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TPG, a cylindrical imaging gas detector with high transparency in the axial direction

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1. Introduction

This note discusses an imaging cylindrical gas detector (called TPG) first proposed at the meeting of the MICE Collaboration held from 5–8 February 2002 in Chicago in order to meet a demand of the MICE experiment[1]. MICE needs two devices capable of measuring both position and momentum of individual traversing particles. One detector module would be positioned upstream of a sector of transverse cooling channel bombarded by a muon beam. A second identical module would be installed downstream the cooling channel. For each muon traversing the cooling channel, the two detectors should provide position and momentum in two planes orthogonal to the beam direction.The ensemble of these measurements for a large set of muons would permit to measure the beam emittance before and after the cooling section, and hence to measure the cooling effect. These measurements require from the detector good spatial and momentum resolution in the transverse plane and minimum contribution to multiple scattering.

The TPG structure is shown schematically in fig. 1. The proposed detector exploits the TPC operation principle and fields configuration[2]. It uses GEM foils[3] in the amplification region. It is equipped by a read-out foil covered by small hexagonal pads[4] that face the last GEM foil and are connected each to either a u, or a v or a w strip (the u, v, w strips are oriented at 120° to each other, run at different depths along the read-out multilayer foil and are connected via preamplifiers to FADC electronics). The acronym TPG is used for brevity to remind the first two (TPC and GEM) of the three techniques mentioned above. Beam particles that traverse the detector cross only thin foils and the detector gas. All structural lumped materials are resident on the detector radial periphery. The pads are small and uniformly distributed on the read-out foil. Materials in the gas containment windows, in the GEM foils and inside the read out foil are uniformly distributed as well.

The TPG features:

- a minimum and uniform amount of material intercepted by a beam of particles directed along the detector axis (z direction)
- a uniform response for all beam particles entering the detector independent on the distance from the detector axis of their entrance point
- high spatial resolution in the transverse plane
- complete tridimentional imaging of trajectories of throughgoing particles
- dE/dx capability

A charged particle traversing the TPG without decaying follows a helical trajectory in the volume of the detector. The transverse momentum of the charged particle is given by

$$P_{\perp} \cong \frac{DB}{600} \tag{1}$$

where $P_{\perp}$ is expressed in GeV/c, D is the diameter of the helix projection on the pad plane expressed in cm, B is the magnetic field of the solenoid expressed in Tesla.

The longitudinal momentum is given by

$$P_{\parallel} \cong \frac{L}{300}\frac{B}{\Theta} \tag{2}$$

where L is the length of th TPG active volume(distance between the HV plane and the first GEM foil) expressed in cm , and Θ is the helix angle expressed in radians. If $\Theta \geq \pi$ the helix projection is longer then half a circumference and D can be determined directly as the maximum distance between any two measured points of the helix projection onto the pad plane. To enable this simple and direct determination of D it is necessary to choose L so that

$$L \geq 300\frac{\pi}{B}P_{max} \tag{3}$$

where P_{max} is the maximum beam momentum. Under these conditions the accuracy for the determination of the transverse momentum is controlled by the TPG position resolution in the read-out plane, since

$$\frac{\triangle P_{\perp}}{P_{\perp}} = \frac{\triangle D}{D} = \frac{2\sigma_{\perp}}{D} \tag{4}$$

In the following we discuss in some details aspects of the TPG structure, operation, and expected performances. We will use parameters relevant for the MICE scenario. However the TPG properties might be interesting also for other cases more demanding than in the foreseen MICE scenario, where a high detector transparency is required only after the TPG read-out plane. In terms of transparency the TPG structure has properties complementary to those of SPC detectors[5], which are cylindrical gas imaging detectors that offer maximum transparency in the radial direction.

2. TPG structure

The active volume of the detector is a cylinder with the diameter of the disk covered by pads of the read-out foil. The active volume extends from the first GEM foil to the HV foil. A series of circular electrodes positioned on the internal wall of the TPG container between the GEM 1 foil and the HV foil assures a constant uniform drift electric field E parallel to the TPG axis inside the active volume. The GEM 1 and HV foils are positioned far enough from the extremities of the solenoidal magnet, so that the magnetic field B is parallel to E and of constant value everywhere inside the active volume. The read-out foil is at ground potential. Gas seal is provided radially by the cylindrical container of the TPG, and at the two extremities by thin foils. On the read-out side the gas containment foil is at ground potential. On the HV side it is set at HV and followed at a convenient distance by a second foil at ground potential. Gas, HV and GEM foils are supported by rings with internal diameter equal or larger than that of the read-out foil disk covered by pads. The front-end electronics is located immediately outside the solenoid. The electronics, the associated cabling, HV cabling and gas piping are all positioned at radial distances larger than the radius of the active volume. The material budget of the TPG for particles traversing it in the axial direction is then solely due to the foils and the detector gas. A He based gas mixture as employed in KLOE[6] can be used to minimize the detector thickness. Preliminary parameters relevant for the design of the MICE-TPG are given in table 1. Notice that in the application foreseen for MICE the material budget upstream of the GEM 1 foil is not too relevant since a scatterer is put near the entrance (read-out side) of the first TPG to enhance the transverse momentum of muons before they enter the cooling channel, and muons enter the downstream TPG from the HV side.

3. TPG operation

The principle of operation of the TPG is basically that of the TPC. Clusters of electrons of primary ionization generated in the active volume (by througoing ionizing particle, or by X-ray absorption, or γ conversion in the chamber gas) move under the action of the drift electric field towards the amplification region. The magnetic field B parallel to the drift electric field reduces transverse diffusion.

Amplification occurs in cascade in the GEM foils. Using GEMs in the amplification region introduces several advantages[3]. Since the amplification field is in average parallel to the magnetic field, $\vec{E} \otimes \vec{B}$ effects that could otherwise affect spatial resolution are absent. Since positive ions are collected mainly onto the GEM electrodes, space charge effects in the drift active volume are minimized. Since the density of holes in the GEM foils is larger than that of the read-out pads, the amplification process is more distributed than the charge collection process. Last but not least GEM foils are more convenient than wires for construction and operational reasons: gain, noise, breakdown probability, sustainable rates, easiness of installation. In ref.[7] are described comprehensively the performances achieved few years after the invention of the GEM structure[3]

Electrons emerging after multiplication from the third GEM impinge onto the read-out foil and are collected directly by the underlying pads. Fig.2 shows the three dimensional structure of the read-out foil. This structure has been developed for planar GEM detectors used for high rate X-ray imaging applications[4] to reduce ambiguities, that originate in a bidimentional read-out when more than one hit is present in the read-out time window.

When a planar detector is hit simultaneously in n different locations (x_i, y_i), the data acquisition records n x_i values and n independent y_j values, and there are n^2 possible localizations (x_i, y_j) of the physical hits, that generate a large number of ambiguities. By using 3 sets of N strips u, v, w, the number of ambiguities is reduced by a factor N because, for any crossing of two strips of two different sets of strips [(u, v), or (u, w), or (v, w)], there is only one out of the N strips of the third set [w or v or u] that belongs to that crossing. This way one can get a granularity of order N^2 in the read-out plane, by utilising only $3N$ electronics channels.

Ideally one would prefer to instrument each individual pad with an independent electronic channel. This way multihits would be no more a problem, as long as the probability that two particles cross the same pad is negligible. However in the case under consideration small and evenly distributed pads are necessary to ensure identical conditions of measurement for all particles, no matter their distance from the detector axis and the direction of their transverse momentum. Under these circumstances, equipping each single pad with a preamplifier and FADC read-out channel would become very hard, because of the too high density of connections that should run along the read-out plane, and economically not affordable, because of the high number of pads (about 800.000 per TPG in the MICE-TPG case). Notice that in classical TPCs used in e^+e^- colliding beam experiments and at extracted beams, pads are elongated and organized in rows concentric to the chamber axis and pattern recognition efficiency and momentum resolution are optimized for tracks emerging from the chamber axis, because particles to be measured originate from the fiducial volume in the center of the detector.

TPG electronics differs from that used in high-rate GEM detectors with bidimentional read-out, because in the TPG case each strip is equipped with FADC read-out electronics, that permits to sample and record the strip signals during a time window exceeding the maximum drift time in the chamber. This permits to slice the TPG active volume along the z drift direction in slices with thickness $\delta z = v_d \delta t$, were δt is the FADC sampling time. Z slices have a thickness δz exceeding 5 mm with 100 $nsec$ FADC sampling time and with typical gas mixtures, that feature $v_d \leq 5$ cm μsec^{-1} . Consecutive Z slices are intercorrelated because the shaping time of the preamplifiers is typically longer than the sampling time. In other words the (x, y) images of consecutive Z slices are similar, like two consecutive images of a movie.

Triple GEM detectors with 3 mm drift gap operated at NTP with Ar/CO_2 70/30 gas filling feature full efficiency and signal over noise ratios in access of 10 for minimum ionizing particles of a beam traversing with normal incidence the detector read-out and GEM foils. Under these circumstances each particle generates a spray of electrons impinging onto the read-out plane with typical transverse size of about 2 mm^2, because two to five contiguous strips with 400 μm pitch in the two x,y orthogonal direction have signals above threshold[7]. The first slice of the TPG near the GEM-1 foil behaves exactly as the drift region of triple GEM detectors. Since FADC electronics with more than 100 nsec sampling time receives in each time sample signal from a Z slice thicker than $5mm$, we expect full efficiency for minimum ionizing particles for each Z slice of the TPG active volume. Hence for each helical trajectory described by a prong traversing the TPG, we expect signal from each Z sector of the TPG active volume and then a number of n helix points given by $n = L/\delta z$.

Let us call helicoid the tridimentional object made by the ensemble of elementary volumes that have for base a hit hexagonal pad positioned at $z = v_d t_1$ and for height above that pad $v_d(t_2 - t_1)$, where t_2 and t_1 are final and initial time over threshold for the pad signal. The helicoids have a thin transverse size at their head (at $t_1 = 0$), because transverse diffusion is there at minimum and the number of contiguous pads at z=0 is low. The helicoid transverse size grows with increasing z, because of transverse diffusion, which is however contained, since the confining magnetic field B is parallel to the drift electric field. A helix is contained inside the associated helicoid. The (x_i, y_i, z_i) coordinates of n points of the helix are given by $z_i = i v_d \delta t$ and by the x_i, y_i center of each helicoid slice i. In absence of noise and ambiguities, the x_i, y_i coordinates can be obtained

a)by the centroid of the contiguous hit strip signals or

b)by the center of gravity of the signals of contiguous hit strips, if the amplitude calibration of the strips is satisfactory and the gains of all channels are equalized.

In case b) position resolutions better than 100 μm in both x and y directions have been achieved with pads read out via strips in large square GEM chambers[7] , and with pads read out individually in prototype drift chambers instrumented with GEMs and pads read out by individual electronic channels[8].

Each track that traverses the TPG generates primary electrons along the helical trajectory and the helical cloud of electrons takes a time T (maximum drift time) to traverse the GEM planes and to absorbed, after multiplication, by the read-out plane. If I is the average intensity of a beam of charged particles that traverse the TPG, in any FADC drift time bin there are on average IT segments of helical clouds that generate after multiplication spots of electrons hitting adjacentc pads in the read-out plane. Each spot is associated to a certain number of contiguous u, v and w strips. This number varies depending on the transverse momentum of the particle, its mass and momentum, its inclination with respect to the strip set and the distance from the beginning of the helix. It will vary from a minimum of 2 to more than 10. Let us call w the average width of a cluster of contiguous strips firing in association to a charge particle. The total number of strips firing during any drift time bin will then be wIT. Efficient suppression of ambiguities requires that $wIT < N$, where N is the total number of u (and v, and w) strips.

If we display all TPG signals of one set (u, or v, or w) of strips in a (time,strip number) plane, helicoid projections will generate sinusoidal patterns. These sinusoidal snakes begin at different times corresponding to different traversal times of the particles through the GEM-1 plane. They have the same total length in time given by the maximum drift time T. The end tail of each snake corresponds to the time of traversal of the HV foil by the particle. Longitudinal diffusion gives some smearing of T.

If the TPG read-out is triggered at a given time (e.g. in the MICE case in coincidence with the RF pulse), individual traversing particles can be identified in three dimensions by their helicoid, and in two dimensions by their u,v and w snakes and ordered and classified in space and time according to the x,y and t values of the helicoid heads.

When two snakes cross in one (drift time, strip number) plane, the (drift time, strip number) bins that are in common cannot be used for centroid nor for center of gravity determinations, but may still be useful for reducing ambiguities in strip crossing of strips of the other two strip sets.

Notice that the amplitude of the sinusoid of a given snake gives directly the transverse momentum of the parent particle and the total phase advance its longitudinal momentum. This information can be used, in case of low intensity beams, which generate small occupancy in the (drift time, strip number) plane, for online beam diagnostics to monitor immediately a particle transverse momentum from the total number of contiguous hit strips, provided the phase advance is $\theta \geq \pi$.

4. TPG expected performances

4.1. Particle identification

Tracks of charged particles moving through the TPG generate connected patterns (helicoid in three dimensions, snakes in the drift time versus strip number planes) that can quickly be identified by a pattern recognition based on the simple topological requirement that associated hits are contiguous in space.

Tracks of beam particles traversing the TPG have a length T in total drift time, while tracks due to electrons and positrons from γ conversions in the chamber gas are shorter and can be easily discarded. Furthermore tracks due to electrons and positrons from conversions will have in the MICE scenario a large phase advance because the longitudinal momentum is one to two order of magnitude smaller than for muons of the beam.

Patterns due to X-ray absorption will be very short in the total drift time.

Particles decaying in the TPG active volume can be easily identified and discarded because of a visible kink in the relative helicoid and in the (u,t),(v,t) and (w,t) sinusoids.

Useful π ,μ , e separation for incoming beams with less than 500 MeV/c momentum is provided by dE/dx, since truncated mean techniques can be applied (with more than 100 samples in the MICE case).

4.2. Spatial resolution

The x, y plane at $z = z_{GEM1} = 0$ is the place where the transverse spatial resolution is optimal (no diffusion). $\sigma_{x,y} \leq 100\ \mu m$ is a reasonable target for a well calibrated TPG.

4.3. Momentum resolution

Assuming an average $\sigma_{x,y} \leq 200\ \mu m$ over all helicoid points to take into account diffusion and multiple scattering contributions for helicoid tail signals, a momentum resolution of the order of 1% appears achievable for $P_{\perp} = 30 MeV/c$ in the anticipated MICE scenario. The transverse momentum cannot be measured very accurately for particles with $P_{\perp} \leq 1 MeV/c$, that are however already too cold for deserving further transverse cooling.

4.4. Transparency

In the MICE scenario the relevant TPG thickness is $3\ 10^{-3}\ X_0$, since the entrance gas window and the read-out and GEM foils do not affect the measurements. It will be convenient to have H_2 gas at NTP along the cooling channel downstream of the HV gas window of the entrance TPG.

4.5. Rate tolerance

In the MICE scenario the instantaneous beam rate I during RF pulse is limited by the condition $wIT < N$. With $w = 6$ end $T \sim 50\ \mu sec$, the advisable beam rate during RF should be around $I \leq 10^6 sec^{-1}$

5. Acknowledgements

6. References

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[8] D.Karlen et al., http://www.physics.carleton.ca/ Karlen/gem

7. Tables

Solenoid		
B	magnetic field	4 Tesla
TPG		
L_{TPG}	length of TPG gas volume	130 cm
$ø_{TPG}$	TPG external diameter	40 cm
ø	active volume diameter	30 cm
L	active volume length	100 cm
GEM foils		
ø	active area diameter	30 cm
l_G	foil thickness	50 μm
d	spacing between GEM foils	2 mm
$ø_h$	GEM holes diameter	70 μm
p_h	GEM holes pitch	150 μm
Read-out foil		
$ø_F$	diameter of area covered by pads	30 cm
l_F	foil thickness	200 μm
d	distance from first nearby GEM foil	2 mm
$ø_p$	diameter of circle containing one pad	300 μm
p_s	pitch between strips	500 μm
$N = N_u = N_v = N_w$	number of strips	600
Material budget		
X_{foils}/X_0	thickness of all TPG foils	$6.3\ 10^{-3}$
X_{gas}/X_0	$1.3\ m\ He/C_4H_{10}\ 90-10$	$1\ 10^{-3}$
Electronics		
δt	FADC sampling time	100 $nsec$
v_d	drift velocity	$\sim 5\ cm\mu sec^{-1}$
δz	thickness of Z slice	$\sim$5 mm

Table 1. MICE-TPG indicative parameters

8. Figures