Windows for final cooling

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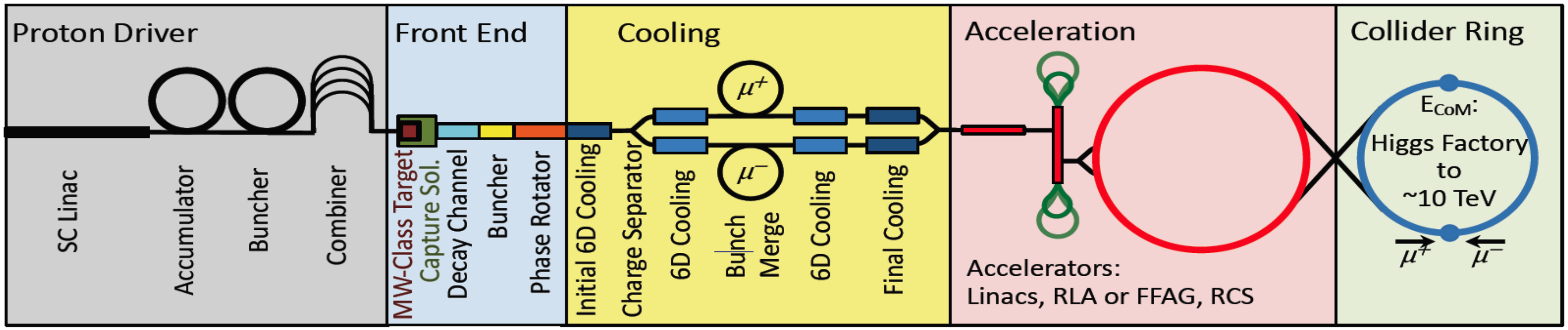
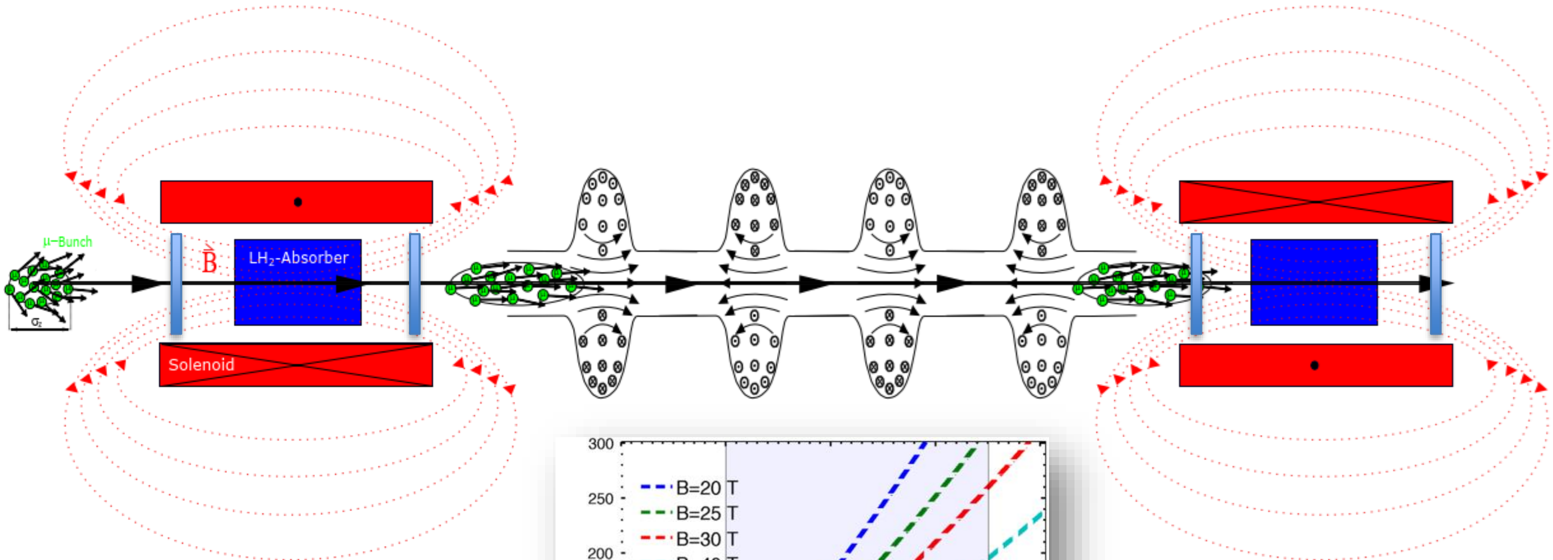
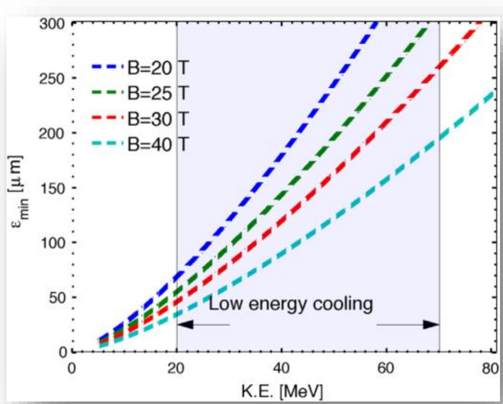
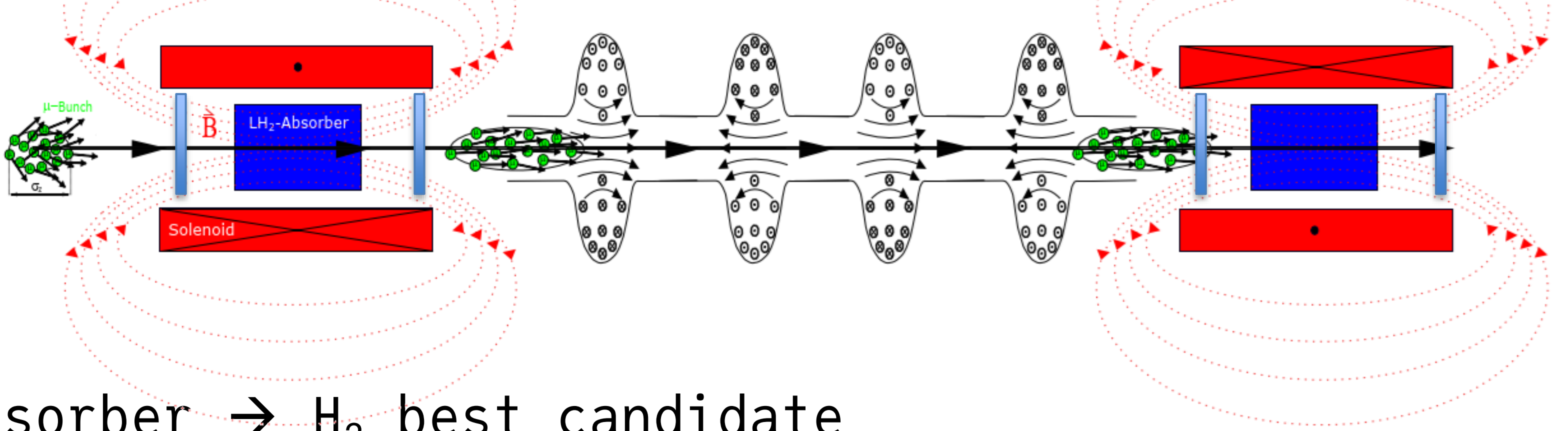
Introduction







Final Cooling



- Absorber → H_2 best candidate
- For liquid/gas absorber → Vacuum windows are required [1]
- Windows may be required even for solids (thermal desorption)
- Low energy → Thin windows

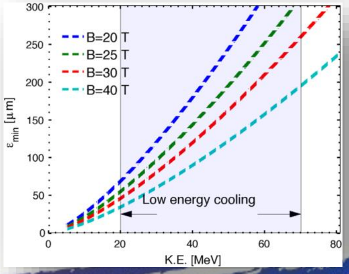
TABLE II. Parameters of the high-field low-energy cooling channel.

Stage [N]	P [MeV/c]	Energy spread σ_E [MeV]	LH_2 thickness [cm]	Drift length [m]	rf length [m]	rf frequency [MHz]	Field flip
1	135.0	2.29	65	0.434	2.25	325	Yes
2	130.0	2.48	60	0.459	2.25	250	Yes
3	129.0	2.78	60	0.450	2.5	220	No
4	129.0	3.10	59	0.458	2.5	201	No
5	122.0	3.60	57	1.629	5.0	201	Yes
6	124.0	4.90	53	2.22	4.5	180	No
7	116.0	3.40	42	2.21	3.25	150	No
8	111.0	3.90	40	2.0	3.5	150	No
9	106.0	3.50	40	3.13	5.0	125	Yes
10	98.0	3.07	35	3.13	5.0	120	No
11	89.4	3.11	20	3.12	5.0	110	No
12	87.9	2.76	20	3.1	8.0	100	No
13	85.9	2.67	20	3.0	7.5	100	Yes
14	79.7	3.08	15	2.7	7.0	70	No
15	71.1	4.0	15	2.6	6.0	50	No
16	71.0	3.80	13	2.5	6.0	20	No
17	70.0	3.80	10	...	...	20	...

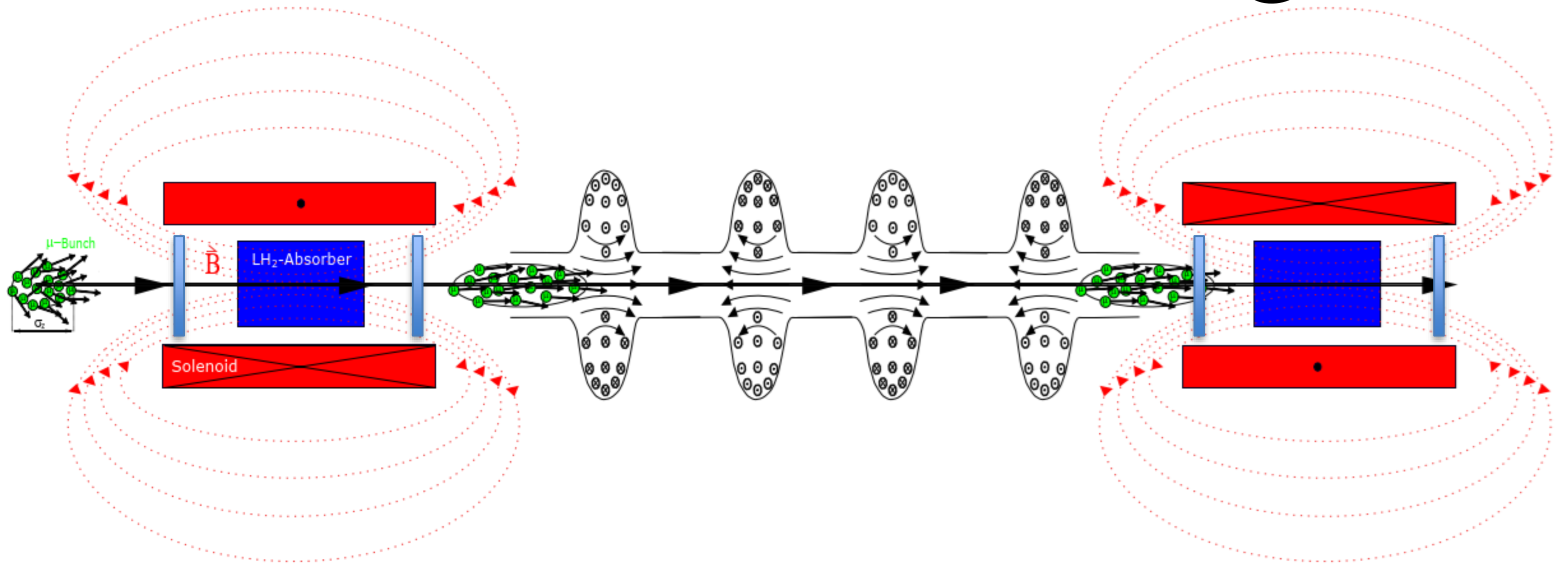
[2]

Initial Momentum (MeV/c)	Initial kinetic energy (MeV)	Final kinetic energy MeV
135	65.8	39.3
130	61.9	36.7
129	61.1	35.7
129	61.1	36.2
122	55.7	30.1
124	57.3	34.2
116	51.2	32.1
111	47.6	28.5
106	44.0	23.5
98	38.5	18.6
89.4	32.7	21.1
87.9	31.8	19.8
85.9	30.5	18.0
79.7	26.7	16.6
71.1	21.7	8.8
71	21.6	11.0
70	21.1	13.2

Parameters:
- 20 to 5 MeV cooling
- 4e12 muons/pulse
- 5 Hz repetition rate
- σ_{RMS}=0.6 mm



Final Cooling



[10]

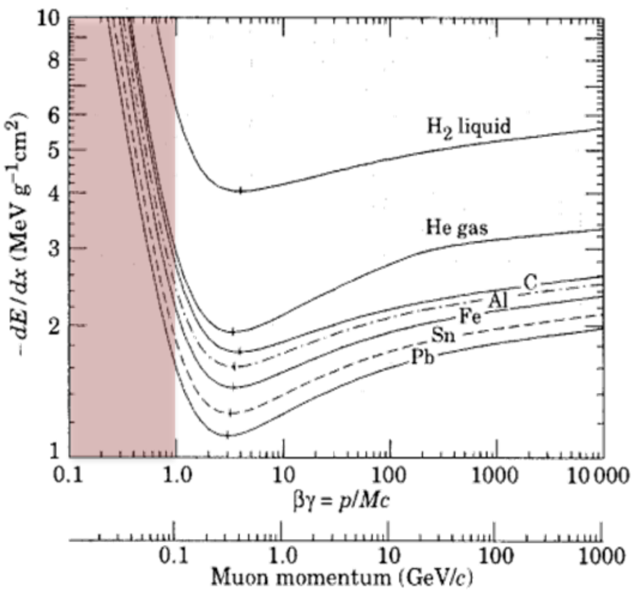
- At 5 MeV → Be range <1.5 mm [3]
- Conventional windows typical at CERN 0.254 mm >15% muon range

Thin windows

- Possible materials:
  - Be, Si_3N_4, C, SiC, etc.?
- To limit beam perturbation <15µm (approx. <1% of power absorbed in the window for 3keV/µm)
- Thin window → Small window → $10\times\sigma_{RMS}$

$$\left\langle -\frac{dE}{dx}\right\rangle_{\text{electronic}} = K\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2Q_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} + \frac{1}{8}\frac{Q^2_{\max}}{(\gamma Mc^2)^2}\right] + \Delta\left|\frac{dE}{dx}\right|$$

		5 MeV	20 MeV
Be	Stopping power [MeV×cm²/g]	11.2	4.0
	Linear stopping power [keV/µm]	2.1	0.7
C	Stopping power [MeV×cm²/g]	12.2	4.3
	Linear stopping power [keV/µm]	2.7	1.0
Si_3N_4	Stopping power [MeV×cm²/g]	11.2	4.0
	Linear stopping power [keV/µm]	3.1	1.1
SiC	Stopping power [MeV×cm²/g]	11.1	4.0
	Linear stopping power [keV/µm]	3.5	1.3



Thin windows: Be

- Well known material
- As thin as 8 µm in commercial x-ray windows[5]
- Aperture 7 mm
- ΔP > 1 bar
- Commercial, but no many suppliers

Figure 1 Typical Assembly of Beryllium Window

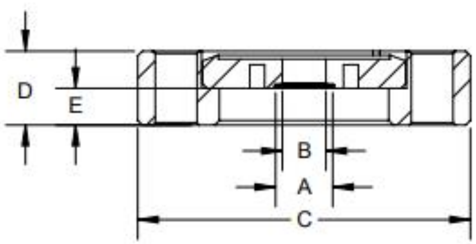


Figure 2 Conflat Flange Geometry

Table 1 Dimensions of Conflat Flange Options (Refer to Figure 2 above)

CF	Foil Thickness (µm)	Foil Diameter (mm) - A	Through Hole Diameter (mm) - B	CF Outer Diameter (mm) - C	CF Thickness (mm) - D	Window Height (mm) - E	Coating	Part ID
1-1/3" OD	8.0	9.2	7.0	33.8	7.2	0.5	DuraCoat Plus	DBM-08-9.2-CF1.3-P
	25.0	16.0	13.0	33.8	7.2	0.5	DuraCoat	DBM-25-16.0-CF1.3
2-1/8" OD	8.0	9.2	7.0	53.6	11.9	6.5	DuraCoat Plus	DBM-08-9.2-CF2.1-P
	25.0	16.0	13.0	53.6	11.9	6.5	DuraCoat	DBM-25-16.0-CF2.1

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Thin windows: C

- Thickness <1 μm
- Different options: Graphenic carbon [6] or diamond [7]
- Research phase

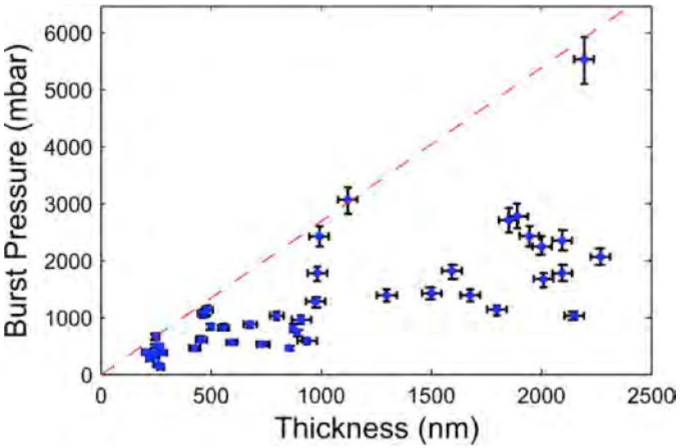


Fig. 4. Measured thickness dependent burst strength of fabricated GC transmission windows with a diameter of 7 mm.

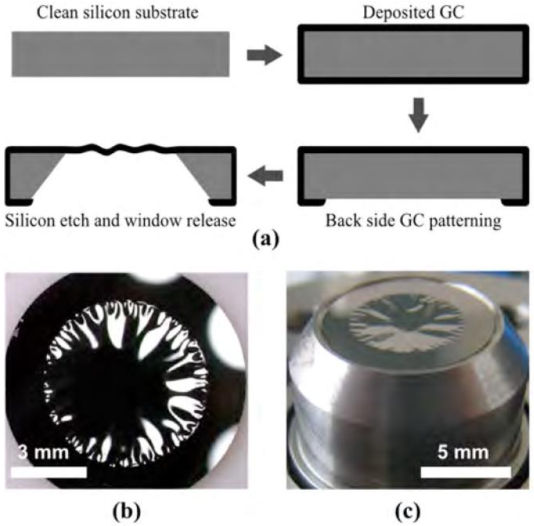


Fig. 2. (a) sketches the fabrication process of the transmission window. (b) shows a top view image of a fabricated GC window. (c) depicts a TO8 housing with a GC window glued into the top of the housing

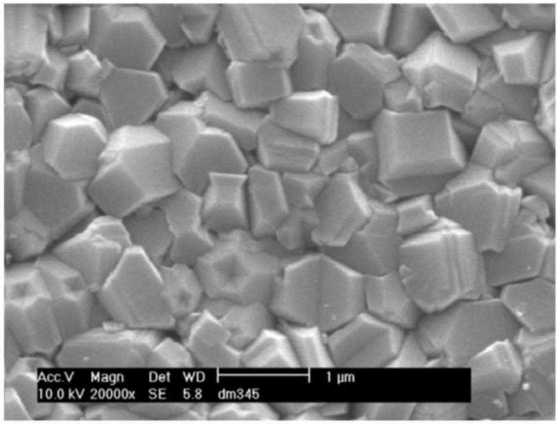
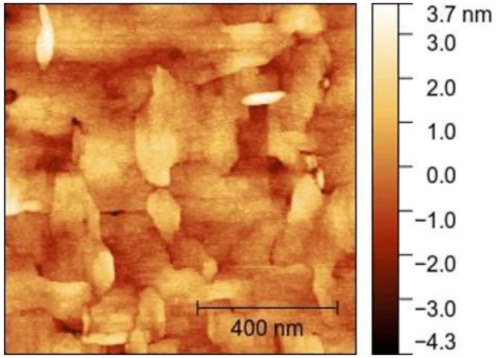


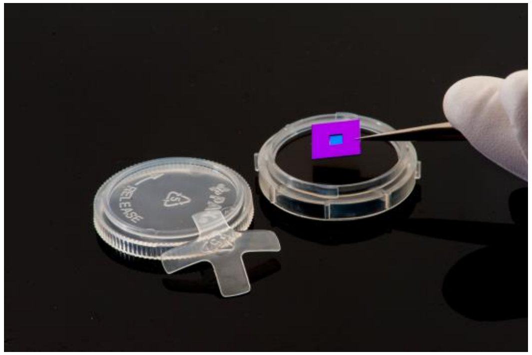
Fig. 4. SEM picture of the diamond film 345#.

Thin windows: SiC

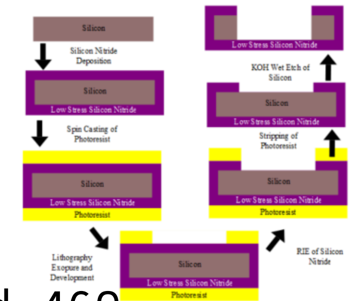
- Thickness <1 µm
- Bulk material has excellent mechanical properties
- No many commercial suppliers [8]



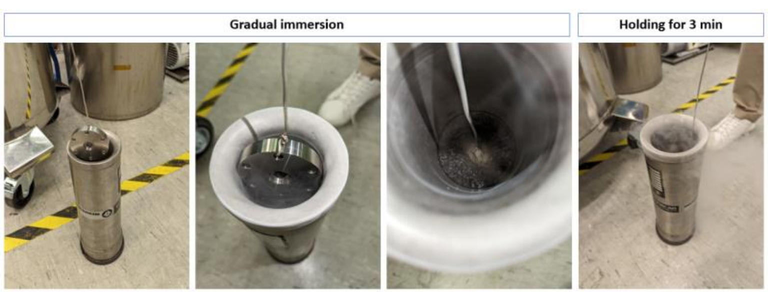
Silson

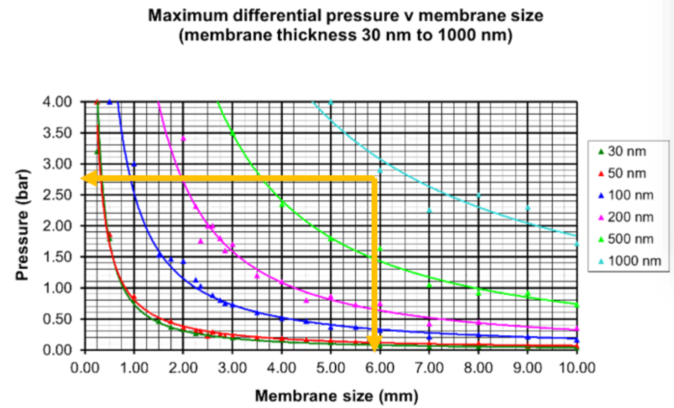


Thin windows: Si_3N_4



- Commercially available: Xray windows i.e. [9]
- Thickness <1 μm
- They can work at cryogenic temperature [10]
- Bulk material has excellent mechanical properties [11]
- Expected ΔT at the conditions described before estimated 460K
- Stress during the pulse reasonable level according to first rough estimate.
- 1 μm 6×6mm window → >5 bar pressure (tested in lab)
- Thermal cycles at 77K





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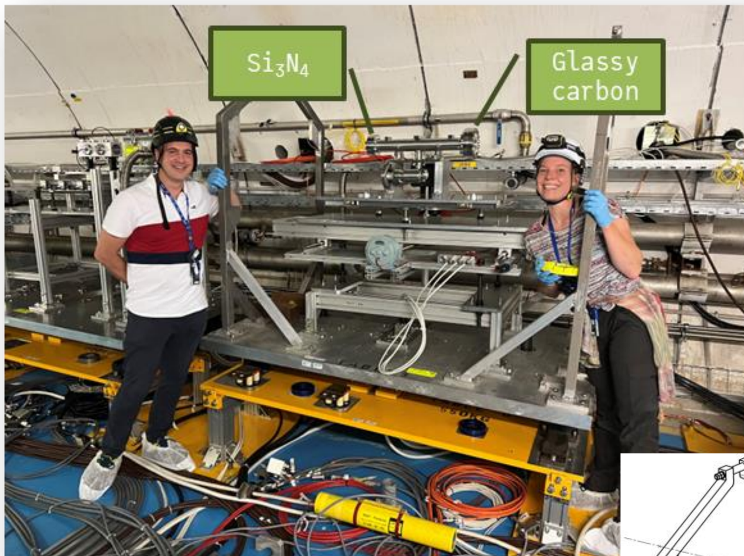
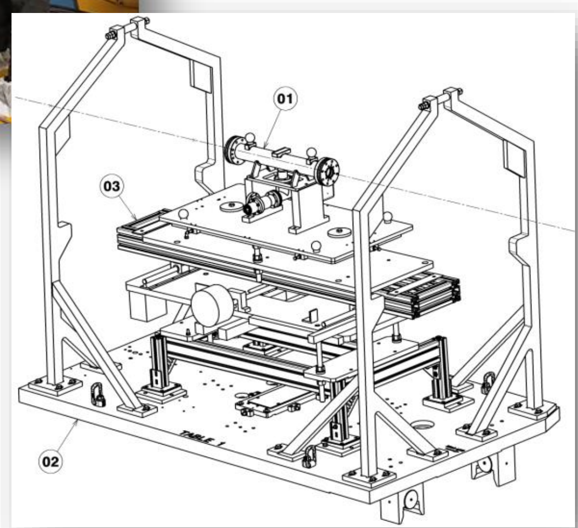
Test of 1μm thick Si_3N_4 window in HiRadMat (Baby-SMAUG)

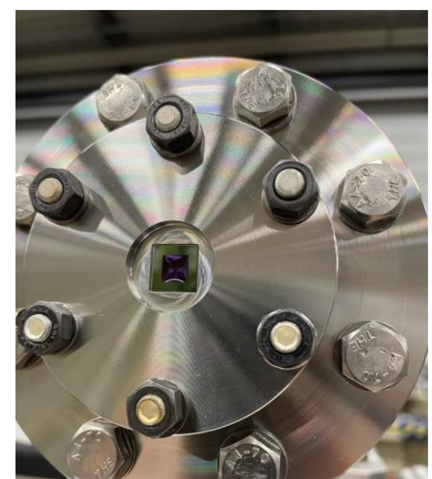
$$\left\langle -\frac{dE}{dx} \right\rangle_{\text{electronic}} = K \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 Q_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} + \frac{1}{8} \frac{Q_{\max}^2}{(\gamma M c^2)^2} \right] + \Delta \left| \frac{dE}{dx} \right|$$

Brightness $\equiv \frac{N_b I_b}{\sigma_x^2 + \sigma_y^2}\, p^+/mm^2$ [12]



- ❑ Test one membrane irradiated under vacuum
- ❑ 4×10^{12} muons/pulse at 5MeV σ_{RMS}=0.6 mm → Maximum power deposited 0.89 kJ/cm³
- ❑ p⁺ equivalent with σ_{RMS}=0.25 mm at 440 GeV → 3.2×10^{12} p⁺/pulse that corresponds to **2.6×10^{13} p⁺/mm²**
- ➢ Objective: Few shots increasing intensity up to failure. Optics Fp2 0.25 mm

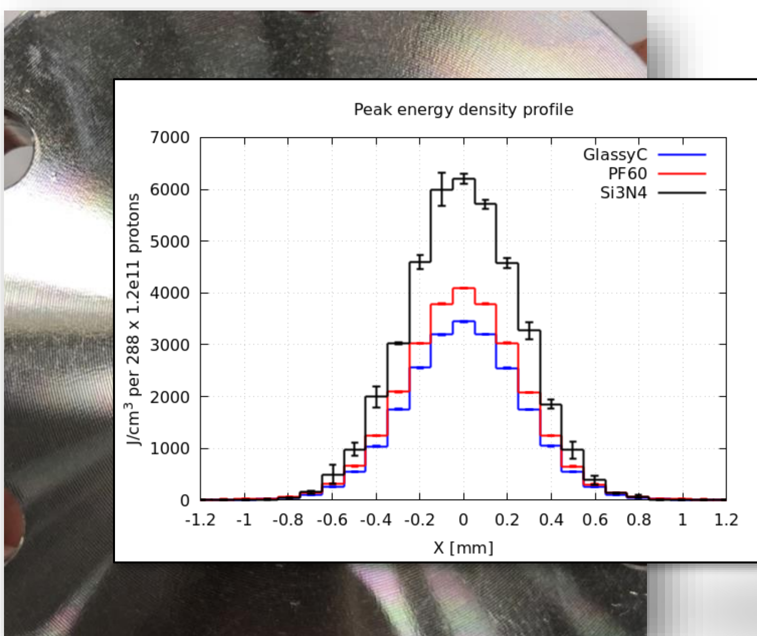


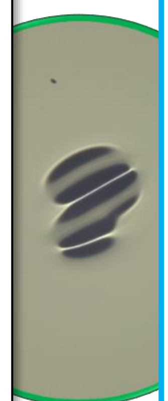


1 μm 6×6mm window

Results

- Leak rate < 5×10^{-10} mbar×l/s (both glassy carbon and Si_3N_4 leak tight)
- Not visible damage while under vacuum
- Indentation visible after venting Si_3N_4.



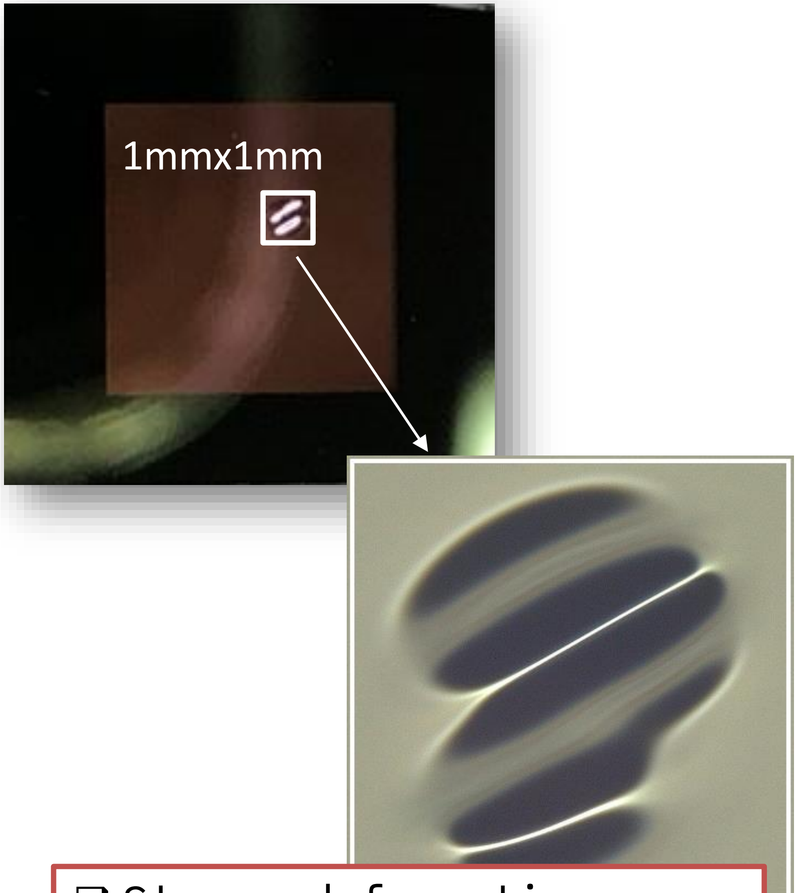


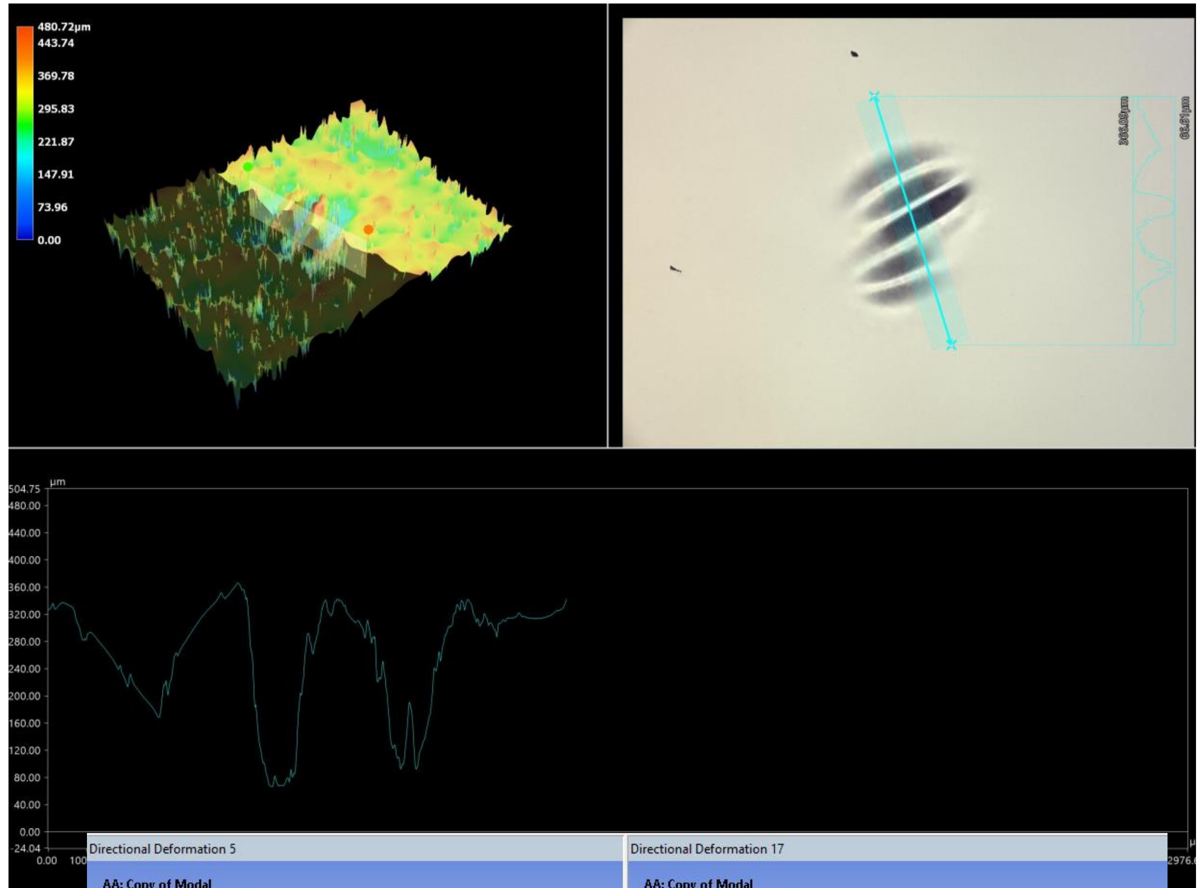
Bethe-Bloch equation
- 15 kJ/cm³
- ΔT>8000 °C

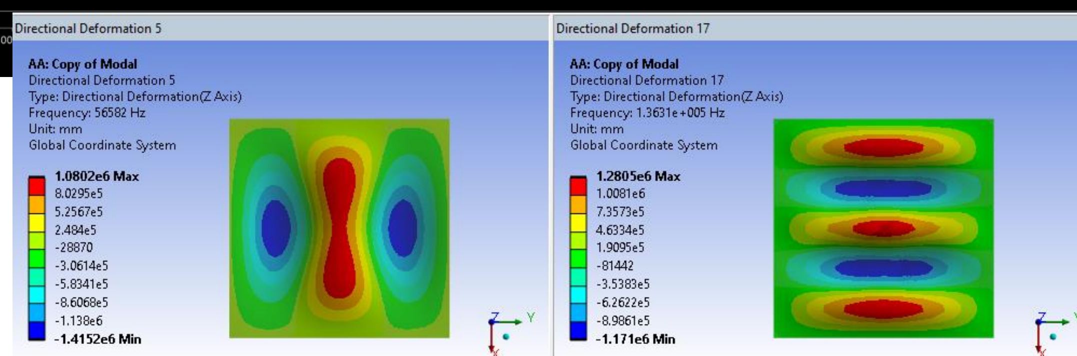
FLUKA [12]
- 6 kJ/cm³
- ΔT>2000 °C

Operational temperature of bulk Si_3N_4 1400°C (no load).
Decomposition at 1900 °C
Why?

Results



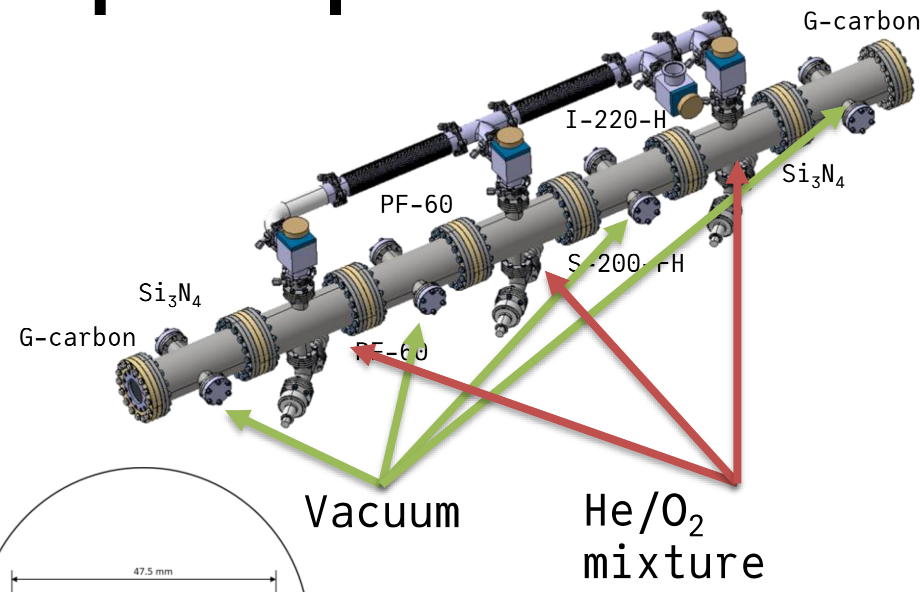


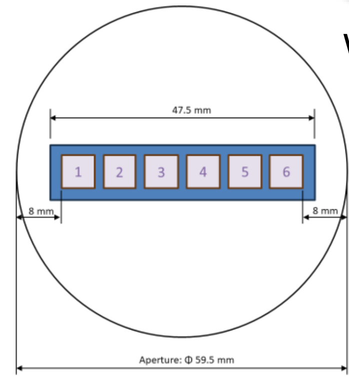


- ❑ Strong deformation on beam spot (>300 µm?)
- ❑ Buckling? Vibrations?
- ❑ SEM imaging was not possible (insulator)

Experimental proposal

- Continuation of HRMT-59 (SMAUG)
- Test Nb-Ti coated PF-60 diffusion-bonded windows and Si_3N_4
- Brightness range between 288 bunches 1.2×10^{11} ppb $\sigma_{RMS}=0.4$ mm (5 and 50 pulses)
- Highest possible brightness fp2 0.25 mm, 288 bunches $>2.1\times10^{11}$ ppb (5 and 50 pulses)
- Test fp2 0.25 mm $>2.1\times10^{11}$ ppb 72+72 bunches with separations 0.22 and 23 μs



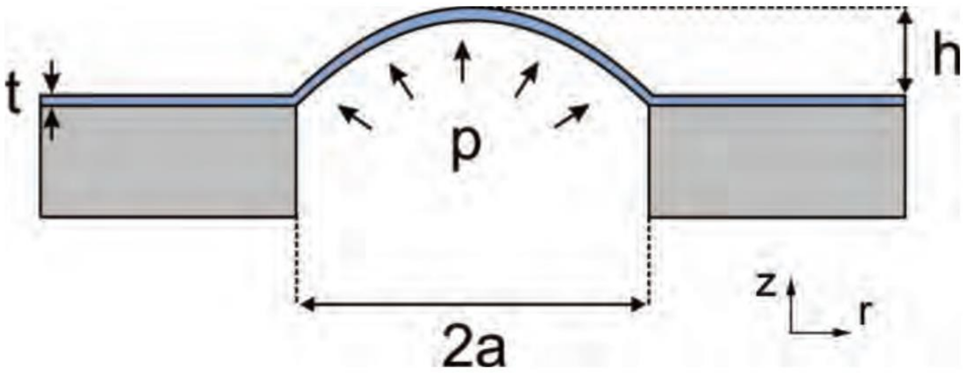


Modifications:

- DN100 → Glue 6 Si_3N_4 windows (10×10 mm frame)
- Low vacuum (10^{-2} mbar) → Pressure difference even with large leaks
- Remotely operated isolation valves
- He/O_2 (Heliox). Oxidation and high sensitivity using leak detector (20% O_2 80% He) → Early detection of any failure
- Pirani gauges → Leak rate by accumulation
- Remote control: Leak detector, valves and gauges

Mechanical tests

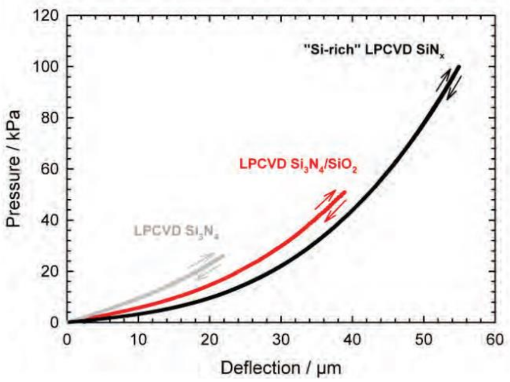
- Mechanical characterization of Si_3N_4 membranes at different temperatures (from cryogenic to high temperature) → Use inputs to better validate thermomechanical models
- For thin membranes Bulge testing is the easiest setup. Measurements of Si_3N_4 membranes at room temperature in [13]

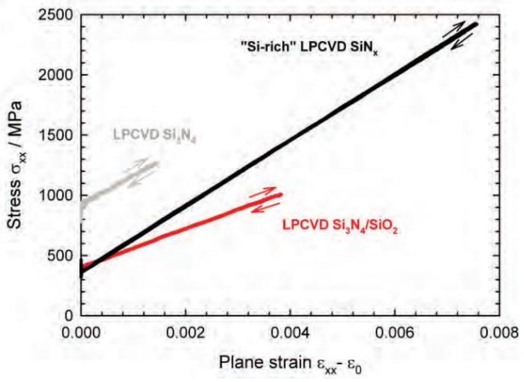


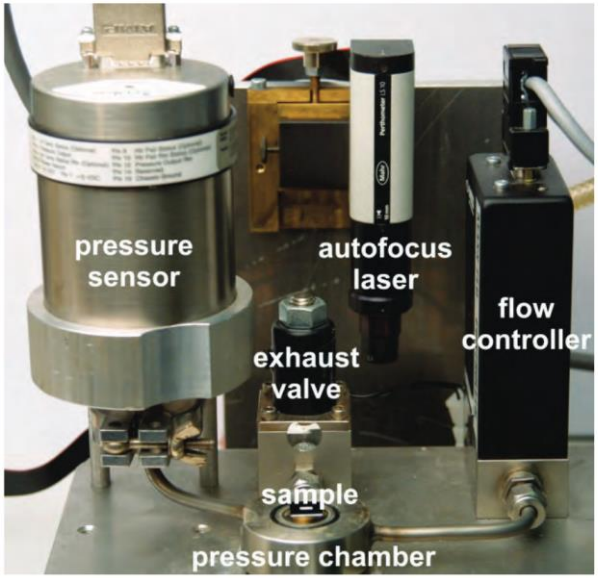
$$p = 4\sigma_0 t \frac{h}{a^2} + \frac{8}{3}\frac{E}{1-\nu} t \frac{h^3}{a^4}$$

$$\sigma_r = \frac{pa^2}{4ht}$$

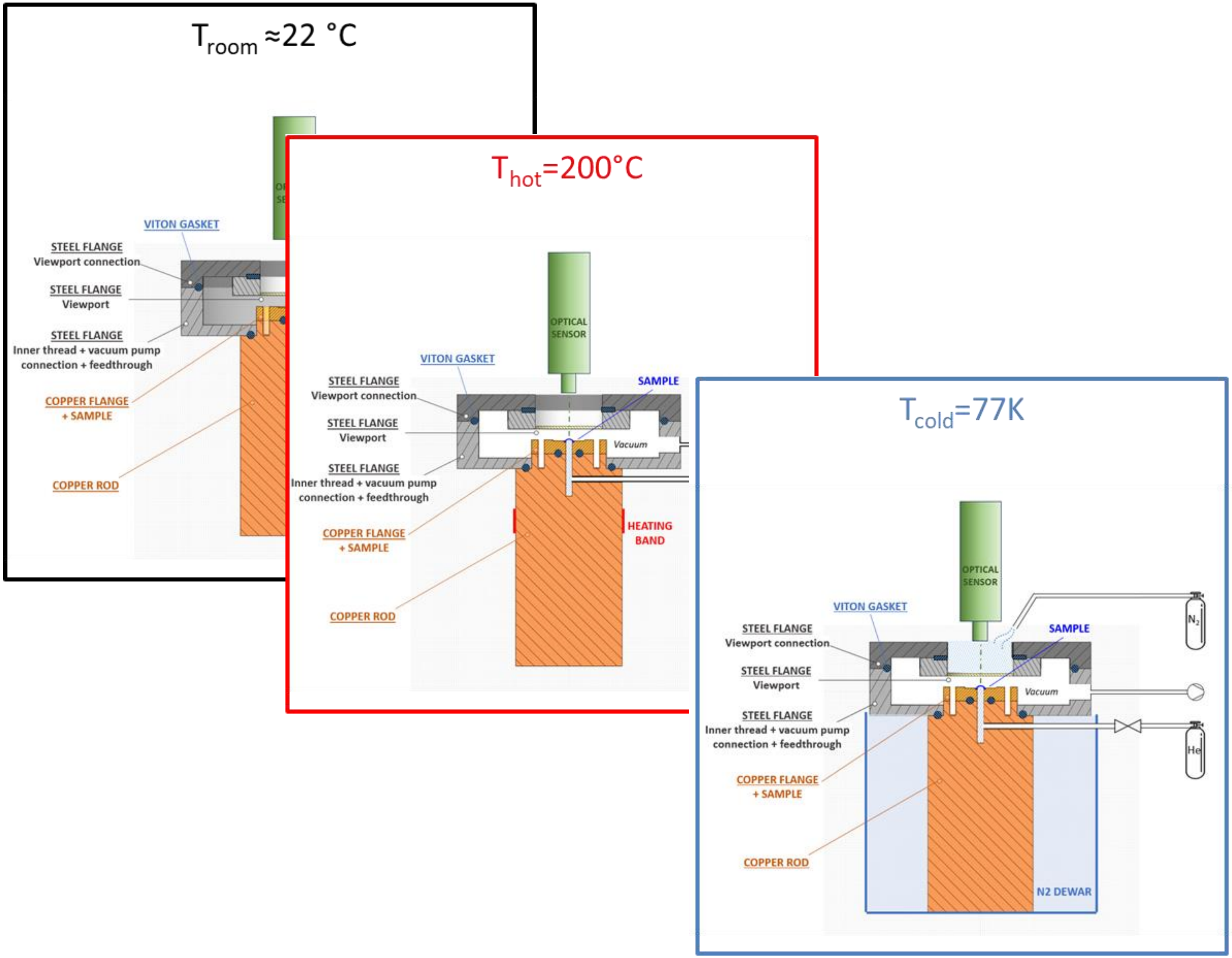
$$\varepsilon_r = \frac{2h^2}{3a^2} + \varepsilon_0$$

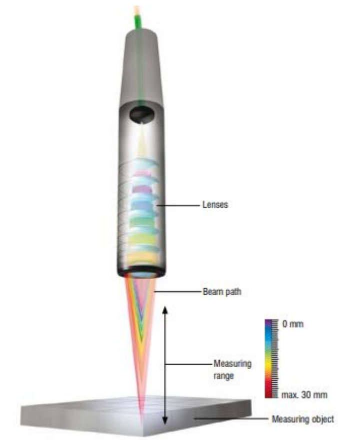


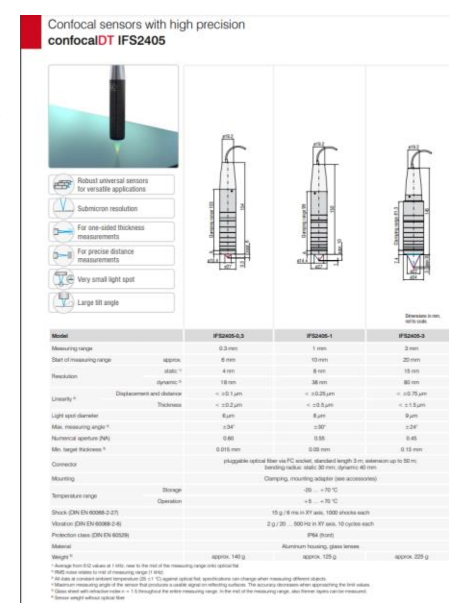




Mechanical tests







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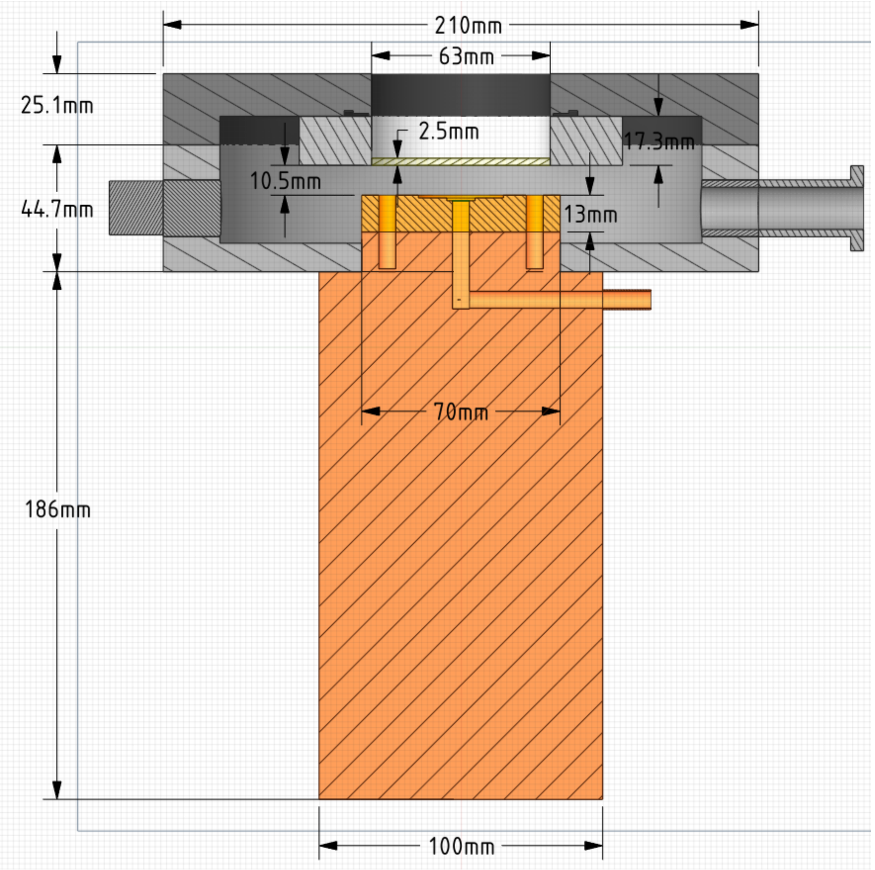

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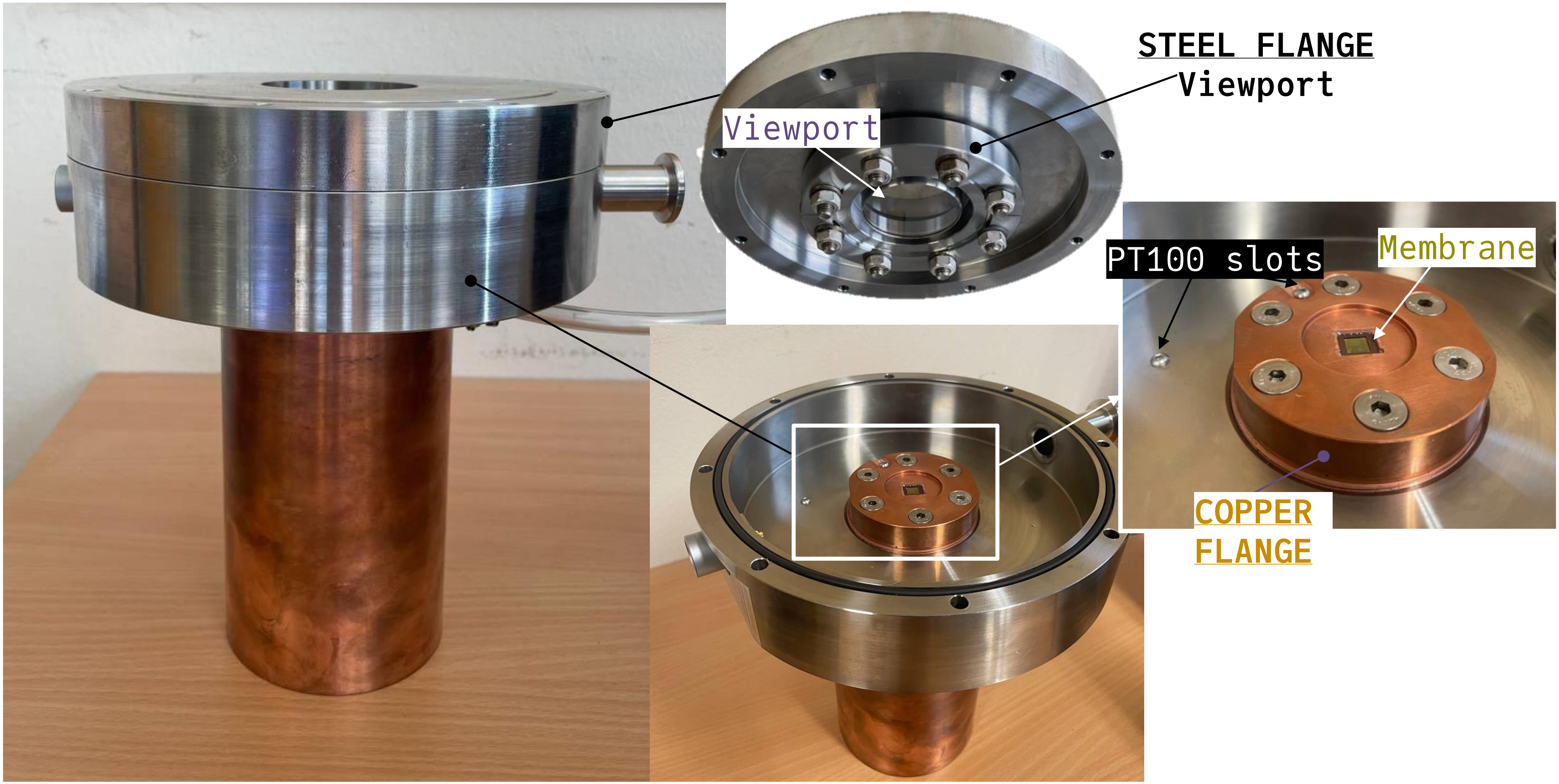
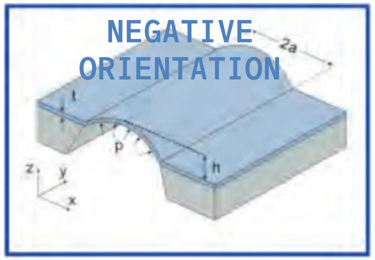
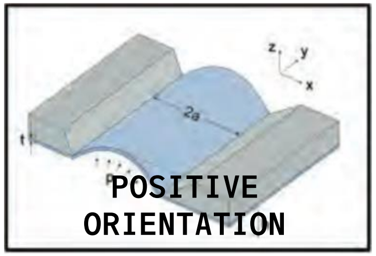


Mechanical tests

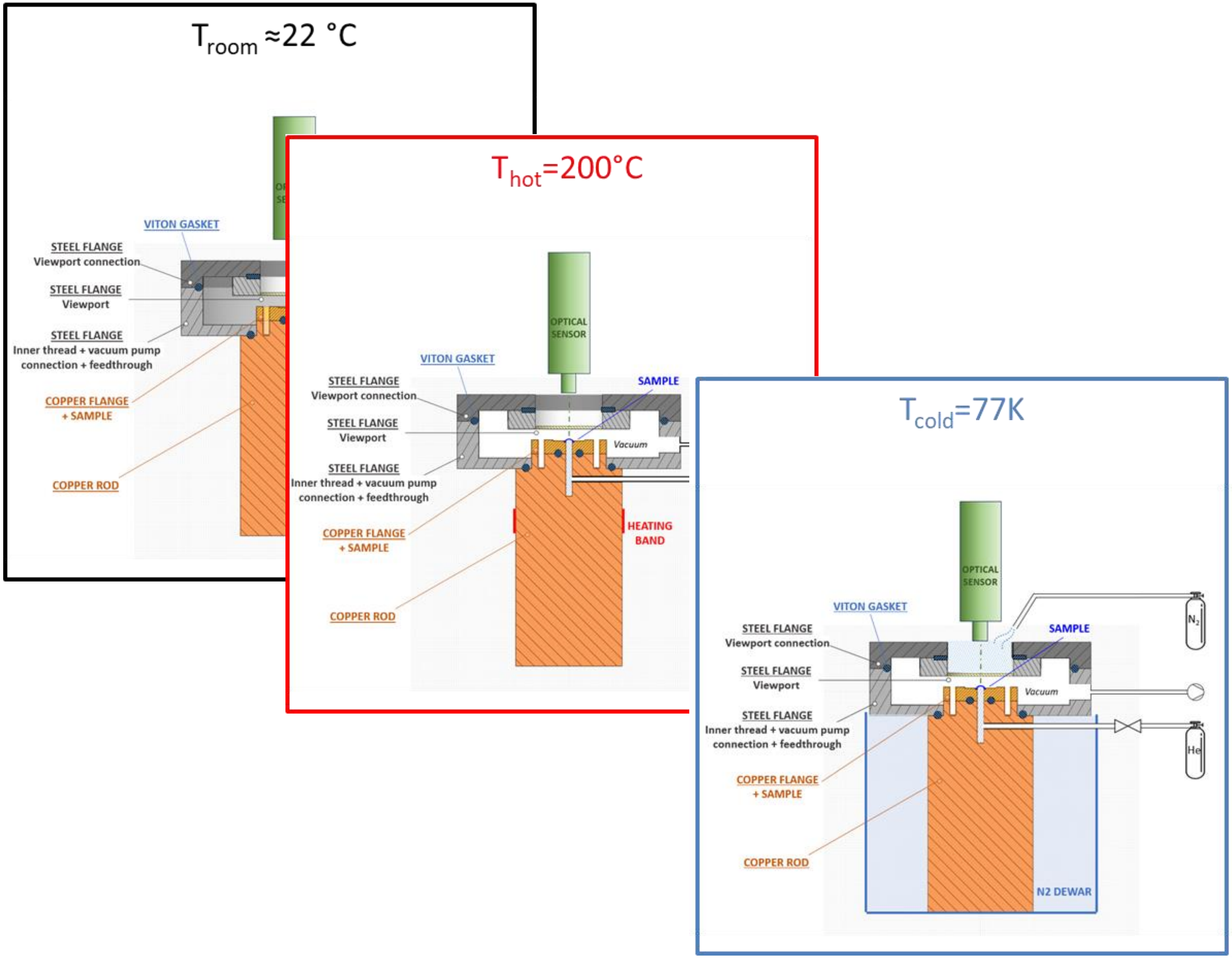
- Pressure tests were performed on square membranes with the following geometry:
  - Si frame: 10 mm x 10 mm, thickness=200 μm,
  - Si_3N_4 membrane: 6mm x 6mm, thickness=1000nm.
- Leak-tight tests of the bulge test setup were successfully performed.
- Different glues were used to bond the sample to the copper flange. This considerably affects the mechanical response of the membrane against the maximum pressure it can withstand.
- Two different ways to mount the membrane (positive and negative orientation in the figure) were investigated.
- Results from pressure tests are shown in the table:

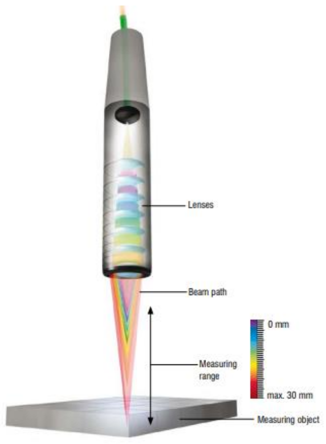


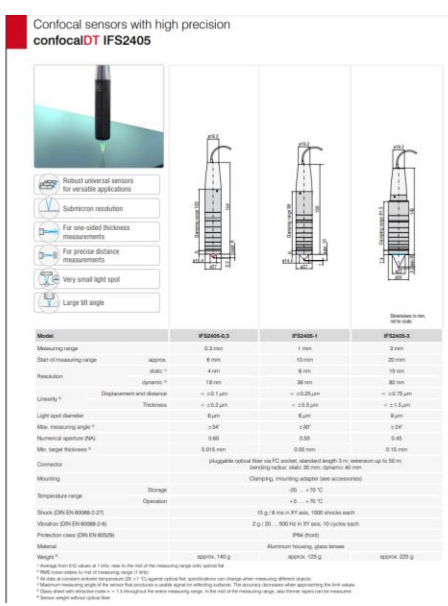


Sample #	Membrane orientation	Glue	Temperature	Max pressure before failure
1	NEGATIVE	Superglue (instantaneous)	295 K	< 1 bar
2	POSITIVE	Superglue (instantaneous)	295 K	2 bar
3	POSITIVE	Araldite bi-component (curing time: 2 h)	295 K	6 bar
4	POSITIVE	Araldite bi-component (curing time: 2 h)	77 K	2 bar

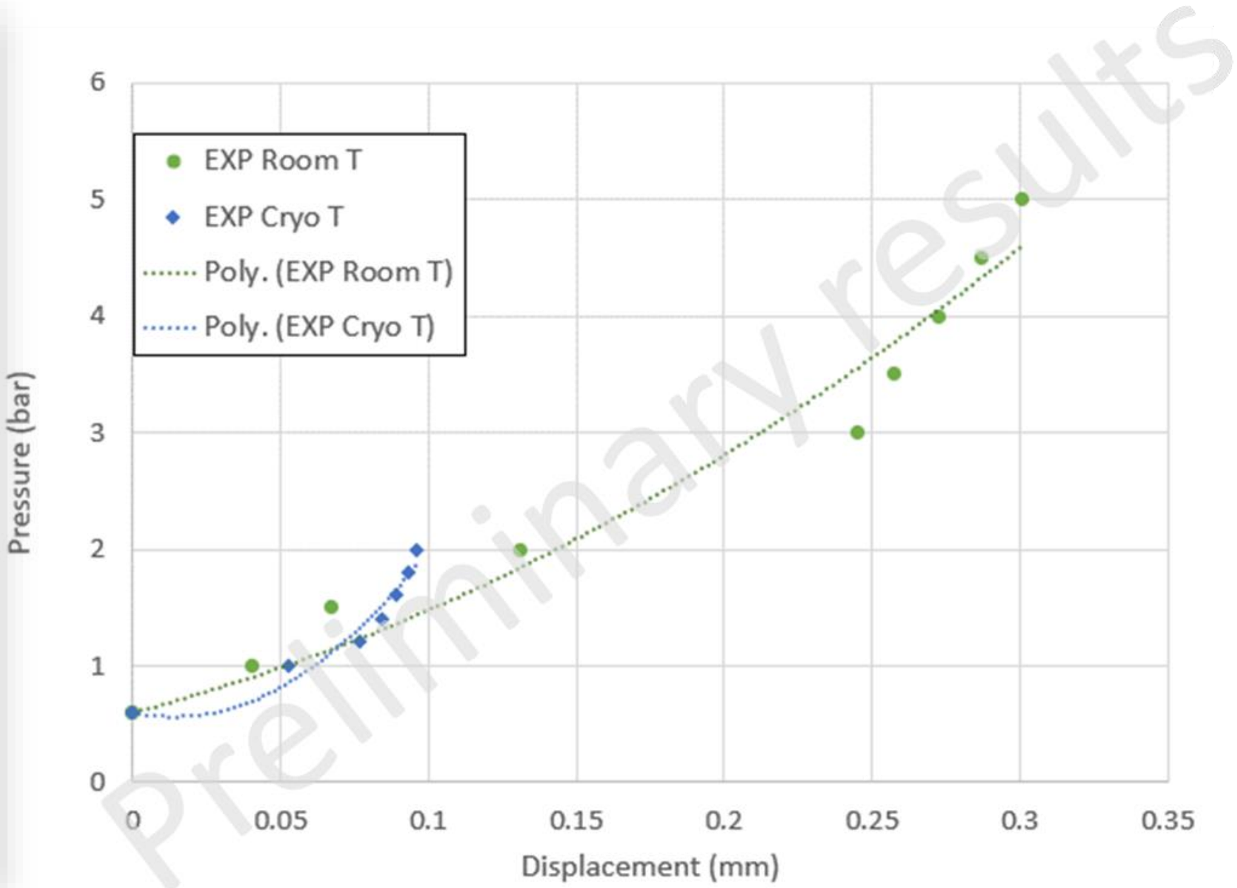
Mechanical tests







Mechanical tests



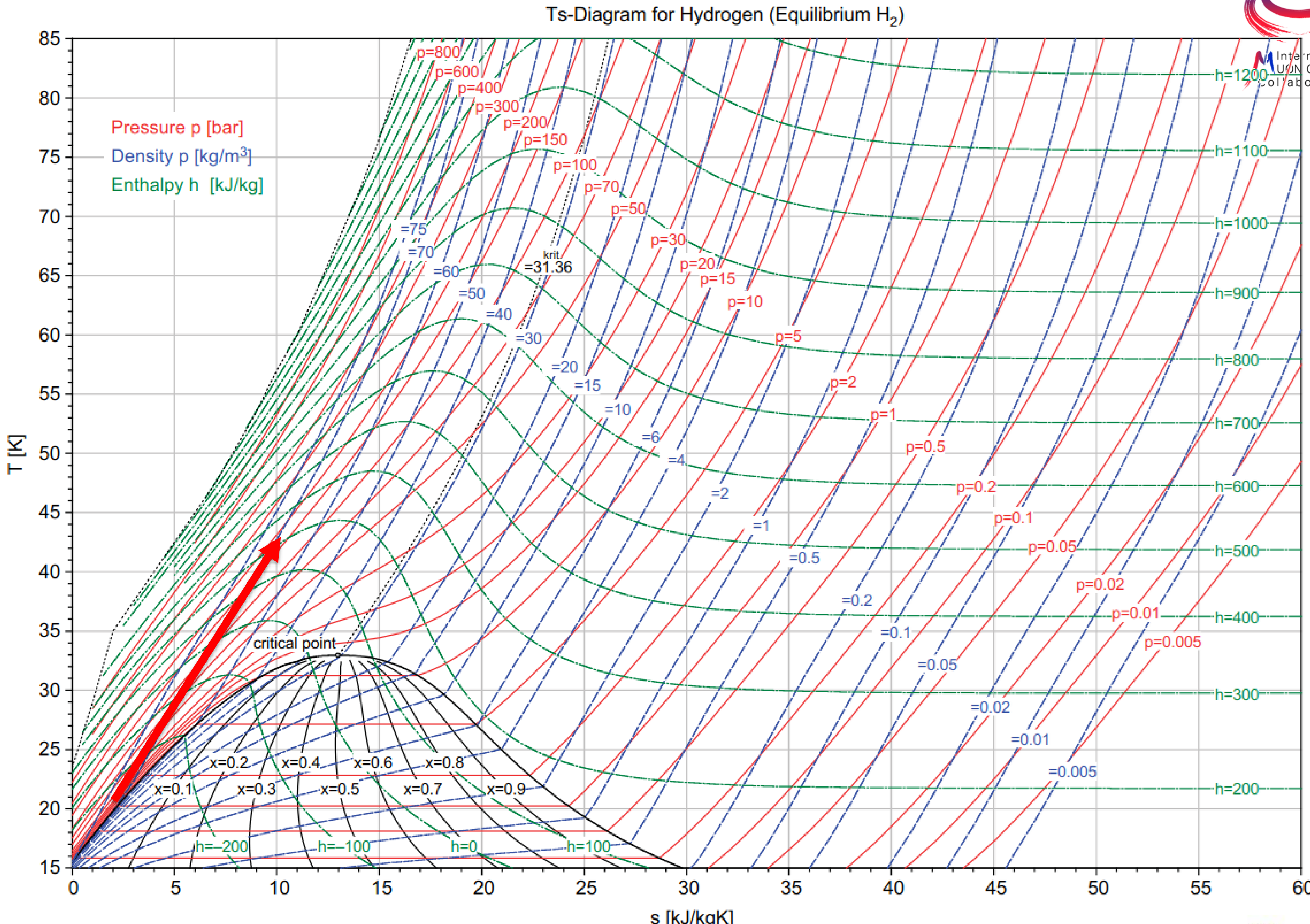
Si_3N_4 windows

- Low energy muons would require very thin windows to limit the impact of the window itself
- Si_3N_4 windows seem a good candidate:
  - Cheap and available
  - Good properties already with on the shelf products
  - Compatible with bright beams
  - Compatible at cryogenic temperature
- Thermomechanical characterization is ongoing, and more beam tests are planned
- The window should separate vacuum from the absorber, at low energy ideally hydrogen. The configuration of the absorber will define the maximum differential pressure the window should sustain

Absorber

$$\epsilon_{min,N} \propto \frac{E}{BL_R(dE/ds)} \quad [2]$$

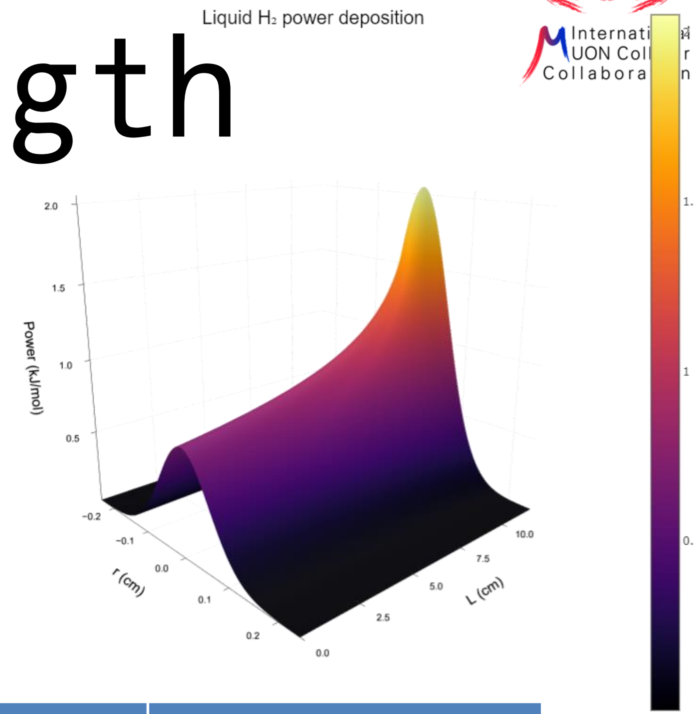
- H_2 best absorber material (out of the scope of MuCol?)
- What is the required density?
- Which length can we expect?
- What is the effect on the window?



Ts-Diagram for Hydrogen (Equilibrium H_2)
Pressure p [bar]
Density ρ [kg/m³]
Enthalpy h [kJ/kg]
T [K]
s [kJ/kgK]
critical point
krit =31.36
x=0.1
x=0.2
x=0.3
x=0.4
x=0.5
x=0.6
x=0.7
x=0.8
x=0.9
p=800
p=600
p=400
p=300
p=200
p=150
p=100
p=70
p=50
p=30
p=20
p=15
p=10
p=5
p=2
p=1
p=0.5
p=0.2
p=0.1
p=0.05
p=0.02
p=0.01
p=0.005
h=1200
h=1100
h=1000
h=900
h=800
h=700
h=600
h=500
h=400
h=300
h=200
h=100
h=0
h=-100
h=-200

Absorber length

20 → 5 MeV from [14][15].
9.6 J, not including heat load from muon decay



H_2 Absorber	Length	Max P (bar)	Max T (K)	P at $3\times\sigma_{RMS}$ (bar) (gaussian beam shape)	T at $3\times\sigma_{RMS}$ (K) (gaussian beam shape)
RT@1bar	124 m	1.3	373	1.04	303
RT@4bar	31 m	5.2	373	4.18	303
20.3K@1bar vapor	8 m	7.5	140	1.8	34
26.1K@4bar vapor	2.1 m	29.2	143	7	40
20.3K@1bar liquid	15 cm	833	128	125	35

$$\left\langle -\frac{dE}{dx}\right\rangle_{\text{electronic}} = K\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2Q_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} + \frac{1}{8}\frac{Q_{\max}^2}{(\gamma Mc^2)^2}\right]$$

$$\text{L} = \int_{E_f}^{E_s} \frac{1}{dE/ds}\,dE$$

Summary

- Several window candidates for final cooling. Si_3N_4 seems very promising
  - Commercially available as vacuum window for x-ray transmission
  - First irradiation tests showed excellent performance, well beyond the requirements
  - Ongoing effort to better characterise the thermomechanical properties of the membranes at different temperatures and understand its behaviour and produce better models.
  - Irradiation in proton facilities
- High density absorber required to have a short solenoid, but high power deposition → High pressure. Compatible with thin window?
- Shock wave and phase change after power deposition in liquid hydrogen → Very challenging CFD problem out of reach of commercial codes
- The design of the H_2 absorber will define the requirements and lifetime of the window, is this out of the scope of MuCol?
- Decouple window and absorber → even thinner windows
  - Pulsed high density vapor?
  - Leidenfrost effect?
  - Staging of steps with different densities (lower at the end)

THANK YOU FOR YOUR ATTENTION!

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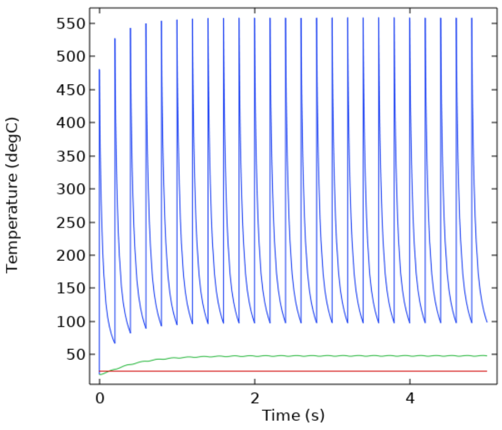
Thin windows

- Approx 1 mm stops the beam completely at 5MeV (1.3 mm for Be)
- Several candidates for thin windows
- Better characterization and evaluation required but first numbers look promising
- Measure mechanical properties (cryogenic to high temperature) for precise thermomechanical simulations. Bulge test [14] with interferometry?
- Pressure in the absorber is critical for the window definition

		5 MeV	20 MeV
Be	ΔT_{inst} [K]	174	61
	Cyclic Thermal Stress (MPa)	485	171
Si_3N_4	ΔT_{inst} [K]	470	169
	Cyclic Thermal Stress (MPa)	228	82
C	ΔT_{inst} [K]	507	180
	Cyclic Thermal Stress (MPa)	1013	360
SiC	ΔT_{inst} [K]	467	168
	Cyclic Thermal Stress (MPa)	224	81



Si_3N_4 Ø 7 mm 1μm at 5 MeV - 0.6 mm gaussian beam
Only room temperature ambient radiation

$$\sigma_{cyc} \approx \frac{1}{2}\alpha E \Delta T$$

$$\Delta T_{inst} = \left(\frac{dE}{dx}\right)\frac{N}{2\pi\sigma^2\rho c}$$