Cooling windows/absorber

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Muon Collider Collaboration Meeting - October 2022

Outline

- Introduction: Final cooling
- Thin windows
- Absorber length and pressure
- Other concepts
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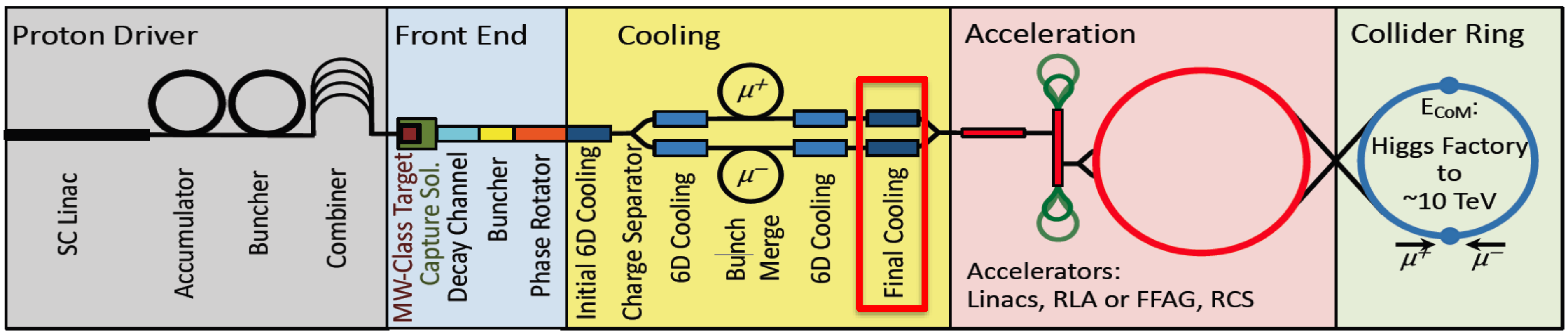
Introduction

Fully driven by muon lifetime, otherwise would be easy



Short, intense proton bunch

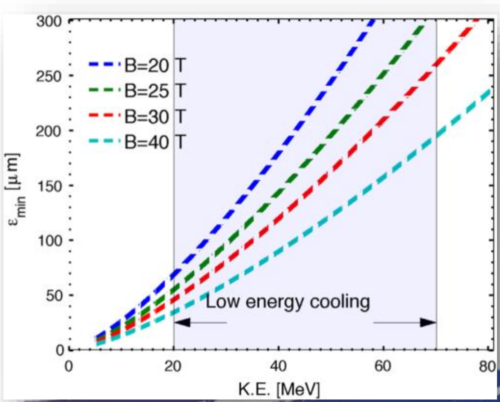
Protons produce pions which decay into muons. muons are captured

Ionization cooling of muon in matter

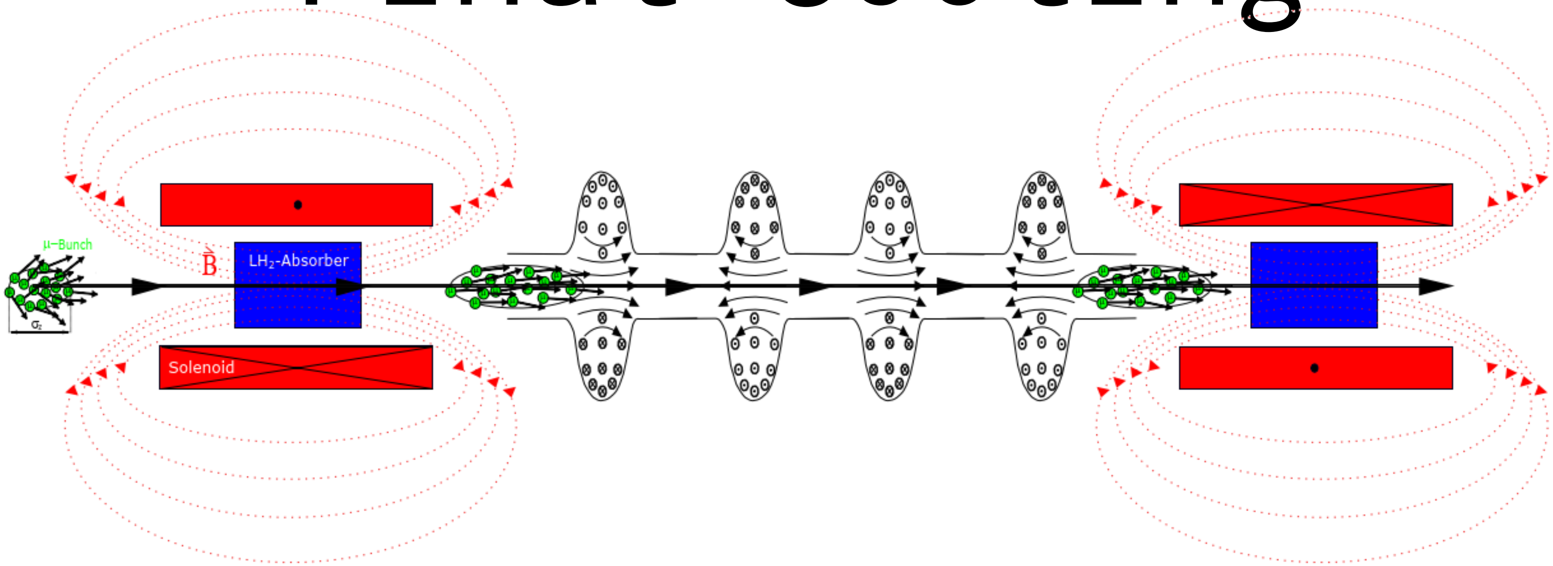
Acceleration to collision energy

Collision

muon kinetic energy from 20 to 5 MeV (last window) [1][2]



Final Cooling



[10]

- ❑ Absorber → H_2 best candidate
- ❑ For liquid/gas absorber → Vacuum windows are required
- ❑ 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	…

[1]

Initial Momentum (MeV)	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

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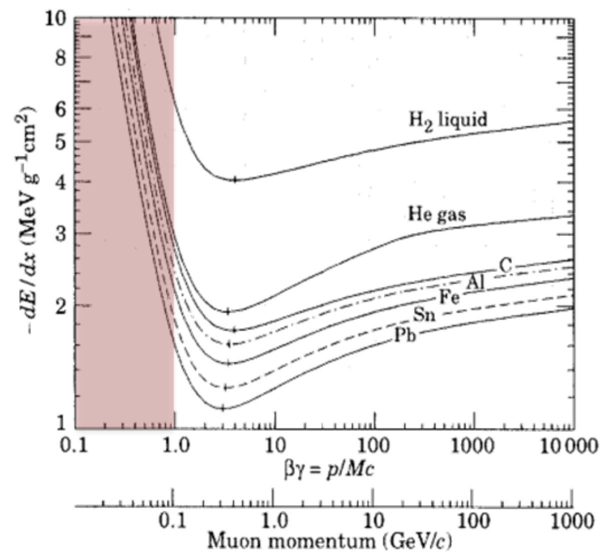
Thin windows

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

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

		5 MeV	20 MeV
Be	Stopping power [MeV×cm²/g]	11.2	4.0
	Linear stopping power [keV/µm]	2.1	0.7
Si_3N_4	Stopping power [MeV×cm²/g]	11.2	4.0
	Linear stopping power [keV/µm]	3.1	1.1
C	Stopping power [MeV×cm²/g]	12.2	4.3
	Linear stopping power [keV/µm]	2.7	1.0
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[3]
- Aperture 7 mm
- ΔP > 1 bar

Figure 1 Typical Assembly of Beryllium Window

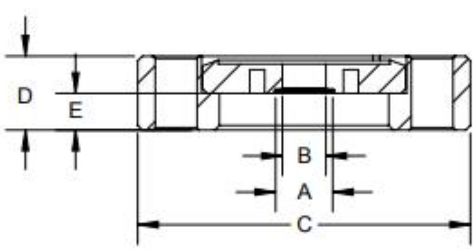


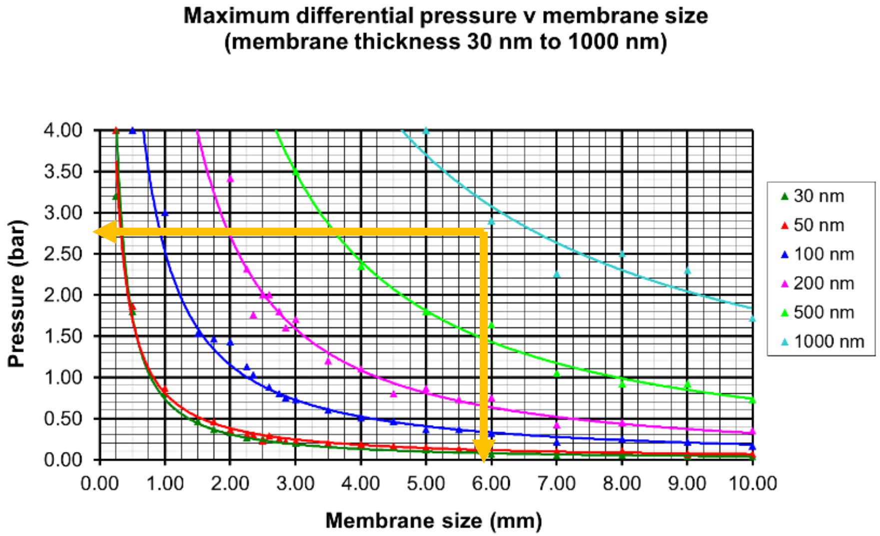
Figure 2 Conflat Flange Geometry

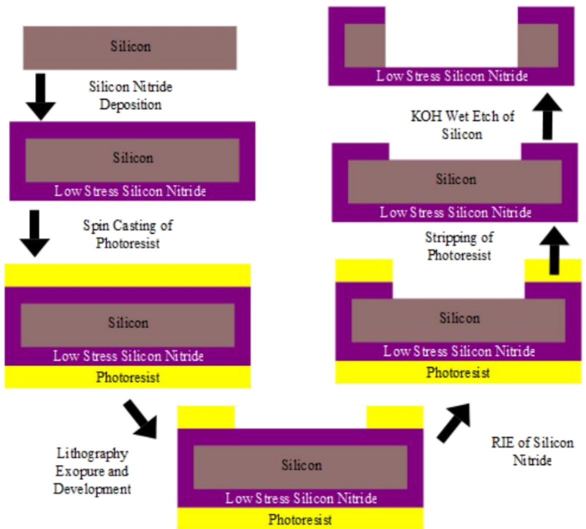
Table 1 Dimensions of Conflat Flange Options (Refer to Figure 2 above)

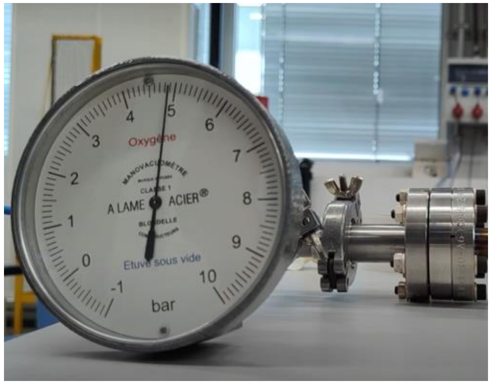
CF	Foil Thickness (µm)	Foil Diameter (mm) - A	Through Hole Diameter (mm) - B	CF Outer Diameter (mm) - C	CF Thickness (mm) - D	Window Height (mm) - E	Coating	Part ID
1-1/3" OD	8.0	9.2	7.0	33.8	7.2	0.5	DuraCoat Plus	DBM-08-9.2-CF1.3-P
	25.0	16.0	13.0	33.8	7.2	0.5	DuraCoat	DBM-25-16.0-CF1.3
2-1/8" OD	8.0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

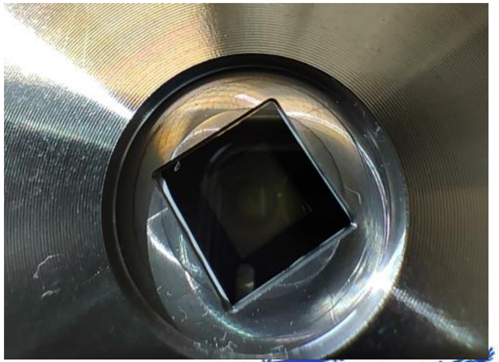
Thin windows: Si_3N_4

- Commercially available: Xray windows i.e. [4]
- Thickness <1 µm
- It can work at cryogenic temperature [11]
- Bulk material has excellent mechanical properties [5]
- 1 µm 6×6mm window → ≈5 bar pressure









Thin windows: C

- Thickness <1 μm
- Different options: Graphenic carbon [12] or diamond [13]

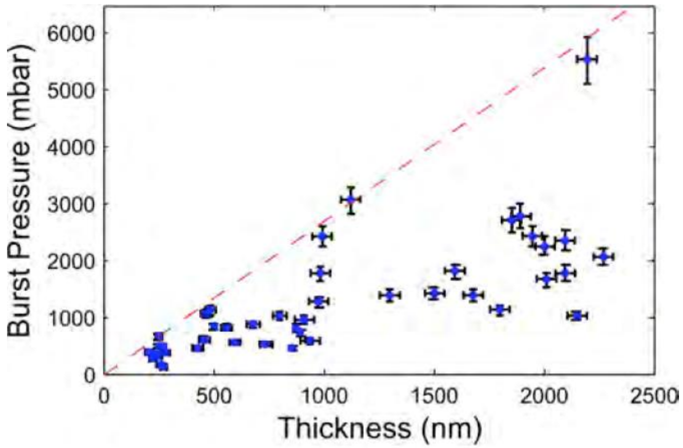


Fig. 4. Measured thickness dependent burst strength of fabricated GC transmission windows with a diameter of 7 mm.

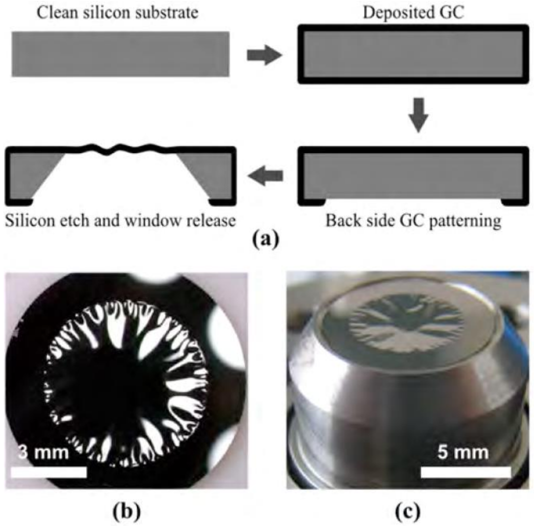


Fig. 2. (a) sketches the fabrication process of the transmission window. (b) shows a top view image of a fabricated GC window. (c) depicts a TO8 housing with a GC window glued into the top of the housing

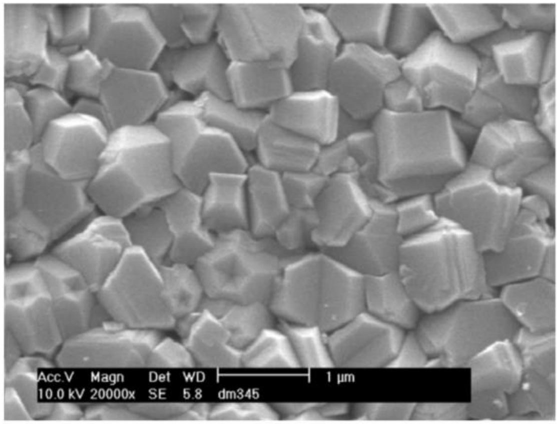
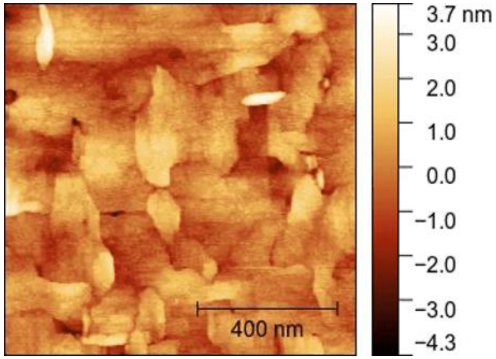


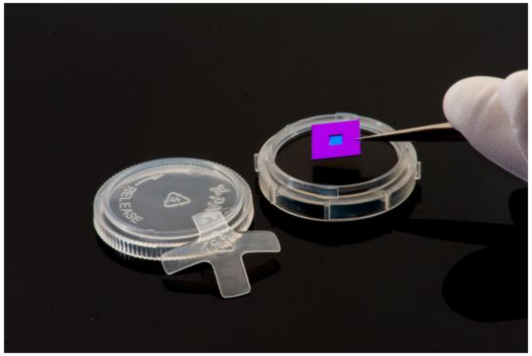
Fig. 4. SEM picture of the diamond film 345#.

Thin windows: SiC

- Thickness <1 µm
- Bulk material has excellent mechanical properties
- No many commercial suppliers [6]



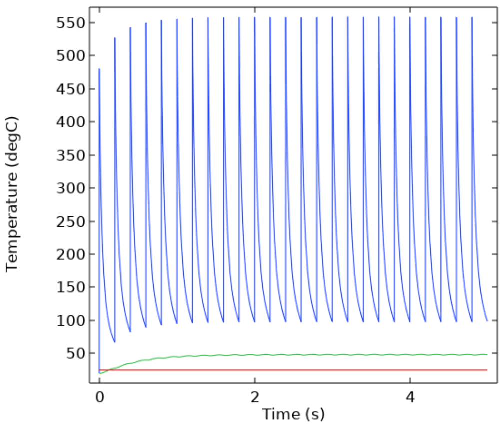
Silson



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

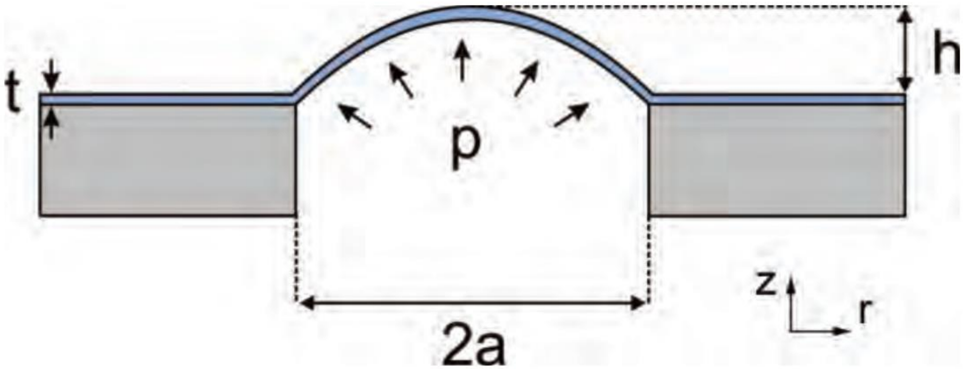


Si_3N_4 Ø 7 mm 1µm at 5 MeV - 0.6 mm gaussian beam
Only room temperature ambient radiation

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

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

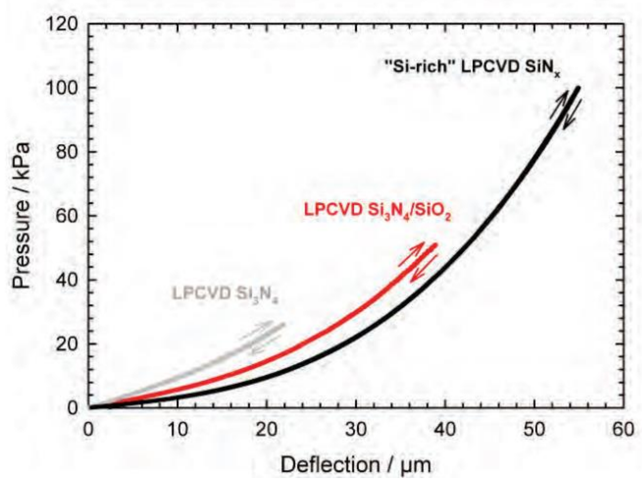
Thin windows

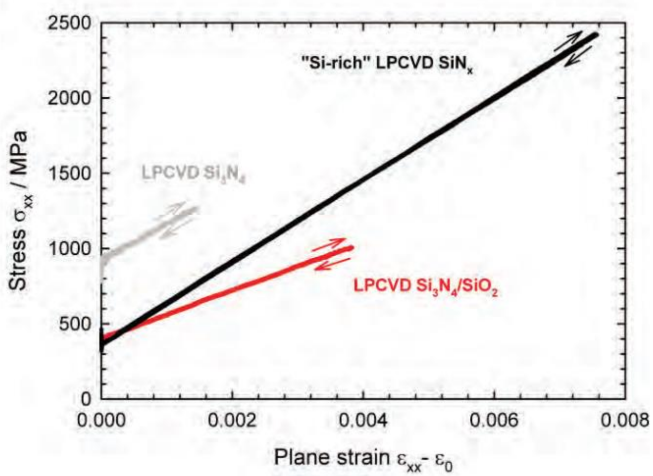


$$\sigma_r = \frac{pa^2}{4ht}$$

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

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





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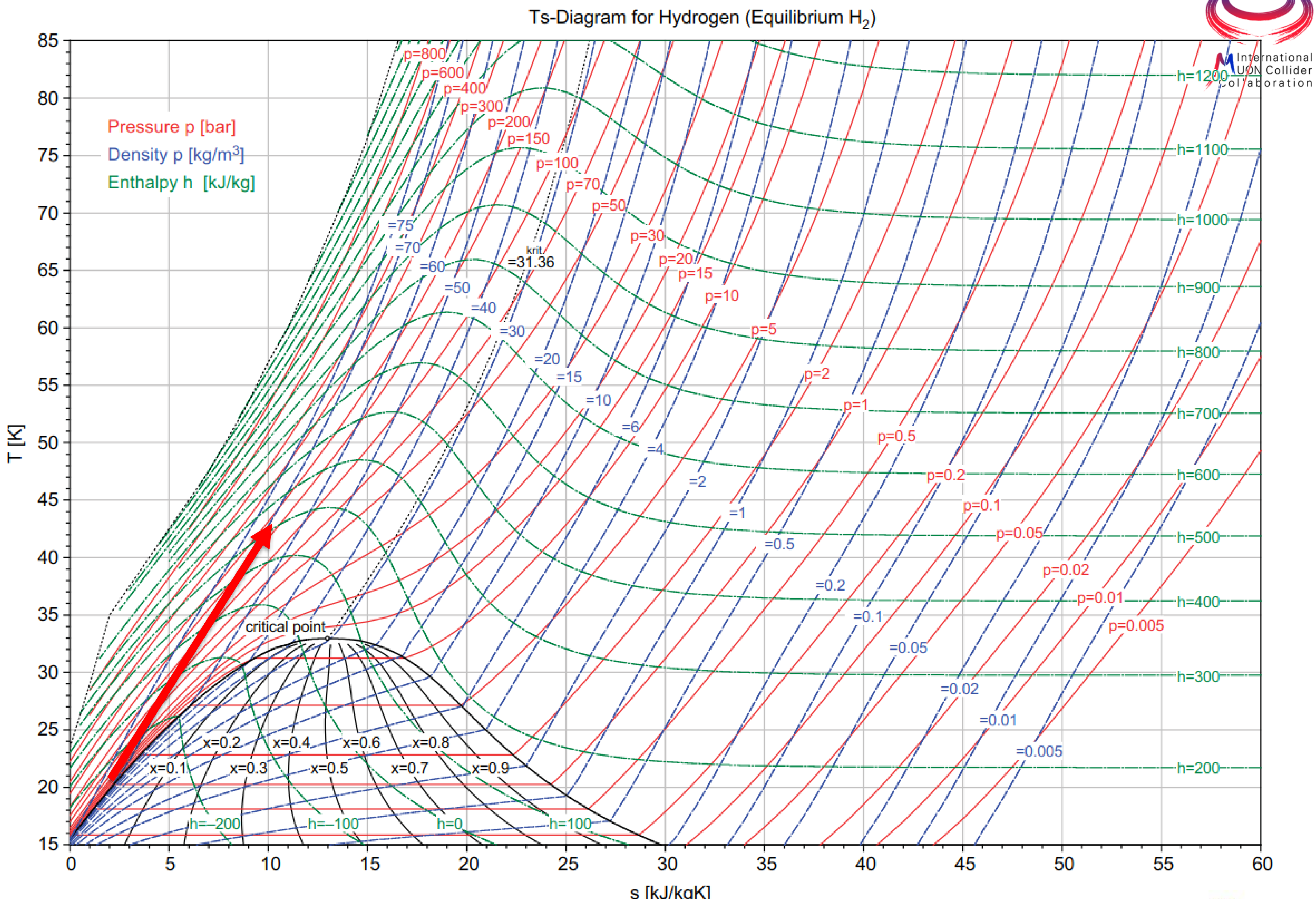
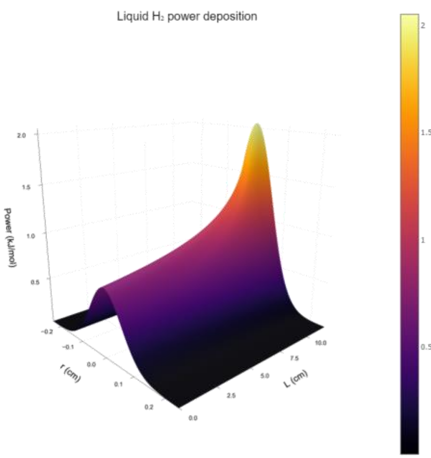
Adsorber

$$\epsilon_{min,N} \propto \frac{E}{BL_R(dE/ds)} \quad [1]$$

- H_2 best absorber material
- What is the required density?
- Which length can we expect?



Ts-Diagram for Hydrogen (Equilibrium H2)
Pressure p [bar]
Density ρ [kg/m3]
Enthalpy h [kJ/kg]
T [K]
s [kJ/kgK]
critical point
krit =31.36



Absorber length

20 → 5 MeV from [8][15]. 9.6 J, not including heat load from muon decay

H_2 Absorber	Length	Max P (bar)	Max T (K)	P assuming power deposited in $3 \times \sigma_{RMS}$ (bar)	K assuming power deposited in $3 \times \sigma_{RMS}$ (K)
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

Is the H_2 absorber compatible with a thin window?
Is there any concept to make both compatible?

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Other concepts? Solid?

- Solid hydrogen can be produced in small pellets
- It is possible to produce 6 mm diameter >10 mm long pellets [16][17]
- Very likely there is a limit to the length of the solid plug produced by condensation → Several plugs in the same tube?
- It will allow to decouple the window from the absorber (vacuum space)

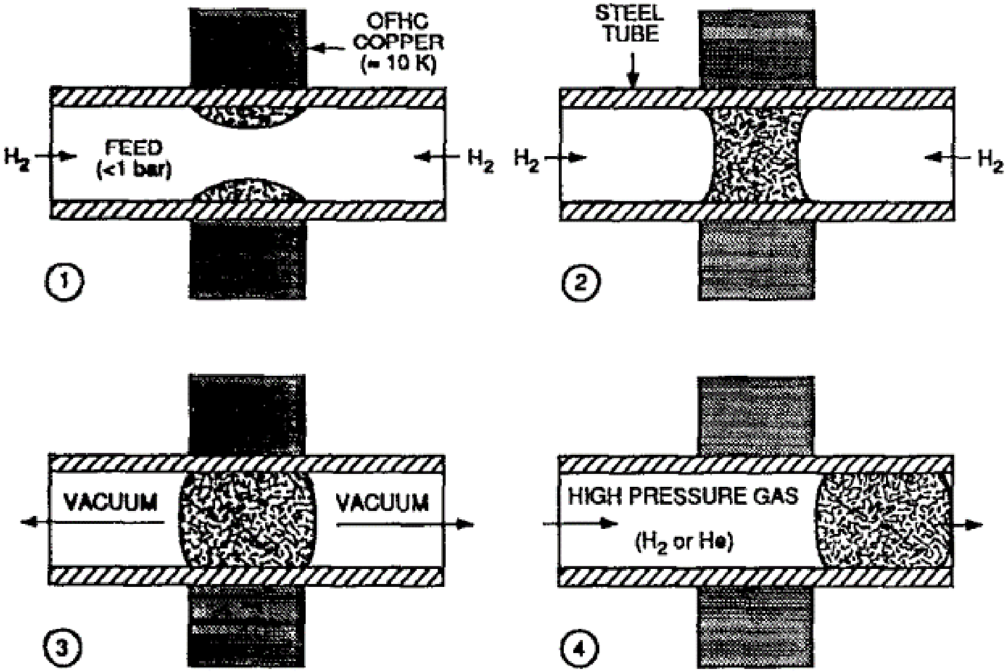
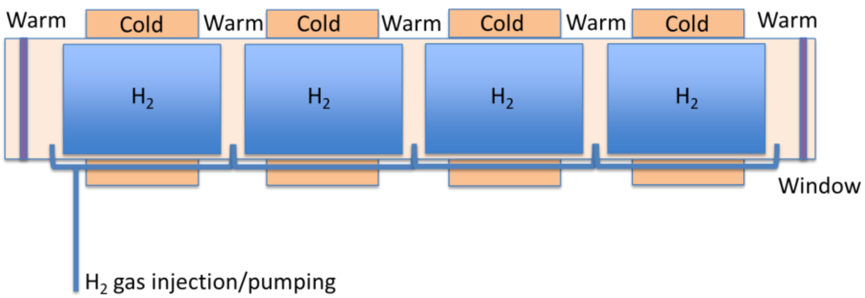


FIG. 1. Principles of operation for a "pipe-gun" pellet injector: (1) introduction of room-temperature gas (pure H_2, D_2, T_2, or a mixture) initiates the solidification process, (2) freezing process continues, filling in the center of the pellet within a few minutes, (3) residual gas is pumped away after sufficient freezing time, and (4) high-pressure gas is admitted at the breech to accelerate the frozen pellet in the tube.



Other concepts? Solid?

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- Power deposition → H_2 will be melted and heat up(>100s bars)
- Will part of this fluid be expelled into the vacuum volume?
- Is there enough time between pulses to recondense the gas produced during the shot?
- Will the shape be preserved?

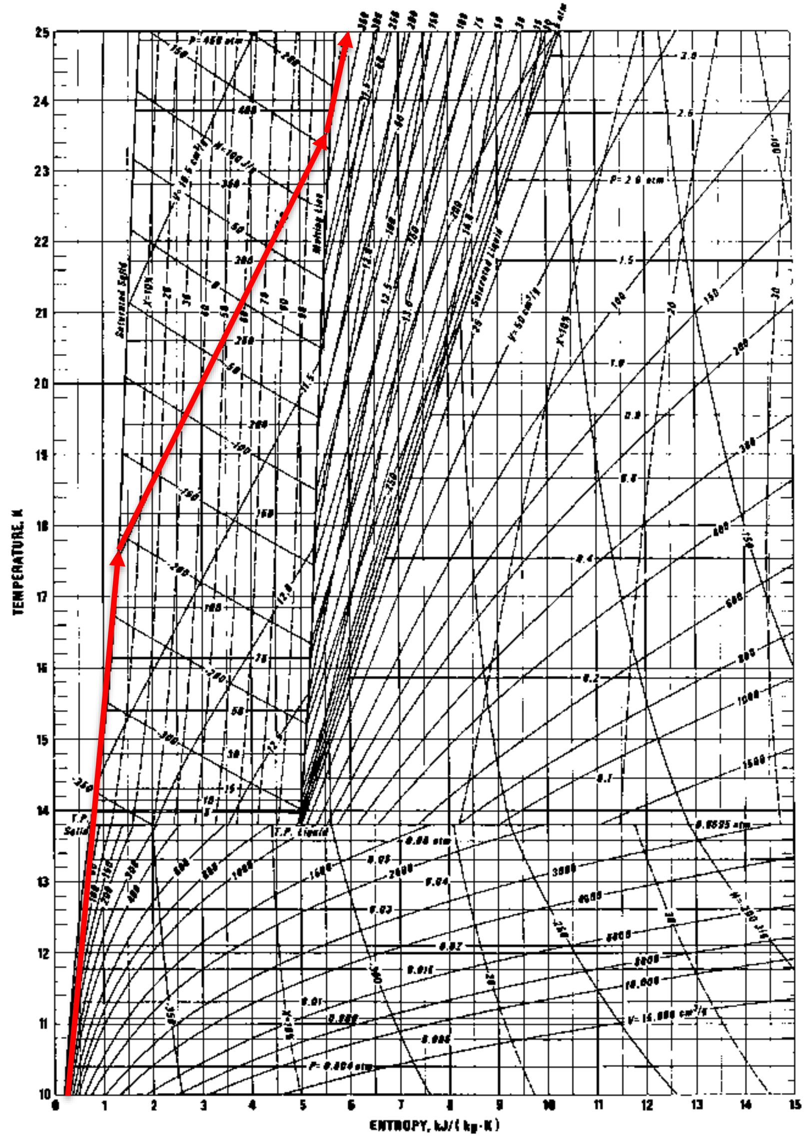
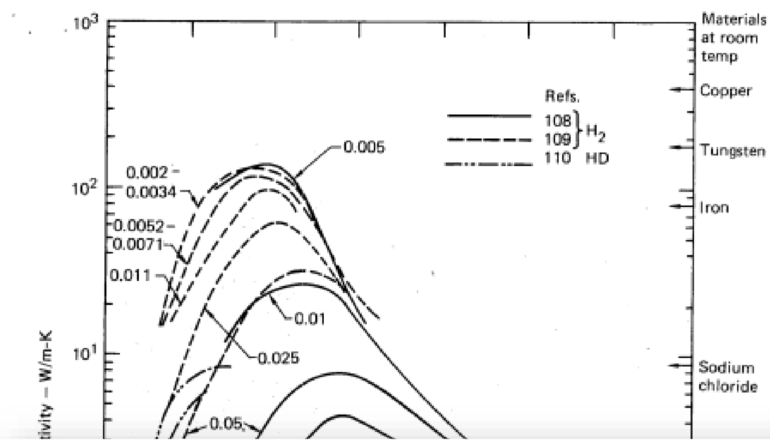


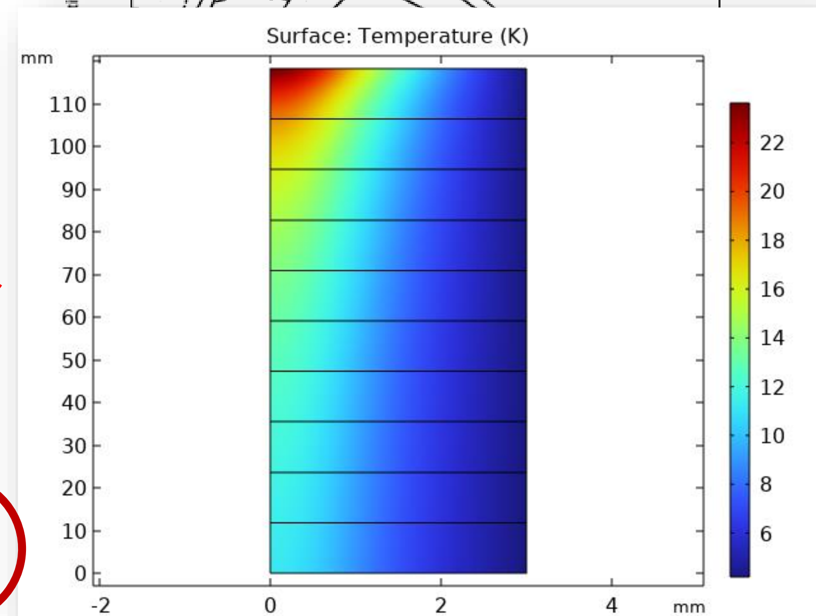
FIGURE 43. Parahydrogen, temperature-entropy diagram (10 to 25 K).

Other concepts? Solid?

- Assuming 10 W/m/K
- From 20 to 5 MeV
- Radius = $5\sigma_{rms}$
- 10 segments with adiabatic boundaries (12 mm long)
- Boundary at 4.2K

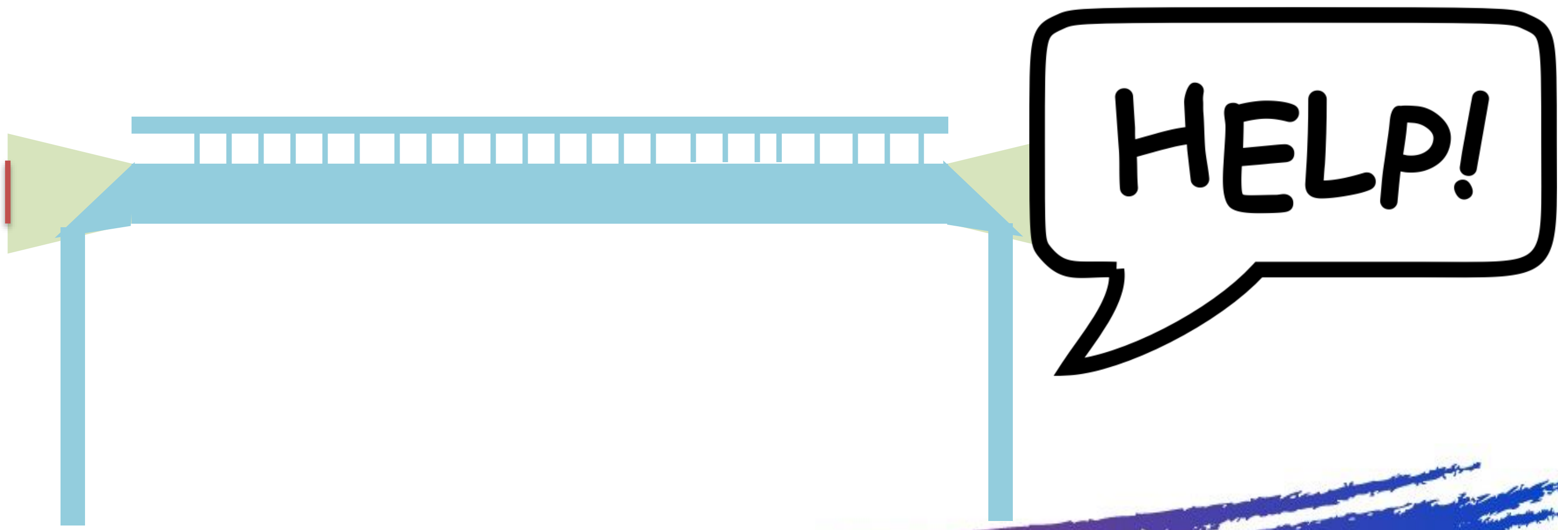
- Last section of the cooling too hot (no longer solid)





Other concepts?

- How to implement inside a small magnet bore?
- Is it possible to take the windows out of the solenoid?
- At 14.5K vapor pressure 100 mbar → Lower ΔP
- Liquid curtain?
- Shutter to expose the liquid for a fraction of time?
- Keep bubble in front of window (extra heat load to absorber)?
- Reproducibility of absorber length?



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Summary

- Several window candidates for final cooling.
  - Systematic study of the different candidates
  - Measurement of mechanical properties at working temperature
  - Thermomechanical simulations
  - Validation in proton facilities with equivalent power deposition

- High density absorber required to have a short solenoid, but 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

- Possible mitigations?:
  - Repetition rate
  - Lower density (long solenoid)
  - Higher energy
  - Decouple window and absorber → new concept

References

[1] H. Kamal Sayed, R.B. Palmer, and D. Neuffer, Phys. Rev. ST Accel. Beams **18**, 091001 (2015).
[2] D.E. Groom and S.R. Klein, Eur. Phys. J. C **15**, 163 (2000).
[3] DuraBeryllium® Windows in Conflat Flanges
[4] Silson - Differential Pressure Windows
[5] R.L. Edwards, G. Coles, and W.N. Sharpe, Experimental Mechanics **44**, 49 (2004).
[6] Silson - Silicon Carbide
[7] AtomicNuclear Properties (lbl.gov)
[8] Isochoric Properties for Hydrogen (nist.gov)
[9] D. Schulte, " *Muon Collider*" , Muon Collider Collaboration Meeting, October 2022
[10] B.M. Stechauner, Final cooling scheme for muon colliders: a door opener for future discovery machines, TU Vienna, 2021.
[11] P.T. Törmä, J. Kostamo, H. Sipilä, M. Mattila, P. Kostamo, E. Kostamo, H. Lipsanen, C. Laubis, F. Scholze, N. Nelms, B. Shortt, and M. Bavdaz, IEEE Transactions on Nuclear Science 61, 695 (2014).
[12] S. Huebner, N. Miyakawa, S. Kapser, A. Pahlke, and F. Kreupl, IEEE Transactions on Nuclear Science 62, 588 (2015).
[13] X. Ying, J. Luo, P. Wang, M. Cui, Y. Zhao, G. Li, and P. Zhu, Diamond and Related Materials **12**, 719 (2003).
[14] B. Merle, *Mechanical Properties of Thin Films Studied by Bulge Testing* (FAU University Press, Erlangen, 2013)
[15] J.W. Leachman, R.T. Jacobsen, S.G. Penoncello, and E.W. Lemmon, Journal of Physical and Chemical Reference Data **38**, 721 (2009).
[16] J. Lafferranderie, G. Claudet, F. Disdier, P. Kupschus, and K. Sonnenberg, in *Fusion Technology 1986* (Pergamon, 1986), pp. 1367– 1373.
[17] S.K. Combs, Rev. Sci. Instrum. **64**, 1679 (1993).

THANK YOU FOR YOUR ATTENTION!