MARMARA UNIVERSITY

FACULTY OF ENGINEERING

ANALYSIS AND MODELLING OF A NON-CONTACT ROTATION SENSOR USING MAGNETOSTRICTION AND PIEZOELECTRICITY

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GRADUATION PROJECT REPORT

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by

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Head of the Department of Mechanical Engineering

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July, 2025 Muhammed Ensar KELEŞ

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ABSTRACT

Analysis and Modelling of a Non-Contact Rotation Sensor Using Magnetostriction and Piezoelectricity

The general purpose of this project is to utilize piezoelectric and magnetostrictive effects and use them in a non-contact rotation sensor. The sensor works on the principle of mechanical deformation in magnetostrictive material caused by the magnetic fields created by the movement of various magnet shapes. This deformation is converted into an electrical signal by the piezoelectric sensor. Of course, the main reason why this sensor is used is that it has advantages such as high sensitivity, compactness, and electromagnetic noise immunity. So, I made different analyses of the magnet we used in the experiment on the computer in order to understand that this system that we will produce and operate will obtain correct results, how its effectiveness will change in possible situations and in which situations it will fulfill its purpose more accurately.

SYMBOLS

mT	: Militesla
mm	: Millimeter
B	: Magnetic flux density
H	: Magnetic field intensity
A	: Ampere
m	: meter
μ_0	: Vacuum permeability
F	: Force
q	: Electric charge
E	: Electric field
v	: Speed
M	: Dipole moment
Fe	: Iron
Ni	: Nickel
N	: North
S	: South
PZT	: Lead Zirconium Titanate
N35	: Neodymium Magnet

ABBREVIATIONS

CW **:** Clockwise

FEA **:** Finite Element Analysis

SI **:** The International System of Units

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1. INTRODUCTION

The main proposal of this project is to model and analyze a non-contact rotation sensor using magnetostriction and piezoelectricity. In this project, I will work in detail on the modeling of a permanent magnet and the examination of its magnetic field in accordance with the experimental setup conditions, and how it will affect the magnetostrictive material.

For this, we will first see the magnetic field in detail. Then, we will examine the permanent magnets that will create this magnetic field and explain the permanent magnet we have. Right after that, we will examine in detail the magnetostrictive material that the magnetic field created by our permanent magnet will affect and we will talk about the working principle of these materials (the magnetostrictive effect). Afterwards, I will give information about the piezoelectric material that the other group will be working on and the sensors that are used to measure rotation in general.

After explaining these, I will finish the introduction part and explain our experimental setup and briefly introduce the programs we will use. Then, I will create models suitable for our experimental set using these programs, make analyses on them and evaluate the results I obtained.

1.1 Magnetic Field

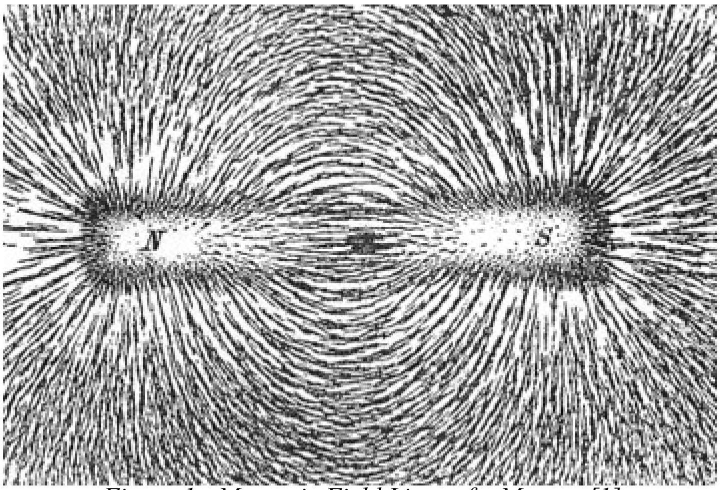


Figure 1 : Magnetic Field Lines of a Magnet [1]

A magnetic field describes the magnetic effect on moving electric charges, electric currents, and magnetic materials. The magnetic field of a permanent magnet (like the one we have in our experiment) attracts ferromagnetic materials such as iron, and they repel or attract each other with other magnets. Additionally, a non-uniform magnetic field exerts very small forces on "non-magnetic" materials through three other magnetic effects: paramagnetism, diamagnetism, and antiferromagnetism. However, these forces are so small that they are generally not visible in everyday life and can only be detected and seen in a laboratory setting. Magnetic fields surround magnetic material as can be seen in the Figure 1. Since both the strength and direction of a magnetic field can vary with location, we can say that it is not a scalar quantity but a vector expression. And the magnetic field is mathematically described by a function that assigns a vector to each point in space. This is called a vector field. [1]

Magnetic fields are composed of moving electric charges and the intrinsic magnetic moments of elementary particles associated with their spin, a fundamental quantum property. Magnetic fields and electric fields are easily thought of as interrelated, and both fields are components of the electromagnetic force, one of the four fundamental forces of nature. [1]

The term magnetic field is used to describe two distinct but closely related vector fields, denoted by the symbols B and H, and these terms have different units. In the International System of Units, the unit of B (magnetic flux density), which is expressed in tesla, which corresponds to newtons per meter per ampere. The unit of H (magnetic field intensity), which is expressed in ampere per meter (A/m). Although B and H both correspond to magnetic fields, they differ in how they account for the medium or magnetization. [1] The relationship between them for vacuum can be given as the formula below ;

$$\frac{B}{\mu_0} = H \tag{1}$$

$$\mu_0 : Vacuum\ permeability$$

The magnetic field vector B (also called magnetic flux density or magnetic induction) at any point can be defined as the vector in the Lorentz force law that accurately predicts the force on a charged particle at that point. [1] The Lorentz force law is shown as follows ;

$$F = qE + q(v \times B) \tag{2}$$

In this equation, F is the force on the particle, q is the electric charge of the particle, E is the external electric field, v is the speed of the particle and × is the cross product (vector product). Also, this equation is in SI units and in vector form. [1]

1.1.1 Magnetic Fields of Permanent Magnets

Permanent magnets are objects that have the property of producing their own permanent magnetic field. They are made of ferromagnetic materials (such as magnetized iron and nickel) and have both a north (N) and a south (S) pole. The magnetic field of permanent magnets can become very complex, especially as you get closer to the magnet. The magnetic field of a small flat magnet is proportional to the strength of the magnet, or magnetic dipole moment (M). The equations are important and depend on the distance from the magnet and the orientation of the magnet. For simple magnets, m represents the direction of a line drawn from the south pole of the magnet to the north pole, as can be seen in the Figure 2. Turning a bar magnet is equivalent to rotating its magnetic dipole moment by 180 degrees. [1]

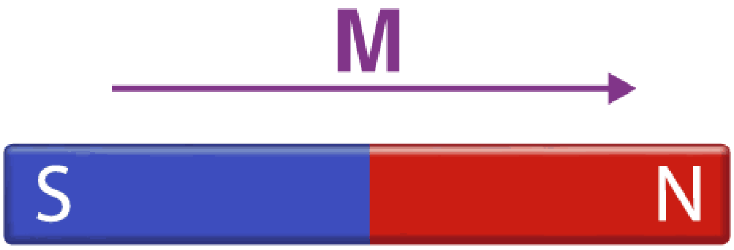


Figure 2 : Magnetic Dipole Moment (M) of A Magnet [7]

The magnetic field of larger magnets can be obtained by considering the combination of many smaller magnets, each with its own m. In this case, the magnetic field produced by our larger magnet will be the net magnetic field of the dipoles of the smaller magnets. [1]

1.2 Magnetostrictive Materials

If we make a general definition, we can define magnetostriction as the change in shape of a material under the influence of a magnetic field. When we look at the history of this term, the magnetostrictive effect was first described by the English physicist James Joule in the 19th century (1842). He observed that a sample of a ferromagnetic material (the material used here is iron) changed its length in the presence of a magnetic field.

Joule actually observed a material with negative magnetostriction. But of course, today we also know materials with positive magnetostriction. The causes of magnetostriction are similar whether it has positive or negative magnetostriction. This change in length (lengthening or shortening) occurs as a result of the rotation of small magnetic domains. This rotation and reorientation causes internal strains in the material structure and the resulting strains in the material cause the material to stretch in the direction of the magnetic field when we have positive magnetostriction, while the opposite is true when we have negative magnetostriction. [2] You can see these processes clearly in Figure 3.

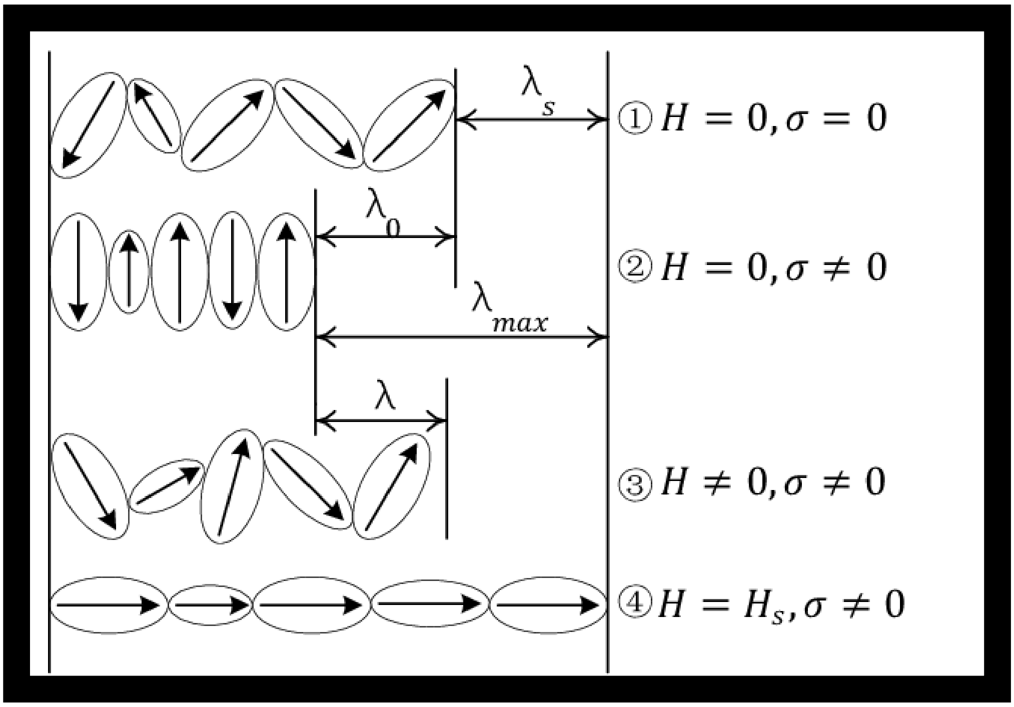


Figure 3 : Schematic of the physical mechanism of magnetostriction [3]

Under normal operating conditions the volume change is negligibly small and therefore during this stretching process the cross-sectional area decreases such that the volume remains constant. [2] You can see this schematically as indicated by 4th item in Figure 3. Applying a stronger magnetic field will cause more domains to be reoriented in the direction of the magnetic field, stronger and more clearly. When all the magnetic domains are aligned with the magnetic field, the saturation point will be reached. In Figure 4 you can see the idealized behavior of the length change with respect to the applied magnetic field. In this figure, point 3 is the saturation point we are talking about. [2]

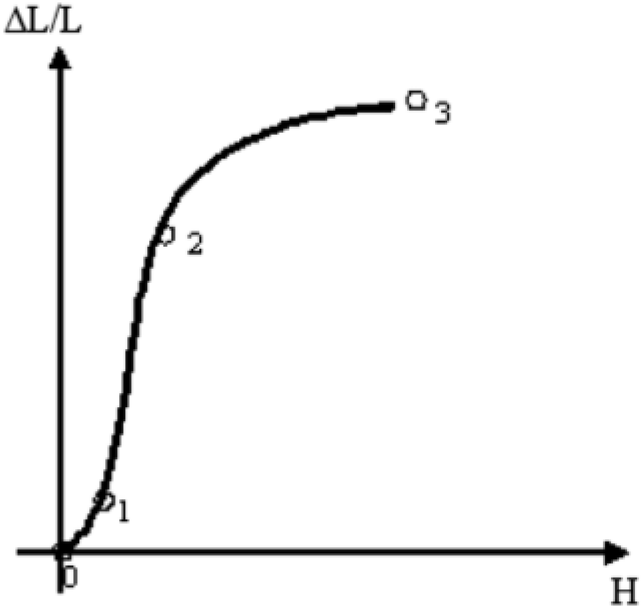


Figure 4 : Strain versus magnetic field [2]

The schematic view of Figure 4, in which the strain versus magnetic field graph is given, is as follows :

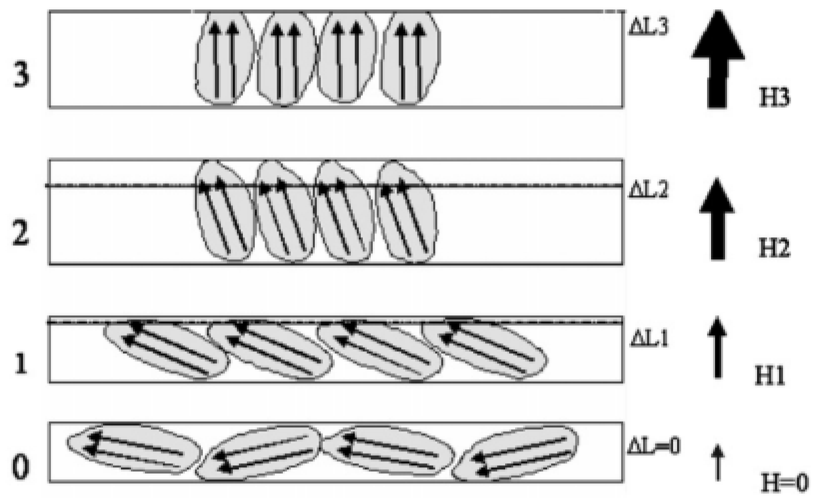


Figure 5 : Strain versus magnetic field , schematically [2]

Actually, I gave a similar schematic view above, but the reason I gave this schematic view here is that this diagram is compatible with the strain graph above and that this figure has the magnetic field direction and stress direction on the vertical axis. In the other figure, the magnetic field and stress direction were on the horizontal axis.

As we see in Figure 4 and Figure 5, between points 0 and 1, a magnetic field that is different from zero but very small affects our magnetostrictive material. As a result, we do not see a big change in the orientation of the magnetic domains and therefore our strain value is so small. Depending on how the material was formed there may be a small amount of a common orientation pattern, which would show itself as a permanent magnet bias. The resulting strain is closely related to how homogeneous the magnetostrictive material is. Between points 1 and 2 there is an almost linear relationship between strain and magnetic field. Many devices are designed for this region because it is easier to predict due to the linear approach in this region. After the second point, since many magnetic field domains are already aligned in the same direction as the magnetic field, the magnetic field and strain relationship we have will become non-linear again. And finally, at the third point, as we mentioned before, there will be a saturation effect. As a result of this effect, no increase in strain will be seen. [2]

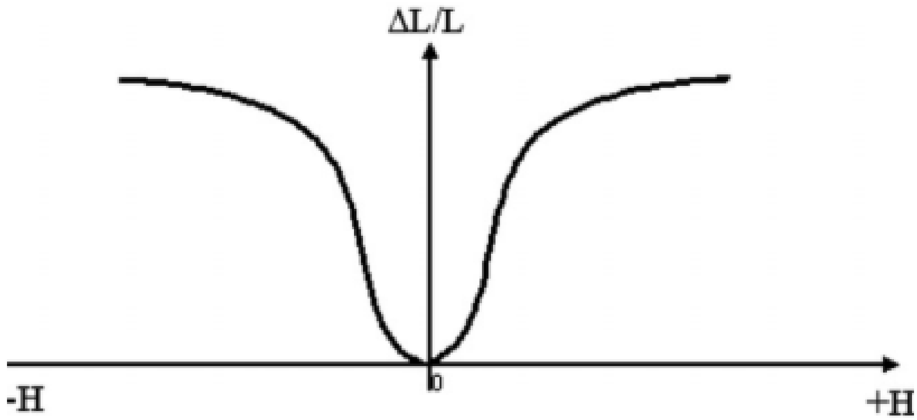


Figure 6 : Strain versus symmetric magnetic field [2]

In the Figure 6, we can see the strain graph for the magnetic field applied in both directions. We see that in the magnetic field in the opposite direction, the magnetic field is negative, but there is no difference in the strain values compared to the elongation values created by the positive magnetic field. [2]

1.3 Piezoelectric Materials

Piezoelectric materials can be briefly considered as a class of materials with a non-centrally symmetric structure. The main feature that we use these materials for is their ability to increase electrochemical and photochemical activities in response to mechanical deformation. When we look at the history of piezoelectricity, the Curie brothers first conducted research on piezoelectricity in crystal physics. In these studies, they discovered an unusual property of certain crystalline minerals and observed voltages induced by compression and tension between these crystalline materials that were proportional to the applied load. This is called the piezoelectric effect. If we go literally, we can deduce that piezoelectricity (piezo means pressure in Greek) means electricity resulting from pressure. [4]

1.3.1 Piezoelectric Materials in Sensors

Piezoelectric sensors work by detecting changes in pressure, force, or strain and converting them into electrical signals (induced voltages). When an external force is applied, certain piezoelectric materials, such as ceramics, crystals, and certain compounds, produce electric dipoles, resulting in an electric charge. The amount of electricity produced is directly proportional to the applied pressure. These sensors are widely used in a number of industries, including nuclear instrumentation, medical technology, and electronics, due to their versatility and sensitivity. Generally, piezoelectric sensors are made from three main types of materials: piezoelectric ceramics, such as lead zirconium titanate (PZT), single-crystal materials, such as quartz and tourmaline, and thin-film materials, such as aluminum nitride. [4]

2. SETUP AND PROGRAMS

2.1 Experimental Setup

We have two experimental setups in this project. The first one is our main experimental setup, which is the experimental setup shown in the Figure 7. The other group working on the project will work with this experimental setup. The elements we have in this experimental setup are shown below;

1. Discs (with Permanent Magnet attached)
2. Magnetostrictive Material
3. 208C01 Force Sensor
4. TB6600 Driver
5. Arduino Uno
6. Fasteners
7. Stepper Motor
8. Sigma Profiles

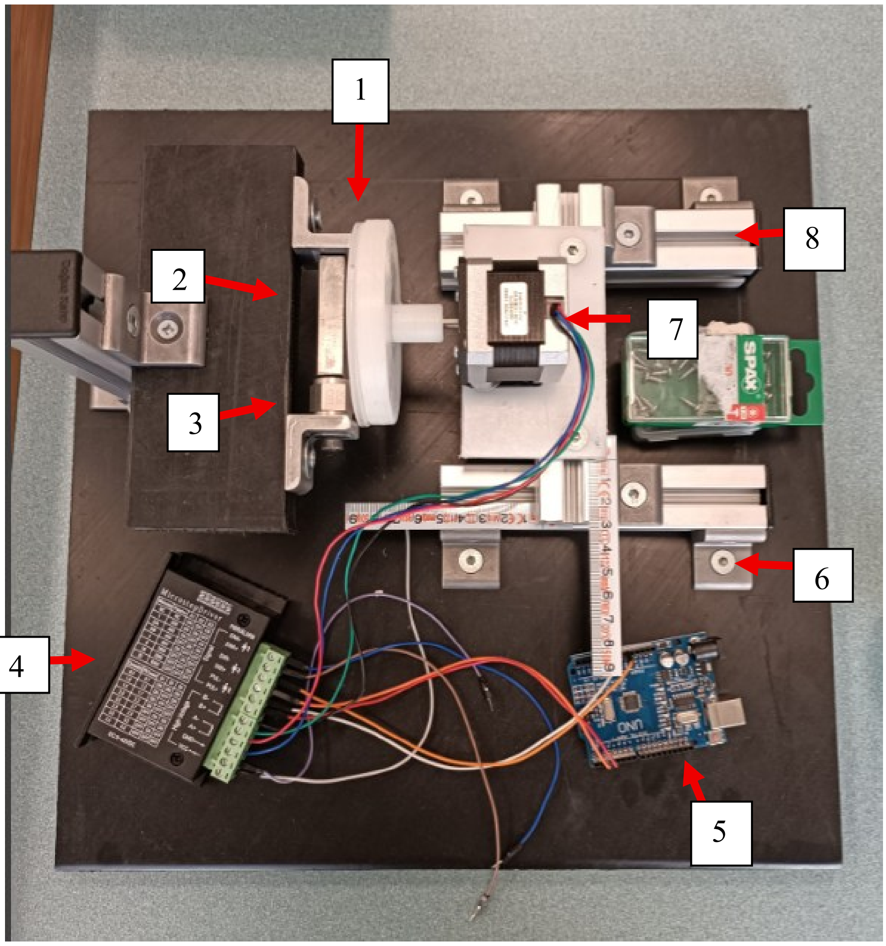


Figure 7 : First Experimental Setup (Main)

The magnetostrictive material we will use in this experiment set is the material in the Figure 8. Our magnetostrictive material consists of a mixture of 60 percent iron (Fe) and 40 percent nickel (Ni).

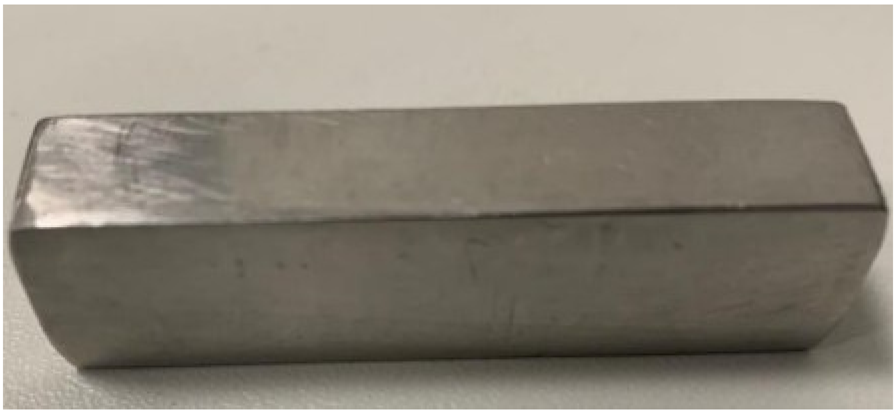


Figure 8 : Our Magnetostrictive Material

The experimental setup that I am working on is the experimental setup shown in Figure 9. My purpose in using this experimental setup is to compare the magnetic field data we obtained from real experiments with our model on Ansys and to see the conformity of our model on Ansys and the data we obtained with reality. The model of the teslameter we have in this experiment setup is Phywe Teslameter Digital and it has three different measurement ranges (20mT, 200mT, 2000mT). The probe we use in this teslameter is the Axial Hall Probe, Phywe 13610‑01, and is characterized by its cable and 300mm long rod shaft. This probe only detects magnetic fields in the direction of the rod. In other words, we can say that it measures magnetic fields parallel to the probe.

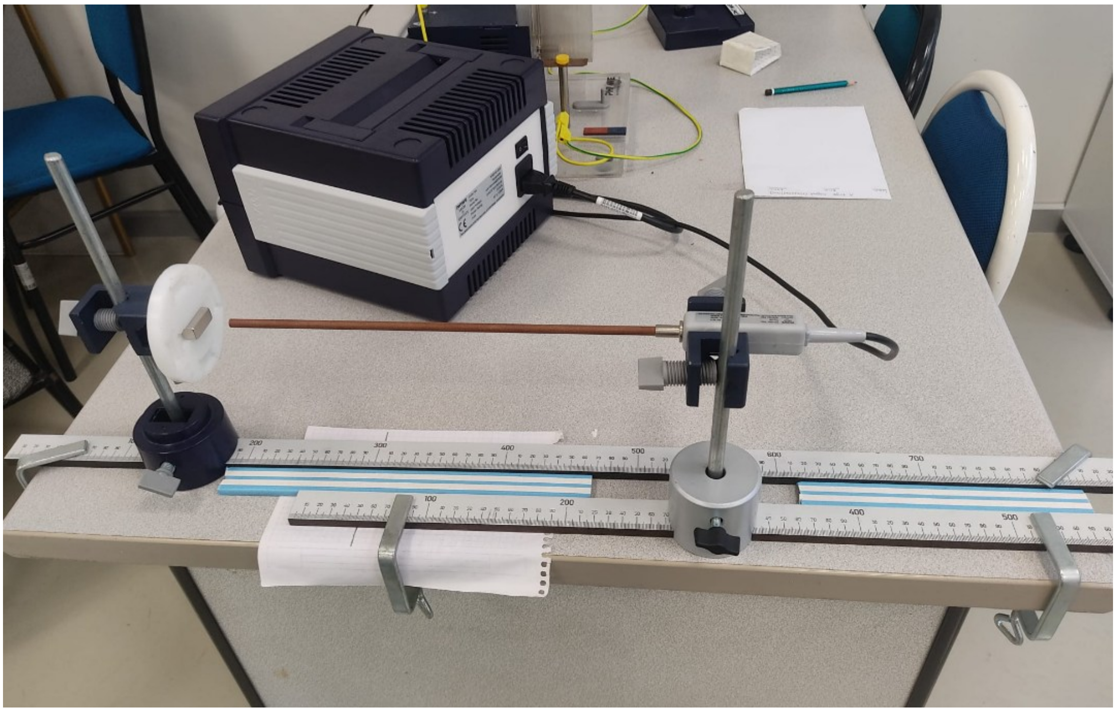


Figure 9 : Second Experimental Setup (For magnetic field measurement)

Of course, before making these measurements, we first reset the teslameter as seen in Figure 10.

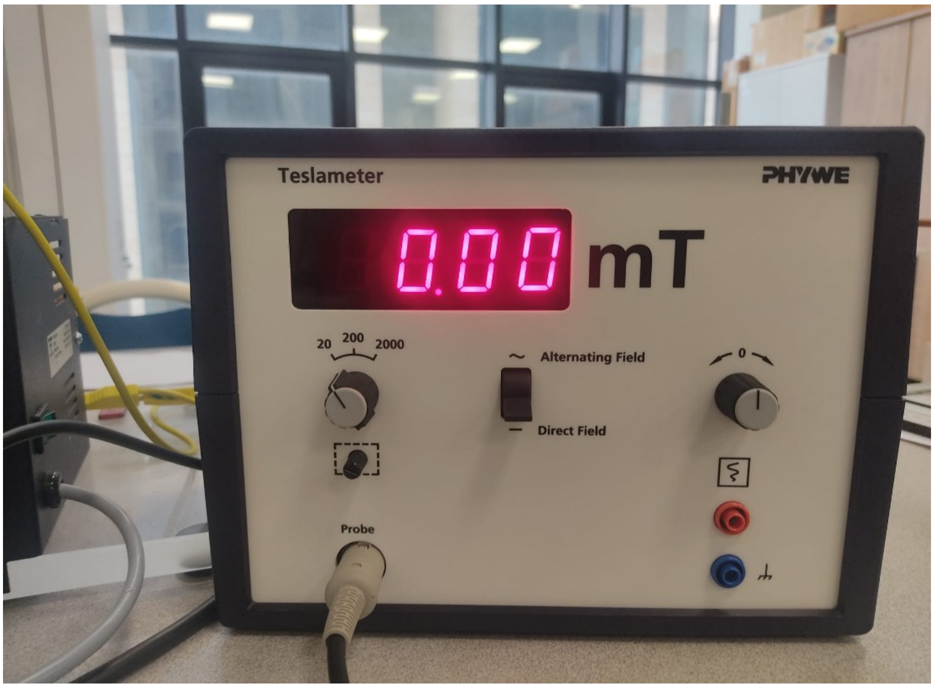


Figure 10 : Zeroing the Teslameter

2.2 Software

2.2.1 Ansys

Ansys software is an analysis software that has been showing and analyzing how its products will work in real conditions for over 50 years. The version I used in these analyses is the student version, which can be downloaded and used over and over again.

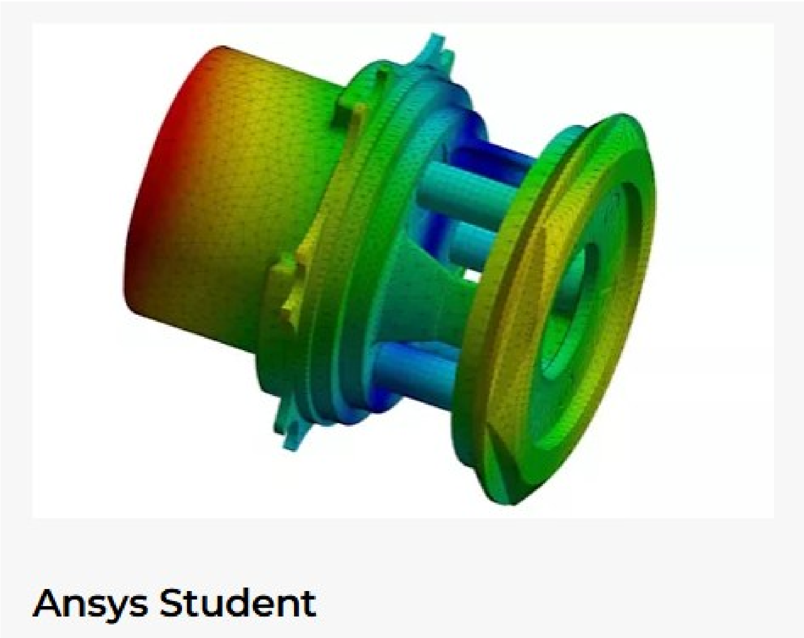


Figure 11 : Ansys Student Version

Ansys Student offers free access to the Ansys Workbench based bundle. This bundle includes Ansys Mechanical, Ansys CFD, Ansys Discovery, Ansys SPEOS, Ansys Autodyn, Ansys optiSLang and Ansys SpaceClaim, Ansys Rocky and many more. [5] Of course, this student version of Ansys is free, meaning it does not contain any paid full version, so it has some limitations. You can see these in Figure 12 and Figure 13, which are declared on Ansys website.

Problem Size Limits

- No Geometry Export

Limits for Ansys Student and Discovery (Refine Mode)

- Structural Physics: 128K nodes/elements
- Fluid physics: 1 Million cells/nodes

Limits for Ansys SPEOS

- Geometry: can support up to 50 bodies and 300 faces
- Number of Triangles: 32K
- No Live Preview, No GPU compute

Limits for Ansys Motion

- 100K Nodes – Number of nodes for each flexible body
- 25K Contacts – Number of triangular patches
- 50 Rigid/Flex Bodies

Figure 12 : Limitations of Ansys Student Version [5]

Limits for Ansys Rocky

- Particle Count limits DEM: maximum of 32K regardless of shape
- SPH Elements limits: maximum of 128K
- No GPU availability
- Limited Rocky modules and scripts are available

Ansys HPC (High-Performance Computing):
Support up to four CPU cores of HPC solutions and 40 SMs of GPU computing on Fluent

Figure 13 : Continuation of Limitations of Ansys Student Version [5]

I performed my analysis using the magnetostatic section of the Ansys Mechanical in the Ansys student version.

Ansys Mechanical is a finite element analysis (FEA) software used to perform structural analysis using advanced solver options, including linear dynamics, nonlinearities, thermal analysis, materials, composites, hydrodynamic, explicit, and more. Mechanical offers a user-friendly, dynamic environment with a complete range of analysis tools, from preparing geometry to connecting other physics for high-fidelity simulations and optimization. Mechanical is known for its customization and scripting capabilities, enabling users to automate repetitive tasks and workflows. [6]

3. PROGRAM DESIGN AND ANALYSIS

3.1 A Permanent Magnet

The programs I used for this project were Ansys 2024 R2 student version and MATLAB. First, I started by analyzing the magnetic field of a single permanent magnet in a volume of air using Ansys. For this, firstly, I chose magnetostatic from the analysis systems on the left.

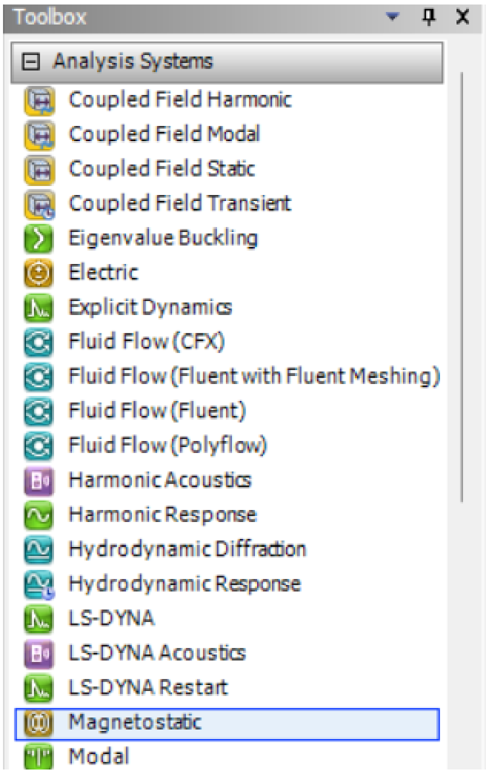


Figure 14 : Analysis Systems

Afterwards, I entered the engineering data section from the opened window to determine my material and environment properties.

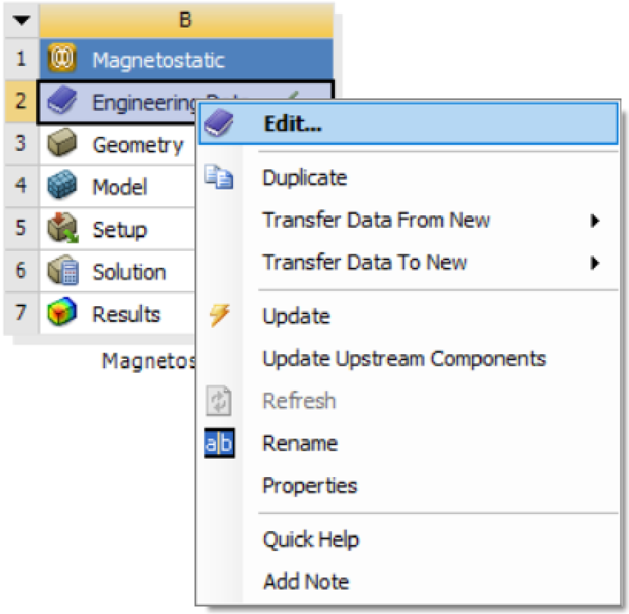


Figure 15 : Engineering Data Section

In this opened window, I first defined the properties of the air. For this, I selected isotropic relative permeability from the linear Soft magnetic material section on the left.

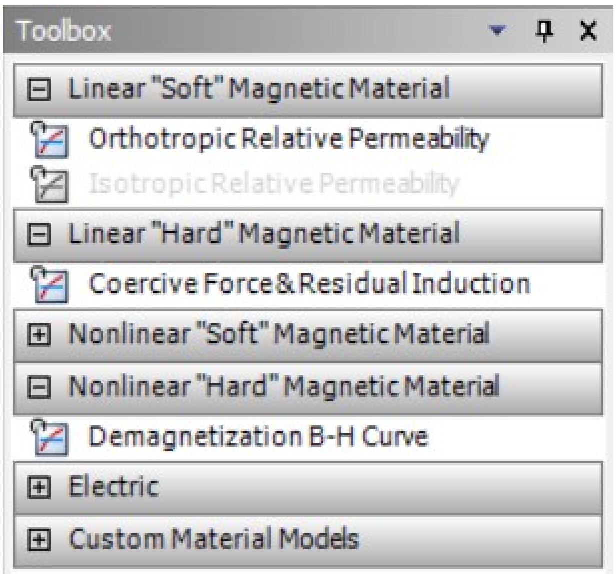
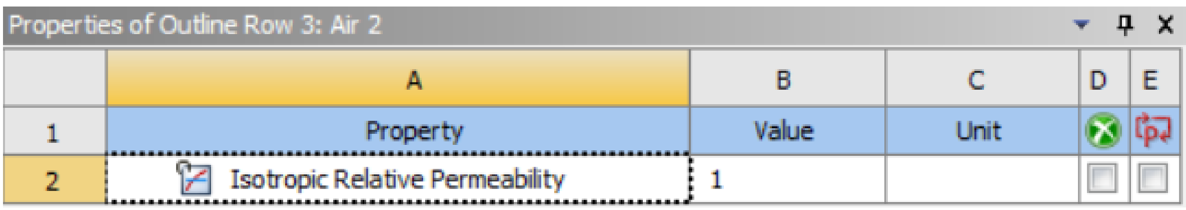


Figure 16 : Air Properties

After selecting this I gave this value as 1 for air.


Properties of Outline Row 3: Air 2

	A	B	C	D	E
1	Property	Value	Unit		
2	Isotropic Relative Permeability	1			

Figure 17 : Air Properties in Engineering Data

In the next step, to determine the properties of my permanent magnet, this time I selected the coercive force and residual induction section in the linear hard magnetic material section from the left. And then, as seen in Figure 19, I adjusted the coercive force and residual induction values of my permanent magnet according to the N35 permanent magnets we have in our experimental setup.

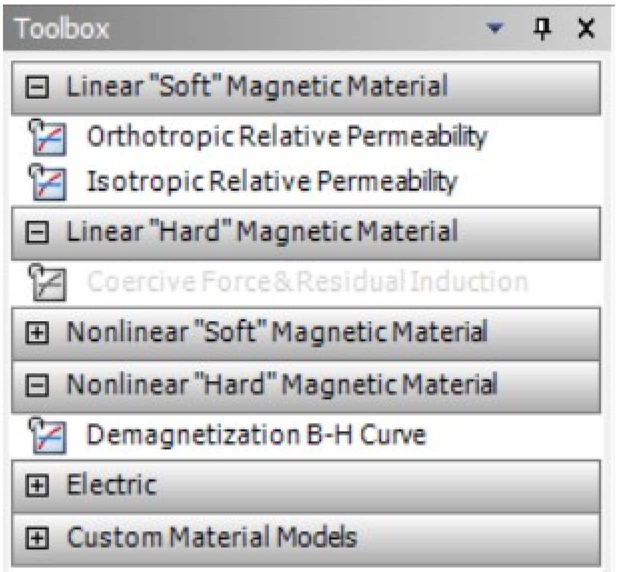


Figure 18 : Permanent Magnet Properties (N35)

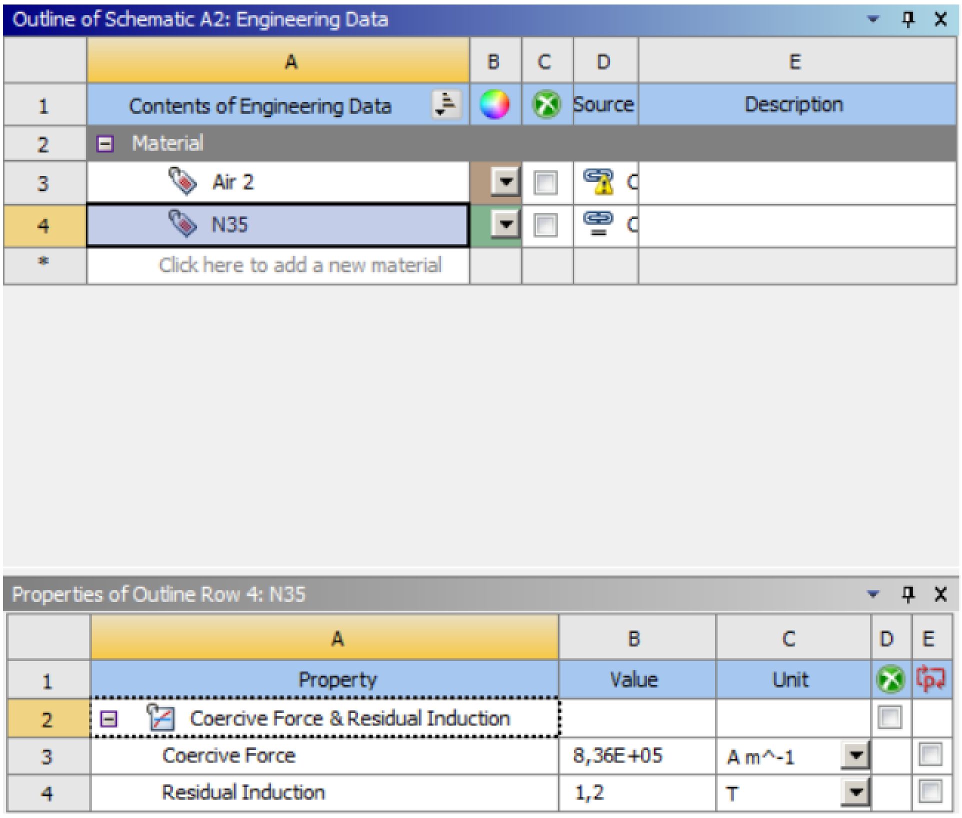


Figure 19 : Permanent Magnet Properties (N35) in Engineering Data

After this, we click on save project from the top left and close the engineering data section.

Since we will use the same materials in the following sections (we will have the same material properties), we will not need to do anything different in the engineering data section.

After determining the properties of my air volume and permanent magnet, it is now time to start creating the geometry of this analysis. We enter the geometry section to transfer the geometry of the magnet and air volume that we have in real life to Ansys. (For this project, we are using the design modeler that appears when we right-click on geometry.)

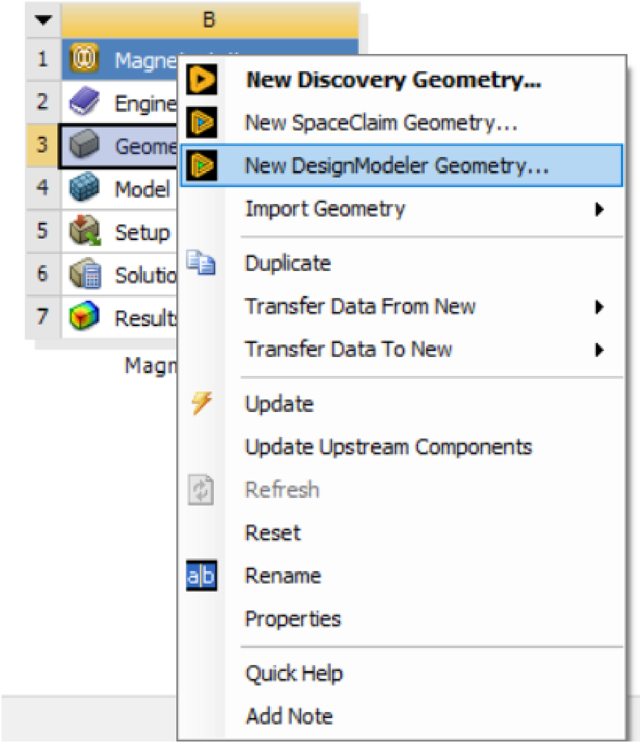


Figure 20 : DesignModeler in Geometry

When we enter the geometry section, we first set the units to millimeters.

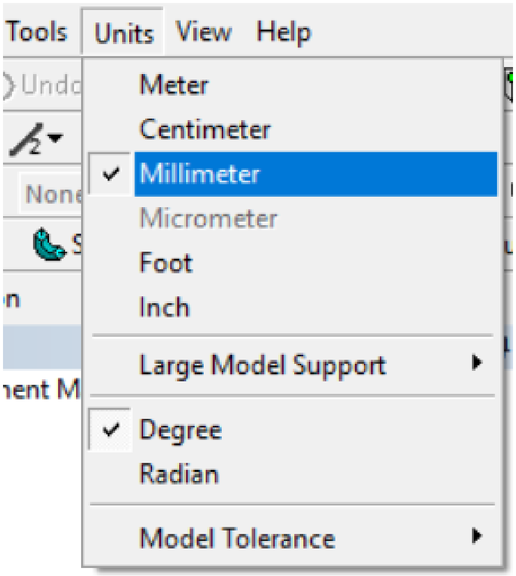


Figure 21 : Units for Geometry

Then, from the create section at the top left, we click on the primitives option and click on the box.

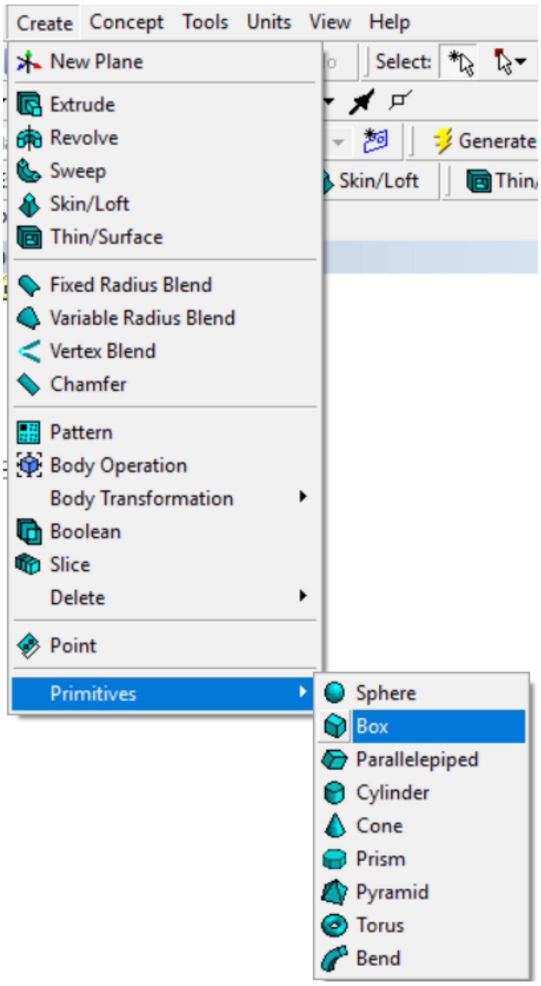


Figure 22 : Box Creating

This box we will create will be our permanent magnet. As seen in the figure below, we enter the x, y and z components of our box and click on generate from the top. As a result, our permanent magnet geometry is created.

Details View	
Details of Box1	
Box	Box1
Base Plane	XYPlane
Operation	Add Material
Box Type	From One Point and Diagonal
Point 1 Definition	Coordinates
FD3, Point 1 X Coordinate	0 mm
FD4, Point 1 Y Coordinate	0 mm
FD5, Point 1 Z Coordinate	0 mm
Diagonal Definition	Components
FD6, Diagonal X Component	10 mm
FD7, Diagonal Y Component	10 mm
FD8, Diagonal Z Component	25 mm
As Thin/Surface?	No

Figure 23 : Details of Permanent Magnet

Then, we move our mouse over the tools section and select the enclosure option.

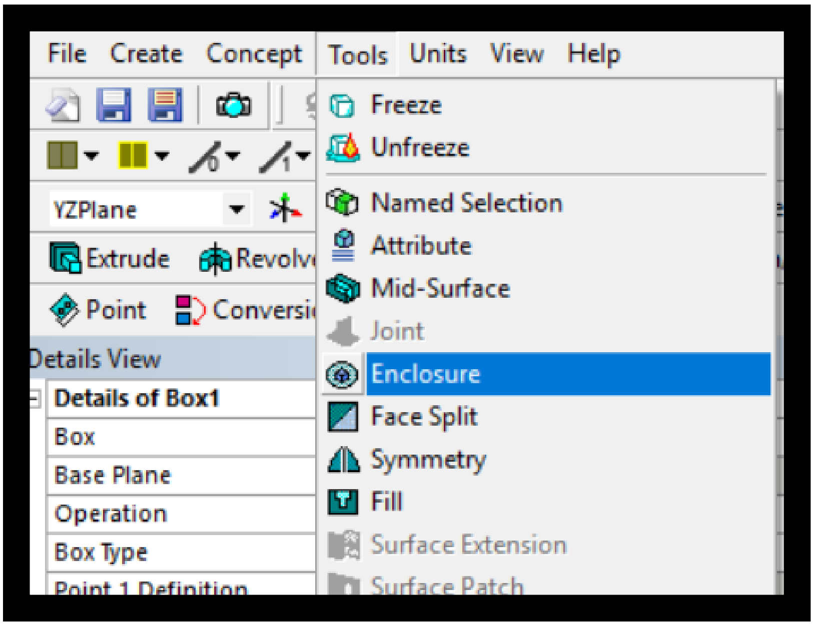


Figure 24 : Enclosure Option

Here we set the details as in the Figure 25 and click generate again.

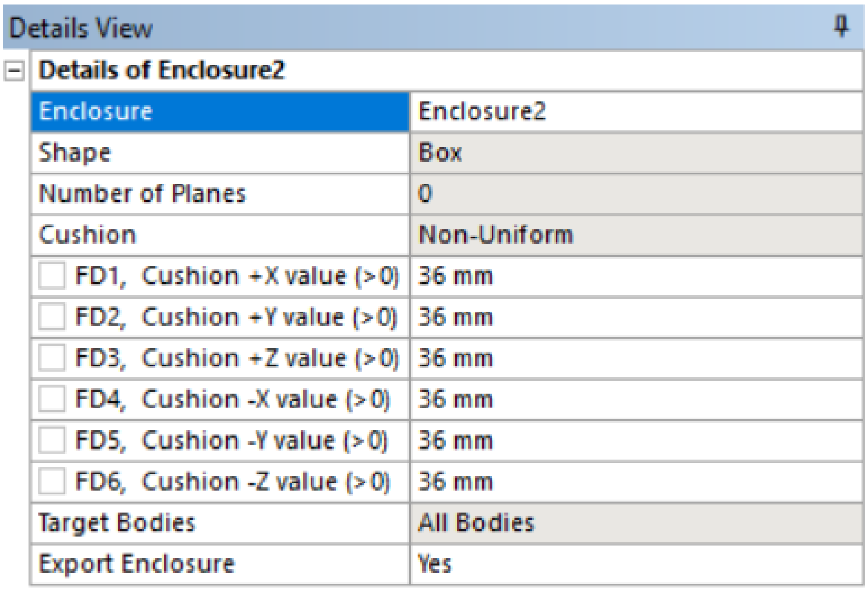


Figure 25 : Details of Enclosure (Air Volume)

As a result of this process, the geometry of the air volume that we will use in our analysis is created. Then, in the left part, we select all the geometries we created and combine them into a single part, as shown in the Figure 26.

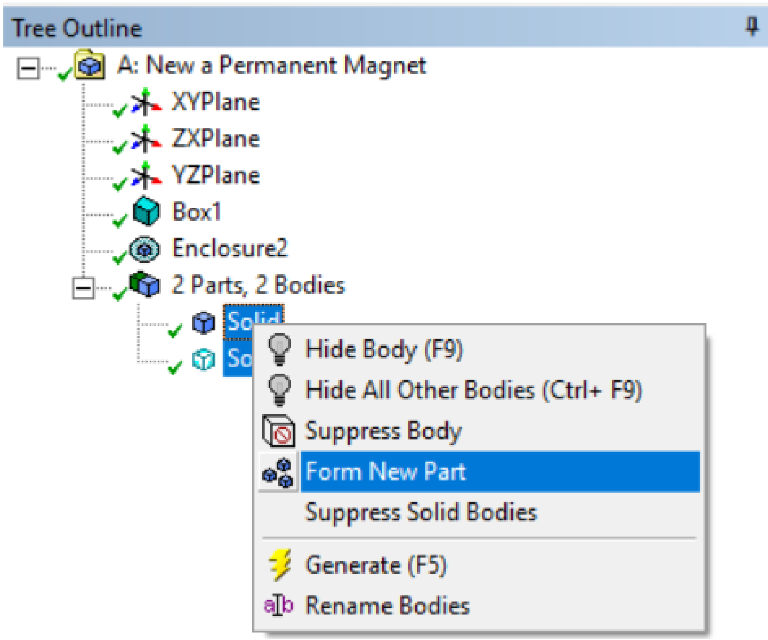


Figure 26 : Form a New Part

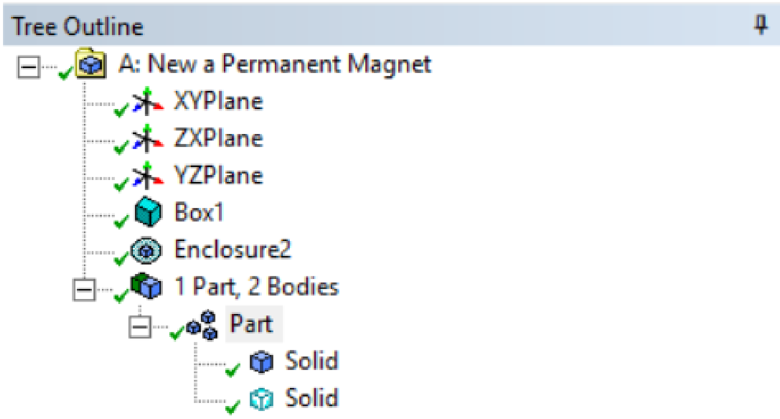


Figure 27 : Final View of Part

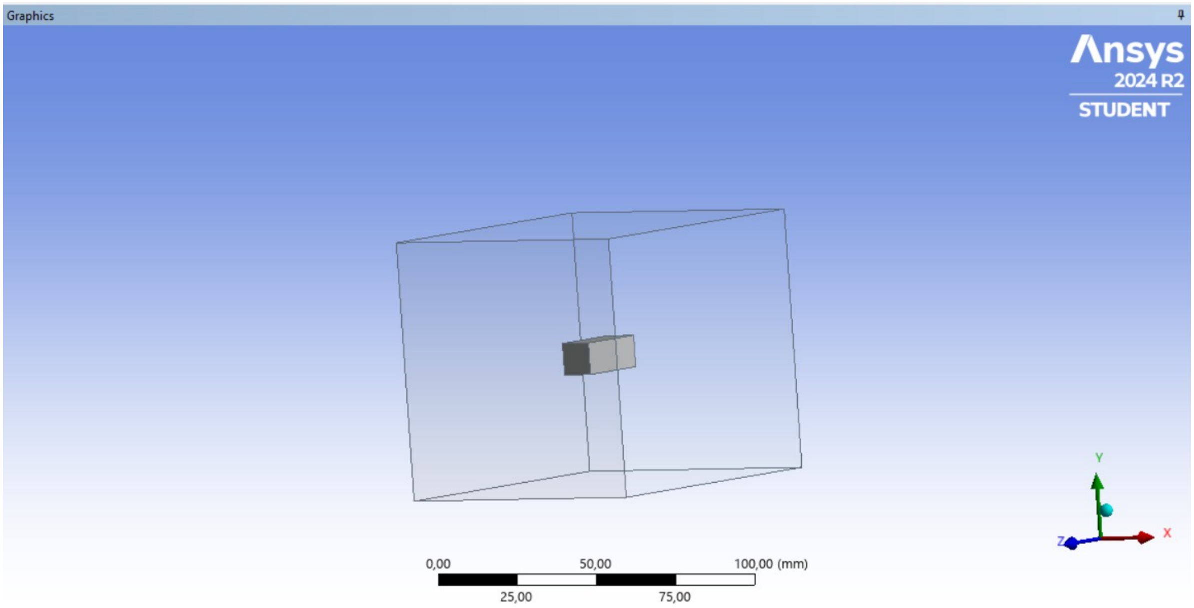


Figure 28 : General View of Our Part

After these processes are completed, we save everything and close the design modeler. Then we enter the model section by clicking edit.

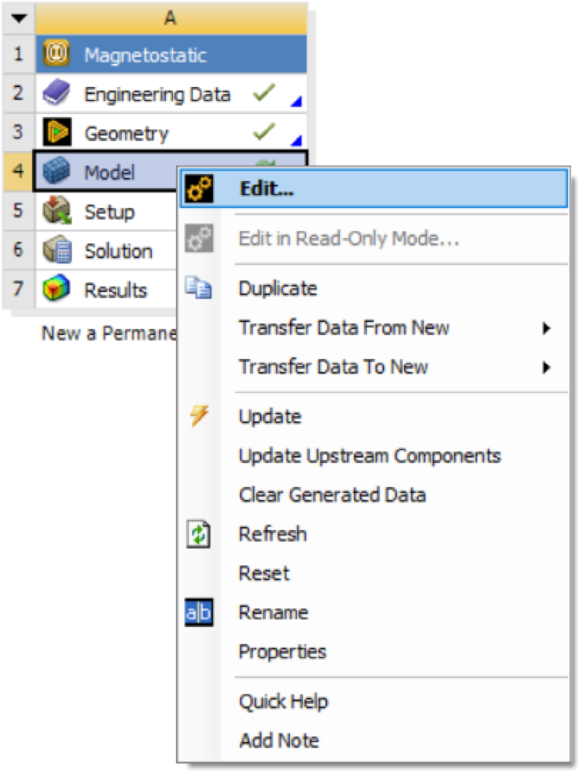


Figure 29 : Model Editing

From the opened model section, we will first look at the coordinate systems section. We come to coordinate systems and select the insert and coordinate system options as in the Figure 30.

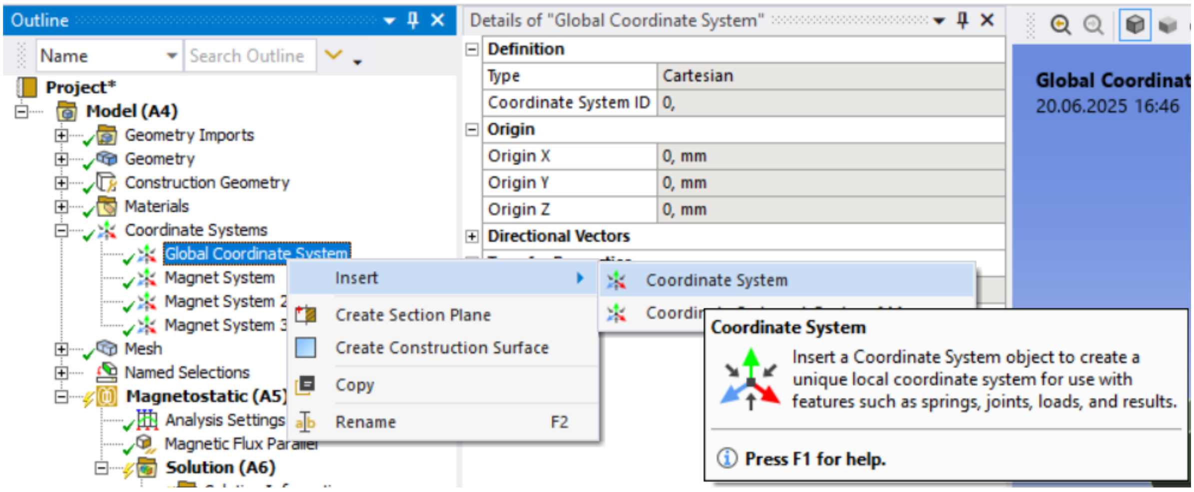
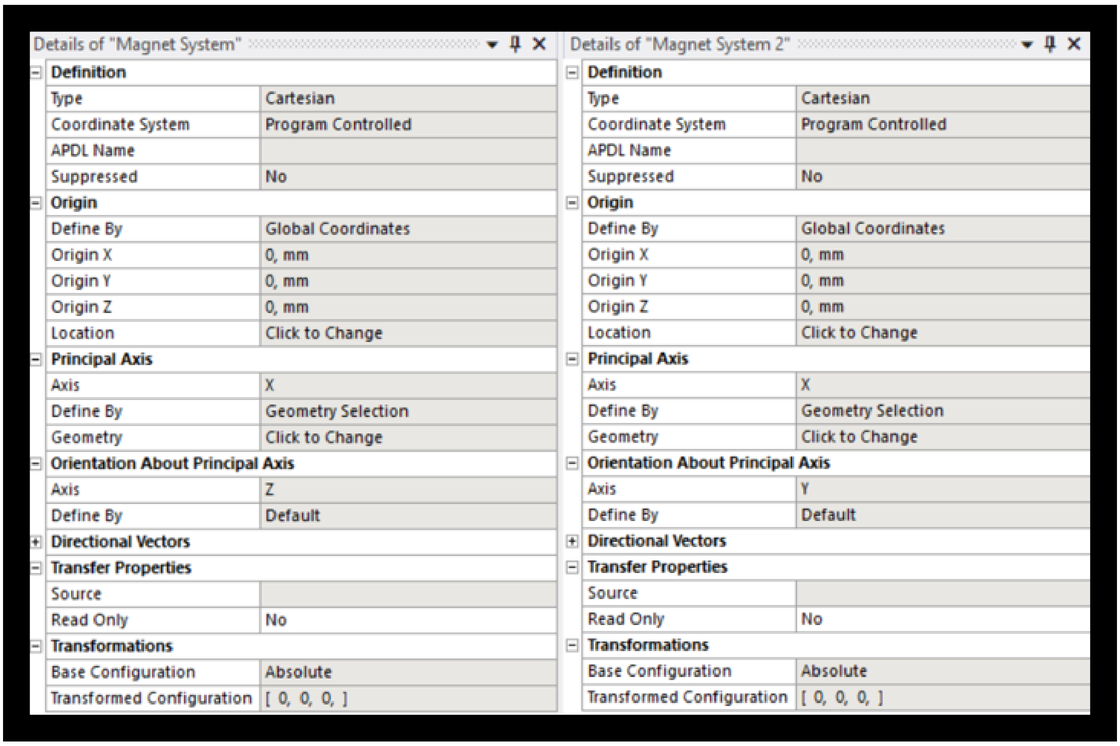


Figure 30 : Insert a new coordinate system

Here, we will create 4 new coordinate systems in this way. The reason we create these is to adjust the polarization of our magnets in the future and to ensure that our magnet rotates. We adjust the 4 coordinate systems from the detail section as seen in Figure 31 and Figure 32.

We adjust these coordinate systems in this way so that they rotate with the object in their polarization. We choose our permanent magnet in each of the coordinate systems except the rotation system.



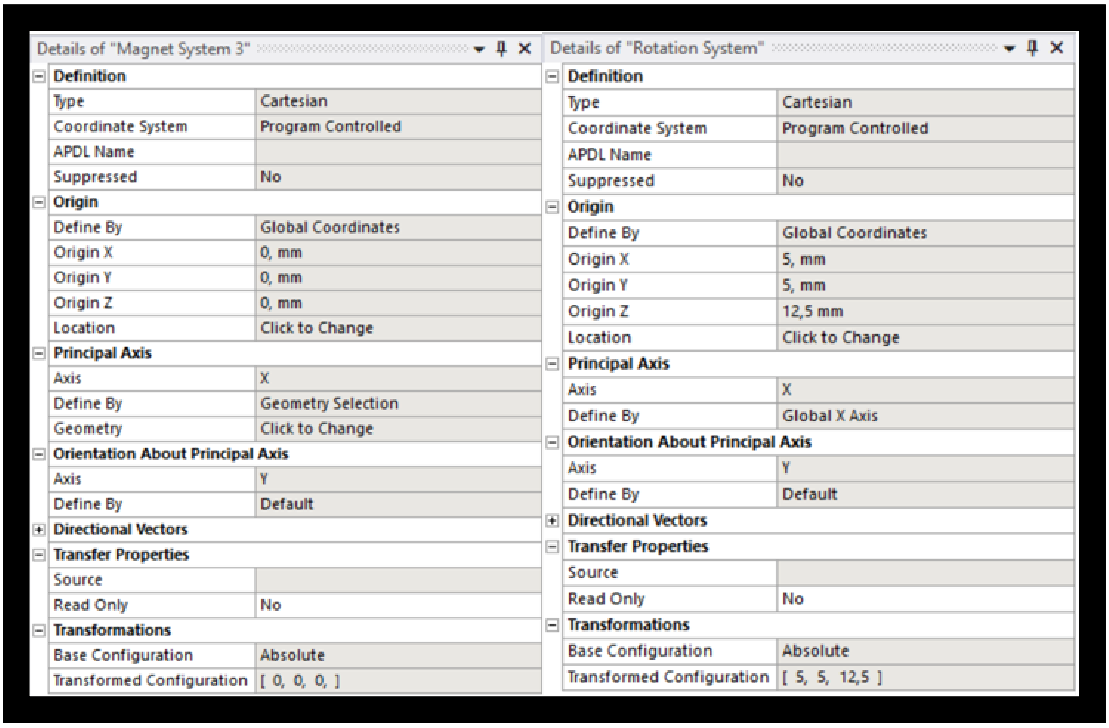
Details of "Magnet System"

Definition	
Type	Cartesian
Coordinate System	Program Controlled
APDL Name	
Suppressed	No
Origin	
Define By	Global Coordinates
Origin X	0, mm
Origin Y	0, mm
Origin Z	0, mm
Location	Click to Change
Principal Axis	
Axis	X
Define By	Geometry Selection
Geometry	Click to Change
Orientation About Principal Axis	
Axis	Z
Define By	Default
Directional Vectors	
Transfer Properties	
Source	
Read Only	No
Transformations	
Base Configuration	Absolute
Transformed Configuration	[0, 0, 0,]

Details of "Magnet System 2"

Definition	
Type	Cartesian
Coordinate System	Program Controlled
APDL Name	
Suppressed	No
Origin	
Define By	Global Coordinates
Origin X	0, mm
Origin Y	0, mm
Origin Z	0, mm
Location	Click to Change
Principal Axis	
Axis	X
Define By	Geometry Selection
Geometry	Click to Change
Orientation About Principal Axis	
Axis	Y
Define By	Default
Directional Vectors	
Transfer Properties	
Source	
Read Only	No
Transformations	
Base Configuration	Absolute
Transformed Configuration	[0, 0, 0,]

Figure 31 : Details of Magnet System and Magnet System 2



Details of "Magnet System 3"

Definition	
Type	Cartesian
Coordinate System	Program Controlled
APDL Name	
Suppressed	No
Origin	
Define By	Global Coordinates
Origin X	0, mm
Origin Y	0, mm
Origin Z	0, mm
Location	Click to Change
Principal Axis	
Axis	X
Define By	Geometry Selection
Geometry	Click to Change
Orientation About Principal Axis	
Axis	Y
Define By	Default
Directional Vectors	
Transfer Properties	
Source	
Read Only	No
Transformations	
Base Configuration	Absolute
Transformed Configuration	[0, 0, 0,]

Details of "Rotation System"

Definition	
Type	Cartesian
Coordinate System	Program Controlled
APDL Name	
Suppressed	No
Origin	
Define By	Global Coordinates
Origin X	5, mm
Origin Y	5, mm
Origin Z	12,5 mm
Location	Click to Change
Principal Axis	
Axis	X
Define By	Global X Axis
Orientation About Principal Axis	
Axis	Y
Define By	Default
Directional Vectors	
Transfer Properties	
Source	
Read Only	No
Transformations	
Base Configuration	Absolute
Transformed Configuration	[5, 5, 12,5]

Figure 32 : Details of Magnet System 3 and Rotation System

Finally, we should have the coordinate systems in the Figure 33.

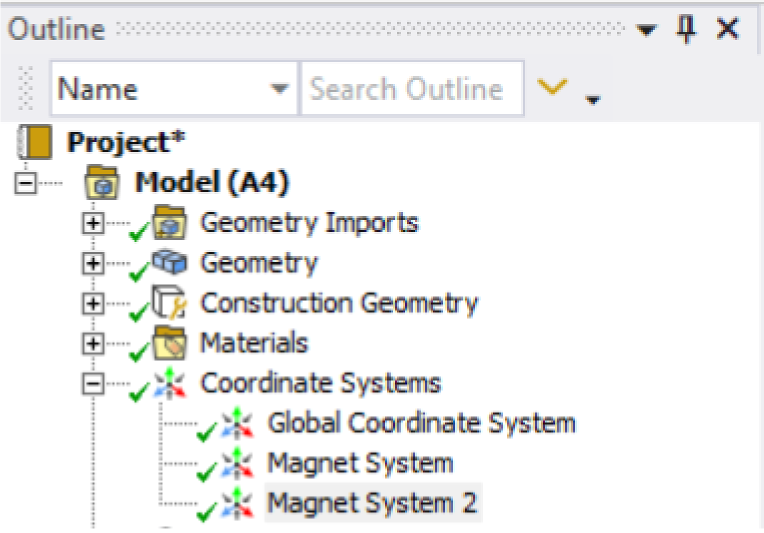


Figure 33 : Coordinate Systems

In the next step, we select the solids from the geometry section and give their assignments. Thus, we determine what material the box and enclosure we just created in the design modeler are made of.

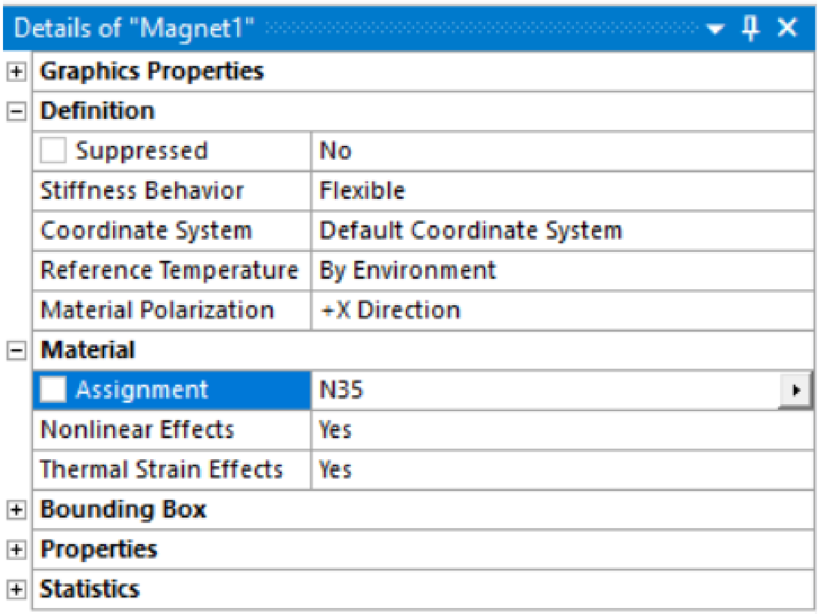


Figure 34 : Assignment for Permanent Magnet

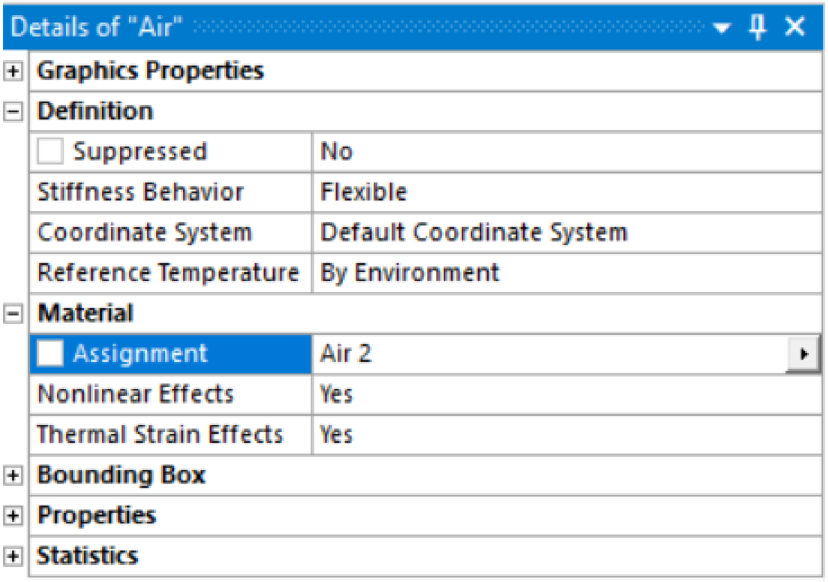


Figure 35 : Assignment for Air Volume (Enclosure)

At the same time, we determine the direction of polarization in our permanent magnet. In the figure below, I first determine a polarization in the +x axis direction according to the global coordinate system.

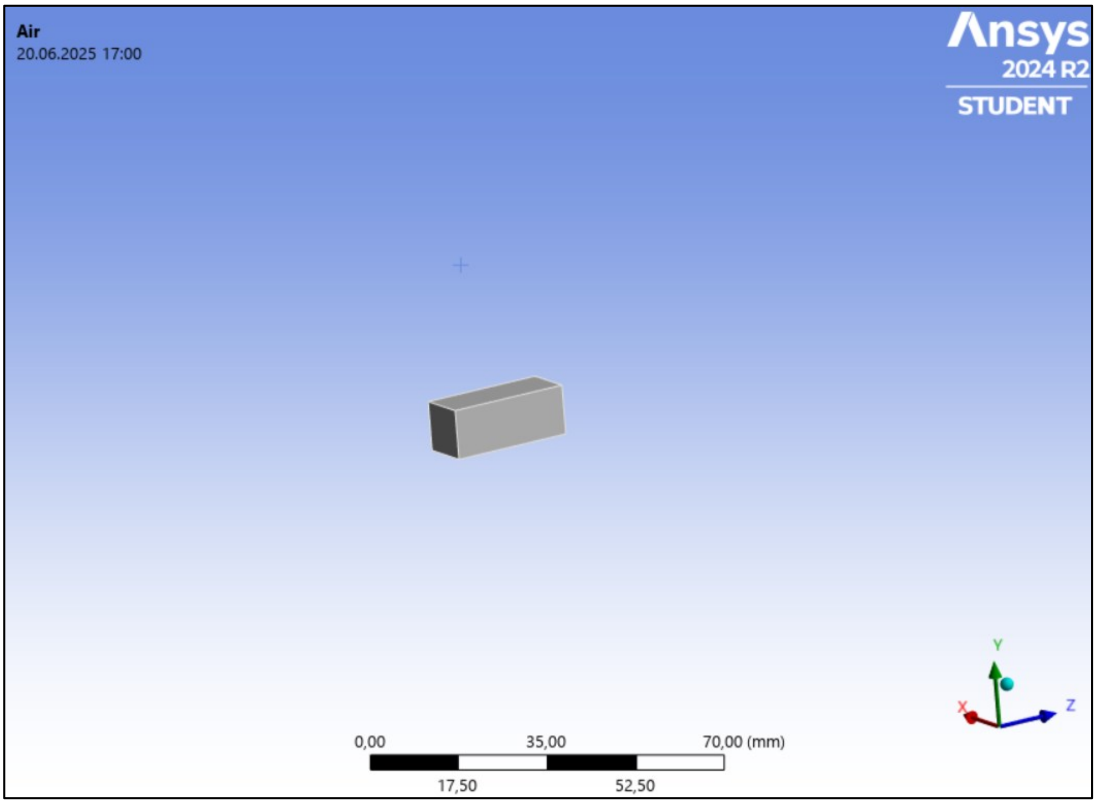


Figure 36 : Global Coordinate System

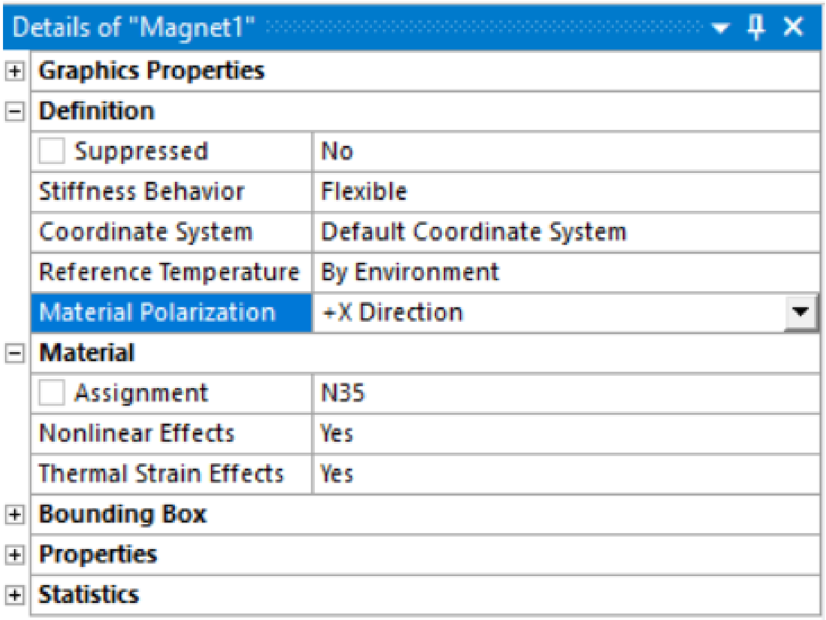


Figure 37 : Magnet Polarization

Afterwards, we enter the mesh creation section. First, we right-click on the mesh option and select the insert and sizing options respectively.

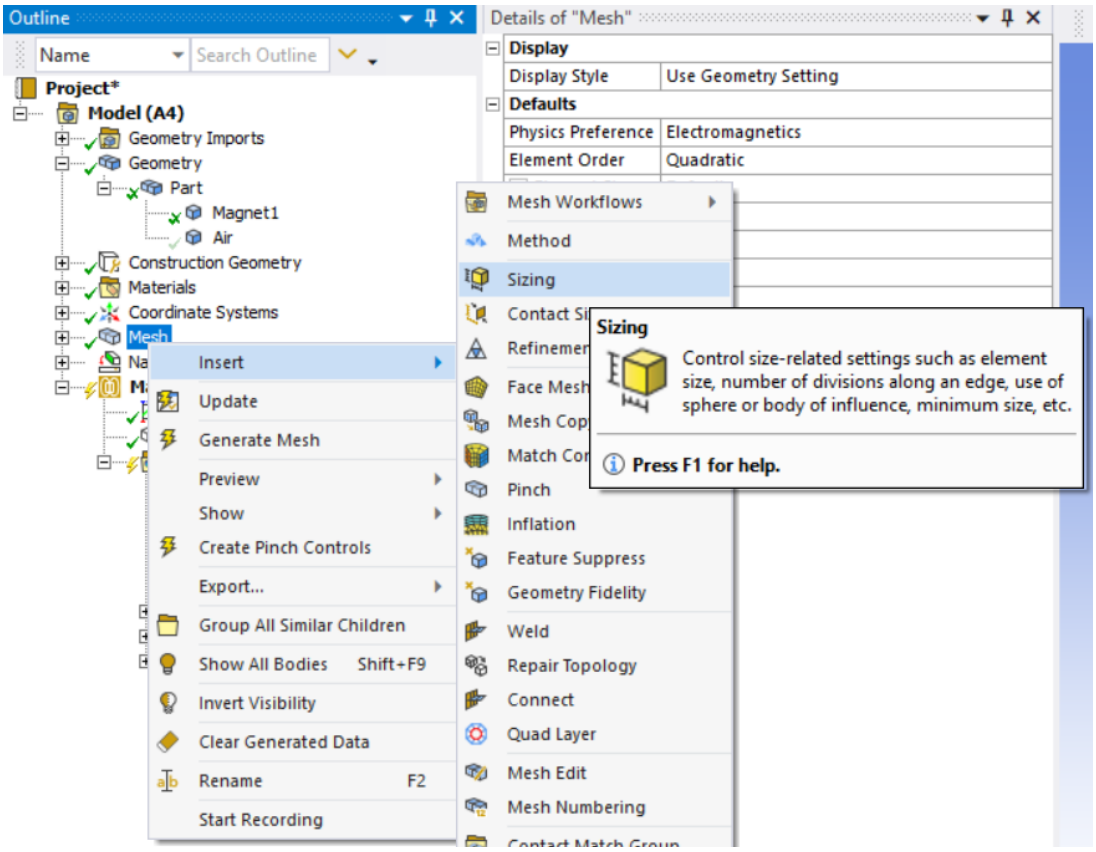


Figure 38 : Mesh Sizing

Then, we click on the green cube icon above and select the entire body, click on the no selection text in the lower left corner and click apply.

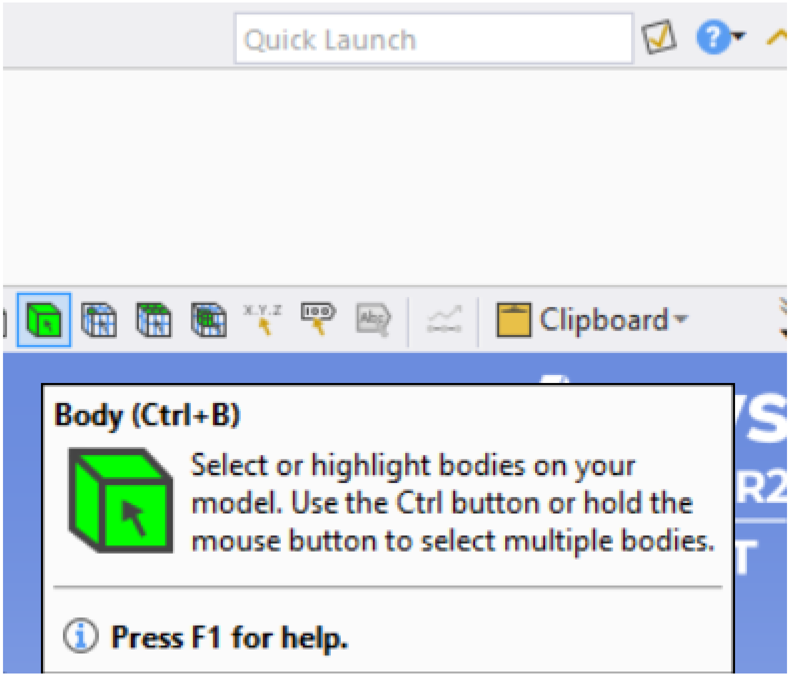


Figure 39 : Body Selection

We set the element size in the default setting of the program.

Details of "Body Sizing" - Sizing	
Scope	
Scoping Method	Geometry Selection
Geometry	1 Body
Definition	
Suppressed	No
Type	Element Size
Element Size	Default (4,7245 mm)
Advanced	
Defeature Size	Default
Behavior	Soft

Figure 40 : Details of Body Sizing

Finally, we right-click on the mesh and click on the generate mesh option.

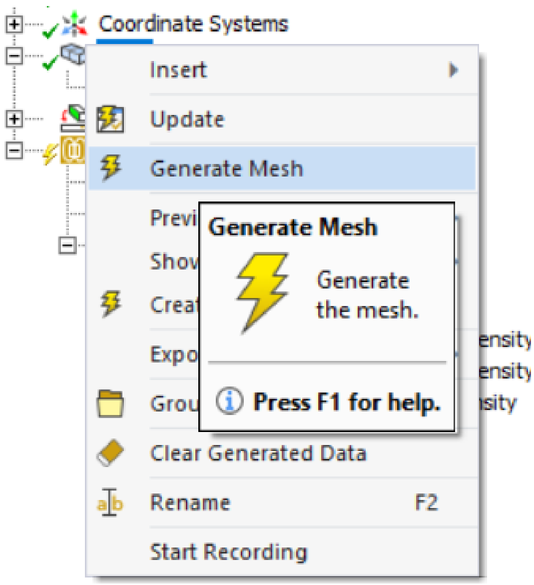


Figure 41 : Generating Mesh

In this way, our Mesh is created as seen in the Figure 42.

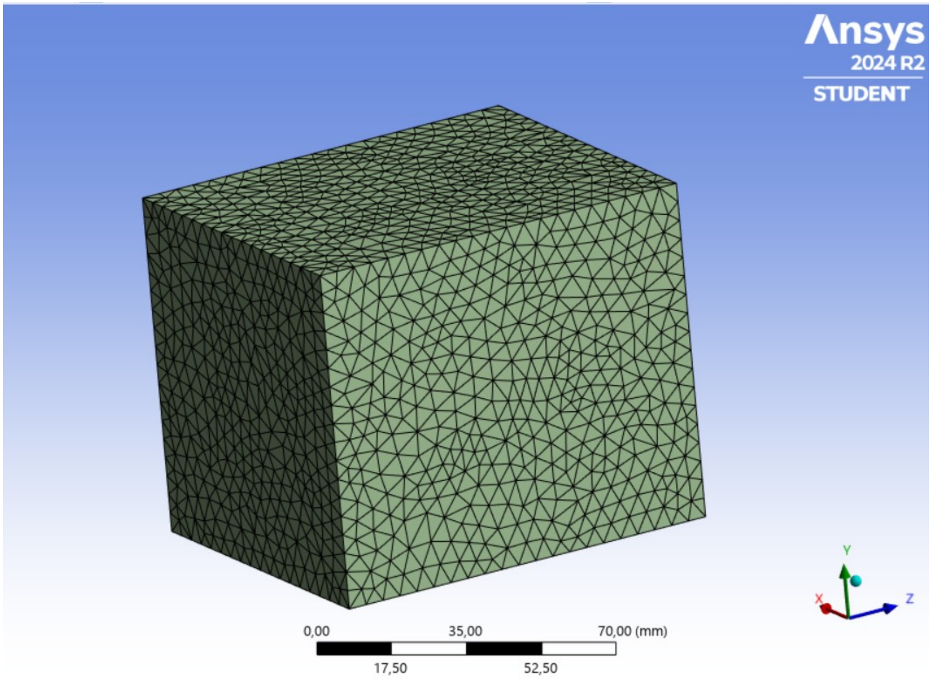


Figure 42 : Mesh View

Then, to complete our analysis, we click on the magnetostatic section and select magnetic flux parallel from the environment section above.

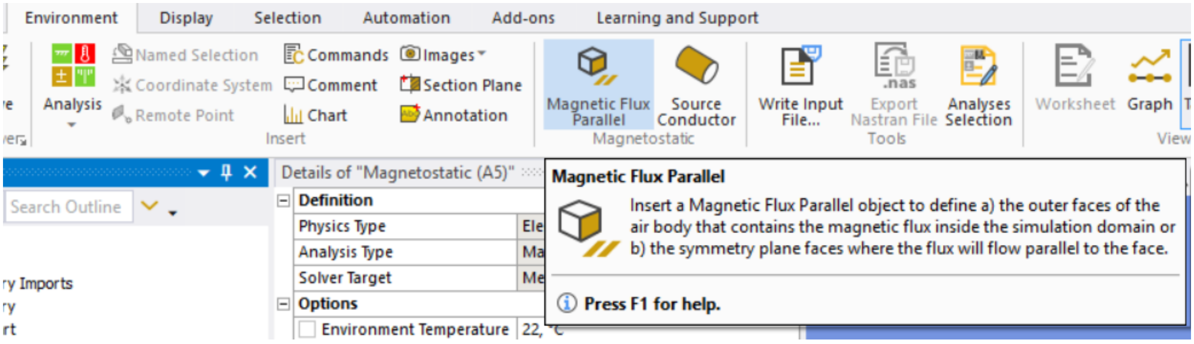


Figure 43 : Magnetic Flux Parallel

Then, we select all surfaces of our air volume as geometry. (Our air volume has 6 surfaces)

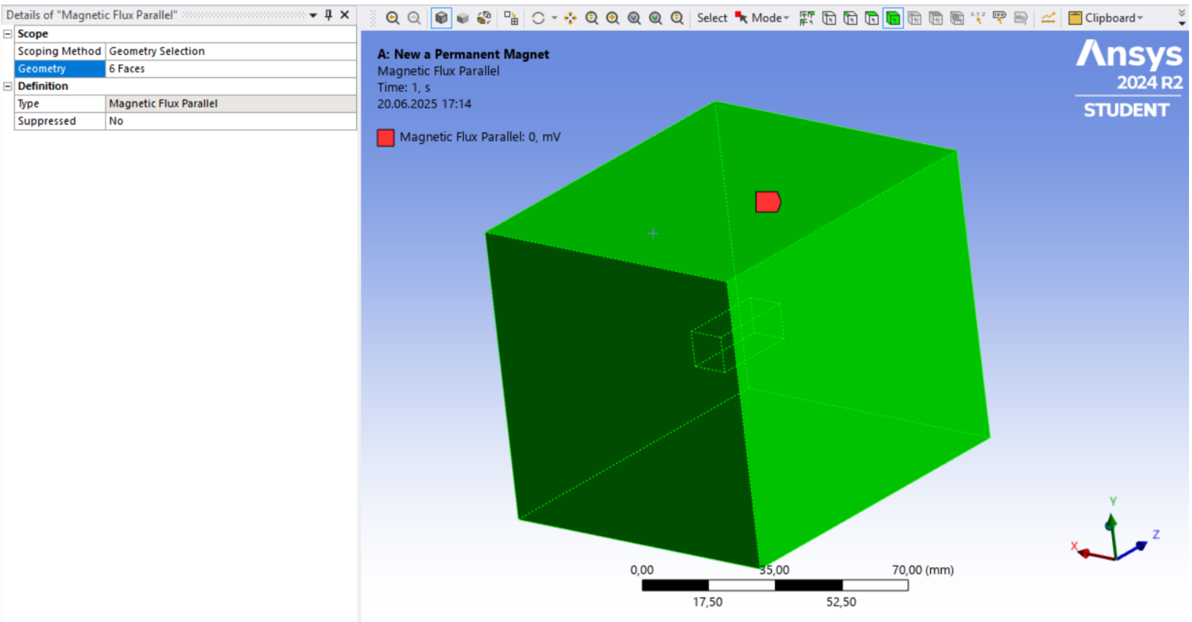


Figure 44 : Selection of 6 Faces

Then, to perform our analysis, we right-click on the solution section and select the insert and directional magnetic flux density options, respectively.

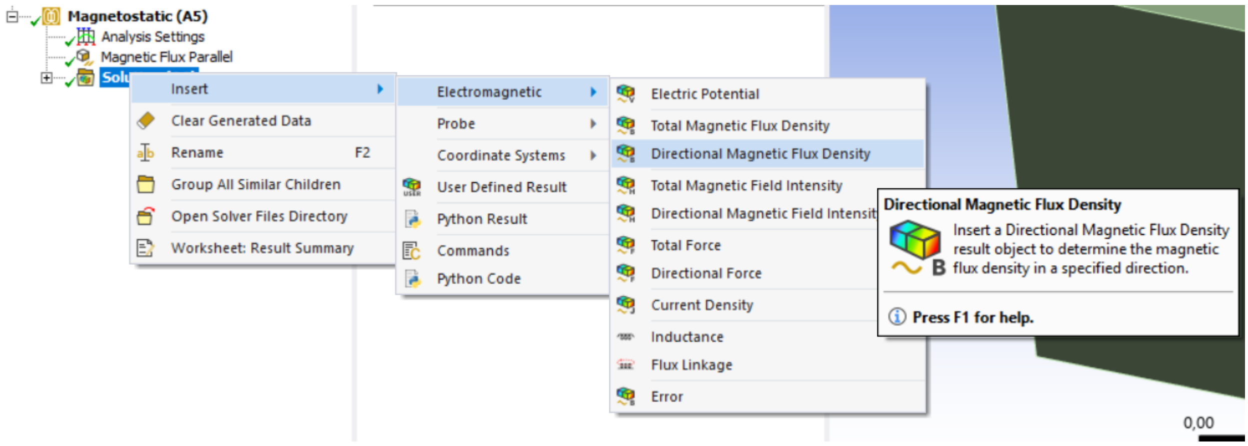


Figure 45 : Directional Magnetic Flux Density (Solution)

Finally, we perform our analysis by clicking on the solve section and get our results.

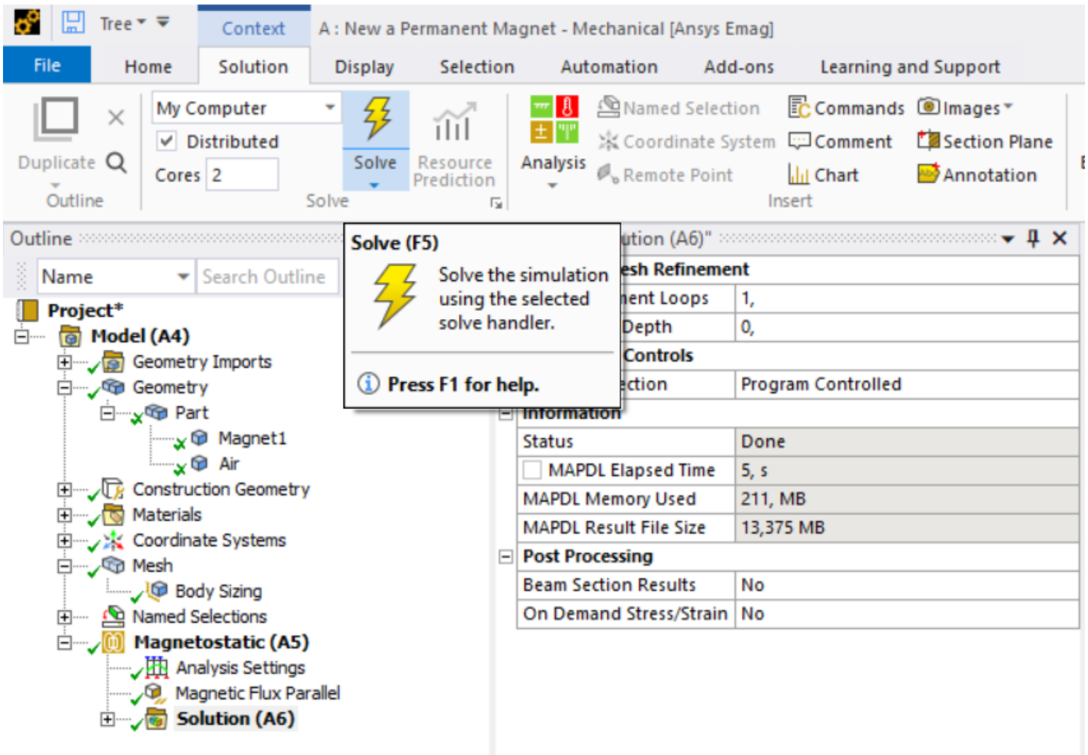


Figure 46 : Solving the simulation

Of course, I will explain and show this analysis section in more detail in the results and conclusions section.

3.2 Two Permanent Magnets

In this model, we will obtain the magnetic field distributions in an air volume by adjusting the polarizations of two permanent magnets, which are identical in material properties and size, in two different ways, such that they are the same and opposite. We do the parts up to the geometry part in the same way as we did for a single permanent magnet. Then, we enter the geometry tab just below the engineering data to create the geometry of the model we have. Then, we click on Create in the upper left corner and from the options that appear, we click on the box as seen in the figure below and create a box, and we do the same thing again to create the second box. We make the adjustments seen in the Figure 47 to the first of these boxes.

Details View	
Details of Box1	
Box	Box1
Base Plane	XYPlane
Operation	Add Material
Box Type	From One Point and Diagonal
Point 1 Definition	Coordinates
FD3, Point 1 X Coordinate	0 mm
FD4, Point 1 Y Coordinate	-10 mm
FD5, Point 1 Z Coordinate	0 mm
Diagonal Definition	Components
FD6, Diagonal X Component	10 mm
FD7, Diagonal Y Component	10 mm
FD8, Diagonal Z Component	25 mm
As Thin/Surface?	No

Figure 47 : Details of Box1

Then we make the adjustments seen in the Figure 48 to the second box.

Details View	
Details of Box2	
Box	Box2
Base Plane	XYPlane
Operation	Add Material
Box Type	From One Point and Diagonal
Point 1 Definition	Coordinates
FD3, Point 1 X Coordinate	0 mm
FD4, Point 1 Y Coordinate	40 mm
FD5, Point 1 Z Coordinate	0 mm
Diagonal Definition	Components
FD6, Diagonal X Component	10 mm
FD7, Diagonal Y Component	10 mm
FD8, Diagonal Z Component	25 mm
As Thin/Surface?	No

Figure 48 : Details of Box2

After creating these two boxes, the model we should have should look like the in the Figure 49 graphics section.

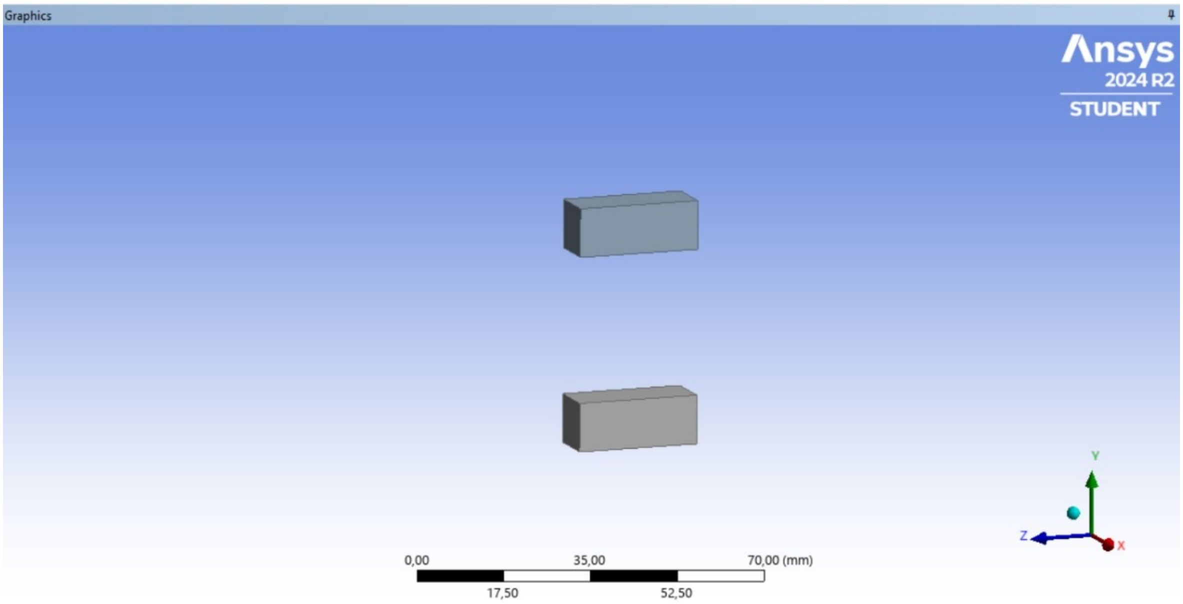


Figure 49 : Graphics of Box1 and Box2

After doing these, now it's time to create another box which will be our air volume. But this time we will create this box not from the box option but from the enclosure option as seen in the Figure 50. To do this, open the tools option and click on enclosure.

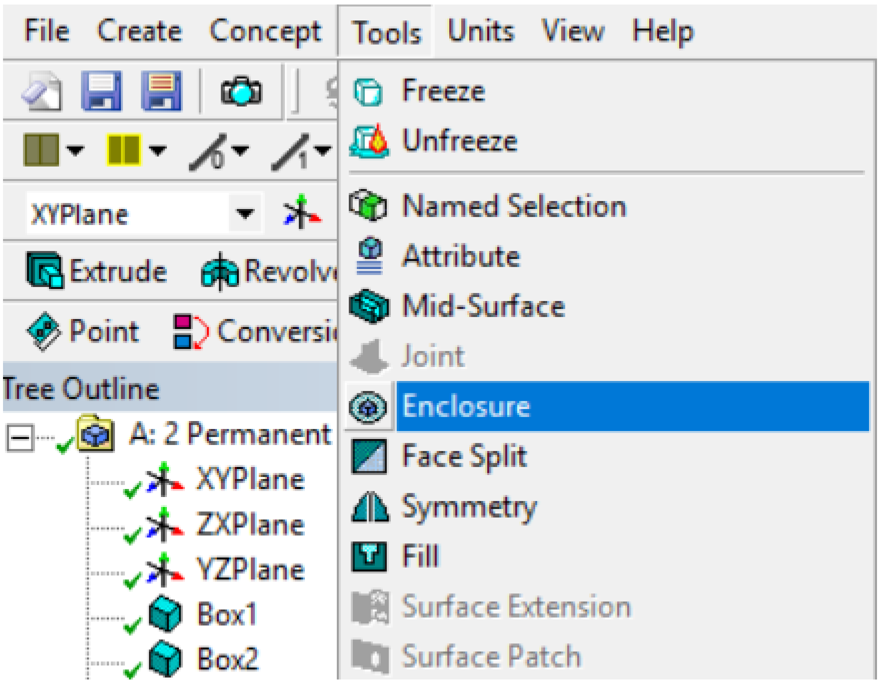


Figure 50 : Enclosure Option

Then, we set the details for the air volume geometry we want, as seen in Figure 51. And we click the Generate button to create this geometry.

Details View	
Details of Enclosure1	
Enclosure	Enclosure1
Shape	Box
Number of Planes	0
Cushion	Non-Uniform
FD1, Cushion +X value (>0)	12 mm
FD2, Cushion +Y value (>0)	12 mm
FD3, Cushion +Z value (>0)	36 mm
FD4, Cushion -X value (>0)	12 mm
FD5, Cushion -Y value (>0)	12 mm
FD6, Cushion -Z value (>0)	36 mm
Target Bodies	All Bodies
Export Enclosure	Yes

Figure 51 : Details of Enclosure Geometry

After doing all of these operations, the image I will obtain in the geometry section should be like the Figure 52.

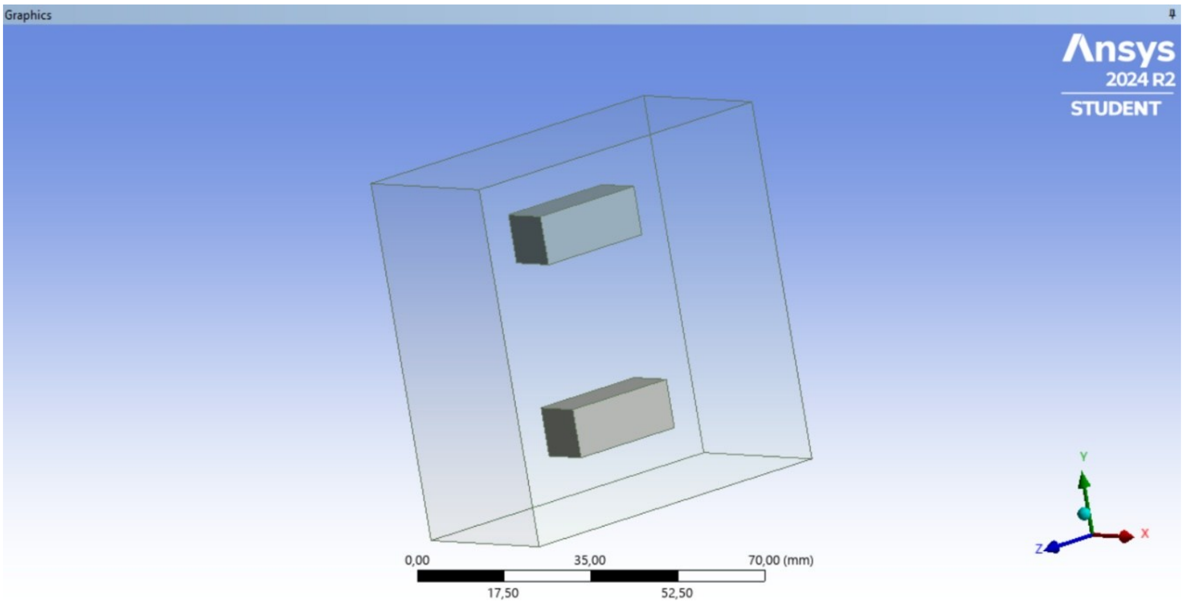


Figure 52 : Graphics of 2 Box and Enclosure

Finally, as seen in the Figure 53 , we select all the solids and click from a new part and merge the 3 separate parts into a single part. Since we are done with the geometry part, we save and close it.

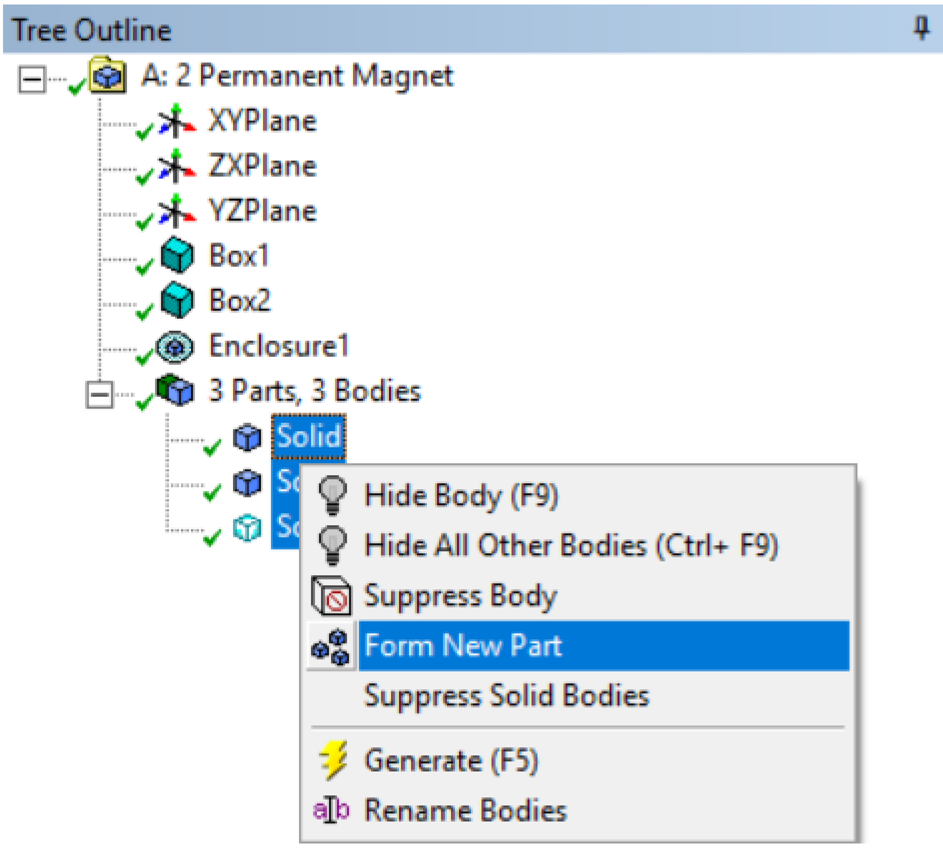


Figure 53 : Form New Part

Afterwards, to fully create our model, we right-click on the model option on the main screen and click on the edit option. In the model and solution section, we do the same things we do for a single magnet.

4. RESULTS

In this section, we will first compare the magnetic field results that we will obtain with our experimental setup in real conditions with the data we obtained in our analysis in the Ansys program and see whether our model on Ansys is compatible with our real experimental setup. And if it is compatible, we will start our other analyses on Ansys.

First, we will start by creating a path 4 mm away from the magnet in our single permanent magnet model on Ansys and then we will obtain the magnetic field values on this path.

Details of "Path 4"	
Definition	
Path Type	Two Points
Path Coordinate System	Global Coordinate System
Number of Sampling Points	83,
Suppressed	No
Start	
Coordinate System	Global Coordinate System
Start X Coordinate	14, mm
Start Y Coordinate	5, mm
Start Z Coordinate	-28,5 mm
Location	Click to Change
End	
Coordinate System	Global Coordinate System
End X Coordinate	14, mm
End Y Coordinate	5, mm
End Z Coordinate	53,5 mm
Location	Click to Change

Figure 54 : Details of Path 4

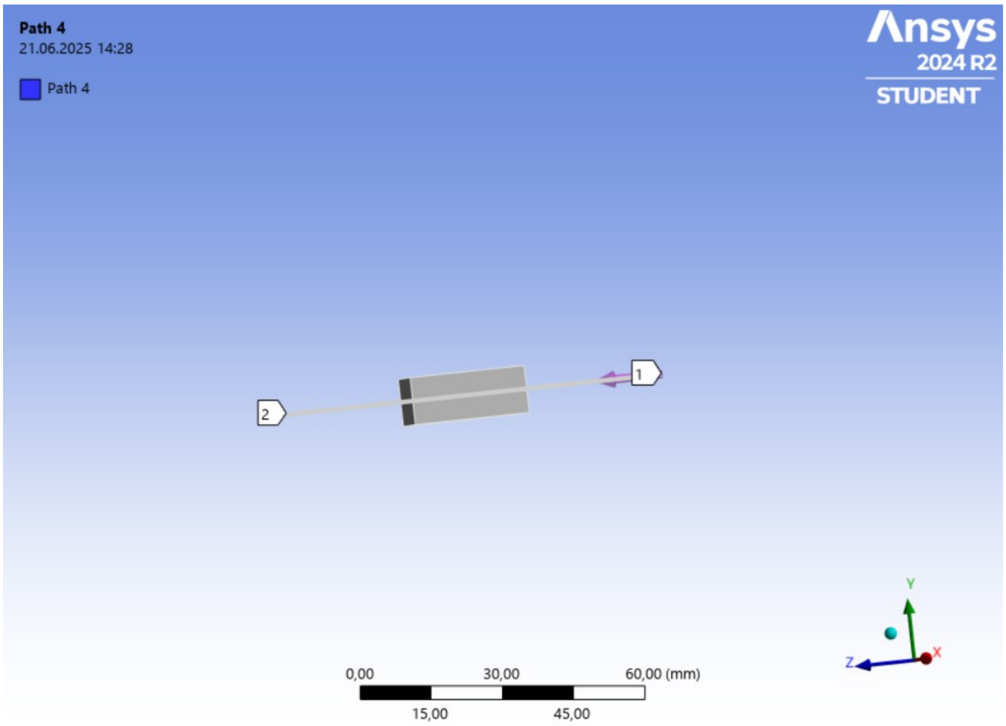


Figure 55 : View of The Path 4

Of course, while doing this, we also need to know the polarization of the permanent magnets in our experimental setup and perform the analysis in a way that will be the same polarization as this polarization. For this, we find a magnet with known north and south poles and determine the polarization of our permanent magnet with the help of this magnet. As a result, we find that our lateral surfaces with an area of 10 mm x 10 mm are the north and south poles of our permanent magnet. And of course, since our other 3 permanent magnets are identical to this permanent magnet, we can say that their polarization will be the same.

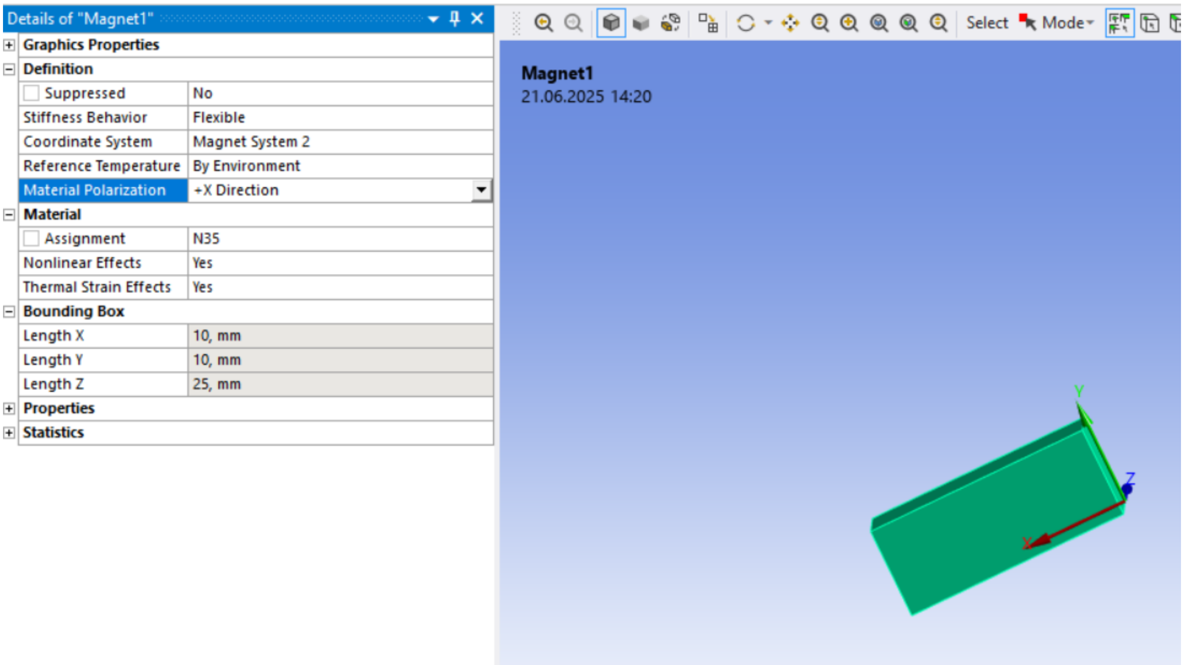
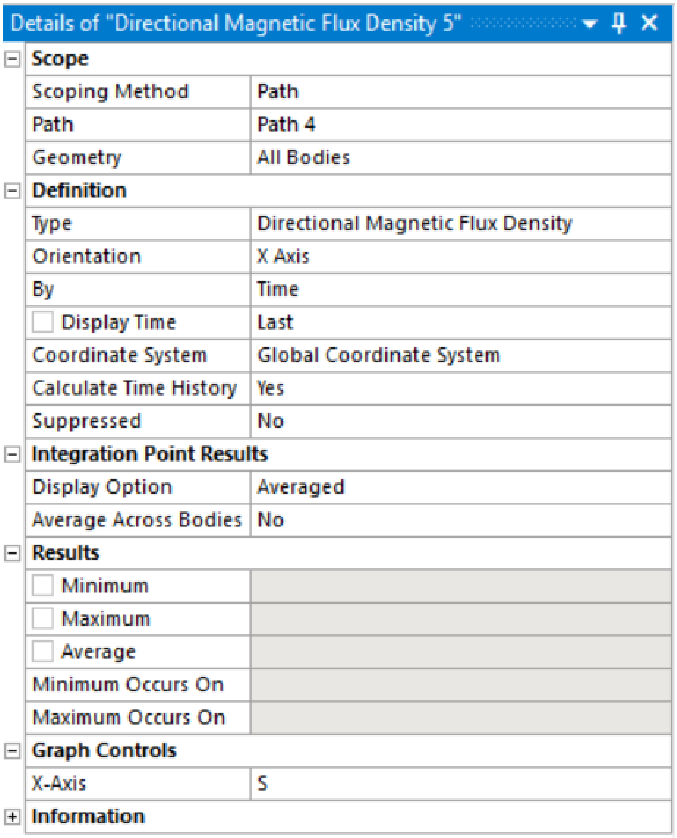


Figure 56 : Polarization of Our Permanent Magnet

Afterwards, we apply these and make our first analysis by doing the analysis part as in the Figure 57. As can be seen in the figure, the values we get here will be the values of the magnetic field on the x-axis. The reason why our measurements in ANSYS are on this axis is that the probe that measures the magnetic field in our real-life experimental setup makes measurements in this direction. You can see what I mean by the x-axis in the Figure 58 .



Details of "Directional Magnetic Flux Density 5"	
Scope	
Scoping Method	Path
Path	Path 4
Geometry	All Bodies
Definition	
Type	Directional Magnetic Flux Density
Orientation	X Axis
By	Time
Display Time	Last
Coordinate System	Global Coordinate System
Calculate Time History	Yes
Suppressed	No
Integration Point Results	
Display Option	Averaged
Average Across Bodies	No
Results	
Minimum	
Maximum	
Average	
Minimum Occurs On	
Maximum Occurs On	
Graph Controls	
X-Axis	S
Information	

Figure 57 : Details of Our First Analysis

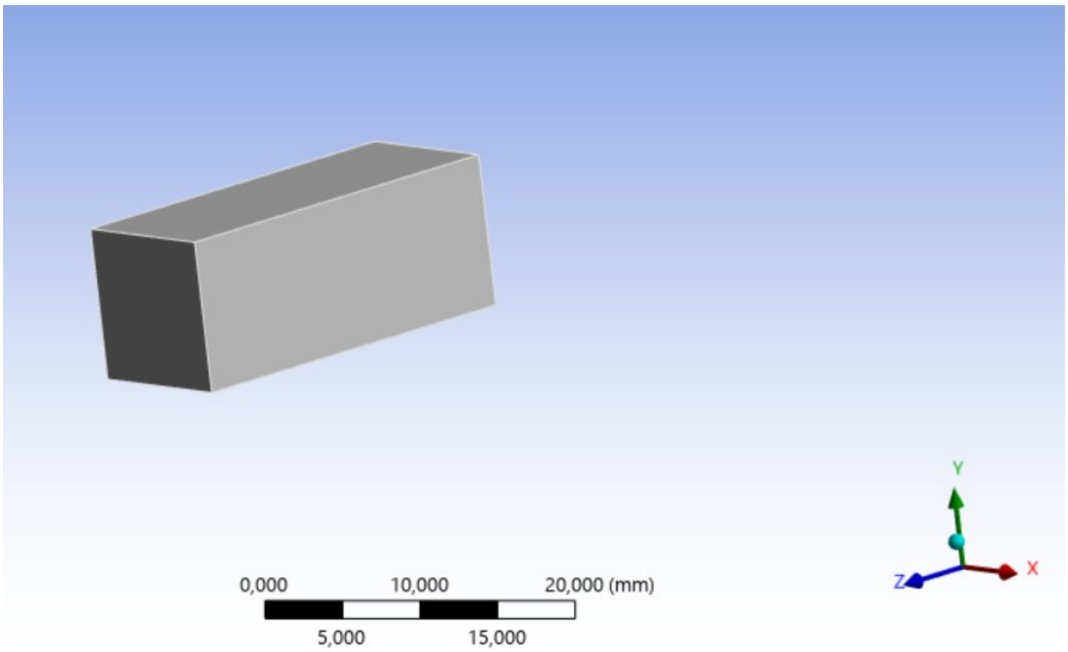


Figure 58 : Global Coordinate System (Default)

The general image we obtained as a result of the analysis is shown in the Figure 59.

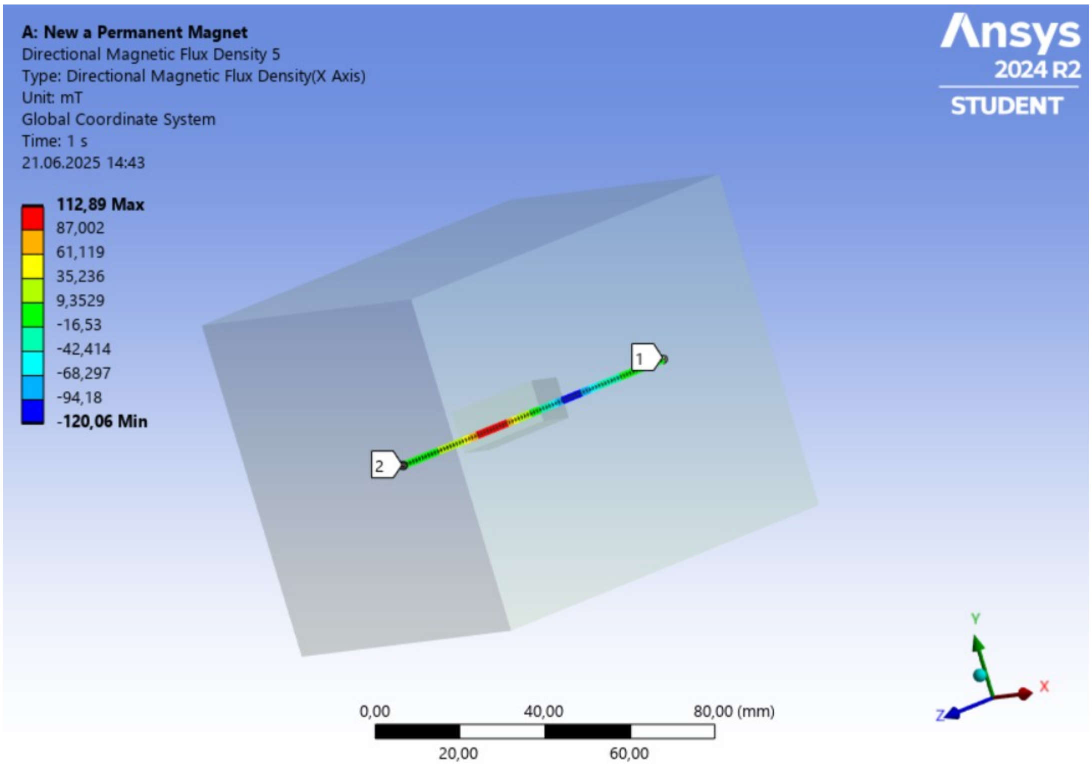


Figure 59 : General View of Analysis

As a result of this analysis, we obtain a graph like in Figure 60 .

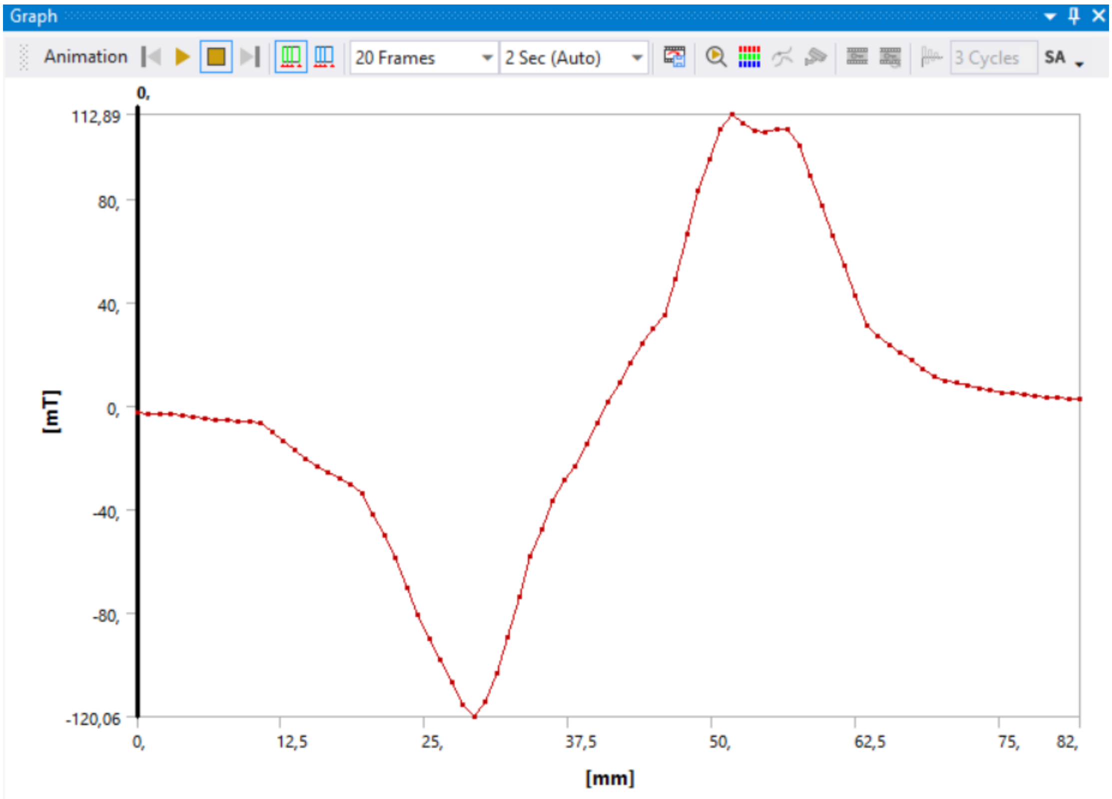


Figure 60 : Graph of First Analysis

In this graph, the center point of our permanent magnet corresponds to exactly 41mm. Now we can make our measurements to compare. The values I obtained are given in the Table 1.

Distance (mm)	Magnetic Field (mT)
10	-6.3
15	-22.9
20	-38.2
25	-86.4
30	-115.1
35	-50.1
40	-5.7
45	30.3
50	102.6
55	106.5
60	70.4
65	24.9
70	9.8

Table 1 : Distance vs Magnetic Field (x=4mm)

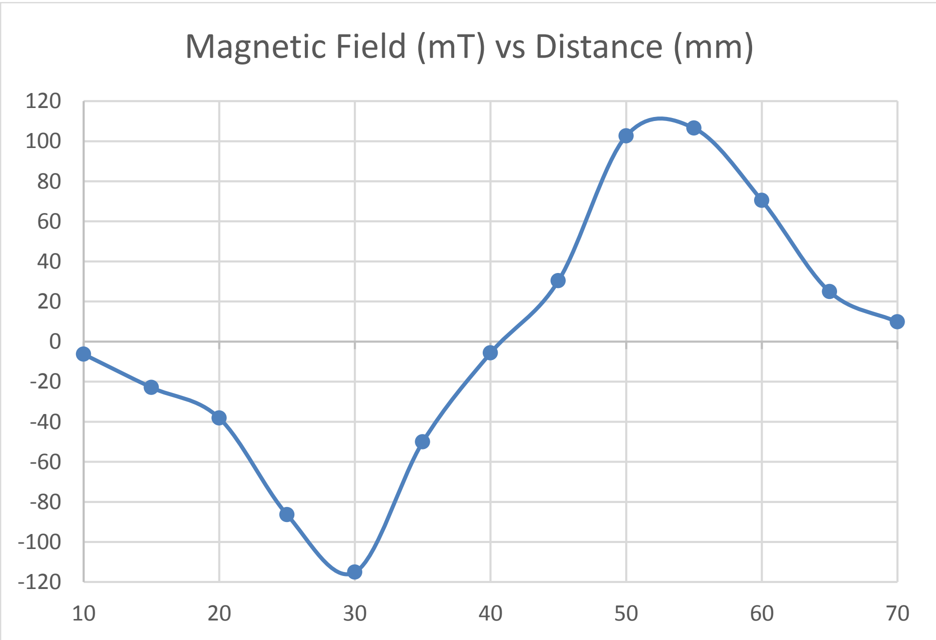


Figure 61 : Experimental Data Graph (x=4mm)

When we compare the graph we obtained on Ansys with the graph of the data we obtained with our experimental setup, we see that although there are small errors, the graphs are generally very similar to each other. Therefore, we can say that our Ansys model and our experimental setup are compatible. Now that we have proven the compatibility of our model with our experimental setup, we can start doing all our analyses through our Ansys model. First, we must determine whether the polarization of the permanent magnet we have is suitable for our purpose by trying different polarization states in our model that we created for a single permanent magnet. Of course, the magnetic field values that we will obtain in these Ansys models will be the values on the z axis in the global coordinate system. The reason for this is that the magnetic field that allows our magnetostrictive material to stretch will be on the longitudinal axis of our material. For this, we will adjust all the analyses we will do as shown in the Figure 62.

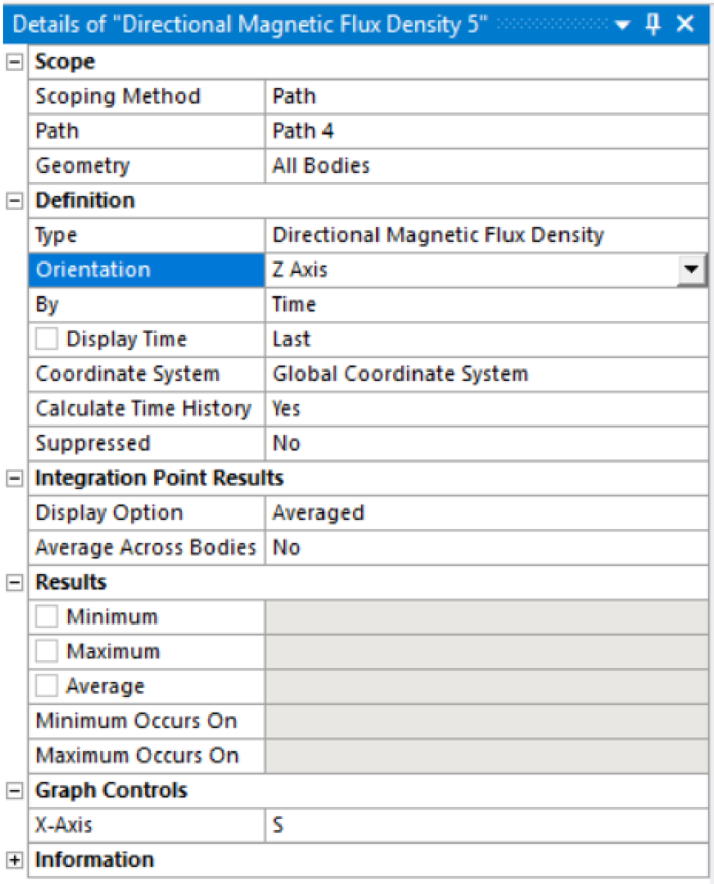
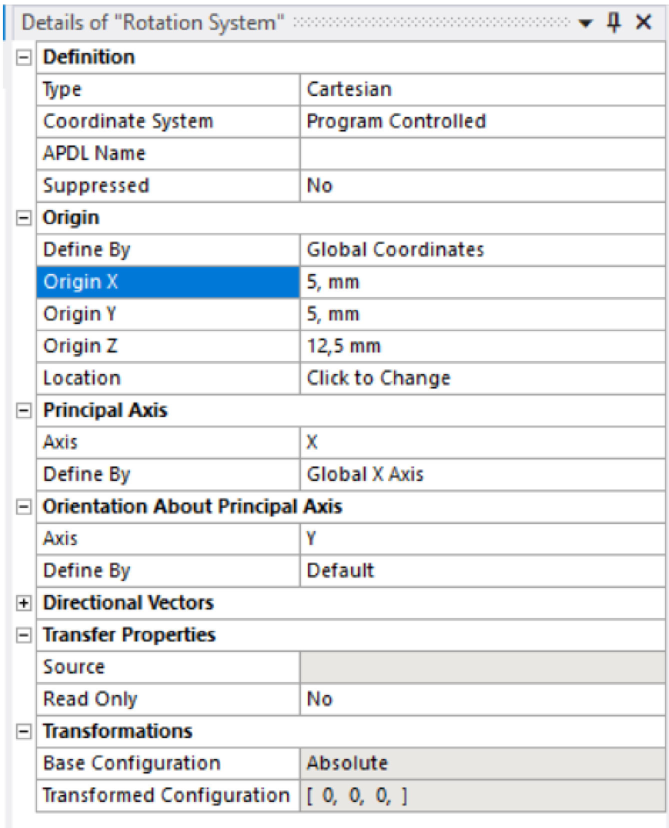


Figure 62 : Details for Z axis component of magnetic field

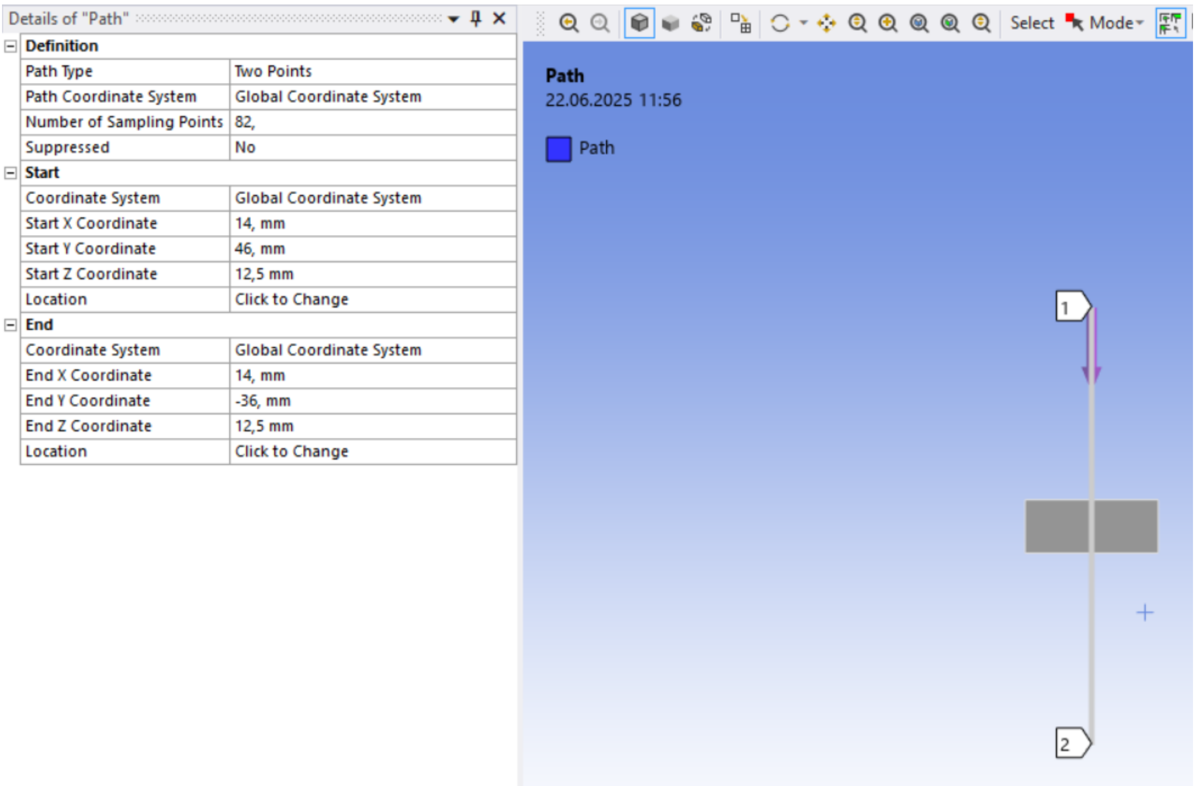
Here I'm creating a new coordinate system to rotate our permanent magnet.



Details of "Rotation System"

Definition	
Type	Cartesian
Coordinate System	Program Controlled
APDL Name	
Suppressed	No
Origin	
Define By	Global Coordinates
Origin X	5, mm
Origin Y	5, mm
Origin Z	12,5 mm
Location	Click to Change
Principal Axis	
Axis	X
Define By	Global X Axis
Orientation About Principal Axis	
Axis	Y
Define By	Default
Directional Vectors	
Transfer Properties	
Source	
Read Only	No
Transformations	
Base Configuration	Absolute
Transformed Configuration	[0, 0, 0,]

Figure 63 : Rotation System (Coordinate System)



Details of "Path"

Definition	
Path Type	Two Points
Path Coordinate System	Global Coordinate System
Number of Sampling Points	82,
Suppressed	No
Start	
Coordinate System	Global Coordinate System
Start X Coordinate	14, mm
Start Y Coordinate	46, mm
Start Z Coordinate	12,5 mm
Location	Click to Change
End	
Coordinate System	Global Coordinate System
End X Coordinate	14, mm
End Y Coordinate	-36, mm
End Z Coordinate	12,5 mm
Location	Click to Change

Figure 64 : Path Details and View

As seen in the Figure 64, I am drawing a path from top to bottom within our air volume. Then, I will rotate our magnet at 30 degrees intervals and obtain values. Then, by combining the data I obtained and transferring it to MATLAB, I will obtain graphs showing the magnetic field change for a point and all points.

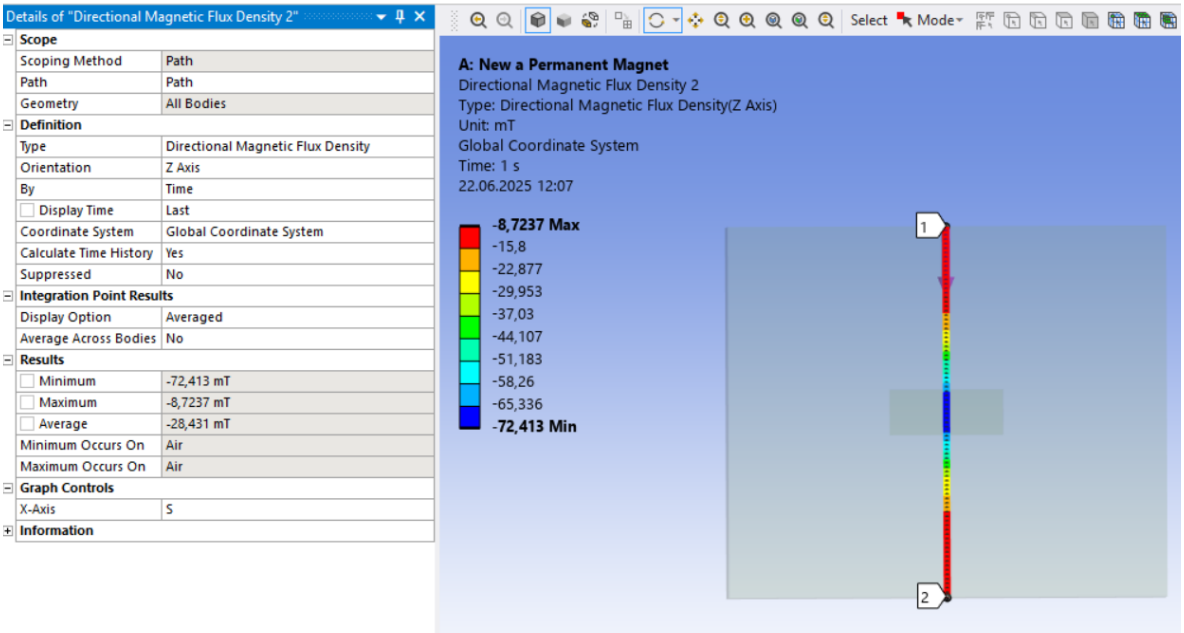


Figure 65 : Analysis of 0 Degree (+Z orientation)(x=4mm)

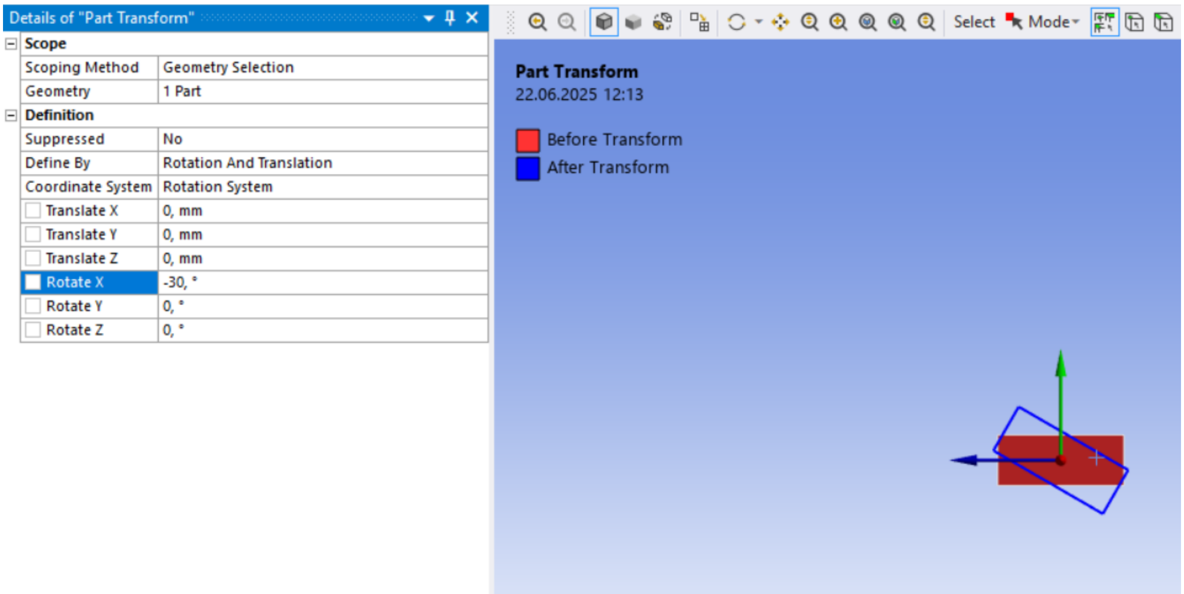


Figure 66 : 30 Degree Rotation (CW)

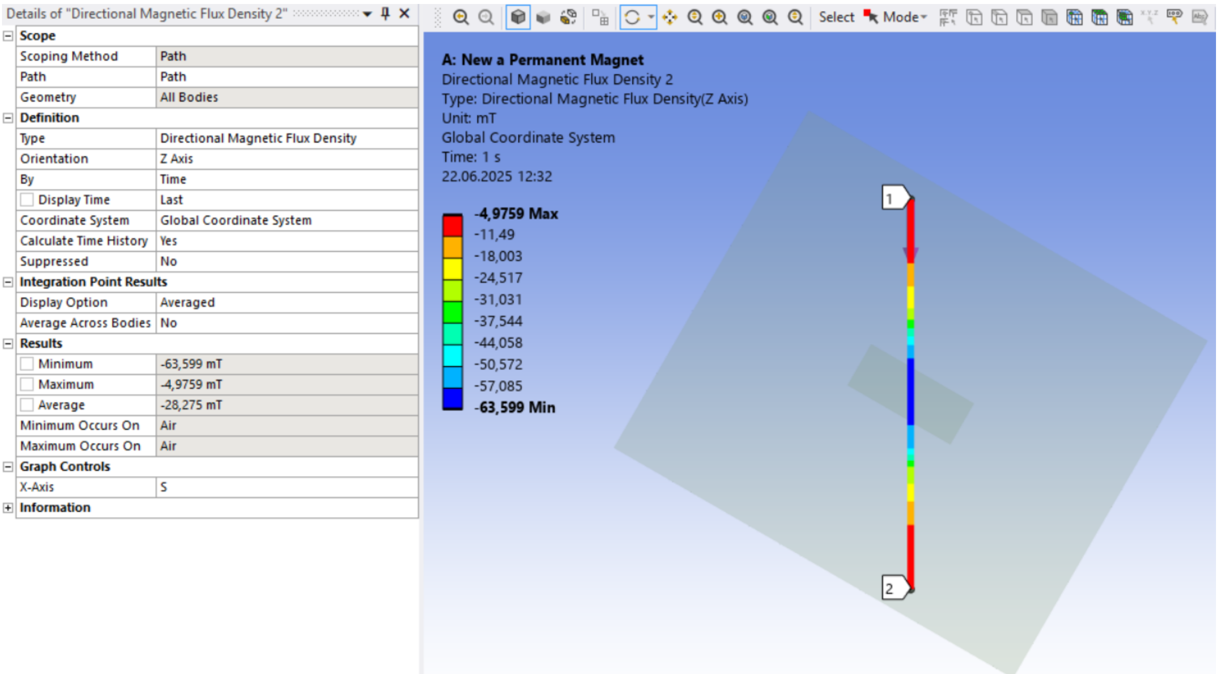


Figure 67 : Analysis of 30 Degree (+Z orientation)(x=4mm)

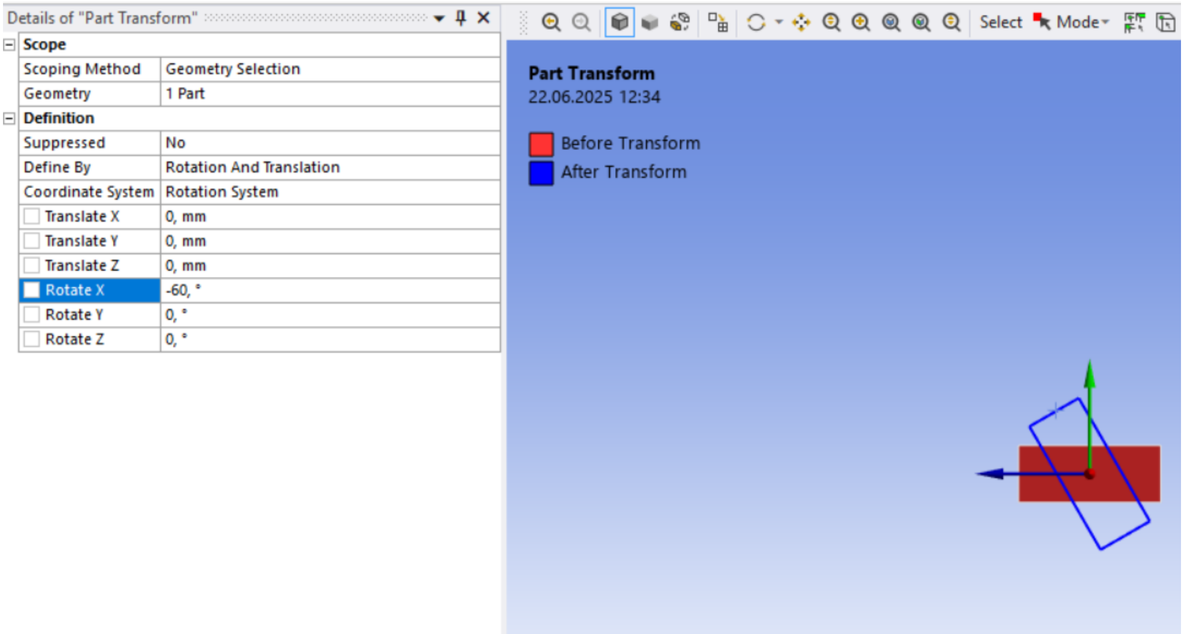


Figure 68 : 60 Degree Rotation (CW)

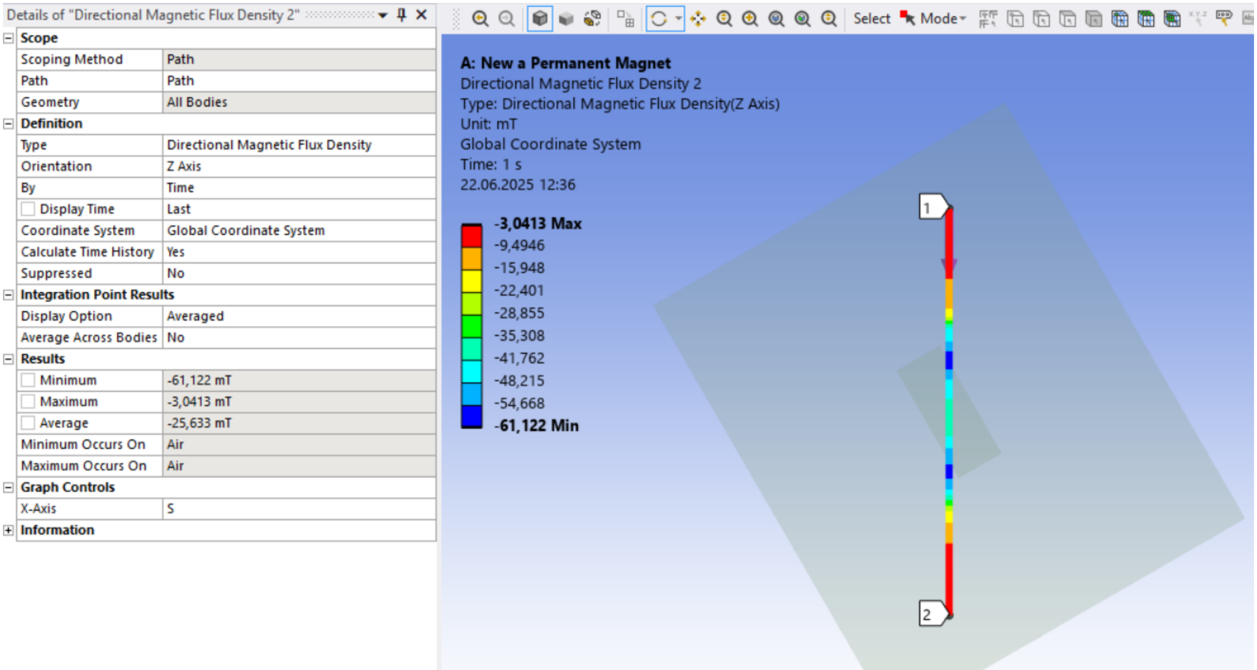


Figure 69 : Analysis of 60 Degree (+Z orientation)(x=4mm)

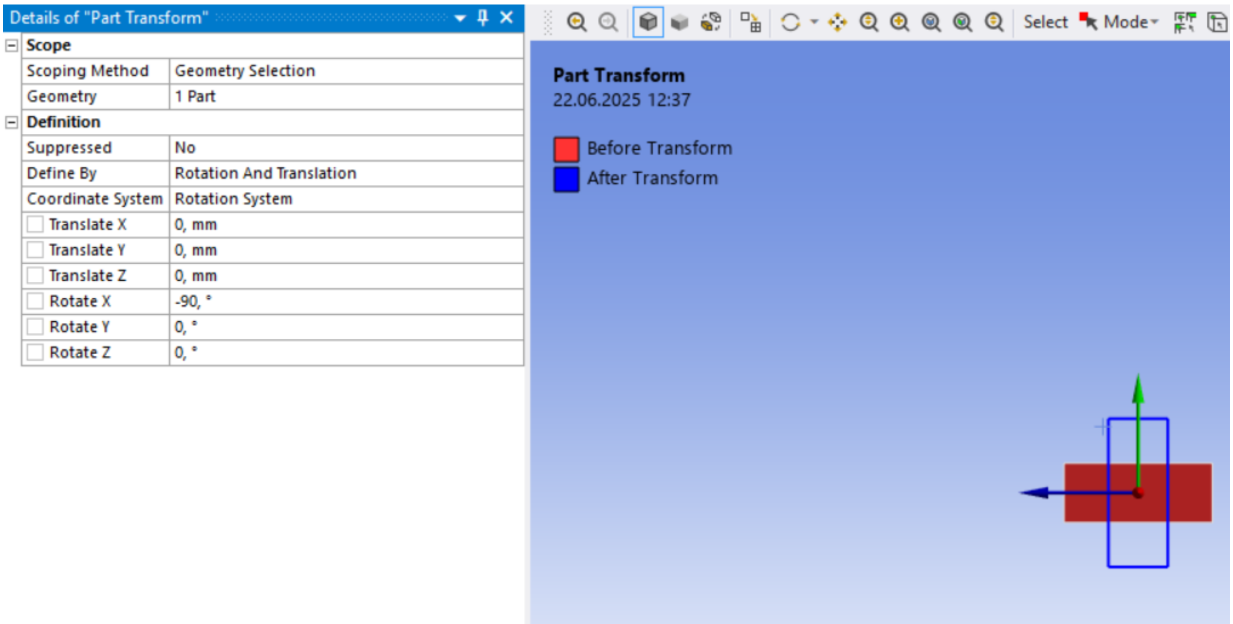


Figure 70 : 90 Degree Rotation (CW)

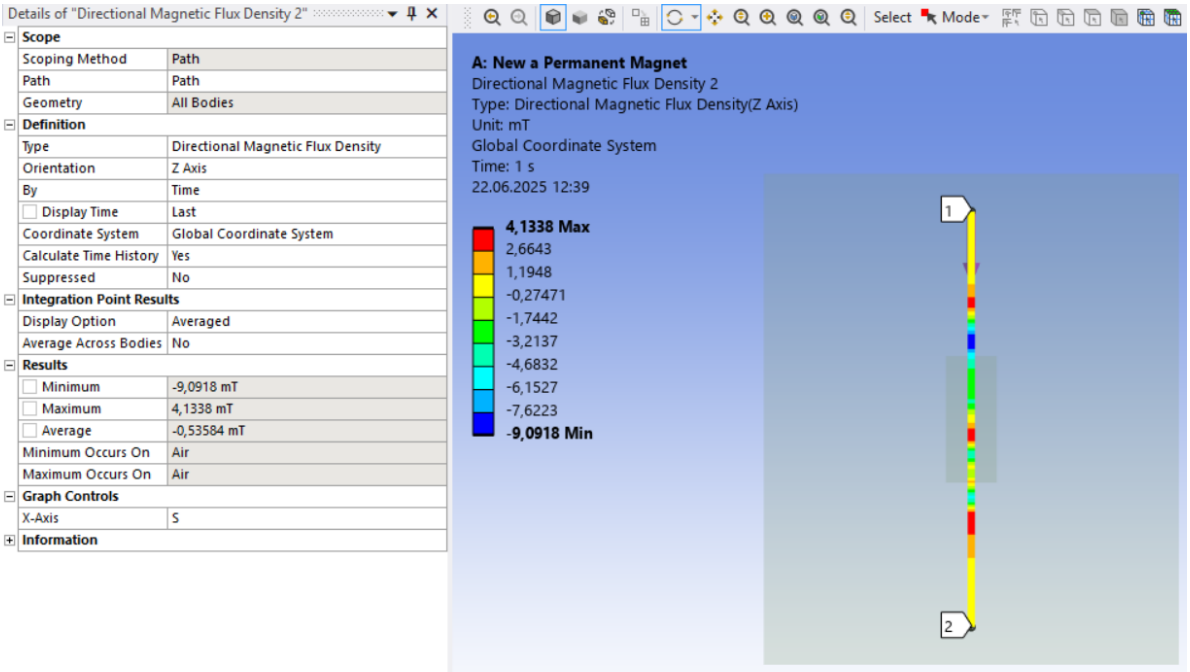


Figure 71 : Analysis of 90 Degree (+Z orientation)(x=4mm)

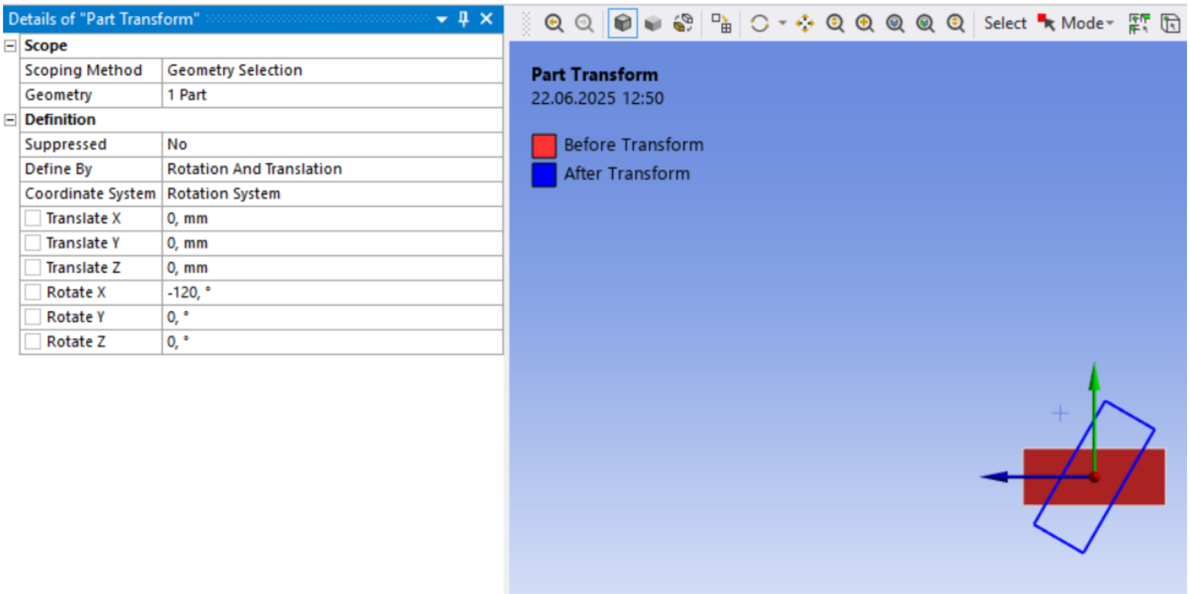


Figure 72 : 120 Degree Rotation (CW)

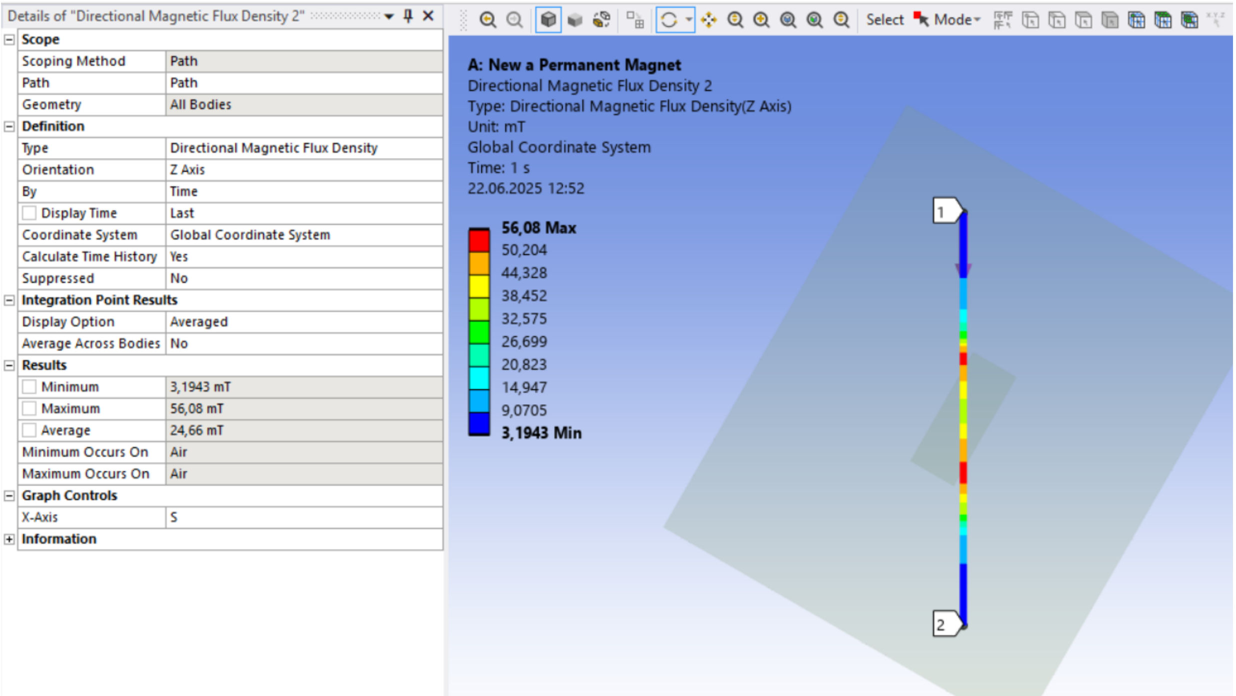


Figure 73 : Analysis of 120 Degree (+Z orientation)(x=4mm)

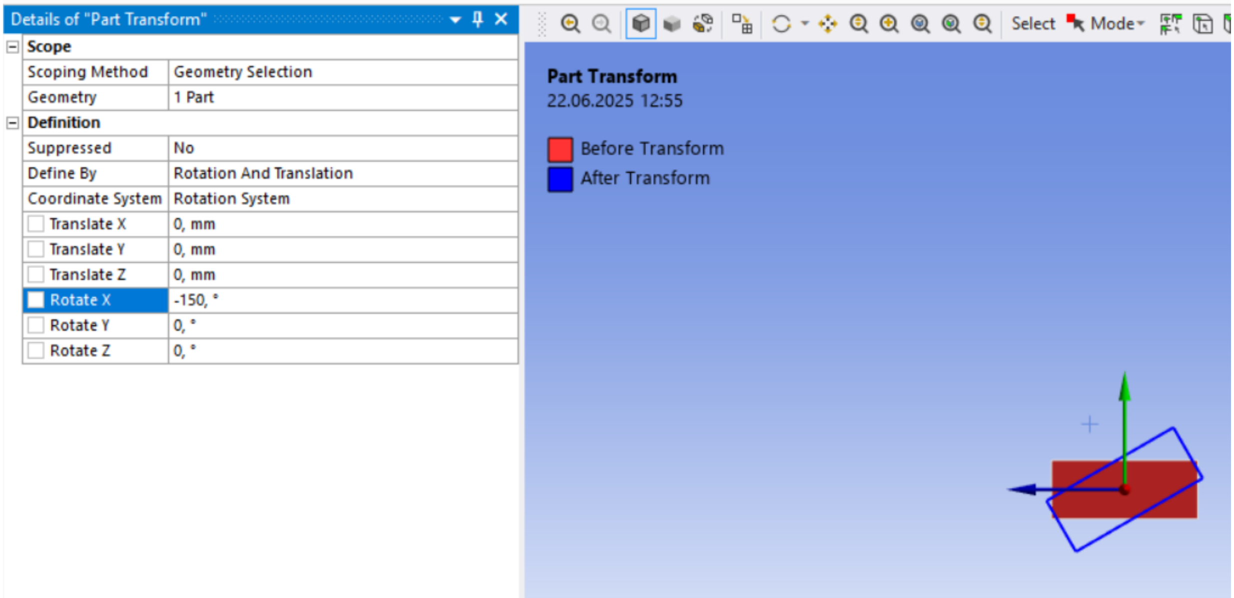


Figure 74 : 150 Degree Rotation (CW)

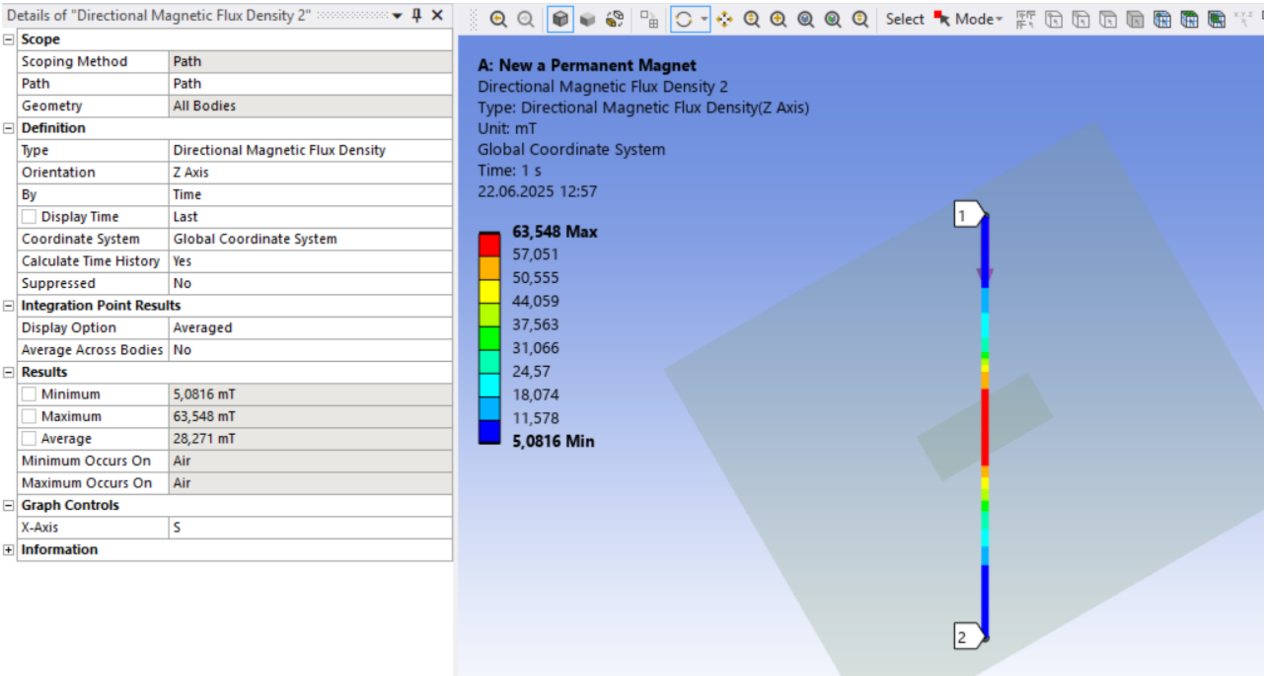


Figure 75 : Analysis of 150 Degree (+Z orientation)(x=4mm)

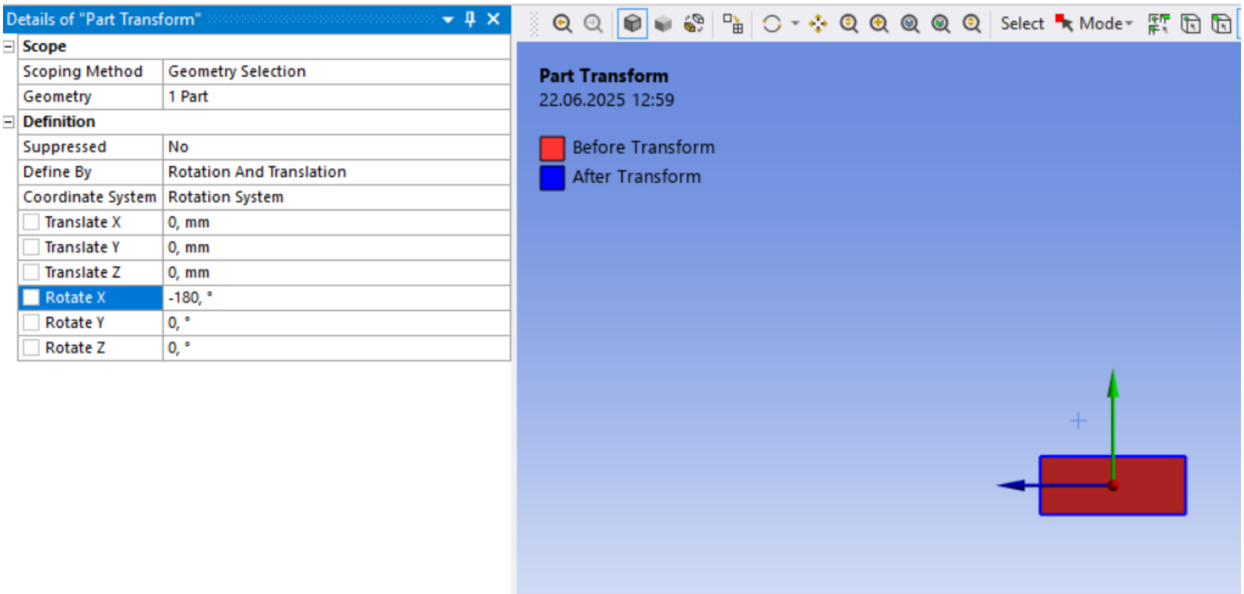


Figure 76 : 180 Degree Rotation (CW)

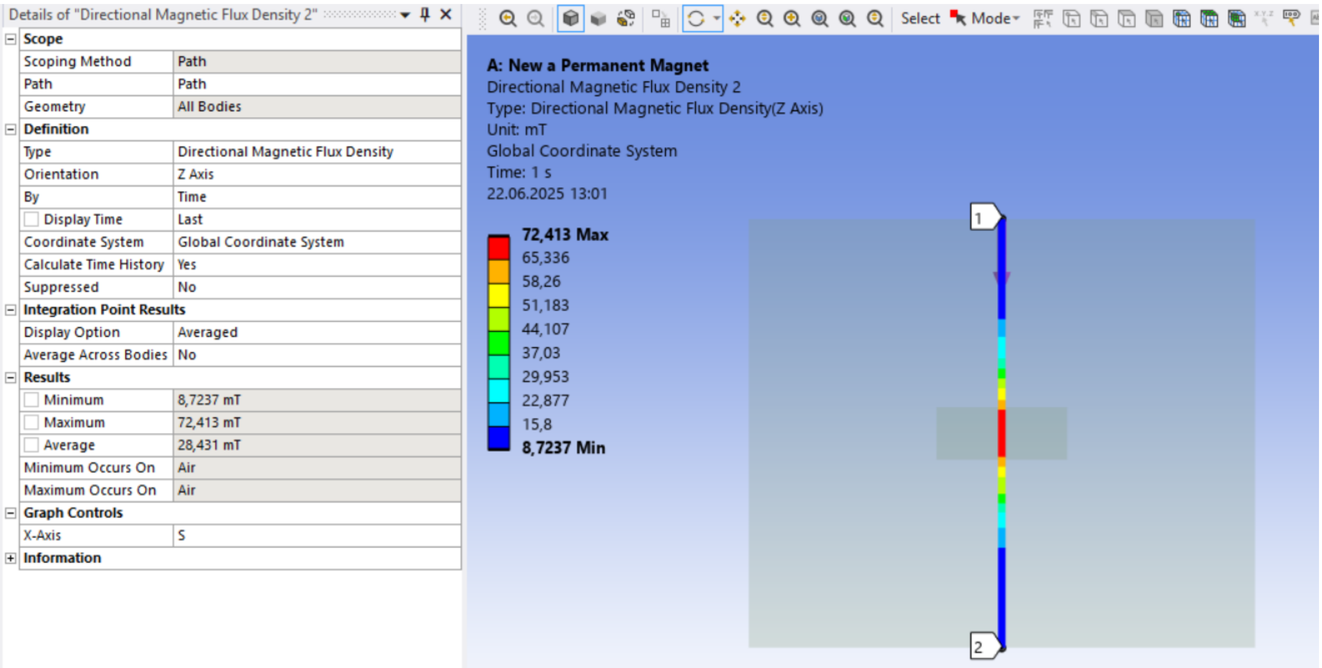


Figure 77 : Analysis of 180 Degree (+Z orientation)(x=4mm)

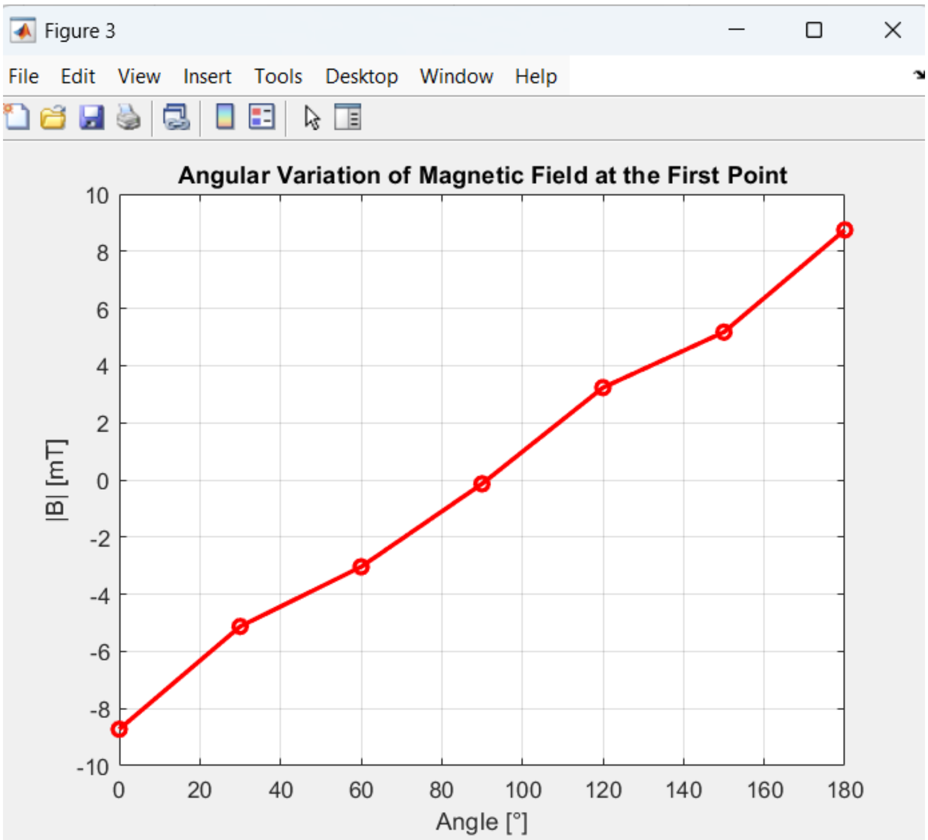


Figure 78 : Magnetic Field of first point (z Direction) of a Permanent Magnet Model (+Z Polarization) (x=4mm)

In the graphs with +Z polarization, we see that at a certain distance the magnetic field starts from a value like -9 mT and at the 0 degree position, it has zero magnetic field at 90 degrees, and at 180 degrees the magnetic field magnitude is still 9mT, but this time the magnetic field is positive.

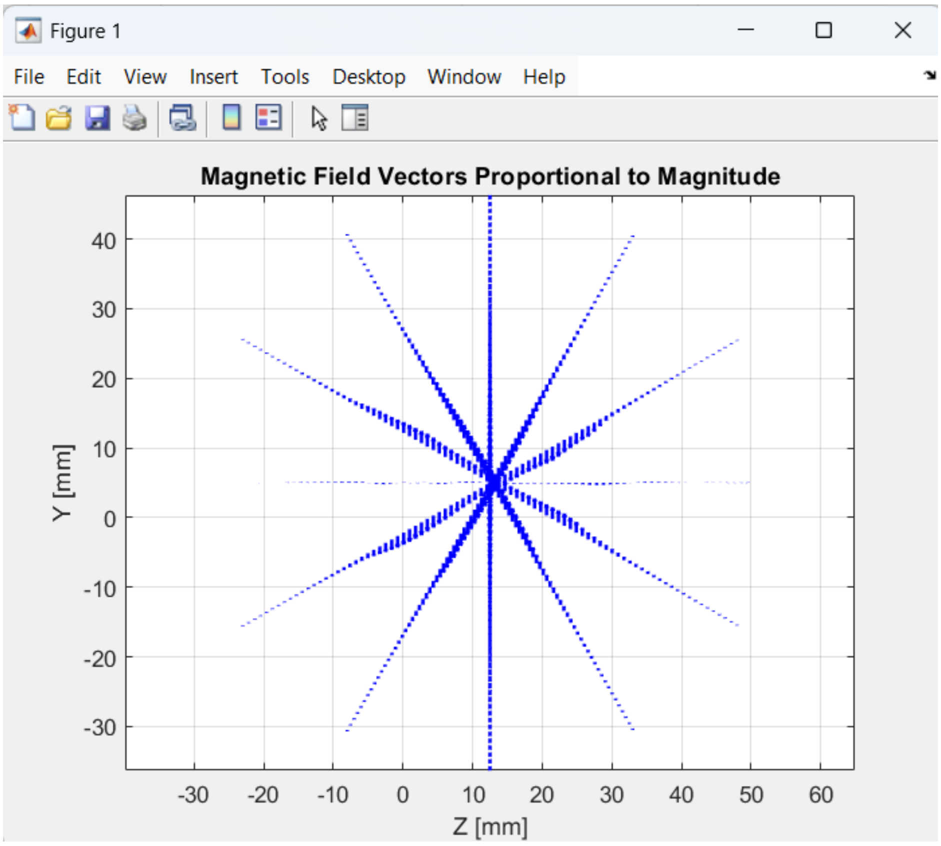


Figure 79 : Magnetic Field Vectors(Z direction) in path for a Permanent Magnet (+Z polarization)(x=4mm)

In this general distribution graph, the magnitude of the magnetic field (Z component) formed on the road when the magnetic field rotates is shown. Although the road appears to be rotating in this graph, the road is actually stationary and the rotating thing is our permanent magnet. My purpose in creating this graph in Matlab is to see the general distribution more clearly. Of course, since we cannot see how the magnetic field at the middle point changes with rotation in this graph (because the points overlap), I created another graph below that includes the magnetic field change at the middle point (in the z direction). You can see this graph in Figure 80.

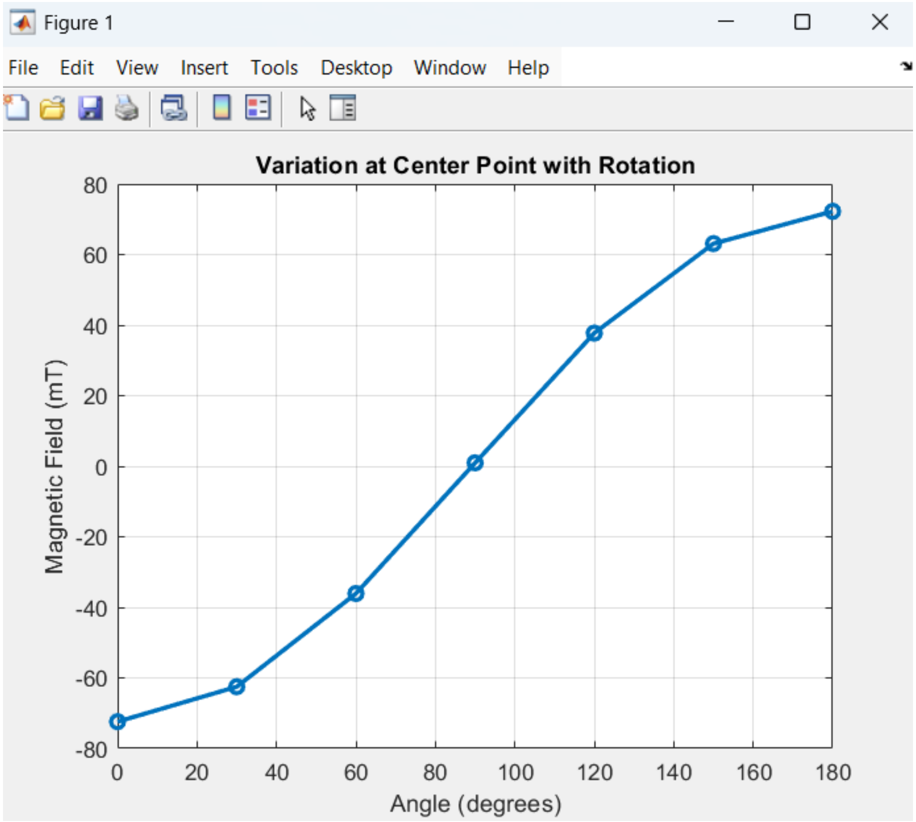


Figure 80 : Magnetic Field of center point (z Direction) of a Permanent Magnet Model (+Z Polarization) (x=4mm)

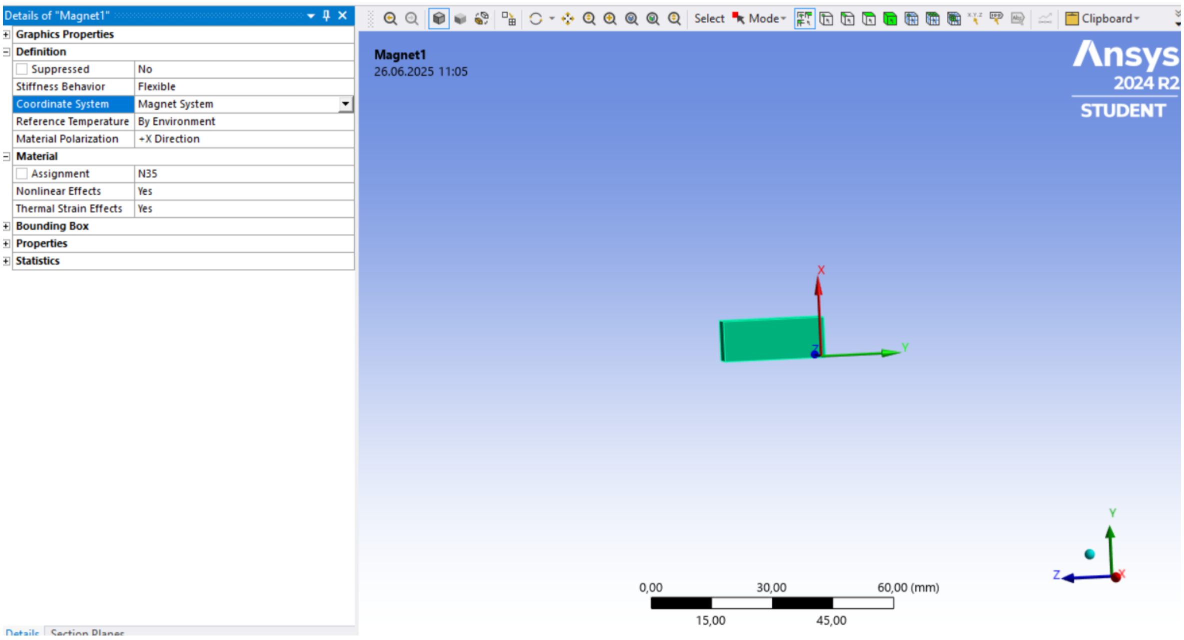


Figure 81 : Magnet System for +Y orientation

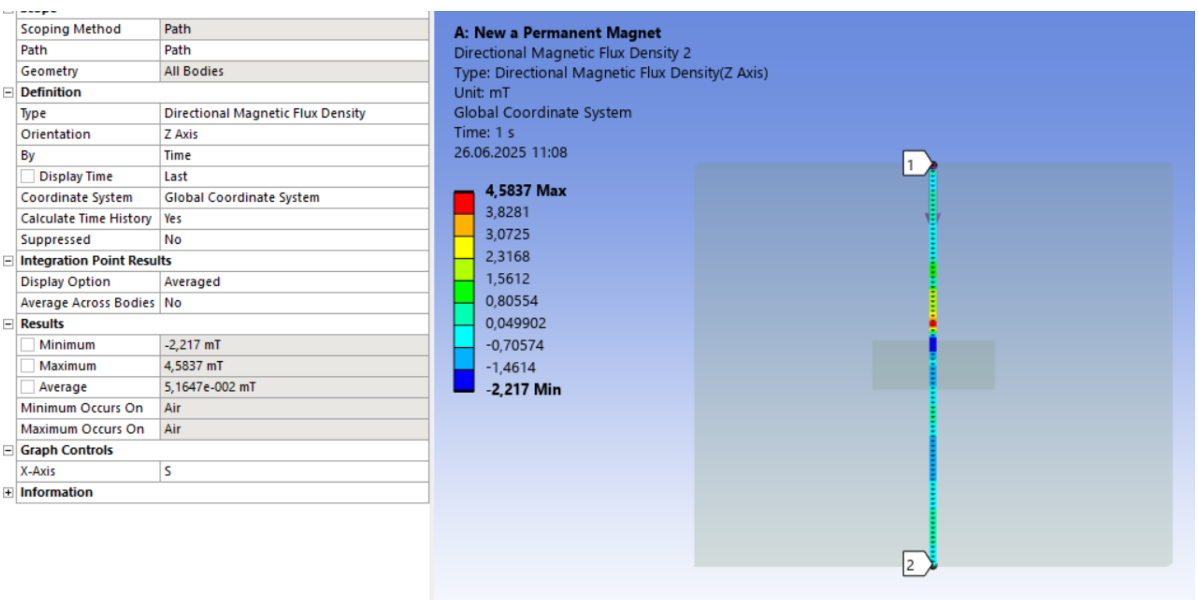


Figure 82 : Analysis of 0 Degree (+Y orientation)(x=4mm)

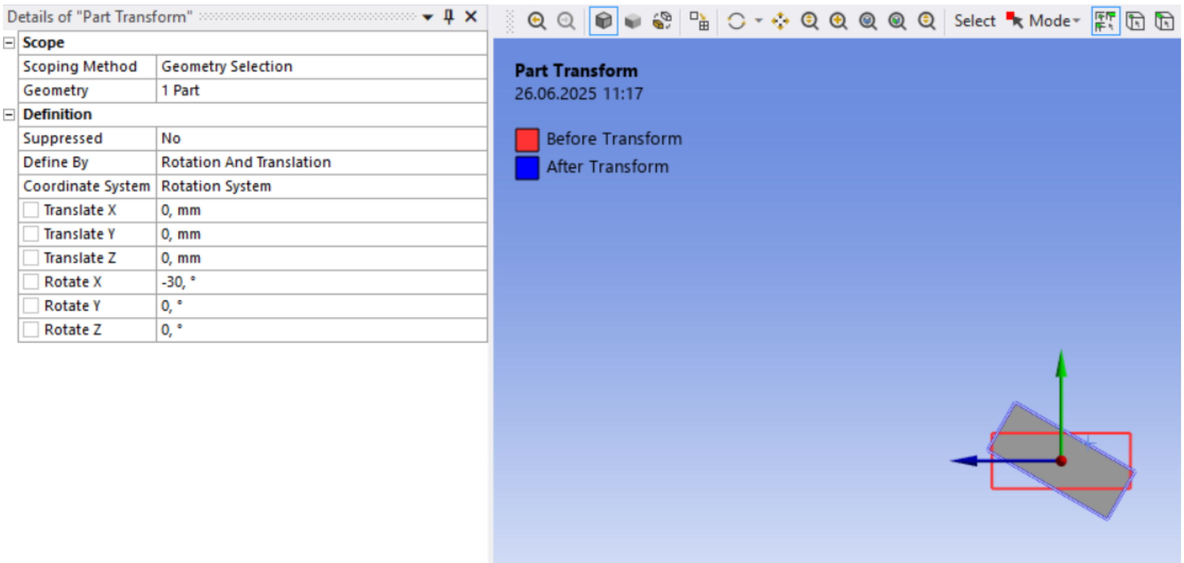


Figure 83 : 30 Degree Rotation (CW)

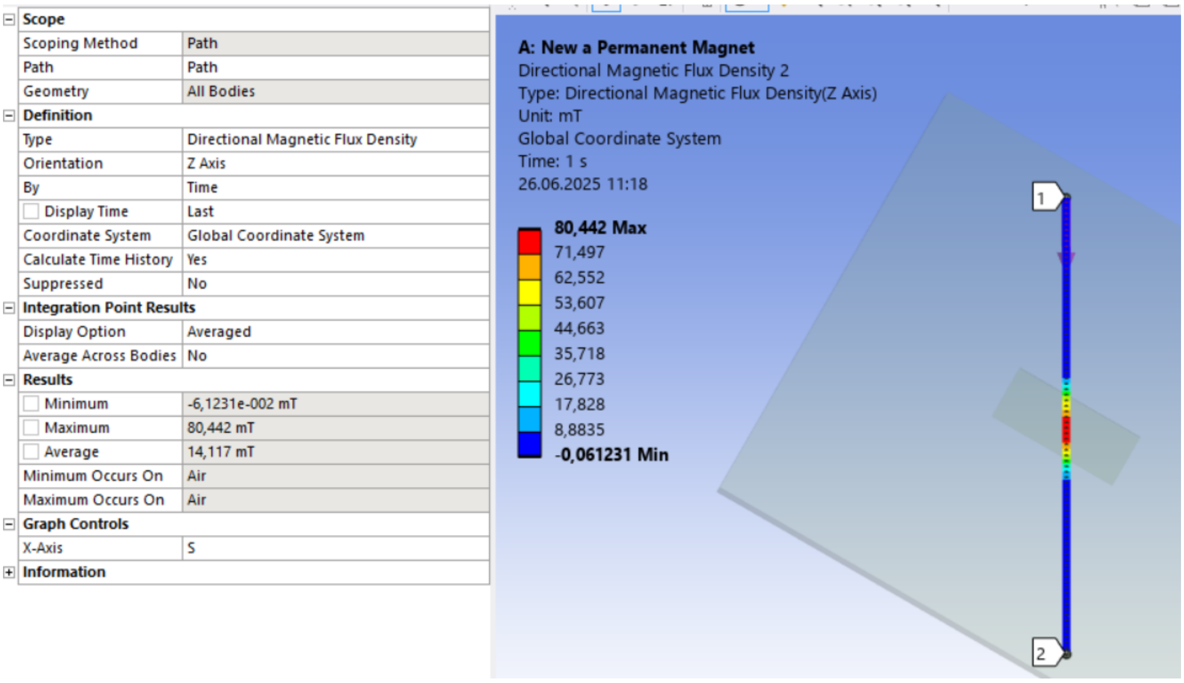


Figure 84 : Analysis of 30 Degree (+Y orientation)(x=4mm)

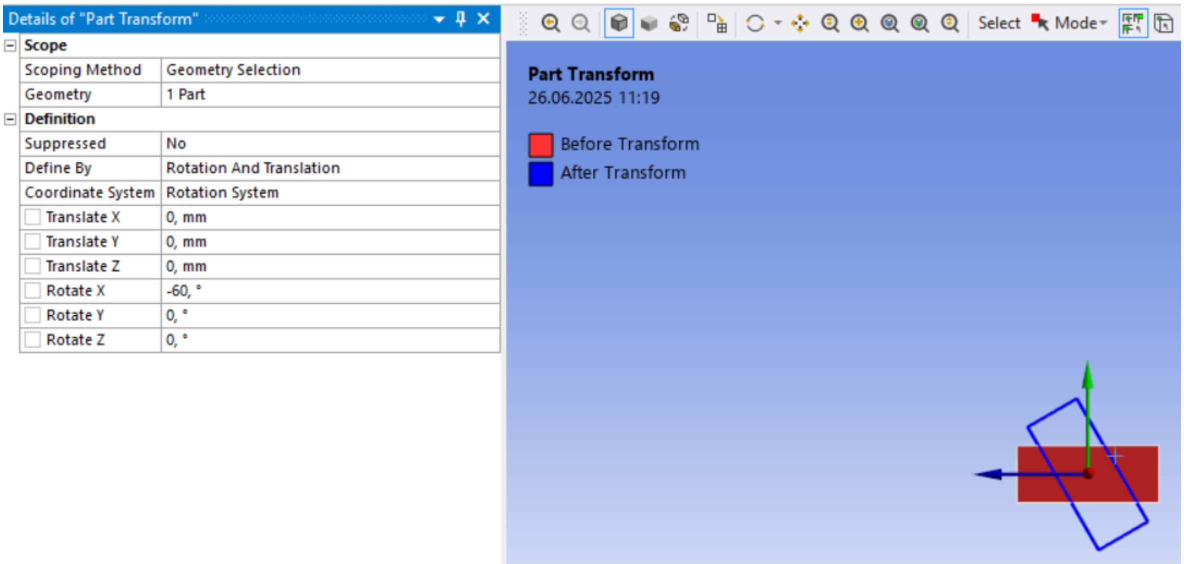


Figure 85 : 60 Degree Rotation (CW)

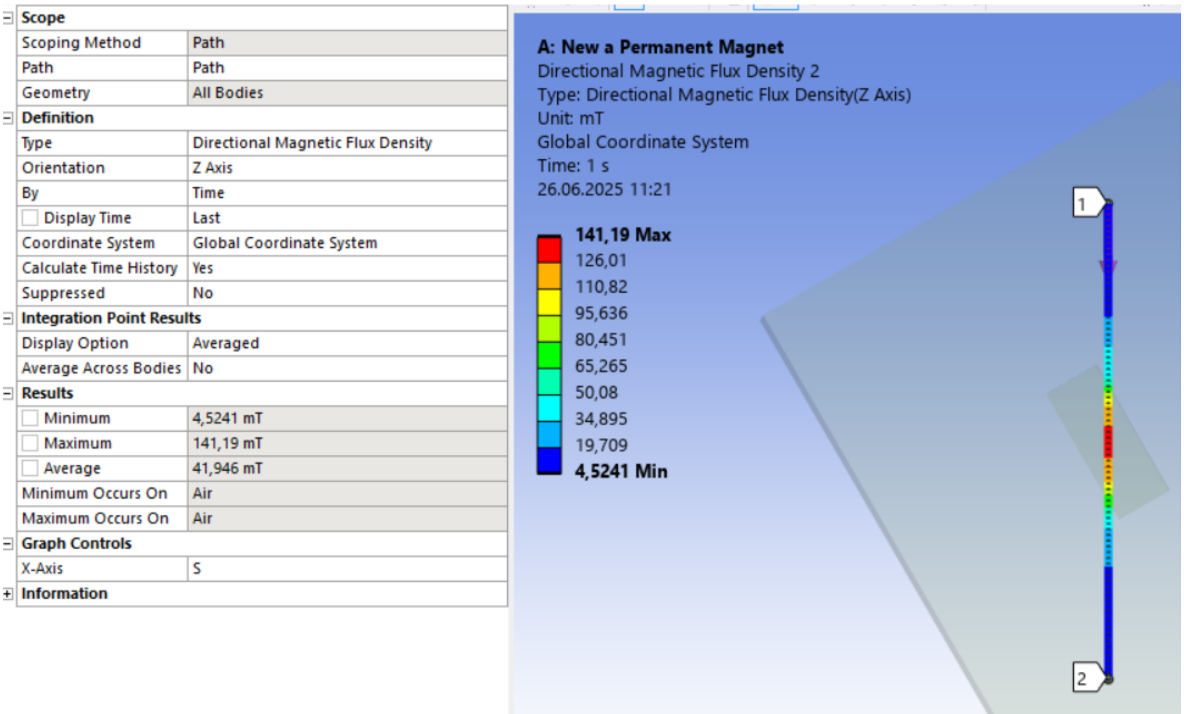


Figure 86 : Analysis of 60 Degree (+Y orientation)(x=4mm)

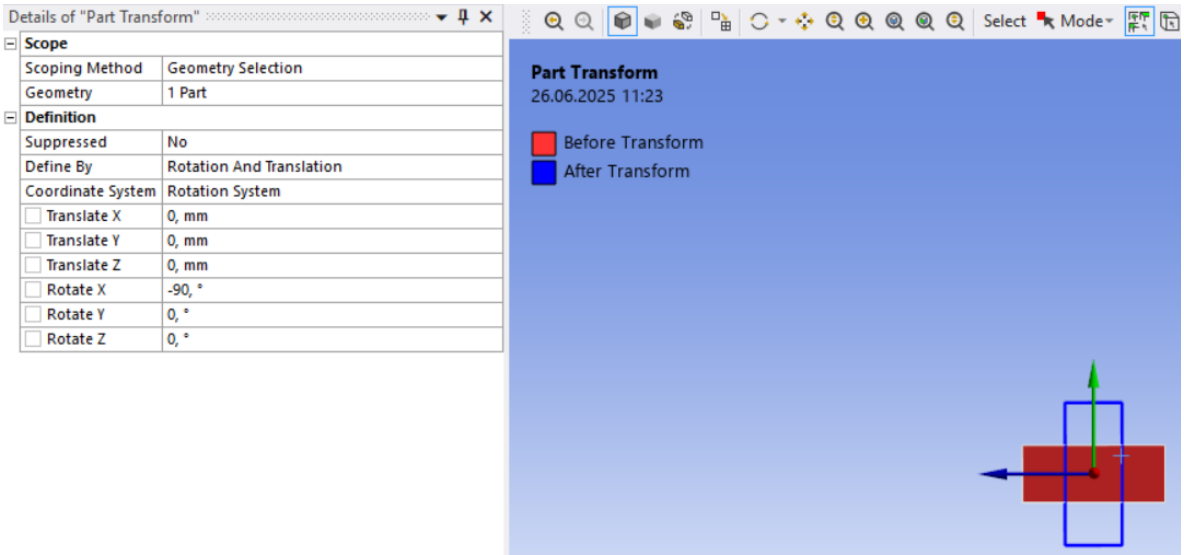


Figure 87 : 90 Degree Rotation (CW)

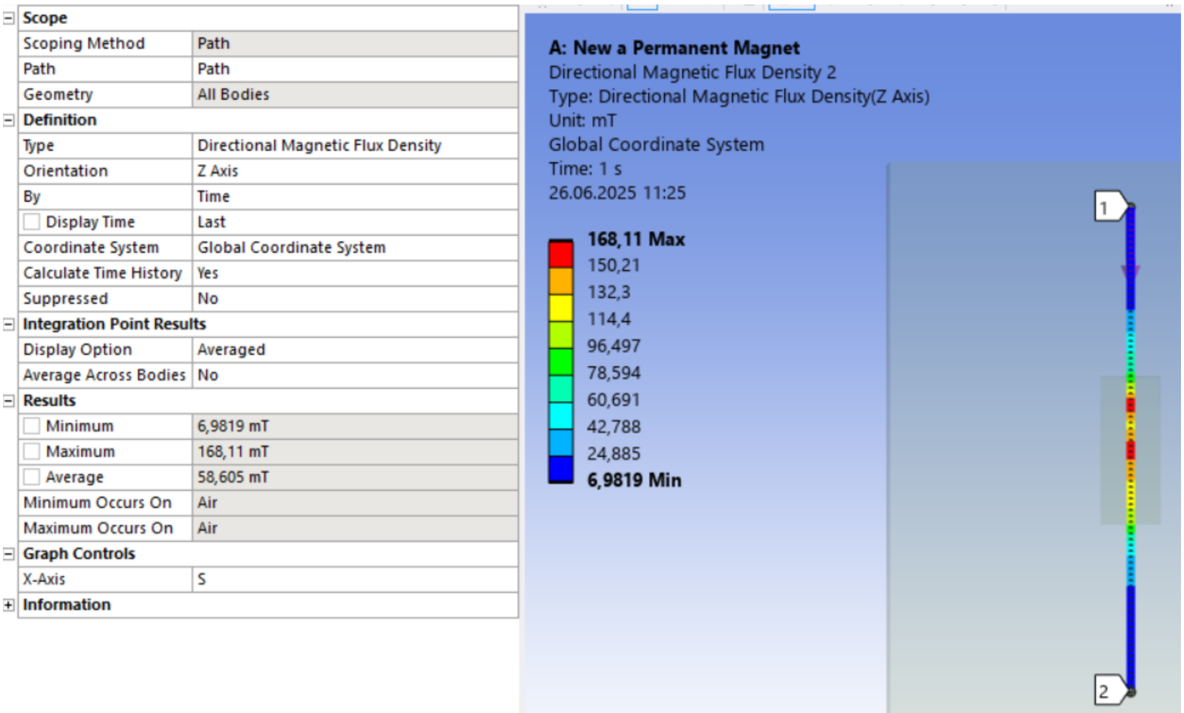


Figure 88 : Analysis of 90 Degree (+Y orientation)(x=4mm)

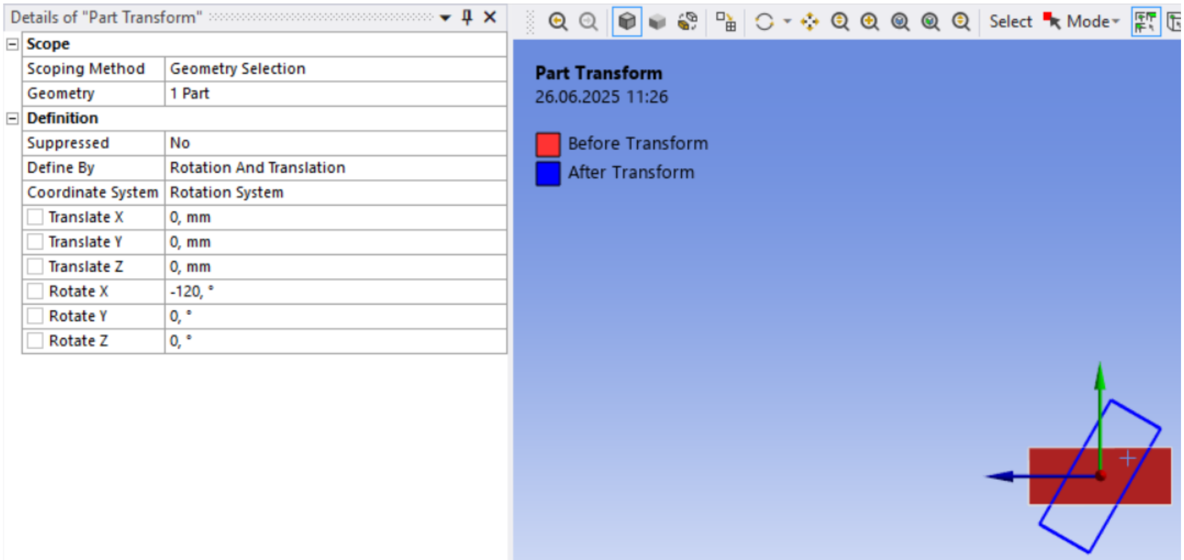


Figure 89 : 120 Degree Rotation (CW)

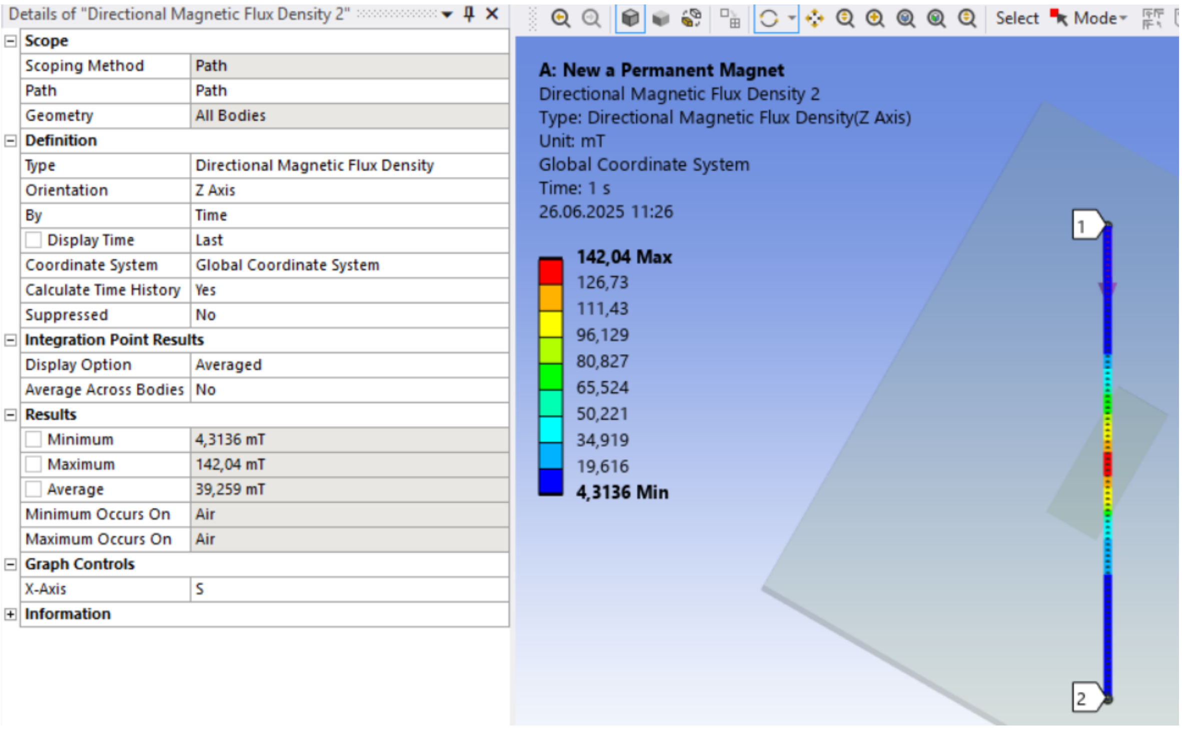


Figure 90 : Analysis of 120 Degree (+Y orientation)(x=4mm)

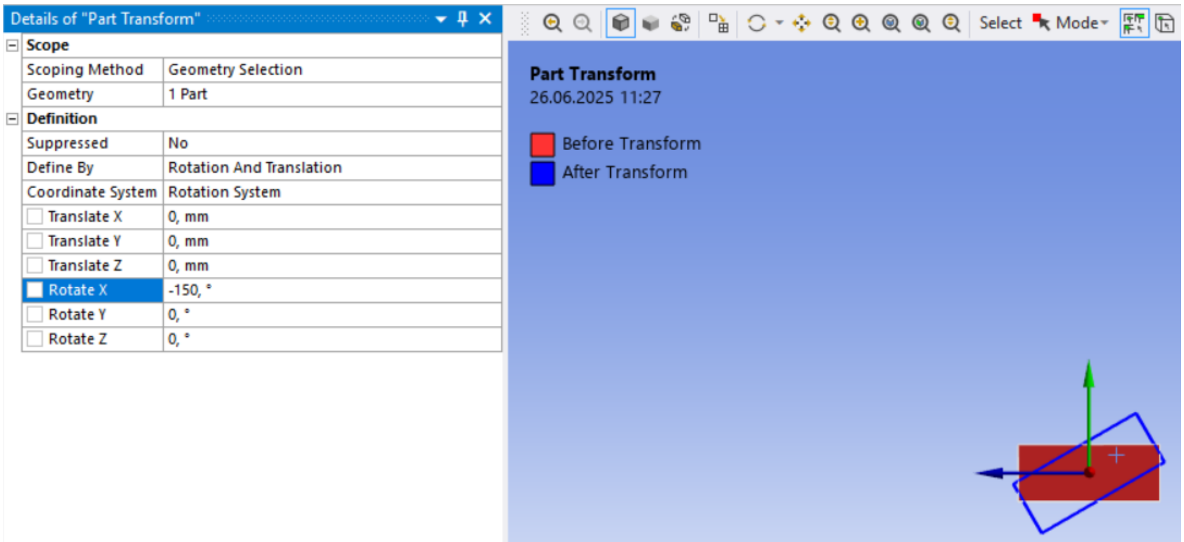


Figure 91 : 150 Degree Rotation (CW)

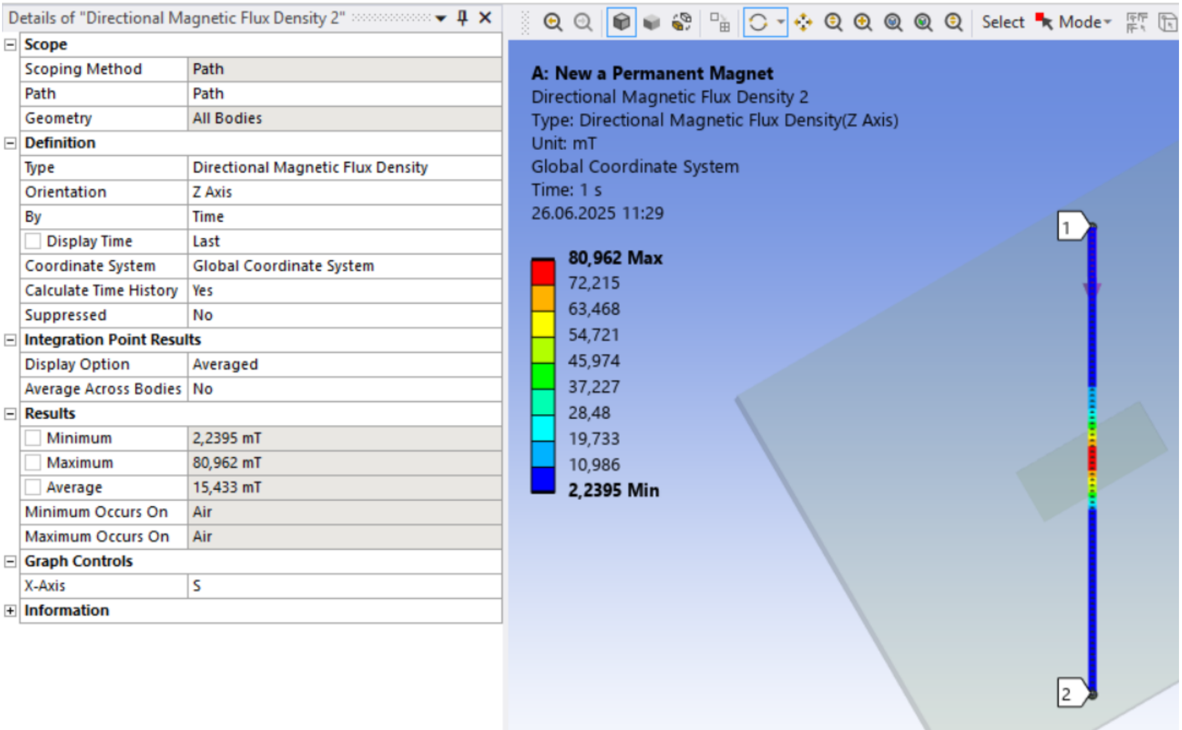


Figure 92 : Analysis of 150 Degree (+Y orientation)(x=4mm)

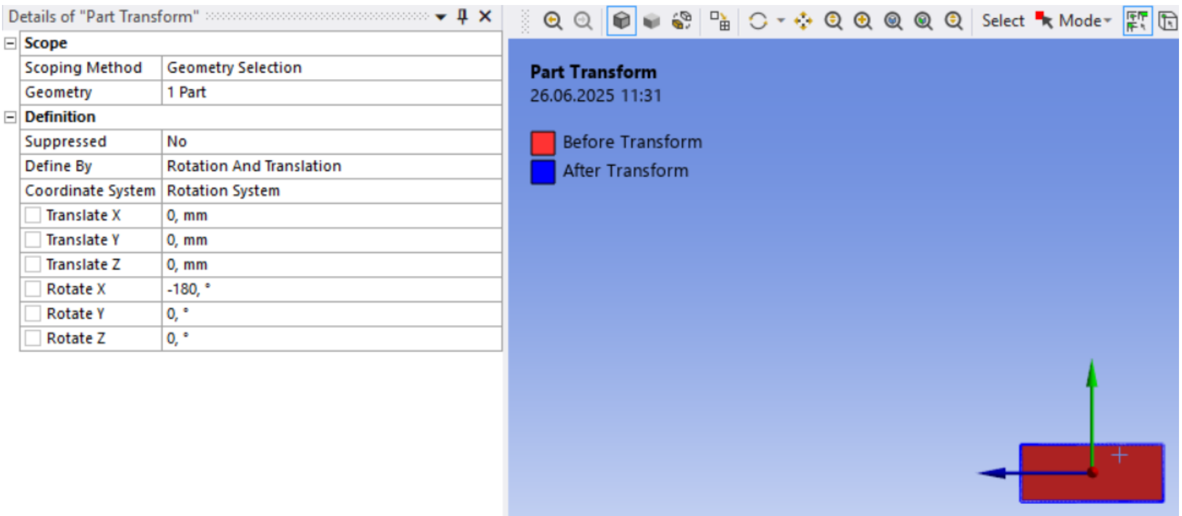


Figure 93 : 180 Degree Rotation (CW)

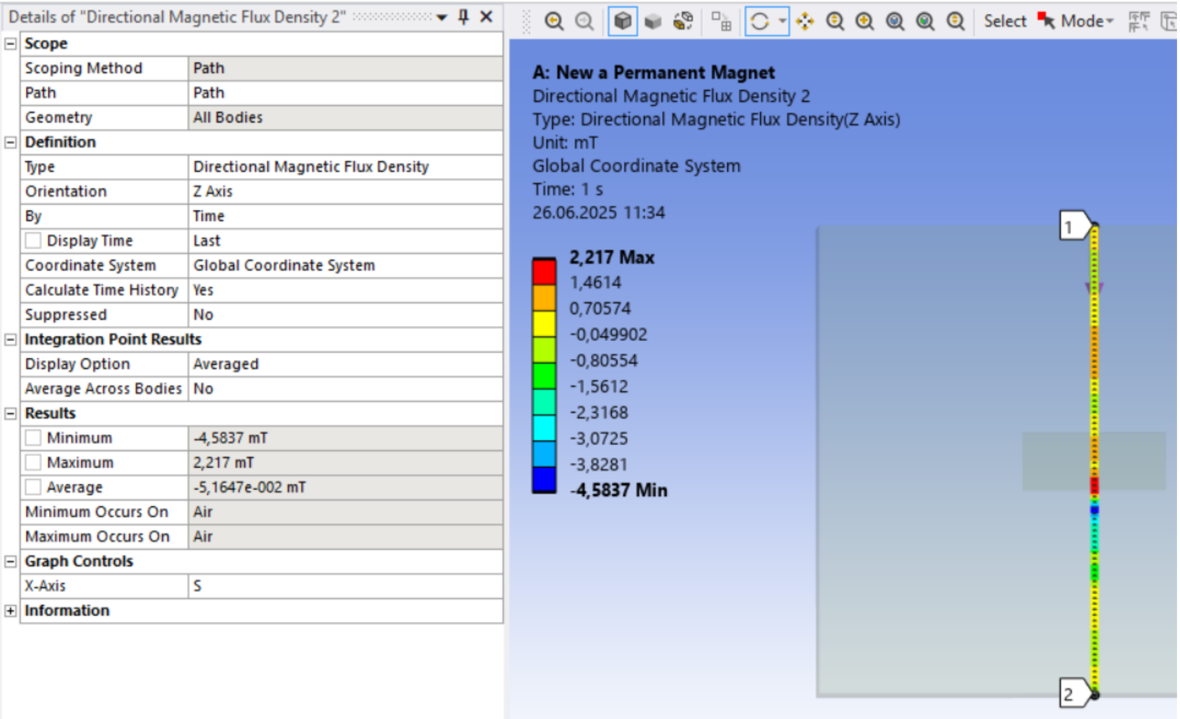


Figure 94 : Analysis of 180 Degree (+Y orientation)(x=4mm)

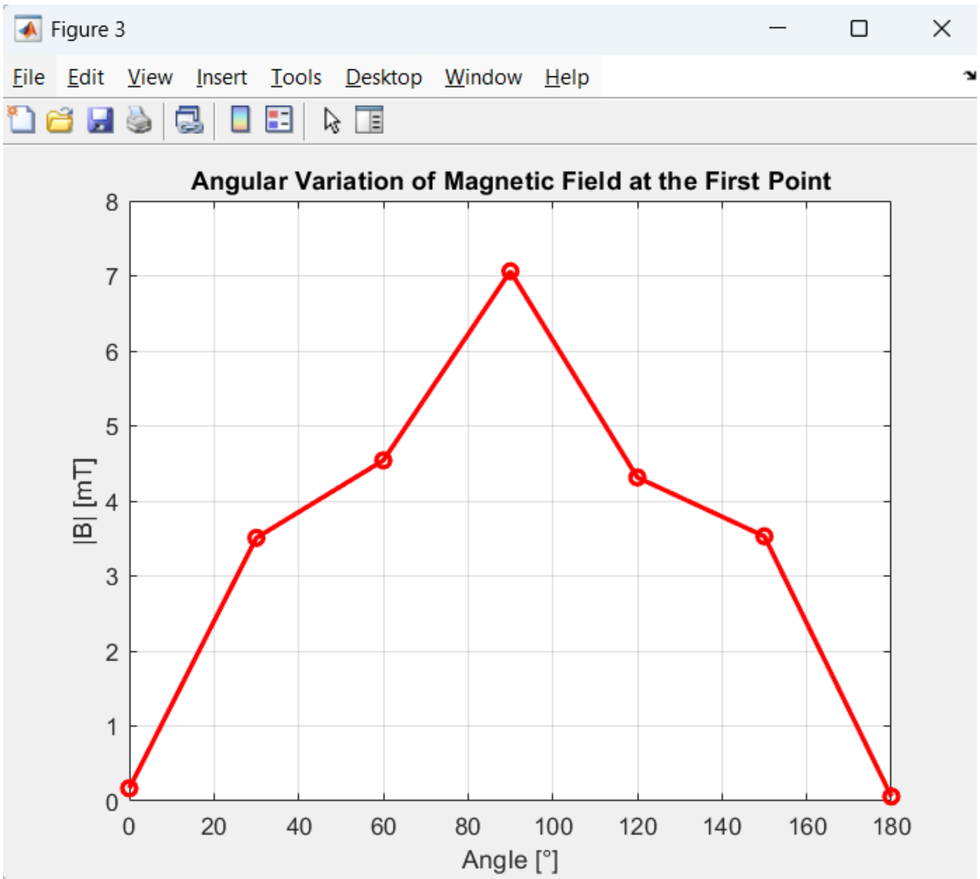


Figure 95 : Magnetic Field of first point (z Direction) of a Permanent Magnet Model (+Y Polarization) (x=4mm)

In the graphs with +Y polarization, we see that at a certain distance (y=41mm) the magnetic field starts from a value like 0 mT and at the 0 degree position, it has maximum magnetic field at 90 degrees, and at 180 degrees the magnetic field magnitude is 0 again.

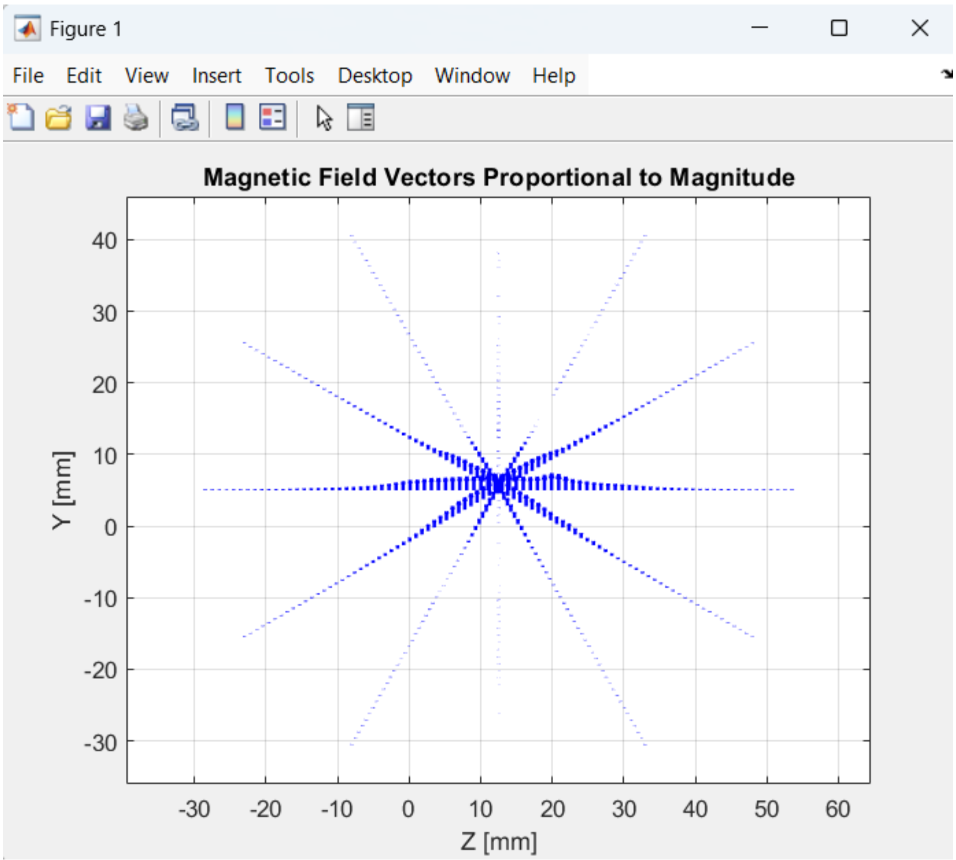


Figure 96 : Magnetic Field Vectors(Z direction) in path for a Permanent Magnet (+Y polarization)(x=4mm)

In this general distribution graph, the magnitude of the magnetic field (Z component) formed on the road when the magnetic field rotates is shown. Although the road appears to be rotating in this graph, the road is actually stationary and the rotating thing is our permanent magnet. My purpose in creating this graph in Matlab is to see the general distribution more clearly. Of course, since we cannot see how the magnetic field at the middle point changes with rotation in this graph (because the points overlap), I created another graph below that includes the magnetic field change at the middle point (in the z direction). You can see this graph in Figure 97.

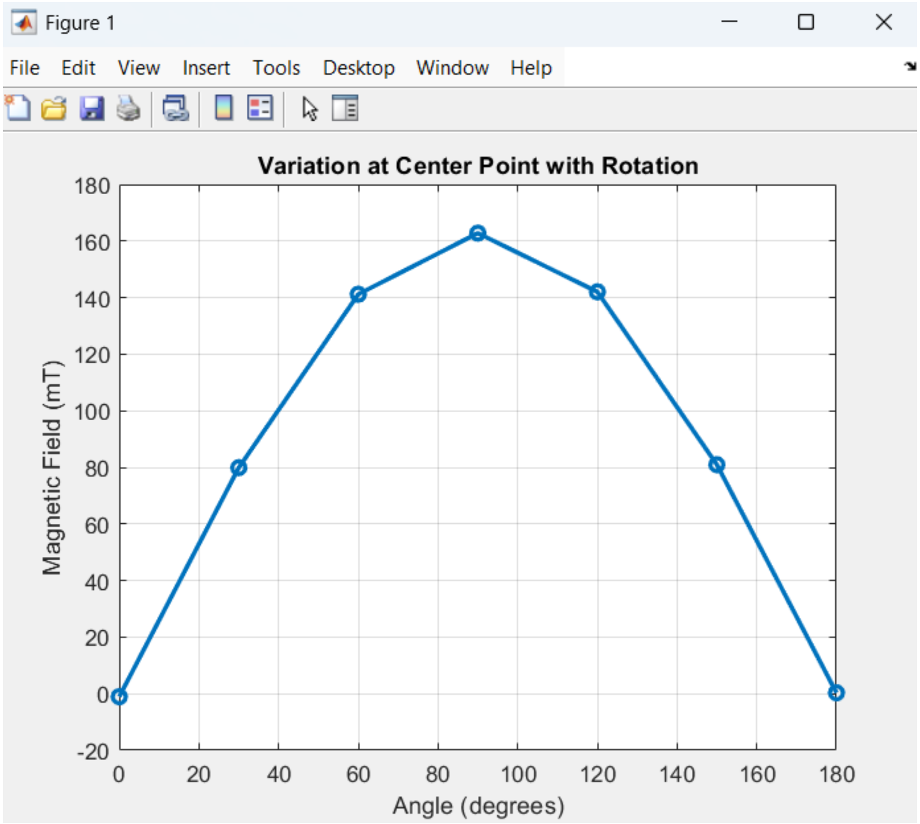


Figure 97 : Magnetic Field of center point (z Direction) of a Permanent Magnet Model (+Y Polarization) (x=4mm)

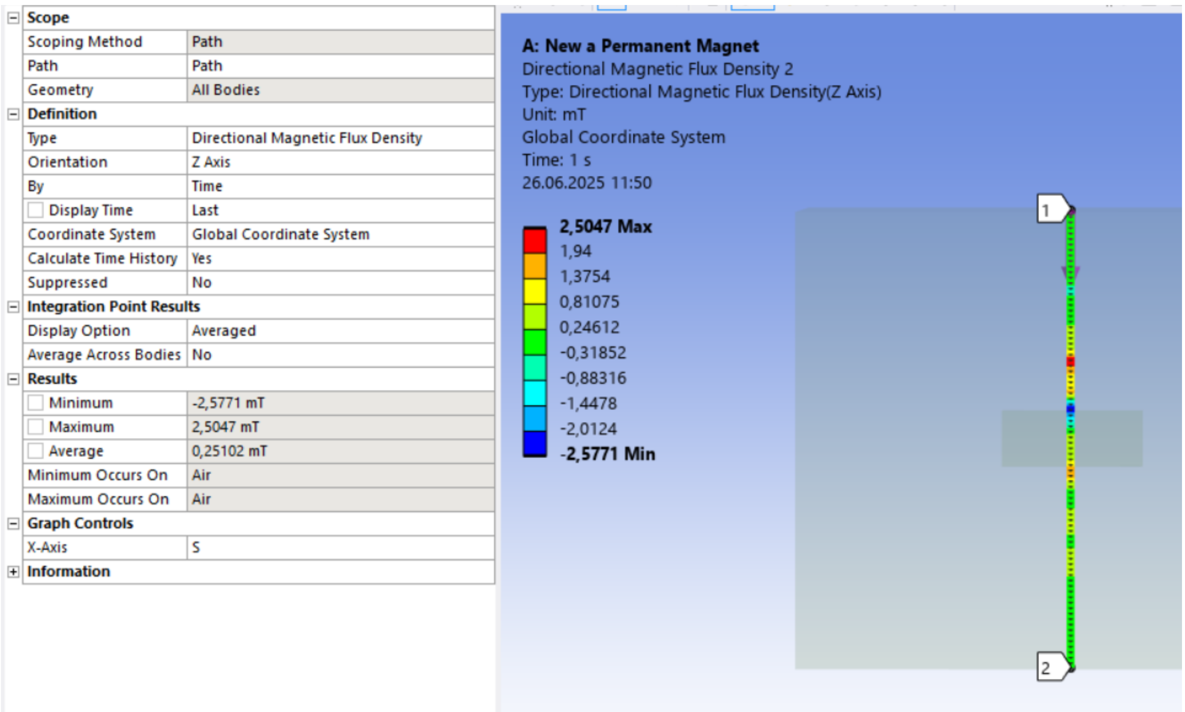


Figure 98 : Analysis of 0 Degree (+X orientation)(x=4mm)

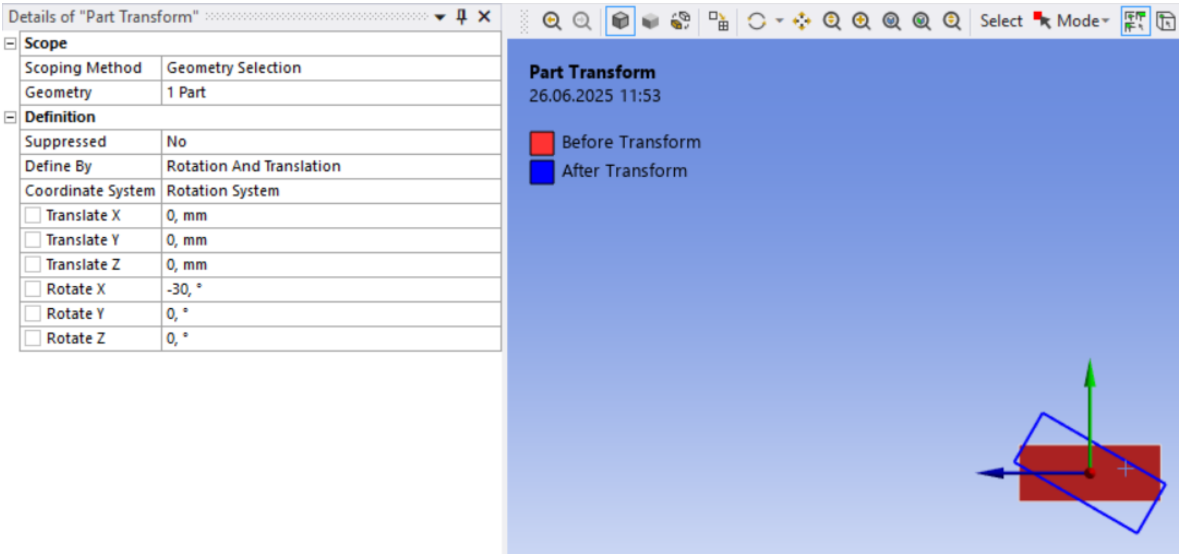


Figure 99 : 30 Degree Rotation (CW)

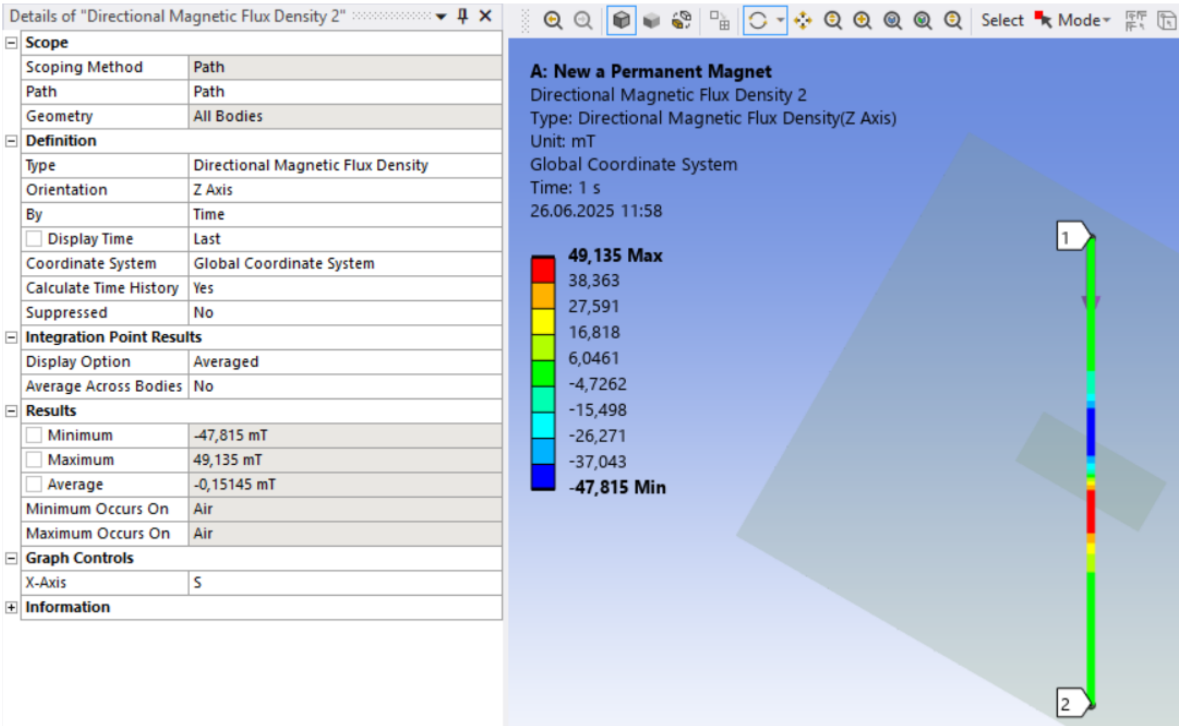


Figure 100 : Analysis of 30 Degree (+X orientation)(x=4mm)

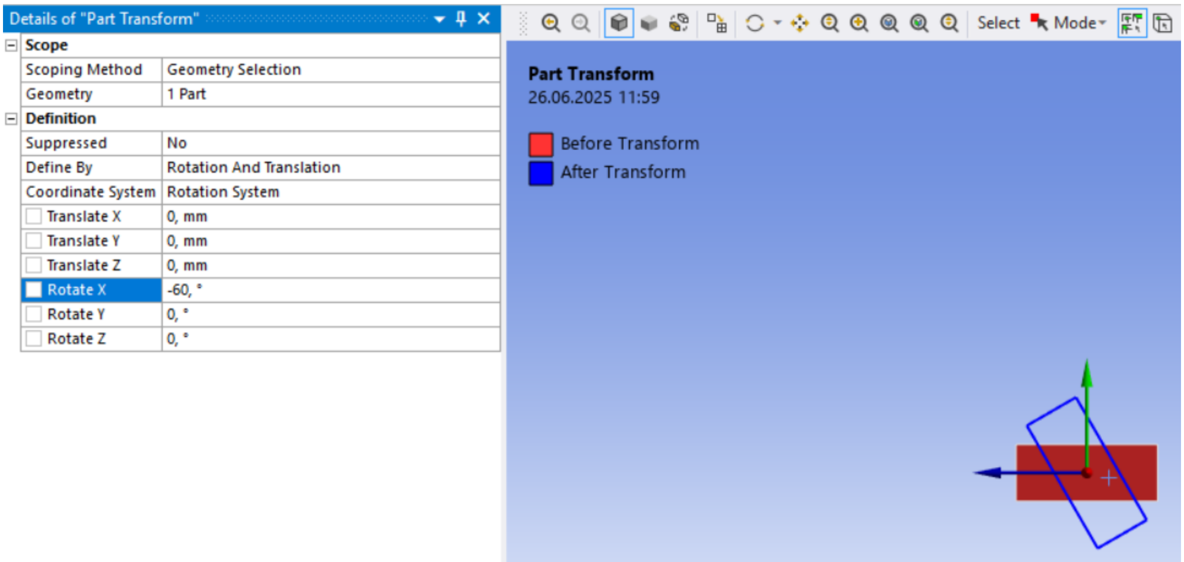


Figure 101 : 60 Degree Rotation (CW)

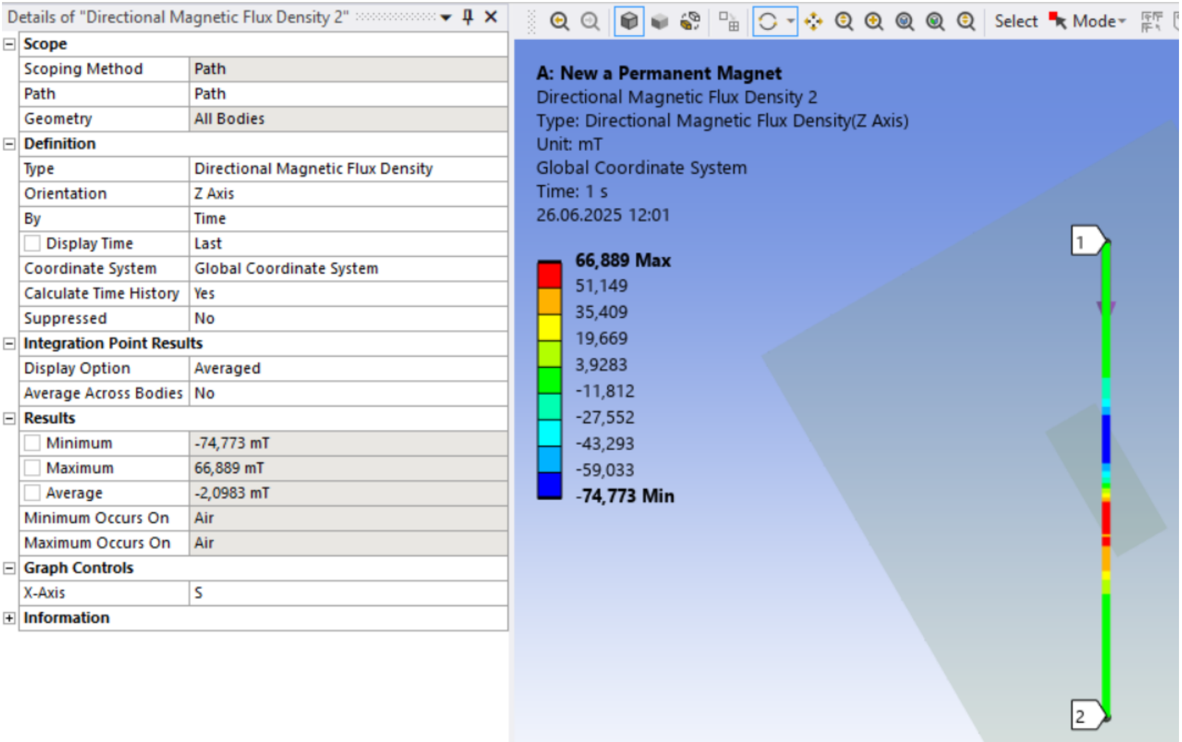


Figure 102 : Analysis of 60 Degree (+X orientation)(x=4mm)

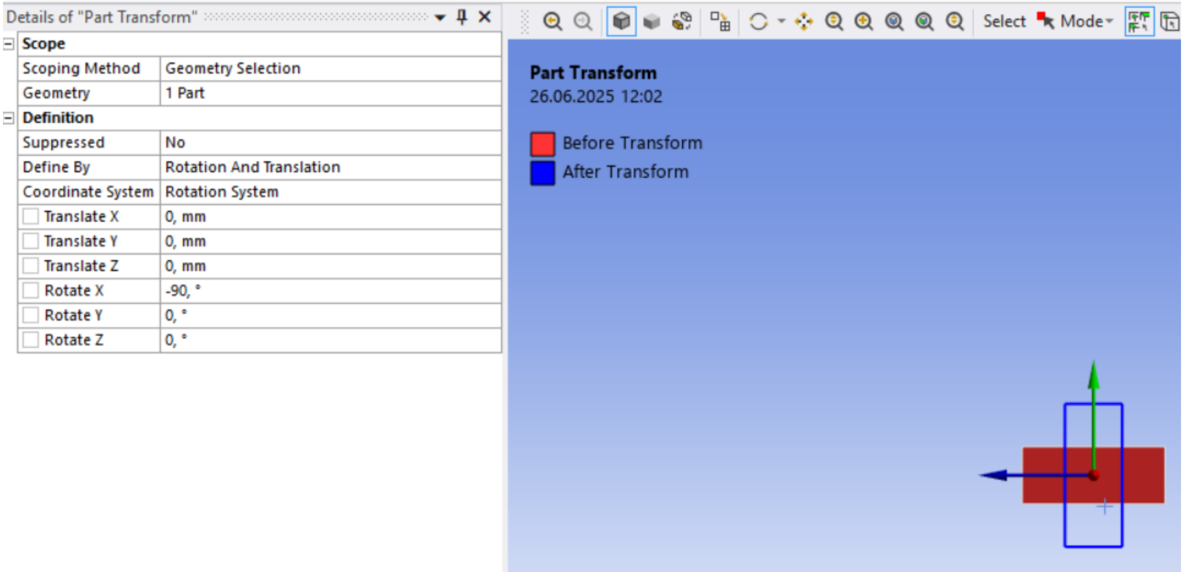


Figure 103 : 90 Degree Rotation (CW)

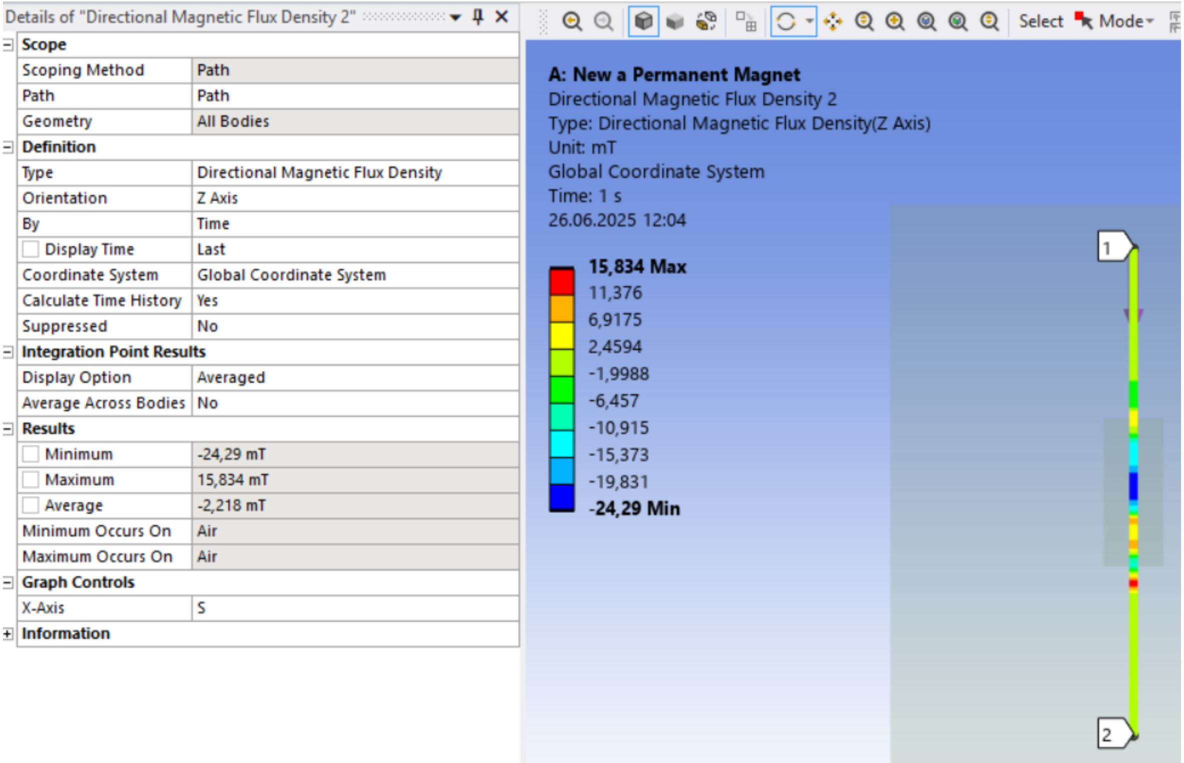


Figure 104 : Analysis of 90 Degree (+X orientation)(x=4mm)

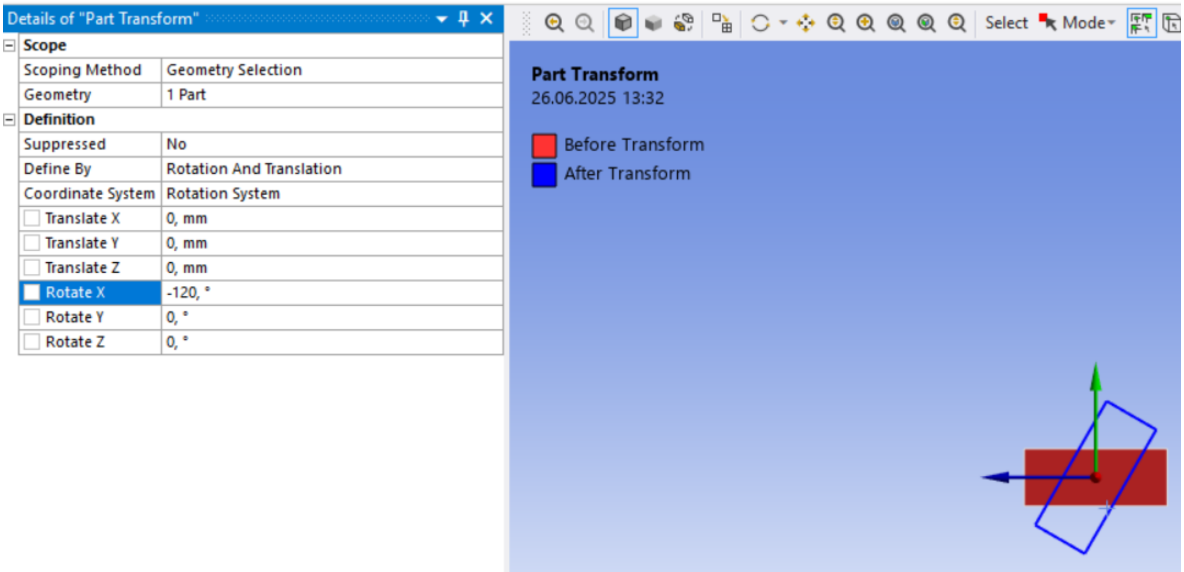


Figure 105 : 120 Degree Rotation (CW)

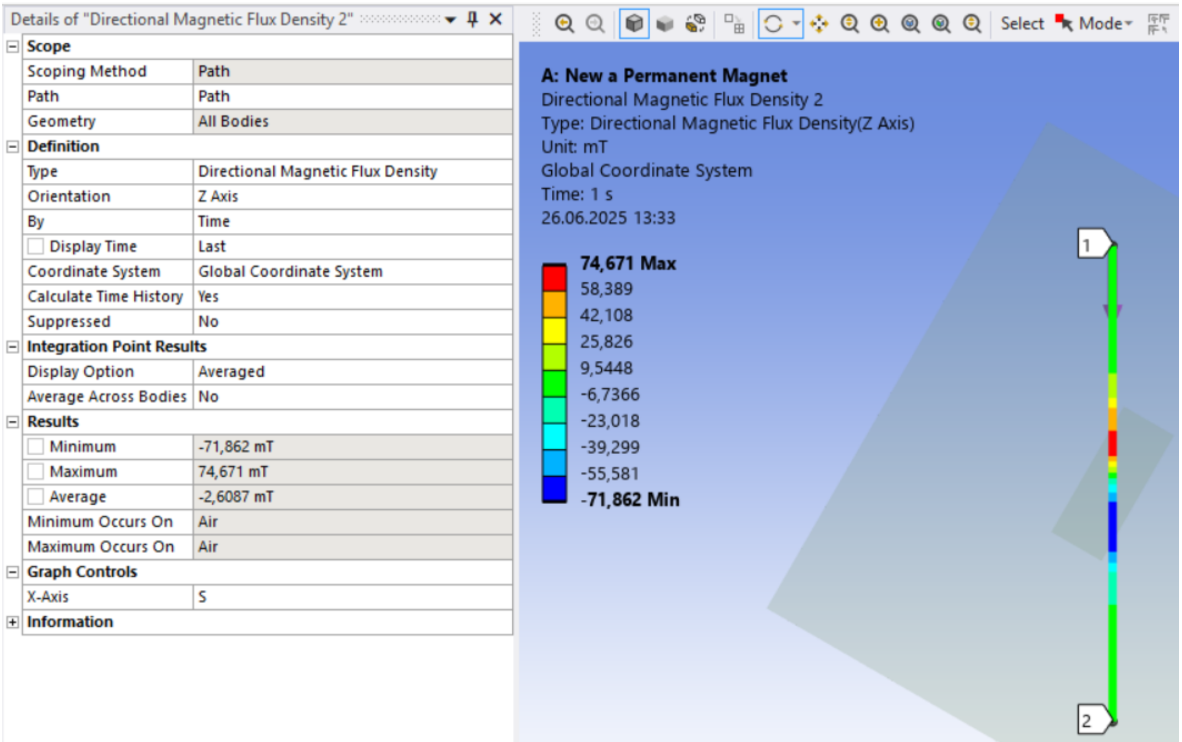


Figure 106 : Analysis of 120 Degree (+X orientation)(x=4mm)

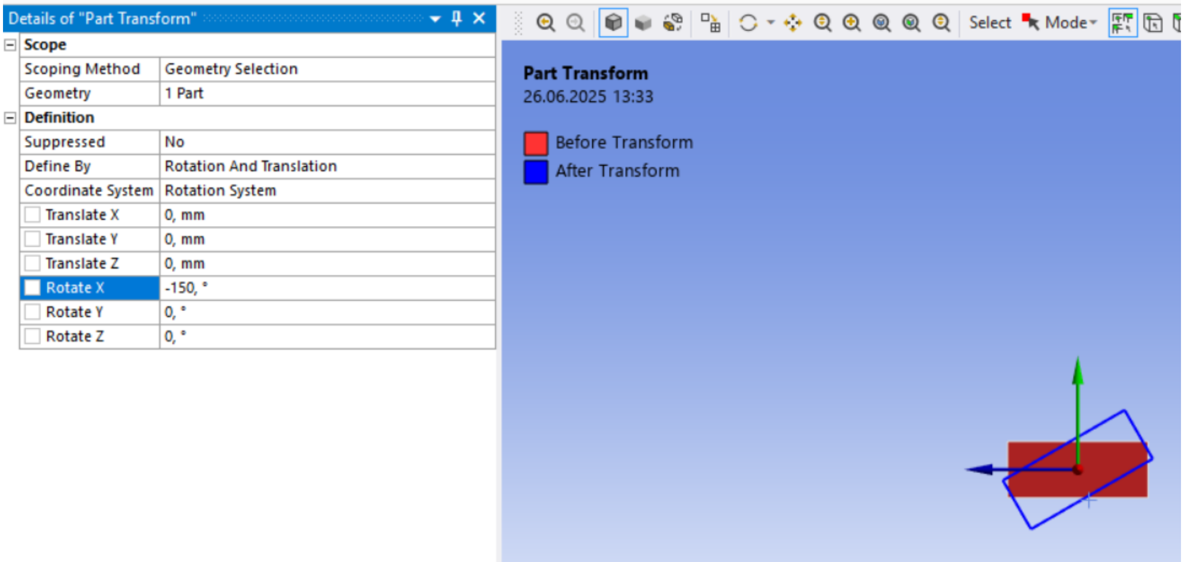


Figure 107 : 150 Degree Rotation (CW)

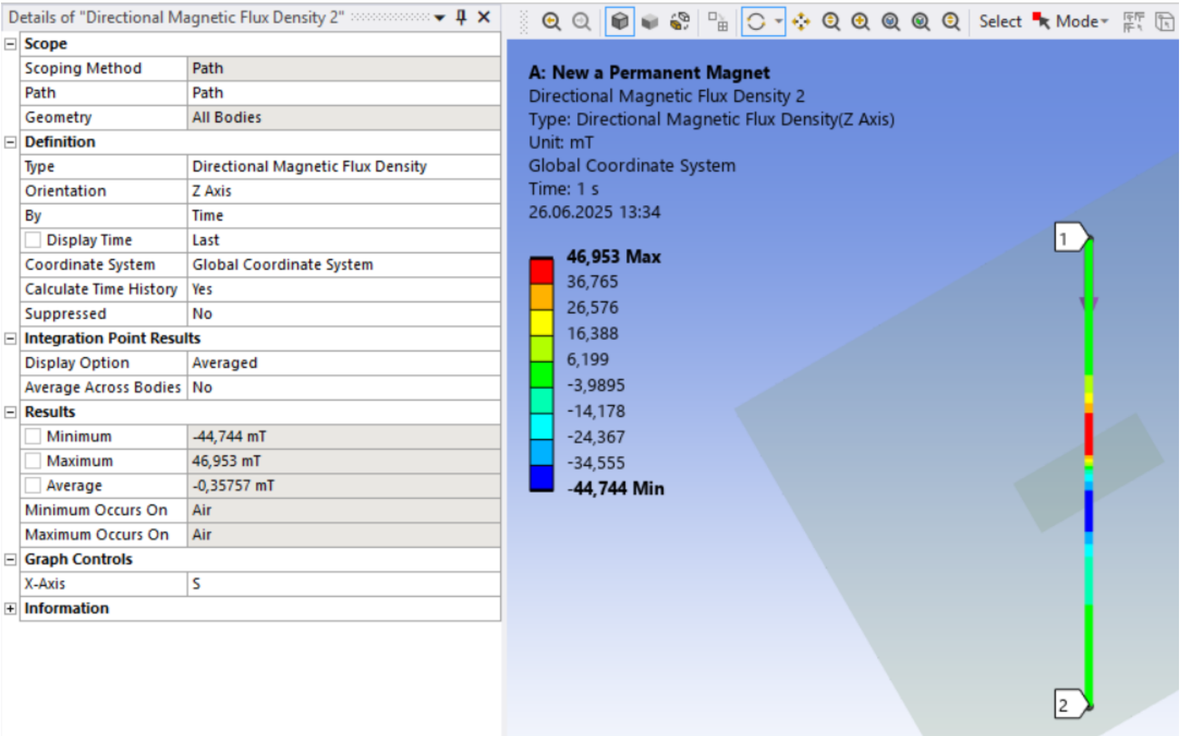


Figure 108 : Analysis of 150 Degree (+X orientation)(x=4mm)

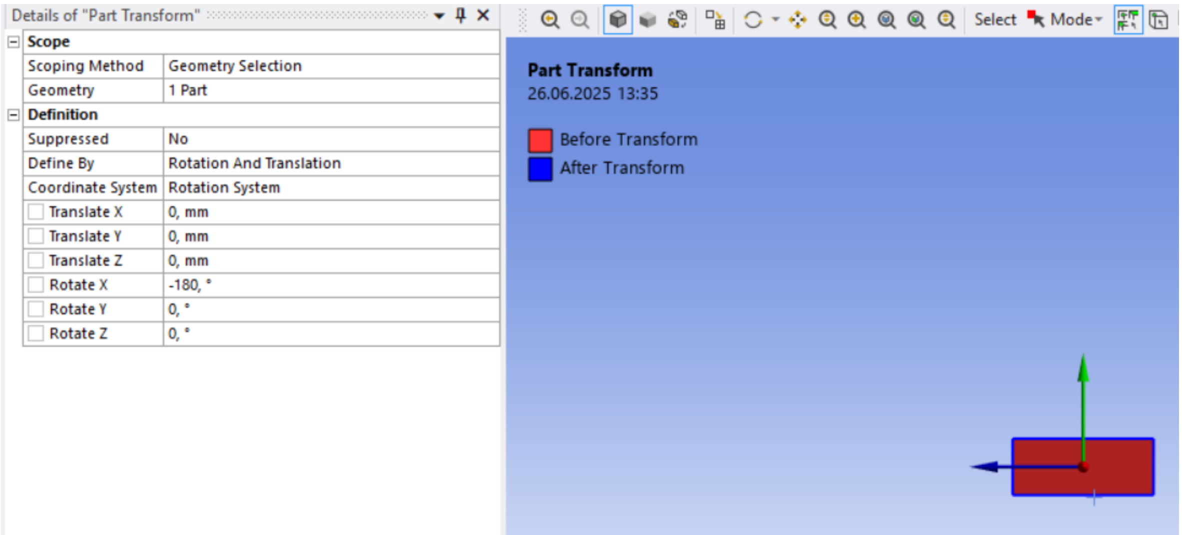


Figure 109 : 180 Degree Rotation (CW)

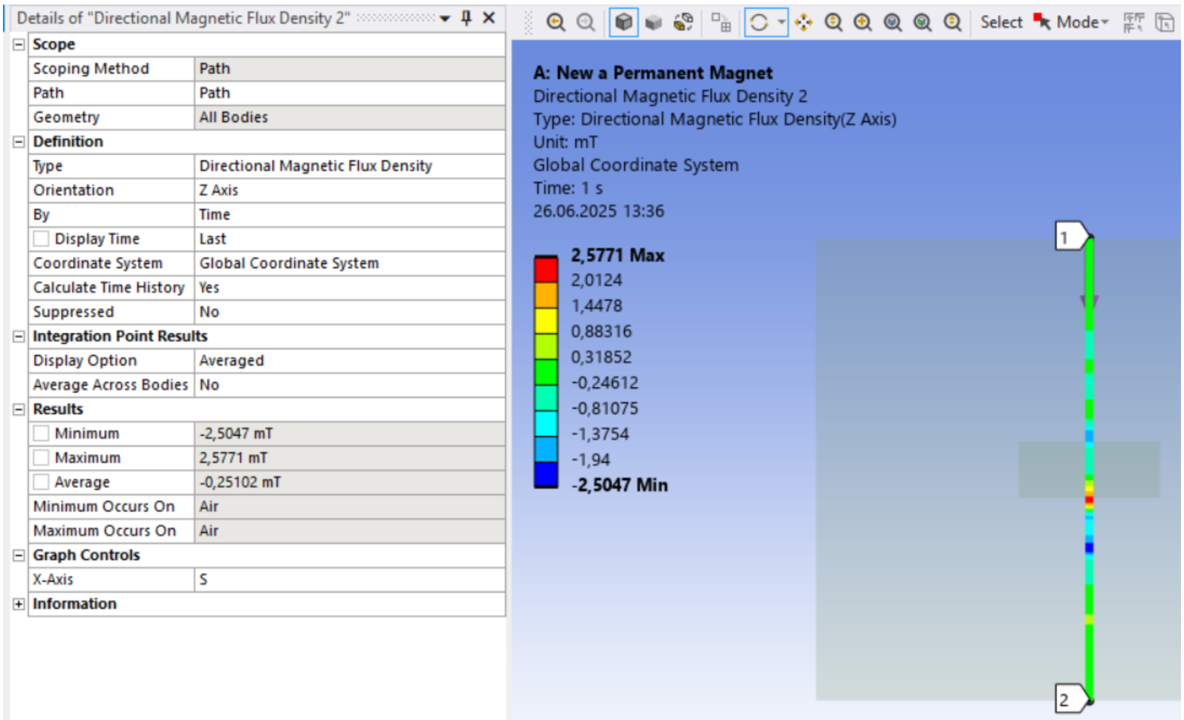


Figure 110 : Analysis of 180 Degree (+X orientation)(x=4mm)

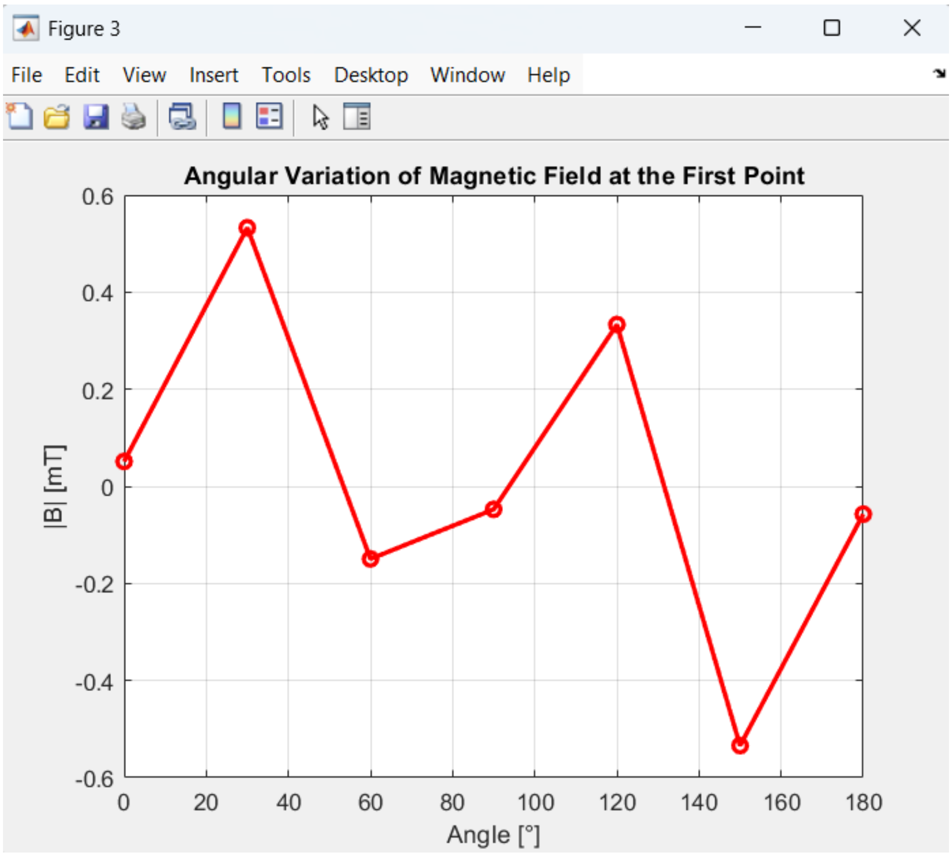


Figure 111 : Magnetic Field of first point (z Direction) of a Permanent Magnet Model (+X Polarization) (x=4mm)

In the graphs with +X polarization, we see that at a certain distance (y=41mm) the magnetic field starts at a value close to 0 and in almost no case does it really move away from 0 to a significant value. So at this point we can say that there is no change with rotation in general. And it can be seen very easily how irregular the small changes are.

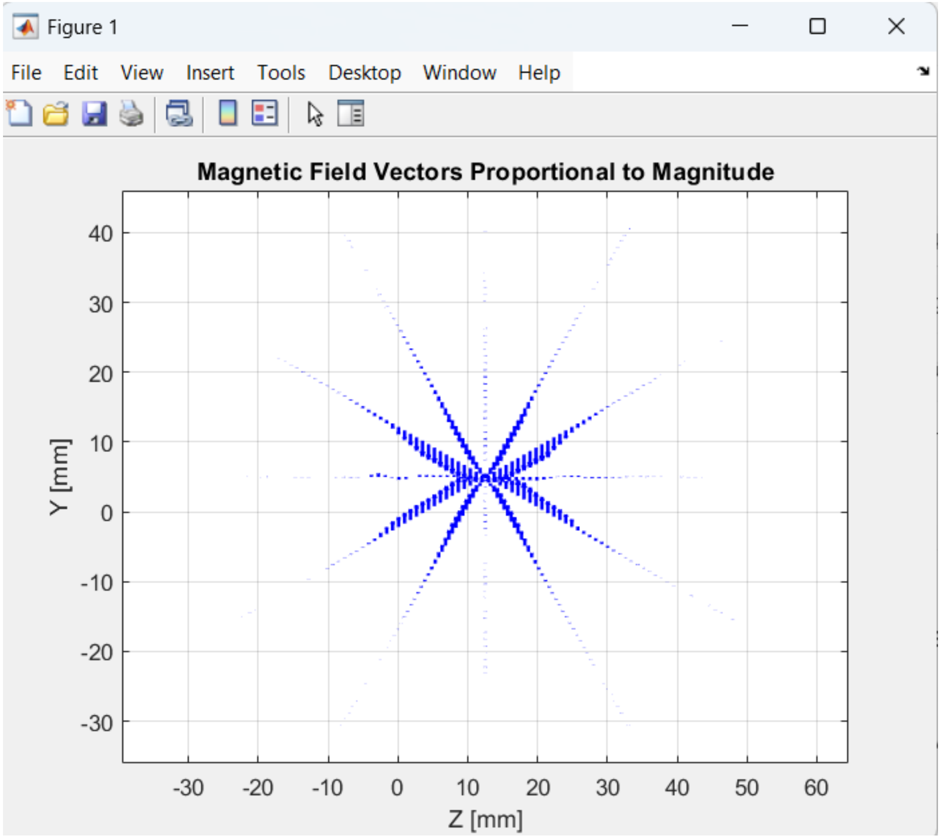


Figure 112 : Magnetic Field Vectors(Z direction) in path for a Permanent Magnet (+X polarization)(x=4mm)

In this general distribution graph, the magnitude of the magnetic field (Z component) formed on the road when the magnetic field rotates is shown. Although the road appears to be rotating in this graph, the road is actually stationary and the rotating thing is our permanent magnet. My purpose in creating this graph in Matlab is to see the general distribution more clearly. Of course, since we cannot see how the magnetic field at the middle point changes with rotation in this graph (because the points overlap), I created another graph below that includes the magnetic field change at the middle point (in the z direction). You can see this graph in Figure 113.

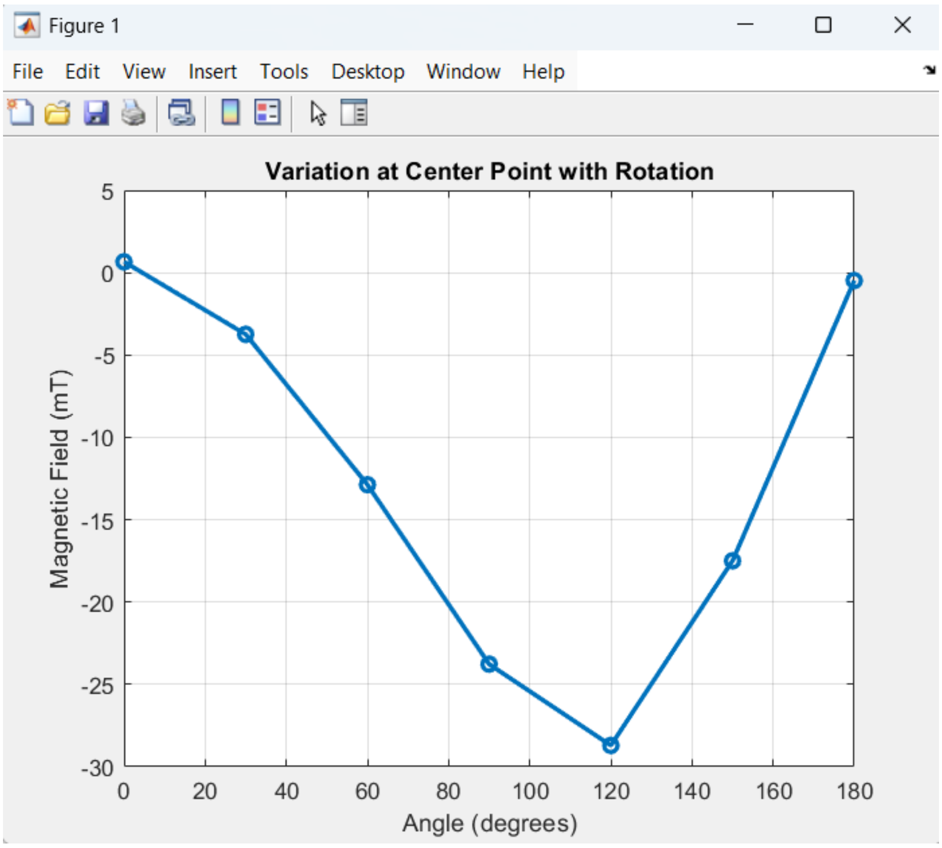


Figure 113 : Magnetic Field of center point (z Direction) of a Permanent Magnet Model (+X Polarization) (x=4mm)

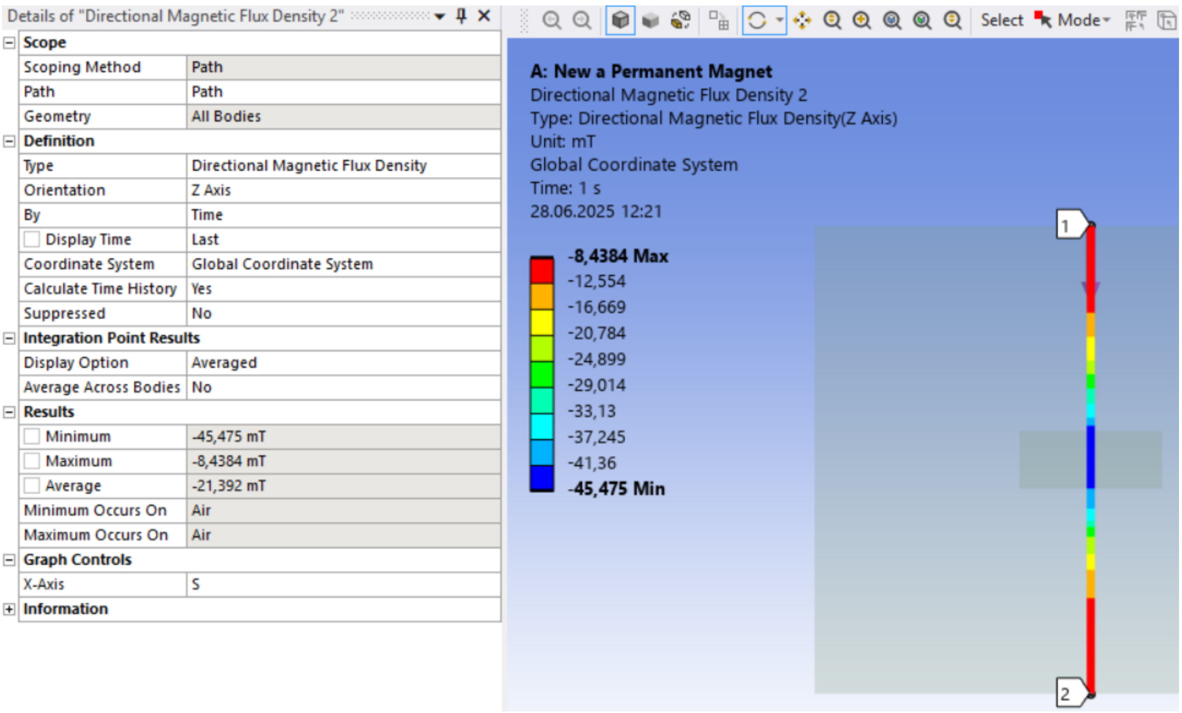


Figure 114 : Analysis of 0 Degree (+Z orientation)(x=8mm)

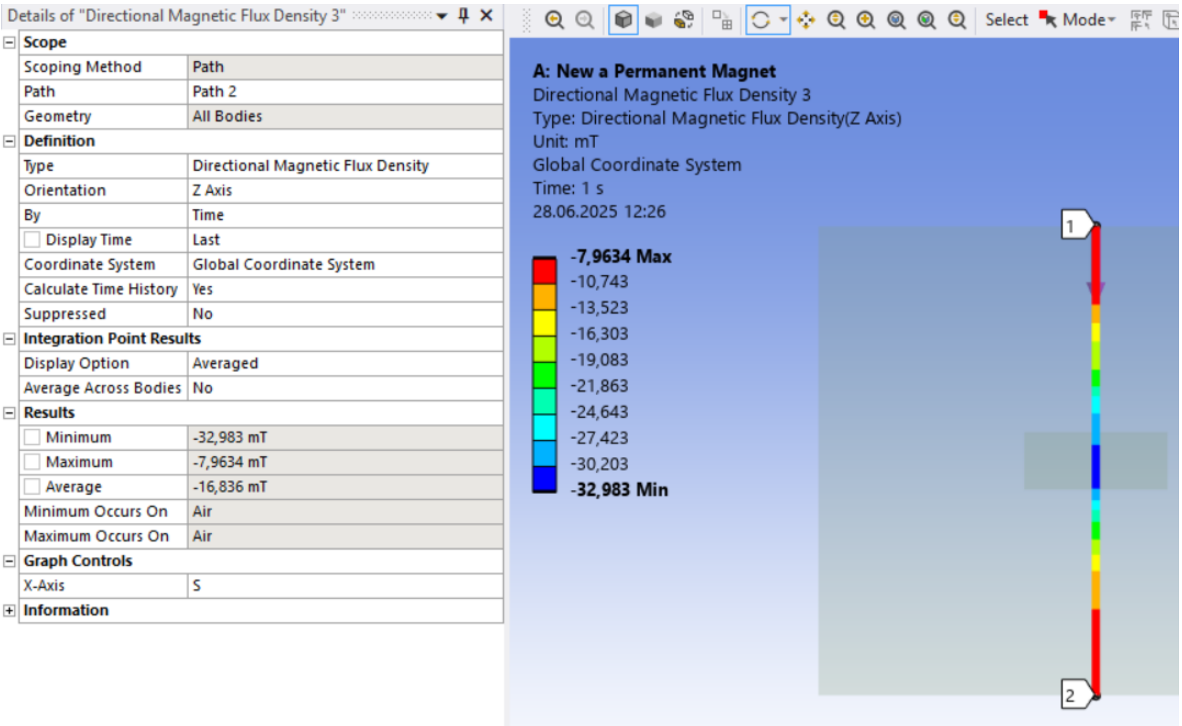


Figure 115 : Analysis of 0 Degree (+Z orientation)(x=12mm)

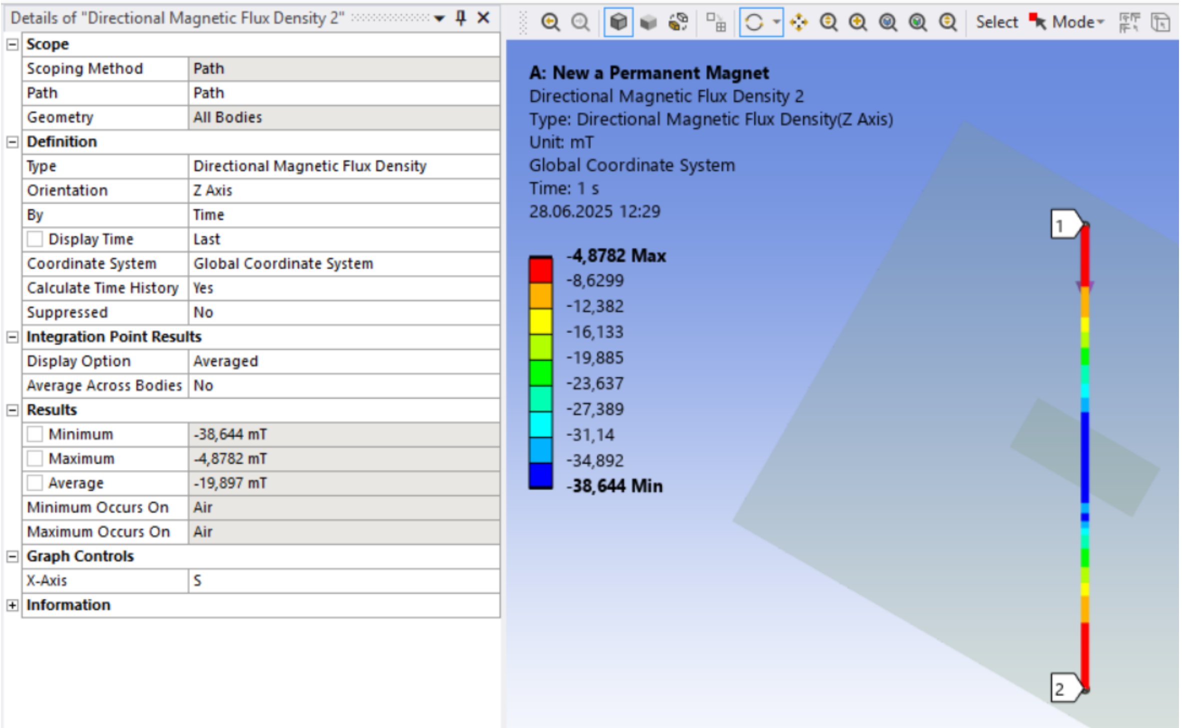


Figure 116 : Analysis of 30 Degree (+Z orientation)(x=8mm)

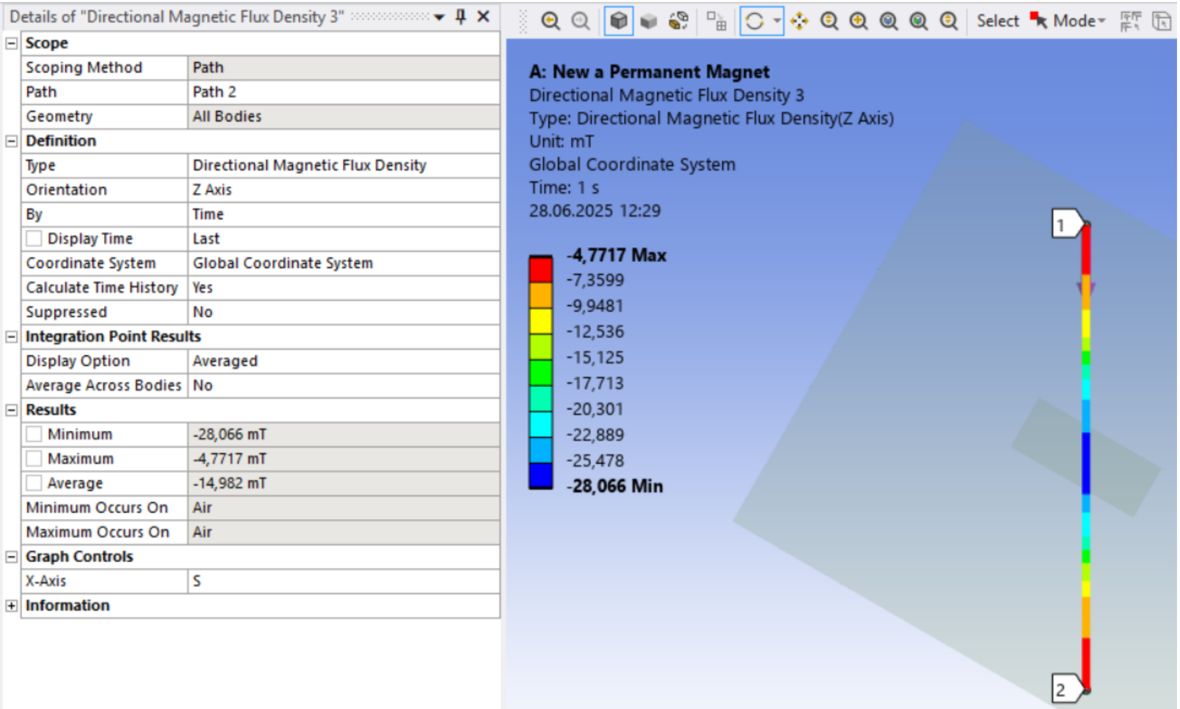


Figure 117 : Analysis of 30 Degree (+Z orientation)(x=12mm)

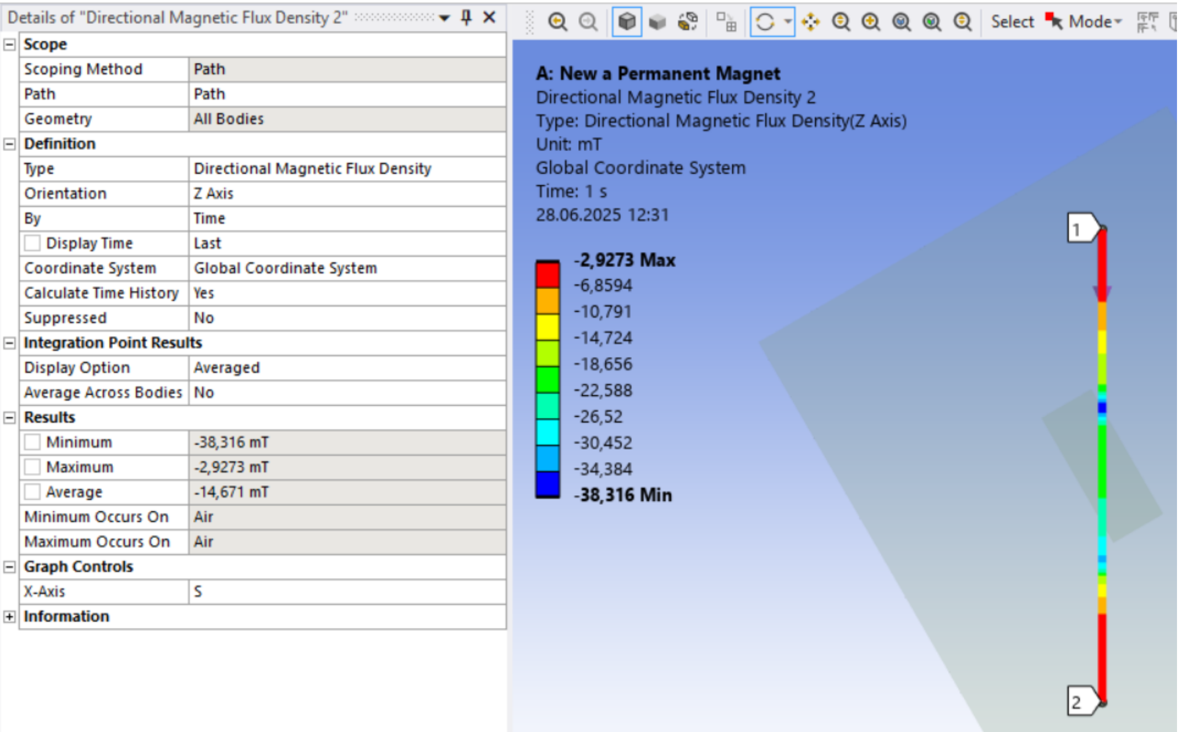


Figure 118 : Analysis of 60 Degree (+Z orientation)(x=8mm)

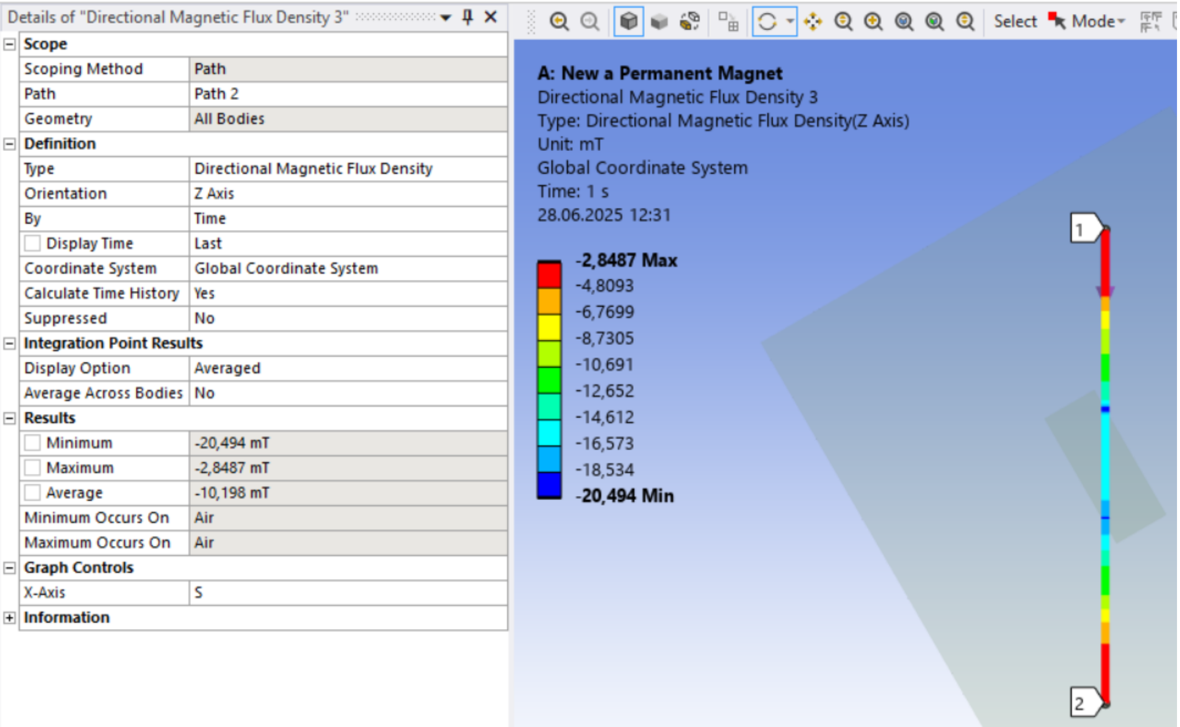


Figure 119 : Analysis of 60 Degree (+Z orientation)(x=12mm)

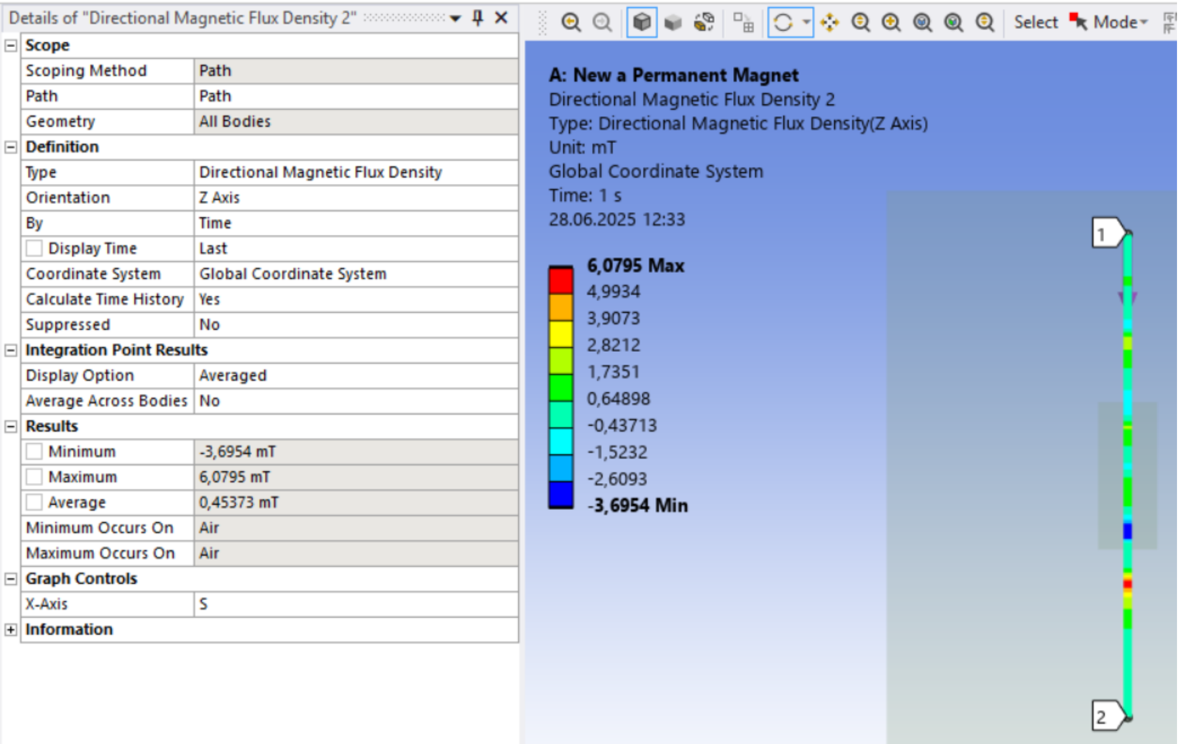


Figure 120 : Analysis of 90 Degree (+Z orientation)(x=8mm)

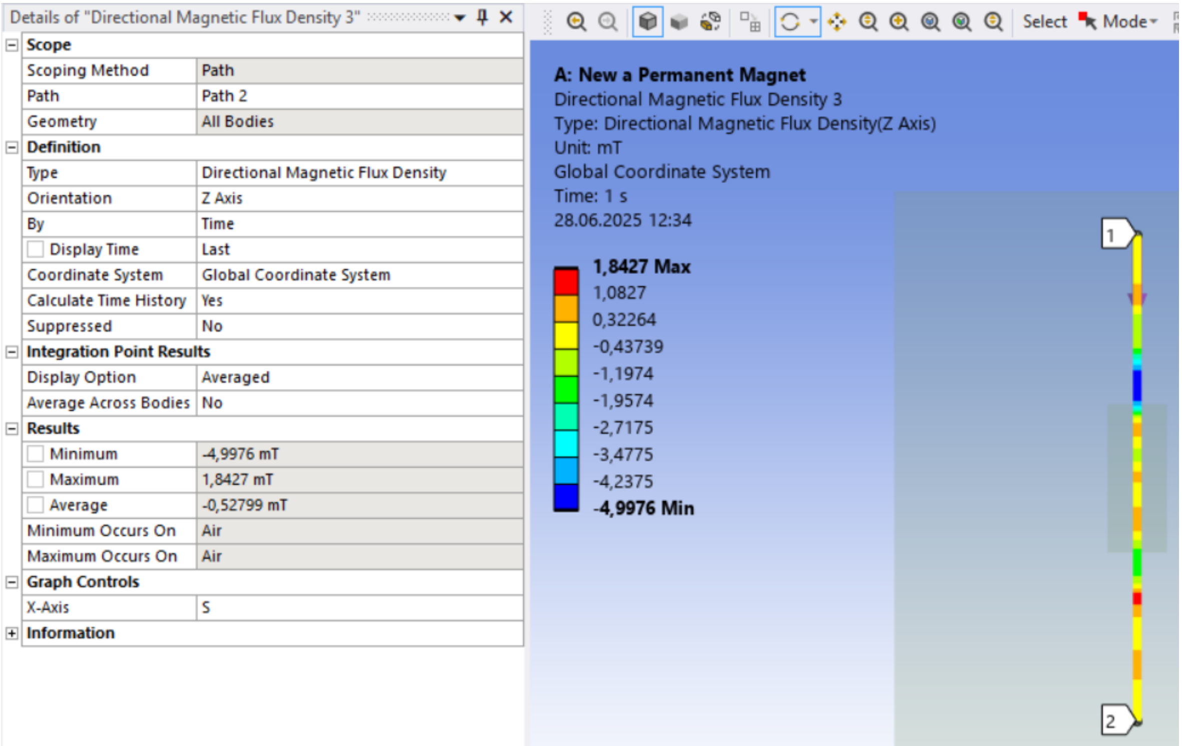


Figure 121 : Analysis of 90 Degree (+Z orientation)(x=12mm)

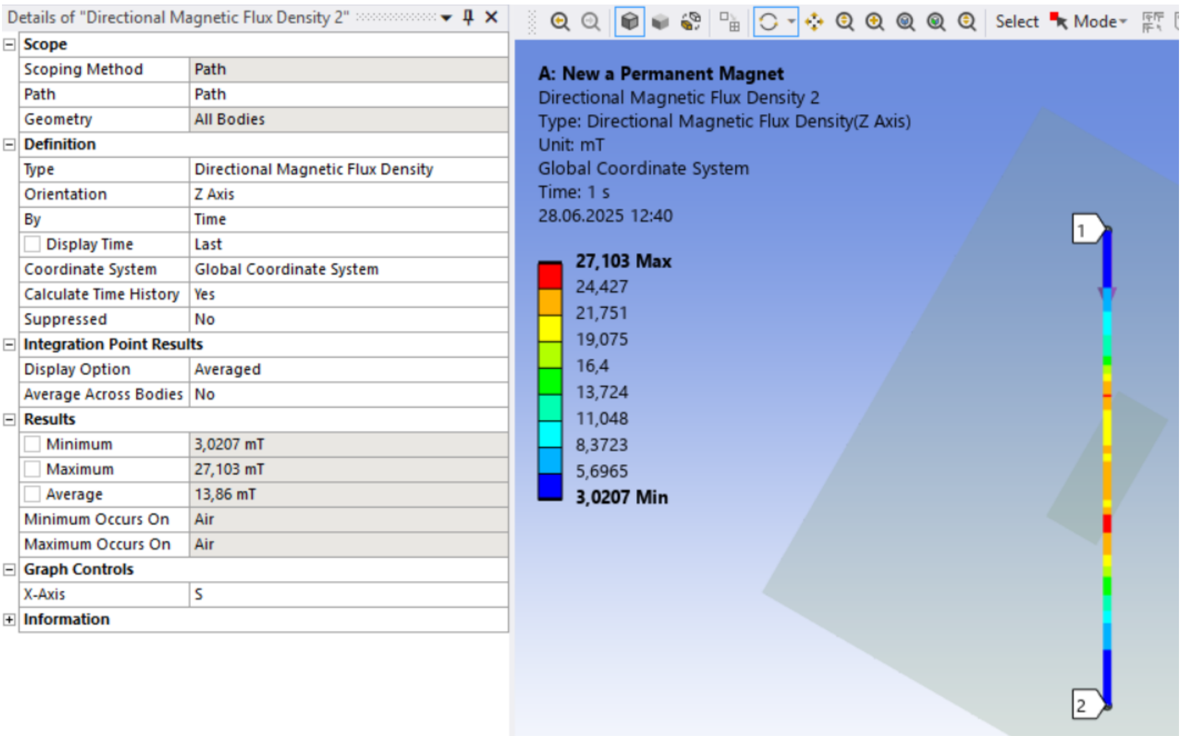


Figure 122 : Analysis of 120 Degree (+Z orientation)(x=8mm)

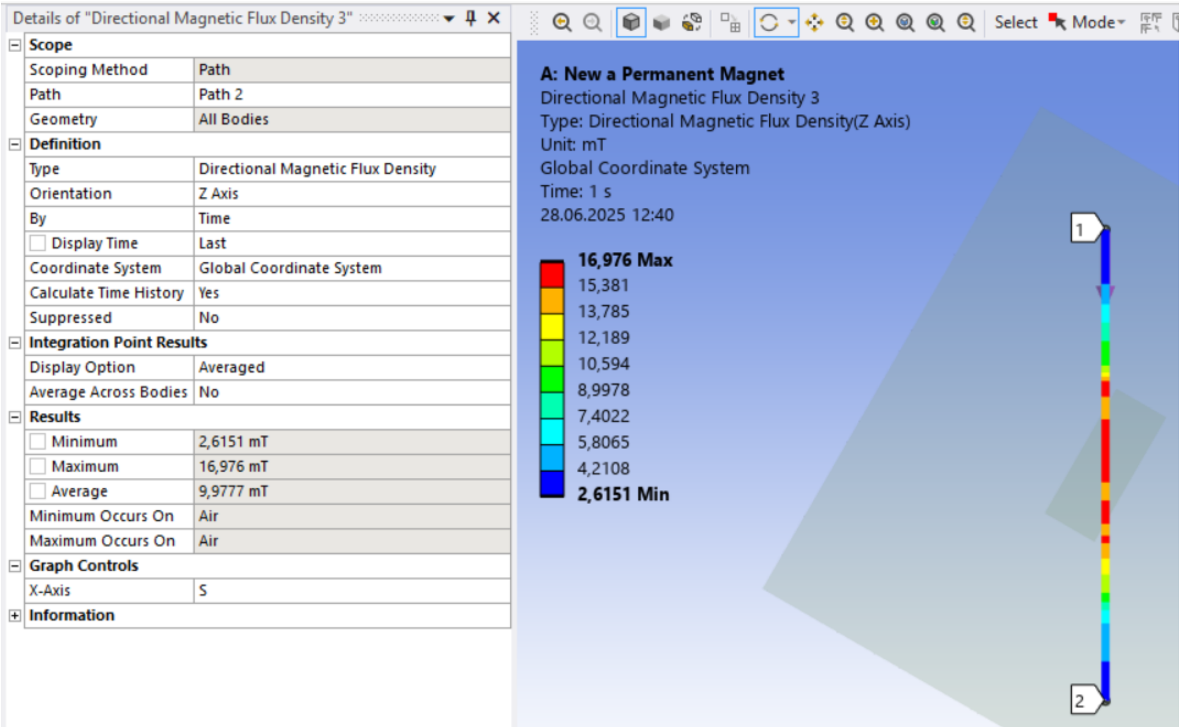


Figure 123 : Analysis of 120 Degree (+Z orientation)(x=12mm)

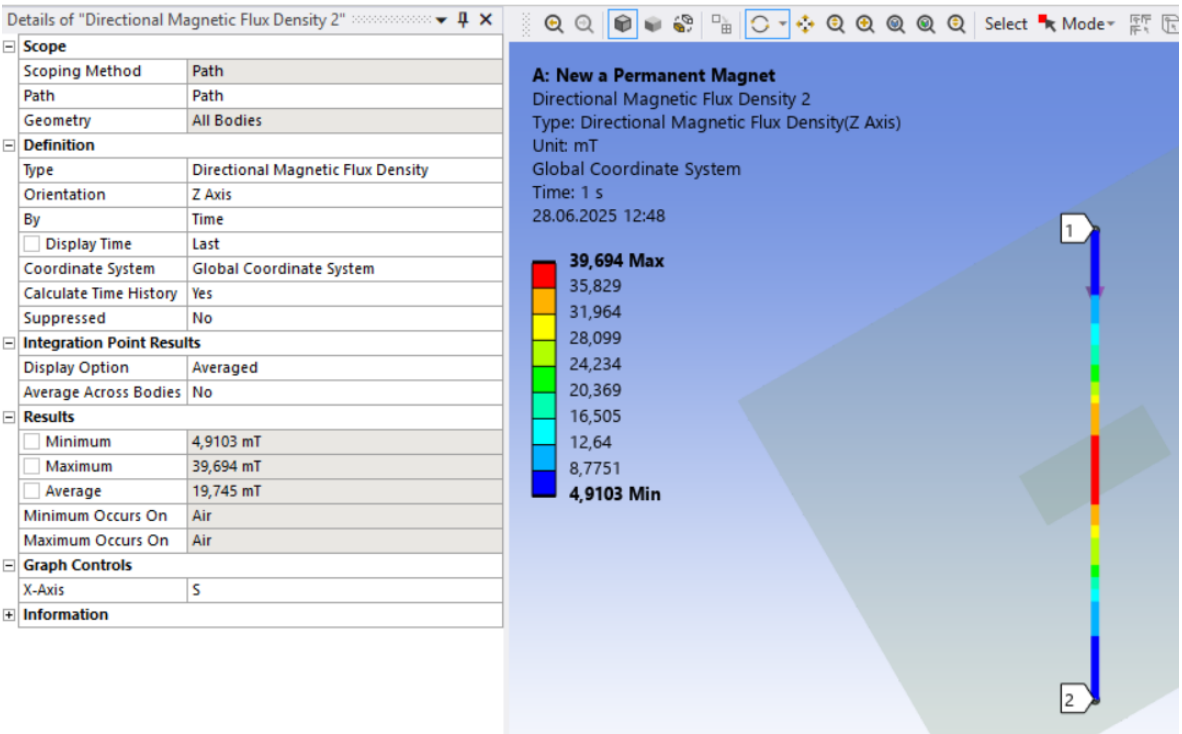


Figure 124 : Analysis of 150 Degree (+Z orientation)(x=8mm)

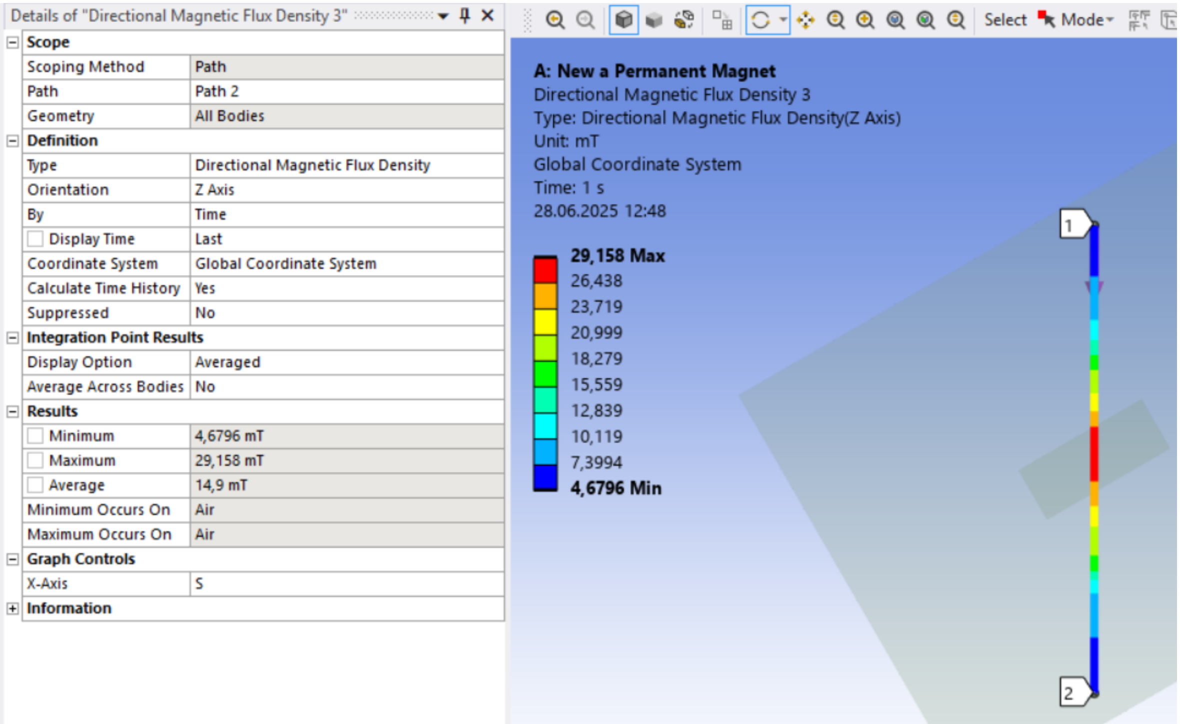


Figure 125 : Analysis of 150 Degree (+Z orientation)(x=12mm)

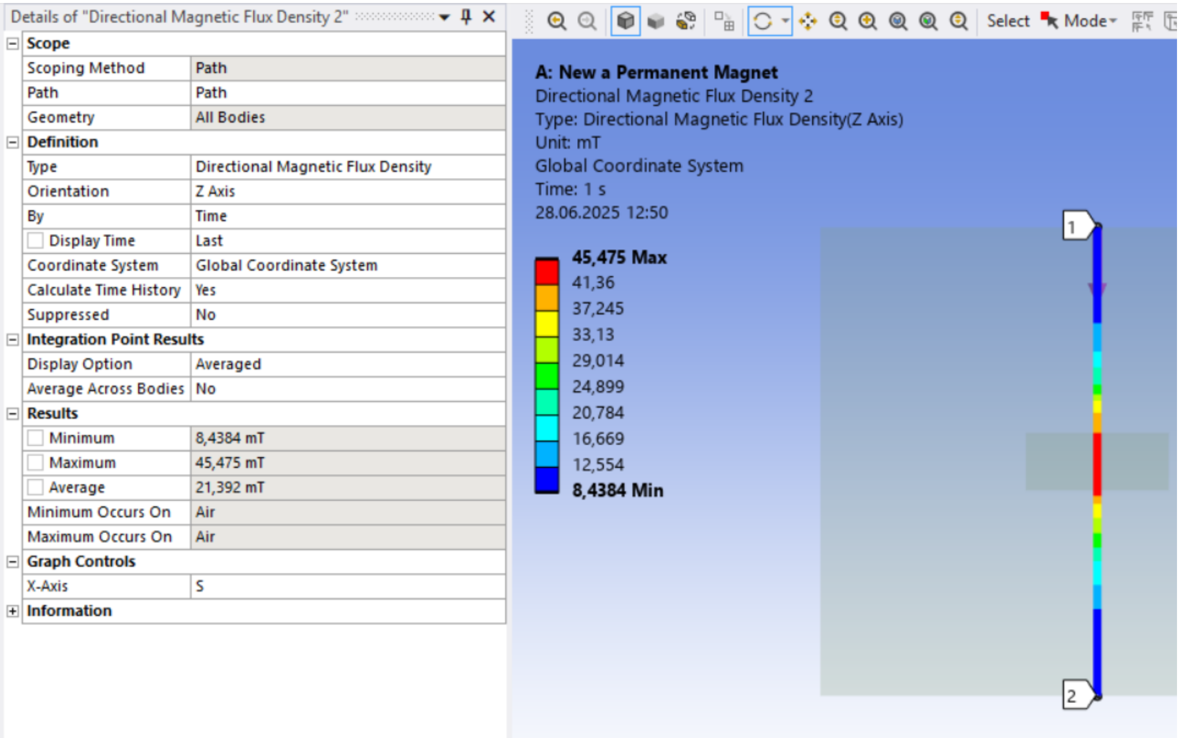


Figure 126 : Analysis of 180 Degree (+Z orientation)(x=8mm)

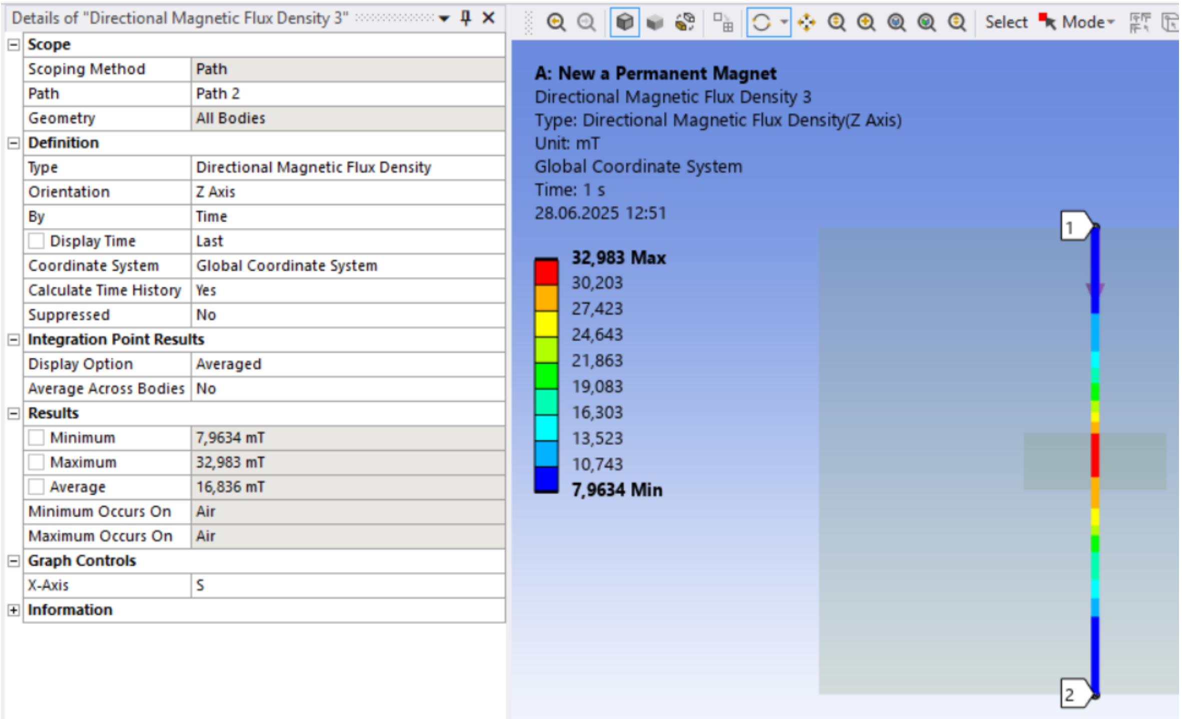


Figure 127 : Analysis of 180 Degree (+Z orientation)(x=12mm)

In this part of our analysis, we increased the distance of our +Z polarized permanent magnet from the magnetostrictive material from 4 mm to 8 and 12 mm and examined what effect this distance had on the data we obtained.

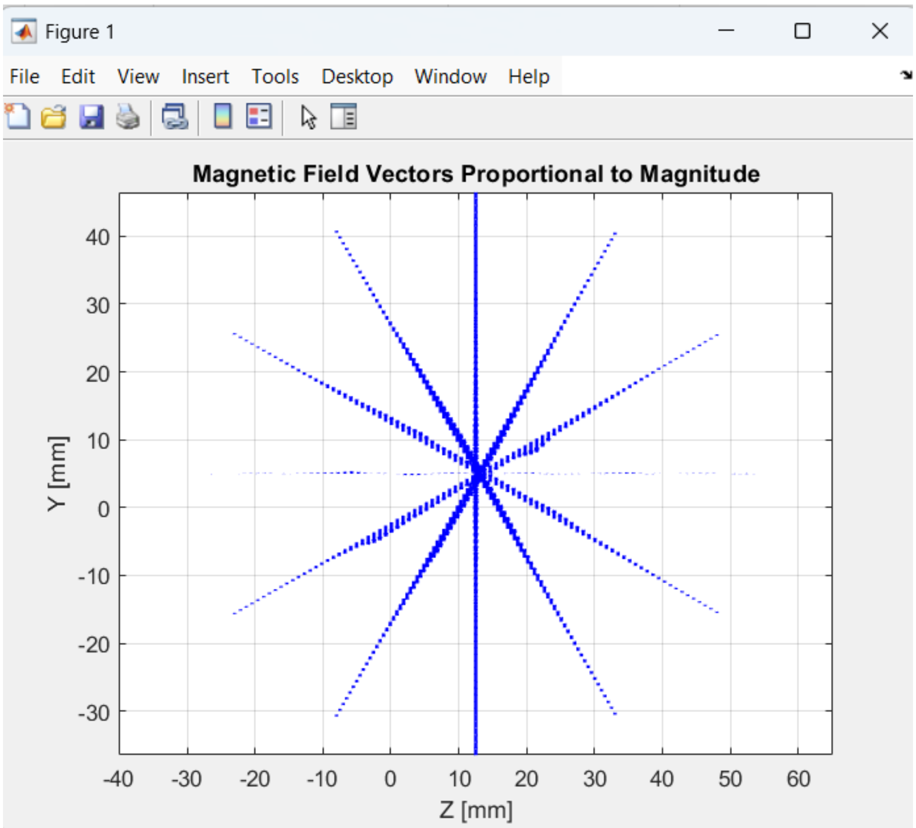


Figure 128 : Magnetic Field Vectors(Z direction) in path for a Permanent Magnet (+Z

polarization)(x=8mm)

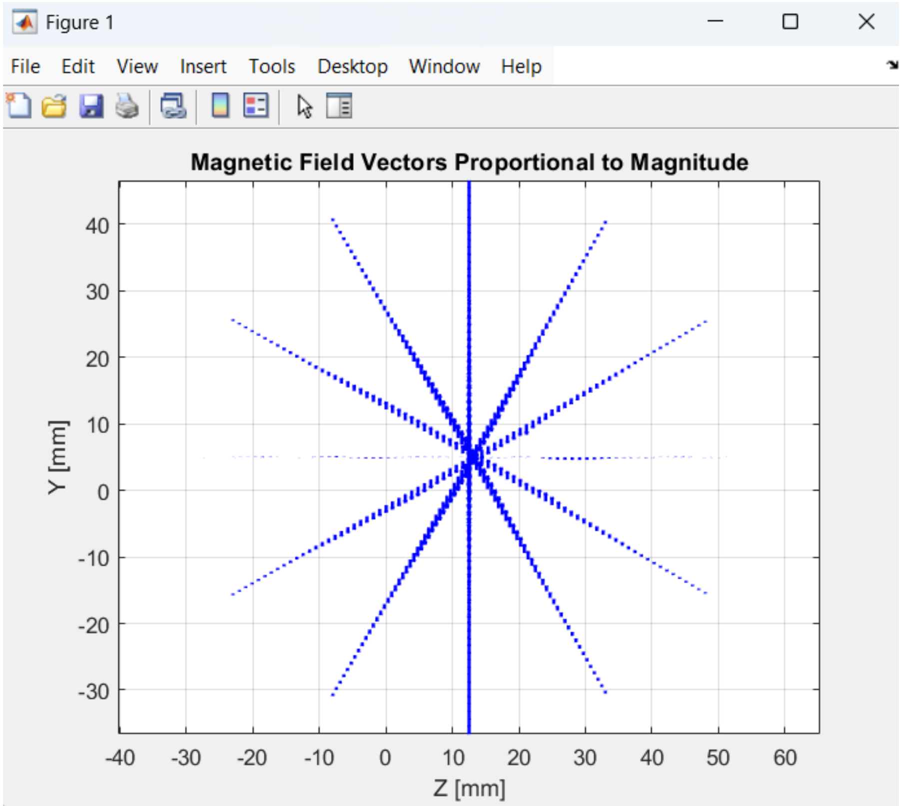


Figure 129 : Magnetic Field Vectors(Z direction) in path for a Permanent Magnet (+Z polarization)(x=12mm)

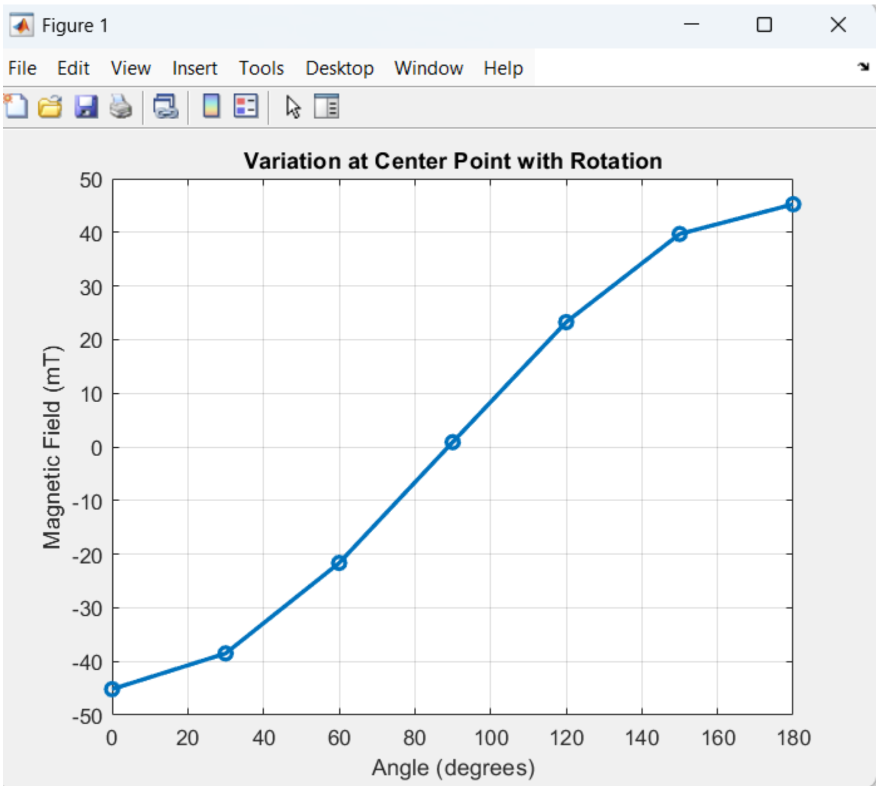


Figure 130 : Magnetic Field of center point (z Direction) of a Permanent Magnet Model (+Z Polarization) (x=8mm)

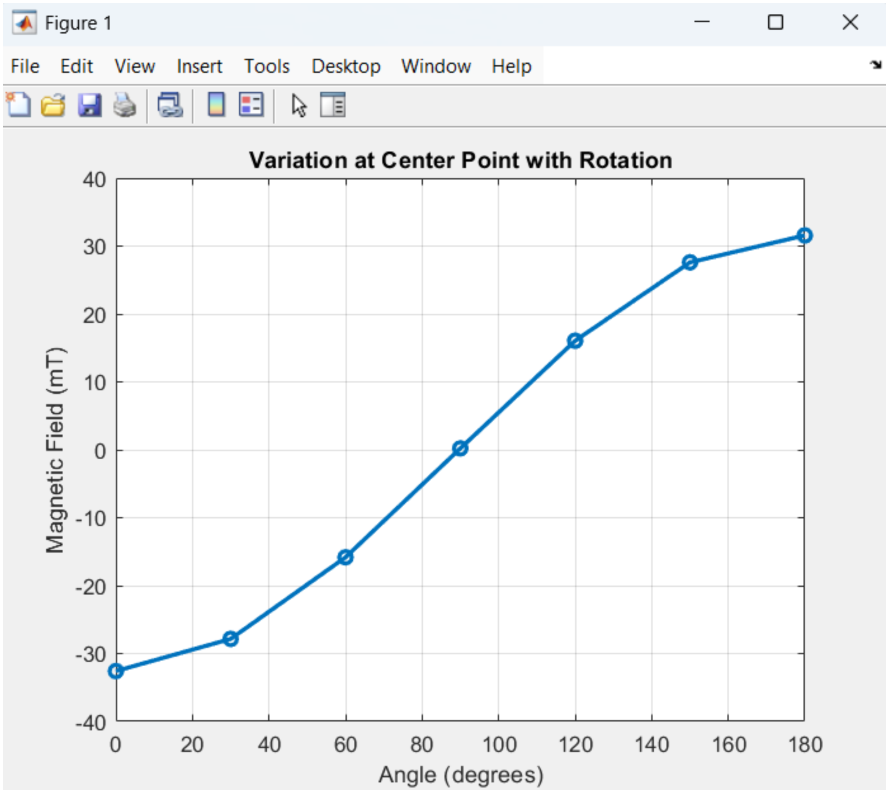


Figure 131 : Magnetic Field of center point (z Direction) of a Permanent Magnet Model (+Z Polarization) (x=12mm)

In these graphs we obtained, we saw that although the magnetic field created by our permanent magnet in +Z polarization decreased as the distance increased, we did not observe much difference in the distribution and change of the magnetic field in general.

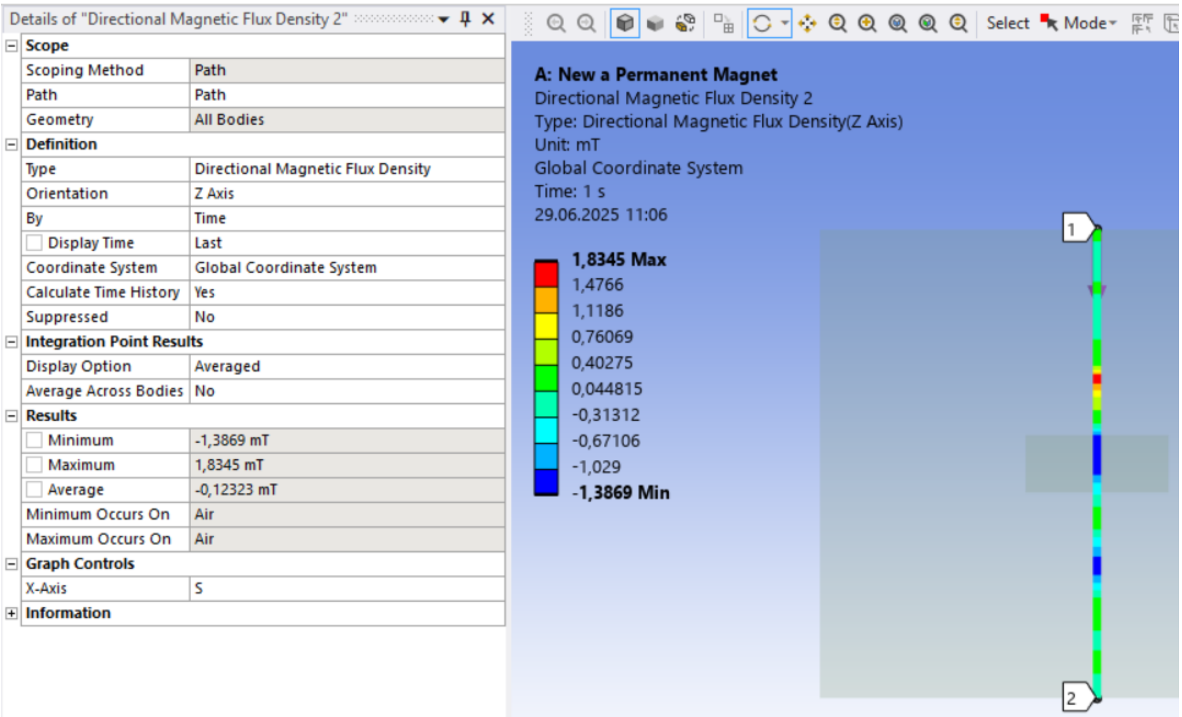


Figure 132 : Analysis of 0 Degree (+Y orientation)(x=8mm)

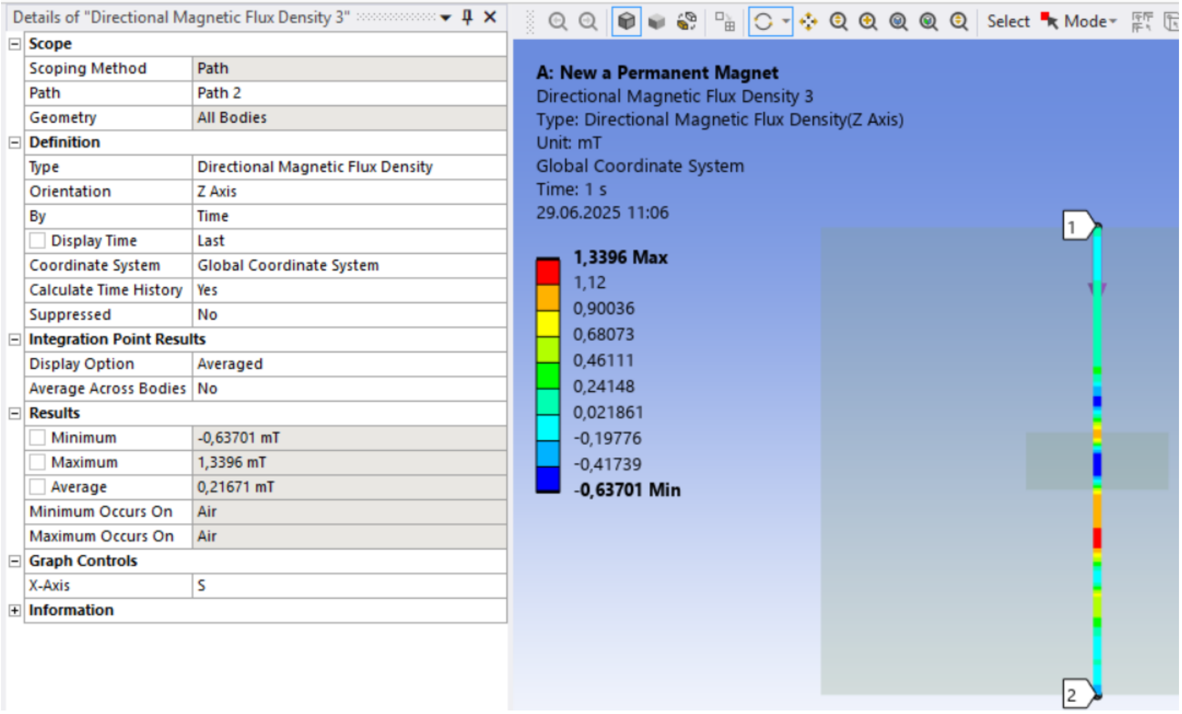


Figure 133 : Analysis of 0 Degree (+Y orientation)(x=12mm)

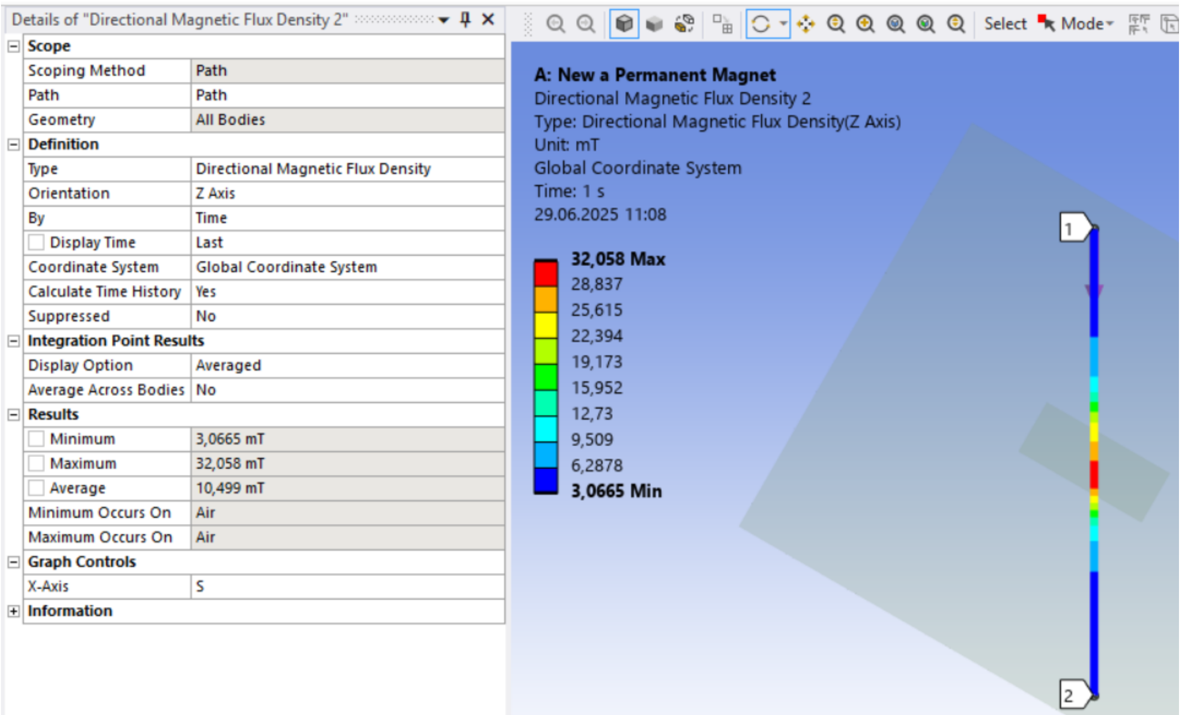


Figure 134 : Analysis of 30 Degree (+Y orientation)(x=8mm)

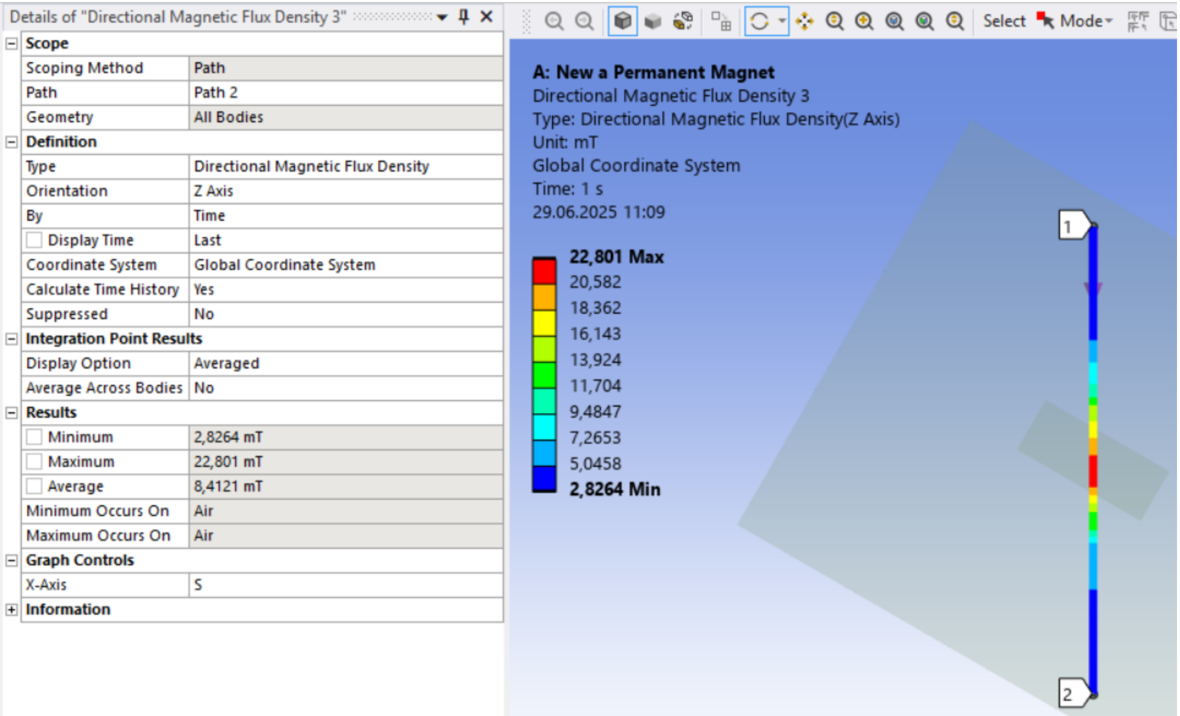


Figure 135 : Analysis of 30 Degree (+Y orientation)(x=12mm)

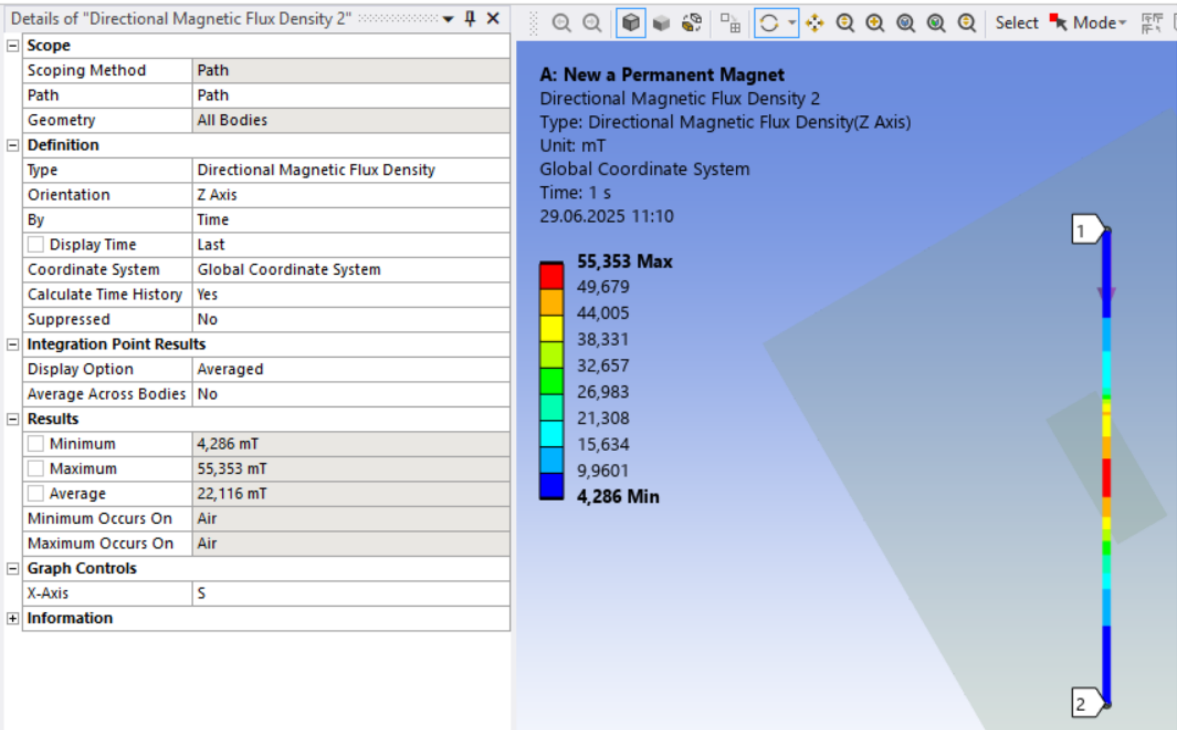


Figure 136 : Analysis of 60 Degree (+Y orientation)(x=8mm)

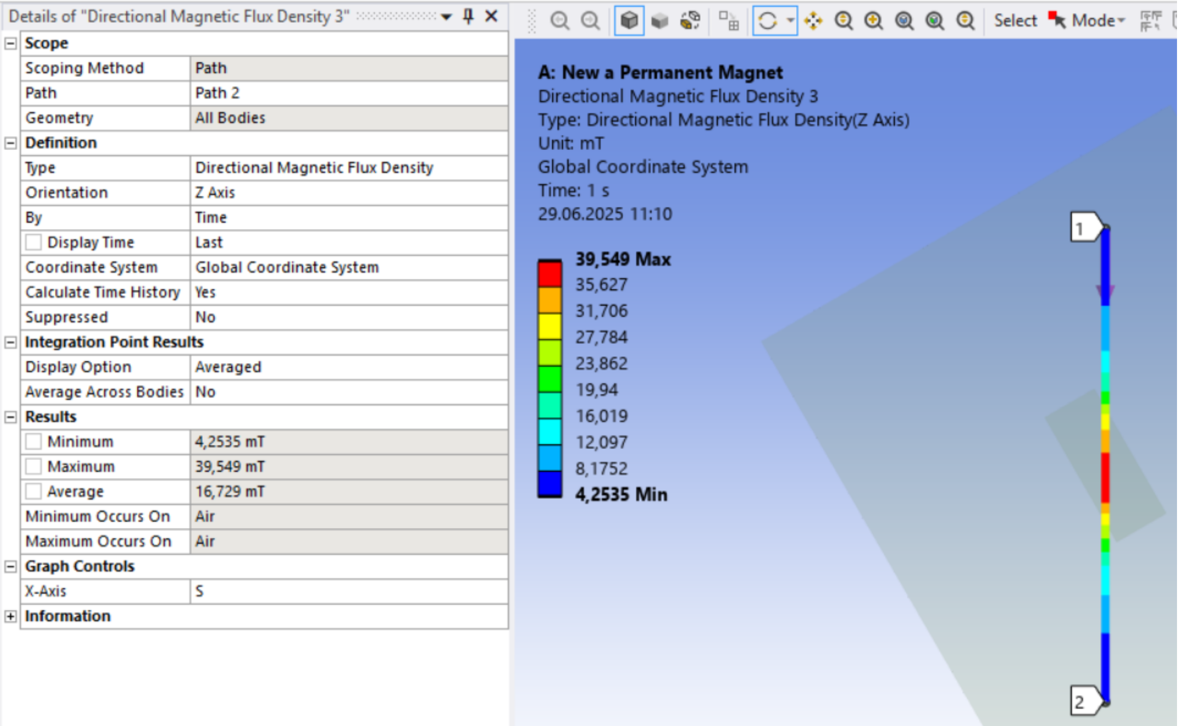


Figure 137 : Analysis of 60 Degree (+Y orientation)(x=12mm)

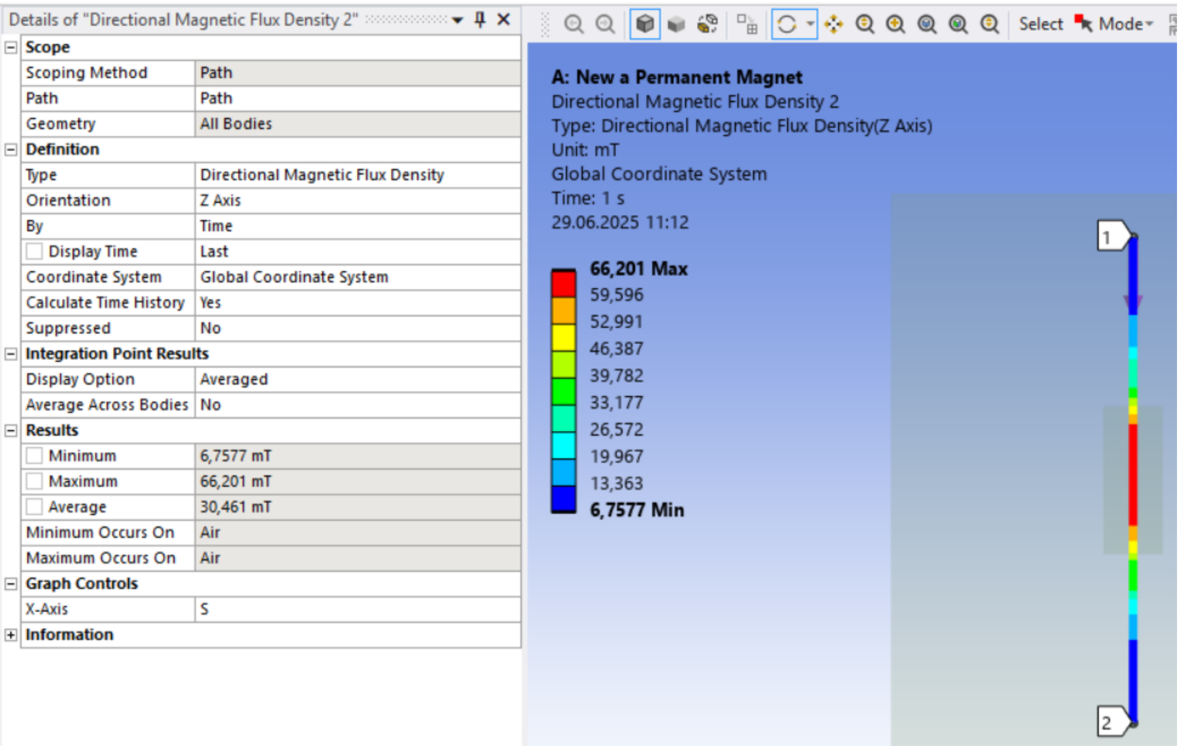


Figure 138 : Analysis of 90 Degree (+Y orientation)(x=8mm)

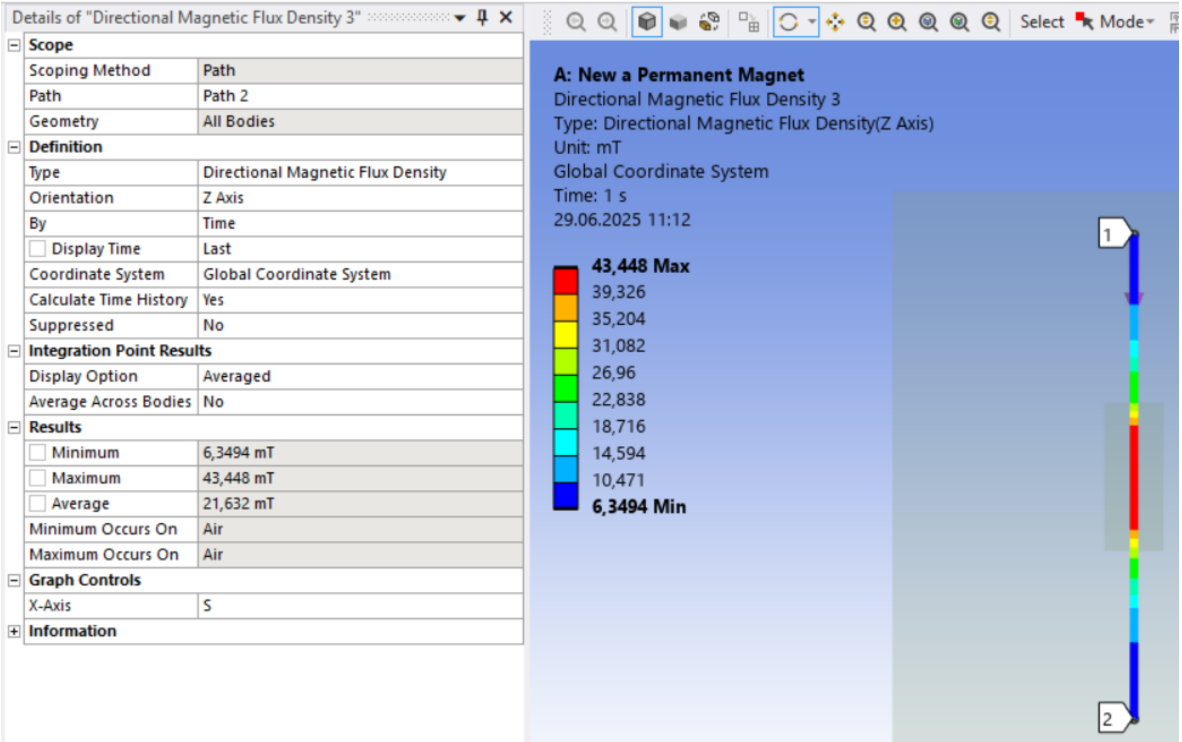


Figure 139 : Analysis of 90 Degree (+Y orientation)(x=12mm)

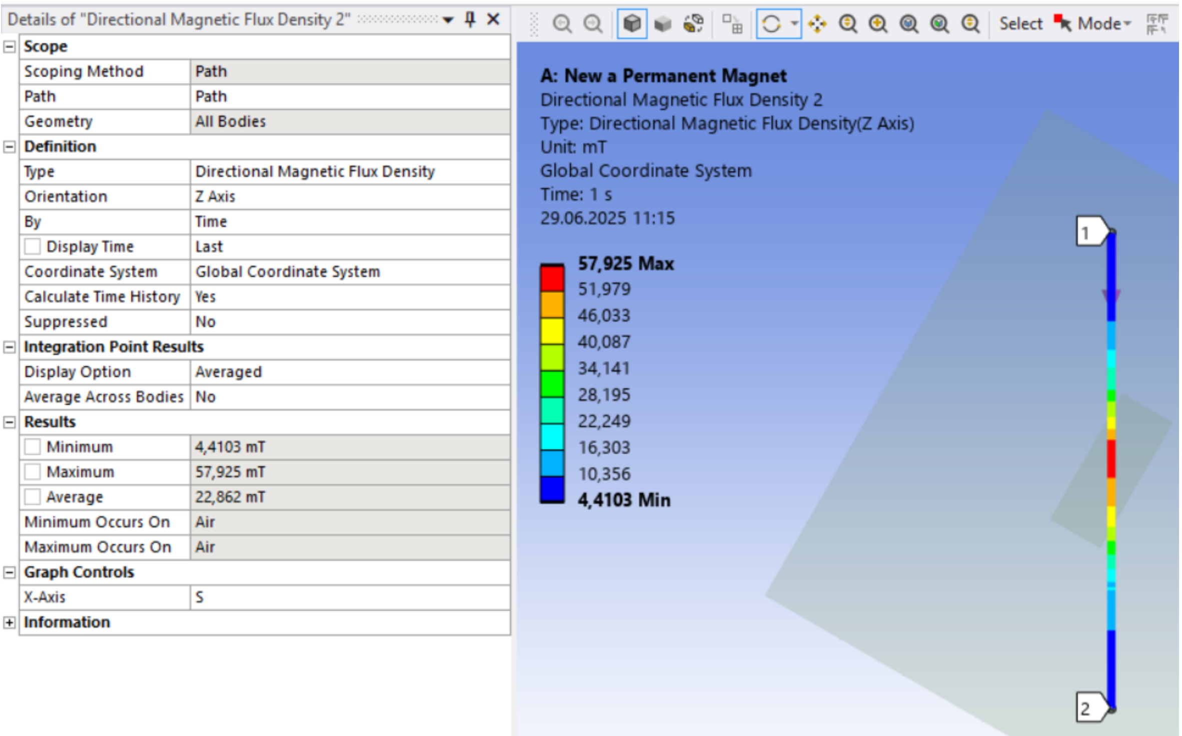


Figure 140 : Analysis of 120 Degree (+Y orientation)(x=8mm)

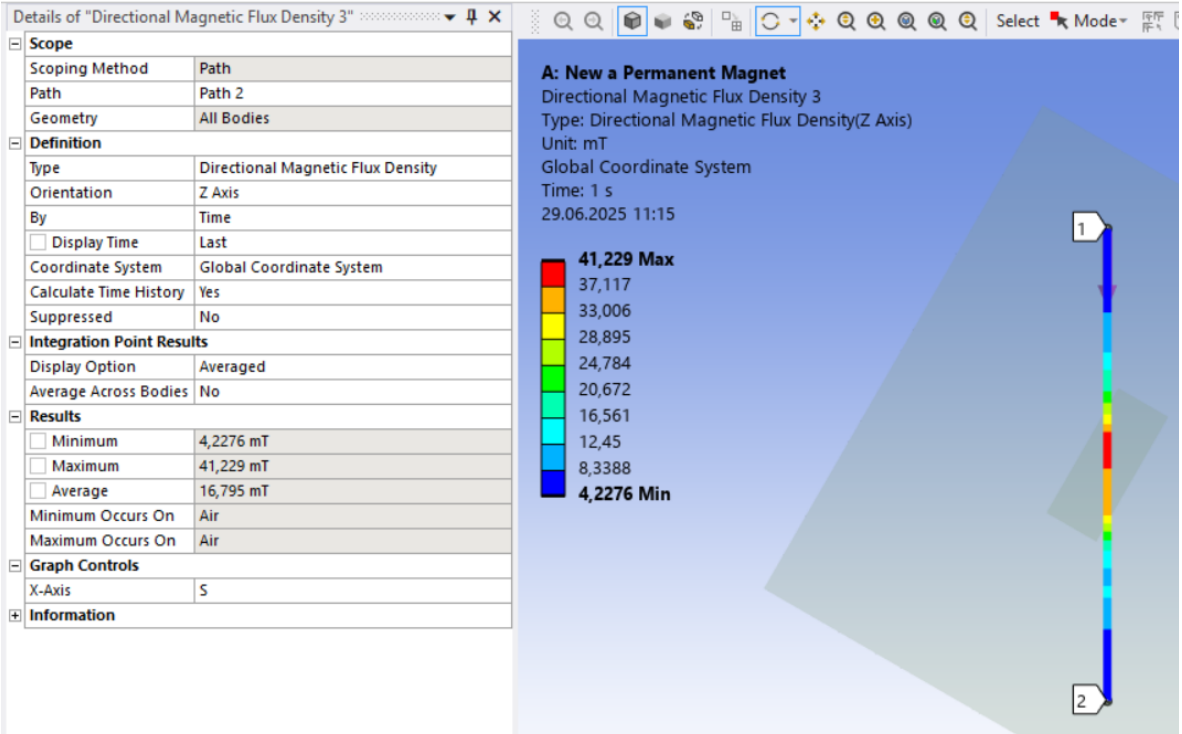


Figure 141 : Analysis of 120 Degree (+Y orientation)(x=12mm)

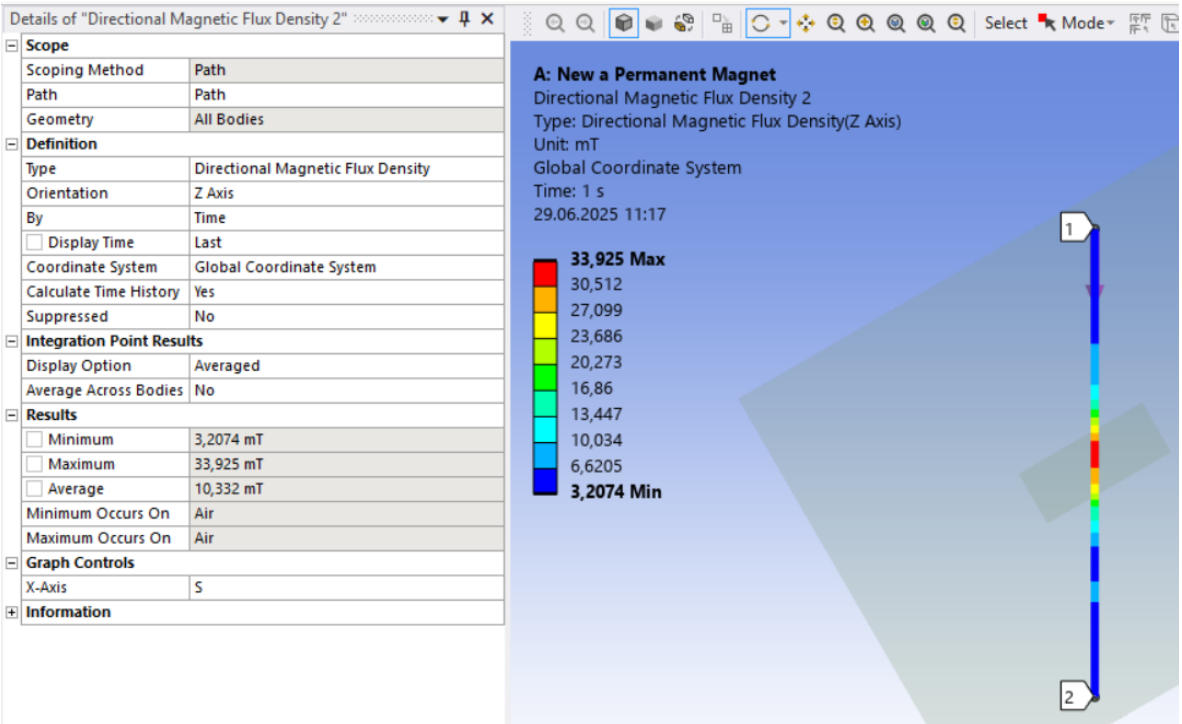


Figure 142 : Analysis of 150 Degree (+Y orientation)(x=8mm)

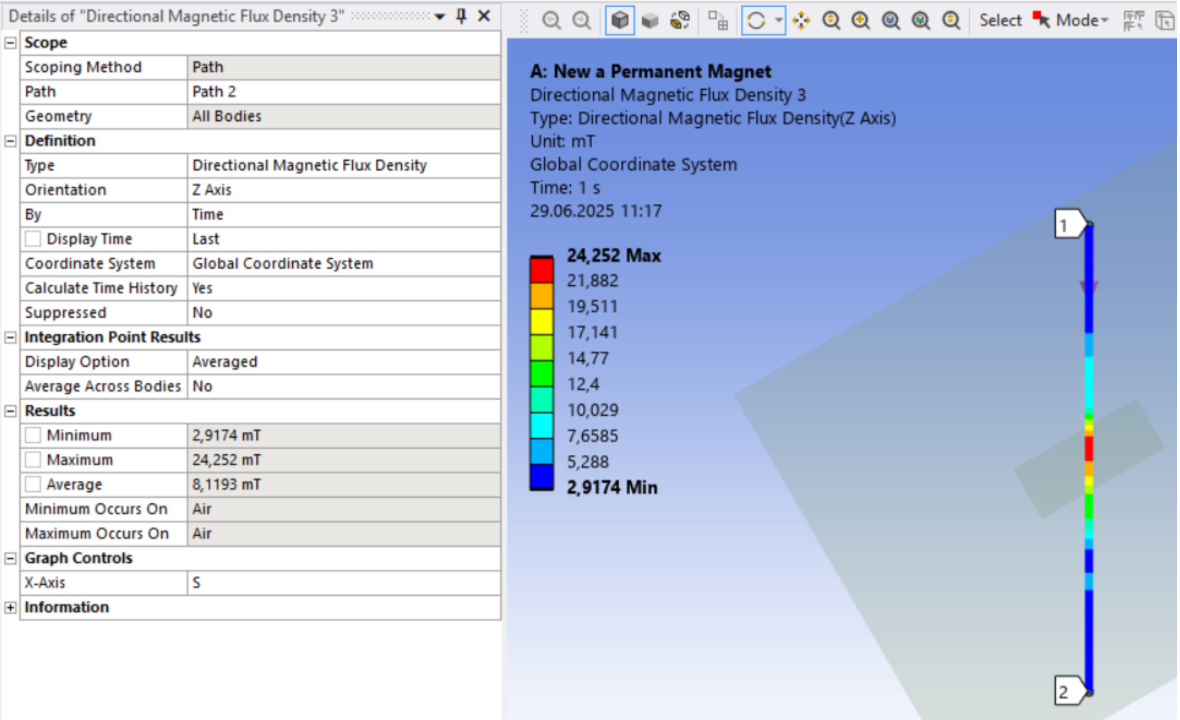


Figure 143 : Analysis of 150 Degree (+Y orientation)(x=12mm)

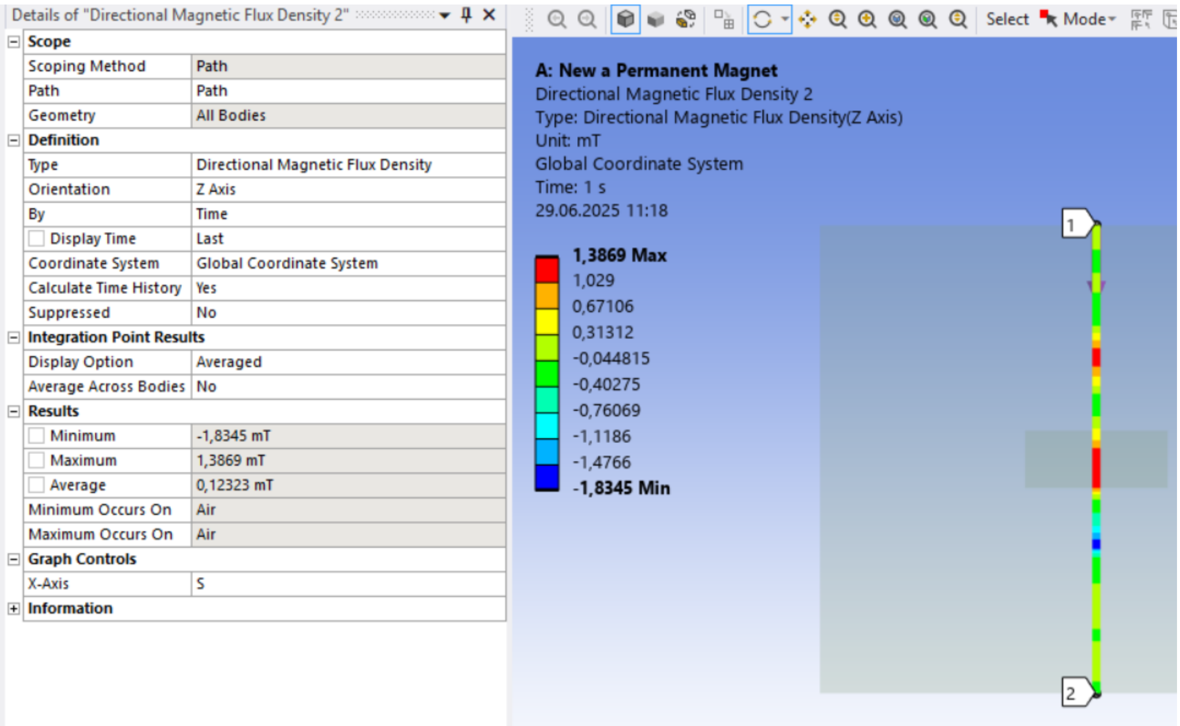


Figure 144 : Analysis of 180 Degree (+Y orientation)(x=8mm)

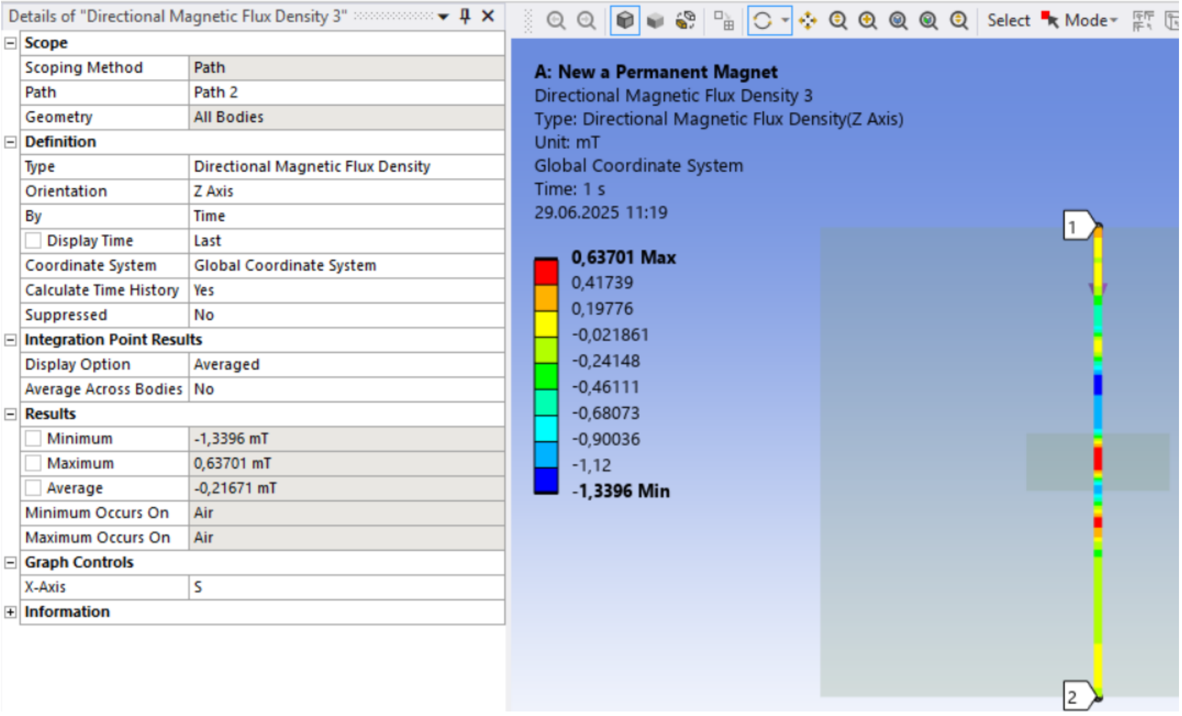


Figure 145 : Analysis of 180 Degree (+Y orientation)(x=12mm)

In this part of our analysis, we increased the distance of our +Y polarized permanent magnet from the magnetostrictive material from 4 mm to 8 and 12 mm and examined what effect this distance had on the data we obtained.

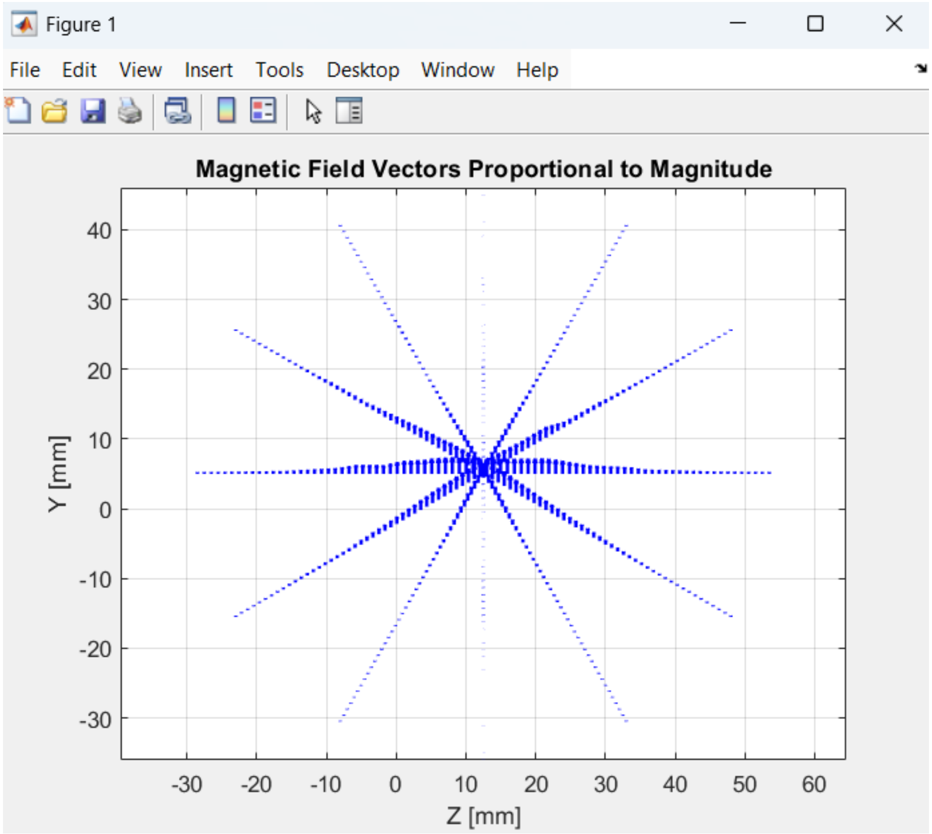


Figure 146 : Magnetic Field Vectors(Z direction) in path for a Permanent Magnet (+Y polarization)(x=8mm)

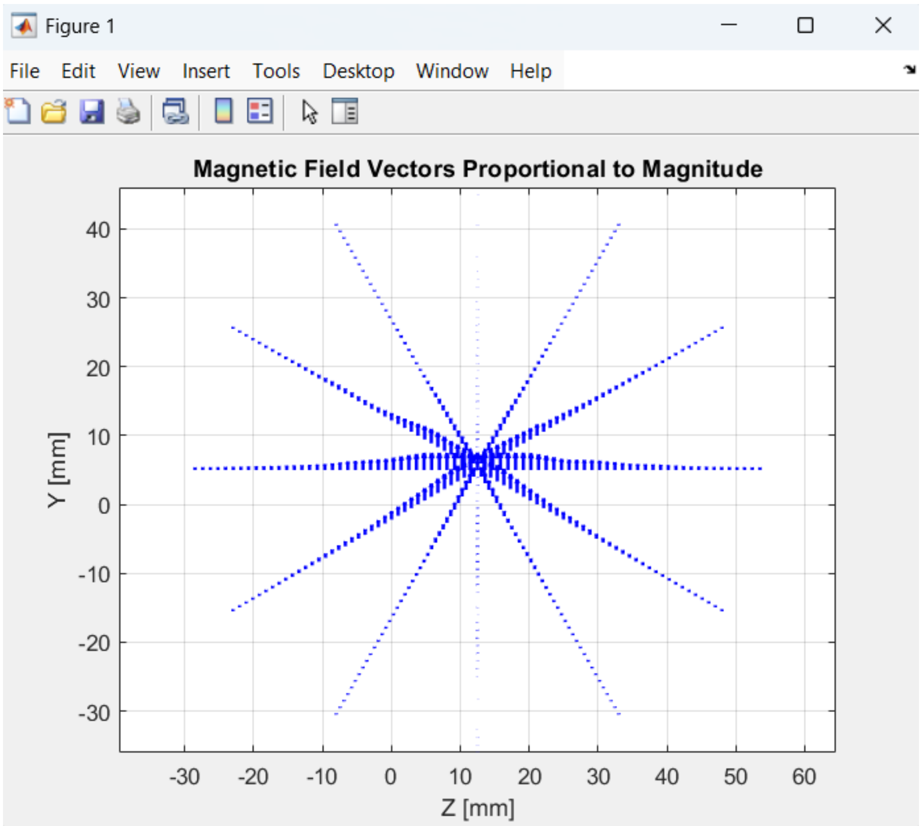


Figure 147 : Magnetic Field Vectors(Z direction) in path for a Permanent Magnet (+Y polarization)(x=12mm)

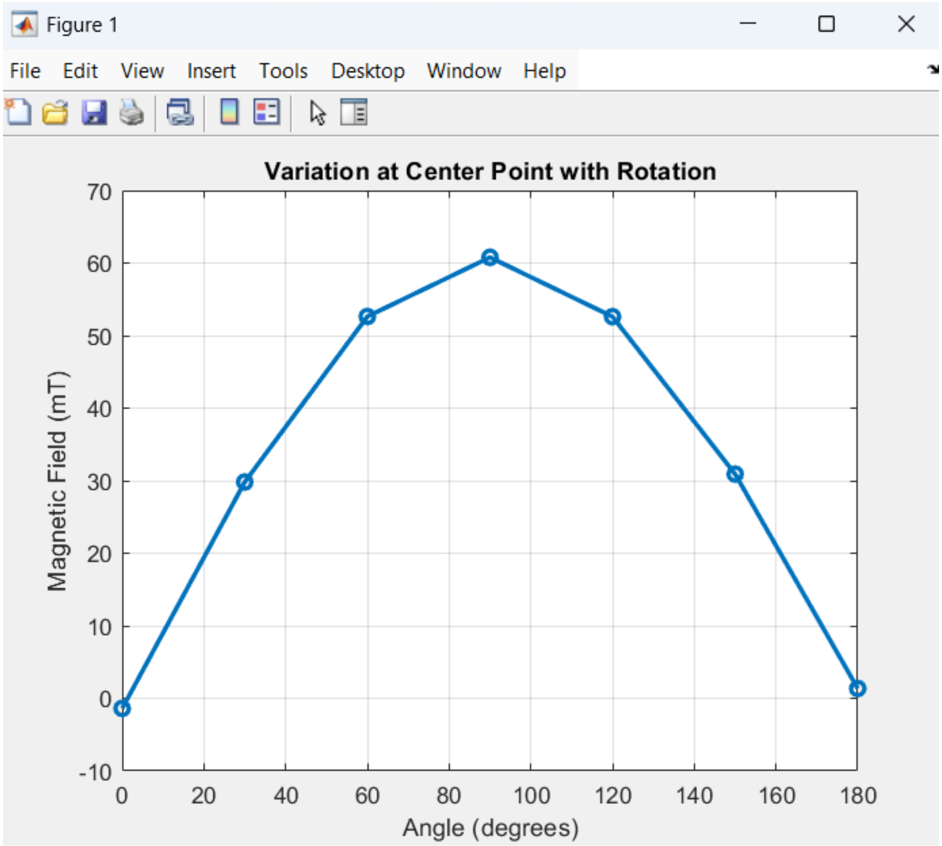


Figure 148 : Magnetic Field of center point (z Direction) of a Permanent Magnet Model (+Y Polarization) (x=8mm)

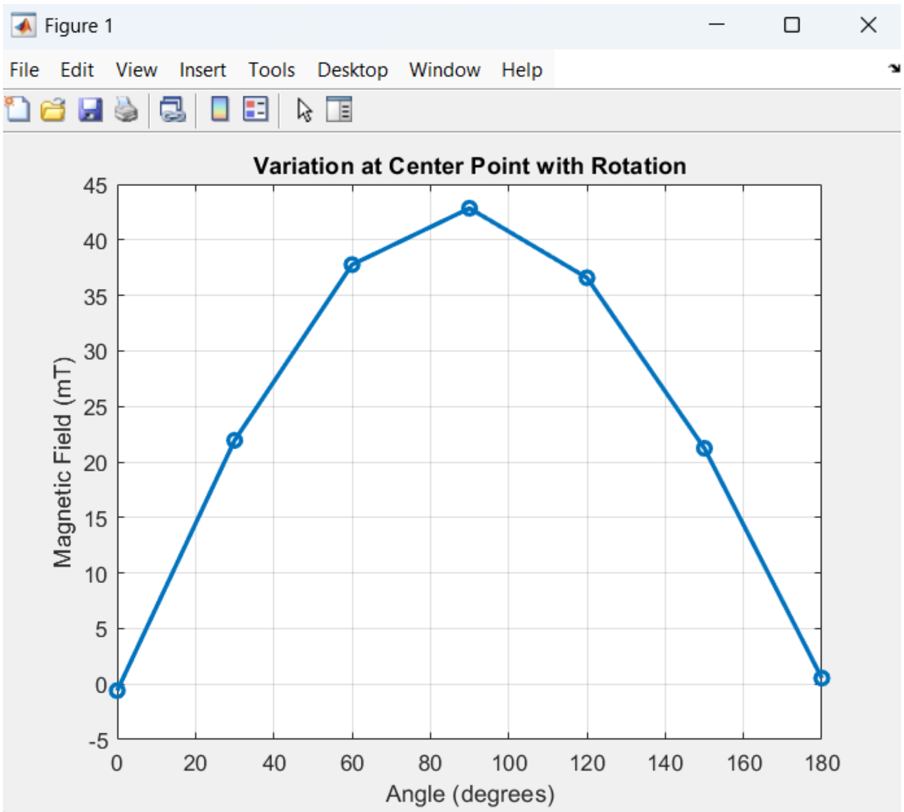


Figure 149 : Magnetic Field of center point (z Direction) of a Permanent Magnet Model (+Y Polarization) (x=12mm)

In these graphs we obtained, we saw that although the magnetic field created by our permanent magnet in +Y polarization decreased as the distance increased, we did not observe much difference in the distribution and change of the magnetic field in general.

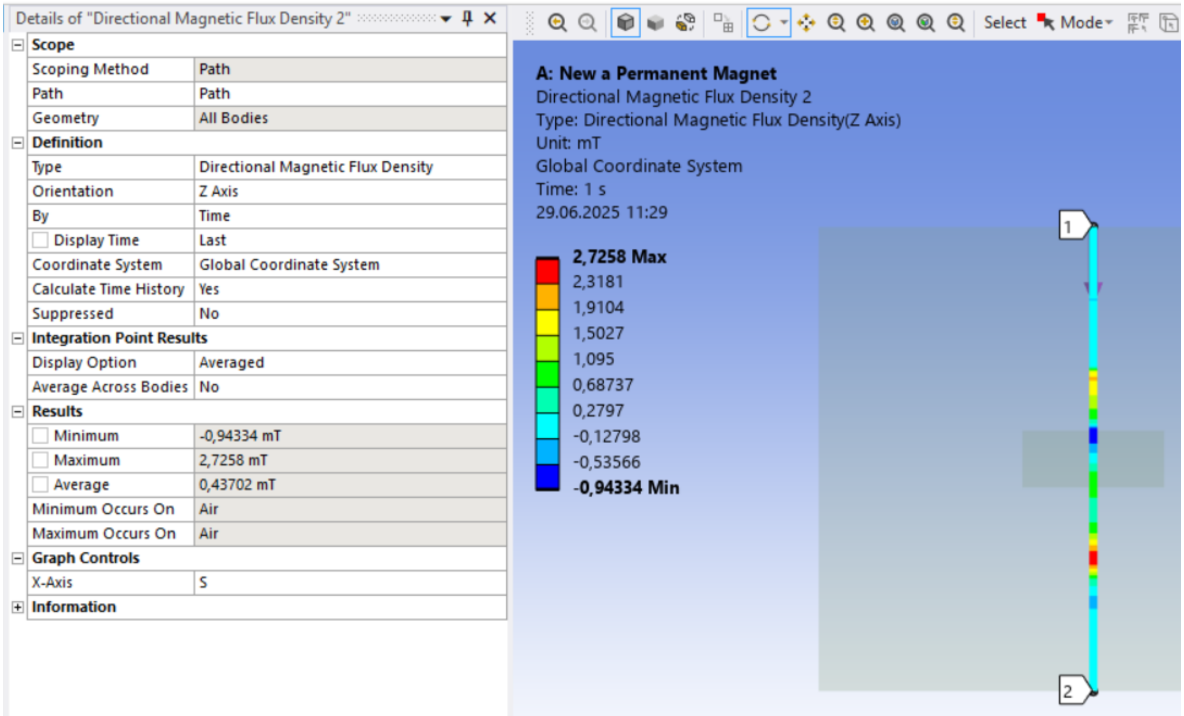


Figure 150 : Analysis of 0 Degree (+X orientation)(x=8mm)

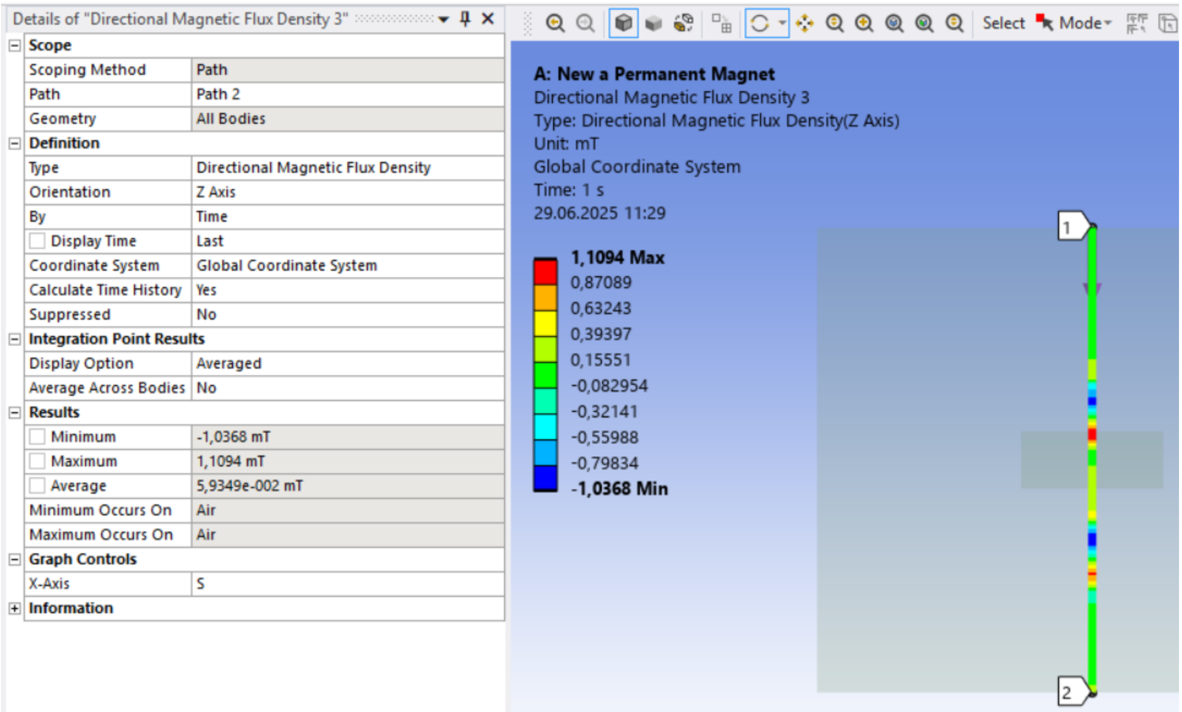


Figure 151 : Analysis of 0 Degree (+X orientation)(x=12mm)

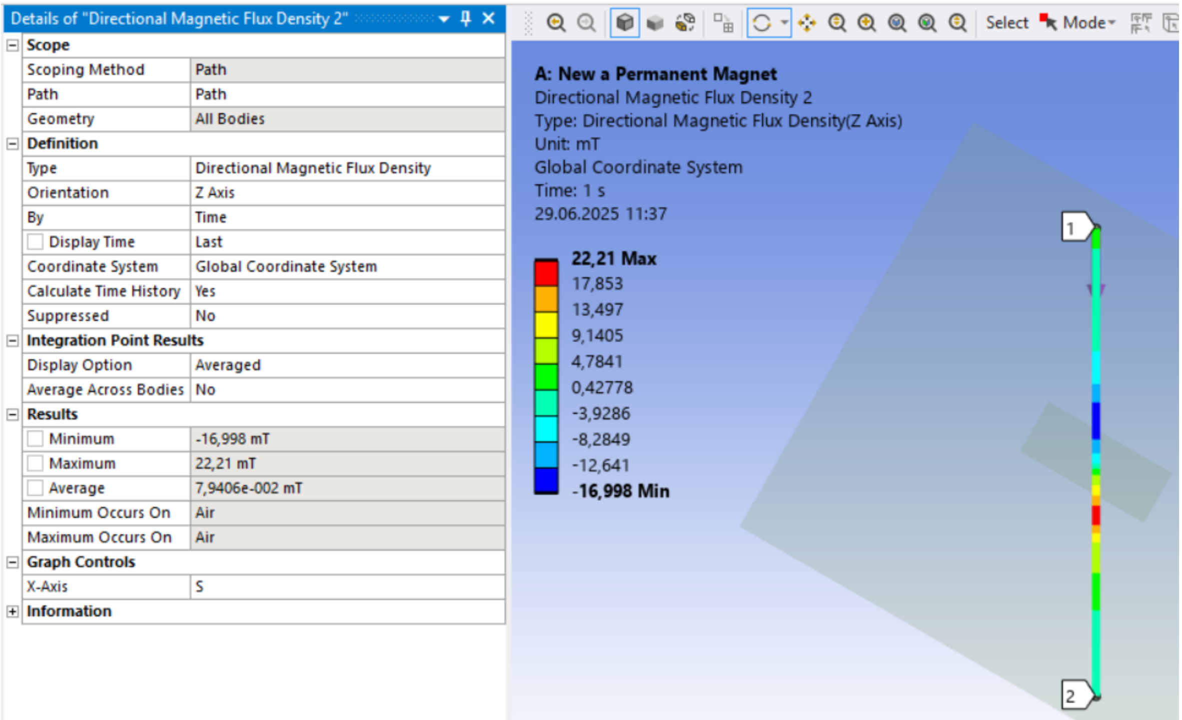


Figure 152 : Analysis of 30 Degree (+X orientation)(x=8mm)

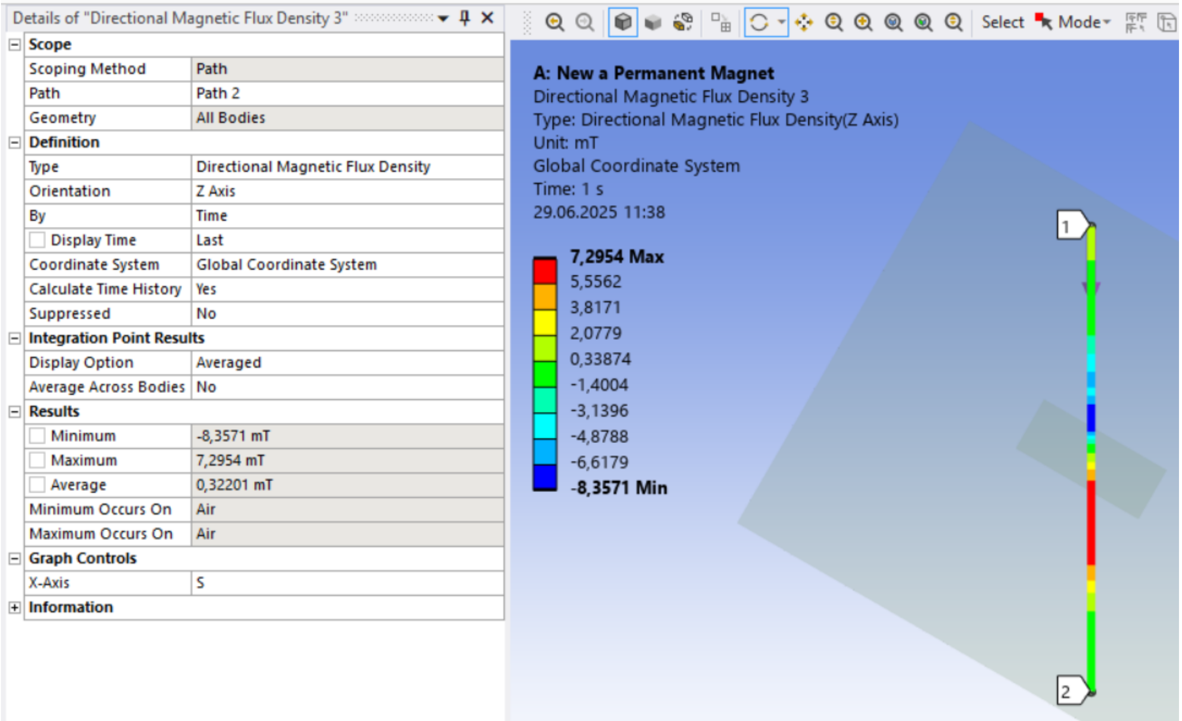


Figure 153 : Analysis of 30 Degree (+X orientation)(x=12mm)

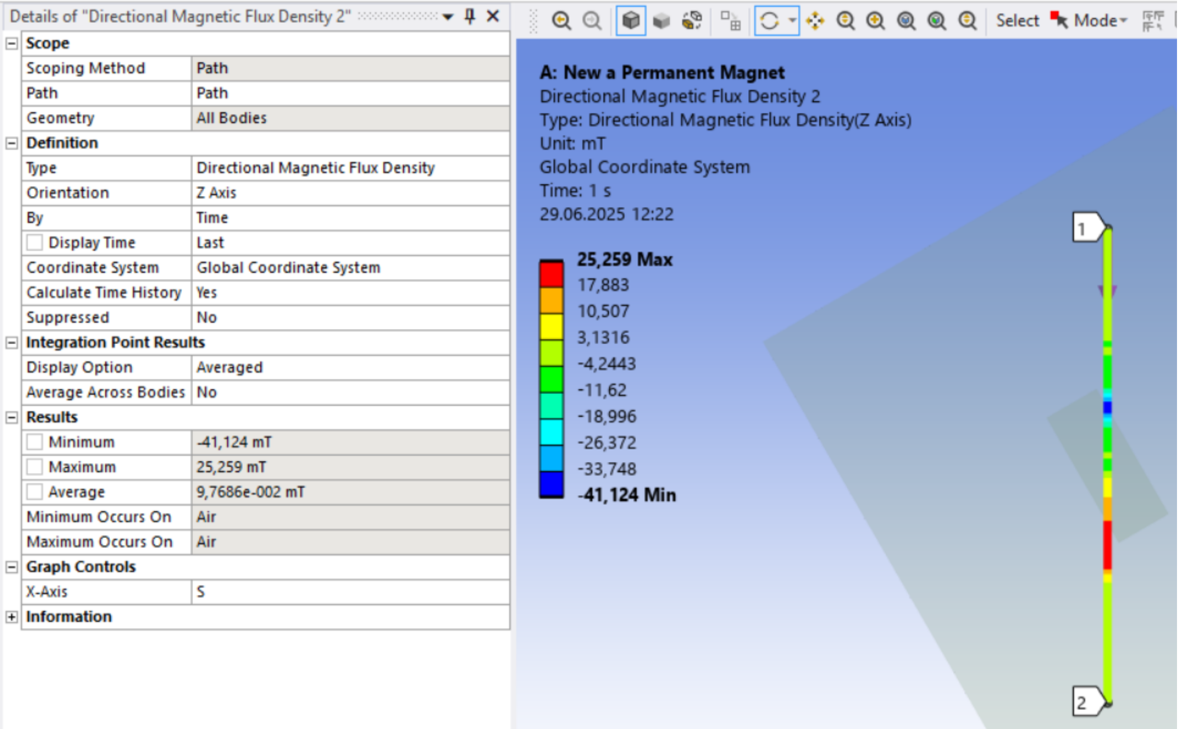


Figure 154 : Analysis of 60 Degree (+X orientation)(x=8mm)

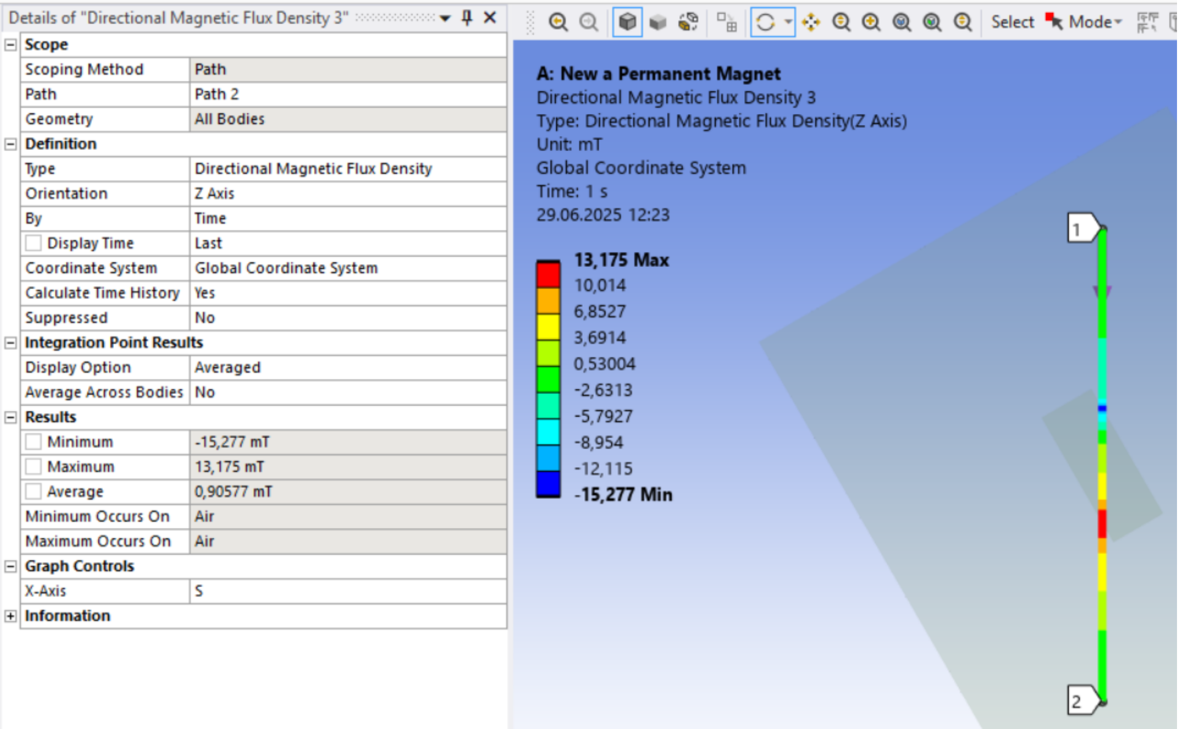


Figure 155 : Analysis of 60 Degree (+X orientation)(x=12mm)

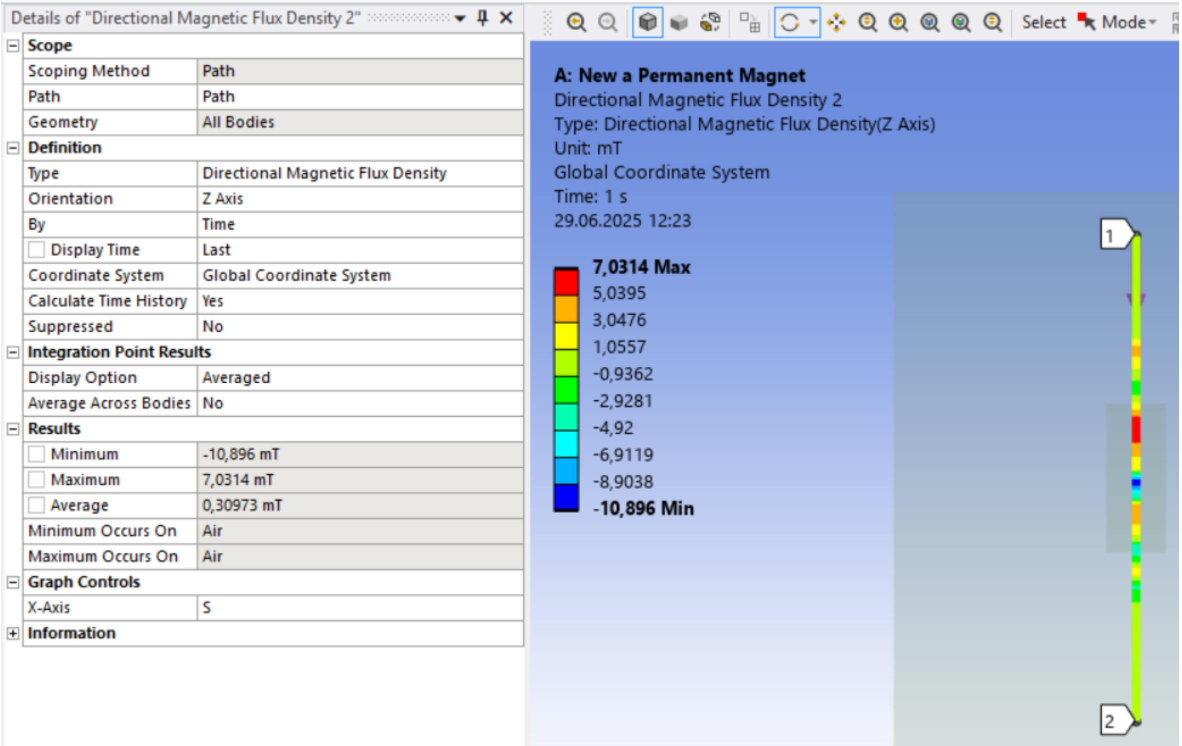


Figure 156 : Analysis of 90 Degree (+X orientation)(x=8mm)

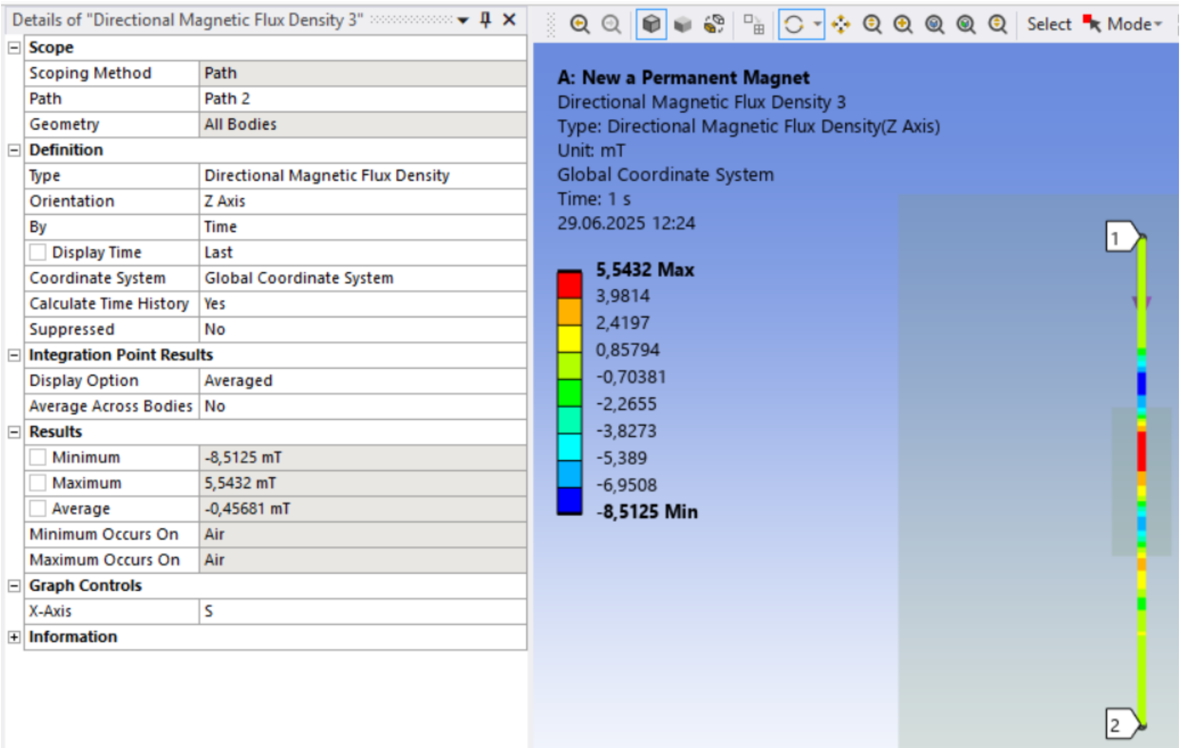


Figure 157 : Analysis of 90 Degree (+X orientation)(x=12mm)

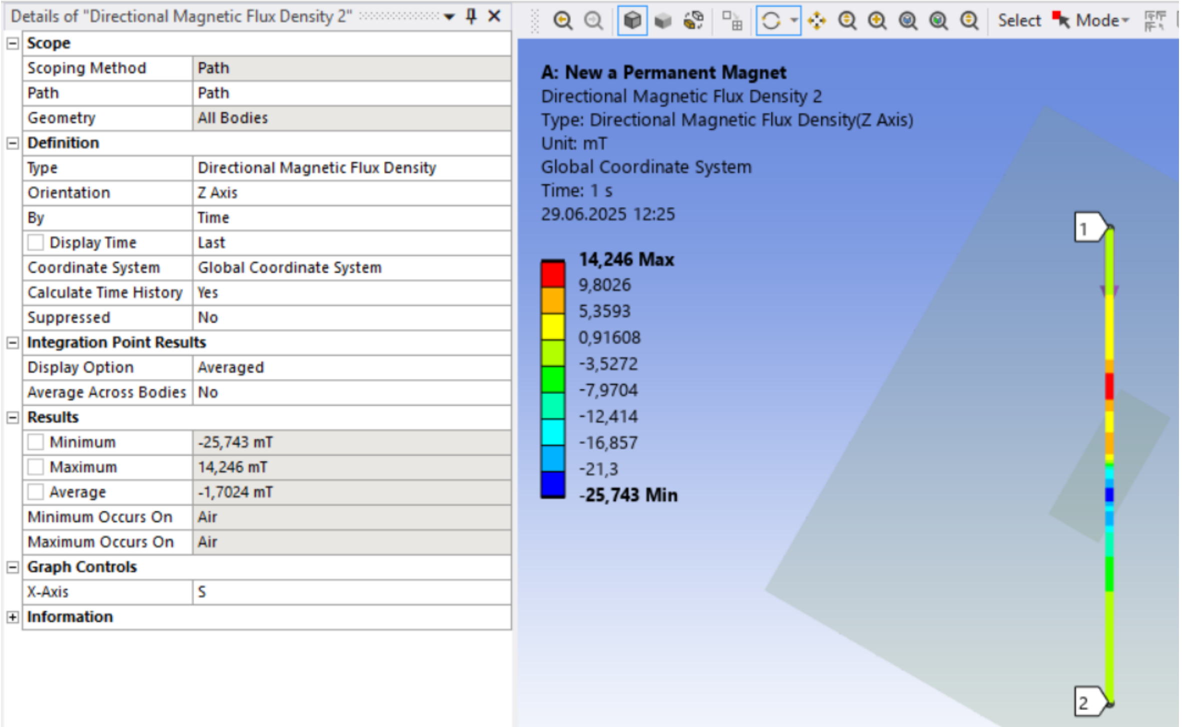


Figure 158 : Analysis of 120 Degree (+X orientation)(x=8mm)

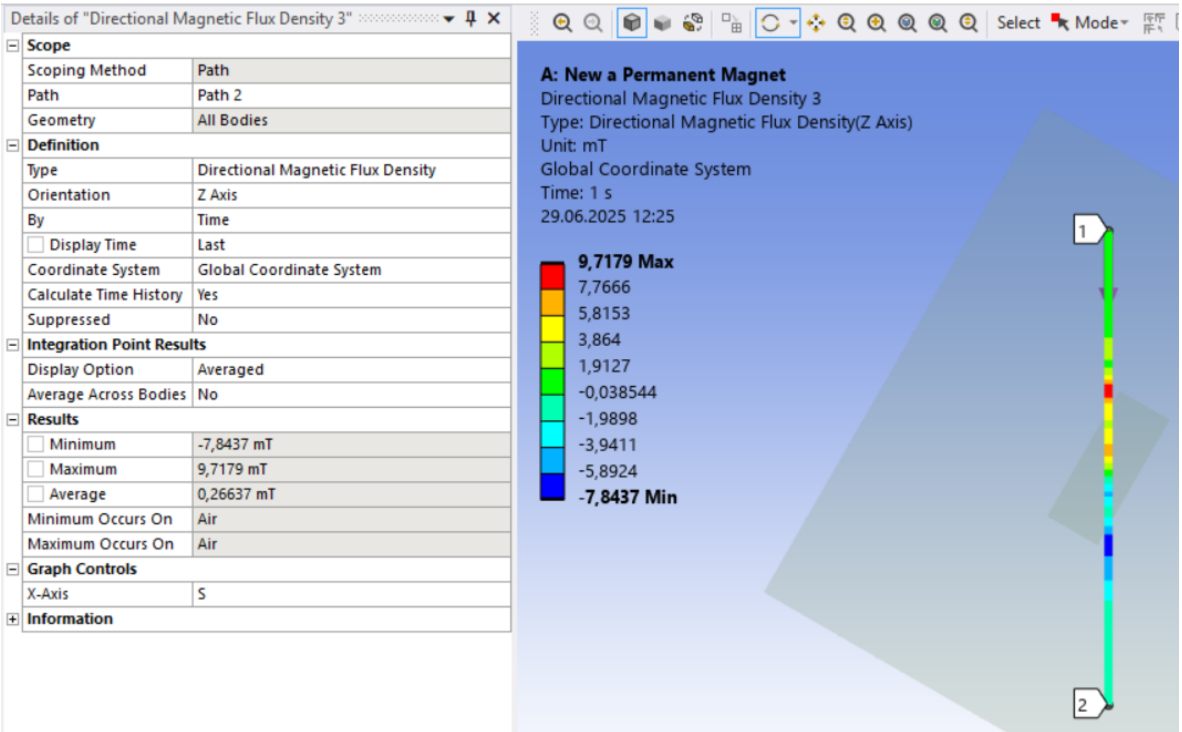


Figure 159 : Analysis of 120 Degree (+X orientation)(x=12mm)

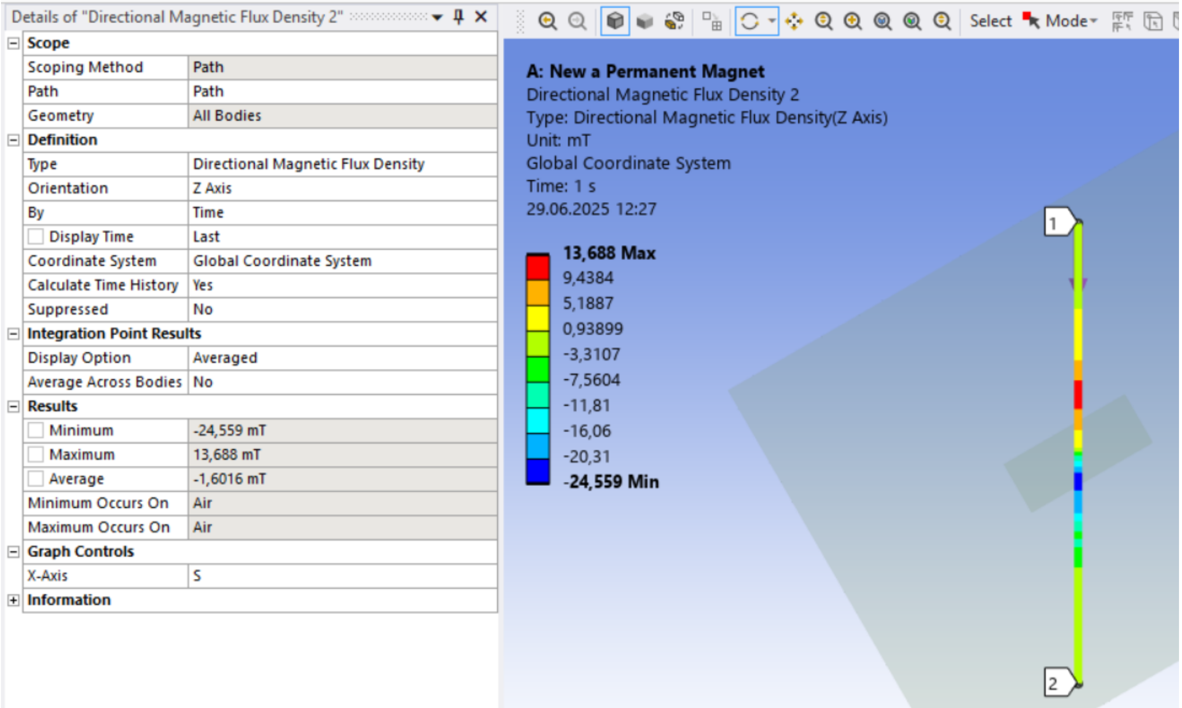


Figure 160 : Analysis of 150 Degree (+X orientation)(x=8mm)

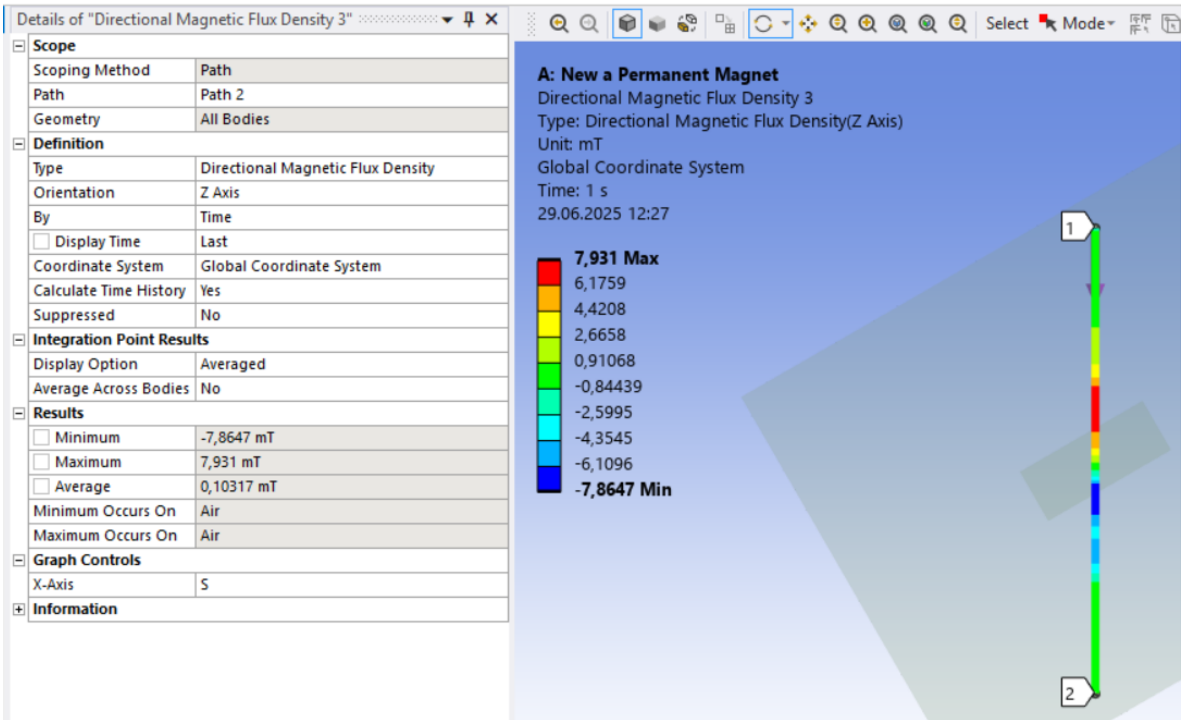


Figure 161 : Analysis of 150 Degree (+X orientation)(x=12mm)

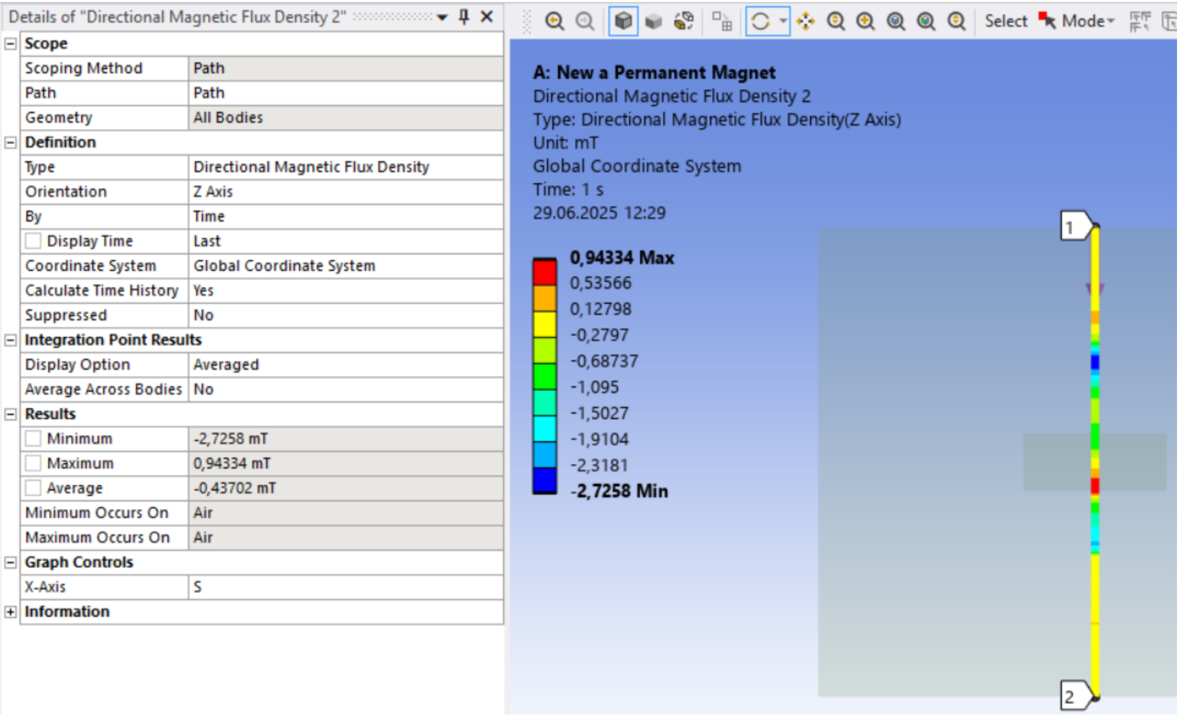


Figure 162 : Analysis of 180 Degree (+X orientation)(x=8mm)

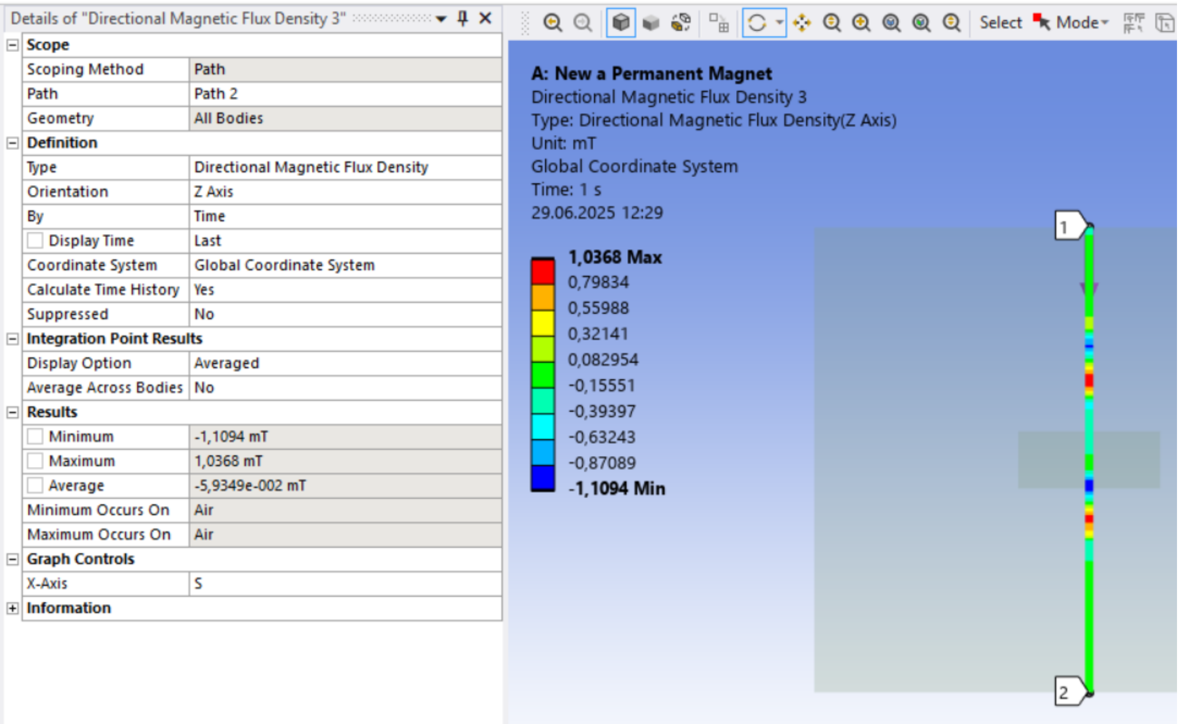


Figure 163 : Analysis of 180 Degree (+X orientation)(x=12mm)

In this part of our analysis, we increased the distance of our +X polarized permanent magnet from the magnetostrictive material from 4 mm to 8 and 12 mm and examined what effect this distance had on the data we obtained.

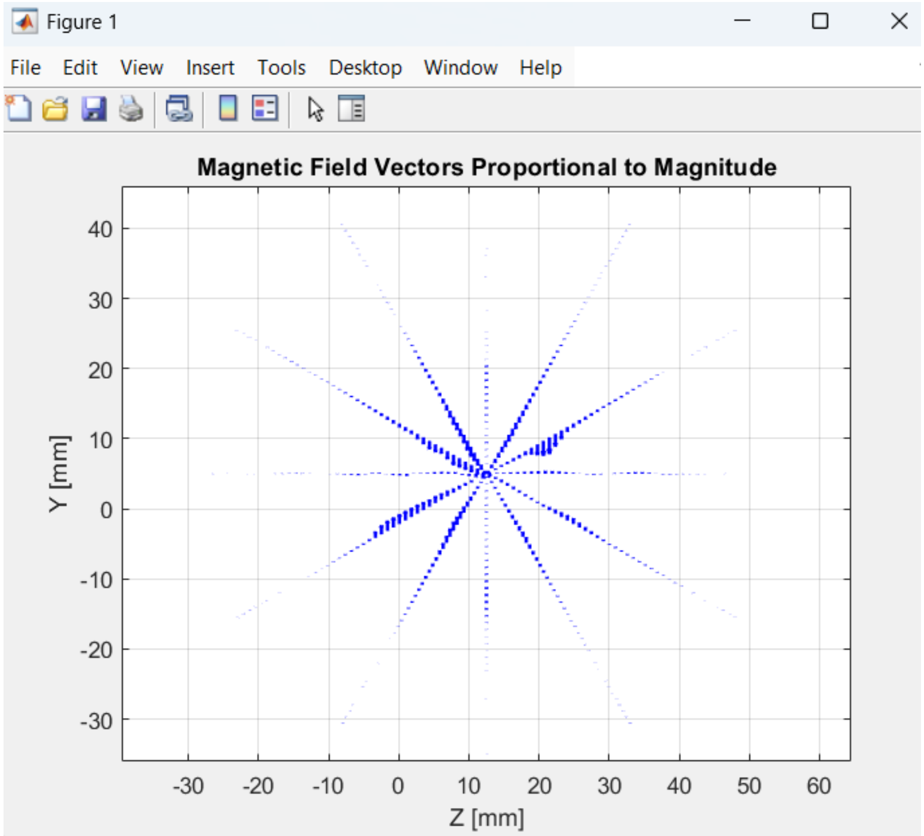


Figure 164 : Magnetic Field Vectors(Z direction) in path for a Permanent Magnet (+X polarization)(x=8mm)

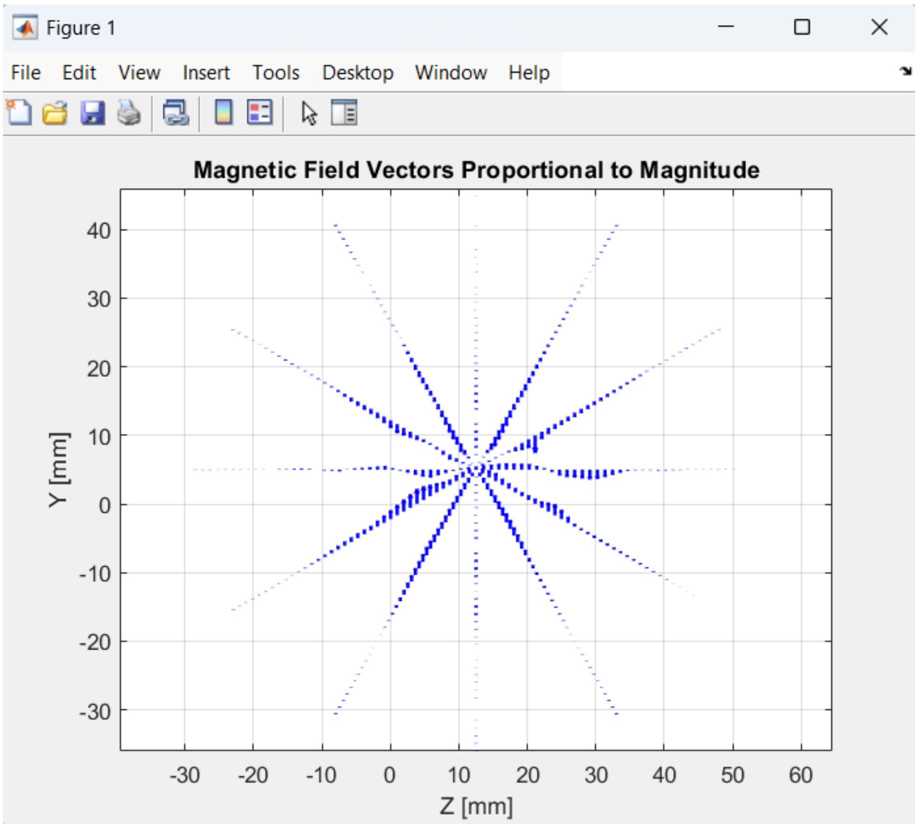


Figure 165 : Magnetic Field Vectors(Z direction) in path for a Permanent Magnet (+X polarization)(x=12mm)

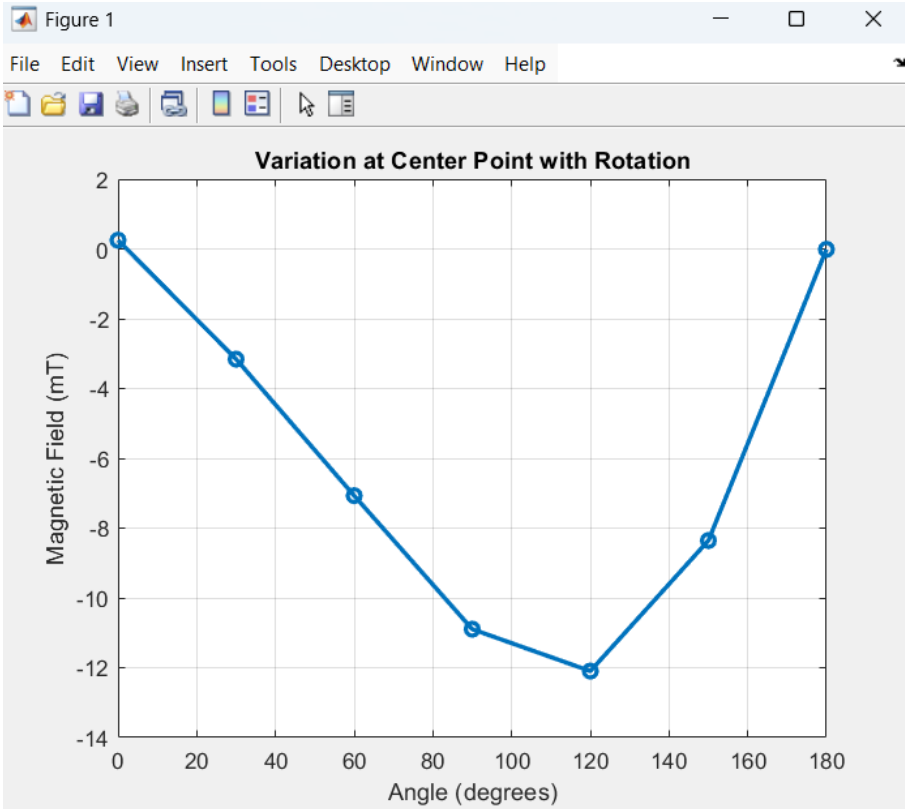


Figure 166 : Magnetic Field of center point (z Direction) of a Permanent Magnet Model (+X Polarization) (x=8mm)

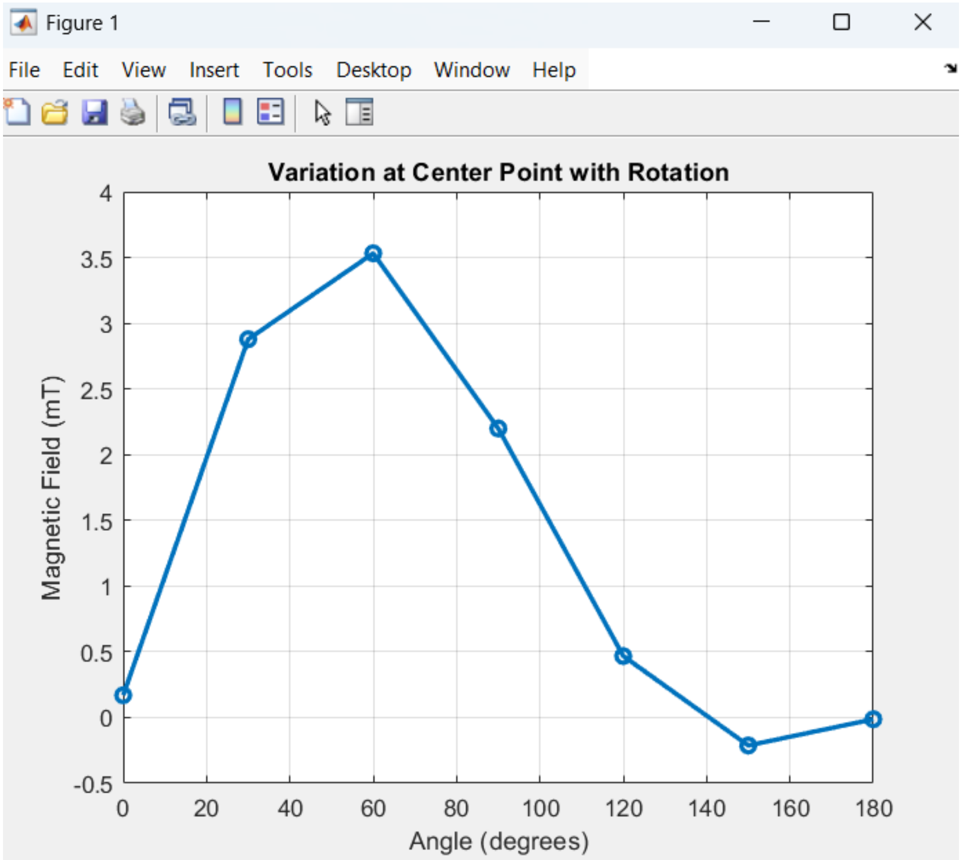


Figure 167 : Magnetic Field of center point (z Direction) of a Permanent Magnet Model (+X Polarization) (x=12mm)

In these graphs we obtained, we can see that the magnetic field created by our permanent magnet in +X polarization changes significantly as the distance increases and that different distributions and changes occur in the magnetic field in general.

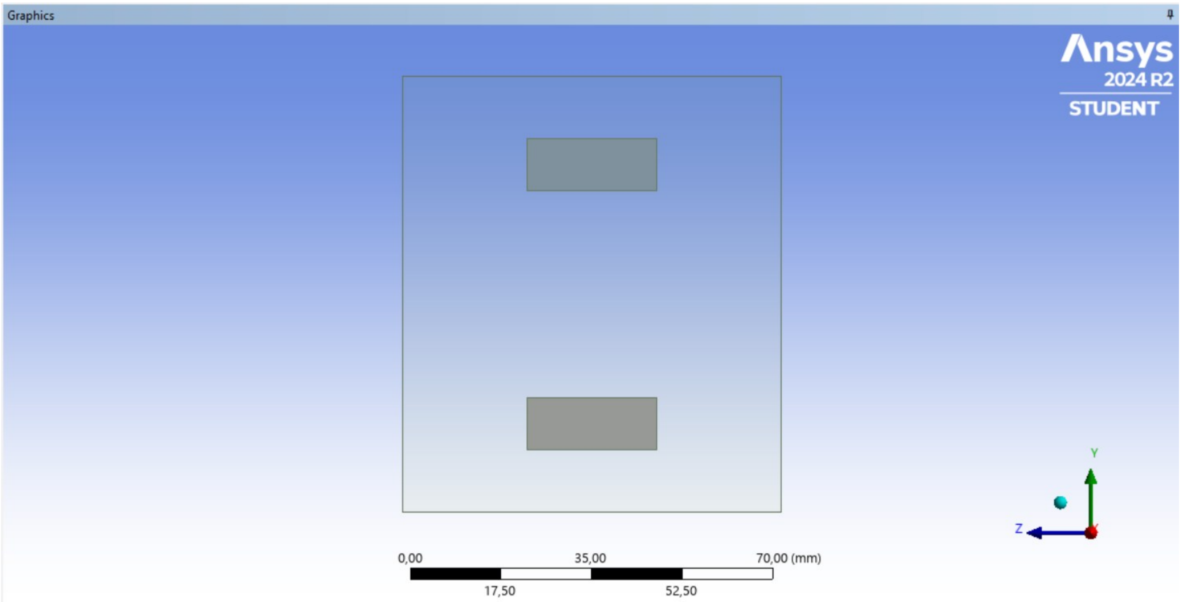


Figure 168 : Two permanent magnet model and our general coordinate system

Now we will analyze our model with two permanent magnets as seen in Figure 168. Since x polarization gives undesirable results and we have x and z polarized permanent magnets, we will use z polarized permanent magnets, namely N35s, and examine them. We will analyze one in which the polarizations of the two magnets are in the same direction and the other in the opposite direction.

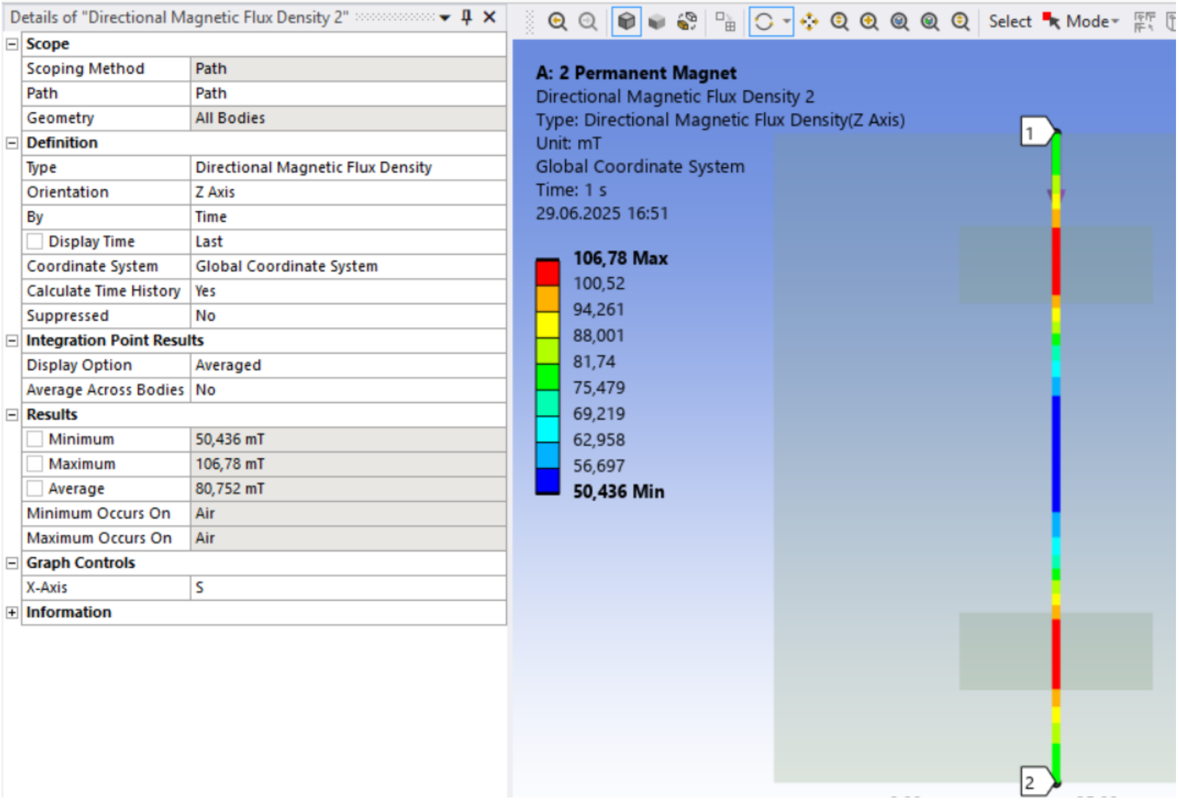


Figure 169 : Analysis of 0 Degree (+Z orientation)(2 Permanent Magnets, Same polarization)(x=4mm)

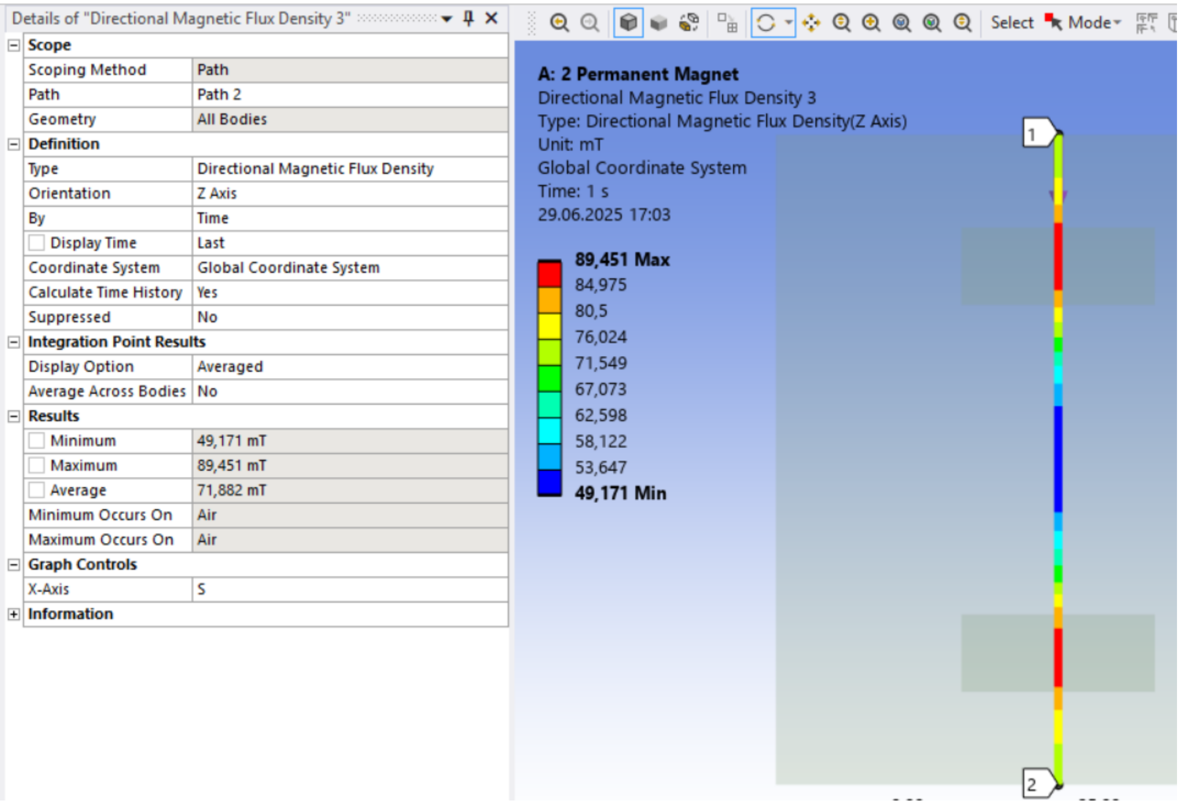


Figure 170 : Analysis of 0 Degree (+Z orientation)(2 Permanent Magnets, Same polarization)(x=8mm)

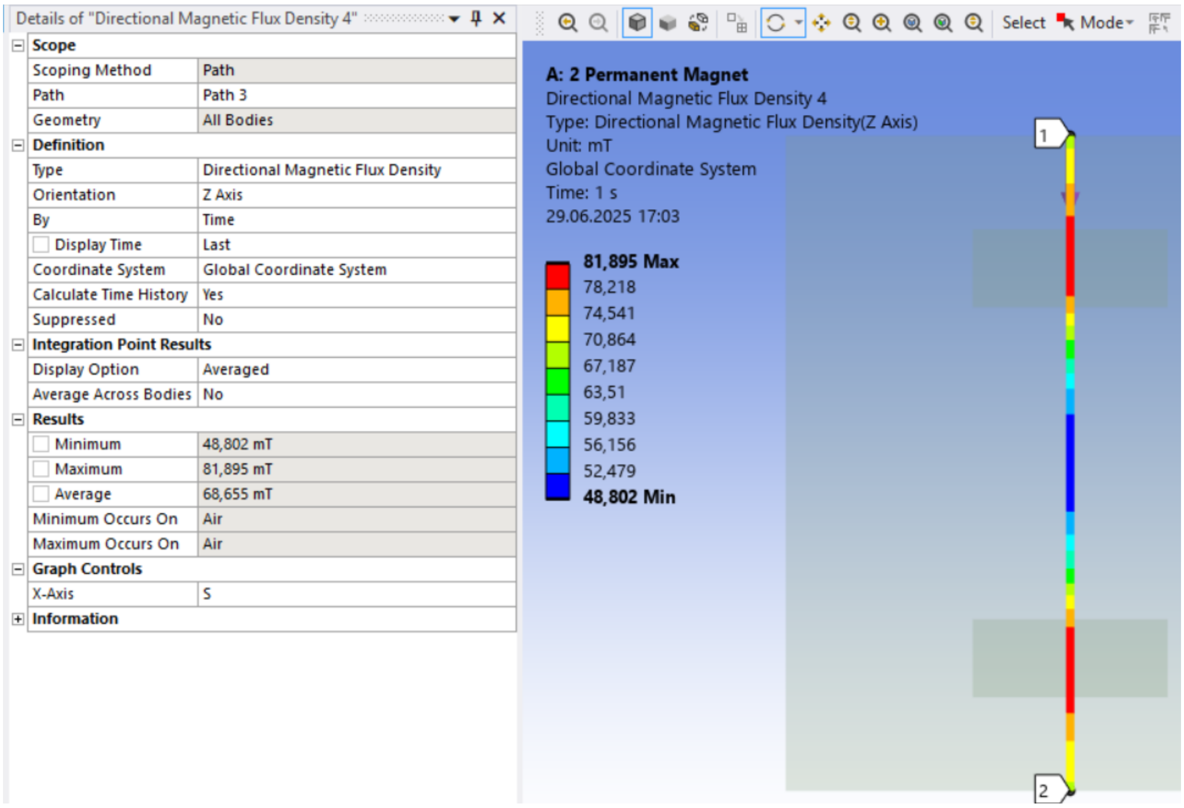


Figure 171 : Analysis of 0 Degree (+Z orientation)(2 Permanent Magnets, Same polarization)(x=12mm)

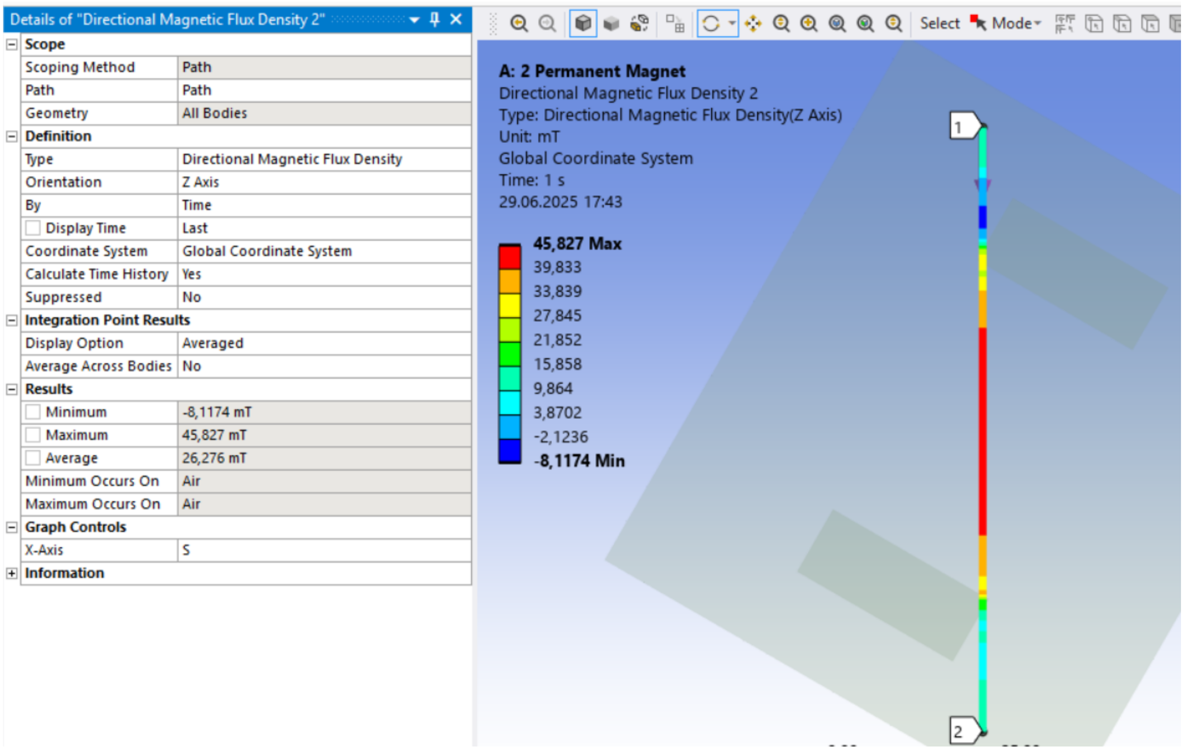


Figure 172 : Analysis of 30 Degree (+Z orientation)(2 Permanent Magnets, Same polarization)(x=4mm)

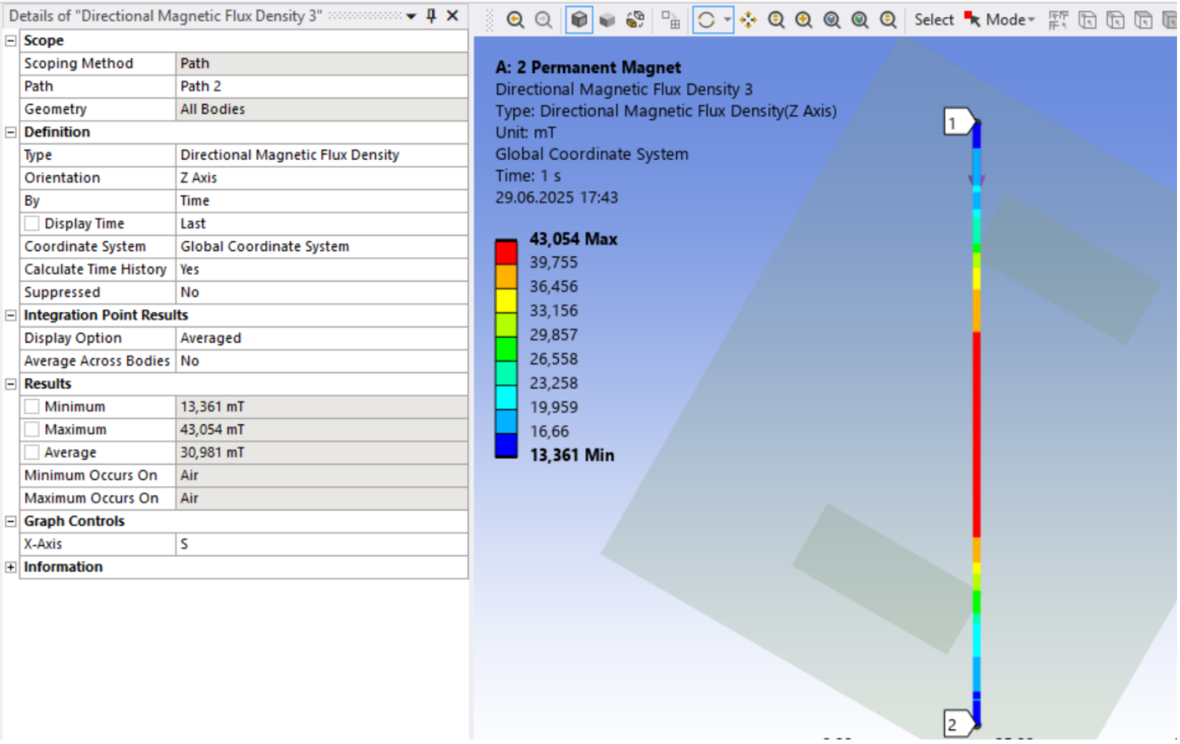


Figure 173 : Analysis of 30 Degree (+Z orientation)(2 Permanent Magnets, Same polarization)(x=8mm)

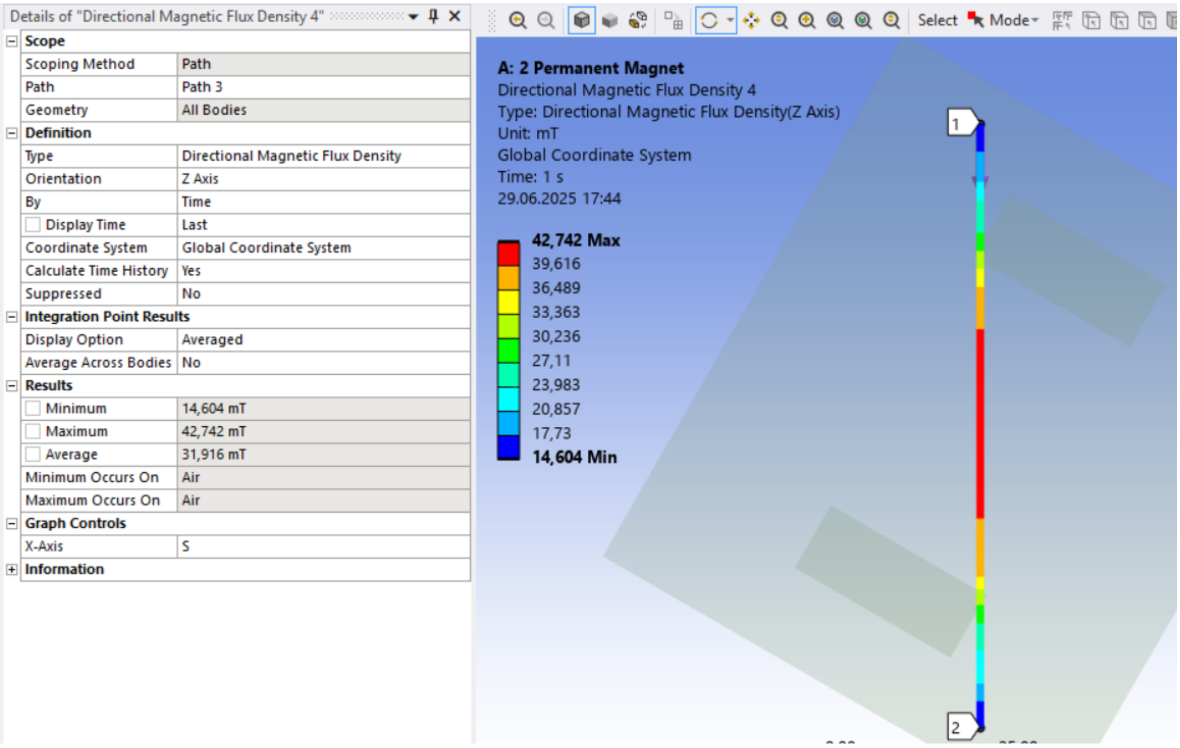


Figure 174 : Analysis of 30 Degree (+Z orientation)(2 Permanent Magnets, Same polarization)(x=12mm)

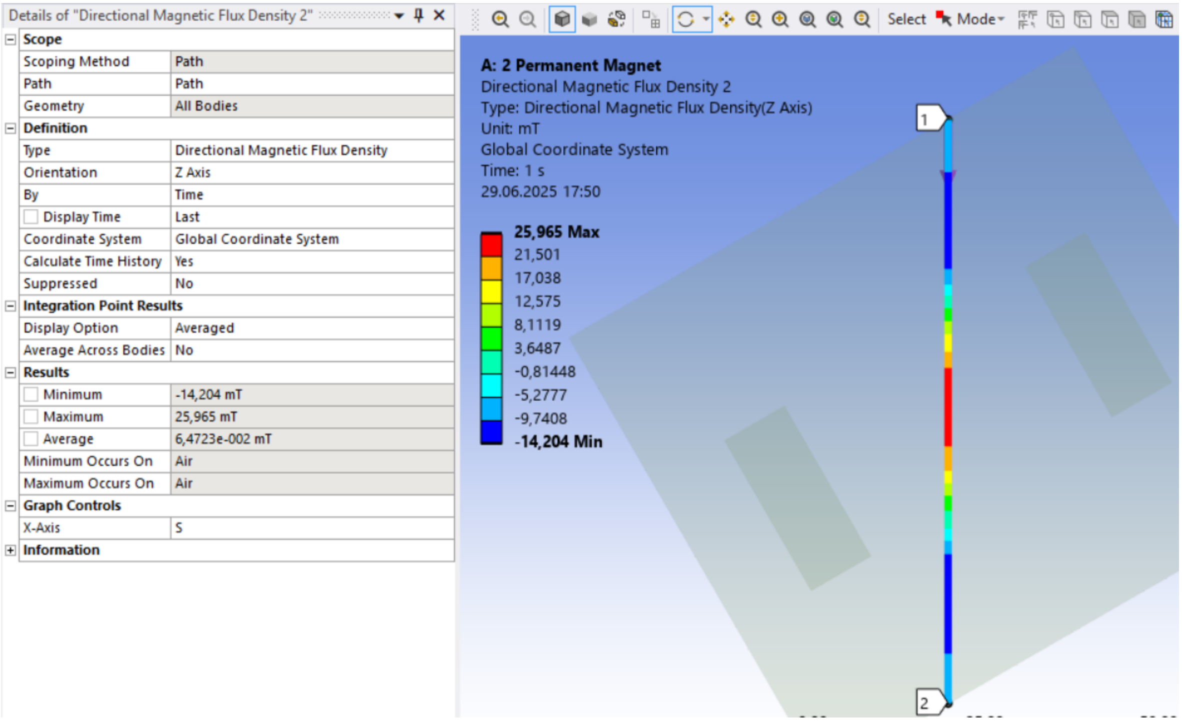


Figure 175 : Analysis of 60 Degree (+Z orientation)(2 Permanent Magnets, Same polarization)(x=4mm)

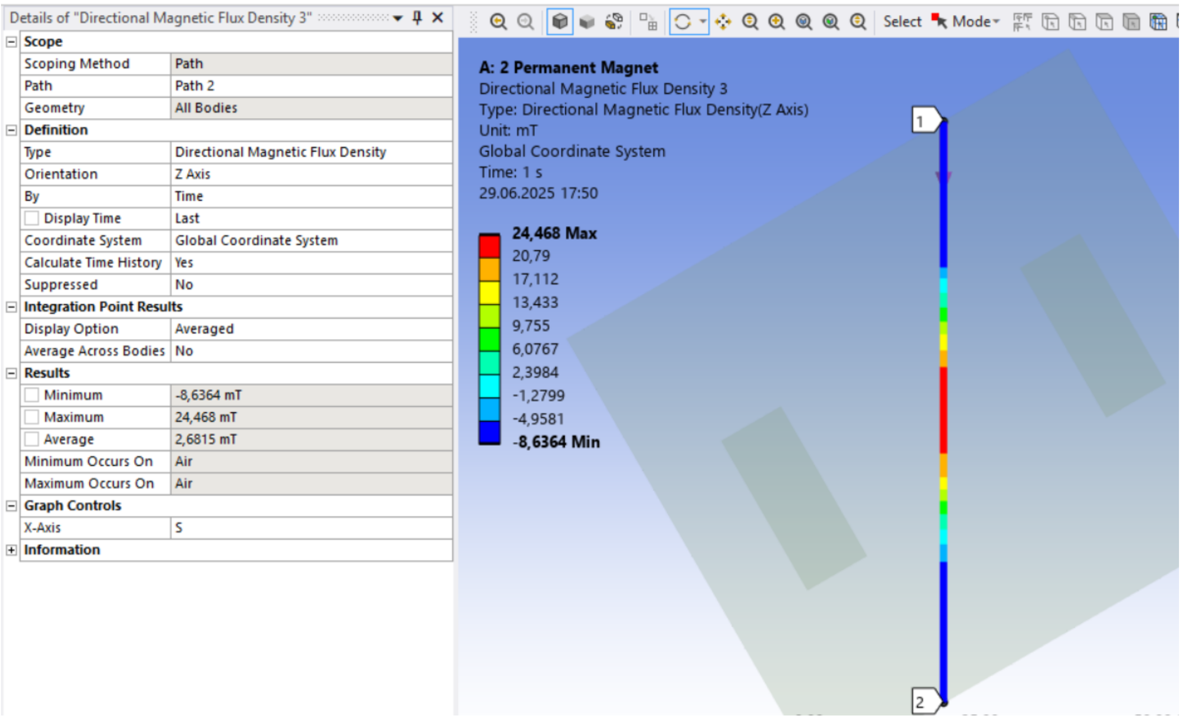


Figure 176 : Analysis of 60 Degree (+Z orientation)(2 Permanent Magnets, Same polarization)(x=8mm)

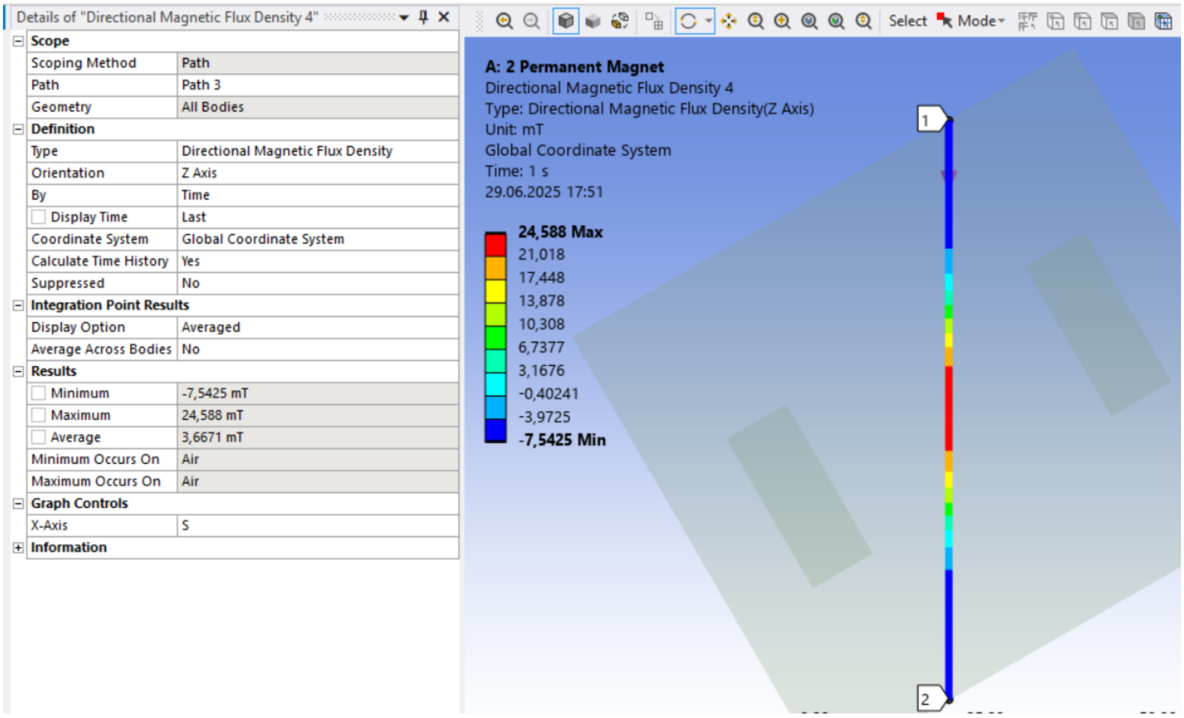


Figure 177 : Analysis of 60 Degree (+Z orientation)(2 Permanent Magnets, Same polarization)(x=12mm)

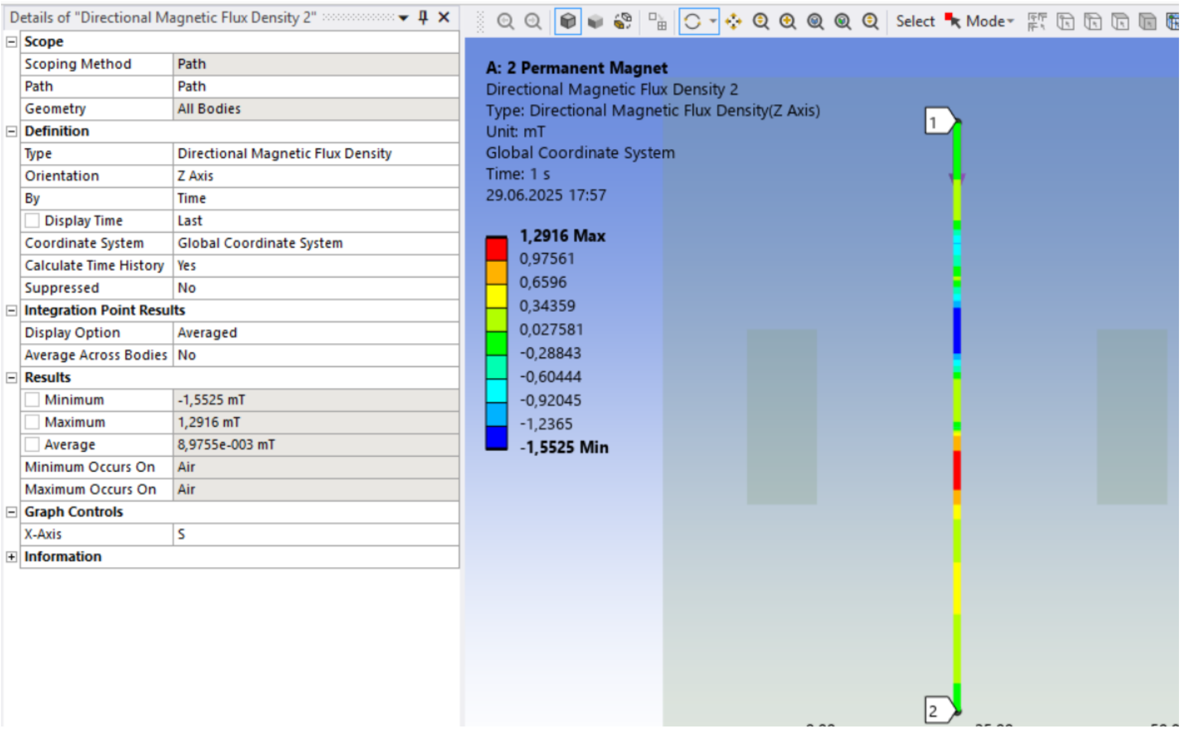


Figure 178 : Analysis of 90 Degree (+Z orientation)(2 Permanent Magnets, Same polarization)(x=4mm)

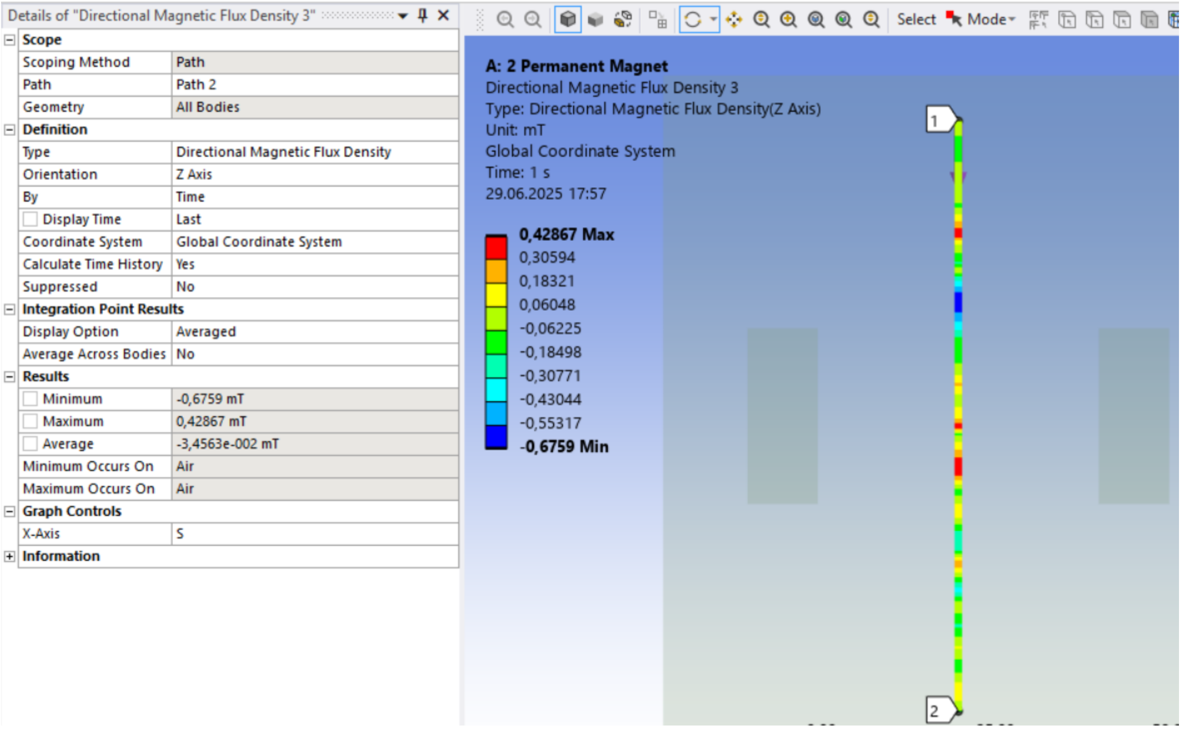


Figure 179 : Analysis of 90 Degree (+Z orientation)(2 Permanent Magnets, Same polarization)(x=8mm)

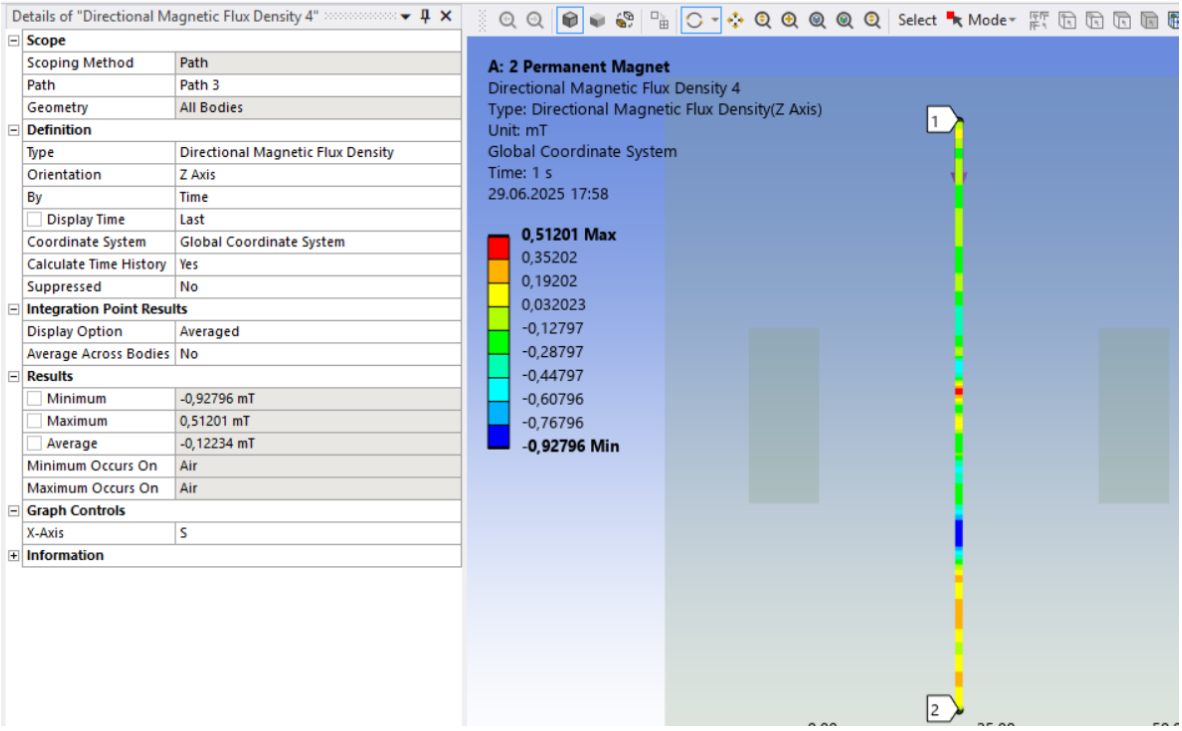


Figure 180 : Analysis of 90 Degree (+Z orientation)(2 Permanent Magnets, Same polarization)(x=12mm)

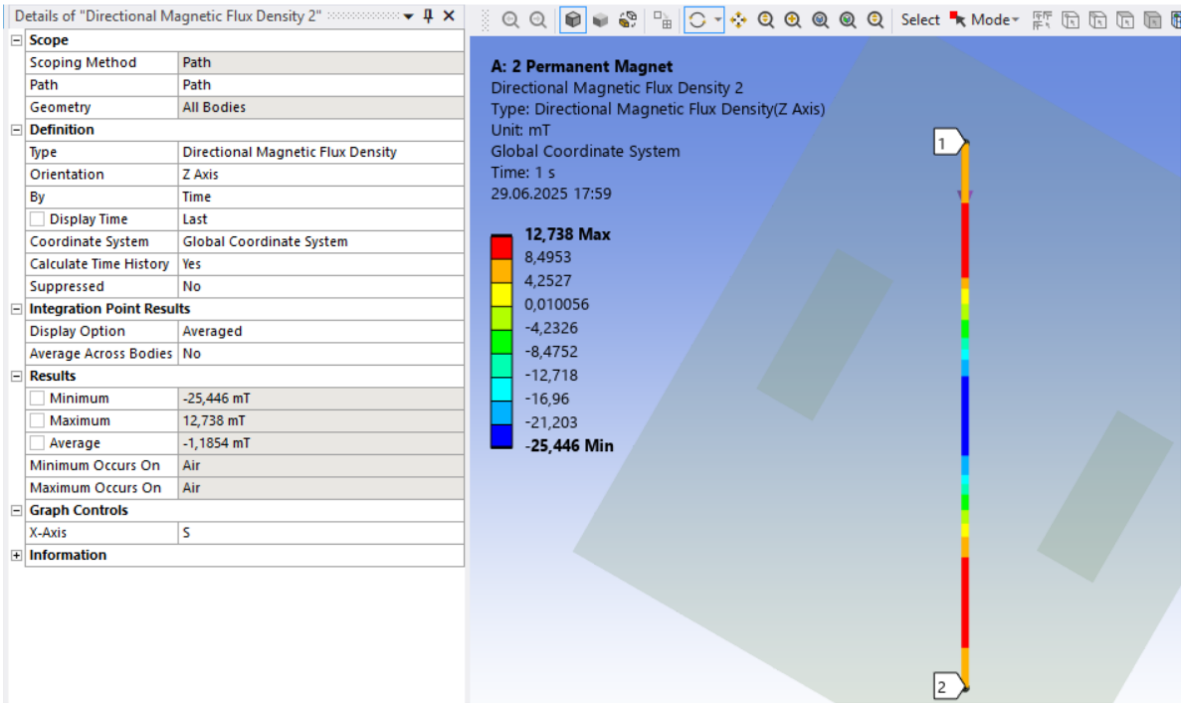


Figure 181 : Analysis of 120 Degree (+Z orientation)(2 Permanent Magnets, Same polarization)(x=4mm)

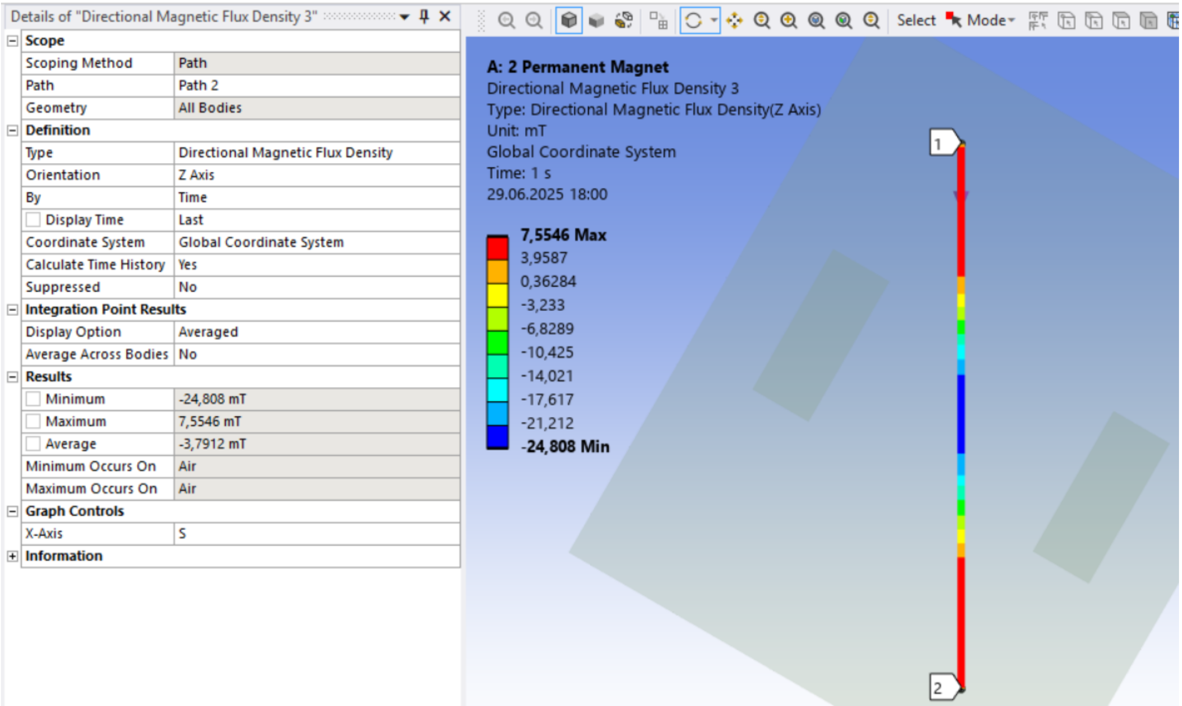


Figure 182 : Analysis of 120 Degree (+Z orientation)(2 Permanent Magnets, Same polarization)(x=8mm)

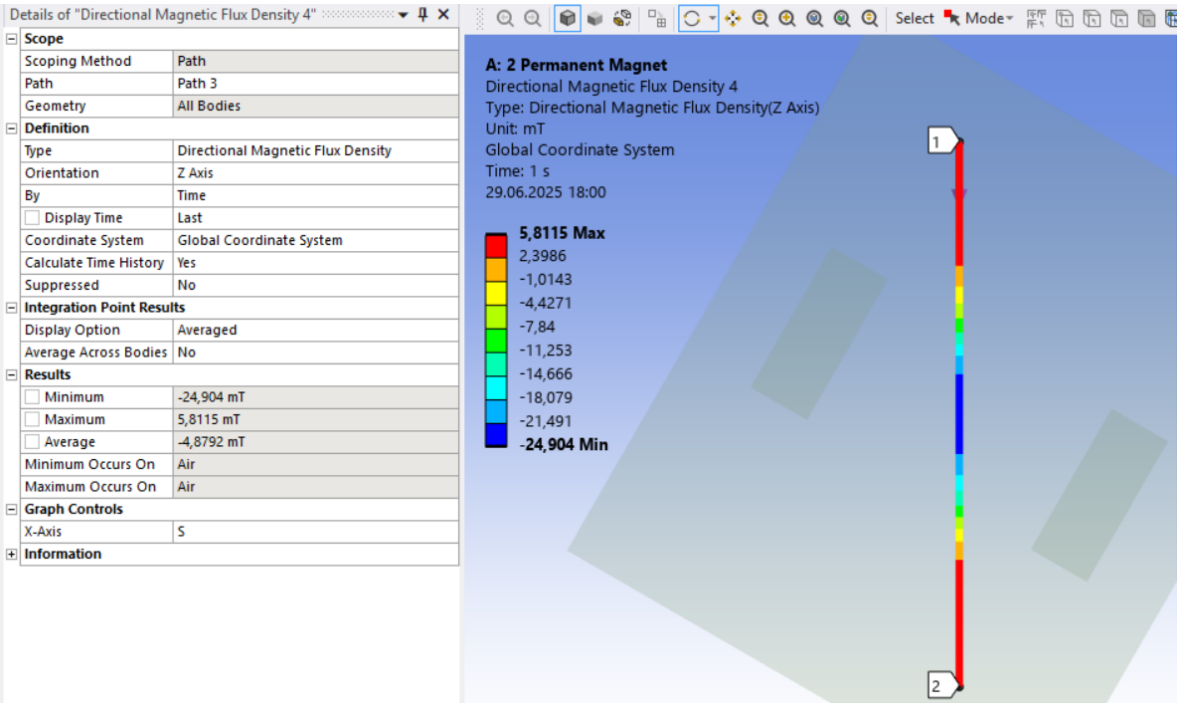


Figure 183 : Analysis of 120 Degree (+Z orientation)(2 Permanent Magnets, Same polarization)(x=12mm)

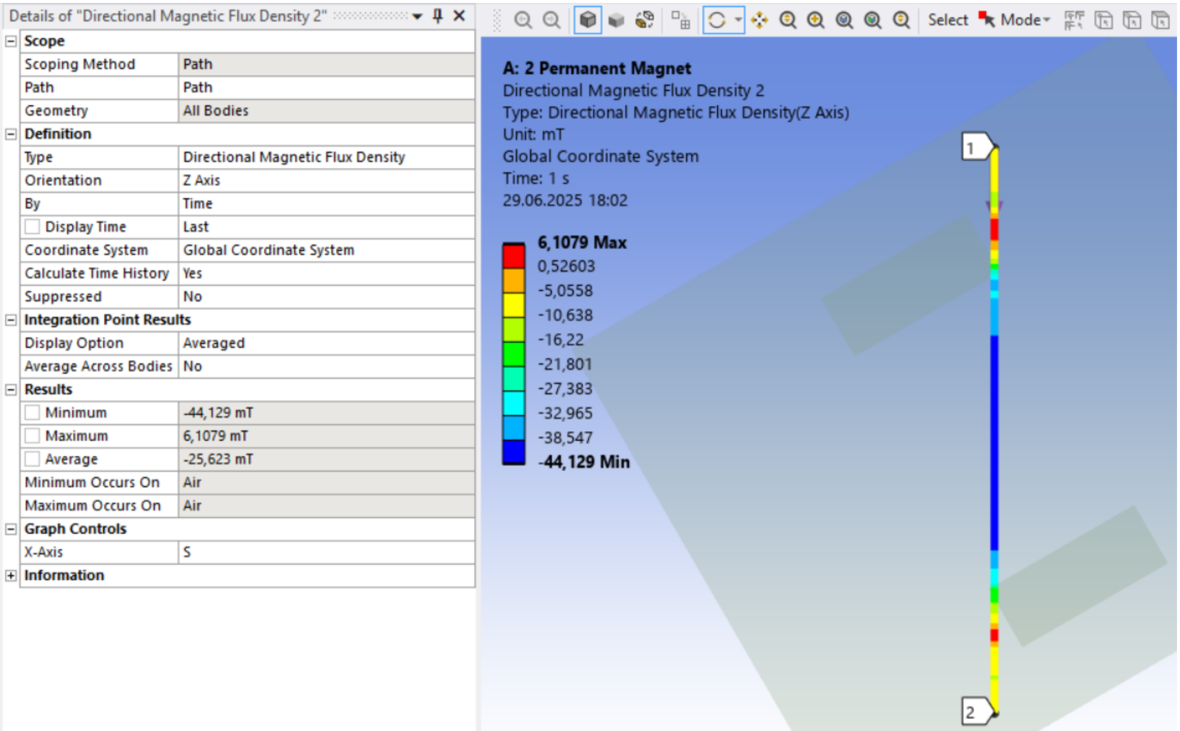


Figure 184 : Analysis of 150 Degree (+Z orientation)(2 Permanent Magnets, Same polarization)(x=4mm)

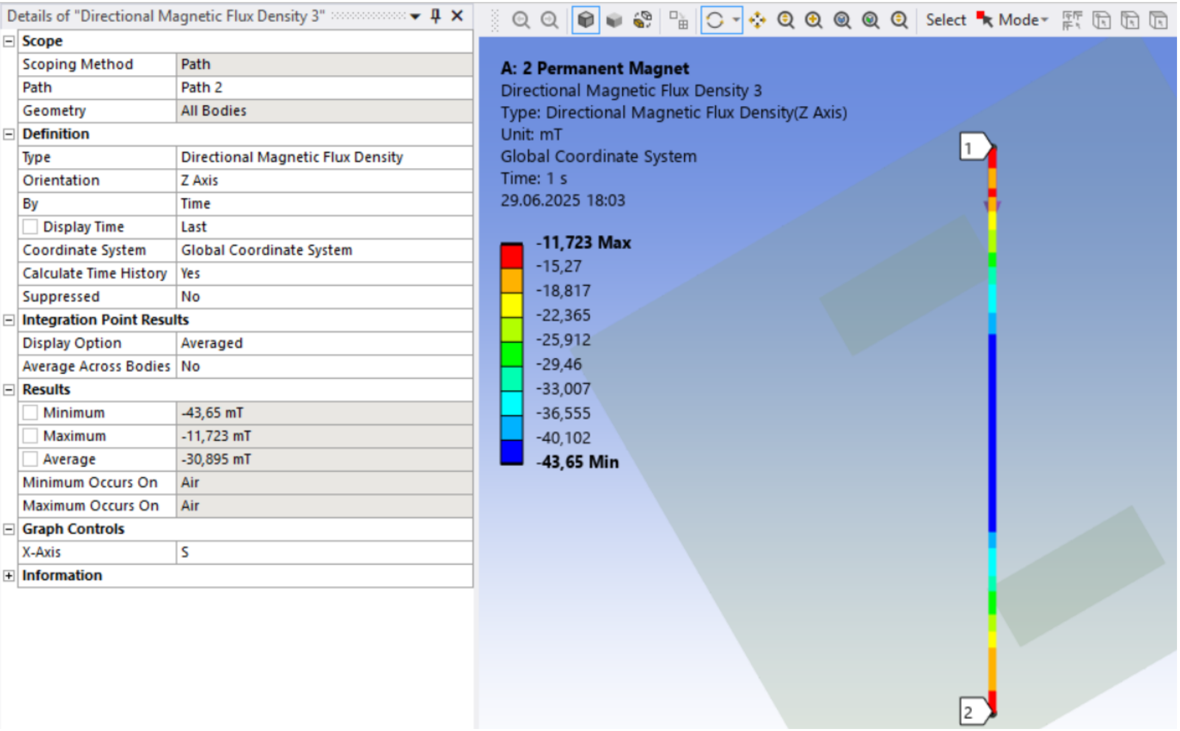


Figure 185 : Analysis of 150 Degree (+Z orientation)(2 Permanent Magnets, Same polarization)(x=8mm)

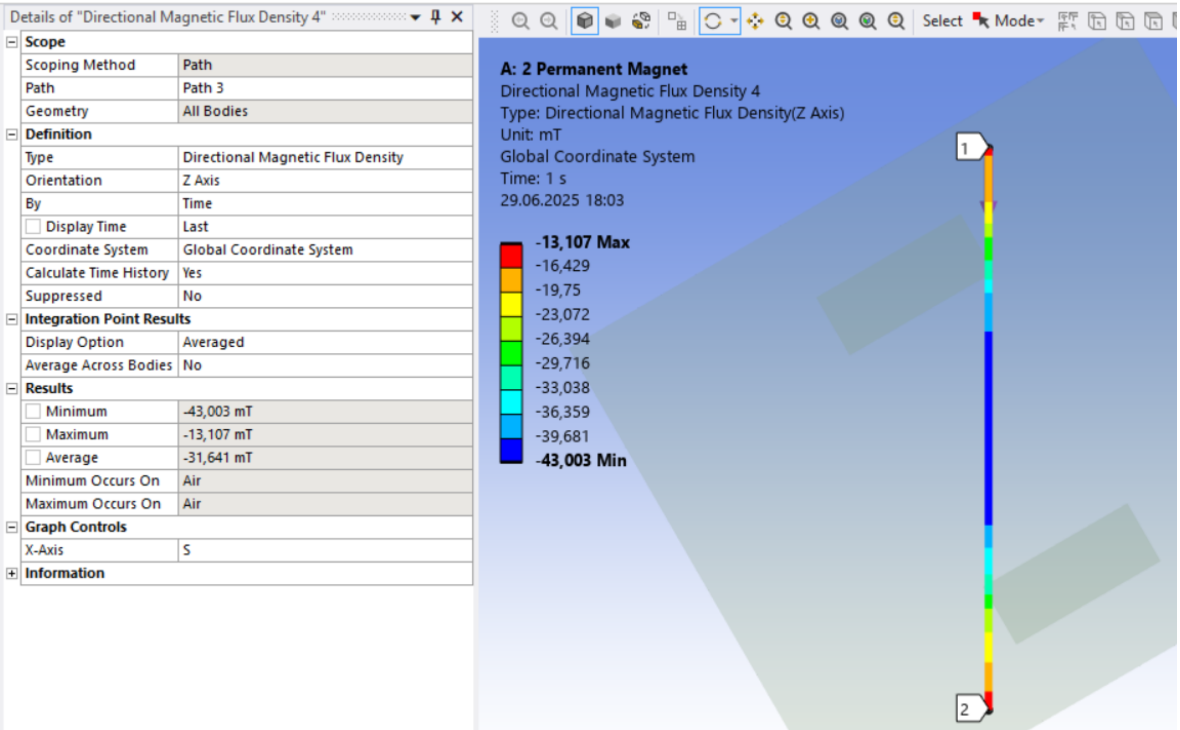


Figure 186 : Analysis of 150 Degree (+Z orientation)(2 Permanent Magnets, Same polarization)(x=12mm)

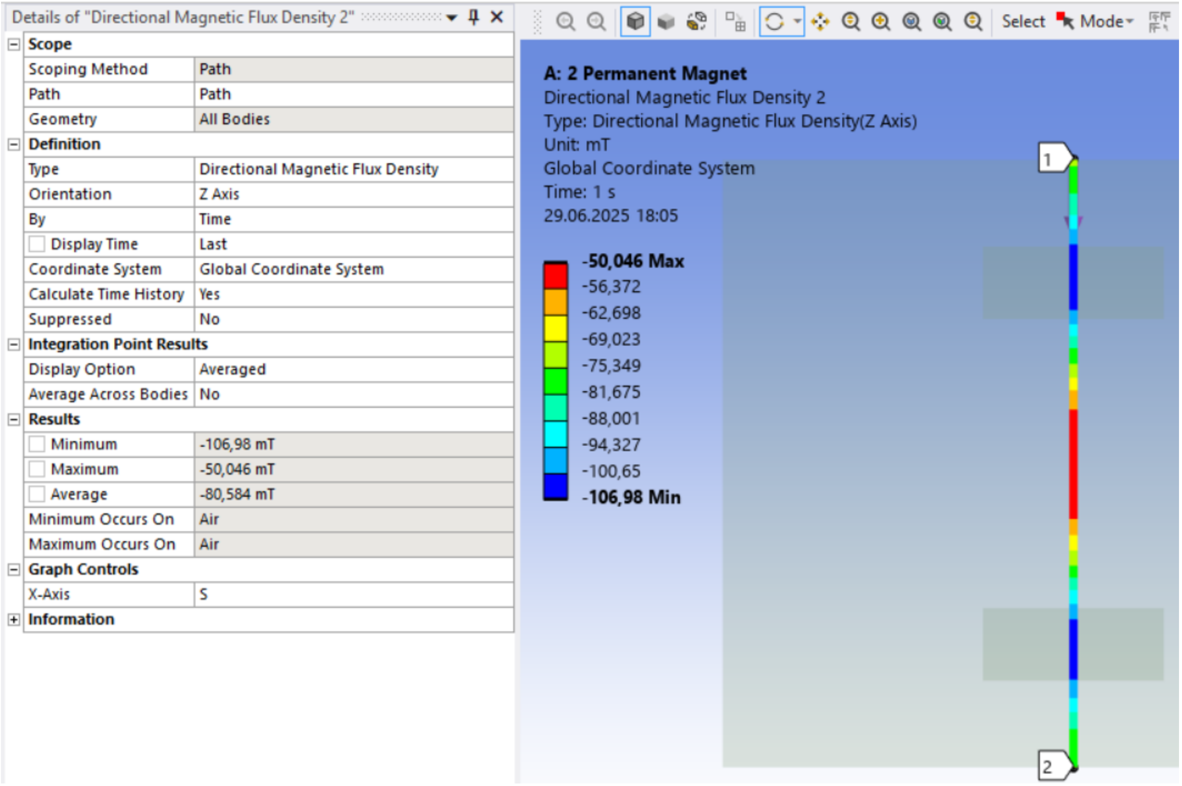


Figure 187 : Analysis of 180 Degree (+Z orientation)(2 Permanent Magnets, Same polarization)(x=4mm)

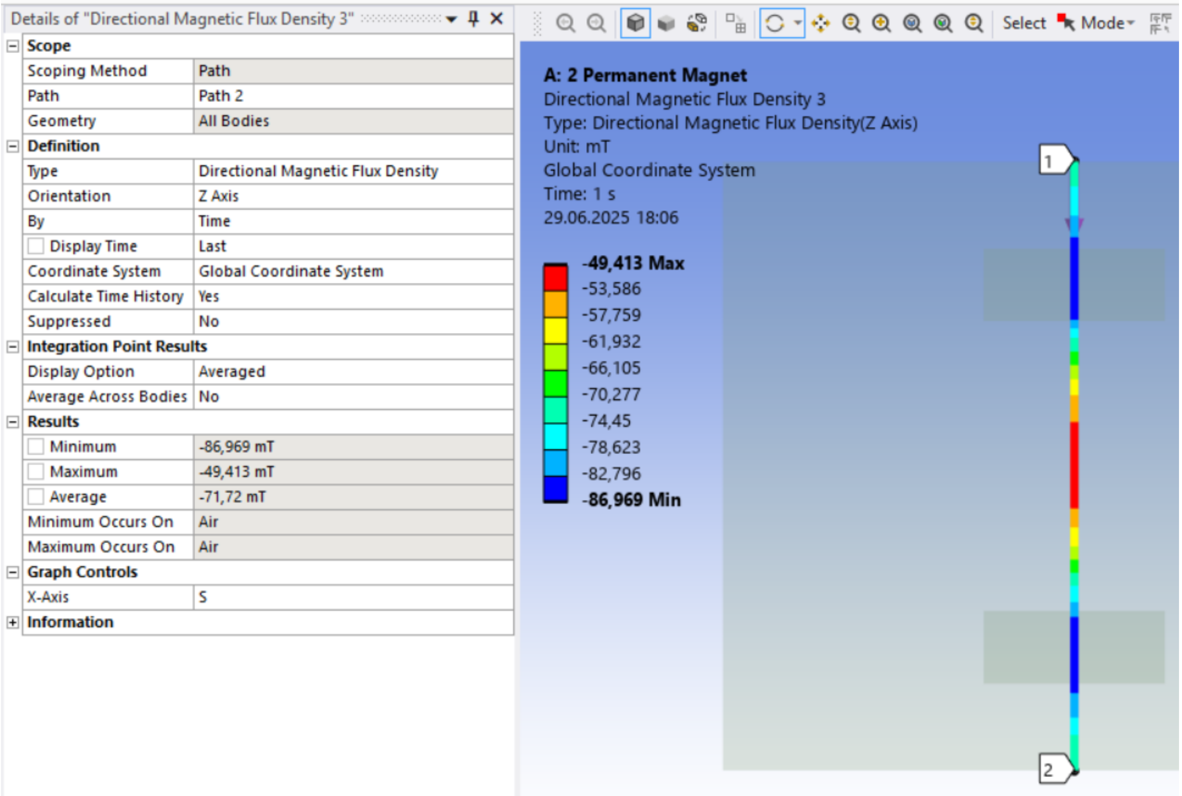


Figure 188 : Analysis of 180 Degree (+Z orientation)(2 Permanent Magnets, Same polarization)(x=8mm)

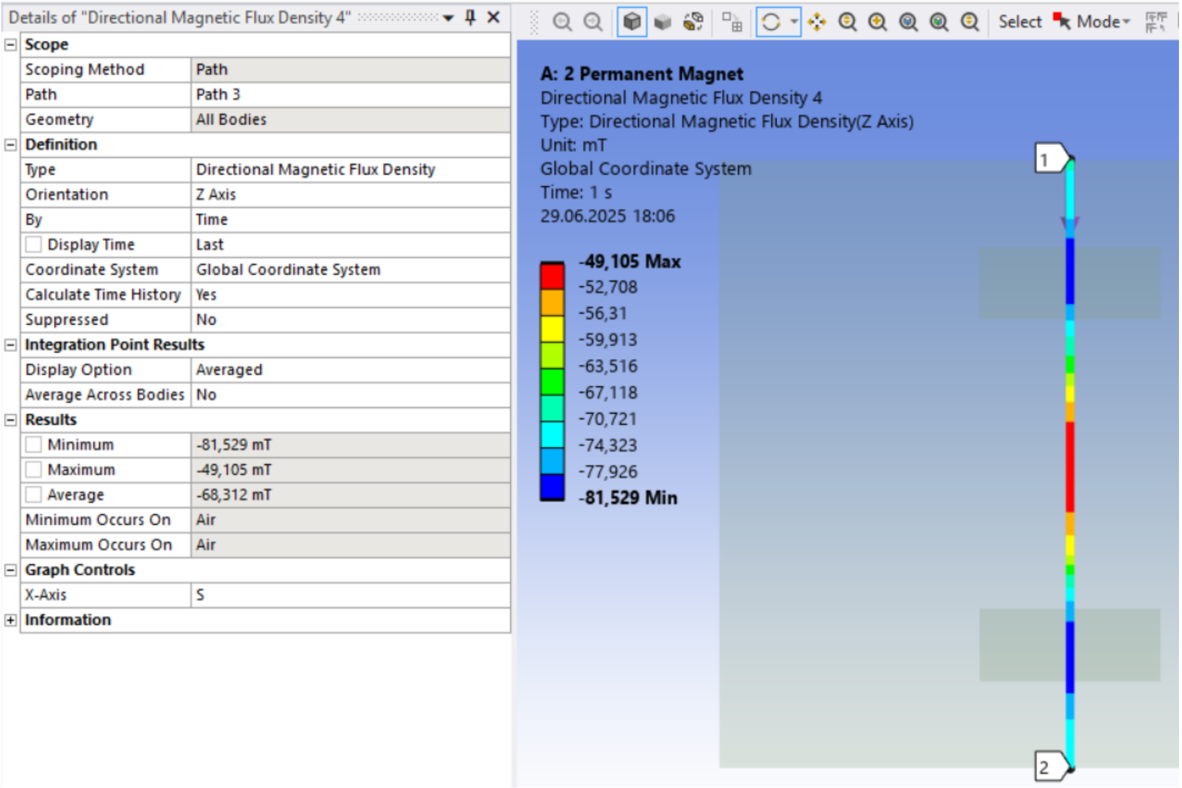


Figure 189 : Analysis of 180 Degree (+Z orientation)(2 Permanent Magnets, Same polarization)(x=12mm)

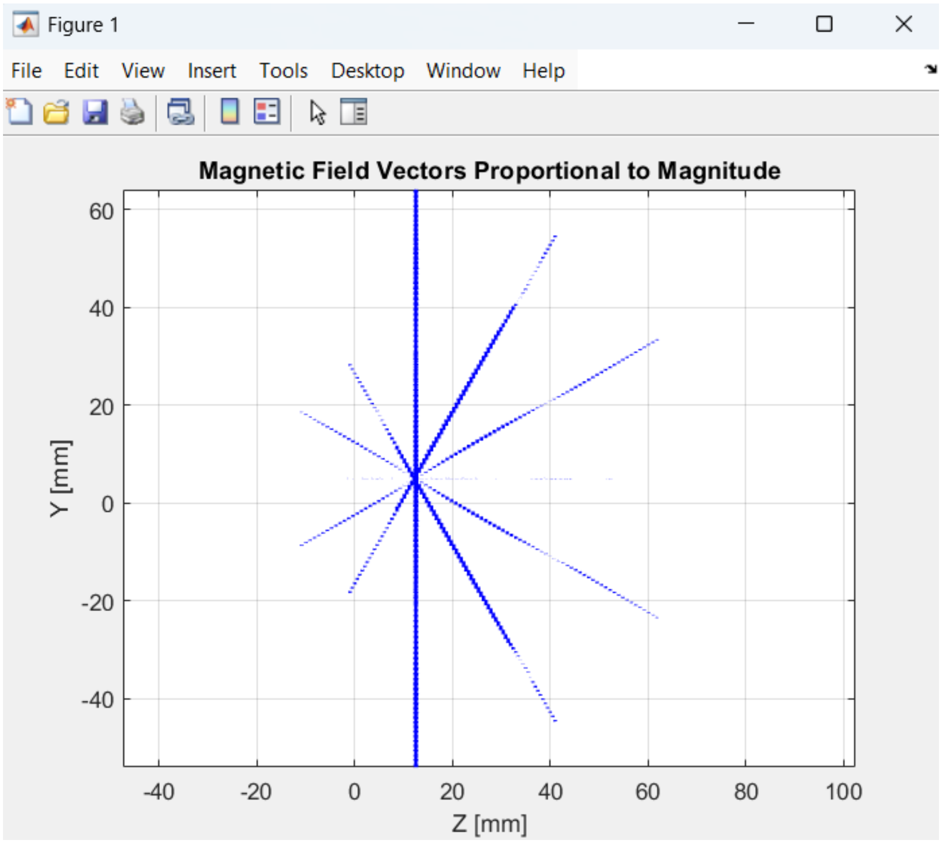


Figure 190 : Magnetic Field Vectors(Z direction) in path for Two Permanent Magnet (+Z polarization, same polarization)(x=4mm)

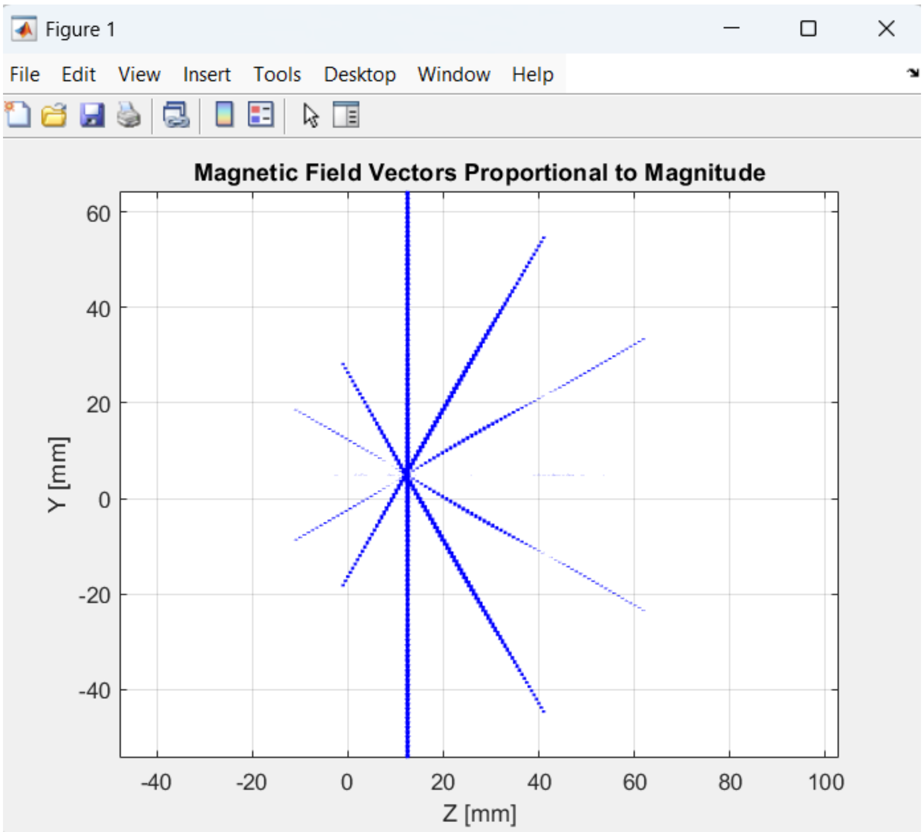


Figure 191 : Magnetic Field Vectors(Z direction) in path for Two Permanent Magnet (+Z polarization, same polarization)(x=8mm)

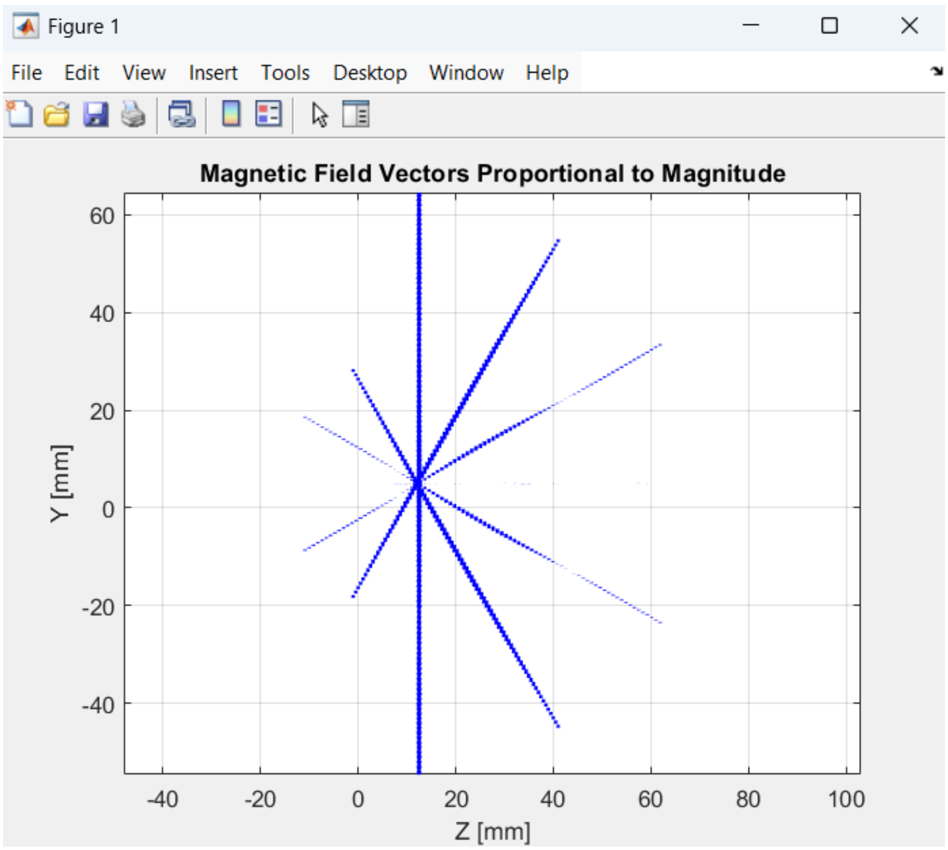


Figure 192 : Magnetic Field Vectors(Z direction) in path for Two Permanent Magnet (+Z polarization, same polarization)(x=12mm)

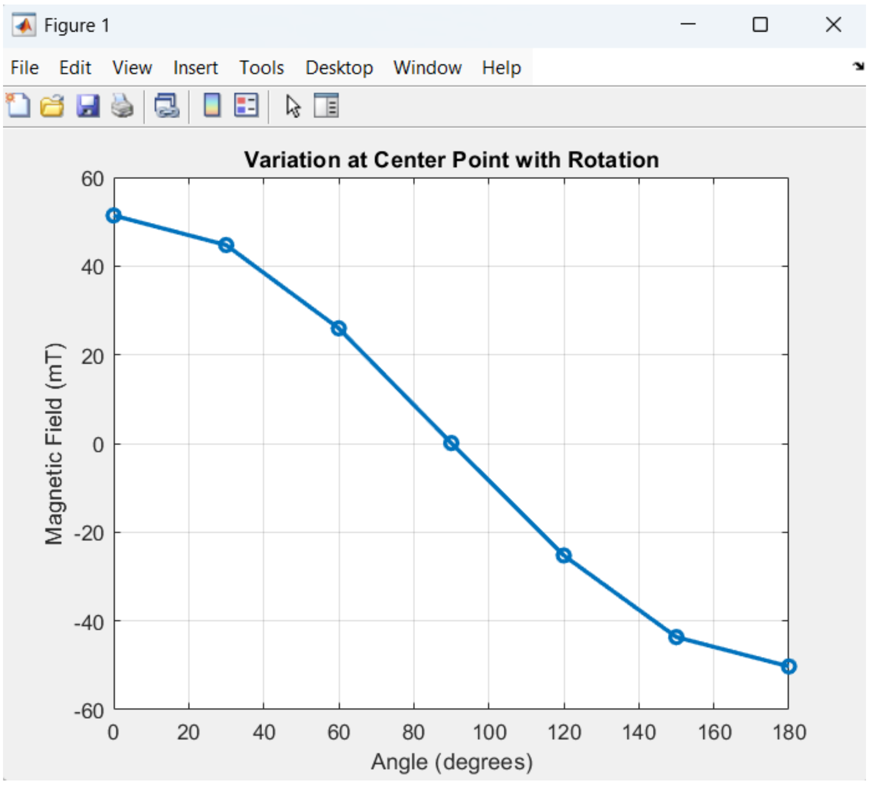


Figure 193 : Magnetic Field of center point (z Direction) of Two Permanent Magnet Model (+Z Polarization, same) (x=4mm)

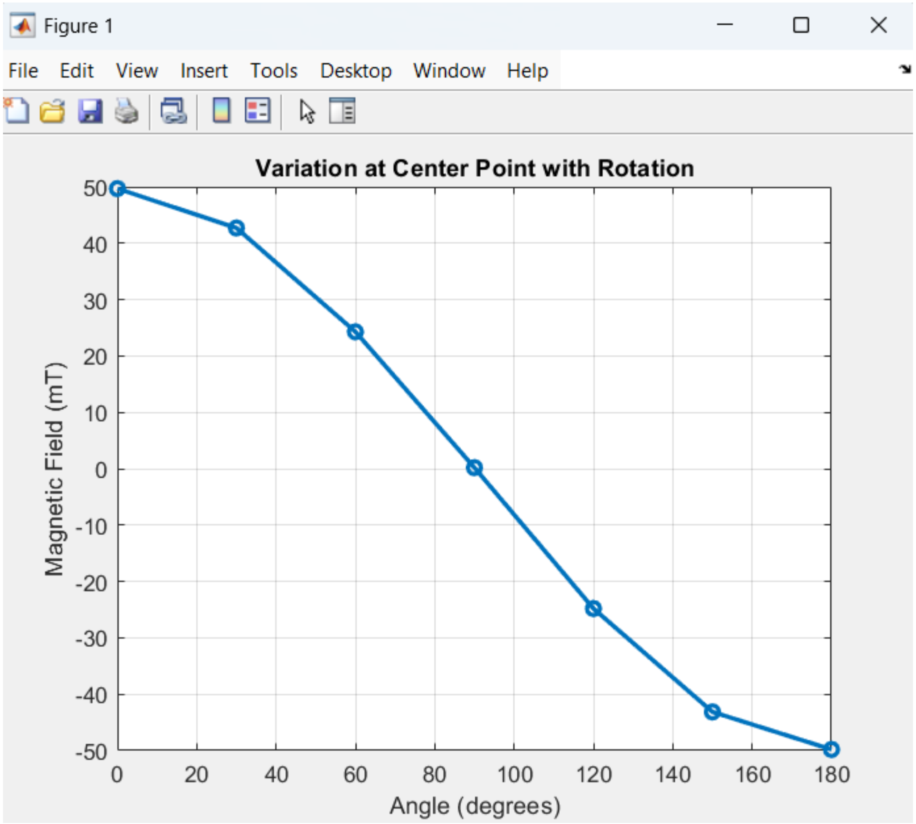


Figure 194 : Magnetic Field of center point (z Direction) of Two Permanent Magnet Model (+Z Polarization, same) (x=8mm)

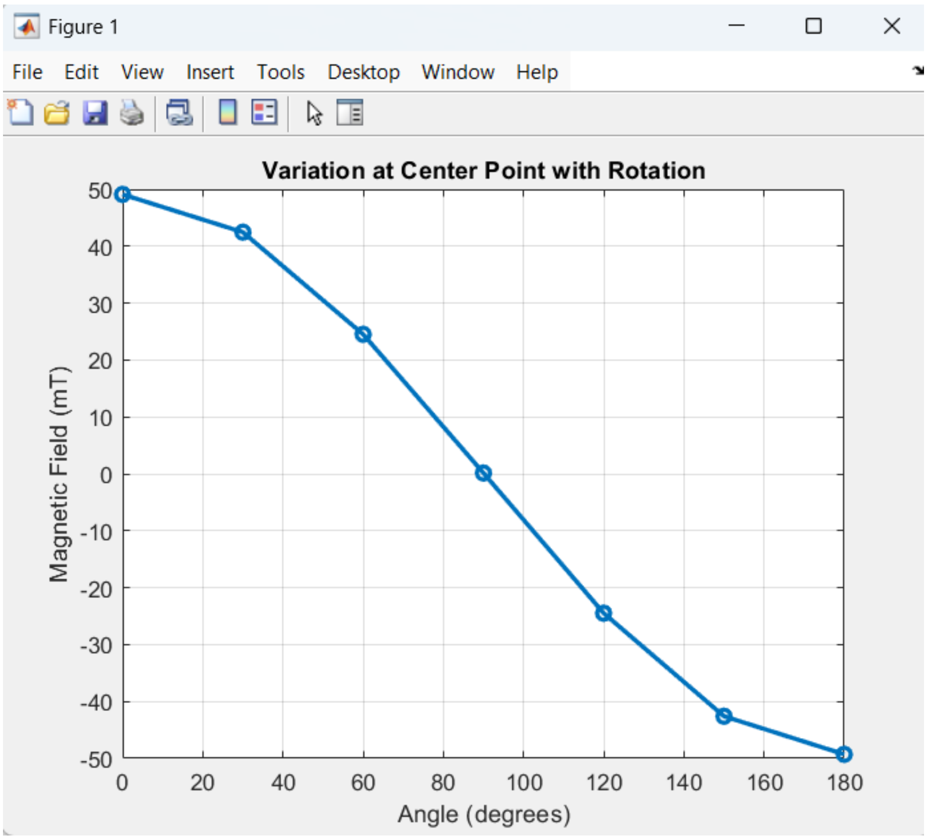


Figure 195 : Magnetic Field of center point (z Direction) of Two Permanent Magnet Model (+Z Polarization, same) (x=12mm)

In the data we obtained from the analysis of two permanent magnets with polarization in the same direction, we see that this model gives very small values when measuring the magnetic field at a certain distance from the center and the magnetic field values are generally very irregular. At the same time, as the distance increases (4mm, 8mm. 12mm), there is almost no change in the magnetic field.

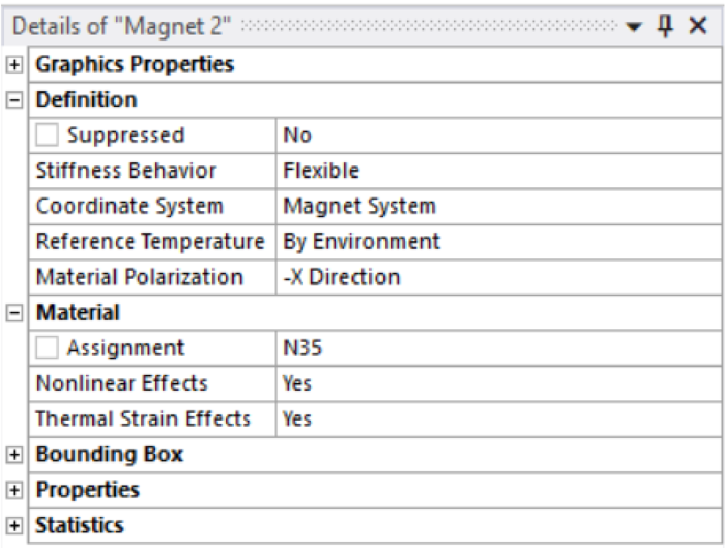


Figure 196 : Adjusting the polarization of the second magnet in the opposite direction

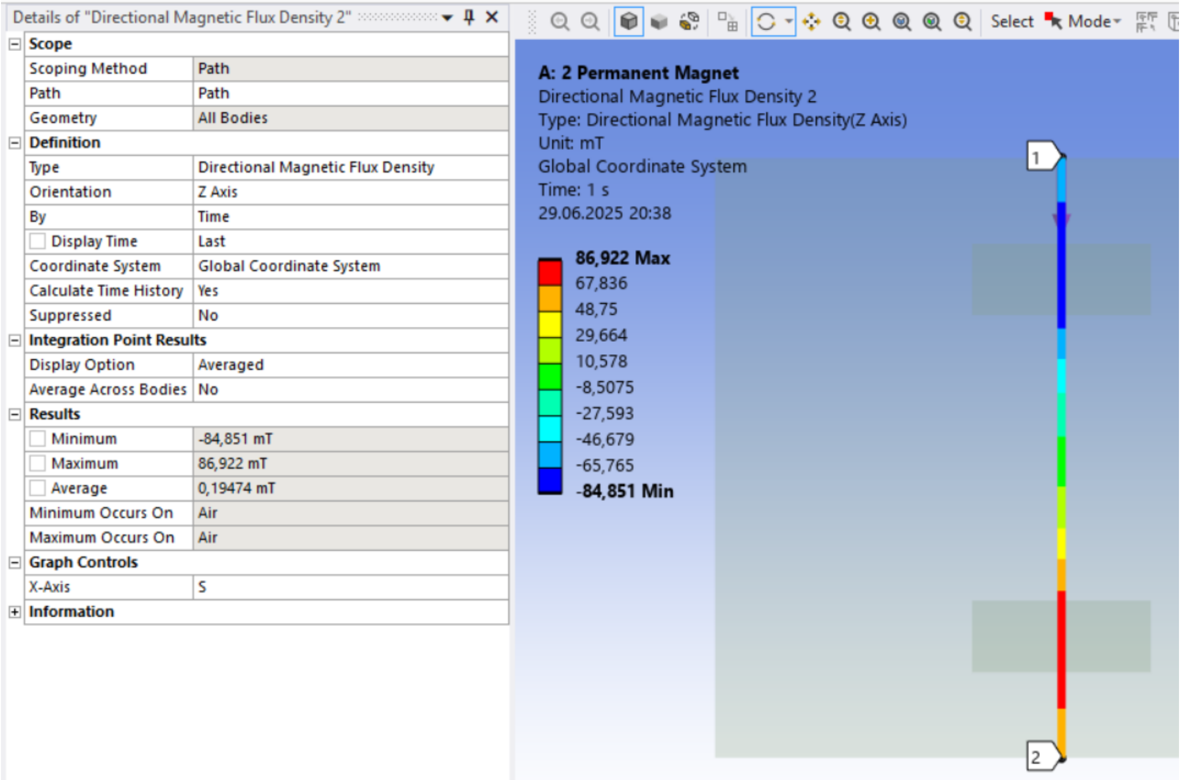


Figure 197 : Analysis of 0 Degree (+Z orientation)(2 Permanent Magnets, Opposite polarization)(x=4mm)

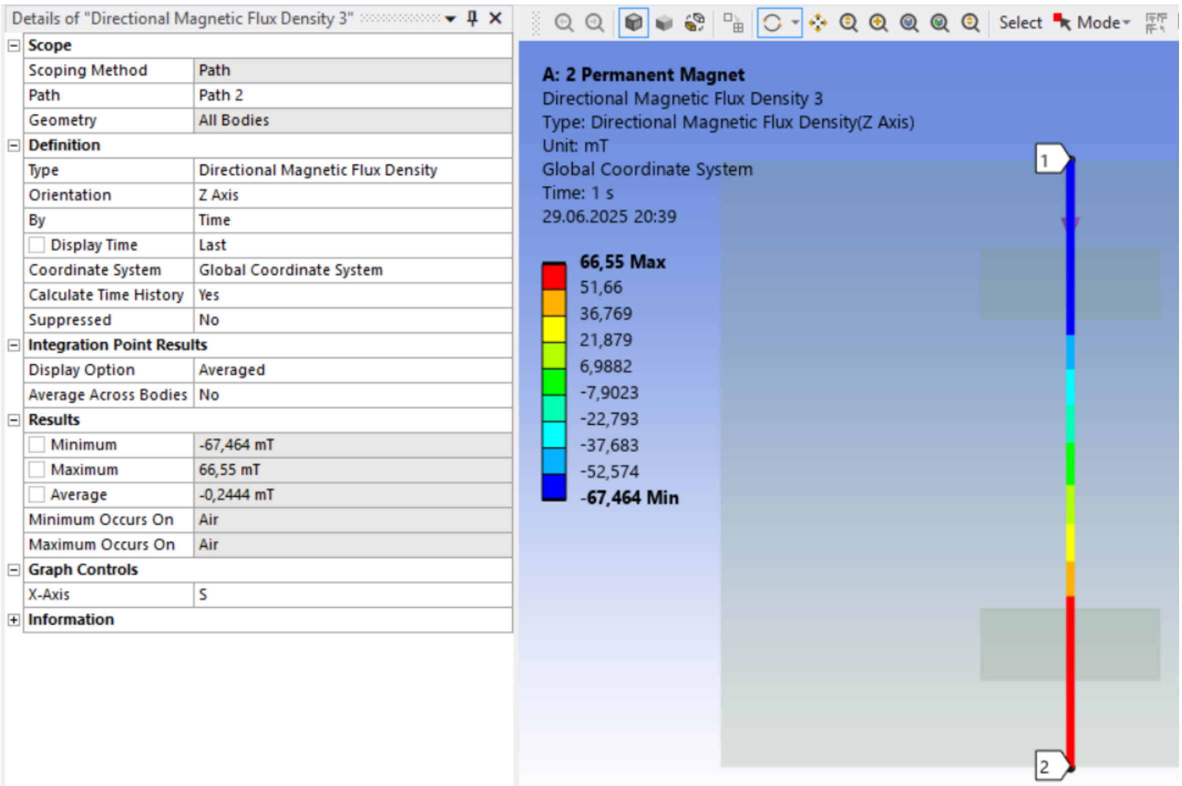


Figure 198 : Analysis of 0 Degree (+Z orientation)(2 Permanent Magnets, Opposite polarization)(x=8mm)

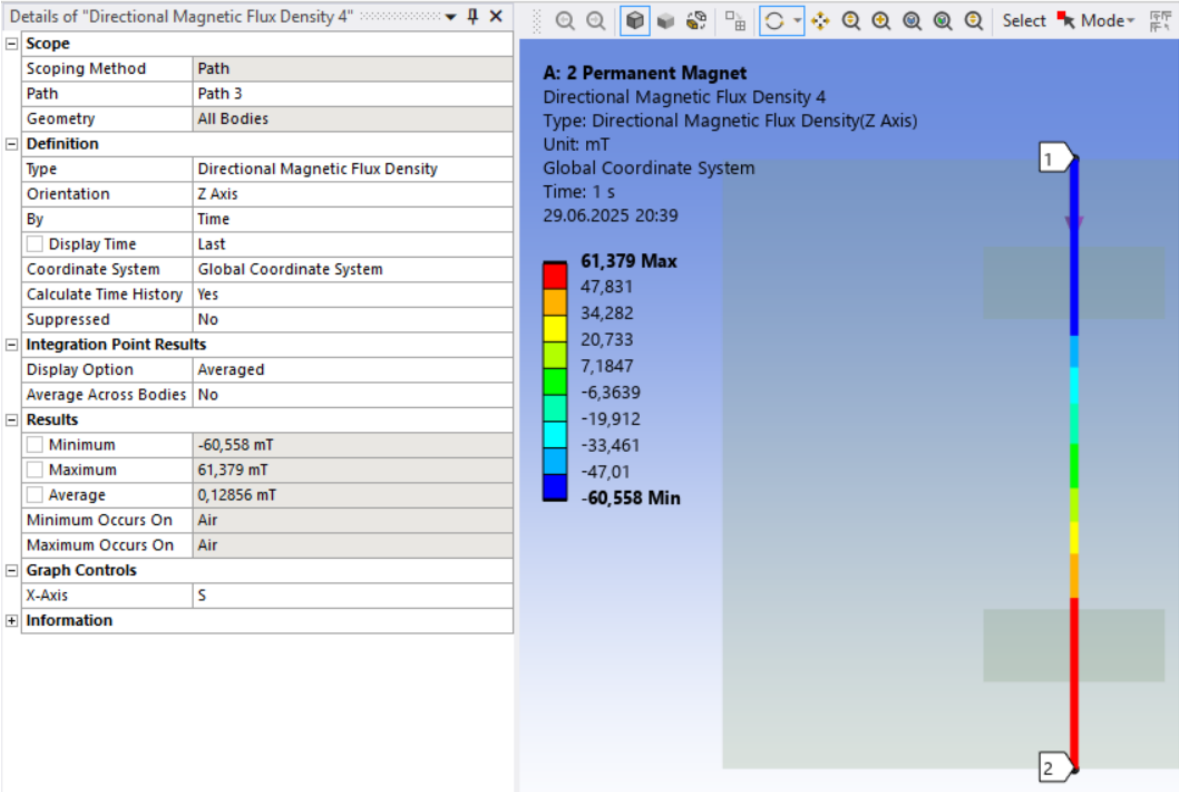


Figure 199 : Analysis of 0 Degree (+Z orientation)(2 Permanent Magnets, Opposite polarization)(x=12mm)

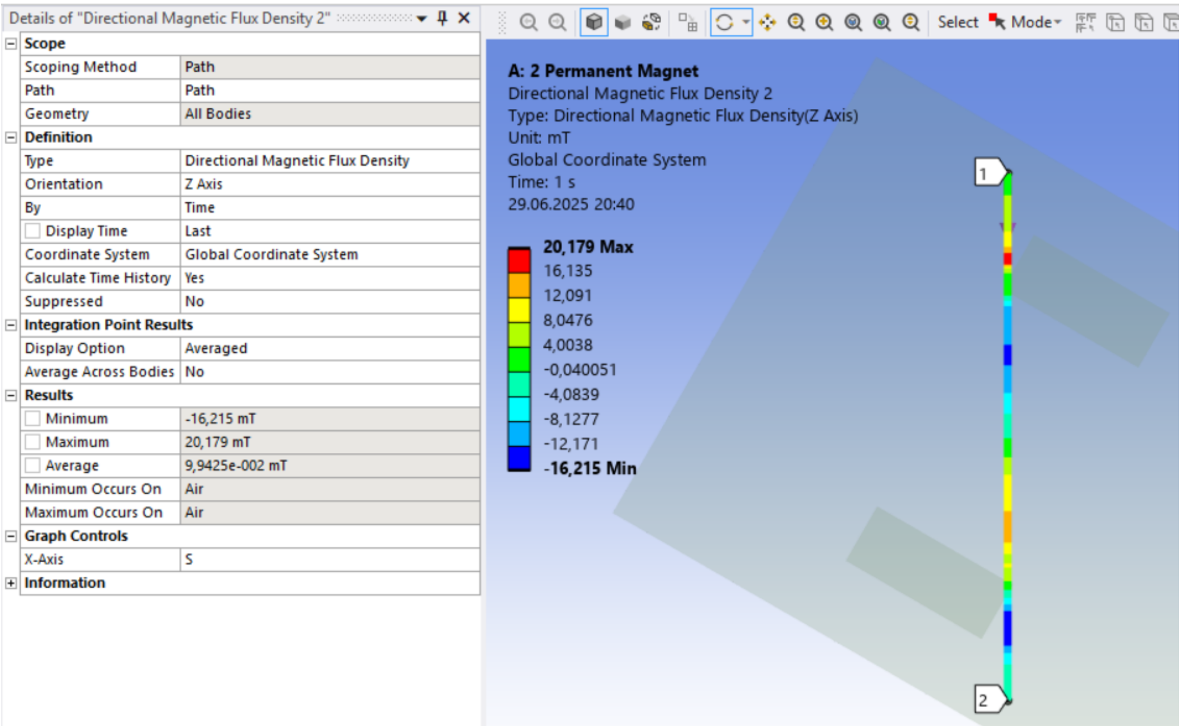


Figure 200 : Analysis of 30 Degree (+Z orientation)(2 Permanent Magnets, Opposite polarization)(x=4mm)

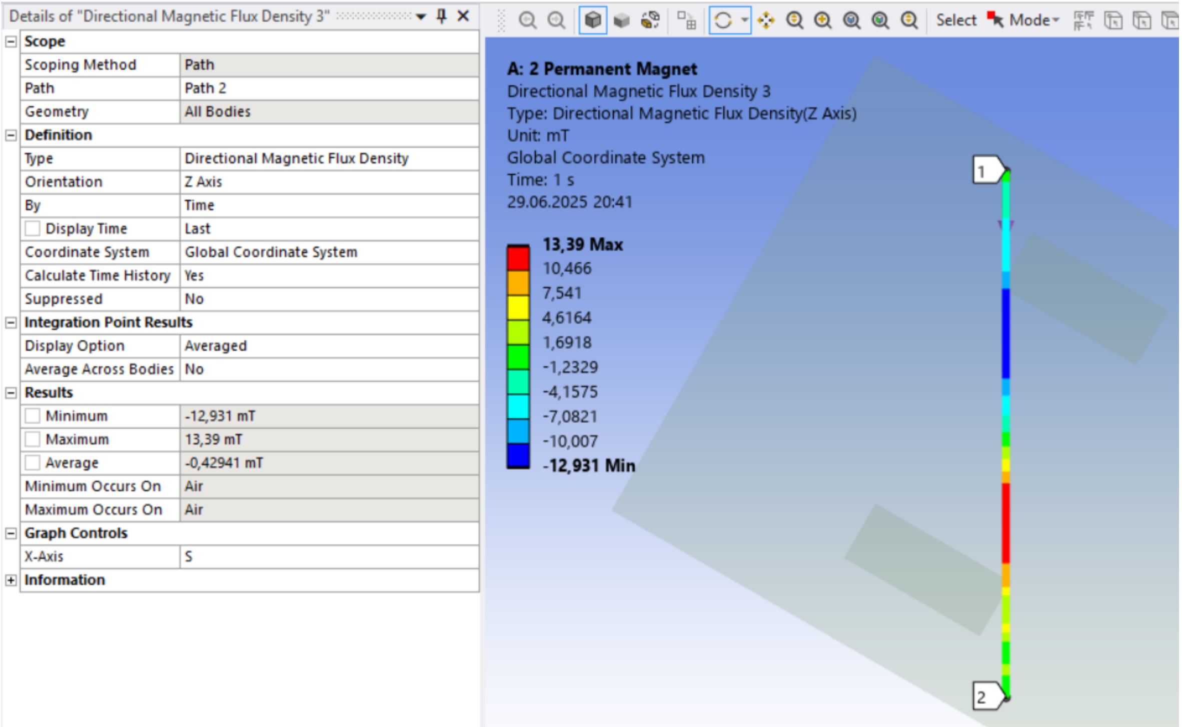


Figure 201 : Analysis of 30 Degree (+Z orientation)(2 Permanent Magnets, Opposite polarization)(x=8mm)

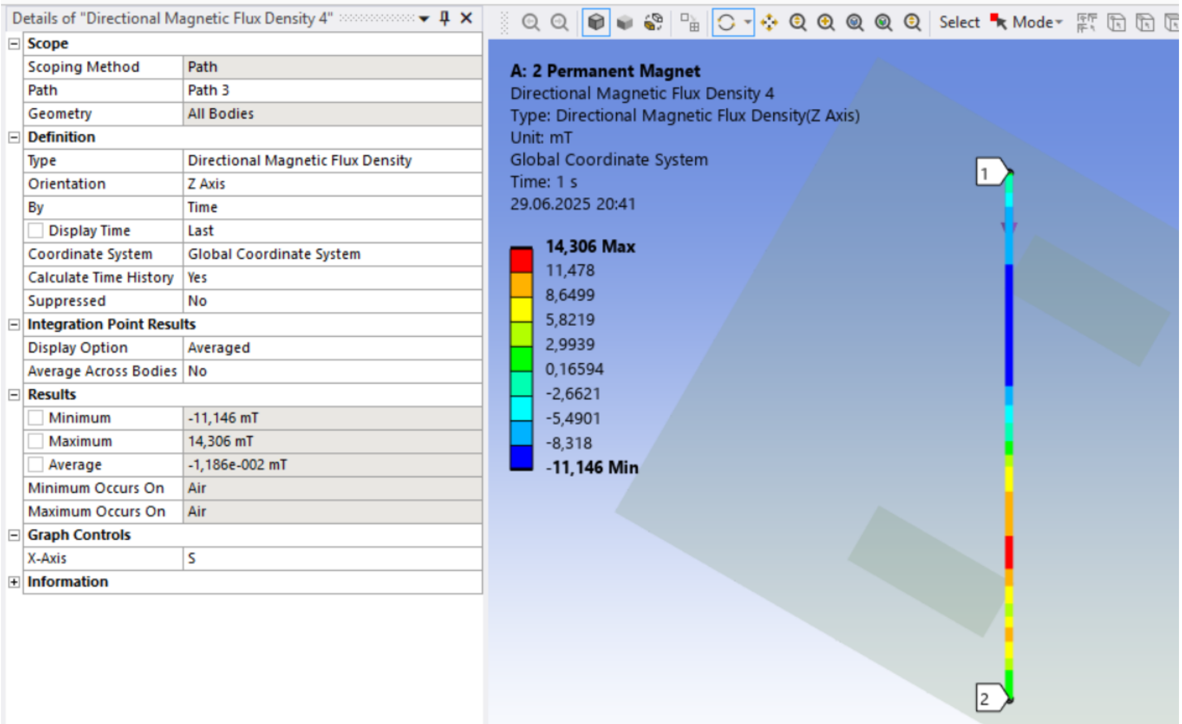


Figure 202 : Analysis of 30 Degree (+Z orientation)(2 Permanent Magnets, Opposite polarization)(x=12mm)

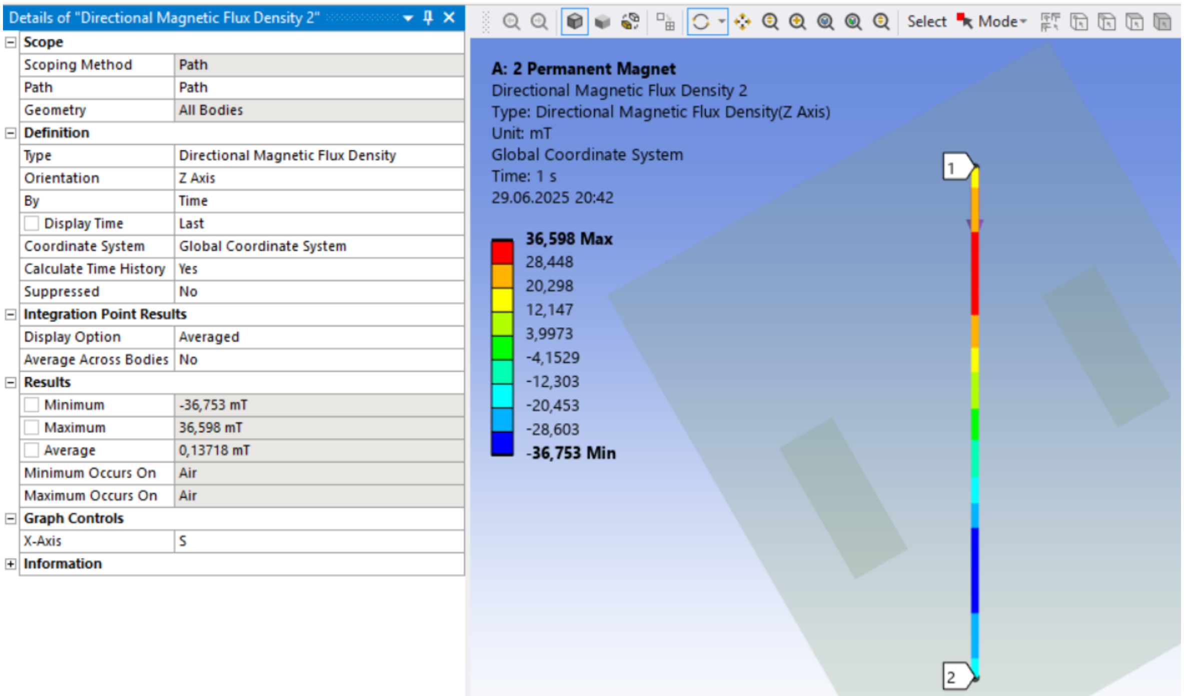


Figure 203 : Analysis of 60 Degree (+Z orientation)(2 Permanent Magnets, Opposite polarization)(x=4mm)

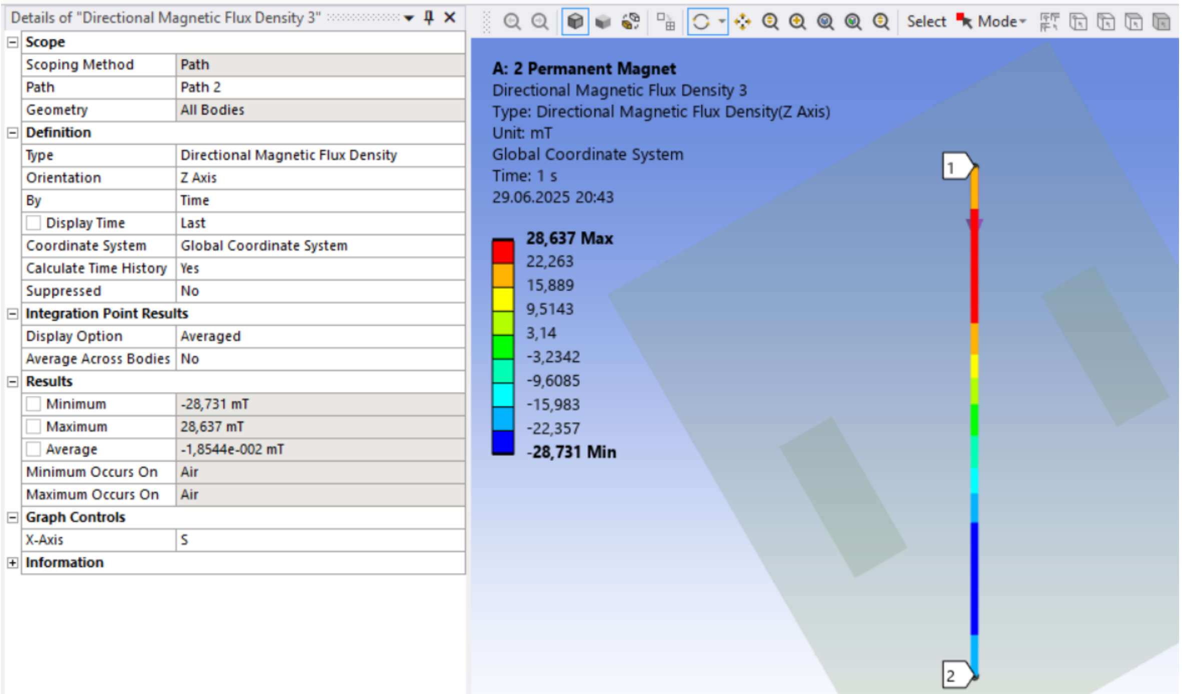


Figure 204 : Analysis of 60 Degree (+Z orientation)(2 Permanent Magnets, Opposite polarization)(x=8mm)

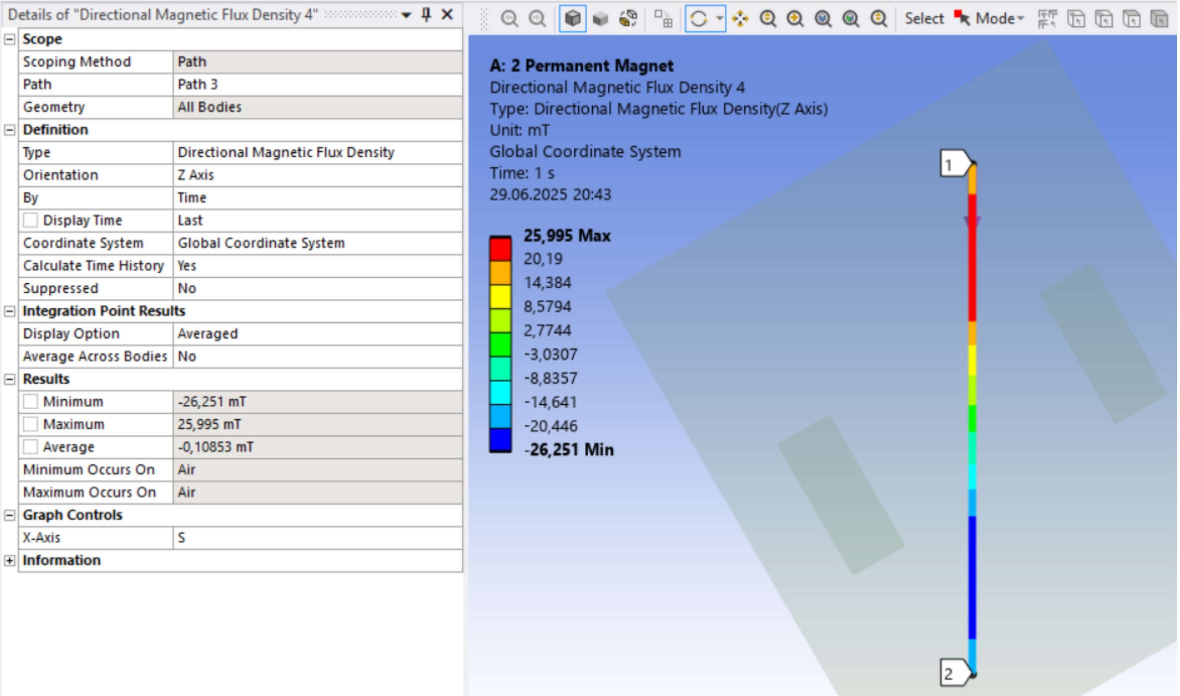


Figure 205 : Analysis of 60 Degree (+Z orientation)(2 Permanent Magnets, Opposite polarization)(x=12mm)

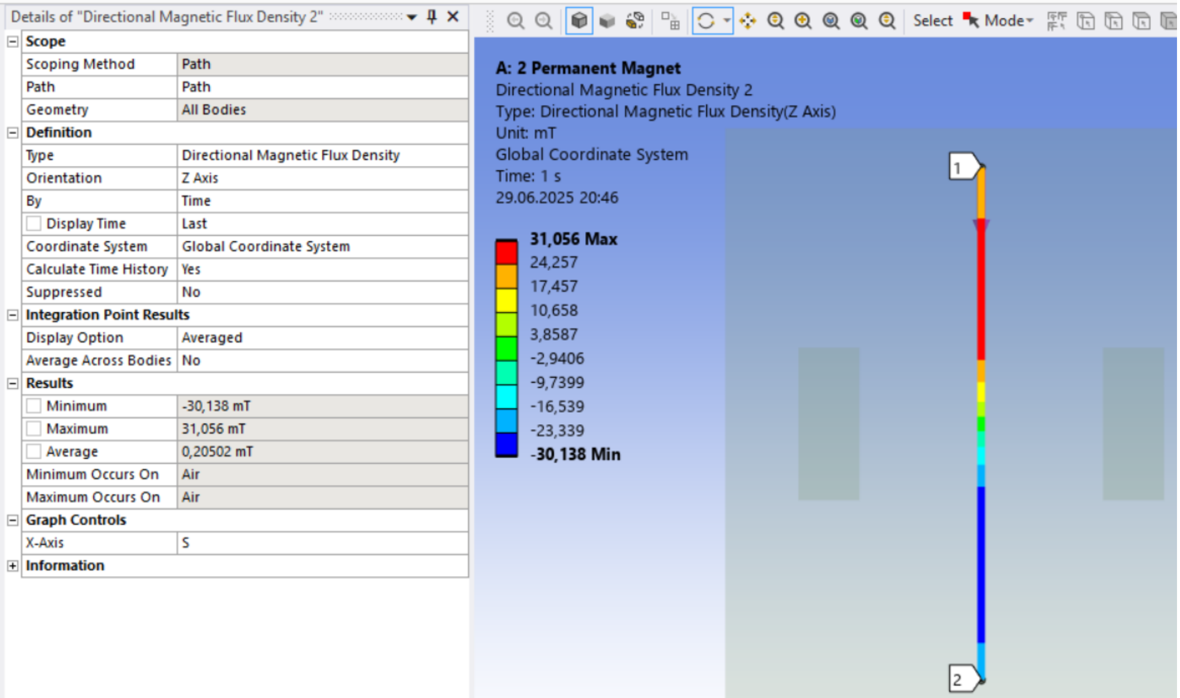


Figure 206 : Analysis of 90 Degree (+Z orientation)(2 Permanent Magnets, Opposite polarization)(x=4mm)

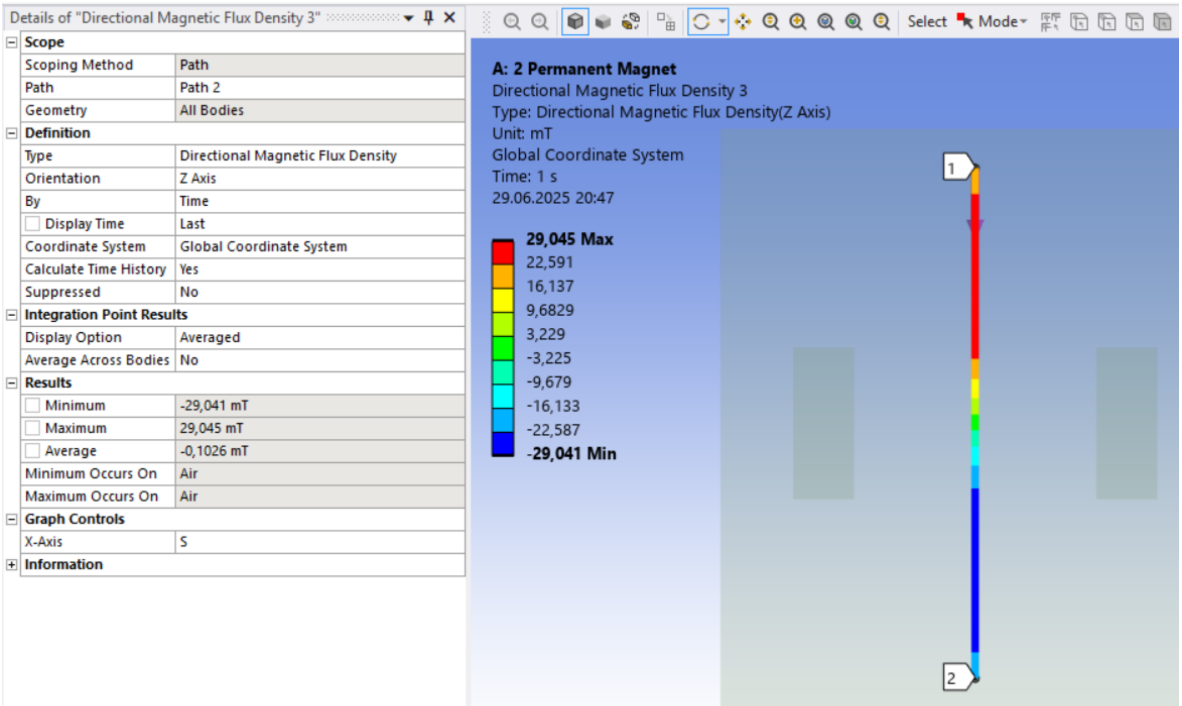


Figure 207 : Analysis of 90 Degree (+Z orientation)(2 Permanent Magnets, Opposite polarization)(x=8mm)

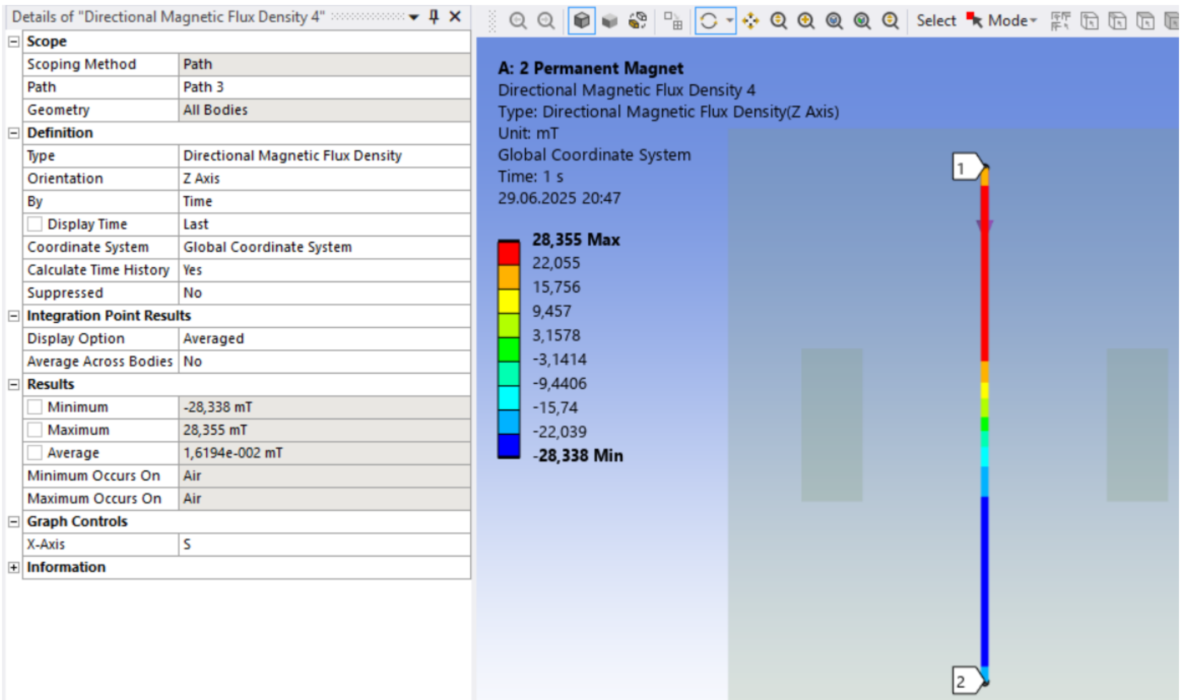


Figure 208 : Analysis of 90 Degree (+Z orientation)(2 Permanent Magnets, Opposite polarization)(x=12mm)

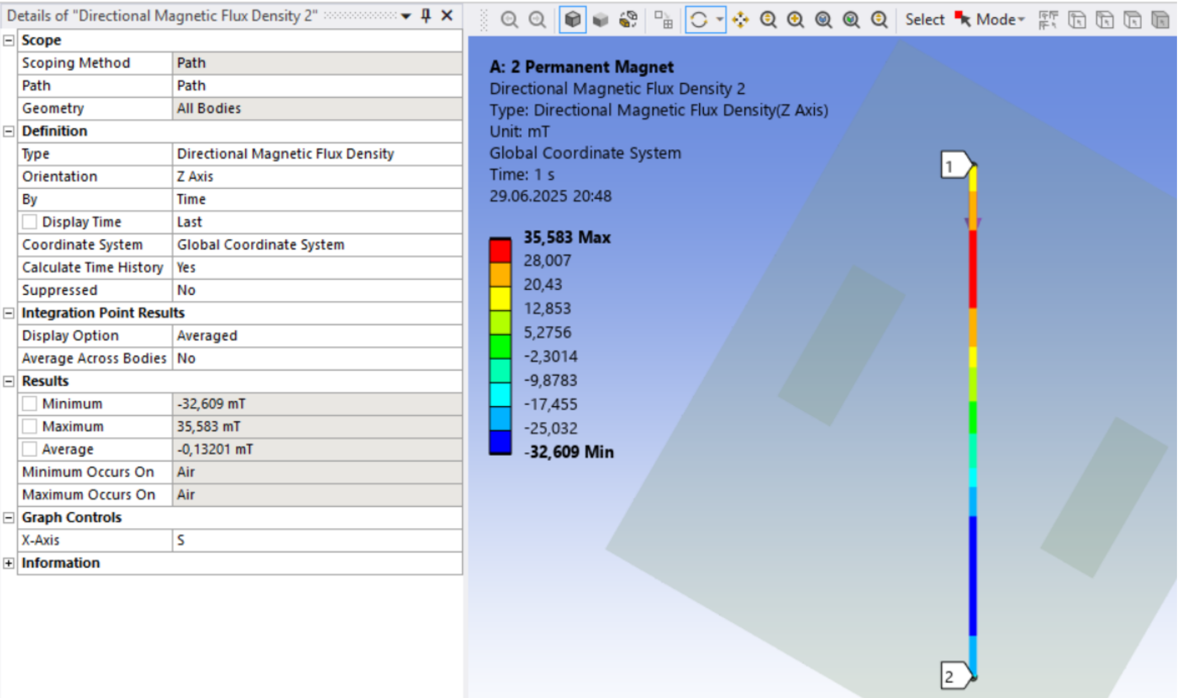


Figure 209 : Analysis of 120 Degree (+Z orientation)(2 Permanent Magnets, Opposite polarization)(x=4mm)

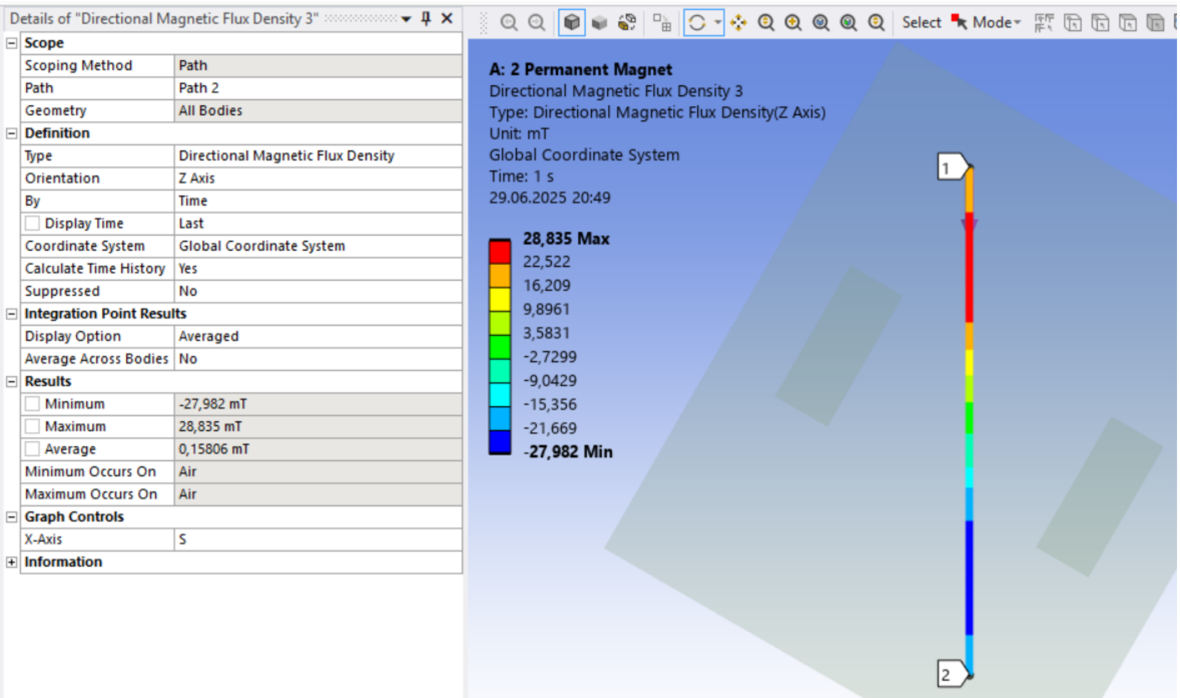


Figure 210 : Analysis of 120 Degree (+Z orientation)(2 Permanent Magnets, Opposite polarization)(x=8mm)

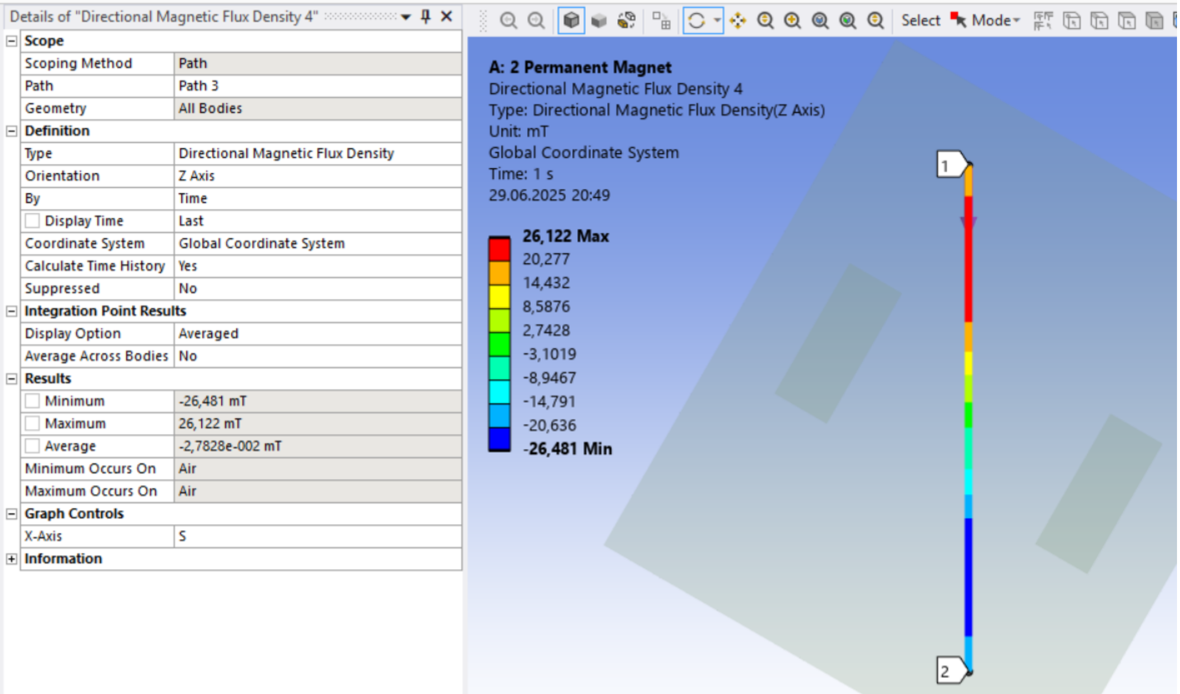


Figure 211 : Analysis of 120 Degree (+Z orientation)(2 Permanent Magnets, Opposite polarization)(x=12mm)

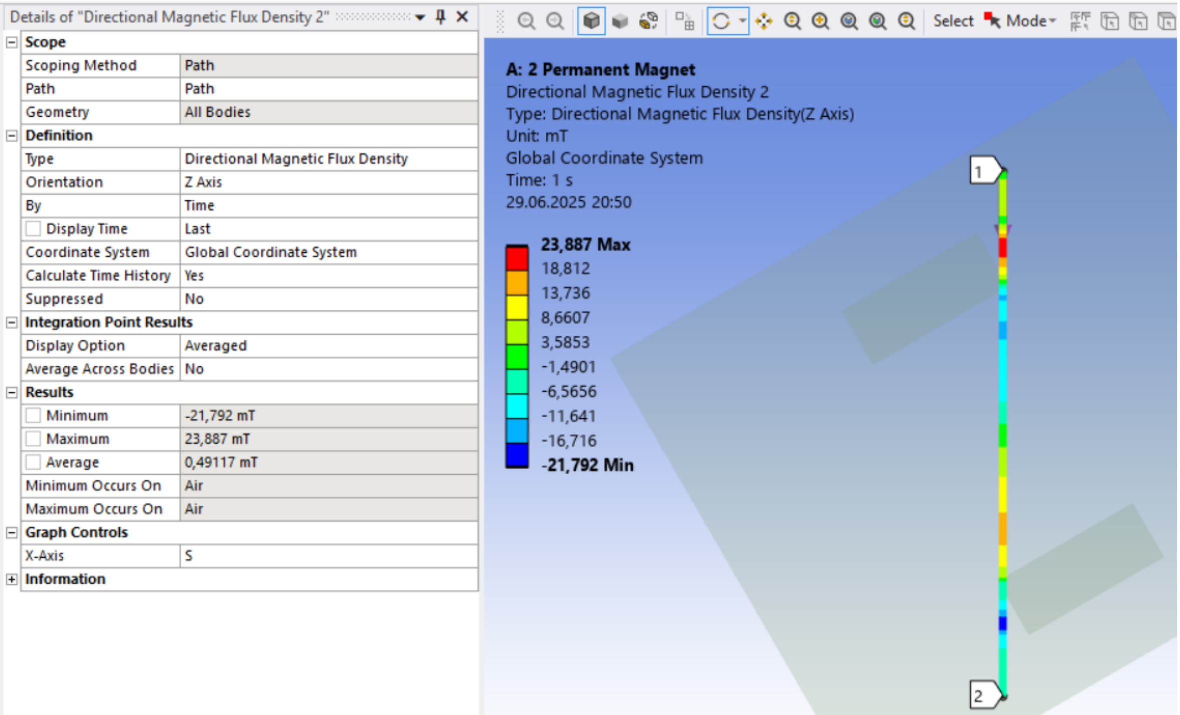


Figure 212 : Analysis of 150 Degree (+Z orientation)(2 Permanent Magnets, Opposite polarization)(x=4mm)

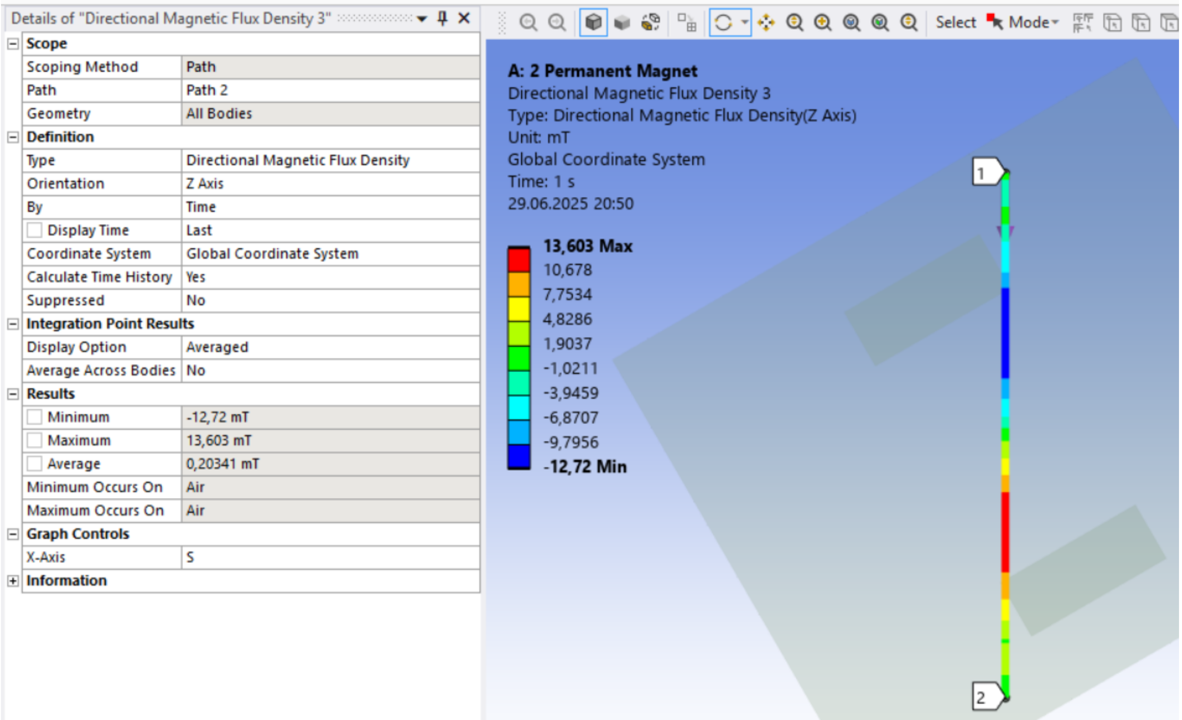


Figure 213 : Analysis of 150 Degree (+Z orientation)(2 Permanent Magnets, Opposite polarization)(x=8mm)

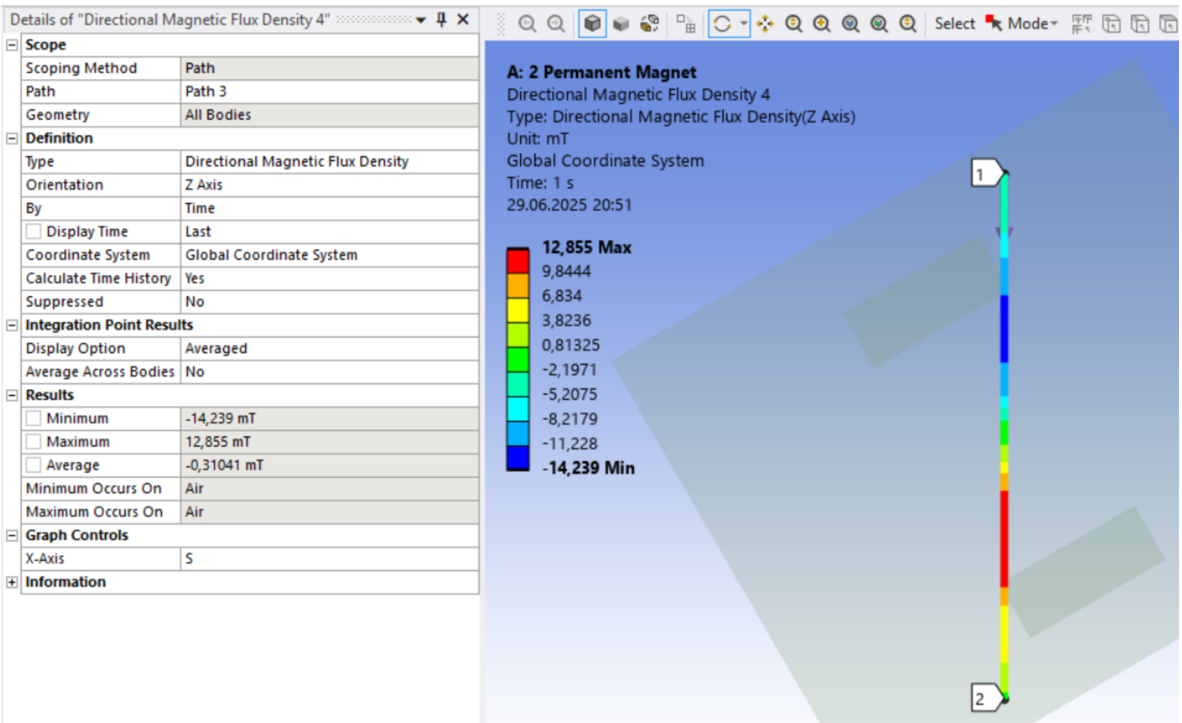


Figure 214 : Analysis of 150 Degree (+Z orientation)(2 Permanent Magnets, Opposite polarization)(x=12mm)

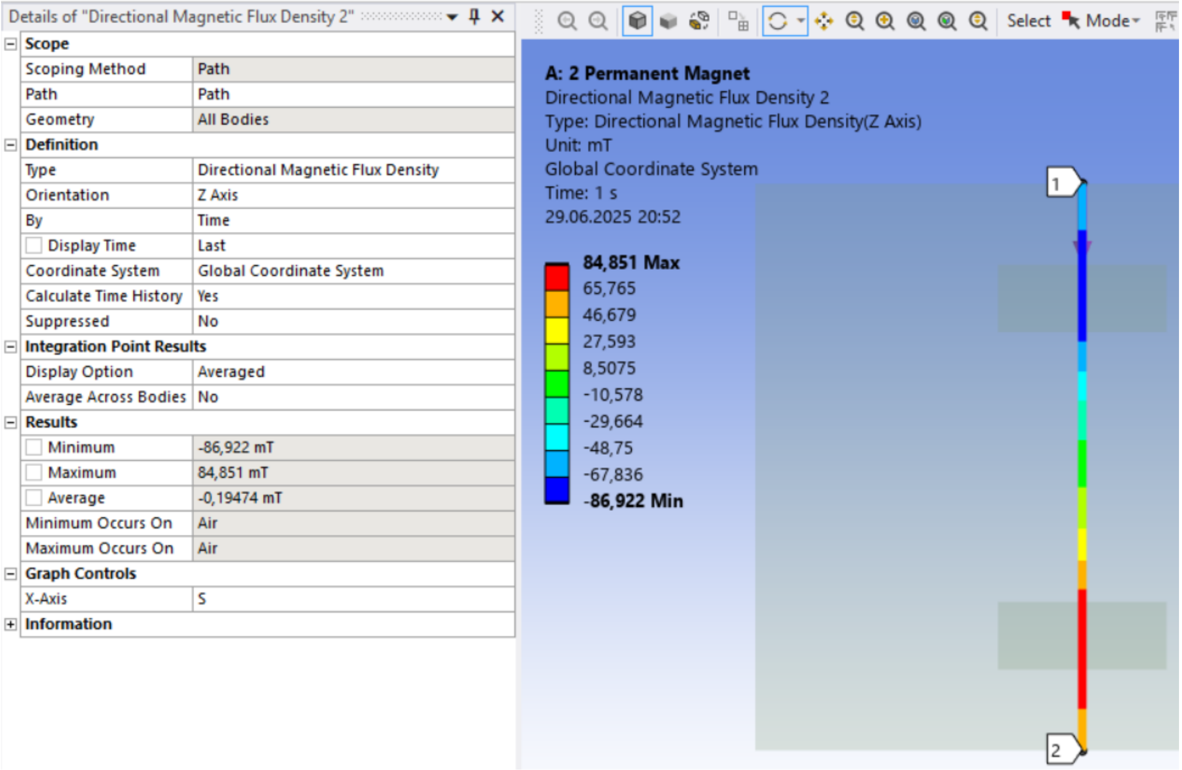


Figure 215 : Analysis of 180 Degree (+Z orientation)(2 Permanent Magnets, Opposite polarization)(x=4mm)

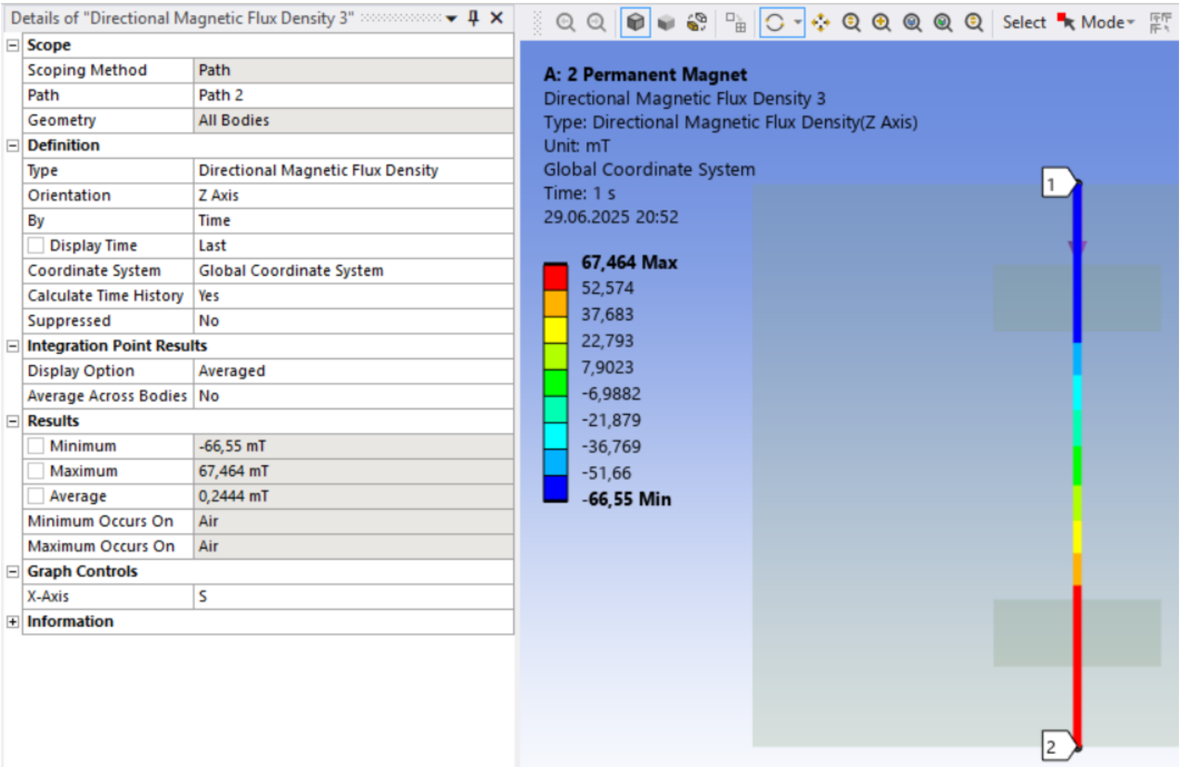


Figure 216 : Analysis of 180 Degree (+Z orientation)(2 Permanent Magnets, Opposite polarization)(x=8mm)

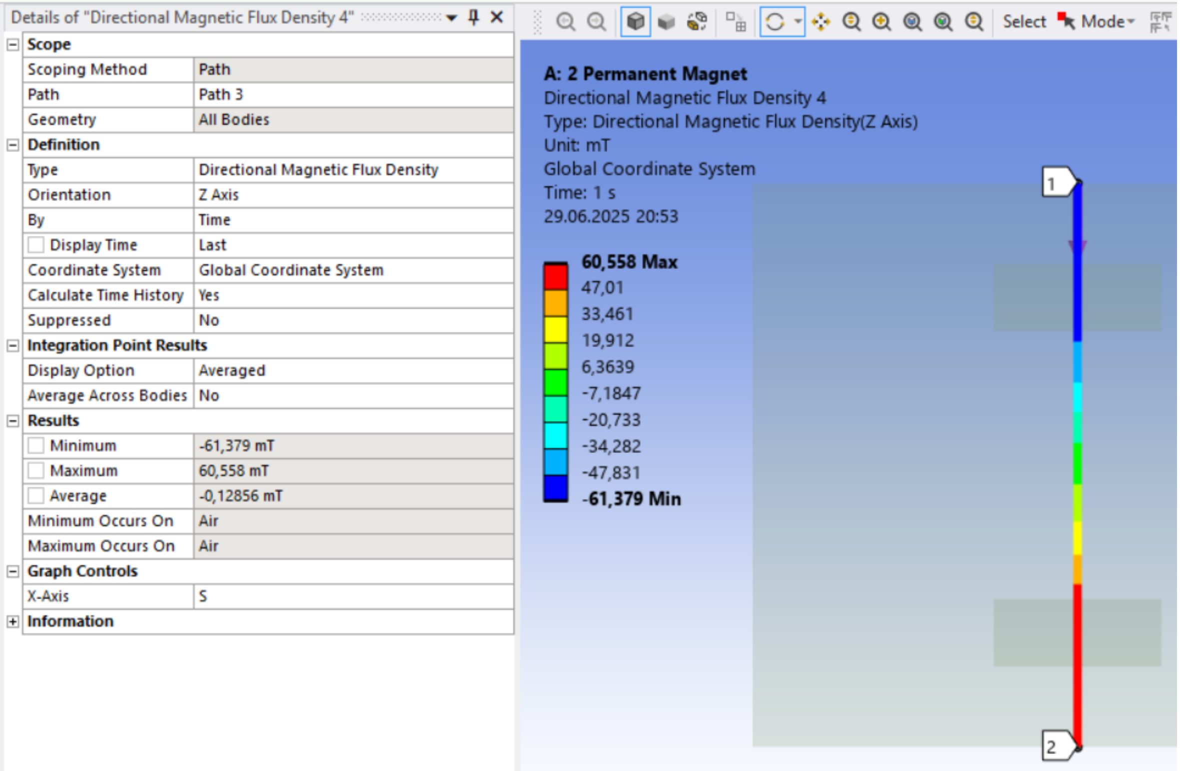


Figure 217 : Analysis of 180 Degree (+Z orientation)(2 Permanent Magnets, Opposite polarization)(x=12mm)

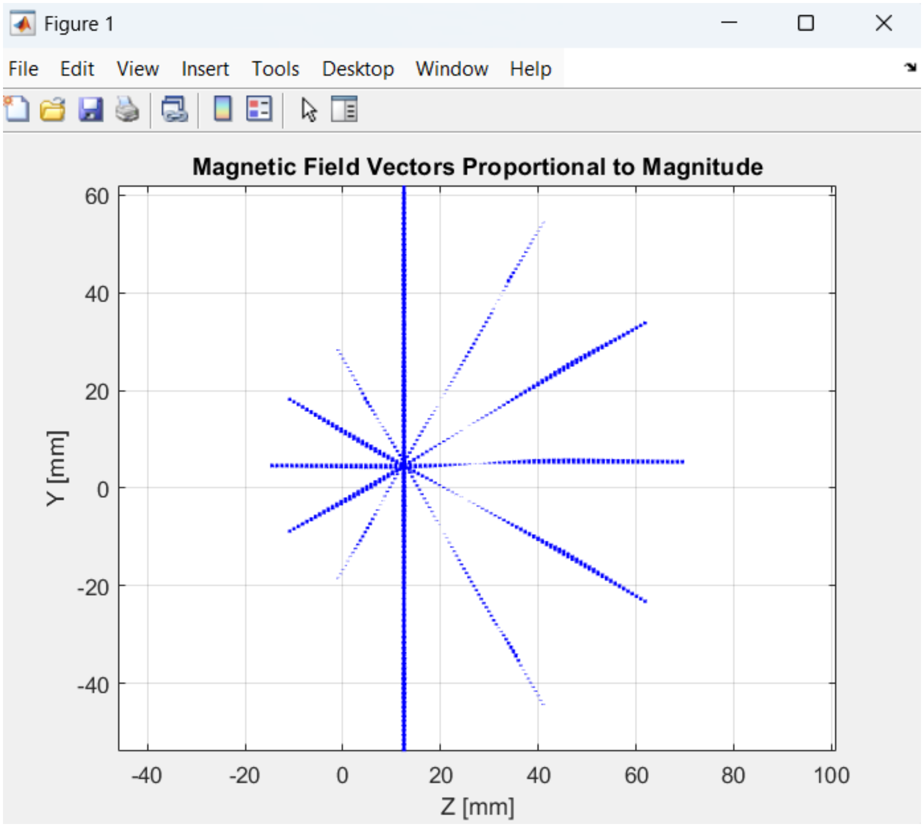


Figure 218 : Magnetic Field Vectors(Z direction) in path for Two Permanent Magnet (+Z polarization, opposite polarization)(x=4mm)

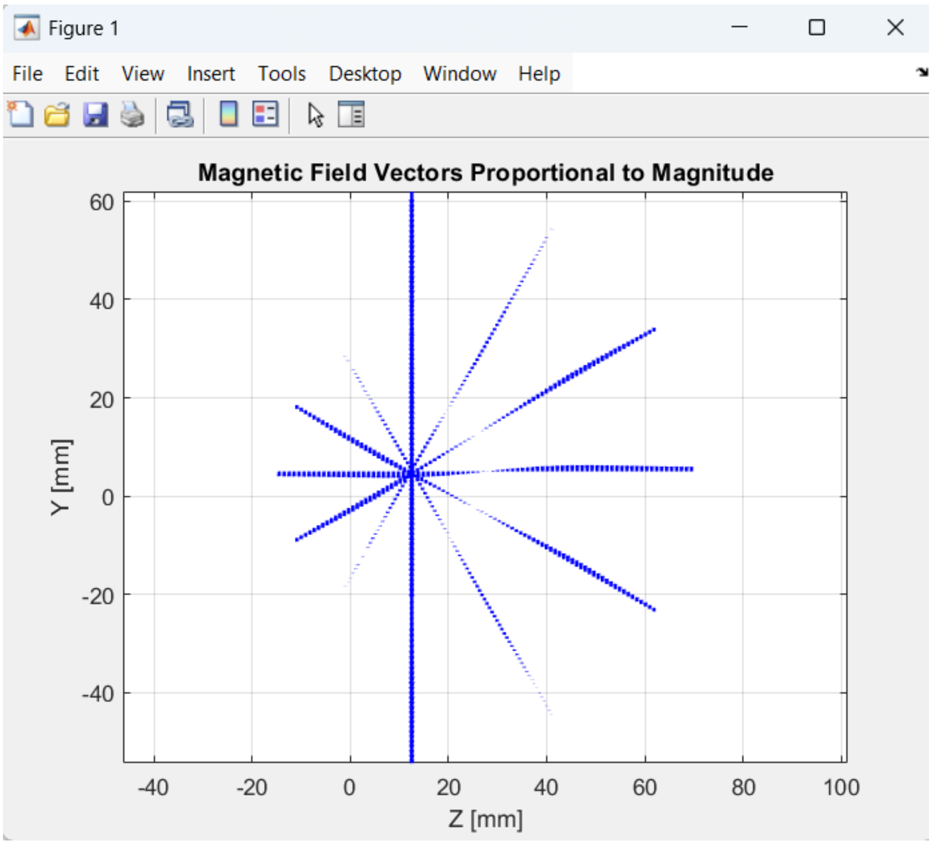


Figure 219 : Magnetic Field Vectors(Z direction) in path for Two Permanent Magnet (+Z polarization, opposite polarization)(x=8mm)

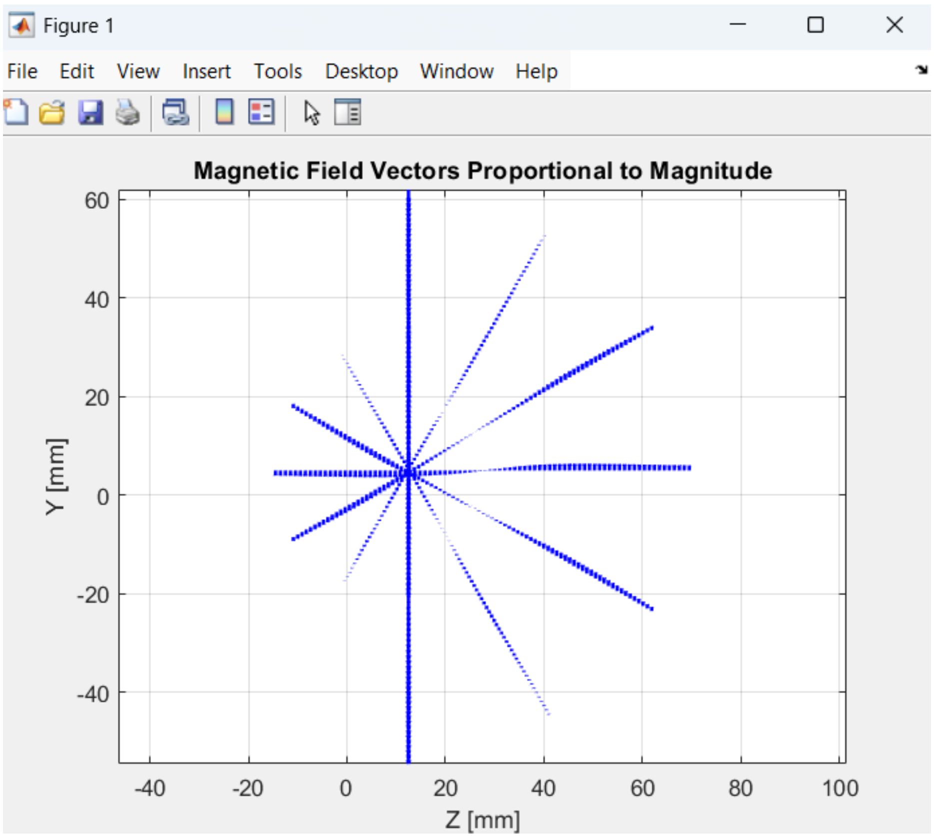


Figure 220 : Magnetic Field Vectors(Z direction) in path for Two Permanent Magnet (+Z polarization, opposite polarization)(x=12mm)

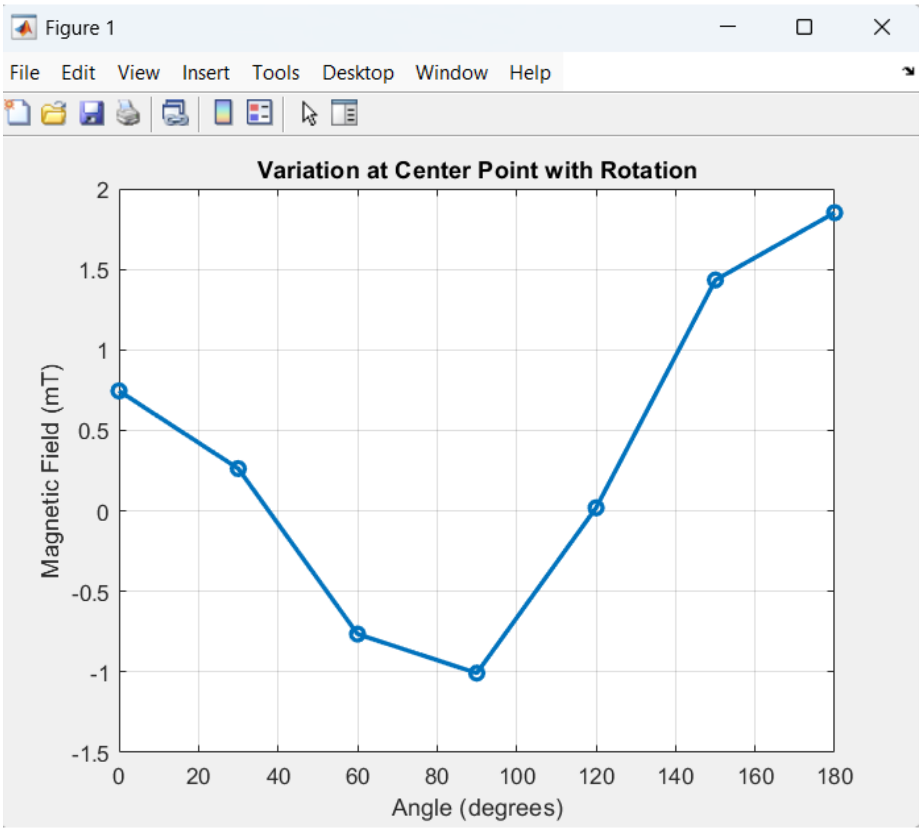


Figure 221 : Magnetic Field of center point (z Direction) of Two Permanent Magnet Model (+Z Polarization, opposite)(x=4mm)

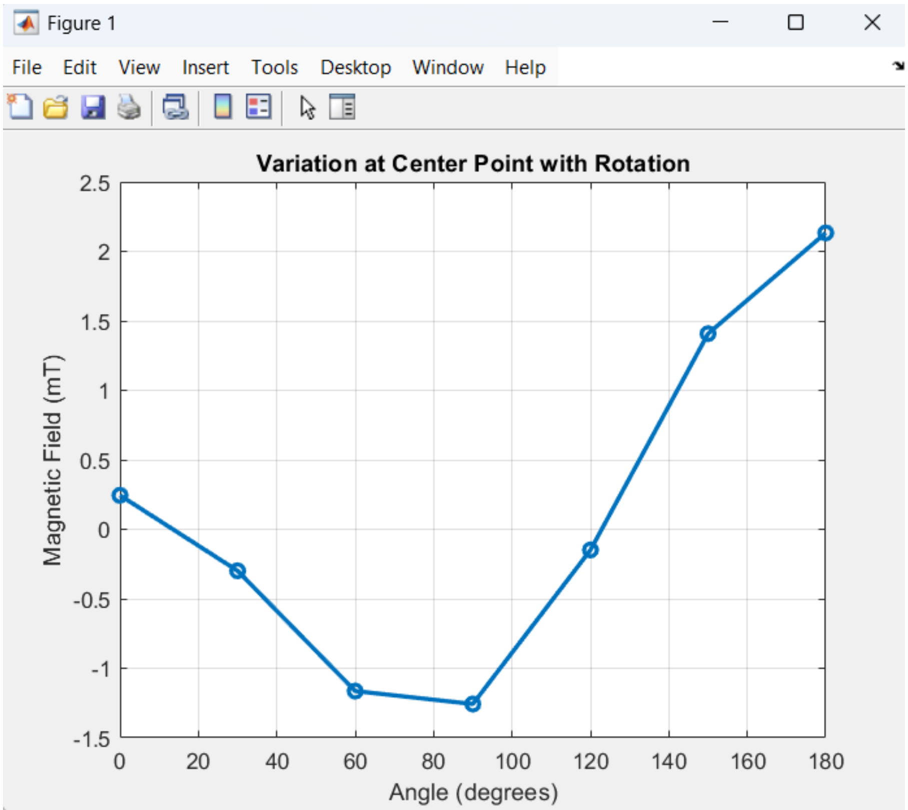


Figure 222 : Magnetic Field of center point (z Direction) of Two Permanent Magnet Model (+Z Polarization, opposite)(x=8mm)

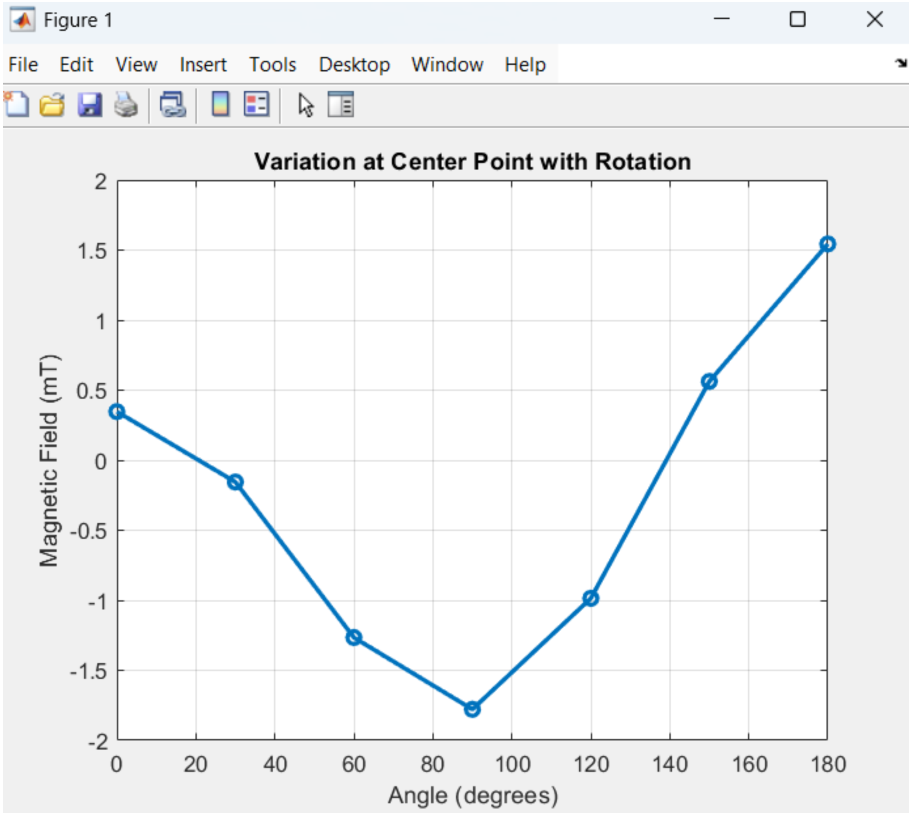
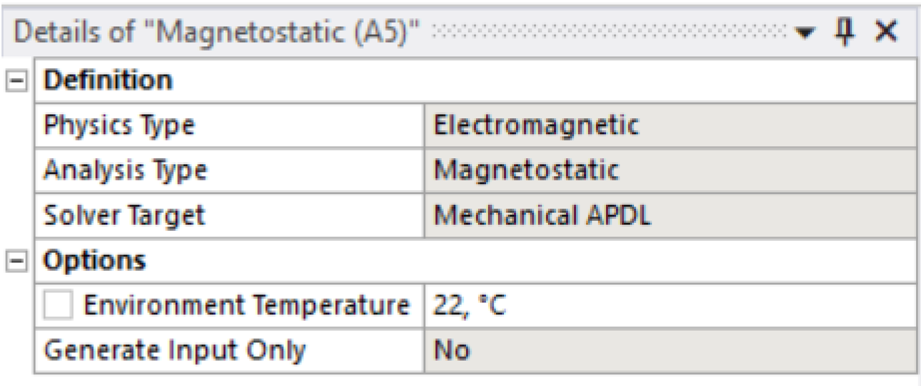


Figure 223 : Magnetic Field of center point (z Direction) of Two Permanent Magnet Model (+Z Polarization, opposite)(x=12mm)

In the results of the model where these permanent magnets are reverse polarized, we see that we have a magnetic field that can be said to be zero in the center and has a very little effect, and the magnetic field change at other points is not as much as we want.



Details of "Magnetostatic (A5)"

Definition	
Physics Type	Electromagnetic
Analysis Type	Magnetostatic
Solver Target	Mechanical APDL
Options	
Environment Temperature	22, °C
Generate Input Only	No

Figure 224 : Environment Temperature of Model

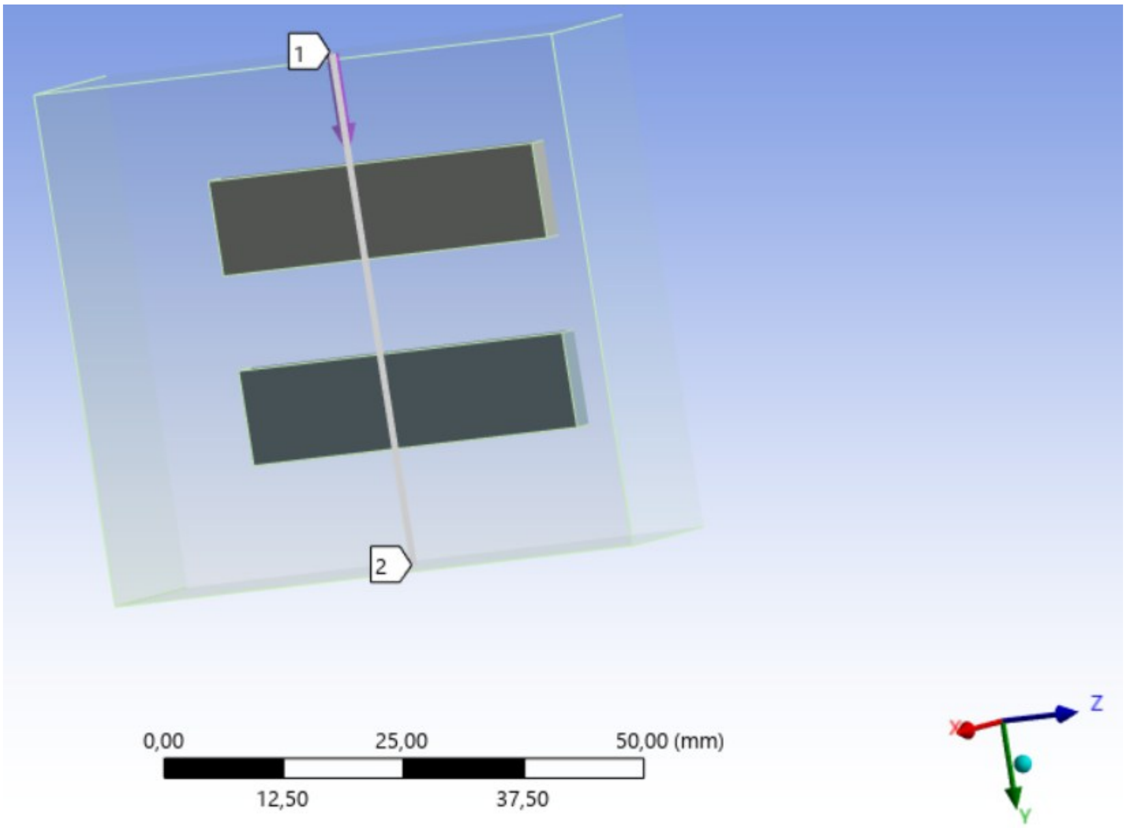


Figure 225 : Main coordinate system of my model and project

5. CONCLUSIONS

We have drawn some conclusions from the graphs we have created with the data we have obtained from our analyses. In this experiment, we took all the magnetic field values we took in the ANSYS, except for the measurements we made to verify our model in ANSYS, in the z direction, since the magnetic field direction that will provide the extension in the magnetostrictive material and allow us to get the value from the piezoelectric sensor is in the +z or -z direction. In order to see which polarization selection in the +z or -z direction (Magnetic field direction) would give better results, we performed our analyses in +Z, +Y and +X polarizations, respectively. Of course, in these analyses, we do not want very low (close to 0) or very high magnetic field values due to the strain-magnetic field graphs we examined in the introduction section. Because these values may give us a non-linear relationship and this may limit the angle measuring ability of our non-contact angle sensor. First, when we looked at a single permanent magnet, we obtained higher magnetic fields at closer distances. In this experiment, we may need to set up our experimental setup closer because we want the magnetic field to be of a certain size in the direction where the magnetostrictive material will extend. However, we do not want very high magnetic field values. Because we may reach saturation point. We also looked at different polarization patterns for a single permanent magnet. We can decide that +X polarization is the worst polarization in terms of measuring angles and obtaining data due to the magnetic field properties. The reason we say this is that the data in my analysis in +X polarization are very irregular and very close to zero at some points. At the same time, we can see that a permanent magnet with +Y polarization will give good results at points close to the center, because the magnetic field values are high and the magnetic field changes are obvious. However, since the amount of magnetic field decreases a lot as we move away from the center and the change decreases a lot, we can say that +Y polarization is a bad choice at points far from the center. In +Z polarization, we have seen that it can be more advantageous because we have a certain magnetic field magnitude both in the center and away from the center and the change of this magnetic field is smooth. And we also have negative and positive magnetic fields. So, based on the graphs we obtained, if we are not going to move this angle sensor more than 15 mm away from the center in the y and z axes, we can use an N35 permanent magnet with +Y polarization. But if we want to establish the angle force relationship both close to the center and far away, it would be more appropriate to use an N35 permanent magnet with +Z polarization. Of course, this will make it easier for us to get logical data from our sensor. We have an N35 permanent magnet with +Z polarization in our experimental setup. In fact, although we have N30 permanent magnets with +X polarization in this experimental setup, we will not continue our further analysis with them because we saw from our Ansys model that they will not give us the results we want and will not work in the sensor we designed. According to the results we obtained from here, we decided that +Z polarization has a better magnetic field distribution in general, so I used Z polarization in two permanent magnet models. When we looked at our models containing two permanent magnets, we saw that the model with the same polarization (The polarization of the two magnets is in the +Z direction) gave us useful results and good results in measuring angles, while the model with opposite polarization (one magnet's polarization is in the +Z direction, the other in the -Z direction) gave very irregular and almost zero magnetic field values. But if we look at it in general, we see that single magnet models, especially N35 permanent magnets with +Z and +Y polarizations, give more proper and understandable results than the analyzes where we have two permanent magnets.

6. REFERENCES

[1] "wikipedia," [Online]. Available: https://en.wikipedia.org/wiki/Magnetic_field.

[2] A. Olabi and A. Grunwald, *Design and application of magnetostrictive materials,* 2006.

[3] Z.-Y. Si, L.-J. Q. Xian-Xu Bai ve W.-M. Zhong, «An enhanced Duhem model of magnetostrictive material-based actuators,» 2019.

[4] M. C. Sekhar, E. Veena, N. S. Kumar, *. C. B. Naidu, *. A. Mallikarjuna and D. B. Basha*, *A Review on Piezoelectric Materials and Their Applications,* 2022.

[5] "Ansys," [Online]. Available: https://www.ansys.com/academic/students/ansys-student.

[6] "Ansys," [Online]. Available: https://www.ansys.com/products/structures/ansys-mechanical.

[7] "byjus," [Online]. Available: https://byjus.com/physics/magnetic-moment/.

7. APPENDIX

Code for Rotation

```
% Read the Excel file
filename = '2magnetx12mm-zpolarizationopposite0degree.xls.xlsx';
data = readtable(filename);

% Extract Y and Z coordinates (columns 3 and 4)
y = data{:, 3};
z = data{:, 4};

% Center of the original shape (in mm)
y_center = 5;
z_center = 12.5;

% Convert to relative coordinates (centered)
y_rel = y - y_center;
z_rel = z - z_center;

% Dummy x values (not used but required for 3D rotation)
x = zeros(size(y_rel));

% Define rotation angles (degrees)
angles = 0:30:180;

% Store results
rotated_all = [];

for theta_deg = angles
    theta_rad = deg2rad(theta_deg);  % Convert to radians

    % Rotation matrix around X-axis
    R = [1, 0, 0;
         0, cos(theta_rad), -sin(theta_rad);
         0, sin(theta_rad),  cos(theta_rad)];

    % Rotate relative coordinates
    original_coords = [x, y_rel, z_rel]';  % 3 x N
    rotated_coords = R * original_coords;  % 3 x N

    % Convert back to absolute positions (shift to center)
    y_rot = rotated_coords(2,:)' + y_center;
    z_rot = rotated_coords(3,:)' + z_center;

    % Combine with angle
    yz_rotated = [y_rot, z_rot, repmat(theta_deg, length(y), 1)];

    % Append
    rotated_all = [rotated_all; yz_rotated];
end

% Create table and export
rotated_table = array2table(rotated_all, ...
    'VariableNames', {'y_rotated', 'z_rotated', 'angle_deg'});

writetable(rotated_table, 'rotated_yz_corrected.xlsx');
```

```
disp('Rotation complete. Output saved to rotated_yz_corrected.xlsx');
Code for first point of path

% Get the number of rows (points) in one path table
N = size(x4mmypolarization0degree, 1);

% Assume all pathnew tables (permanentmagnet4mm to permanentmagnet4mm13) have
the same structure
% Combine rows from each table in interleaved order:
% e.g., [permanentmagnet4mm(1,:); permanentmagnet4mm2(1,:); ... ;
permanentmagnet4mm(2,:); permanentmagnet4mm2(2,:); ...]

combinedData = [];

for i = 1:N
    combinedData = [combinedData;
        x4mmypolarization0degree(i,:);
        x4mmypolarization30degree(i,:);
        x4mmypolarization60degree(i,:);
        x4mmypolarization90degree(i,:);
        x4mmypolarization120degree(i,:);
        x4mmypolarization150degree(i,:);
        x4mmypolarization180degree(i,:)];
end

% Extract columns: Assuming the structure [index, X, Y, Z, B]
X = combinedData(:,2);
Y = rotated_table(:,1);
Z = rotated_table(:,2);
B = combinedData(:,5);

% Ensure columns are numeric (convert from table if needed)
Y = table2array(rotated_table(:,1));
Z = table2array(rotated_table(:,2));
B = table2array(combinedData(:,5));

% Define vector components for quiver plot
U = zeros(size(B));  % Horizontal component (zero)
V = B;               % Vertical component (proportional to magnetic field)

% Plot the vector field (quiver plot)
figure;
quiver(Z, Y, U, V, 0.5, 'b', 'LineWidth', 1.5);  % 0.5 = scale factor
xlabel('Z [mm]');
ylabel('Y [mm]');
title('Magnetic Field Vectors Proportional to Magnitude');
axis equal;
grid on;
% --- Plot B field variation for each point over angular steps ---

% Assume each point has 7 measurements (0°, 30°, ..., 180°)
num_steps = 7;
num_points = size(B, 1) / num_steps;

% Validate the total number of rows is divisible by 7
if mod(size(B,1), num_steps) ~= 0
    error('Total number of rows is not divisible by 7.');
end
```

```
% Define angles in degrees
angles = 0:30:180;

% Define subplot grid layout (e.g., 10 rows x 9 columns = 90 points)
rows = 10;
cols = 9;

% Create a large figure with subplots
figure('Units','normalized','Position',[0.05 0.05 0.9 0.9]);
for i = 1:num_points
    idx_start = (i-1)*num_steps + 1;
    idx_end = i*num_steps;
    Bi = B(idx_start:idx_end);  % B values for one point at different angles

    subplot(rows, cols, i);
    plot(angles, Bi, '-o', 'LineWidth', 1.2);
    title(sprintf('Point %d', i));
    xlabel('Angle [°]');
    ylabel('|B| [T]');
    grid on;
end

% Add a super title for the full figure
sgtitle('Angular Variation of Magnetic Field for All Points');

% --- Plot angular B variation for the first point only ---

idx_start = 1;
idx_end = num_steps;
Bi_first = B(idx_start:idx_end);

figure;
plot(angles, Bi_first, '-or', 'LineWidth', 2);
xlabel('Angle [°]');
ylabel('|B| [mT]');
title('Angular Variation of Magnetic Field at the First Point');
grid on;
xlim([0 180]);
```

Code for center point of path

```
% Clear workspace
clear all; clc;

% Define the angles and filenames
angles = 0:30:180;
numAngles = length(angles);
values = zeros(1, numAngles);  % To store the value at row 43

% Loop through all angle files
for i = 1:numAngles
    angle = angles(i);
    % Construct filename - adjust this to match your actual naming convention
    filename = sprintf('2magnetx12mm-zpolarizationopposite%ddegree.xls.xlsx',
angle);

    % Read the Excel file
    data = readtable(filename);
```

```
    % Extract the 43rd row and desired column (adjust column index if needed)
    % Example: column 5
    values(i) = data{43, 5};
end

% Plotting
figure;
plot(angles, values, '-o', 'LineWidth', 2);
xlabel('Angle (degrees)');
ylabel('Magnetic Field (mT)');
title('Variation at Center Point with Rotation');
grid on;
```