MUON Collider Collaboration: Final Cooling

International MUON Collider Collaboration

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Overview

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Tracking codes: ICOOL an RF-Track

Discussion on the technical challenges of absorbers

1. **Heat dissipation of windows**
2. **Thermodynamic of hydrogen absorbers**

Why final cooling?

Table 1.1: Parameter list defined by the international muon collider collaboration.

Parameter	Symbol	Units	3 TeV	10 TeV	14 TeV
Luminosity	$\mathcal{L}$	$10^{34}\,\text{cm}^{-2}\text{s}^{-1}$	1.8	20	40
Muons/bunch	N	10^{12}	2.2	1.8	1.8
Repetition rate	f_r	Hz	5	5	5
Beam power	P_{beam}	MW	5.3	14.4	20
Collider circumference	C	km	4.5	10	14
Average bending field	$\langle B \rangle$	T	7	10.5	10.5
Norm. long. emittance	$\epsilon_{\text{L,N}}$	MeV m	7.5	7.5	7.5
Energy spread	σ_E/E	%	0.1	0.1	0.1
Bunch length	σ_z	mm	5	1.5	1.07
Interaction point beta	β	mm	5	1.5	1.07
Norm. trans. emittance	$\epsilon_{\perp,\text{N}}$	μm	25	25	25
Interaction point beam size	$\sigma_\perp$	μm	3.00	0.90	0.63

Emittance:

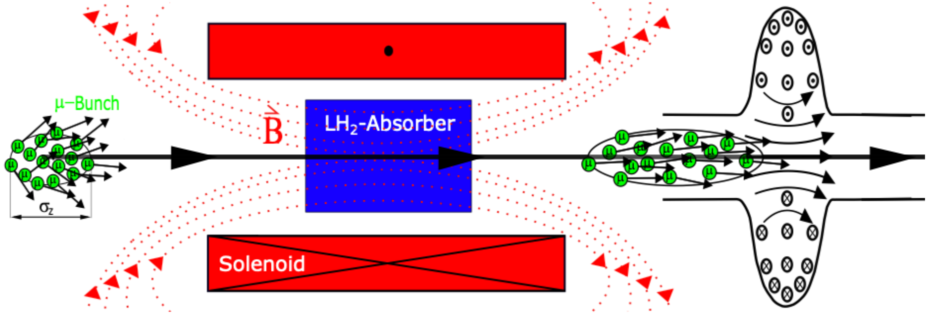
- In past, ϵ_{trans} = **55 μm** [1]
- Goal is to reach **25 μm**

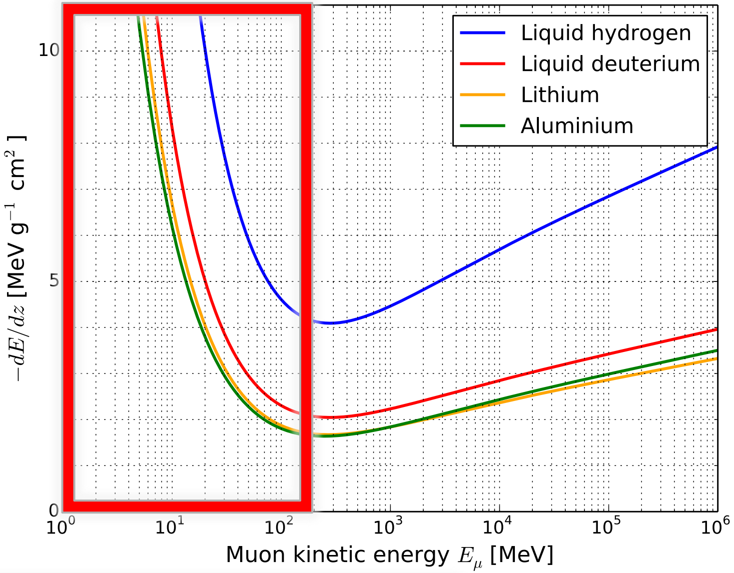
[1] H. K. Sayed,10.1103/PhysRevSTAB.18.091001

Ionization cooling

$$\frac{d\epsilon_{\perp,\mathrm{N}}}{ds} = -\frac{\epsilon_{\perp,\mathrm{N}}}{E\beta^2}\left\langle\frac{dE}{ds}\right\rangle + \frac{\beta_\perp(13.6[\mathrm{MeV}])^2}{2\beta^3 mc^2 L_\mathrm{R}}$$

$$\frac{d\epsilon_{\mathrm{L,N}}}{ds} = -\epsilon_{\mathrm{L,N}}\frac{d}{dE}\left\langle\frac{dE}{ds}\right\rangle + \left\langle\frac{d\epsilon_{\mathrm{L,N}}}{ds}\right\rangle_{\mathrm{Straggle}}$$





$$\mathcal{L} \propto \frac{\gamma^3}{C}\frac{N^2}{\epsilon_{\perp,\mathrm{N}}\epsilon_{\mathrm{L,N}}}$$

Tracking ionization cooling

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- Initial beam parameters from 6D-cooling: $\boldsymbol{\varepsilon_{\perp} = 300\ \mu m}$, and $\boldsymbol{\varepsilon_L = 1.5\ \mathrm{mm}}$
- Goal: find a method for efficient **emittance reductions** $\boldsymbol{\varepsilon_{\perp} = 25\ \mu m}$
- Have chosen **ICOOL** for optimizing parameter:
  1. Initial beam energy
  2. Magnetic field strength
  3. Absorber type and length
  4. Matched beam optics

Acknowledgement to Elena Fol

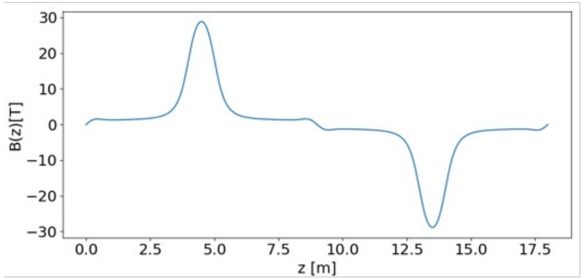
ICOOL example

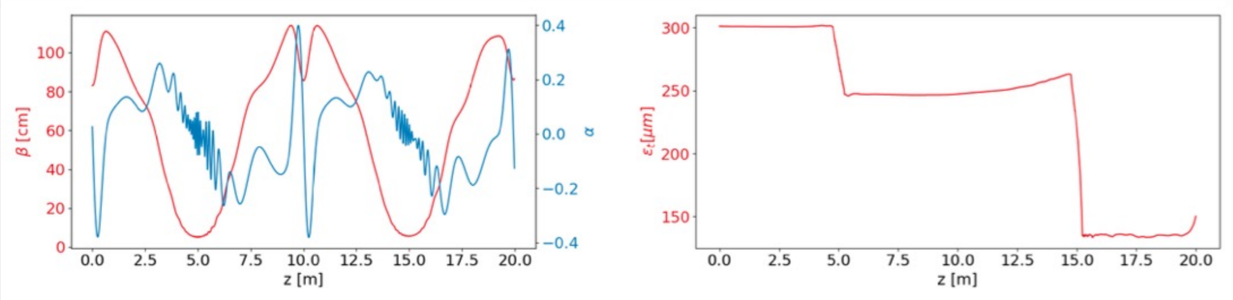
Acknowledgement to Elena Fol

- 2 cells without RF structure
- Optics matching mitigates emittance blow up
- Varying initial parameters for finding:
  1. Min correlation α in absorbers
  2. Max $\varepsilon_\perp$ decrease, min ε_L increase
  3. Max transmission

[2] Varying free parameters

$$\min_p \frac{\Delta\epsilon_{\parallel}}{(\Delta\epsilon_{\perp}\Delta N)} + \bar{\alpha}$$





[2] E. Fol et al, doi:10.18429/JACoW-IPAC2022-WEPOMS047

RF-track example

- **RF-Track** by *A. Latina (CERN)*
  - ➢ Tracking code for of low-energy LINACs
  - ➢ Space charge effect included
  - ➢ User interface Python/Octave as user interface
- Same parameter optimizer used, but RF-structure included
- Preliminary results for the first **4** cells (RF-track still under development)

RF-Track Reference Manual [3]
(draft)
Version 2.0.4
Andrea Latina

	Cell configuration						Beam parameters (end of the cell)				
	Length [m]	LH thickness [m]	Drift [m]	1. Freq [MHz]	1. Vmax [MV]	2. Phase	Emittance Tr. [mm mrad]	Emittance Long. [mm]	Bunch length [mm]	Pz [MeV/c]	Pz spread
							300,0	1,56	49,9	135	3,5
1	7,4	0,21	0,9	321	17,9	57	278	2,18	73,5	121,3	3,85
2	5,56	0,17	0,56	266	10,4	46,1	256	2,27	69,3	105,78	3,5
3	5,45	0,11	0,7	249	10,8	81,3	243	3,7	134,5	102,2	5,4
4	4,6	0,11	0,85	201	10,48	76,3	**229**	**6,4**	**400**	**95,6**	**6,7**

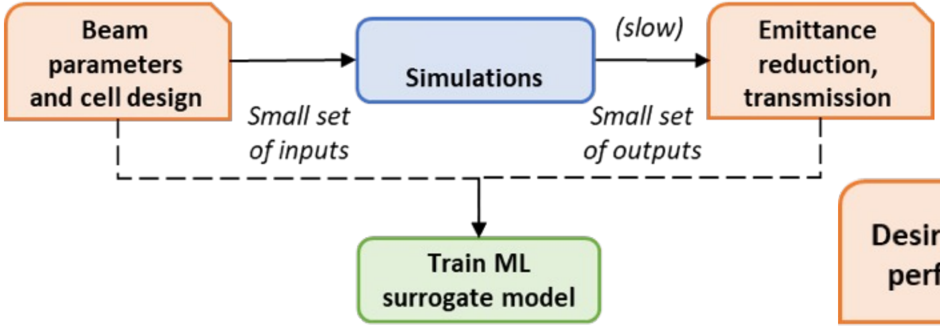
Acknowledgement to Elena Fol

Note: numbers are preliminary, ionisation cooling in RF-Track is still under development

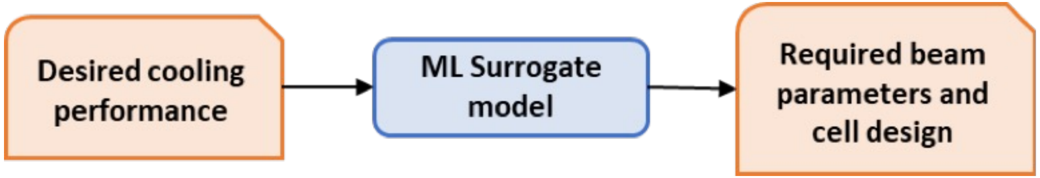
[3] https://twiki.cern.ch/twiki/bin/view/ABPComputing/RF-Track

Surrogate modeling [4]

- Optimization routines are time-consuming processes
- Initial and final parameter from the optimized simulations will be stored
- Surrogate model allows an automatic mapping between initial condition and simulated results



Acknowledgement to Elena Fol



[4] E. Fol et al, doi:10.18429/JACoW-IPAC2022-WEPOMS046

Technical risks on absorbers

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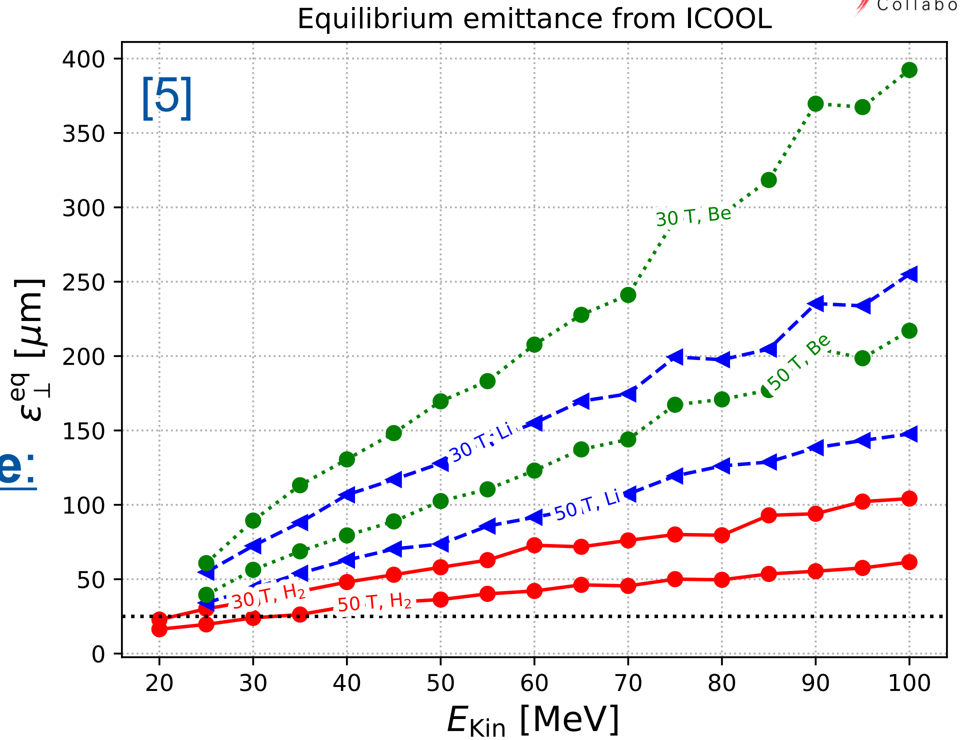
- Due to the **target parameters** the beam size is small at the end of the cooling channel
- High **field magnets** up to **50 T** and $\boldsymbol{\varepsilon_{\perp} = 25\mu m}$ → **1mm** beam size in diameter
- Follows: energy **storage** in a **small volume**
- Question: what does this mean for the **absorbers** (last cell)?

Absorber choice in the last cell

$$\epsilon_{\perp}^{\mathrm{eq}} = \frac{\beta_{\perp}(13.6[\mathrm{MeV}])^2}{2\beta mc^2 L_{\mathrm{R}} \left\langle \frac{dE}{ds} \right\rangle}$$

Achieving the **target** trans **emittance**:

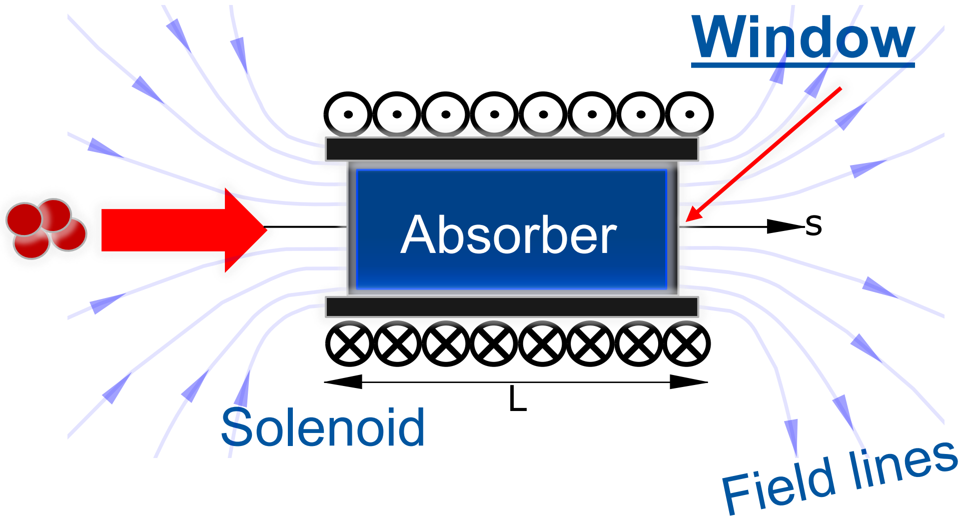
- **Hydrogen**
- **Strong** B-fields
- **Low** beam energy



[5] B. Stechauner, 10.34726/hss.2022.97540

Absorber confinement

- H_2 can be solid, liquid, gaseous, supercritical,…
- Mitigate muons-window interactions
- Requirements: low Z and thin
- Candidates: Be and Si_3N_4



Heat dissipation in the window

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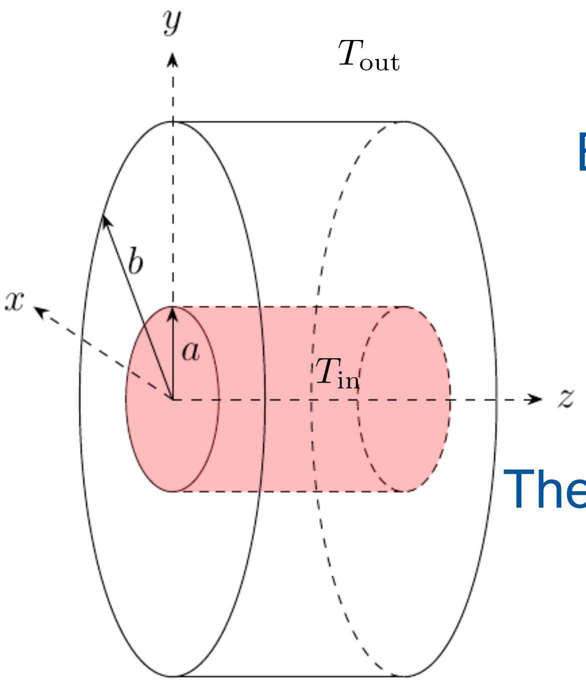


Beam channel volume depends on **emittance**, **field** and window **thickness**

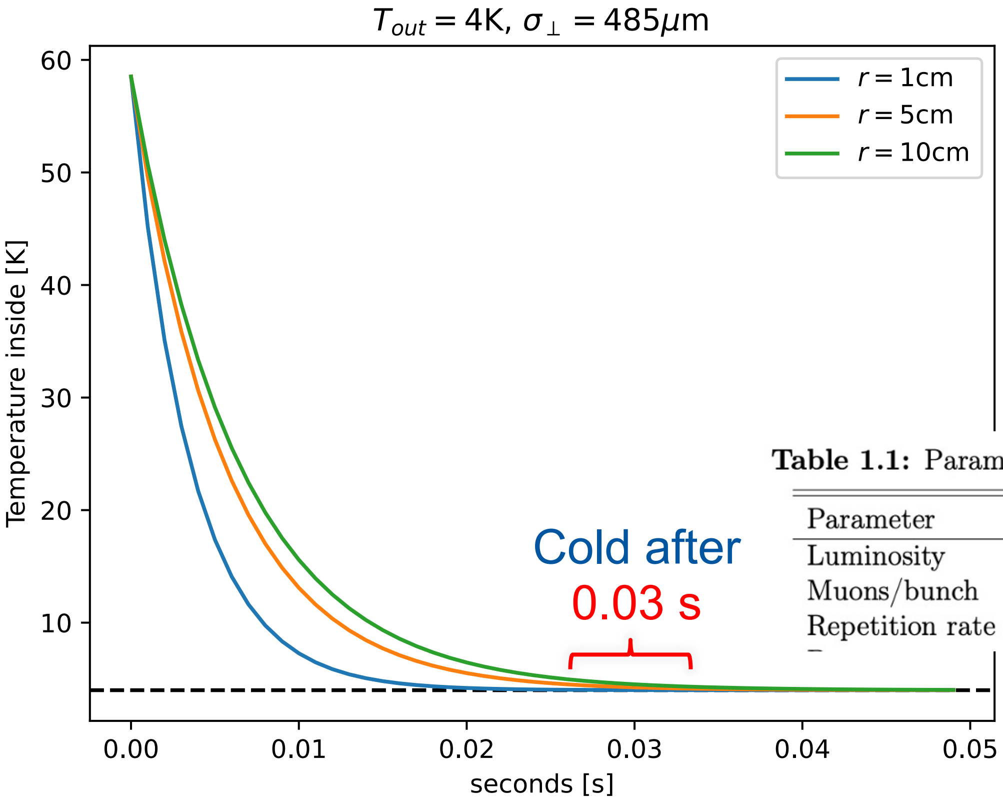
Beam causes an **instantaneous** temperature increase

Heat **dissipation** from inside to the edge

$$\frac{dQ}{dt} = -\lambda \cdot A \cdot \frac{dT}{dr}. \Rightarrow \int_{T_{in}}^{T_{out}} dT = -\frac{\Delta Q}{\Delta t \cdot \lambda} \frac{1}{2\pi L} \int_a^b \frac{dr}{r}$$

Thermal conductivity

$$\Delta Q = 2\pi L \,\lambda \,\frac{T_{in} - T_{out}}{\ln(b/a)} \,\Delta t$$



Example:

- Beryllium,
- norm emittance is **25 μm**
- Solenoid field is **50 T**
- Window in steady cooled **4 K** bath

final conditions

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Repetition rate	f_r	Hz	5	5	5

0.2 seconds

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Thermodynamics in liquid H_2

- $\epsilon_{\perp,\mathrm{N}}$ reductions = storing energy in the absorber

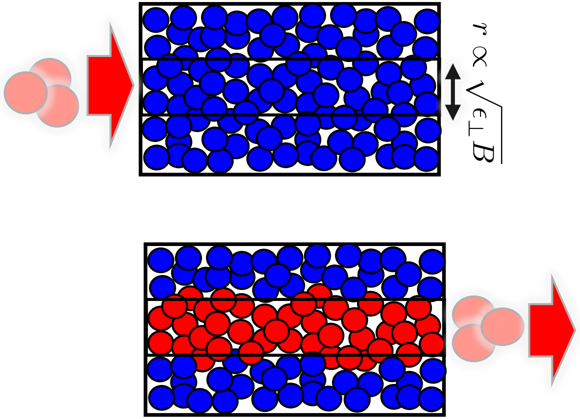
$\rho = 70\,\mathrm{kg\,m^{-3}}$ $\quad B = 50\,\mathrm{T}$

$A = 0.002\,\mathrm{kg\,m^{-3}}$ $\quad \epsilon_{\perp,\mathrm{N}} = 25\,\mu\mathrm{m}$

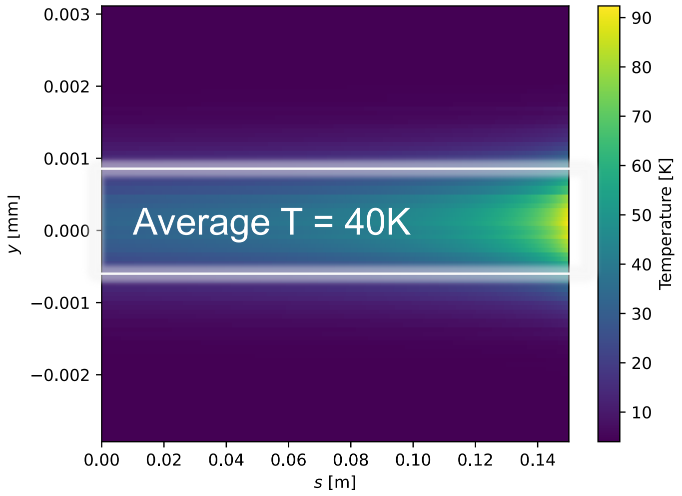
$$n = \frac{\rho V}{A}$$

$$p = \frac{nRT}{V} = \frac{\rho RT}{A}$$

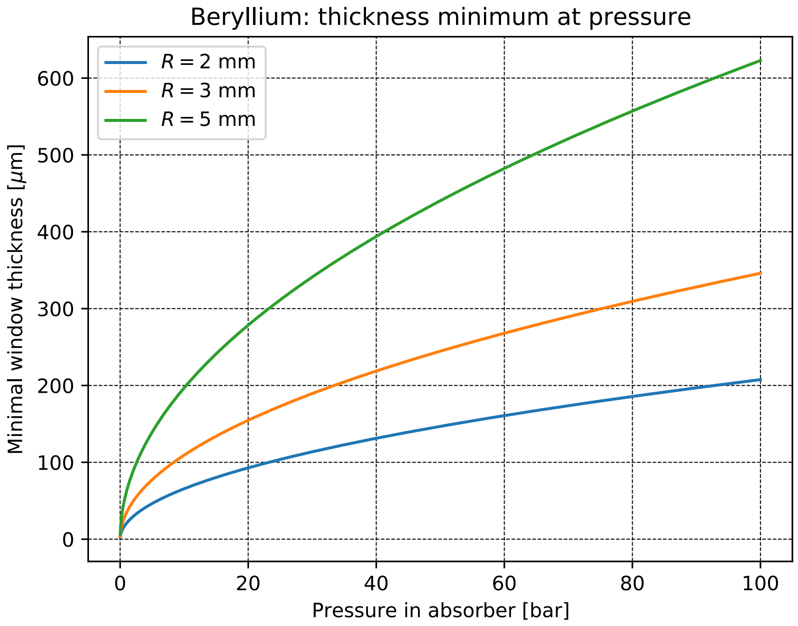
$$p = \frac{70\,\mathrm{kg\,m^{-3}} \cdot 8\,\mathrm{J\,mol^{-1}\,K^{-1}} \cdot 40\,\mathrm{K}}{0.002\,\mathrm{kg\,mol^{-1}}} \approx 100\,\mathrm{bar}$$

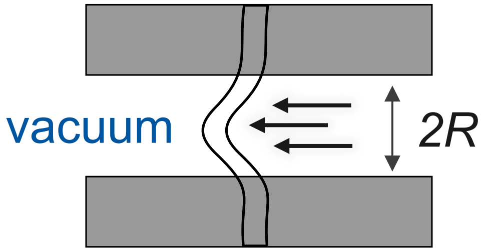


20MeV to 5Mev



Minimum window thickness





d…window thickness [m]
p...pressure [Pa]
R...radial size [m]
ν ...Poisson's ratio
σ_{max}…Maximum yield strength [N m^{-2}]

$$d = \sqrt{\frac{3}{8} p (1 + \nu) \frac{R^2}{\sigma_{\mathrm{max}}}}$$

- Thick windows influences the beam
  1. Longitudinal emittance
  2. Lifetime

Alternatives to liquid H_2

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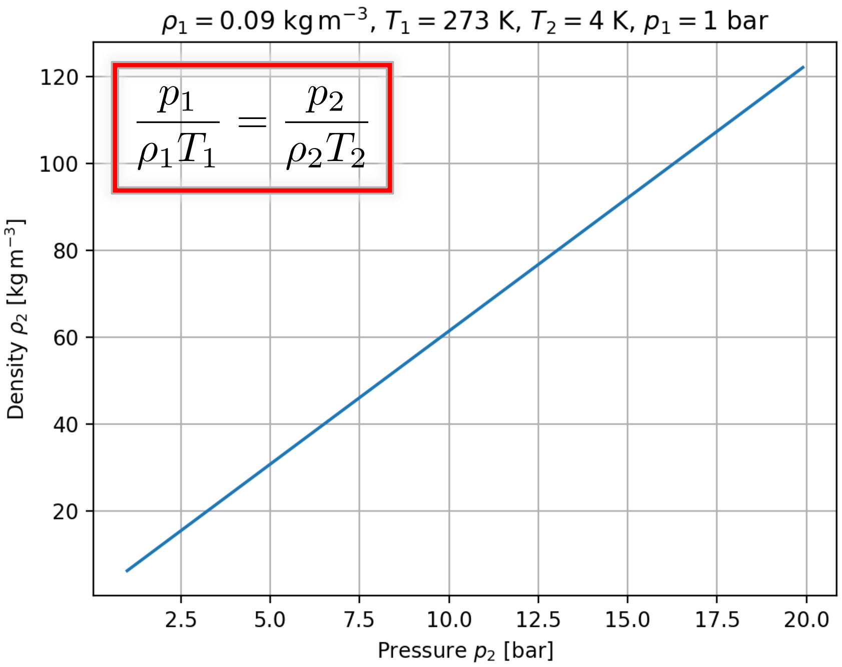
- Liquid H_2 plays an important part in final cooling
- The low $\boldsymbol{\varepsilon_{eq}}$ guarantees high cooling performance for beams with:
  1. High initial beam **momentum**
  2. High initial **transverse emittance**

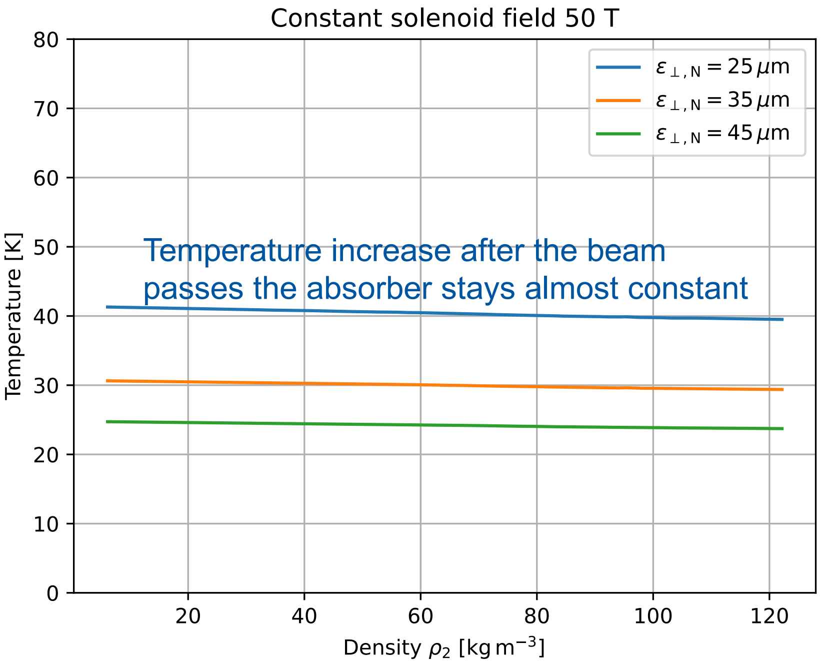
  } First cells

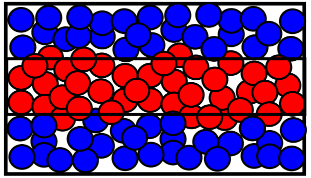
- But small beam sizes at low energies cause **huge pressures**
- **What about vaporized H_2**?

Vaporized H_2 ?

Initial beam 10MeV -> 5MeV







$$\Delta Q = \left\langle \frac{\partial E}{\partial s} \right\rangle \rho L \qquad \Delta Q = c\, m\, \Delta T$$

$$\Delta Q = \left\langle \frac{\partial E}{\partial s} \right\rangle \frac{m}{V} L$$

$$\Delta Q = \left\langle \frac{\partial E}{\partial s} \right\rangle \frac{m}{\pi\, \beta_\perp \epsilon_\perp\, L} L \qquad \Delta T = \frac{\Delta Q}{m\, c}$$

$$\Delta T = \frac{1}{\pi\, \beta_\perp \epsilon_\perp\, c} \left\langle \frac{\partial E}{\partial s} \right\rangle$$

- The **temperature increase** in gas absorbers depends only on the **beam size ($\varepsilon_\perp \beta_\perp$)**, the **spec. heat capacity (c)** and the **Bethe-Bloch** value for this gas
- It does **NOT** depend on the **gas density**!
- **Low** gas **densities mitigate** the **pressure increase** caused by the beam
- But low densities cause longer absorbers and **longer solenoids**

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Summary

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- First simulation with ICOOL and RF-Track:
  - ✓ **Emittance reduction** achieved by optimizing initial cooling condition
  - ✓ $\varepsilon_\perp$ reduction: $\mathbf{300\mu m}$ to $\mathbf{230\mu m}$ in the first 4 cells in RF-Track
  - ✓ Results trained in a surrogate model for saving simulation time
- Heat **dissipation** of Be windows is fast (**cooled** down after some **10 ms**)
- Liquid H_2 at small beam sizes and low energies leads to a **huge pressure increase** inside the absorber
- **Vaporized** H_2 at low densities leads to **low pressures** but to **longer** absorbers

Outlook

- We focus on engineering works of H_2 absorbers design
- We are going to accelerate the development of RF-Track and compare it with ICOOL to generate an optimized baseline design

Special thanks to

Andrea Latina & *Jose Antonio Ferreira Somoza*