Implementation of ACTS into sPHENIX Track Reconstruction

Joseph D. Osborn[1,*] for the sPHENIX Collaboration

[1]Oak Ridge National Laboratory, Oak Ridge, TN, USA

Abstract. sPHENIX is a high energy nuclear physics experiment under construction at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory. The primary physics goals of sPHENIX are to measure jets, their substructure, and the upsilon resonances in p+p, p+Au, and Au+Au collisions. sPHENIX will collect approximately 200 PB of data over three run periods utilizing a finite-sized computing center; thus, performing track reconstruction in a timely manner is a challenge due to the high occupancy of heavy ion collisions. To achieve the goal of reconstructing tracks with high efficiency and within a 5 second per event computational budget, the sPHENIX experiment has recently implemented the A Common Tracking Software (ACTS) track reconstruction toollkit. This paper reports the performance status of ACTS as the default track fitting tool within sPHENIX, including discussion of the first implementation of a TPC geometry within ACTS.

1 Introduction

The sPHENIX experiment is a next-generation jet and heavy flavor detector being constructed for operation at the Relativstic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) [1]. The primary physics goal of sPHENIX is to study strong force interactions by probing the inner workings of the quark-gluon-plasma (QGP) created in heavy nucleus-nucleus collisions, as outlined in the 2015 Nuclear Physics Long-Range Plan [2]. sPHENIX will also probe the structure of protons and nuclei in proton-proton and proton-nucleus collisions to study spin-momentum correlations and hadron formation [3]. To achieve these goals, the detector has been designed as a precision jet and heavy-flavor spectrometer. Jets,

*e-mail: osbornjd@ornl.gov

and their structure, can resolve strong force interactions at different scales when parton flavor is selected due to the difference in mass between heavy and light quarks. Similarly, the measurement of $\Upsilon(1S)$ and its first two excited states allow different screening temperatures of the QGP to be accessed. To achieve these physics goals, precise tracking capabilities are required.

Accomplishing these goals in the environment that will be provided by RHIC will be a substantial challenge. The accelerator will deliver $\sqrt{s_{NN}}$ = 200 GeV Au+Au collisions at rates of up to 50 kHz, while sPHENIX will only trigger on these events at rates of approximately 15 kHz. Because of the electron drift time in the TPC, at 50 kHz the TPC will contain charge deposited by an average of 2 to 3 collisions at any given time. A central Au+Au event can produce as many as 1,000 particles; thus, the occupancy of the detector in any given bunch crossing will be extremely large. These conditions will lead to nearly 200 PB of data collected over the course of a three year running period. This data will be processed on a finite-sized computing center at BNL, which additionally necesitates that the tracking be computationally efficient and fast. To achieve these goals in an environment where detector hit occupancies are expected to be $\mathcal{O}$(100,000), the sPHENIX Collaboration has implemented the A Common Tracking Software (ACTS) package as the default track reconstruction toolkit.

The ACTS track reconstruction toolkit [4, 5] is an actively developed open source software package with contributors from several different particle physics collaborations. ACTS is intended to be an experiment-independent set of track reconstruction tools written in modern C++ that is customizable and fast. The development was largely motivated by the High-Luminosity Large Hadron Collider (HL-LHC) that will begin data taking in 2027. sPHENIX expects roughly comparable hit occupancies in the heavy ion environments and rates that RHIC will deliver to what is expected at the HL-LHC; thus, ACTS is a natural candidate for track reconstruction at sPHENIX. In this paper, the ACTS implementation and track reconstruction experience in sPHENIX will be discussed. This includes the first implementation of a TPC geometry in ACTS. Additionally, the current computational and physics performance of the track reconstruction in sPHENIX will be shown, and future directions and improvements that are actively being developed will be discussed.

2 sPHENIX Detector and Physics Requirements

The sPHENIX spectrometer is a midrapidity barrel detector with full azimuthal and pseudorapidity $|\eta| < 1.1$ coverage. The primary subdetectors are three tracking detectors, an electromagnetic calorimeter, and two hadronic calorimeters. An engineering drawing of the detector is shown in Fig. 1. The tracking detectors are a monolothic active pixel sensor (MAPS) based vertex detector (MVTX), a silicon strip detector called the Intermediate Tracker (INTT), and a time projection chamber (TPC). The MVTX has three layers of silicon staves that cover a radial distance of approximately $2 < r < 4$ cm from the beam pipe. The INTT has two layers of silicon strips and covers approximately $7 < r < 10$ cm. The TPC is the primary tracking detector within sPHENIX and is a compact, continuous readout gas electron multiplier based TPC. In total, the sPHENIX tracking geometry consists of 53 layers spanning the radial distance from $2 < r < 70$ cm. Additional details about each of the detectors can be found in the sPHENIX Technical Design Report [6].

The track reconstruction requirements are largely driven by the physics requirements for the $\Upsilon(nS)$ states, large transverse momentum jets, and jet substructure. To measure the first three upsilon states, e^+e^- pairs from upsilon decays must be resolved with a mass resolution of less than 100 MeV. Therefore, tracks with a momentum of 4-8 GeV must have a resolution of approximately less than 1.2%. To resolve high momentum tracks for jet substructure measurements, tracks with $p_T > 10$ GeV must have a resolution of approximately

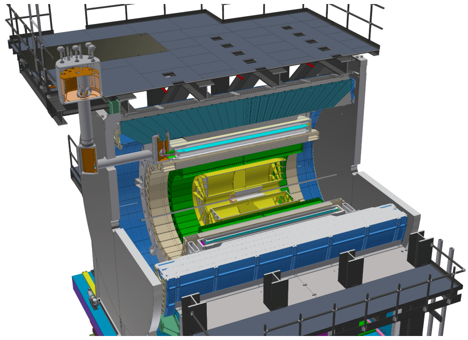

Figure 1. An engineering diagram of the sPHENIX detector design. The MVTX and INTT are two subdetectors that are composed of silicon staves, shown in orange and grey, respectively. The TPC is a continuous readout GEM-based detector, and the TPC cage is shown in yellow.

$\Delta p/p \simeq 0.2\% \cdot p$. In addition to these requirements, the tracking must be robust against large combinatoric background environments present from pileup, particularly within the TPC. Since the drift time is longer than the bunch spacing provided by RHIC, there is potential for significant out-of-time pileup sampled in the TPC.

3 sPHENIX-ACTS Implementation

3.1 Geometry

The first step for implementing ACTS into the sPHENIX software stack is to properly translate the tracking detector geometry into the analagous ACTS geometry. The main detector element used for track fitting is the `Acts::Surface`. ACTS has an available ROOT `TGeometry` plugin that can take the relevant active `TGeo` objects and convert them into `Acts::Surfaces`. Since sPHENIX already has a detailed and well-tested GEANT4 geometry description that uses the ROOT `TGeoManager`, this plugin was a natural choice. The left panel of Fig. 2 shows the MVTX and INTT active silicon surfaces as implemented within ACTS. The geometry is imported directly from the `TGeoManager`, so any changes in the sPHENIX GEANT4 description are automatically propagated to the `Acts::Surface` description.

The sPHENIX TPC geometry is implemented in a different way from the silicon detectors due to the underlying ACTS surface philosophy. Within ACTS, measurements and track states can only exist on a surface. Unfortunately, this is not ideal for TPC or drift chamber geometries which utilize a three dimensional volume structure. In the sPHENIX TPC, measurements are still readout on the pad planes; however, their truth position can be anywhere within the TPC volume. For this reason, a different approach was taken for the TPC geometry implementation within ACTS. Rather than importing the TPC geometry from the `TGeoManager`, the ACTS TPC surfaces are constructed individually as plane surfaces that approximate cylinders, as shown in the right panel of Fig. 2. The plane surfaces span 3° in azimuth and half the length of the TPC in z and are used to approximate the TPC readout geometry. Measurements are then associated to these surfaces based on what pad plane they were read out on and where they were physically measured on that pad plane.

Figure 2. (left) A 3D rendering of the sPHENIX silicon detectors as implemented in ACTS. The small blue layers are the MVTX, and the large green layers are the INTT. (right) A 3D rendering of the sPHENIX TPC layers as implemented in ACTS. Surfaces are created in place of the TPC pad rows to form cylindrical approximations of the TPC. The MVTX and INTT layers can be seen within the inner TPC layer.

3.2 Track Reconstruction Strategy

To perform track reconstruction, the relevant sPHENIX objects are mapped to the corresponding ACTS objects and passed to the ACTS track reconstruction tools. In practice, the only objects that ACTS requires are the detector geometry and corresponding measurements. Thus, the first step in track reconstruction is to build the ACTS geometry and translate the sPHENIX measurement objects into ACTS measurement objects. A variety of ACTS track reconstruction tools exist within the sPHENIX Fun4All framework that can subsequently be run with the ACTS translated measurements and geometry object [7].

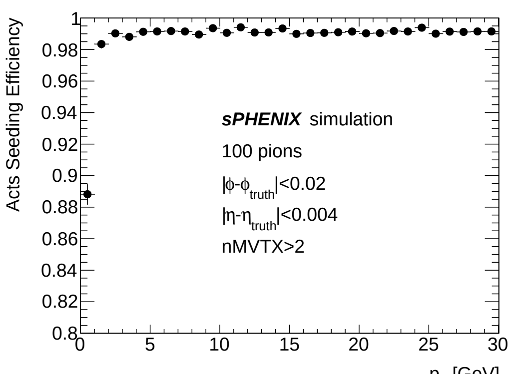

Figure 3. The ACTS seeding efficiency as implemented in the sPHENIX MVTX. The efficiency is defined as the number of reconstructed seeds in the labeled azimuth and pseudorapidity ranges for truth tracks which have three MVTX hits.

The current sPHENIX track reconstruction strategy uses several ACTS tools in various stages of the reconstruction. First, the ACTS seeding algorithm is run with the measurements in the MVTX. The result of the seed is propagated to the INTT to find associated measurements to form silicon track seeds. The ACTS seeding algorithm only returns three measurements combined as a "triplet" seed, so it is a natural candidate for the MVTX which has three layers. Figure 3 shows the ACTS seeding efficiency as implemented in the MVTX for events which have 100 pions thrown in the sPHENIX acceptance, where the effiiciency is defined as in the caption. These seeds are given to the ACTS initial vertex finding algorithm since the silicon layers primarily determine the track position and event vertex resolution in sPHENIX.

A separate cellular automaton based seeder, developed internally to sPHENIX, creates seeds of at least 20 measurements in the TPC. These seeds are then connected to the silicon track seeds with azimuthal and pseudorapidity matching criteria and are then provided to the ACTS Kalman Filter track fitting tool. The ACTS fitter takes the fully constructed track seed and an initial vertex estimate to fit the tracks. Examples of the current track fitting performance are shown in Fig. 4 in events where 100 pions are thrown in the nominal sPHENIX acceptance. The left panel shows the p_T resolution, while the right panel shows the $x-y$ distance of closest approach resolution. Both show excellent performance in these low multiplicity events. Figure 5 shows the current single $\Upsilon(1S)$ invariant mass resolution, which is about 81 MeV. Evaluation of the track fitting software is ongoing in central events with 50 kHz pileup, which is more characteristic of the types of occupancies sPHENIX will experience when the detector is commissioned in 2022.

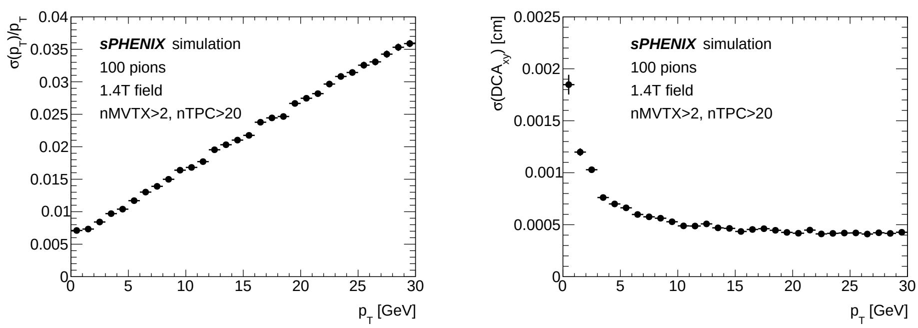

Figure 4. (Left) The track p_T resolution as a function of p_T. (Right) The distance of closest approach resolution in the $x-y$ plane as a function of p_T.

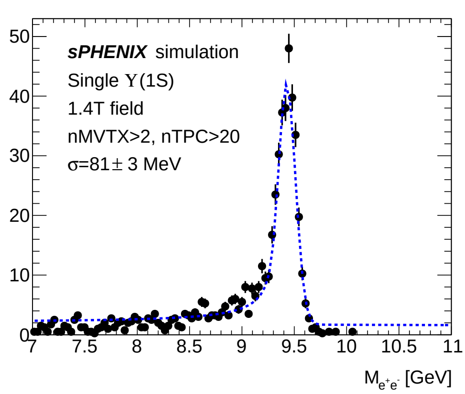

Figure 5. The $\Upsilon(1S)$ mass resolution in single upsilon events using the sPHENIX-ACTS tracking implementation. The fit shown is a double sided crystal ball function and is used to extract the peak width.

Another important performance test of the ACTS track fitting package is the time required per track fit. The nominal computational speed goal is to be able to run the track reconstruction in 5 seconds per event or less on the BNL computational center that will process the sPHENIX data. Figure 6 shows the computational time per ACTS track fit as a function of p_T for the sPHENIX geometry, which averages about 50 layers per track in the Kalman filter fit. The time per track fit is approximately 0.7 ms, which scales approximately linearly with the number of surfaces the fit visits. For a central Au+Au collision which produces ~1000 tracks, this corresponds to a track fit time of approximately 1 second per event, leaving 80% of the timing budget for the initial track seeding. As track fitting is often one of the more time consuming steps in track reconstruction, this is a major step towards achieving the 5 second total track reconstruction time per event.

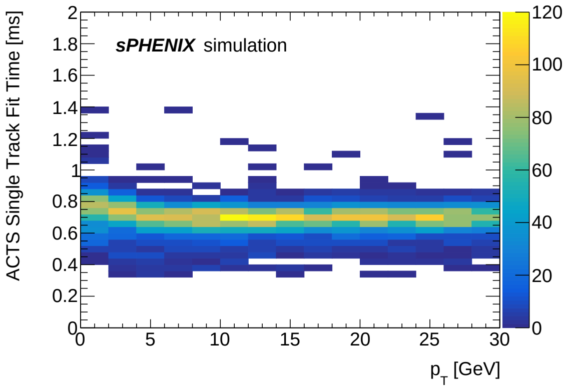

Figure 6. The time per ACTS track fit as a function of p_T in the sPHENIX geometry. This time corresponds to the time taken to run the ACTS track fitting tool on track seeds that were constructed with the various tools described in the text.

4 TPC Space Charge Distortions

The track reconstruction procedure presented here is limited by the absence of TPC space charge distortions in the simulation. Space charge distortions occur in the TPC due to $E \times B$ effects that are present when the TPC gas is ionized from the track trajectory. The space charge distortions displace the true position of the measurements in the TPC to a position that is inconsistent with the true track trajectory. Implementing space charge distortions in both the simulation and track reconstruction is an ongoing effort within the sPHENIX collaboration.

The track reconstruction with space charge distortions will proceed by utilizing the `Acts::Propagator` machinery to extrapolate track seeds to the TPC layers to determine their estimated position. The residuals of the actual TPC measurements with the trajectory at a given TPC layer will then be determined. This will provide the average distortion in a given (r, ϕ, z) bin and time interval. However, the reconstruction of tracks including space charge distortions within ACTS presents a new challenge. Due to the distortion of the measurements, their position on the ACTS surface is inconsistent with the track trajectory. There are two ongoing development strategies to correct the measurement position based on the average distortions. The first is to physically move the measurements on the surface based on the calculated average distortion in a given (r, ϕ, z) bin. Since the surfaces are two dimensional, this requires including the radial distortions in the measurement movement along the surface in azimuth and z. The second is an ACTS three-dimensional fitter which would provide the option for measurements to either be associated to a detector surface or a detector volume. This would allow for measurements to be moved in all three dimensions based on the average distortion. Both strategies are currently under development and evaluation.

5 Conclusion

The sPHENIX experiment is a high energy nuclear physics experiment being constructed at RHIC to be commissioned in 2022 and begin data taking in 2023. Measuring jets, their substructure, and the Upsilon resonances in both p+p and Au+Au collisions are the primary physics goals for the experiment. sPHENIX will collect data in a high rate environment making track reconstruction on a finite sized computing center at Brookhaven National Laboratory a technical challenge. To address these challenges, the track reconstruction software has been completely rewriten to implement various ACTS track reconstruction tools. In this paper, the current performance of this implementation into the sPHENIX software stack has been presented. This required building an approximation to the sPHENIX TPC geometry into ACTS, which is nontrivial due to the constraint that measurements in ACTS must be associated to a surface. Several of the ACTS tools, including seeding, vertexing, and track fitting, are now a part of the default track reconstruction chain for sPHENIX physics analyzers. The performance of the track reconstruction in low multiplicity environments has been tested and tuned, and analysis in high multplicity heavy ion environments is ongoing. Additionally, there are several avenues of ongoing development for the handling of space charge distortions in the TPC, both within sPHENIX and by the primary ACTS developers. These developments will continue to improve the track reconstruction framework in sPHENIX.

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