MECE 6397

DESIGNING-MODELLING-OPTIMIZATION

TERM PROJECT

DESIGN OF SUPERCONDUCTING MAGNETIC ENERGY STORAGE SYSTEM

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Superconducting Magnetic Energy Storage:

Purpose:

SMES stands for ***Superconducting Magnetic Energy Storage***, and is a French invention. The energy is stored via an electric current sent in a coil made of a superconducting wire. Once the coil is short circuited (closed), the current stays forever since there is no loss and produces a magnetic field as in MRI coils. The energy is hence stored in the coil in a magnetic and electric form and can be recovered in a very short amount of time.

SMES is a grid-enabling device that stores and discharges large quantities of power almost instantaneously. The system is capable of releasing high levels of power within a fraction of a cycle to replace a sudden loss or dip in line power. Strategic injection of brief bursts of power can play a crucial role in maintaining grid reliability especially with today's increasingly congested power lines and the high penetration of renewable energy sources, such as wind and solar.

A typical SMES consists of two parts – cryogenically cooled superconducting coil and power conditioning system – which are motionless and result in higher reliability than many other power storage devices. Ideally, once the superconducting coil is charged, the current will not decay and the magnetic energy can be stored indefinitely.

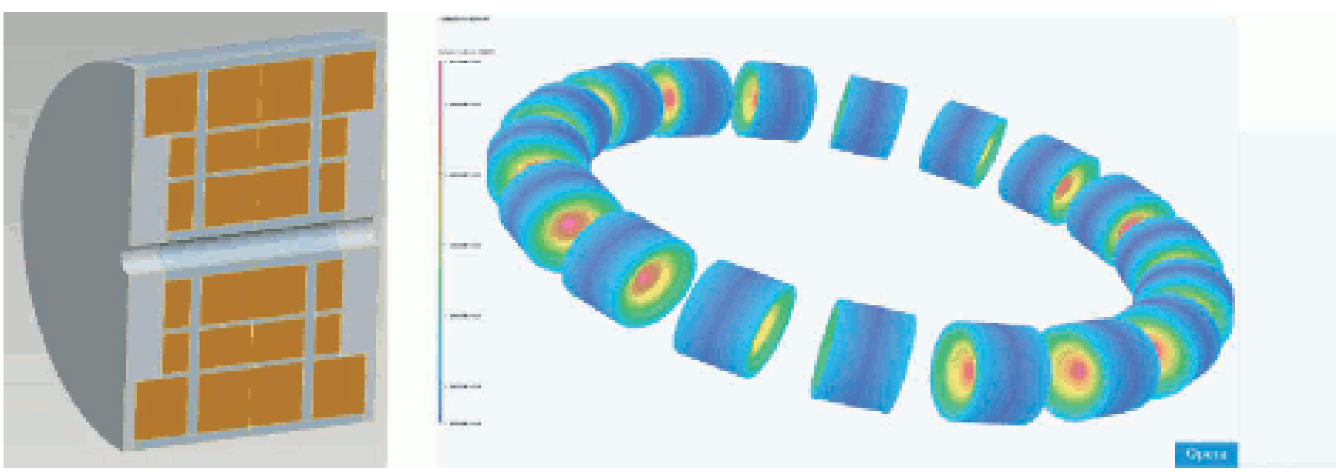


Fig 1: A typical SMES components

Benefits of SMES:

Improves power quality for critical loads and provides carryover energy during momentary voltage sags and power outages

- Improves load leveling between renewable energy sources (wind, solar) and the transmission and distribution network
- Environmentally beneficial as compared to batteries; superconductivity does not rely on a chemical reaction and no toxins are produced in the process
- Enhances transmission line capacity and performance – SMES features a high dynamic range, an almost infinite cycling capability, and an energy recovery rate close to 100%
- Ultra-high field operation enables long-term storage SMES systems in a compact device with cost advantages in material and system costs.
-

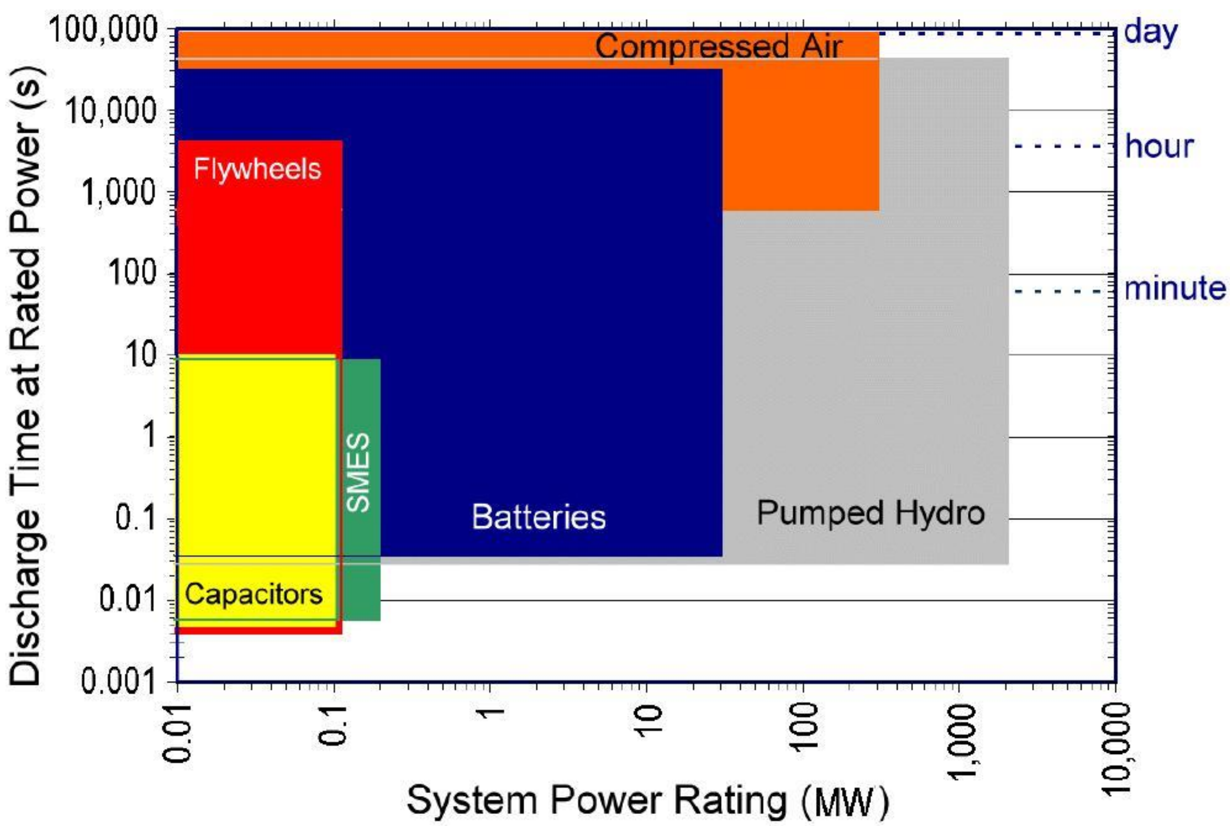


Fig 2: Comparison Of Power Rating

Low-temperature superconducting (LTS) wire using liquid helium and operating near absolute zero has existed since the 1950's. ***Dr. Paul Chu at the University of Houston discovered the***

material YBa2Cu3O7-X (YBCO), an inorganic ceramic material which is superconducting at liquid-nitrogen boiling point temperature (77°K) and hence was called a high temperature superconductor (HTS).

Physics of the system:

Physical Phenomenon:

Cooling of superconducting is carried out using liquid helium at 4.2K or Liquid Nitrogen at 77K

A ***solenoid*** made up of circular coils of YBCO tapes acts as a superconducing material (Produces electromagnetic field). At low temperature of 20K YBCO tapes are placed over steel substrate. These YBCO tapes are placed between copper layers, which act as a structural support and also cool the superconducting tapes.

When the entire apparatus is placed in liquid Nitrogen, (at 77K)It reduces the temperature of the apparatus and thus providing the suitable conditions for energy storage in superconductor.

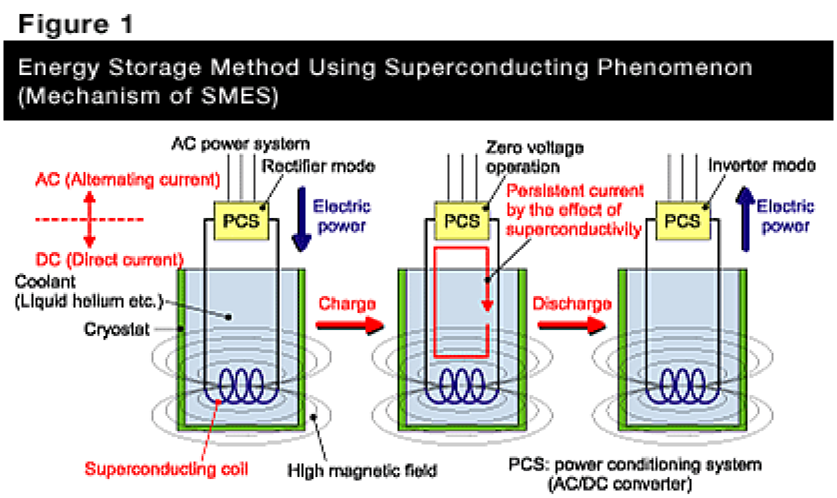


Fig 3: Enegy storage method in SMES

Charging is conducted by converting alternating current into direct current which exites the superconducting coil. Similarly when DC is converted to AC the system acts as a battery SMES Is basically characterized by direct energy storage without any conversion which reduces electrical resistance during energy conversion. This implies that SMES provides and optimum means of energy storage. However, in order to store energy in large scales the coil should be exited up to higher magnetic fields which in turn need really large currents.

Fundamental Equations:

Magnetic energy stored:

Magnetic Energy stored in Superconductor is given by:

$$E = \frac{1}{2} L I^2$$

where E -> Energy Stored

L-> Inductance

I-> Current in the coil

For cylinder coil with rectangular cross section of mean radius of coil is *R*. w and h are width and depth of the conductor. *f* is called form function which is different for different shapes of coil. ξ (xi) and δ (delta) are two parameters to characterize the dimensions of the coil.
Magnetic energy stored is a function of coil dimensions, number of turns and carrying current as shown below -

$$E = \frac{1}{2} R N^2 I^2 f\left(\xi, \delta\right)$$

Where E -> energy measured in joules,

I -> current measured in amperes

f(ξ,δ) -> form function, joules per ampere-meter

N -> number of turns of coil.

Lorentz Force:

For Continuous charge distribution in motion Lorentz Force.

$$\mathrm{d}\mathbf{F} = \mathrm{d}q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$

Total Lorentz Force is the volumetric integration of force acting over entire region and is given by dividing above equation by small volume - dv.

$$\mathbf{F} = \iiint (\rho \mathbf{E} + \mathbf{J} \times \mathbf{B})\, \mathrm{d}V.$$

In our case Lorentz Force $= \iiint (\mathrm{J} \times \mathrm{B})dV$

Von Mises Stress:

Von Mises yield criterion is expressed as:

$$J_2 = k^2$$

where J_2 – Second Stress variant

The Von Mises Stress generated is given by :

$$\sigma_v^2 = \tfrac{1}{2}[(\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{11} - \sigma_{33})^2 + 6(\sigma_{23}^2 + \sigma_{31}^2 + \sigma_{12}^2)]$$

Where σ 11, σ 22, σ 33 , σ12, σ 23, σ 31 are stress in respective direction of the given body.

Literature Review:

A 0.5 MVA/1MJ superconducting magnetic energy storage system has been installed in a superconducting power substation [1]. It is actually used to overcome the power fluctuations, current harmonics and reactive power of the downstream load. The superconducting magnetic energy storage system which utilizes the superconducting coil as the energy storage element, has been found out to have good characteristics such as high efficiency, quick response, no deterioration. A SMES is planned to be developed to protect critical load.

DESIGN 1 MJ SOLENOID SYSTEM USING YBCO TAPES

Design Problem Definition:

Objective:

1. To design a SMES solenoid with 1 MJ energy storage capacity using YBCO tapes with a current margin of 40% checked for allowable Von Mises Stress, Lorentz Force and within operational Magnetic Flux Density.
2. To determine the time taken for thermal stabilization of the system in the process of taking it to cryogenic stage.

Components of The System:

- Stainless steel substrate
- Copper layers
- Pan cake coils
- YBCO tapes

Design Variables:

The following are the design variables that are need to be considered while designing SMES system

- Height and width of tape
- Number of turns and number of layers of the tape.
- Vonmeisess stress
- Thermal Properties
- Filler fraction
- Current margin
- Magnetic flux density

Height and width are to be varied to obtain optimum energy density and it also decides the range of Lorentz and vonmeises stresses.

Number of turns and layers: to obtain the required energy density.

Thermal Properties: To decide optimum cooling mechanism to resist the temperature increase and efficient cooling of the system.

Filler Fraction to increase the strength of YBCO tapes.

Name	Expression	Description
H	0.16 [mm]	Height of Superconductor tape
W	12 [mm]	Width of Superconductor tape
Ri	0.2 [m]	Inner radius of Solenoid
$\mathbf{N_{layers}}$	3	Number of tapes in Z-direction
$\mathbf{N_{turns}}$	352	Number of tapes in r-direction
$\mathbf{T_{cu}}$	9 [mm]	Thickness of Copper
$\mathbf{T_{steel}}$	34 [mm]	Thickness of Steel
$\mathbf{T_{iso}}$	1 [mm]	Thickness of isolation between different tapes

Table 1: various parameters assumed for the design

Design Process:

1. Calculate optimum number of coils and layers to reach 1MJ limit.
2. Check for vonmeises stresses
3. Change the number of coils and layers to obtain optimum configuration.
4. Calculate filling fraction.
5. Design of SMES structure with Copper as cooling material and verification of stress and Lorentz force within the permissible limits.

Initially a single tape of Rectangular cross section is considered. The YBCO tapes are placed on steel substrate. Based on the Volume

E(J) is calculated for various combinations of number of coils and number of turns ***(Parametric Sweep).***

Parametric Sweep:

N_{layers}	N_{turns}	Energy Stored
2	150	0.15
2	175	0.19
2	200	0.23
2	225	0.27
2	250	0.32
2	275	0.37
2	300	0.43
2	325	0.49
2	350	0.53
3	250	0.58
3	275	0.68
3	300	0.78
3	325	0.89
3	350	0.99
3	352	1
3	355	1.02
3	360	1.04

Table 2: Parametric Sweep

Simulation Method:

The modelling process started off with creating a rectangular cross section (Basically considered a single HTS tape).

The material properties of coils i.e. YBCO tapes, copper layers, stainless steel boundary, surroundings are defined ***using interpolations*** of structural, electrical and magnetic and conduction properties.

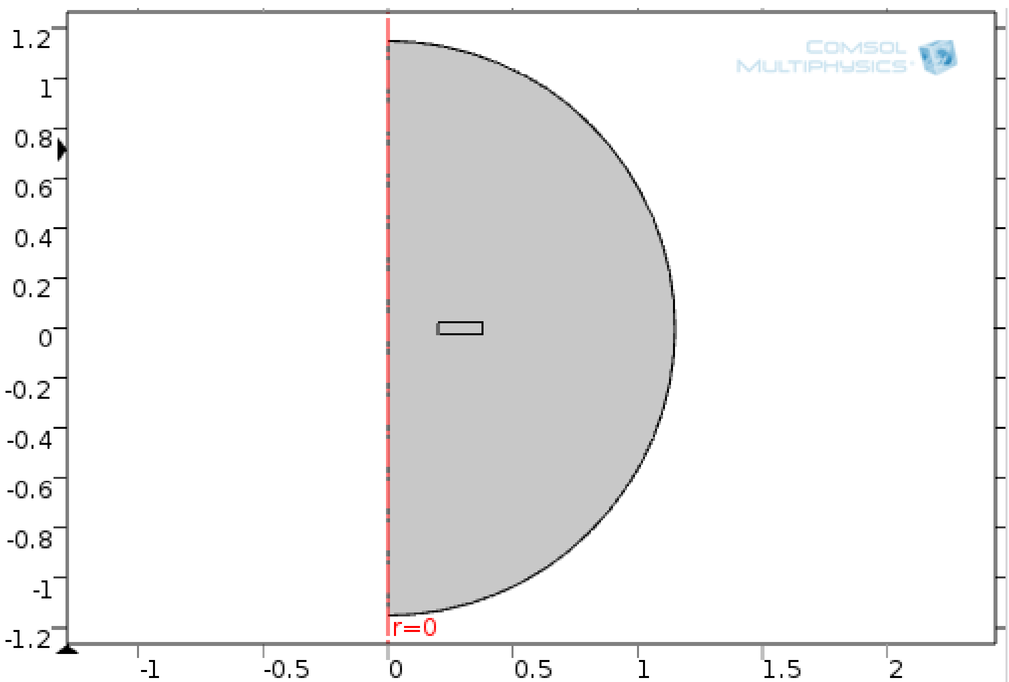
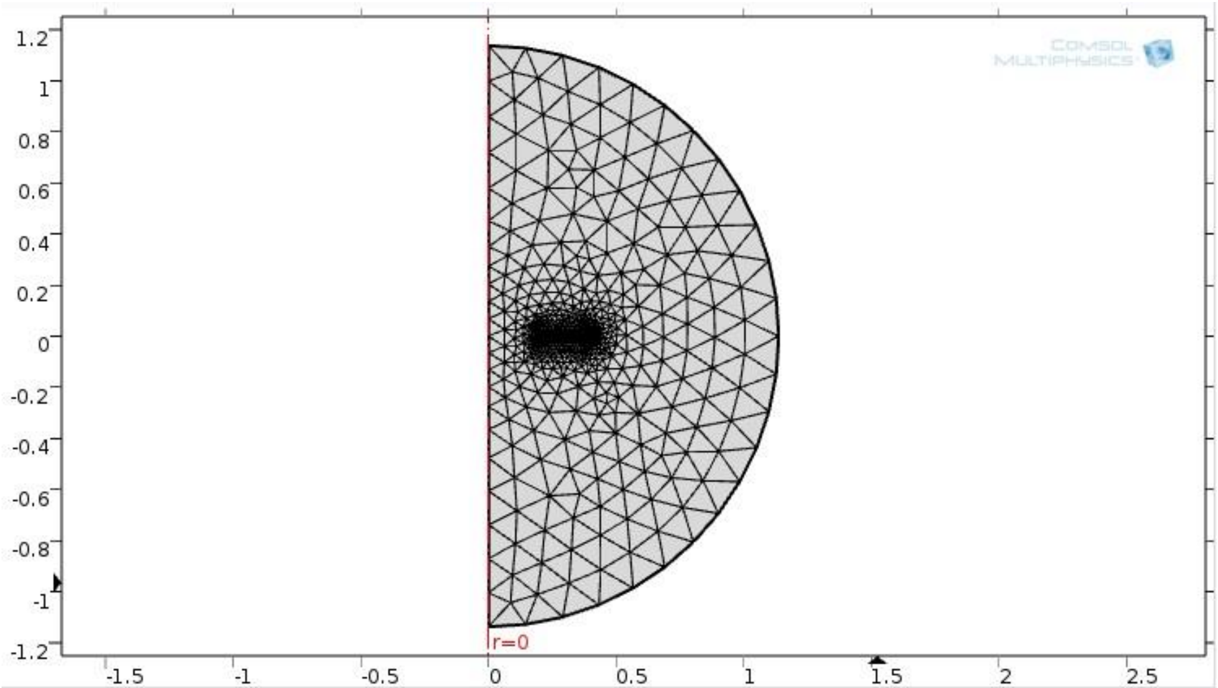
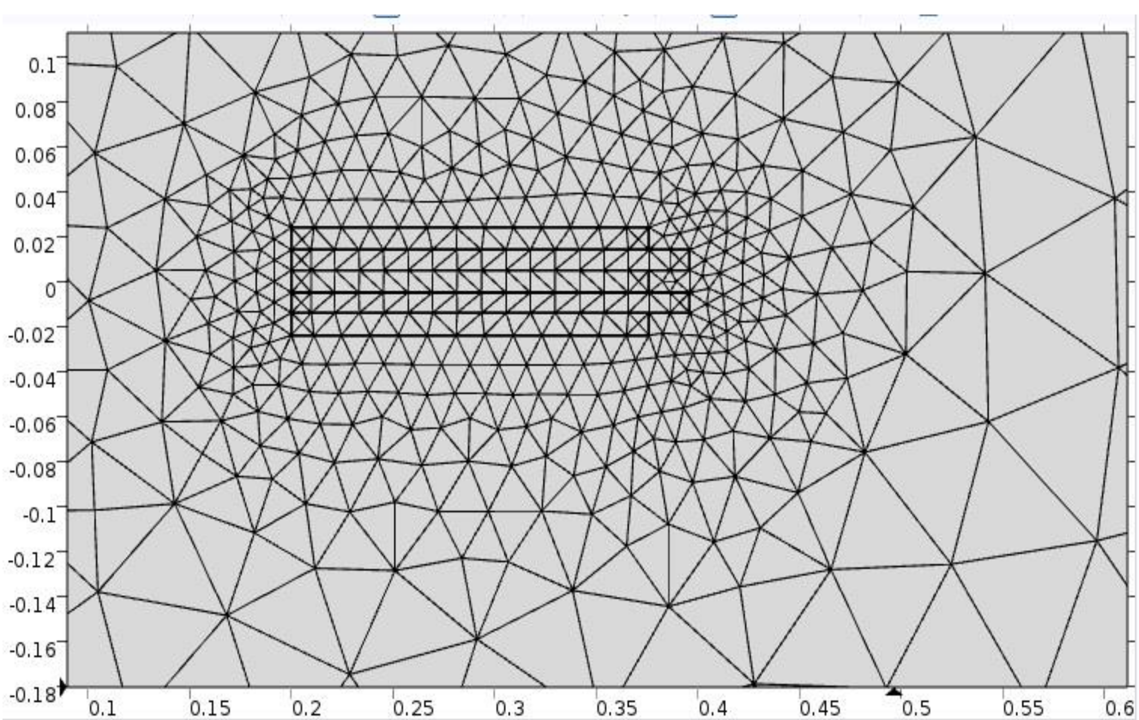


Fig 4: Modelling rectangular single HTS tape

Meshing:





Material Properties:

- **YBCO TAPE - – SUBSTRATE – STEEL:**

  As most of the YBCO tape is made of steel, the thermal properties of steel are considered for YBCO. The Electrical property of YBCO is considered to be that of the air. Initial Temperature is 20K.

- **Nitrogen:**

  To maintain the YBCO tape, we use Liquid Nitrogen as medium in which its placed. The Initial temperature mentioned is 77K

Cooling system: Copper coils

- **Copper :**

The cooler is made of Copper, so Copper material properties are added in the file.

Equations Used:

External current density:

$$Je = (\text{Filling fraction})*(\text{Current Margin})*(JcB)(Bmax)\ \ A/m^2$$

$$Bmax = maxop1(mf.normB)$$

The Bmax is obtained from interpolation of YBCO Tapes:

Filling Fraction:

Filling Fraction (ff) = (2 * 265 * 0.2 * 4) /(3*4 + 2*6)*(0.15 +0.1)*265= 0.287

The Filling Fraction obtained theoretically, by calculation and by simulation is equal.

Various interpolation graphs have been used to asses few parameters like temperature variation in cryocooler, copper, HTS material.

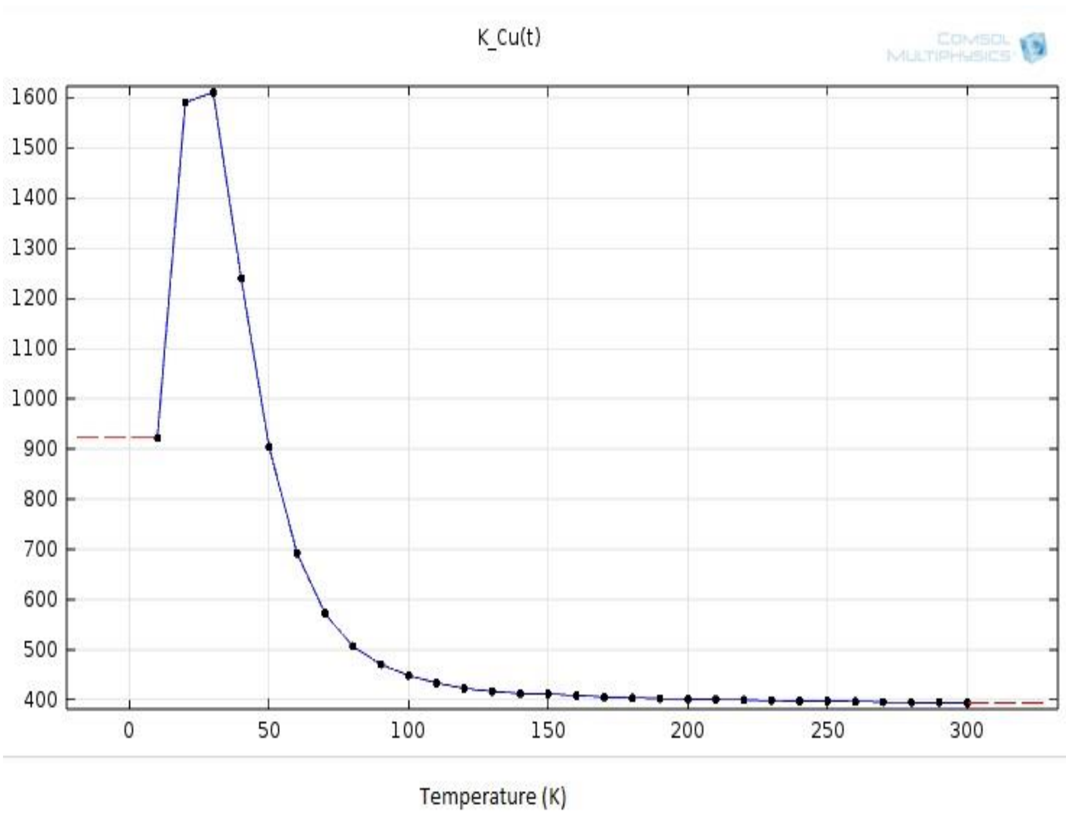


Fig5: conductivity vs temperature graph of Copper

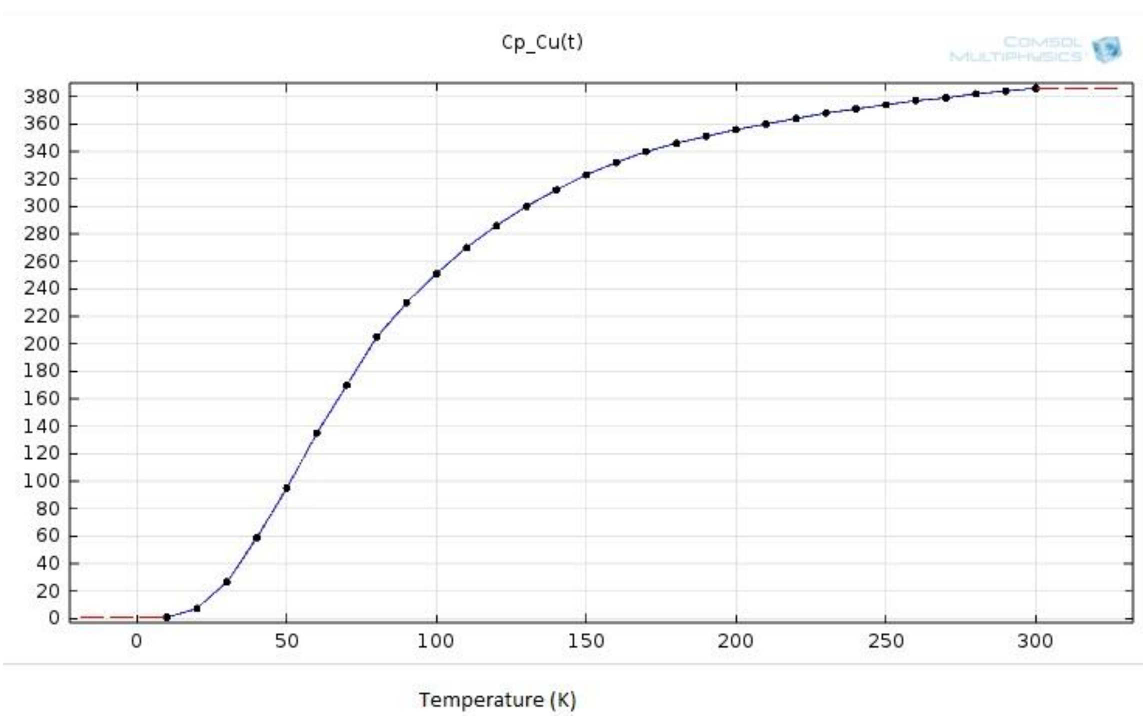


Fig 6: Heat VS temperature graph of Copper

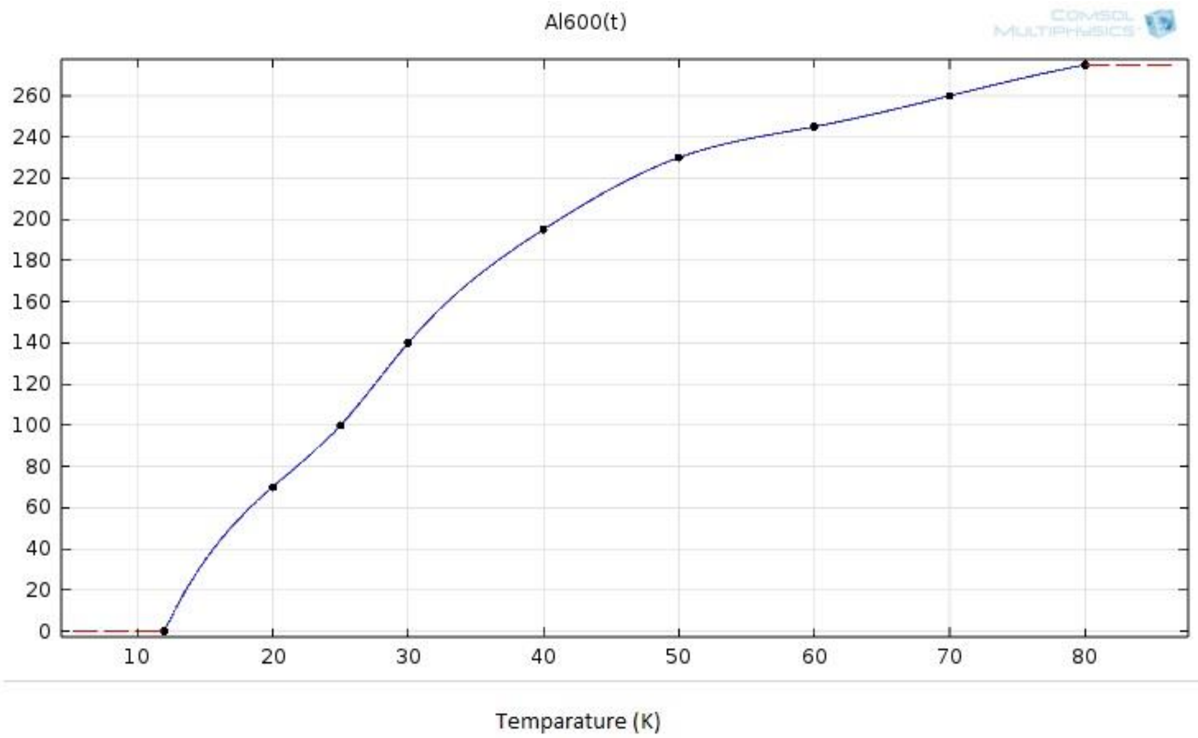
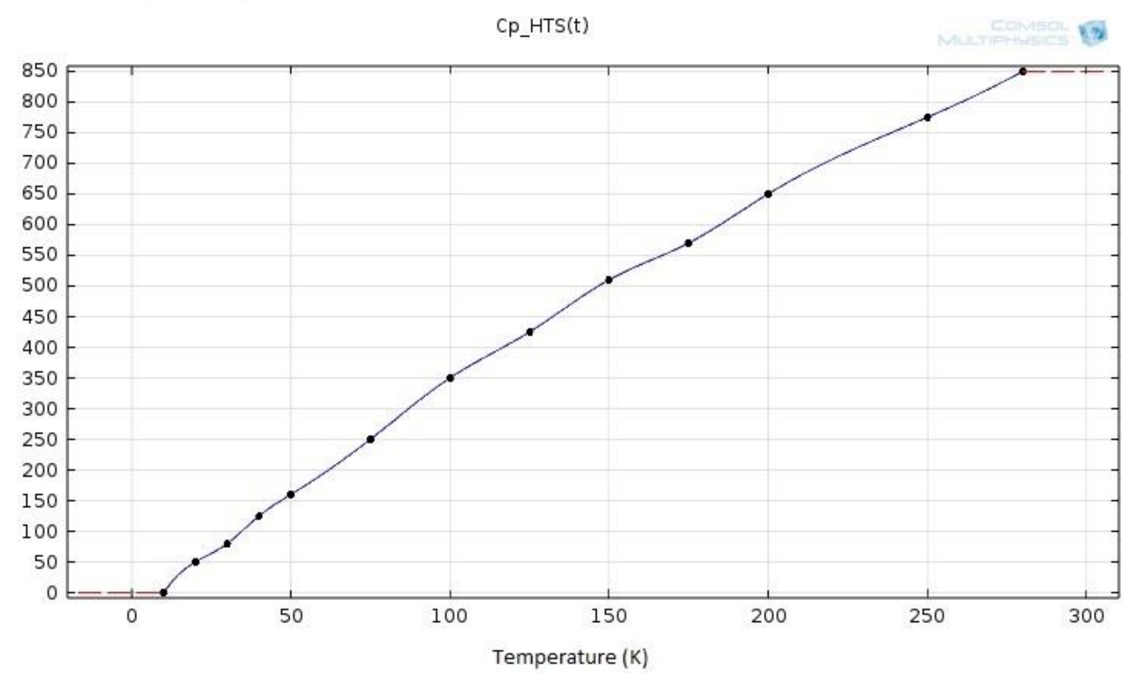


Fig7: Specific Heat VS temperature graph of High temperature Superconducting YBCO



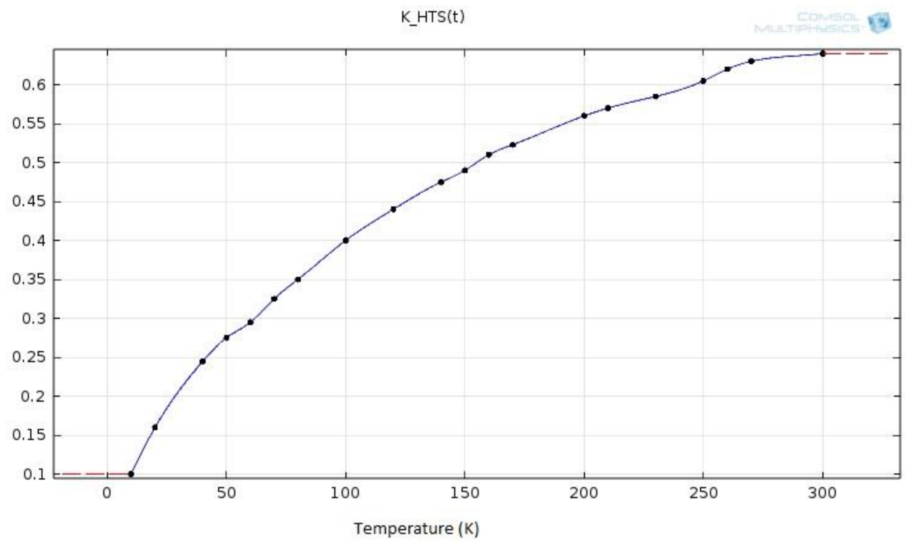


Fig8: Conductivity VS temperature graph of High temperature superconducting YBCO

Simulation Tool Description:

COMSOL basically uses finite element methods to solve for the parameters at each and every node. COMSOL Multiphysics is a finite element analysis, solver and for various physics and engineering applications, especially coupled phenomena, or multiphysics. COMSOL Multiphysics also offers an extensive interface to MATLAB and its toolboxes for a large variety of programming, preprocessing and post processing possibilities.

Simulation:

Solver Settings:

Time independent solver configuration is considered for magnetic and mechanical analysis. For heat transfer simulation time dependent solver configuration is assumed.

Results And Discussions:

Magnetic Field:

Figure 10 shows the domain considered for YBCO tape. It is axisymmetric about Z-direction. Insulation properties are applied for the outer boundary as shown in figure.

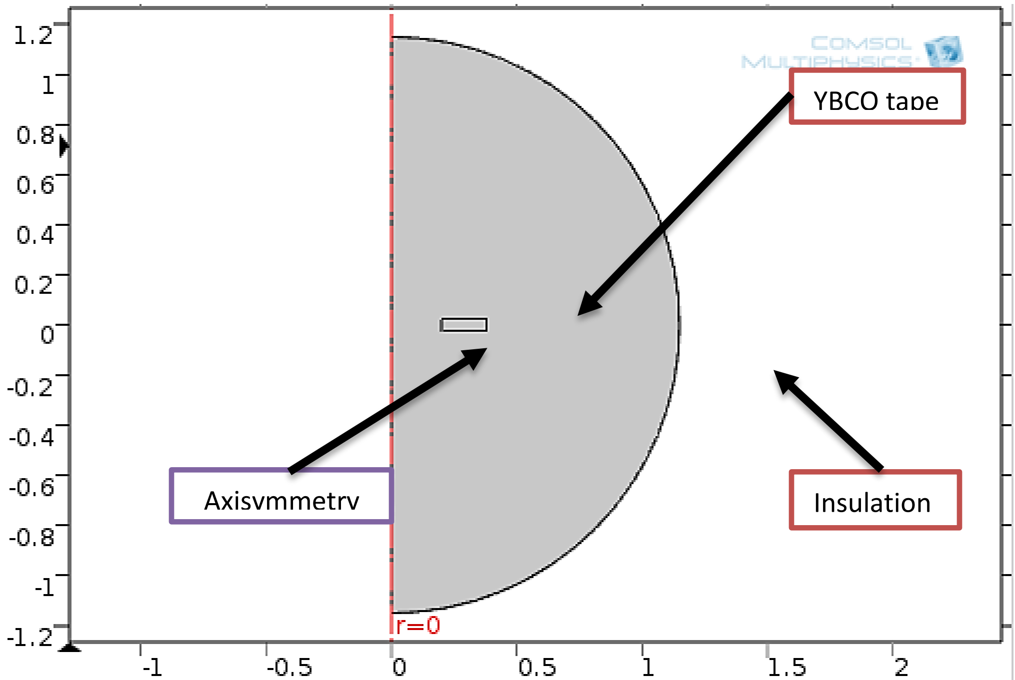
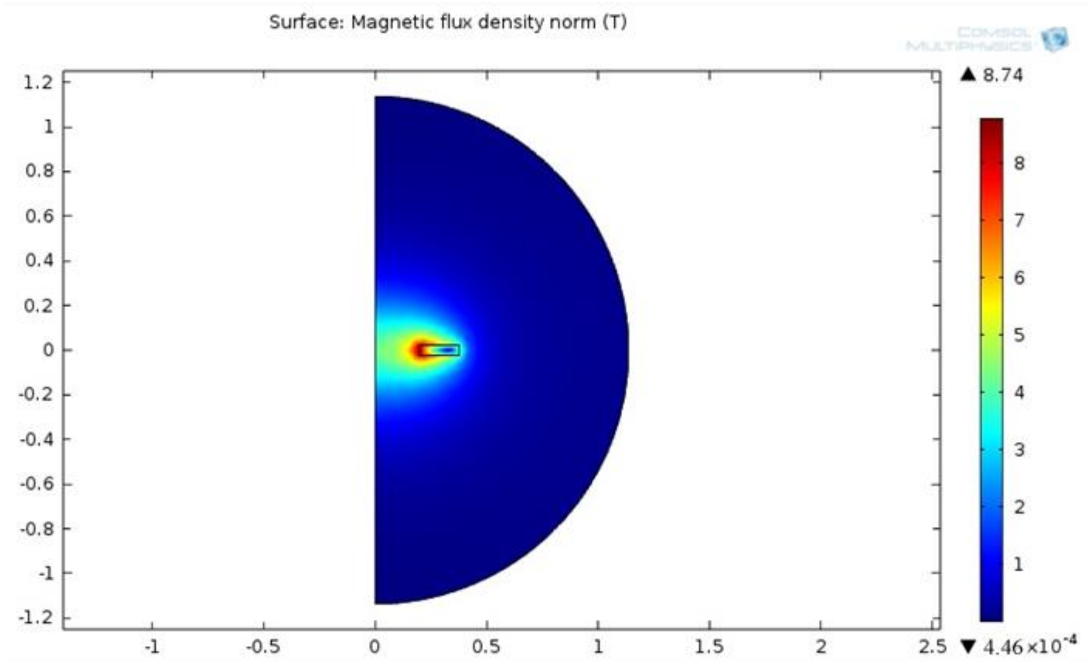
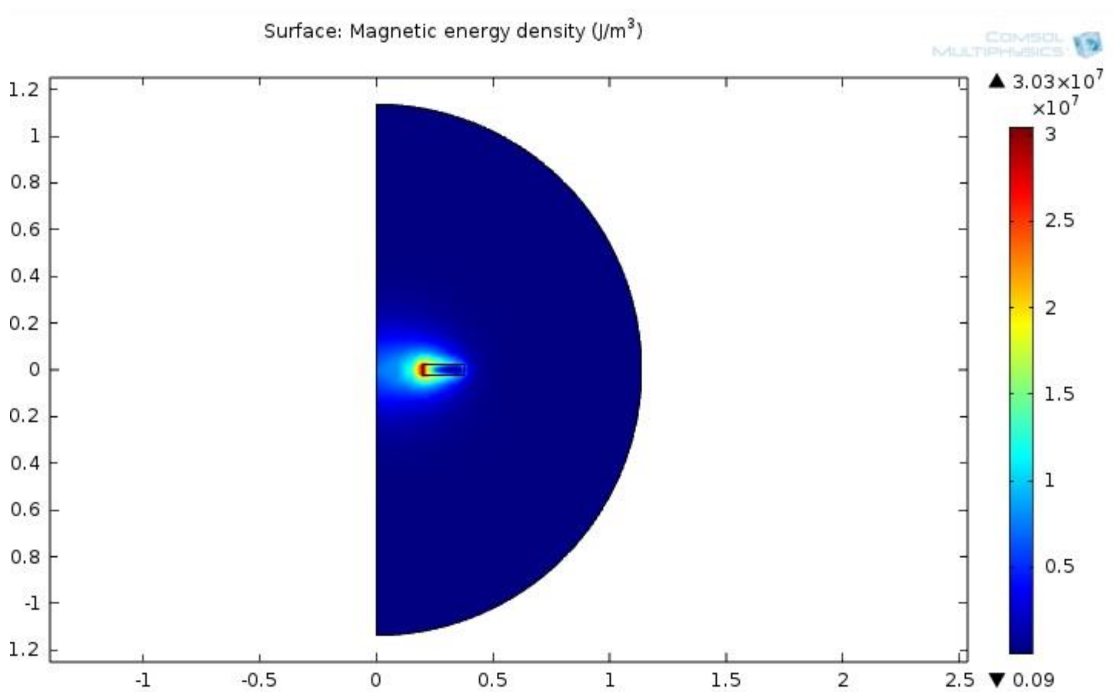


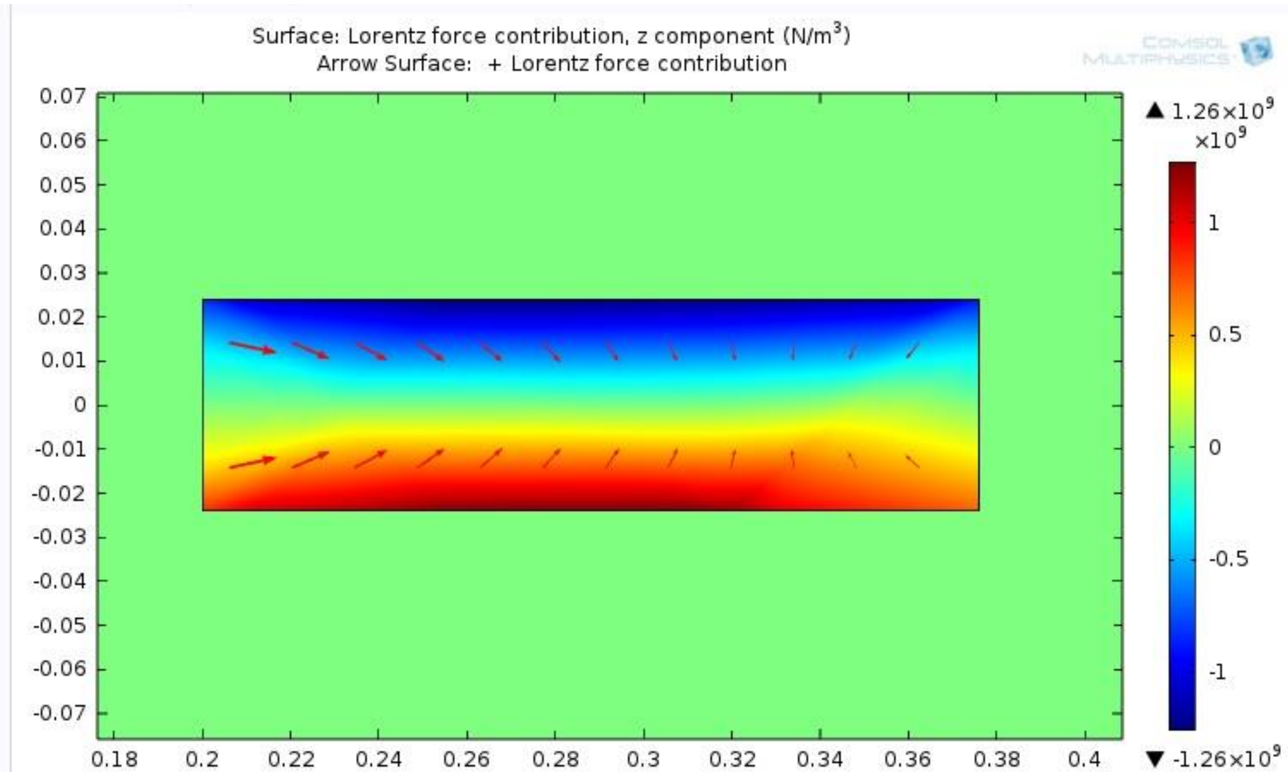
Figure10: YBCO Domain


Surface: Magnetic flux density norm (T)
COMSOL MULTIPHYSICS
▲ 8.74
8
7
6
5
4
3
2
1
▼ 4.46×10^{-4}
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1
-0.5
0
0.5
1
1.5
2
2.5


Surface: Magnetic energy density (J/m^3)
COMSOL MULTIPHYSICS
▲ 3.03×10^7
×10^7
3
2.5
2
1.5
1
0.5
▼ 0.09
1.2
1
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
-1
1.2
-1
-0.5
0
0.5
1
1.5
2
2.5

For number of layers four and number of turns 352, Current density from simulations is 2.27 e8 A/m^2. So, the total current in solenoid is

$$I = 2.27*10^8*(3*0.01+2*0.009)+(0.00015+0.00034+0.00001)*352 = 1917696\ A$$



Design Suitable structure for SMES

The geometry is rebuilt as below, which contains 3 YBCO coils and 2 layers of copper.

The Initial geometry considered has the total current of 1917696 A and the current density is 3.48 $*10^8$(A/m^2).

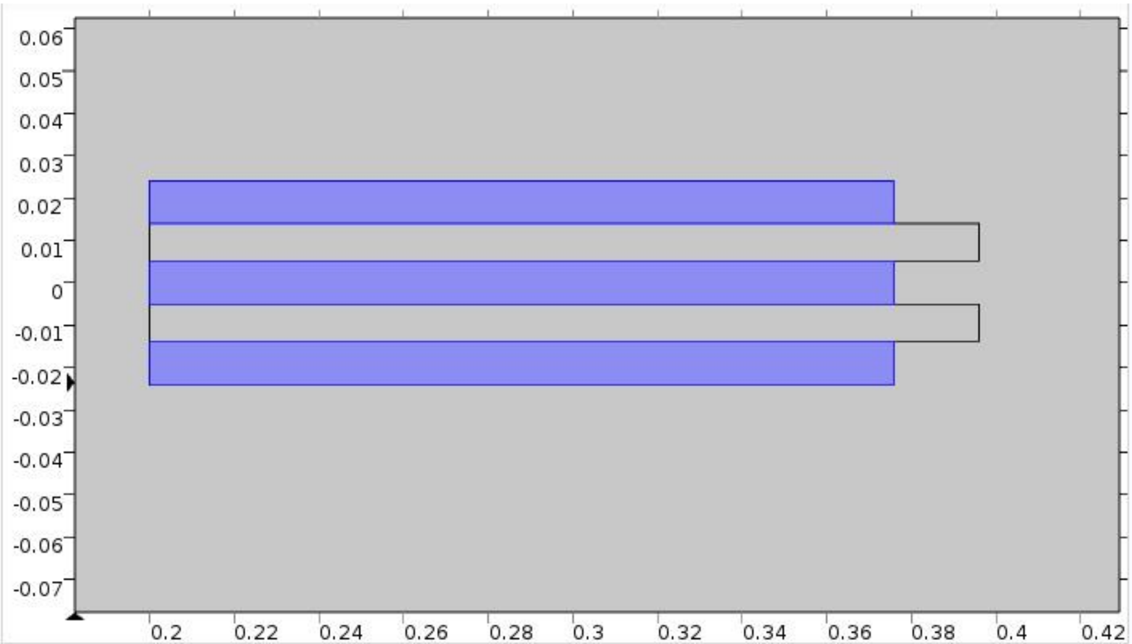
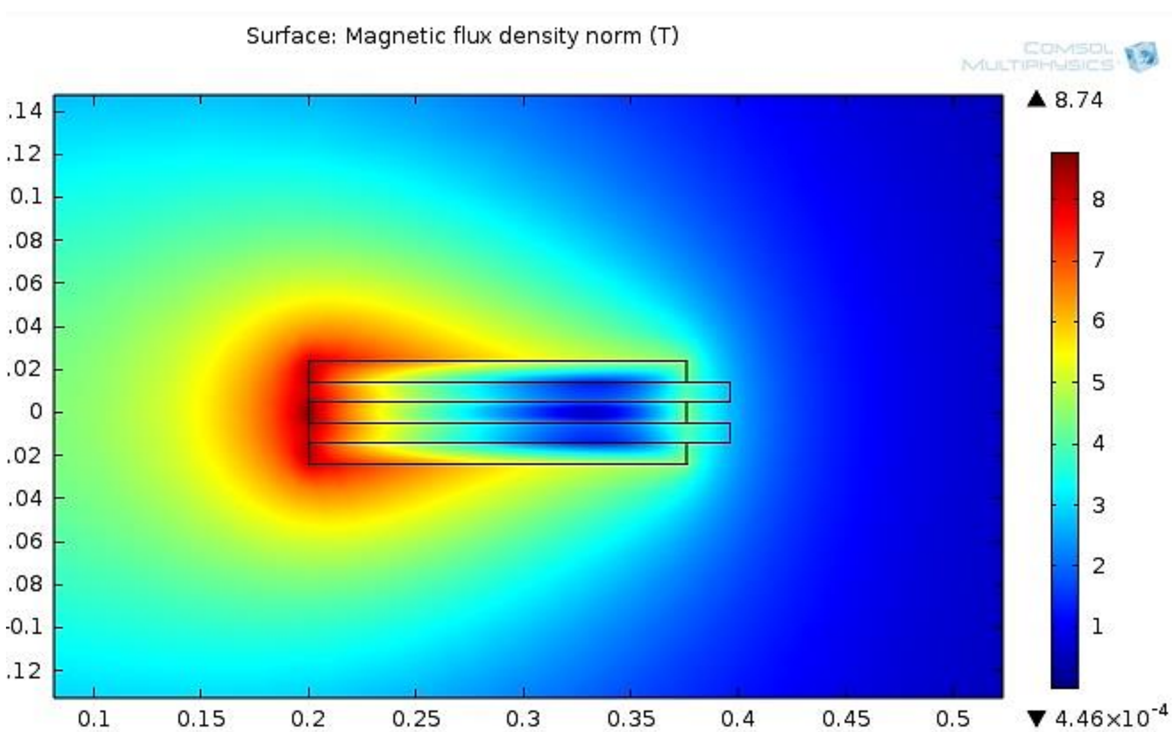
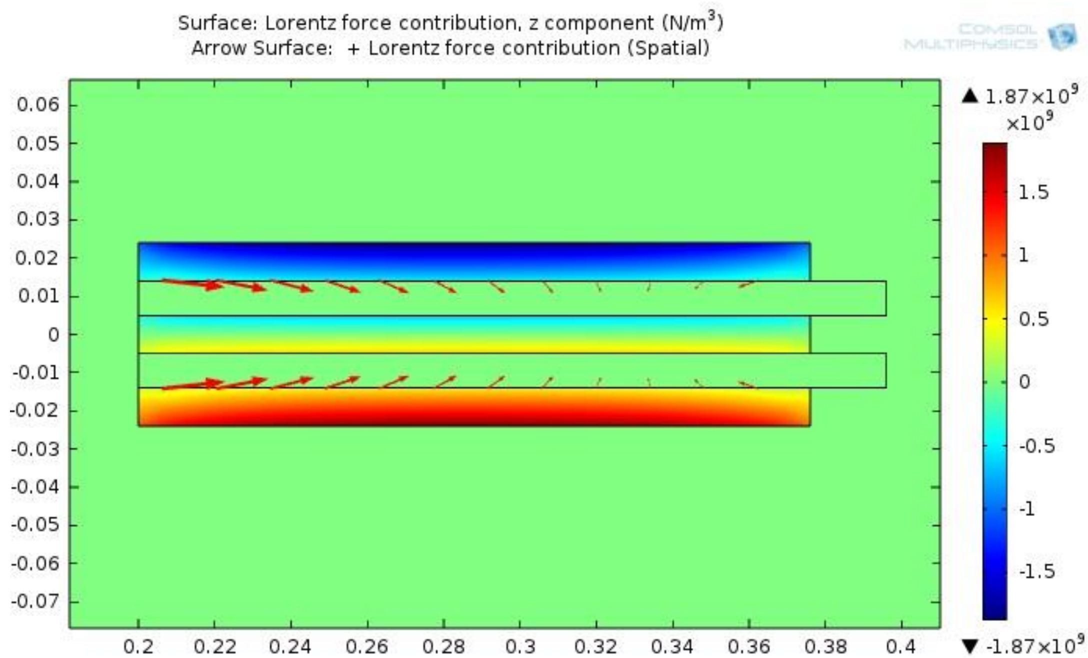


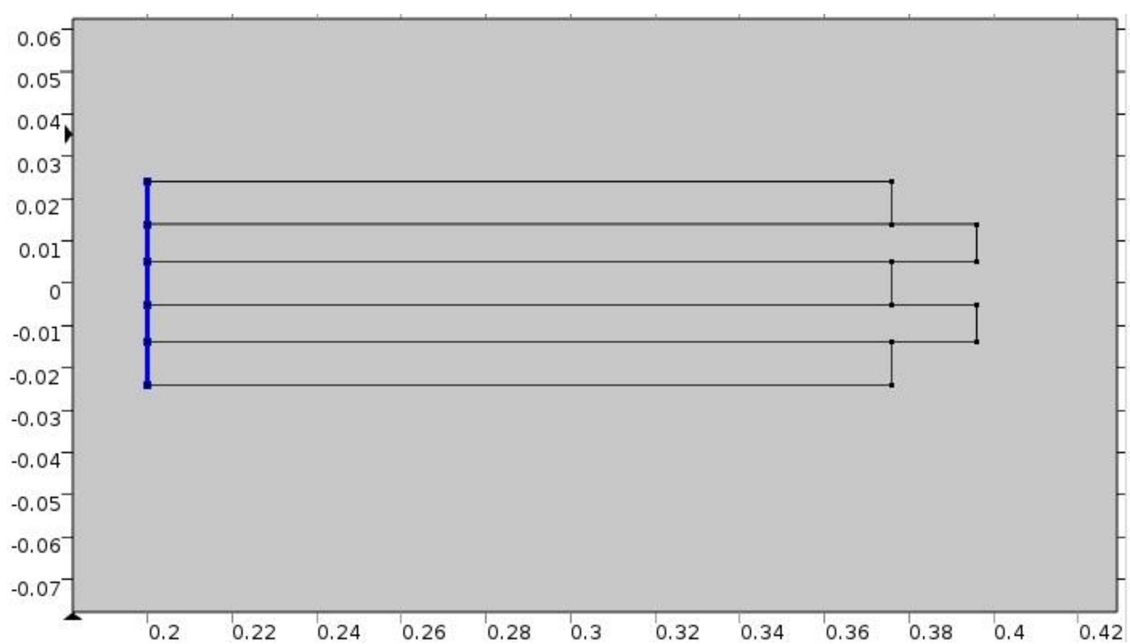
Figure11: Suitable Structure for SMES

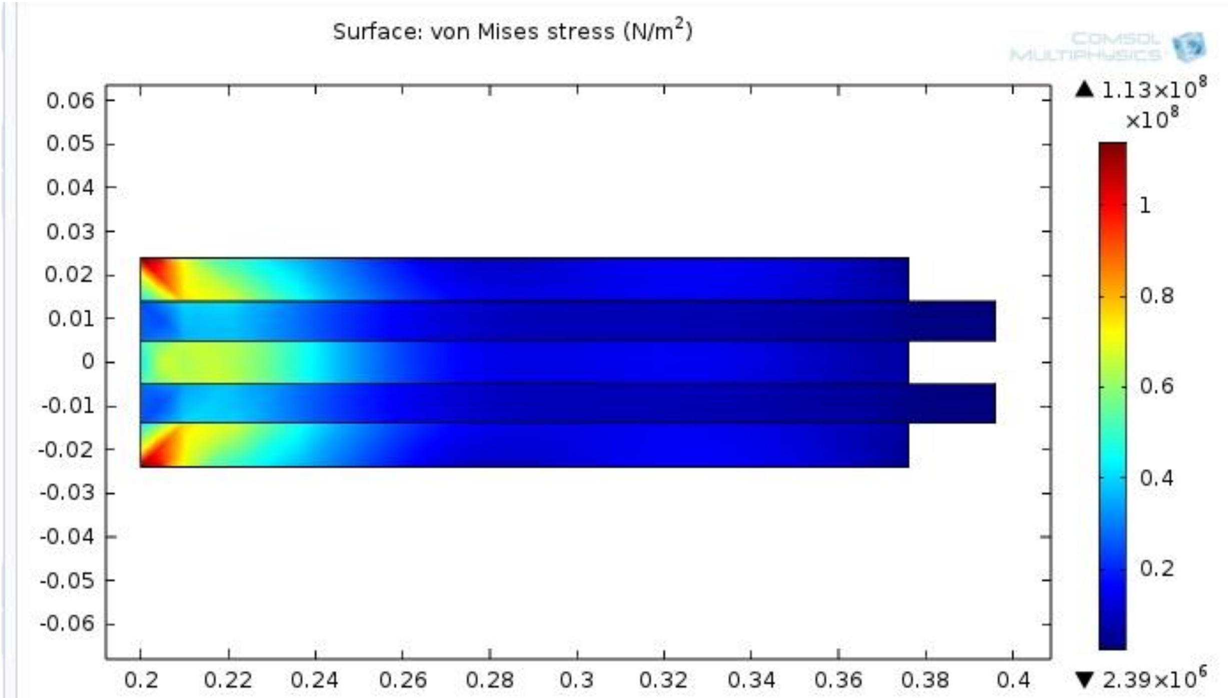




Stress Analysis:

Boundary conditions: The line in blue color shown in below figure is set to fixed constraint.

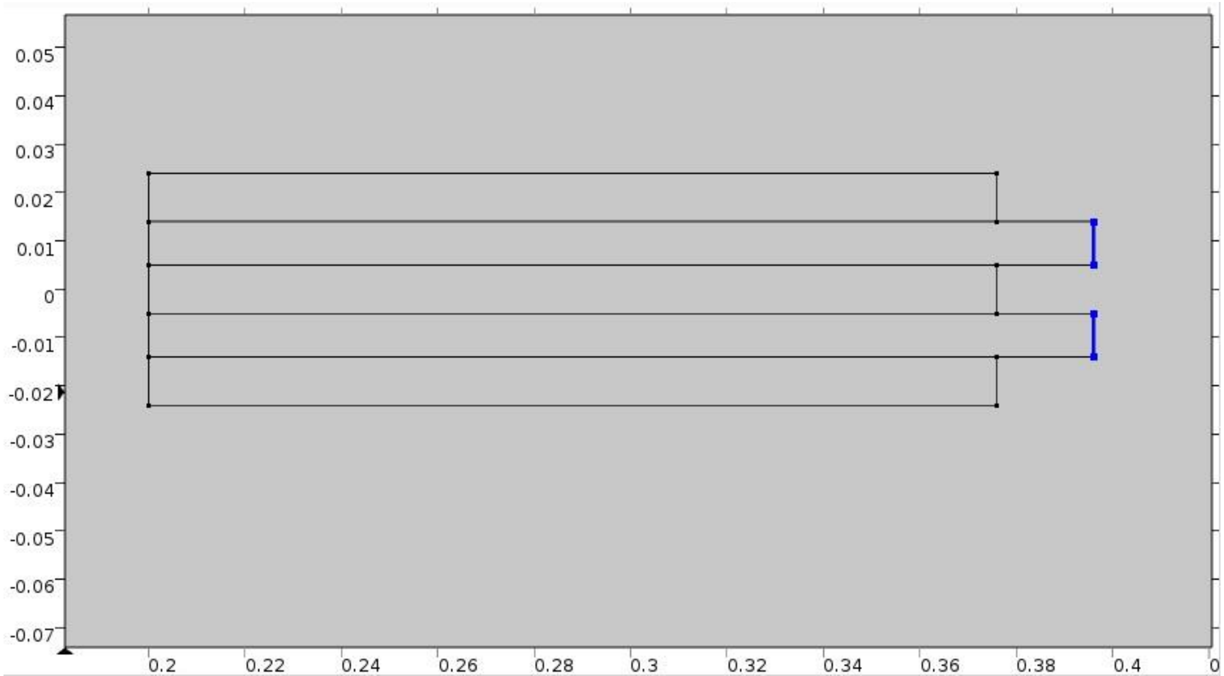




Cryocooler design for SMES:

For cooling purpose in the SMES system, conduction cooling has been used. The cryocooler considered is Al600. The SMES is considered as thermally stable when the temperature difference observed is less than 2 k between the hottest point the pancakes and the cooling boundary.

The heat source in the system is because of electromagnetic heating which occurs in HTS coils


0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
0.2
0.22
0.24
0.26
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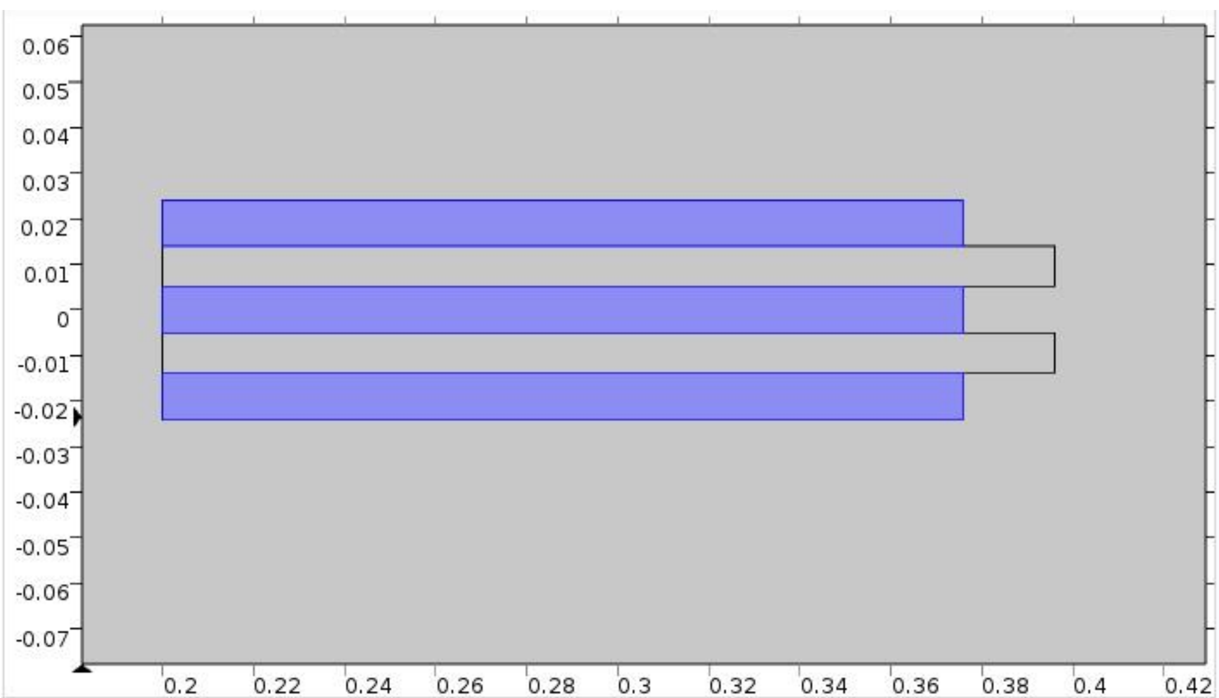
0.32
0.34
0.36
0.38
0.4


0.06
0.05
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0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
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-0.07
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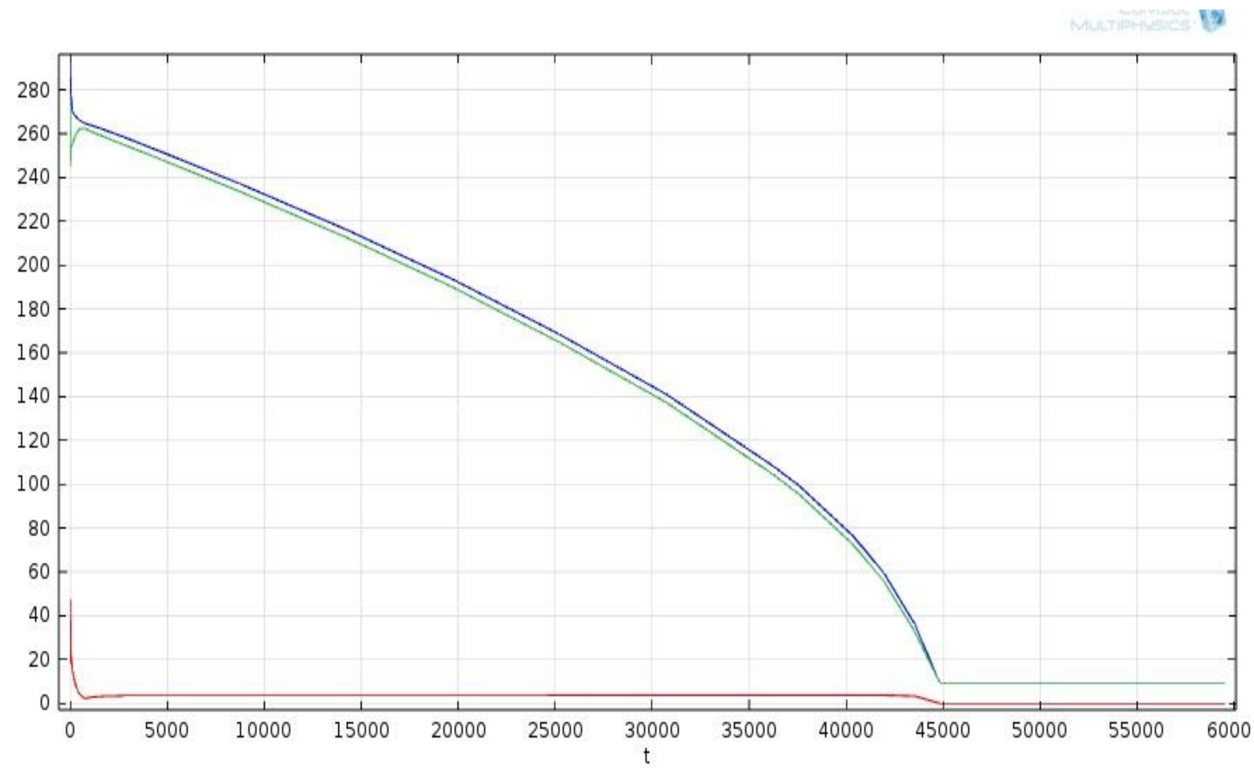
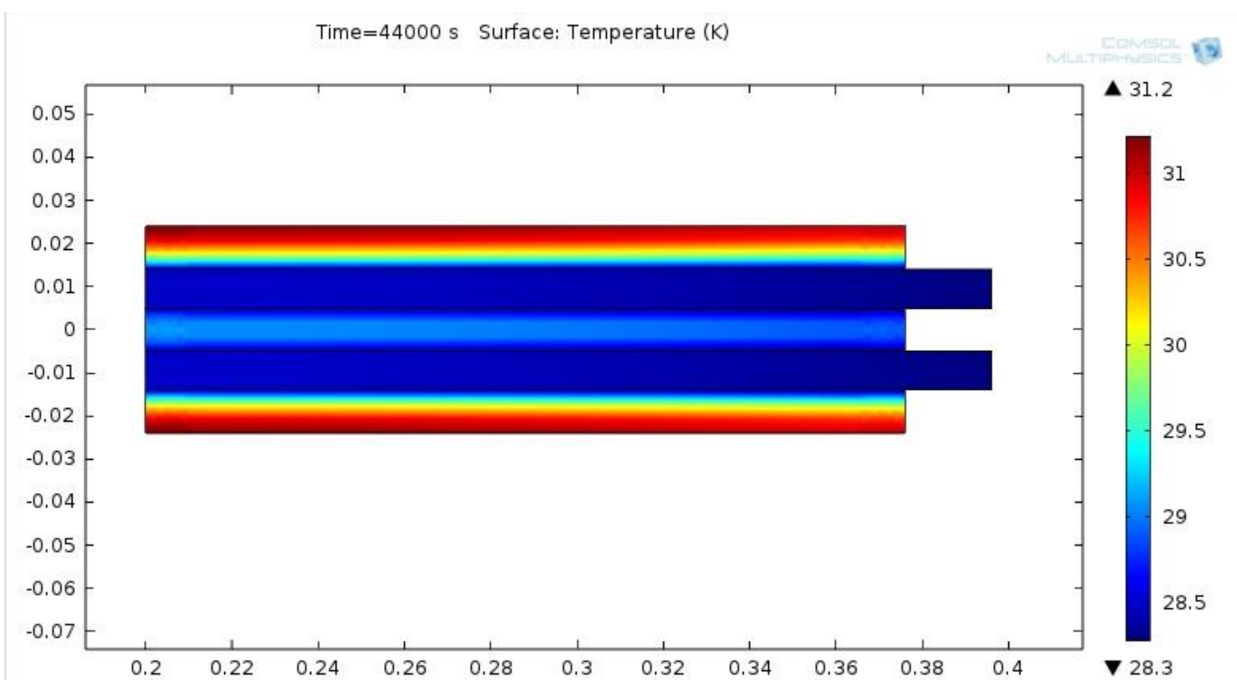
0.38
0.4
0.42



COMSOL MULTIPHYSICS
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
50000
55000
6000
t



Time=44000 s Surface: Temperature (K)
COMSOL MULTIPHYSICS
▲ 31.2
31
30.5
30
29.5
29
28.5
▼ 28.3
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
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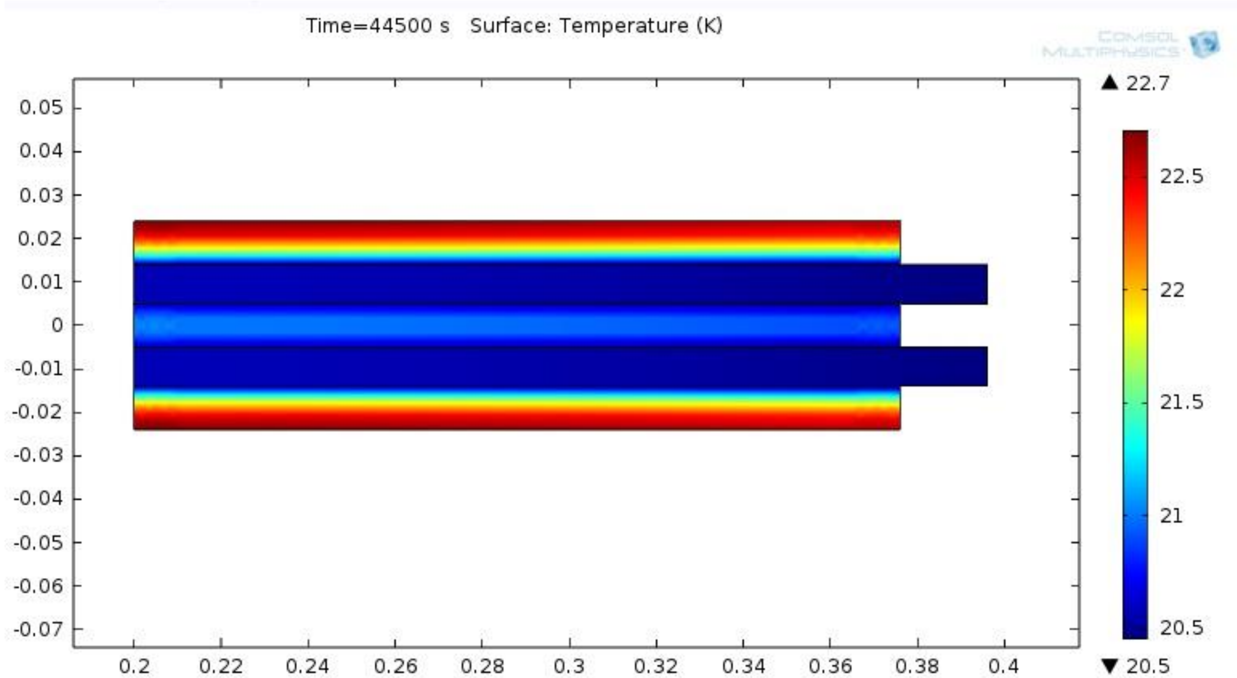

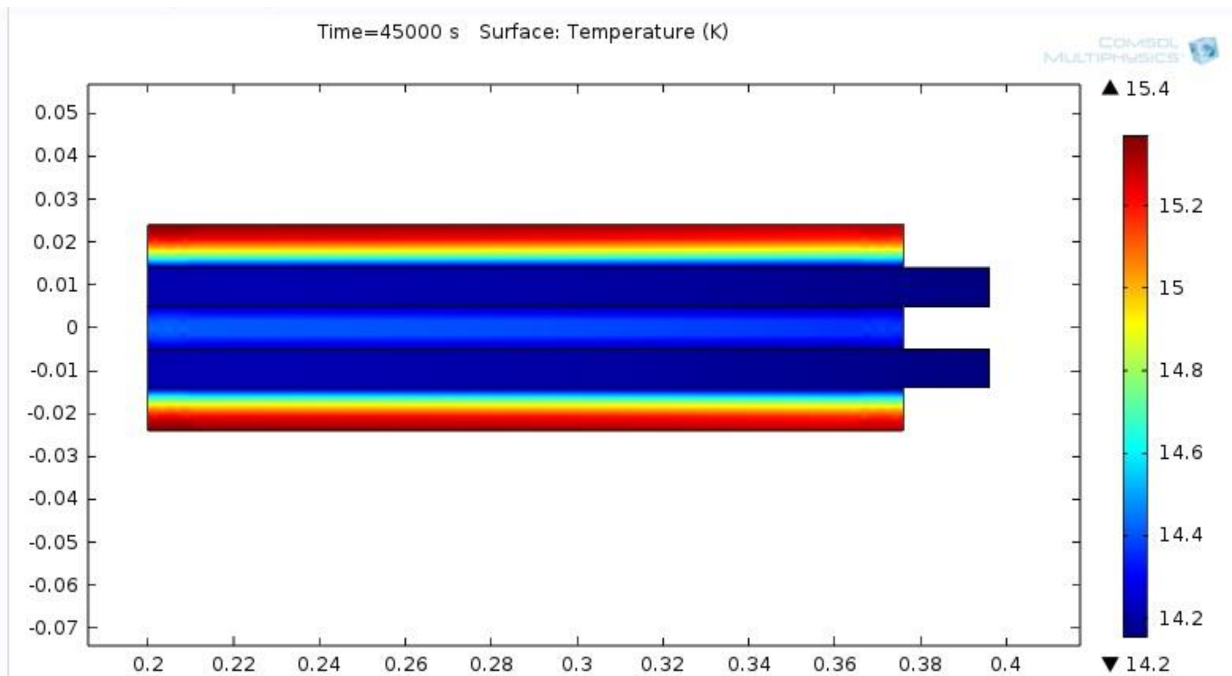

Conclusion:

A 1MJ solenoid system has been designed based on YBCO tapes with a current margin of 40% along with a design to resist the Lorentz forces. A cryocooling system using cryocooler cools the system when connected to the tips of copper plates. The time taken for thermal stabilization has also been calculated and obtained as 45000s using a cryocooler. The system gets heated up basically by YBCO tapes which results in the increase of temperature due to conduction.

References:

[1] IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 12, NO. 1, MARCH 2002- by K. C. Seong, H. J. Kim, S. W. Kim, J. W. Cho, Y. K. Kwon, S. R. Hahn, H. J. Jeon, and I. K. Yu

[2] Connecting Tests of 1MJ • SMES System and 1kA-25 Ω Class Magnetic Persistent-Current-Switch (PCS) H. Honma, H. Morimoto, Y. Koizumi

[3] [1] T. Katagiri, H. Nakabayashi, and Y. Nijo et al., "Field test result of 10 MVA/20 MJ SMES for load fluctuation compensation," IEEE Trans. Appl. Supercond., vol. 19, no. 3, pp. 1993–1998, Jun. 2009.