PROCEEDINGS OF SCIENCE

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GPU-based Track Finding in the J-PARC muon g-2/EDM experiment

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The quest for precise measurements of the muon's anomalous magnetic moment, prompted by the observed discrepancy between theoretical and experimental results by other experiments worldwide, is the motivation of the upcoming muon g-2/EDM experiment at J-PARC. The precise reconstruction of the positron tracks from muon decays plays a vital role, which is currently accomplished by a Hough transformation technique. However, due to the track-finding bottleneck in the reconstruction pipeline, a 40-fold reduction in computational time is essential. We present here the overview and status of a GPU(Graphics Processing Units)-based approach to address this problem. The basic idea is to leverage the capability of GPU to optimize the track finding through parallel execution utilizing multiple GPU threads. This allows for significant acceleration in computation. Initial studies have shown encouraging results but also indicate additional refinements required for high pileup conditions.

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1. Introduction

The Standard Model (SM) has been immensely successful in describing elementary particles and their interactions [1], but it's not the final word on physics at the smallest scales. Many experiments seek new physics beyond the SM [2]. Many experiments are engaged in seeking signatures of New Physics via precision measurements [3]. Notably, there's a significant discrepancy (more than 3σ) between the observed and predicted values of the muon's anomalous magnetic moment [4] $a_\mu = \frac{g-2}{2}$, (where g is the Lande g-factor of the muon). In fact, the SM prediction of $a_\mu(\mathrm{SM})$ quoted in Ref. [4] deviates by more than 3.5σ from the experimental measurements $a_\mu(\mathrm{exp})$. This deviation may be the result of physics beyond the SM. This is a major motivation for new measurements of a_μ [4][5].

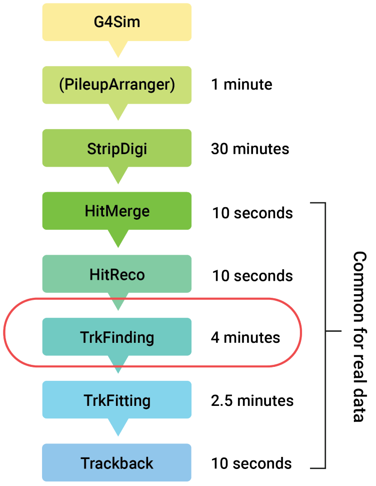
2. Overview of the Experiment

The experiment measures a_μ and η. They are defined by the relations [6].

$$a_\mu = \frac{g-2}{2} \quad \text{with} \quad \vec{\mu}_\mu = g\left(\frac{e}{2m}\right)\vec{s}, \quad \vec{d}_\mu = \eta\left(\frac{e}{2mc}\right)\vec{s} \tag{1}$$

e, m,$\vec{s}$, g and η represent the electric charge, mass, spin vector, Landé g-factor and is a corresponding factor for the EDM of the muon respectively. The spin precession vector with respect to its momentum in a static magnetic field $\vec{B}$ and electric field $\vec{E}$ is given as [6]

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right] \tag{2}$$



Processed with Intel(R) Core(TM)
i7 -4771 CPU @3.50GHz

Figure 1: Standard processing order of simulation, digitization and track reconstruction.

Here $\vec{\omega}_a$ and $\vec{\omega}_\eta$ are precession vectors due to $g-2$ and EDM. $\vec{\beta}$ and γ are the velocity (in units of c) and Lorentz factor of the muon, respectively. JPARC utilizes ultra-cold muons, enabling the use of a weak magnetic field for focusing without the need for an electric field. Under these conditions, Eq. (5) simplifies to [6, 7].

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}(\vec{\beta}\times\vec{B})\right] \tag{3}$$

The J-PARC experiment initiates with a 3 GeV proton beam colliding with a graphite target, yielding pions that decay into muons (μ). These muons are directed to a Mu production target, where ultra-cold, polarized muons are generated. Accelerated to 300 MeV$/c$, maintaining their transverse momentum ($P_T \sim 2.3\,\mathrm{keV}/c$), the resulting muon beam remains highly straight ($P_T/P_L \sim 10^{-5}$). Injected into the storage ring, muons follow a $3D$ spiral trajectory until decay ($\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$), exhibiting an angular distribution asymmetry due to weak decay parity non-conservation and helicity conservation. In the muon rest frame, the positron reaches its maximum momentum and is fully polarized when the two neutrinos are emitted in opposite directions. Consequently, the event rate of higher-energy positrons boosted in the rest frame fluctuates periodically in sync with the muon precession frequency [6][7][8].

3. Current Challenges in Track Finding

The standard processing sequence for high pileup rate is depicted in Figure 1. Currently, data collection operates at approximately 10^4 muons every 7 minutes (24 muons/sec/CPU). With 1000 CPUs, the data processing rate reaches about 2.4×10^4 muons per second. However, the experiment is expected to yield data from roughly 10^{13} muon decays. The beam intensity will be 4×10^4/Pulse (25Hz) or 10^6 muons per second. Hence, the software must handle data from approximately 10^6 muon decays per second. This indicates a need for a 40-fold improvement in software processing speed based on the calculations above.

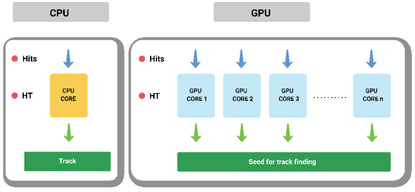
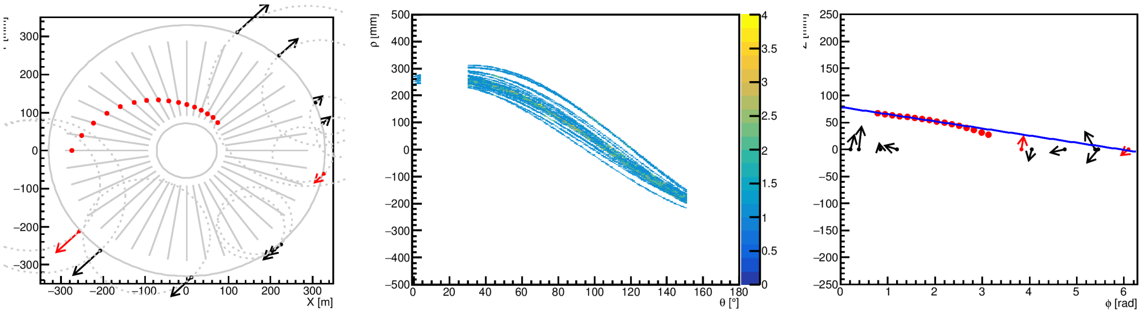


Figure 2: Process of track finding in CPU and track finding approach in GPU

4. Result and Discussion



(a) **(b)** **(c)**

Figure 3: (a) Top view of Reconstructed hits in vanes (b) Each reconstructed hit is transformed into a curve in Hough Space (ρ, θ) and (c) Track identification using coordinates of the maximum bin count from Hough Space.

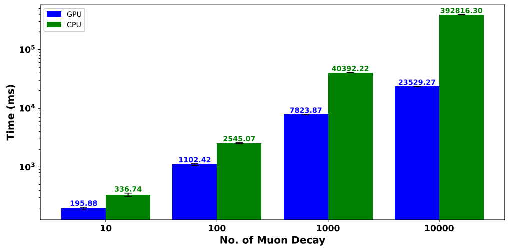


Figure 4: Result of the computation time in Track Finding observed in CPU and GPU

To achieve the required processing speed, we propose a GPU-based track-finding approach 2. Leveraging the capability of GPU for parallel computation might help us with fast computation. Here, hits from each time window are passed through each thread, and each thread does the Hough transformation [9], and the seed for the track is searched. The example of the process is shown in Figure 3. As a first step, we have identified a track for one time window. Further, we use the following configuration of CPU and GPU system: 11th Gen Intel® Core™ i7-11700 @ 2.50GHz × 16 and NVIDIA Quadro P620 with 2GB memory respectively. Figure 4 shows computation time is reduced around by a factor of 4 and 12 for 1000 and 10000 pile-up events respectively.

5. Future Work

We've seen good initial results and are now moving the whole track-finding code to a GPU for better performance. Our focus is on computing and comparing execution times, particularly under the challenging conditions of the highest pileup rate, estimated at around 10^6 muon decays per second.

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