Central Tracking Task Force

Goal

To identify issues in current CLAS12 central tracking software and propose a path forward to obtain the maximum efficiency, resolution, and speed.

Members

- Yuri Gotra (PI)
- Veronique Ziegler (core)
- Mac Mestayer (core)
- Maurizio Ungaro (external, MC expert)
- Rafayel Paremuzyan (external)
- Maxime Defurne (external)

Charge

- Assess the current CLAS12 central tracking efficiency, resolution, and execution speed
- Assess limitations in hardware, reconstruction software, calibrations, tracking algorithms, ...
- Quantify the expected improvement in efficiency, resolution, and execution time provided by the proposed solutions
- Define a work plan to move forward provide a time chart and milestones for:
  1. assessment
  2. definition of alternative solutions
  3. validation (data and Monte Carlo)
  4. implementation in the current reconstruction framework
- Estimate resources needed in the different phases of the project
- Evaluate synergies with other projects at the lab providing a list of shared resources and common goals

Resources

- Time: 3 months (March - May)
- Deliverable: 2 page reports, wiki page with full documentation and minutes of the meetings and presentations

Assessment of Hardware Limitations

- **Technical specs for the CVT (original SVT-4 design)**
  - 5% momentum resolution at 1 GeV (50 μm sensor spatial resolution)
  - 5 mrad azimuthal angle resolution
  - 10÷20 mrad polar angle resolution (due to 3˚ strip stereo angle)
  - 90% tracking efficiency at 10^{35} cm^{-2} luminosity
- **Operational performance of the CVT detector systems**
  - With BMT expected polar angle resolution is 5 mrad due to 90˚ stereo angle
  - Measured SVT spatial resolution is better than the specs (30÷50 μm)
  - Measured BMT spatial resolution is within the specs (150÷200 μm)
  - Number of masked (hot) channels is within a fraction of a percent
  - Noise performance is within the design estimates
  - Misalignments of the SVT fiducials are hundreds of microns in X, Y, Z as designed
  - SVT sensor-to-sensor misalignments are within 10 μm (most 1÷3 μm)
  - SVT side-to-side misalignments are on the order of fiducial misalignments
  - BMT tile-to-tile misalignments are within 1.5 mm
  - CVT performance from realistic MC (merged background, 50 nA) matches the specs: resolution (momentum 5%, angular 5 mrad, Z vertex 500 μm), efficiency up to 90%
- **Design changes**
  - Tungsten shield (51 μm) on the scattering chamber to reduce γ background
  - Reduced SVT operation temperature to ensure stable operation and prevent reverse annealing (unplanned exposure during first beam tuning)
  - Active SVT sensor cooling
  - Improved detector insulation
  - Redesigned purging system

Detailed detector design and performance in the SVT and Micromegas NIM papers

Assessment of Software

- **General comments on CVT software development and resources**
  - SVT geometry implemented by Maurizio and Peter
  - SVT-4 background rates, occupancy, radiation damage were simulated by Maurizio
  - SVT-4 tracking code has been developed by Veronique
    - validated on MC, performance match technical specs
  - BMT geometry implemented by Saclay group and Maurizio
  - CVT decoding implemented by Saclay group, Gagik, Raffaella, Nathan
  - SVT-BMT tracking has been developed by Veronique
  - Performance on ideal MC geometry matched technical specs
  - On the CVT tracking validation stage Veronique was assigned to development of the DC tracking code (CVT priority de-weighted due to first publication schedule)
  - Due to the issues with tracking efficiency at nominal luminosity pattern recognition algorithm was replaced with Cellular Automaton by Francesco
  - Millepede-based CVT alignment code has been developed by Jerry
  - Due to the issues with Millepede alignment package Maxime and Francesco volunteered to work on CVT alignment and later started development of the CVT tracking package based on Veronique's package
  - Contribution of 2 FTE (Maxime, Francesco), a number of issues with original tracking were solved, some problems are still remaining, alignment package needs further work
  - Tracking validation: CVT team, Raffaella, Stepan, Francois
  - Momentum resolution of the **misaligned** tracker is worse than 10%
  - Set path forward to develop the tracker alignment software, the **most critical step** to ensure that CVT tracking is matching detector performance

Insufficient resources at critical tasks lead to stress for key contributors

Assessment of Tracker Alignment

- **Alignment Challenges**
  - Merging two different detectors
  - Large (w.r.t. forward tracking) number of components (102 elements)
  - SVT module thickness (3 mm)
  - Space between BMT layers
- **Alignment strategy**
  - **CVT components**
    - 18 BMT tiles
    - 84$\times$3 SVT sensors (no side-to-side precise CMM alignment)
  - **SVT**
    - 3 fiducials on each module + fiducials on the SVT support tube
    - Precise CMM alignment of the sensors to module fiducials
    - CMM alignment sensor-to-sensor within few μm during module assembly
    - FaroArm survey of all fiducials, 20 μm precision, survey data in the DB
    - Alignment of the SVT support tube with FaroArm
  - **BMT**
    - Fiducials on the BMT support tube
  - **CVT**
    - BMT alignment to the SVT fiducials with FaroArm during tracker integration
    - CVT alignment to the beamline during installation in the hall
    - Track-based alignment
- **Alignment samples**
  - **Cosmic muons**
    - Large samples collected during tracker integration, commissioning, and operation
    - Decoded and reconstructed data on the SVT RAID disk
    - No background, double number of hits, good for relative alignment
    - Lower occupancy for horizontal tracks (beam right/left barrel sides)
  - **Zero field empty target runs**
    - Low luminosity runs (4-5 nA beam current)
    - Taken during each run period (maintenance, CVT and target position changed)
    - Adequate statistics for alignment
    - Decoded and reconstructed data on the SVT RAID disk
    - Can be used for relative alignment of CVT vs. DC

Assessment of Alignment Algorithms

- **Millepede package** (5 years of development)
  - Original track-based alignment strategy
  - Developed by Jerry and Peter
  - SVT geometry and misalignments DB implemented and tested on MC
  - Alignment of Type 1 (vertical) SVT tracks validated on MC and cosmic samples
  - Issues with Type 2 SVT tracks, development stopped
    - Affected by issues with residual calculation, CVT geometry, and track fitting
    - Need merging SVT and BMT in the algorithm
    - Further development would require expertise with Millepede code
- **Saclay group package** (the only available option now)
  - Developed by Maxime
  - Standalone package using custom straight track reconstruction package
  - 3 rotation and 3 translation D.O.F.
    - BMT tiles
    - SVT modules
    - SVT vs. BMT
    - CVT
  - Validated on the MC samples
  - Good improvement of CVT residuals in data
  - Fast convergence
  - SVT side-to-side translation in XY plane implemented
  - Issues handling large number of SVT components
  - Can converge to local minima
  - Moving tracks, not sensors
- **Kalman Filter** (using CMS approach, under evaluation)

Path Forward: Assessment of Tracking

- Tracking packages
  - **Helical track reconstruction (default package)**
    - Developed by Veronique, original SVT-4 code adapted to SVT+BMT tracker
    - *Cellular Automaton* pattern recognition developed by Francesco
    - Fast
    - Resilient to misalignments
    - Need the beam position as input (bias)
    - Remaining dependencies possibly related to track intercept issues
    - Not handling misalignments corrections
    - Using SVT regions in the fit
    - MC SVT residuals ~70 μm
  - **Helical track reconstruction (exploratory package)**
    - Developed by Maxime and Francesco based on Veronique's code
    - Fully unbiased
    - Robust track intercept computations
    - Handle alignment corrections
    - Using SVT clusters in the fit
    - MC SVT residuals ~30 μm
    - More sensitive to detector misalignments
    - Slower to execute on data (might be improved by using Gagik's matrix inversion)
    - Developers are no longer available for coding
  - **Straight track reconstruction (default package)**
  - **Straight track reconstruction (Maxime's package)**

Merging strategy is in the works

Path Forward: Alternative Solutions

- **Alignment**
  - **Using Kalman Filter alignment algorithm**
    - E. Widl and R. Fruhwirth "*A Large-scale Application of the Kalman Alignment Algorithm to the CMS Tracker*", CHEP'07, Journal of Physics 119(2008) 032038
    - Avoid inversion of large matrices
    - Tested on the large-scale CMS silicon tracker (587 TPB, 1654 TIB, 3884 TOB modules aligned)
    - Split alignment steps using BST or BMT as external reference
    - Reduced computation time and memory usage
    - Local CLAS expertise with Kalman Filter (Veronique, Maxime)
- **Tracking**
  - **Artificial Intelligence**
    - Apply machine learning algorithms on the data, reconstruct recorded patterns of tracks, associate each hit with one track
    - Wealth of possible ML techniques (NN, Convolutional NN, Recurrent NN, reinforcement learning, clustering techniques, Monte Carlo Tree Search …)
    - Fast growing ML community, good opportunity to team-up
    - Local expertise in machine learning (Gagik et al.)

Synergies With Other Projects

- Common goals with other CLAS Task Forces
  - **CLAS12 Software**
    - Central tracking and geometry service are listed as high priority tasks
  - **Analysis Framework**
    - Kinematic fitting, momentum corrections, fiducial cuts, vertexing
  - **Forward Tracking**
    - Algorithms for efficiency, resolution, vertexing
  - **BG Merging and Efficiency**
    - Realistic MC simulations, understanding tracking efficiencies
  - **High Lumi**
    - Studies essential for understanding CVT performance in future data taking
  - **Nuclear Target**
    - Background rates, integrated doses, occupancies, MC tuning
  - **Artificial Intelligence**
    - Pattern recognition, speed up track reconstruction
- Shared Resources
  - **Manpower**
    - Members of the central tracking TF are also contributing to other CLAS TFs
  - **Software validation tools**
  - **Code development**
    - Common algorithms can be used (i.e. tracking efficiency)
  - **MC samples** can be shared among the TFs

Coordination of activities is essential for success

Path Forward: Alignment

- Converge on alignment algorithm
- The largest source of misalignments
- Most important D.O.F.
- BMT internal misalignments
- SVT vs. BMT misalignments, dominant contribution
- CVT vs. FTrk misalignment
- Beam position corrections
- Global CVT alignment
- Effects on resolution
- Validation of the CVT survey data
- Develop and validate alignment procedure

Work in progress to identify outstanding issues and establish priorities

Path Forward: Hardware Limitations

- Analyze results of the nuclear target test
  - Dose rates and TID expected (from neutron and gamma monitors, leakage current trends)
  - Comparison with FLUKA and GEANT predictions
- FSSR2 tolerance to the voltage difference at the preamp input (pinhole in the coupling capacitor)
- Study detection efficiency in the SVT sensors with pinholes
- Effects of changing of the SVT depletion voltages
- SVT discriminator threshold settings
- Channel status in CCDB
- Evaluate options for better CVT thermal insulation

Work in progress to identify outstanding issues and establish priorities

Path Forward: Tracking and Validation

- Momentum and angular resolution using elastic peak, mass resolution with exclusive channels
- Bias in theta
- 90-degree theta peak for low momenta tracks with missing hits
- Study seeding algorithm inefficiencies with background
- Pattern recognition strategies, reducing combinatorics and event processing time
- Handling high multiplicity events
- Improving background hit rejection algorithm using timing information
- Energy loss corrections
- SVT standalone tracking
- Validating primary vertex reconstruction
- Reconstruction of displaced/secondary vertices
- Validation procedures and reference plots
- Momentum and angular resolution using elastic peak, mass resolution with exclusive channels
- Efficiency definitions and methods
- Efficiency studies using common CVT-DC tracks
- Efficiency studies using data-only approach and realistic MC samples
- Validation of processing speed for the new tracking code
- Validation of the straight tracking code

Work in progress to identify outstanding issues and establish priorities

Resource Estimate For Different Phases

- Identify available resources for CVT tracking and alignment tasks
    - Required expertise
    - Avoid double/triple/… counting resources (i.e. FTrk 1.2 FTE in CY2020)
    - Code development
        - Veronique (assigned to many tasks in other projects)
        - Rafayel? (now 30% online, 30% fiducial cuts)
        - Maxime, available for advising on tracking and alignment, not as developer
- Where to put resources
    - Assigning priorities
    - Coordinate with CCC
- Collaboration support
    - Task outsourcing (topics where external contribution would be helpful)
    - Mostly validation tasks which do not require development of the tracking code
    - Interest in the CVT tracking
        - If your analysis requires hadron reconstructed in the central tracker, consider contributing to CVT validation tasks

Work in progress to identify outstanding issues and establish priorities

Milestones and Task Length Estimate

Critical step for CVT alignment algorithm development

- **CLAS geometry package (joint effort with Software TF)**
  - Interfaces and methods for detector implementation and misalignments by 06/01/20
  - Need resources to implement CVT detector geometry

High priority tasks (to be complete by next production cooking)

- **Track-based alignment**
  - Development and validation of algorithm
- **Merging two tracking packages**
- **Tracking efficiency at nominal luminosity and background rejection**
- **Momentum and angular resolution**

Medium priority tasks

- **Reducing event processing time**
- **Reconstruction of primary and secondary vertices**
- **Lorentz angle corrections**
- **Estimate SVT longevity based on results of the nuclear target test**

Work in progress to identify outstanding issues and establish priorities

Path Forward: Implementation

- **Current CVT development activity**
  - Merging strategy for two tracking packages (start from the default or exploratory package)
  - Standardization of the helix definition for the pattern recognition and Kalman Filter
  - Initialization of the covariance matrix and Kalman Filter convergence
  - Validation of Kalman Filter and possible extraction into a common library
  - Improving the track propagation to the surface algorithm
  - Implement and validate current official method of computing residuals
  - Study the effect of track propagation in the magnetic field on the residuals
  - Handling of the misalignments implemented
  - SVT standalone track reconstruction implemented
    - Validation in progress (SVT residuals up to 30 μm on low-lumi data)
    - Effect of the SVT survey misalignments on residuals
  - SVT and BMT channel status in CCDB