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Final cooling optimal path and code comparison

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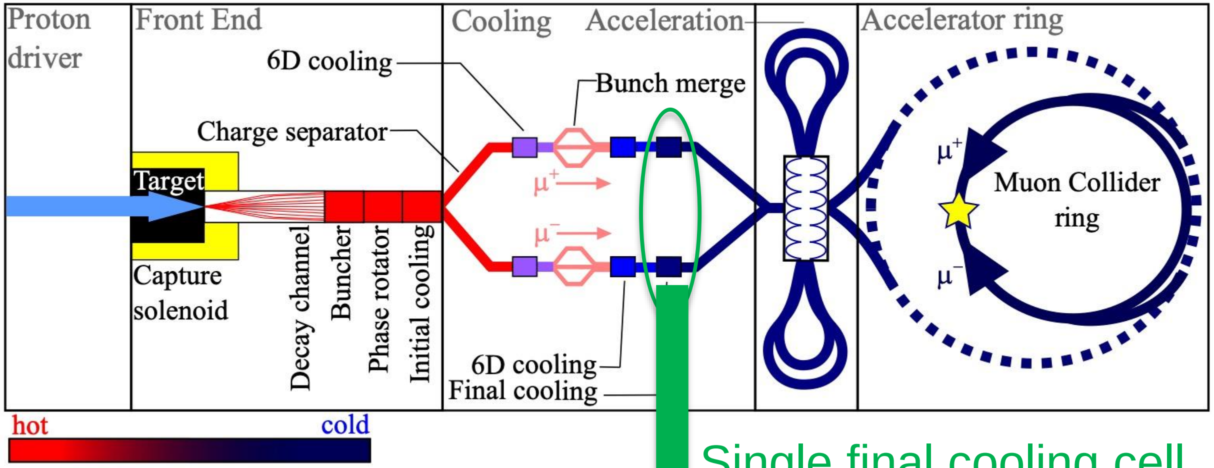
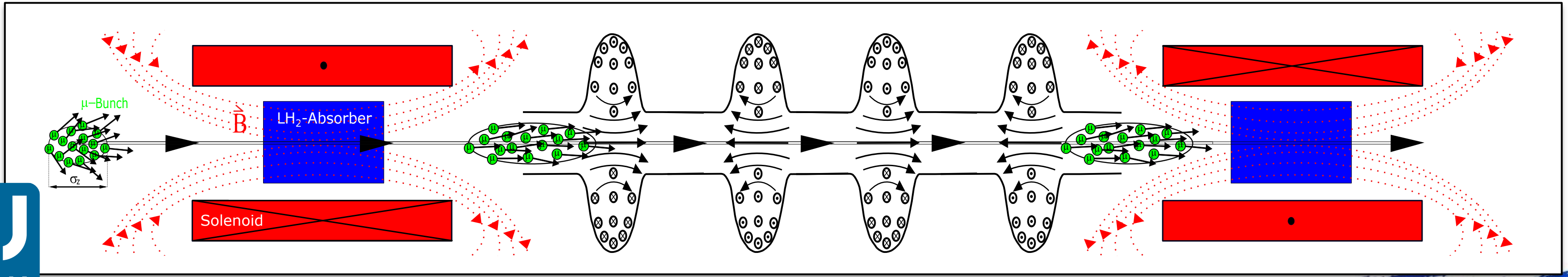
Final cooling: an overview



Single final cooling cell



Outline

- Code comparison for ionization cooling
  1. RF-Track vs ICOOL / G4Beamline
  2. Physics implementations: overview & current status

- Optimal initial beam and machine parameters for final cooling

- Thermodynamical aspects of hydrogen absorbers

Simulation tools for Ionization Cooling (IC)

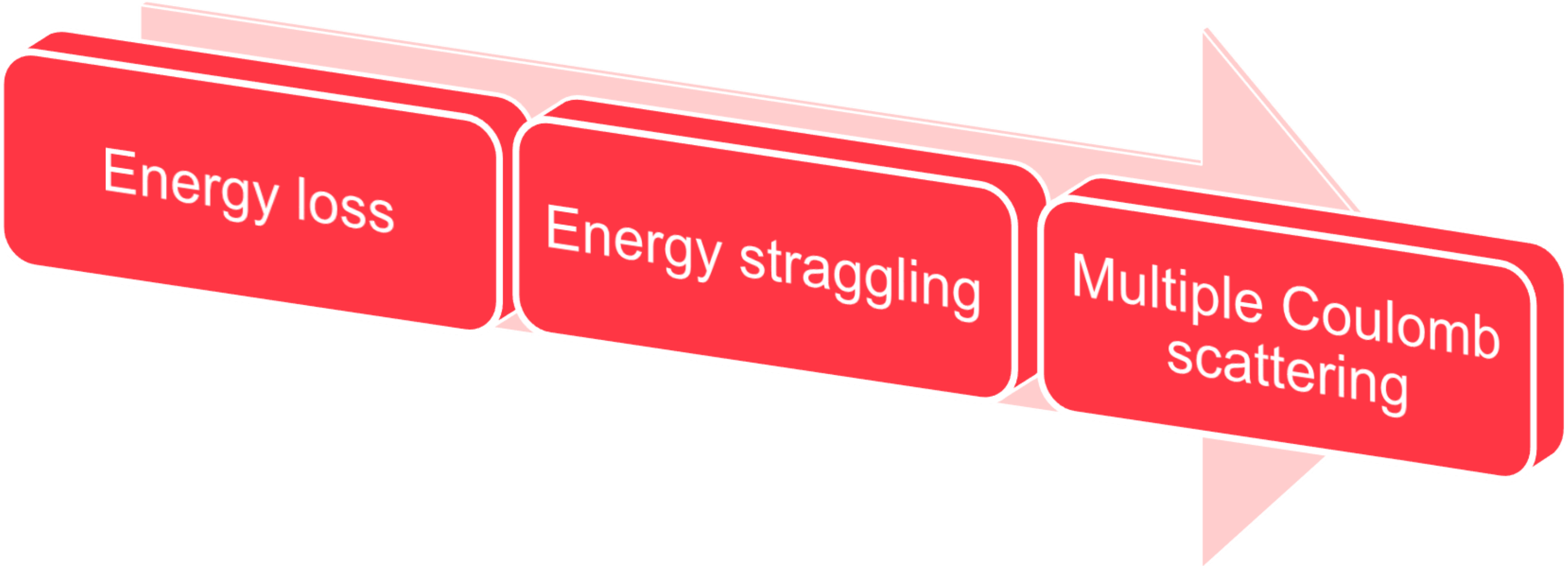
ICOOL [1]

G4Beamline [2]

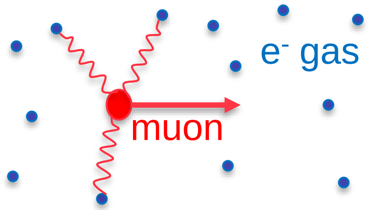
RF-Track [3]

- ICOOL & G4Beamline (G4Bl) used for IC simulations in the past
- The IMCC started to use RF-Track as a third option
  - ✓ Student-friendly program
  - ✓ Fast simulation tool, collective effects included
  - ✓ More info. from E. Fol's talk: https://indico.cern.ch/event/1250075/contributions/5357365/

Physics processes implementation in RF-Track



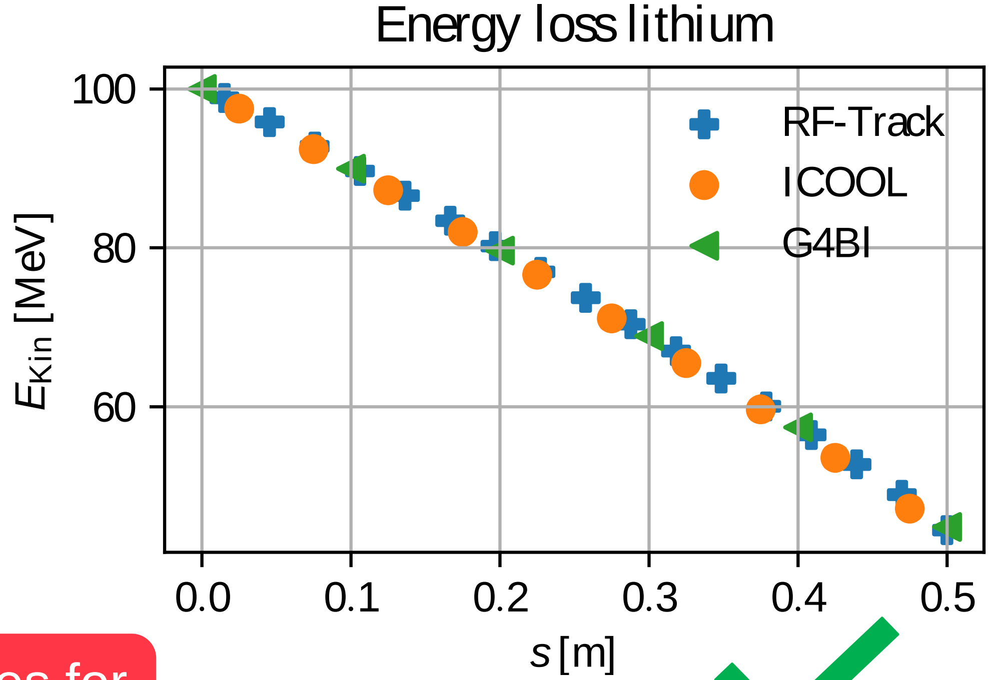
Energy loss in matter in RF-Track [4]



Energy losses follow Bethe Bloch Equation

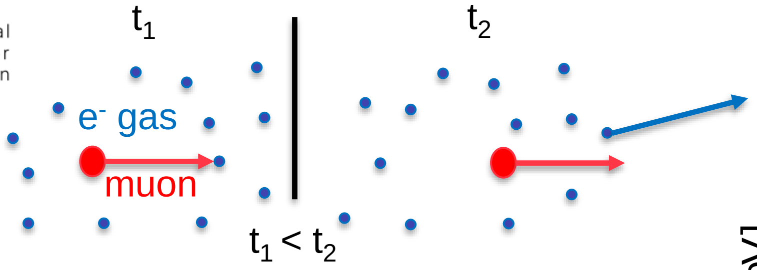
Energy loss of muons depends on:

- Energy of the particle
- Material properties
- Path length



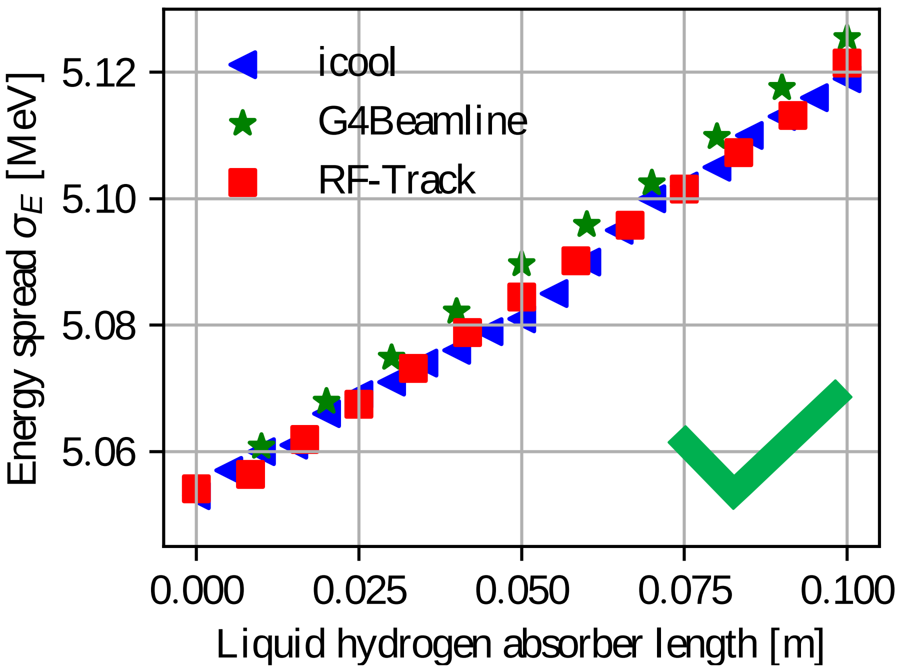
Programs have similar values for energy loss through material

Energy straggling in RF-Track [4]



Heave charged particles in matter can collide directly with electrons: this leads to a stochastic growth of the energy spread

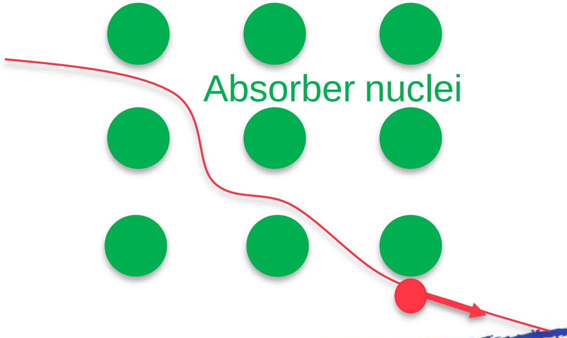
Plot: 100 MeV mean energy and 5.05 MeV spread: RF-Track data in in good agreement with ICOOL and G4Bl



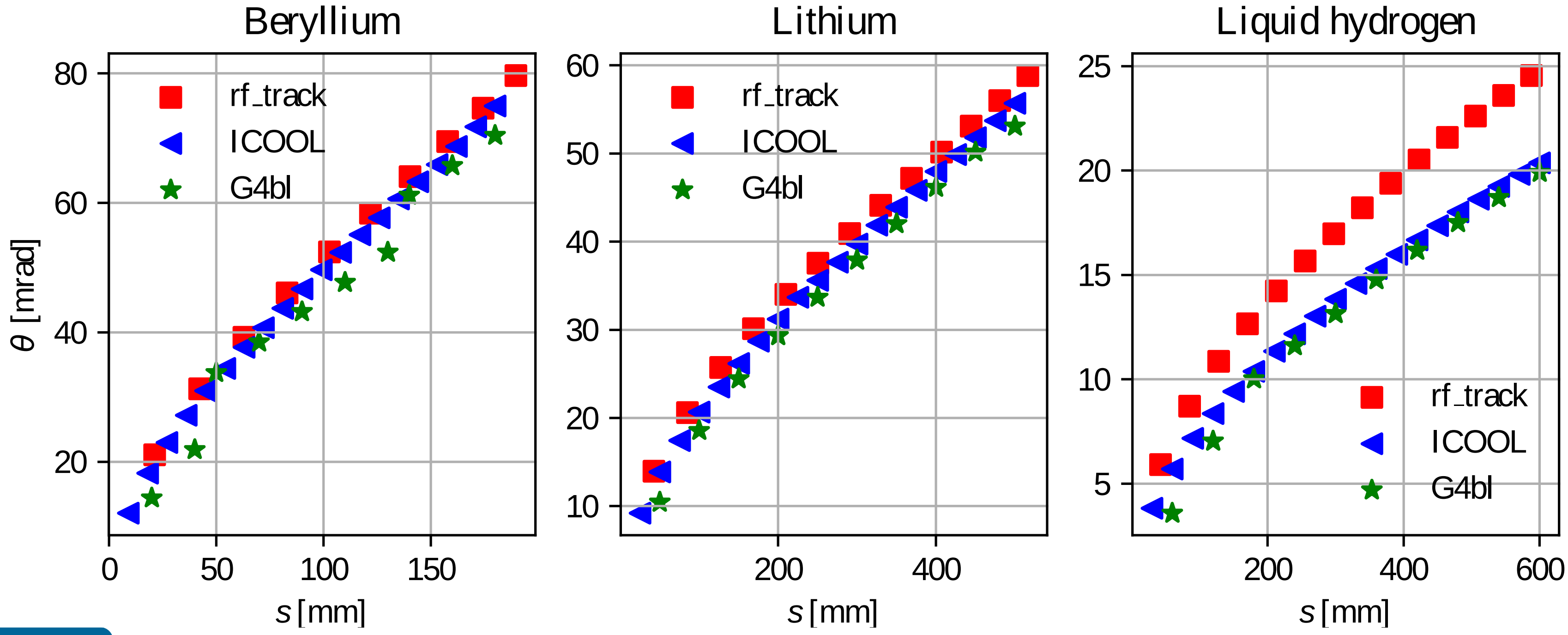
Multiple Coulomb scattering

- Charged particles are deflected by the nuclei inside material
- A rms scattering angle is given by the **Highland** formula [4]
- RF-Track:
  1. Muon deflection follows Gaussian number generator
  2. The std of the Gaussian follows Highland without log-term

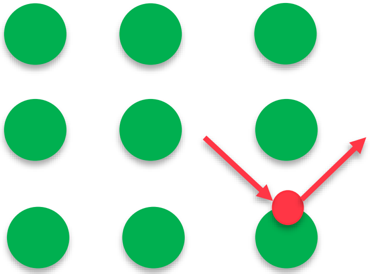
$$\theta = \frac{13.6[\mathrm{MeV}]}{\beta p c} z \sqrt{\frac{s}{L_\mathrm{R}}}\left[1 + 0.038 \ln\left(\frac{s}{L_\mathrm{R}}\right)\right]$$

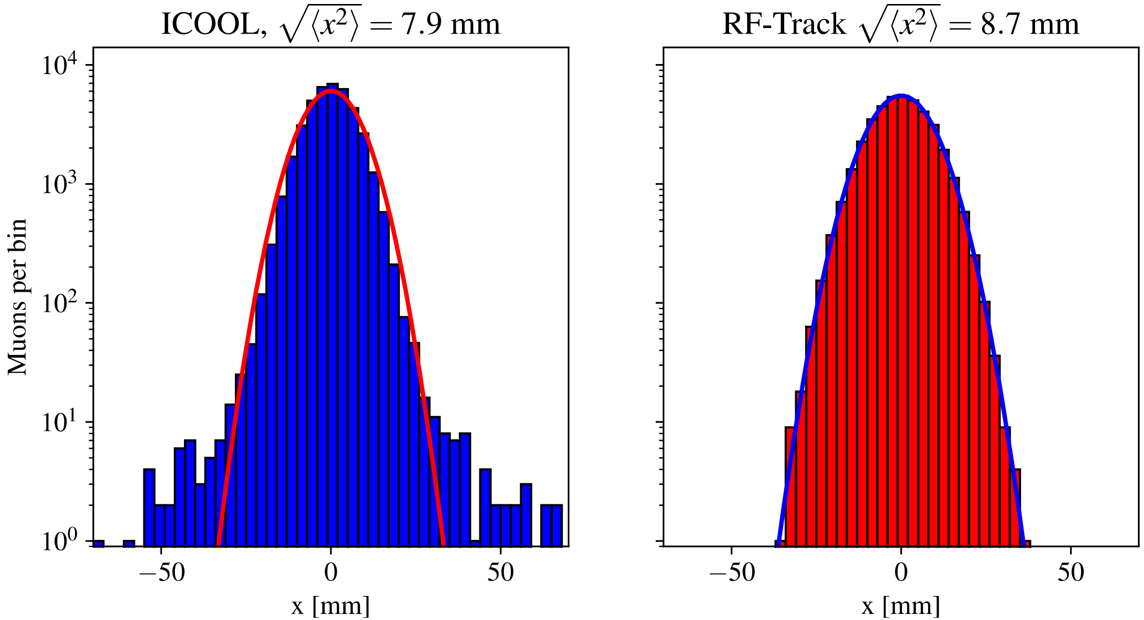


Multiple Coulomb scattering benchmarking [4]



Scattering profile analysis of liquid H_2





- Tails: hard scattering effects from the absorber's nuclei
- ICOOL particle displacements are not Gaussian anymore
- For very low Z, Highland over-estimates scattering

Current progresses on RF-Track

- Testing scattering theory for low Z-materials:
  1) Usually with screening potential Z(Z+1)
  2) But hydrogen has a single electron [5]
  3) un-screened potentials: lower scattering due to a smaller radiation length

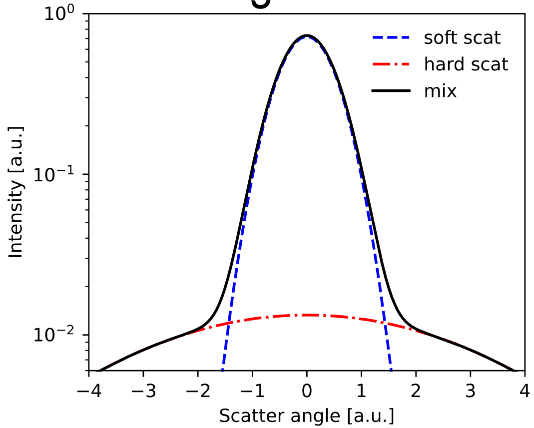
Radiation length

$$L_X \propto \frac{1}{Z(Z+1)} \rightarrow \frac{1}{Z^2}$$

- Hard scattering tails:
  1. Gaussian mixture model [6,7]
  2. A core Gaussian describes multiple Coulomb scattering
  3. A second Gaussian with a $\sigma_2 > \sigma_1$ describes the tails

$$f(\theta) = (1-\epsilon) \cdot \phi(\theta; 0, \sigma_1) + \epsilon \cdot \phi(\theta; 0, \sigma_2)$$

$$\phi \text{...Gaussian} \qquad \epsilon \text{...tail weight}$$



RF-Track can be helpful fo:

Find the recipe for final cooling

Absorber length →

Initial Energy →

Energy spread →

Solenoid field →

→ $$\min \frac{\Delta\epsilon_{\mathrm{L,N}}}{\Delta\epsilon_{\perp,\mathrm{N}}}$$

↓

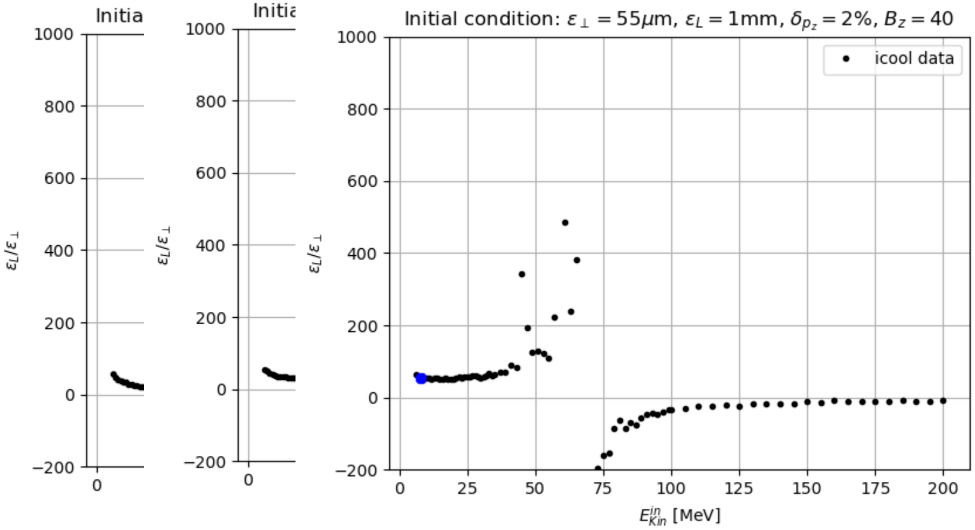
$$\max \mathcal{L} \propto \frac{1}{\epsilon_{\perp} \cdot \epsilon_{L}}$$

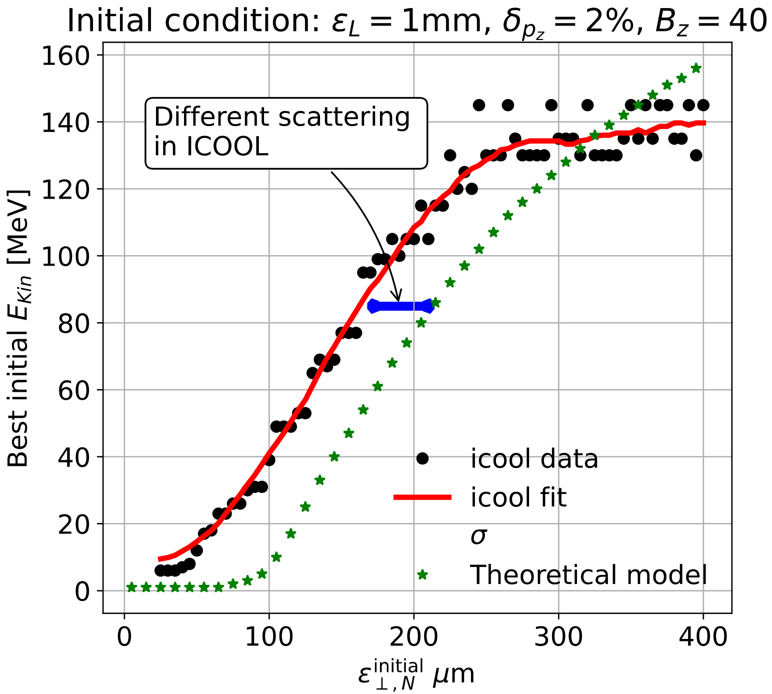
Results with ICOOL

- Constant solenoid field, e.g. 40T
- Constant longitudinal parameters
- Scan over initial Ekin for different trans. emittances

$$\min \frac{\Delta\epsilon_{L,N}}{\Delta\epsilon_{\perp,N}}$$

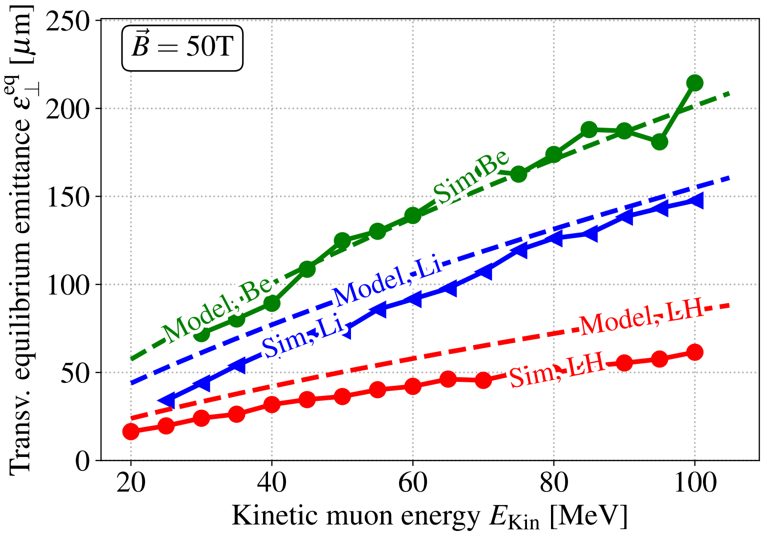
! Decay losses were not included





ICOOL: very time-consuming simulations

Last cooling cell in the final cooling section



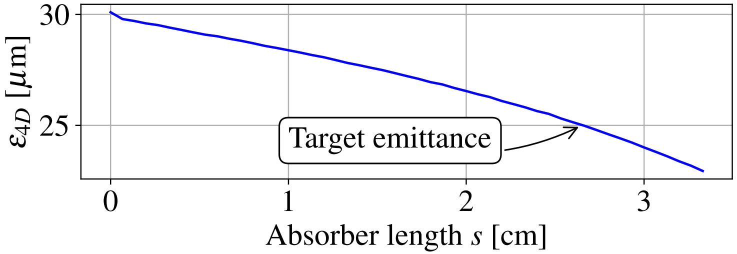
- Transverse target emittance of 25 microns is achieved in the last cooling cell
- Equilibrium emittance estimates the required parameters

Liquid hydrogen (LH)

Low beam energy

High magnetic solenoid field

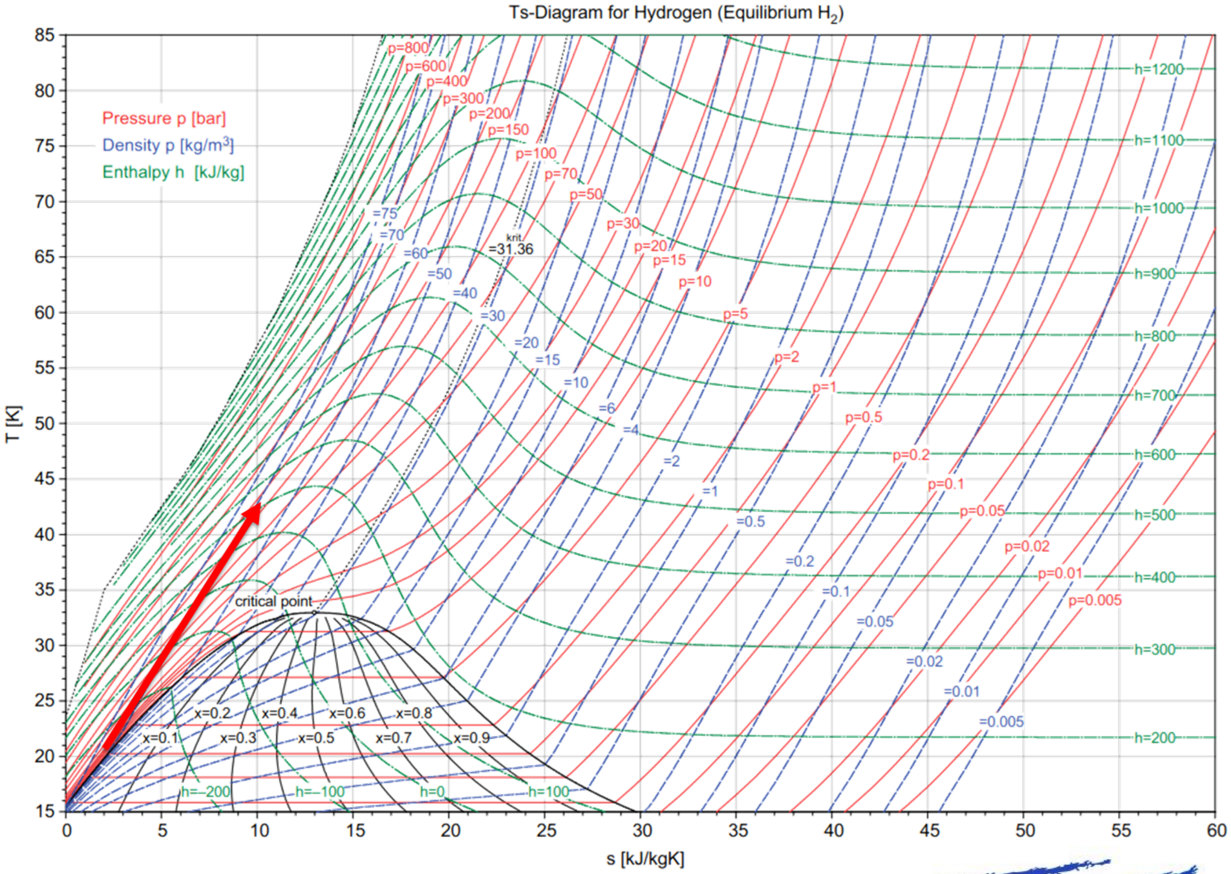
10 MeV to 5 MeV



LH problematics at very low beam sizes

Contradictory requirements:

- High density to limit the length of the superconducting solenoid (<50 cm)
- Low density to limit the pressure increase after power deposition and allow the use of thin windows



J Ferreira Somoza

LH problematics

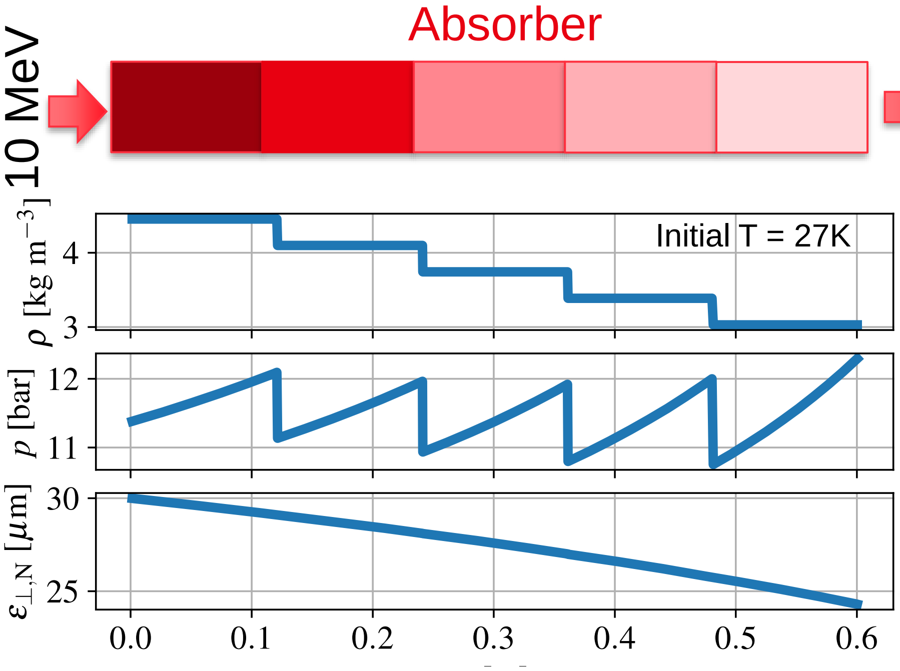
E_{kin} depositon example : From 20 MeV to 5 MeV

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

Acknowledgement to J Ferreira Somoza

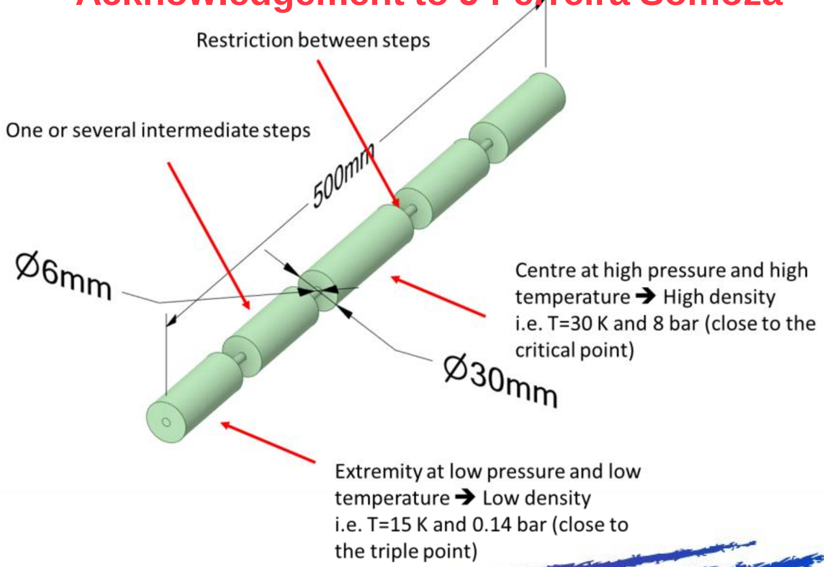
LH absorber alternatives

Analytical estimation from [9]:



- How to decouple the window from the absorber? Temperature gradient?
- Window temperature warmer to produce H_2 bubble?

Acknowledgement to J Ferreira Somoza



Conclusion

- Ionization cooling simulations with RF-Track
  1. Energy loss and straggling of muons: RF-Track shows good results in comparison to ICOOL and G4Beamline
  2. For low-Z materials: RF-Track overestimates the scattering angle
  3. Under development: testing new scattering dynamics with liquid H_2, Gauss mixture model for hard scattering effects
- Optimal path estimation for each final cooling cell
- Thermodynamic studies for absorbers

} Goal: simulate it with RF-Track

Reference list

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