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Commissioning and preliminary performance of the MEG II drift chamber

M. Chiappini [a,*], G. Chiarello [a,*], A.M. Baldini [a], H. Benmansour [a,b,c], G. Cavoto [e,f], F. Cei [a,b], A. Corvaglia [g], F. Cuna [g,h], G. Dal Maso [c,d], M. Francesconi [a,b], L. Galli [a], F. Grancagnolo [g], M. Grassi [a], M. Hildebrandt [c], F. Ignatov [i], M. Meucci [e,f], A. Miccoli [g], W. Molzon [j], D. Nicolò [a,b], A. Oya [k], D. Palo [j], M. Panareo [g], A. Papa [a,b,c], F. Raffaelli [a], F. Renga [e], P. Schwendimann [l], G. Signorelli [a], G.F. Tassielli [m,n], Y. Uchiyama [k], A. Venturini [b], B. Vitali [a,f], C. Voena [e]

[a] INFN Sezione di Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy
[b] Dipartimento di Fisica dell'Università, Largo B. Pontecorvo 3, 56127 Pisa, Italy
[c] Paul Scherrer Institut (PSI), 5232 Villigen, Switzerland
[d] Swiss Federal Institute of Technology ETH, 8093 Zürich, Switzerland
[e] INFN Sezione di Roma, Piazzale A. Moro 2, 00185 Rome, Italy
[f] Dipartimento di Fisica dell'Università "Sapienza", Piazzale A. Moro 2, 00185 Rome, Italy
[g] INFN Sezione di Lecce, Via per Arnesano, 73100 Lecce, Italy
[h] Dipartimento di Matematica e Fisica dell'Università del Salento, Via per Arnesano, 73100 Lecce, Italy
[i] Budker Institute of Nuclear Physics of Siberian Branch of Russian Academy of Sciences, 630090 Novosibirsk, Russia
[j] Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA
[k] ICEPP, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
[l] Department of Physics, University of Washington, Seattle, WA 98195-1560, USA
[m] INFN Sezione di Bari, Via E. Orabona 4, 70125 Bari, Italy
[n] Dipartimento Interateneo di Fisica "M. Merlin" dell'Università, Via Amendola 173, 70125 Bari, Italy

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ABSTRACT

In the quest for Lepton Flavor Violation (LFV) the MEG experiment at the Paul Scherrer Institut (PSI) represents the state of the art in the search for the charged LFV decay $\mu^+ \rightarrow e^+\gamma$, setting the most stringent upper limit on the BR($\mu^+ \rightarrow e^+\gamma$) $\leq 4.2 \times 10^{-13}$ (90% C.L.). An upgrade of MEG, MEG II, was designed and it recently started the physics data taking, with the aim to reach a sensitivity level of 6×10^{-14}. The Cylindrical Drift CHamber (CDCH) is a key detector in order to improve the e^+ angular and momentum resolutions at the 6.5 mrad and 100 keV/c level. The CDCH is a low-mass single volume detector with high granularity: 9 layers of 192 drift cells each, few mm wide, defined by 12000 wires in a stereo configuration for longitudinal hit localization. After the assembly, the CDCH was transported to PSI for the commissioning phase and it has been integrated into the MEG II experimental apparatus since 2018. The operational stability was reached in 2020 and the complete readout electronics was tested for the first time in 2021. A preliminary analysis of 2020–2021 data is presented.

1. The MEG II Cylindrical Drift CHamber (CDCH)

The MEG II positron spectrometer consists of a low-mass single volume drift chamber (CDCH) [1], followed by a pixelated Timing Counter (pTC) [2], based on scintillator tiles read out by SiPMs, for a precise measurement of the e^+ momentum vector and time, respectively. Both detectors are placed inside the COBRA superconducting gradient-field magnet.

Design. The main CDCH features are: a full azimuthal coverage around the μ^+ beam stopping target to improve the geometric acceptance for signal e^+ and use extended tracking procedures to reach a tracking efficiency of $\sim 70\%$; an extremely low material budget to minimize the multiple Coulomb scattering and γ background (from bremsstrahlung and annihilation-in-flight) for a total radiation length of 1.5×10^{-3} X_0 per track turn; a high density of sensitive elements to exploit four times more hits compared to the previous MEG drift chamber. The CDCH has a cylindrical shape with a length of $\sim$ 191 cm and a diameter of $\sim$ 60 cm. The filling gas mixture is He:iC_4H_{10} (90:10) [3], a good compromise between transparency and single-hit resolution, measured on prototypes to be $\sigma_H < 120$ μm [4]. Some additives are added to reach the operational stability. The active region extends radially for $\Delta R \sim 8$ cm and it is formed by 9 concentric layers of 192 drift

* Corresponding authors.
E-mail addresses: marco.chiappini@pi.infn.it (M. Chiappini), gianluigi.chiarello@pi.infn.it (G. Chiarello).

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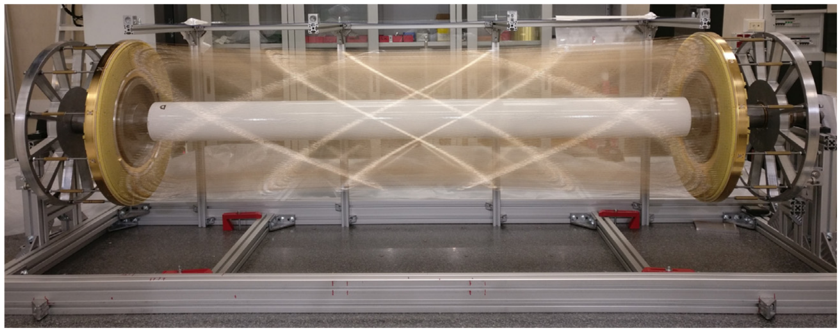

Fig. 1. The fully wired MEG II CDCH.

cells each, defined by 11904 wires. The single drift cell is quasi-square with a 20 μm gold-plated tungsten sense wire surrounded by 40 and 50 μm silver-plated aluminum field wires, with a 5:1 field-to-sense wires ratio. The wires are not parallel to the CDCH axis, but form an angle varying from 6° in the innermost layer (L9) to 8.5° in the outermost one (L1). This stereo angle has an alternating sign, depending on the layer, allowing the reconstruction of the longitudinal hit coordinate Z. In order to exploit an increased μ^+ beam intensity compared to MEG, the cell width is ∼ 6 mm to ensure a sustainable occupancy, especially for the inner layers placed at ∼ 17 cm from the beam axis (∼ 1.5 MHz/cell).

Construction. The CDCH is the first drift chamber ever designed and built in a modular way [5]. In fact, given the high wire density (12 wires/cm^2), wires are not strung directly on the chamber but soldered at both ends on the pads of two PCBs, which are then radially stacked by means of PEEK spacers in the twelve 30°-sectors of the spoke-wheel-shaped endplates (Fig. 1). At the innermost radius, a 20 μm one-side-Al Mylar foil separates the CDCH gas volume from the He-filled target region. At the outermost radius, a 2 mm-thick Carbon Fiber (CF) support structure encloses the sensitive volume and keeps the endplates at the correct distance, ensuring the proper mechanical wire tension. Wiring, assembly and maintenance phases are performed inside cleanrooms. The assembly station allows to adjust the chamber geometry[1] which is recorded during the construction and maintenance periods thanks to a coordinate measuring machine and a laser tracker. The CDCH construction at INFN Pisa (Italy) lasted from late 2016 to early 2018.

2. CDCH commissioning

The CDCH was transported to PSI in the summer 2018 for the commissioning phase [6] and full integration in the MEG II experimental apparatus. The commissioning period lasted for the past three years with continuous improvements.

Final working point. The High-Voltage (HV) Working Point (WP) is set, through Garfield simulations, to values ranging from 1400 V for L9 to 1480 V for L1. The WP is chosen as the value to get a gas gain $G_G = 5 \times 10^5$, to be sensitive to the single ionization cluster and exploit cluster timing techniques [7]. A HV tuning of 10 V/layer is used to compensate for the variable cell dimensions with R and Z due to the stereo geometry. Inside the endcap regions 216 Front-End (FE) boards [8] per side are plugged to the wire-PCBs. Each board has eight differential channels, a low-noise double amplification stage and a high bandwidth (∼ 400 MHz). The ionization signal is read out from both sides to improve the hit Z reconstruction with the charge division and time difference methods. The FE electronics cooling system is embedded in the board holders and dry air is flushed inside the endcaps to avoid water condensation. The electrostatic stability was tested on 2 m-long 3-wire prototypes and the stable lengthening was experimentally found through systematic HV tests at different endplate distances/CDCH length to account for possible deviations from the nominal geometry. The final wire elongation is set to +5.2 mm (65% of the elastic limit).

Integration into the MEG II apparatus. Additional structures are connected to the endplates in ± Z-directions. Aluminum cylinders are installed at the inner radius to couple the chamber to the MEG II beam line. CF cylindrical covers are mounted at the outer radius to enclose the endcap regions. The CDCH mechanics proved to be stable (at ∼ few μm level) and adequate to sustain a full MEG II run. The CDCH is integrated into the MEG II experimental apparatus since winter 2018. The signal and HV cabling, the cooling and gas mixture distribution piping are successfully tested.

Investigations on wire breakings. Wire breaking problems arose during the assembly and final lengthening operations with consequent delays in construction and commissioning. In total 107 Al(Ag) cathode wires broke and in particular the 40 μm wires were affected (90%). The problem was deeply investigated [9] performing optical inspections with microscopes, chromatography, practical tests and SEM/EDX analyses. Each broken wire piece can randomly make big parts of the detector not operational, thus we developed a safe procedure to extract them from the chamber. Electric field simulations of the effect of a missing cathode wire on isochrones returned a negligible impact on e^+ reconstruction. Analyses showed that the origin of the breaking is the galvanic corrosion of the Al core in presence of water condensation on wires from ambient humidity. Air moisture condensation occurs inside cracks in the Ag coating even at low relative humidity levels < 40%. We found a good linear correlation between the number of broken wires and exposure time to humidity. Keeping the wire volume in an inert atmosphere proved to be effective to stop the corrosion and subsequent wire breaking.

Investigations on anomalous currents. During the detector operation in 2019 we experienced anomalously high currents, up to 400 μA. This behavior started after an anode-cathode short circuit caused by a very short wire segment not seen during a previous broken wire extraction procedure and thus remained inside the chamber. Everything was working properly up to that time. Investigative HV tests were performed after replacing the outer CF shell with a transparent one. Corona-like discharges were directly spotted. Accelerated aging tests on prototypes [10] returned no design issues or discharges. In 2020 we started a gas optimization with additives in the standard mixture to try to recover the normal operation. Oxygen proved to be effective in reducing the high currents, fully cured with the addition of up to 2% O_2, then gradually reduced. Isopropyl alcohol proved to be crucial to keep the current level stable. The CDCH is now operated in stable conditions at full MEG II beam intensity with the standard gas mixture + isopropyl alcohol (1.5%) + O_2 (0.5%). From 2020 measurements we do not observe a significant gain reduction due to O_2 attachment.

[1] Endplate planarity, parallelism and mutual distance.

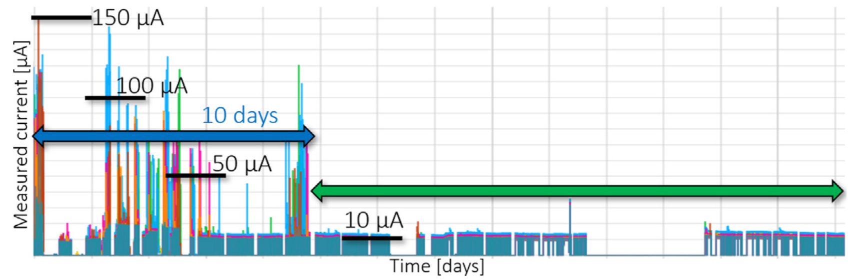

Fig. 2. Conditioning period with μ^+ beam and 2% O_2 content (blue arrow, 10 days). The higher current level (up to 150 μA) is visible before reaching the operational stability around 10 μA (green arrow). Colors refer to different CDCH sectors.

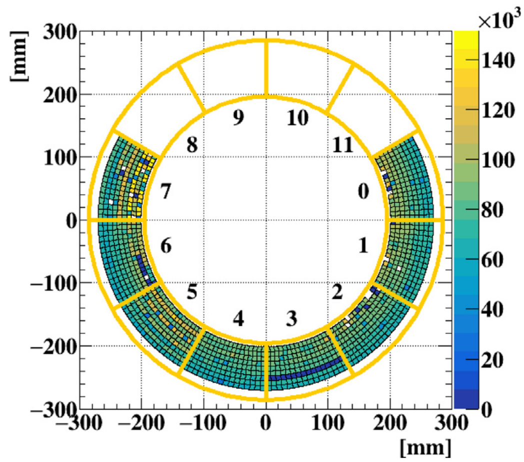

Fig. 3. Example of CDCH occupancy (number of hits per drift cell) with 2021 full readout. The four upper sectors are out of acceptance for signal e^+ and are usually not read out. The dead channels (blue cells) will be recovered during the 2022 maintenance work.

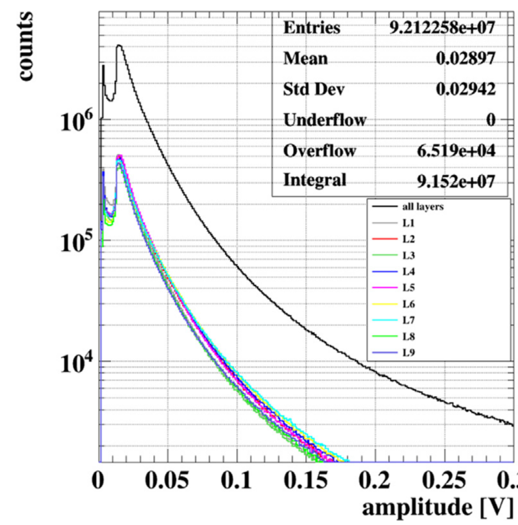

Fig. 4. Signal amplitude distribution showing a good uniformity between layers (different colors, the black histogram is the sum of all the layers).

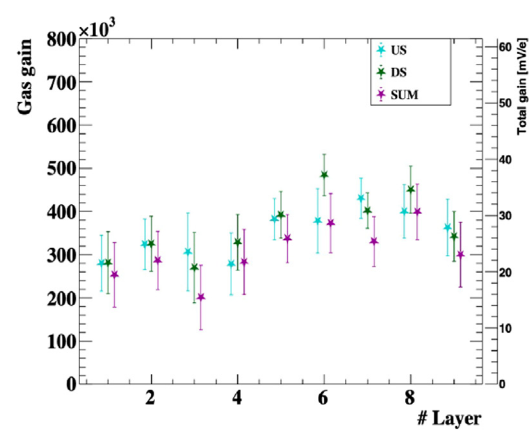

Fig. 5. Gas gain vs. layer number. G_G is computed using the signal amplitude recorded from one wire end or the sum of the two sides (different colors).

3. Start of the physics data taking

The CDCH was tested during the engineering runs 2018, 2019 and 2020 performing HV scans around the WP with different ionization sources: e^+ from μ^+ decays and cosmics. During the 2021 physics run the full electronics readout was tested for the first time. In MEG the full signal waveform is recorded, then a fine analysis is made offline to get the hit information (timing, signal amplitude and integral, position in the detector). The reconstruction algorithms were tuned and the CDCH performance evaluated on data to obtain the first experimental resolutions on e^+ track parameters and efficiency.

Conditioning. The first phase before starting the data taking is the detector conditioning at increasing μ^+ beam rate (Fig. 2). The O_2 content is raised to 2% to lower the initially high current level (up to ∼ 150 μA) to the standard one (∼ 10–20 μA) in presence of beam ionization. Then O_2 is gradually reduced to 0.5%, while the isopropyl alcohol is kept constant at 1.5%. After the conditioning period a good stability[2] in the whole chamber is reached with the current level proportional to the beam rate up to intensities never reached before. The measured currents translated into accumulated charge/cm agree with the design value: ∼ 0.1 C/year/cm.

Preliminary performance. With the detector equipped with the full DAQ electronics we recorded the expected occupancy (Fig. 3). The signal amplitude distributions show a good uniformity between different layers, a sign that the 10 V scaling of the HV works (Fig. 4). The gas gain is determined from the signal amplitude distribution from cosmic ray events.[3] The Monte Carlo (MC) distribution is fitted to data with the total gain (G_T) = FE gain $(G_{FE}) \times G_G$ as the only free parameter to be tuned. G_{FE} is determined by the FE response to single-electron signals produced by laser ionization in a prototype. G_G is then obtained as G_T/G_{FE}. Another way exploits the measured current level, taking into account the hit rate and the number of electrons per hit. Both methods return $G_G = (2\text{–}4) \times 10^5$, in agreement with the expectation

[2] We can see the gas gain variations with the atmospheric pressure P according to $\Delta G_G/G_G = -k(\Delta P/P)$, where k is a constant.

[3] A clean environment to avoid pile-up effects.

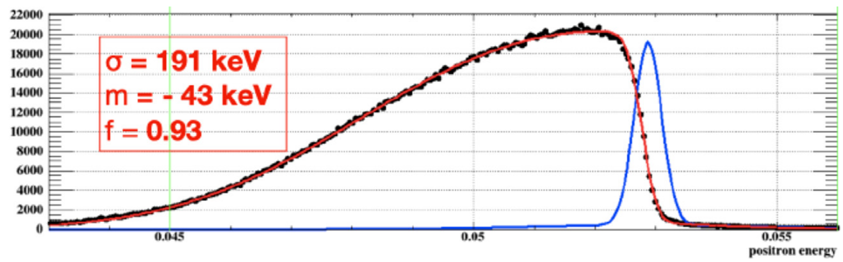

Fig. 6. Preliminary reconstructed e^+ energy from μ^+ decay fitted with [theoretical spectrum × acceptance] ⊗ double-gaussian resolution function.

(Fig. 5). The current full MC tracking performance is quoted, with still margin for improvements: momentum resolution $\sigma_p = 100$ keV/c; angular resolutions $\sigma_\theta = 7.2$ mrad, $\sigma_\phi = 5.0$ mrad; position resolutions at target $\sigma_Z = 1.8$ mm, $\sigma_Y = 0.8$ mm; tracking and pTC matching efficiencies $\epsilon_T = 69\%$, $\epsilon_M = 89\%$. A preliminary analysis of 2021 data return: $\sigma_p \sim 200$ keV/c (Fig. 6); $\sigma_\theta = 9.2$ mrad, $\sigma_\phi = 5.0$ mrad; $\sigma_Z = 2.7$ mm; hit efficiency $\epsilon_H \sim 70\%$. The hit-track residual gives a measurement of how misalignments, σ_H and other systematics (B field) combine to determine the reconstruction performance. After the application of hardware and software (preliminary) detector alignment the distribution shows $\sigma_{core} \sim 180$ μm. Data analysis and continuous developments are ongoing.

4. Conclusions and prospects

Despite the COVID-19 pandemic we completed the 2020 and 2021 commissioning of all the MEG II sub-detectors and the experiment recently started the physics data taking. The CDCH faced two major problems along the path: corrosion of Al wires and high currents. Both were solved after great efforts. Some preliminary results from 2020–2021 data have been presented.

Beyond $\mu^+ \rightarrow e^+ \gamma$. In 2016 the Atomki collaboration measured an excess in the angular distribution of the internal pair creation in the ^{7}Li$(p, e^+e^-)^8$Be nuclear reaction [11]. A possible interpretation is the production of a new physics boson mediator[4] of a fifth fundamental force that describes the interaction between dark and ordinary matter [12]: $pN \rightarrow N'^* \rightarrow N'(X \rightarrow)e^+e^-$. MEG II has all the ingredients to repeat the Atomki measurement: a Cockcroft–Walton p accelerator (used for the γ detector calibrations) and the spectrometer for the e^+e^- measurement. The first dedicated data taking was recently completed and the data analysis is ongoing.

Construction of a second chamber. Given the problems of Al wire breaking and the following analysis pointing out the defects on Ag coating, R&D work started to find an alternative wire solution and explore the possibility to build a second chamber (CDCH2) as insurance against possible future wire breakings in the CDCH. Several coating options were investigated including gold and nickel, showing the same weakness to corrosion of the 40 μm Al(Ag) wire. Also a 50 μm pure Al wire was considered. This showed immunity to corrosion and we tried several fixing techniques on the wire-PCBs, including soldering with special solder wires, ultrasonic soldering and gluing. The final choice for the CDCH2 wiring will be taken soon, while the wiring and assembly stations are ready at INFN Pisa.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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