A Functional 3D-Printable Magnet Model of the ATLAS Toroid

Julia Woithe*, Alexandra Jansky†, Oliver Keller‡ and Tiago Gonçalves
S’Cool LAB Team, CERN, 1211 Geneva 23, Switzerland
* julia.woithe@cern.ch
† alexandra.jansky@cern.ch
‡ oliver.michael.keller@cern.ch

Received June 22, 2020

The ATLAS detector is the largest particle detector at the LHC and one of the most complex machines ever built. It allows precise measurements of particles emanating from proton collisions. Due to its complexity, introducing the ATLAS detector in the high-school physics classroom can be challenging. Nonetheless, we show how to use 3D printing to provide a hands-on classroom activity by constructing a functional 3D model of the toroidal ATLAS magnet system. This model can be used to discover, visualize and explain the shape of a toroidal magnetic field and to start a discussion about the role of magnetic fields in particle detectors in general.

Keywords: ATLAS detector; magnetic fields; high school students; particle physics; models.

1. Introduction

Particle physics is an exciting field of research that easily captures the interest of high-school students and their teachers. In particular, the research tools used in particle physics are fascinating machines, such as the 46 m long and 25 m high ATLAS detector. However, engaging students with hands-on particle physics experiments can be very challenging because the equipment required is often too expensive for schools. We present a 3D-printable functional model of one of the most important components of the ATLAS detector, namely its toroidal magnet system. This model allows students to produce, explore and manipulate a toroidal magnetic field. In the following, we summarize the properties of the ATLAS magnet system, introduce the 3D-printable model and provide classroom ideas. Online, we offer additional resources: .stl files for 3D printing, a video explaining the assembly process, a student worksheet and ideas for a cardboard version of the model.

2. The Toroidal Magnet System of the ATLAS Detector

The LHC accelerates several thousand bunches of 100 billion protons each up to an energy of 8 TeV per proton. Bunches travelling in opposite directions meet at four different points along the LHC ring. One of these points lies in the center of the ATLAS detector, which has been assembled...
in a cavern 100 m underground and is the largest of the particle detectors at the LHC. The detector was designed to record the collisions of these high-energy protons. Studying proton collisions with a multipurpose detector like ATLAS allows physicists to search for dark matter, matter–antimatter asymmetry, extra dimensions and microscopic black holes as well as supersymmetry or additional Higgs bosons.

ATLAS is one of the largest physics instruments ever built, consisting of multiple detector subsystems arranged in cylindrical layers around the collision point. Each subsystem measures only a specific set of particle properties. However, the combination of all information allows the track reconstruction of particles emanating from the collisions, which forms the basis of advanced data analysis. Here, strong electromagnets are essential components of particle detectors. In total, four different magnet systems provide magnetic fields for the ATLAS detector. A solenoid magnet surrounds the inner detector, the barrel toroid provides the magnetic field in the central muon detectors, and the magnetic fields of the two end-cap toroids enhance the bending power in the end-cap region of the muon detector.

The barrel toroid comprises eight 25 m long superconducting air-core coils surrounding one of the detector subsystems, the so-called calorimeter. Together, these coils produce a unique donut-shaped toroidal magnetic field providing the “T” for the name “ATLAS”, which was originally derived as the acronym of A Toroidal LHC Apparatus. It is only thanks to this toroidal magnetic field that ATLAS is able to precisely measure the momentum of muons and anti-muons, which is crucial for many of the particle physics analyses.

3. Building Instructions

The 3D model of the toroidal magnet system scaled 1:100 has been designed using FreeCAD. The model is made of four different components, see Fig. 1. The key component is the coil frame, which will house 80 turns of copper wire. To simplify the printing process, the coil frame was separated into two identical halves with a jigsaw-puzzle-like connection. Similar to the support structure of the real ATLAS magnet, inner struts and outer struts were designed. These are used to maintain the distance between the eight coils. In addition, feet were designed to be connected to the two bottom coils.

Online, we provide the final design files, recommended printer setting, as well as a video documenting the full assembly process, which contains detailed building instructions complementing the information below. The following material and equipment are needed to build the model:

- 3D printed parts (8 coil frames, 16 inner struts, 16 outer struts, and 4 feet)
- cyanoacrylate glue (super glue)
- cutter
- enameled copper wire (Ø 0.5 mm, 500 m length)
- pliers
- lighter
- soldering iron and solder
- 2 × 4 mm banana sockets
- experiment cables with 4 mm banana plugs
- power supply (12 V DC) or battery pack
- multimeter (optional)
- sandpaper to remove the enamel layer (optional)

We printed all pieces using PLA plastic and an Ultimaker 2+ 3D printer. Here, the printing process for all parts takes approximately 60 hours. Brims and support structures were removed after the printing process using a cutter knife. After gluing the two halves of each coil frame together using multipurpose cyanoacrylate glue (common super glue), 80 turns of enameled copper wire (Ø 0.5 mm, 500 m length) are coiled up around each coil frame. Two small holes drilled into the plastic at one of the short sides of the frame help to fix the two ends of the wire. Then, the model is built step-by-step by

![Fig. 1. 3D designs of (a) coil frame, (b) inner strut, (c) outer strut and (d) foot.](image)
gluing struts between the coil frames. Finally, the four feet are attached to the two coil frames at the bottom. After removing the insulation, the ends of the copper wire are soldered together to connect the coils in series. We recommend checking the electrical resistance of each connection with a multimeter. Finally, the two remaining ends of the wires are fastened in banana sockets, which will later connect the model to a DC power supply.

4. Ideas for the Classroom

To explore the model with high-school students, we recommend a stepwise assembly process guided, for example, by our student worksheet. Here, a pair of students can first make one coil, connect it to a 12 V DC power supply and then visualize the shape of the magnetic field of their coil drawing magnetic field lines with the help of compasses or other probes such as 3D compasses or smartphone apps. Subsequently, a second coil is attached and connected in series. Students will notice how the magnetic fields of the two coils sum-up when visualizing the magnetic field. At this stage, the two coils can also be fixed around an electron tube to demonstrate the effect of the magnetic field on electrically charged particles.

Finally, the full toroidal system is assembled, glued together, and the copper wires of the individual coils are soldered together. When building the model, high school students will not only explore magnetic fields, field lines, and the use of magnetic fields in particle detectors but also apply their learning about electric circuits and electrical resistance.

When assembling and exploring the model of the ATLAS toroid in the classroom, we consider the comparison of the model toroid (Fig. 2) with the real ATLAS toroid (Fig. 3) to be crucial. Teachers can also use this opportunity to discuss the use of models in physics. Hence, in the following, we highlight intriguing similarities and differences between the central toroidal magnet system of the ATLAS detector (called “ATLAS toroid” in the following) and the model toroid presented above, see also Table 1.

The model we describe was designed to have visual similarities with the real ATLAS toroid, at a 1:100 scale. Indeed, due to the assembly of 8 air coils, the shape of the magnetic fields of both the ATLAS toroid and the model toroid look strikingly similar. Also, the voltage needed to operate the model toroid (12 V) is comparable to the voltage of the ATLAS toroid (16 V). However, the resulting magnetic field of the model toroid (0.8 mT) reaches only a fraction of the field of the ATLAS toroid (0.5 T). This can be explained by the immense electric current of up to 20.5 kA flowing through the coils of the ATLAS toroid. Instead of 56 km of superconducting Niobium-Titanium (NbTi) cables, the model toroid uses 500 m of copper wire leading to a much higher electrical resistance of 31 Ω, almost 200,000 times the resistance of the ATLAS toroid. But, contrary to the ATLAS toroid, which needs liquid helium to cool the coils to 4.5 K, the model toroid can be operated at (class-) room temperature.

In summary, this 3D-printable and functional model of the toroidal magnet system of the ATLAS detector can enrich physics education by allowing students to discover the shape of magnetic fields, specifically of a toroidal magnet system. However,
Table 1. Comparison of the ATLAS toroid and the 3D-printed model toroid.

| ATLAS Toroid | Model Toroid |
|--------------|--------------|
| Inner diameter | 9.4 m | 9.3 cm |
| Outer diameter | 20.1 m | 20.1 cm |
| Length | 25.3 m | 24.7 cm |
| Mass | 830 t | 860 g |
| Number of coils | 8 | 8 |
| Material | Niobium-Titanium | Enamelled copper wire |
| Operating temperature | 4.5 K | Room temperature |
| Turns per coil | 120 | 80 |
| Total length of conductor | 56 km | 500 m |
| Nominal current | 20.5 kA | 0.4 A |
| Voltage | 16 V | 12 V |
| Electrical resistance | 0.160 mΩ | 31 Ω |
| Average magnetic field | 0.5 T | 0.8 mT |

this activity can also initiate a general discussion about the role of electromagnets in particle physics as well as other fields of research and technology.

References
1. The ATLAS Collaboration, The ATLAS Experiment at the CERN Large Hadron Collider, J. Instrument. 3, S08003 (2008).
2. The S’Cool LAB Team, ATLAS Magnet Model including 3D printing files, video instruction, student worksheet and cardboard alternative, https://cern.ch/scoolab/atlas-magnet-model.
3. 3D compasses such as S’Cool LAB’s 3D-printable model or Magnaprobe (Pasco).
4. Smartphone Apps such as MagnetMeter (free for Android).

Julia Woithe is a physics and mathematics teacher, who joined CERN in 2013. In the framework of her PhD project in physics education research, she developed, empirically evaluated, and managed S’Cool LAB, the hands-on particle physics learning laboratory at CERN. Currently, she is coordinating the development and implementation of the Science Education Labs in CERN’s Science Gateway Project.

Alexandra Jansky is a physics education researcher and communicator. In the past years, she investigated students’ conceptions on randomness and probability in the scientific context as a doctoral student at the University of Vienna. Besides doing research, she worked in CERN’s S’Cool LAB team. Since October 2019, she is responsible for the content development of the Science Gateway Education Labs.

Oliver Keller holds a diploma in engineering and designed embedded systems in the industrial sector before joining CERN in 2013. His M.Sc. thesis in applied physics resulted in a novel tool for visualising natural radioactivity combining CERN pixel detectors with means of augmented reality. He is currently developing further citizen science instruments and educational experiments based on silicon sensors within a PhD project in cooperation with the University of Geneva. Oliver is passionate about making things and an advocate of open standards, data and methods.
Tiago Gonçalves worked with the S’Cool LAB team to design and 3D print the ATLAS toroid model as part of CERN’s summer student programme 2016. In 2017, he graduated from the University of Nottingham with an integrated Master’s degree in Theoretical Physics. Subsequently, he taught Physics in secondary schools in the UK for a few months, as part of a teacher training programme. For the moment, he has left the prospects of a teaching career to join the monastery at Ampleforth Abbey, England.