Study of cluster reconstruction and track fitting algorithms for CGEM-IT at BESIII *

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Abstract: Considering the effects of aging on the existing Inner Drift Chamber (IDC) of BESIII, a GEM-based inner tracker, the Cylindrical-GEM Inner Tracker (CGEM-IT), is proposed to be designed and constructed as an upgrade candidate for the IDC. This paper introduces a full simulation package for the CGEM-IT with a simplified digitization model, and describes the development of software for cluster reconstruction and track fitting, using a track fitting algorithm based on the Kalman filter method. Preliminary results for the reconstruction algorithms which are obtained using a Monte Carlo sample of single muon events in the CGEM-IT, show that the CGEM-IT has comparable momentum resolution and transverse vertex resolution to the IDC, and a better z-direction resolution than the IDC.

Keywords: BESIII, CGEM-IT, simulation, cluster reconstruction, Kalman filter

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1 Introduction

The Beijing Spectrometer III (BESIII) [1] is a detector of high precision that operates at the Beijing Electron–Positron Collider II (BEPCII) [2], a high luminosity, multi-bunch e^+e^- collider running at the τ-charm energy region. The Main Drift Chamber (MDC) of BESIII is a key subdetector for charged track reconstruction with good spatial and momentum resolution. The MDC comprises two parts, the Inner Drift Chamber (IDC) and the Outer Drift Chamber (ODC). However, the existing IDC is suffering from aging problems after five years of operation, resulting in an obvious decrease in its gas gain and spatial resolution [3].

Gas Electron Multiplier (GEM) detectors [4] are characterized by significant radiation tolerance, high rate capability, outstanding spatial resolution and limited radiation length, so they can be ideal to serve as an inner tracker. A Cylindrical-GEM Inner Tracker (CGEM-IT) is therefore proposed as an option for the upgrade of the IDC for BESIII. The proposed CGEM-IT consists of three independent layers of CGEM detectors with outer radii 87.5 mm, 132.5 mm and 175 mm and lengths 532 mm, 690 mm and 847 mm in the axial direction. Each CGEM detector is composed of a cathode, three GEM foils and a two-dimensional readout anode in a concentric arrangement, as shown in Fig. 1. High voltages are applied on each GEM foil, which is full of micro bi-conical holes, providing strong electric fields in the holes to amplify the ionized electrons from the track to be measured. Such an inner tracker combined with the ODC is expected to offer excellent spatial resolution: about 100 μm in the $r\phi$ view and about 200 μm in the z direction, where r is the radius, ϕ is the azimuth angle and z is the coordinate along the central axis of the CGEM detector. The development of simulation and reconstruction software for the CGEM-IT is essential to study its performance in track measurement and for design optimization of the detector.

In this paper we will introduce the full simulation package for the CGEM-IT, describe the implementation of the cluster reconstruction and track fitting algorithms

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for this detector in the BESIII Offline Software System (BOSS) [5] framework, and present preliminary results on the resolution of the CGEM-IT and the performance of reconstructed tracks using a Monte Carlo sample of single-muon events.

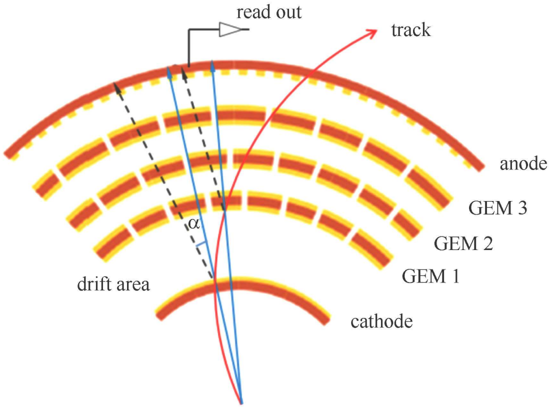

Fig. 1. (color online)The structure of a CGEM detector consisting of one cathode, three GEM foils and one anode. When a track (red solid curve) traverses one CGEM, ionization occurs in the drift area (the gap between the cathode and the first GEM foil). The electrons are multiplied in the holes of the GEM foils and drift towards the readout anode. The position in the anode plane is obtained by digitization with (black dashed lines) and without (blue solid lines) taking into account the Lorentz angle α and electron diffusion.

2 Simulation of CGEM-IT

Reliable Monte Carlo (MC) simulation plays an important role in describing the geometry and material of a detector and its response in track measurements. A full simulation package based on GEANT4 [6] has been developed for the CGEM-IT and the BOSS framework has been modified correspondingly.

2.1 Simulation procedure

Figure 2 shows the flow chart of the simulation procedure. The geometries and materials of the CGEM-IT, including the micro holes in the GEM foils, are fully and exactly constructed according to the preliminary design of the CGEM-IT. Each GEM foil is a copper clad Kapton foil as thin as 54 μm with holes evenly distributed on it. The holes are of the same size with an external diameter of 70 μm. The space between the cathode and the first GEM foil is defined as the drift area, i.e. sensitive volume. The simulation is processed event by event. The final states (primary tracks) and the initial momenta of each event are produced by an event generator.

To simulate the process when a charged primary track traverses the CGEM-IT, the track in the drift area is propagated in discrete steps along the trajectories, during which all possible interactions between the track and CGEM-IT are considered including ionization, Coulomb multiple scattering and so on. The information of each step in the drift area is recorded as Cgem Hit. These Cgem hits are summed up to get the position and total energy loss of the track segment in the drift area as Cgem Truth. Then an algorithm called Cgem Digitizer converts the Cgem Truth to the electronic readout signal named Cgem Digi.

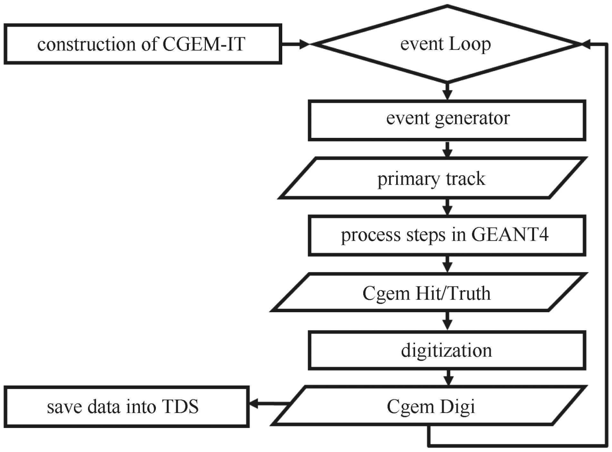

Fig. 2. Flow diagram for the simulation of CGEM-IT.

2.2 Digitization

The electrons ionized by a charged particle crossing the drift region will be multiplied in the micro holes of the GEM foil and drift towards the anode where signals are induced. Three GEM foils are assembled to multiply the number of electrons by a factor up to 10^6[3].

Both the magnetic field and diffusion of the electrons have an impact on the drift properties and charge distribution in the readout anode [7]. The presence of an axial magnetic field makes the drift line deviate from the direction of the electric field, and the deviation angle is defined as the Lorentz angle, as shown by the dashed lines in Fig. 1. The effect of diffusion will enlarge the cluster of multiplied electrons. In this work, a simplified digitization model is used, in which the Lorentz angle α and electron diffusion are not considered. As shown by the solid lines in Fig. 1, the entrance and exit points in the drift area are projected to the anode plane as the extent of the signal in the readout anode. The readout anode of each layer is segmented with 650 μm pitch XV patterned strips with a stereo angle that changes depending on the layer geometry. The fired strips are determined by the size of the cluster of multiplied electrons. The charge deposited in the drift area is multiplied by an expected gain and shared by the fired strips. The identifier of each fired strip as well as its collected charge is recorded as one Cgem Digi just like real experimental data.

There are two different strip readout methods, binary and analog [3], leading to different digitization models. The binary readout method sets a fixed threshold on the total charge of the fired strips and the reconstructed position is the geometrical center of these strips. In the analog readout method, the distributions of charge deposited along two readout coordinates will be recorded. The collected charge of each strip is obtained by the integration of the distributions so that one can set a threshold on the single strip and reconstruct the charge centroid of fired strips as the position of the cluster, which results in a better spatial resolution compared to the binary readout method. The precise shape of the charge distributions will be determined by a beam test on the CGEM planar prototype afterwards. In this paper, the digitization model is based on the binary readout method, where total deposited charge is shared equally by the fired strips.

2.3 Modification of BOSS framework

As the CGEM-IT is a new detector added to BESIII, the existing BOSS framework does not provide the necessary interfaces for software related to the CGEM-IT. We therefore update the framework by adding the components for data processing with the CGEM-IT. The information of Cgem Digi and Cgem Truth is stored in the Transient Data Store (TDS) and can be accessed by the reconstruction algorithms via the event data service.

3 Cluster reconstruction for CGEM-IT

When the multiplied electrons reach the readout anode, a group of X and V strips will be fired. One cluster is defined in the anode plane and consists of continuous fired strips in the X direction and V direction that have intersections. Figure 3 shows one example of the composition of such a cluster. Next we will discuss the cluster reconstruction and the obtained spatial resolution.

3.1 Cluster reconstruction algorithm

Firstly, the information of the fired strips is retrieved from the raw data, including the strip ID, strip type (X or V) and collected charge. Then sets of continuous fired strips in the X and V directions are found and defined as X-clusters and V-clusters respectively. Next, possible intersections between X-clusters and V-clusters are searched for and saved as XV-clusters. The position in X (V) of each cluster is acquired by calculating the charge weighted geometrical center of the fired strips that compose this cluster:

$$X=\frac{\sum\limits_{i=1}^{N_X}X_iQ_i}{\sum\limits_{i=1}^{N_X}Q_i}, \tag{1}$$

$$V=\frac{\sum\limits_{i=1}^{N_V}V_iQ_i}{\sum\limits_{i=1}^{N_V}Q_i}, \tag{2}$$

where i is the index of strips, X_i (V_i) is the middle position of strip i, Q_i is the charge collected by each strip and N_X (N_V) is the number of fired X-strips (V-strips). The corresponding position in absolute cylindrical coordinates (r,ϕ,z) is given by

$$\begin{cases} r=R \\ z=(V-X\cos\theta)/\sin\theta \\ \phi=X/R \end{cases}, \tag{3}$$

where R is the radius of the anode in which the cluster is found, and θ is the stereo angle between X-strips and V-strips. To obtain the middle positions where charged particles pass the CGEM in the drift area, a correction to the reconstructed positions of clusters is required. According to the simplified digitization model, the position of a track in the drift area has the same azimuth angle ϕ and the same z as the cluster, but with a different radius. The corresponding output data model is defined by a class RecCgemCluster, including the following information: layer ID, GEM ID, cluster type (X, V or XV), collected charge and reconstructed position.

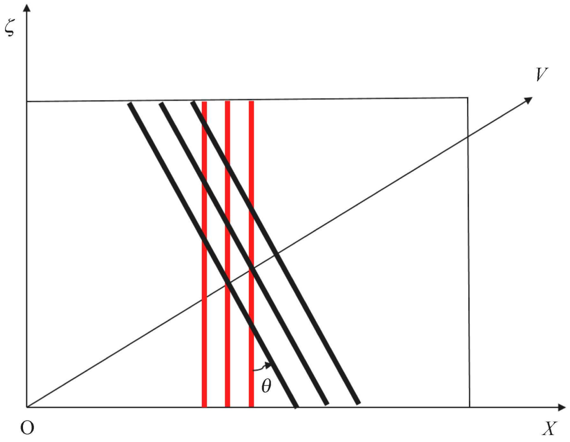

Fig. 3. (color online) Schematic of one cluster induced by a charged track, composed of 3 X-strips and 3 V-strips on an unrolled anode plane, where the stereo angle θ is the angle between X-strip and V-strip, the X-axis is perpendicular to the X-strips, the V-axis is perpendicular to the V-strips and the ζ-axis is parallel to the X-strips.

3.2 Spatial resolution for CGEM-IT clusters

The spatial resolution for CGEM-IT clusters is an essential performance indicator of the cluster reconstruction algorithm. The residuals in the X and V directions are defined as:

$$\delta_X = X_{\rm rec} - X_{\rm truth}, \quad (4)$$

$$\delta_V = V_{\rm rec} - V_{\rm truth}, \quad (5)$$

where $X_{\rm rec}$ and $V_{\rm rec}$ are the reconstructed positions in the drift layer in the X-direction and V-direction while $X_{\rm truth}$ and $V_{\rm truth}$ are the true positions. For a Monte Carlo sample of μ^- with a momentum of 1.0 GeV/c, the distribution of the residuals in X and V are shown in Fig. 4. Note that the distribution of residuals in X is not a pure Gaussian, but rather a superposition of rectangular and Gaussian. The Gaussian part (filled region in Fig. 4(a)) comes from clusters with multiple strips while the rectangular part (dashed line in Fig. 4(a)) comes from clusters with a single strip. The RMS (Root Mean Square) of this curve is 217.1 μm and defined as the resolution in the X-direction. A fit of the distribution of residuals in V to a Gaussian function gives a resolution of 129 μm.

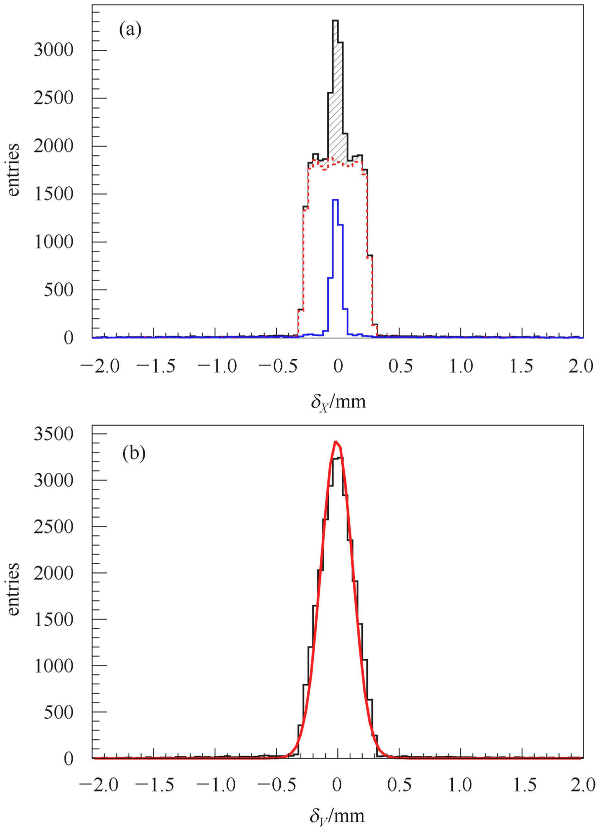

Fig. 4. (color online) The position residuals in X (a) and V (b) of the cluster for a Monte Carlo sample of single 1.0 GeV/c μ^- tracks. The contribution from clusters with multiple strips (filled region) and from clusters with a single strip (dashed line) are shown in (a). The solid line in (b) is the Gaussian fit curve for the residuals distribution in the V-direction.

4 Track fitting by Kalman filter with CGEM-IT clusters

In a uniform magnetic field a charged particle moves along a helical trajectory. So a track can be described by a helix model with 5 parameters (d_ρ, ϕ_0, κ, d_z, $\tan\lambda$) [8], where d_ρ and d_z are the signed distance of the closest point to the pivot in the x-y plane and z direction respectively, ϕ_0 is the azimuth angle of the pivot to the helix center, κ is $1/p_{\rm t}$ with the same sign as the charge of the track and $\tan\lambda$ is the slope of the track.

The track finding algorithm [8, 9] and track fitting algorithm by Kalman filter [10] currently in service using MDC hits can be easily adopted to accomplish the same task using ODC hits only. To incorporate the cluster measurements by the CGEM-IT, the track fitting by Kalman filter is extended to be able to extrapolate tracks found with ODC hits into the CGEM-IT and fit the track with these additional clusters in the right sequence.

In this section, we will discuss the extension of Kalman-filter-based track fitting to use the CGEM-IT clusters and present the obtained resolutions for the track parameters after track fitting.

4.1 Implementation of track fitting by Kalman filter

The description of geometries and materials of the CGEM-IT is implemented in the initialization of the track-fitting algorithm and is identical to that in the simulation package. The reconstructed clusters are retrieved as input.

The track parameters and their covariance matrix in the ODC are propagated into the CGEM-IT by many small steps, during which the effects from inhomogeneous magnetic field, energy loss and multiple scattering in the material are included. When the track is extrapolated into a drift area of the CGEM-IT, the measured position from the CGEM-IT cluster and the predicted track parameters are combined to update the track parameters. This process is repeated for the subsequent regions, with each iteration yielding more accurate track parameters and their covariance matrix, and stops at the original point. The obtained track parameters are taken as the reconstruction results for this track.

4.2 Vertex resolution

To obtain the vertex resolution of the reconstructed tracks, the residuals of d_ρ and d_z are calculated, which are the differences between the fitted values and the truth at the generation level. Figure 5 shows the distribution of the residuals for the Monte Carlo sample single μ^- with 1.0 GeV/c, and a Gaussian fit yields a resolution of 192 μm in d_ρ and 0.33 mm in d_z.

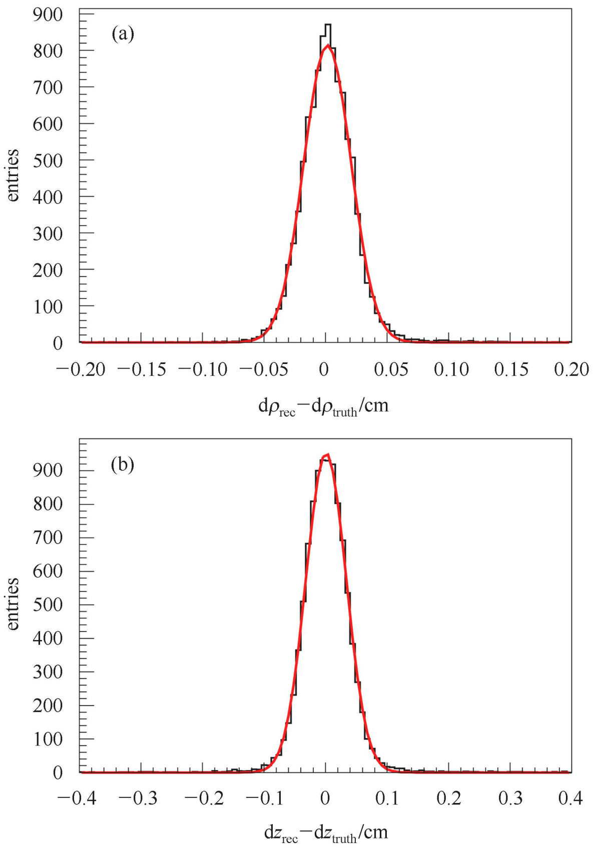

Fig. 5. (color online) d_ρ (a) and d_z (b) residuals for single 1.0 GeV/c μ^- tracks with the CGEM-IT. The curves are the results of a Gaussian fit.

The vertex resolution in d_ρ and d_z for single μ^- tracks with different momenta for the CGEM-IT and IDC is displayed in Fig. 6. These results reflect that a tracking system using the CGEM-IT has a comparable d_ρ resolution and a significantly improved d_z resolution relative to the case using the IDC.

4.3 Momentum resolution

The momentum resolution is represented by the distribution of the momentum residual, which is defined by:

$$\delta_{\rm p}=p_{\rm rec}-p_{\rm truth}, \tag{6}$$

where $p_{\rm rec}$ is the reconstructed momentum at interaction point and $p_{\rm truth}$ is the momentum at the generation level. The $\delta_{\rm p}$ distribution curve for 1.0 GeV/c muons is shown in Fig. 7 as an example. This curve is fitted by a Gaussian function and the obtained standard deviation 5.5 MeV/c is regarded as the momentum resolution.

Figure 8 summarizes the momentum resolutions for single muon samples simulated with different momenta for the CGEM-IT and IDC. These figures illustrate that their momentum resolutions are at a comparable level. The CGEM-IT has a larger material budget and offers only three layers of measurements compared with the IDC. However, the good spatial resolution in two dimensions of the CGEM-IT compensates for the disadvantages, so that a comparable momentum resolution can be achieved.

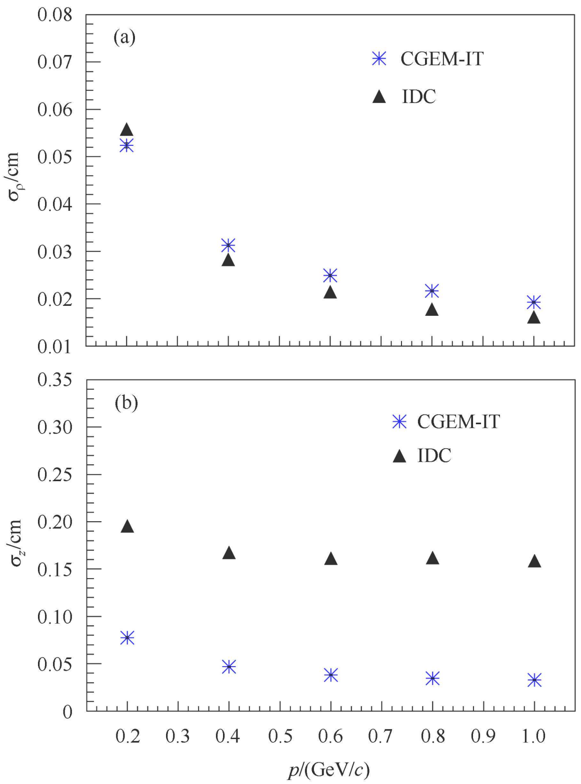

Fig. 6. (color online) d_ρ (a) and d_z (b) resolutions of single μ^- tracks with different momenta for the CGEM-IT and IDC.

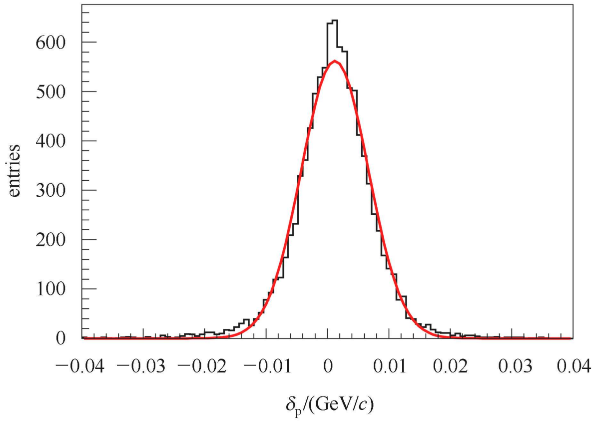

Fig. 7. (color online) Distribution of momentum residuals for 1.0 GeV/c μ^- tracks, fitted by a Gaussian function (red solid line).

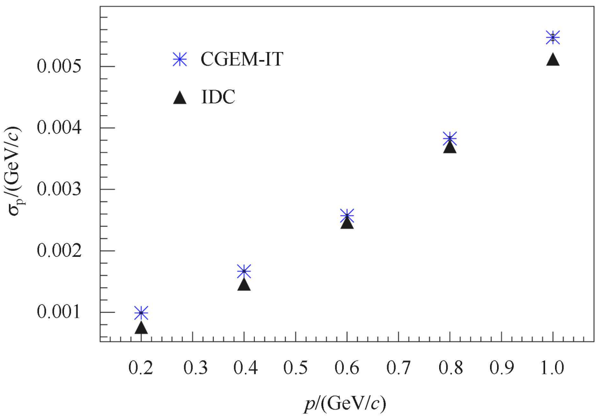

Fig. 8. (color online) Momentum resolutions of the reconstructed muon at different momenta, using full simulation of single μ^- events in the CGEM-IT and IDC.

5 Summary and outlook

In order to solve the aging problems of the IDC in BESIII, it is suggested that a CGEM-IT be used to upgrade the IDC. In this paper, we present the implementation of the software for the CGEM-IT. The general flow for the CGEM-IT, including simulation, cluster reconstruction and track fitting is realized. The results for a set of simulated μ^- events indicate that the vertex resolution in z direction is significantly improved by the CGEM-IT, while the momentum resolution and vertex resolution in the r direction stay at the same level with respect to IDC. The preliminary results demonstrate that the CGEM-IT and the implemented track reconstruction software can basically fulfill the track reconstruction task as a replacement for the IDC.

The implementation of a more detailed digitization model based on the analog readout method will improve the spatial resolution of the CGEM-IT. Further studies should also be performed to reach a better understanding of the detector, including developing the track segment finding algorithms for the CGEM-IT and joint tracking algorithms for the CGEM-IT and ODC, and optimizing the reconstruction software for an environment with noise and background.

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