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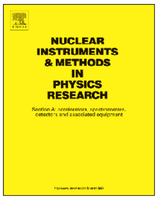

Measurement and tricubic interpolation of the magnetic field for the OLYMPUS experiment

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ABSTRACT

The OLYMPUS experiment used a 0.3 T toroidal magnetic spectrometer to measure the momenta of outgoing charged particles. In order to accurately determine particle trajectories, knowledge of the magnetic field was needed throughout the spectrometer volume. For that purpose, the magnetic field was measured at over 36,000 positions using a three-dimensional Hall probe actuated by a system of translation tables. We used these field data to fit a numerical magnetic field model, which could be employed to calculate the magnetic field at any point in the spectrometer volume. Calculations with this model were computationally intensive; for analysis applications where speed was crucial, we pre-computed the magnetic field and its derivatives on an evenly spaced grid so that the field could be interpolated between grid points. We developed a spline-based interpolation scheme suitable for SIMD implementations, with a memory layout chosen to minimize space and optimize the cache behavior to quickly calculate field values. This scheme requires only one-eighth of the memory needed to store necessary coefficients compared with a previous scheme (Lekien and Marsden, 2005 [1]). This method was accurate for the vast majority of the spectrometer volume, though special fits and representations were needed to improve the accuracy close to the magnet coils and along the toroidal axis.

1. Introduction

OLYMPUS is a particle physics experiment comparing the elastic cross-section for positron–proton scattering to that of electron–proton scattering [2]. This measurement has been of interest recently because it tests the hypothesis that hard two-photon exchange is responsible for the proton form factor discrepancy [3,4]. OLYMPUS took data in 2012 and 2013 at the DORIS storage ring at DESY, in Hamburg, Germany. During data taking, beams of electrons and positrons were directed through a windowless hydrogen gas target. The scattered lepton and recoiling proton from elastic scattering events were detected in coincidence with a toroidal magnetic spectrometer. The spectrometer's support structure, magnet, and several subdetectors were originally part of the BLAST experiment [5]. Several new detectors were specially built for OLYMPUS to serve as luminosity monitors. A schematic of the apparatus is shown in Fig. 1.

The OLYMPUS spectrometer used a magnetic field for two purposes. First, the field produced curvature in the trajectories of charged particles so that the detectors could measure their momentum. Typical momenta of particles from elastic scattering reactions ranged from 0.2 to 2 GeV/c, corresponding to sagittas as small as 5 mm in the OLYMPUS tracking detectors. Secondly, the magnet acted as a filter, preventing low-energy charged particles (from background processes like Møller or Bhabha scattering) from reaching the tracking detectors.

The OLYMPUS magnet consisted of eight coils, identical in shape, each with 26 windings of hollow copper bars potted together with epoxy. The coil shape is shown in Fig. 2. The coils were arranged to produce a toroidal field, with the beamline passing down the symmetry axis of the toroid. During OLYMPUS running, the coils carried 5000 A of current, which produced a peak field of approximately 0.3 T.

Knowledge of the spectrometer's magnetic field was necessary

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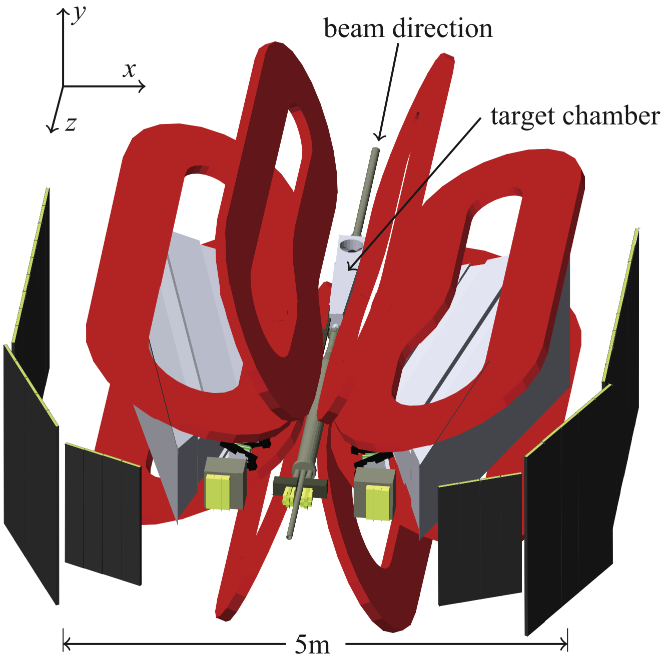
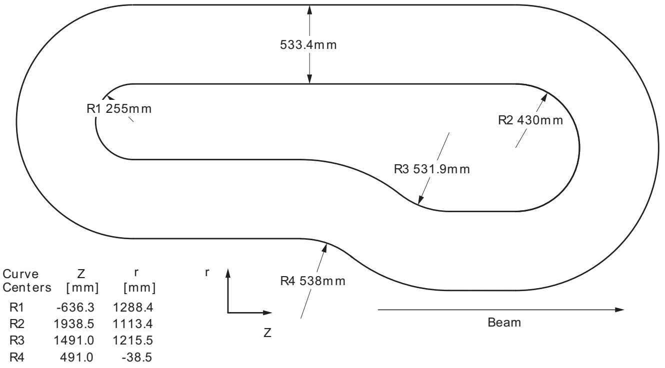


Fig. 1. This schematic shows how the eight magnet coils are situated around the OLYMPUS detectors.



Curve Centers	Z [mm]	r [mm]
R1	-636.3	1288.4
R2	1938.5	1113.4
R3	1491.0	1215.5
R4	491.0	-38.5

Fig. 2. Individual magnet coils were narrower at the upstream end to accommodate the target chamber.

for reconstructing particle trajectories through the OLYMPUS spectrometer. However, calculating the field using the design drawings and the Biot–Savart law was not feasible for two reasons. First, the positions of the copper bars within the epoxy were not well known. Secondly, the coils were observed to deform slightly when current passed through them due to magnetic forces. Instead, at the conclusion of data taking, extensive field measurements were made of the magnet in situ. A measurement apparatus, consisting of a three-dimensional Hall probe actuated by a system of translation tables, was used to measure the magnetic field vector at over 36,000 positions in both the left- and right-sector tracking volumes.

This paper presents both the measurement technique and the subsequent data analysis used to characterize the field of the OLYMPUS magnet. Section 3 describes the measurement apparatus, the measurement procedure, and the techniques used to establish the Hall probe position. Section 4 describes how we fit the magnetic field data with a numerical field model to allow us to calculate the field at positions we did not measure. Section 5 describes the special interpolation scheme we developed to facilitate rapid queries of the magnetic field. Finally, Section 6 describes the special modifications to our field model that were needed in two regions where the model did not perform adequately.

2. Coordinate system

This paper makes frequent references to positions and directions in the standard OLYMPUS coordinate system. In this system, the x-axis points left from the beam direction, the y-axis points up, and the z-axis points in the direction of the beam. The coordinate origin is taken to be the center of the target. OLYMPUS has two sectors of detectors, which lie to the left ($x > 0$) and right ($x < 0$) of the beamline, centered on the $y=0$ plane. Since the magnet has toroidal symmetry, it is sometimes convenient to work with cylindrical coordinates. We use r to refer to the radius from the z-axis and ϕ to refer to the azimuthal angle from the xz plane. For example, a point on the positive y-axis lies at $\phi = 90°$.

3. Field measurements

The magnetic field measurements at OLYMPUS were more involved than those made during the BLAST experiment, detailed in a previous article [6]. Like at BLAST, preliminary field measurements along the beamline were made to align the coils during the toroid's assembly; in addition, a detailed survey was made after data taking was complete. This was important because OLYMPUS compared scattering with electrons to scattering with positrons; the magnetic field introduces differences in trajectories between the two species. Field inaccuracies directly contribute to the systematic error.

The measurement apparatus was built from a system of translation tables, a schematic of which is shown in Fig. 3. The apparatus was originally built to measure the field of the undulator magnets of the FLASH free electron laser at DESY [7]. The entire apparatus was supported by a pair of two-dimensional translation stands, which had 1 m of range in the x- and y-directions. These stands were moved synchronously and were made to act as a single table. This table supported a three-dimensional translation table with 4 m of range in the z-direction and 0.2 m of range in the x- and y-directions. This system of translation tables was used to move a three-dimensional Hall probe at the end of a carbon fiber rod, held parallel to the x-axis. The range of motion in x and y was extended beyond the 1.2 m range of the translation tables by using rods of different lengths and different brackets to connect the rods to the tables. To allow the Hall probe and rod to move through the magnet volume without obstructions, the detectors and parts of the beamline were removed before the apparatus was assembled.

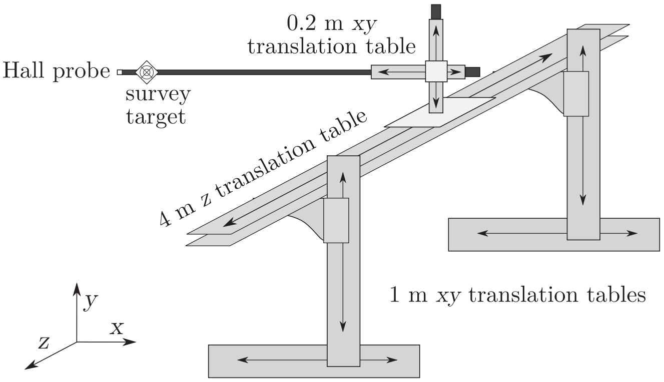


Fig. 3. Two 1 m xy tables supported a long xyz table, which could scan 4 m in the z-direction. In this configuration, the apparatus is assembled to measure the field on the $x > 0$ side of the toroid.