Software Mini-Workshop, online, 17.10.2024

RF-Track

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Overview

- Focus on **RF-Track [1]** as a novel simulation tool for final cooling
- Overview of implemented particle-matter interaction models
- Compare **RF-Track** with **ICOOL[2]** and **G4BL[3]**
- To-Dos
- Conclusion

About the RF-Track software

- **C++** code for accelerator physics simulations.
- Utilizes GNU Scientific Library (**GSL**) and the **FFTW** library .
- Software supports **parallel processing** for increased computational efficiency in complex particle tracking within field maps.
- Users have the option to interface with **RF-Track** using **Python** or **Octave**.
- **Collective Effects:**
  - Space charge forces
  - Short- and long-range wakefields
  - Beam loading phenomena
- **Single-Particle Effects:**
  - Incoherent synchrotron radiation
  - Magnetic multipole kicks
  - Multiple Coulomb scattering

Many **RF-Track** contributions [4-8]

Particle-material interactions that are relevant for ionization cooling

Implementation into the **RF-Track** code

Reference materials for benchmarkings studies

- Performed benchmarkings:
  1. Absorbers
     I. Liquid hydrogen
     II. Lithium hydride
     III. Beryllium
  2. Solenoid
  3. Single final cooling cell

Parameter	Unit	Magnitude
Material		LiH
Thickness	mm	65.37
Density	g cm^{-3}	0.69
Li6 Fraction	by mass	0.814
Li7 Fraction	by mass	0.043
H Fraction	by mass	0.143
Momenta		171.55, 199.93, 239.76
Material		liquid H_2
Thickness	mm	349.6
Density	g cm^{-3}	0.07053
Momenta	MeV c^{-1}	164.9, 199.0, 237.1
Material		liquid H_2
Thickness	mm	10
Density	g cm^{-3}	0.07053
Momenta	MeV c^{-1}	30
Number of particles		10^6

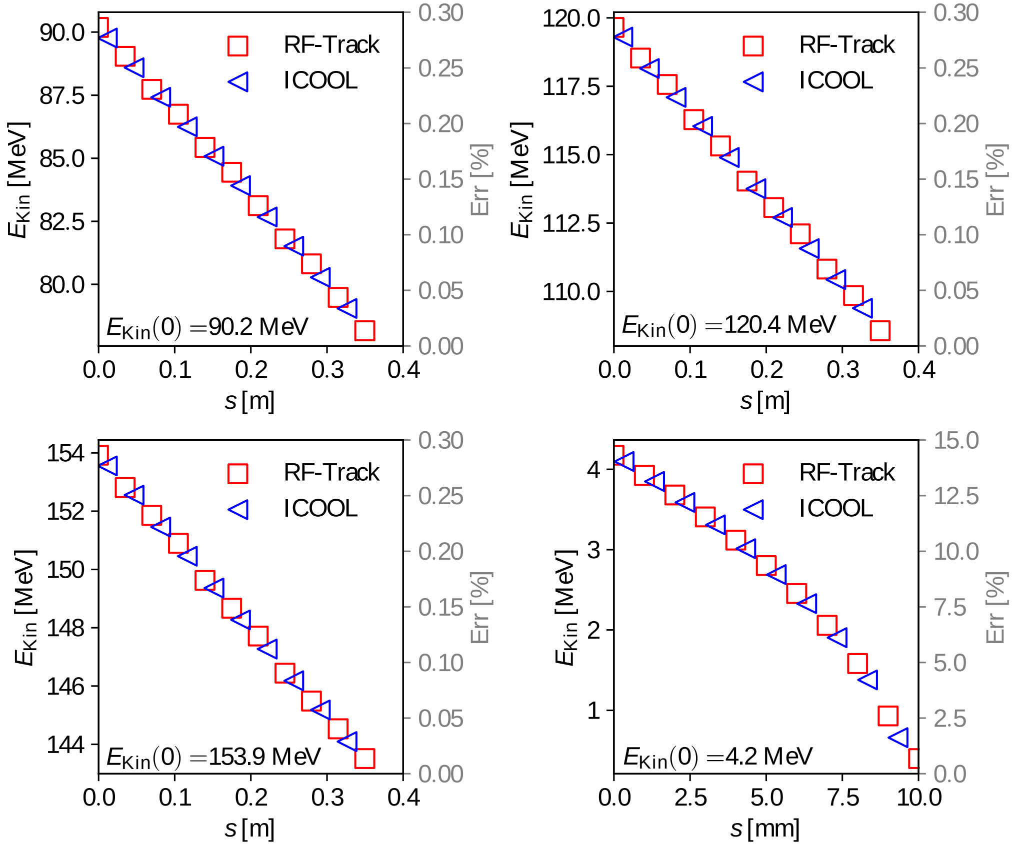
Energy loss liquid hydrogen

Bethe-Bloch equation

$$-\left\langle \frac{\partial E}{\partial s} \right\rangle = K \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \left(\frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} \right) - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Energy loss of muons depends on:

- Energy of the particle
- Material properties
- Path length



- Compare **RF-Track** energy loss of liquid hydrogen with **ICOOL**
- Error is less than 0.3%
- Results show good agreement.
- Error **increase** in case of particle **losses** (see lower right plot).

Energy loss lithium hydride (LiH)

- The ICOOL manual presents **LiH** with a different density and a varying composition of **Li6** and **Li7** compared to the LiH sample form **MICE.**
- Mixing a specific material with **ICOOL** might require some additional clarification, as the process isn't immediately intuitive.
- Therefore, **RF-Track** energy loss benchmarking of **LiH** with **G4Bl.**

How to mix material in **RF-Tack** and **G4BL** – code example:

RF-Track

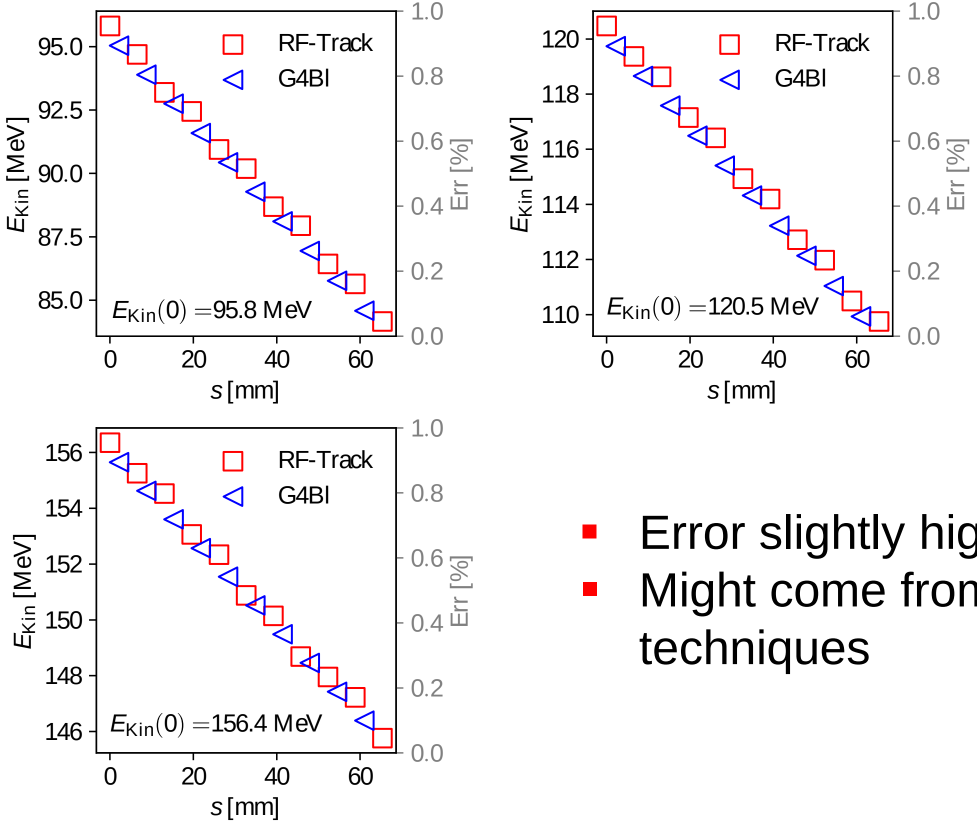
```
frac_Li = 0.86
frac_H = 0.14
A_Li_Mice, A_H = 6.05, 1.0079 #atomic numbers
Li = RF_Track.Absorber(abs_len, X0_Li, Z=3., A=A_Li_Mice, rho_LiH * frac_Li, I=40.)
H = RF_Track.Absorber(abs_len, X0_H, Z=1., A=A_H , rho_LiH * frac_H, I=21.)
V.add(Li, 0, 0, 0, 'entrance')
V.add(H, 0, 0, 0, 'entrance')
```

G4Bl

```
material Li6 Z=3 A=6 density=0.539
material Li7 Z=3 A=7 density=0.534
material LiH Li6,0.814 Li7,0.043 H,0.143 density=0.69
```

Special thanks to D. Kaplan

Energy loss lithium hydride (LiH)



- Error slightly higher, than compared to LH
- Might come from different mixing techniques

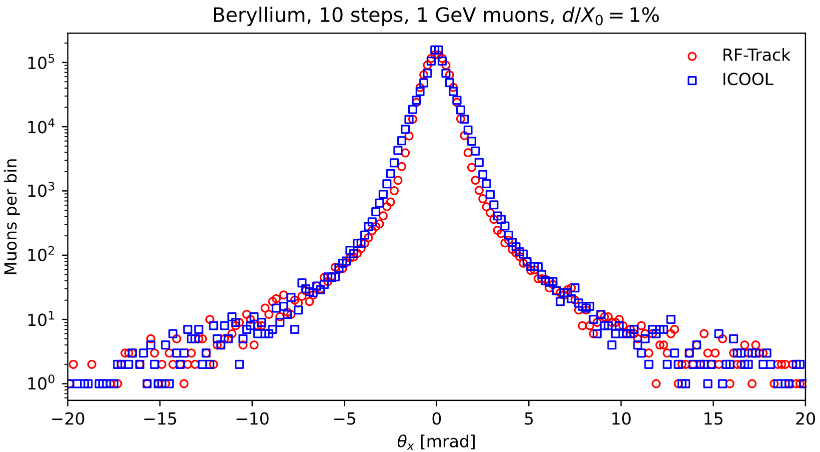
Semi-Gaussian distribution as scattering model in RF-Track [9,10]

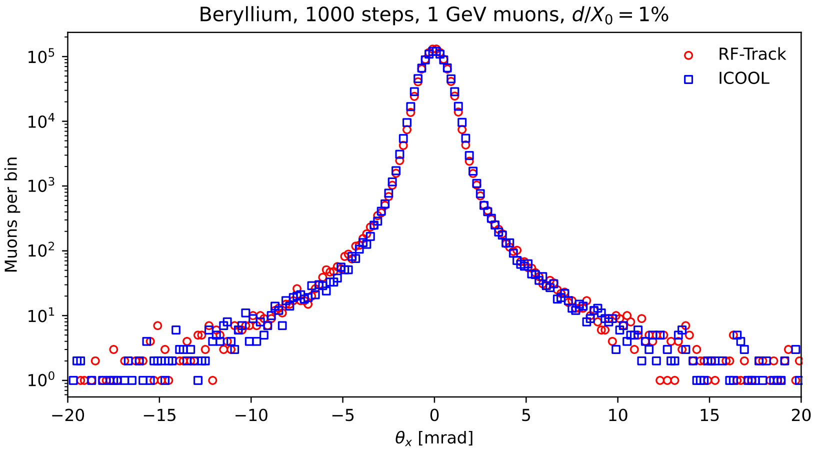
$$f(\theta) = (1-\epsilon)\frac{\theta e^{\frac{-\theta^2}{2\sigma^2}}}{\sigma^2} + \epsilon\frac{2a^2\theta}{(\theta^2+a^2)^2}$$

- The tail weight factor ϵ indicates the probability of a particle to be long ranged scattered
- The first term represents the **core** Gaussian of the distribution
- Term 2 shows a non-Gaussian single scattering distribution (**tails**)
- ICOOL and **G4BI** use the **Moliér** algorithm from the Gant4 library.

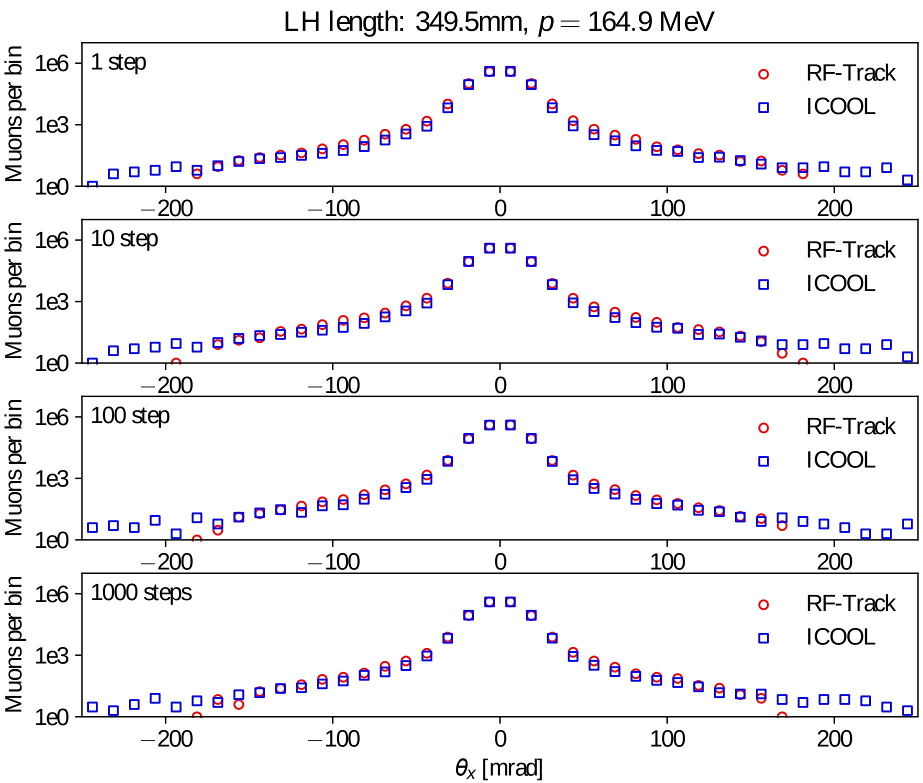
First try: ICOOL vs RF-track: Beryllium

- 1E6 muons for each simulation
- Start: 1 GeV mono energetic pencil beam
- Absorber length: 1% of radiation length
- The shape of the distribution changes minimally with the number of integration steps.
- The Moliér model lacks on the convolution property, indicating potential for further improvement.





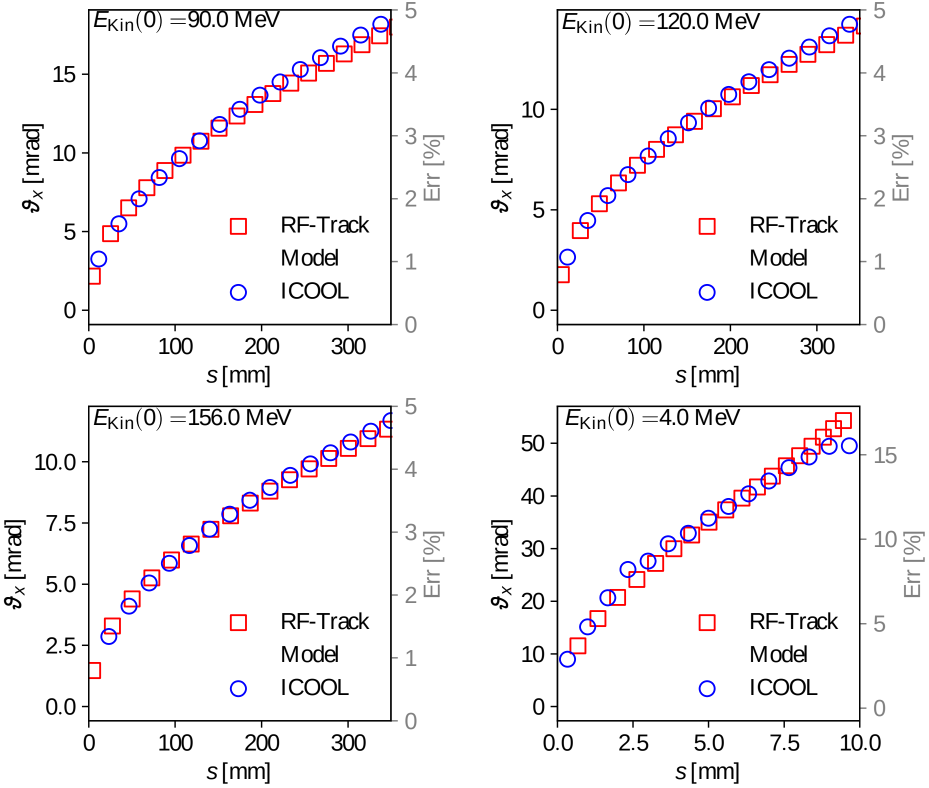
ICOOL vs RF-Track: Liquid hydrogen



- 1E6 muons for each simulation.
- Example with 1, 10, 100 and 1000 steps.
- Excellent agreement is observed with **ICOOL**.
- Exception: the **ICOOL** model overestimates the tails slightly .

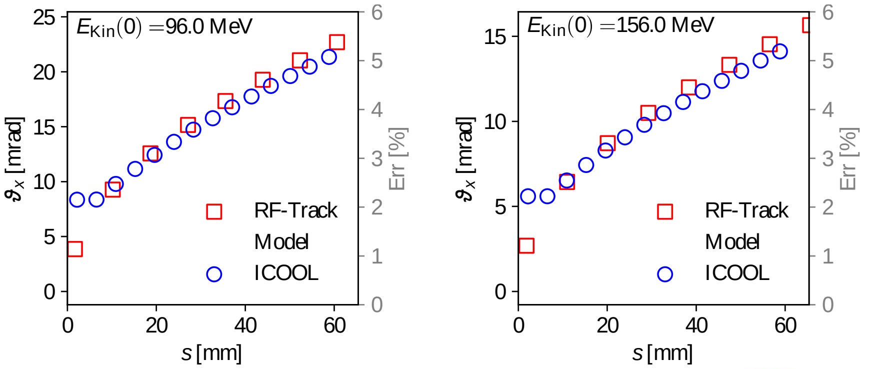
Std. scatter angle benchmarks

Liquid hydrogen Examples

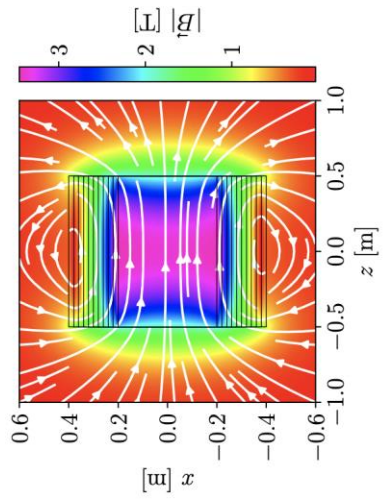


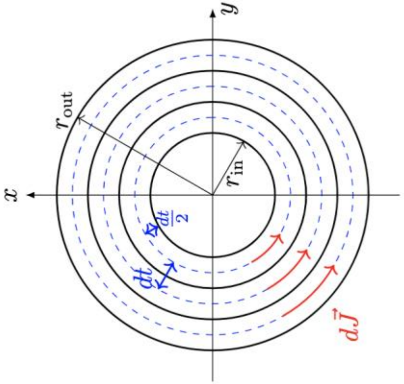
- Error are in the range of 5%.
- Exception: low energy example, due to high losses.

LiH Examples



Solenoid model



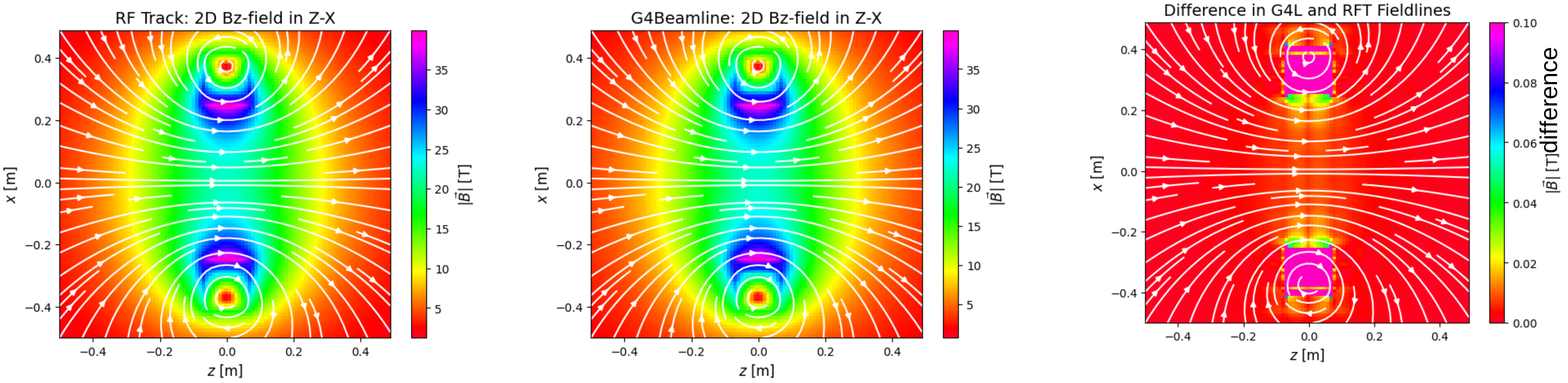


- **RF-Track** uses the current sheet model for solenoids.
- The model is based on **elliptical integral functions**.
- These functions come from GSL but require more computational time to evaluate field strength for all particle positions.
- **Solution**: **RF-Track** creates a meshgrid of the 3D solenoid field and uses an interpolation function to provide field strengths during particle tracking.

Solenoid field benchmarking

Parameter	Unit	Magnitude
Coil inner radius	mm	250.0
Coil radial thickness	mm	169.3
Coil outer radius	mm	419.3
Coil length	mm	140.0
Current density	A/mm^2	500.0
Particle species		$\mu+$
Particle momentum	MeV/c	200.0
Particle z start	mm	-500.0
Particle z end	mm	500.0
Particle radial step	mm	10.0
Particle maximum radius	mm	200.0

- Comparison **RT-Track** with **G4BL**.
- Sheet number: 200
- We find slightly differences in the off-axis and coil regions.



Analysis from R. Taylor

Solenoid field: particle tracking benchmarking

Parameter	Unit	Magnitude
Coil inner radius	mm	250.0
Coil radial thickness	mm	169.3
Coil outer radius	mm	419.3
Coil length	mm	140.0
Current density	A/mm^2	500.0
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Particle z start	mm	-500.0
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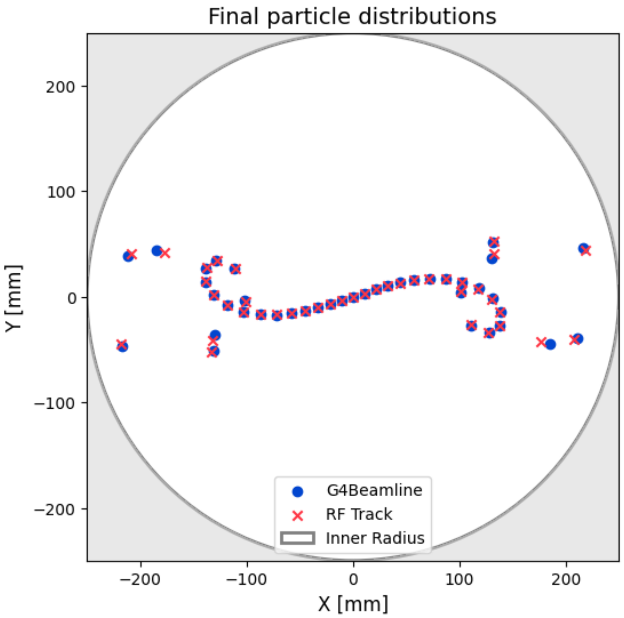
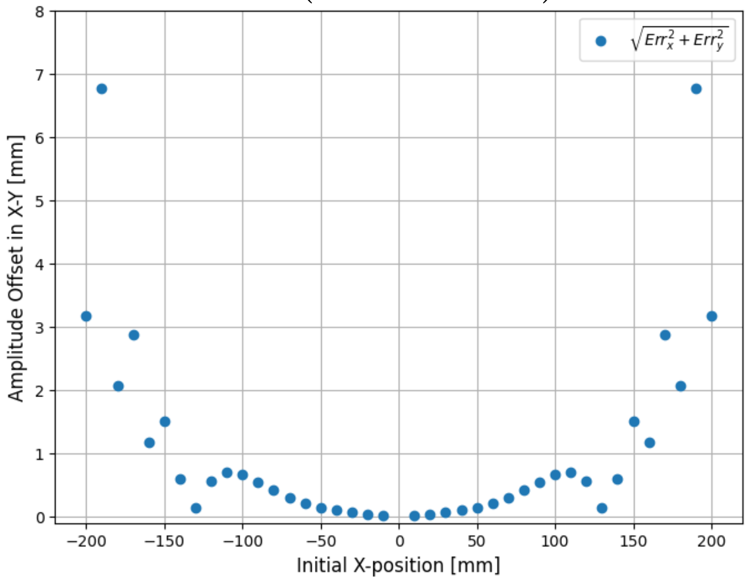
Particle radial step	mm	10.0
Particle maximum radius	mm	200.0



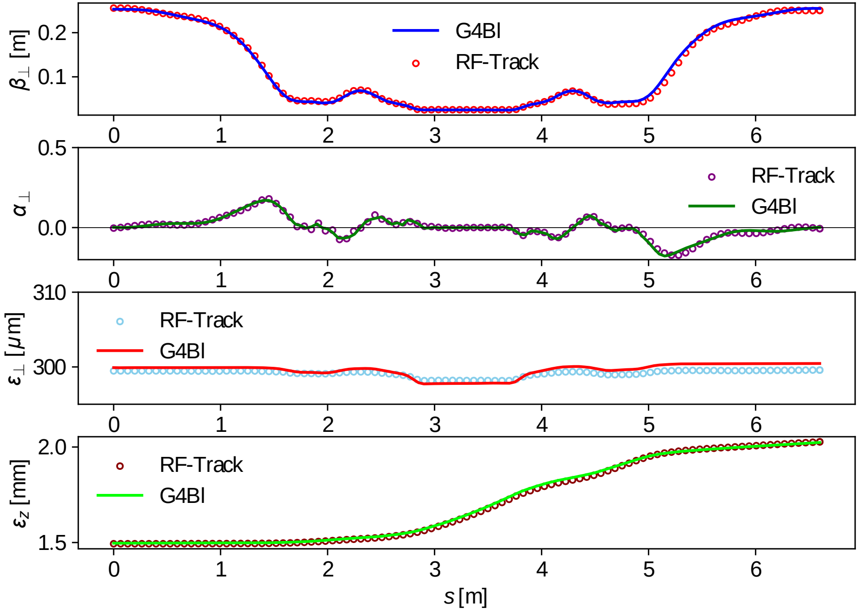
$$Err_x = abs(x_{RF} - x_{G4})$$



Analysis from R. Taylor

Final cooling cell example

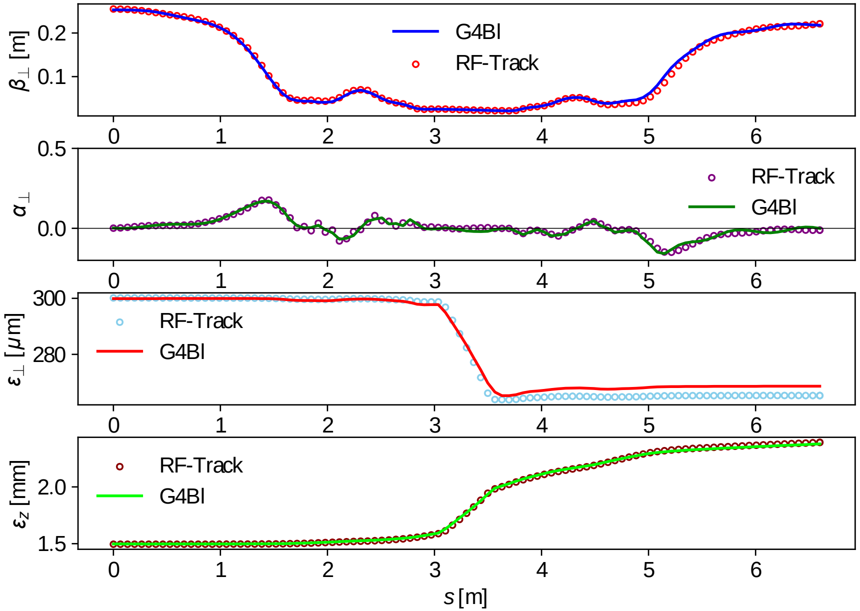
No absorber



Computation time

	RF-Track	G4Beamline
time	5 min 1 s	15 min 55 s

With absorber



Slightly higher cooling with **RF-Track**, which must be investigated.

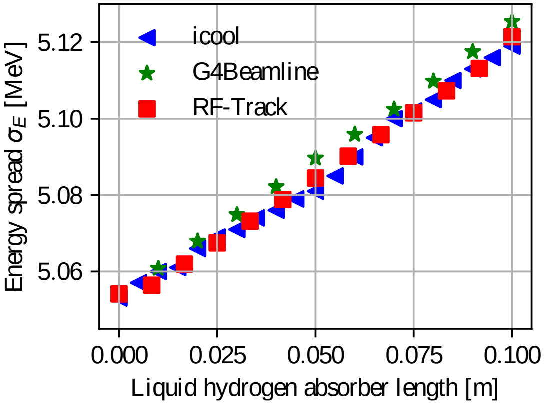
Computation time

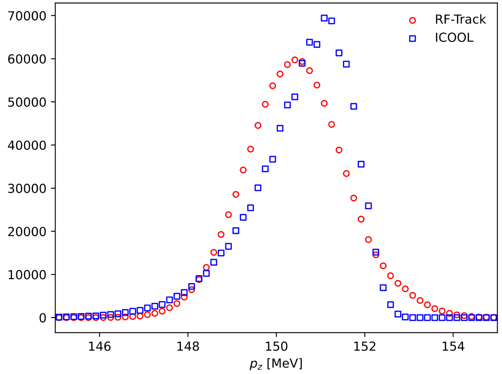
	RF-Track	G4Beamline
time	9 min 3 s	16 min 57 s

Initial emittances taken form [11]

To-do list for RF-Track

- **RF-Track** assumes the energy fluctuation as normal distributed.
- It must be Vavilov/Landau distributed.
- The Gauss approximation is valid for very thick materials.





- Comparison of tracking in cavities.
- RF-Track uses TM011 mode; G4BL uses TM010 mode.
- TM011 is the better option, since we consider window less cavites in final cooling.

Summary & outlook

- Energy loss model **in RF-Track** show high agreement with **ICOOL** and **G4BL**
- A multiple Coulomb scattering model based on a semi-Gaussian mixture model was added in **RF-Track** and compared with **ICOOL**.
- Results were compared with **ICOOL**, showing excellent benchmarking results.
- This new tool enables an optimized design of ionization cooling channels for a future muon collider.
- Next step: Focus on longitudinal beam distributions

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Thank you for your attention

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- [9] R. Frühwirth, M. Liendel: Mixture models of multiple scattering: computation and simulation.
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- [11] B. Palmer: Muon final cooling in 30-50T solenoids.