The MAGIX focal plane time projection chamber

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Abstract. The MAGIX experiment is a versatile system optimized for low-energy nuclear and particle physics measurements. The setup is currently under development and will be installed at the MESA electron accelerator, at the Institute for Nuclear Physics of the University of Mainz. The main detectors of that experiment are a couple of high-precision magnetic spectrometers, each of them equipped with a GEM-based TPC at the focal plane to achieve a momentum resolution and angular resolution at the scattering vertex respectively of \( \delta P / P < 10^{-4} \) and \( \approx 1 \) mrad on scattered electron momenta between 1 MeV/c and 105 MeV/c. The limiting factor to achieve those results is the amount and uniformity of the material before the focal plane and even the presence of the TPC field cage can be relevant. Therefore we developed, and hereby introduce, an open field-cage TPC to fulfil those challenging requirements.

1. Introduction

Within the next 3 years, the Institute for Nuclear Physics of the Mainz University will build a new high-intensity electron accelerator, called MESA, which operates in two modes: extracted beam up to 155 MeV at 150 \( \mu \)A and energy recovering up to 105 MeV at 1 mA. MESA will serve three main experiments: P2 [1], dedicated to the precise measurement of the weak mixing angle, darkMESA [2], which will operate parasitically behind the P2 beam dump to search for dark sector particles, and MAGIX, located on the energy-recovery branch of the accelerator with an extensive program based on low-energy electron scattering on fixed targets. A schematic view of this new accelerator complex is shown in fig. 1.

MAGIX will have a wide experimental program including, but not limited to:

- Measurement of electromagnetic form-factors, including a new measurement of the proton charge radius;
- Measurement of cross-sections of quasi-elastic and non-elastic processes at very low momentum transfers, including nuclear reactions of astrophysical relevance, e.g. \( ^{12}C(\alpha, \gamma)^{16}O \);
- Few-body physics experiments, including double-polarization measurements;
- Dark sector searches [3], including the search for both the visible and invisible decays of the hypothetical dark photon;
- Test of effective field theories in light nuclei.
Those projects have different requirements, imposing different challenges to the experimental setup, including a momentum resolution on the scattered electrons $\approx \delta P / P < 10^{-4}$ and an angular resolution at the scattering vertex of the order of 1 mrad for electrons with energies as low as 1 MeV.

At the centre of the MAGIX experiment there is a scattering chamber with a gas jet injector [4] which allows to create a dense atomic stream of the target element without any additional containment and achieve luminosities up to $10^{35} \text{cm}^{-2} \text{s}^{-1}$.

Pivoting around the scattering chamber, two identical magnetic spectrometers will be used to measure the direction and momenta of the scattered particles. At the focal plane of each spectrometer we will install a GEM-based TPC and a set of fast scintillators. This article will be focused on the design of those TPCs.

2. The MAGIX focal plane detectors

The design of the spectrometer’s magnetic system defines a rectangular, horizontal focal plane with a size of $650 \times 140 \text{mm}^2$. Considering a 30% momentum acceptance up to a central momentum of 200 MeV/c, to obtain a resolution $\delta P / P < 10^{-4}$, we need a tracker in that plane with a position resolution better than 100 $\mu$m. Additionally, to reconstruct the scattering angle at the vertex with a resolution $\delta \theta_v < 1 \text{ mrad}$, the tracker should measure the particle angle at the focal plane with a resolution $\delta \theta_f < 3 \text{ mrad}$. Finally, to reduce many systematic errors involved in measuring the scattering cross-sections at the per mille level, the efficiency and uniformity of the tracker should also reach similar levels up to particle rates of at least 1 MHz.

Due to the required size and resolution, the most cost-effective solution for the spectrometers trackers is a gas detector. Among the different layouts, we chose a TPC, deployed with its
readout plane perpendicular to the focal plane, as the multiple samples available on each track will improve the tracking efficiency to the required level and, most importantly, because a TPC can be designed so that there is no material between the track samples, thus minimizing any error due to multiple scattering in that material. Due to the short drift length, of about 15 cm, the TPC will be able to operate efficiently at rates higher than the required 1 MHz.

To cope with those rates, the gas amplification system of the MAGIX focal plane TPCs is based on a stack of up to 4 GEMs, installed on a readout board segmented in 9216 rectangular pads, $2 \times 8 \text{ mm}^2$ large, arranged in 24 parallel rows. This readout plane will be produced in a single PCB panel to avoid any dead areas and will also integrate the high voltage distribution system.

The electronics for the readout of the MAGIX focal plane TPC will be based on the VMM3a ASIC [5]. Two of those ASICs are going to be installed on carrier boards (hybrids) which also include the front-end protection system and a serialization interface compatible with the SRS system [6]. A total of 72 such hybrids are installed directly on one side of the readout board with an integrated support and cooling system.

To achieve the utmost precision in the expected experimental conditions we need to be able to constantly monitor and calibrate the field distortions in the TPC. This will be achieved with a UV laser system that will be used to produce ionization tracks in the gas volume as well as to illuminate a custom pattern etched in the cathode in a similar way as that used by the T2K experiment [7].

3. An open field cage TPC

At the energies at which MAGIX will operate, the most relevant source of systematic errors for the single particle track reconstruction will be the multiple scattering in the materials before the focal planes of the spectrometers. To minimize those effects, MAGIX will use a gas jet target and the scattering chamber will be connected to the spectrometers with a moving vacuum seal to eliminate any material before the focal plane detectors themselves.

Using a gas detector implies the presence of a window to separate the sensitive volume from the spectrometers’ vacuum chambers. In the case of MAGIX, this will be made using a 125 $\mu$m thin Kapton foil. The presence of this foil alone will introduce a systematic error in the measurement of the particle angles of about 2 mrad for 100 MeV electrons, which is similar to the required precision of the detector system. Therefore we need to avoid any additional material in the particle path before it enters the sensitive volume.

On the other hand, to guarantee a homogeneous electric field inside the sensitive volume, a TPC requires a field cage surrounding it, that is a set of conductors at well defined potentials which constrains that field to be perpendicular to the readout system. This field cage can be constructed using a set of strips or wires surrounding the sensitive volume to obtain an electric field uniformity $\delta E/E < 10^{-3}$, which is required to achieve the expected accuracy without additional calibrations.

Unfortunately, adding a complete field cage, even using thin foils and strips, not only introduces additional material but does it non uniformly. To avoid it we designed the MAGIX focal plane TPC with an open field cage, which only surrounds the sensitive volume on three sides leaving open that faces the spectrometer vacuum chambers.

Such a design would evidently introduce relevant field distortions in the whole sensitive volume. To mitigate that effect below the per mill level, we will include an extension of the field shaping elements well within the spectrometer vacuum (fig. 2). To separate the vacuum volume, where the extension plates are installed, from the fiducial volume filled with the counting gas, there will be a 125 $\mu$m Kapton foil, installed in a 1 mm gap between the main field cage and the extension set. To reduce the lever arm between the vacuum foil and the focal plane, the TPC will be positioned in such a way that the spectrometer focal plane is perpendicular to the first
Figure 2. Schematic view of the MAGIX focal plane TPC showing the inner field cage in orange and the extension in blue, as simulated using the FEM program CST Studio Suite. The scattered particles enter the TPC from the right side, at small angles ($\leq 10\,\text{deg}$) from the $y$ axis. The origin of the reference system is set represented by the green point, set on the plane of the foil separating the vacuum volume from the fiducial one, filled with the counting gas, at the same height of the top GEM layer and the anode of the extension set. The focal plane is represented by the yellow plane, at $y \approx 16\,\text{mm}$.

Figure 3. Value of the maximum deviation of the drift component of the electric field along the drift path of an ionization electrode produced at the TPC cathode in the centre of the focal plane.

row of the readout plane, as shown in yellow in fig. 2.

To validate this solution we used an FEM simulation, performed with the program CST Studio Suite\(^1\), to estimate the minimum length of the extension plates necessary to achieve a field uniformity better than $10^{-3}$ on the focal plane. The quantity we chose to summarize the field uniformity is the maximum relative deviation of the drift component of the electric field ($E_z$) from its nominal value on any relevant drift path, that is $\frac{E_{z\text{max}} - E_{z\text{min}}}{2E_{z\text{nom}}}$. When applying this definition to the drift path ending at the centre of the first readout row, that is at the centre of the focal plane, we obtain the result summarized by the plot in fig. 3.

\(^{1}\) https://www.cst.com/
Figure 4. The map of the magnitude of the electric field at the focal plane of the spectrometer system. The magnitude of the nominal field used in the simulation is $10^5 \text{ V m}^{-1}$ and everywhere on the focal plane the distortion is lower than $10^{-3}$.

Considering those results we decided to design our detector with extensions protruding 30 cm in the spectrometer’s vacuum, twice as wide as the drift length. In this configuration the map of the magnitude of the electric field at the spectrometer focal plane is shown in fig. 4 and shows that the required field uniformity is achievable everywhere in the sensitive volume.

4. Outlook and conclusions
The open field cage TPC designed for the focal plane detectors of the MAGIX spectrometers is an innovative concept to optimize the material uniformity and its amount in a tracking detector. It takes advantage of the additional space available in the MAGIX spectrometers’ vacuum chambers to define an extension of the field cage which does not interact with the incoming particles. Depending on the length of the extension, it is possible to obtain field uniformities of arbitrary magnitude. In the case of the MAGIX focal plane TPCs, it is sufficient to extend the field cage for about 30 cm to achieve the required $10^{-3}$ field uniformity.

A small prototype of such a detector, with a standard field cage and equipped with 5 VMM3 hybrids connected to an SRS system, was build in Mainz earlier in 2019. At the beginning of May 2019 that system was installed at the test-beam line of the MAMI accelerator of the Institute for Nuclear Physics in Mainz and successfully tested. The data of that test are currently being analysed.

It should be noted that in this static simulation we did not study the effects of to the possible charging-up of the vacuum foil separating the fiducial volume from the spectrometer vacuum. To measure the potential distortions due to the charging up of that foil we will perform a specific experiment in the upcoming months.

A full scale detector, including the open field cage and a vacuum chamber that can be attached to the MAMI test-beam line, is currently under development and will be completed in
2020. This full-scale prototype will be used to test all the components of the system, validate and optimize the design so that the 2 detectors for the MAGIX spectrometers could be built and commissioned by 2021.

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