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The KLOE-2 experiment at DAΦNE

A. Di Cicco(*) on behalf of the KLOE-2 Collaboration
Dipartimento di Matematica e Fisica, Università "Roma Tre" - Roma, Italy

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Summary. — KLOE-2 is the main experiment of the INFN Frascati National Laboratories and represents the continuation of KLOE. The previous apparatus, consisting in a huge Drift Chamber and an Electromagnetic Calorimeter, both immersed in a 0.5 T magnetic field, has been upgraded with new detectors to perform high-precision CPT symmetry and quantum coherence tests using neutral kaons, $\gamma\gamma$-physics studies and searches of particles of hidden dark matter sectors. KLOE-2 started its data taking in November 2014 and is presently collecting data, achieving record performance in terms of peak luminosity and maximum daily integrated luminosity, which will allow to integrate more than $5\,\mathrm{fb}^{-1}$ of data in the next 2 years.

1. – Introduction

KLOE-2 is the main experiment of the INFN Frascati National Laboratories (LNF) and represents the continuation of the KLOE experiment [1], upgraded with state-of-the-art detectors to improve its discovery potential.

KLOE-2 started its first data taking campaign at the DAΦNE $\mathrm{e}^+\mathrm{e}^-$ collider in November 2014 and is presently taking data with the aim of collecting more than $5\,\mathrm{fb}^{-1}$ in the next 2 years. Record performance in terms of peak luminosity ($L_{peak} = 2\times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$) and maximum daily integrated luminosity ($L_{max} = 13\,\mathrm{pb}^{-1}/\mathrm{day}$) were achieved with the innovative *crab-waist* beam collision scheme, which will be employed in the upgrade of the B-factory currently under construction at the KEK Laboratory in Japan and is considered a valid option in several future projects.

KLOE-2 will perform CPT symmetry and quantum coherence tests using neutral kaons with an unprecedented accuracy, high-precision studies of $\gamma\gamma$-physics processes, such as $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-\pi^0$, and searches of hidden-sector dark matter particles [2].

2. – The KLOE-2 detector

Along with the pre-existing KLOE detector, new detectors have been installed inside the interaction region and along the beam lattice in order to enhance track and

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(*) E-mail: `alessandro.dicicco@roma3.infn.it` vertex reconstruction, photon and electron/positron detection to accomplish the KLOE-2 physics program: a novel cylindrical GEM Inner Tracker (IT), four tagging stations (LETs and HETs) for $\gamma\gamma$-physics studies and new calorimeters (QCALTs and CCLATs) to enlarge the angular acceptance of the apparatus.

2˙1. *Drift Chamber and Electromagnetic Calorimeter.* – The KLOE detector consists in a huge Drift Chamber (DC) and an Electromagnetic Calorimeter (EMC), both immersed in a 0.5 T axial magnetic field. Track reconstruction with high momentum resolution ($\sigma_p/p = 0.4\%$) is accomplished by the Drift Chamber [3], while cluster reconstruction is performed by the Pb-scintillating fibers Electromagnetic Calorimeter [4] with excellent time ($\sigma_t = 54\,\text{ps}/\sqrt{E\,(\text{GeV})} \oplus 140\,\text{ps}$) and good energy ($\sigma_E/E = 5.7\%/\sqrt{E\,(\text{GeV})}$) resolutions. With its stereo-geometry, the DC provides $\simeq 150\,\mu$m spatial resolution in the bending plane, $\simeq 2$ mm along the beam line, $\simeq 3$ mm on decay vertices inside the DC fiducial volume and $\simeq 6$ mm on decay vertices close to the interaction point (IP). The EMC has barrel and end-cap modules specially shaped to ensure a 98% of a solid angle coverage. A superconductive coil provides a 0.5 T axial magnetic field.

DC and EMC performance turn out to be very stable in time, despite the very different operational conditions of the present KLOE-2 data taking, with about a factor of five more background than the past KLOE run.

2˙2. *The taggers.* – Low Energy Taggers (LETs) and High Energy Taggers (HETs) have been installed with the aim of detecting electrons and positrons scattered in $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-\pi^0$ reactions, which deviate from the equilibrium orbit during the propagation along the accelerator lattice with energy below 510 MeV.

Two identical LET stations [5] have been placed symmetrically at 1 m at both sides of the IP, in order to tag electrons and positrons with energy $160 < E < 400$ MeV. Each LET station consists in an array of 5×4 LYSO crystals, each read out by a Silicon photomultiplier (SiPM), with $1.5 \times 1.5\,\text{cm}^2$ section and 12 cm length, pointing to the average direction of the arriving particles ($\sim 11°$ with respect to the beam line). The two stations are rotated by an angle of 17° with respect to the horizontal plane in order to maximize the number of collected positrons and electrons. The energy resolution of the LET calorimeters, less than 10% in the energy range $150 < E < 400$ MeV, has been measured with electrons of energy between 50 and 500 MeV at the Frascati Beam Test Facility and it well matches the requirements. Equalization of the LET crystals response and time calibration have been performed by selecting minimum ionizing particles (MIPs) as high-momentum tracks from cosmic-ray muons collected without circulating beams in DAΦNE. The absolute energy scale calibration is performed with radiative Bhabha scattering events ($e^+e^- \to e^+e^-\gamma$), with the photon and one lepton reconstructed in the KLOE main detector and the other one detected in the LET.

The HET stations [5] are position detectors for measuring the deviation of $e^\pm$ from the main beam orbit. Together with time information, this measurement allows to tag scattered the electron and positron with energy grater than 420 MeV in $\gamma\gamma$ processes. The two HET detectors are placed at 11 m away from the IP, in symmetrical positions. The sensitive area of each HET station is a set of twenty-eight $3\times5\times6\,\text{mm}^3$ plastic scintillators with an additional larger one used for coincidence purposes – which are placed at different distances from the beam-line, in such a way that the distance between the impinging particle and the beam can be measured knowing which scintillator has been fired.

The KLOE-2 apparatus is synchronized with the DAΦNE bunch crossing, which occurs every $T_{bc} = 2.7$ ns. Since HET stations are far from the main detector installation, their time synchronization with KLOE-2 detectors is obtained using dedicated runs of radiative Bhabha scattering events. After calibrations, the HET taggers are able to nicely reproduce the DAΦNE bunch time structure. The time resolution of the HET detectors is less than T_{bc} as needed to disentangle leptons coming from two consecutive bunch crossings.

A measurement of the counting rate on both HET stations has been also performed. The counting rate timeline on HET stations is expected to be affected by an intra-bunch scattering contribution, which depends on the second power of the beam current. This dependence has been observed in dedicated runs without circulating beams and the intra-bunch contribution has been measured to be $< 30\%$ for electrons and $< 6\%$ for positrons.

A preliminary study of the reaction $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-\pi^0$ has been performed using a sample of $52\,\mathrm{pb}^{-1}$, exploiting both HET stations for tagging scattered $e^\pm$ with their time compatible with 2 clusters measured by the EMC. About 100 events in the π^0 mass range have been observed with simple selection criteria, proving the capability of these detectors to serve as $\gamma\gamma$-physics taggers.

2˙3. *The tile and crystal calorimeters.* – Two new Quadrupole CALorimeters with Tiles, QCALTs [6], have been installed around the DAΦNE *low-β* quadrupoles, at both sides of the IP, with the goal of improving the acceptance for rejecting $K_L \to 3\pi^0$ background events in CP-violating $K_L \to 2\pi^0$ decays. Each calorimeter, 1 m long, consists in a dodecagonal structure, arranged as a sampling of 5 layers of 5 mm thick scintillator plates, alternated with 3.5 mm thick tungsten plates, for a total $\sim 5\,X_0$ thickness. The active part of each plane is divided into 20 tiles of $5 \times 5\,\mathrm{cm}^2$ area with 1 mm diameter wavelength shifter fibers embedded in circular grooves. Each fiber is then optically connected to a SiPM, for a total of 2400 channels. QCALT calorimeters have a $\sim 2\,\mathrm{mm}$ resolution along the beam axis and a time resolution of $\sim 1\,\mathrm{ns}$. Time calibration and channel-by-channel equalization is performed using cosmic-ray muon runs acquired with and without magnetic field.

In order to enlarge the angular acceptance for particles coming from the IP from 20° to 10°, with the aim of improving multi-photon detection in rare decays such as $K_S \to \gamma\gamma$, $\eta \to \pi^0\gamma\gamma$ and $K_S \to 3\pi^0$, two identical Crystal CALorimeters with Timing (CCALTs) [6] have been mounted very close to the IP, near the first focusing quadrupoles of DAΦNE. Each CCALT module is made of 4 aluminum shells, with projective geometry, containing 4 LYSO crystals readout by SiPM. Tests performed at the Frascati Beam Test Facility allowed to measure an energy resolution better than 5% and a time resolution of about 49 ns (120 ps) at 100 MeV (500 MeV) energy. Similar performance are measured with cosmic-ray muons, used also for calibration and equalization of CCALT channels.

2˙4. *The Inner Tracker.* – To improve the resolution on decay vertices close to the IP, reconstructed from low-momentum charged secondaries, the Inner Tracker (IT) has been inserted in the free space between the beam pipe and the DC inner wall, at 25 cm from IP. This novel ultra-light detector, with its total material budget below 2% of a radiation length X_0, allows to minimize dead spaces, the multiple scattering of low-momentum tracks and the probability of photon conversions. The resolution on vertices close to the IP is expected to improve of about a factor 3 [7].

The IT is composed by four concentric Cylindrical GEM (CGEM) [8] detectors, with radii from 13 cm, to preserve the K_SK_L quantum interference, up to 20.5 cm, due to the constraint from DC inner wall. Each layer, with a total active length of 70 cm, is a triple-GEM detector with 5 concentric cylindrical electrodes: a cathode, to set the drift field, 3 GEM foils acting as multiplication stages, and an anode/readout plane. The anode plane is a multi-layer circuit: longitudinal X strips, with a 650 μm pitch, and V pads are patterned at the same level on the same substrate; V pads are then connected through internal vias to form V strips, with a pitch of about 650 μm, which angle with respect to X strips is in the range 25°–27°. The total amount of front-end channels is $\sim$30000. Strip signals are read out by front-end 64-channel GASTONE ASIC chips, with digital output, specifically developed for KLOE-2 [9] and then collected by FPGA-based boards and then acquired [10].

The IT is filled with a Ar:iC_4H_{10} 90:10 gas mixture to maximize the effective gain but limiting the discharge probability measured with α-particles. The measured efficiency [11] with cosmic-ray muon tracks reconstructed by DC is 98% for the single-view and 95% for the two-views.

Efficiency measurements allowed to optimize the IT operational parameters with colliding beams starting from late 2014, during the first KLOE-2 data taking campaign, as a function of the beam currents and background conditions, which are carefully kept under control thanks to three indicators of the machine background level sent online to DAΦNE operators: the current measured on the IT inner layer, the total current measured in the DC and the background level measured on both EMC end-caps.

In order to measure efficiency and resolutions, dedicated procedures were developed to exploit cosmic-ray muon data and Bhabha scattering events, profiting of the excellent DC track reconstruction performance. DC track reconstruction is also exploited for IT alignment and calibration.

To achieve the best IT reconstruction performance, two effects must be taken into account: a non-radial track effect and the presence of the KLOE-2 magnetic field. The first, due to a non-zero angle between the impinging track and the radial direction of ionization electrons motion, induces a shift and a spread of the reconstructed hit position on the readout plane. The second, is due to the Lorentz force acting on the signal electron cloud which is further shifted and spread. The combination of these two effects results in a focusing or a defocusing of the electron cloud, depending on the impact parameter of the track on the cylindrical detectors. These effects must be studied and measured independently: cosmic-ray muon runs acquired without magnetic field have been used to evaluate the non-radial correction, while the magnetic field influence has been investigated using cosmic-ray muon data and Bhabha scattering events. A first set of alignment and calibration parameters has been obtained: preliminary results of about 400 μm are within expectations for the Inner Tracker resolutions. This validates the method and also suggests how to improve the alignment and calibration procedure in order to get the best detector performance.

Online monitoring of IT temperature is available and used to keep IT operation safe, as well as offline software tools for checking IT occupancy, clustering performance and channel status (noisy/dead strips) in time [11].

3. – Conclusions

KLOE-2 is successfully taking data on the DAΦNE electron-positron collider. Online and offline monitors of the detector, together with a feedback for DAΦNE, allow to keep beam-induced backgrounds and sub-detectors behaviour under control, for achieving optimal data taking conditions with the aim of collecting more than $5\,\mathrm{fb}^{-1}$ in the next two years.

Sub-detectors operation has been optimized and their performance are within expectations, as measured by acquiring cosmic-ray muon runs, Bhbaha scattering events and collision data for future physics analysis.

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