Abstract. The experiment BESIII, running at the accelerator BEPCII in Beijing (P.R.C.), is going to be updated with the replacement of the Inner Drift Chamber with a Cylindrical triple-GEM Inner Tracker (CGEM-IT). In the R&D stage, two standalone C++ codes were implemented: GTS (Garfield-based Triple-GEM Simulator), for digitization and tuning of simulated data to the experimental ones, and GRAAL (GEM Reconstruction And Analysis Library), for the reconstruction and analysis of the experimental events collected in testbeams. GTS simulates the triple-GEM response to the particle passage, treating each stage separately: ionization, GEM properties, gas mixture, magnetic field and finally the induction of the signal on the anode. The necessary information was extracted by GARFIELD++ simulations, parametrized and used as input in GTS. This speeds up the simulation, since GTS performs only samplings instead of the full digitization chain. The simulated events were reconstructed with the same procedure used for experimental data and tuning factors were evaluated to obtain a satisfactory match. GRAAL is used in the analysis of the testbeam experimental data. It provides several levels of reconstruction: from the cluster formation, gathering contiguous firing strips, to the spatial position and the signal time reconstruction. Two algorithms are used: the charge centroid and the micro-TPC, which exploit the charge deposition on the strips and the time information. Also a merging of the two algorithms is available to efficiently weight the two outcomes and obtain the best estimate of the spatial coordinate. Moreover, GRAAL performs tracking and alignment. Both codes are going to be made available also for other MPGDs simulation and reconstruction.
1. Introduction: CGEM-IT project in BESIII

The BESIII (BEijing SPECTrometer III) experiment [1] is a charm - τ factory installed in the interaction point of the BEPCII (BEijing Electron Positron Collider II) e+e− collider in Beijing, P.R.C. [2]. The accelerator upgrade was completed in 2004: the first test run took place in 2008 and the data taking begun in 2009. The center of mass energy in the range 2 − 4.6 GeV is tuned to grant BESIII with the accessibility of a wide range of physics topics:

- charmonium spectroscopy,
- open charm physics,
- light hadron physics,
- XYZ states,
- form factors and QCD tests,
- τ physics.

BESIII is one of the most important players on the XYZ research scenario and has the biggest sample of J/ψ ever collected, with 10 billion events.

The spectrometer surrounds the interaction point as it is shown in fig. 1 and is composed by:

- a superconducting solenoid, with a field of 1T,
- a Time Of Flight detector, with a time resolution of $\sigma_t = 80/90$ ps (barrel/endcap),
- a Main Drift Chamber, with a position resolution of 130 µm in xy plane and 2 mm in the z coordinate. The momentum resolution is $\Delta p/p = 0.5\%$ at 1 GeV/c,
- a CsI(Tl) Electromagnetic Calorimeter, with an energy resolution $\Delta E/\sqrt{E} = 2.5\%$ and 5% in the barrel and endcap respectively, at 1 GeV,
- an RPC Muon chamber, with a spatial resolution $\delta_{r\phi} = 1.4 − 1.7$ cm.

The luminosity reached the design value of $1 \cdot 10^{33}$ cm$^{-2}$ s$^{-1}$ in 2016. Due to the continuous increasing of luminosity, the MDC was subjected to intense radiation doses. This led to a problem of aging for the innermost layers, with a gain loss of about 4% per year, as shown in fig. 2. Since the MDC is composed by two independent drift chambers, inner and outer, sharing the same He-based gas mixture, and the aging affects mostly the inner chamber (IDC), then the collaboration decided to replace the IDC with a new, upgraded, inner tracker: the CGEM-IT, Cylindrical GEM Inner Tracker. The CGEM-IT is built by three layers, each one consisting
in a triple-GEM tracker (see fig. 3).

GEM (Gaseous Electron Multiplier) were invented by Fabio Sauli in 1997 [3]. A GEM foil is a polymeric foil (kapton, 50 µm thick) covered on both sides by a copper layer (3 – 5 µm thick). On the foil, thousands of tiny holes (with a diameter 50 µm) are created with a photolithographic technique (see fig. 4 and fig. 5) When a voltage difference of some hundreds of Volts is applied to the copper layers, an electric field of some tens of kilovolts per centimeter is created inside the holes. The GEM foil is placed inside an electric drift field which drives the electrons generated by ionization into the holes where they undergo avalanche multiplication. Often, more foils are stacked together in order to reach gains of the order of $10^4$ – $10^5$ with lower voltages, thus lowering the discharge rate. In the CGEM-IT, three layer of triple-GEM are assembled together, so three stages of multiplication are used in each of them.

The BESIII CGEM-IT is the second detector of its kind in the world, the first being the one build and used in KLOE-2 (Laboratori Nazionali di Frascati, Italy [4]). The construction technique is in fact inherited from the first CGEM, but some features were improved. For example, the analogue readout was introduced and a custom ASIC chip was designed (TIGER [5, 6]) to readout both charge and time of each firing strip and be able to apply two different algorithms for position reconstruction.

The software written to perform digitization and tuning of the simulation to experimental data as well as the one used in the reconstruction of the testbeam collected events will the object of the next sections.

**Figure 3.** Scheme of the CGEM-IT.

**Figure 4.** Microscopic view of a GEM foil.

**Figure 5.** Section of a hole: yellow is kapton, green is copper.
2. GTS: digitization

In the R&D stage of the realization of a new detector, simulations are a key tool to infer the performance of the detector in working conditions. In particular, a custom software which reproduces the response of the detector to the passage of particles is necessary. It must resemble the results obtained during testbeams in order to be validated and to provide reliable predictions about the performance of the detector in conditions different from the ones tested on beam.

In the case of a GEM-based detector, the starting point is the ionization of the gas produced by the charged particle and the final outcome is the signal formed on the anodic plane. Existing tools such as GARFIELD++ [7] provide a complete simulation of all the physical processes involved up to the signal formation, with a description of the avalanche multiplication at microscopic level. The counter part of such a detailed simulation is that it is CPU-time consuming and so it is not possible to embed it in the simulation package of the offline software of the experiment. To cope with this problem, a more agile software, named GTS (Garfield-based Triple-GEM Simulator) [8, 9], has been developed, to model the behavior of some variables of interest with respect of some key parameters as the applied high voltage, the electric field, the gap dimensions, the possible presence of the magnetic field etc.

As already described in literature [10], the simulation of the whole chain from the ionization to the signal formation can be divided in four independent steps. For each step, the starting point is a simulation run with GARFIELD++ in the relevant portion of the triple-GEM and with only the processes of interest switched on, in order to extract the parameters on which GTS simulation will be based. The geometry and the electric field have been implemented using ANSYS [11]. The triple-GEM relevant geometric and electric characteristics used in the CGEM-IT are summarized in tab. 1.

### Table 1. Triple-GEM characteristics of the CGEM-IT.

| parameter       | value                      |
|-----------------|----------------------------|
| gap thickness   | 5/2/2/2 mm                 |
| high voltage    | 275/275/275 V              |
| fields          | 1.5/3/3/5 kV/cm            |
| gas mixture     | Ar:i-C$_4$H$_{10}$ (90:10) |
| mag. field      | 1 T                        |

The four stages that GTS simulates are:

1. **Ionization** - When a charge particle passes through the gas, it creates electron-ion pairs. If the electron has enough energy, it can create further ionizations and secondary electrons. The number of primary and secondary ionizations and their position along the ionizing track are evaluated with GARFIELD++ simulations of the drift gap. In GTS, the ionization positions are extracted from an exponential function, since, being the ionization a Poissonian process, the inter-cluster distance along the track follows an exponential distribution. The number of ionizations follows directly from this sampling while the number of secondary electrons per each primary cluster is extracted from GARFIELD++ simulations. In this stage, two approximations are applied: the ionization electrons are generated only in the drift gap, the secondary electrons have the same origin as the primary ones.

2. **GEM properties** - A GEM can be fully described by its transparency and its gain. The transparency is defined as the product of the collection efficiency and the extraction
efficiency. The collection efficiency is the ratio between the number of electrons entering the holes divided by the number of generated electrons before the GEM foil. The extraction efficiency is the ratio between the number of electrons exiting from the hole divided by the number of electrons inside the hole, generated in the avalanche. Typical values of transparency for a GEM foil are around $60 - 70\%$, but that depend on the electric field applied in the gaps before and after the foil itself. 

GARFIELD++ simulations have been run, by shooting ten thousand electrons from a plane placed 150 $\mu$m before the GEM and counting the number of electrons which arrive up to a plane placed 150 $\mu$m after the GEM. Only the drift of the electrons is considered, without the gain multiplication effect.

The gain is the multiplication of the number of electrons due to the extreme electric fields in the holes. The fluctuations follow the Polya distribution written in eq.(1)

$$P(G) = C_0 \left(\frac{1 + \theta}{1 + \theta} \right)^{\theta} \left(\frac{G}{\overline{G}}\right)^\theta \exp \left[- \left(\frac{1 + \theta}{\overline{G}}\right)^{\theta} \right]$$

where $\overline{G}$ is the mean gain and $\theta$ is a parameter connected to the variance of the distribution. This intrinsic gain multiplied by the transparency gives the effective gain. 

GARFIELD++ simulations were run, shooting ten thousand electrons with the avalanche multiplication switched on and evaluating the instrinsic gain of each of the three GEMS, then a combination of the obtained results provided the effective gain histogram, from which GTS samples the gain value of the triple-GEM for each electron.

3. Drift properties - The triple-GEM is inserted between a cathode and an anode. Three gaps are defined, as shown in fig. 6, where the electrons are subjected to a drift field which leads them through the holes of the GEM foils up to the anode. The drifting of the electrons is determined by the presence of the gas and the possible magnetic field. The transverse and longitudinal diffusion due to the materials enlarge the charge distribution on the anode. The Lorentz force due to the magnetic field, when present, bends the trajectories of the electrons in their path to the anode and introduces a shift in the mean value position of the charge distribution on the anode. These effects affect both the spatial and the temporal distributions.

GARFIELD++ simulations were run, by shooting ten thousand electrons in each gap separately, with a magnetic field of 1T and evaluating their distributions, both spatial and temporal, after their drift to the next GEM foil.

4. Signal formation - As the electrons enter the induction gap, they begin inducing a current on the anode. The anode is divided in strips and the induced charge depends on the position
Figure 7. Spatial diffusion effect in the different gaps evaluated by simulations: in the drift gap the effect on the charge distribution depends on the distance from the cathode, since the electrons from ionization originate in different points. In the other gaps all the electrons come from the GEM foils, so there is no position dependence [12].

of the electron and it ends when the electron arrives on the strip. The instantaneous current induced by a charge in motion on an electrode is well described by the Shockley-Ramo theorem [13, 14] and can be computed as in eq. (2)

$$i(t) = q_e \times v_{drift} \times W_{loc}$$

where $q_e$ is the electron charge, $v_{drift}$ is the drift velocity of the electron, evaluated by GARFIELD++ simulations, and $W_{loc}$ is the weighting field which is the electric field generated by the electrode with an applied voltage of 1V, when all the other electrodes are set to 0. This theorem was used to simulate the full induction of the electrons in GTS. Once all the electrons have arrived to the anode, the signal is finished and the charge on the $i$-th strip equals the number of electrons collected by that strip. For this reason, a fast induction was also implemented in GTS by simulating the charge as the number of electrons collected by $i$-th strip and the signal time from the time of arrival distribution of the electrons on the $i$-th strip. The fast induction provides the same results as the full induction with a CPU-time 30 times faster.

The final part of the GTS code reproduces the effect of the electronics on the measurement. In the testbeams, the APV-25 ASIC [15] was used as readout chip. The APV-25 samples the signal 27 times, one every 25 ns. This was simulated as an integrator of the induced signal and a CR-RC shaper with $\tau = 50$ ns.

After the induction step, the output of GTS resembles the one obtained in a real detector: charge and time from each firing strip. At this stage the same kind of reconstruction can be applied to simulation as well as to real data. In the following section, the code used for testbeam data reconstruction will be presented.
3. GRAAL: reconstruction of testbeam data

In order to reconstruct the experimental data collected during testbeams, another standalone code was implemented, called GRAAL: GEM Reconstruction And Analysis Library [9, 12]. The code is written in C++ and a sketch of the block diagram is in fig. 8. The code performs the full reconstruction procedure from the anode strip, which provides the raw data, to a complete offline reconstruction.

Several testbeams have been conducted to set the GEM working point in the H4 beam line at SPS, CERN North Area. Two types of chamber were used, both planar and the cylindrical prototype with the same dimensions of the middle layer of the final CGEM-IT which will be installed in BESIII (see fig. 9). Thanks to the dipole magnet GOLIATH, a dipolar magnetic field up to the intensity of $1.5 \, \text{T}$, in both polarities, was available. The used beam was composed of muons of momentum 150 GeV/c. Figure 10 shows the basic setup, composed by a trigger system (plastic scintillators), tracking stations (planar triple-GEMs, with double view readout) and the test detectors, inside the magnetic field (planar triple-GEMs or the cylindrical prototype, with different settings). The adopted electronics for the readout was the ASIC chip APV-25.
GRAAL can perform the following reconstruction steps:

1. **Hit digitization** - As already said, the chambers were readout by the APV-25 ASIC. Invented by the CMS Collaboration, the chip has 128 channels and performs 27 charge samplings (one every 25 ns). A typical event lasts 4/5 time bins and the APV-25 provides both charge and time for each strip. The highest value of charge $Q_{max}$ is the hit charge, while the time must be reconstructed, with a Fermi-Dirac fit of the rising edge of the sampled signal (see fig. 11).

   $$Q(t) = Q_0 + \frac{Q_{max}}{1 + \exp\left(-\frac{t-t_{FD}}{\sigma_{FD}}\right)}$$  

From eq.(3) the strip time $t_{FD}$ and the associated error $\sigma_{FD}$ can be computed.

2. **Cluster reconstruction** - A series of contiguous firing strips, i.e. strips which record a charge higher than a threshold, are grouped in a cluster. Two algorithms have been adopted for position reconstruction: charge centroid and micro-TPC ($\mu$-TPC).

   The **charge centroid** method computes the position as the average of the positions of the firing strips in the cluster, weighted by the collected charge on each strip (eq.(4)):

   $$x_{cc} = \frac{\sum_i q_ix_i}{\sum_i q_i}$$  

The $\mu$-TPC mode was first adopted by the ATLAS MicroMegas group [16] and uses the drift gap of the triple-GEM as a tiny Time Projection Chamber. The position is reconstructed in the middle of the drift gap by a linear fit of the primary ionization reconstructed positions (eq.(5)):

   $$x_{\mu-TPC} = \frac{gap/2 - b}{a}$$

   $a, b =$ fit parameters

Each primary ionization position is calculated by the time measurement on each strip and by knowing the drift velocity of the electrons in the induction gap.

A sketch of the idea behind both methods is drawn in fig. 12 and fig. 13.

3. **Track reconstruction and alignment** - The trackers were used to fit a track and compute the point where the track passes on the test detector plane. This point is used, with the position reconstructed on the test detector itself, to compute the residual distribution as $\delta x = x_{expected} - x_{test}$. The residual distributions can be used for alignment purposes,
Figure 12. Charge centroid position reconstruction method. 

Figure 13. $\mu$-TPC position reconstruction method.

Figure 14. Example of alignment procedure with a comparison of plot before (left) and after (right). First row: residual distribution to correct for the shift between the expected and reconstructed position. Second row: tilt in $xy$ plane [12].

taking into account: displacements, tilts and rotations of the chambers with respect to their expected position. An example of the effect of the alignment procedure is shown in fig. 14. Analogous procedure was applied also to the cylindrical chamber, to correct for rotations around the cylinder axis, a shift of the center in the plane orthogonal to the axis or the shift of the center along the beam direction.

4. Test beam results

In order to compute efficiency and resolution, the residual of the position measured on one chamber against the one measured on the other was used, in order to reduce systematics and to eliminate the effect of tracking. The assumption this procedure is based on is that both chambers have the same efficiency and resolution and thus the single chamber characteristics
can be extracted as shown in eq.(6) for the efficiency and eq.(7) for the resolution

\[ \epsilon_1 \epsilon_2 = \frac{N_e}{D_e} = \epsilon^2 \rightarrow \epsilon = \sqrt{\frac{N_e}{D_e}} \]  
\[ \sigma_{\text{residual}}^2 = \sigma_1^2 + \sigma_2^2 = 2\sigma^2 \rightarrow \sigma = \frac{\sigma_{\text{residual}}}{\sqrt{2}} \]  

where \( D_e \) is the number of events with successful track reconstruction, \( N_e \) is the number of events with residual within \( 5\sigma \), while \( \sigma_{\text{residual}} \) is the width of the distribution of the residual. The resolution obtained with the charge centroid in case of orthogonal tracks without magnetic field and the corresponding measured efficiency \( vs \) the gain value is reported in fig. 15; the resolution computed with both the charge centroid and the \( \mu \)-TPC mode with respect to the track incident angle (in case of magnetic field equal to 1T) is reported in fig. 16. The gain value chosen as working point is around ten thousand, where the efficiency is already on the plateau. It is clear from the resolution curves that the charge centroid method and the \( \mu \)-TPC are anticorrelated: in the so-called focusing area around the Lorentz angle (which corresponds to \( 27^\circ \) in case of \( \text{Ar:}^{1+}\text{C}_4\text{H}_{10} \) (90:10) and \( B = 1 \) T) the charge distribution on the anode is shrunked and the cluster size is small, so the charge centroid works better than the \( \mu \)-TPC; in the de-focusing area it is the opposite. For this reason a combination of the two reconstructed positions, opportunely weighted, is used to obtain a stable result (see fig. 17), where the resolution stays below 150 \( \mu \)m. The weights are in this case evaluated as a function of the incidence angle and the position is computed by applying eq.(8):

\[ x_{\text{merge}} = w_{cc} (x_{cc} - \Delta_{cc}) + (1 - w_{cc}) x_{\mu-TPC} \]  

5. Comparison of the simulation to experimental data

To be reliable as a predictive tool, the simulations first of all are required to reproduce the testbeam experimental data collected during the testbeams. The set with planar triple-GEM chambers was used and the matching between the experimental and simulated data was evaluated on four sentinel variables: cluster charge, cluster size, position resolution computed with charge centroid and \( \mu \)-TPC reconstruction methods.
Figure 17. Spatial resolution vs incident angle obtained with magnetic field equal to 1T with the three procedures: charge centroid (black dots), the $\mu$-TPC (blue squares) and the merge procedure (red triangles) [12].

Figure 18. Matching between simulation (red) and experimental (black) data for the four sentinel variables, in a angle scan with magnetic field of 1T [12].

Two main tuning factors, on the gain value and on the sigma of the spatial diffusion, were applied to obtain a matching level within 30% for different incident angles: the gain was multiplied by a factor 4.5 and the diffusion by a factor 2. The obtained matching is shown in fig. 18

6. Conclusions
In this paper, two standalone codes, implemented for the simulation of a triple-GEM as well as for the reconstruction and analysis of experimental data from it, have been described.
For the GTS simulation code, the basic approach was taken from literature, but was extended to a wider range of configurations: detector gain, incident angle of the track, magnetic field. Eventually it was tuned to real data, collected during testbeams and reconstructed with the same methods used in the second software described here, GRAAL. The simulation provides a performance close to the one obtained with the real data (within 30%). The reconstruction code, GRAAL, which provides a lot of tools for tracking, alignment and analysis, is a tool that can be applied not only to GEM, planar and cylindrical, but also to other MPGDs with segmented anode. For example, it is currently used for $\mu$-RWELL reconstruction [18].

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