IEEE/CSC & ESAS European Superconductivity News Forum (ESNF) No. 23 January 2013
Invited presentation 4LE-01 given at ASC 2012.

# Quench Analysis
# Of High Field REBCO Coils

W. Denis Markiewicz[1]
Jan Jaroszynski[1], Aixia Xu[1], Dmytro Abraimov[1], Hongyu Bai[1],
Heath Hartley[1], and Michael S. Walker[2]

1. National High Magnetic Field Laboratory
Florida State University

2. Intermagnetics General Corporation

Applied Superconductivity Conference
October 7-12, 2012
Portland, Oregon

[Annotations added after the presentation was delivered are in (small) blue font.]

# Quench Analysis
# Of High Field REBCO Coils

## Contents

# YQUENCH Analysis Code

YQUENCH analysis code for REBCO (YBCO) coils.

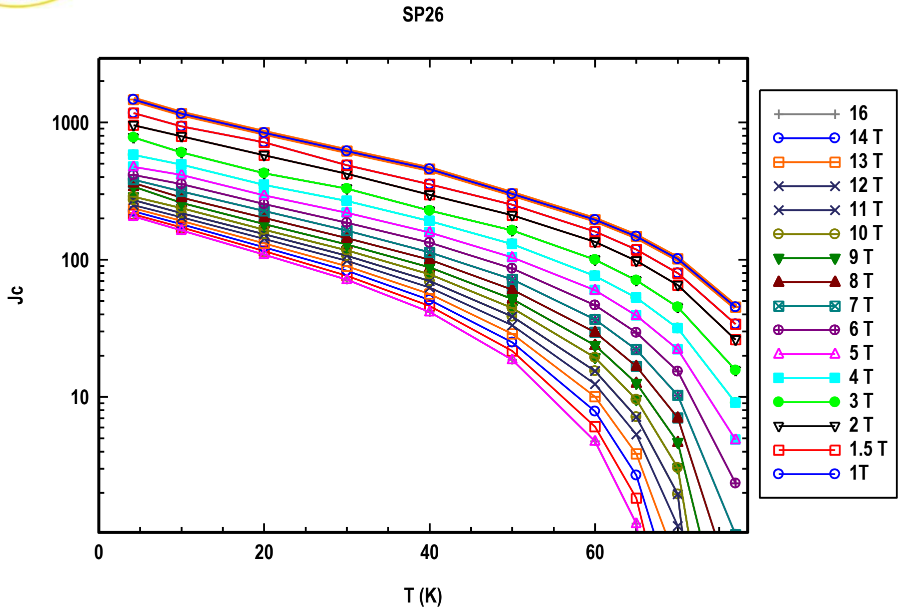
Finite difference thermal analysis,
analytic electrical and magnetic analysis.

Conductor properties and thermal conductivity
as function of field and temperature.

No explicit quench propagation velocity.

The name YQUENCH is in recognition of the early code QUENCH by Martin Wilson. Pronounced why-quench, the name invokes with humor the serious question as to the reasons that a YBCO coil might quench, given the high stability of the conductor.

# Conductor Properties




$Ic_{perp}(B,T)$

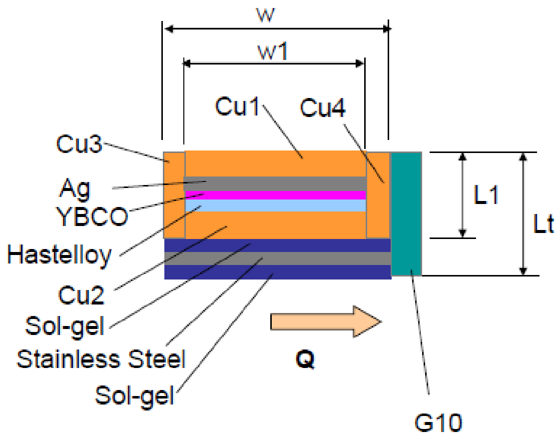
$Ic\ (T,\theta)$

Extensive characterization of temperature dependence of REBCO critical current as input to quench analysis.

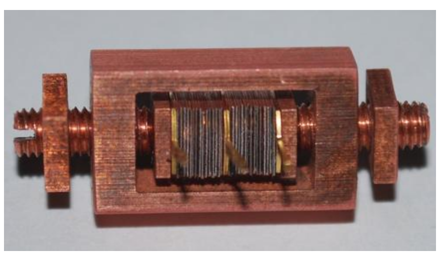
Analytic expressions, to be presented elsewhere, fit extensive data on the temperature and field orientation dependence of the critical current.

# Thermal Conductivity

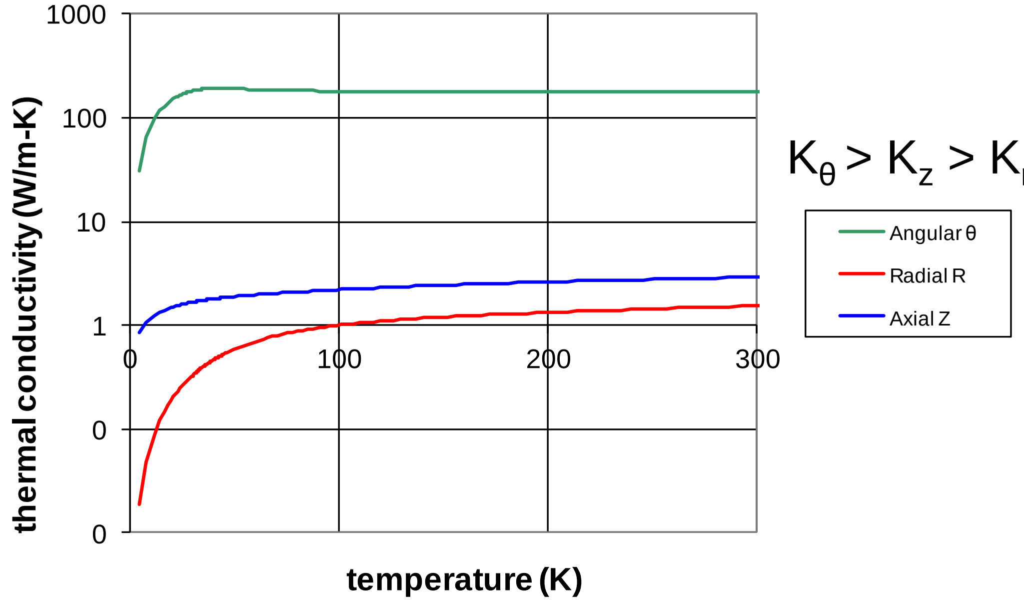
## Analysis $K_\theta$ and $K_z$




## Measurement $K_r$



**Themal Conductivity of Winding Composite in Angular, Axial, and Radial Direction**




Thermal conductivity of windings determined by analysis and measurement.

H. Bai 2LPQ-01

# Quench Protection Coil

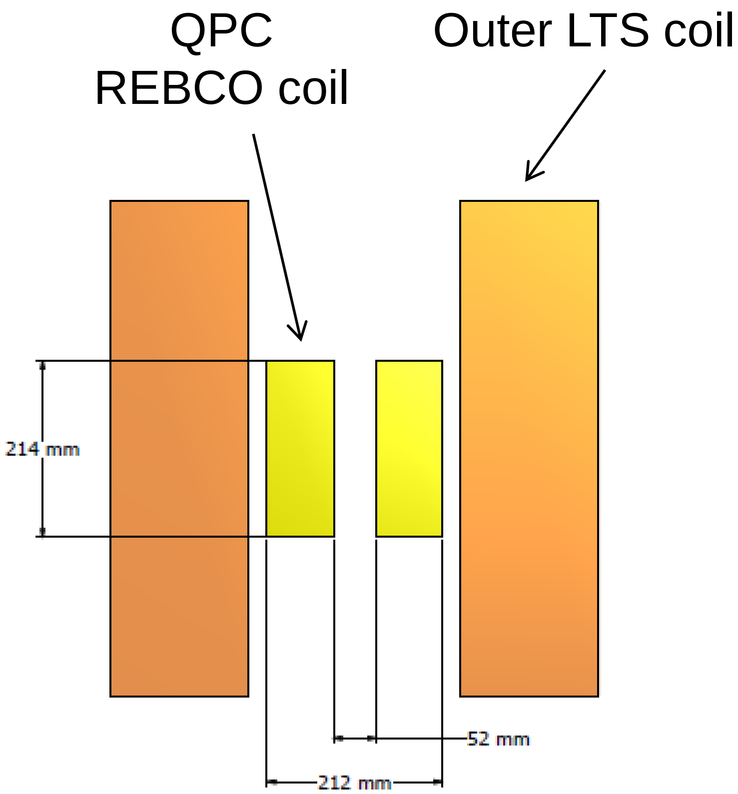
Pancake wound

Dry wind

Steel co-wind reinforcement

Un-insulated conductor

Insulated co-wind turn insulation




| | |
|---|---|
| Field total | 32 T |
| Field increment QPC | 17 T |
| Inner winding diameter | 52 mm |
| Outer winding diameter | 212 mm |
| Winding length | 214 mm |
| Operating Current | 180 A |
| Current density average | 200 $A/mm^2$ |
| Current density copper | 440 $A/mm^2$ |

The Quench Protection Coil is a representative high field REBCO coil chosen to illustrate aspects of protection analysis.

# Quench Protection Coil

## Conductor Copper Thickness Variations

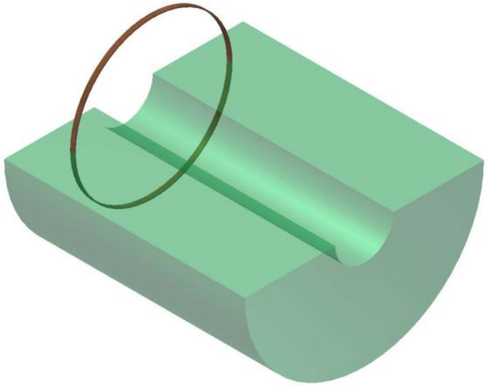
| | Coil 1 | Coil 2 | Coil 3 |
|---|---|---|---|
| Current (A) | 180 | 180 | 180 |
| Copper thickness (µm) | 100 | 80 | 60 |
| Copper current density ($A/mm^2$) | 440 | 549 | 732 |
| Average current density ($A/mm^2$) | 200 | 222 | 250 |

Versions of the Quench Protection Coil have decreasing amounts of copper in the conductor with corresponding increase in current density.

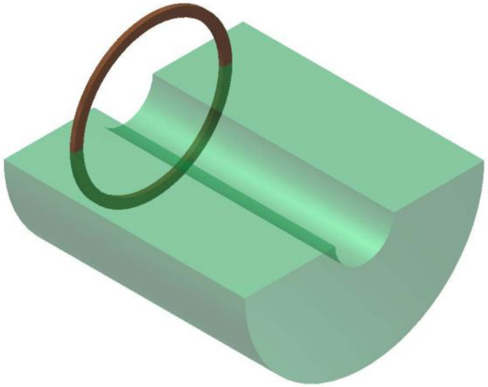
# Quench Initiation by Low Critical Current

In this presentation, the source of quench is limited to the case of low critical current in a turn or arc segment of a turn.

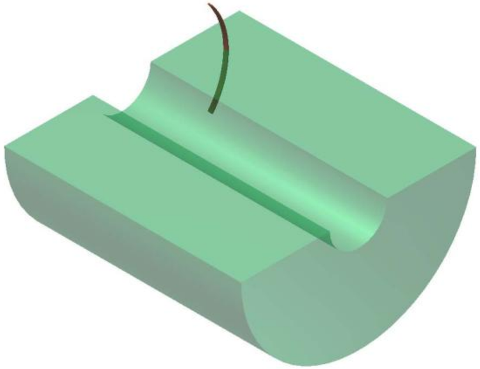
Analysis of quench initiated by
significantly reduced critical current
in single and multiple turns of conductor,
and in a short arc segment of a turn.



Single Turn Ring

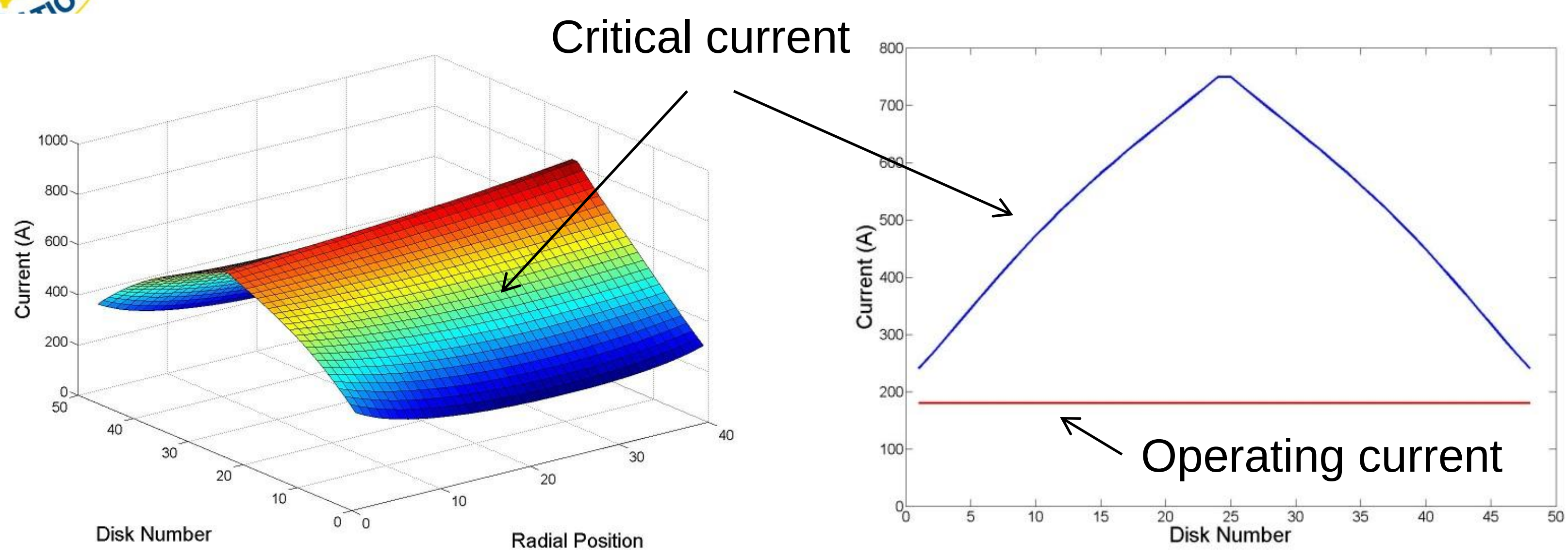


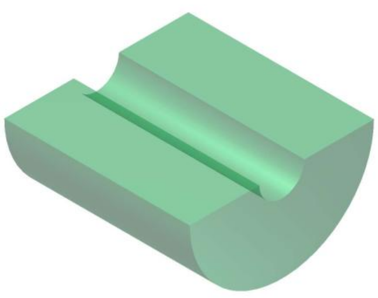
Multiple Turn Ring



Single Turn Arc

# Coil Critical Current



The REBCO coil is assumed to contain conductor with uniform critical current specification.

The variation of field and field angle gives a large distribution of local critical current in the coil.

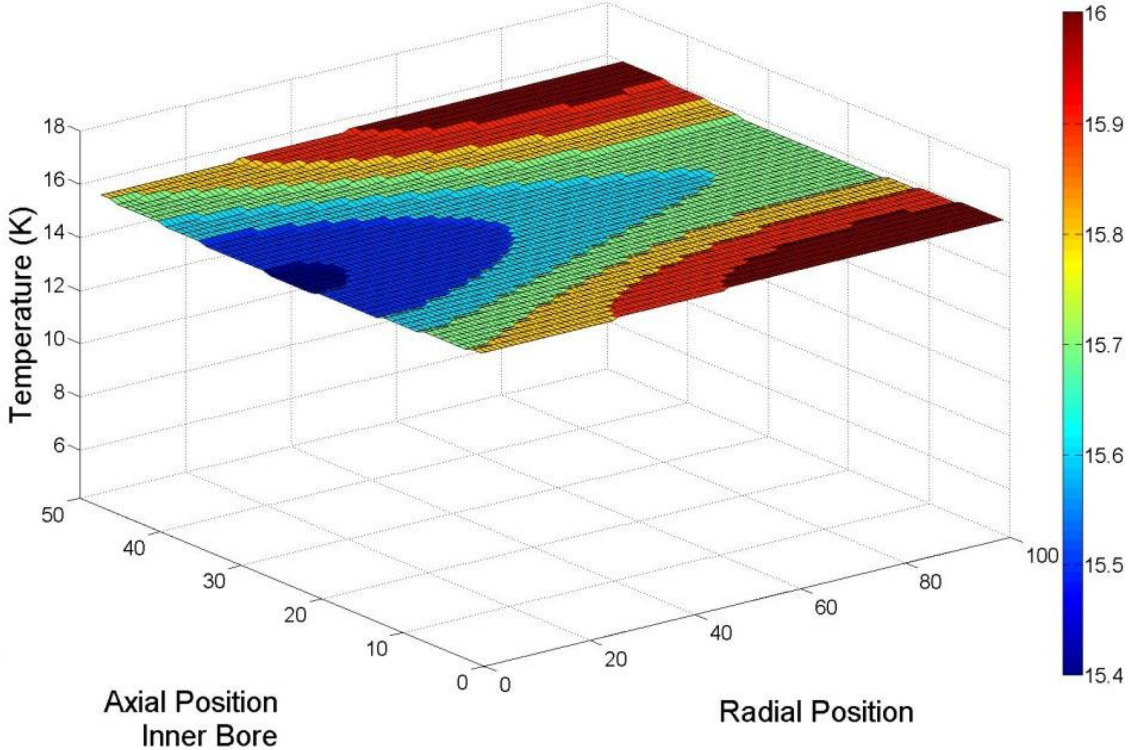
| | | | |
|---|---|---|---|
| Disk or pancake number | 1 | 5 | 24 |
| Critical current/Operating current | 1.34 | 1.91 | 4.52 |

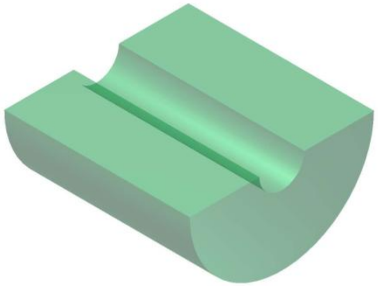
# Ramping Loss Heating

With no surface cooling, the QPC quenches during ramp to field. The temperature profile just prior to quench is shown.

No surface cooling.

Quench during ramping.



Ramping loss heating is calculated for REBCO coil under various conditions of coil surface cooling.

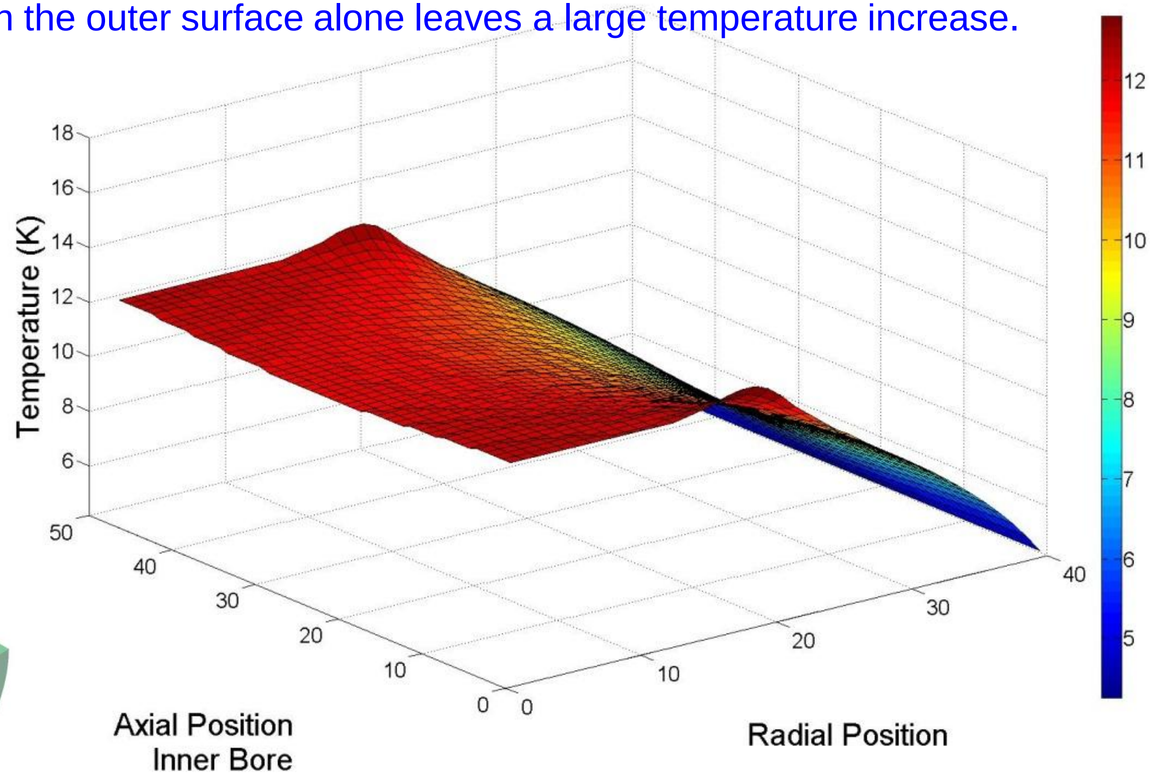
A. V. Gavrilin 1LPS-05 J. Lu 2MPA-05

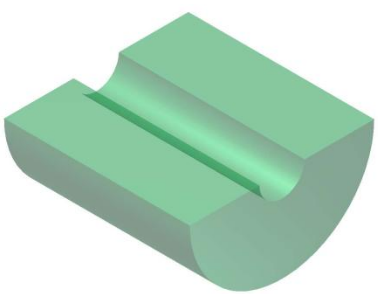
# Ramping Loss Heating

The efficiency of cooling on various surfaces depends on the directional thermal conductivity. Radial thermal conductivity is least effective, and cooling on the outer surface alone leaves a large temperature increase.

Cooling on radial outer surface only.

Significant temperature increase.



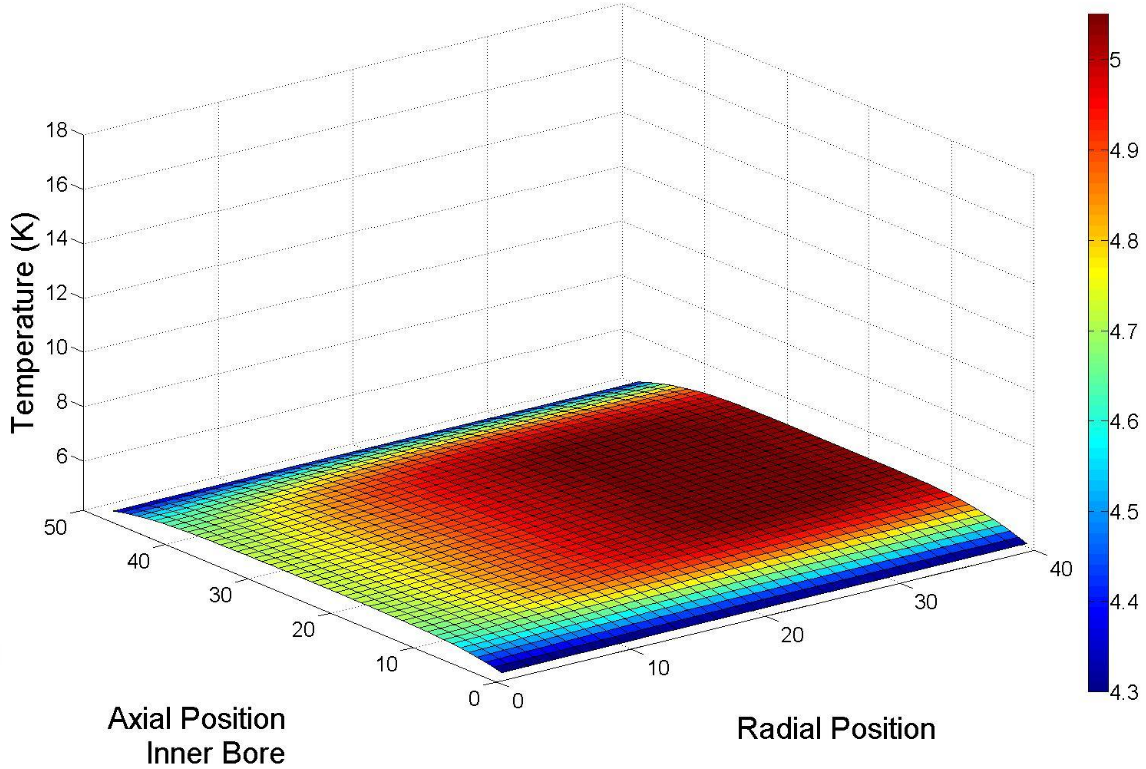
Ramping loss heating is calculated for REBCO coil under various conditions of coil surface cooling.

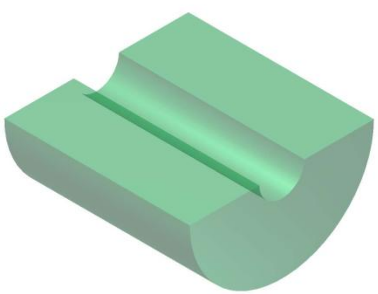
# Ramping Loss Heating

Axial thermal conductivity is greater and with 50% heat transfer area to liquid helium at the coil ends, the entire length of the coil is effectively cooled.

Cooling on axial end surfaces only.

Limited temperature increase.



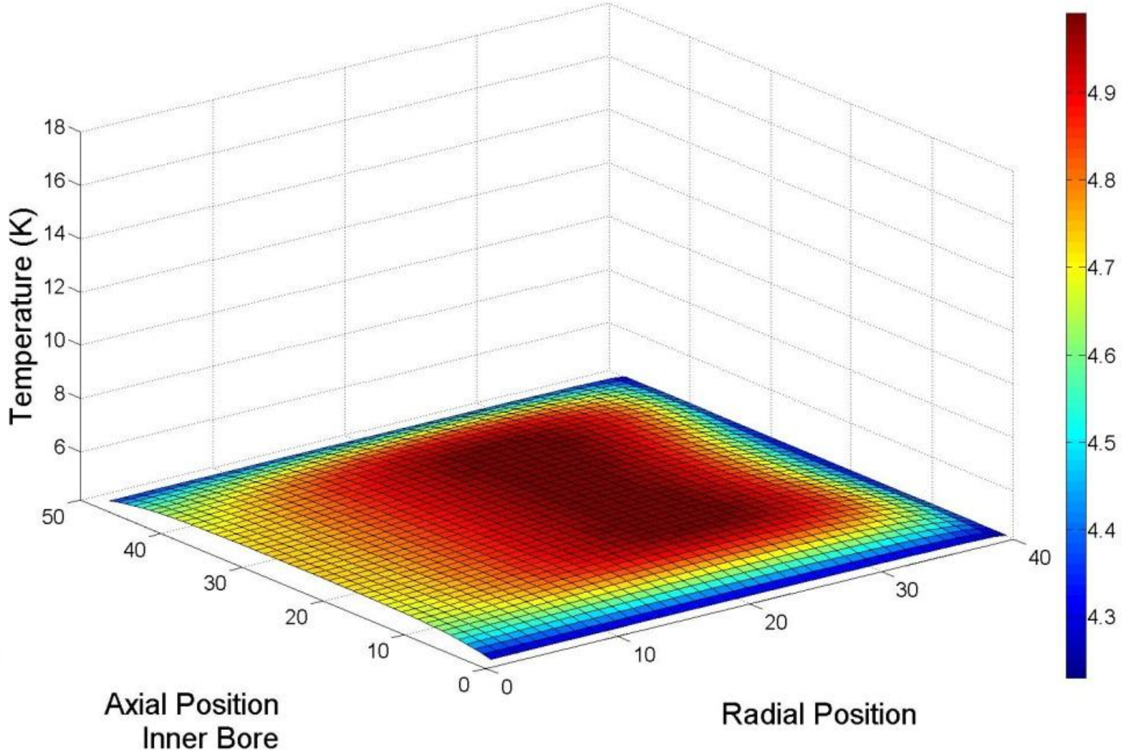
Ramping loss heating is calculated for REBCO coil under various conditions of coil surface cooling.

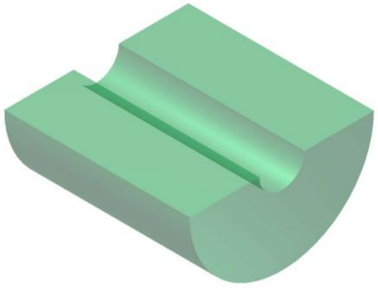
# Ramping Loss Heating

Given the effectiveness of surface cooling, the temperature increase of ramping loss is ignored in the subsequent quench analysis.

Cooling on end and outer surfaces.

Lowest temperature increase.

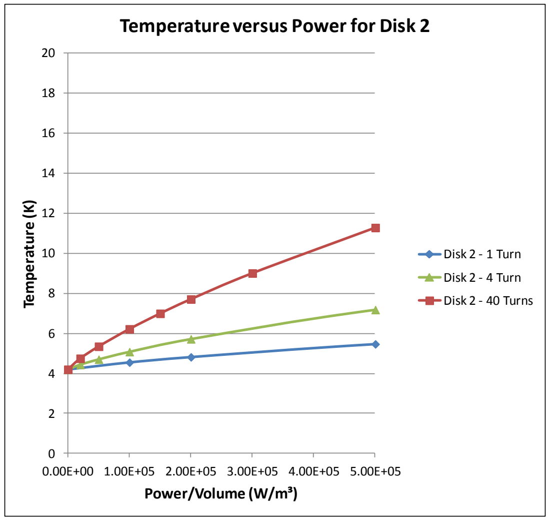


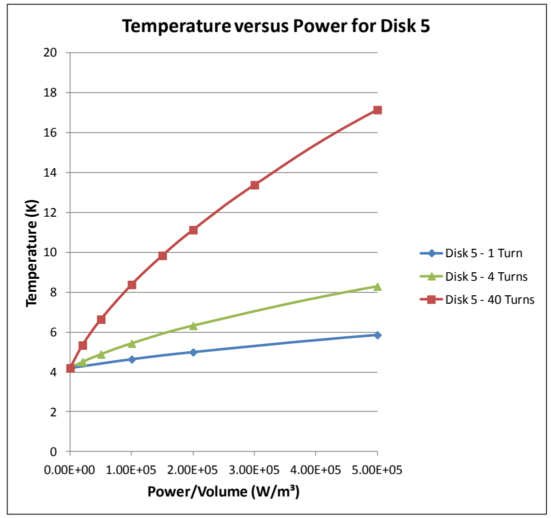



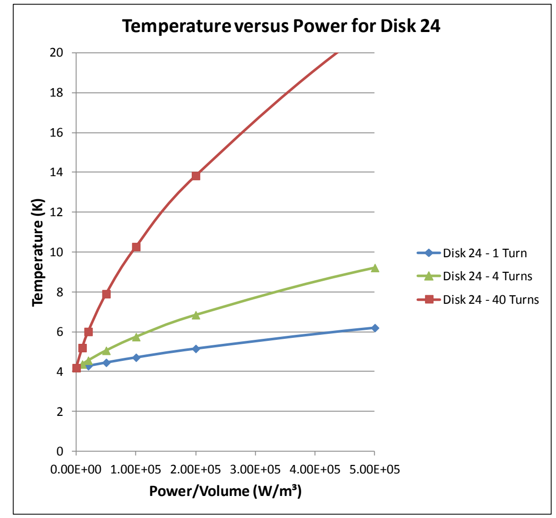
Ramping loss heating is calculated for REBCO coil under various conditions of coil surface cooling.

# Cooling Capacity of Windings

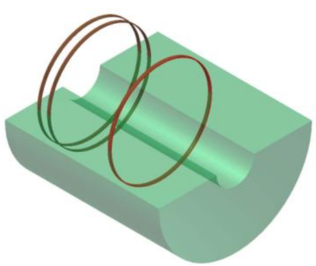
Temperature rise calculated from local steady state heat load.



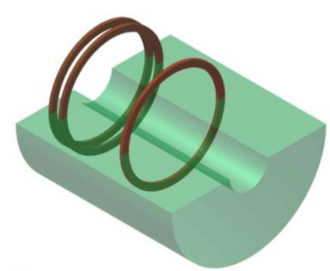




Temperature depends on location and extent of source.
Coil ends are cooler, larger sources warmer
on per unit volume basis.

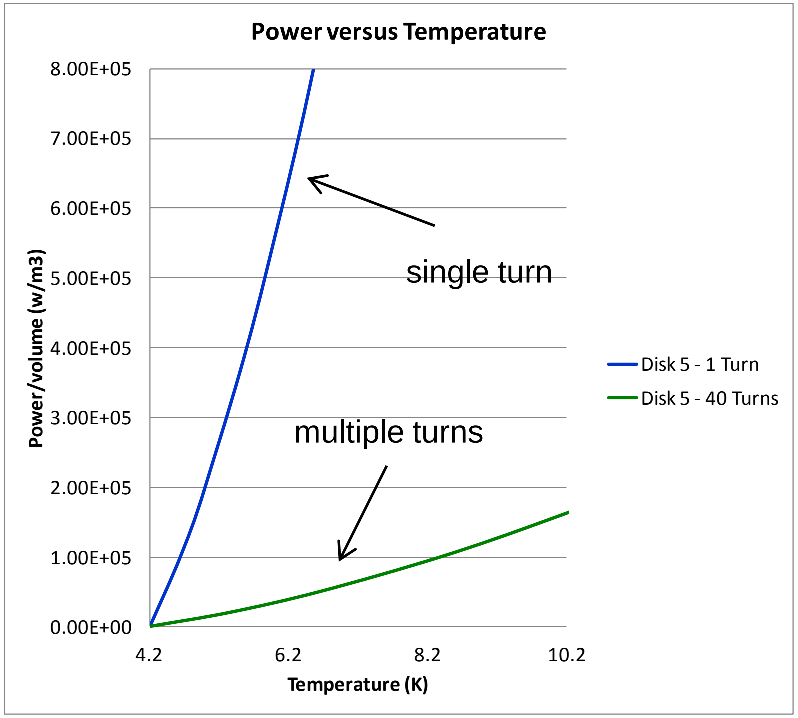


In order to select the initial conductions for a quench in a realistic manner, the stability of turns was examined. For a single turn, a reasonable correlation between a heat balance stability condition and calculated thermal runaway was observed.



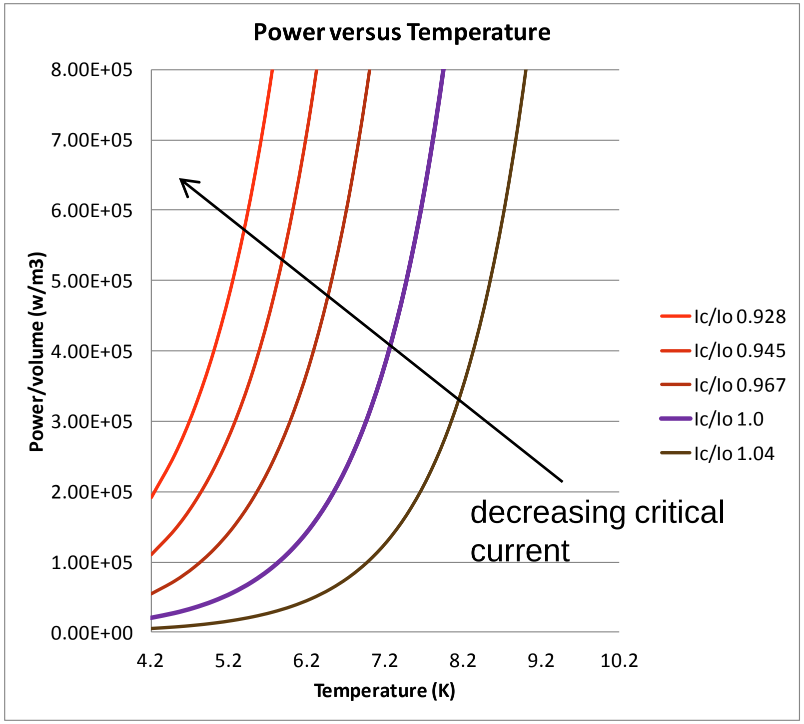
# Cooling and Heating

## Cooling of windings to helium




Cooling power/volume for rings of conductor at selected location as function of temperature.

## Power dissipation in conductor




Power/volume in conductor at constant operating current of 180 A, as function of temperature for decreasing critical current.

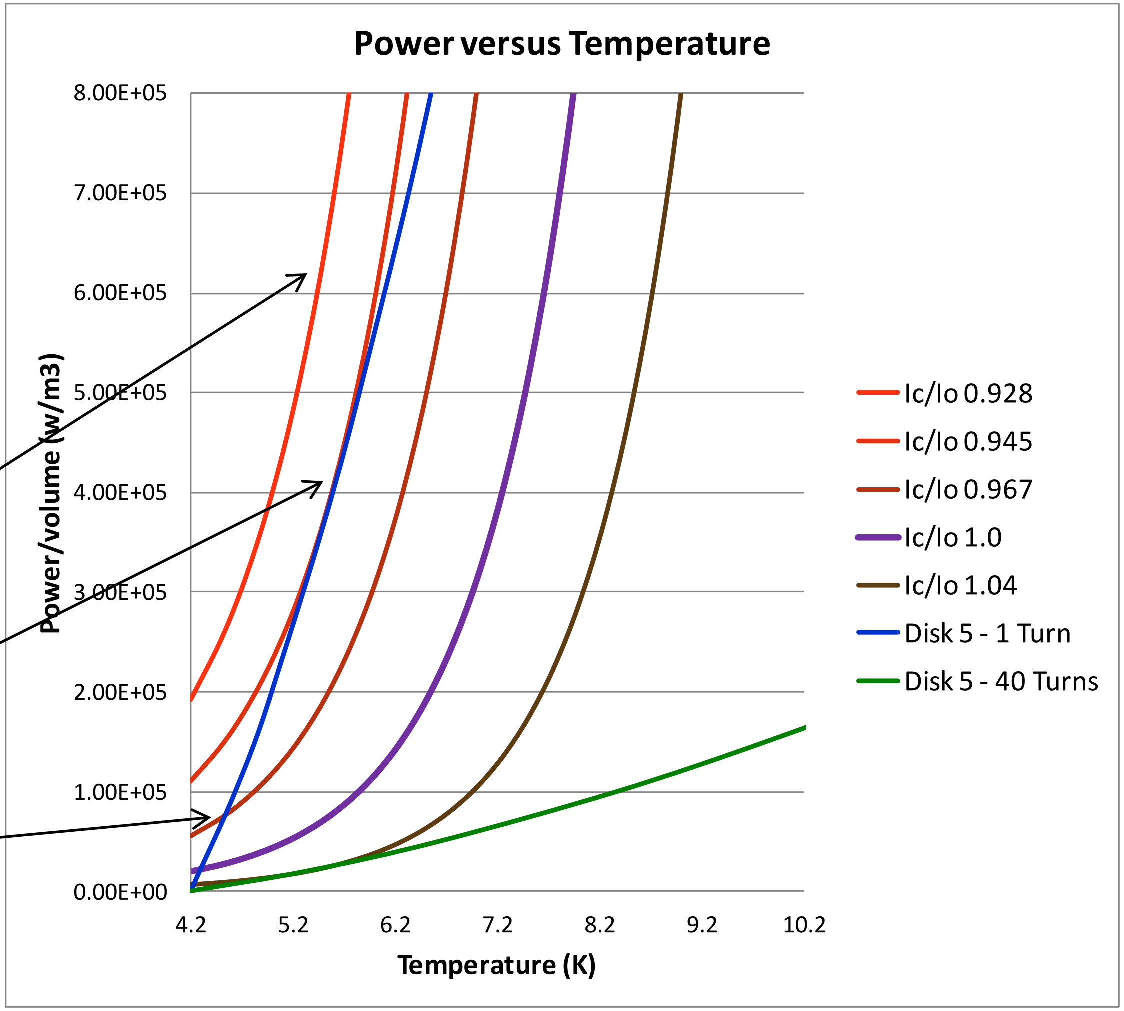
# Stability Criterion

Stability is a balance between heating and cooling, as described by Rakhmanov. As the local critical current is reduced further below the operating current, the increased conductor heating results in thermal runaway.

unstable

stability limit

stable



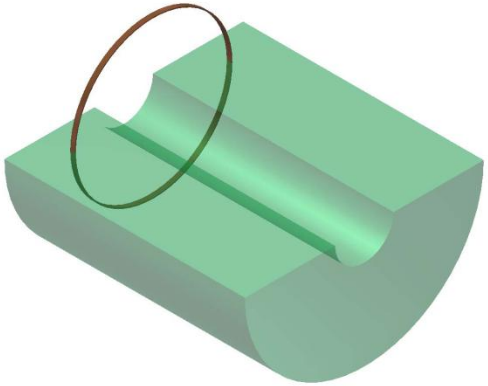

A. L. Rakhmanov et al, Cryogenics 40 (2000) 19-27
V. S. Vysotsky et al, IEEE Trans. Appl. Supercond. 11, 1824 (2001)

# Quench of Single Turn

Quench of the QPC is examined
for quench initiated by a single turn.

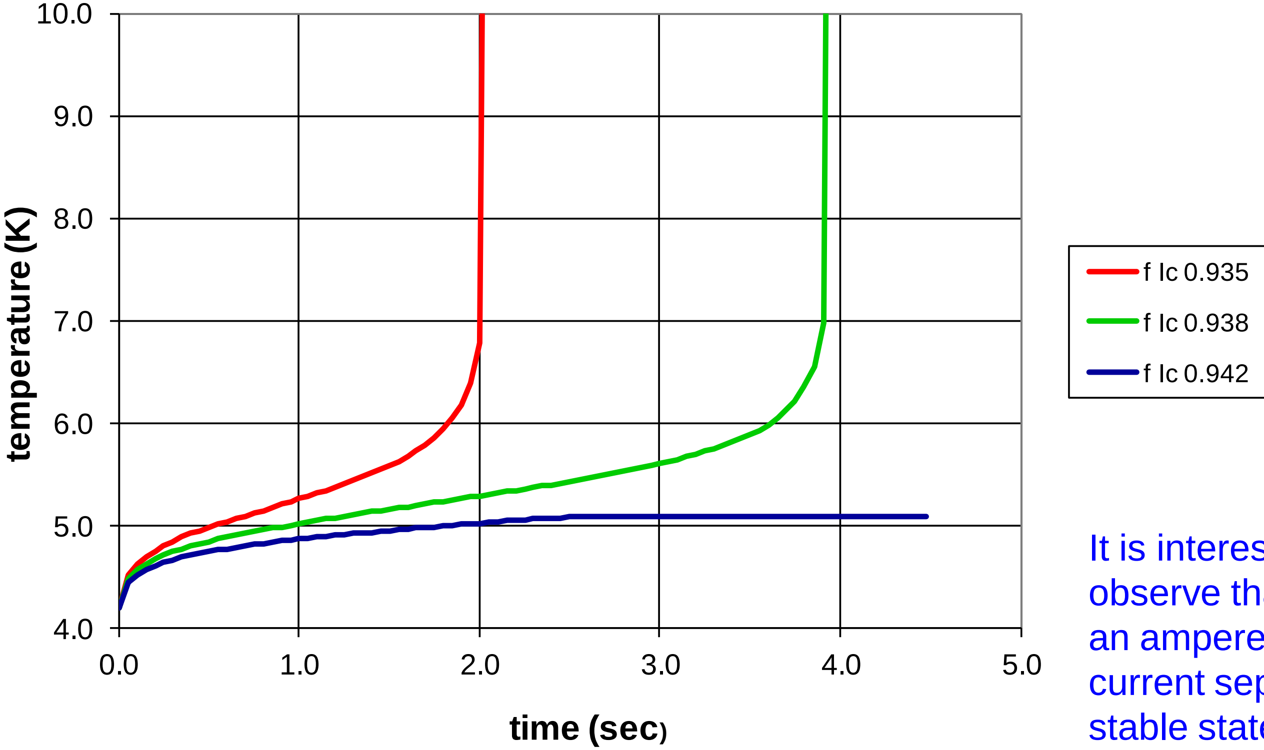
As the critical current of the single turn ring is reduced,
the power dissipation increases.

As thermal stability is exceeded, rapid thermal runaway occurs and quench is initiated.



Single Turn Ring

# Quench Initiation of Single Turn Temperature versus Time




It is interesting to observe that a faction of an ampere of critical current separates a stable state from one that experiences thermal runaway in a matter of seconds.

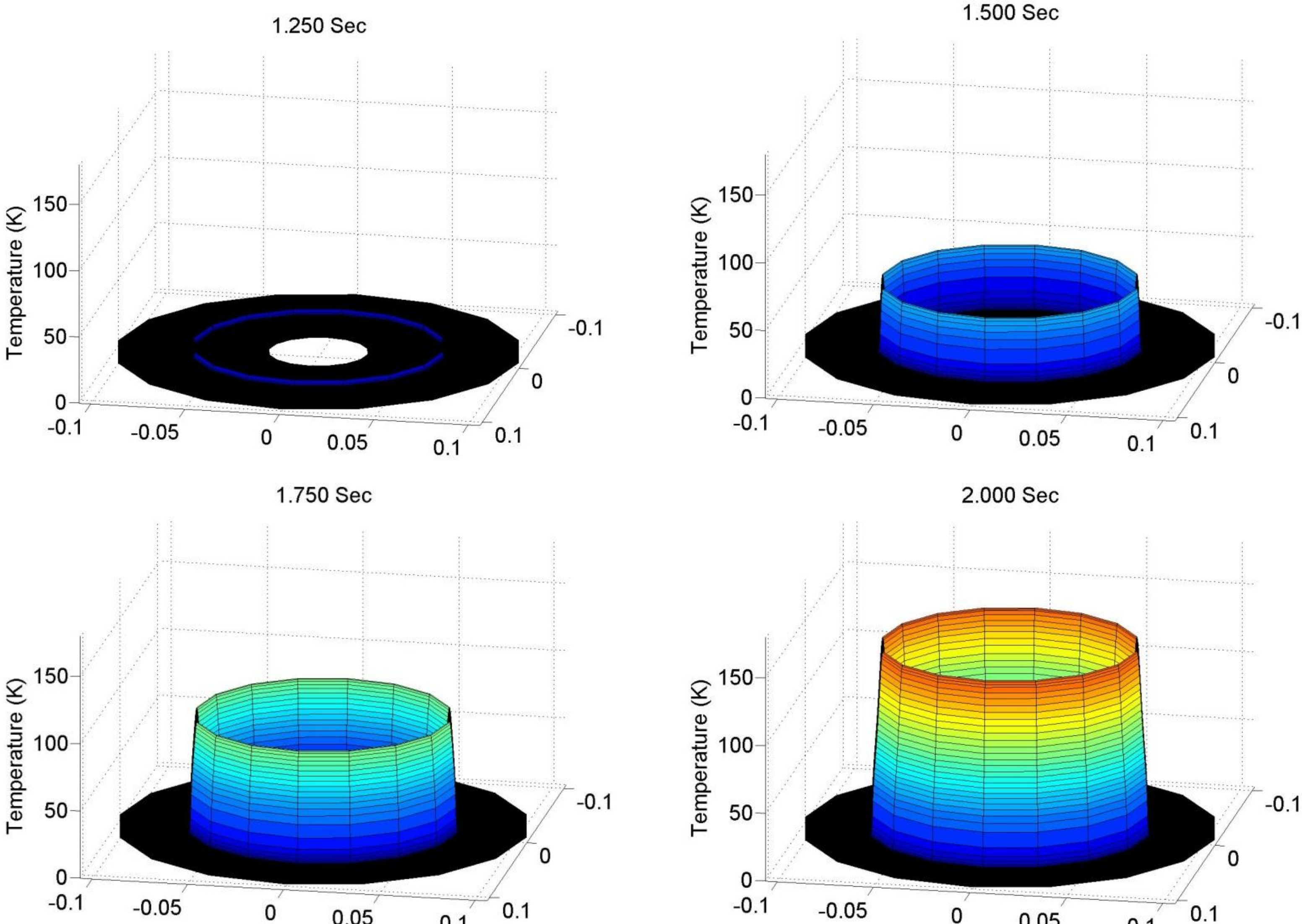
Thermal runaway and quench onset at the limit of stability for a single turn.

Stability critical current ~0.92 x operating current.

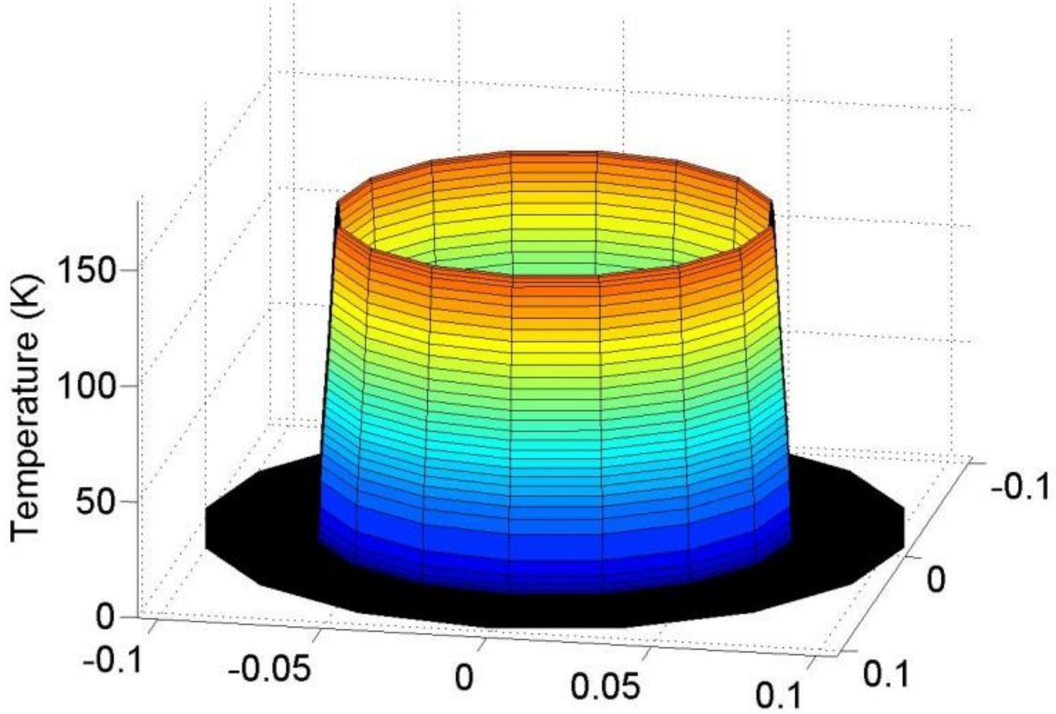
Stable temperature limit ~ 5.1 K.

# Evolution of quench in single turn without protection.

## The temperature evolution of a single turn quench in disk 5 of QPC.



# Evolution of quench in single turn without protection.




Unprotected quench of single turn,
temperature continues to rise without significant
radial or axial quench propagation.

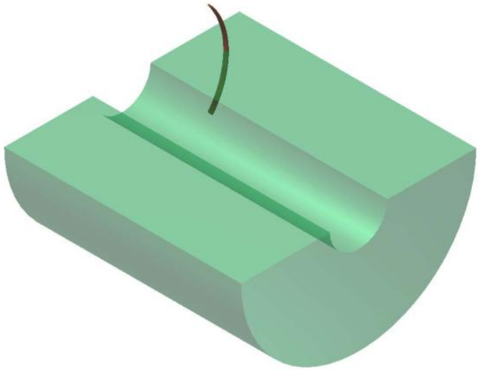
IEEE/CSC & ESAS European Superconductivity News Forum (ESNF) No. 23 January 2013

# Quench of Single Turn Arc

Quench of the QPC is examined
for quench initiated by a single turn arc
of 80 mm length.

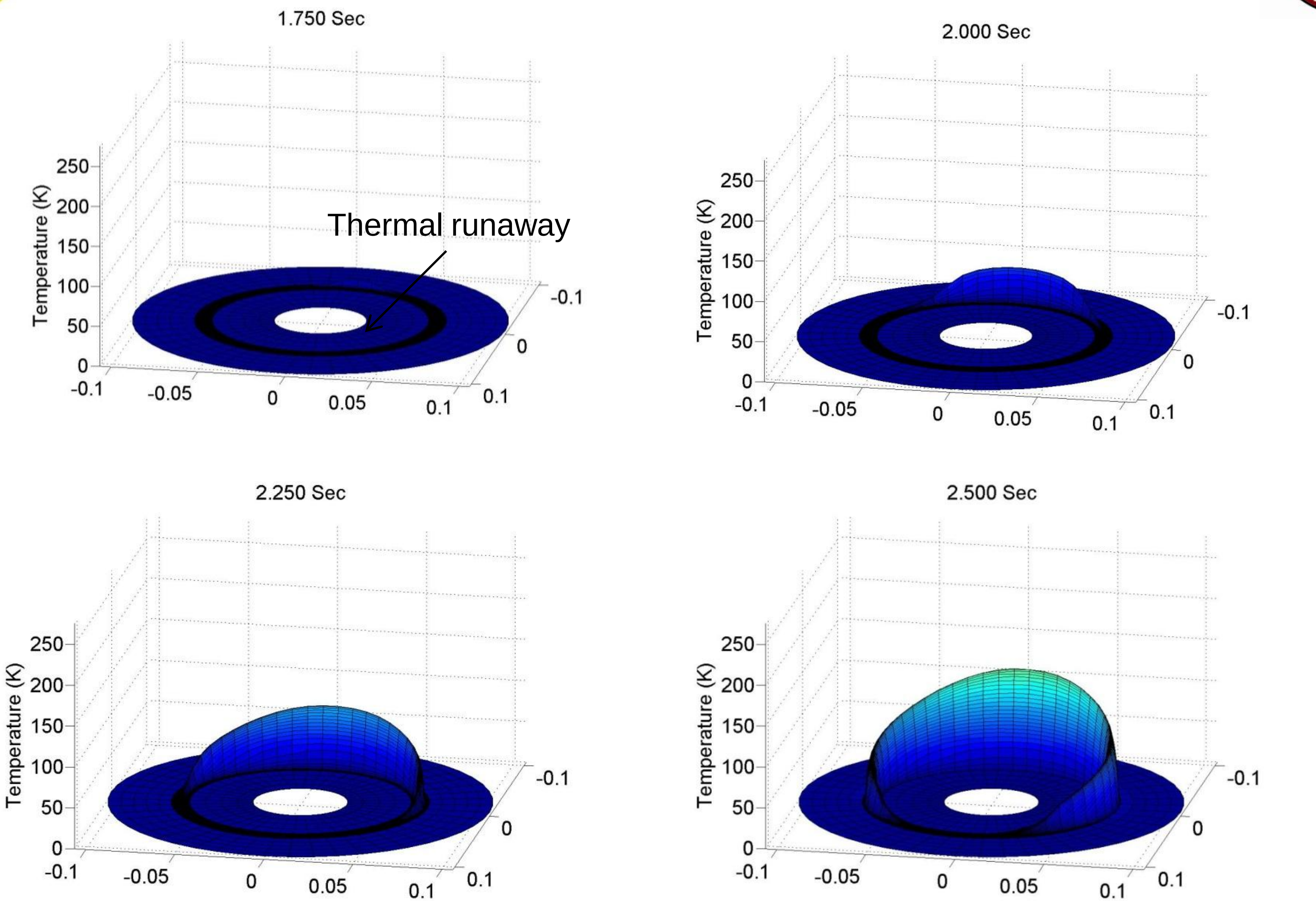
As the critical current of the single turn ring is reduced,
the power dissipation increases.

As thermal stability is exceeded, rapid thermal runaway occurs and quench is initiated.

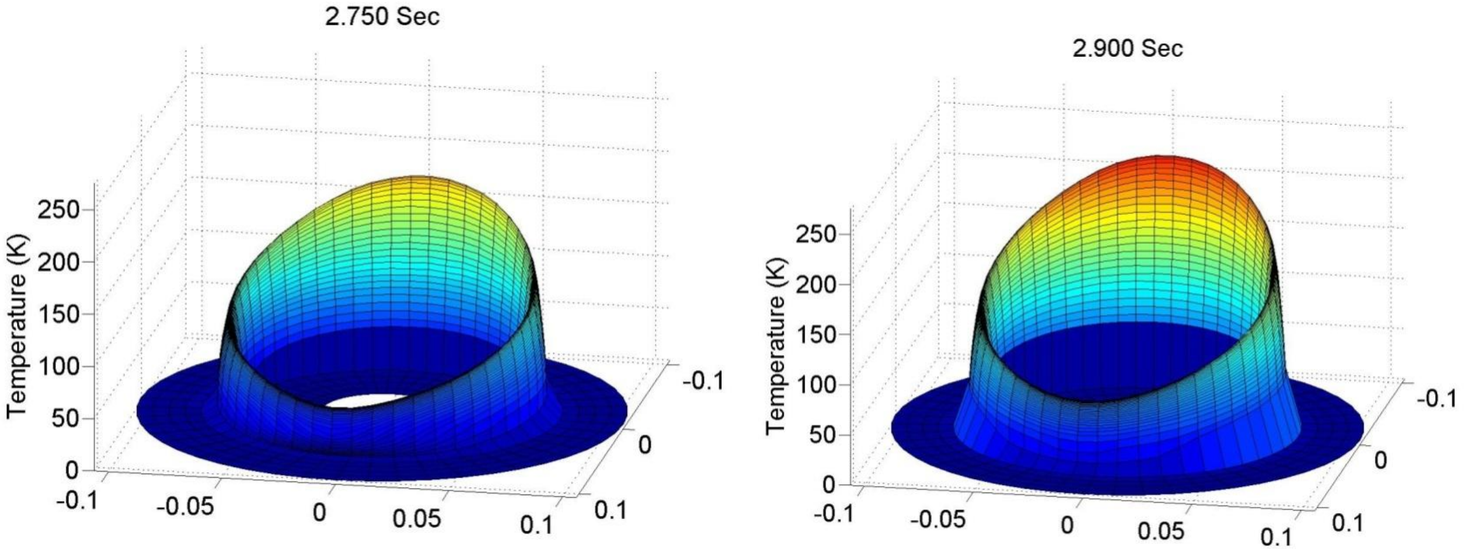


Single Turn Arc

# Evolution of quench in single turn arc without protection.



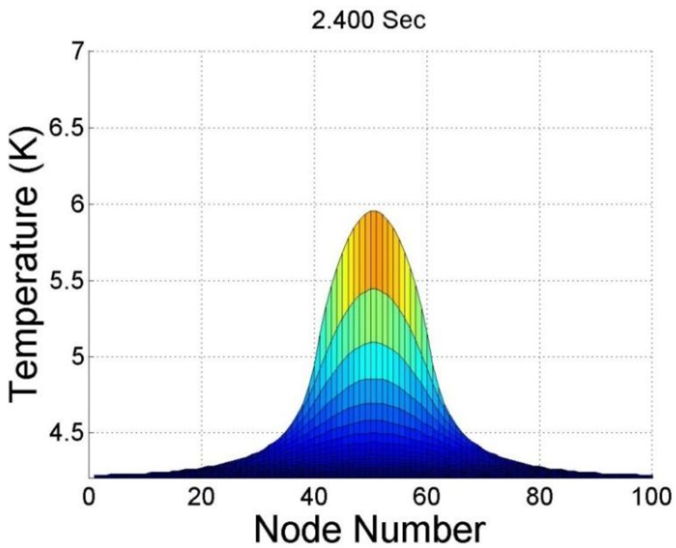
# Evolution of quench in single turn arc without protection.

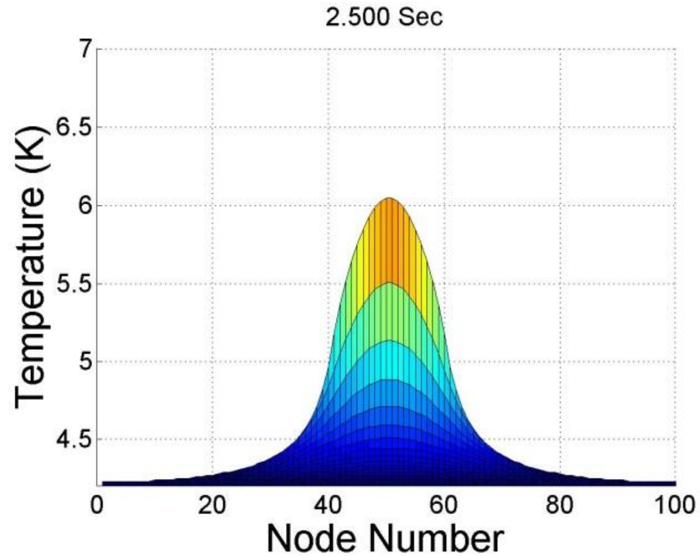


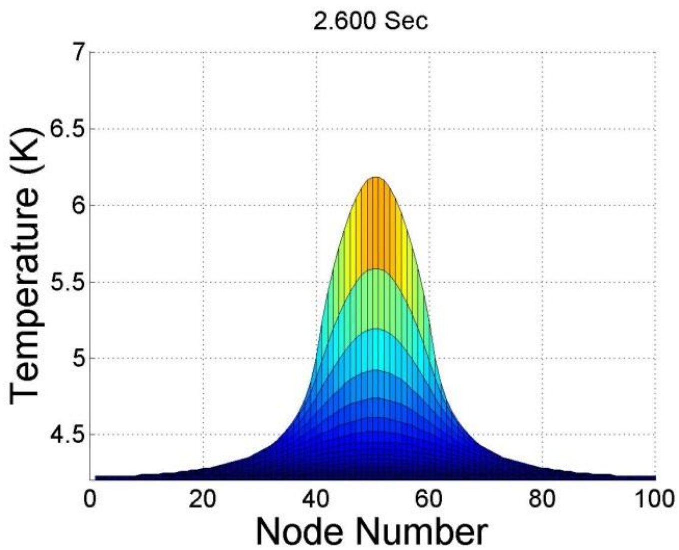

Unprotected quench of single turn arc,
temperature continues to rise without significant
radial or axial quench propagation,
but with full angular spread.

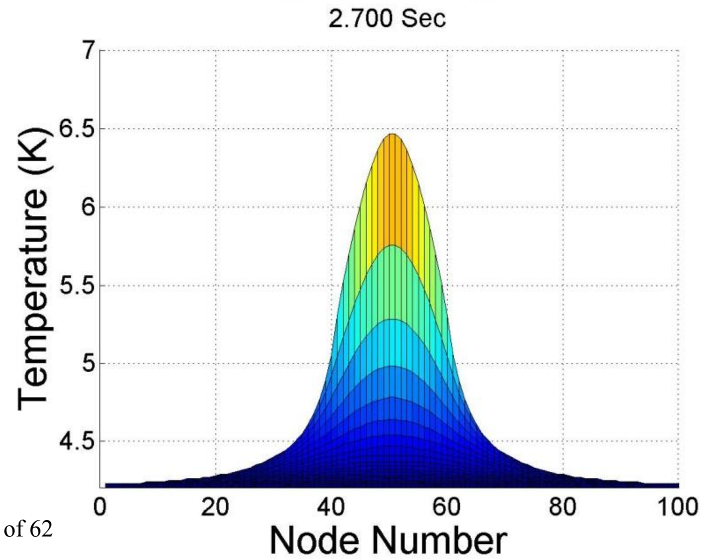
# Prior to Thermal Runaway

Prior to thermal runaway, the temperature increase is slow and the constant spread reflects the lack of quench propagation.



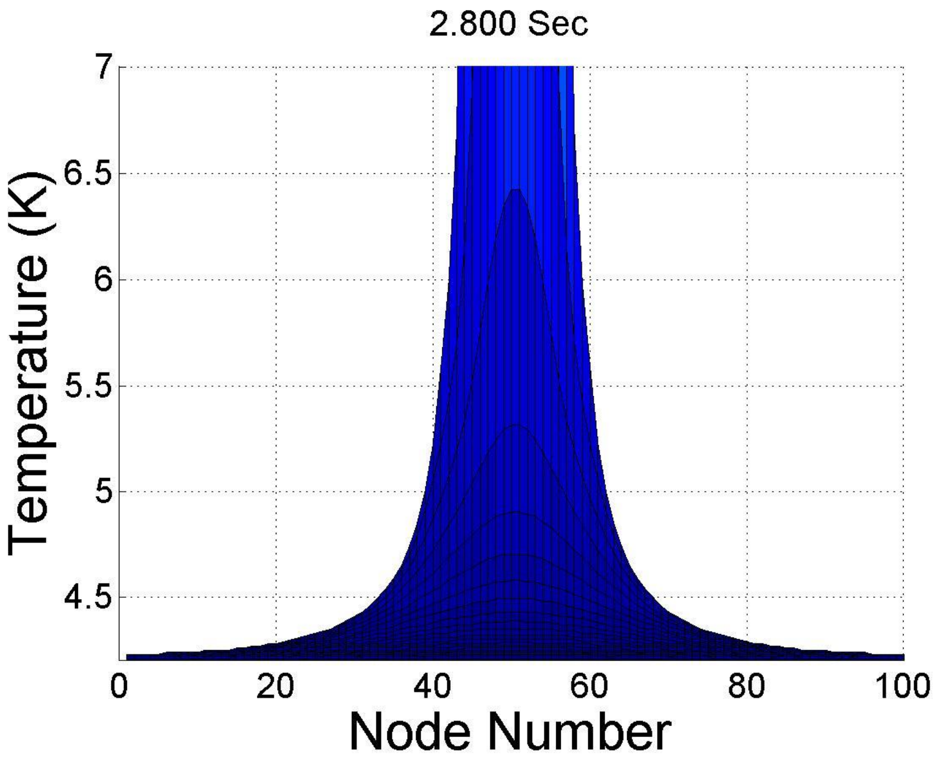



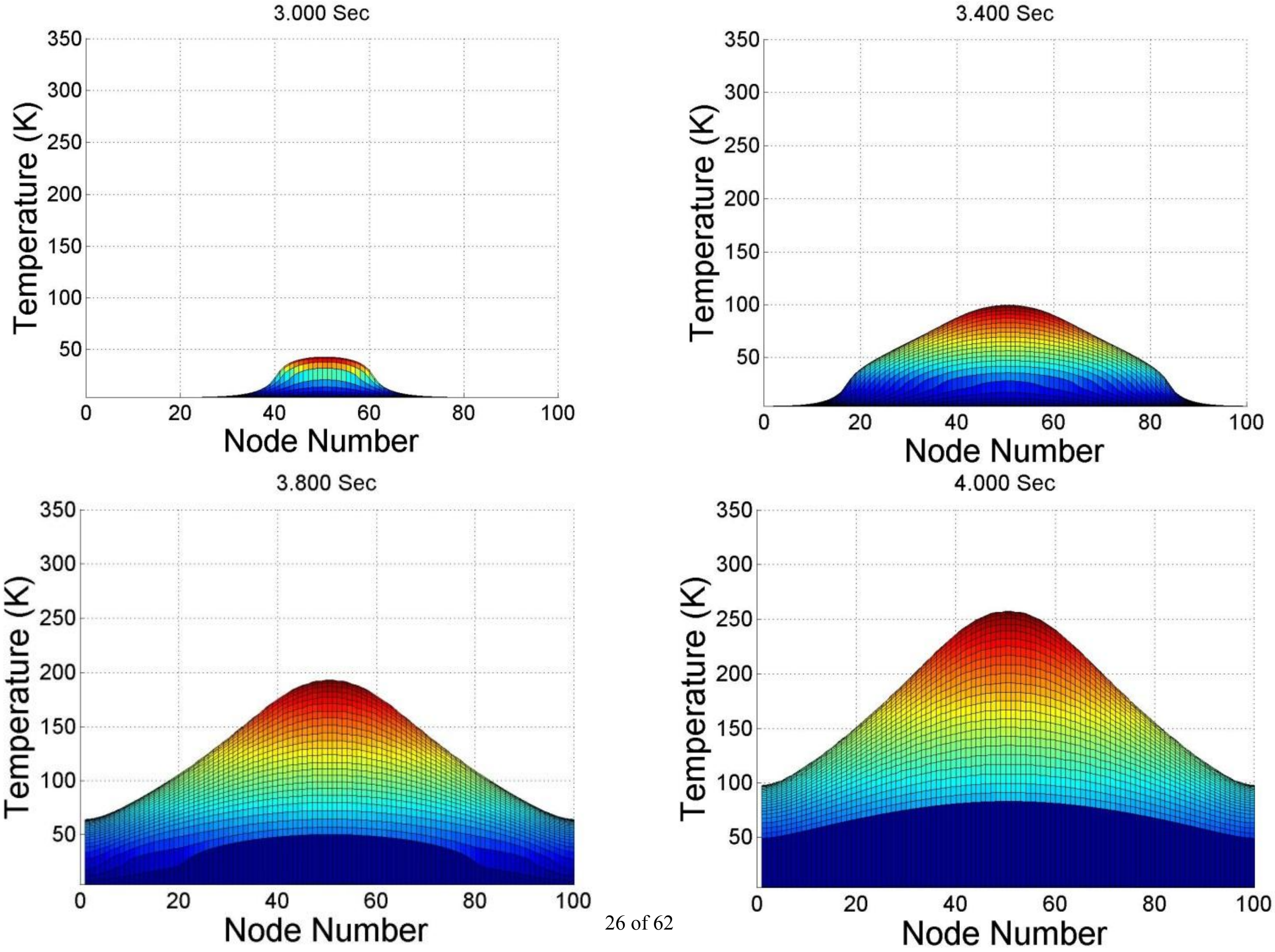
# Thermal Runaway

Thermal runaway is characterized by a rapid increase in temperature.

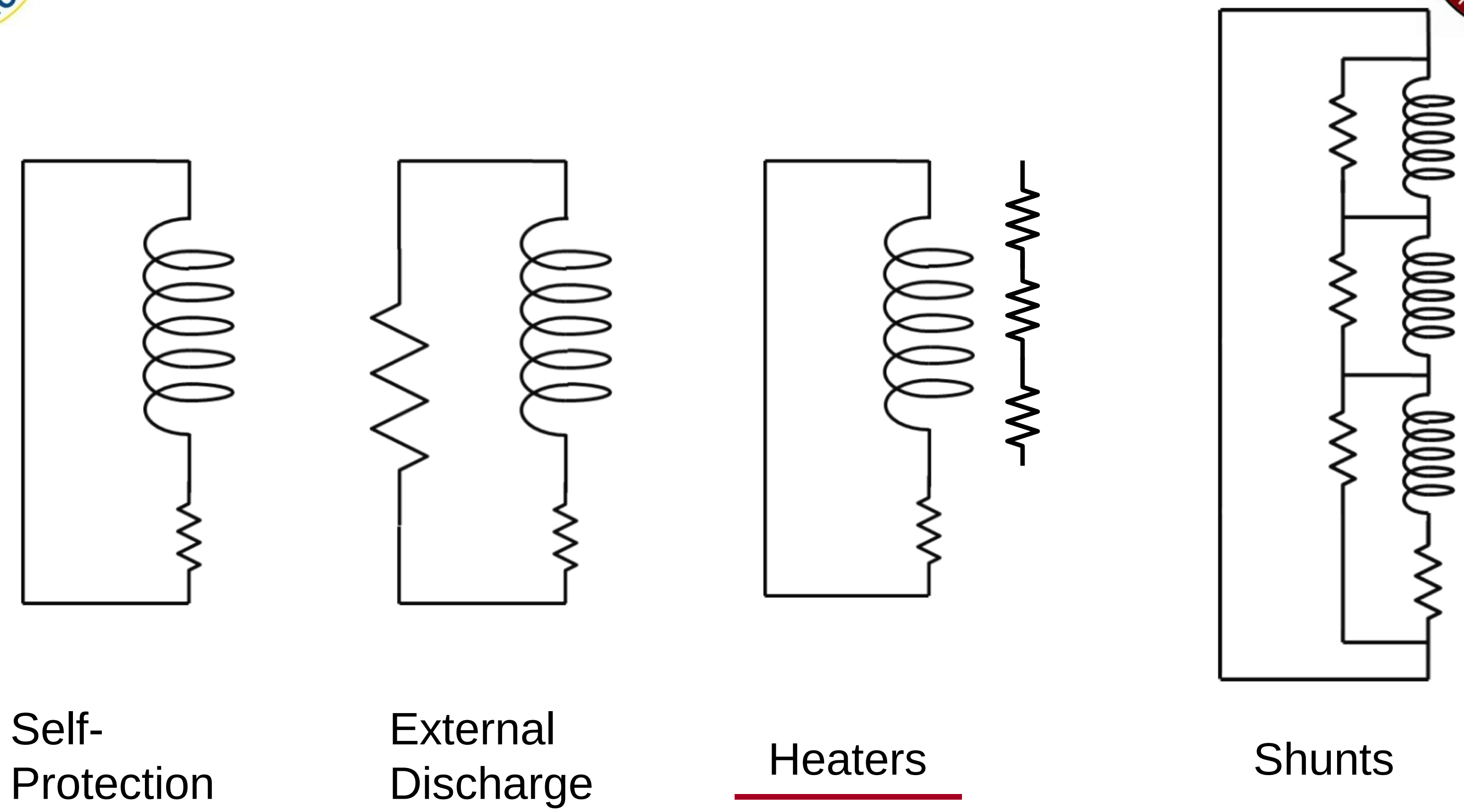


# After Thermal Runaway

Following thermal runaway, increased temperature spreads by thermal diffusion along the direction of the conductor.

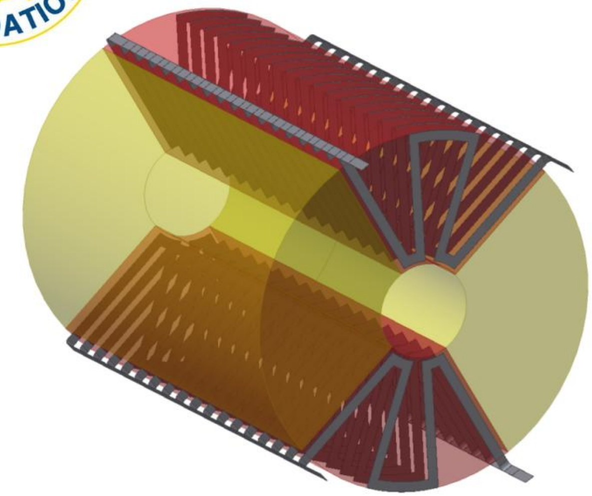


# Classic Protection Schemes




Self-protection methods rely on quench propagation which is limited for REBCO conductor. External discharge of low current coils is typically associated with high voltage. Distributed heater protection is examined here. Shunts have been used historically on tape magnets and may find application to REBCO coils.

# Distributed Heater Quench Protection



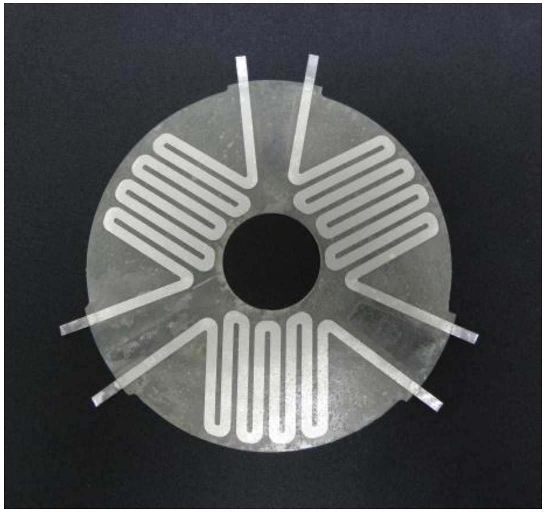
distributed heater concept

test coil heater spacer

Active protection system.

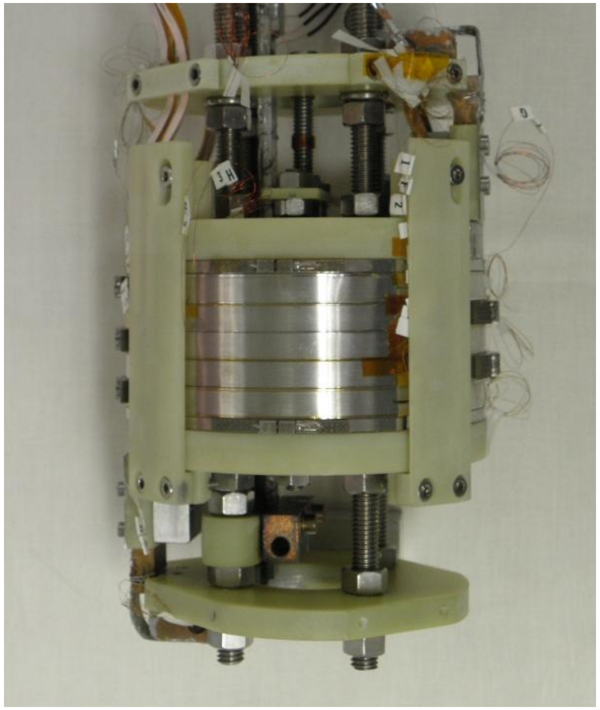
Heater elements embedded in spacers between modules.

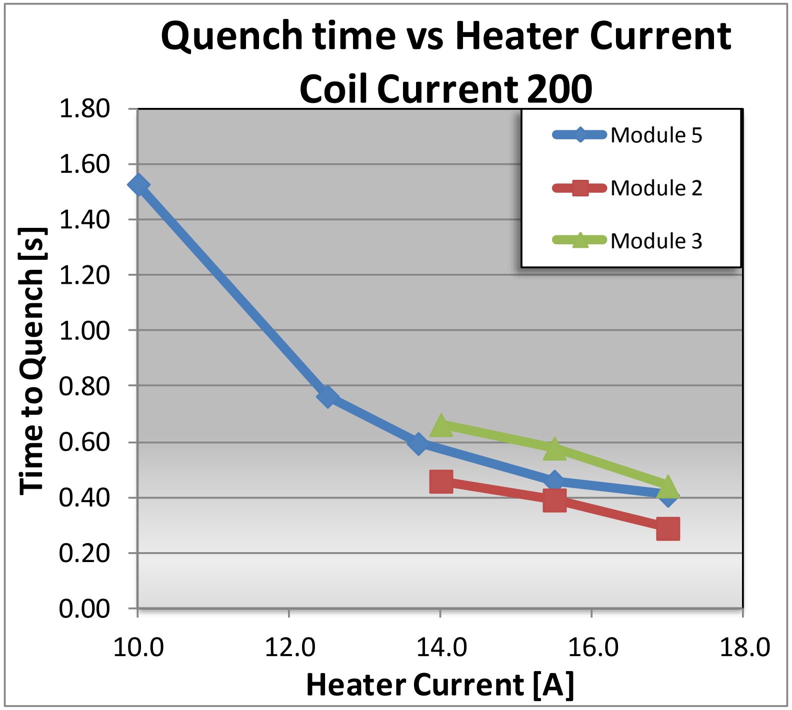
Design considerations:
  number of heaters in coil,
  heater element distribution in spacer,
  heater operation power.



32 T magnet heater spacer

# Heater Performance Test






Test coil O.D. 124 mm, tested in 20 T background field, heater tests at 200 A operating current over range of currents, power.

Data establishes value of heater rise time parameter in YQUENCH.

P.D. Noyes et al, IEEE Trans. Appl. Superconduct., **22**, 3, 4704204 (2012)

# Discharge of Quench Protection Coil with Heaters

Heater performance and design considerations associated with the heaters are demonstrated through the forced quench of the QPC by activation of the heaters.

# Heater Design Aspects

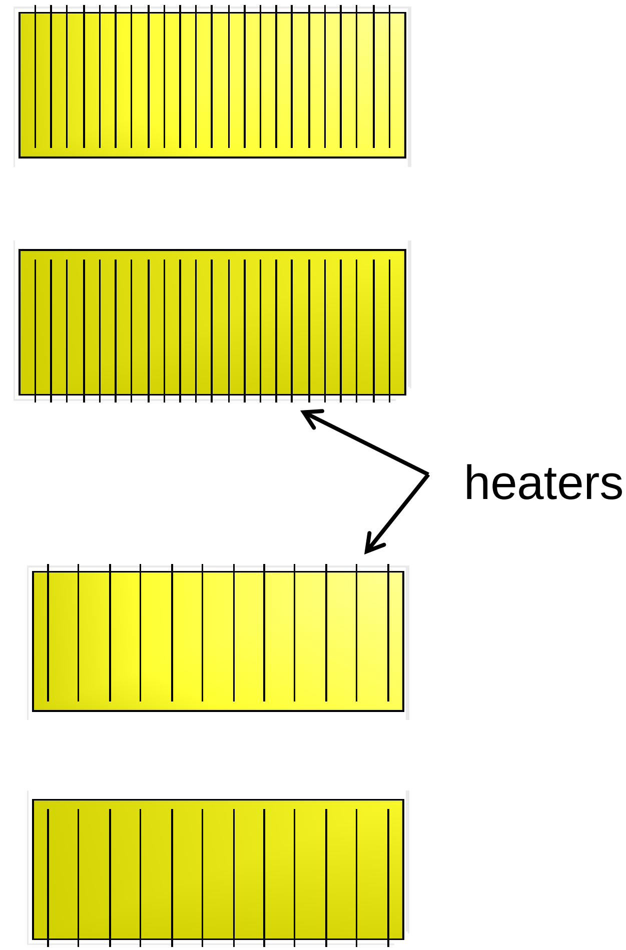
Heater power requirements
are large n x 10 kW.

Motivation to limit heater distribution.

Heaters placed

every double pancake

or every other double pancake.



# Heater Design Aspects

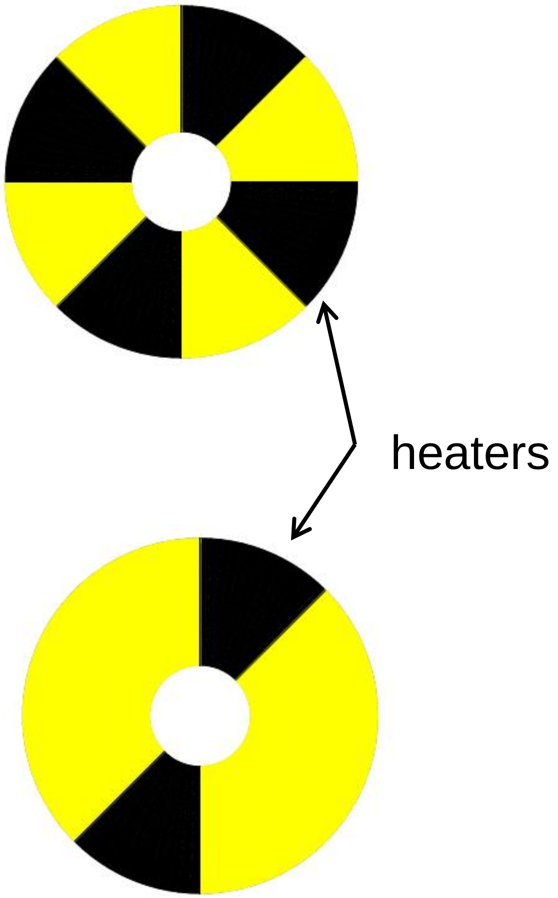
Heater power requirements
are large n x 10 kW.

Motivation to limit heater distribution.

Heaters placed

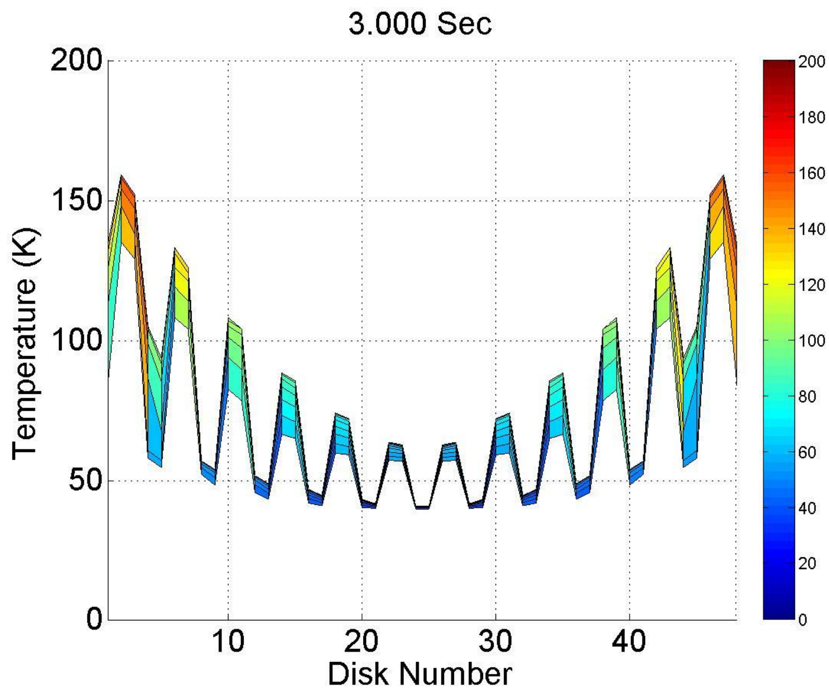
50 % disk coverage

or 25 % disk coverage.



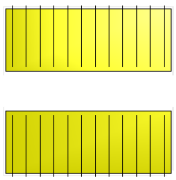
# Module Temperature Rise with Heaters

In this and subsequent examples, it is seen that the heaters are relatively inefficient, quenching only the ends of the coil. This is largely the result of large critical currents in the center of the coil. One strategy for protection is reduced critical currents where the radial field is limited.




coil axis

Every other module (DP)



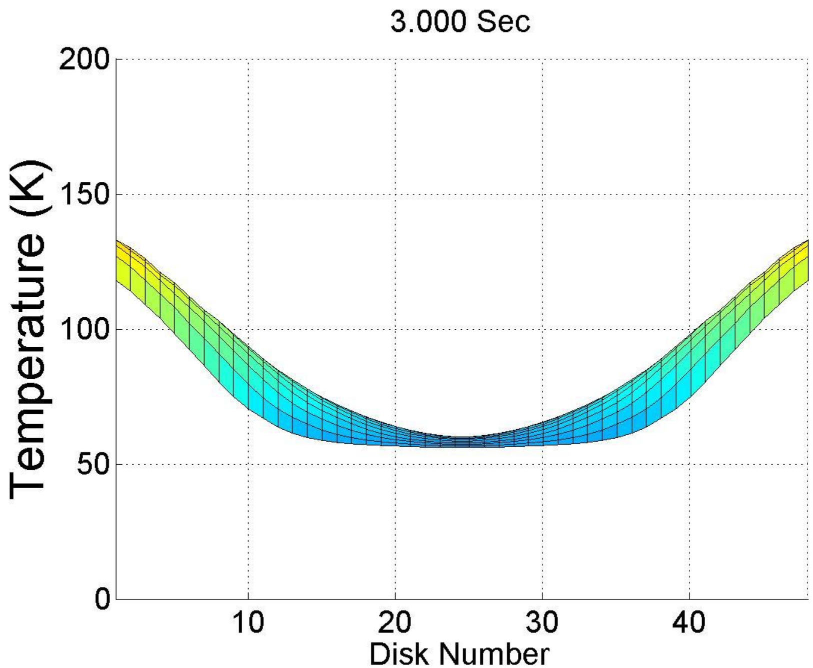
50 % coverage

Heating is largely limited to disks adjacent to the protection heaters.

The heaters primarily quench the end modules of the coil, leaving central modules superconducting.

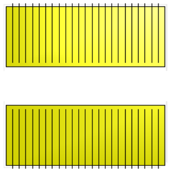
# Module Temperature Rise with Heaters

In this set of examples, the coil is quenched by the action of the heaters and as a result, the maximum temperature is relatively low. In an actual quench situation, the temperature at the origin of quench has already increased significantly by the time the heaters are activated.




coil axis

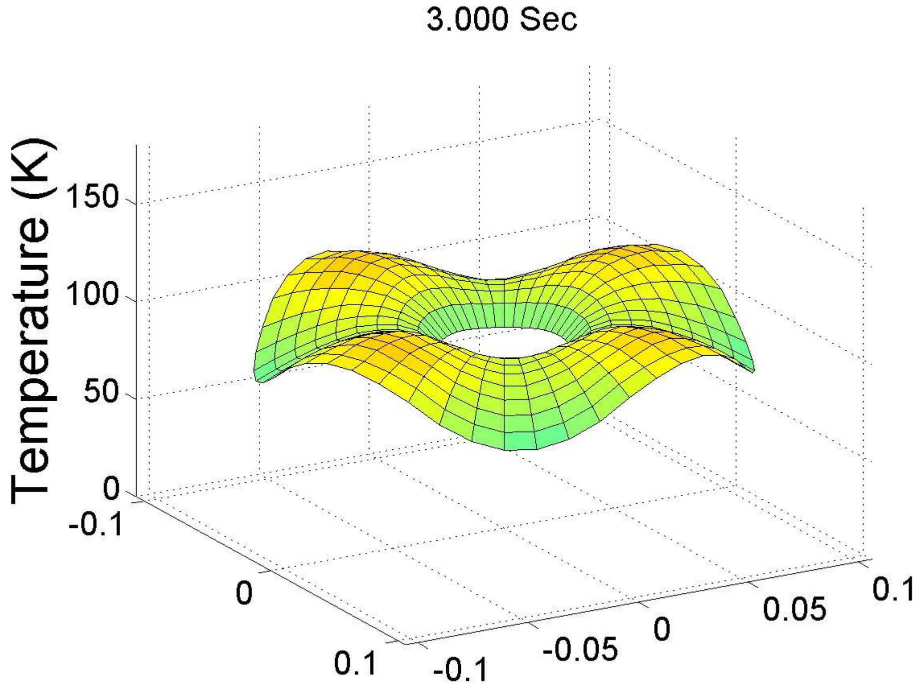
Every module (DP)



50 % coverage

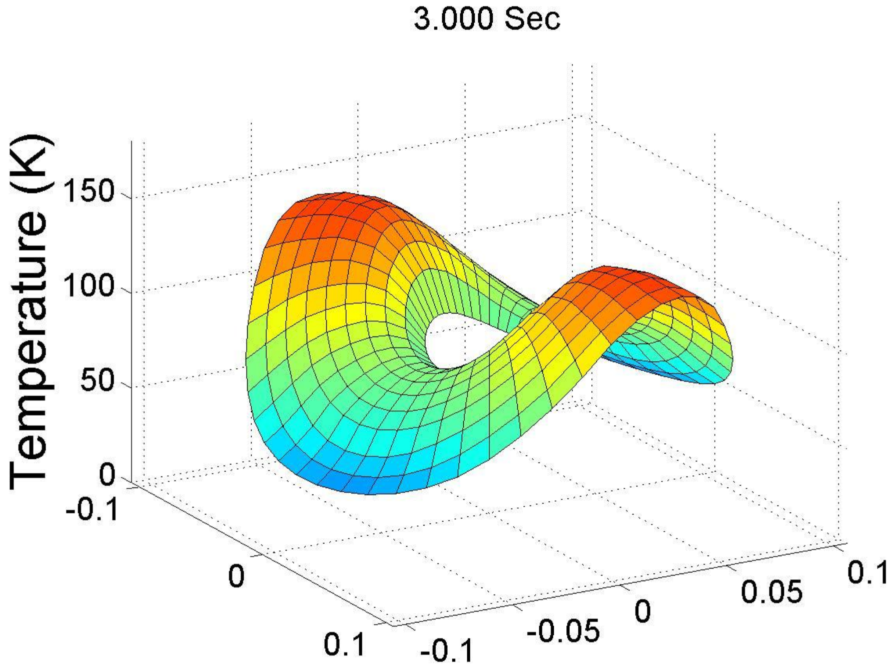
Heaters every double pancake eliminates axial gradients at expense of heater power.

# Module Temperature Rise with Heaters




Heater disk coverage of 50 % and four fold symmetry gives relatively uniform temperature in pancake.

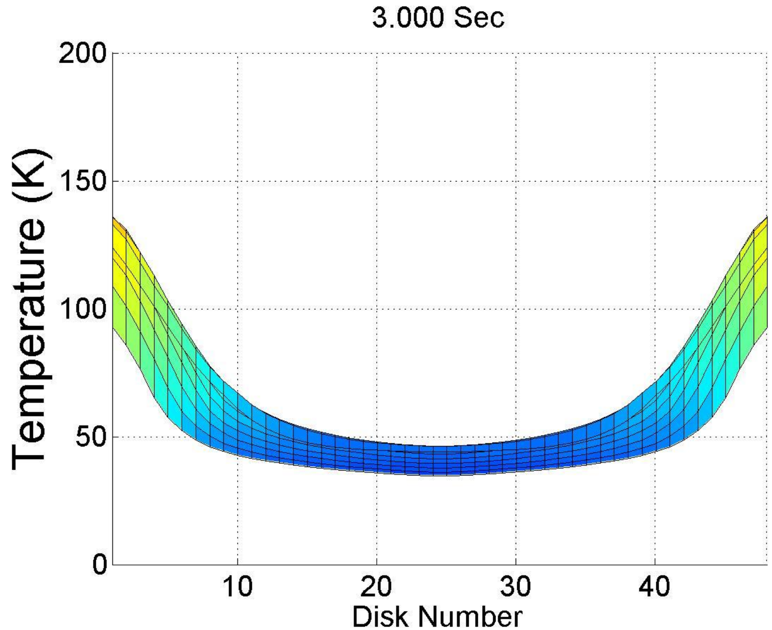
# Module Temperature Rise with Heaters



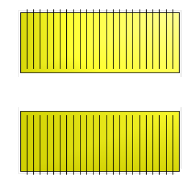

Heater disk coverage of 25 % and two fold symmetry reduces heater power requirements accordingly, but gives larger temperature distribution in pancake.

# Module Temperature Rise with Heaters

The rather limited quench temperature rise is partly the result of the limited stored energy in the example coil, but it is also the result of a relatively rapid increase in coil resistance and consequent rapid current decay, as will be seen subsequently.




Every module (DP)



25 % coverage

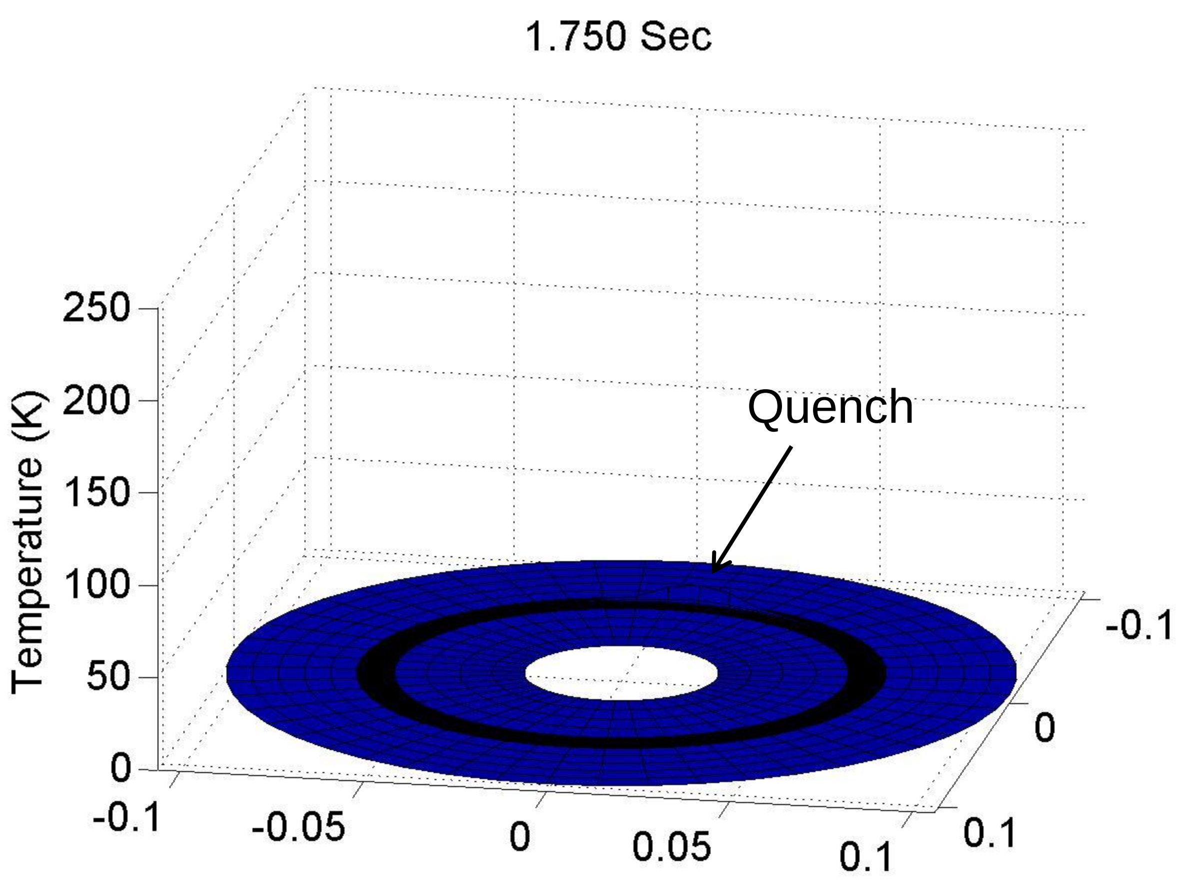
coil axis

Reduction of heater coverage reduces overall heater power requirements at expense of reduced heater efficiency at center of coil.

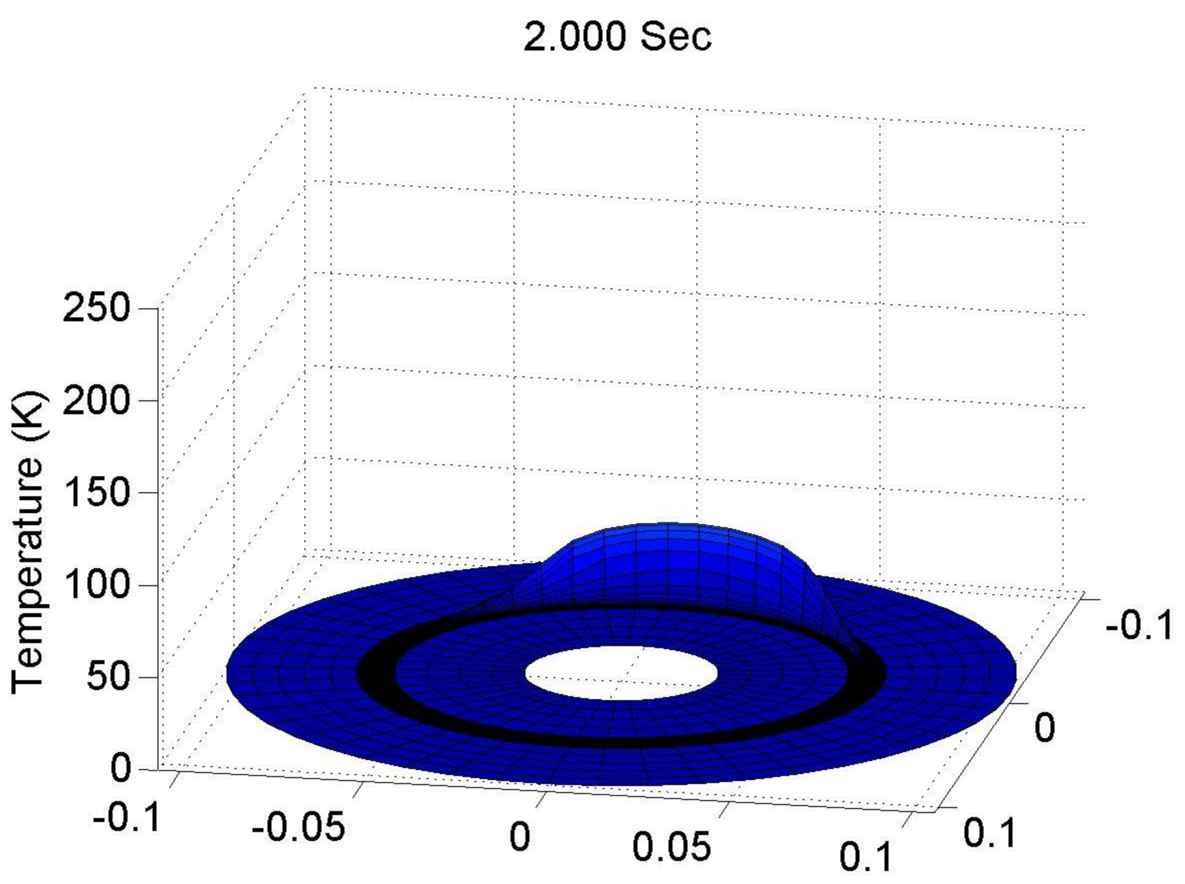
# Quench Protection Coil
# with Arc Quench
# and Protection Heaters

The action of the protection heaters is shown for a quench in disk (pancake) 5 of the QPC initiated by low critical current in an arc segment. The temperature rise in the disk is given in a sequence of slides, showing the local hotspot and more general temperature increase resulting from the heaters. Then the effect on the critical current is shown, starting with the local low critical current of the segment that initiates the quench and showing the general collapse of the critical current as a result of the temperature increase caused by the heaters.

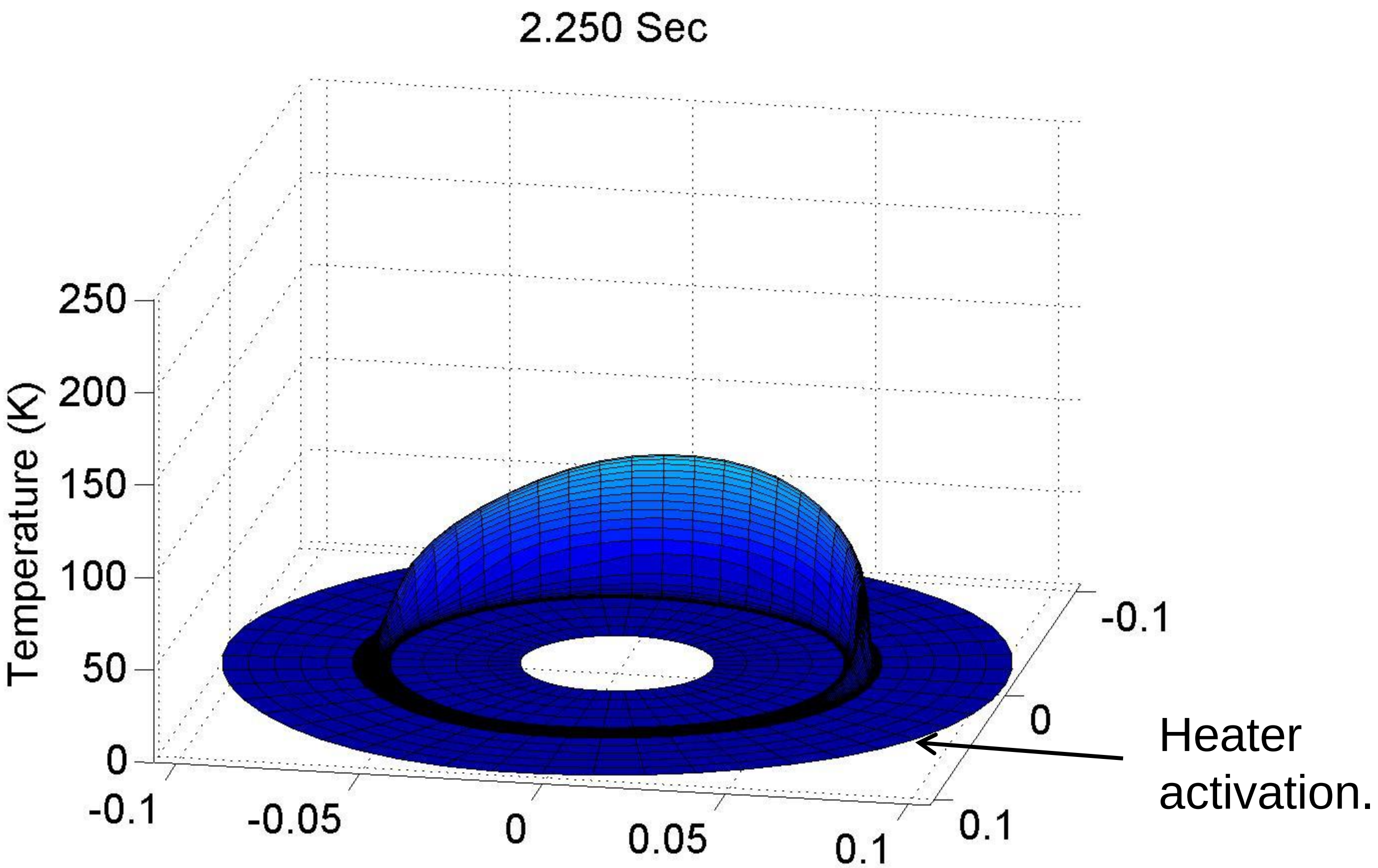
# Temperature of Quench Initiation Disk



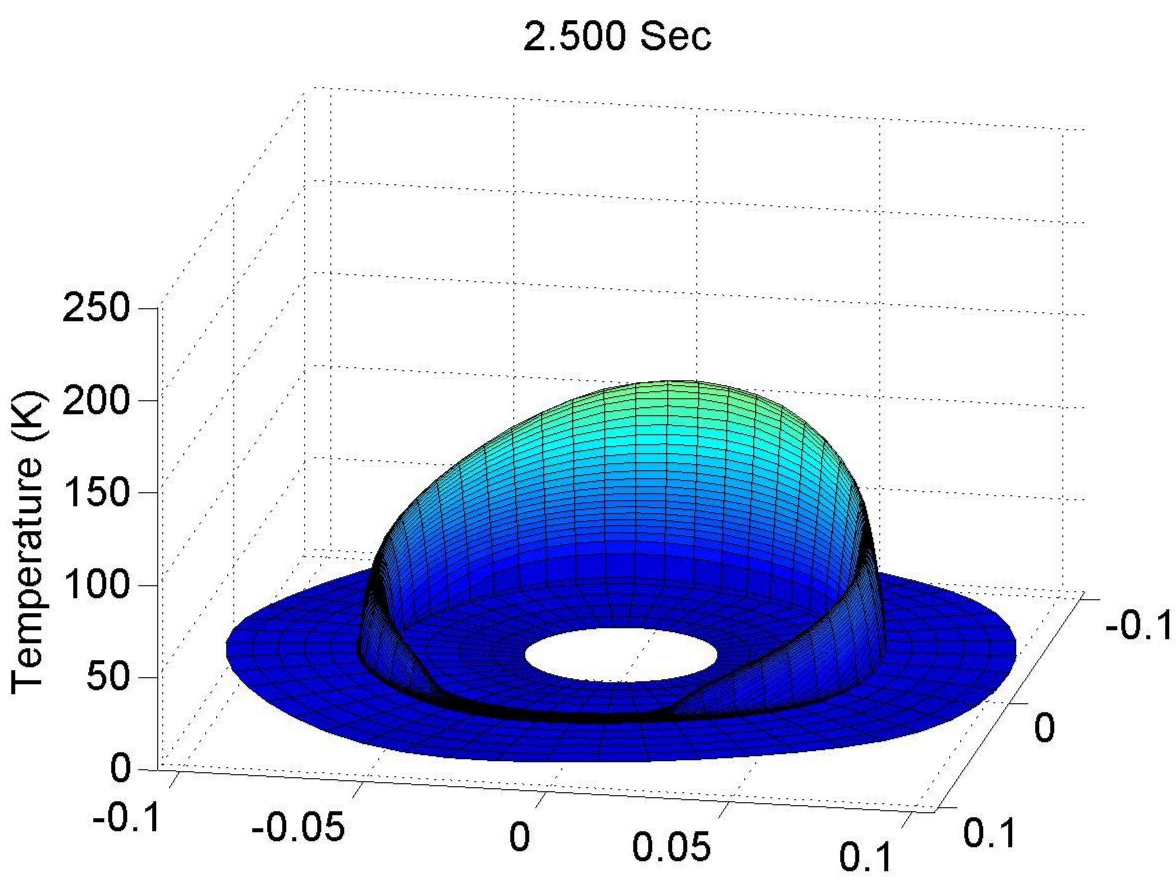
# Temperature of Quench Initiation Disk



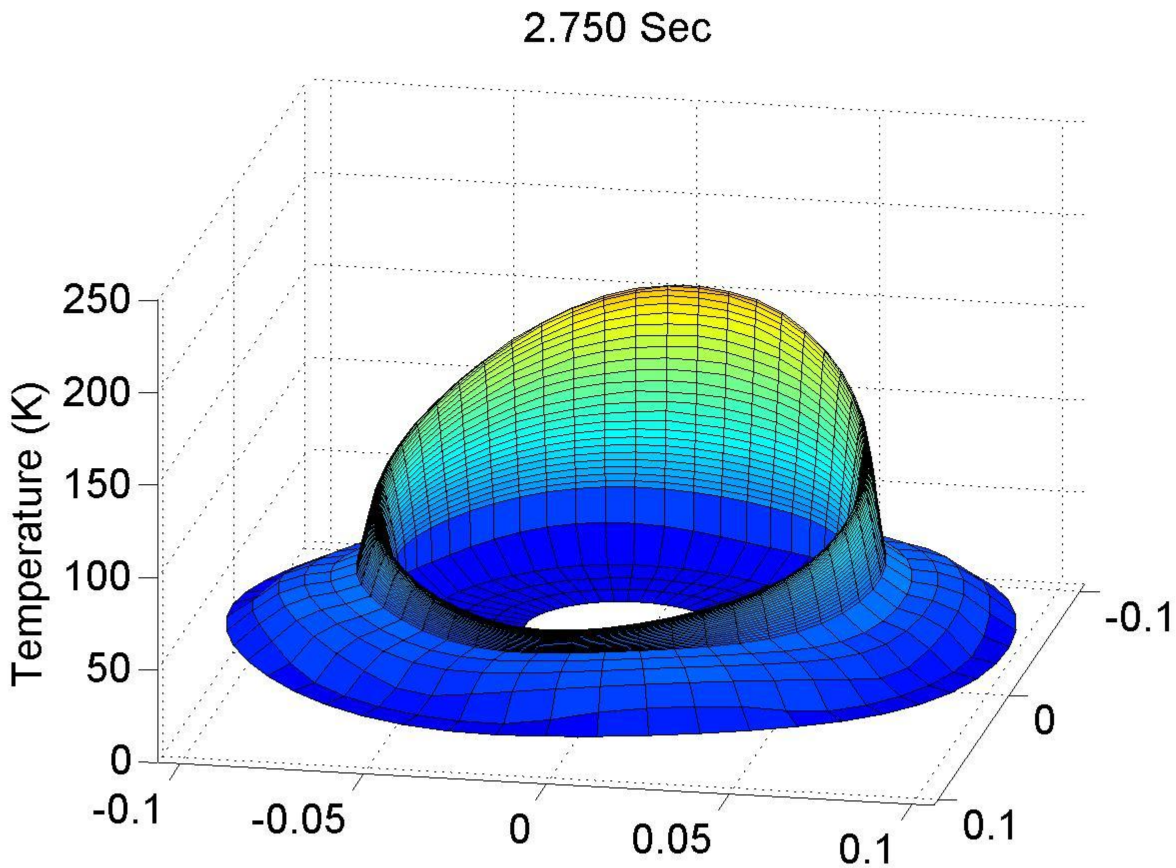
# Temperature of Quench Initiation Disk



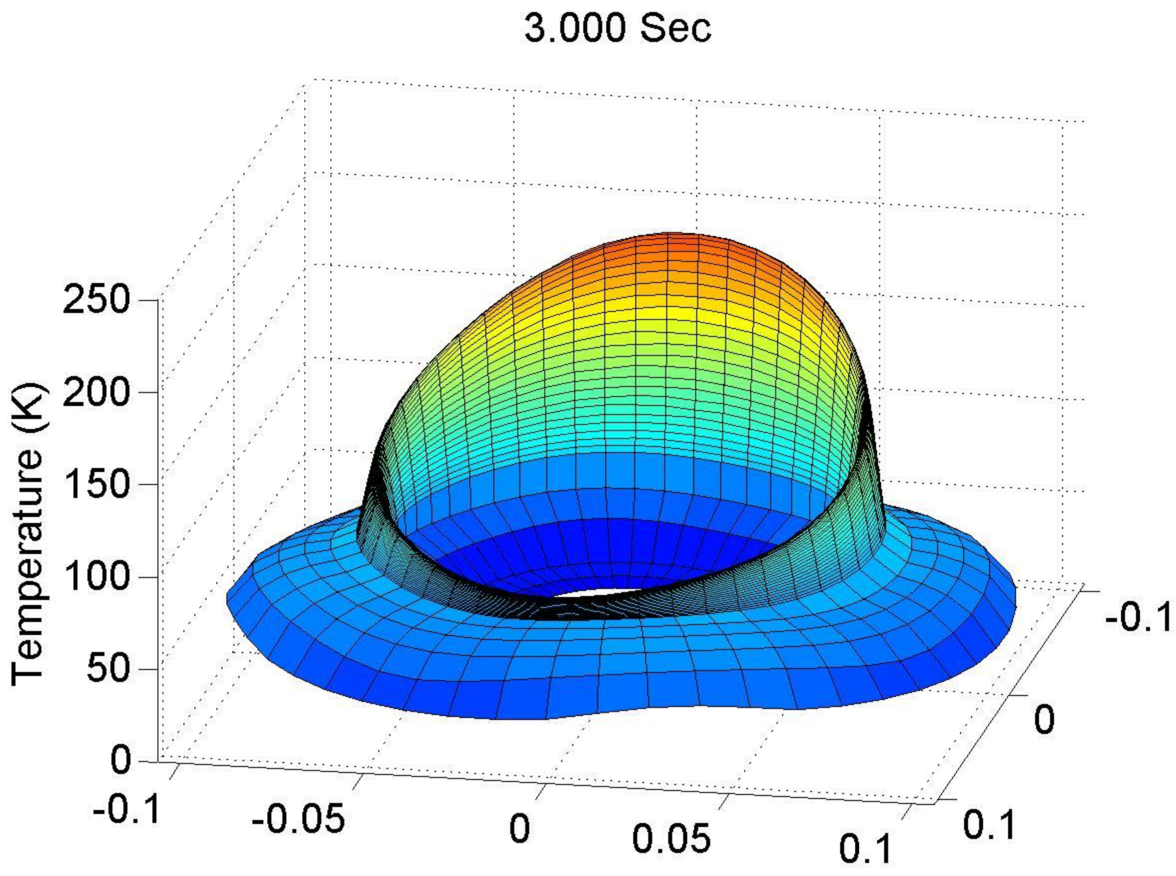
# Temperature of Quench Initiation Disk



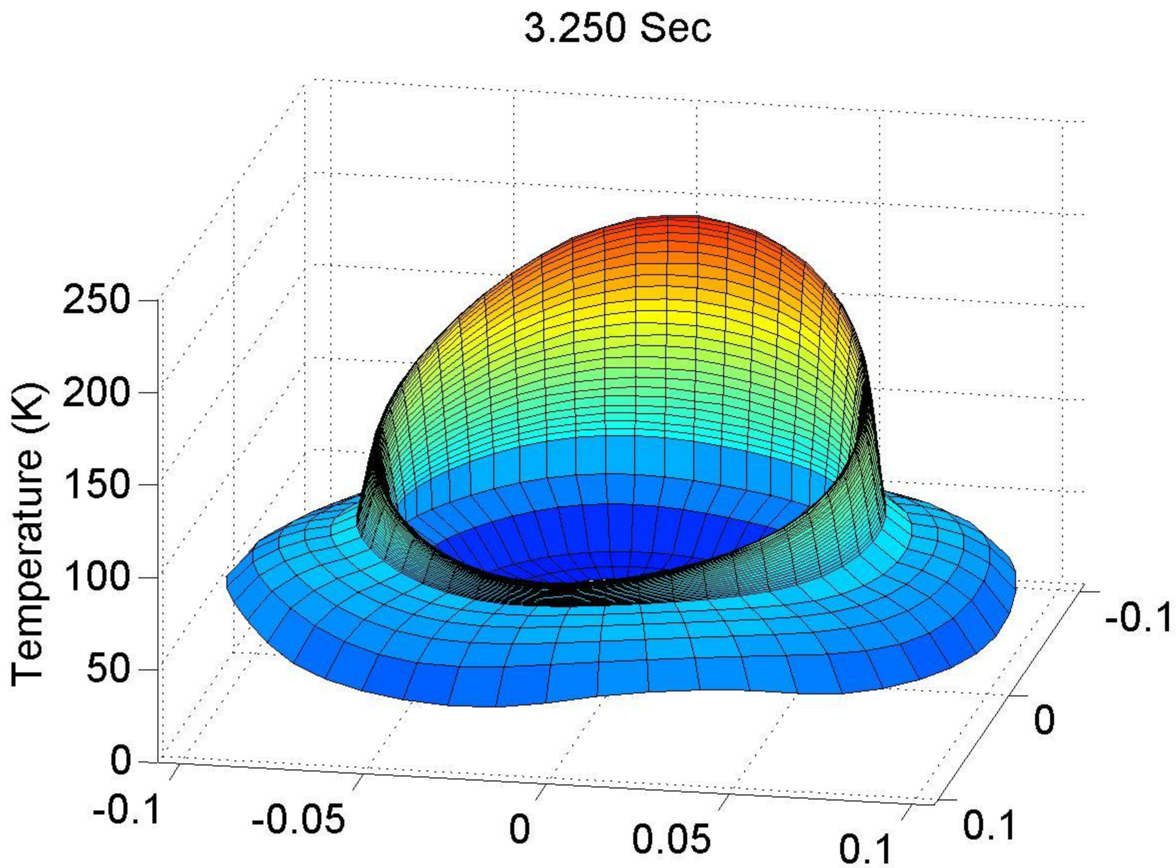
# Temperature of Quench Initiation Disk



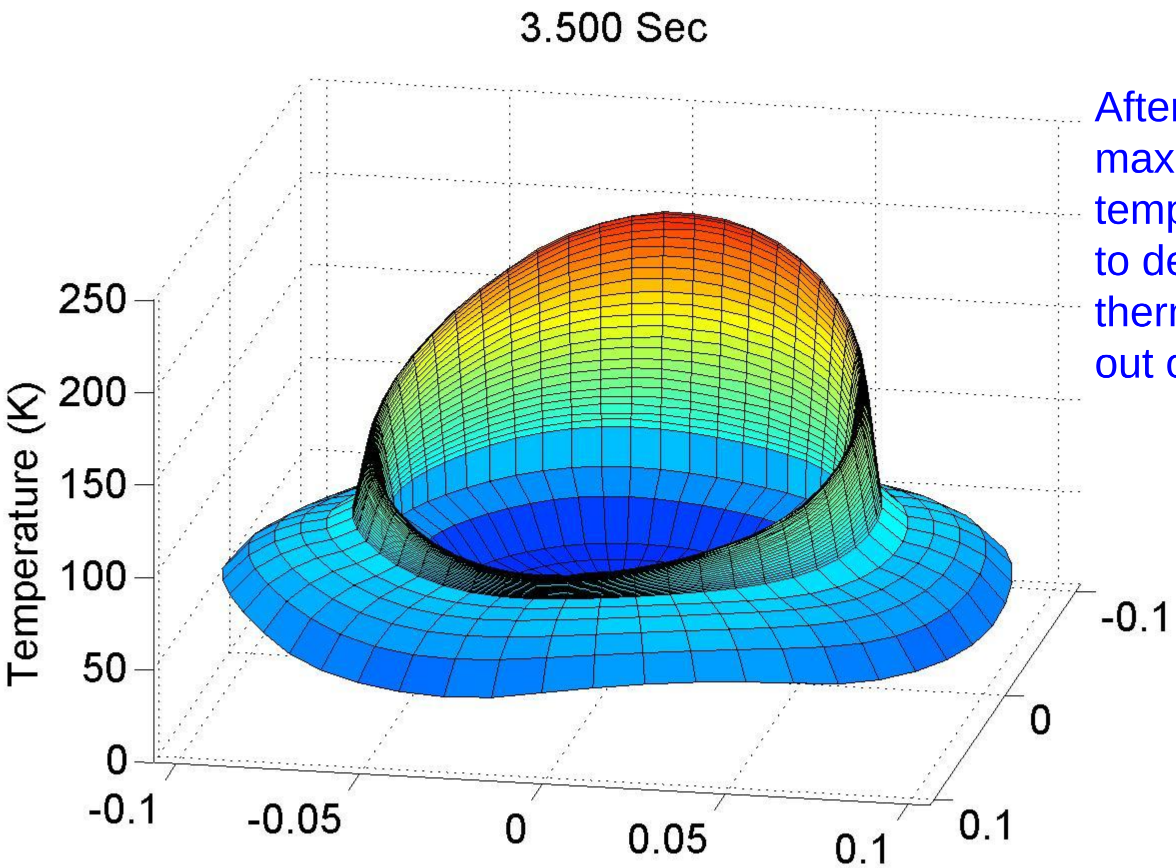
# Temperature of Quench Initiation Disk



# Temperature of Quench Initiation Disk

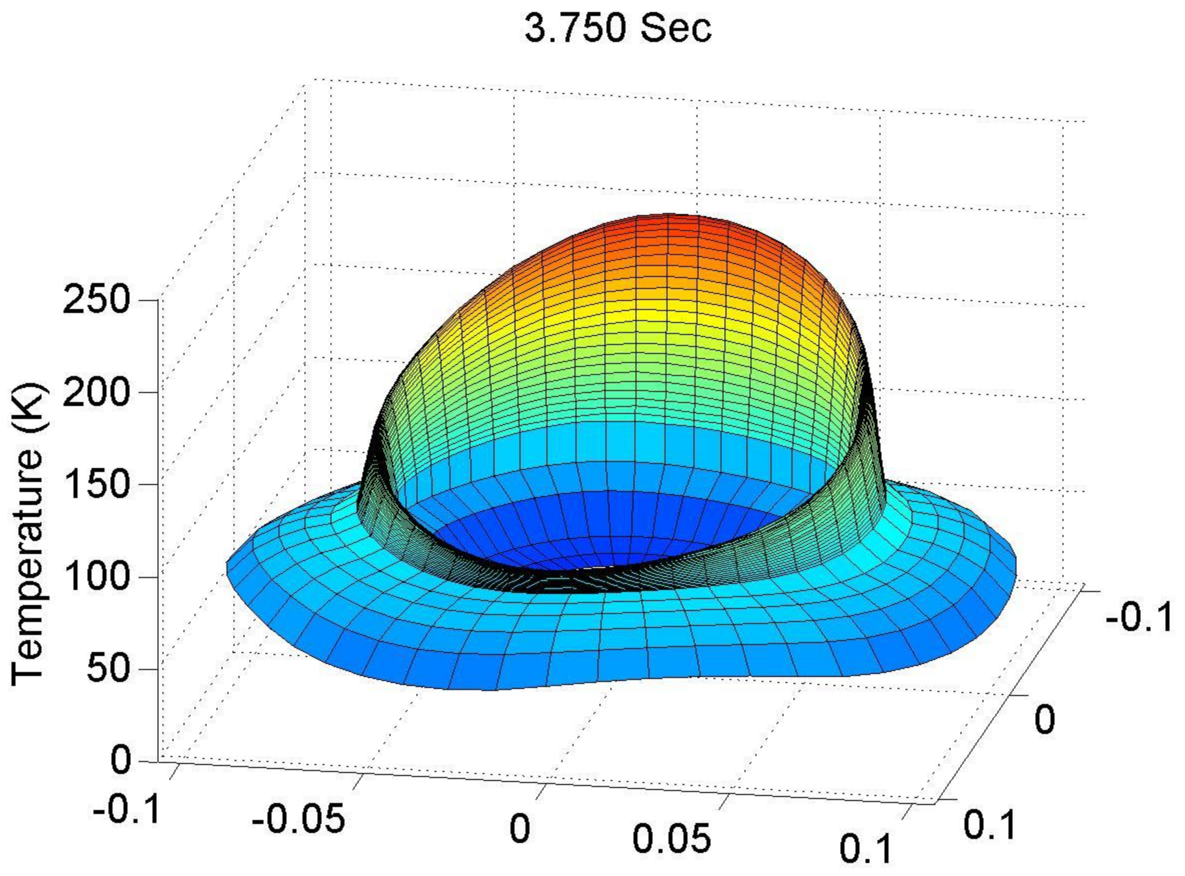


# Temperature of Quench Initiation Disk

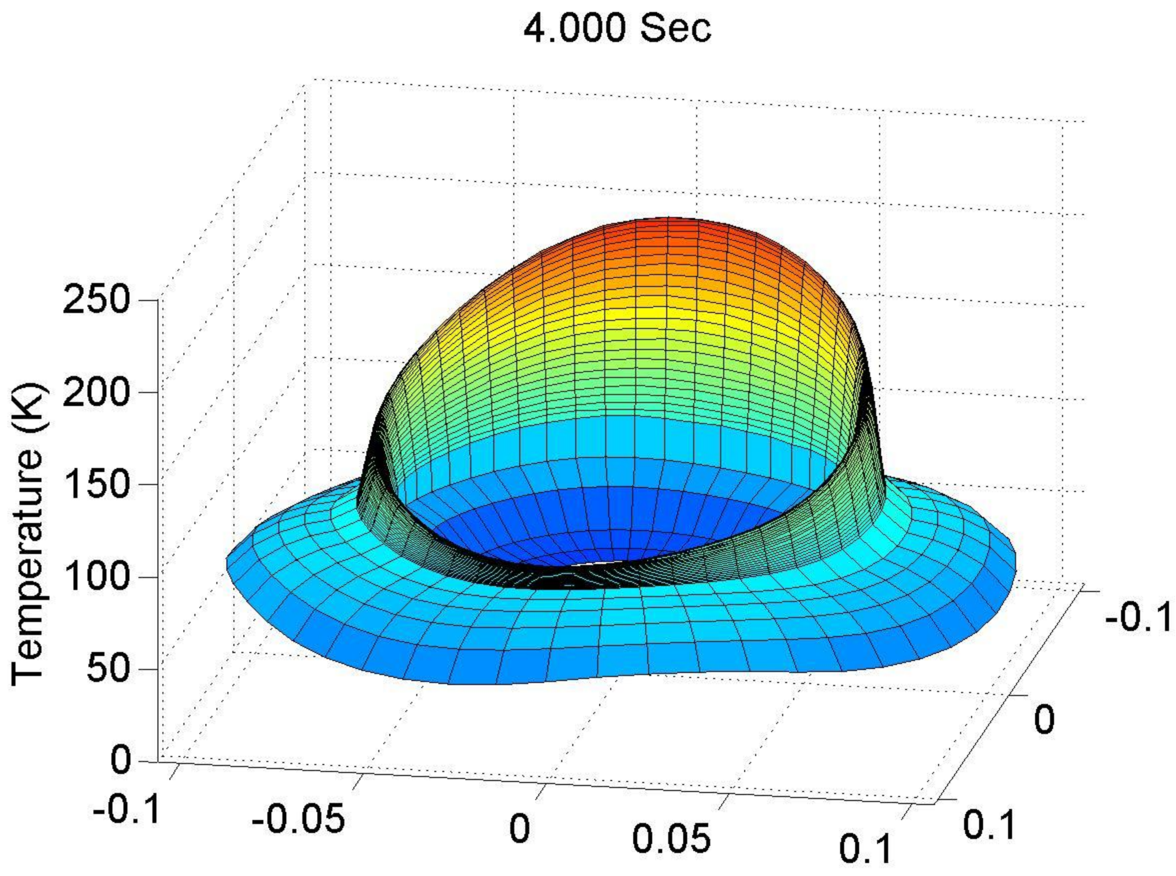



After this time, the maximum temperature begins to decrease due to thermal conductivity out of the hotspot.

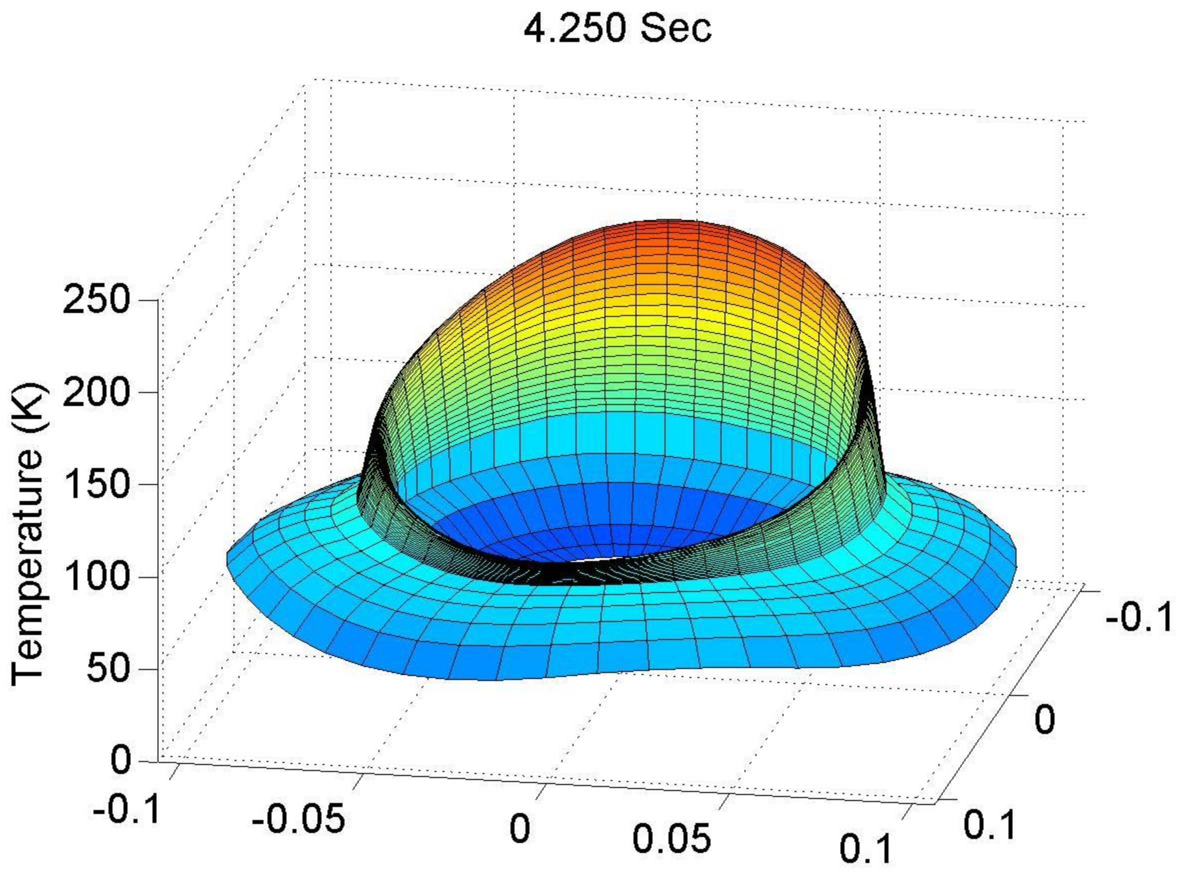
# Temperature of Quench Initiation Disk



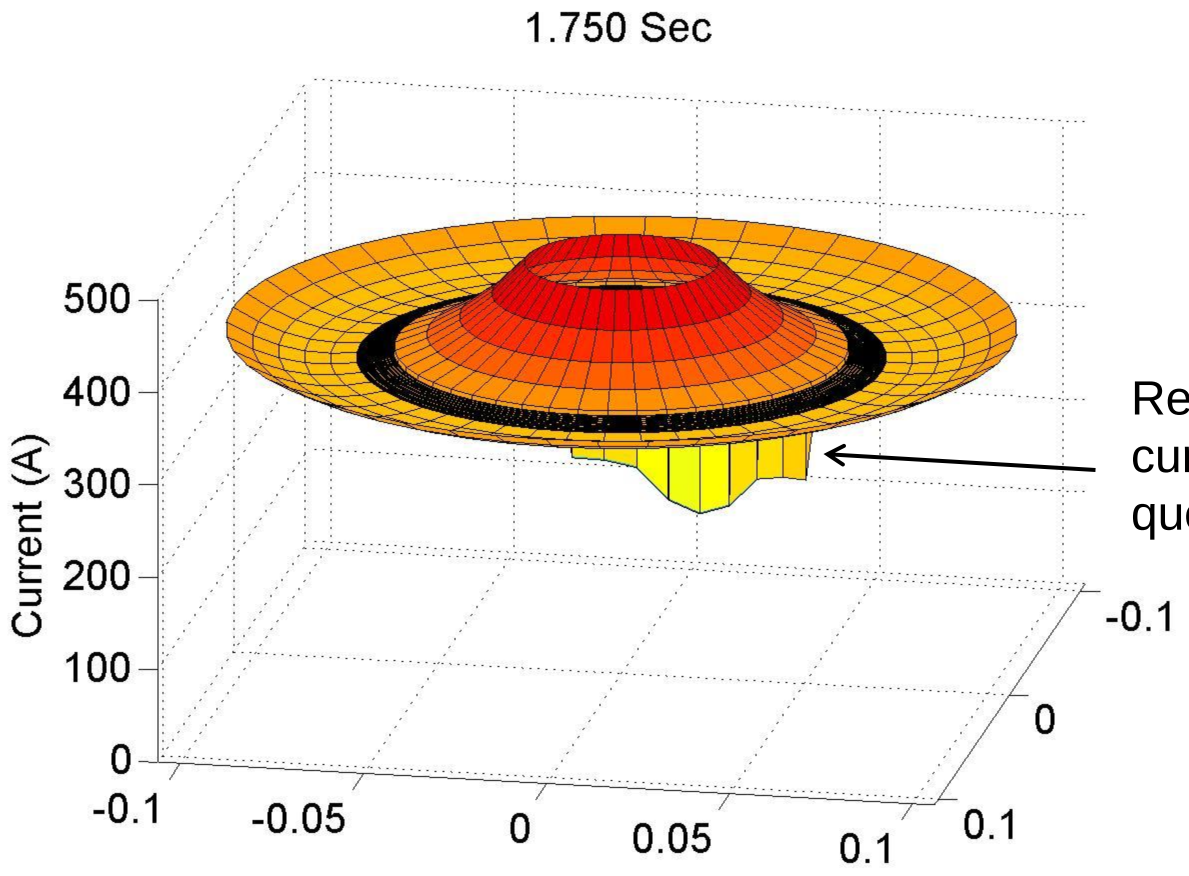
# Temperature of Quench Initiation Disk



# Temperature of Quench Initiation Disk

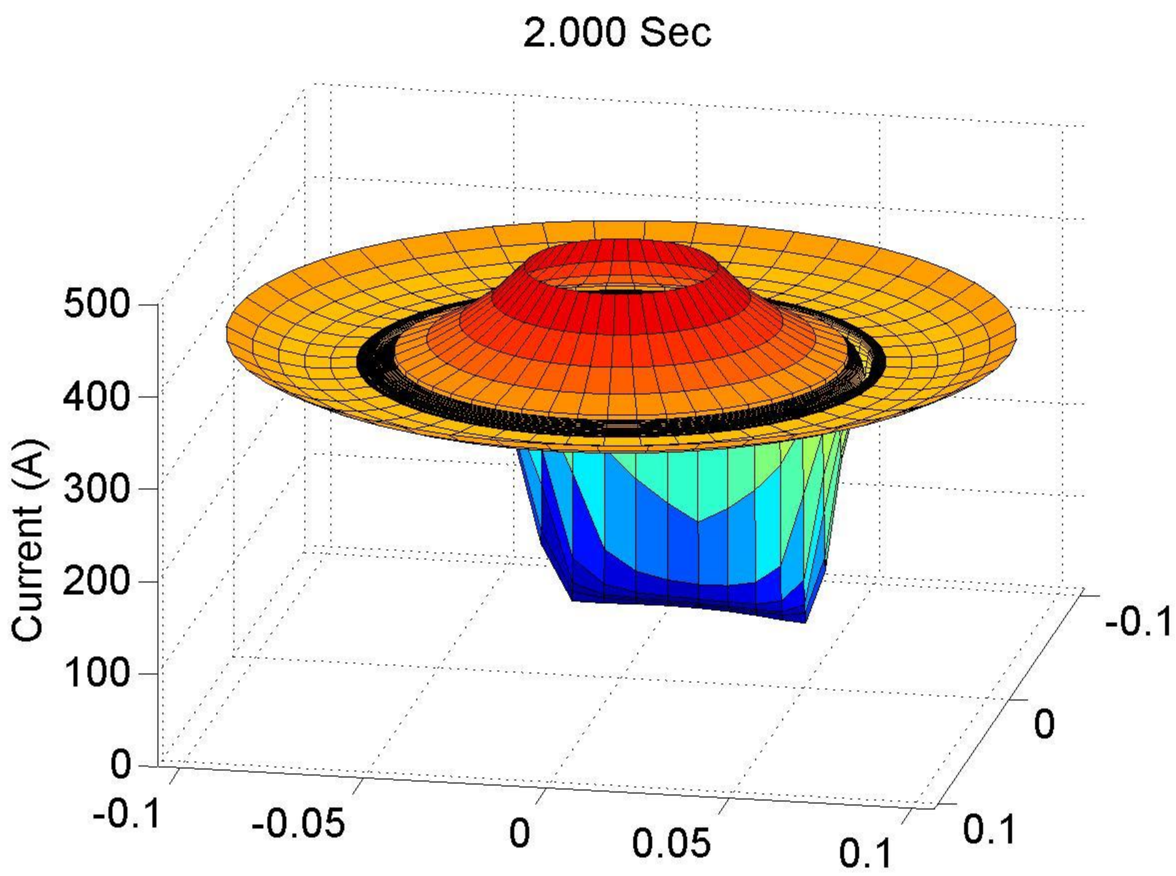


# Critical Current of Quench Initiation Disk

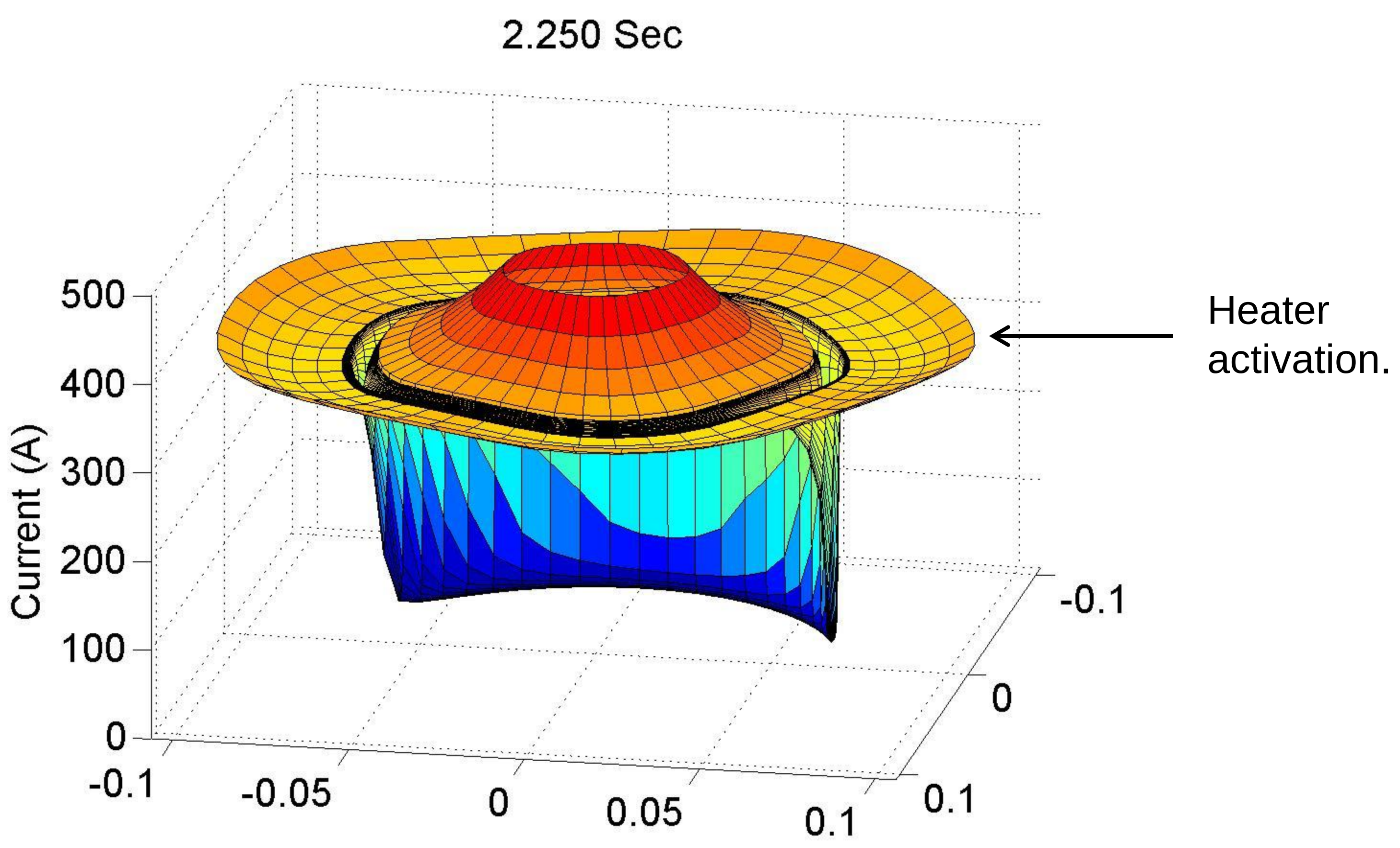



Reduced critical current initiates quench.

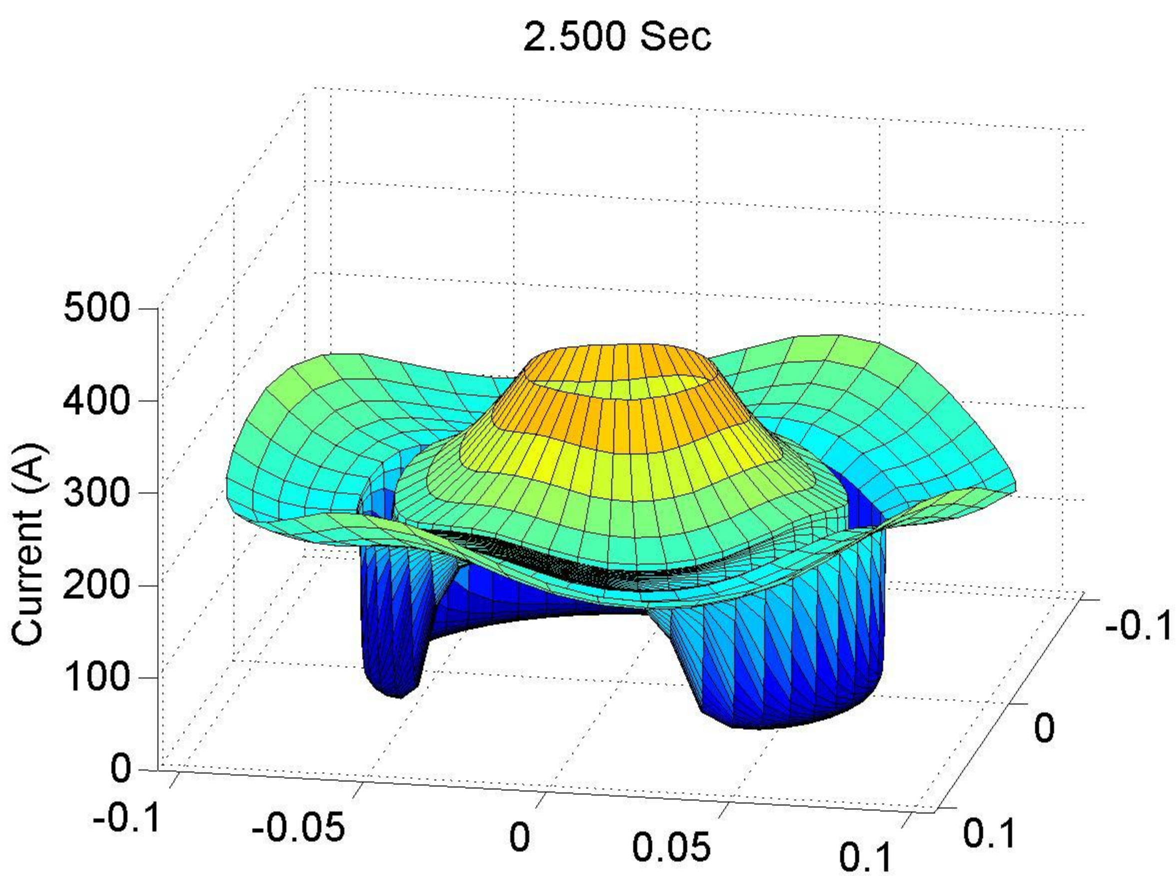
# Critical Current of Quench Initiation Disk



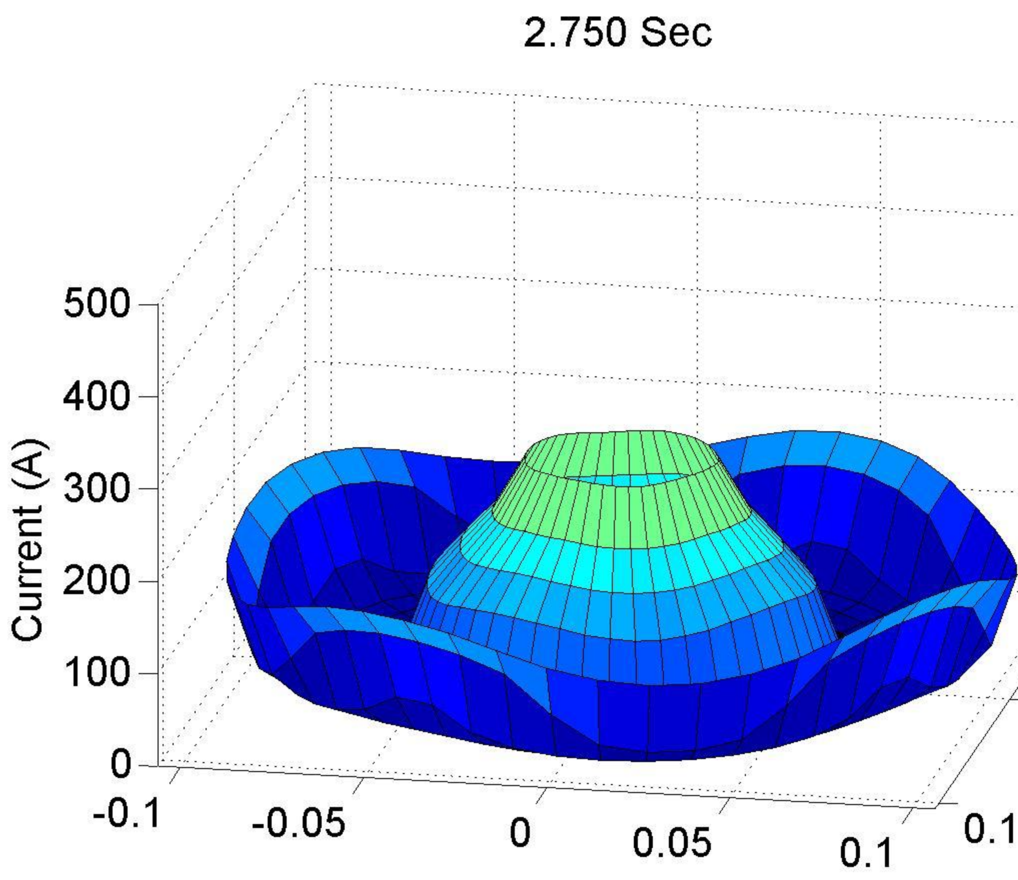
# Critical Current of Quench Initiation Disk



# Critical Current of Quench Initiation Disk



# Critical Current of Quench Initiation Disk



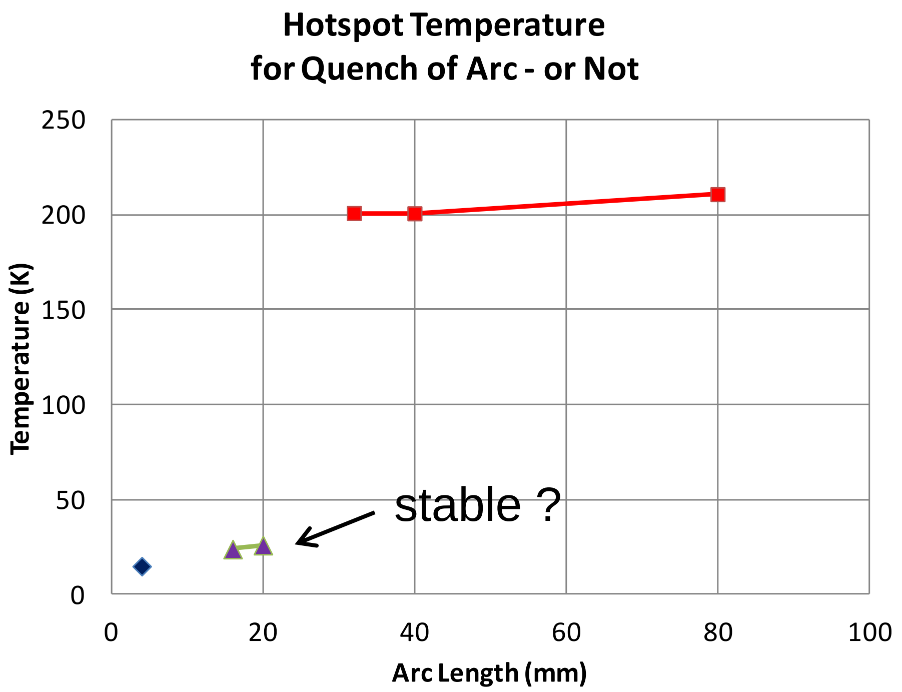

Collapse of critical current as a result of heating.

# Protection of Short Arc Quench

Analysis of short arc quench gives uniform hotspot temperature with decreasing length, down to 32 mm.

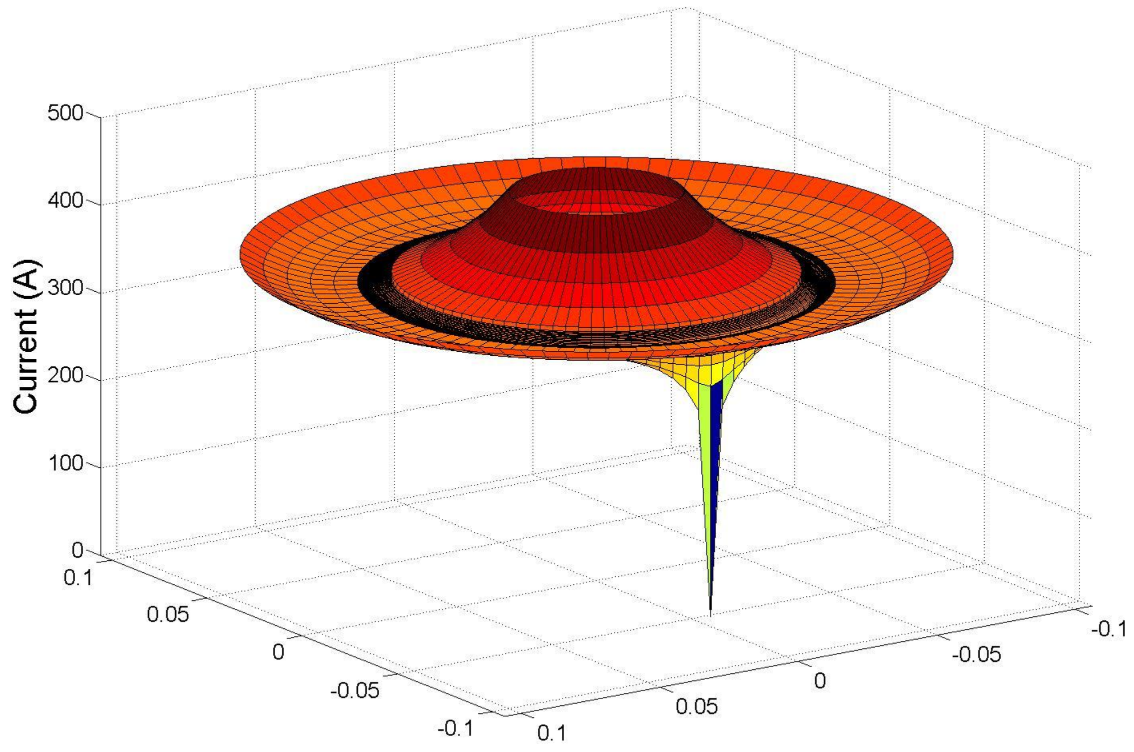
Arc of 4 mm length found to be fully stable independent of critical current.

Stability of intermediate lengths uncertain.



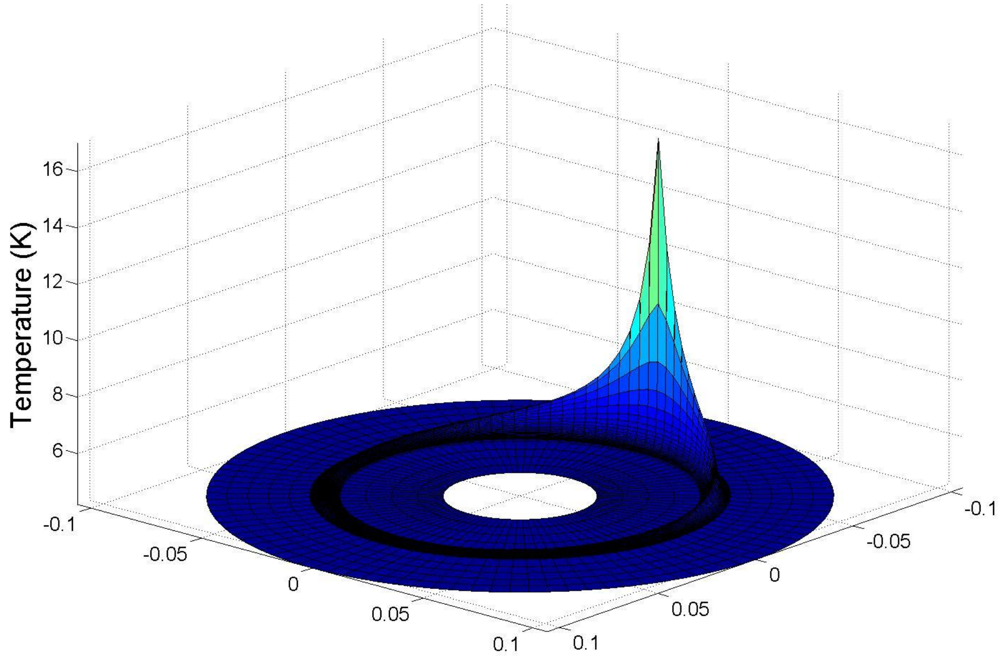

Can a short length of conductor go normal, fail to be detected and result in a high hotspot temperature? Apparently not. In fact, very short lengths may be fully stable.

# Protection of Short Arc Quench



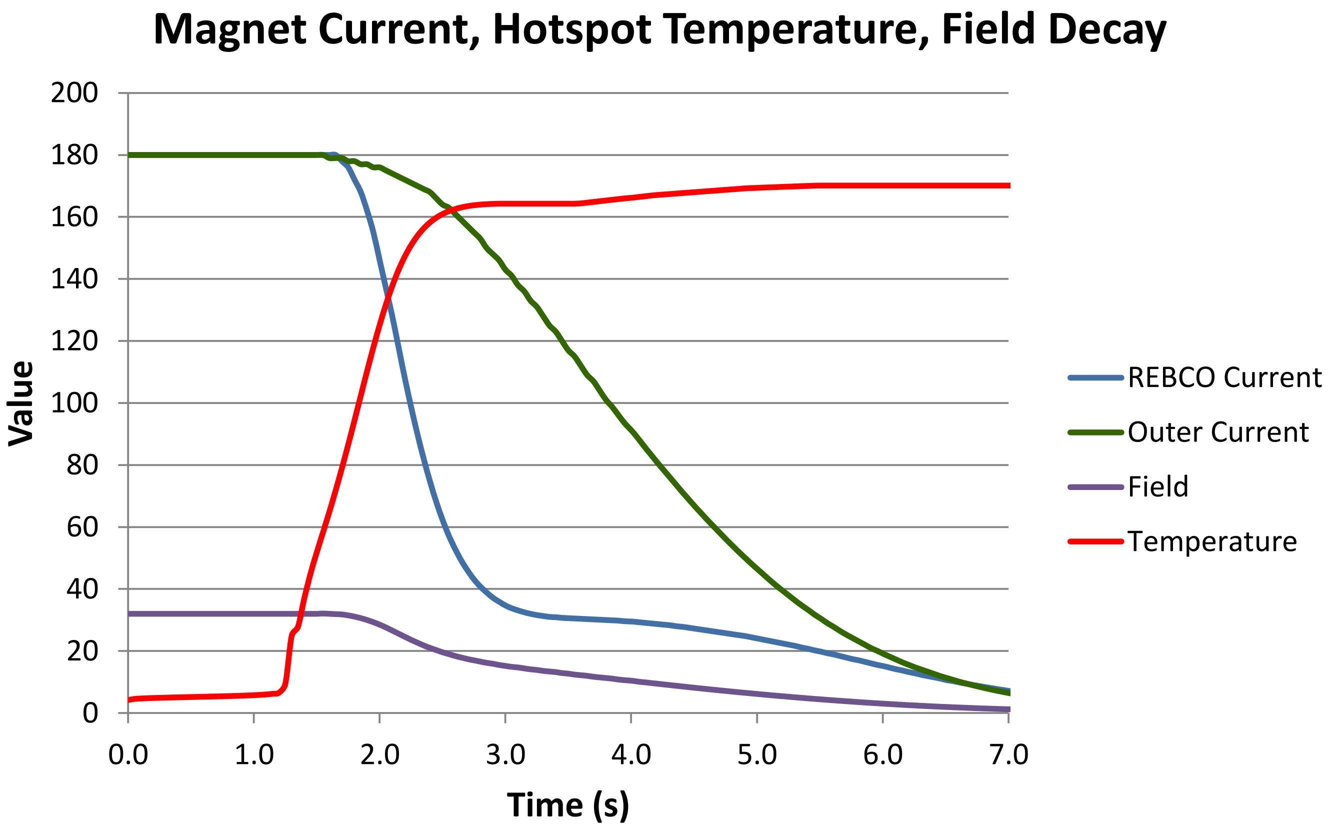

Stable critical current distribution of normal 4 mm arc.

# Protection of Short Arc Quench




Stable temperature distribution of normal 4 mm arc.

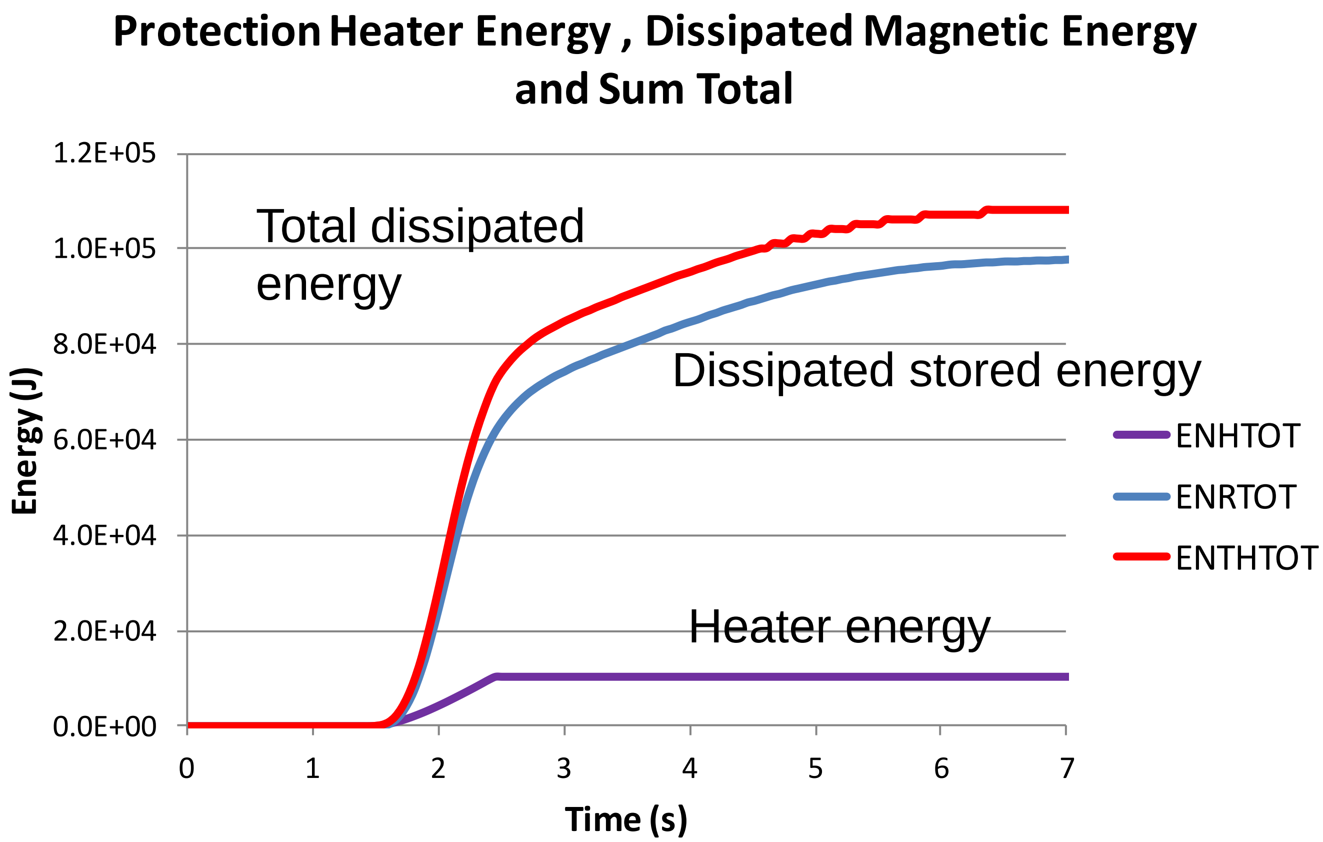
# Quench Evolution




Characteristicly,

the current decay of the REBCO coil is rapid with distributed heater protection.

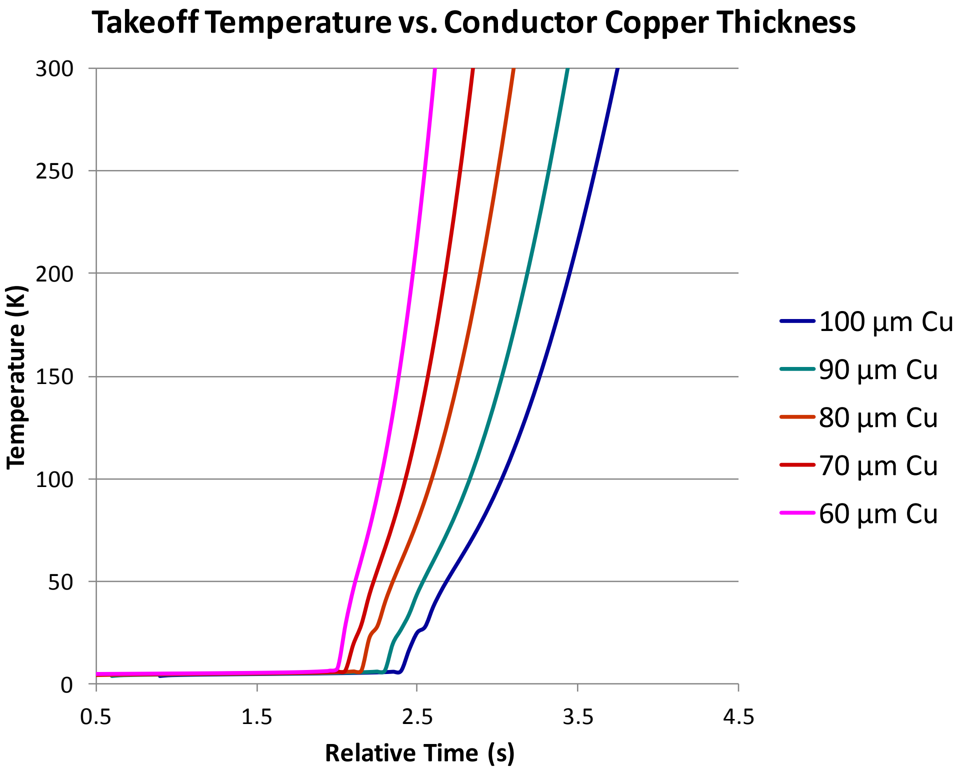
# Quench Evolution




Heater power requirement for this example is 10 kW for 1 sec.

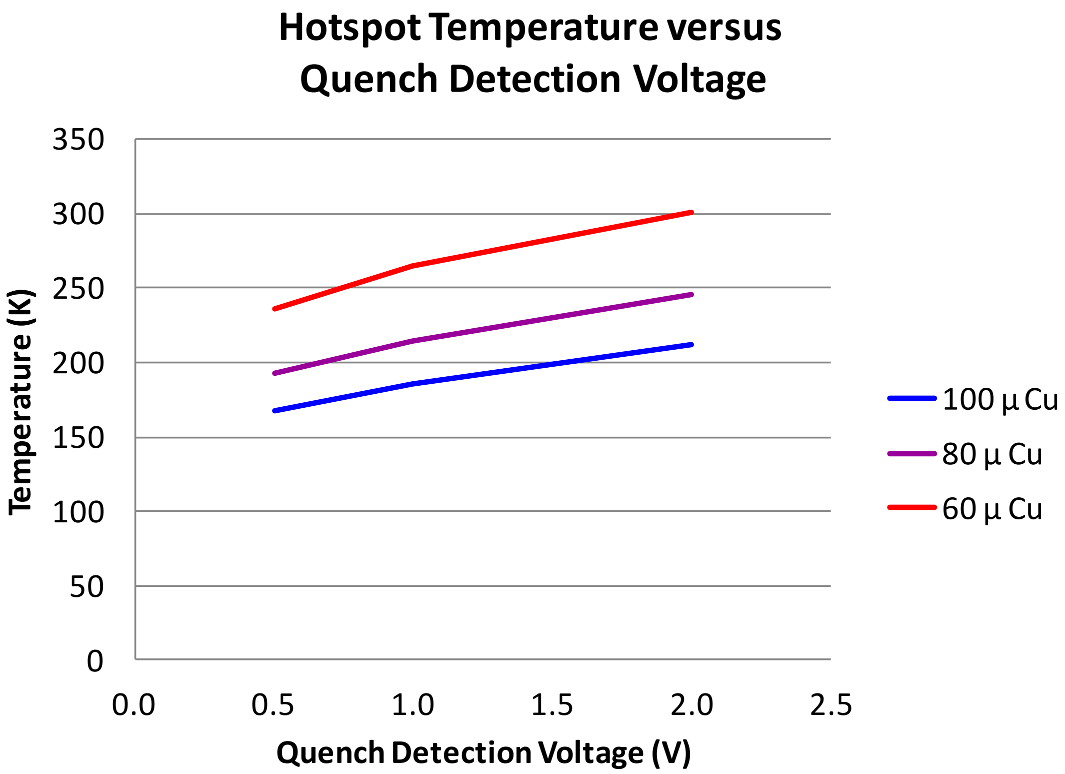
The heater energy dissipated in the coil is a small fraction of the dissipated stored energy.

# Decreasing Copper Thickness




Decreased conductor copper thickness results in faster temperature rise and reduced time for quench protection, as seen here for the initial temperature rise at constant operating current.

The hotspot temperature of the example QPC is recalculated for various copper thicknesses. As the quench detection sensitivity increases, the hotspot temperature is reduced.




| | | | |
|---|---|---|---|
| Copper thickness (µm) | 100 | 80 | 60 |
| Copper current density (A/mm2) | 440 | 549 | 732 |

# Discussion and Summary

- Quench in REBCO high field coil examined for case of locally reduced critical current.
  - Quench current depends on size and location of reduced critical current region.
    - Rate of temperature increase after thermal runaway depends on the copper content of the conductor, independent of the initial conditions of quench.
- Significant quench velocity along conductor is observed after thermal runaway.
  - Protection heater effectiveness depends on local critical current.
    - Copper current density of 400 – 500 A/mm$^2$ appears feasible with heater protection.

[Annotations added after the presentation was delivered are in (small) blue font.]