

# Study of Azimuthal quench propagation in 11 T dipole magnet



Samuele Mariotto

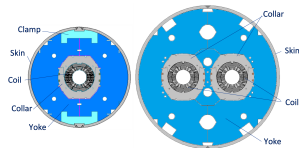
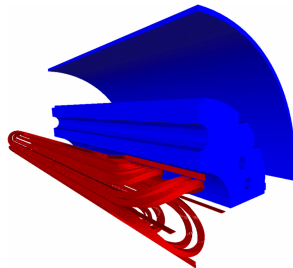
University of Studies of Milan

Supervisor  
Prof. Emanuela Barzi

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## Overview

- 1 Superconducting magnet
  - Quench Heaters
- 2 Quench Difference Time and Contact Resistance
  - Problem: Discrepancy between Data and Model
  - Possible Solution
- 3 Heat transfer
  - Model Details
  - How does the program work?
- 4 Original Model Results
  - Quench Delay Time
  - Quench Delay Time Difference
- 5 Upgrade of the model
  - New Material Properties
  - New Heat Generation
  - Final Results



# Superconducting Magnet

## Principal types

DIPOLE: Bending of the beam axis.  
Gives radial force to particles to create a circular beamline.

QUADRUPOLE: Focusing of the beam along the axis, i.e. keeping the size of the bunch limited or squeezing of bunches in interaction points.



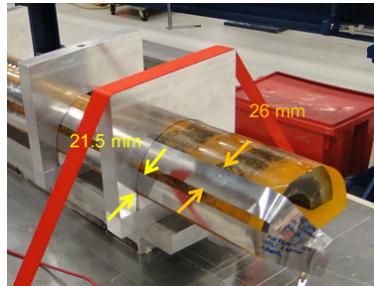
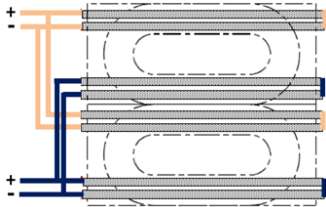
## Quench

Transition of the superconducting material to the resistive state due to an increase of temperature in the superconducting coils.

Protection of the magnet by means of:

- External Resistance: high energy dissipated externally to the magnet
- Quench Heaters: stainless steel strips used to heat uniformly the superconducting coils to prevent hot spots of temperature in the material.

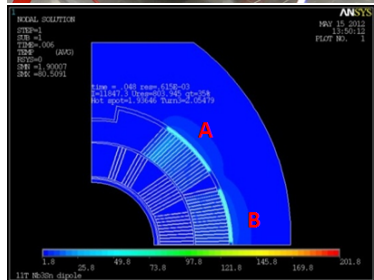
# Heaters of 11 T Dipole



Propagation of the heat in radial direction through the insulated layers of the coils. Non simultaneous quench developments in the coil.

Quench delay time is measured from the activation time of the quench heaters to the detection of the quench in the single turn.

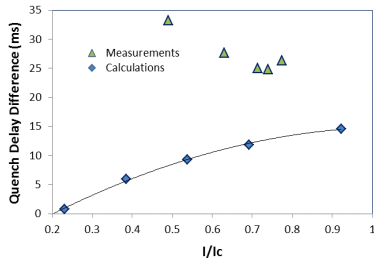
**We are interested in:  
Quench Difference Delay Time**



## Discrepancy

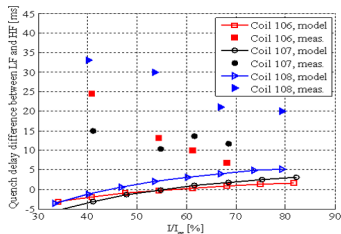
### Quench difference delay Time

Difference of quench delay time measured between HF turns and LF turns of the same coil.



### FERMILAB Measurements

Decrease with higher operational current.  
Seem to diverge as the current goes to 0.



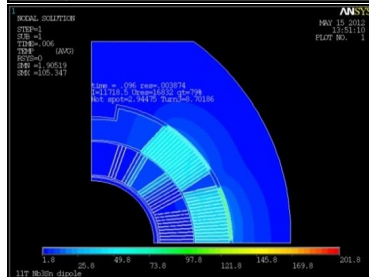
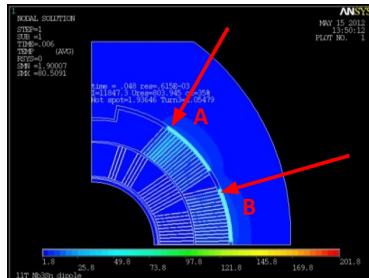
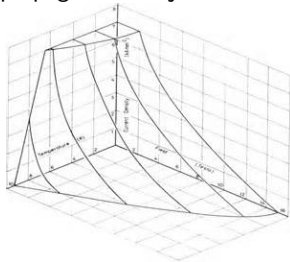
### CERN Simulations

Increase with higher operational current.  
Goes to 0 as the current goes to 0.

## When the quench starts?

At same heat flow, it depends on the values of magnetic field and magnet current.

Quench starts in turns with higher magnetic field (A in Figure) and propagates in adjacent turns.



| Operational Current (A) | Operational Temperature (K) |
|-------------------------|-----------------------------|
|-------------------------|-----------------------------|

11,850

1.9

## Why there is difference between turns?

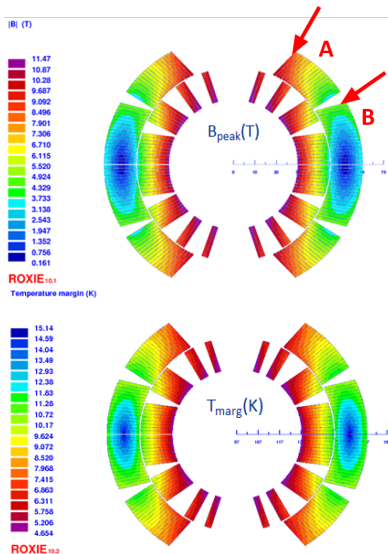
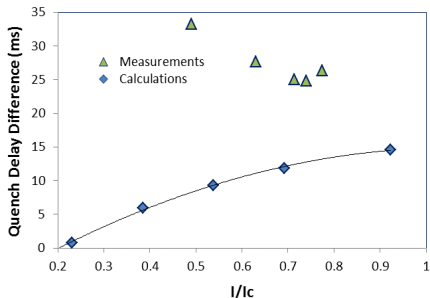
Study the phenomenon as function of magnet current.

Higher current = Higher  $\Delta B_{AB}$ .

In principle, a larger Quench Delay Difference.

Problem: discrepancy

Why then the data differ from this Behaviour?

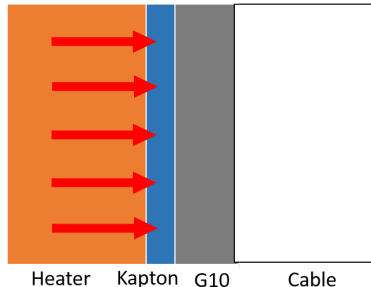
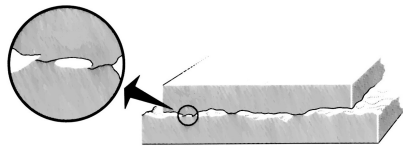


## Contact Resistance

A possible solution is including in the existing model also the **CONTACT RESISTANCE** between the materials located between the quench heaters and the coil.

Contact resistivity includes the following interfaces:

- Stainless steel (quench heaters) to Kapton
- Kapton to G10
- G10 to Cable





## Parametrization

We need to consider both the thermal resistivity and the contact resistivity as two resistances in series, obtaining:

$$k(T) = \frac{1}{\lambda(T)\Delta L + R_{th}^{contact}(P)} \quad (1)$$

$$k(T) = \frac{1}{\lambda(T)\Delta L + \frac{1}{\alpha P + \beta}} \quad (2)$$

$$k(T) = \frac{1}{\lambda(T)\Delta L + \frac{1}{\alpha''\gamma I^2 + \beta}} \quad (3)$$

- Pressure determines the amount of actual surface that is in contact and the size of the gap between the layers.
- We can describe pressure as function of the magnetic field intensity and the magnet current.

Known parameters

## Heat Transfer

Equation of the heat transfer.

$$\frac{\partial}{\partial x} \left[ k(T) \frac{\partial T}{\partial x} \right] + \frac{\rho(T) I^2}{A^2} = c_p^c(T) \delta(T) \frac{\partial T}{\partial t} \quad (4)$$

Where:

$k(T)$  : thermal conductivity of the material

$\rho(T)$  : electrical resistivity of the stainless steel in the quench heaters

$c_p^c(T)$ : specific heat of the material at fixed T and pressure.

$\delta(T)$  : density of the material at fixed T.

Original Model Approximations:

- Heat from the heaters is generated first, and then it all propagates through the insulation.
- Rest of the interface is made of insulating layers.

### Effect

Neglect the heat generation in time in the quench heaters.

## Simplified Equation

I wrote a C++ code using the finite element technique, i.e. each element has its own physical parameters at fixed temperature (1.9K).

$$\tilde{k}(\theta) \frac{\partial^2 \theta}{\partial x'^2} + \frac{\partial \tilde{k}(\theta)}{\partial \theta} \left( \frac{\partial \theta}{\partial x'} \right)^2 = \tilde{c}_p^c(\theta) \tilde{\delta}(T) \frac{\partial \theta}{\partial t} \quad (5)$$

Where:

$$\tilde{k}(\theta) = \frac{k(T)}{k(T_0)}$$

$$\tilde{\delta}(\theta) = \frac{\delta(T)}{\delta(T_0)}$$

$$\tilde{c}_p^c(\theta) = \frac{c_p^c(T)}{c_p^c(T_0)}$$

$$\theta(x', t') = \frac{T(x, t)}{T_0}$$

$$t' = \frac{t}{\frac{c_p^c(T_0) \delta(T_0) L^2}{k(T_0)}}$$

$$x' = \frac{x}{L}$$

## Simplified Equation

$$\begin{aligned} \frac{\partial \theta}{\partial t} \Big|_{i,j} &\approx \frac{\theta_{i,j+1} - \theta_{i,j}}{z} & \frac{\partial \theta}{\partial x'} \Big|_{i,j} &\approx \frac{\theta_{i+1,j} - \theta_{i,j}}{2h} \\ \frac{\partial^2 \theta}{\partial x'^2} \Big|_{i,j} &\approx \frac{\theta_{i+1,j} - 2\theta_{i,j} + \theta_{i-1,j}}{h^2} & \frac{\partial \theta}{\partial x'} \Big|_{0,j} &\approx \frac{\theta_{1,j} - \theta_{0,j}}{h} \\ x' = ih, i = 0, 1 \dots N; t' = jz, j = 0, 1, 2 \dots; r = \frac{z}{h^2} \end{aligned}$$

$$\theta_{i,j+1} = \theta_{i,j} + \frac{r}{(\tilde{c}_p)_{i,j} \tilde{\delta}_{i,j}} \left[ \tilde{k}_{i,j} (\theta_{i,j+1} - 2\theta_{i,j} + \theta_{i-1,j}) + \frac{1}{4} \left( \frac{\partial \tilde{k}}{\partial \theta} \right)_{i,j} (\theta_{i+1,j} - \theta_{i-1,j})^2 \right]$$

Boundary conditions: Set the initial temperature of the heater after the generation of heat and the initial temperature of all the materials

$$\theta_{0,j} = 1 \quad \theta_{i,0} = (\theta_0)_i \quad (6)$$

### Original Model Approximation:

Consider specific heat, density and conductivity constant in all the simulation (not as functions of temperature).

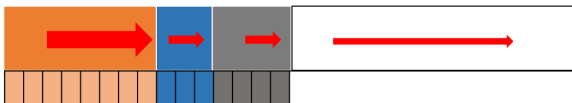
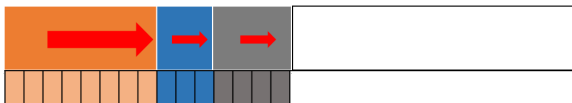
## Simulation

Single Turn with  
portion of the heater  
and insulation.

$$\frac{k_{cable}(T)}{k_{heater}(T)} = 100$$

Input temperature of  
1.9 K for cables and  
insulations elements.  
Fixed  $T_{max}$  for the  
heaters elements.

Simulation ends when  
the cable reaches  
 $J_{critic}(B, T)$



## Magnetic Field Map

We use the magnetic field map as input data: Roxie can be used to recreate the magnetic field strength as function of the position.

$$B(x, y) = \epsilon(x, y)I$$

$$k(T) = \frac{1}{\lambda(T)\Delta L + \frac{1}{\alpha''\gamma(x,y)I^2 + \beta}}$$

### Original Model Approximation:

Average Intensity of magnetic field for the cable in order to have unique value of the critical current.

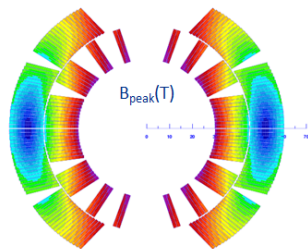
| Turn HF (T) | Turn LF (T) |
|-------------|-------------|
|-------------|-------------|

|      |     |
|------|-----|
| 10.5 | 5.8 |
|------|-----|

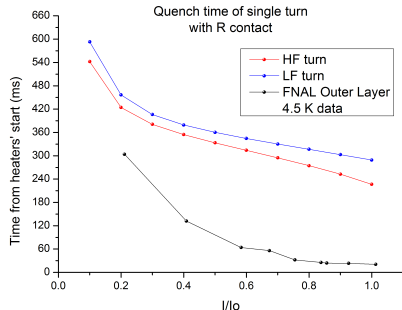
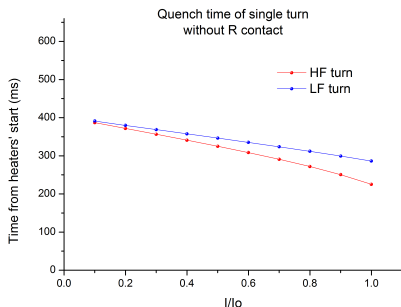
|B| (T)



ROXIE<sub>10.1</sub>

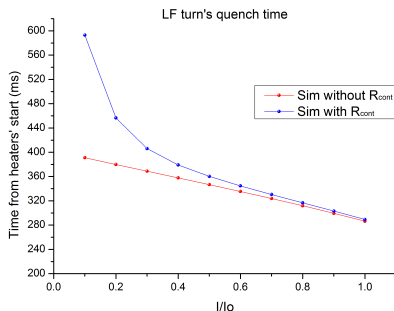
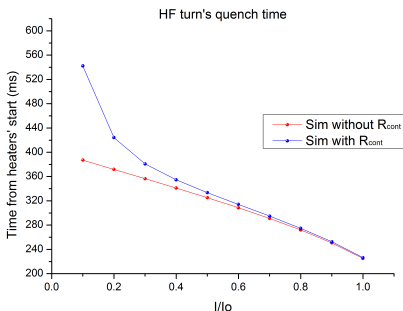


## Turns Quench Delay Time



- Quench time of the HF turn is lower than LF turn quench time, as expected.
- Both simulations with and without contact resistance have higher values than Fermilabs measurements.
- Simulation with contact resistance has the same shape of the Fermilabs measurements (however they are not compatible with absolute values).
- At high current, values of quench time in HF turn with or without contact resistance are the same. This is observed also for the LF turn.

## Turns Quench Delay Time



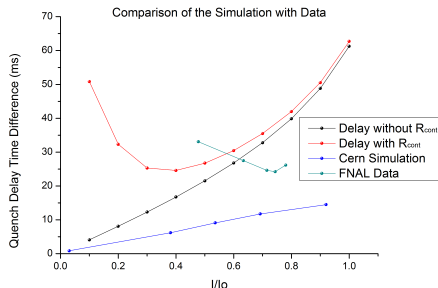
- At high value of current, in both the HF and LF turns, the value of quench time is the same with or without contact resistance.
- Values of the quench time are different from the FNALs data.
- Shape of the lines (especially at high current) are different. This fact is more evident in the quench difference delay time but it is a hint of a problem in the model.



## Difference Delay Time

### Positive Elements

- At low current the quench delay time increases as current goes to 0 as the measurements do.
- At high current, the simulations with and without contact resistance converge.



### Bad Elements

- Our simulation is not consistent with Cerns simulation.
- Value of the simulation with contact resistance is still different from Data.
- Shape of the simulation: At high current, with or without contact resistance, the quench delay time seems to diverge before saturating.
- Up to here (Mid Term Presentation at Fermilab 09/24/2016)

## Cern input data

### Upgrade:

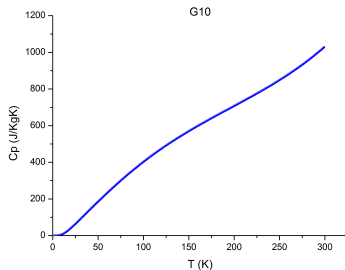
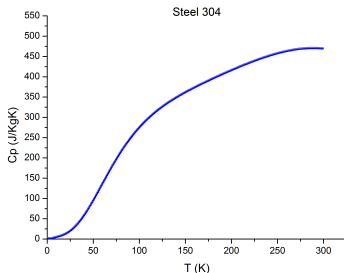
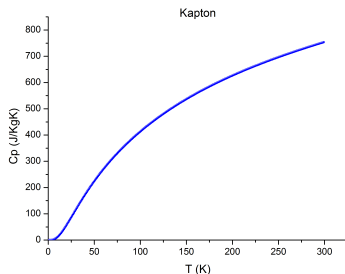
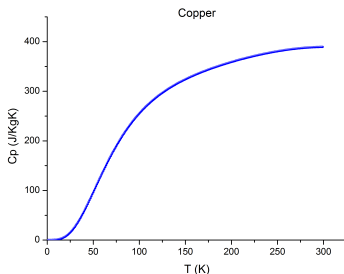
- New Parameters: Cern database of the Material properties at Cryogenic Temperature.
- Add time dependence in heat generation
- Segmented Cable in finite elements (no calculation of MPZ but fixed dimension ( $0.5\text{ mm}$ ) of quenched material).
- Use of maximum magnetic field in the cable as quench criterion

All data are taken from NIST (National Institute of Standard and Technology) database.

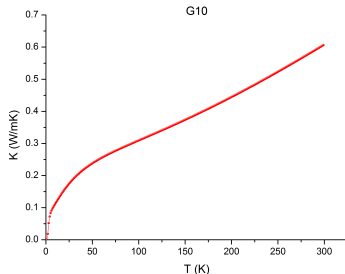
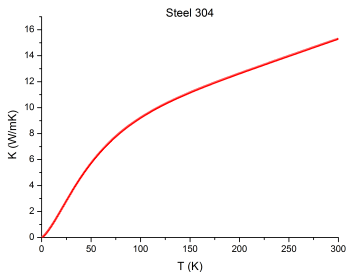
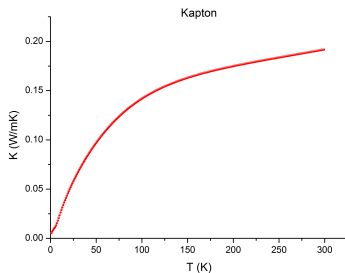
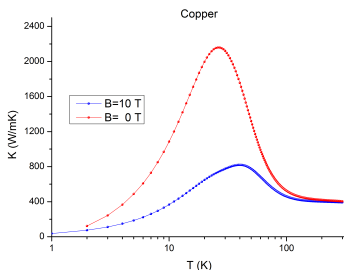
The  $Nb_3Sn$  specific heat which has a strong dependence from the Magnetic Field Intensity is calculated with *MATPRO*.

We used polynomial parametrizations and considered the difference composition of the cable: *Cu* (35.25%), *Nb<sub>3</sub>Sn* (39.85%), *Epoxy Fiberglass* (24.9%).

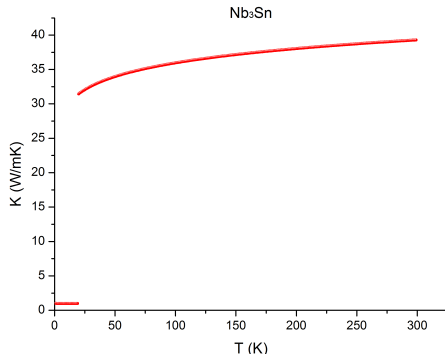
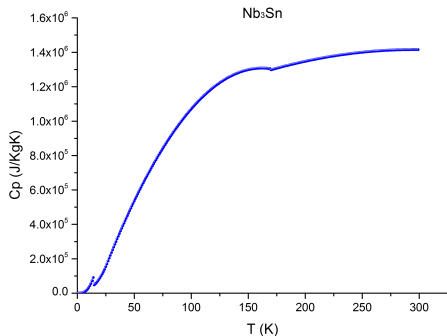
## Specific Heat (NIST)



# Thermal Conductivity (NIST)



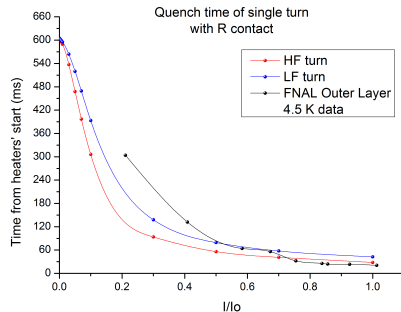
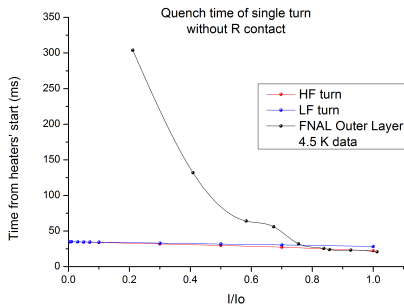
## Material Properties: $Nb_3Sn$



### highlights

- Accurate description of the Specific Heat at low temperature.
- Discontinuity of the thermal conductivity over  $20 K$  due to different parametrization used.

## New Model with different Parameters

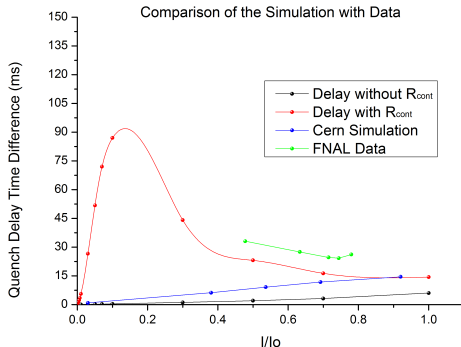


- This model differs from the previous one for the new parametrization of the material properties.
- Without considering the contact resistance the single delay times cannot describe the shape of the FNAL Data as we obtained in the previous model.
- Considering the contact resistance there are, however, some discrepancy between data taken at FNAL and our simulation. We need to improve our model.

## New Model with different Parameters

### Positive Elements

- At low current the quench delay time difference goes to 0 as we expected
- With higher current the quench delay time difference decreases with (approximately) the same shape of measurements.
- Parameters used:  
 $\alpha = 0.00002$   $\beta = 0.4$



### Bad Elements

- Simulation without contact resistance is not describing the Cern's simulation.
- We underestimate the quench difference delay time (and probably the single quench delay time). Hypothesis of a problem in the heat generation.
- We need firstly to describe and replicate the Cern's simulation to validate our program.

## Heat Generation

### Peak Power Density

- Minimum Power density to induce the quench in the cable.
- Exponential decay of the Power Density

### Model Used

New equation for the heat transfer

$$\frac{\partial}{\partial x} \left[ k(T) \frac{\partial T}{\partial x} \right] + \frac{\rho(T) I^2}{A^2} = c_p^c(T) \delta(T) \frac{\partial T}{\partial t}$$

Temperature of the Stainless Steel is no longer fixed at  $t = 0$ .

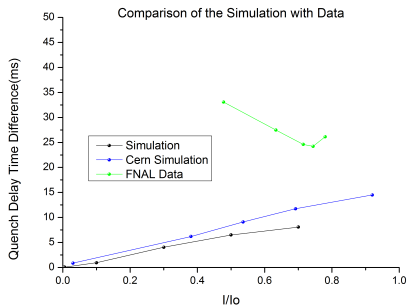
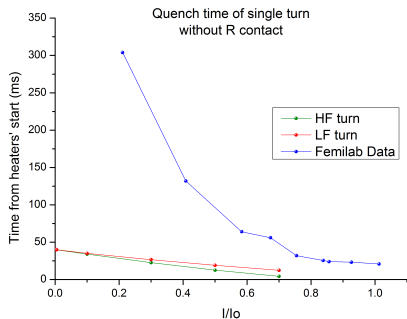
| Peak Power Density<br>$W/cm^2$ | Tau<br>$ms$ | Test    |
|--------------------------------|-------------|---------|
| 25.23                          | 37.152      | MBHSP01 |
| 55.82                          | 31.296      | MBHSP02 |

$$\theta_{i,j+1} = \theta_{i,j} + \frac{r}{(\tilde{c}_p^c)_{i,j} \tilde{\delta}_{i,j}} \left[ \tilde{k}_{i,j} (\theta_{i,j+1} - 2\theta_{i,j} + \theta_{i-1,j}) + \frac{1}{4} \left( \frac{\partial \tilde{k}}{\partial \theta} \right)_{i,j} (\theta_{i+1,j} - \theta_{i-1,j})^2 \right] + \frac{\delta Q_i}{(\tilde{c}_p^c)_{i,j}}$$

$$\frac{\delta Q_i}{(\tilde{c}_p^c)_{i,j}} = \frac{Power_{i,j}}{\Delta l} \frac{kL^2}{k_0(T_0)T_0(\tilde{c}_p^c)_{i,j}\tilde{\delta}_{i,j}}$$

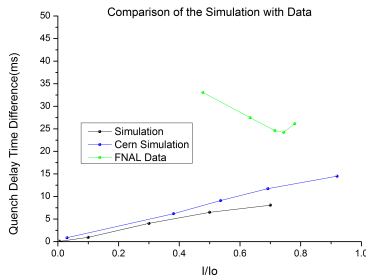
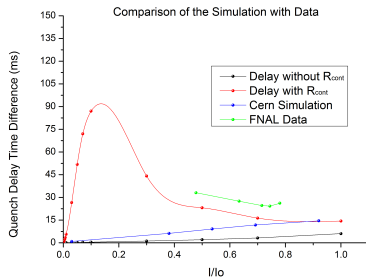
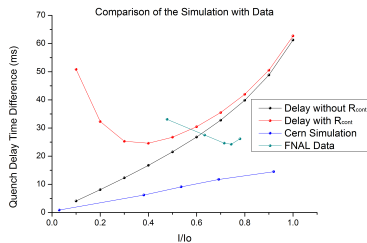


## Quench Difference and Delay Time



- Simulation without Contact Resistance seems to be in good agreement with Cern's Simulation  $\Rightarrow$  Validation of our Program
- Difference in quench difference delay time: difference Peak Power density used and difference Time way to declare the quench in the cable
- Data with Contact Resistance: WORK IN PROGRESS

## Summary



## Next Steps

- Solve the problem of the program Velocity of Running
- Select the best value of the parameters starting from the values:  $\alpha = 0.00002$   $\beta = 0.4$ .
- Improve order of polynomial dependance of  $R_{cont}$  from current. Other dependences?

## Conclusion



Thank you for your Attention

## References



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A Novel Computer Code for Modeling Quench Protection Heaters in High-Field  $Nb_3Sn$  Accelerator Magnets

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E. Barzi(1998)

Gas/Vapour-cooled binary current leads - Copper part

*Technical division Report*(TD-98-026)