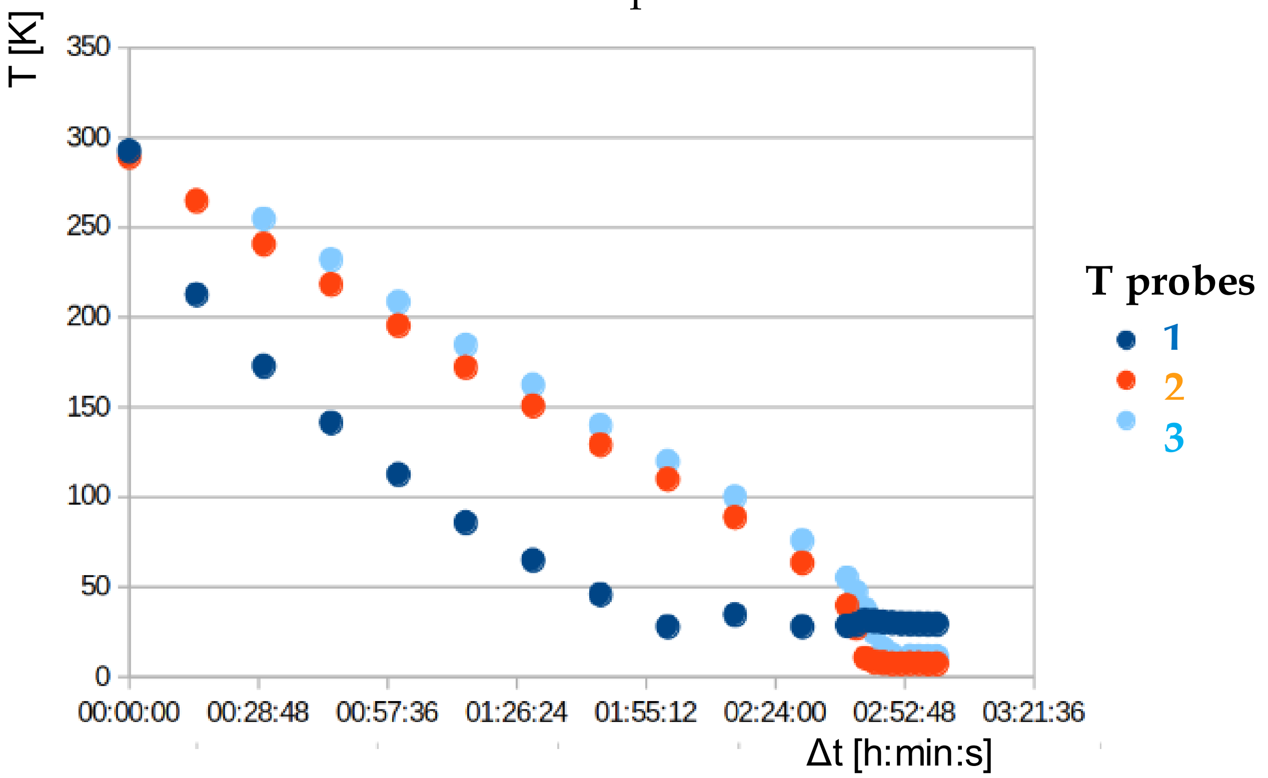
- Perform the same tests and measurements at cryogenic T :
  - **ΔP steps**
  - **permeability to He**
  - **cycling**
  - **window deformation (*upgraded setup in backup slide*)**
- Characterize several **thermal switches** (time constant);



Testbench at T_{cryo} : operational performances



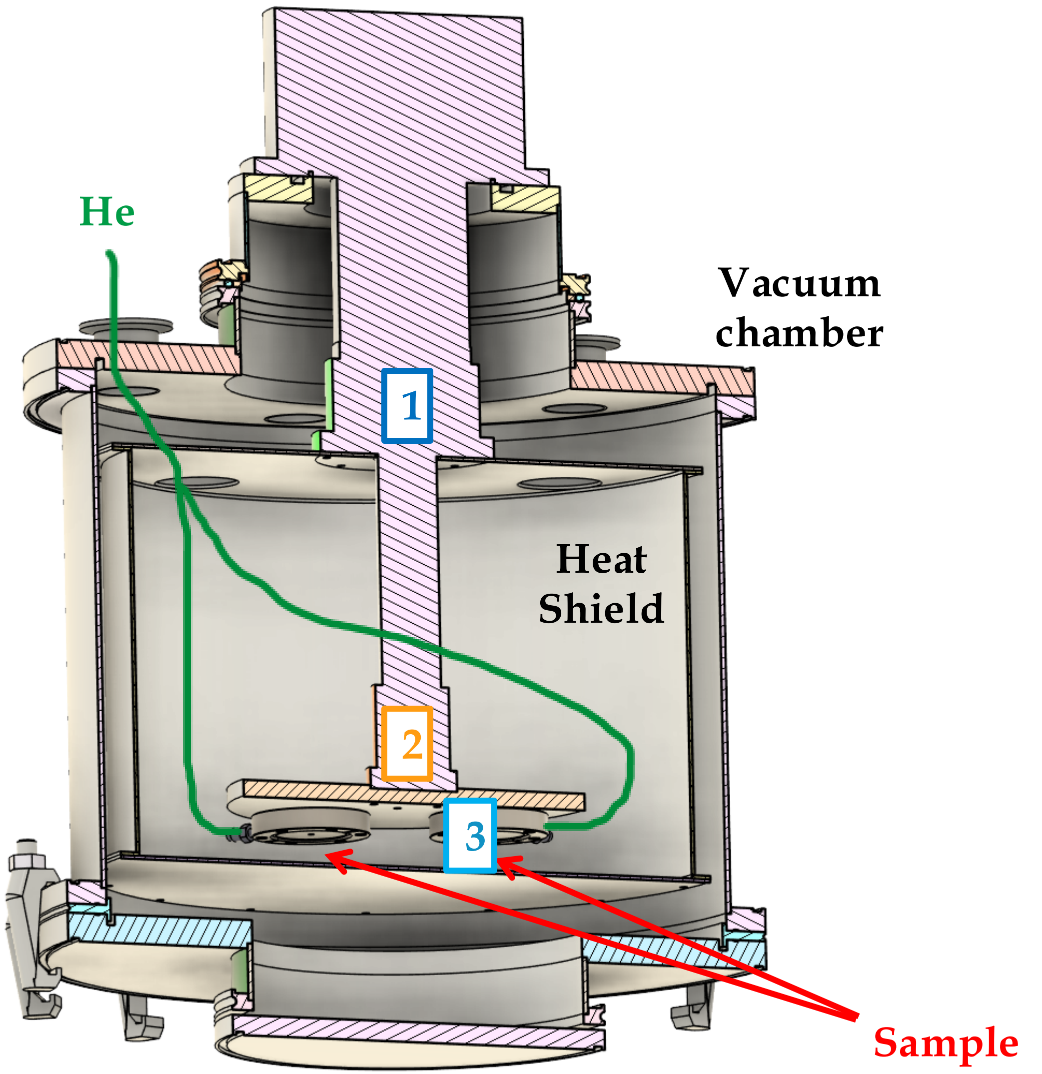
First tests in which the samples are cooled down :



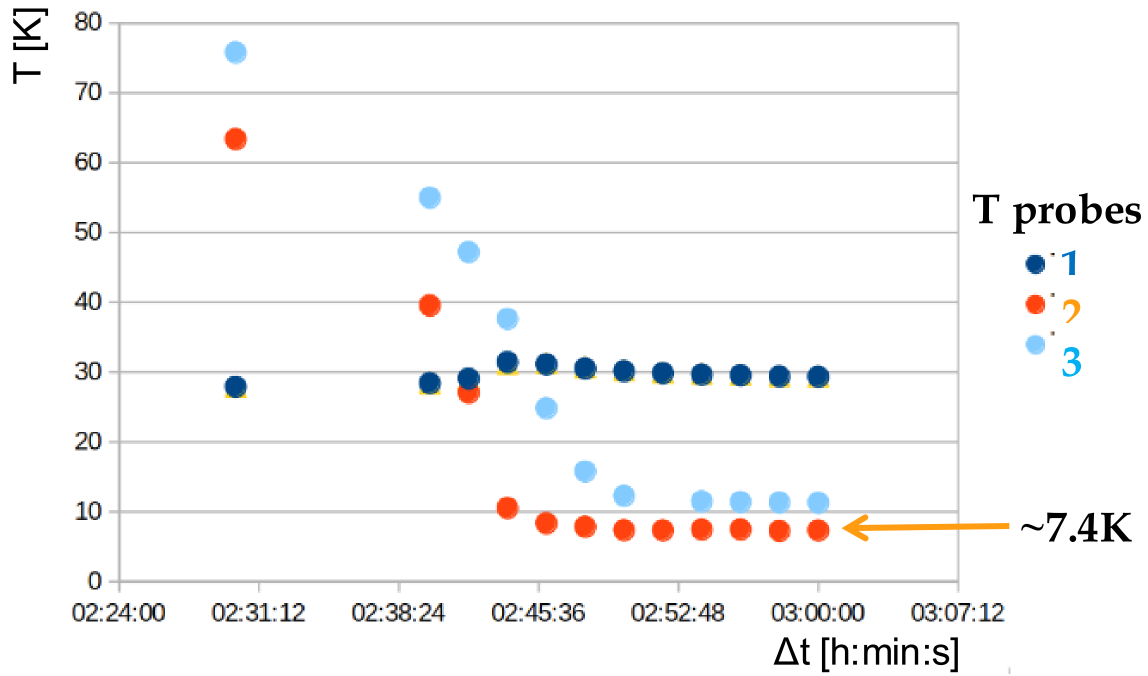
The time constant will be shorter for the final target (less material).

Only half an hour is needed to cool the cryocooler part alone

Testbench at T_{cryo} : operational performances



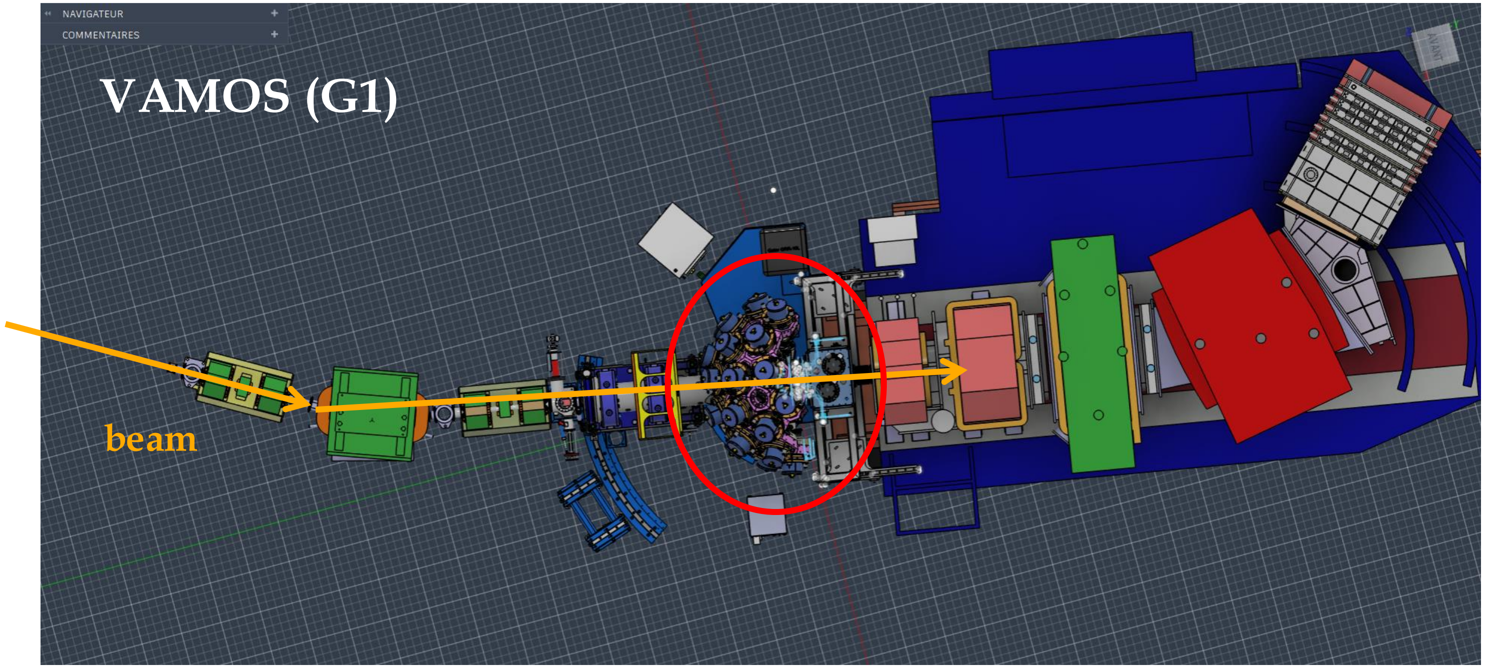
The $T_{samples}$ reaches ~10K :
almost the target operating range !

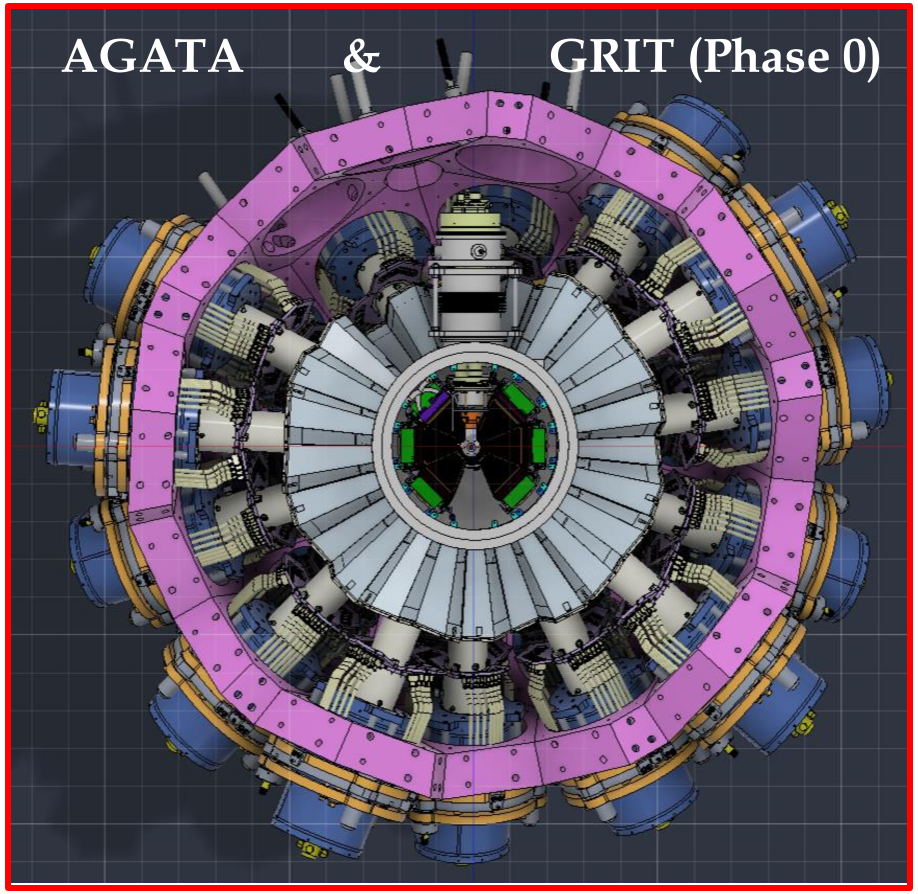


For the prototype and final target: Pulse-Tube cryocooler with higher performances (T_1<30K and T_2<4K for P_{th} = 0W)

Compatibility with AGATA-GRIT

Compact design to ensure the integration within the **GRIT** and **AGATA** arrays

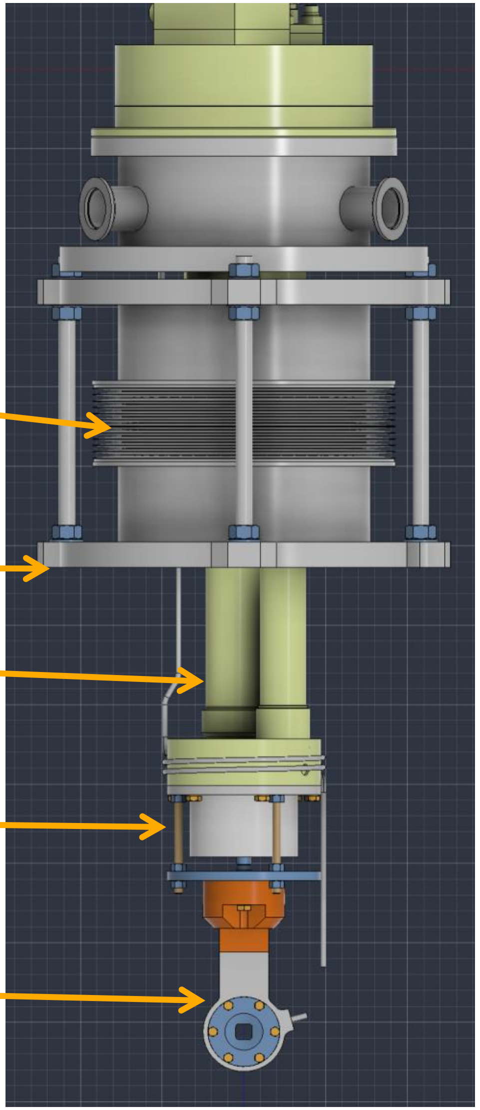




Compatibility with AGATA-GRIT

Compact design to ensure the integration within the **GRIT** and **AGATA** arrays

Target body and heat shield in **Al** to reduce the gamma absorption
=> requires coupling the GEANT4 simulations with the AGATA algorithm.



(without its heat shield)

Compatibility with AGATA-GRIT

Compact design to ensure the integration within the **GRIT** and **AGATA** arrays

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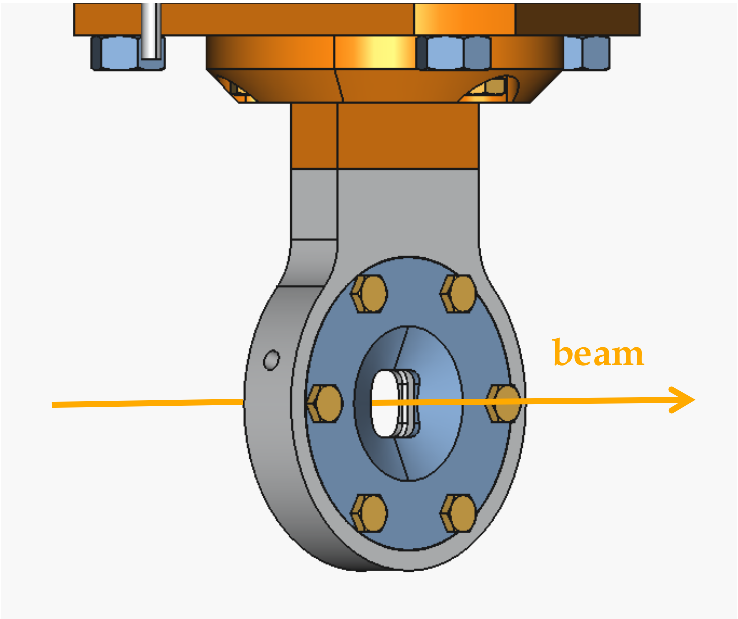


<u>Target prototype</u>
body radius : 25 mm

Windows: 10x10mm

Emission cone: +-65°

Prototype gas cell
thickness : 1.5mm
=> 1.02 mg/cm^2
@T=6K/P=1bar

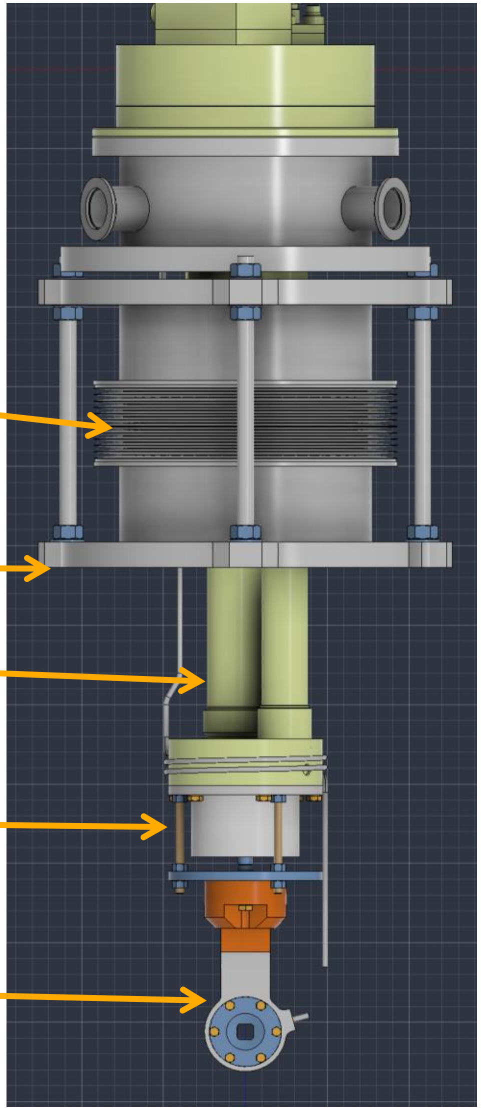
Extension to align the target

Flange connected to the GRIT chamber

Cryocooler

Thermal switch

Target body



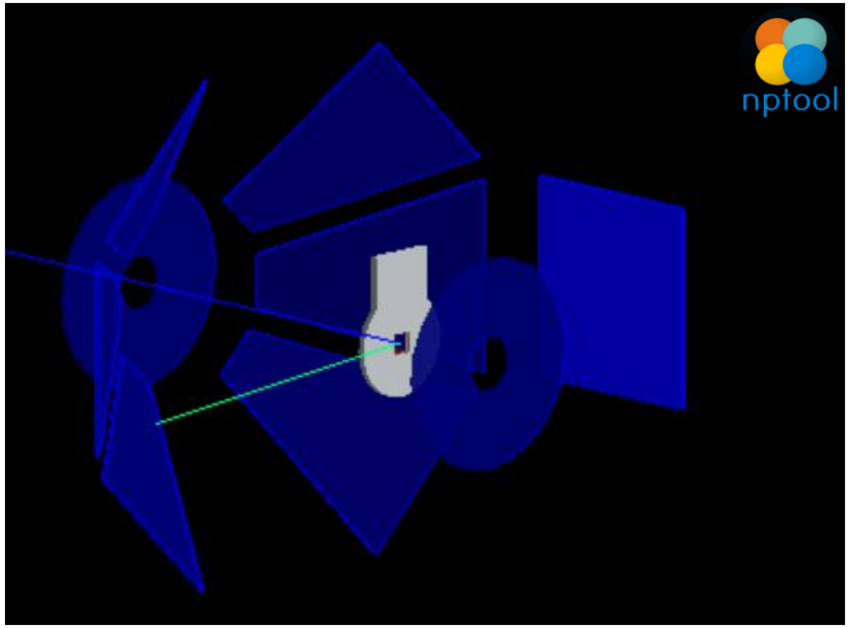
(without its heat shield)

Size selected for the gas cell = f(windows deformation , density(^{3}He))
=> Different targets could be designed for different experiments

NPTool Simulations

NPTool simulations of the cryogenic target :
- Size of the gas cell
- Windows and their deformation
- Ice Layer
- Frame/Target Body
- GRIT array (Phase 0)

They enable several studies:
- Acceptance in Ec(Lab) and Theta(Lab)
- Shape and resolution of the reconstructed E*
- Gamma-ray absorption (*details in backup slides*)

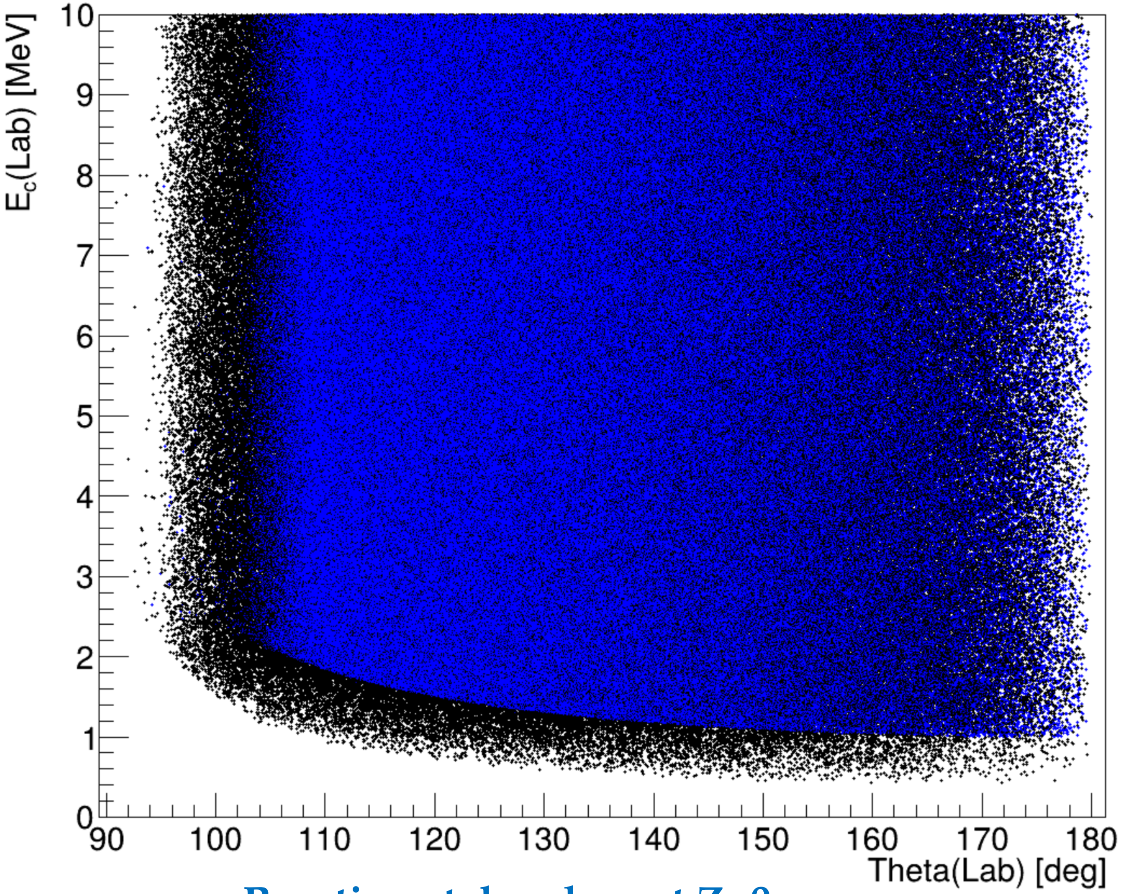


Cryogenic target within GRIT (Phase 0)

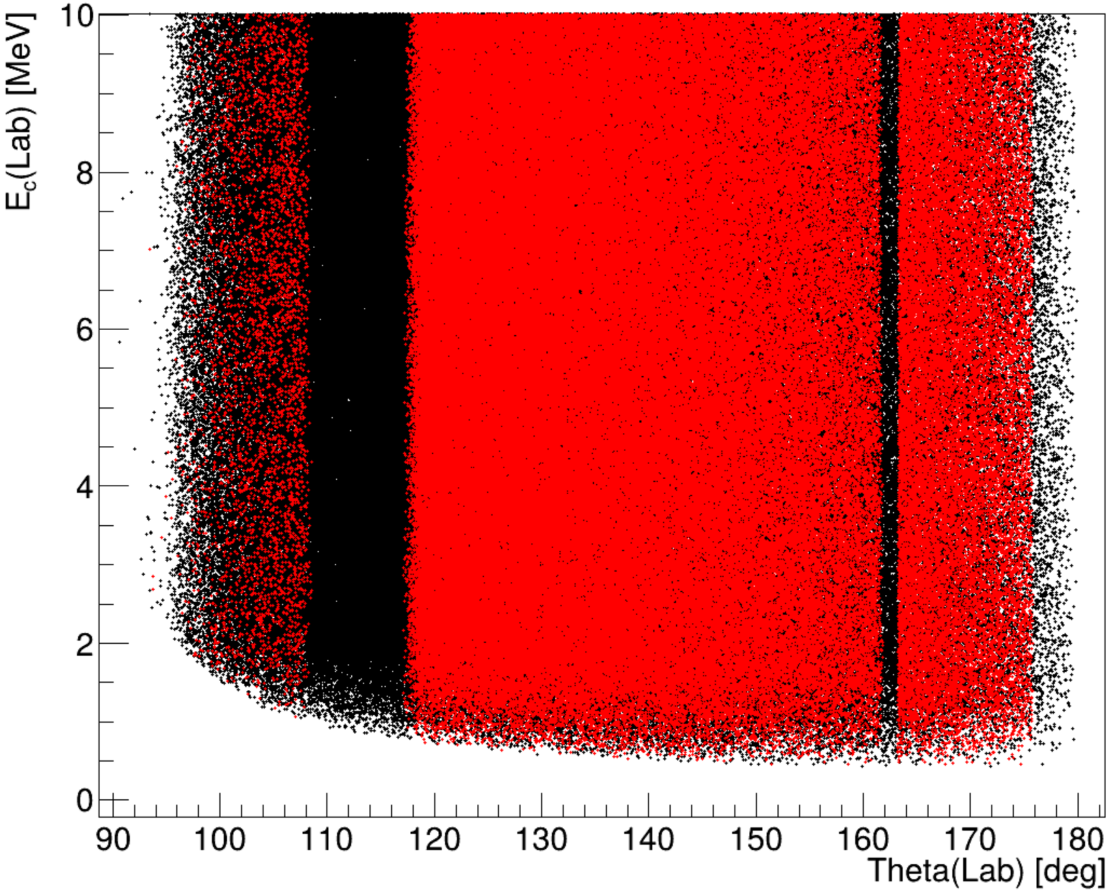
+ relevant material for gamma-ray detection efficiency study

Simulation of Target Acceptance

Source of deuterons + Target filled with ^{3}He (T=6K , P=1bar) + Windows in SiRN (2um thick)



- Reactions take place at Z=0
- Reactions occur uniformly throughout the thickness of the target

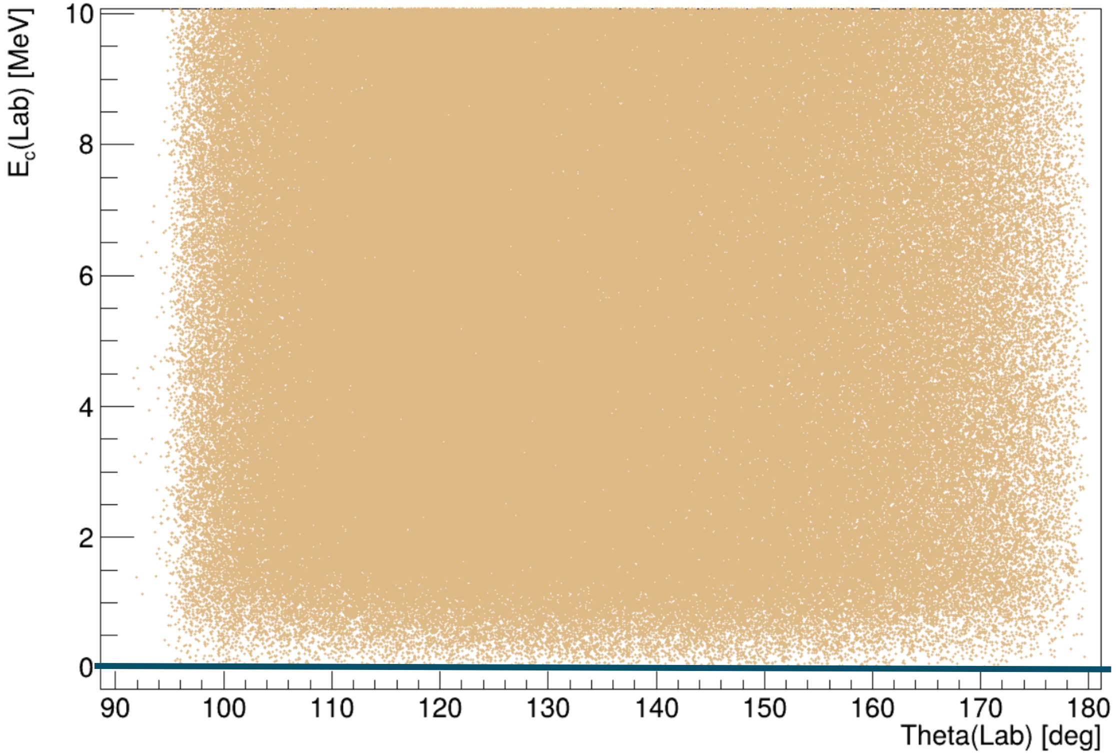


- Acceptance for a 2π detector
- Acceptance for GRIT (Phase0)

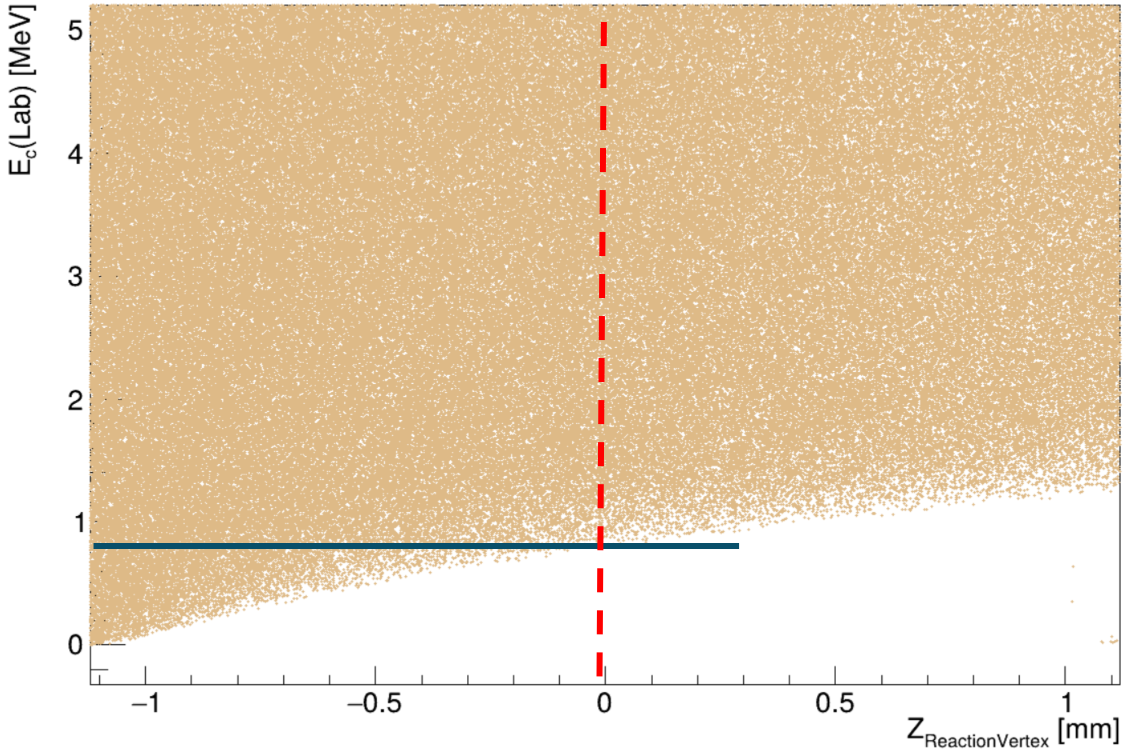
Simulation of Target Acceptance

Source of deuterons

+ Target filled with ^{3}He (T=6K , P=1bar)



E_c(d) > 0 MeV + GRIT threshold



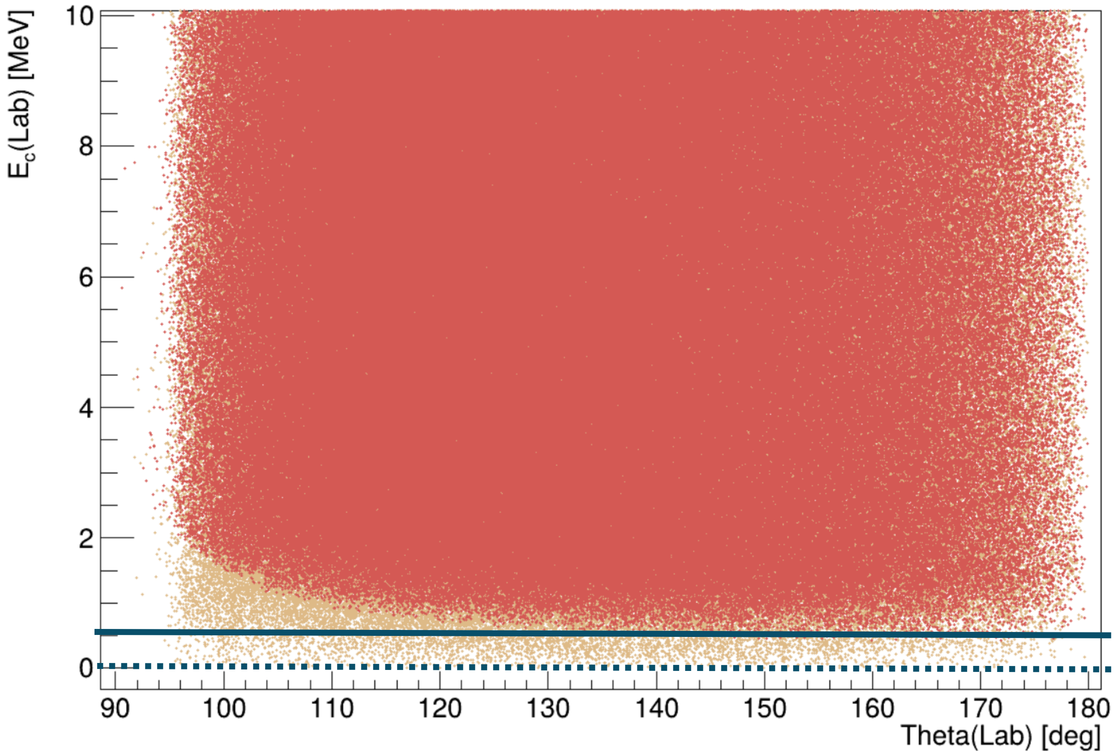
E_c(d) > 0.8 MeV (Mid-target)

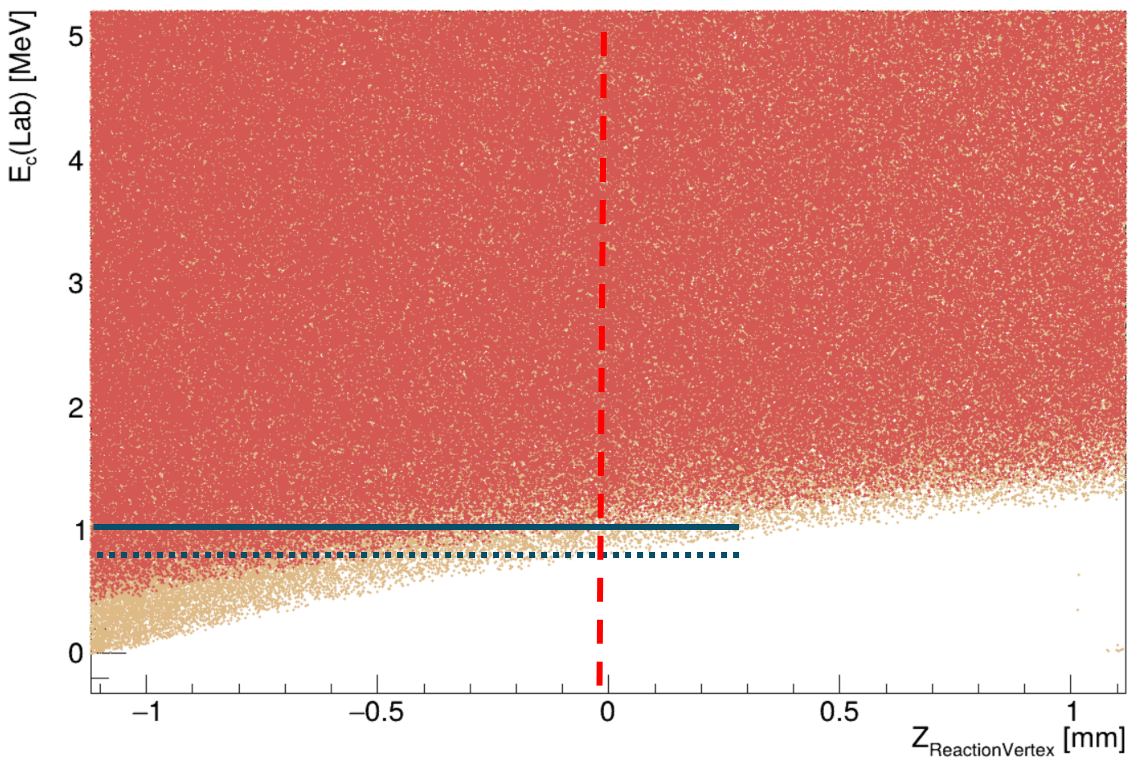
Simulation of Target Acceptance

Source of deuterons

+ Target filled with ^{3}He (T=6K , P=1bar)

+ Windows in SiRN (2um thick)





E_c(d) > 0.5 MeV + GRIT threshold

E_c(d) > 1 MeV (Mid-target)

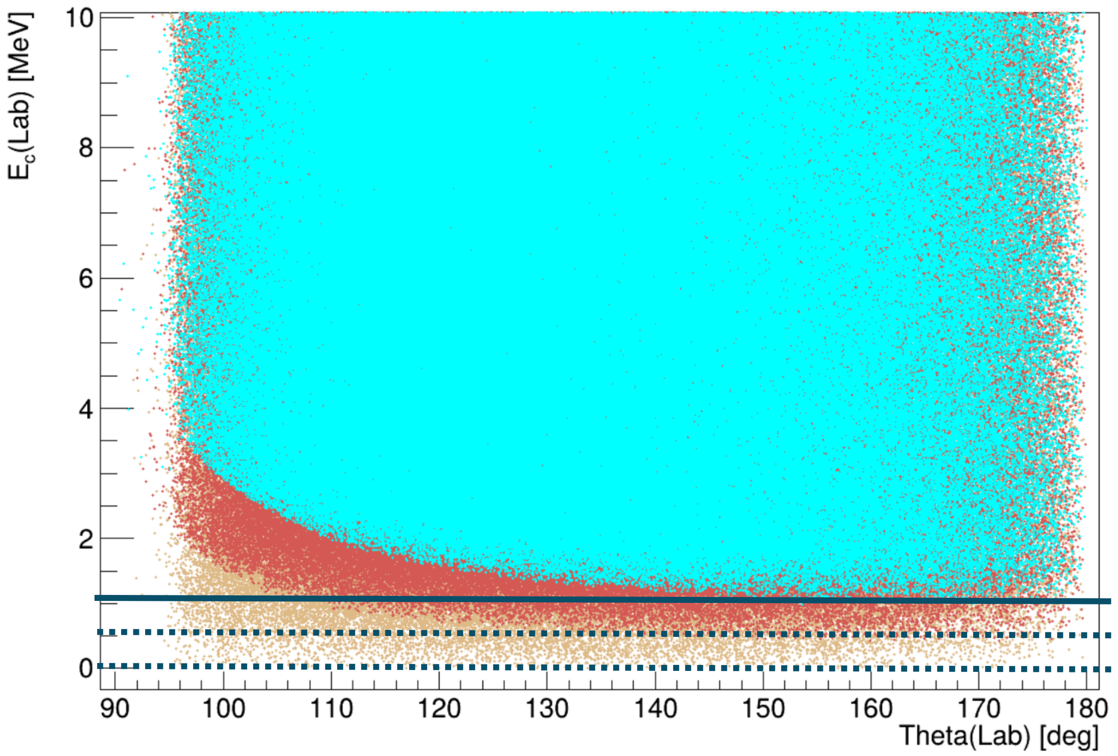
Simulation of Target Acceptance

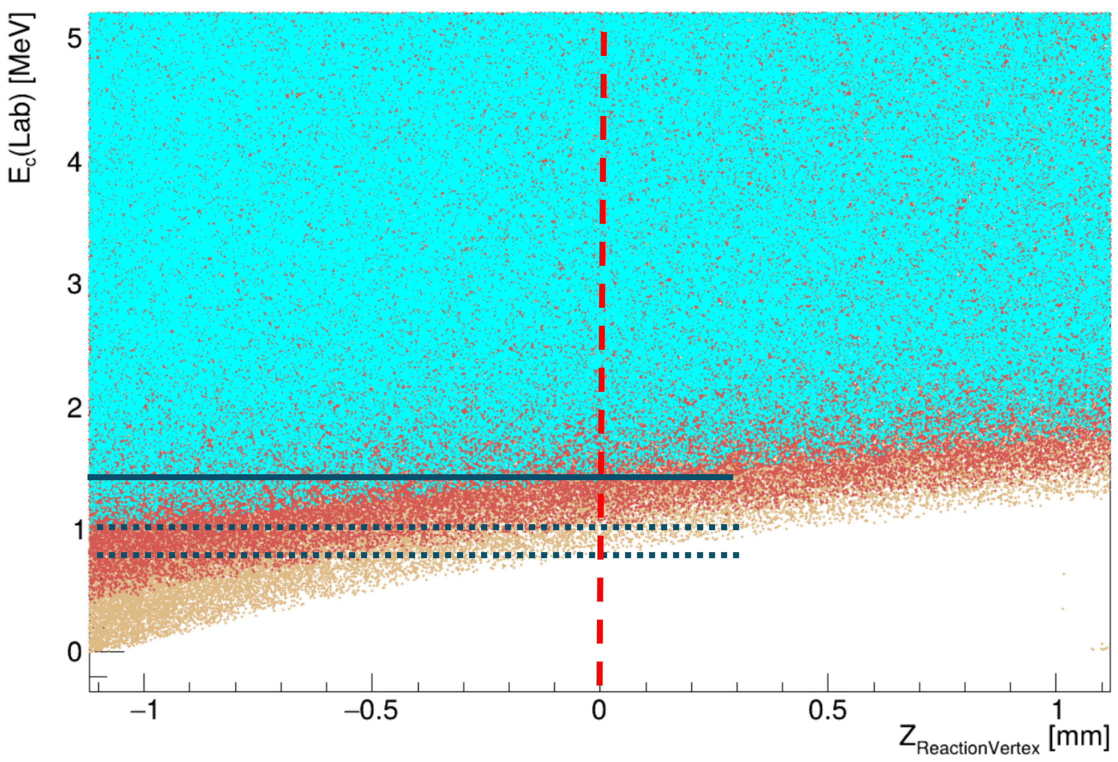
Source of deuterons

+ Target filled with ^3He (T=6K , P=1bar)

+ Windows in SiRN (2um thick)

+ Ice layer (11um thick / window)





$E_c(d) > 1$ MeV + GRIT threshold

$E_c(d) > 1.4$ MeV (Mid-target)

What are the next steps ?

Windows

- [ΔP steps , permeability to He, cycling] tests at low temperatures;
- Mapping of the window surface with ΔP>0 at low temperatures;

→ Membranes with side lengths of 10 mm and 14 mm

de-icing

- Test thermal switches to warm up the target (time constants, induced ΔT , …)
- Estimate the growth rate of ice on the prototype under a controlled atmosphere (type of gas, P_{gas}, T_{target})

- Evaluate the performances of the prototype target (leak rate, Tmin, thermal shrinkage...)
- Commissioning of the cryogenic target @VAMOS in 2027 or 2028 depending on beam availability
- Coupling of the cryogenic target to the VAMOS-GRIT-AGATA setup for 2030 (2nd year of the campaign)

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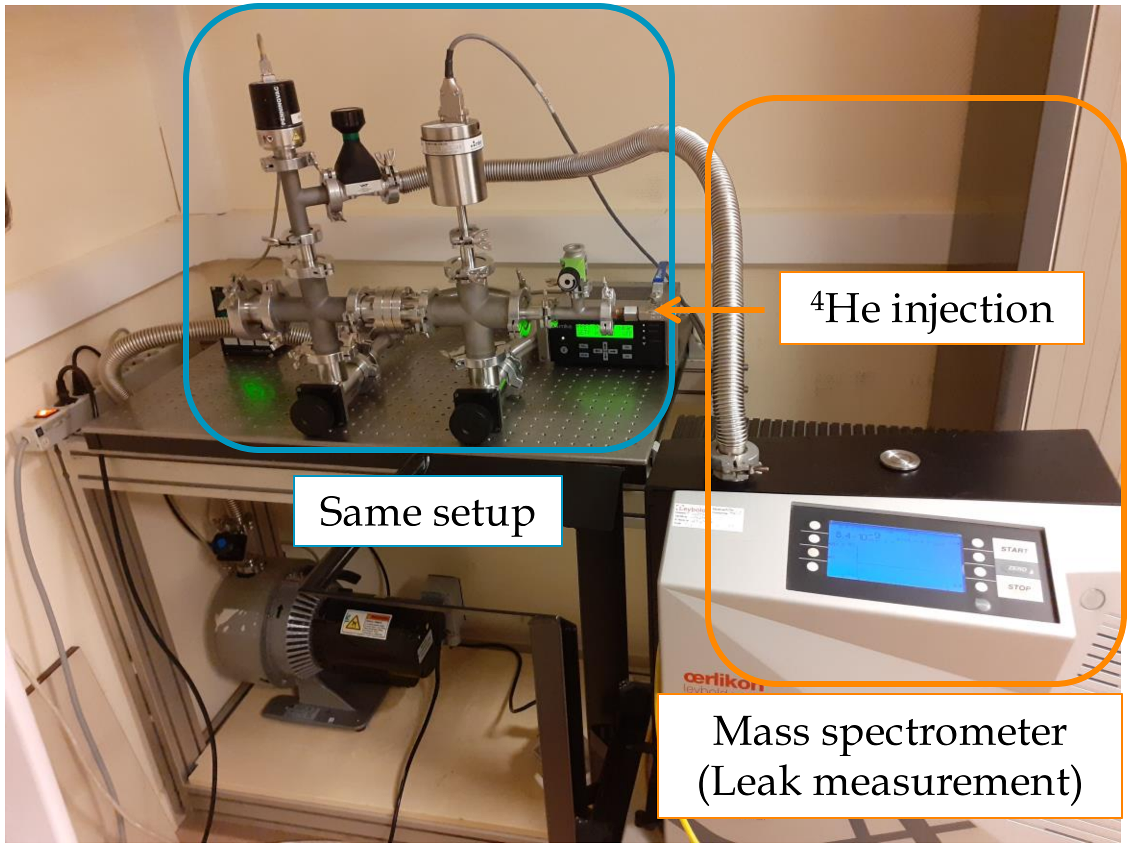
Thank you for your attention !

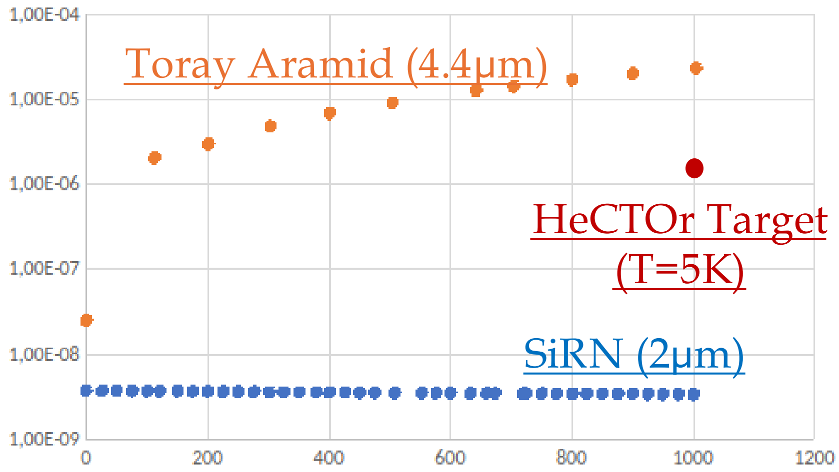
Backup slides

Testbench at T_{std} : permeability of the windows



The last test to be performed for these samples on this testbench is the cycling : ΔP = 0bar ⟷ ΔP = 1bar (~50x)

Leak rate [mbar.L/s] with respect to the He pressure [mbar]



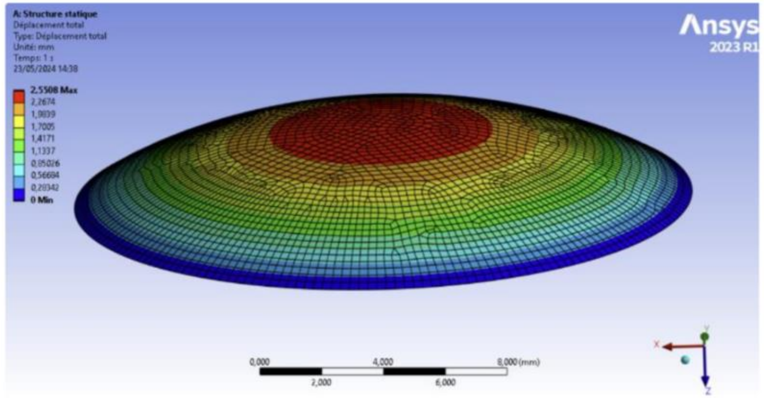
The permeability of the **Aramid sample** is larger than the overall leak rate of the **HeCTOr target body at T=5K** (**1.4 10^{-6} mbar.l/s**, i.e. 1L in 20 years).

The permeability of the **SiRN samples** is much better. The leak rate remains at the background level, regardless of the ΔP.

Determination of the window profile

For circular windows:
App. hyperbolic profile
Central deflection D = f(ΔP,R,thickness,…)

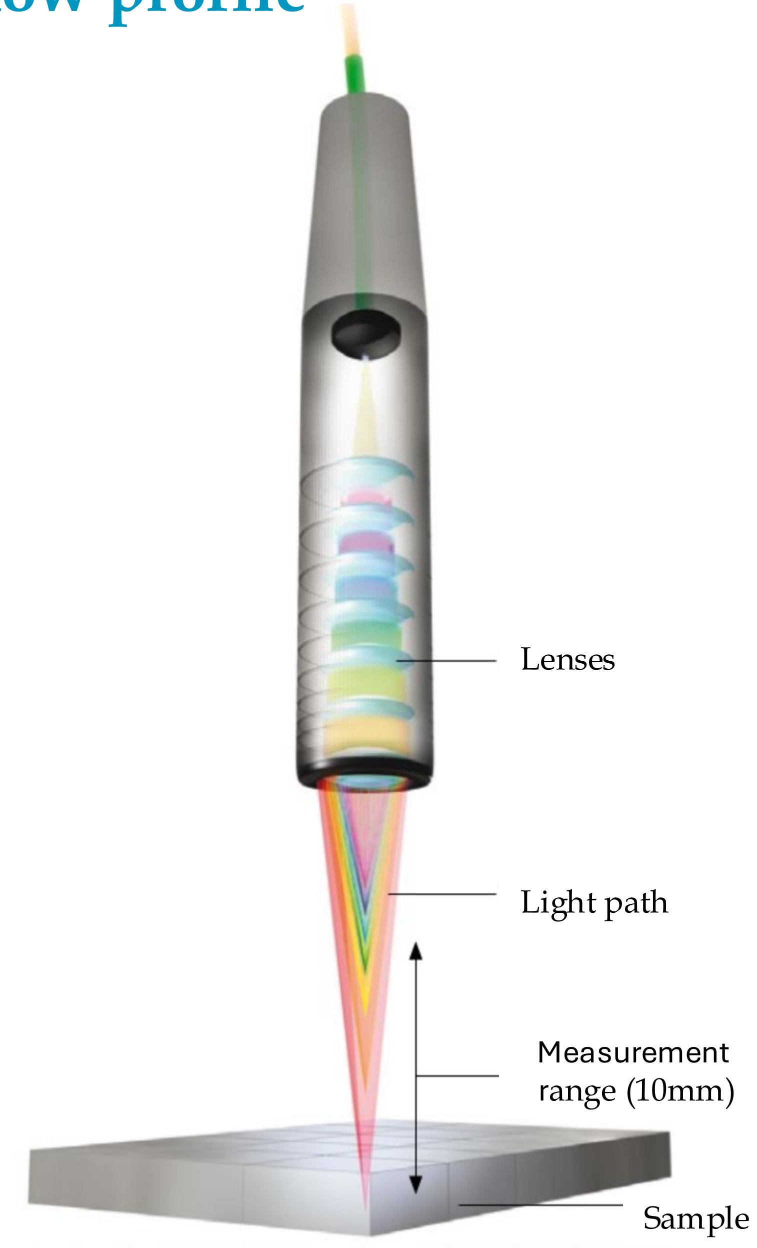
HeCTOr : 3.8µm thick Havar => $D = 0.70(5)$ *mm*
Calculation for the SiRN (2µm) => $D \sim 0.4$*mm*



Modelisation of deformations with ANSYS
for a circular window

For square windows :
cos(Xπ/L)cos(Yπ/L) profile with few corrections

Require a mapping of its surface at different ΔP and T
➡ Measure with a <u>confocal microscope</u>



Confocal Microscope

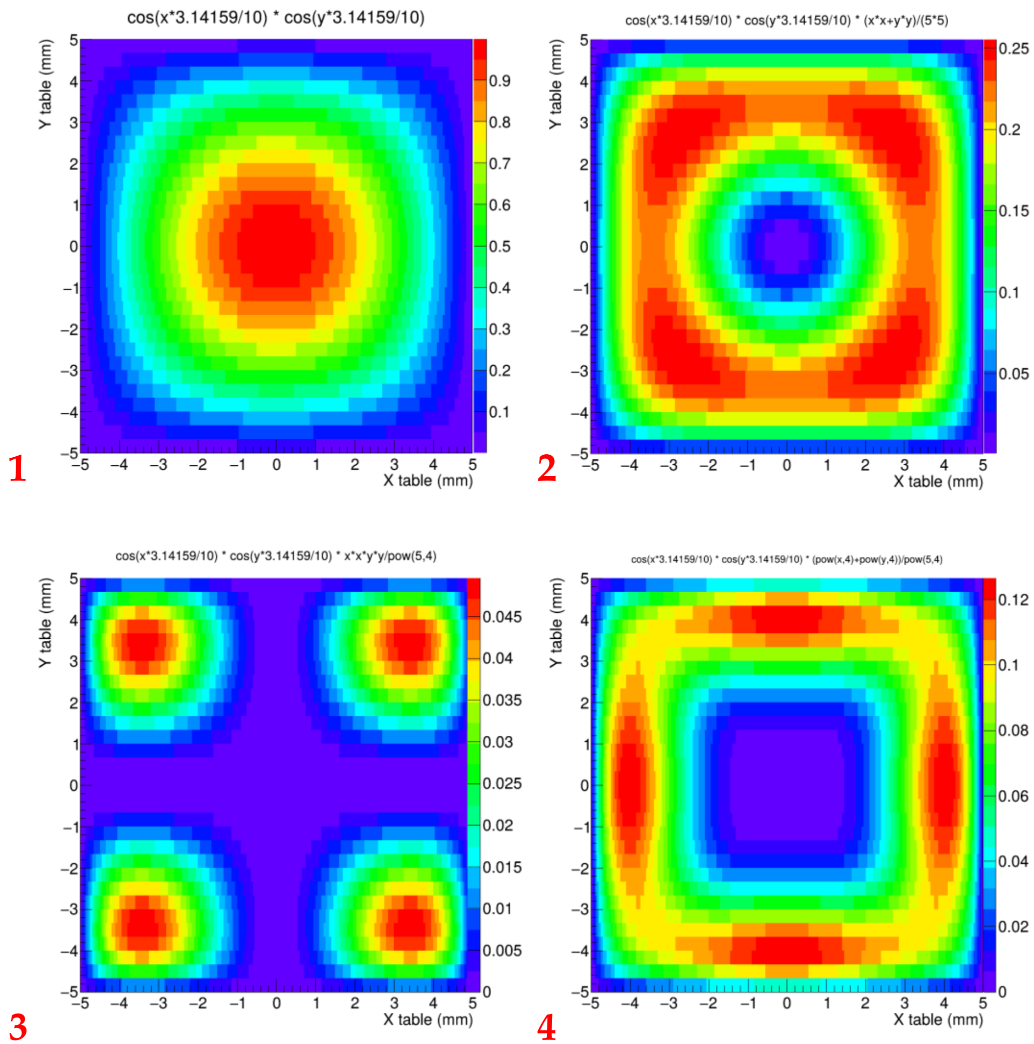
Surface parametrization with respect to ΔP

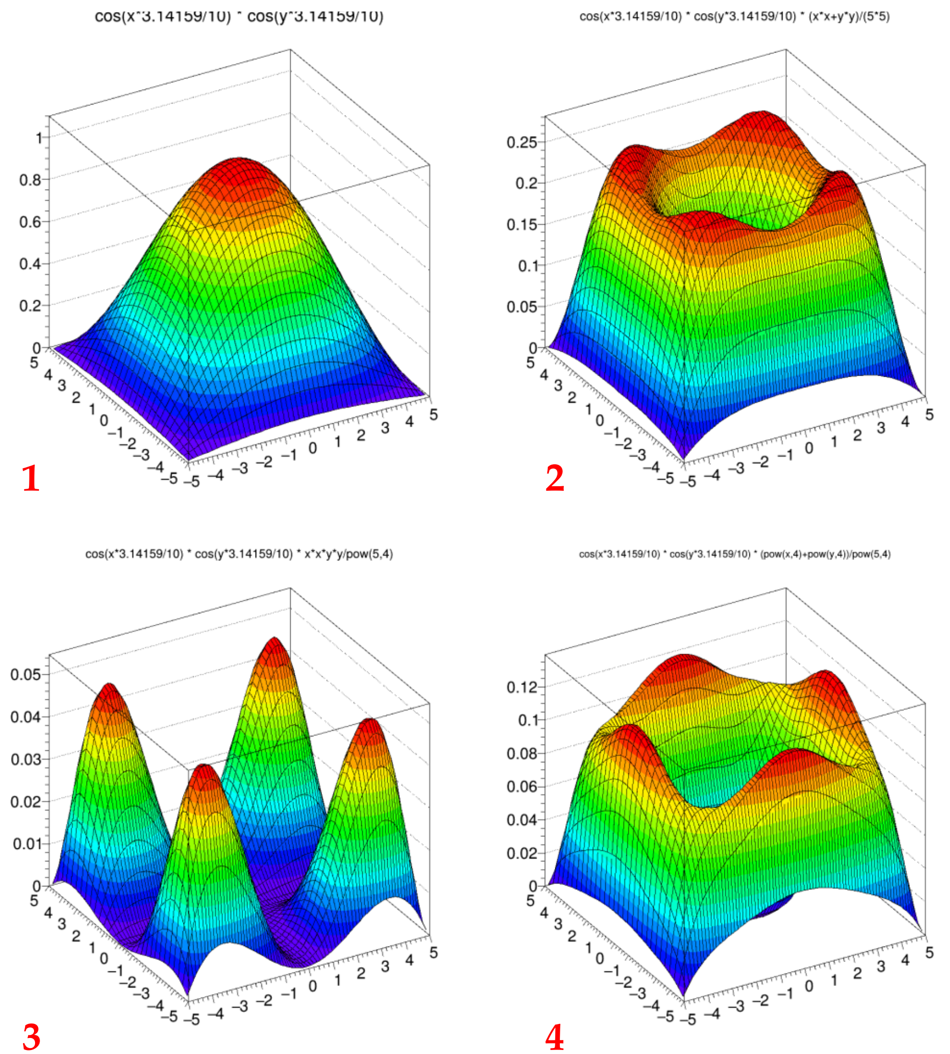
Function used to reproduce the shape of the square membrane:

- D. Maier-Schneider, J. Maibach, and E. Obermeier, Journal of Microelectromechanical Systems **4** (1995)
- M. Rahman and S. Chowdhury, IEEE ISCS (2010)

$$w(x,y)=\left[\overset{1}{1}+w_1\overset{2}{\left(\frac{x^2+y^2}{a^2}\right)}+w_2\overset{3}{\left(\frac{x^2y^2}{a^4}\right)}+w_3\overset{4}{\left(\frac{x^4+y^4}{a^4}\right)}\right]\cos^2\left(\frac{\pi x}{2a}\right)\cos^2\left(\frac{\pi y}{2a}\right)w_0$$

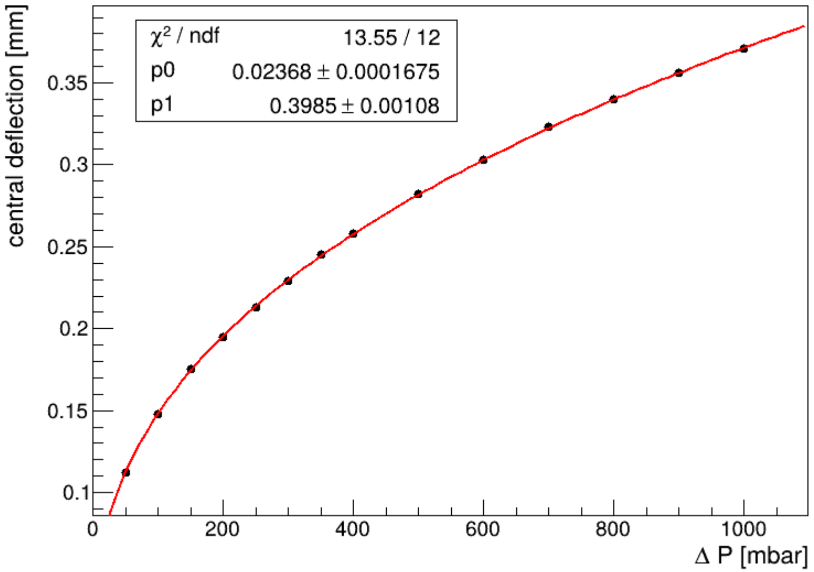
+ w_0 , w_1 , w_2 , w_3 are functions of ΔP !





Surface parametrization with respect to ΔP

1

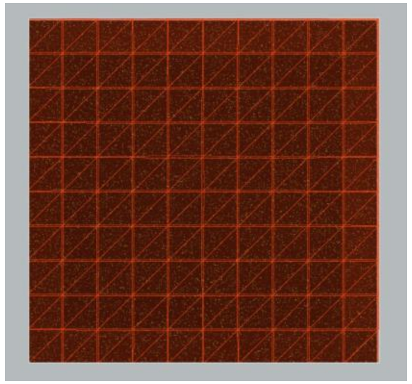


Parametrization of the squared membrane shape :

- D. Maier-Schneider, J. Maibach, and E. Obermeier, Journal of Microelectromechanical Systems **4** (1995)
- M. Rahman and S. Chowdhury, IEEE ISCS (2010)

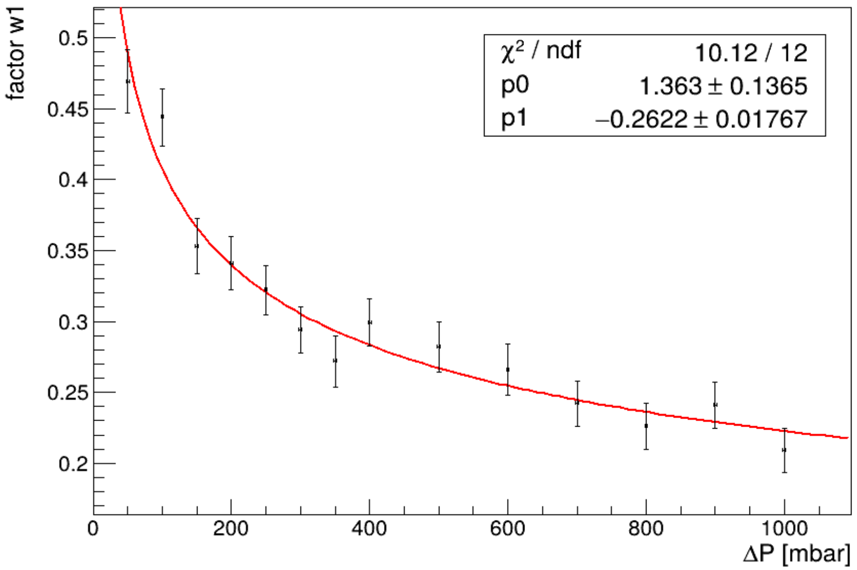
+ w_0 , w_1 , w_2 , w_3 are functions of ΔP !

$$w(x,y)=\left[\underbrace{1}_{1}+w_1\underbrace{\left(\frac{x^2+y^2}{a^2}\right)}_{2}+w_2\underbrace{\left(\frac{x^2y^2}{a^4}\right)}_{3}+w_3\underbrace{\left(\frac{x^4+y^4}{a^4}\right)}_{4}\right]\cos^2\left(\frac{\pi x}{2a}\right)\cos^2\left(\frac{\pi y}{2a}\right)w_0$$

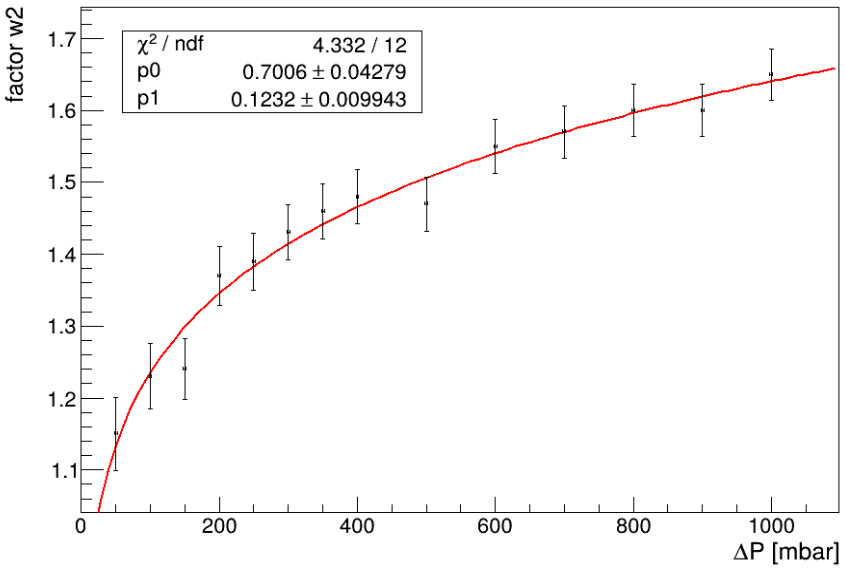


In simulation : parametrized G4TesselatedSolid

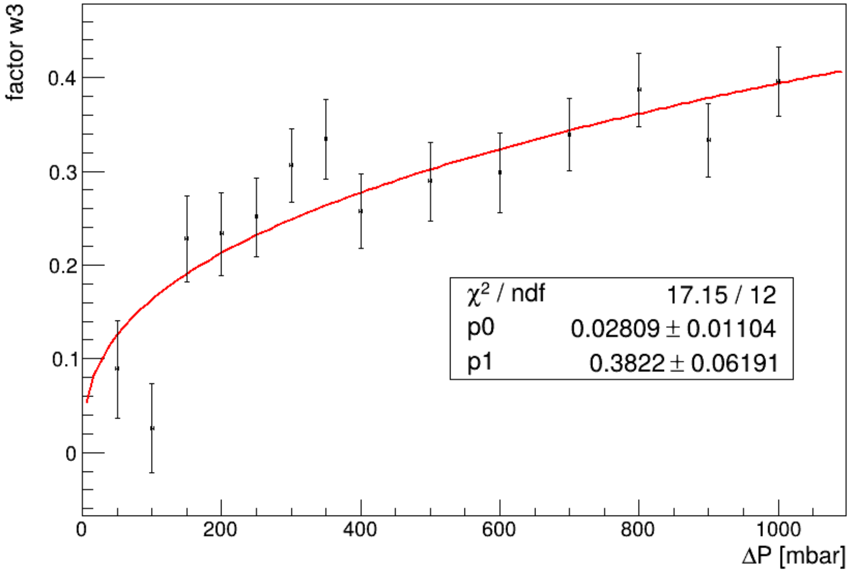
2



3



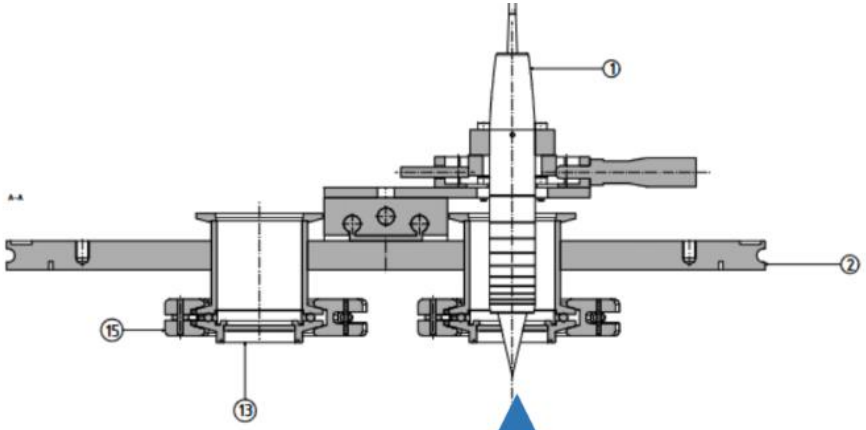
4

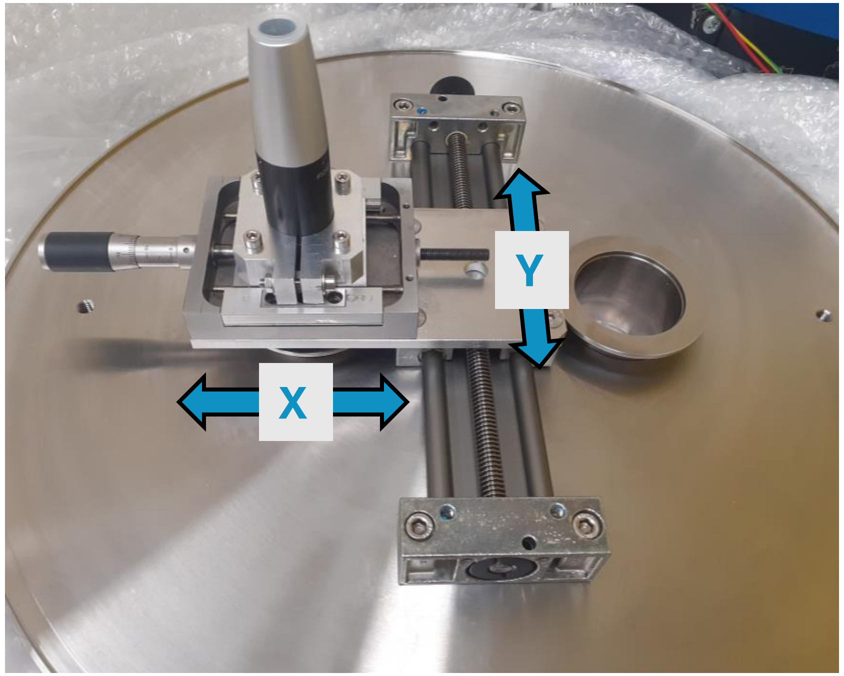


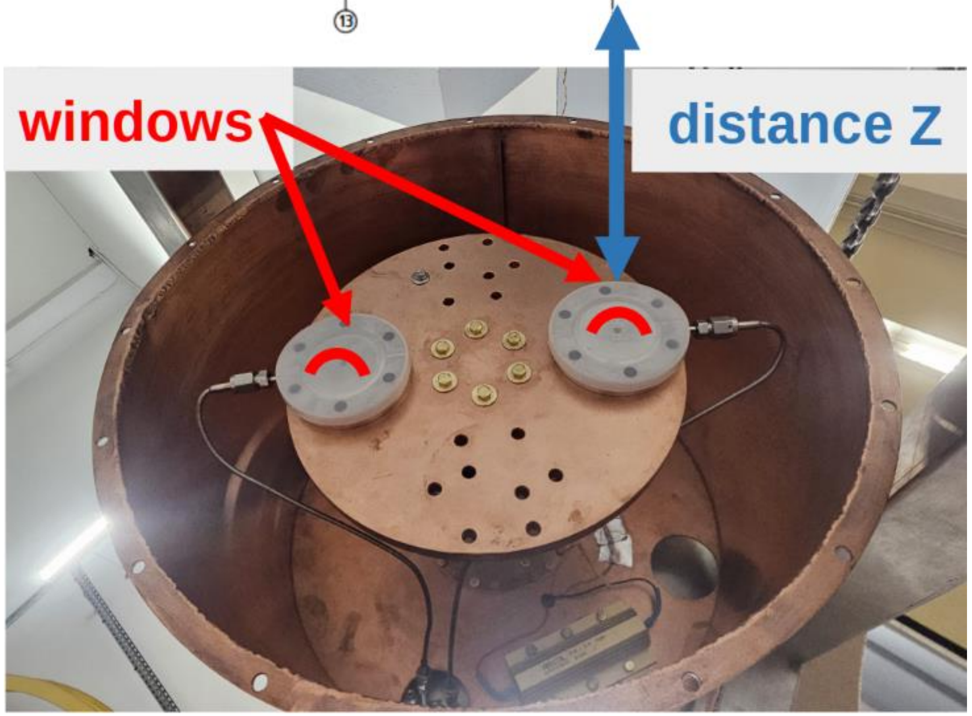
Testbench at T_{cryo} : lastest upgrade

Deformation mapping in cryogenic environment :
- dedicated flange
- (X,Y) translators
- confocal microscope

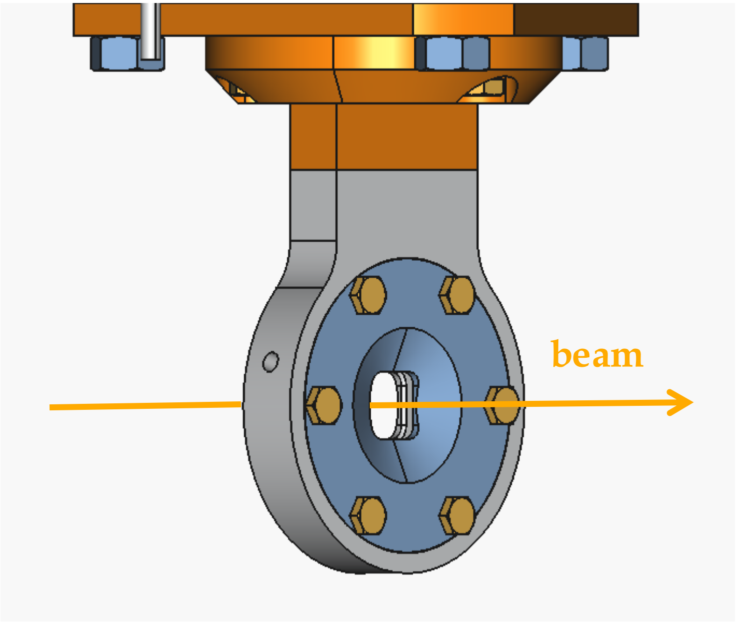
Related measurements are coming soon !







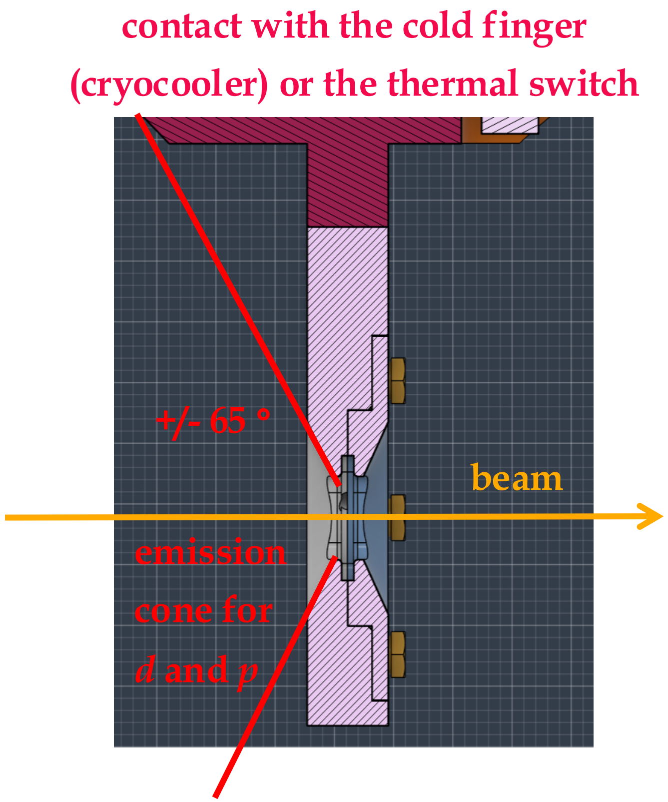
Design of the target prototype



Target prototype
body radius : 25 mm

Windows: 10x10mm

Prototype gas cell
thickness : 1.5mm
=> 1.02 mg/cm^2
@T=6K/P=1bar



- Size selected for the gas cell = f(windows deformation , density(^{3}He))

=> Different targets could be designed for different experiments

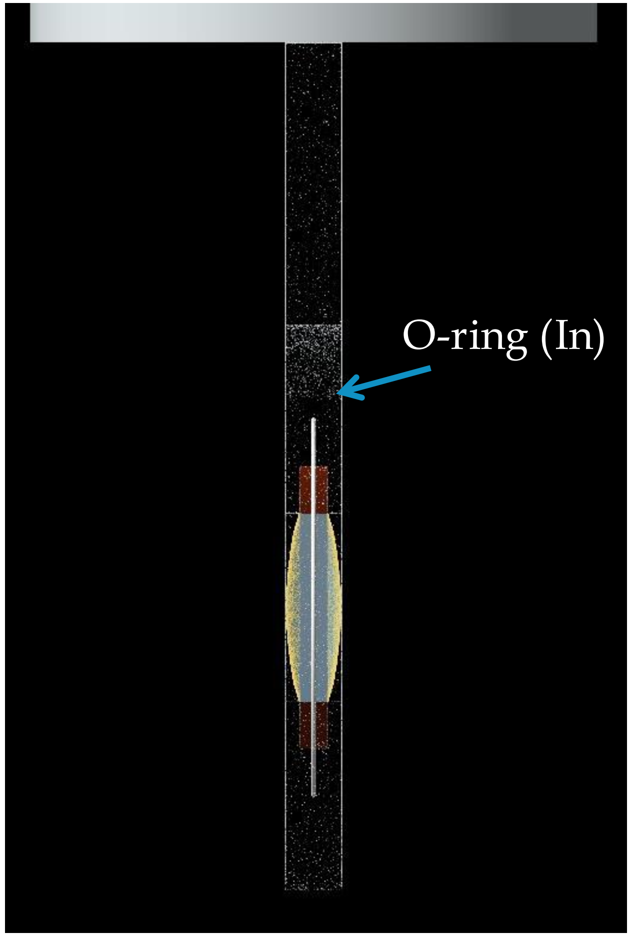
- Default configuration : both sides with an emission cone (angular acceptance of +- 65°)

=> Flat and thin (0.5mm thick) layer could be used instead to study the elastic channel

Simulation dedicated to gamma-ray studies

Simulation content :

- GRIT chamber
- GRIT array (Phase 0)
- Heat shield
- Thermal switch
- Target body



Outputs :
Energy and angle of the gamma-rays escaping the GRIT chamber volume

Cross-section view of the target

Transfert reactions in inverse kinematics with an ^{3}He target

Examples of reactions of interest for the ATRACT Project:

- **Proton shell evolution** : ^{34}Si(^{3}*He,d*)^{35}P @ 20 A MeV
  => deuterons recoiling with high energy (few MeV) , gamma-ray needed

- **Unbound proton-rich nuclei** : ^{24}Si(^{3}*He,d*)^{25}P @ 30 A MeV
  => low beam intensity, deuterons with very low energy (below 1 MeV)

- **Nuclear astrophysics** : ^{69}Cu(^{3}*He,d*)^{60}Zn, ^{56}Ni(^{3}*He,d*)^{57}Cu and ^{57}Cu(^{3}*He,d*)^{58}Zn
  => low beam intensity, deuterons with very low energy (below 1 MeV), gamma-ray needed

- **np pairing** : ^{60}Zn(^{3}*He,p*)^{62}Ga @ 10 A MeV
  => proton recoiling with high energy ~10 MeV, gamma-ray needed

Details about the ^{24}Si(^{3}*He,d*) reaction study

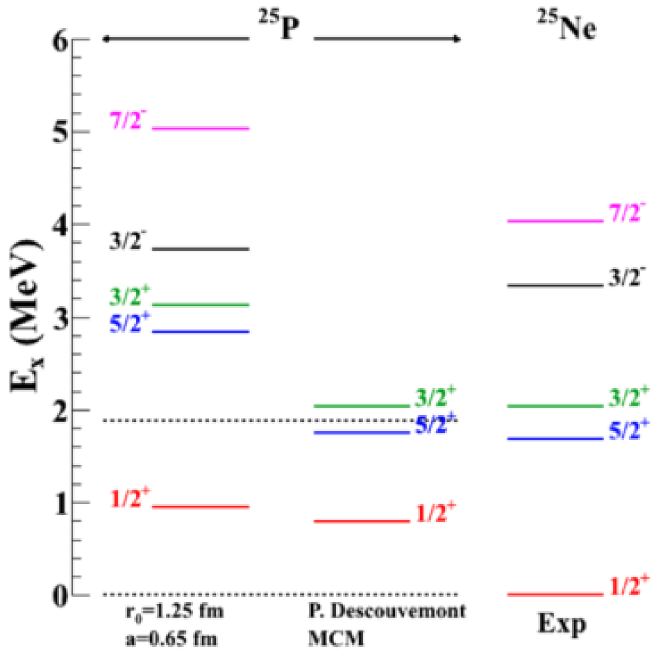
Mirror symmetry and proton-rich unbound nuclei: Case of ^{25}P

➠ **Mirror asymmetry for the low *l*-orbitals (Thomas-Ehrman-shift)** induced by weakly-bound proton (particularly the outermost proton in $s_{1/2}$ state)

→ weakening of Coulomb potential due to the spatial extension of s-wave.

→ New interpretation : the difference in s.p. energies that lead to an asymmetry between the neutron and protons s.p. WF.

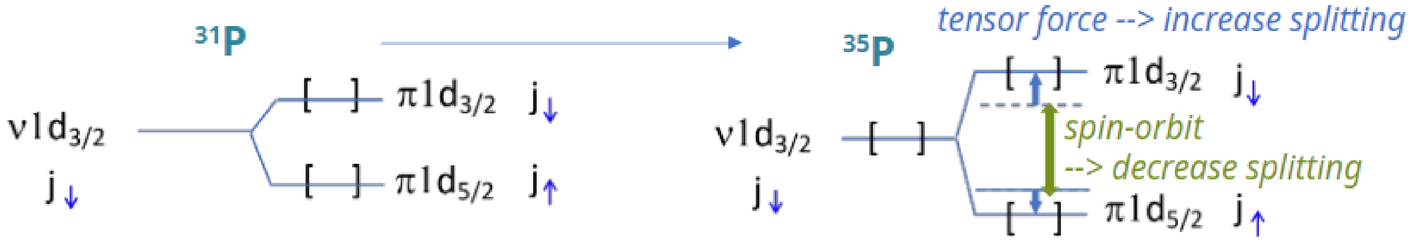
Method: ^{24}Si(^{3}He,d) ^{25}P to perform the spectroscopy of ^{25}P



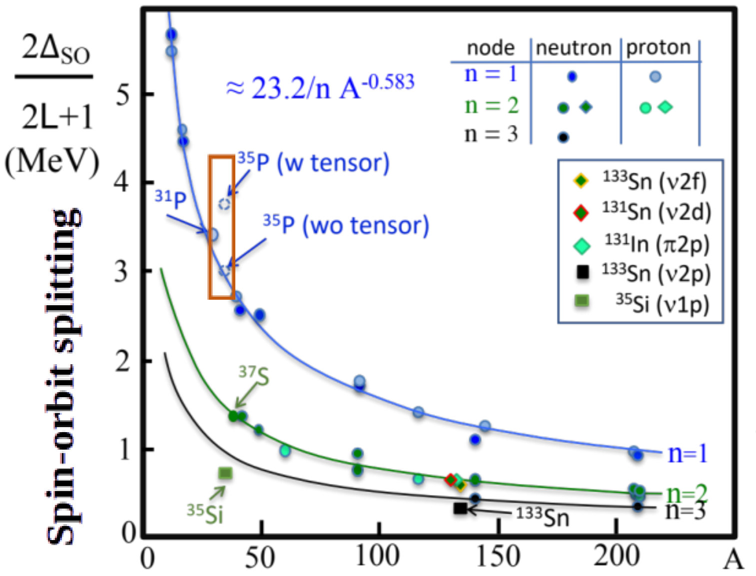
Details about the ^{34}Si(^{3}*He,d*) reaction study

Proton-shell evolution : evolution of the **proton single particle states along the Si and Ni chains**

- evolution of the Z = 16 and Z = 28 shell gaps
- role of spin-orbit and tensor forces



Method: **^{34}Si(^{3}He,d)** and ^{34}Si(d,^{3}He) to identify the centroids of each the spin-orbit partners.



Details about the ^{69}Cu(^{3}*He,d*)^{60}Zn, ^{56}Ni(^{3}*He,d*)^{57}Cu and ^{57}Cu(^{3}*He,d*) reactions study

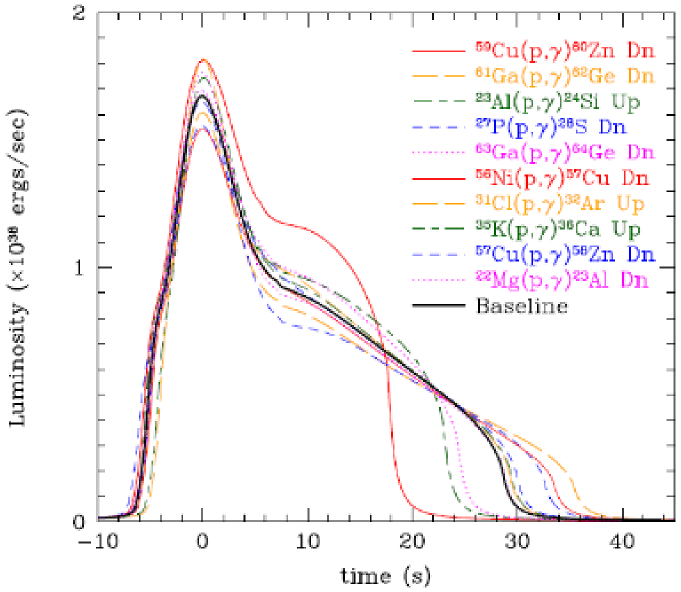
Nuclear astrophysics: Explosive hydrogen burning

. Proton captures during outburst of classical novae and type I X-ray bursts

. Main challenge is to understand the observed light curves

. Sensitive studies give 10 key reactions and particularly : ^{69}Cu(p,ɣ)^{60}Zn, ^{56}Ni(p,ɣ)^{57}Cu and ^{57}Cu(p,ɣ)^{58}Zn

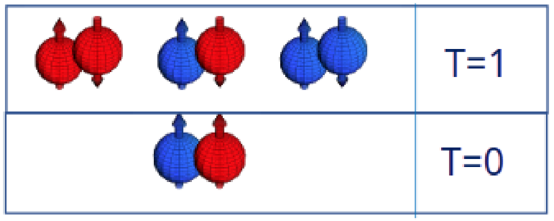
Method: One-proton transfer reactions ^{69}Cu(^{3}He,d)^{60}Zn, ^{56}Ni(^{3}He,d)^{57}Cu and ^{57}Cu(^{3}He,d)^{58}Zn with low beam intensities, low energy deuterons and ɣ-ray coincidence needed



Cyburt+, ApJ 2016

Details about the ^{60}Zn(^{3}*He,p*) reaction study

Neutron-proton pairing in the *fp*-shell
Two-nucleon transfer reactions are the best probe for pairing and **(^{3}He,p) and (p,^{3}He)** allows to populate both T=0 and T=1 channel.



Method: Cross-sections to the first 0+ and 1+ states for the two-nucleon transfer reaction **^{60}Zn(^{3}He,p) ^{62}Ga** and, simultaneously ^{60}Zn(^{3}He,d)^{61}Ga the intermediate reaction