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# MultiPhysics Analysis of Trapped Field in Multi-Layer YBCO Plates

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# Outline

- What are Trapped Flux Magnets (TFM)
- Applications of Trapped Flux Magnets
- Performance of bulk YBCO TFM
- Principle of flux trapping
- Modeling superconducting material
- Definition of the problem
- Implementation in COMSOL
- Simulation results

# What are Trapped Flux Magnets

- Superconductors exhibit a non-measurable electrical resistance when operating below a critical surface (J, B, T)
- Lenz' law states

$$e = -\frac{d\phi}{dt}, e = \rho . j \xrightarrow{\rho = 0} \phi = \iint_S \vec{B} d\vec{S}$$

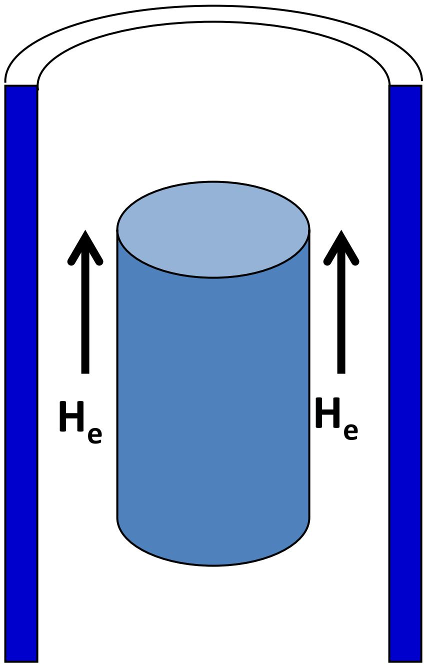
*is constant*

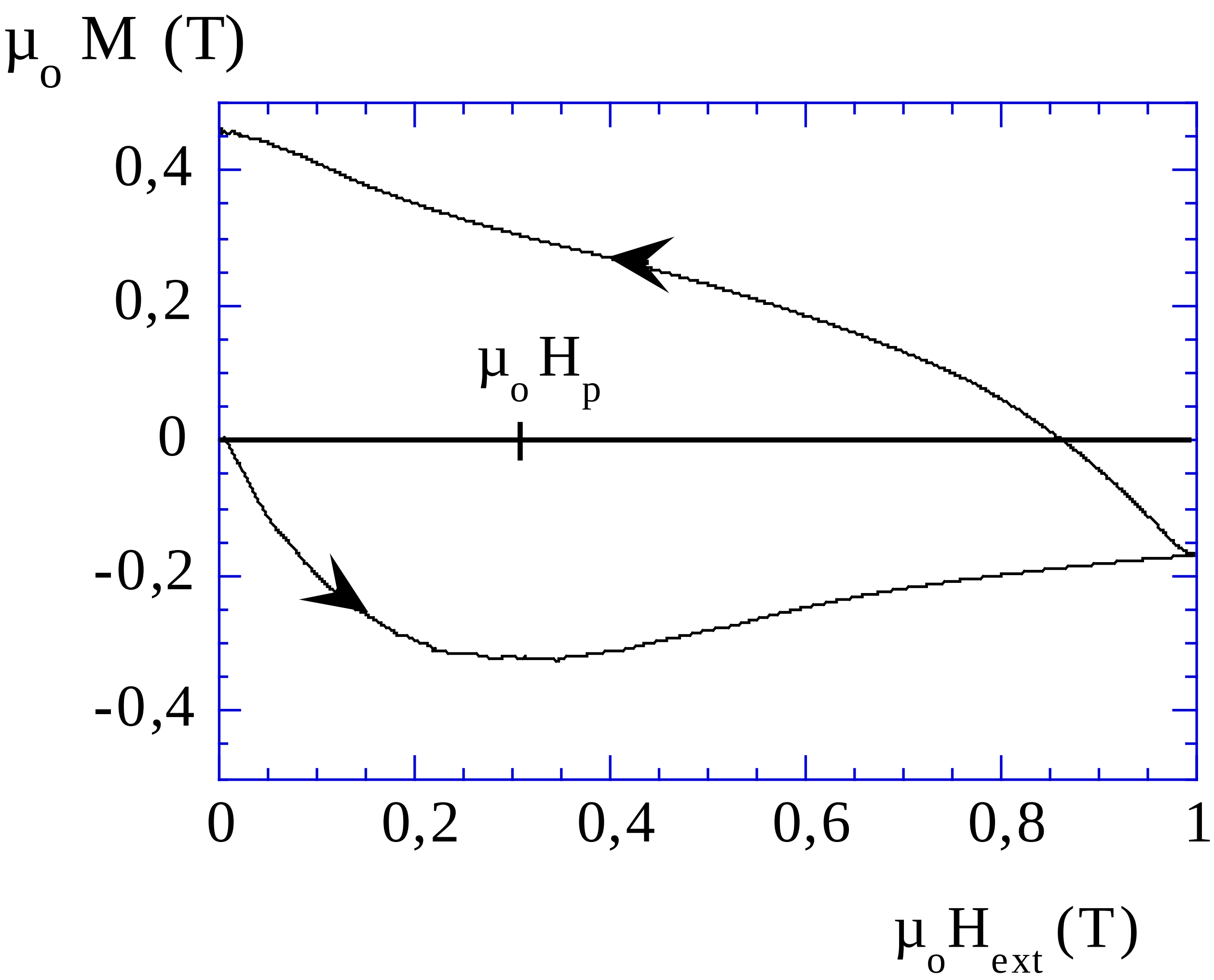
Trapped flux magnets:
YBCO single grain
17 T @ 29 K
Constant magnetic flux

Permanent magnets:
NdFeB, SmCo…
< 1 T @ room temperature
Contant magnetization

# Magnetization of a Superconductor

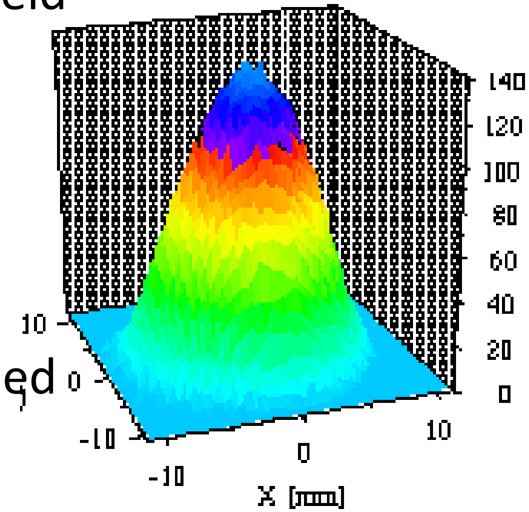
- Lenz law
- Critical state model
  - J = O or ± $J_c$





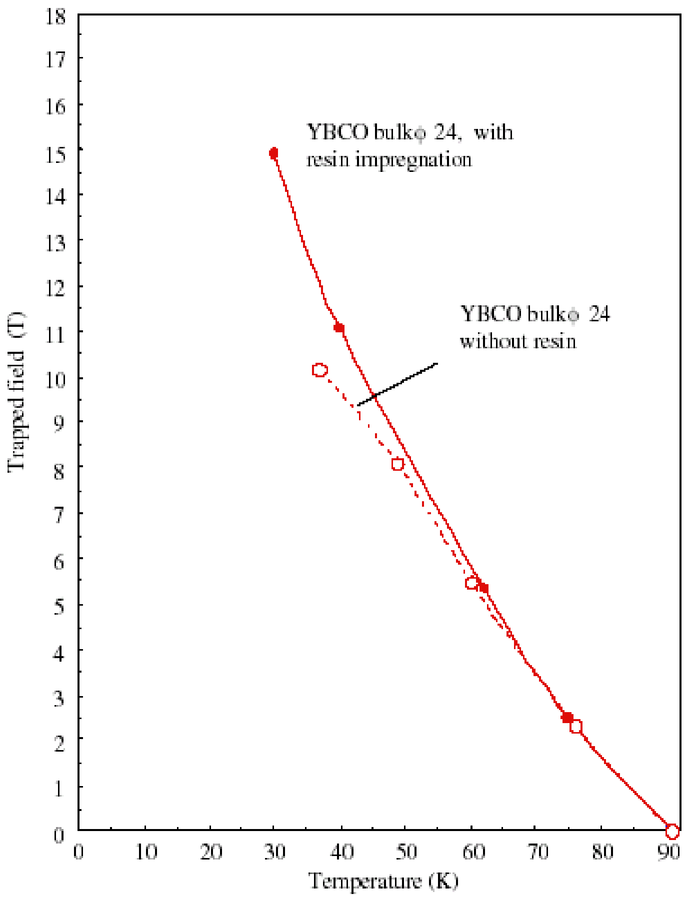
# Flux Trapping Methods

- Field cooling
  - Cool down of the superconductor under applied field
  - Very effective
  - Require large magnets providing Btrapped
- Zero field cooling
  - Requires full saturation in current
  - Require large magnets providing at least 2*Btrapped
- Pulsed magnetization
  - Require energy storage for pulse generation
  - Generates losses in the superconductor (flux flow)
- Flux pumping
  - Complex to set up
  - Requires controllable temperature and magnetic gate material



# Single Domain YBCO Plates as Trapped Field Magnets

- Flux Trapping up to 17 Tesla at 30K !



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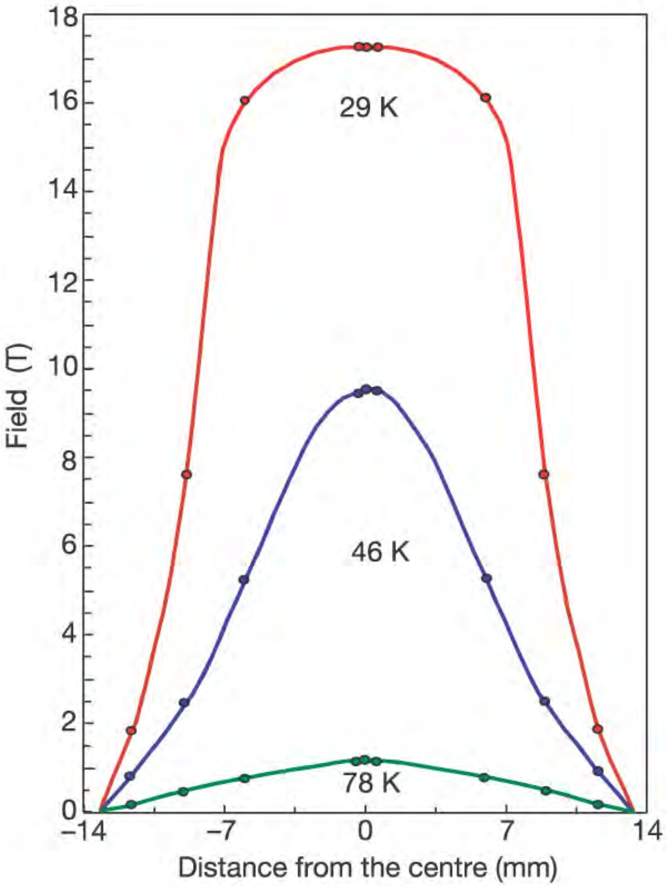
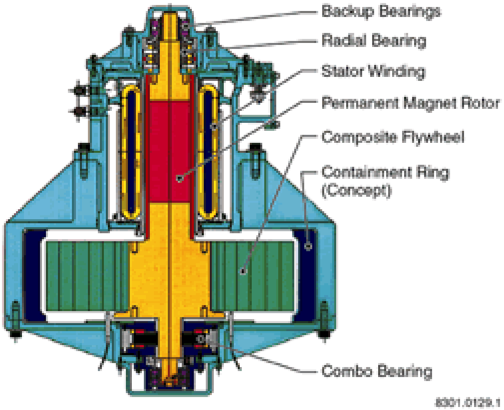
Resin impregnated YBCO pellets

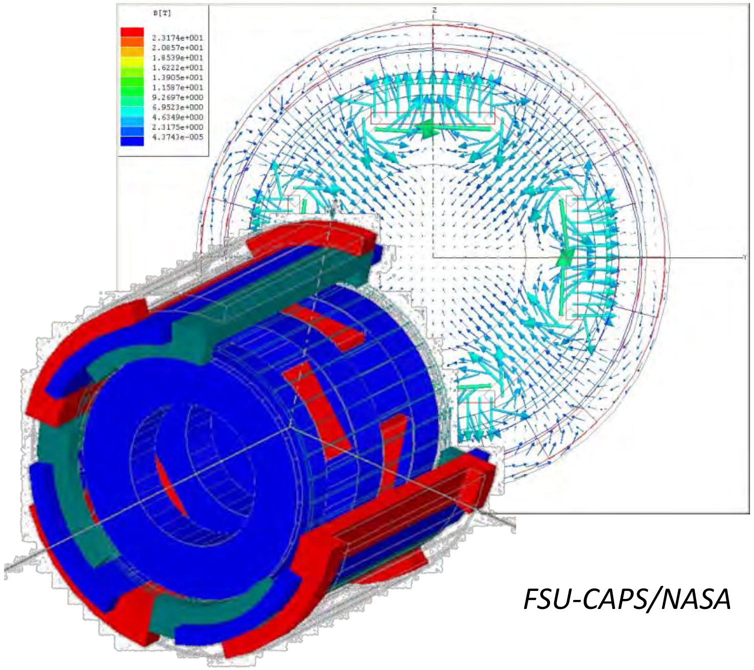


# Applications of Trapped Flux Magnets

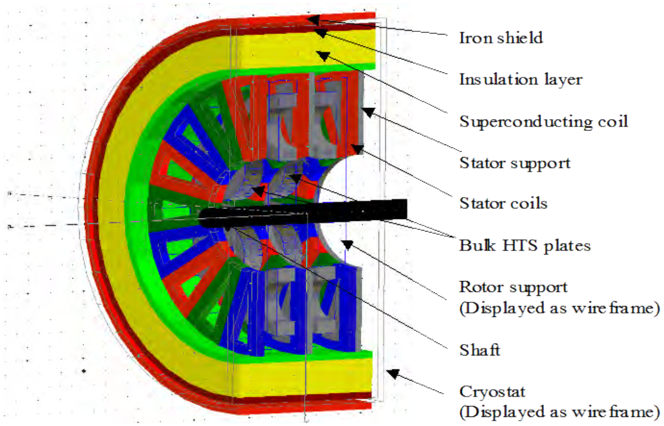
- High power density rotating machines
  - Challenges: trapping the flux
  - Not very scalable
  - Very high excitation field
- Magnetic bearings (Flywheels)
  - Intrinsically stable
  - No control required



*Georgia Tech design*



*FSU-CAPS/NASA*



*FSU-CAPS/NASA*

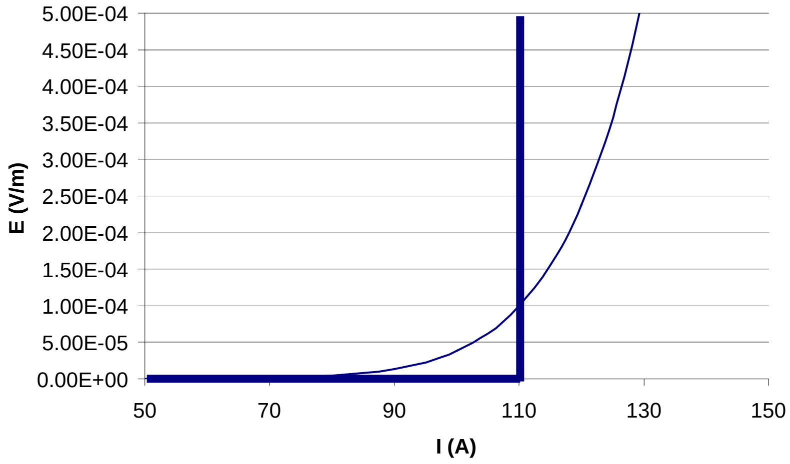
# Modeling of Bulk Superconducting Material

## Equations to solve:

For a given operating temperature:

$$E = E_c \left( \frac{j}{j_c} \right)^n$$

Bean's model



Valid Maxwell's equations:

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

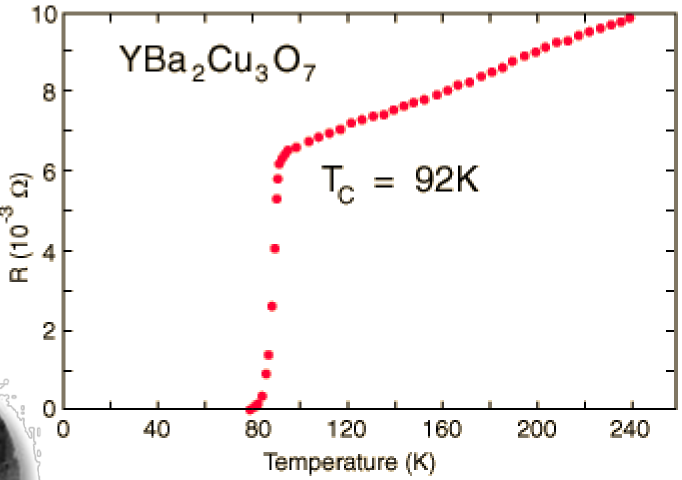
$$\vec{\nabla} \times \vec{B} = \vec{j}$$

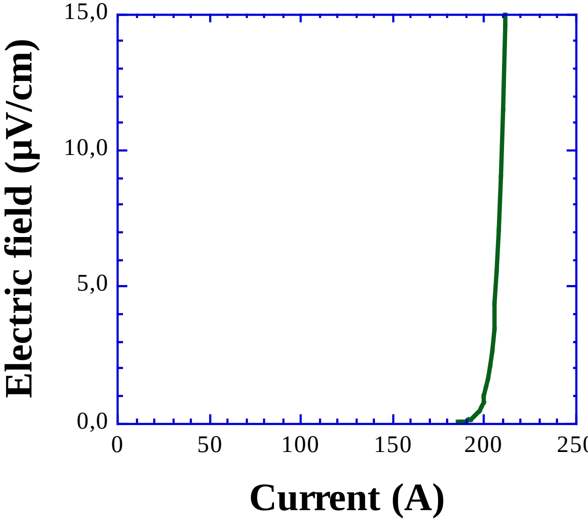
Magnetic behavior:

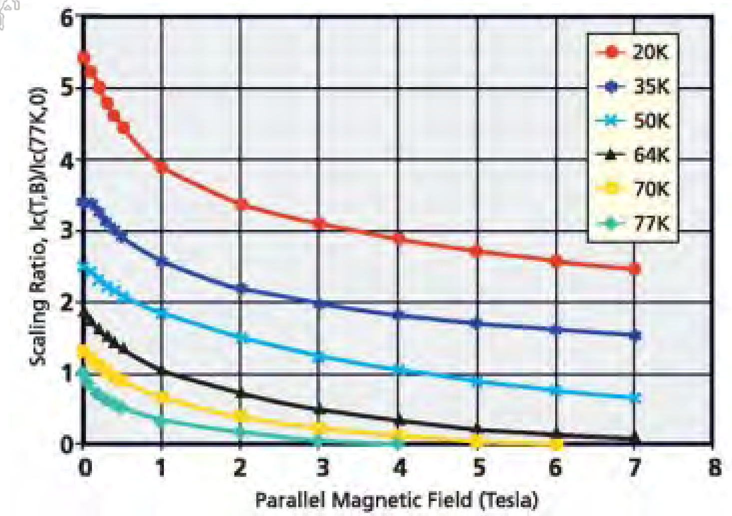
$$\vec{B} = \mu_0 \vec{H}$$

# YBCO Bulk Material Properties

- Tc ~ 92 K
- Jc depends on B and T
- Non-linear E(J) characteristic (Ohm’s law not valid anymore)

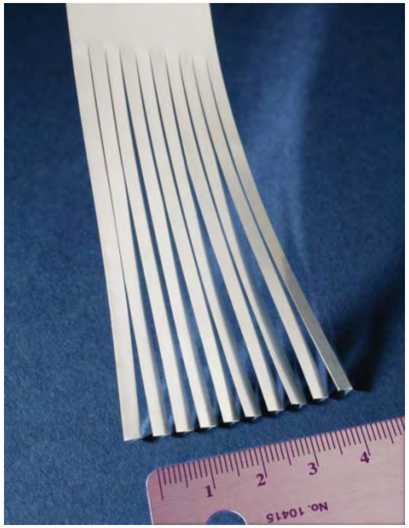






# Why Multilayer FTM

- Bulk material
  - Ceramic material
  - Structural limits (forces on vortexes)
  - Problem to grow large grains
- Multilayer configuration
  - Deposition of films (proved technology)
  - Stack more stable mechanically (better pinning)
  - Lower packing factor but higher current density
- Need to evaluate the configuration through numerical analysis
  - Flux trapping capability
  - Stability against thermal disturbances



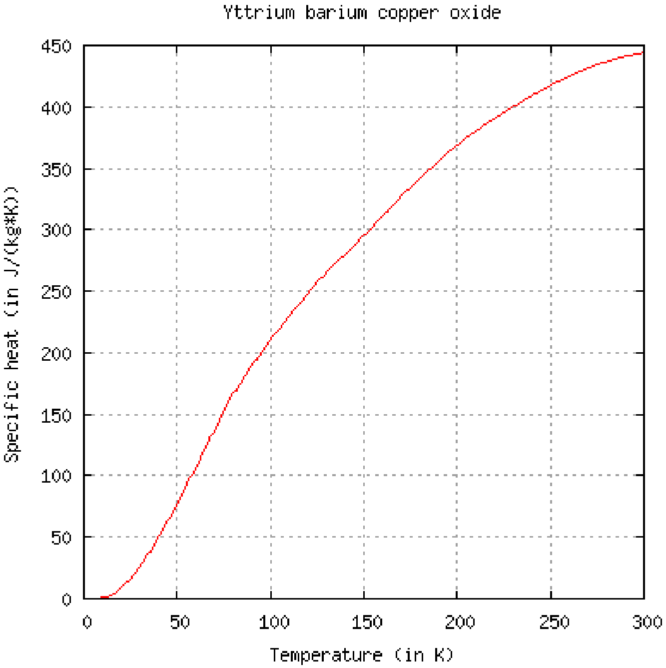
*American Superconductor*

# Model Implemented for YBCO

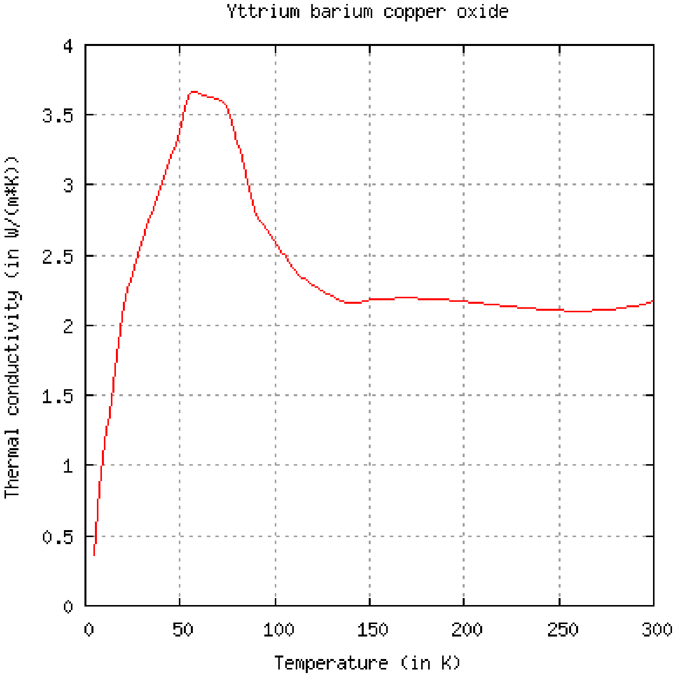
Electrical conductivity model:
Non-linear with strong dependence
upon E, T and B

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

Permeability of vacuum: $\mu_r = 1$



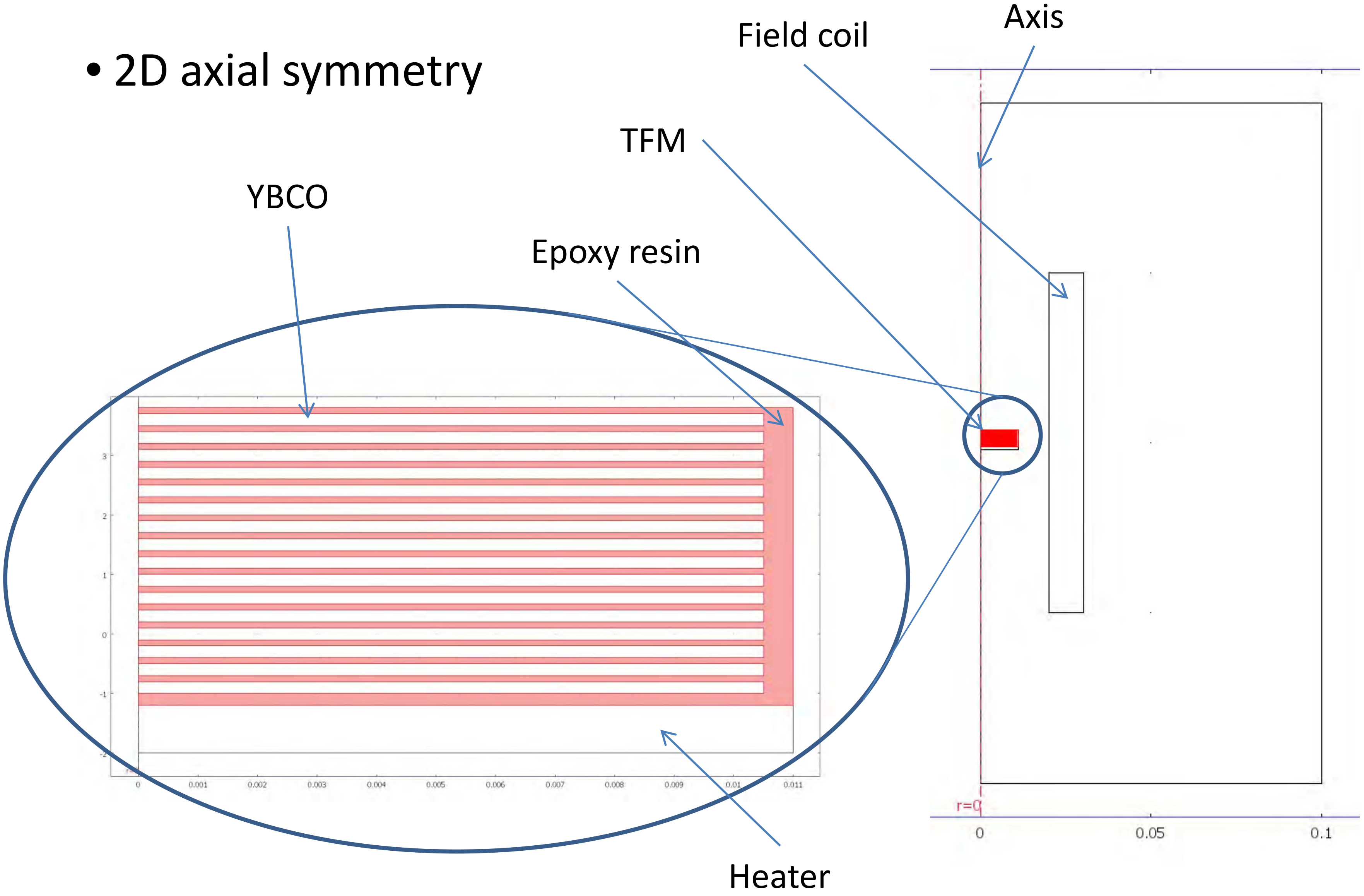
*Specific heat of YBCO*



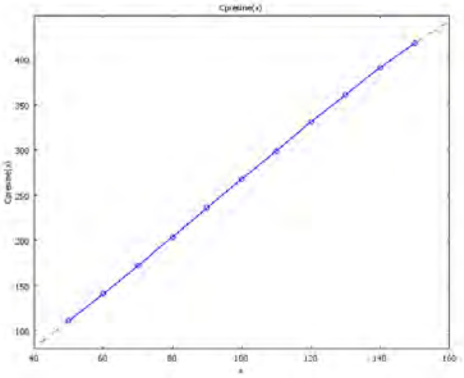
*Thermal conductivity of YBCO*

# Geometry Implemented

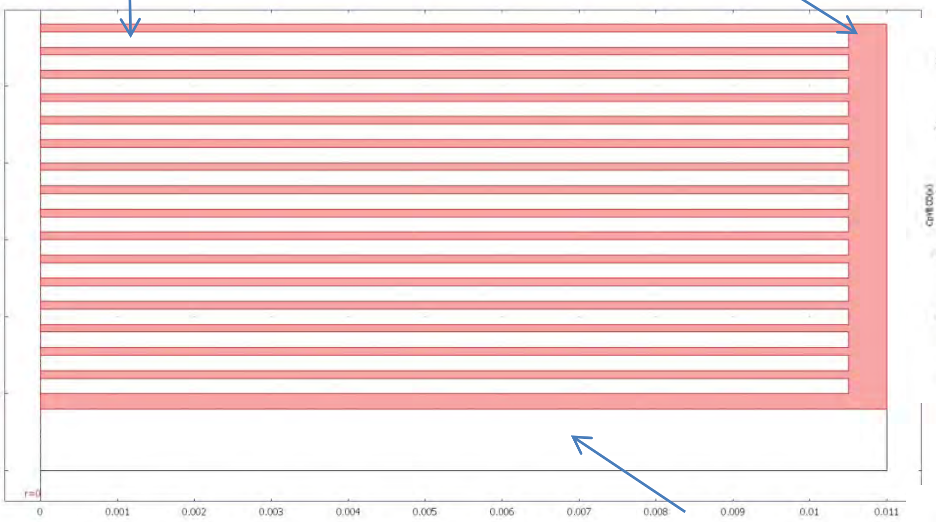
- 2D axial symmetry



# Thermal Model



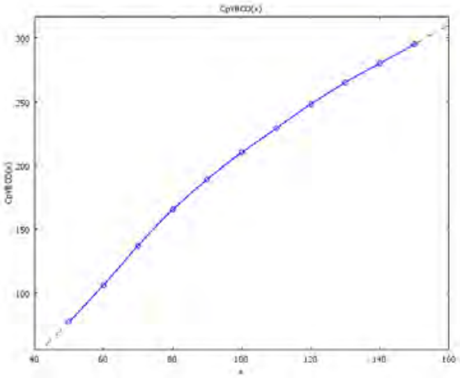
*Heat capacity of resin*



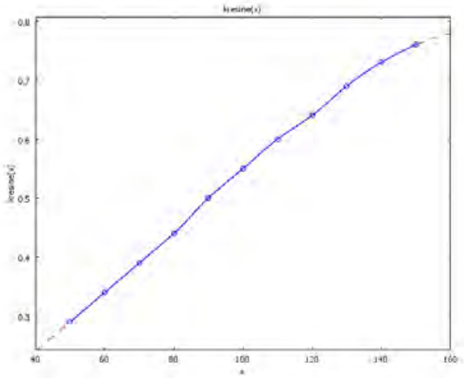
YBCO

Epoxy resin

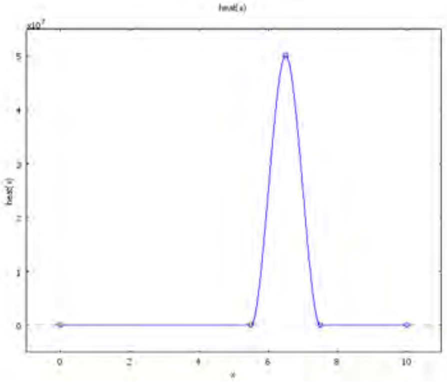
Heater



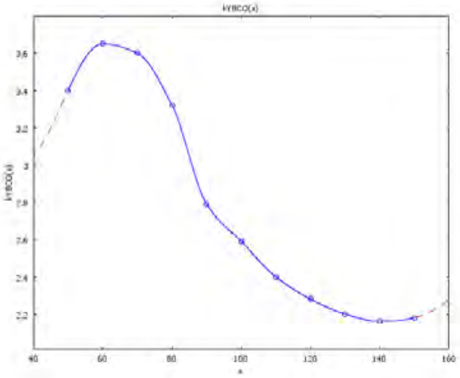
*Heat capacity of YBCO*



*Thermal conductivity of resin*



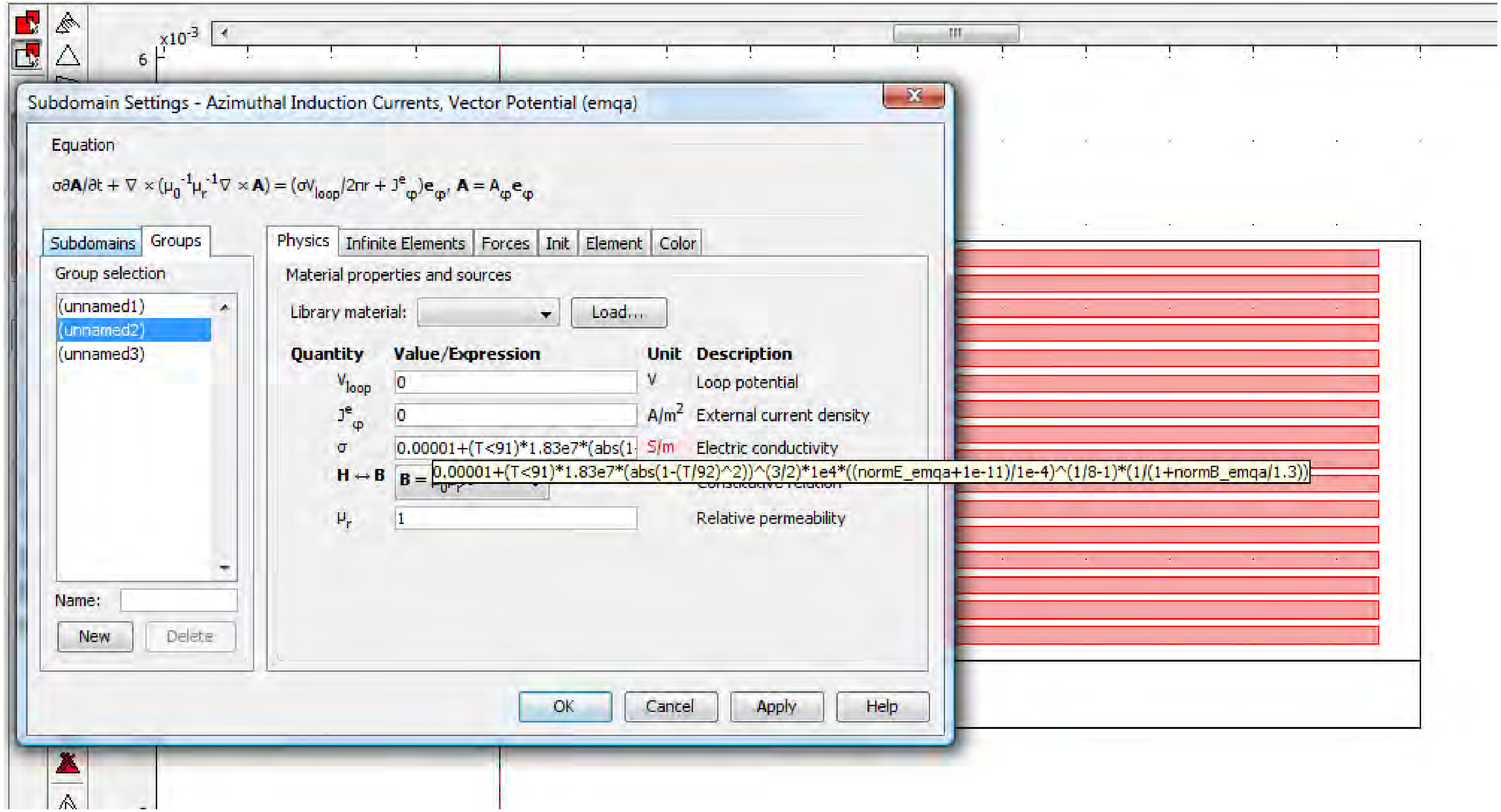
*Heat pulse*



*Thermal conductivity of YBCO*

# Electromagnetic Model

- Linear variation of current density in field coil
- Non linear electrical conductivity in superconductor



Subdomain Settings - Azimuthal Induction Currents, Vector Potential (emqa)

Equation

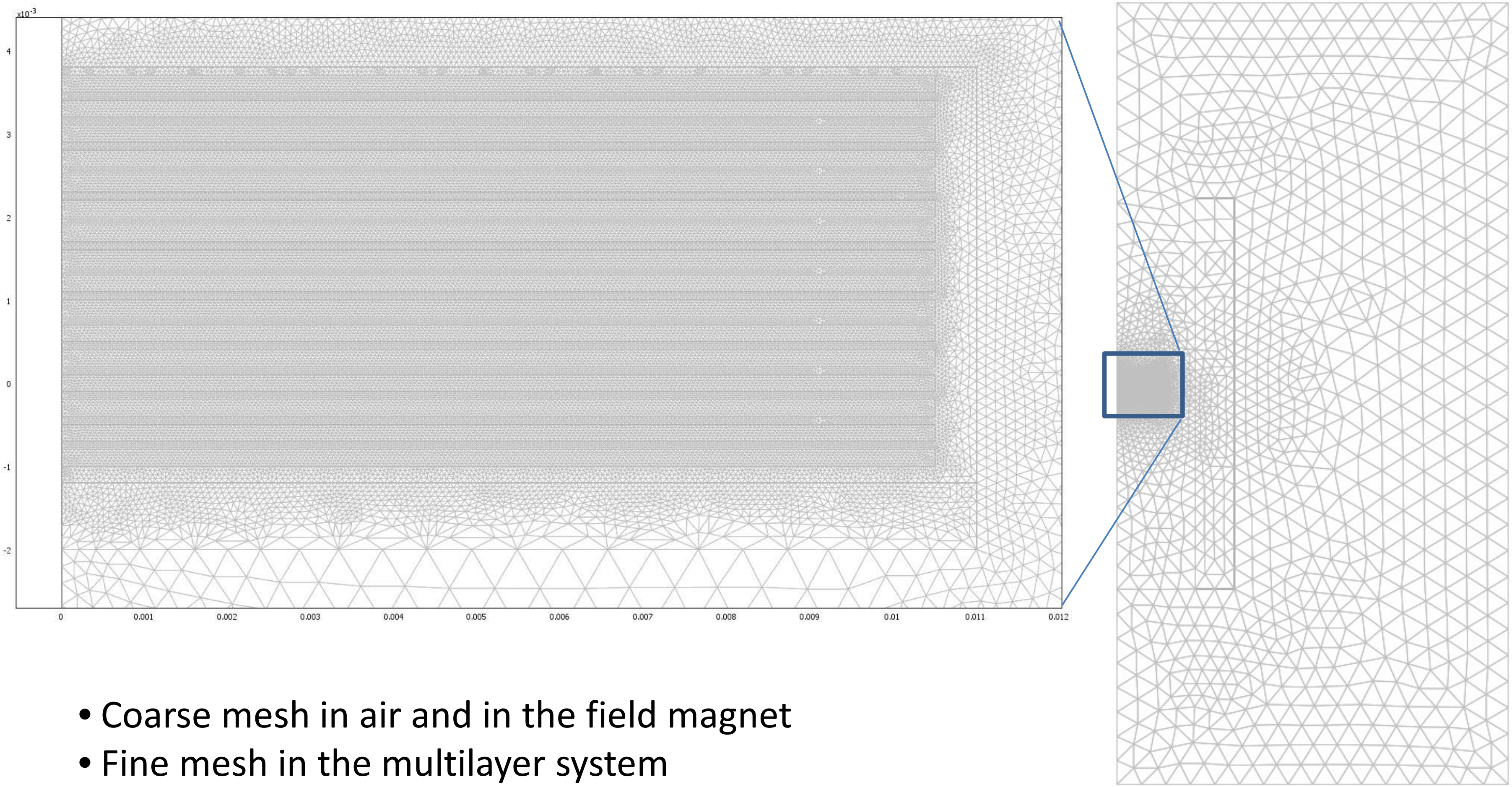
$\sigma\partial\mathbf{A}/\partial t + \nabla \times (\mu_0^{-1}\mu_r^{-1}\nabla \times \mathbf{A}) = (\sigma V_{loop}/2\pi r + J^e_\varphi)\mathbf{e}_\varphi,\ \mathbf{A} = A_\varphi\mathbf{e}_\varphi$

Group selection: (unnamed2)

Material properties and sources

| Quantity | Value/Expression | Unit | Description |
|---|---|---|---|
| $V_{loop}$ | 0 | V | Loop potential |
| $J^e_\varphi$ | 0 | A/m$^2$ | External current density |
| $\sigma$ | 0.00001+(T<91)*1.83e7*(abs(1-(T/92)^2))^(3/2)*1e4*((normE_emqa+1e-11)/1e-4)^(1/8-1)*(1/(1+normB_emqa/1.3)) | S/m | Electric conductivity |
| H ↔ B | B = |  | Constitutive relation |
| $\mu_r$ | 1 |  | Relative permeability |

# Mesh



- Coarse mesh in air and in the field magnet
- Fine mesh in the multilayer system
- ~ 80,000 elements
- Number of d.o.f. ~305,000

# Simulation

**Initial state**

Steady state analysis

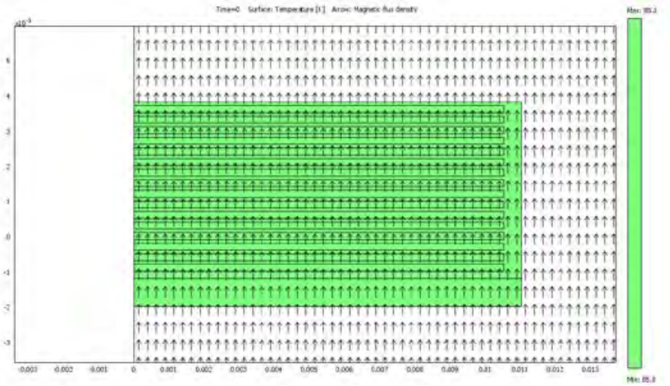
- Bcoil applied
- T = 85 K

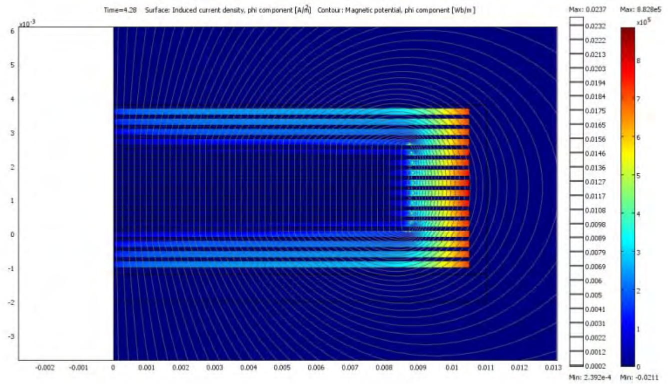
**Transient analysis**

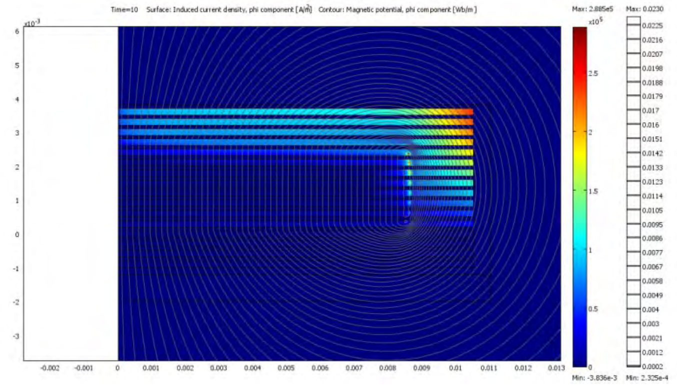
- Jcoil ramped down to 0
- Constant temperature

**Transient analysis**

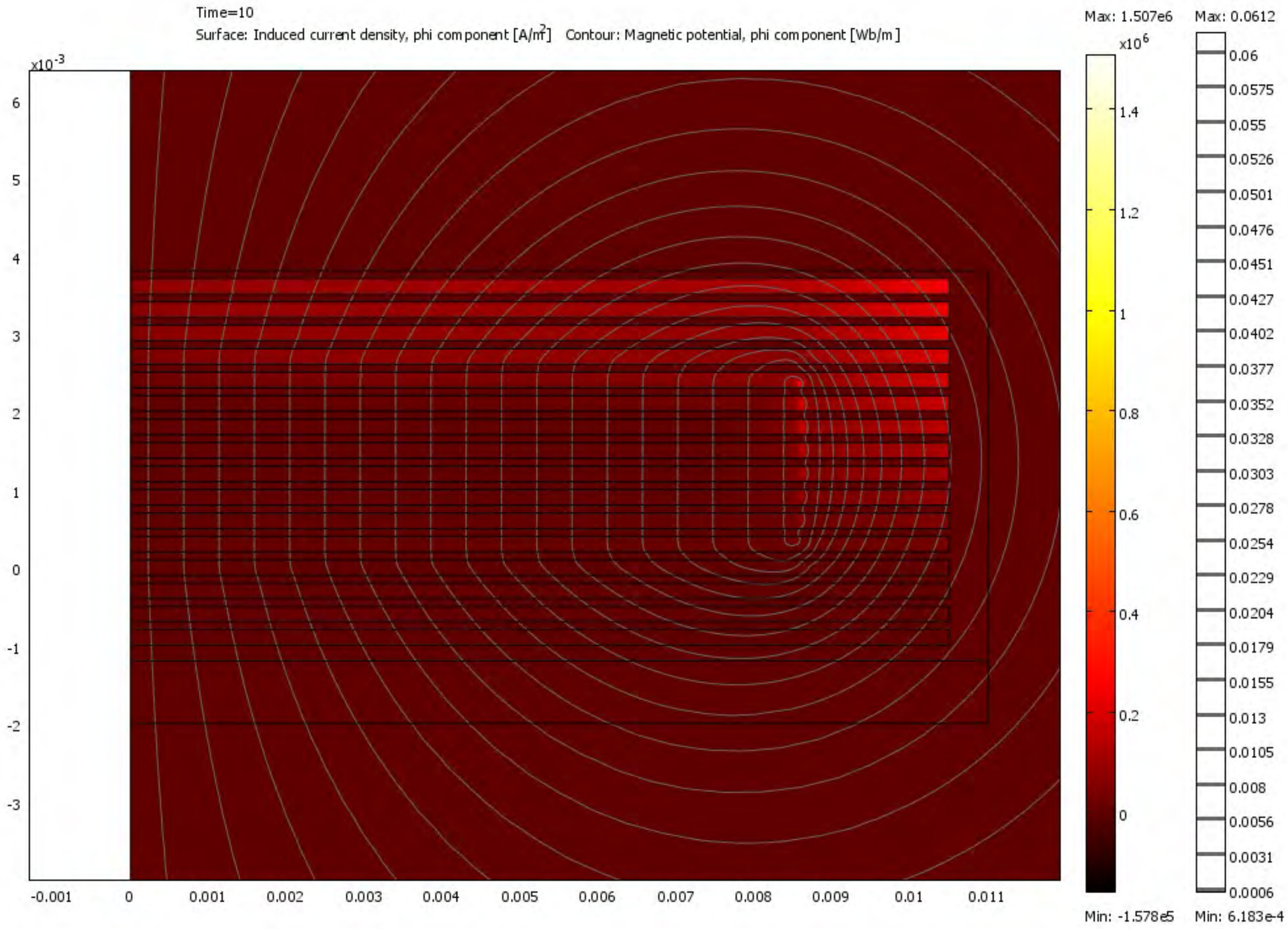
- Jcoil=0
- pulse of heat applied





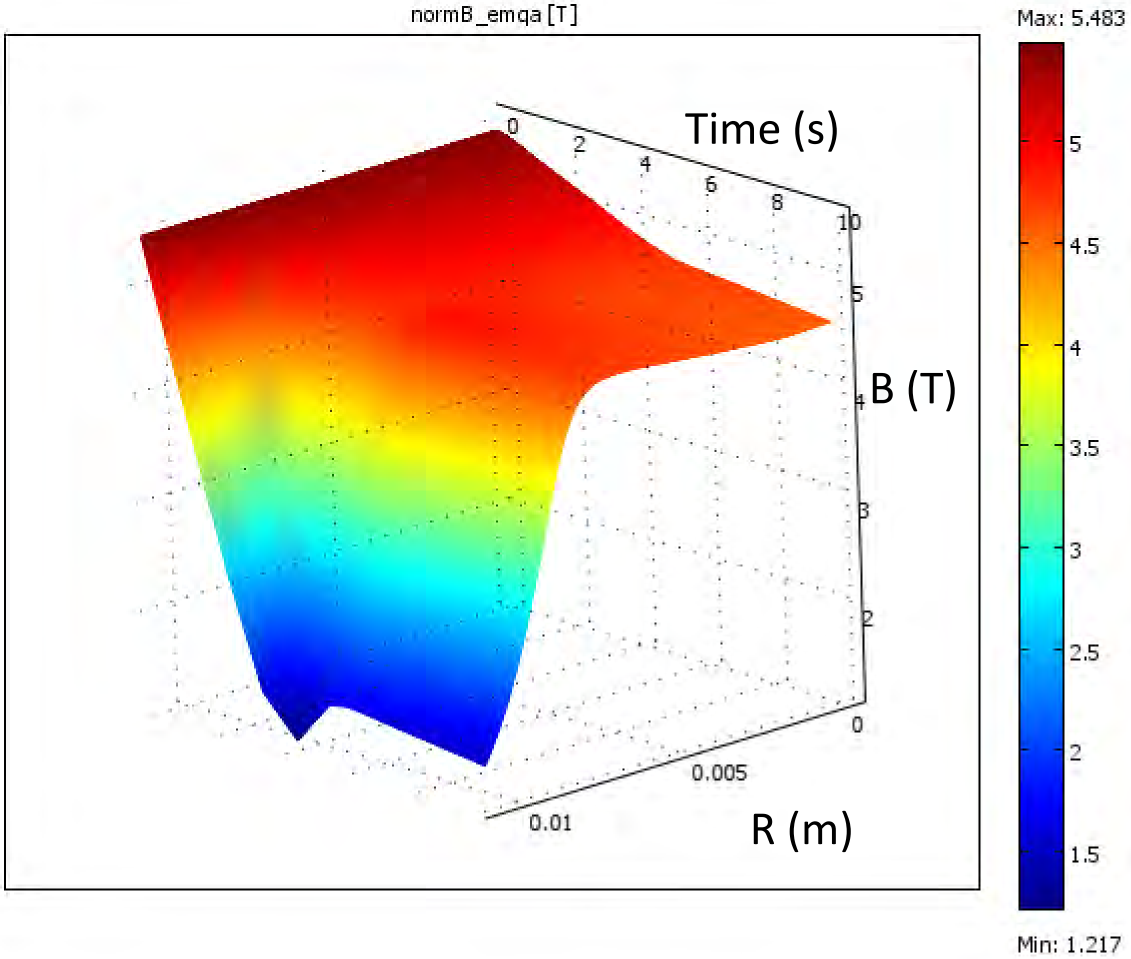


# Simulation Results



# Flux density Variation Above TFM

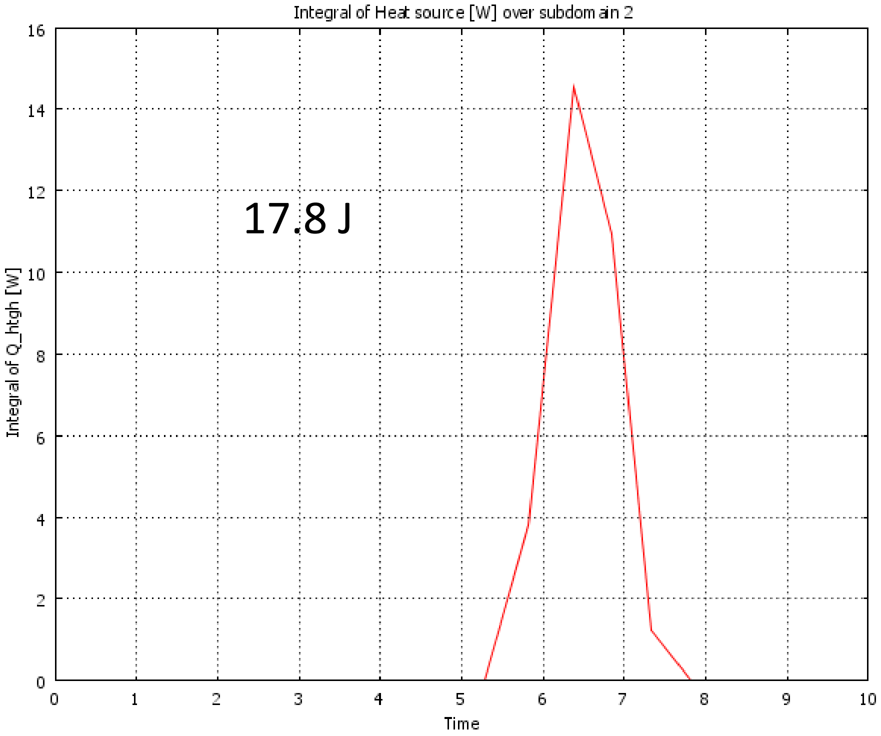
- Field variation of about 7% after heat pulse is applied

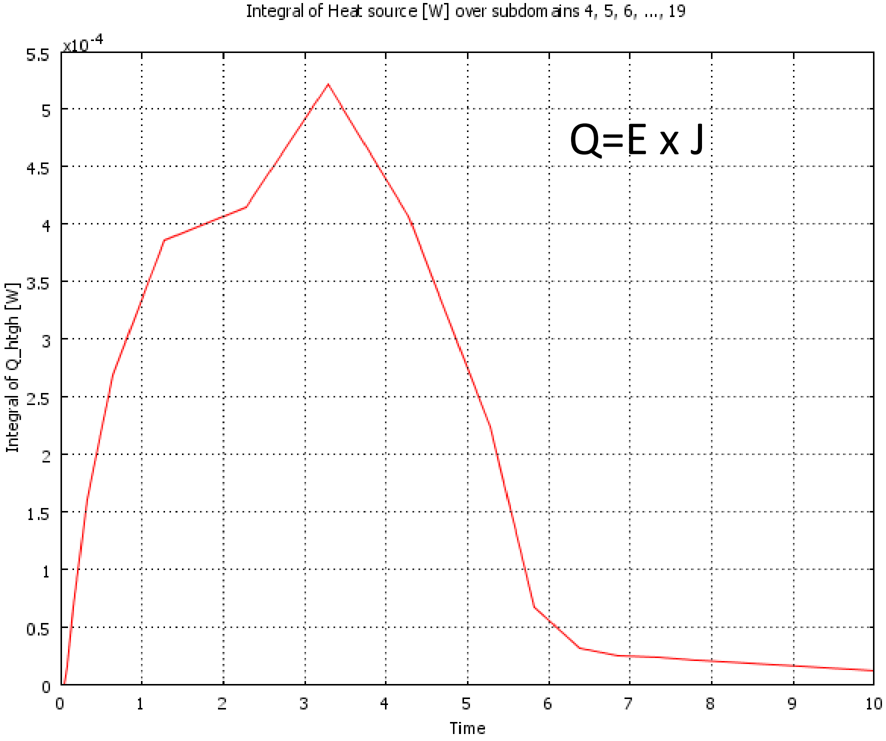


# Heat Loads

- Heat pulse in heater
  - peak at 14 W
  - ~ 18 J

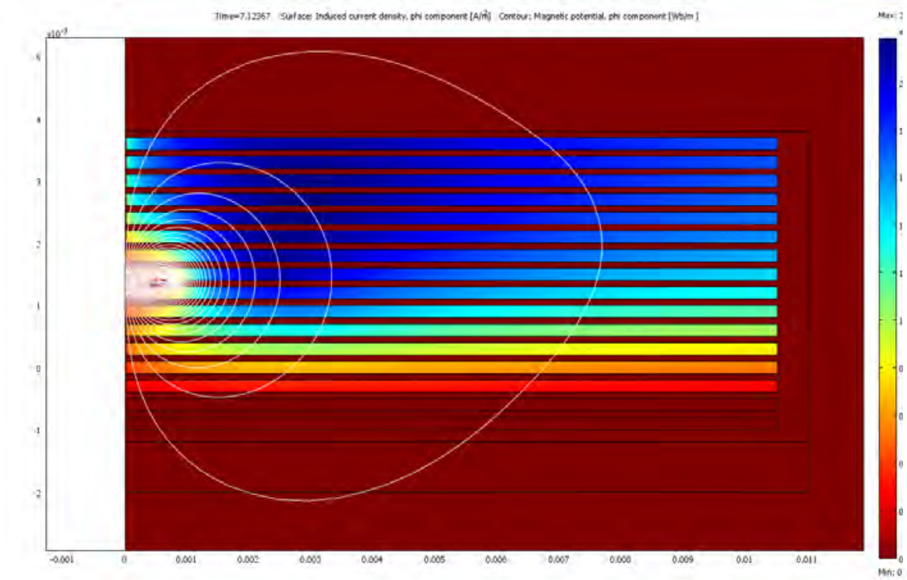
- Losses in superconductor
  - Peak ~0.6 mW
  - ~ 2 mJ
  - Depends on speed of flux variation

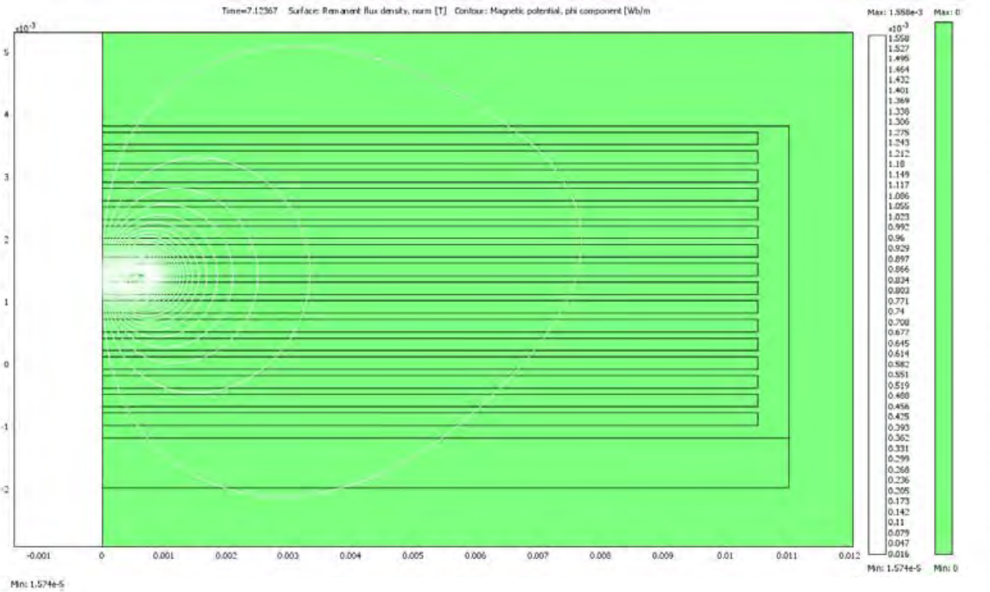




# Large Heat Pulse

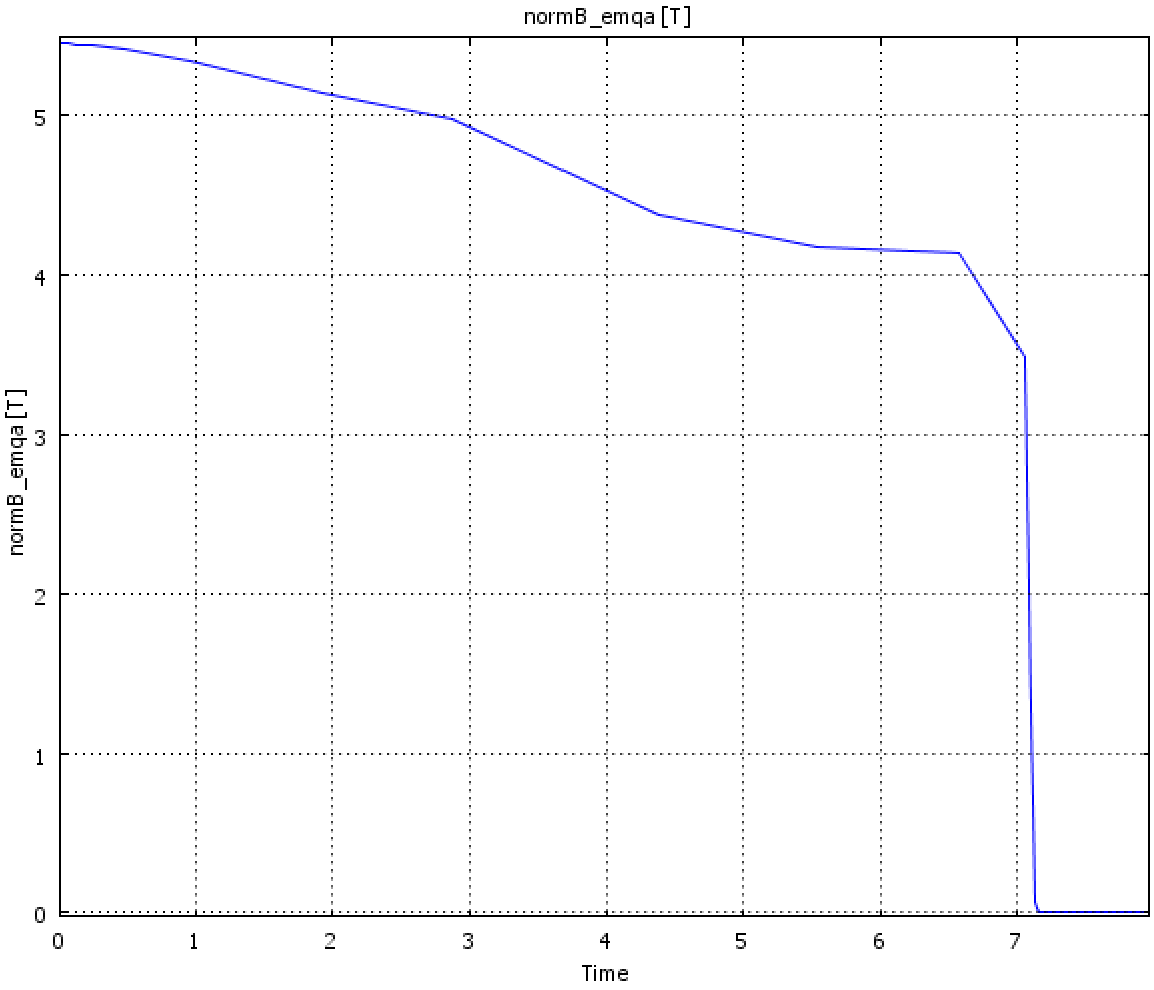
- In case of a large heat pulse trapped flux is dissipated





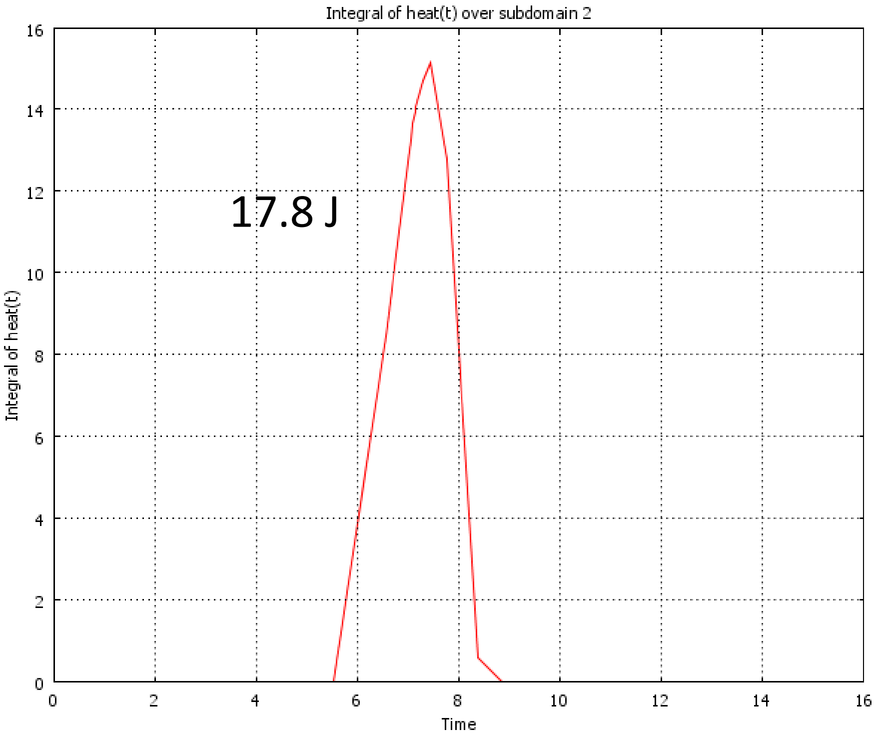
# Measured Flux Density for Large Heat Pulse

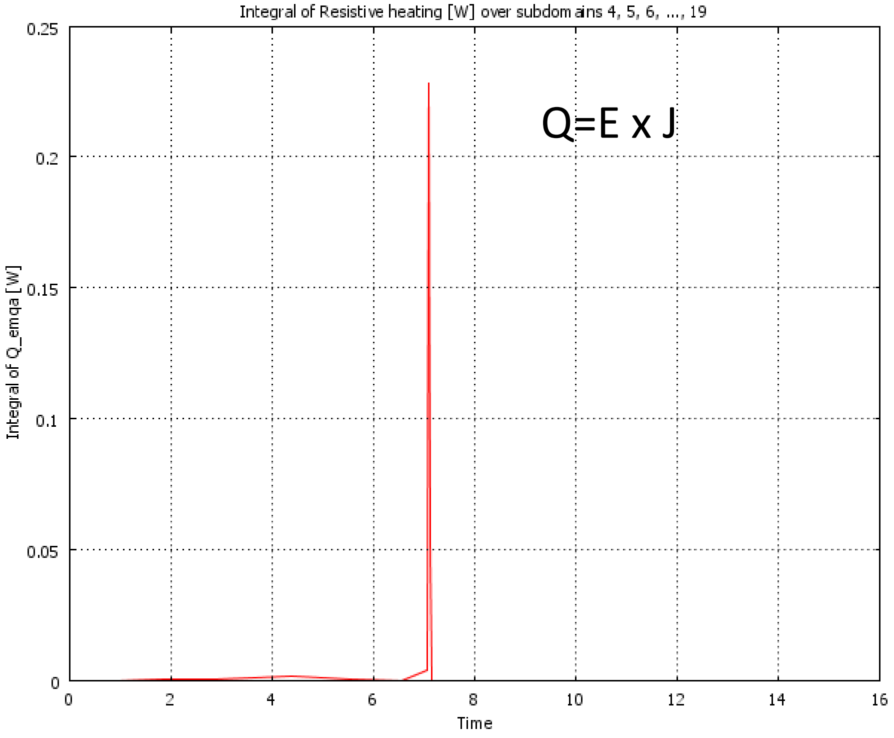
- All the energy is dissipated at the beginning of the heat pulse



# Heat Loads

- Heat pulse in heater
  - peak at 15 W
  - ~ 20 J
- Losses in superconductor
  - Peak ~0.22 W
  - ~ 20 mJ
  - Depends on speed of flux variation





# Conclusion

- Multilayer TFMs are very promising
  - Remove existing limitations of bulk material
  - Allow for larger size

- Comsol allows for a better understanding of the physics of TFMs
- Comsol was able to handle the challenging simulation
  - Highly non linear problem
    - Electrical conductivity depending non-lineraly on E
    - Non linear thermal properties
  - Electromagnetics-thermal coupling