Track Fitting with GENFIT for the STCF Experiment

Authors: Lu Zhenna, Zhou, Mr. Hang, Jia, Ms. Xiao-qian, Hello! Please provide the Chinese text (with any LaTeX and ···structure if applicable) that you would like me to translate into English., Qin, Dr. Xiao-shuai, Huang, Dr. Xing-Tao, Liu, Dr. Jianbei, Zhang, Dr. Jin, Dr. Jin Zhang

Date: 2026-01-12T11:40:29+00:00

Abstract

Track fitting is a key step in charged particle reconstruction at the Super Tau-Charm Facility (STCF), where tracks cover a wide momentum range and detector background is non-negligible. In this work, the GENFIT2 toolkit is integrated into the baseline reconstruction chain of the STCF offline software framework, and the deterministic annealing filter (DAF) is adopted as the default track fitting algorithm. The DAF is applied to reduce the influence of background hits and to obtain reliable estimates of track parameters. The fitting performance is studied based on full detector simulation. The results show stable track parameter resolutions over a broad momentum range under different background conditions, which is suitable for detector optimization and physics performance studies at STCF.

Full Text

Track Fitting with GENFIT2 for the Super Tau-Charm Facility

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Track fitting is a key step in charged particle reconstruction at the Super Tau-Charm Facility (STCF), where tracks cover a wide momentum range and detector background is non-negligible. In this work, the GENFIT2 toolkit is integrated into the baseline reconstruction chain of the STCF offline software framework, and the deterministic annealing filter (DAF) is adopted as the default track fitting algorithm. The DAF is applied to reduce the influence of background hits and to obtain reliable estimates of track parameters. The fitting performance is studied using single particle samples and the $\psi(3686) \rightarrow \pi^+\pi^- \mathrm{J}/\psi$, $\mathrm{J}/\psi \rightarrow \mu^+\mu^-$ decay channel based on full detector simulation. The results show stable track parameter resolutions over a broad momentum range under different background conditions, which is suitable for detector optimization and physics performance studies at STCF.

Keywords: STCF, track fitting, GENFIT2, deterministic annealing filter

Introduction

The Super Tau-Charm Facility (STCF) [?, ?] is the next generation electron-positron collider in China, currently in the technical design phase. It is intended for precision studies of hadron structure and the properties of non-perturbative strong interactions, as well as exploring the asymmetry between matter and antimatter, and searching for particles and physics beyond the Standard Model [?, ?]. It is designed to operate in a center-of-mass energy range from 2 to 7 GeV/c, with a peak luminosity of about 5×10^{34} cm^{-2} s^{-1} at $\sqrt{s} = 4$ GeV/c, providing a significantly higher luminosity and an extended energy coverage compared with BEPCII/BESIII [?, ?]. The high luminosity and wide energy coverage of STCF improve the statistical precision of physics observables in the τ-charm region, while also imposing greater demands on detector performance and event reconstruction.

In this context, charged-particle tracking [?] plays a central role in the reconstruction chain and directly impacts the determination of particle momenta and interaction vertices. In general, tracking involves track finding for hit association and track fitting for the precise determination of the track parameters. Track finding employs local approaches, such as pattern recognition \cite{8-10}, combinatorial Kalman filter (CKF) [?, ?, ?], and cellular automaton (CA) [?], as well as global approaches based on the Hough transform [?, ?]. Track fitting typically relies on Kalman filter [?] and nonlinear filtering methods, including deterministic annealing filter (DAF) [?, ?] and Gaussian sum filter (GSF) [?]. At STCF, these track finding and fitting approaches must operate under challenging conditions characterized by a broad momentum spectrum, ranging from 50 MeV/c to 3.5 GeV/c, with a substantial fraction of tracks below 400 MeV/c as shown in Fig. 1.

At the stage of STCF detector design and optimization, reliable evaluation of detector performance and physics potential relies on a complete reconstruction chain under realistic experimental conditions. In previous studies, a Hough-transform-based track finding algorithm has been developed in STCF [?], achieving high efficiency under background conditions and detector hit inefficiencies. The accurate determination of track parameters depends on the track-fitting stage, particularly under the high-background conditions associated with high-luminosity operation. This work focuses on the implementation and performance study of track fitting in the STCF reconstruction workflow.

Track fitting at STCF needs to perform robustly in the presence of background and to accommodate changes in detector geometry during detector optimization. The GENFIT2 [?] toolkit is introduced in the STCF reconstruction software, as it provides an experiment-independent interface to detector geometry and material description, and has been successfully used in experiments such as BelleII [?] and PANDA [?]. Its modular design supports track propagation in magnetic fields and detector material [?, ?], as well as established fitting approaches such as Kalman filter and the deterministic annealing filter. These features allow the track-fitting procedure to be configured for the specific detector configuration and experimental environment. In this work, GENFIT2 is adopted and optimized for the STCF baseline reconstruction and performance is studied. The paper is organized as follows. Section II gives a brief introduction of the STCF detector. Section III provides the implementation and studies of GENFIT2 in STCF. Section IV presents the track fitting performance in STCF.

STCF Detectors and the Tracking System

The layout of the STCF detector system is shown in Fig. 2. Starting from the interaction region and moving outward in radial direction, the detector comprises a tracking system composed of an Inner Tracker (ITK) and a Main Drift Chamber (MDC). Particle identification is provided by a ring-imaging Cherenkov detector (RICH) [?] and a DIRC-like time-of-flight detector (DTOF) [?] in both the barrel and endcap regions. The detector includes a homogeneous electromagnetic calorimeter (EMC) [?], a superconducting solenoid with an axial magnetic field of 1 T, and a muon detector (MUD) located at the outermost region. The particle identification system provides separation of charged hadrons with momentum from 700 MeV/c to 2 GeV/c. The electromagnetic calorimeter measures the energy and direction of electromagnetic showers, and the outer muon detector provides additional information for muon identification.

The STCF tracking system consists of ITK and MDC. ITK is located close to the beam pipe covering a polar angle range of 20°–160°. It copes with the high counting-rate environment in this region and improves the precision of vertex reconstruction. Two technological options have been proposed for the ITK during the conceptual design phase, based on μ-RWELL detectors [?] as a baseline and monolithic active pixel sensors (MAPS) as an alternative option. In this work, detector description and performance studies are based on the µ-RWELL ITK configuration adopted in the current STCF baseline design. The µ-RWELL-based ITK consists of three cylindrical layers placed at radii of 60, 110, and 160 mm from the beam axis. Each layer has a thickness of approximately 6.5 mm and provides a spatial resolution of approximately 100 µm in the r-ϕ direction and about 400 µm along the z direction.

MDC is located outside the inner tracker and provides the main tracking volume at larger radii for momentum measurement. It operates with a He/C_3H_8 (60/40) gas mixture and covers a radial range from 200 mm to 840 mm. The chamber consists of eight super-layers, each consisting of six layers of drift cells. From the innermost to the outermost region, the super-layer configuration follows the sequence AUVAUVAA. The axial layers (“A”) are parallel to the beam axis, while the stereo layers (“U” and “V”) are inclined with respect to the beam axis, providing additional spatial information along the beam direction. The MDC provides spatial resolutions ranging from 120 µm to 130 µm.

Implementation and Studies of GENFIT2 in STCF

This section describes the baseline track fitting strategy of the STCF offline software, based on the GENFIT2 framework. The Offline Software System of the Super Tau-Charm Facility (OSCAR) [?, ?] provides the unified software environment for detector design studies, performance evaluation, and physics studies. It comprises external libraries (such as DD4hep [?], PODIO [?], ROOT [?], and Geant4 [?]), core software for data-processing, and applications specific to the STCF experiment. For physics simulation and algorithm validation, high-precision event generators including KKMC [?] and EVTGEN [?] are used to model τ-charm processes. In addition, a basic particle gun is also available for generating single-particle events for basic performance studies. The detector geometry is described with DD4hep using XML-based [?] configurations, and Geant4 is used for full simulation of particle interactions in the detector.

Interface between STCF offline software and GENFIT2

The interface is designed to incorporate GENFIT2 as a standard track fitting component of the baseline reconstruction chain, as illustrated in Fig. 3 [Figure 3: see original paper]. Track candidates produced by the upstream tracking algorithms, including GNN-based hit filtering [?] and Hough-transform-based track finding, are fed to GENFIT2, providing initial track parameters together with associated candidate hits.

The detector geometry used for track fitting is described with DD4hep and transferred to GENFIT2 via the ROOT TGeo geometry [?]. The same geometry description is used consistently in simulation and track fitting. Material information is passed together with the geometry and handled by the internal material-effects model of GENFIT2. The consistency between the geometry and material descriptions affects the accuracy of the fitted track parameters, as material effects enter directly into track propagation. The magnetic-field information is also provided through the interface and used during track propagation.

ITK hits are converted into PlanarMeasurement objects in GENFIT2 for track fitting. Each hit is associated with a local detector plane, where the measurement and covariance matrix are defined in the local coordinate system. For MDC measurements, the WireMeasurement representation of GENFIT2 is used. MDC measurements are associated with a sense wire and a drift distance, and the virtual detector plane is therefore constructed dynamically for each track extrapolation during the fitting process. The virtual detector plane is defined by the sense wire and the point of the closest approach between the track and the sense wire. In this plane, a local coordinate system is constructed, where the basis vector $\vec{v}$ is aligned with the wire direction and the orthogonal vector $\vec{u}$ is defined perpendicular to the wire, as depicted in Fig. 4 [Figure 4: see original paper]. Once the plane is defined, each MDC hit is represented by a WireMeasurement object that contains both left and right measurements on the plane, as well as the associated covariance matrix in the local plane. The measurements are then passed to the track fitting stage and the left-right ambiguities of these measurements are resolved with DAF.

In the OSCAR framework, track states are provided in a unified five-parameter helix representation, defined by d_0, z_0, $\tan\lambda$, ϕ_0, and κ, as illustrated in Fig. 5 [Figure 5: see original paper]. The definition of each parameter is as follows: - d_0 is the signed distance of the point of closest approach (POCA) to the origin in the x-y plane. - z_0 is the distance in the z direction to the POCA. - ϕ_0 is the angle between the tangent to the helix at the POCA in the x-y plane and the x axis. - $\tan\lambda$ is the tangent of the dip angle. λ takes values between 0 and π. $\tan\lambda$ is equal to dz/ds, where s is the arc length. - κ is the signed curvature of the helix in the x-y plane.

This parameterization is used for storing reconstructed tracks and for subsequent performance studies and physics analyses within OSCAR. During track fitting, for track extrapolation through the detector geometry, magnetic field, and material, GENFIT2 uses an internal seven-dimensional track state $(\vec{x}, \vec{T}, q/p)$ which is composed of the position $\vec{x}$, the momentum direction unit vector $\vec{T}$ and charge over momentum of the track. For consistency with the OSCAR framework, the fitted track state is converted at the point of closest approach with respect to the z-axis into the five-parameter helix representation used in OSCAR. The corresponding covariance matrix is transformed at the same point and provided together with the track parameters as the final reconstruction output.

Track fitting with Deterministic Annealing Filter

In the high-luminosity environment of STCF, the detector operates with a non-negligible background occupancy. During track finding, hits spatially close to the particle trajectories may be included in track candidates. Such hits can remain associated with the candidates after track finding and are subsequently passed to the track fitting stage. To mitigate the impact of such hits on the reconstructed track parameters, a robust fitting approach is required at the fitting stage.

The deterministic annealing filter is a track fitting algorithm implemented in the GENFIT2 framework. Unlike the standard Kalman filter, which assigns equal weights to all measurements at each update step, the DAF extends the Kalman filter by introducing measurement weights together with an annealing mechanism. It is used to improve the robustness of track fitting in the presence of background hits and outliers. In each DAF iteration, the Kalman filter is applied to the full set of measurements, and the forward and backward filtering results are combined in a smoothing step to obtain the track-state estimate for the current iteration. Based on the smoothed track state, a weight is assigned to each measurement according to its residual, allowing different measurements to contribute to the parameter update with different weights.

In subsequent iterations, the inverse covariance matrix of each measurement is scaled by the corresponding weight, so that measurements with smaller weights have a reduced influence on the track-parameter estimation. The weighting procedure is coupled to an annealing process controlled by the annealing parameter T. At early iterations, T is large and the weight differences among measurements are small. As the iterations proceed, T is gradually reduced, hits with large residuals are progressively assigned smaller weights, while hits with small residuals acquire larger weights, until the weight distribution stabilizes and the fit converges. Further details of the DAF algorithm and its implementation can be found in Ref. [**?**].

The noise rejection of the DAF is studied within the OSCAR framework using simulated 1 GeV/c muon tracks with a background level corresponding to the nominal occupancy. Background simulation is included in the OSCAR framework, and hits produced by background particles are mixed with signal hits before reconstruction. The noise hits considered in this study originate from background particles and remain in the track candidates after the Hough-transform-based track finding. These noise hits, located close to the track candidates, are passed to the subsequent DAF track-fitting stage. As shown in Fig. 6 [Figure 6: see original paper], the weights of signal hits evolve toward unity over the iterations. The isolated small distributions observed during the iterations are mainly attributed to ITK hits, which are separated from the distribution of MDC hits due to the different spatial resolutions of the two detectors. For noise hits, shown in Fig. 7 [Figure 7: see original paper], the weight distribution separates into two components: one component consists of hits whose weights decrease toward zero and are removed from the fit, while the other component converges to weights close to unity and remains associated with the reconstructed track.

To further understand the noise hits that remain associated with the track after the DAF iterations, a study is performed for noise hits with weights close to unity. Fig. 8 [Figure 8: see original paper] shows the residual distributions of noise hits, separated by their final weights. Noise hits with large weights ($w \geq 0.99$) are concentrated at small residual values, while noise hits with small weights ($w \leq 0.01$) exhibit a much larger residual. This separation reflects the different spatial compatibility of the noise hits with respect to the fitted track.

ITK hit retrieval for low momentum tracks

At low transverse momentum, track segments in the ITK are strongly deflected by multiple scattering and energy loss in the detector material. These effects lead to hits in the inner layers that deviate significantly from an ideal helical trajectory. In the current reconstruction chain based on a Hough-track-finding method, track candidates are searched for using a Hough transform with circular templates in the transverse plane. Although the track-finding procedure successfully identifies track candidates, ITK inner layer hits associated with low-momentum tracks are often not selected at the track finding stage.

As a consequence of missing ITK inner layer hits at the track finding stage, the constraints on the track origin and direction are weakened for low-momentum tracks, leading to degraded track-parameter and vertex resolutions. To address this effect, an ITK hit retrieval procedure is applied after the track finding stage. As illustrated in Fig. 9 [Figure 9: see original paper], the reconstructed track is extrapolated backward from the first valid measurement in the MDC toward the ITK layers. The inward extrapolation is performed using a Runge-Kutta-based propagator through the interfaces provided by the GENFIT2 framework. At each ITK layer, the extrapolated track position is compared with the measured hit positions, and compatible hits are selected based on the spatial distance d_i $(i = 1, 2, 3)$ between the extrapolated position and the corresponding ITK hit. The matching window is chosen to account for extrapolation and detector resolution uncertainties, and optimized using simulation. Fig. 10 [Figure 10: see original paper] and Fig. 11 [Figure 11: see original paper] compare the reconstruction performance for single muons with momenta in the range 50–100 MeV/c that miss ITK hits at the track-finding stage, showing more concentrated parameter resolutions after ITK hit retrieval. These results indicate that this procedure provides a practical improvement to the baseline reconstruction for low-momentum tracks with missing ITK information.

Multi-hypothesis track fitting

When charged particles traverse detector material, energy loss depends on the assumed particle kind and is explicitly taken into account in the track fit. An incorrect particle hypothesis therefore introduces biases in the fitted track parameters. While this effect is typically small at high momentum, at low momentum material effects depend sensitively on the particle kind and need to be properly accounted for when selecting the particle hypothesis.

In high energy physics experiments, track fits are typically performed under multiple particle hypotheses; for BESIII five hypotheses—e, μ, π, K, and p—are employed and all fit results are retained [**?**]. At the STCF, given the large data volume expected at high luminosity, performing track fits under all five particle hypotheses for the full data set leads to increased demands on computing resources and storage.

To study the impact of different particle hypotheses on track fitting, tracks are fitted under different mass hypotheses and the relative momentum residuals are compared with the OSCAR simulation. Due to the presence of bremsstrahlung [**?**, **?**], electrons require additional corrections, which are not considered in this study. Single-particle samples of different particle types (μ, π, K, and p) are generated at fixed momenta of [100, 150, 200, 250, 300, 350, 400, 450, 500] MeV/c, with a uniform distribution in the azimuthal angle ϕ and a polar angle fixed to $\theta = 60°$. The relative transverse momentum residual, $\Delta p_T^{\mathrm{rel}}$, is defined as $(p_T^{\mathrm{reco}} - p_T^{\mathrm{MC}})/p_T^{\mathrm{MC}}$, where p_T^{reco} denotes the reconstructed transverse momentum and p_T^{MC} the corresponding Monte Carlo truth value. The resulting residual distribution is approximately Gaussian and its mean value $\bar{\mu}$ is used to quantify the bias of the reconstructed transverse momentum. Fig. 12 [Figure 12: see original paper] shows the relative momentum residual distributions of the above sample of generated pion with $p = 350$ MeV/c, obtained using four particle hypotheses in the track fitting. The residual distributions obtained with the μ and π hypotheses are centered close to zero, while those obtained with the K and p mass hypotheses show substantial deviations. For a lower momentum of $p = 100$ MeV/c, the relative residual distribution obtained with the π hypothesis is noticeably closer to zero than that obtained with the μ hypothesis, as shown in Fig. 13 [Figure 13: see original paper]. Moreover, the use of the correct particle hypothesis yields well-behaved residual distributions for low-momentum tracks.

In Fig. 14 [Figure 14: see original paper], the mean relative momentum residuals for the generated μ, π, K, and p tracks are plotted versus the transverse momentum under different particle hypotheses. Kaons and protons at very low momentum are not included, since their large energy loss in the detector material makes it difficult for them to reach the MDC. In Figs. 14(a) and 14(b), differences between the hypotheses π and μ are observed for the π and μ tracks at momenta below 200 MeV/c. At higher momentum, the fitting results obtained with the hypotheses π and μ become similar, and either hypothesis can be used for the fitting of the tracks. In Figs. 14(c) and 14(d), for K and p tracks, fits obtained with incorrect hypotheses exhibit obvious deviations, demonstrating that alternative particle hypotheses cannot be used for accurate track fitting in this momentum range. According to this study, three particle hypotheses (π, K, and p) are retained in the current implementation. For low-momentum tracks below 200 MeV/c, the μ hypothesis is additionally included.

Performance

Performance studies are carried out using single-particle samples and the $\psi(3686) \to \pi^+\pi^-\mathrm{J}/\psi$, $\mathrm{J}/\psi \to \mu^+\mu^-$ decay channel, based on full detector simulation and the baseline reconstruction chain, with track fitting performed using the GENFIT2 framework within OSCAR. To evaluate the robustness of the baseline algorithm, the studies are performed under different background levels. Background hits are simulated within the OSCAR framework [?] and mixed with signal hits before track reconstruction. Table 1 lists the average number of background hits per event in the ITK and MDC, with labels corresponding to the ITK layer indices and MDC super-layer indices.

The quality of track fitting

The track parameter resolutions are evaluated by comparing the fitted track parameters to their corresponding truth values. Single-muon samples are generated with a fixed polar angle of $\theta = 60°$ and a uniformly distributed azimuthal angle ϕ, with a momentum of $p = 1$ GeV/c. Gaussian fits are applied to the pull distributions, where the pull for a given track parameter v is defined as $\mathrm{pull}(v) = (v_{\mathrm{fit}} - v_{\mathrm{truth}})/\sigma_{\mathrm{fit}}$, with v_{fit} denoting the fitted value of the track parameter, v_{truth} the corresponding Monte Carlo truth value, and σ_{fit} the estimated uncertainty of the fitted parameter. Fig. 15 [Figure 15: see original paper] shows the pull distributions of the track parameters evaluated at the point of closest approach. The fitted Gaussian distributions are approximately consistent with standard normal distributions.

Fig. 16 [Figure 16: see original paper] shows the parameter resolution obtained from Gaussian fits, with nominal background. The distribution closely follows a Gaussian distribution, yielding a relative momentum resolution that remains below 0.5%, which satisfies the performance requirements of the STCF tracking system.

Performance of physics events

The tracking performance is also studied using the $\psi(3686) \to \pi^+\pi^- \mathrm{J}/\psi$, $\mathrm{J}/\psi \to \mu^+\mu^-$ decay channel. For both muons and pions in this channel, the transverse momentum of particles is correlated with its polar angle. In general, tracks with lower transverse momentum correspond to larger polar angles. Figures 17 and 18 show the d_0 and z_0 resolutions, as well as the relative momentum resolution, for muon and pion tracks under different background conditions. For tracks at lower momentum region, the tracks traverse fewer detector layers, resulting in relatively poorer resolutions. Comparisons performed at different background levels show no observable change in track quality. It clearly shows that the reconstructed track parameters exhibit stable resolutions across different background levels.

Conclusion

In this work, the GENFIT2 track fitting toolkit is integrated into the STCF experiment and studied in the OSCAR full simulation. The deterministic annealing filter is applied to address the requirements of track fitting in high background conditions, and its noise rejection behavior is studied under background levels relevant to current STCF simulation studies. The reconstruction performance is evaluated using single particle samples and physics decay channels. The results show that the track fitting performance is stable under different background levels and provides reliable track parameter resolutions over a wide range of transverse momenta. Further studies will focus on very low-momentum tracks ($p_T < 100$ MeV/c), including the treatment of multi-turn trajectories. In addition, fitting strategies for electron tracks affected by bremsstrahlung will be investigated. GENFIT2 is currently adopted as the default track fitting approach in the STCF baseline reconstruction chain, used for physics studies as well as detector optimization, and it exhibits potential to be a reliable track fitting software for the STCF experiment.

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Note: Figure translations are in progress. See original paper for figures.