The Central Tracker for SCT and CMD3 detector

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Abstract

The CMD-3 experiment has been operating at the VEPP-2000 electron-positron collider, at the Budker Institute of Nuclear Physics, since December 2010. Its main goal is to measure the hadronic cross sections necessary to evaluate the anomalous magnetic moment of the muon. The discrepancy between the theoretical calculations and the experimental results obtained at the Brookhaven experiments[1] is approximately 3.7 σ .

The comparison between the results of the new "g-2" experiment at Fermilab and the theoretical calculation with the new experimental contributions from CMD-3 could confirm the discrepancy, which is a new important hint of New Physics.

A key element for the success the CMD-3 experiment is the tracking detector, which is a drift chamber built in the year 2009 at INFN of Lecce[2]. Due to aging effects, its replacement is necessary, so that an innovative tracking detector, named **TraPId** (Tracking and Particle Identification), has been designed: an ultra-light drift chamber equipped with cluster counting/timing readout techniques, which exploits the expertise gained with the successful construction of

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the MEG II drift chamber. The drift chamber proposed for CMD-3 will be also the prototype for the tracking system of the future Super Charm-Tau Factory Detector (SCTD).

In this paper, the new design of TraPId is described, with a focus on the mechanical design of the end plates, their novel tension recovery scheme and the expected performances.

Keywords: , Gas Detector, Tracking

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1. Introduction

TraPId, the Central Tracker proposed by the Bari and Lecce INFN groups for the detector at SCTF, is an ultra-light drift chamber equipped with cluster counting/timing readout techniques. Main peculiarities of this design are the high transparency in terms of multiple scattering contributions to the momentum measurement of charged particles and the very promising particle identification capabilities.

TraPId is a down sized drift chamber from a larger one designed for the IDEA detector at both FCC-ee[3] and CEPC[4], the proposed future circular e+e- colliders. It is inspired by the original design of the KLOE drift chamber, successfully operated at the Daphne facility of the Frascati INFN Laboratories from 1999 until 2019 and culminated with the construction of the MEG II drift chamber, which has just completed the commissioning phase at the PSI laboratories in Zurich and is in data taking mode.

A drift chamber prototype for TraPID, which will be used as the central drift chamber of the CMD-3 experiment at VEPP-2000[2] is going to be developed and tested by groups from INFN Lecce, INFN Bari and BINP.

2. The mechanical design of the SCTF drift chamber prototype (CMD-3)

The construction of CMD3 drift chamber is driven by two main purposes:

- Maximize the transparency in terms of radiation length.
- Maximize the mechanical stability by reducing to acceptable limits the deformations of the endplates under the total load of the wires.

A significant reduction in the amount of material at the end plates is obtained by separating the gas containment function from the wire tension support function. The wires are anchored to a self-sustaining light structure (”wire-cage”) surrounded by a thin skin (”gas vessel”) of suitable shape to compensate for the gas differential pressure with respect to the outside. Schematically, the wire-cage consists of a set of radial spokes, constrained at their inner ends into a tiny cylinder and extended to the outer endplate rim, thus subdividing the chamber in identical sectors. The chamber layout is obtained by stacking up radially, between adjacent spokes in each sector, printed circuit boards (PCB), where the wires ends are soldered with a well defined pitch, alternated with spacers to set the proper cell width. In order to minimize the deformations due to the wire load, it is necessary to create a system of adjustable tie-rods that steers the wire tension to the outer end plate rim, where a rigid cylindrical carbon fibre support structure, bearing the total wire load, is attached.

Layout of the CMD-3 drift chamber. Figure 1 represents the schematic layout of the CMD-3 drift chamber, which is divided in 4 concentric super-layers A, B, C and D and 24 identical sectors. Marked with black circles, from the inner to the outer radius, the inner, the middle and the outer cylinders are indicated. The red circles mark the separations between the different super-layers.

Super-layer A is made of open jet-cells with wires arranged axially. Each cell defines one of the 24 sectors and includes 12 sense wires (red dots), azimuthally staggered with respect to field wires plane (black dots). The green dots represent two guard wire layers, at the two ends of the super-layer. As shown in Figure 2, the cell width increases from the inner to the outer radius up to the value of 28.4 mm.

The middle cylinder at 120 mm radius divides the axial super-layer A from the next one, so that one could insert a thin mylar foil to separate the two volumes and use two different gas mixtures, to compensate the much longer drift times of the super-layer A. The mechanical design is being developed including this possibility.

Super-layers B, C and D are made of single-wire cells with the wires arranged in an appropriate stereo angle configuration with 4 layers of 4 (5) cells per each sector B (C) and 8 layers of 6 cells per each sector D, as shown in 3. The square cell size increases from 8.7 mm at the innermost radius to 12.4 mm at the outermost radius.

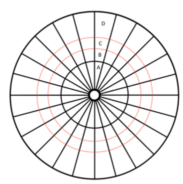

Figure 1: Schematic layout of the CMD-3 drift chamber. Marked with black circles, from the inner to the outer radius, the inner, the middle and the outer cylinders are indicated. The red circles mark the separations between the different super-layers

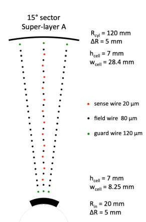

Figure 2: Cell structure in super-layer A: red dots represent sense wires, green dots represent guard wires and black dots represent field wires.

The wire cage. The structural parts of the CMD-3 drift chamber mechanics will be built in carbon fibre. Key elements of the structure are: the spokes, the inner ring, the intermediate ring, the outer ring and the outer cylinder, all illustrated in Figure 4. In order to limit the spokes deformation, a set of stays, the tension

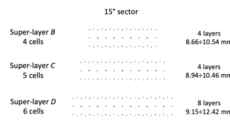

Figure 3: Cell layout in one layer of super-layers B, C, D. Red crosses represent sense wires, red and blue dots represent field wires. Red and blue wires are arranged at opposite stereo angles. Contiguous layers have stereo angles reversed.

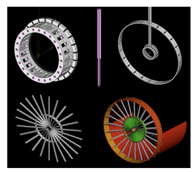

Figure 4: Top left: the inner ring. Top center: the spoke. Top right: assembly of the spoke with the inner and intermediate rings. Bottom left: assembly of the 24 spokes with the inner and intermediate rings. Bottom right: the outer ring and half of the outer cylinder; the wire holding PCBs in super-layer A and the first PCBs of super-layer B are visible.

of which can be adjusted, are strung between the spokes and the structural outer ring. The whole system, shown in Figure 5, acts like a harp cable stayed bridge structure, with the outer ring acting like the tower (the pylon) and with the spoke representing the bridge deck.

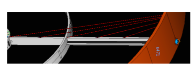

Figure 5: The arrangement of the system outer ring (pylon), spoke (bridge deck) and stays as in a harp cable stayed bridge structure.

Preliminary Finite Element Analysis. Such an innovative concept of drift chamber endplate necessitates of the support of accurate calculations to guarantee the mechanical stability of the system. Preliminary investigations, using Finite Element Analysis, have been performed under much simpler conditions, just to establish the feasibility of the concept.

The total load due to the wire tension is of the order of 500 Kg (we assume 20 μm tungsten wires for sense, 40 and 80 μm aluminum field wires and 120

μm aluminum guard wires) or, approximately, 20 Kg per spoke. We assume a uniformly distributed load along the spoke length, with the spoke fixed at both end and free to translating along the simmetry axis. Using a 133 GPa low modulus carbon fiber and tensioning with three stays of 14 Kg placed at 10° at the inner ring, 24 Kg at 14° at the intermediate ring and 20 Kg at 21° midway between the intermediate and the outer rings, the maximum deflection obtained is within $\pm 25\ \mu m$ as shown in Figure 6. The preliminary FEA confirms

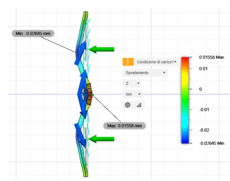

Figure 6: Spoke deflection under a load of 20 Kg uniformly distributed. Three stays per spoke applied at the inner ring and at the intermediate ring and midway between the intermediate and the outer rings.

that such a concept is applicable to the drift chamber of CMD-3. Obviously, a long campaign of finite elements calculations is needed to reproduce the correct constraints configurations, using the final version of the materials and shapes for the different components. Also, the reduction of the amount of material used in the endplates is the goal of the optimization of all parameters with the constraint of maximizing the stability of the entire structure.

3. Development of a fast digitizer-FPGA board for cluster counting

The use of helium based gas mixtures in the TraPId drift chamber, aimed at minimizing the multiple scattering contribution to the momentum measurement for low momentum particles, because of the low ionization cluster densities produced, introduces a sensible bias in the impact parameter reconstruction, particularly for short impact parameters and, hence, for small drift cells.

The Cluster Counting/Timing technique, which consists in measuring the arrival times on the sense wires of each individual ionization cluster, overcomes this impasse and offers the possibility of greatly improving the particle identification capabilities. However, in order to apply this technique, it is necessary to have read-out interfaces capable of processing high speed signals to efficiently isolate peaks due to different ionization clusters. [5, 6]

Requirements on drift chamber performances impose analog to digital conversions at sampling rates of the order of 1-2 GSa/s with at least 12-bit resolution. These constraints, together with a maximum drift time, usually of the order of several hundred ns, and with a large number of readout channels impose some sizable data reduction, still preserving all relevant information. To this purpose, fast readout algorithms have been successfully implemented online in real time on a FPGA at a single channel level. At the start of the processing procedure, a counter providing the timing information is activated. As the FPGA implemented algorithm identifies a peak in the real time scanning of the sense wire signal, its relative amplitude and time are stored in internal memories, which are continuously loaded as new peaks are found. At the occurrence of a trigger signal, the reading procedure is enabled and only the data related to the found peaks, in a time interval corresponding to the maximum drift time, is transferred to the external storing devices, provided it satisfies *ad hoc* established filtering criteria.

This procedure, once applied to each readout channel, results in data reduction by factors between one and two orders of magnitude with respect to the full sampled signals. The goal of this R&D activity is to be able to implement, within a single FPGA board, more sophisticated peak finding algorithms on as many analog to digital conversion channels as possible, for parallel pre-processing in order to reduce costs and system complexity of the data acquisition system. Moreover, such a procedure provides, in conjunction with analogous information coming from contiguous channels, details which can be used to correlate hits to form track segments in real time, which can be used to try exploiting the possibility of defining a trigger based on track segments with latency compatible with the maximum drift time. After the successful tests performed with a single drift channel, new and more sophisticated hardware has been acquired, to treat simultaneously two channels and to prove the feasibility of correlating contiguous hits. The described CluTim algorithm is being improved, both in terms of counting efficiency (currently at approximately 80% level) and in terms of fake rate contamination (at level of 1-2%). Next step is to develop a 4-channel system and include the hits correlating algorithms to define track segments within the maximum drift time[7].

4. Tracking and particle identification expected performances

The key element for TraPId detector is to obtain competitive resolutions for the track reconstruction parameters and better particle separation capabilities. The cluster counting and timing techniques are the recipe to achieve this goal[8].

Tracking resolution: the cluster timing technique. In a conventional drift chamber only the time of the first cluster is used to estimate the track impact parameter, resulting in a systematic bias. Cluster timing techniques use the information provided by the later clusters to form a weighted average of the impact parameter estimates, provided by the different clusters. Figure 7 shows the cluster counting improvement respect to the other techniques.

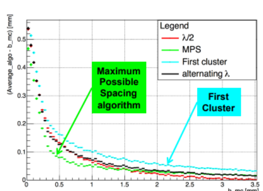

Figure 7: Cluster timing allows to reduce the average spatial resolution from 100 μm down to 85 μm in a 8 mm cell.

The analytical parameterisations of transverse momentum resolution and angular resolutions are the following:

$$\Delta_{p_t}/p_t = \frac{8\sqrt{5}\sigma_{xy}}{0.3BR_{out}\sqrt{N}}p_t \oplus \frac{0.0523}{\beta BL}\sin\theta\sqrt{L/X_0} \quad (1)$$

$$\Delta\phi_0 = \frac{4\sqrt{3}\sigma_{xy}}{R_{out}\sqrt{N}} \oplus \frac{0.0136}{\beta p}\sin\theta\sqrt{L/X_0} \tag{2}$$

$$\Delta\theta = \frac{\sqrt{12}\sigma_z}{R_{out}\sqrt{N}}\frac{1+\tan^2\theta}{\tan^2\theta} \oplus \frac{0.0136}{\beta p}\sqrt{L/X_0} \tag{3}$$

where N is the number of measuring points, p is expressed in GeV/c, B in Tesla and R_{out}, the outer drift chamber radius and σ_{xy} and σ_z, respectively the transverse and longitudinal spatial resolutions, are measured in m. l/X_0 is the track length in terms of the equivalent radiation length traversed. The symbol $\oplus$ represents the sum in quadrature of the two terms, the first of which is the contribution to the resolution due to the measurement errors and the second one is the contribution due to multiple scattering. The total momentum resolution is expressed as:

$$\frac{\Delta p}{p} = \frac{\Delta p_t}{p_t} \oplus \frac{\Delta\theta}{\tan\theta} \tag{4}$$

By using the design values for the parameters and by applying the cluster timing technique, the expected performances are:

$$\Delta_{p_t}/p_t = 6.6\times10^{-4}p_t \oplus 1.8\times10^{-3} \tag{5}$$

$$\Delta\phi_0 = 1.1\times10^{-4} \oplus \frac{5.3\times10^{-4}}{p} \tag{6}$$

$$\Delta\theta = 3.8\times10^{-4} \oplus \frac{5.3\times10^{-4}}{p} \tag{7}$$

Particle identification with cluster counting technique. The cluster counting technique could improve the particle separation capabilities respect to the traditional method of the dE/dx.

The techniques takes advantages of *Poissonian* nature of the primary ionization and offers a more statistically significant way to infer mass information, indeed simulations studies, shown in Figure 8, with Garfield++ software, proved that the cluster counting technique improves the particle separation capabilities by a factor of two with respect to the dE/dx method[9].

Particle identification at the level of 3.6% with cluster counting allowing for π/k separation $\geq 3\sigma$ over a wide range of momenta.

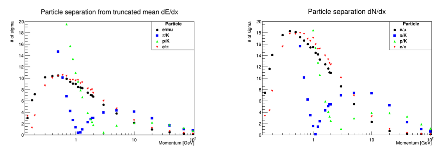

Figure 8: Top: P.Id. obtained with the dE/dx technique in Garfield++. Bottom: P.Id. obtained with the dN/dx method in Garfield++.

5. Conclusion

The TraPId chamber designed for CMD3 experiment will serve as a prototype of the ultra-low mass drift chamber for SCTF. A material budget $< 1.5 \times 10^{-2} X/X_0$ in the radial direction and $< 5 \times 10^{-2} X/X_0$ in the forward and backward directions (including HV and FEE services) can be built today with the novel technique adopted for the successful construction of the MEG2 drift chamber. Competitive tracking and particle identification performances can be achieved exploiting the cluster counting and timing techniques. A beam test is ongoing (a part of it is already been run in November 2021) to fine tune the predictions on performance of cluster counting for flavor physics and for jet flavor tagging both in fast and in full simulation.

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