# G4BEAMLINE SIMULATION FOR THE COMET SOLENOID CHANNEL

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## *Abstract*

The COMET is an experiment to search for the process of muon to electron conversion in a muonic atom, and is in its design phase to be carried out at J-PARC in near future. The experiment uses a long superconducting solenoid channels from a pion production target to a detector system. In order, to study the solenoid channel the G4beamline is used for the magnetic field calculation and beam tracking. This paper reports the status of the simulation studies for the muon beam transport solenoid.

## INTRODUCTION

Searches for the charged lepton flavor violating (cLFV) processes are very important to study the physics beyond the standard model of the elementary particle physics. Among the cLFV processes, a coherent neutrino-less conversion of muons to electrons ($\mu^- - e^-$ conversion), in the presence of a nucleus, $\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$, is much attractive due to their upgradability with powerful proton divers such as J-PARC main ring and the Project-X in FNAL. Two experimental searches for the $\mu^- - e^-$ conversion have been proposed: COMET [1] for the J-PARC and Mu2e [2] for the FNAL. The both experiments are in their design phase, therefore a lot of simulation studies and R&D programs are underway. The COMET stands for COherent Muon to Electron Transition. It was approved as a stage-1 experiment by the Program Advisory Committee (PAC) for Nuclear and Particle Physics Experiments at the J-PARC 50GeV Proton Synchrotron in July 2009, after the Conceptual Design Report (CDR) [3] submission. Design works for the COMET are continued aiming a full approval (stage-2) from the PAC.

## COMET SOLENOID CHANNEL

Figure 1 illustrates a layout of the COMET experiments. The all apparatus are located under a solenoidal field in superconducting magnets. An 8 GeV proton beam from the J-PARC Main Ring (MR) is collided with a target to produce pions. The pions thus produced are captured with high efficiency using a 5 T superconducting solenoid magnet (capture solenoid) surrounding the pion-production target. The muons, which are produced by pion decays, are captured and transported through subsequent solenoids (muon beam transport solenoid) and are brought to a muon-stopping target in the detector solenoid. The muon beam line is composed of a combination of straight and curved superconducting solenoids. The curved solenoids are used to select the charge and momentum of muons in the beam line and have a compensating dipole magnetic field overlaid. The expected muon beam intensity is enormous, about $10^{11}$ $\mu^-$/sec, which would be the highest in the world. Finally, muons are stopped in a stopping target in the muon target solenoid. An electron emitted by $\mu^- - e^-$ conversion is delivered to the detector section through the curved spectrometer solenoid.

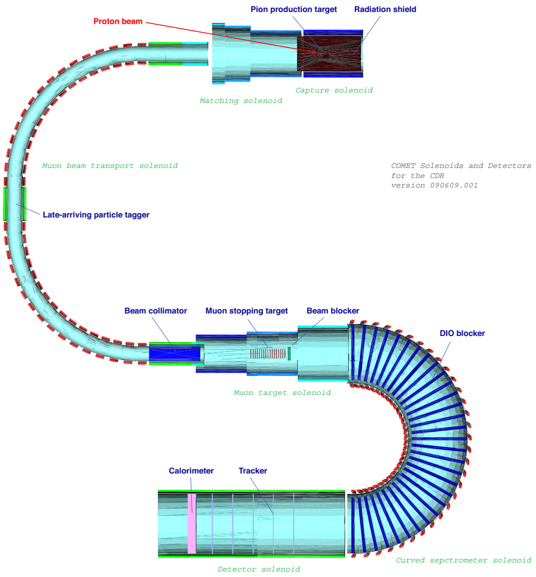

Figure 1: The CDR design of the solenoid channel used in the tracking studies.

The solenoids will be constructed by arranging coil ”pancakesh electrically and thermally connected in series along the curve or the straight line. In order to study the solenoid channel, simulation codes which can treat a realistic solenoidal magnetic field made by the coil pancakes are needed. Three simulation codes were used for the CDR studies: the MARS15 [4] for the hadron production at the production target; the G4beamline-1.16 [5] to optimize the capture solenoid, the muon beam transport solenoid, and the muon target solenoid; geant4 for the detector section. Hadron production codes in the geant4 were also used in some studies. This paper describes results of simulation studies of the muon transport and the muon target solenoid using the G4beamline, and the solenoid design in the CDR. A design detail and study results of the capture solenoid is reported in another paper [6].

## MUON BEAM TRANSPORT STUDY

The muon beam transport is composed of two 90° curved solenoid magnets and a straight solenoid magnet

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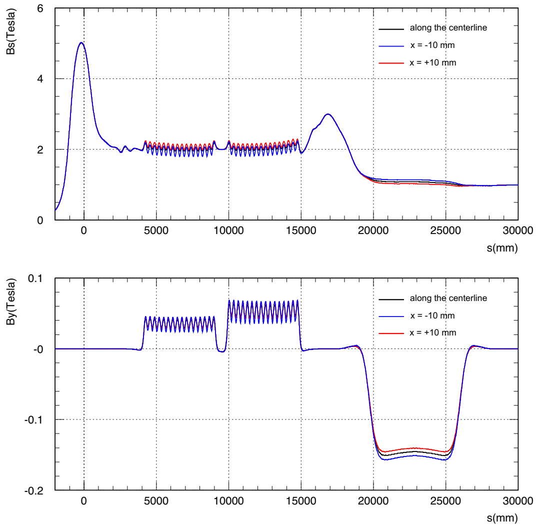

Figure 2: The magnetic field configuration of the solenoid channel from the capture section to the detector section of the present experiment. $B_s$ is a central magnetic field of the solenoid magnets. $B_y$ is a correction magnetic field.

between the two. The requirements for the muon transport section are

- the muon transport should be long enough for pions to decay to muons. For instance, for about 20 meters, the pion survival rate for pions with the reference momentum is about $2 \times 10^{-3}$,
- the muon transport should have a high transport efficiency for muons with a momentum of 40 MeV/$c$, and
- the muon transport should select muons with low momentum and eliminate muons of high momenta ($p_\mu >$ 75 MeV/$c$) to avoid backgrounds from muon decays in flight.

The last item above is one of the important requirements for the muon beamline; an ability to select electric charge and momenta. That is, negatively-charged muons with momenta around 40 MeV/$c$ should be selected. At the same time, it is necessary to eliminate energetic muons having a momentum larger than 75 MeV/$c$, since their decays in flight would produce spurious signals of ~105 MeV electrons. Therefore, such energetic muons and other unwanted particles need to be strongly suppressed before the stopping target using the curved solenoid with a late-arrival particle tagger and a beam collimator.

The selection of electric charge and momentum of beam particles can be performed by using curved (toroidal) solenoids, which makes the beam dispersive. It is known that, in a curved solenoid, the center of the helical trajectory of a charged particle drifts towards the perpendicular direction to the curved solenoid plane. The magnitude of drift ($D$[m]) is given by

$$D = \frac{1}{qB}\left(\frac{s}{R}\right)\frac{p_L^2 + \frac{1}{2}p_T^2}{p_L}, \tag{1}$$

$$= \frac{1}{qB}\left(\frac{s}{R}\right)\frac{p}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right), \tag{2}$$

where $q$ is the electric charge of the particle (with its sign), $B$[T] is the magnetic field at the axis, and $s$[m] and $R$[m] are the path length and the radius of curvature of the curved solenoid, respectively. Here, $s/R(=\theta_{bend})$ is a bending angle $\theta_{bend}$ and $D$ is proportional to $\theta_{bend}$. $p_L$ and $p_T$ [GeV/$c$] are longitudinal and transverse momenta, respectively. $\theta$ is a pitch angle of the helical trajectory. Charged particles with opposite signs move in opposite directions. This can be used for charge and momentum selection if a suitable collimator is placed after the curved solenoid.

To keep the center of the helical trajectories of the muons with reference momentum $p_0$ in the bending plane, a compensating vertical dipole field should be applied. The magnitude of the compensating dipole field is given by

$$B_{\mathrm{comp}} = \frac{1}{qR}\frac{p_0}{2}\left(\cos\theta_0 + \frac{1}{\cos\theta_0}\right), \tag{3}$$

where the trajectories of negatively charged particles with momentum $p_0$ and pitch angle $\theta_0$ are corrected to be on-axis.

The present design of the COMET beamline utilizes two curved solenoids with a bending angle of 90° in the same bending direction. Each of them has a magnetic field of 2 T and a radius of curvature of 3 m. Adjusting the inner radius of the solenoid to act as the collimator would bring down cost of this design. A momentum dispersion in the curved solenoid is very important and useful for eliminating high energy muons above 75 MeV/$c$, which would otherwise contribute to background events by their decay in flight. The COMET muon beamline has a bending angle of 180°, which is twice larger than that in Mu2E, and therefore the momentum dispersion is twice better. A compensating field of 0.030 T for the first 90° and 0.050 T for the second 90° were applied. We propose two options to realize this dipole field: tilting coils and additional dipole coils. In the tracking simulation these compensating fields are calculated by tilting the solenoid coils. Tuning of a magnitude of the compensating field using tilting coils were also studied [7].

The muon beam collimators are placed in front of the muon-stopping target to eliminate muons that would not be stopped in the muon-stopping target and other charged particles that would become backgrounds. The function of the beam collimator and the beam blocker is to block the beam particles so that they do not enter the torus section. Table 1 shows geometrical dimension of the beam collimator, the beam blocker and the muon-stopping target. The loss in the muon stopping rate due to the beam collimator is only 11%.

### *Tracking results*

Tracking simulation studies were performed using G4beamline, which is a single-particle tracking code based on GEANT4. The magnetic field of the solenoids can be

Table 1: Geometrical dimensions of the muon beam collimator, beam blocker and muon stopping target.

| Beam Collimator | |
|---|---|
| Inner Radius | 150 mm |
| Lower Jaw | -100 mm from the beam center |
| Length | 1.2 m |
| Material | Tungsten |
| **Muon Stopping Target** | |
| Shape | Layers of flat disks |
| Disk Radius | 100 mm |
| Disk Thickness | 200 $\mu$m |
| Number of disks | 17 |
| Disk spacing | 50 mm |
| Material | Aluminum |

computed by G4beamline using a realistic configuration of coils and their current settings. A magnetic field configuration used in the studies is shown in Fig. 2. MARS was used to generate secondary particles from the production target. The particles were recorded on the surface of the production target. Then particle tracking was performed using G4beamline using QGSP_BIC as the physics model.

The muon beam profiles just after the beam collimator are presented in Fig. 3, where the total momentum distribution, correlation of transverse versus longitudinal momenta, the arrival time distribution and the transverse beam profiles are shown.

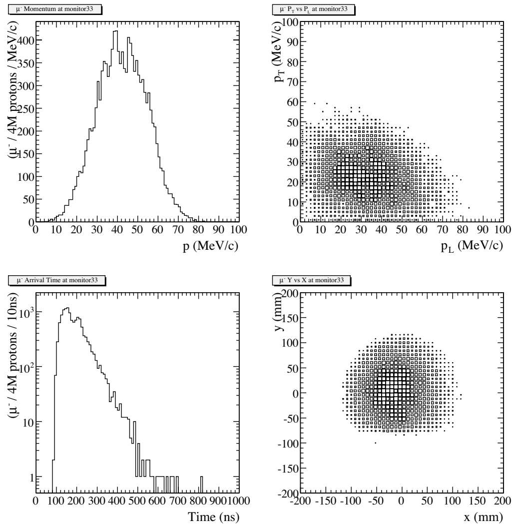

Figure 3: Plots for muons just after the beam collimator. Total momentum (top-left), correlation between transverse and longitudinal momentum (top-right), time of flight relative to the time when the proton beam hit the production target (bottom-left), and beam profile (bottom-right) are shown.

The momentum distribution of muons as they enter the stopping target solenoid is shown in Fig. 4, where the muons which stopped in the target disk are shaded. The net stopping efficiency is 0.29 with this configuration.

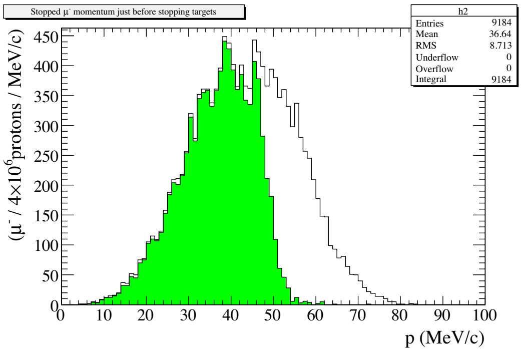

Figure 4: Momentum distribution of the muons as they arrive at the muon-stopping target. Of these muons, those that are stopped in the muon-stopping target are given in the shaded histogram.

## SUMMARY

The G4beamline was used to study the solenoid channel of the COMET for its CDR. The code is very useful and easy to use for a beam tracking in a solenoidal magnetic field. There are still a lot of rooms to improve its performance, although the COMET CDR shows a set of design parameters. For example, a study to re-optimize the magnetic field profile of the muon beam transport is underway. The magnitude of a field in the curved solenoids would increased to 3 T to avoid a field bump before the stopping target. The results of further studies will be reported in a technical design report, which will be submitted to the PAC in December 2010.

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