Precise Magnetic Field Mapping of the EMPHATIC Phase 1 Magnet with COMSOL ®

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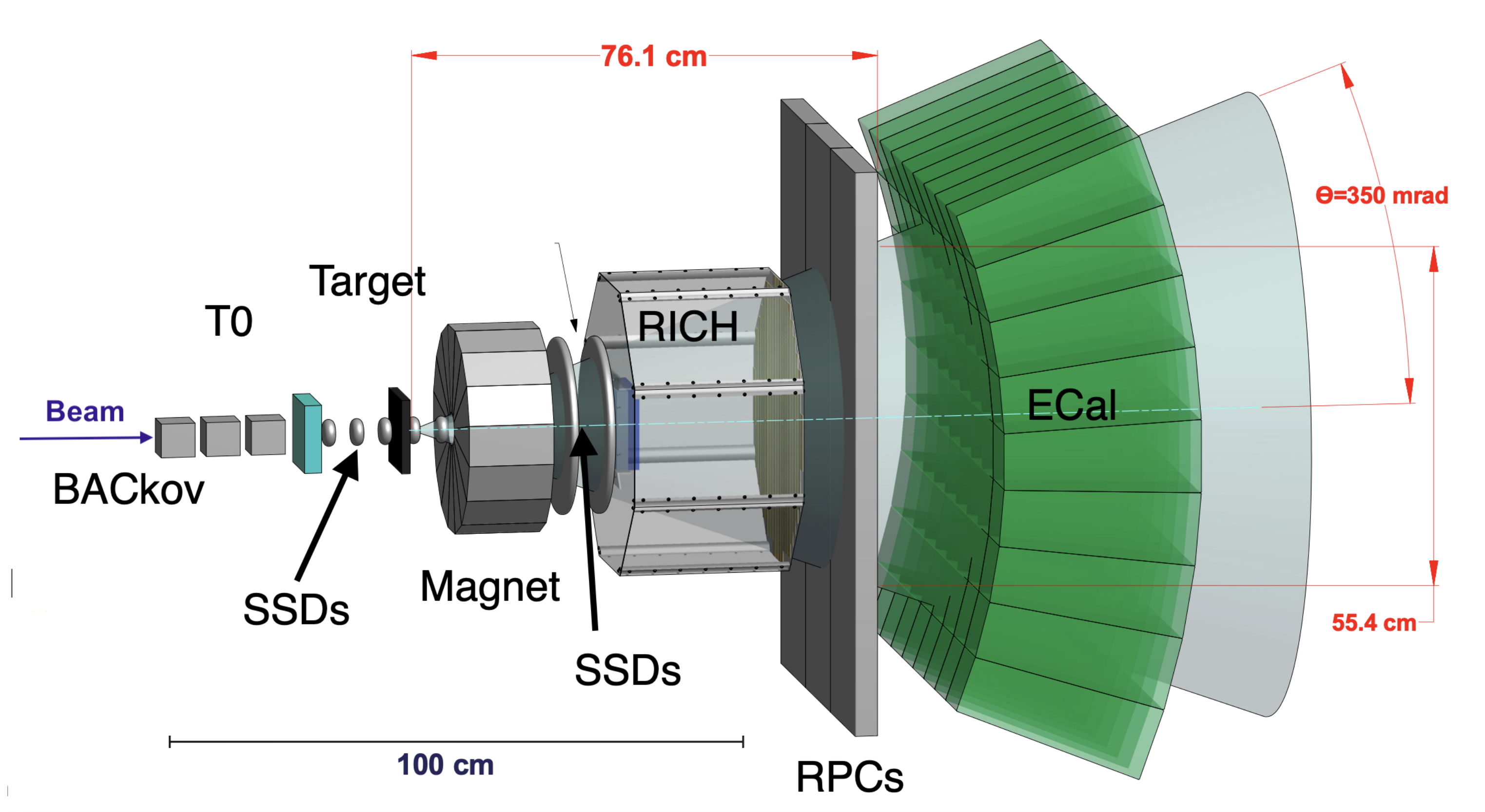
Introduction

- **Hadron production uncertainties** are the dominant systematic in neutrino flux predictions; new data is needed to improve the physics reach of GeV-scale neutrino experiments
- **EMPHATIC** aims to reduce these uncertainties with precise hadron production measurements
- A compact **Halbach array magnet** is used for momentum measurement of secondary particles
- **COMSOL® modeling** improves the magnetic field map, increasing tracking precision and acceptance
- **Enhanced flux predictions** are critical for advancing neutrino physics experiments

EMPHATIC



- **E**xperiment to **M**easure the **P**roduction of **H**adrons **A**t a **T**est beam **I**n **C**hicagoland
- **Table-top-sized spectrometer** (<2m in length) at the FNAL Test Beam Facility (FTBF)
  Aims:
  - **Better than 10% uncertainties on hadron scattering and production cross section measurements** at 2-120 GeV/c using various target materials
  - First-ever measurement of the **hadron spectrum downstream of a target and horn**
- **Silicon strip detectors (SSDs)** with $\sim$17.3 μm resolution for precise tracking
- **Halbach array permanent magnet** ($\int B.dl$ = 0.2 Tm) providing an asymmetric dipole field
- **Upstream PID**: gas Cherenkov detectors and beam aerogel Cherenkov (BACkov) detector
- **Downstream PID**: compact aerogel ring imaging Cherenkov **(ARICH)** detector, **time-of-flight (ToF)** system, and **lead-glass calorimeter**
- **Phase 1**: Angular acceptance of 100 mrad, with future design aiming for 350 mrad acceptance

EMPHATIC MAGNET

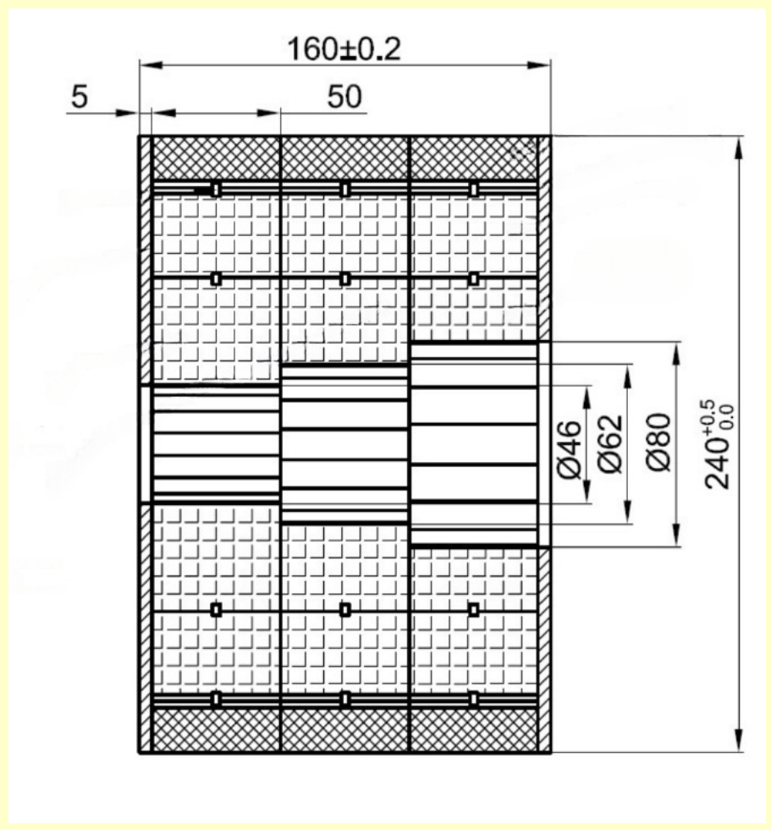


Figure 1. Technical Drawing of the Magnet

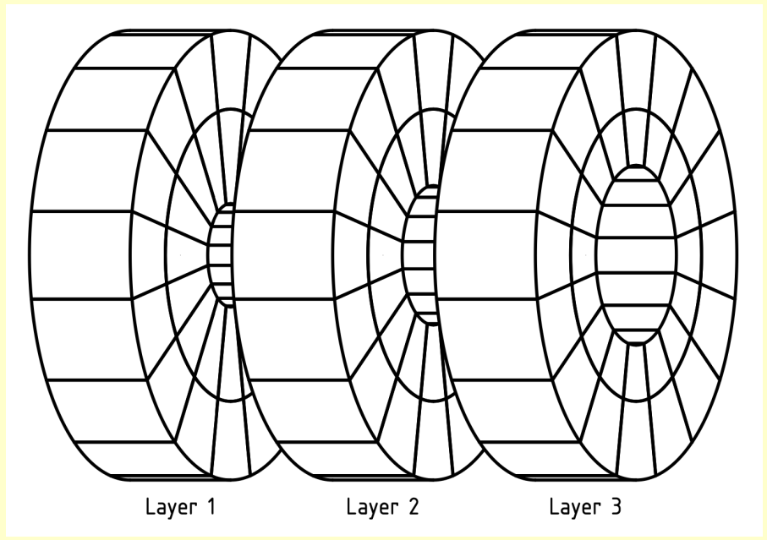


Figure 3. Layers with increasing Radii

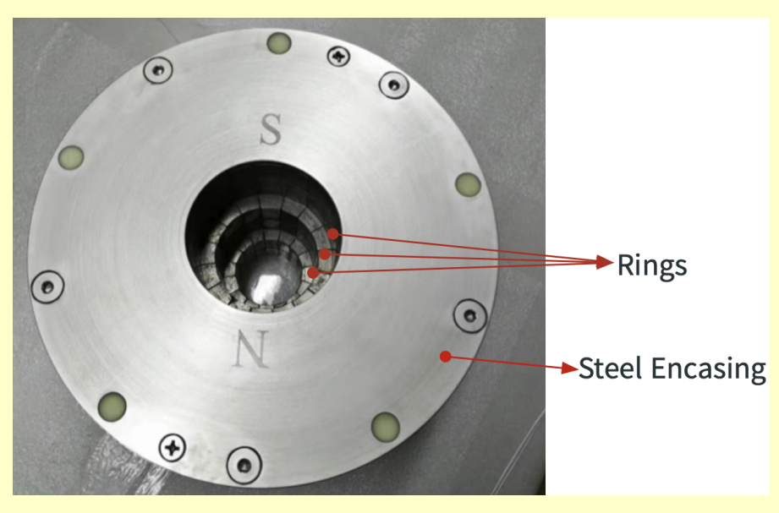


Figure 2. EMPHATIC Phase 1 Magnet

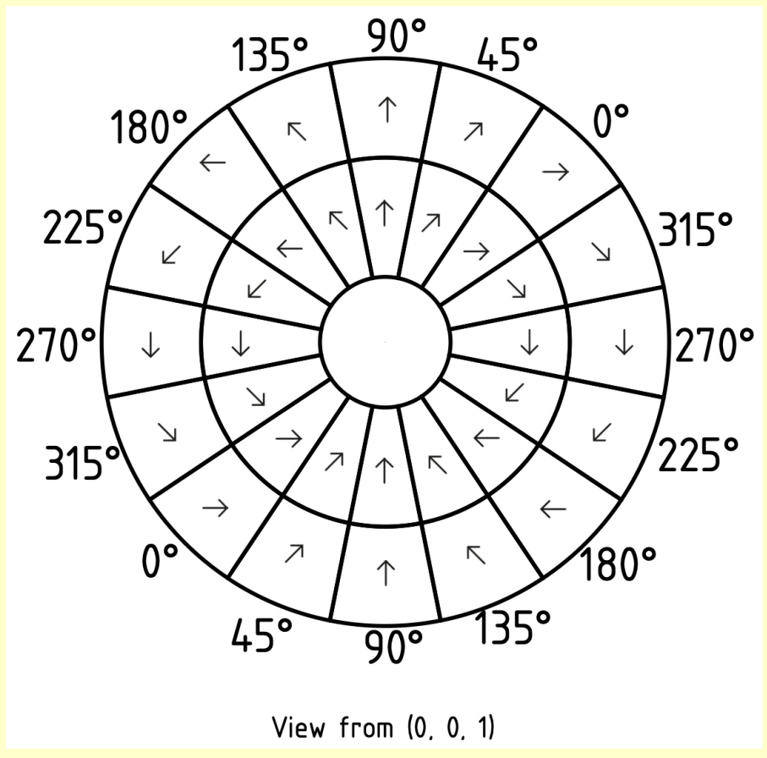


Figure 4. Magnetisation directions (same for all three layers)

- **Halbach array magnet** arrangement amplifies the magnetic field on one side and cancels it on the other side
- Magnets are arranged in a circular pattern with rotating magnetisation vectors
- Used in particle accelerators, magnetic bearings, and electric motors for efficient, focused magnetic fields

Phase 1 Magnet

- **Design**: A 3-layer Halbach array using 48 N52 Neodymium magnets (16 per layer)
- **Field Strength**: 1.44 T within the NdFeB material
- **Mass**: $\approx$ 50 kg
- **Stray Field**: $\approx$ 0.2 T at the aperture
- **Enclosure**: Stainless steel shell, max operating temperature 80°C
- **Supplier**: China Magnets Source Materials Limited

Measured Field Data

By Fermilab's AP-STD (March 2023), with a 5 mm grid mapping central and fringe fields (upstream/-downstream).

- Format of magnetic field map: 6 columns - `x`, `y`, `z`, `Bx`, `By`, `Bz`
- **4095** field map points
- **Variation:** `x` from -15 mm to +15 mm, `y` from -15 mm to +15 mm, `z` from -140 mm to +310 mm

COMSOL ® Modelling of Phase 1 Magnet

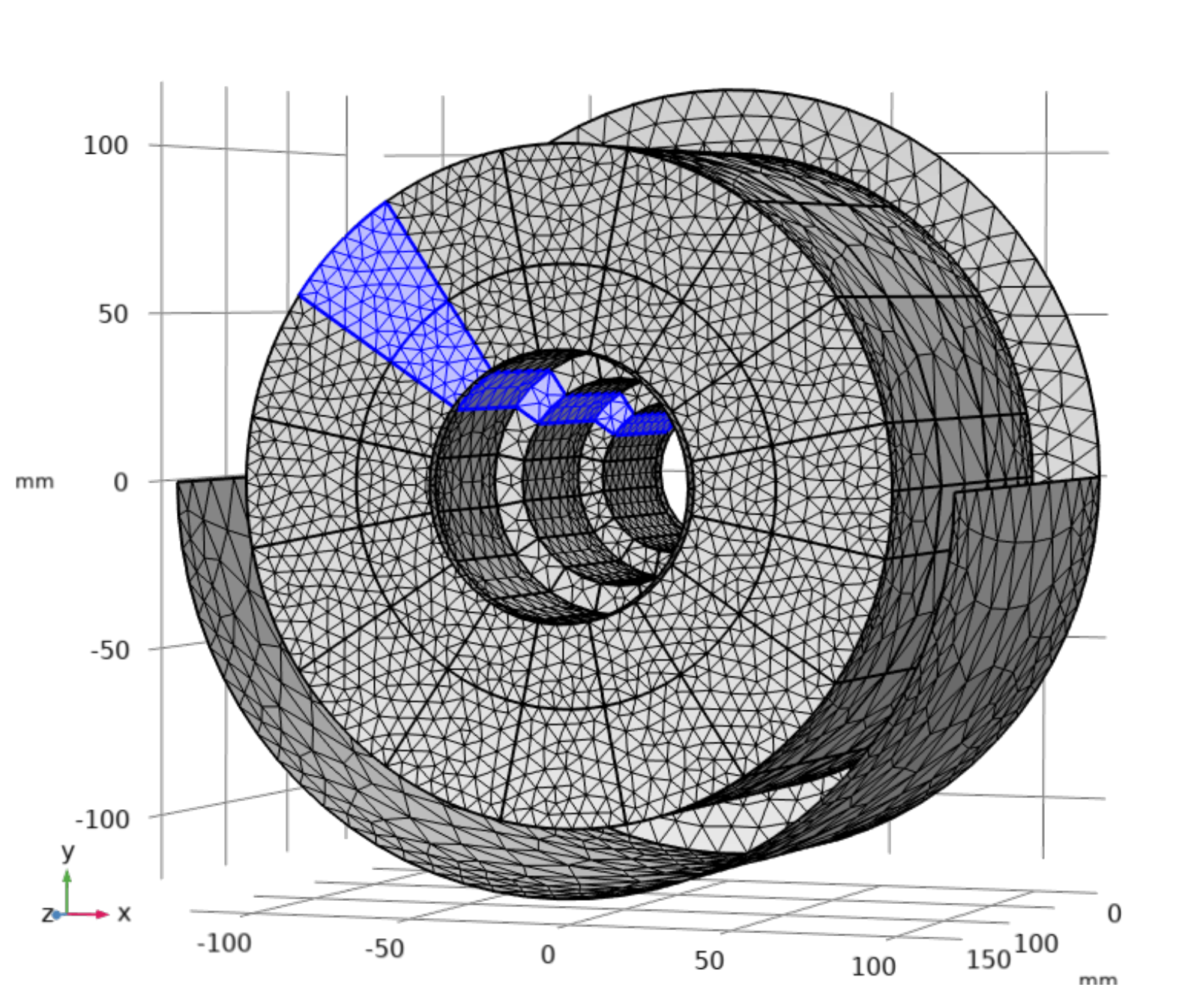


Figure 5. Magnet modeled with COMSOL 6.1

- **COMSOL Multiphysics**: Advanced simulation software for modeling physical systems using finite element analysis (FEA), integrating multiple physical phenomena through a unified interface
- **Configuration**
  - **Mesh**: *Extra Fine* — Ensures high precision with detailed element size
  - **Interface**: *Magnetic Fields, No Currents (mfnc)* — Computes magnetostatic fields from permanent magnets and current-free sources
- Defines **144 parameters**, corresponding to a total of 48 components in each layer (with 3 parameters per component)
- The initial model (without optimisation) defines a magnetic field strength of **1.44 T** for each component
- The COMSOL ® simulation does not account for the epoxy volume, leading to an expected **5% lower measured field** compared to the design
- **License courtesy:** Fermilab and University of Notre Dame

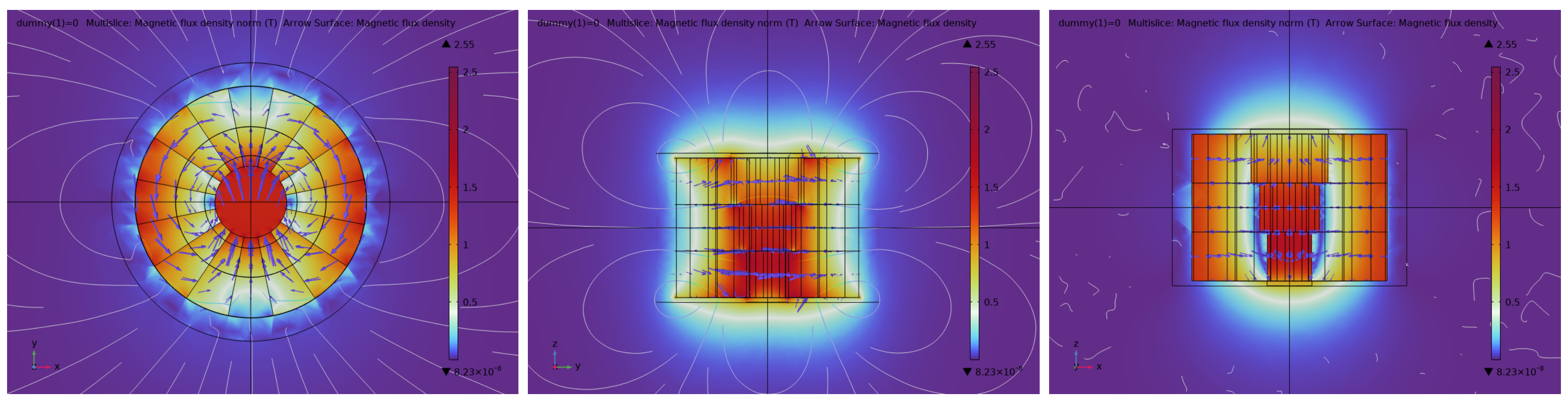


Figure 6. Magnetic field maps generated by COMSOL ® in the **xy**, **yz**, and **zx** planes

Fitting the Magnetic Field Map

- **Iterative COMSOL® Optimisation:** were performed by varying the magnetisation of the Neodymium pieces to refine the COMSOL ® map to closely match the experimental data
- **Chi-Squared Minimization:** The following χ^2 is minimized:

$$\chi^2 = \sum_{i=1}^{N_{\text{DataPoints}}} \left(\frac{(b_{x,i} - b_{x,\text{pred},i})^2}{\sigma^2} + \frac{(b_{y,i} - b_{y,\text{pred},i})^2}{\sigma^2} + \frac{(b_{z,i} - b_{z,\text{pred},i})^2}{\sigma^2} \right)$$

where $b_{x,i}, b_{y,i}, b_{z,i}$ are observed components, b_x, pred, i, $b_{y,\text{pred},i}$, $b_{z,\text{pred},i}$ are predicted, and σ is the constant uncertainty (=0.01T).

- **Explored Various Algorithms:** Only the MINUIT2 SCAN algorithm was effective

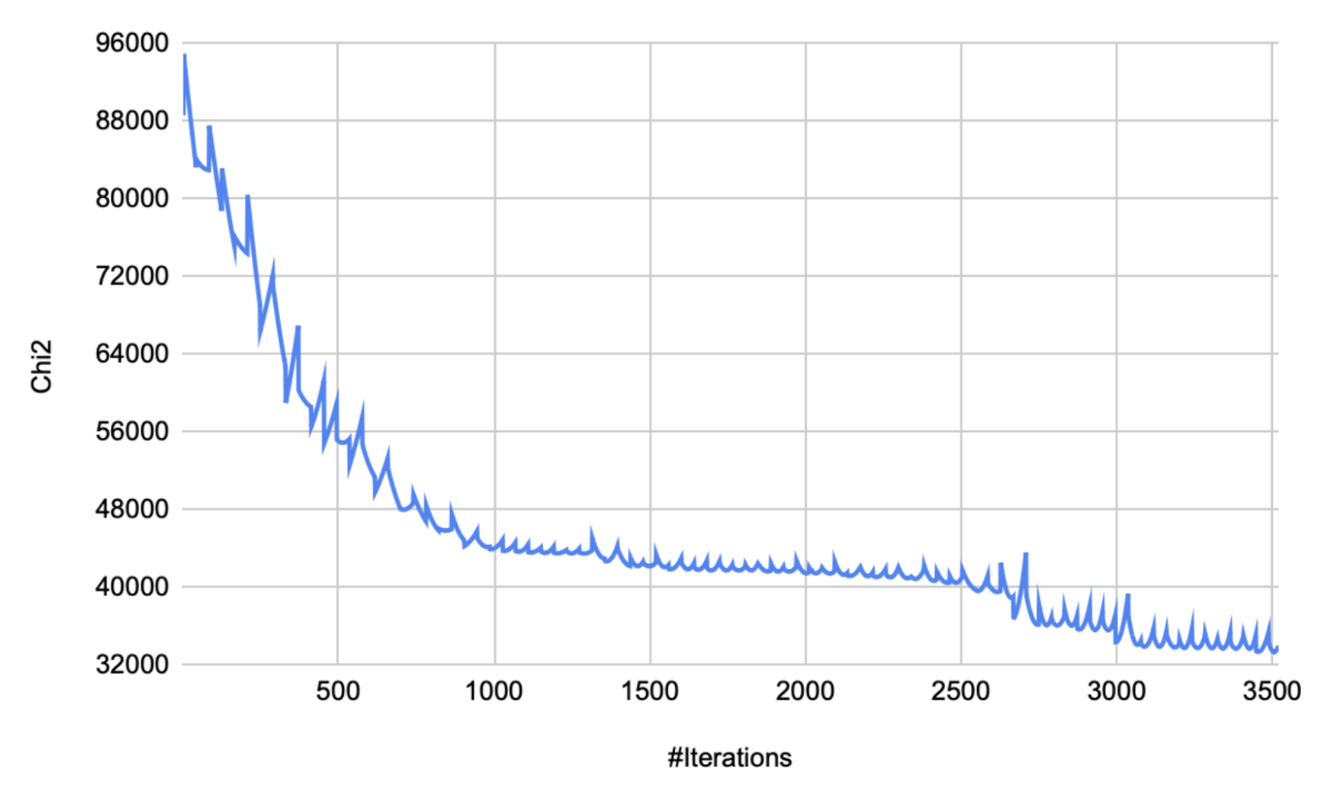


Figure 7. Representative Chi-squared minimization with extensive parameter space exploration and months of iterations

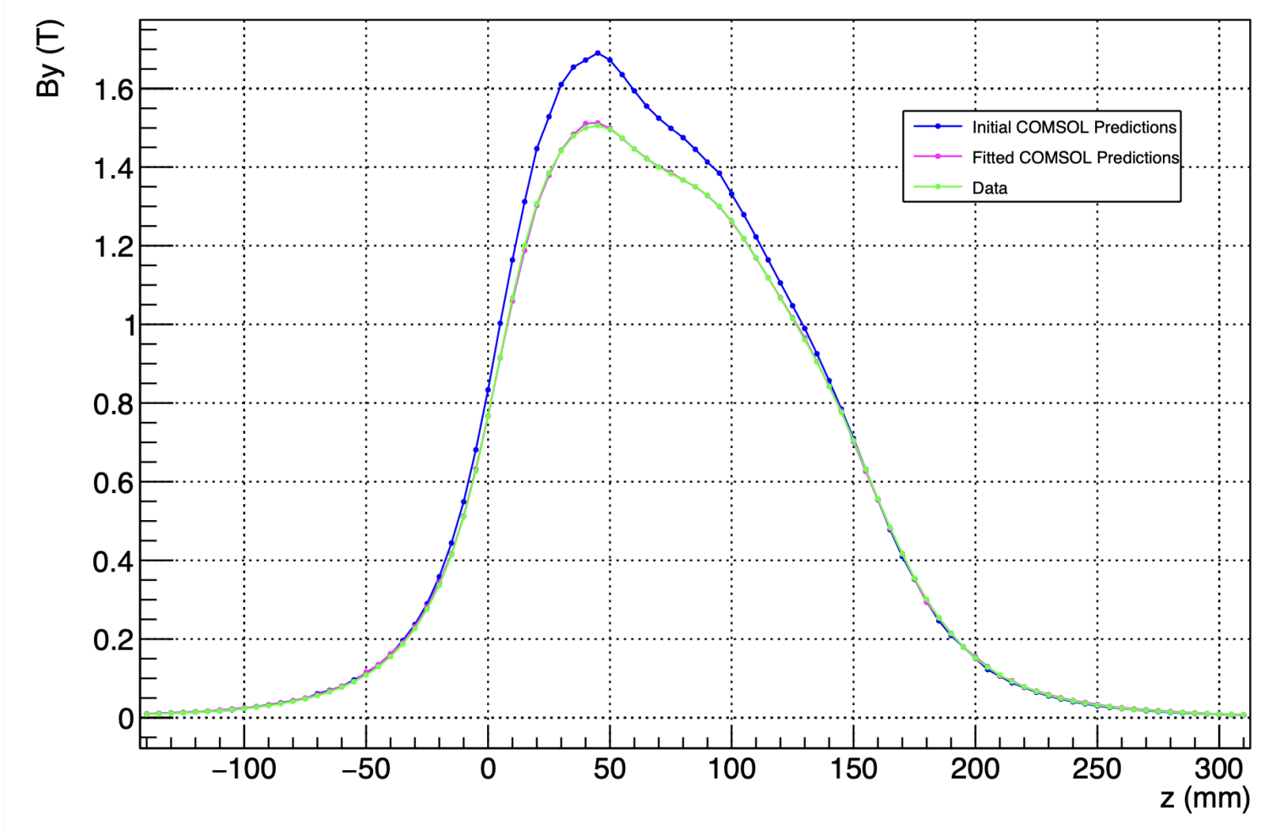


Figure 8. Comparison of initial and present COMSOL ® predictions to evaluate improvements

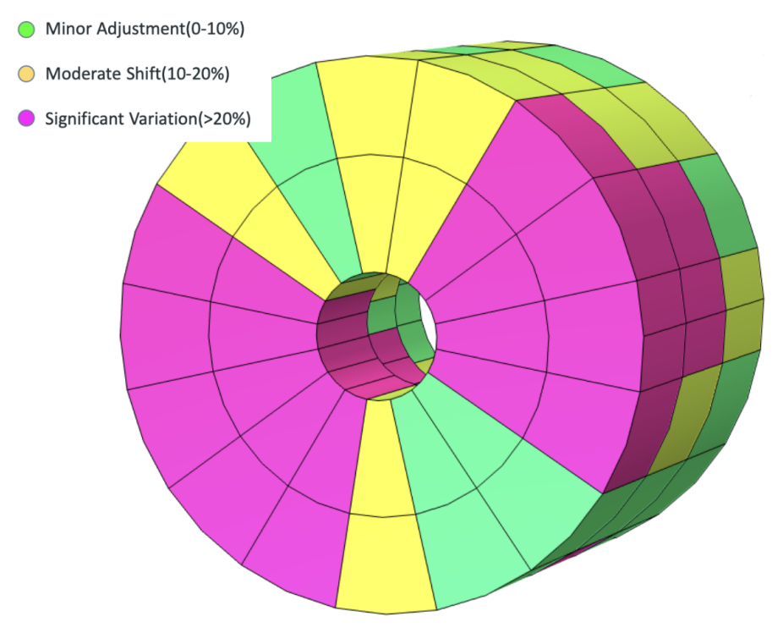
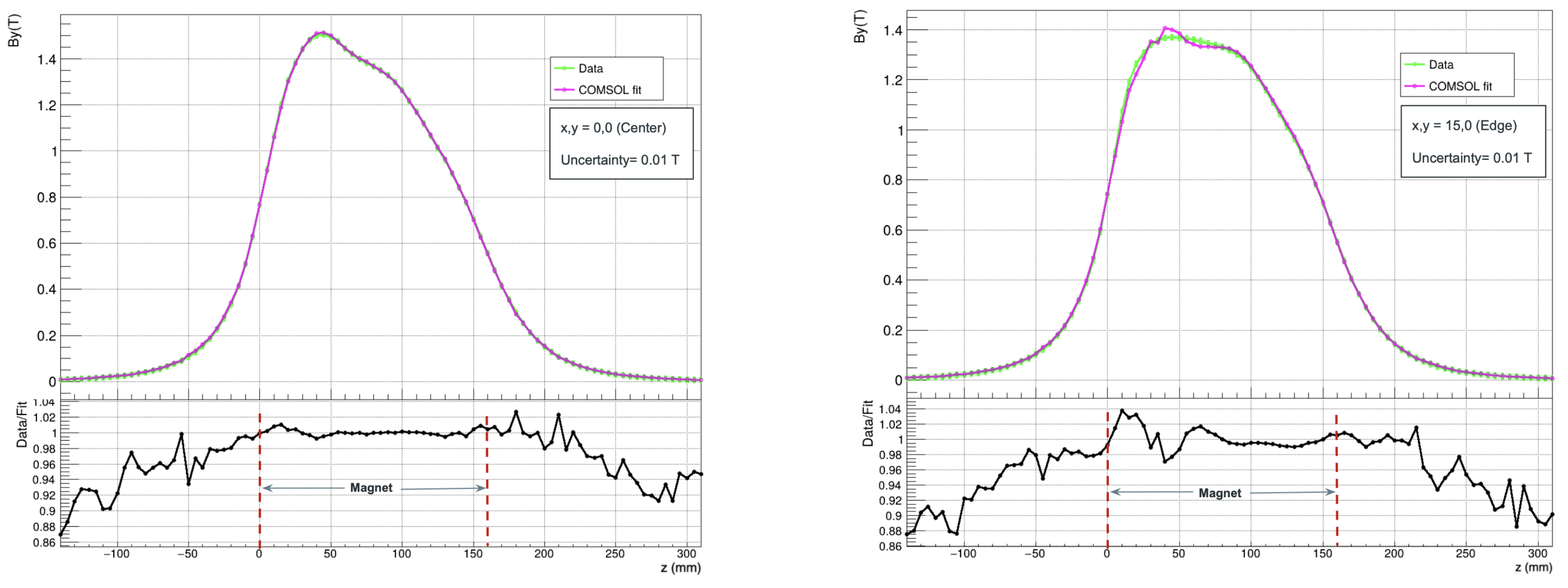


Figure 9. Analysing Relative Parameter Changes across corresponding segments after the Fit



Center (x,y=0,0)

Edge (x,y=15,0)

Figure 10. COMSOL ® fit plots at two positions: center and edge.

Results and discussion

- This COMSOL ® model can generate 1 mm or 0.5 mm resolution maps within minutes, using fit parameters, and covers the entire magnet, including edges up to 22 mm
- Observation: After optimisation, the discrepancy between the data and the fit within the magnet is generally **∼1-2%**, with a maximum of **∼5%** at the edges.

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