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The cylindrical-GEM inner tracker detector of the KLOE-2 experiment

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ABSTRACT

The KLOE-2 experiment represents the continuation of KLOE. It acquired 5.5 fb^{-1} data from November 2014 to March 2018 with the aim of collecting the largest sample of ϕ mesons at the DAΦNE e^+e^- collider at Frascati National Laboratory of INFN.

A new tracking device, the Inner Tracker, was installed at the interaction region of KLOE-2 and it was operated together with the Drift Chamber to improve track and vertex reconstruction capabilities of the new experimental apparatus. The Inner Tracker is a four-layer cylindrical triple-GEM detector with each layer equipped with an X-V strips-pads stereo readout. Although GEM detectors have been extensively used in high energy physics experiments, the IT, with its fully-cylindrical geometry is a frontier detector and KLOE-2 is the first experiment which benefited of this novel detector technology operated at a collider.

The operation of the Inner Tracker will be presented, together with the results of the alignment and calibration and tracking–vertexing performance of such a unique detector.

1. The KLOE-2 experiment

The KLOE-2 experiment represents the continuation of KLOE. Its data taking campaign ended in March 2018 and a data sample of about 5.5 fb^{-1} have been collected at the DAΦNE electron-positron collider at Frascati National Laboratory of INFN. In order to confront a rich physics program – mainly devoted on tests of discrete symmetries and quantum mechanics, measurement of light hadron decays, γ-γ physics processes and search of dark forces mediators [1] – the Drift Chamber (DC) and the Electromagnetic Calorimeter (EMC) of the forerunner KLOE apparatus have been upgraded with new calorimeter systems and a tracking detector, Inner Tracker (IT), all immersed in a 0.52 T axial magnetic field. This novel fully-cylindrical GEM detector has been installed between the inner wall of the DC and the beam pipe with the aim of reducing track extrapolation length, therefore improving the resolution on decay vertices close to the interaction point (IP), which are reconstructed from low-momentum secondaries. Although GEM detectors are used in high energy physics experiments at hadron colliders, KLOE-2 is indeed the first experiment profiting of novel cylindrical GEM chambers, whose technology has been totally developed within INFN.

2. The Inner Tracker

The Inner Tracker – shown in Fig. 1 – upgrades the KLOE tracking system operating together with the DC [2]. The new ultra-light IT allows to limit the multiple scattering of low-momentum tracks and the photon-conversion probability at KLOE-2. The resolution on vertices close to the IP is expected to improve by a factor of ~2 by profiting of the presence of the IT inside the interaction region of KLOE-2.

The IT is composed of four concentric cylindrical triple-GEM tracking layers (Fig. 2) [3]. Each layer, with a total active length of 70 cm, is a triple-GEM detector with 5 concentric cylindrical electrodes. The special requirements of manufacturing GEM foils of unprecedented size to build the IT have driven many activities, followed and supported within the RD51 Collaboration [4], during the whole R&D phase.

The anode plane is a multi-layer kapton/copper flexible circuit with longitudinal X strips and V pads, which are connected through internal vias to form V strips. Strip signals are read out by front-end 64-channel GASTONE ASIC chips, with digital output, expressively developed for KLOE-2 [5] and then collected by FPGA-based boards and then acquired [6].

The IT has been operated with a Ar:iC$_4$H$_{10}$ 90:10 gas mixture. Since late November 2014, when the commissioning phase of KLOE-2 started, IT efficiency measurements have driven the activities devoted

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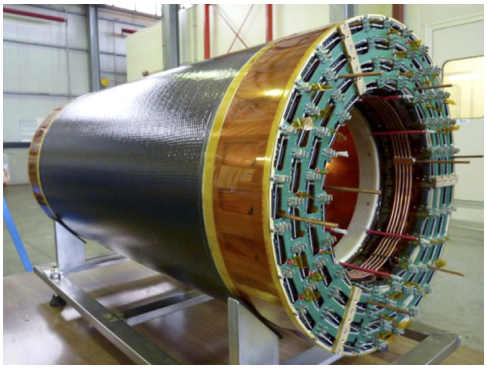

Fig. 1. The Inner Tracker detector before its installation in the KLOE-2 interaction region.

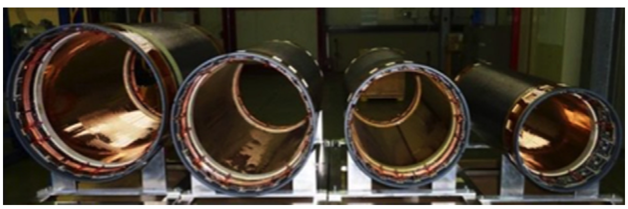

Fig. 2. The four cylindrical-GEM layers before assembling them to build the Inner Tracker.

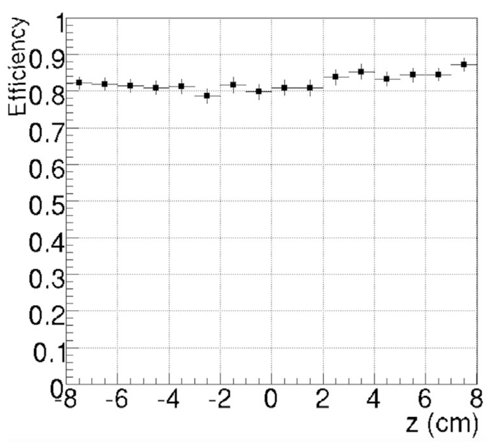

Fig. 3. Two-view efficiency as a function of the longitudinal z-coordinate measured using Bhabha scattering events for IT Layer#1.

to optimize detector operation with colliding beams [7], whose working point was set to GEM1/GEM2/GEM3 voltages of 280/280/270 V with electric fields set at 1.5/3/3/6 kV/cm.

Efficiency measurements has been performed by using cosmic-ray muon tracks reconstructed by the DC in the KLOE-2 B-field, selecting tracks crossing the IT at two points and retaining IT clusters closest to the expected positions given by the extrapolated tracks. Single-view and two-view efficiencies up to 98% and 95%, respectively, have been measured with cosmic-ray muons. The tow-view efficiency as a function of the longitudinal z-coordinate, obtained by analyzing a sample of Bhabha scattering events and following the same strategy as for cosmic-ray muon data analysis, is shown in Fig. 3: the average efficiency value is in agreement with measurements performed with cosmic-ray muon data with a safer IT working point set with the accelerator providing collisions [7].

To achieve the optimal IT reconstruction performance, two effects must be taken into account: a non-radial track effect and the presence of

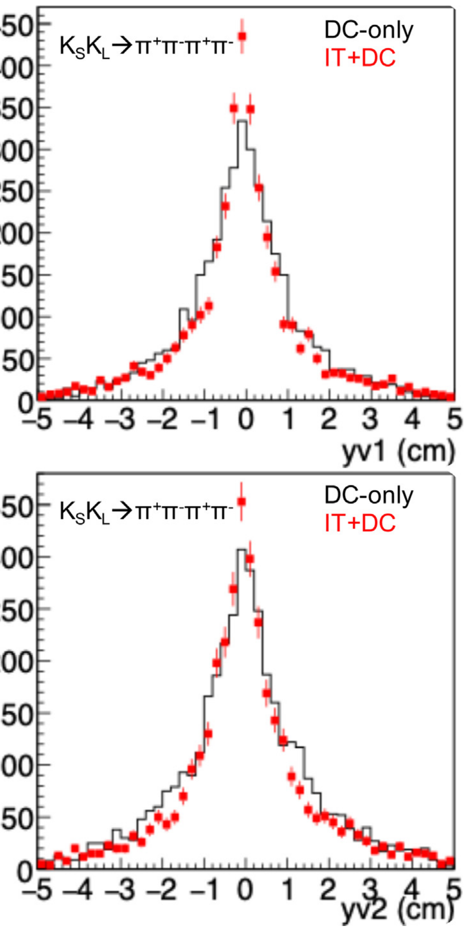

Fig. 4. Comparison between y-coordinate distribution of the two vertices for $K_SK_L \rightarrow \pi^+\pi^-\pi^+\pi^-$ events. DC-only reconstruction is the solid histogram, while red points is the integrated IT+DC reconstruction.

the KLOE-2 magnetic field. The combination of those two effects results in a focusing or a defocusing of the electron cloud, depending on the impact parameter of the track on the cylindrical IT layers. These effects must be studied and measured independently as described in [8].

A nice improvement has been achieved by inserting a first set of alignment and calibration constants in the IT reconstruction Nevertheless, a more refined set of calibration parameters has been produced for obtaining residual distributions centered around zero within $\sim$50 μm and with an average width of $\sigma_x \sim 350$ μm along the x-coordinate, to be compared with the starting point value of $\sim$1.5 mm. Similar improvements holds also for residuals along y and z coordinates, thus allowing to reach expectations.

3. Track and vertex reconstruction using the Inner Tracker

Track and vertex reconstruction at KLOE-2 benefits of the presence of the novel IT detector, whose installation close the IP allows to equip the space between the beam pipe and the DC. Clusters reconstructed by the IT are added to DC tracks by using the Kalman filter algorithm and then track parameters are updated considering both DC and IT information; IT+DC tracks are then used to make vertices whenever IT hits are attached to DC tracks.

Bhabha scattering events, $\phi \rightarrow \pi^+\pi^-\pi^0$ and $K_S \rightarrow \pi^+\pi^-$ events have been used as benchmark channels for testing the integrated tracking and vertexing with processes occurring close to the IP, where the reconstruction performance are expected to largely benefit from the IT. They are clean event topologies in which two tracks are connected to one single vertex in the beam pipe region around the IP. The first set of alignment and calibration parameters, obtained as described in the previous section, has been used to account for both non-radial track and B-field effects for IT cluster reconstruction.

A first good improvement on vertex spatial position reconstruction has been observed using both $K_S \to \pi^+\pi^-$ and $\phi \to \pi^+\pi^-\pi^0$ decays, by applying simple requirements to select events:

(a) one vertex with position in transverse plane $\rho_{VTX} < 5$ cm and along the longitudinal direction $|z_{VTX}| < 5$ cm,
(b) only two tracks of opposite charge connected to the selected vertex with transverse momentum of at least 10 MeV/c and 100 MeV/c for $K_S \to \pi^+\pi^-$ and $\phi \to \pi^+\pi^-\pi^0$, respectively.

and looking at the y-coordinate of reconstructed vertices. This quantity is a good benchmark to test vertex resolution in the region close to the IP, since it is negligibly affected by beam size effects (order of 10 μm along the vertical direction) for $\phi \to \pi^+\pi^-\pi^0$ decays, while it is the convolution of beam size, K_S lifetime and vertex resolution for $K_S \to \pi^+\pi^-$ decays. The standard deviation of the vertex y-coordinate distribution for $\phi \to \pi^+\pi^-\pi^0$ decays is reduced from 3 mm using DC-only reconstruction to about 1 mm using integrated IT+DC reconstruction, while it goes from ∼1 cm to ∼0.7 cm for $K_S \to \pi^+\pi^-$ decays [9].

A first look at $K_S K_L \to \pi^+\pi^-\pi^+\pi^-$ events – an interesting physics channel for Quantum Mechanics tests at KLOE-2 – has demonstrated that improvements holds also for topologies with two reconstructed vertices, each connected to two tracks. Events with:

(a) two vertices with position in transverse plane $\rho_{VTX} < 5$ cm and along the longitudinal direction $|z_{VTX}| < 5$ cm,
(b) only two tracks of opposite charge connected to each selected vertex having transverse momentum of at least 10 MeV/c

have been selected to check the y-coordinate distribution of vertices. In Fig. 4 the y-coordinate distribution of the two selected vertices is compared for DC-only (solid histograms) and integrated reconstructions (red points): an average improvement on the distribution width of almost 50% allowed to reach resolution along the vertical coordinate of the order of about 1 cm using the new IT+DC reconstruction.

An additional improvement is expected to reach expectations by using the more refined set of calibration constants and after fine tuning the integrated reconstruction.

4. Outlook and conclusions

KLOE-2 is the first high-energy physics experiment equipped with a fully-cylindrical GEM detector. The technology used for building this novel detector has been entirely developed at Frascati National Laboratory of INFN and good expertise has allowed to operate it on a lepton collider for the very first time. Encouraging results concerning alignment and calibration, IT+DC integrated tracking and detector operation optimization have been of interest for other experiments, which are going to use the cylindrical-GEM technology (BESIII) or are planning to use it. Operation with colliding beams has been optimized thanks to the implementation of a new HV scheme and the co-operation with DAΦNE operators, who were provided with online feedbacks concerning detector status as monitored during the data acquisition by dedicated tools. Alignment and calibration of the IT – never done before for such a GEM detector with digital front-end electronics – gave successful results, which are accompanied by good results concerning IT+DC tracking and vertex reconstruction observed using $\phi \to \pi^+\pi^-\pi^0$ and $K_S \to \pi^+\pi^-$ decays as well as $K_S K_L \to \pi^+\pi^-\pi^+\pi^-$ event topologies. Further improvements are expected by using more refined calibration constants for the IT cluster reconstruction and additional tests are ongoing using KLOE-2 data for other physics channels, which are of interest for the experiment physics program.

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