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The HELIX Drift Chamber Tracker Design, Analysis and Calibration

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The High Energy Light Isotope eXperiment (HELIX) is a balloon-borne superconducting magnet spectrometer designed to measure abundances of light cosmic-ray isotopes. HELIX, which undertook its first engineering flight in the Spring of 2024, identifies cosmic rays through measurements of their velocity, rigidity and charge. These measurements, and in particular, measurements of beryllium isotopes up to 10 GeV/n will be used to investigate cosmic-ray propagation models. The magnetic rigidity measurements are performed using a Drift Chamber Tracker (DCT), housed within a 1 Tesla superconducting magnet which deflects incoming cosmic rays. Three planes each containing seventy-two layers of sense wires are used to measure the positions of the deflected cosmic rays with a spatial resolution goal of 70 μm for Z>3. To ensure a precise gas composition and drift field a collection of housekeeping sensors was used, resulting in the DCT performing successfully in the flight. Presented here are details of the design and construction of the DCT as well as calibration and preliminary analysis of flight data.

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1. The High Energy Light Isotope eXperiment

HELIX is a balloon-borne cosmic-ray (CR) detector which is used to perform precise measurements of beryllium "clock" isotopes with an ultimate goal of measuring the ^{10}Be/^{9}Be ratio [1]. HELIX utilises 3 different detectors to measure the rigidity, charge and velocity of incident CRs. The HELIX Time Of Flight (TOF) system consists of 3 planes of scintillator paddles each located at different heights on the instrument's frame : the top and bottom planes are located 2.3 meters apart at the top and bottom of the instrument, respectively with the trigger-defining bore panel lying below the Drift Chamber Tracker (DCT) close to the centre of the instrument. The TOF measures the charge of incident particles as well as the particle's velocity from the time difference between the particle hitting the top and bottom panels. The 1 Tesla superconducting magnet which previously flew as part of the HEAT experiment [2] provides an approximately uniform magnetic field which deflects the trajectories of transiting CRs as they pass allowing the measurement of their rigidity. The magnet consists of two Nb-Ti superconducting coils which are held in a 260 L liquid He cyrostat with a maximum hold time of ~7 days. For particles with energies greater than ~ 1 GeV/n the Ring Imaging Cherenkov Detector (RICH) [6], a sillicon photomultiplier (SiPM) based detector with an aerogel radiator [3, 4] is used for high velocity measurements.

A mass resolution of ~2.5% is required to precisely perform mass-resolved measurements of beryllium isotopes required for the science goal of HELIX. This requirement translates to a collection of precision requirements for each individual subsystem. Below we discuss the specific requirements of the DCT and how they are achieved with the added spatial constraint brought on by the allowed space for the DCT within the magnet's bore. We will also discuss some calibration methods, simulation results and details describing the conditions experienced during flight.

2. The Drift Chamber Tracker

The DCT is a gas-filled drift chamber containing a 90:10 ratio of CO_2 to argon with an active volume of 45 cm × 45 cm × 58 cm. Due to the nature of balloon flights and the varying environments that are experienced, the DCT is housed in a custom-built vessel which keeps the contents at a constant pressure of 1 atm and near constant temperature. The DCT and its custom vessel are located within the bore of the superconducting magnet, a picture of which is shown in Figure 1. The DCT is used to measure the transiting particle's trajectory in two orthogonal planes. The bending plane, perpendicular to the magnetic field direction and the non-bending plane which is parallel to the planes defined by the sense wires.

2.1 Event Reconstruction

The DCT consists of three identical cells, each with a central, vertical plane defined by 72 sense wires which are amplified and read out at 80 MHz. An electric field of ~ 1 kV/cm is applied across each cell, to cause the electrons to drift at a near constant velocity towards the columns of sense-wire planes. The hit position in the bending plane is determined from measurements of the CR's drift time which is defined as the time from trigger to the time the produced elections reach the sense wire. The hit position in the non-bending plane is determined from the ratio of charges read at each end of the sense wires. Every sense wire in the detector is alternatively staggered 0.3 mm

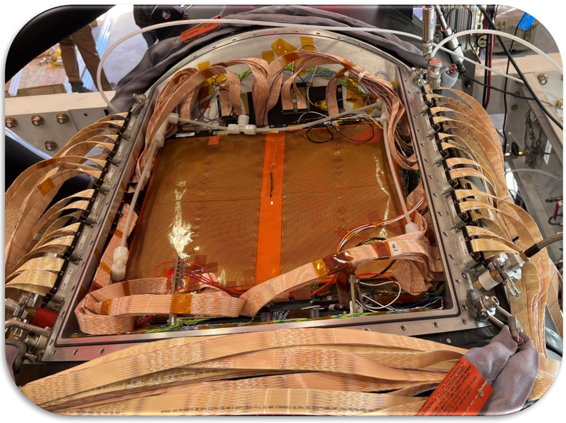

Figure 1: The DCT inside the magnet's bore during the Sweden campaign

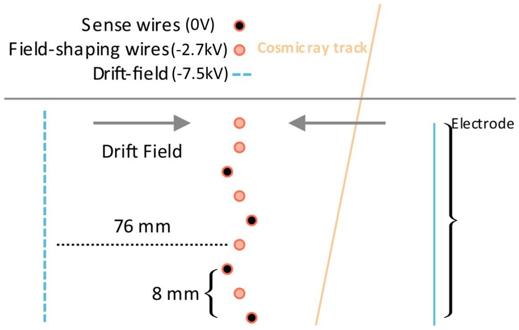

Figure 2: A schematic representation of the layout of the DCT wires. The black dots are the sense wires which are alternately staggered 0.3 mm left and right. The red dots are the field shaping wires and the yellow line is an example path that an incident cosmic ray may take.

within the bending plane allowing for the resolution of the left/right ambiguity when reconstructing a track from the positions inferred by timing, through the use of a line finding method such as a Hough transform [5]. The layout of the wires including the stagger is shown in Figure 2 where the black dots are the staggered sense wires and the red dots are the field shaping wires which avalanche the drifted ionization electrons. The goal position resolution of the DCT is 70 μm.

2.2 Garfield++ Simulations

In order to reconstruct hit positions based on drift time, a simulation of a single section of the drift chamber is performed with Garfield++ [7]. The simulation consists of the sense wires held at ground voltage, gain wires at -2700 V, and the drift mesh at -7500 V. The field-shaping circuit boards are modeled at the extreme Y positions in the simulation. This is a simplified 2-D model of one column of the DCT. Electrons are placed at locations in this one section of the DCT simulation and tracked using the Garfield++ AvalancheMC method. For each electron, we record the drift time and starting location and allow the simulation to inform us of the endpoint of that electron. Sense wire-specific isochrones are constructed by parsing the endpoint of the electrons. These isochrone maps are generated with different values of magnetic field and gas temperature in the simulation. Examples of two isochrone maps for one of the central wires in the DCT are shown in Figure 3 and

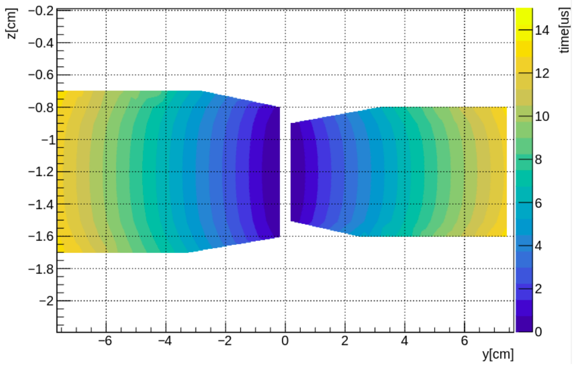

Figure 3: Isochrone map of a single sense wire from the Garfield simulation where the sense wire is located at y = 0 cm and z = -1.2 cm, where x = 0 cm, y = 0 cm and z = 0 cm corresponds to the center of the DCT. The drift times of electrons from the cosmic-ray tracks are shown as contours, a representation of the time-to-space mapping for hit reconstruction. In this simulation there is no magnetic field.

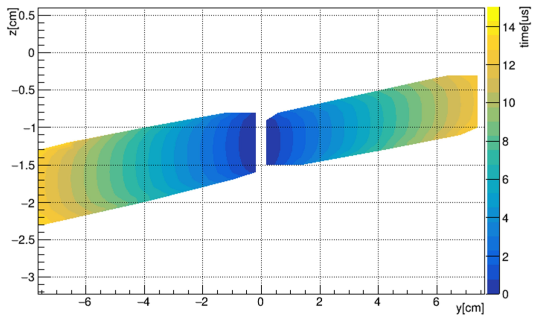

Figure 4: A similar isochrone map as that shown in Figure 3 but with a 1 T magnetic field. Once again the sense wire is located at y = 0 cm and z = -1.2 cm

Figure 4. In Figure 3 the magnetic field is off whereas in Figure 4 the magnetic field is one Tesla. The right and left sides of the sense wire located at the center of the plot show the impact of the Lorentz angle from the magnetic field.

In order to accurately produce an isochrone map of the DCT an electric field map is produced which is shown in Figure 5. This is produced through Garfield++ simulations of the electric field-shaping circuit boards that are used within the DCT. In the field map the grounded sense wires can be seen at y=0 cm with two planes of -7500 volts placed at y=7.62 and y=-7.62 cm. The contours of the map show a nearly constant drift electric field for the majority of the sense wires, with the outliers being located at the extreme z positions, this corresponds to the edges of the detector.

Each of these maps is loaded into the analysis framework, where the input information of the sense wire ID and detected drift time are converted into two isochrones, one on the right side of that sense wire and one on the left. In the display of Figure 6, showing an event with magnetic field powered on, the left and right isochrones are shown for the reconstruction per hit. Each isochrone as an output is post-processed and interpolated at a finer level of granularity to avoid these maps limiting the resolution of the reconstruction. Per hit, each isochrone's midpoint in the vertical direction is used as a first pass position. The gray circles are shown at the locations chosen in

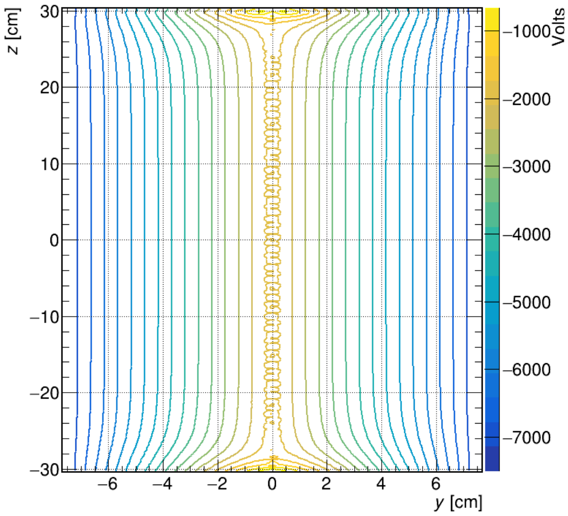

Figure 5: Voltage map of the DCT center column, spanning full detector height, as calculated numerically in the Garfield++ simulation. Most of the DCT active region shows constant electric drift field, as designed. Distortions of the field for the top and bottom sense wires impact the time-to-space mapping in hit reconstruction.

this manner per isochrone. These arrays of two hits per sense wire are fed into a Circular Hough Transform to resolve the left/right ambiguity, where one track is easily discernible because of the stagger of the alternating sense wires. Next, the resolved hits, shown as cyan circles on top of the original gray ones, are analyzed with GenFit [8] to provide a coarse tracking solution. With this track, a local angle of the particle at each hit location is calculated. With this coarse tracking incident angle information, another track reconstruction is run by correcting the hit position along the original isochrone using this particle's incident angle, corresponding to the fastest ionization electron creating the trigger for that sense wire. This process is iterative and development of the analysis tools is ongoing, and appears likely to achieve the resolution expected for beryllium measurements.

In the current state of the DCT analysis we obtain a peak spatial resolution of ~130 μm. This preliminary value is achieved with a portion of data taken during the end period of the flight after the magnet was powered down. The resolution is determined from the residuals of straight line fits to these events. No cuts are yet placed on the charge of the particles used in these measurements and as a result this is likely a conservative estimate of the DCT's spatial resolution. Figure 7 shows the DCT's resolution as a function of the drift distance from the sense wire to the hit location.

3. Flight and Housekeeping

In its first flight, the HELIX payload launched from the Esrange base near Kiruna, Sweden on May 28, 2024 and landed roughly 6.3 days later on Ellesmere Island in northern Canada with the payload floating at an average altitude of 35 km. During the night and day cycle of the flight, temperatures regularly fluctuated between highs of ~30°C and lows of ~-15°C. Across the instrument, temperatures would also vary with differences of up to ~30°C between the top and

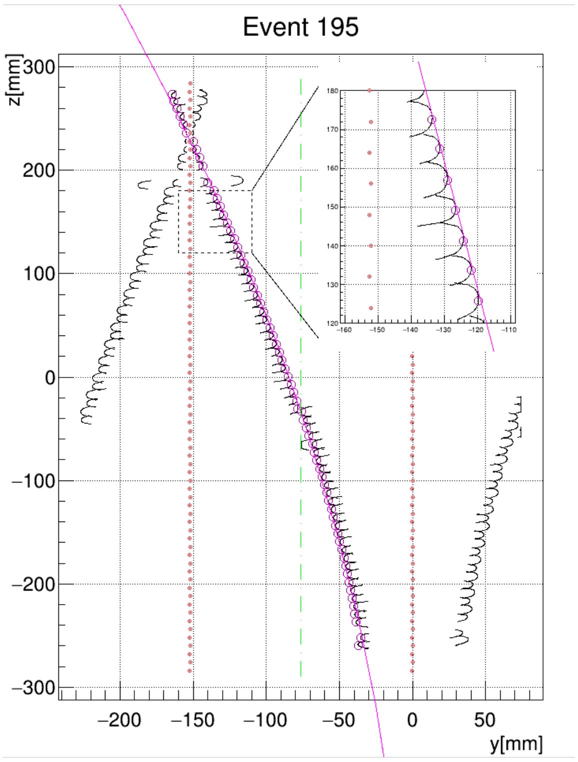

Figure 6: An example magnet-on event with isochrone for each hit visualized. The inset shows a coarse estimate of the hit position along each wire's isochrone. This example track also shows how each track is first resolved on both sides of the sense wire prior to solving the left/right ambiguity

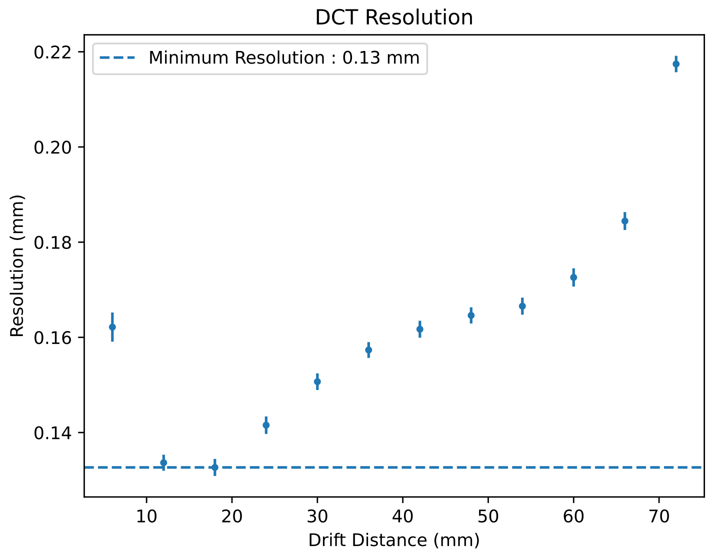

Figure 7: Preliminary DCT bending plane resolution with respect to the distance drifted from the hit location to the sense wire plane.

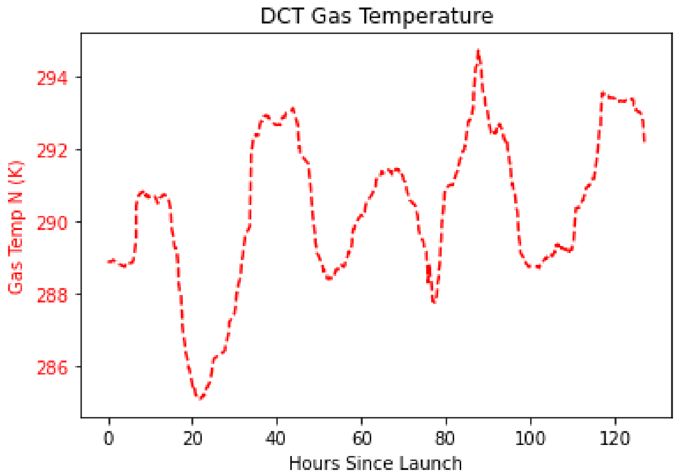

Figure 8: DCT gas temperature fluctuations throughout the flight measured at the input gas flow port. This is used as a proxy for the time dependence of the gas temperature in the active volume which is useful for calibration.

bottom. For this reason an accurate and detailed housekeeping system was required to monitor the state of all subsystems. In order to maintain a mostly constant drift velocity within the DCT, gas composition and density and electric field strength must be carefully maintained. The HELIX housekeeping system is capable of measuring temperature with an accuracy better than 0.5°C and adjustments to temperature within the DCT can be made with external heaters. The internal gas temperature of the DCT was measured to fluctuate between roughly 285 K and 295 K as shown in Figure 8. The electric field in the DCT is produced by two high-voltage power supplies which are also closely monitored and controlled by the HELIX housekeeping system. A Starlink™ communications system was used to maintain contact between the ground team and HELIX.

4. Conclusions

In the Spring of 2024 The HELIX experiment successfully undertook its first engineering flight from the Esrange base in Kiruna, Sweden to Ellesmere Island, Canada where it was recovered with minimal damage. During the flight the HELIX DCT collected data for ~6 days with the magnet powered on for ~5 days with the last day of data collection carried out with no magnetic field. In order to achieve the spatial resolution goal of 70 μm detailed calibrations are underway. These calibrations use both a simulation and data driven approach. Garfield simulations of the electric field are used to produce voltage maps of the DCT from which isochrone maps, which show an electron's drift time at any point in the detector, can be derived.

5. Acknowledgements

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