MultiPhysics Analysis of Trapped Field in Multi-Layer YBCO Plates

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Abstract: superconductors have the unique capability of trapping magnetic flux. This feature has the potential to enable and improve several applications including high power density rotating machines. Current material used as trapped flux magnets (TFM) is single domain YBCO that present numerous limitations in terms of performance, stability and size. One way to overcome the limitations is to use thin layers of YBCO deposited on disks and stack them. Multi-layer trapped flux magnets were successfully modeled and analyzed using COMSOL MultiPhysics through coupled electromagnetic and thermal transient simulations. Simulations allow for a better understanding of how the current redistributes during thermal disturbances and validate the potential of the technology.
Keywords: trapped flux magnets, superconductors, YBCO, non-linear problem

1. Introduction

Trapped Flux Magnets (TFM) are very attractive for application to power devices. The major limitation of flux trapping capabilities of bulk YBCO stems from mechanical problems. Indeed, Lorenz forces can become very important when stored magnetic energy increases. As most of the stress is applied locally on pinning centers in the material, a failure usually results in destruction of the material structure. In order to improve flux trapping capability in TFMs, mechanical reinforcement can be done using epoxy impregnated fiber glass cloth and a record of 17 T trapped at 29 K was achieved. However, due to the ceramic nature of YBCO, it remains structurally weak and can very likely fail if electro-thermal instabilities occur. We have studied the feasibility of TFMs based on multi-layer configurations that could be achieved by stacking disks made of coated conductors. The multi-layer configuration would bring a much better stress distribution and should lead to more stable flux trapping. Even though packing factor remains an issue for stacked coated conductors, it is expected that YBCO can be deposited advantageously in multiple layer configuration specifically developed for this specific application. The paper presents a FEA electromagnetic-thermal analysis of flux trapping in YBCO multi-layers plates using COMSOL MultiPhysics.

2. Flux trapping in superconductors

Because of their unique properties, superconductors can trap magnetic flux and act as “permanent” magnets. The phenomenon can be explained by the critical state model in which current density can only be $\pm J_c$ or 0. Since magnetization of superconductors is hysteretic in nature, the magnetic state of the material depends of the temperature and external field history.

2.2 Flux trapping methods

Several methods to trap magnetic flux in a superconductor can be used. Their effectiveness and practicality differ from one method to another.

- Field cooling

Field cooling consists of a cool down of the superconductor under applied field. This method is very effective but requires a large magnet generating at least the value of flux density desired in the superconductor.

- Zero field cooling

If zero-field cooling is performed, the superconducting material will first react by shielding flux variation and will expel magnetic flux from its volume. The method then requires full saturation in current and necessitates large magnets providing at twice the value of flux density desired in the superconductor.

- Pulsed magnetization

Pulse magnetization is identical in principle to zero field cooling, however, because the flux variation is very fast, the superconductor can enter a flux flow regime and generate losses decreasing the magnitude of the critical current density. Additionally, the method requires energy storage for pulse generation.

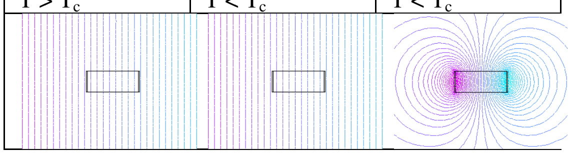
- Flux pumping

Recently flux pumping techniques have been developed requiring a complex to set up, controllable temperature and magnetic gate material. This method represents a very promising alternative as no large field source is needed.

Field cooling is the most effective way to trap magnetic flux in a superconducting material. After a field cooling, a superconducting plate behaves like a permanent source of magnetic field. Its major differences with permanent magnets are:

- a much larger magnetization
- operation at constant flux instead of constant magnetization (trapped flux magnets cannot be "defluxed")

Table 1: Field cooling of a superconducting plate

Step 1	Step 2	Step 3
$B_{ext} = B_{max}$	$B_{ext} = B_{max}$	$B_{ext} = 0$
$T > T_c$	$T < T_c$	$T < T_c$
		

3. Applications of TFMs

Trapped flux magnets enable the development of several superconducting devices requiring constant magnetic flux or large values of magnetic flux density.

- Magnetic bearings

Some applications, such as flywheels or high speed electrical machines, require frictionless bearings. TFMs can be advantageously used as they can provide very large forces and do not require active control. Indeed, since the magnetic flux intrinsically remains constant, any variation is automatically compensated by induced persistent currents.

- Rotating machines

High specific power rotating machine require large excitation field that can be produced by TFMs [1]. The major challenge is to magnetize the superconductor without adding weight or volume to the machine. An example of such machine is shown in figure 1 [2]. The machine takes advantage of the flux trapping capability of superconducting plates to create, shape and concentrate magnetic flux leading to a very high power density.

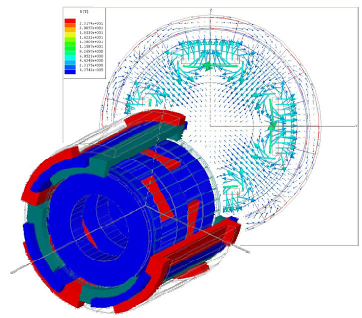


Figure 1. Illustration of Bean's model

4. Properties of YBCO

The most widely used material in TFMs is YBCO. YBCO is a ceramic that becomes superconducting below 92 K and exhibits very high current density in single domain blocks. A flux density of 17 T has been trapped in a small YBCO plate at 29 K [3]. While bulk YBCO is a very attractive option, it presents severe limitations:

- Brittle material that can develop cracks
- Stress applied by the Lorentz forces on pinning centers can lead to mechanical failure
- Size limited to a few centimeters with homogeneous properties
- Cannot be bent

Figure 2. Single grain YBCO cylinder (www.can.cz)

Superconductors exhibit a highly non-linear electrical conductivity as shown in figure 3 and equation (3).

$$E = E_c\left(\frac{J}{J_c(B,T)}\right)^{n(B,T)} \qquad (3)$$

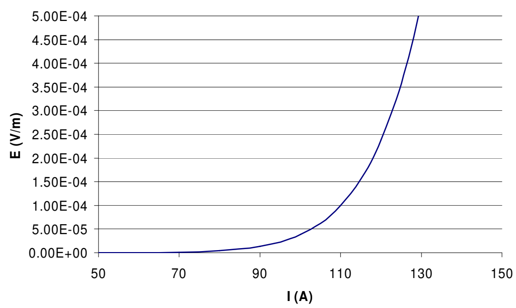


Figure 3. E(I) characteristic of superconductors

The critical current density of YBCO is depending on the temperature and on the applied magnetic flux density. It can be parameterized as follows:

$$J_c(B,T) = J_c(0,0)\left(1-\frac{1}{T_c}\right)e^{-\frac{B}{90\left(1-\frac{T}{T_B}\right)}} \qquad (4)$$

The parameters J_c(0 T, 0 K), T_c and T_b can be obtained experimentally. Current flows in the a-b plane of the material and current density in the c-axis of the material is negligible.

5. Multilayer configuration

YBCO can be deposited in thin films and turned into tapes. YBCO is the basis for second generation conductors or coated conductors and can be deposited on large areas. Up to 10 centimeter wide ribbons are currently manufactured and cut into 4 mm wide tapes to make conductors. Disks coated with YBCO film can be manufactured and stacked to form cylinders. The electrical properties would then be strongly anisotropic as current is allowed to flow only in parallel planes (a-b planes) and no current is flowing between layers. YBCO is deposited on substrate and the filling factor of a stack is a lot less than 50 %. However, current density in YBCO films or thin layers is orders of magnitude larger than in large block and therefore compensate for the low filling factor. Such a configuration brings numerous advantages:

- Material can be bent
- Intrinsically mechanically reinforced
- Improved flux pinning
- Larger systems can be built

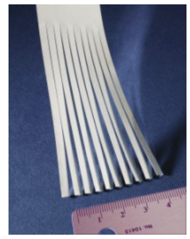


Figure 3. YBCO conductor from American Superconductor Inc. [4]

Commercially available wide conductors can be used, however, the stabilization layers necessary for stable conductor operation are not requires in TFM and a higher filling factor can be achieved with a dedicated configuration.

6. Problem definition

6.1 Geometry

The system is modeled in 2D with axial symmetry, which is a valid approximation for the system of interest since YBCO can be deposited uniformly. The geometry implemented in COMSOL is shown in figure 4.

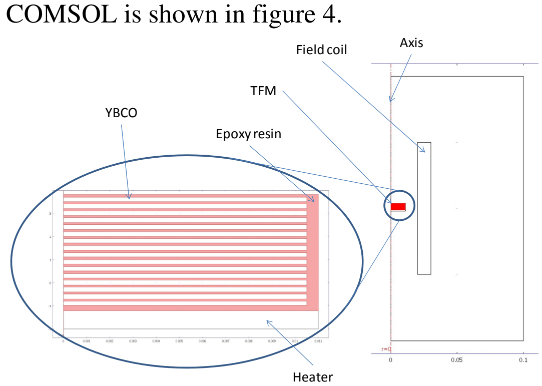


Figure 4. Geometry implemented in Comsol

The system is modeled with homogeneous YBCO layers 0.15 mm thick and separated by 0.1 mm layers of resin insulation.

6.2 Material properties

- YBCO

YBCO exhibits non-linear electrical and thermal properties. In COMSOL, conductors are modeled with their electrical conductivity, based on equation (3), the conductivity of YBCO can be expressed as follows.

$$\sigma[S/m] = \frac{J_{c0}}{E_c}\left(1-\left(\frac{T}{T_c}\right)^2\right)^{\frac{3}{2}}\left(\frac{1}{1+\frac{B}{B_0}}\right)\left(\frac{E}{E_c}\right)^{\frac{1}{n}-1} \quad (5)$$

Where T_c is the critical temperature, J_{c0} is the value of the critical current density at 0 K and 0 T, E_c is the electrical field magnitude defining J_c, B_0 and n are determined experimentally.
The electrical field E is a parameter of the electrical conductivity which would pose a problem in most FEA package but COMSOL allows for this dependence to be modeled.

Specific heat and thermal conductivity of YBCO are plotted as a function of temperature in figure 5.

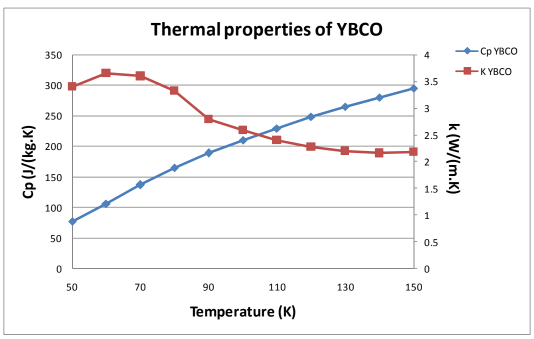


Figure 5. Thermal properties of YBCO

- Resin

G10 resin is used to hold the YBCO layers together. Its thermal properties are shown in figure 6.

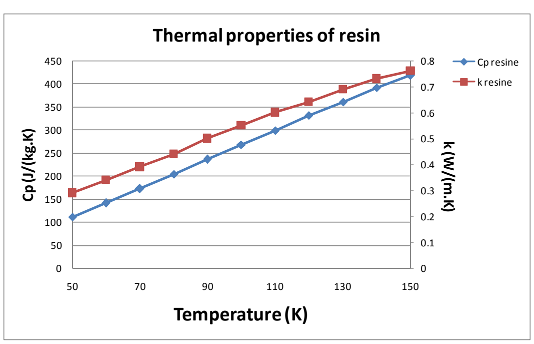


Figure 6. Thermal properties of G10 resin

6.3 Mesh, Sources and boundary conditions

The mesh, represented in figure 7, is composed of about 80,000 elements leading to a system with over 300,000 degrees of freedom. The mesh is kept coarse in the surrounding air and in the field coil.

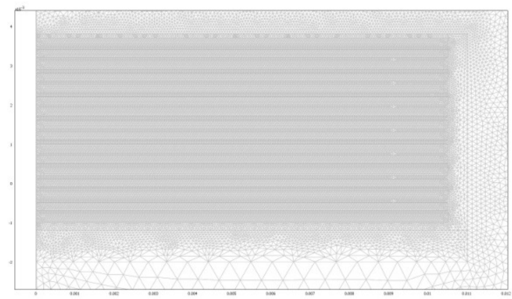


Figure 7. Mesh in the multi-layer component

The thermal simulation only considers the YBCO, resin and heater. A heat exchange condition is set on the resin simulating cooling. The heat pulse applied to the heater is shown in figure 8.

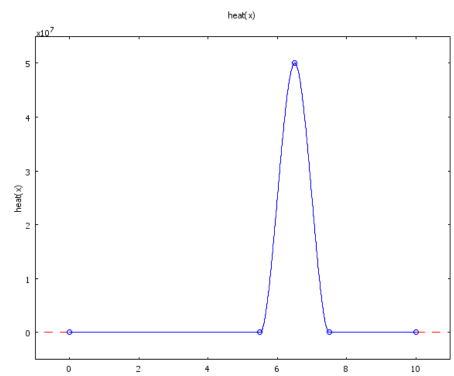


Figure 8. Heat pulse.

The field coil generates a flux density on the TFM which is ramping down linearly from 5 T to 0 T.

7. Simulation sequence

Since field cooling requires full field penetration before the YBCO becomes superconducting, the initial condition corresponding to this state needs to be computed first. When a superconductor is cooled down under field, part of the magnetic flux is expelled from its volume; if the applied field is below H_{c1}, which is of a few mT, then the material is diamagnetic (Meissner effect), if the applied field is greater than Hc1, then the material is in the mixed state and normal zones are developed allowing quanta of flux to go through the material. In the case presented, the material is in the mixed state and the resulting partial diamagnetism which is typically of a few percents is neglected. The simulation sequence is the following:

1. Initial state (steady state): maximum external field applied, T=85 K
2. Transient analysis part 1: external field ramped down, no external heat source
3. Transient analysis part 2: no applied field, apply pulse of heat

8. Simulation Results

Once the flux is trapped, the TFM is excited with a heat pulse. This thermal disturbance can lead to a decrease of the trapped flux or a complete demagnetization of the material. A critical value for the heat pulse leading to non-stable behavior can be determined. This relates to the minimum quench energy (MQE) for quench studies which is the minimum amount of energy leading to instability of the material. The two cases are described in this section.

8.1 Current penetration

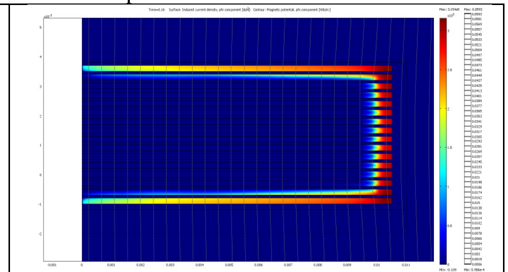
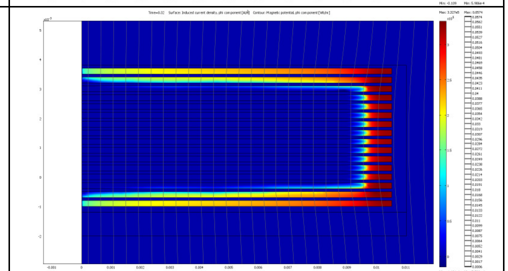
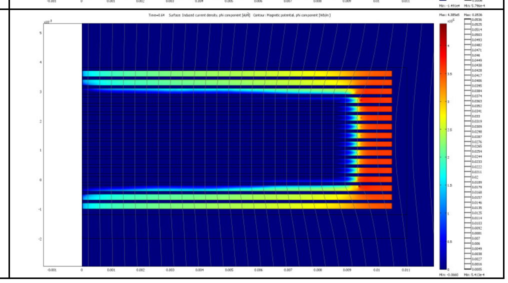
As predicted by the critical state model, the current induced by a decreasing magnetic flux penetrates from the side in the material. Since all the layers are magnetically coupled, the stack behaves as a single block of YBCO. The magnitude of the current density strongly depends on the applied flux density leading to a lower current value in the central part of the TFM.

In table 2:

1- The applied field ramp-down starts, current penetrates in the superconductor
2- As the field keeps decreasing, current penetration increases, current density is already lowered in the center of the TFM
3- All the field is generated by the TFM

The current can penetrate until the material is fully saturated for larger applied field values.

Table 2: current penetration in the TFM

1	
2	
3	

8.2 Stable behavior

A heat pulse of 18 J is applied to the TFM once the field coil is completely ramped down. As shown in following table, the current in the layers closer to the heater heat up, thus becoming dissipative. The heat exchange is high enough to maintain the top layers in the superconducting state; the trapped flux is nearly unchanged. Indeed, when the current in the bottom layer is dissipated, the associated flux variation is compensated by a redistribution of the current in the top layers; the current penetrates deeper in the material. In table 3:

1- Current starts penetrating in the material
2- Magnetic flux is trapped
3- Heat pulse is generated decreasing current magnitude in the lower layers
4- After current redistributes to keep flux variation to a minimum

Table 3: stable behavior – Color represents current density and lines the flux lines.

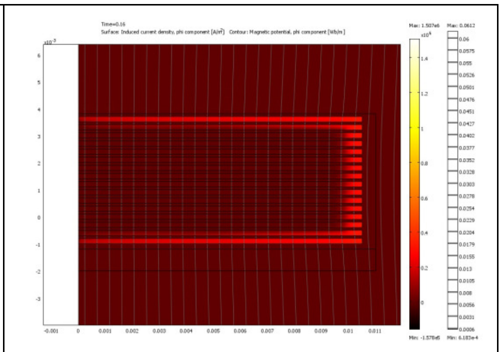
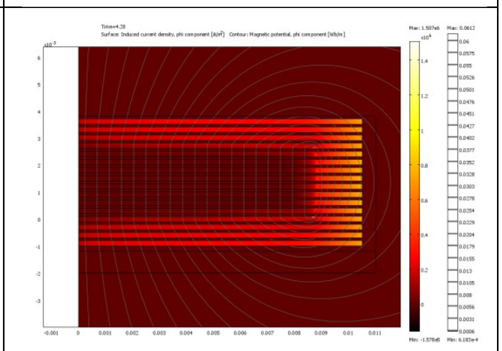
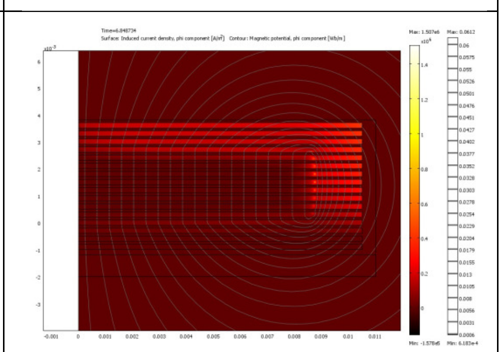
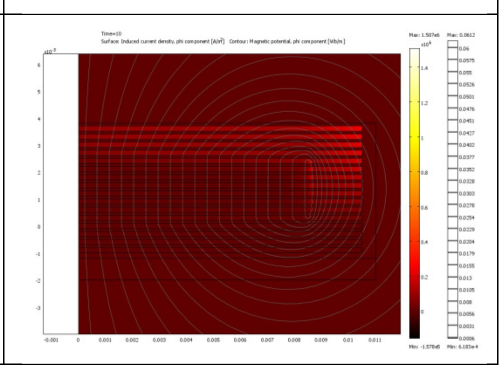
1	
2	
3	
4	

Figure 9 shows the flux distribution on the top of the TFM during the first 10 s. The initial distribution is the uniform field generated by the field coil. The end of the simulation shows the field trapped in the superconductor.

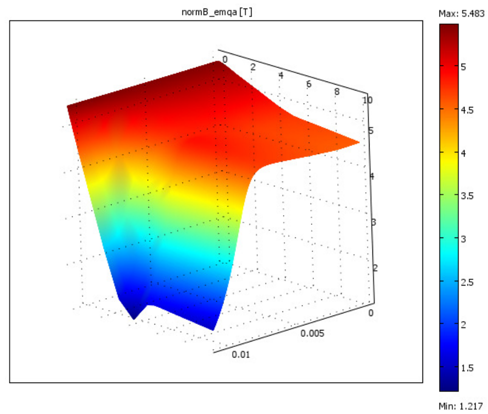


Figure 9. flux distribution on top of the TFM

During flux trapping, magnetic flux is changing in the area where current is flowing. Any change of flux creates an electrical field as predicted by Faraday's law of induction. The simultaneous presence of electrical field and current density creates losses. Such losses can be calculated by integrating **J×E** over the volume of superconductor. The instantaneous power, shown in figure 10, peaks at 0.5 mW and leads to a 0.2 mJ of dissipated energy in the material, which in this case is negligible. However, for faster flux variation, these losses can become significant.

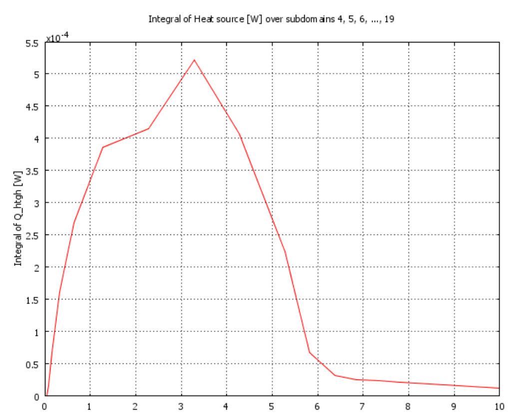
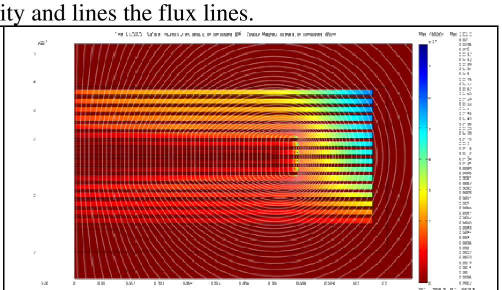
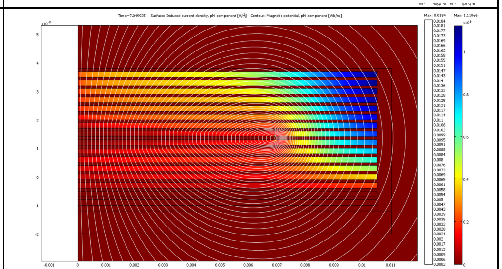
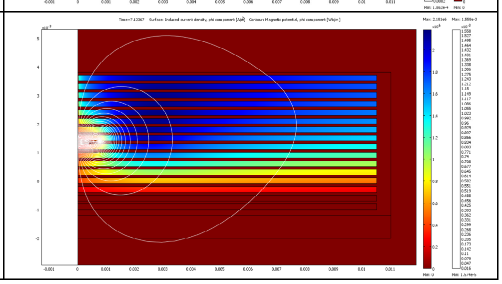


Figure 10. Heat dissipated in the superconductor

8.3 Unstable behavior

In some cases, an avalanche phenomenon can occur destroying the magnetization of the material. This can happen for large energy deposition such as heat pulse and/or weak cooling. In the presented simulation, the heat pulse was increased by 20 % leading to instability. The following table shows the simulation results.

Table 4: unstable behavior – Color represents current density and lines the flux lines.

1	
2	
3	

In table 4:

1- No external field. The flux is trapped and the heat pulse starts
2- Current redistributes and penetrates deeper in the material
3- An avalanche phenomenon dissipates all the stored energy
4-

The magnitude of the flux density at the center top of the TFM is shown in figure 11. The entire trapped field disappears at the beginning of the pulse, evidence of the instability. Figure 12 shows the energy dissipated in the superconductor. A peak of 0.25 W appears at the beginning of the pulse releasing the stored energy.

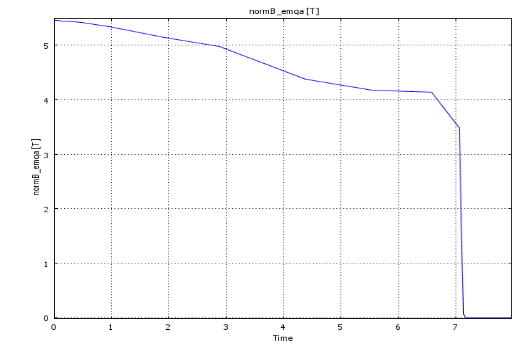


Figure 11. Flux distribution the center top of the TFM

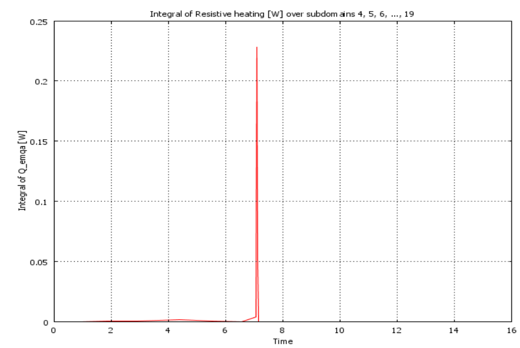


Figure 12. Heat dissipated in the superconductor

9. Conclusion

Multi-layer trapped flux magnets present a very interesting alternative to bulk blocks of ceramic YBCO. A model was developed to investigate their stability against thermal disturbances. Modeling superconducting material is not trivial because of the strong non-linearity of the electrical conductivity. COMSOL allows for a better understanding of the behavior of trapped flux magnet through successful coupled electromagnetic and thermal simulations.

10. References

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4. www.amsuper.com