The Advancement of Cooling Absorbers in COSY Infinity

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Introduction

Muons are useful for the study of **high energy phenomena**, since

- they are fundamental (unlike protons), which means they offer clean collisions and in a smaller facility, and
- they to not emit synchrotron radiation (unlike electrons), and so circular acceleration with a very compact footprint is possible.

Muons are also useful as a **neutrino source**, since it is possible to make a source of neutrinos that is pure, intense, high energy, and both neutrinos and anti-neutrinos can be produced. This makes for a more precise measurement:

- a pure beam means that we can understand the mixture of neutrinos in our beam very well,
- an intense beam means that we can look for oscillation with lots of neutrinos,
- a high energy beam means that the chance of seeing each neutrino is higher,
- and the presence of neutrinos and anti-neutrinos means that we can measure the difference between matter and antimatter.

Together these factors make for a very precise experiment. However, muons are not without their challenges:

- Muons are tertiary particles (protons $\rightarrow$ pions $\rightarrow$ muons), hence large initial phase space.
- Muon mean rest frame lifetime is 2.2 μs.
- **Ionization cooling** is the only technique fast enough to reduce the large initial beam size in a short enough time.
- This requires the beam to traverse matter, where it loses momentum in all directions, with subsequent energy restoration in the longitudinal direction.

The stochastic processes of interest are straggling (fluctuation about a mean energy loss), angular scattering, and transverse position corrections. All simulations were performed using an initial pencil beam of momentum 172 MeV/c through 109 mm of liquid hydrogen. The step size for COSY was the full 109 mm. These data were also compared to two other codes, ICOOL [2] and G4Beamline [3], where the step sizes were both 1 mm.

COSY Infinity

COSY Infinity [1] is an arbitrary-order beam dynamics simulation and analysis code. It can determine high-order transfer maps of combinations of particle optical elements of arbitrary field configurations. However, stochastic effects (random effects, such as those observed in cooling absorbers) do not fit well into the transfer map paradigm. For this reason, the development of stochastic processes in COSY is reported here.

Results: Angular Scattering

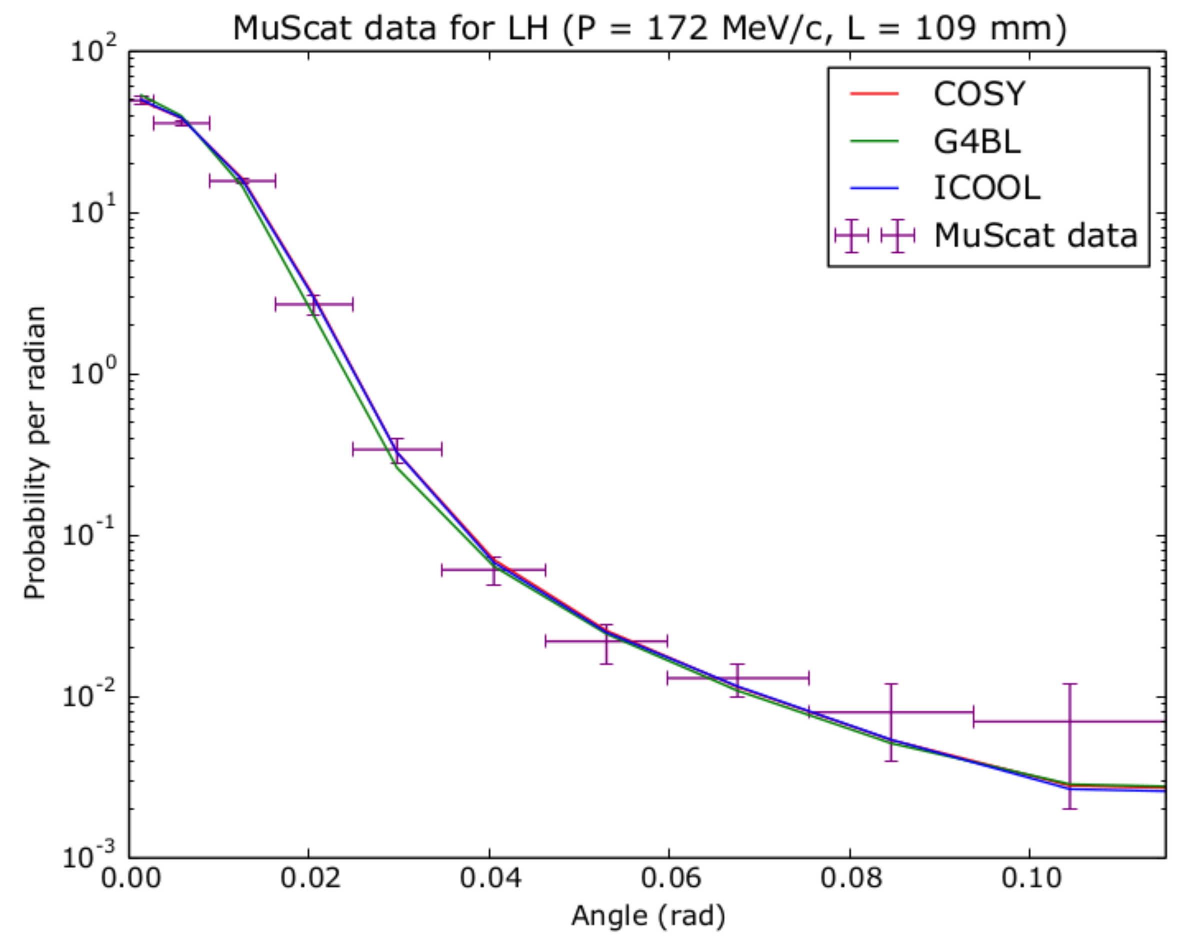

Figure 1: Angular scattering comparison between COSY (red), G4Beamline (green), ICOOL (blue), and the data points from [6] (purple).

- Derivation for small and large angles performed separately.
- Angular distribution peak is quite nearly Gaussian in θ [4] up until some u_0.
- Tail follows the Mott cross section [5].
- Full distribution:

$$g(u) = \begin{cases} e^{-\frac{1}{2}\frac{1-u}{1-u_\sigma}} & \mid u_0 < u \\ \zeta \cdot \frac{1+\frac{1}{2}(\beta\gamma)^2(1+u-b)}{(1-u+b)^2} & \mid u \le u_0 \end{cases}.$$

- $u =\cos\theta$.
- ζ, b ensure continuity and smoothness.
- u_σ, u_0 emperically chosen.
- Good agreement is shown between COSY (red) and the MuScat experiment [6] (purple).

Results: Transverse Phase Space

- Transverse position depends on scattered angle θ.
- Picked out of Gaussian distribution with mean μ_T and standard deviation σ_T.
- $\mu_T = \frac{\theta\rho_c L}{\mu_w}$.
- $\sigma_T = \max\left(L\theta_\sigma\sqrt{\frac{1-\rho_c^2}{3}}, \left|\frac{LP_T/P_Z}{\sigma_w}\right|\right)$.
- Model based on documentation by [7], with novel emperical parameters μ_w and σ_w.
- Correlation coefficient: $\rho_c = \sqrt{3}/2$.
- θ_σ corresponds to aforementioned u_σ.
- L is the absorber length; P_T, P_Z are the (scattered) transverse and longitudinal momenta.
- COSY phase space appears narrower. This may be misleading, as the discrepancy in not in the bulk but in the tails.

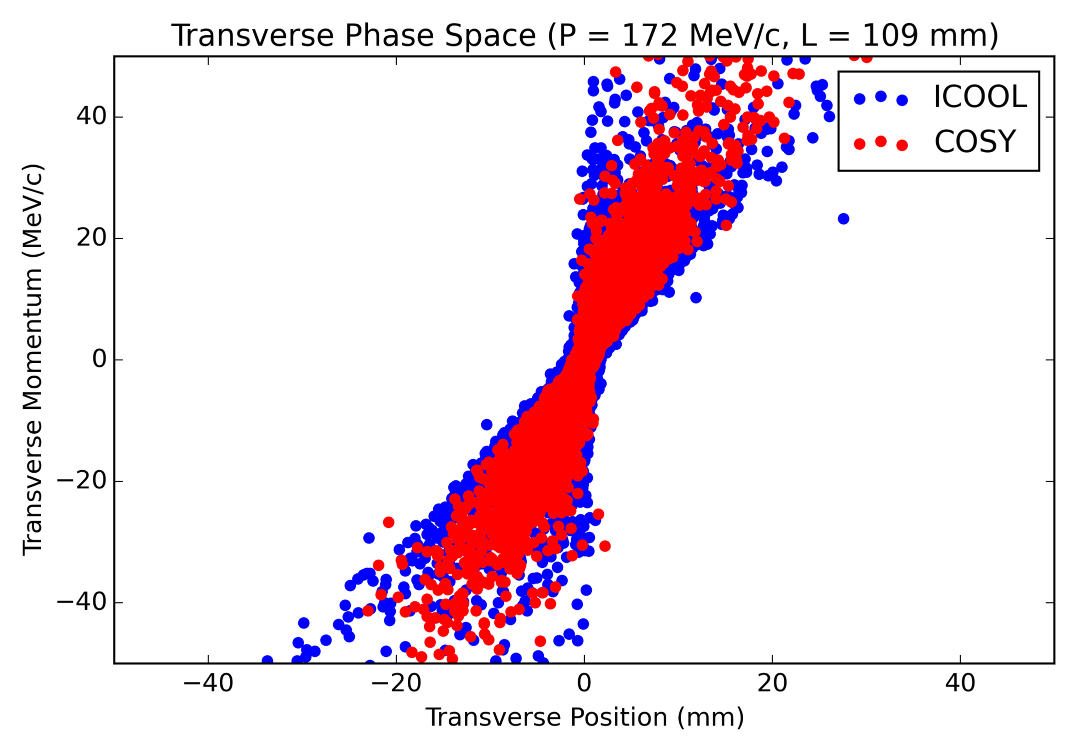

Figure 2: Transverse phase space comparison between COSY (red) and ICOOL (blue).

Results: Straggling

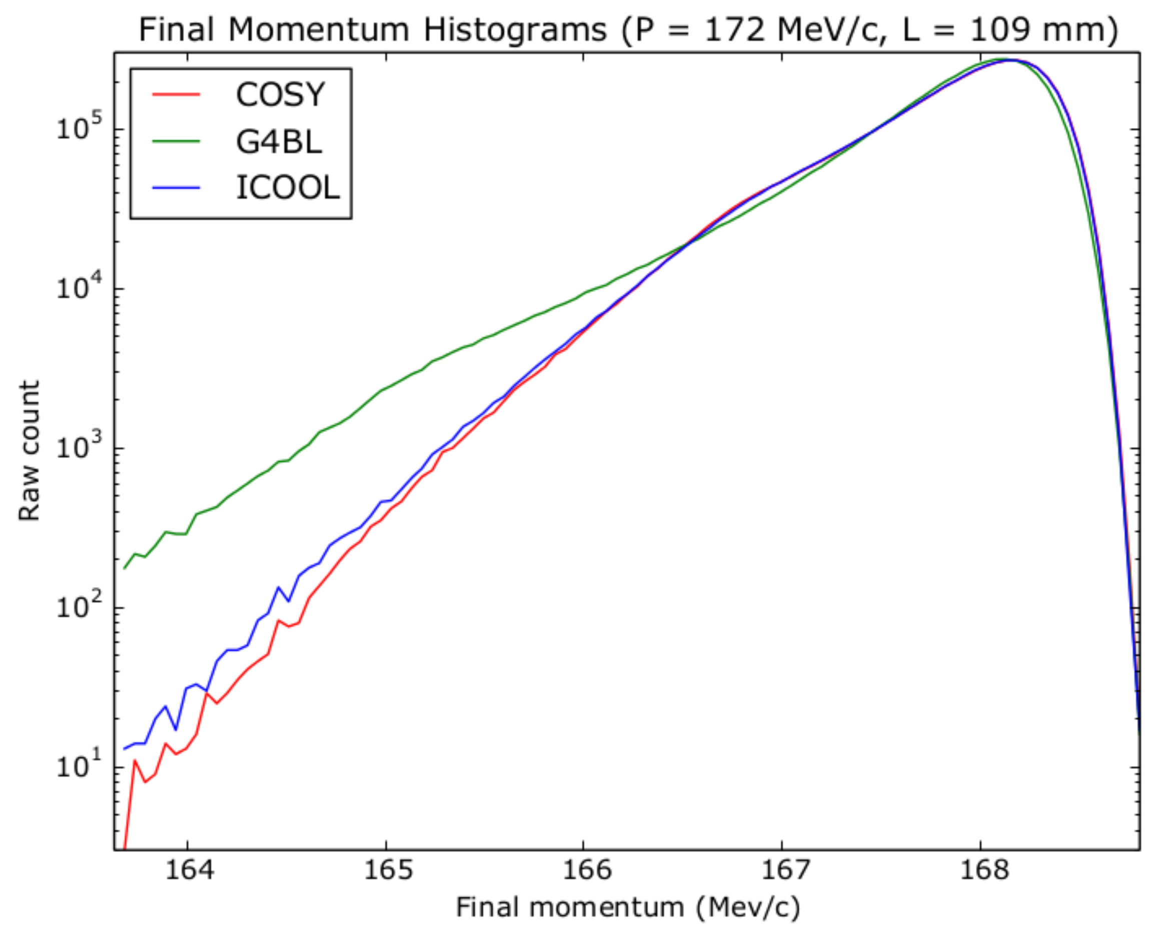

Figure 3: Straggling comparison between COSY (red), G4Beamline (green), and ICOOL (blue).

- Based on Landau theory [8].
- Tail disagrees with G4Beamline. This could be due to a regard for both ionization and excitation cross sections (Landau theory only regards ionization) or the synthetic width correction algorithm that G4Beamline employs.

Conclusions

- Both transverse and longitudinal analyses agree well with ICOOL, G4Beamline, and experimental data (when available).
- While not shown, it is reported here that good agreement hs been achieved between COSY and other data from [6] (e.g. 3.73 mm of Be).
- μ_T and σ_T (transverse phase space parameters) may need further adjusting.
- Further benchmarking should be done, but is expected to agree well.

References

[1] M. Berz, K. Makino, COSY Infinity, `http://www.cosyinfinity.org`.

[2] R. C. Fernow *et al.*, ICOOL Simulation Code, `http://www.cap.bnl.gov/ICOOL/`.

[3] T. Roberts, G4beamline, `http://www.muonsinternal.com/muons3/G4beamline`.

[4] S. Goudsmit and J. L. Saunderson (1940), Phys. Rev. 57, p. 24.

[5] D. Griffiths (2008) Introduction to Elementary Particles, 2nd Ed.

[6] D. Attwood *et al.* (2006), NIM B251, p. 41.

[7] J. Beringer *et al.* (PDG) (2013) PR D86, 010001 chpt. 31.

[8] L. Landau, J. Phys 8, p. 201.