

1 Preamble - Download Python before you arrive

In this workshop, you will model the magnetic field produced by a simple solenoid and eventually (hopefully) model the magnetic field produced by a tokamak, starting with STEP. Durham has developed a bespoke Python code application called “Fusion Magnet Engineering Workshop” that will allow you to do this.

It is best to download Python before you arrive (in case of permission issues that need to be resolved). The version of Python required is v3.13 (do not install a newer version).

2 Installation

2.1 Download python installer

- a) Go to the official Python website (<https://www.python.org/downloads/windows/>) and click on the Python 3.13.15 link, which looks like this,

Stable Releases

- Python 3.13.15 - Aug. 5, 2026

Note that Python 3.13.15 *cannot* be used on Windows 7 or earlier.

- b) Scroll down the page (if necessary) and click on the Python install manager for your operating system.

Files

macOS

Download macOS installer

Windows

Download Python install manager

Source release

Download XZ compressed source tarball

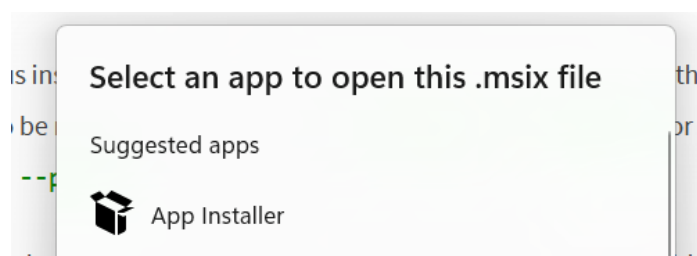
- c) Then click “Download Installer” for your operating system. The one for Windows is shown here.

Files

Windows

Download Installer (MSIX)

- d) If you’re using Windows, you might need to use the app installer.



- e) Allow Python to be added to your path but **DO NOT** install CPython!
- f) Go to the Command prompt (to do this click “Start” and search for “Command Prompt”) and type: **py install 3.13** - *note that instead of typing the commands given in this document, feel free to copy and past them into the Command Prompt.*

2.2 Download ‘Fusion Magnet Engineering Workshop’

Download the zip file “Fusion Magnet Engineering Workshop.zip” from the Icy Durham Practical Course website – once downloaded it should appear in the “Downloads” folder in File Explorer. Right-click the zip file and select “Extract All”. Choose a location to extract it to – for simplicity, choose “This PC” (directory C:\).

In “Command Prompt” type **cd C:\Fusion Magnet Engineering Workshop** (this is the directory that contains main.py, which will run the app). This directory should now appear in the Terminal prompt.

2.3 Create virtual environment

The application only works with Python 3.13 and this must be run in a virtual environment. To create this environment type **py -3.13 -m venv .venv** (make sure to include the spaces). Then type **.venv\Scripts\activate** to activate the virtual environment. Typing **python --version** checks that the Python version is indeed 3.13.

2.4 Install packages

Type **python -m pip install numpy scipy matplotlib** to install the necessary packages required to run the application.

2.5 Set tkinter

tKinter is a Graphical User Interface package for Python. This Python application only works with tkinter 8.6 – we will check it is in principle available. Again, using the Command Prompt, type, **python -c "import tkinter; print(tkinter.TkVersion); print(tkinter.TclVersion)" – 8.6**. This should result in “8.6” being printed to the screen.

Type **py -3.13 -c "import sys; print(sys.base_prefix)"** to find where python 3.13 is installed on your device. Suppose it prints **C:\FILEPATH** (where this should be replaced by whatever path is printed to your screen) - type:

```
set TCL_LIBRARY=C:\FILEPATH\tcl\tcl8.6
```

Then type,

```
set TK_LIBRARY=C:\FILEPATH\tcl\tk8.6
```

This will set the app to use tkinter version 8.6. Note: there are no spaces in these two commands.

Type **python main.py** to run the app, and you are now ready to go.

3 Introduction

In this workshop, you will:

- i) Create a model of a simple multi-turn copper solenoid, analyse the field profile, and eventually think creatively and connect what you have learnt with Ampere’s law.
- ii) Investigate the field profile of a fusion tokamak.
- iii) Replace the copper turns of the solenoid with high temperature superconducting (HTS) turns and investigate the effect on the magnetic field from changing the solenoid’s geometry.

4 Modelling a copper solenoid coil

4.1 Set up the model

The app is initially set up to model a solenoid with the following default characteristics,

- a) an *inside* radius, $r_{in} = 20$ mm (40 mm bore diameter)
- b) an *outside* radius, $r_{out} = 30$ mm (10 mm coil thickness)
- c) and *length*, $L = 80$ mm

The solenoid will be made of copper wire with a cross-sectional area of 1.0 mm^2 , which at room temperature carries ~ 11 A.

Figure 1 provides a brief overview of what the app's main screen represents and Figure 2 shows the initial main screen when you first open the app.

We have a visible outer boundary, which represents the extents of the computational domain. All space outside of this boundary will be ignored. We then have a horizontal z-axis at the bottom that is aligned with the central axis of the solenoid. Here, we only deal with a cross-section of the solenoid where the turns of the solenoid rotate about the z-axis. Using the app we can change the dimensions and position of the solenoid cross-section and the characteristics of the turns.

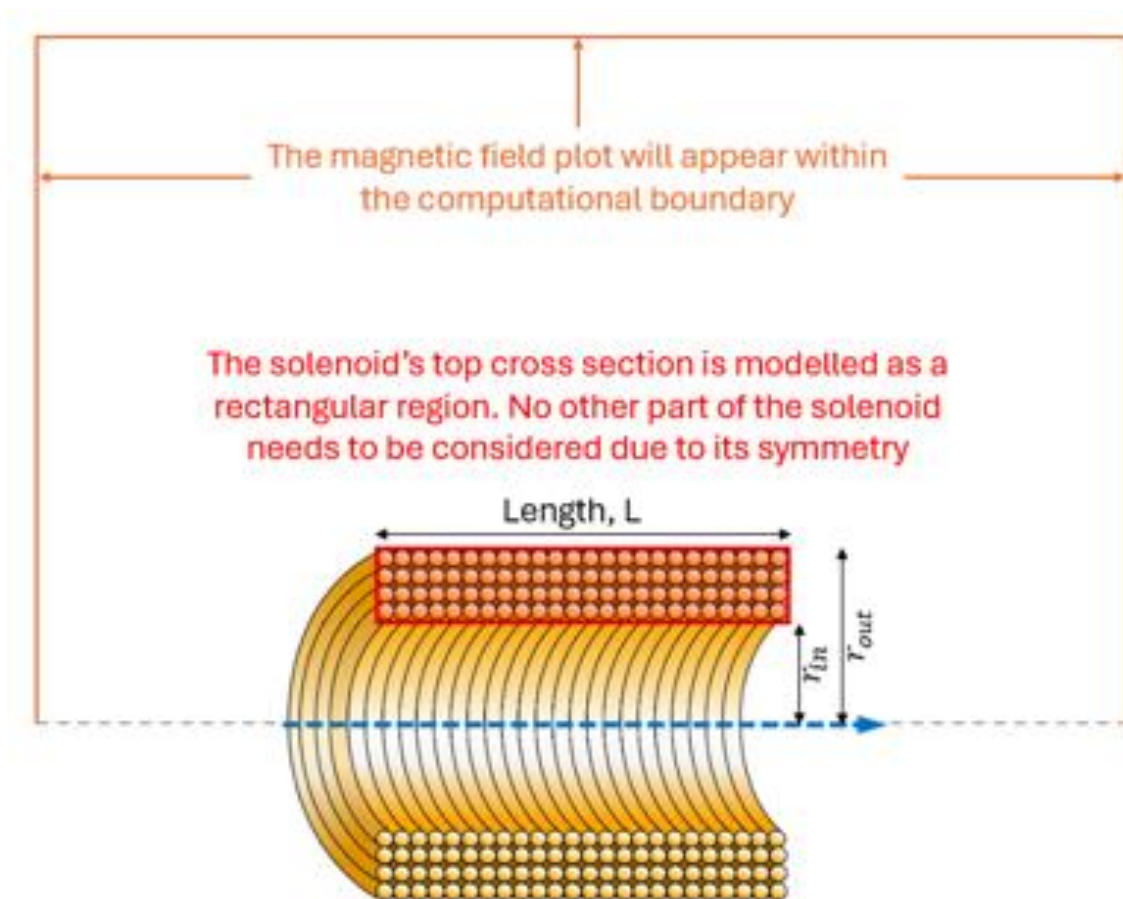


Figure 1: The main definitions of the model; the computational domain (everything within the outer boundary), the *boundary* and the *solenoid's cross-section*.

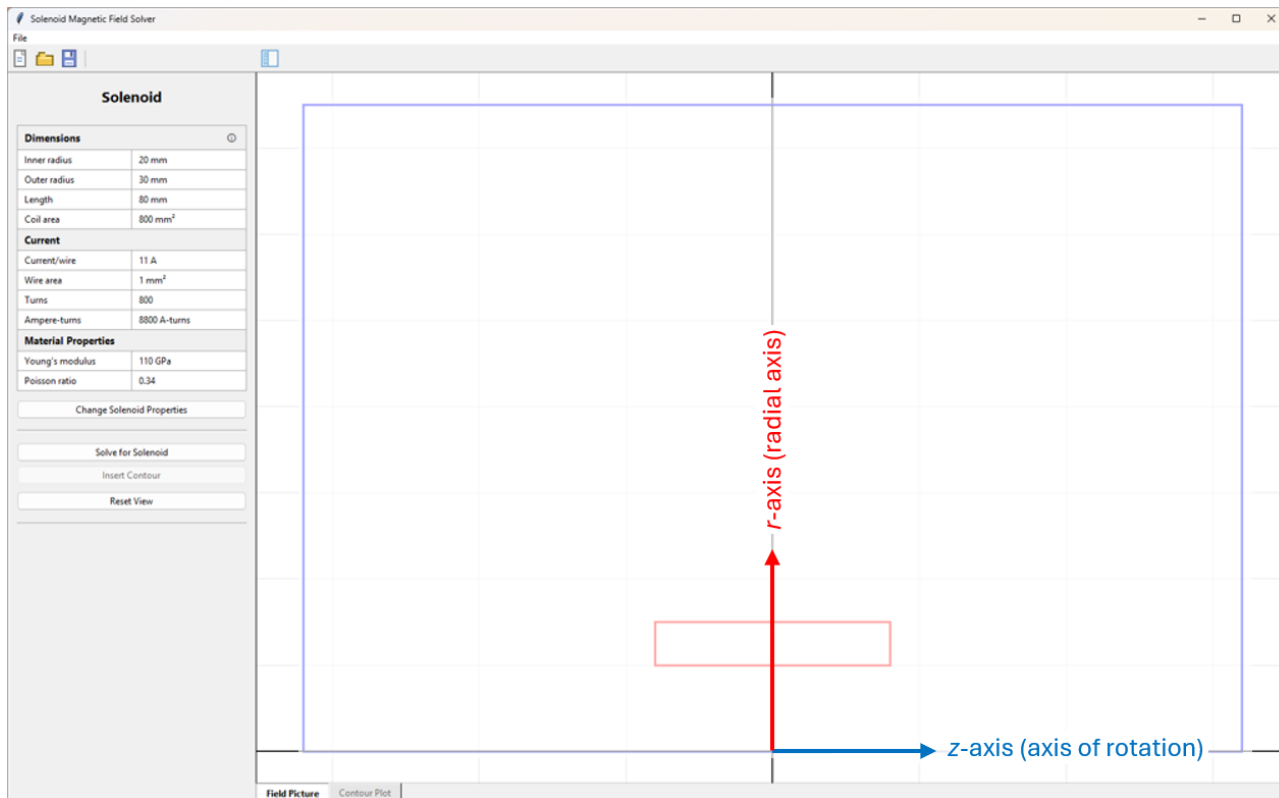


Figure 2: The app window when first opened, showing the default solenoid characteristics in the left panel and the directions of the z and r axes.

4.2 Solve the model:

Click the “Solve for Solenoid” button in the left panel. A colour field of the magnetic field strength with magnetic field lines will be shown. Various “Maximum Values” can be found in the right panel.

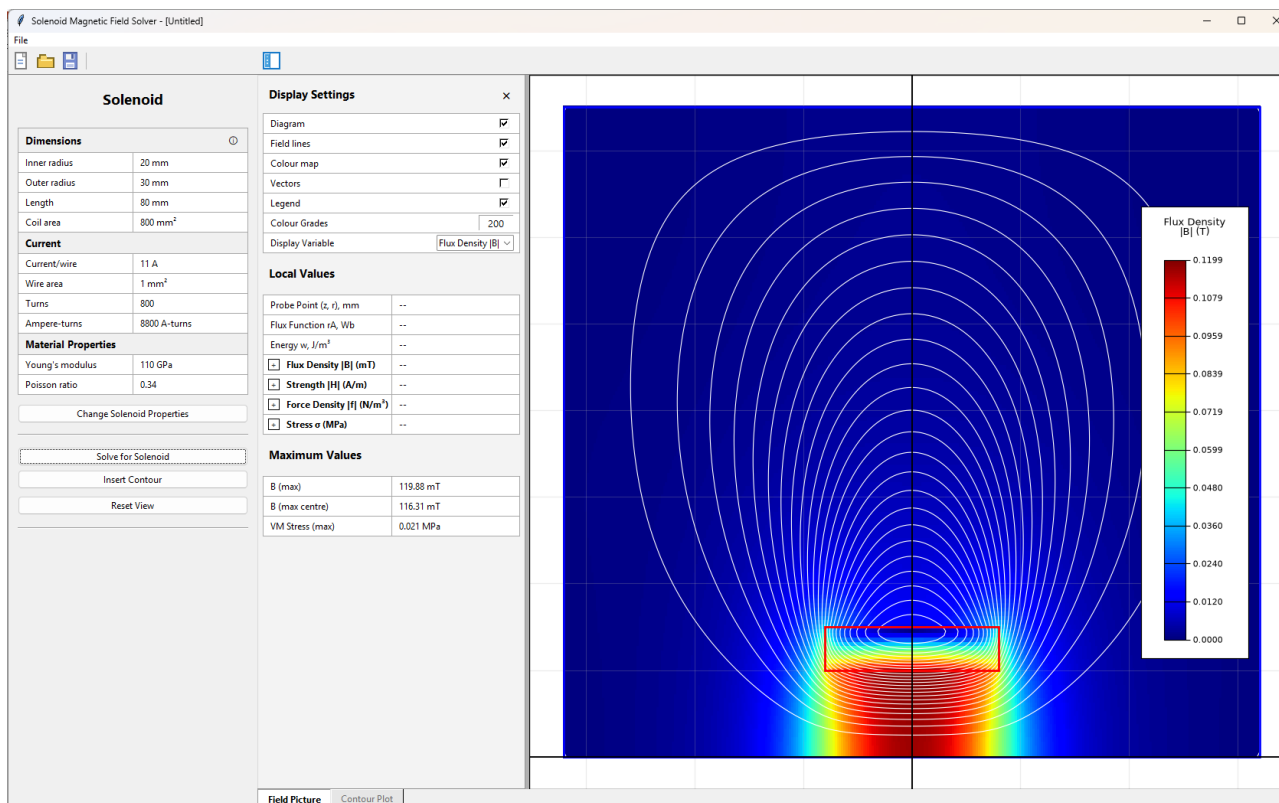


Figure 3: The app window after solving the solenoid model using the currently entered parameters in the left panel.

4.3 First Task: Check the model's maximum field:

Check how realistic the model's maximum field result is by using the equation (4.1) below for the maximum field generated at the centre of a finite solenoid.

$$B_{max} = \frac{\mu_0 NI}{2(r_{out} - r_{in})} \ln \left[\frac{r_{out} + \sqrt{r_{out}^2 + \frac{L^2}{4}}}{r_{in} + \sqrt{r_{in}^2 + \frac{L^2}{4}}} \right] \quad (4.1)$$

5 Main tasks

1. Find out the direction of the magnetic field: Use the right-hand thumb rule (the current is directed out of the page). Check your answer: on the right panel under "Display Settings", tick "Vectors" to see the direction and magnitude of the magnetic field.
2. Find the relevant variables:
 - a. What is the area of the whole cross-section of the solenoid's turns, A , in terms of L , r_{in} and r_{out} .
 - b. For a wire of cross-sectional area, a , how many wires go through the solenoid in terms of A and a (assume 100 % packing density).
 - c. If each wire carries a current, I , find the total current, I_T , going through the cross-sectional area, A , of the whole cross-section of the turns in terms of L , r_{in} , r_{out} , a and I (this is why these are the relevant variables).
3. Choose one of the variables that determine the size of the solenoid from the RHS of equation (4.1) and:
 - a. Calculate six different magnetic fields for six different values of the variable you have chosen. Click the "Change Solenoid Dimensions" button in the left panel and change the dimension of the variable you have chosen – the new dimensions should appear in the "Dimensions" section of the left panel. Click the "Solve for Solenoid" button to recalculate the magnetic field (Tip: You don't want to make the solenoid too large or else the computation will take too long, so restrict each of the six dimension changes to nothing greater than 5 or 10 mm).
 - b. Plot and fit your data with equation (4.1) (use Excel or any software package you are comfortable with and have access to).
 - c. Can you explain to what degree your computational data agree with the equation?
 - d. Call a demonstrator over and show them your graph with datapoints and an analytic fitted line.
 - e. Would equation (4.1) be useful to approximate the field of a tokamak's
 - i. central solenoid?
 - ii. toroidal field coil?
 - f. Now let's try to think creatively and join up what you knew before the course about magnetic fields, and connect it with the new material from this course:
 - i. Look up and write down Ampere's law – it can be used to describe the spatial dependence of the magnetic field produced by an infinitely long straight wire carrying a current.
 - ii. Each toroidal field (TF) coil in ITER has 134 turns, each carrying 67 kA. Each turn is a cable with a diameter of about 5 cm (see the wall-display outside the experimental labs). The inner radius of the TF coil is ~ 1 m and the outer radius is ~ 8 m. Using Ampere's law, calculate (i) a very rough value for the maximum magnetic field near the turns and (ii) the field at the centre of the plasma (NB: a very rough and simple calculation is preferred).
 - iii. How would you improve the accuracy of your calculations (i) using the tools from the course and (ii) more generally. Feel free to discuss this with other students (there's not one unique answer). Estimate the error bar on your

calculated magnetic field values. When a small group of you have settled on your answers, ask a demonstrator for their opinion on the answers you have.

5.1 Explore the field profile of a copper solenoid:

1. After solving the magnetic field, the “Insert Contour” option should become available under the “Solve for Solenoid” button on the left panel.
2. Click “Insert Contour” and type in the start and end coordinates.
3. Click “Insert” and a red contour line should appear on your magnetic field plot.
4. Click the bottom right tab “Contour Plot” to see how the magnetic field varies along the length of the contour line. You can adjust the start and end points and move the entire line, and the contour plot will change accordingly.
5. Change the variable in the right panel under “Display Settings” called “Display Variable” and the variable on the y-axis of the contour plot will change accordingly.
6. Right-click on the contour line to align it vertically or horizontally.

5.2 Export data:

If you want to analyse the data yourself, you can export the data from the field plots and contour plots. Click “File” then “Export Solenoid Data” in the app menu bar and go to “Field Data” or “Contour Data” and select the data you would like to export. Choose a location to save the exported data to in File Explorer. The exported data will be saved as a text file.

6 Zac’s tokamak

How does a tokamak work?

1. The current in each toroidal field (TF) coil flows in a closed loop: inward towards the central solenoid (CS) along the top limb, down the inner limb, outward along the bottom limb, and upward along the outer limb. Predict the direction of the magnetic field inside the TF coils (hint: it’s all in the name!)
2. The central solenoid has an alternating current which moves in the z-direction. Explain how this induces a current in the plasma moving in the azimuthal direction around the tokamak.
3. The current in the plasma moves in the positive azimuthal direction (anticlockwise from a plan view). What direction will the magnetic fields from the plasma move in?
4. What important feature of a tokamak have we ignored in our application which affects the magnetic field? What is their purpose?

To explore the magnetic field profile of a tokamak, select “File” then “Open Tokomak Window” in the app menu bar and a plan view of a STEP-like tokamak will appear (see Figure 4):

1. Insert a straight contour, keeping the azimuthal angle constant.
 - a. How does the magnetic field change with distance?
 - b. What relationship is this? Export the contour data and try to fit it to the relationship you predict.
2. Insert a circular contour in plan view and change the radius.
 - a. Can you spot a repeating pattern in $|B|$? How often does it repeat?
 - b. Why is the field roughly constant at low radii but oscillates at high radii?

Ignoring the heat of plasma, what would happen to a frog in a tokamak? (figure out a fun activity with this).

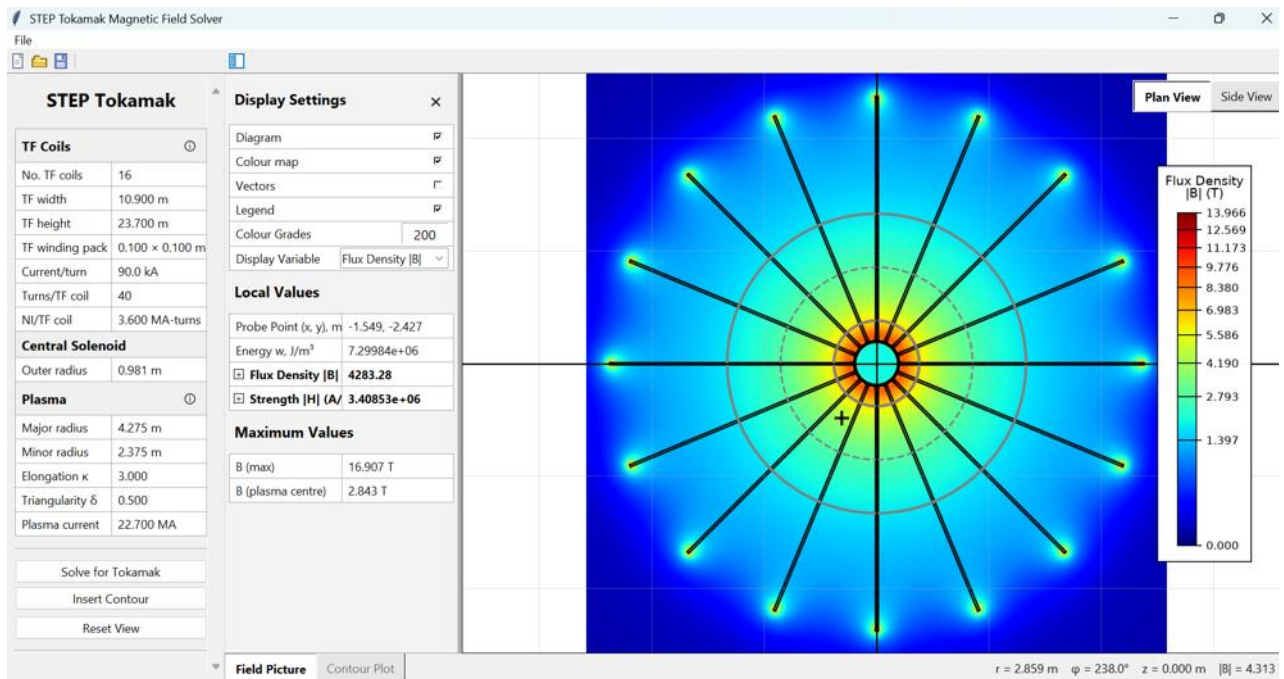


Figure 4: The app window after solving the Tokamak model.

7 Additional tasks

7.1 Replace the copper turns with a high temperature superconducting tape

HTS tape comes in all shapes and sizes, but a widely used width is 4 mm with a thickness of ~ 0.1 mm. This thickness is mostly occupied by “normal” material i.e. copper and a Hastelloy substrate, for instance, and the superconducting material (REBCO) only occupies about $1/100^{\text{th}}$ of the tape’s thickness. However, we will ignore these complications and use a tape cross-section of 4 mm x 0.1 mm i.e. again we assume a 100 % packing density and that the current is carried by the whole cross-section of the tape.

7.1.1 HTS coil at 77 K:

At 77 K the critical current of the HTS, in zero applied field, is around 140 A. However, every part of the HTS used to wind the coil will experience the local field generated by every other part of the coil, and so, since the tape’s critical current is field (and temperature) dependent, the solenoid’s field will reduce the critical current of the tape.

So, with the dimensions of our (original) solenoid and the HTS tape we are using, there’s a maximum field that can be generated by the coil where the HTS reaches its maximum current. The maximum current, given our solenoid characteristics and temperature, is ~ 43 A and this should generate a maximum field of ~ 1.14 T within our solenoid bore.

1. Using this information change the solenoid’s properties and re-solve the model.
2. Does your maximum field agree with ~ 1.14 T? If not, why not?

7.1.2 HTS coil at 20 K:

For magnetically confined fusion, it is expected that the HTS magnet system will be at 20 K. At this temperature, the optimum current for our solenoid is ~ 292 A.

1. Adjust the solenoid’s properties.
2. What is the maximum field the solenoid can generate at 20 K?

3. At this current and magnetic field, what are the three or four other most important issues you should be concerned about for this superconducting magnet?
4. What direction will the forces be acting in from within the solenoid? Use Fleming's left-hand rule

In the "Display Settings" section of the right panel, select "Force Density" from the "Display Variable" dropdown box. This will show the force distribution acting within the solenoid due to the magnetic field.

Now select "Stress" from the dropdown box. The maximum von Mises stress (VM Stress) is shown at the bottom of the right panel in the "Maximum Values" section.

1. Compare the maximum von Mises stress to the yield stress of steel (250 MPa). If it exceeds the yield stress of steel, the solenoid will plastically deform.
2. Estimate the maximum current a steel solenoid can withstand before plastically deforming (hint – it's quite a bit!).