MAP Technical Note – 558
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Verification and validation tasks for ICOOL

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1. Definitions

According to John Cary [1]

"Verification is ensuring that the code is solving the equations correctly.
Validation is ensuring that the correct equations are being solved."

For MAP cooling simulations we take verification to mean agreement with some other commonly-used code, and validation to mean agreement with cases where we know the answer, either theoretically or experimentally.

2. Verification tasks

Compare ICOOL simulations of interactions with matter with G4beamline.

materials = {H_2, LiH, Be}
absorber lengths = {300 μm, 1 cm, 5 cm}
momenta = {100, 200, 300} MeV/c
observables = {mean energy loss, scattering angle distribution, energy loss distribution, change in emittance}

3. Validation tasks

<u>Particle tracking</u>

For a given initial position and momentum, we compare the final position and momentum with theoretical predictions after traversing the following fields.

3.1 180° bend in uniform dipole field

We check tracking in a uniform dipole field using DIP model 1 for ICOOL version 3.26. The radius of curvature of a particle moving in a constant dipole field is

$$\rho = \frac{p}{e\,B}$$

where $e \equiv 0.299792458$ if the units are ρ [m], p [GeV/c] and B [T]. The coordinate system in ICOOL is defined with respect to a reference particle with momentum p_o. If p_o = 0.200 GeV/c and B = 1 T, then ρ_o = 0.667128190 m. The total pathlength for a 180° bend is

$$L = \pi\,\rho_o$$

For this example L = 2.095845022 m. The results for tracking of an on-momentum particle is shown in the table. We expect the x and p_x variables to be identically zero at the end of tracking.

p [GeV/c]	step [m]	Δx [m]	Δpx [GeV/c]
0.200	10^{-6}	2.95 10^{-16}	5.32 10^{-18}
	10^{-3}	2.95 10^{-16}	5.37 10^{-18}
	1	1.01 10^{-16}	2.91 10^{-17}

For an off-momentum particle we expect x at the end of tracking to be

$$x_{off} = 2\left(\rho - \rho_o\right)$$

and $p_{x,off}$ = 0. Taking p = 0.220 GeV/c, we find that ρ = 0.733841009 m and x_{off} = 0.133425639 m. The results of tracking are shown in the table.

p [GeV/c]	step [m]	Δx [m]	Δpx [GeV/c]
0.220	10^{-6}	-1 10^{-9}	-1.53 10^{-12}
	10^{-3}	-1 10^{-9}	-1.44 10^{-12}
	10^{-2}	-1 10^{-9}	2.46 10^{-11}
	10^{-1}	-6.6 10^{-8}	2.61 10^{-7}
	1	-1.0 10^{-2}	8.97 10^{-4}

3.2 One Larmor wavelength in uniform solenoid field

We check tracking in a uniform solenoid field using SOL model 1 for ICOOL version 3.26.The angular velocity of a singly-charged particle inside a uniform solenoid field is

$$\omega = \frac{e\,B_S}{m\,\gamma}$$

where $e \equiv 0.299792458$ if the units are m [GeV/c^2] and B_S [T]. The rotation angle after traveling an axial distance L is

$$\theta = \omega\, t = \frac{e\,B_S\,L}{p_z}$$

When $\theta = 2\pi$ the particle has traveled one Larmor wavelength

$$\lambda_L = 2\pi \frac{p_z}{e\,B_S}$$

and the position and momentum of the particle should return to their initial values. We take $p_z = 0.200$ GeV/c, and $B_S = 1$ T. This gives $\lambda_L = 4.191690044$ m and a radius of curvature $\rho = 0.066712819$ m. We start the tracking with $x_o = 0.10$ m and $p_{yo} = 0.020$ GeV/c. We check the accuracy by examining y and p_x at the end of tracking where both quantities should be 0. The results are given in the table.

p [GeV/c]	step [m]	y [m]	p_x [GeV/c]
0.200	10^{-6}	$9.80\ 10^{-12}$	$2.97\ 10^{-12}$
	10^{-5}	$9.65\ 10^{-12}$	$2.89\ 10^{-12}$
	10^{-4}	$9.66\ 10^{-12}$	$2.90\ 10^{-12}$
	10^{-3}	$9.65\ 10^{-12}$	$2.89\ 10^{-12}$
	10^{-2}	$-1.67\ 10^{-10}$	$-5.01\ 10^{-11}$
	10^{-1}	$-1.74\ 10^{-6}$	$-5.22\ 10^{-7}$
	1	$-4.54\ 10^{-3}$	$-1.36\ 10^{-3}$

<u>Spin vector tracking</u>

For a given initial spin orientation, compare the final spin orientation after traversing the following fields with theoretical predictions.

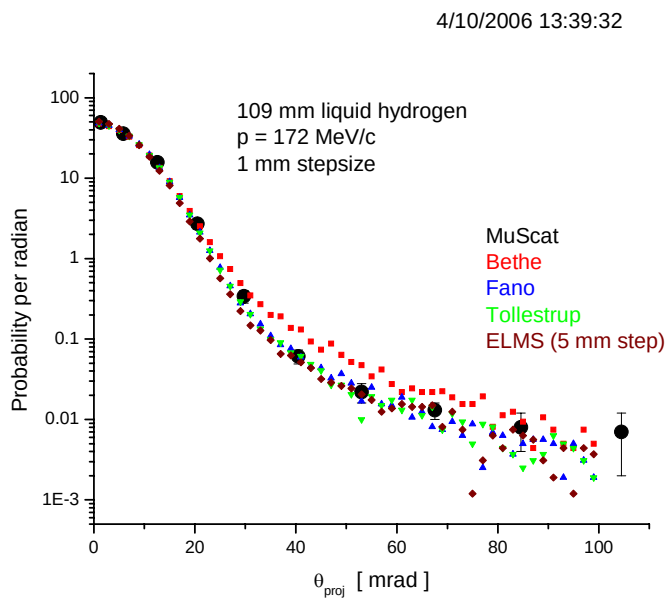
3.3 uniform dipole field

3.4 uniform solenoid field

Interactions in matter

3.5 comparison of scattering angle distributions with MuScat

A detailed comparison of the results of the MuScat muon scattering experiment with the scattering models in ICOOL was given in a technical note [2]. The result for liquid hydrogen is shown in the figure.



The Fano, Tollestrup and ELMS scattering models in ICOOL all agree fairly well with the measurements.

3.6 comparison of mean energy loss in materials with MICE

3.7 comparison of scattering angle distributions with MICE

3.8 comparison of transverse emittance with MICE

References

[1] John Cary, Office of High Energy Pjysics Report on the Muon Accelerator Program Review, August 2010, p.8.

[2] R. Fernow, Scattering in ICOOL, Muon collaboration technical note 336, April 2006.