Precision tracking micro-pattern gaseous detectors at Budker Institute of Nuclear Physics

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Introduction

Micro-pattern gaseous detectors (MPGDs) can operate at very high particle flux demonstrating consistently high efficiency and coordinate resolution in tens microns scale. Tracking MPGDs are developed and applied in several experiments at Budker INP [1], [2].

Eight two-coordinate cascaded Gas Electron Multiplier based [3] detectors (GEM-detectors) have been working at the Tagging System of KEDR experiment (TS KEDR) at VEPP-4M electron-positron collider since 2010 [4], [5]. TS KEDR is dedicated to study two-photon physics.

Three triple-GEM-detectors are integrated into Photon Tagging System of the DEUTERON facility at VEPP-3 storage ring [6], [7]. Strip pitch of the readout structure is 500 um and the spatial resolution was measured to be less than 50 µm. The material budget of each detector is low - about 0.3% of radiation length, which suppresses multiple scattering.

Triple-GEM detectors having orthogonal strips with a pitch of 250 µm and low material budget were assembled for the Test Beam facility at VEPP-4M collider [8], [9] and demonstrated excellent efficiency above 99% and spatial resolution better than 50 µm.

Cascaded GEM-detector with pad readout has been mounted for the Laser Polarimeter for precise energy measurements at VEPP-4M collider [10], [11].

MPGD is proposed for upgraded tracking system of the CMD-3 detector at VEPP-2000 collider [12], [13]. The upgraded system will include a new cylinder tracking and trigger detector as well as two end-cap discs. Micro-RWELL technology is used for the upgrade. The first two end-cap discs are assembled.

The cylindrical detector and end-cap discs for CMD-3 are considered as the prototypes for the Inner Tracker of future Super Charm-Tau Factory [14]. Compact Time Projection Chamber (TPC) [15] is considered as one of the options [16] for the Inner Tracker with the readout detector based on MPGD technology. The prototype of the TPC is being assembled.

Tagging System of KEDR experiment

Tagging system (TS) of KEDR experiment at VEPP-4M collider (Fig. 1) consists of 8 tracking stations which measure momentum of scattered electrons and positrons. Physics goals of the system are: measurement of the cross-section $\gamma^*\gamma^* \rightarrow$ hadrons, study of C-even resonances and search for exotic states.

The main source of background in the TS is the process of single Bremsstrahlung (SBS) at the colliding beam. The angular distribution of SBS electrons is more peaked at zero angle compared to that of electrons in $\gamma^*\gamma^*$ processes. 2D-readout at each TS station will improve the signal/background ratio by rejecting events with small vertical angles.

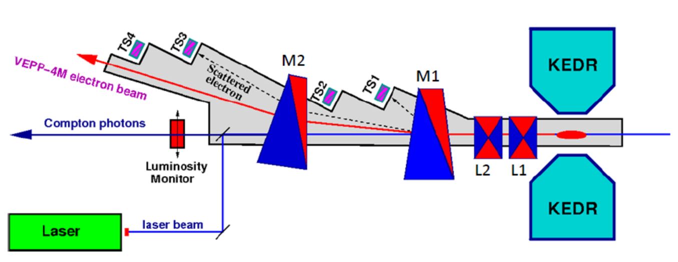

Fig. 1. Tagging System of KEDR experiment.
TS1-4 tracking stations are shown.
L1, L2 – quadrupole magnets;
M1, M2 – dipole magnets.

Each tracking station of the TS includes the hodoscope of drift tubes with triple-GEM detector in front of it. The hodoscope of drift tubes determines a track coordinate and angle in the collider orbit plane, the triple-GEM detector precisely measures two coordinates of a track. The system of GEM detectors was put into operation in 2010 and it is still working successfully.

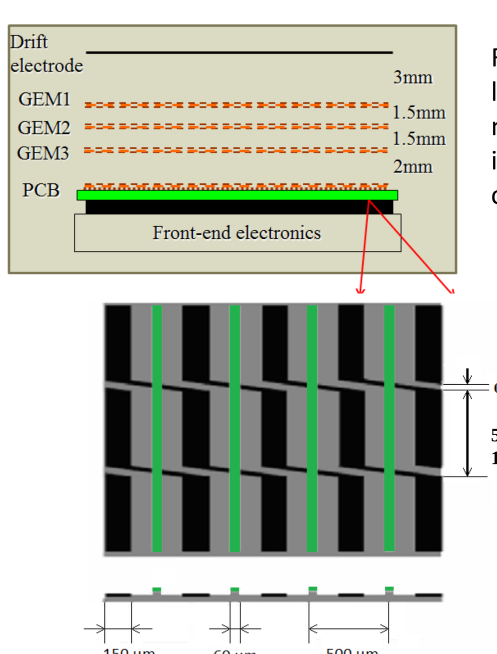

Fig. 2. GEM-detector for TS KEDR.

Readout structure of each triple-GEM detector has two layers of strips - the straight electrodes for a precise measurement of the coordinate in the orbit plane and the inclined (stereo) electrodes for the measurement of the coordinate in the perpendicular direction (Fig. 2).

Within a range of ±1 cm from the horizontal axis the angle between inclined and straight strips is 30° providing spatial resolution in vertical direction about 200 µm while the resolution provided by the straight strips is ~70 µm. Outside the region of ±1 cm around the horizontal axis the angle is about 11° that allows to get the resolution of ~1.5 mm in vertical (Fig. 3).

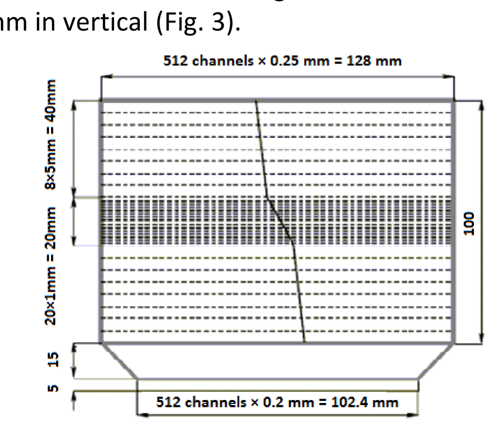

Fig. 3. Readout structure of GEM-detector for TS KEDR.

The whole system includes six triple-GEM detectors of 128x100 mm² with 512 analogue channels and two detectors of 256x100 mm² with 1024 analogue channels. The detectors have efficiency around and above 95% and operate at the gains between 20000 and 40000.

DEUTERON facility

DEUTERON facility was build for nuclear physics investigations. The experiments with DEUTERON facility (Fig. 4.) are carried out in the following way: the electron or positron beam in the VEPP-3 storage ring passes through the first correction magnet and hits the internal target of polarized protons or deutrons. Electrons that lost part of their energy in interactions with the target leave the equilibrium orbit due to the main dipole magnet and pass through the GEM tracking detectors. The veto counters S1 and S2 allow to reject background from single Bremsstrahlung events. The energy of electrons passing through the tracking detectors is in the range of 0.5 - 1.0 GeV, thus low content of material in these detectors is necessary to guarantee better momentum resolution.

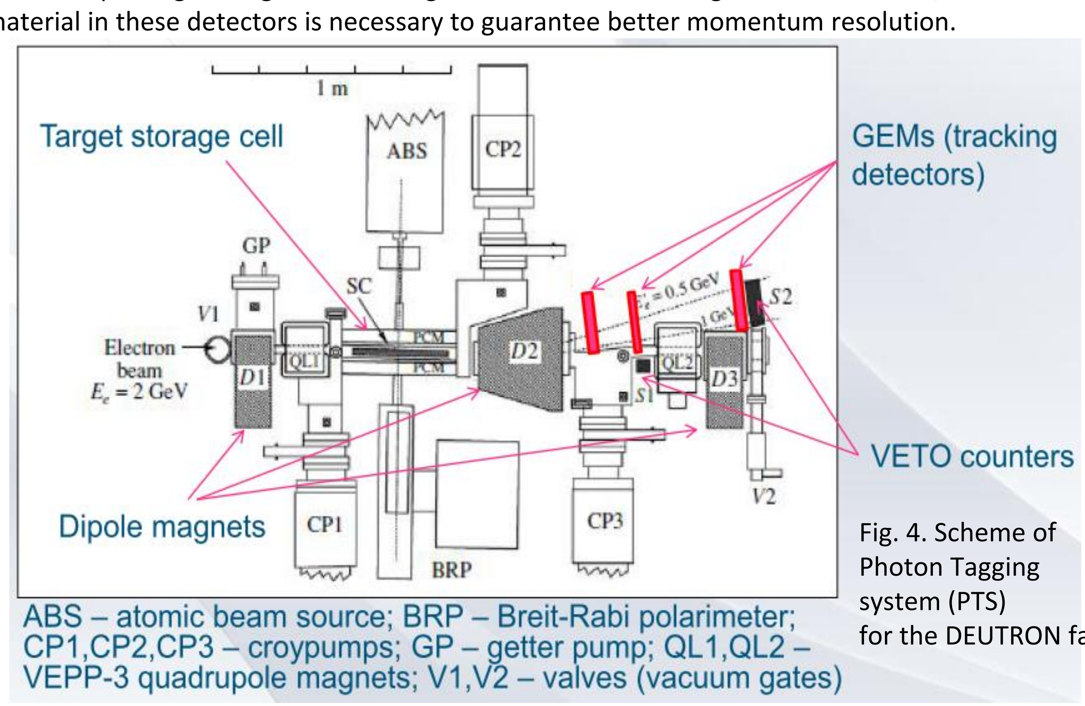

Fig. 4. Scheme of Photon Tagging system (PTS) for the DEUTRON facility

Triple-GEM detectors for PTS are assembled of light components. All GEMs are etched to reduce thickness of copper electrodes. The readout plane is prepared on a thin flexible plastic foil rather than on a glass fiber support. The final material budget of these detectors is reduced down to ~0.25% of radiation length. The general structure of the DEUTRON-PTS detectors (Fig. 5) is similar to that of the KEDR-TS ones. The drift cathode is made of 20 µm thick aluminised mylar. The readout structure has two layers of straight and inclined strips with the design similar to that of the inner part of the KEDR-TS detectors.

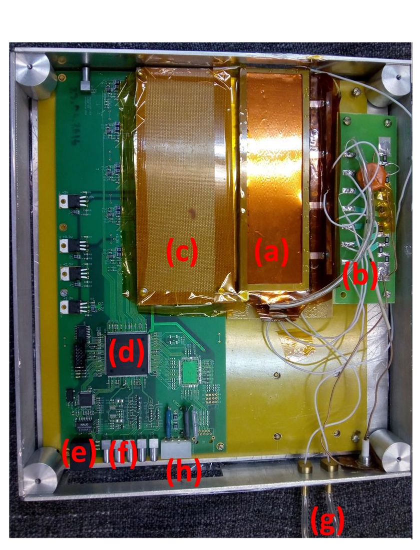

Fig. 5. Elements of Detector # 4 for DEUTERON facility:
(a) sensitive area 160mm×40mm,
(b) high voltage,
(c) front-end chips APC128 (covered),
(d) FPGA,
(e) Ethernet,
(f) trigger inputs,
(g) gas inlet-outlet,
(h) power ±5V.

The strip pitch in each layer is 0.5 mm and the layers are shifted with respect to each other by 250 µm. The stereo angle is 30° over the whole sensitive area.

Dimensions of the detectors are 160x40 mm² and they have 640 analogue electronic channels each.

In total four DEUTRON-PTS detectors were assembled.

Spatial resolution of the detector №3 was measured to be 46.6±11.1 µm [17].

Spatial resolution of the detector №4 was measured to be 38.5±9.3 µm [18].

Gain and efficiency of the detectors are shown in Fig. 6.

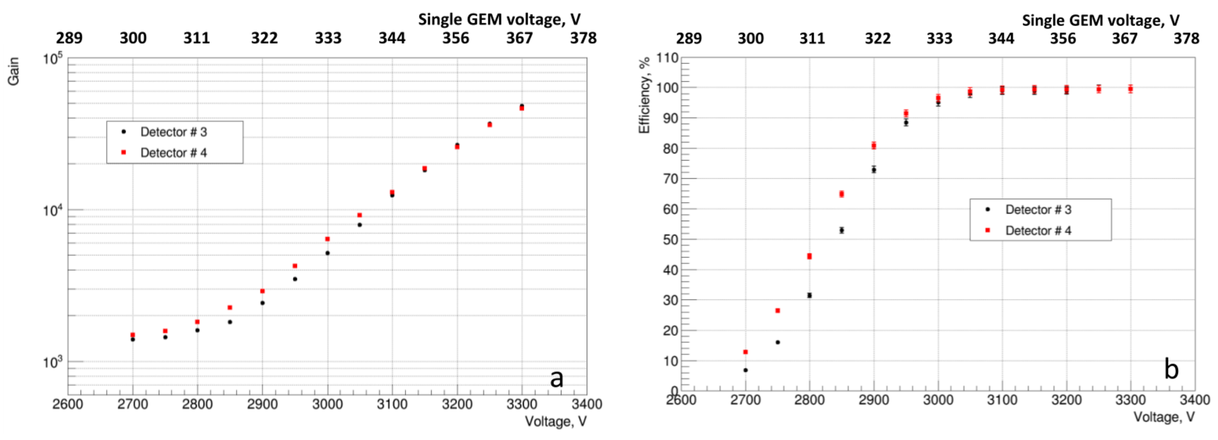

Fig. 6. Gain (a) and efficiency (b) as a function of single GEM voltage for two detectors measured with 2 GeV electrons at Test Beam facility of VEPP-4M collider.

Test Beam facility

Test Beam facility (TBF) (Fig. 7) was built at VEPP-4M collider for generation of test beams of electrons and photons in a wide range of energies. The function of the facility is to test detectors for particle physics. TBF has been operating since 2011. Four triple-GEM detectors will be installed for the upgrade of TBF.

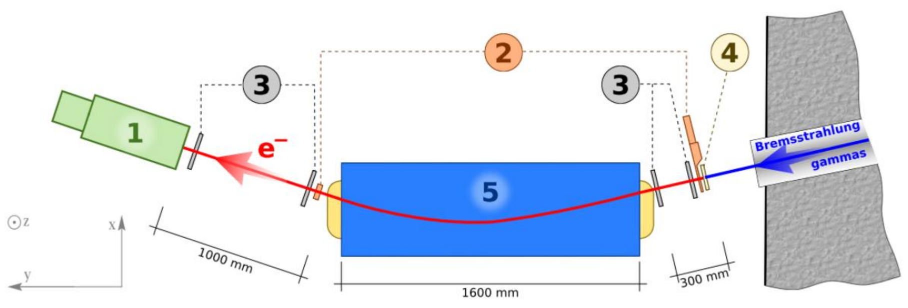

Fig. 7. Test Beam facility:
1 – BGO/NaI calorimeter;
2 – trigger scintillation counters;
3 – GEM detectors;
4 – iron target;
5 – bending magnet.

The detector design was finalized according to the results of simulation studies of the limits of spatial resolution of the GEM detectors [19], [20]. The first detector of TBF was put into operation in 2016: GEMs, flexible readout structures and electronics PCBs were made at the CERN Workshop. The detector was assembled at BINP. Spatial resolution of the first TBF detector was measured to be 31.5±8.4 µm.

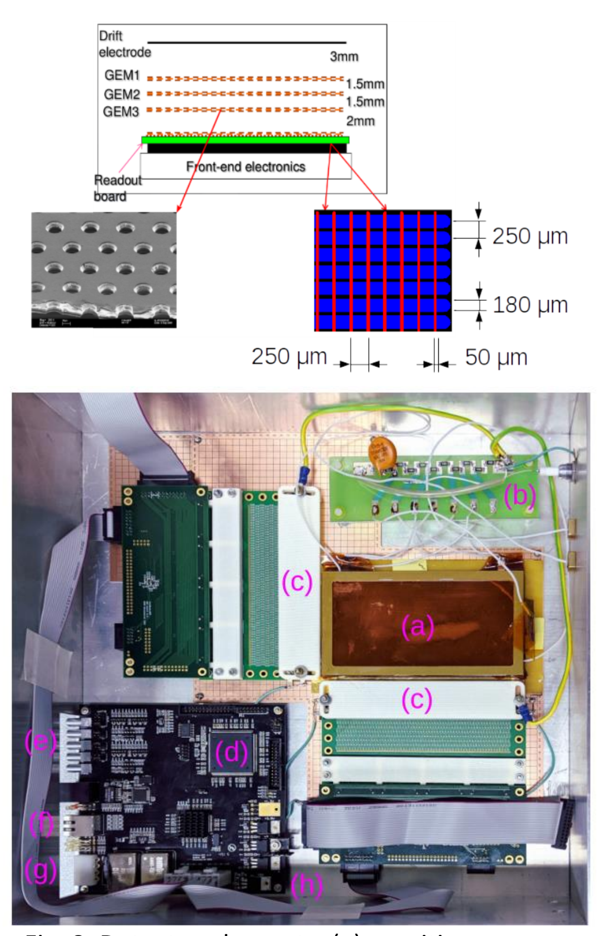

Fig. 8. Detector elements: (a) sensitive area,
(b) high voltage, (c) DAQ boards, (d) FPGA,
(e) trigger inputs, (f) 1GBit Ethernet,
(g) power +12V/1A, (h) analog power for DAQ boards.

The detector consists of a triple-GEM, orthogonal X-Y readout structure and detector electronics. Electronics is based on the APC128 ASIC, six of these chips are used covering 768 channels in total. These channels are connected to the readout structure, which has two layers: 512 vertical strips (red colored) and 256 horizontal strips (blue colored), both directions have a 0.25 mm pitch. Thus, the detector sensitive area is 128x64 mm² (Fig. 8).

In order to minimize multiple scattering the detector elements have a reduced thickness of copper down to 1-2 µm at each GEM side.

Ar(75%)-CO_2(25%) gas is used in the detector.

The triple-GEM detector with thinner copper layers can have the total amount of material seen by particles of ~0.15% of radiation length.

At present three of four TBF detectors have been assembled.

The second TBF detector was installed at the Test Beam facility and studied with the electron beam in February 2020.

Spatial resolution of the second TBF detector was measured to be 43.7±5.1 µm

Data taken during February 2020 runs show that the detector works well despite having several dead channels and detection efficiency reaches over 99.0% at the effective gain of ~ 3.5 · 10⁴ and 99.9% at the gain of ~ 4.5 · 10⁴.

Laser Polarimeter

Laser Polarimeter facility [21] at VEPP-4M collider (Fig. 9) is developed for beam energy calibration by Resonant Depolarization technique. The essential part of this facility is GEM-based detector (Fig. 10).

The existing facility is working well using the Touschek effect for measurement of polarization at the energies below 2 GeV. But at higher energies the efficiency of the Touschek polarimeter is rather small. For higher energies it was proposed to develop Laser Polarimeter which is based on the effect of up-down asymmetry of Compton back-scattering of circularly polarized photons by vertically polarized electrons. The difference of average vertical scattered angle for left and right circular polarization depends on the beam polarization.

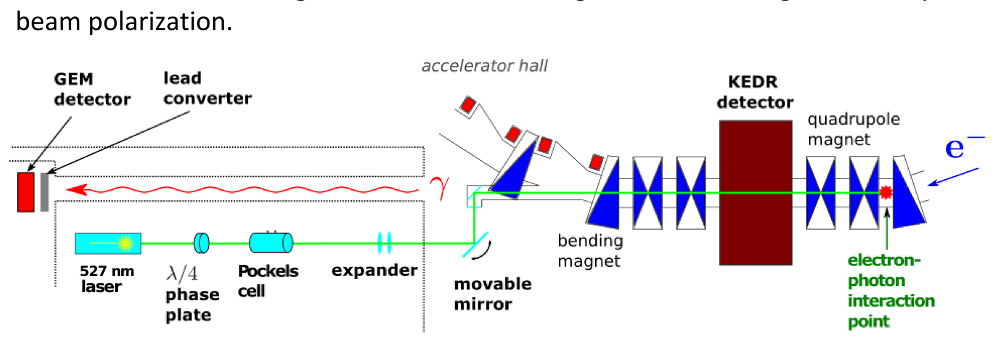

Fig. 9. Laser Polarimeter facility at VEPP-4M collider.

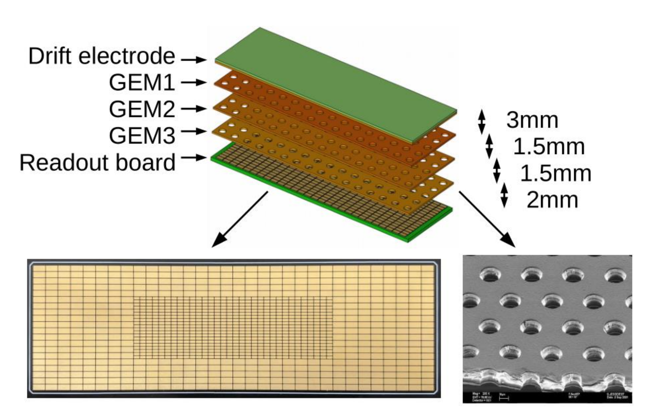

Fig. 10. GEM-detector for Laser Polarimeter.

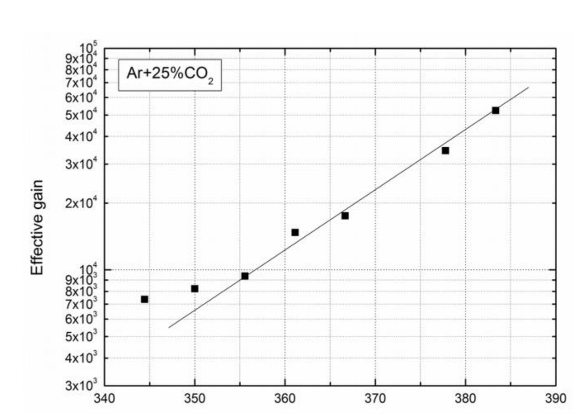

Fig. 11. Amplification factor of the detector as a function of voltage on single GEM.

The development of the design was started in 2015 and during 2018 the detector was finally assembled. The sensitive area of the detector is 128x40 mm² and consists of triple-GEMs with the pad readout structure. The readout structure is a rectangular grid of 1120 pads, which are 2x1 mm² sized in center and 4x2 mm² on the edge. The readout electronics is based on custom ASIC DMXG64A chip, developed at BINP. Gain on voltage dependence for the detector is shown in Fig. 11.

Upgrade of CMD-3 detector

CMD-3 (Fig. 12) is a general-purpose detector at VEPP-2000 collider intended to measure parameters of the light vector mesons.

CMD-3 contains a thin cylindrical Z-chamber. Present Z-chamber is the double-layer cylindrical MWPC that consists of three cylinders with cathode and anode readout.

Z-chamber has been operated for ten years at VEPP-2M collider with CMD-2 detector and for six years at VEPP-2000 with CMD-3. Hence, some of its parameters degraded with time and the upgrade of Z-chamber is needed.

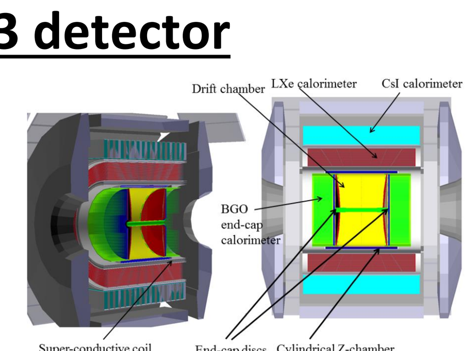

Fig. 12. CMD-3 Detector.

MPGD technology was chosen as the best technique for construction of the new Z-chamber. This choice was based on success of the KLOE-2 inner tracker project where cylindrical GEM technology was exploited. As the diameter of Z-chamber is larger than that of the KLOE-2 inner tracker, in order to facilitate the technology, we propose to make the new detector with microresistive WELL (µ-RWELL) structure, rather than triple GEM.

Z-chamber of CMD-3 detector is a triple cylinder with central cathode 630 mm in diameter and 750 mm long (Fig. 13). The inner side of the outer cylinder and outer side of the inner cylinder are covered with µ-RWELL on top of the double-layer strip readout structure. Strips that measure Z-coordinate follow with a pitch of 1.5 mm and trigger pads are oriented along Z-coordinate and have pitch of 15 mm.

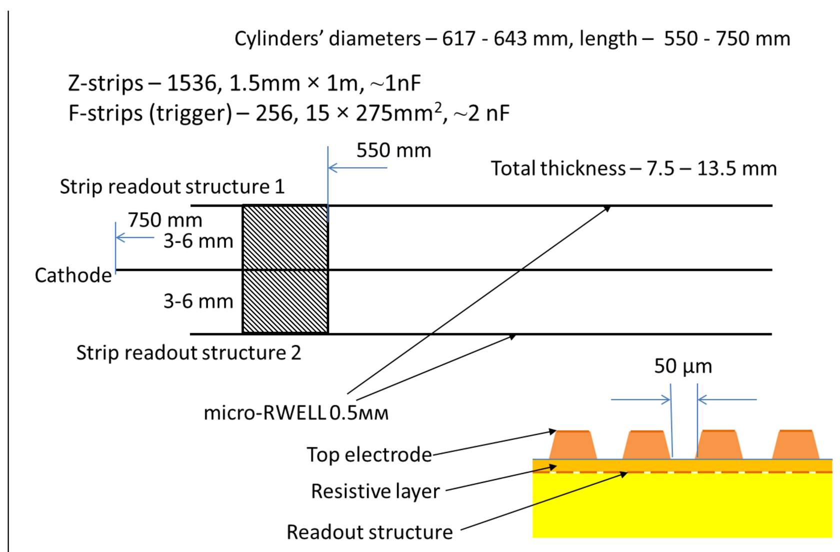

Fig. 13. Cross section of proposed cylindrical Z-chamber for CMD-3

End-cap discs based on µ-RWELL structures are proposed for the upgrade. End-cap discs will increase the acceptance of trigger for charged particles and improve the precision of track polar angle measurements. The CMD-3 end-cap discs have 50 cm diameter sensitive area with 10 cm diameter hole in the middle of the vacuum pipe. The sectors are divided in two groups: the area between R=5 cm and R=15 cm is divided into 144 sectors and the region from R=15 cm to R=25 cm has 288 sectors. The quarter-rings (Fig. 14) have 2 mm pitch in radius. Contacts to all electrodes are routed through inner layers of the readout PCB to the connectors at the disc edge.

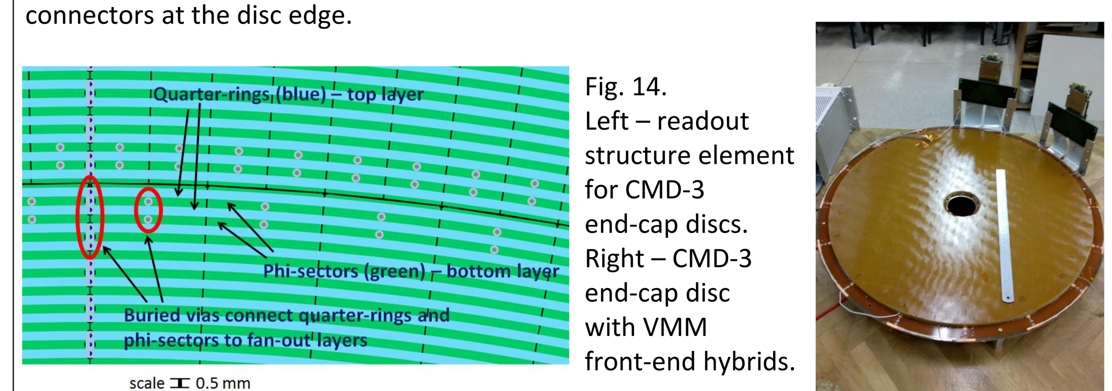

Fig. 14. Left – readout structure element for CMD-3 end-cap discs. Right – CMD-3 end-cap disc with VMM front-end hybrids.

First tests of 10x10 cm² µ-RWELL prototypes with different gas mixtures demonstrated the ability of this single-stage detector to provide gas amplification up to 20000 – 30000 (Fig. 15). However, to provide safe operation we either have to increase gas gap or to add the second amplification stage. The results of the gain measurements with GEM on top of the µ-RWELL are shown in Fig. 16. The final selection of the approach between wider gas gap (6 mm) or additional GEM will be done on the basis of tests of two prototypes of end-cap discs partly equipped with VMM-based electronics.

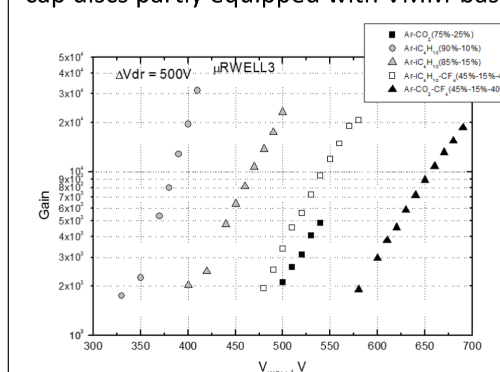

Fig. 15. Gain as a function of voltage on top electrode of µ-RWELL for different gas mixtures. Voltage across the drift gap is 500 V.

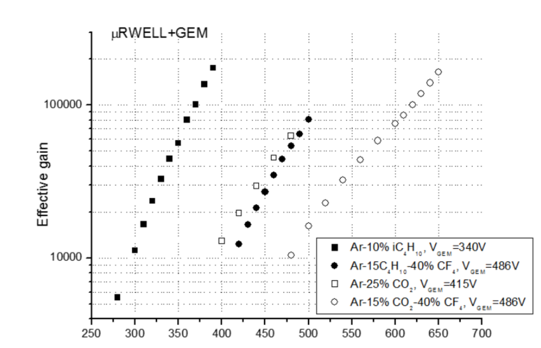

Fig. 16. Gain on voltage on top electrode of µ-RWELL for different gases. Transfer gap and drift gap are 3 mm. Voltages across the drift and the transfer gap are 500 V.

Inner Tracker of Super Charm-Tau Factory

End-cap discs and new Z-chamber for CMD-3 are considered as prototypes for the tracking system of the Super Charm-Tau Factory Detector (SCTD) (Fig. 17). SCT is electron-positron collider with "Crab-Waist" collision scheme, that will operate in the energy range of 1.5 - 3.5 GeV per beam, provide luminosity up to 10^{35} cm^{-2} s^{-1} and longitudinal polarization of electrons in the interaction point. Physics program of SCT requires construction of a general purpose magnetic detector with a field of about 1.5 T.

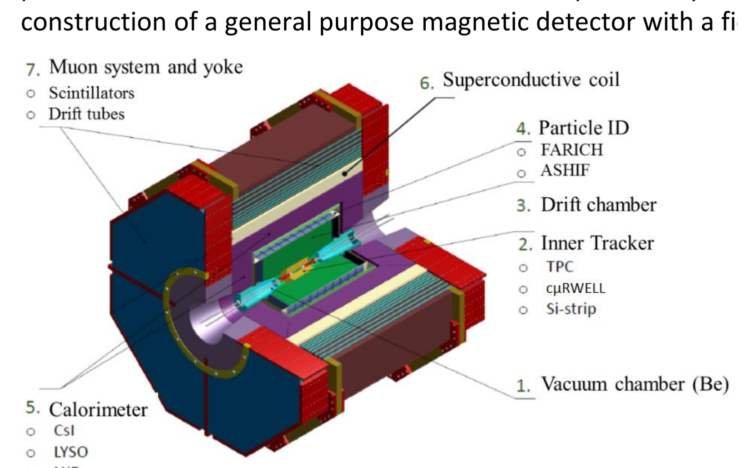

Fig. 17. Super Charm-Tau Factory Detector.

Different options for subsystems are indicated.

Inner Tracker of SCTD has to measure momenta of soft hadrons; complement the drift chamber in measuring the momenta; detect secondary vertices of short-lived particles. The simulation of charged pions propagation in the perpendicular direction to the beam axis was carried out with DD4HEP program based on GEANT4. Three options were considered: 4-layered Silicon microstrip detector, 4-layered cylindrical Gas Electron Multiplier (GEM) detector and Time Projection Chamber (TPC). The simulation results show that TPC with thin inner wall (Fig. 18) provides reconstruction of pions with momenta higher than 55 MeV/c. Hence TPC option of the Inner Tracker with thin inner wall is the most attractive one, because of the lowest threshold for low momentum hadrons and the possibility to use energy deposition along a track to distinguish between low momentum hadrons and background electrons and positrons.

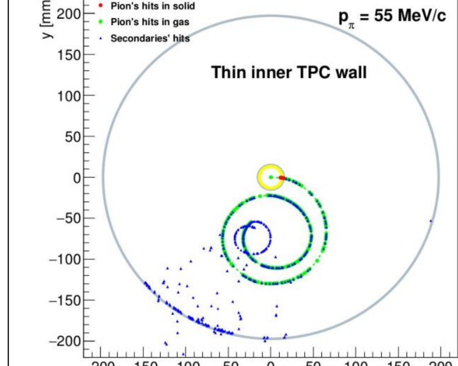

Fig. 18. Simulation (GEANT4, DD4HEP) of pion passing through TPC with thin inner wall (50 µm Kapton + 100 µm Teflon + 5 µm Copper).

Gas Ar(80%)-CO_2 (20%).
Magnetic field 1.5 T.

Pion was gun perpendicular to beam axis.

TPC operation depends on positive Ion Back Flow (IBF) from the readout end-caps to the main field cage, that is determined by the background particle flux in the region of the Inner Tracker. The simulation of the background created by electron-positron collisions in the SCTD was described in [22]. We performed the simulation of electric field distortion due to space charge of ions for a given background, IBF of 1% and for different gas mixtures [16]. The simulation shows that the deviations of drift lines in Ar is about 1.5 mm, what is comparable with transversal diffusion on the path of 30 cm, and these track deviations can be compensated in analysis of experimental data.

References

[1] L.I. Shekhtman et al., Development of high resolution tracking detectors …, 2014 JINST 9 C08017.
[2] L.I. Shekhtman et al., High resolution micro-pattern gas detectors for particle …, 2017 JINST 12 C07037.
[3] F. Sauli, GEM: A new concept for electron amplification …, Nucl. Instrum. Meth. A 386 (1997) 531.
[4] V.M. Aulchenko et al., Upgrade of the KEDR tagging system, Nucl. Instrum. Meth. A 494 (2002) 241.
[5] V.M. Aulchenko et al., Operation of the triple-GEM detectors in the tagging …, 2011 JINST 6 P07001.
[6] D.M. Nikolenko et al., Experiments with internal targets …, Phys. Atom. Nucl. 73 (2010) 1322.
[7] V.N. Kudryavtsev et al., The development of high resolution coordinate detectors …, 2014 JINST 9 C09024.
[8] G.N. Abramov et al., Extracted electron and gamma beams in BINP, 2014 JINST 9 C08022.
[9] G.N. Abramov et al., Measurement of the energy of electrons extracted …, 2016 JINST 11 P03004.
[10] V.E. Blinov et al., Laser Polarimeter at VEPP-4M, 2017 JINST 12 C08020.
[11] V.V. Kaminskiy et al., The GEM-based detector for tracking …, 2020 JINST 15 C08019.
[12] L.I. Shekhtman et al., Development of µ-RWELL detectors …, Nucl. Instrum. Meth. A 936 (2019) 401.
[13] G.V. Fedotovich et al., Application of micro-pattern gas …, 2020 J. Phys.: Conf. Ser. 1498 012042.
[14] https://ctd.inp.nsk.su/c-tau/
[15] V.K. Vadakeppattu et al., Time Projection Chamber as Inner Tracker …, 2020 JINST 15 C07021.
[16] T.V. Maltsev et al., Simulation of different options of the Inner …, EPJ Web Conf. 212 (2019) 01011.
[17] V.N. Kudryavtsev et al., Study of GEM-based detectors …, 2020 J. Phys.: Conf. Ser. 1498 012005.
[18] V.N. Kudryavtsev et al., Spatial resolution of the detectors …, 2020 JINST 15 C05018.
[19] V.N. Kudryavtsev et al., Study of spatial resolution …, Nucl. Instrum. Meth. A 845 (2017) 289-292.
[20] V.N. Kudryavtsev et al., Limits of a spatial resolution …, 2017 JINST 12 C06015.
[21] V.E. Blinov et al., Status of laser polarimeter at VEPP-4M, 2020 JINST 15 C08024.
[22] L.I. Shekhtman, et al., Simulation of physics background …, EPJ Web Conf. 212 (2019), 01009.