PROGRESS OF THE MATTER-DOMINATED MUON ACCELERATOR LATTICE SIMULATION TOOLS DEVELOPMENT FOR COSY INFINITY*

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Abstract

COSY Infinity 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. For precision modeling, design, and optimization of next-generation muon beam facilities, its features make it the ideal code. The one component that needs to be included in COSY is the algorithm necessary to follow the distribution of charged particles through matter. Muon beams are tertiary production particles and high-intensity collection necessitates a large initial phase space volume. Therefore, accurate modeling of the dynamics and correction of aberrations is imperative. To study in detail some of the properties of particles passing through material, the transfer map approach alone is not sufficient. The interplay of beam optics and atomic processes must be studied by a hybrid transfer map–Monte-Carlo approach in which transfer map methods are used when there is no material in the accelerator channel, and Monte-Carlo methods when particles pass through material. Progress on the development of the hybrid algorithm is reported.

INTRODUCTION

Muon beams are tertiary production particles and high-intensity collection necessitates a large initial phase space volume. The resultant spray of muons must be collected, focused, and accelerated well within the muon lifetime (2.2 μs in the rest frame). The only technique fast enough to reduce the beam size within the muon lifetime is ionization cooling. Muons traverse a certain amount of material in order to lose energy in both longitudinal and transverse direction due to ionization. The energy is then restored in the longitudinal direction only, leading to an overall reduction in the transverse direction (cooling). In order to achieve cooling in the longitudinal direction, emittance exchange is used, usually involving wedge-shaped absorbers.

In order to carefully simulate the effect of the absorbers on the beam, one needs to take into account both deterministic and stochastic effects in the ionization energy loss. The deterministic effects in the form of the Bethe-Bloch formula with various theoretical and experimental corrections fit well into the transfer map methods approach, where the effect of the lattice on the particles is evaluated first by producing the so-called transfer map, and then applied to a given initial distribution of particles. The arbitrary-order simulation code COSY Infinity [1] is a key representative of the transfer map codes. COSY was chosen because of its built-in optomization tools, speed, its ability to produce high-order transfer maps, and its ability to control individual aberrations.

However, the stochastic effects are not easy to take into account in the framework of the transfer map paradigm. To compensate, we are interfacing COSY with select parts of another code, ICOOL [2], which was written specifically to study the ionization cooling of muon beams. The implementation of the stochastic effects due to various geometries and materials into COSY is reported with the most recent results.

CODE SELECTION PROCESS FOR STOCHASTIC PROCESSES

A variety of codes exists which would complement COSY. Initially, it was hoped that the implementation of a fragment separator into COSY that used a Monte-Carlo approach [3] could be repurposed; however, the libraries were heavily oriented towards electrons, protons, and heavy ions, with no muon data. Other codes that were considered included MUSIC [4], MARS [5], and GEANT4 [6], but were discarded either due to the code focusing on cosmic ray muons, difficulty in interfacing, or sheer bulk.

ICOOL was eventually chosen due to its modularity, compactness, and the fact that, like COSY, is written in FORTRAN. ICOOL's main purpose is to simulate particle-by-particle propogation through electromagnetic fields and matter, with roughly twenty built-in materials to call. The processes included are decays, delta rays, multiple scattering, energy loss, and straggling. Although built for muons, ICOOL can also keep track of other relevant particles such as electrons, pions, kaons, and protons. Additionally, ICOOL can either generate a beam with uniform or Gaussian distribution, or it can read particle information from an input file. This is advantageous since COSY also has a similar input/output file method, which makes direct comparison between the two codes simple.

INTERFACING DETAILS

While ICOOL has routines to calculate particles through, for example, an RF cavity, those were not used since there are corresponding routines in COSY that work faster since the transfer map is only calculated once and then applied to simultaneously to all particles. Therefore, only the routines that directly dealt with absorbers were interfaced. Currently, the following routines have been implemented into COSY: flat absorber (a cylindrical block of arbitrary thickness and radius), radially-symmetric wedge (where

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the thickness of the wedge dz is given by the third order polynomial $dz = a_0 + a_1 r + a_2 r^2 + a_3 r^3$), and an arbitrary-order polynomial absorber (a symmetric or asymmetric absorber of order n such that thickness dz is given by $dz = a_{10}x + a_{01}y + a_{11}xy + \ldots + a_{nn}x^n y^n$). The polynomial absorber is of the most significance, as there exists a routine in COSY (WA) with similar functionality and could be used to account for the deterministic effects. This will further limit the use of the slow particle-by-particle tracking using ICOOL routines to only account for stochastic effects. The ultimate goal is to have COSY do the deterministic part, propagate the beam through a negative drift back to the beginning of the absorber again, and then call the stochastic ICOOL routines that would do multiple scattering and energy straggling for the particles without the loss of energy due to ionization.

As previously mentioned, both ICOOL and COSY are written in FORTRAN. Therefore, the initial task was to gather the relevant subroutines from ICOOL and compile them with COSY which would allow COSY to call ICOOL subroutines. Next, ICOOL and COSY had to exchange information about the same beam. For that, $(6 \times n)$ arrays were used, where the six columns held coordinates and n was the number of particles. When COSY runs its polynomial absorber subroutine it constructs a transfer map based on the absorber, runs the vector through the map (which includes the negative drift), and write the vector to a temporary file. ICOOL would then read this temporary file, run the particles through the stochastic processes, and write a second temporary file with the updated particles. In turn, COSY would read this new file, assign the particle coordinates back to the vector, and delete both of the temporary files. Observe that this process can have anything before or after the wedge, as well as repeat the wedge any number of times. Ultimately, those temporary files will be replaced by direct interaction of the codes.

Additionally, it was mentioned that ICOOL only has 20 materials through which to propagate particles. Its routines read strings, such as 'GHE' (gaseous helium), and then read its libraries to find parameters that match (i.e. Z-number, A-number, ionization potential, etc.). However, COSY takes the parameters themselves as arguments, and as such is not limited to a certain list of materials. To alleviate this, subroutines were placed in COSY and ICOOL such that any absorber routine could accept a string or vector argument for the "material" argument. If, for example, the polynomial absorber was given an argument 'LH' (liquid hydrogen), ICOOL would give the parameters to COSY from its library. If the argument given was a vector containing Z-number, A-number, ionization potential, etc. (as is customary in COSY routines), then ICOOL would read a dummy material named 'XXX' and associate it with the vector contents. In this manner, all relevent information that was needed by either program could be stored into one input variable and be read by both COSY and ICOOL subroutines.

In the interest of benchmarking, it should be noted that at this point it is possible to "turn on" the deterministic processes in ICOOL and run it by itself. Indeed, at this point it is possible to have any combination of (ICOOL, COSY) with (deterministic, stochastic), except for COSY+stochastic of course.

SIMULATION RESULTS

The following compares pure ICOOL and the COSY-ICOOL hybrid with one another. All simulations were done using a flat liquid hydrogen absorber of length 32 cm. The absorber is preceded and followed by a drift of 10 cm. The initial beam consists of 1000 muons with a mean momentum of 200 MeV/c. Beam parameters are summarized below in Table 1 for both initial and final distributions.

Table 1: Distribution Parameters and Simulation Results (Stochastics on)

Parameter	Initial	ICOOL	COSY-ICOOL
avg(x) (mm)	0.157	-1.673	-1.641
std(x) (mm)	96.71	100.24	100.36
avg(y) (mm)	1.817	1.165	1.097
std(y) (mm)	103.48	105.16	105.23
avg(p_x) (MeV/c)	-0.703	-0.641	-0.650
std(p_x) (MeV/c)	10.09	9.81	10.33
avg(p_y) (MeV/c)	-0.325	-0.187	-0.221
std(p_y) (MeV/c)	9.91	9.58	10.21
avg(p_z) (MeV/c)	200.0	188.6	188.6
std(p_z) (MeV/c)	0.0	0.96	0.98

It is clear from Table 1 that there is a good agreement between the two codes. The source of discrepancy is the stochastic treatment of multiple scattering as evidenced by Figs. 1–3. These plots were produced by a different simulation with a beam emanating from a single point with a 5% spread in momentum.

SUMMARY AND FUTURE DIRECTIONS

Interfacing of COSY and ICOOL was successful. It is now possible to simulate realistic matter-dominated lattices in COSY. However, further investigation is in order: the hybrid method has only been shown to work for simple absorber configurations; the interaction between the codes as well as the overall performance of the hybrid code can be optimized significantly; interaction with the end-user can be streamlined.

For the future, it is anticipated that COSY will make use of a one-time analysis of the absorber for faster simulations. When turning on stochastic processes, the simulation can easily take up to 400% longer, and in a realistic cooling channel a beam may have to pass through several absorbers of the same geometry. To that end, it has been proposed that when COSY encounters an absorber, it will propagate the beam through using both deterministic and stochastic processes as previously described. It will then produce a trans-

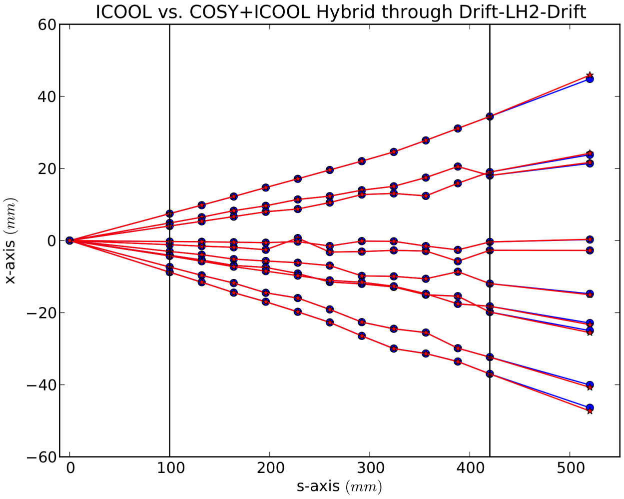

Figure 1: Comparison of individual trajectories. All particles start at the same point with a 5% momentum spread.

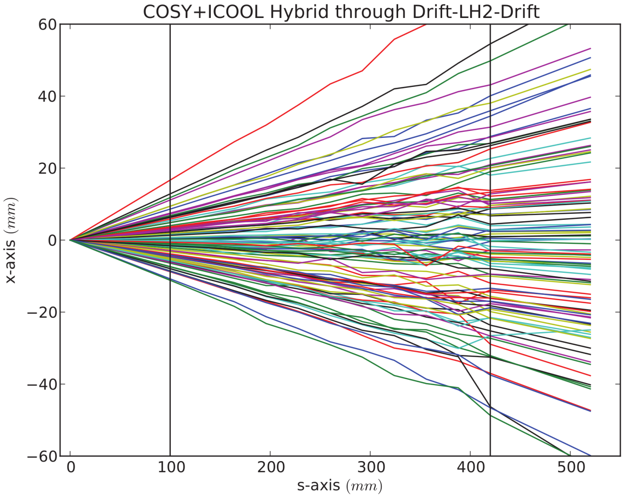

Figure 2: Particle tracks as calculated by the COSY-ICOOL tandem. All particles start at the same point with a 5% momentum spread.

fer map taking into account all the effects, which will then be re-used for future absorbers of the same geometry in the beamline. How this map depends on various properties of the beam will be determined and then approximated (i.e. if the map depends linearly on total momentum, etc.). Using this method would greatly reduce the computation time involved in realistic simulations of muons through matter.

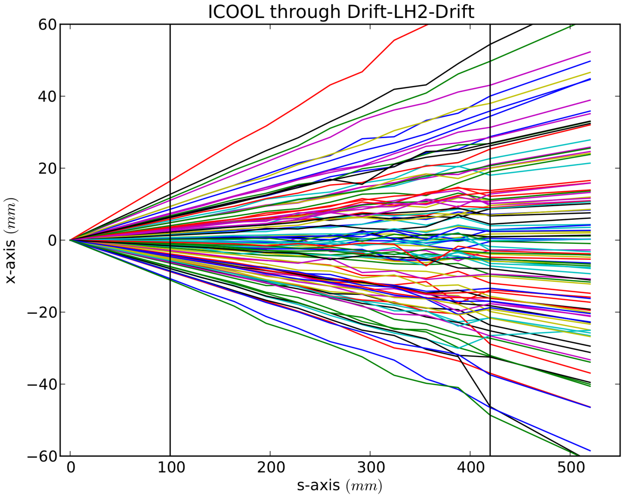

Figure 3: Particle tracks as calculated by pure ICOOL. All particles start at the same point with a 5% momentum spread.

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