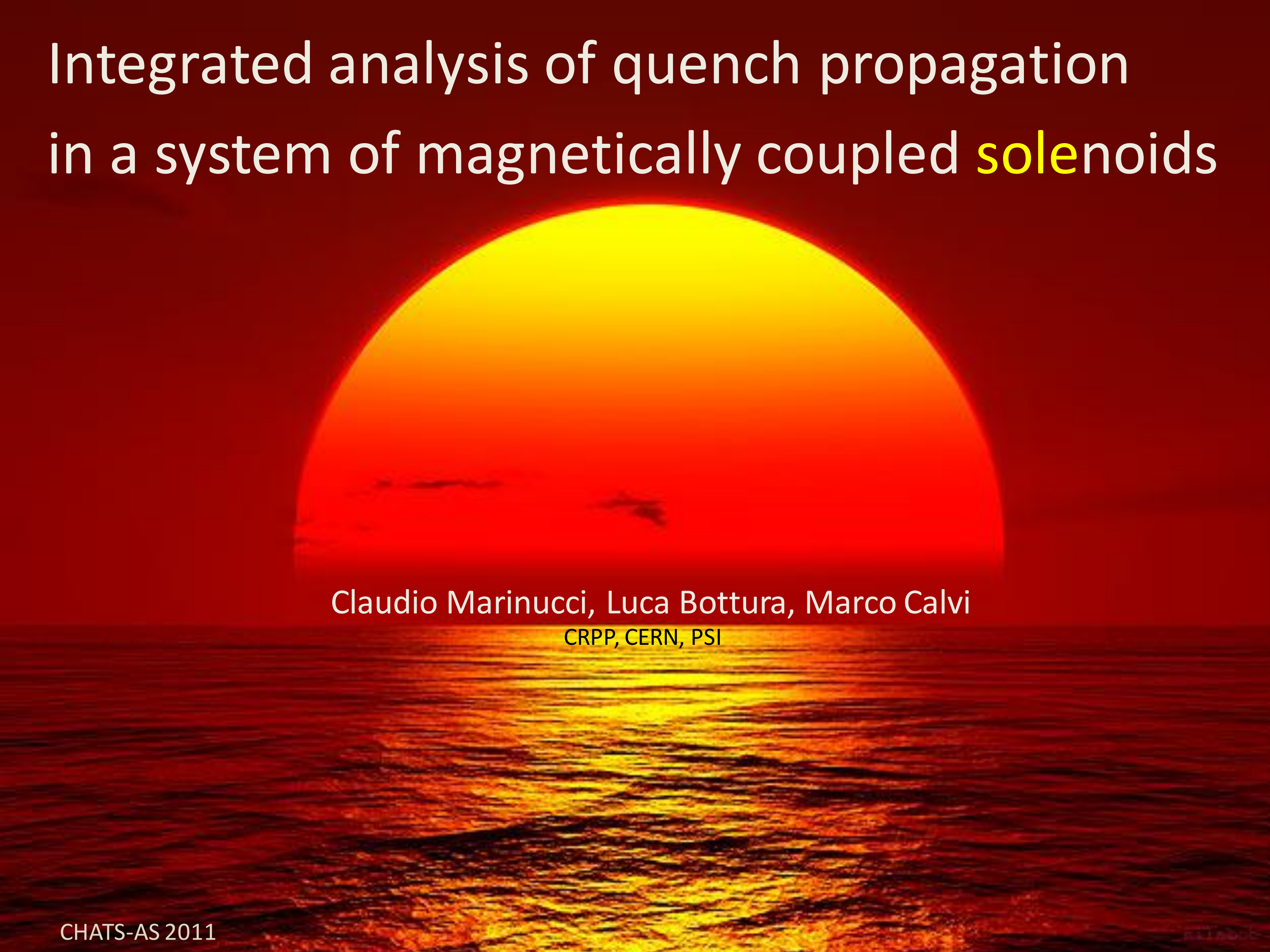
Integrated analysis of quench propagation in a system of magnetically coupled solenoids



Claudio Marinucci, Luca Bottura, Marco Calvi

CRPP, CERN, PSI

CHATS-AS 2011

Outline

Introduction

Model

- From 1D to 3D (THEA)
- POWER, SUPERMAGNET

Results

- Reference case
- Parametric studies

Summary

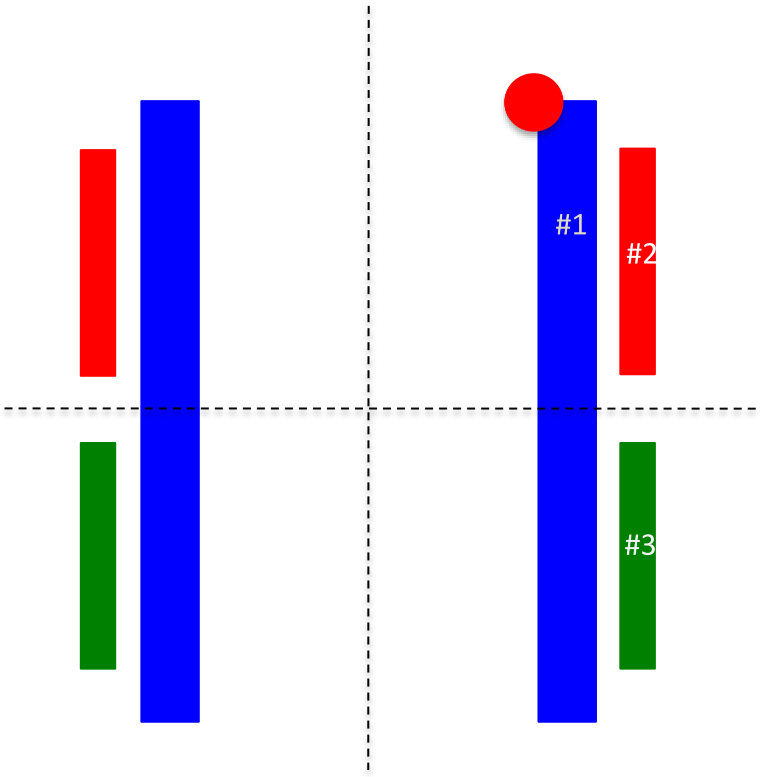
Problem

Quench in coupled solenoids

Given a system of magnetically coupled SC solenoids protected without external dump resistor, i.e. stored energy dumped in He

Further to heat perturbation and quench in one coil

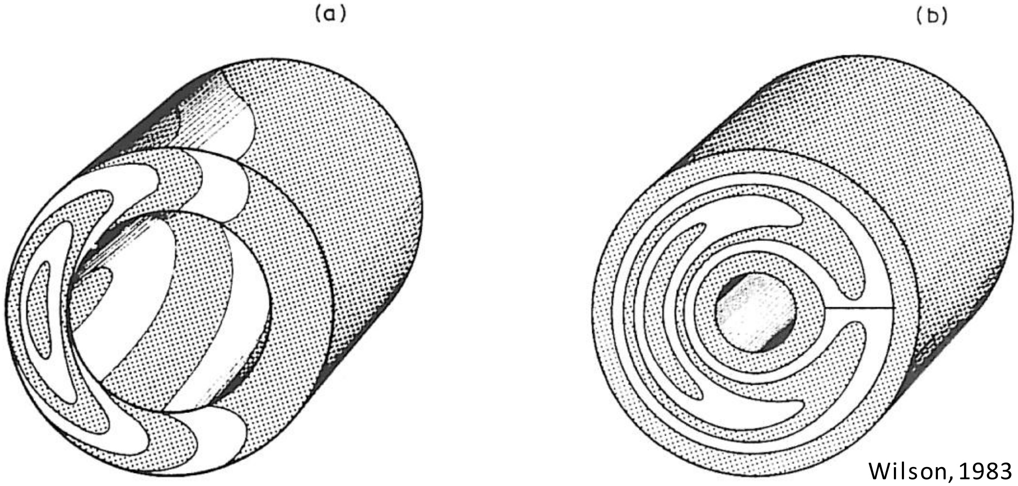
Compute the evolution of currents, voltages and temperatures in all coils taking into account **turn-to-turn and layer-to-layer thermal contacts**



Normal zone propagation in solenoids

Longitudinal and transversal propagation
Growth of normal zone bounded 1D, 2D and 3D
Thin vs. thick solenoid
Analytical solutions

Propagation speed ?
Large energy stored ?
Coupled systems ?



Wilson, 1983

Fig. 9.6.(a) Growth of normal zone in thin solenoid: after a certain time, the zone hits inner and outer boundaries; (b) growth of normal zone in a thick solenoid: the zone meets itself at the right-hand side before it hits any boundary.

GPS

Goal

To demonstrate the capability of the model and test its potential to extrapolation to configuration “other” than CICC’s

Procedure

Longitudinal and **transversal** quench propagation

Thermal and electrical analysis in parallel

Solution

CryoSoft™ codes

- THEA
- POWER
- SUPERMAGNET

Integrated analysis

Outline

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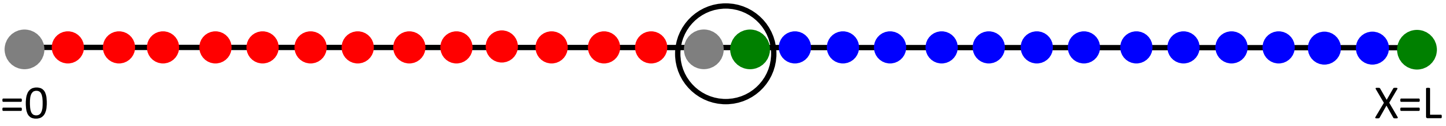
From 1-D to 3-D



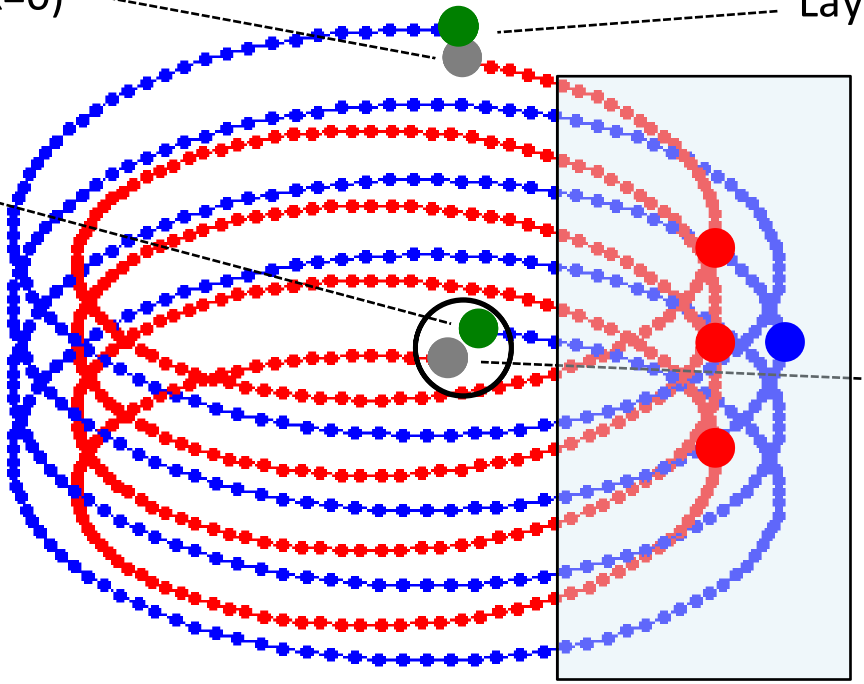
Layer 1, Turn 1-4

Layer 2, Turn 1-4

X=0

X=L

Example: 2 Layers, 4 Turns



Layer 1, Turn 1 **start** (X=0)

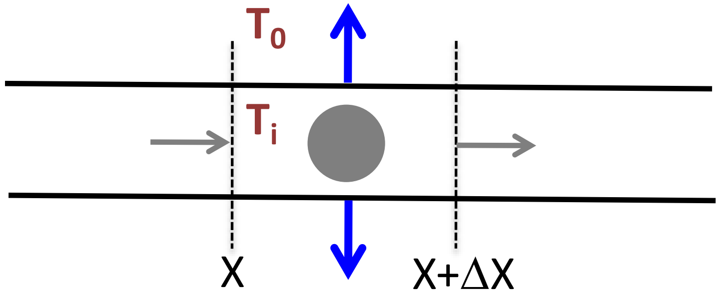
Layer 2, Turn 4 **end** (X=L)

Layer 2, Turn 1 start

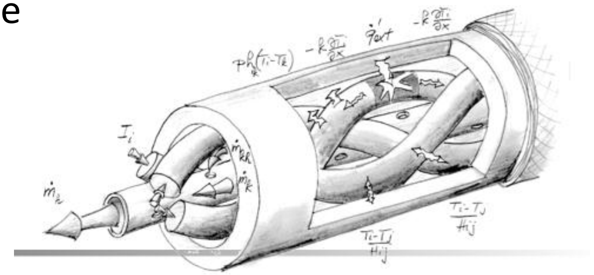
Layer 1, Turn 4 end

Thermal connections between layers and turns are required

THEA model



Finite element code for the **T**hermal, **H**ydraulic and **E**lectric **A**nalysis of superconducting cables (CICC, also but not only)



THEA is a 1-D code **with 3-D capability**

X (along conductor length)

$$AC\gamma\frac{\partial T_i}{\partial t} = A\frac{\partial}{\partial X}\left[k(T_i)\frac{\partial T_i}{\partial X}\right] + \rho(T_i)\frac{I^2}{A_{Cu}} + p_W h(T_i - T_0)$$

Diffusion

Longitudinal

Joule,

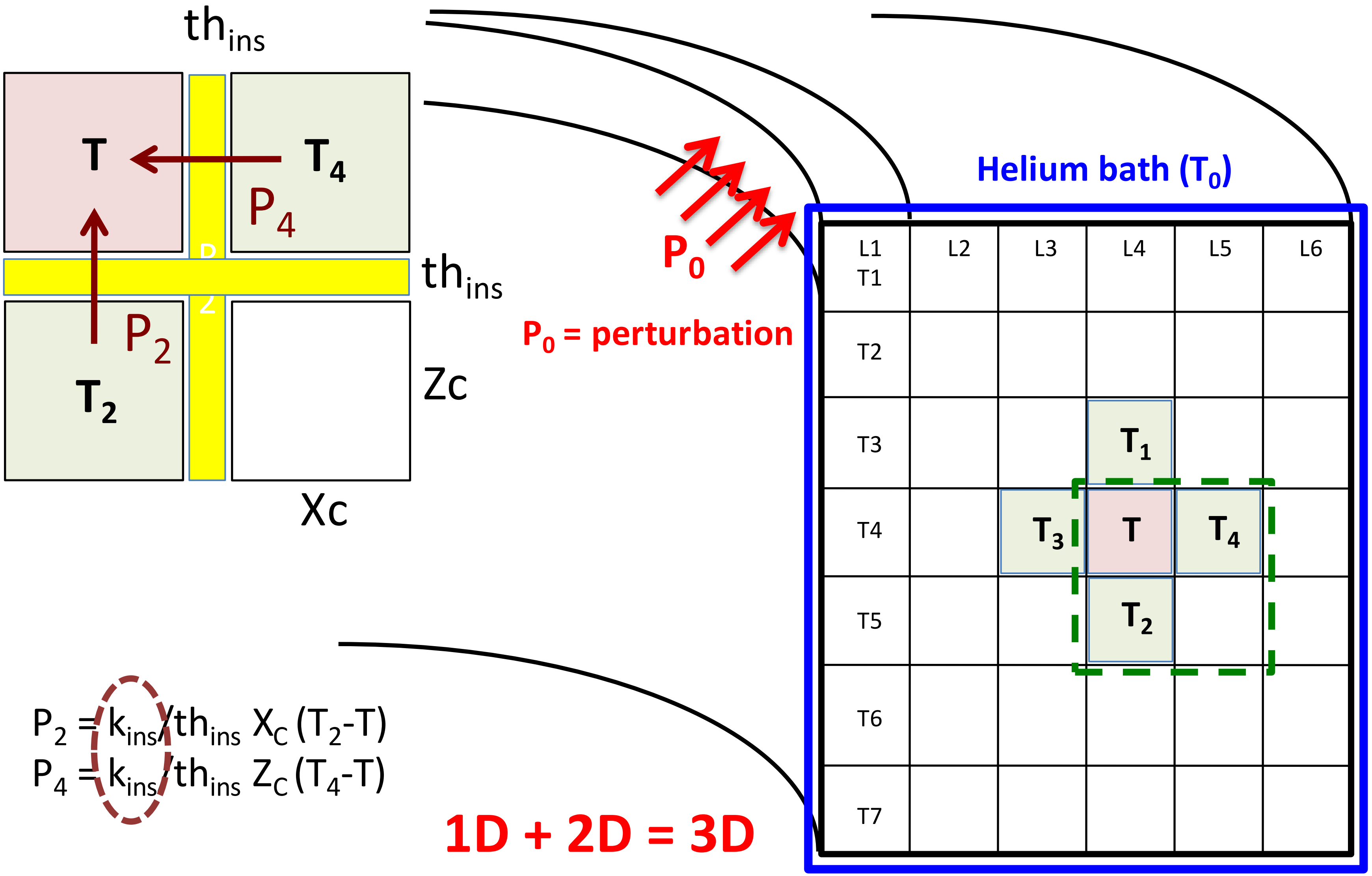
Heat exchange among solids and with coolants

Transversal

THEA transversal thermal model

User routine

Example: 7 Turns, 6 Layers



P_0 = perturbation

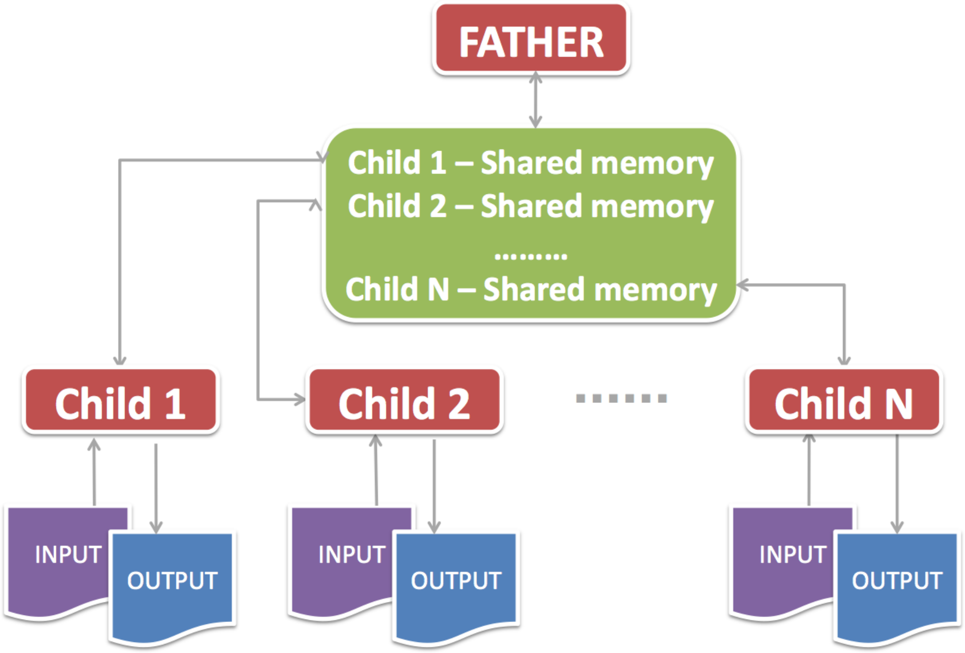
L1	L2	L3	L4	L5	L6
T1					
T2					
T3			**T_1**		
T4		**T_3**	**T**	**T_4**	
T5			**T_2**		
T6					
T7					

$P_2 = k_{ins}/th_{ins}\ X_C\ (T_2 - T)$
$P_4 = k_{ins}/th_{ins}\ Z_C\ (T_4 - T)$

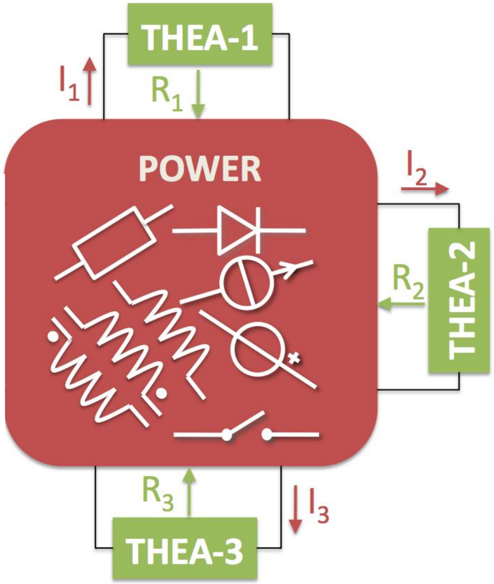
1D + 2D = 3D

SUPERMAGNET model

SUPERMAGNET joins and manages existing [and validated] tools in a customizable, flexible, and powerful environment for the analysis of superconducting magnet systems



Calvi, Bottura, Marinucci, CHATS-AS 2008 (Tsukuba)

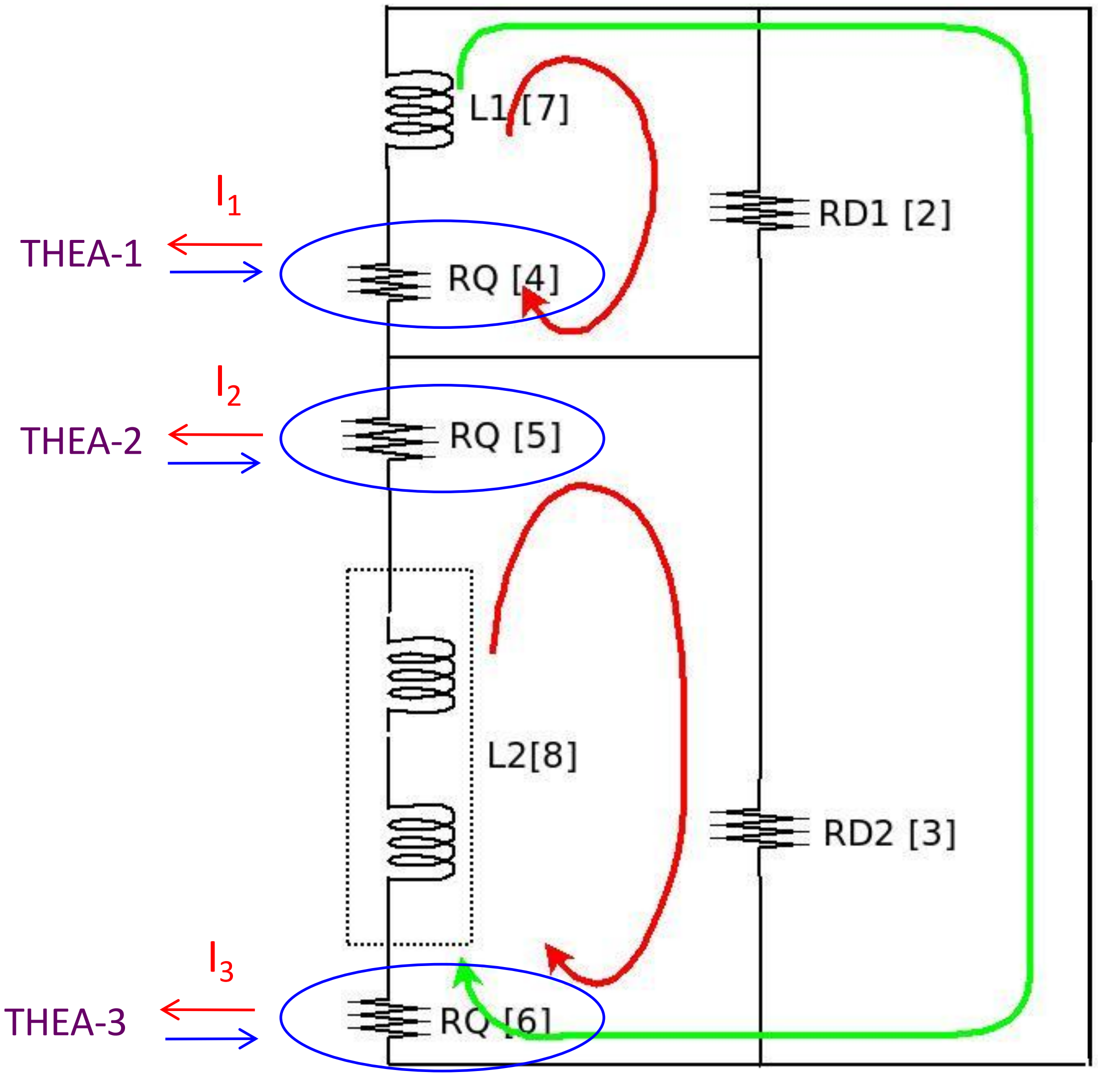


This analysis:
3x THEA (1 per coil)
POWER
SUPERMAGNET

POWER model

POWER is a program for the simulation of **electric networks** (resistances, inductances, current and voltage sources)

Protective resistors RD1 & RD2 to limit voltages in system



Outline

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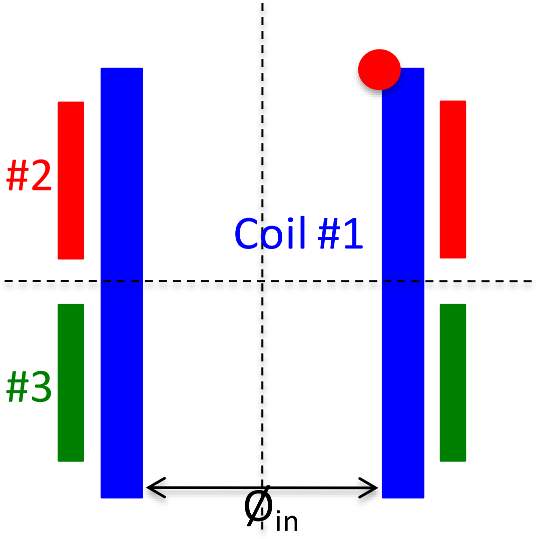
Reference case

Simple model magnet



		Coil #1	Coil #2,#3
A_{cu}	mm^2	0.329	0.164
A_{NbTi}	mm^2	0.239	0.119
X_c,Z_c	mm	0.70	0.53
RRR	-	100	100
N_{layer}	-	18	18
N_{turn}	-	255	135
$Ø_{in}$	mm	80	120
L	m	1183	910
$Z_{Winding}$	mm	230	86
$X_{Winding}$	mm	14.1	10.1

Squared conductor (all coils)

Magnetic field: B = 7 T, constant in time and space (all coils)

Inductances:

L1 = 0.61 H, L2 = 1.47 H, M12 = 0.69 H (I_0 = 147 A, E = 37 kJ)

Protective resistors: RD1 = 0.5 Ohm, RD2 = 1 Ohm

Insulation: th_{INS} = 50 μm, k_{INS} = 0.100 W/mK (th. conductivity of glass-epoxy @20K)

Helium bath: T_0 = 4.2K, h = 100 W/m^2K

Perturbation: P_0 = 10 W/m in Coil #1 along 1 m (4 turns) for 10 ms

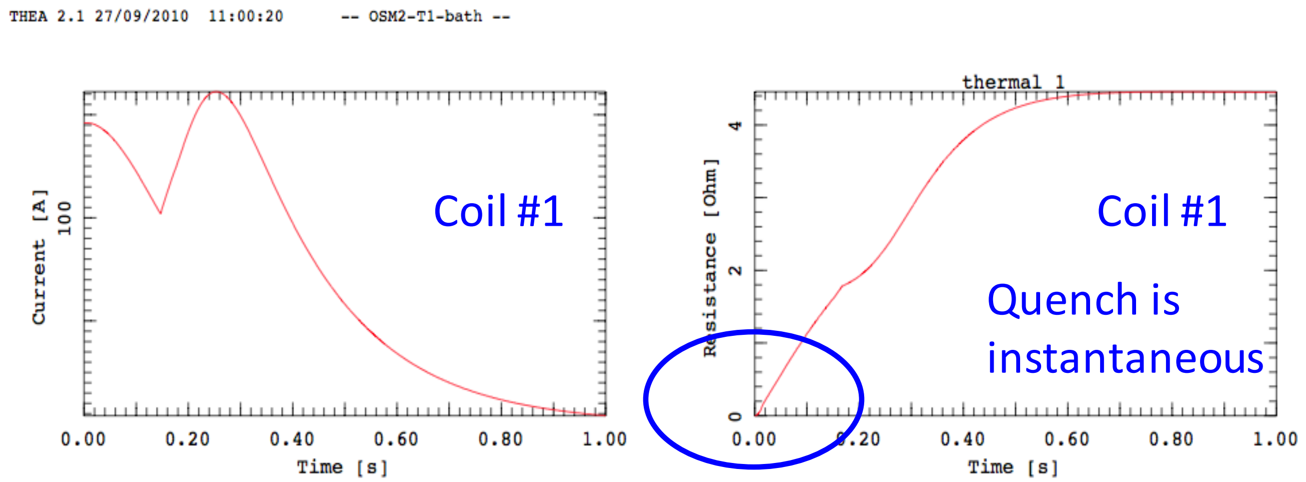
FEM: 5000/4000 elements (Coil #1/Coil #2,#3)

Parametric studies

Results of reference case

Current and resistance

Quench in Coil #1 generated by 10 W heat input

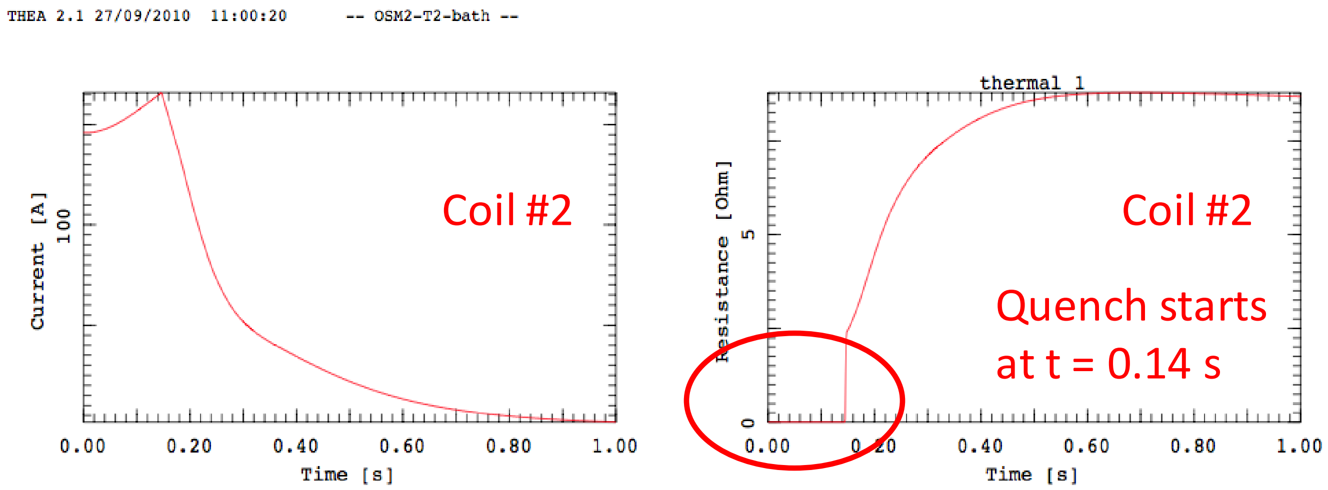


Coil #1

Coil #1

Quench is instantaneous

Quench in Coil #2 induced by current overloading ($I>I_c$)



Coil #2

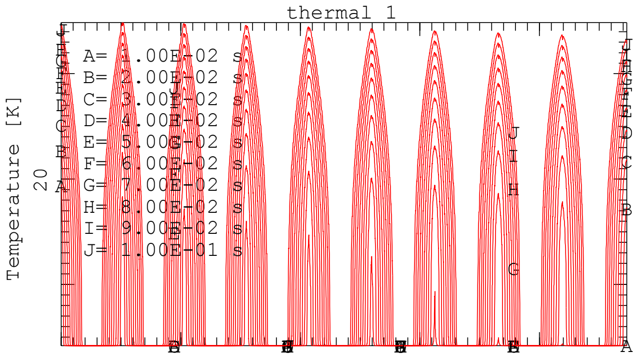
Coil #2

Quench starts at t = 0.14 s

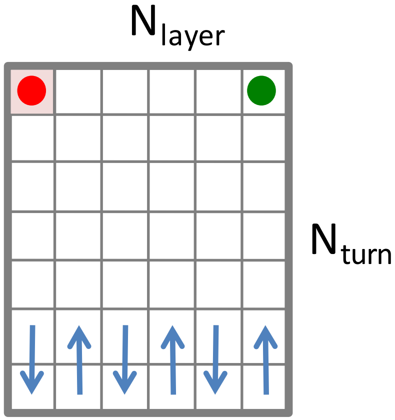
Results of reference case

Temperature distribution in X @ **0.01s < t < 5s** (Coil #1)

Local normal zones
in first 100 ms in all layers

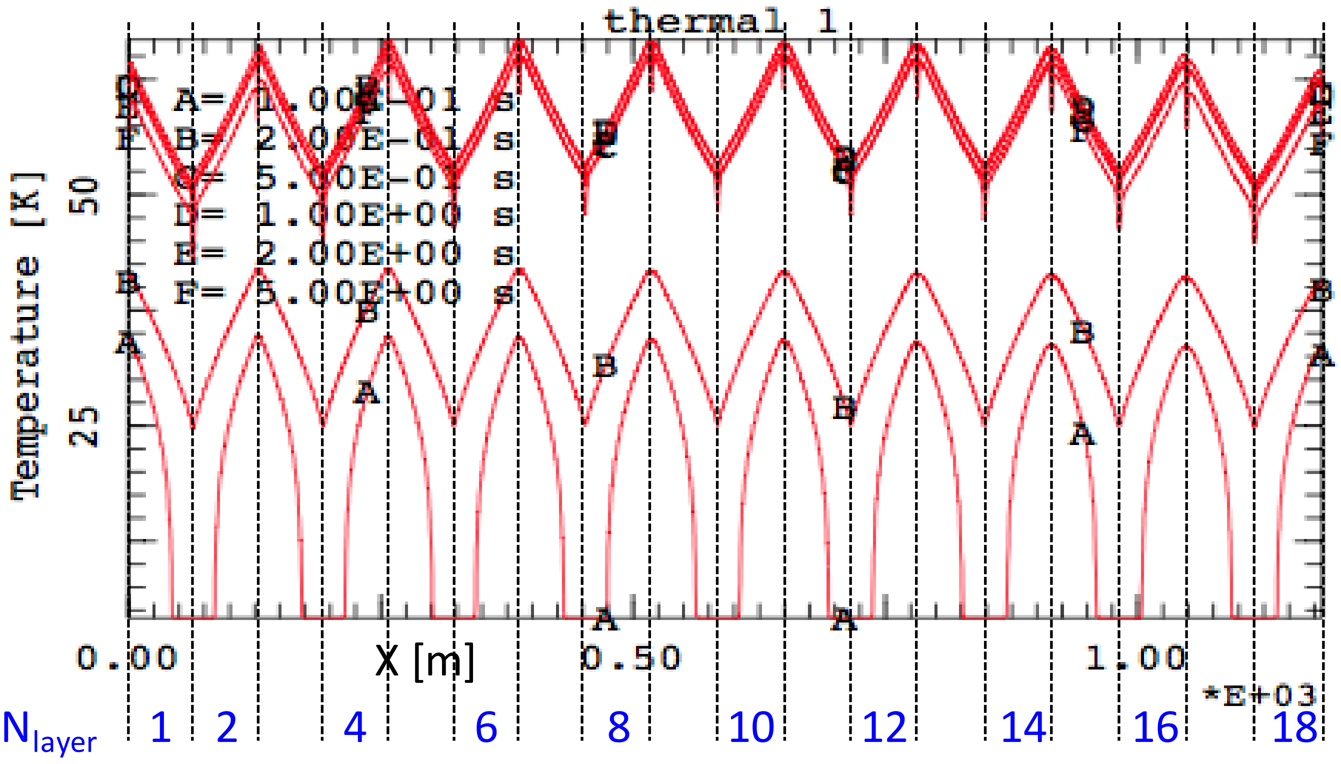


Coil #1



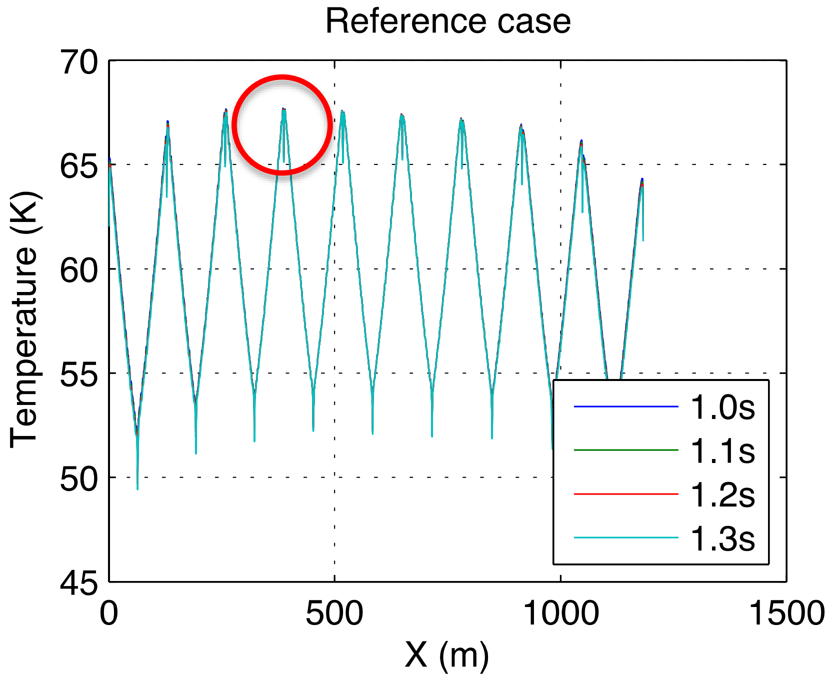
1 layer = 255 turns (278 elements)

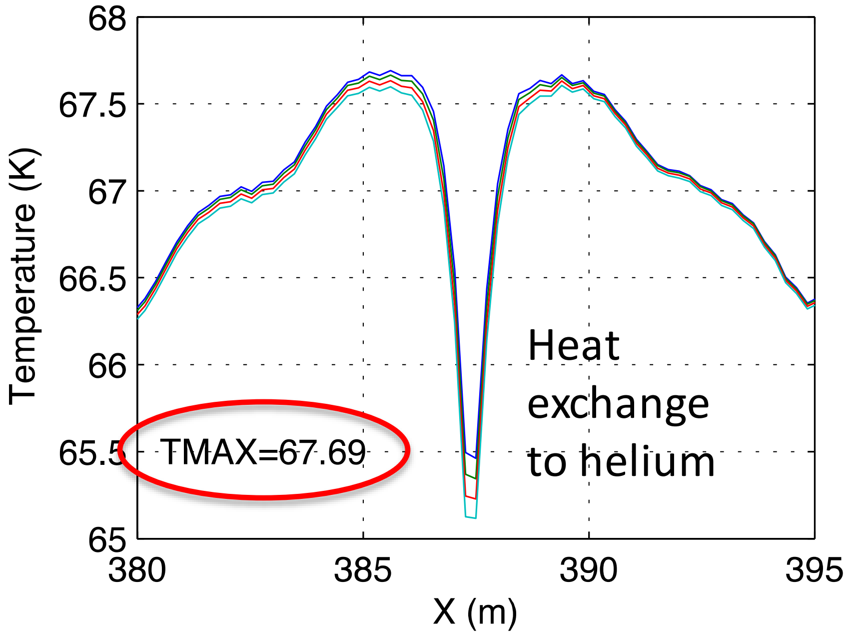
Full normal length
after 200 ms



Results of reference case

Temperature in Coil #1

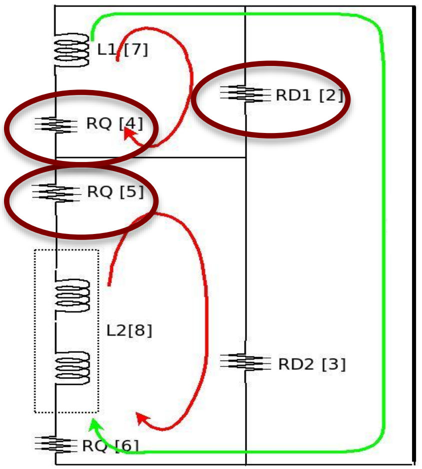

Reference case

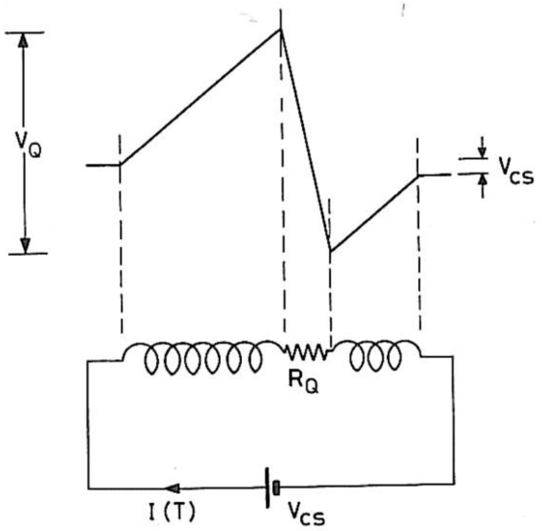

TMAX=67.69

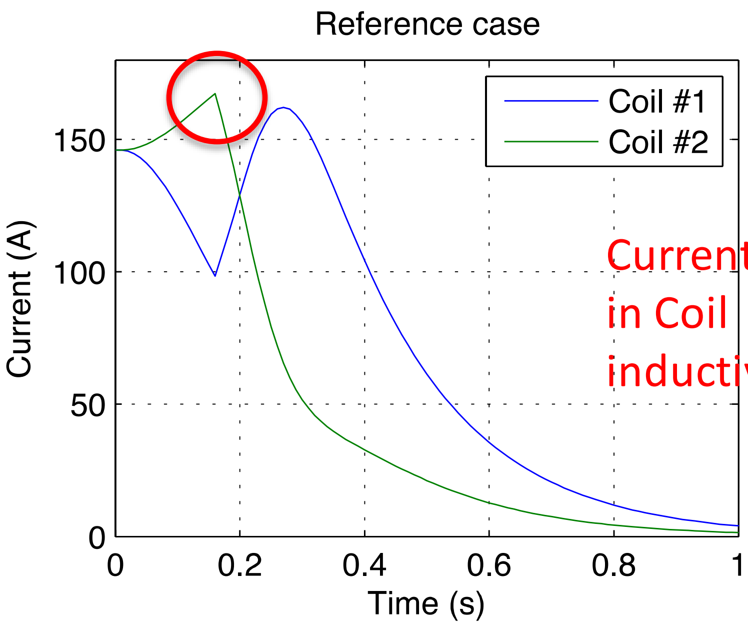
Heat exchange to helium

Results of reference case

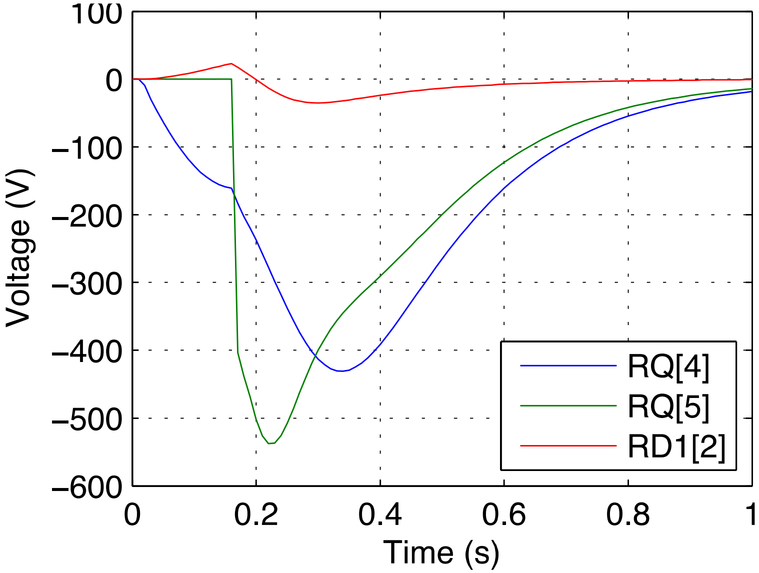
Current and voltage





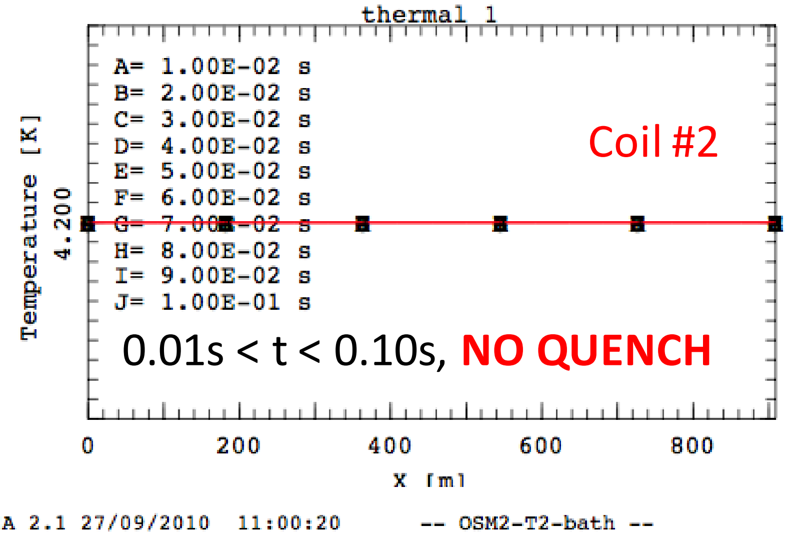


Current overload in Coil #2 due to inductive coupling



Results of reference case

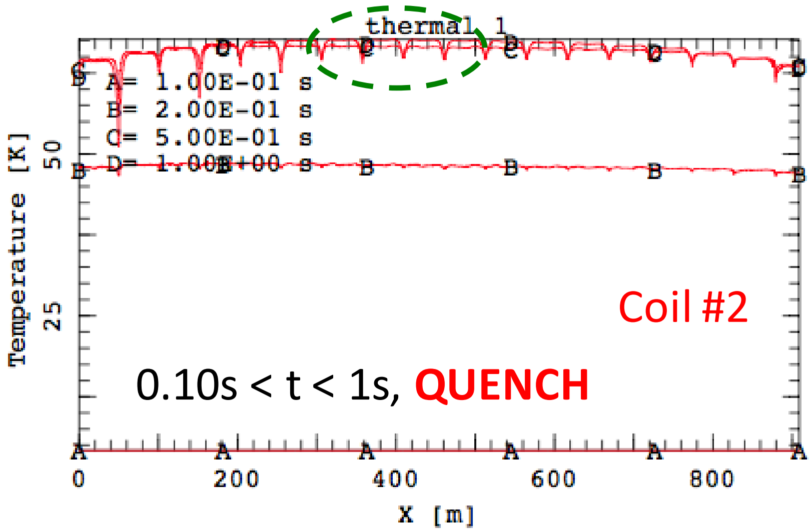
Quench induced in Coil #2



Coil #2

0.01s < t < 0.10s, **NO QUENCH**

Quench in Coil #2 is current driven -> full length is normal from start of quench



Coil #2

0.10s < t < 1s, **QUENCH**

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Parametric studies

1. Thermal conductivity of insulation

k_{INS} = 0.0 – 0.200 W/mK

reference case: 0.100 W/mK, glass epoxy at 20K

2. Heat transfer coefficient to He bath

h = 0 – 500 W/m^2K

reference case: 100 W/m^2K

3. Protective resistor RD1 and RD2

multiplying factor = 1 – 5

reference case: 1 (RD1 = 0.5 Ohm, RD2 = 1.0 Ohm)

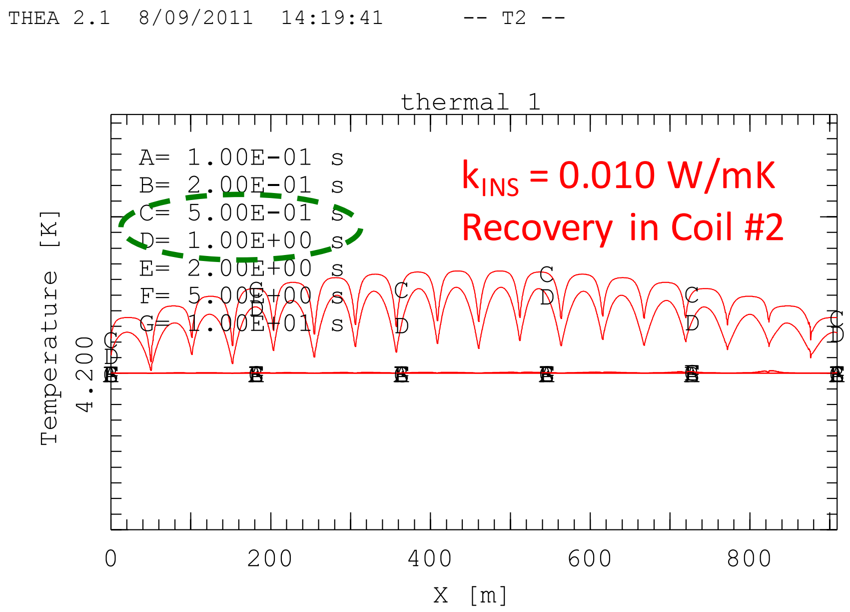
Parametric study #1

Current vs. Time

For lower k_{INS}
(worse thermal coupling between layers and turns)

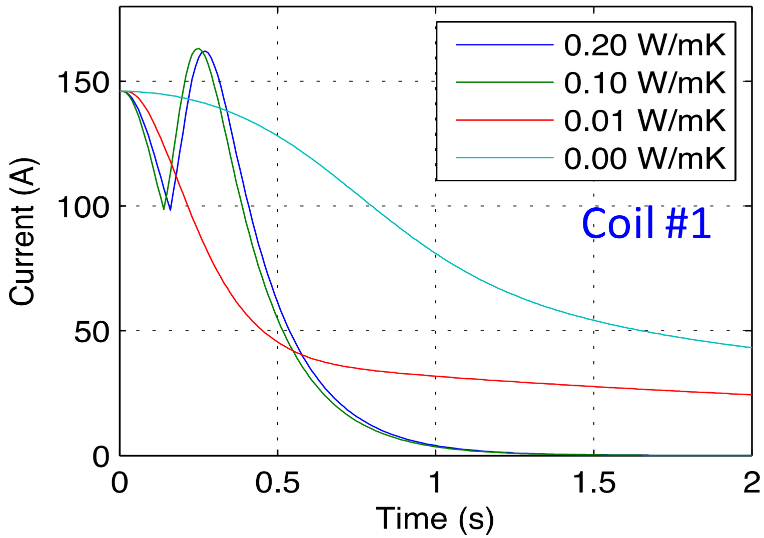
* Longer current decay time constant

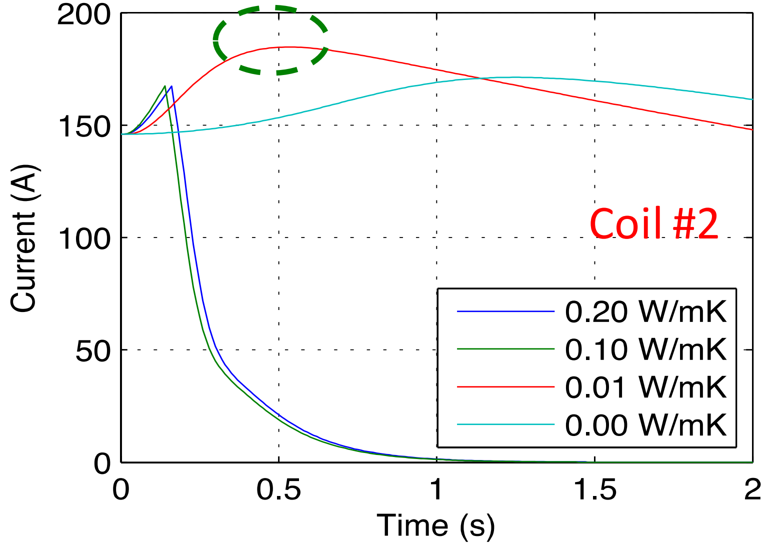
* Quench in Coil #2 starts at a later time
(no quench for $k_{INS} = 0.010$ and 0.0 W/mK)



$k_{INS} = 0.010$ W/mK
Recovery in Coil #2

Thermal conductivity of insulation (Coil #1)

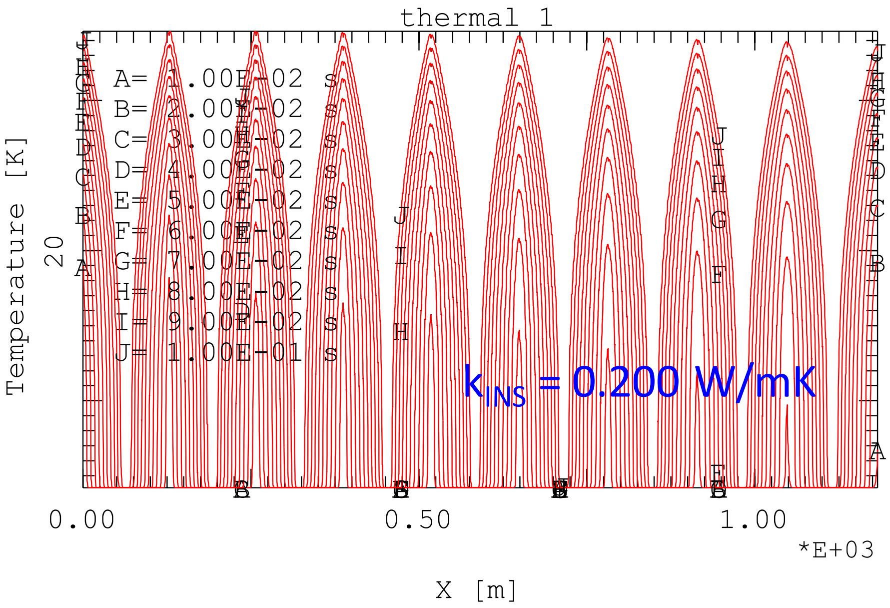




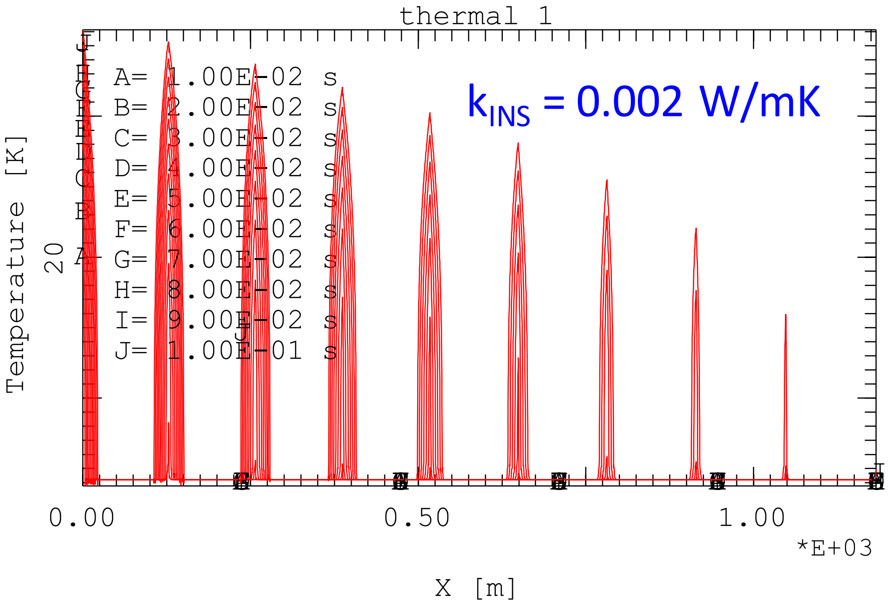
Parametric study #1

T vs X @ 0.01s < t < 0.10s (Coil #1)

Coil #1



k_{INS} = 0.200 W/mK



k_{INS} = 0.002 W/mK

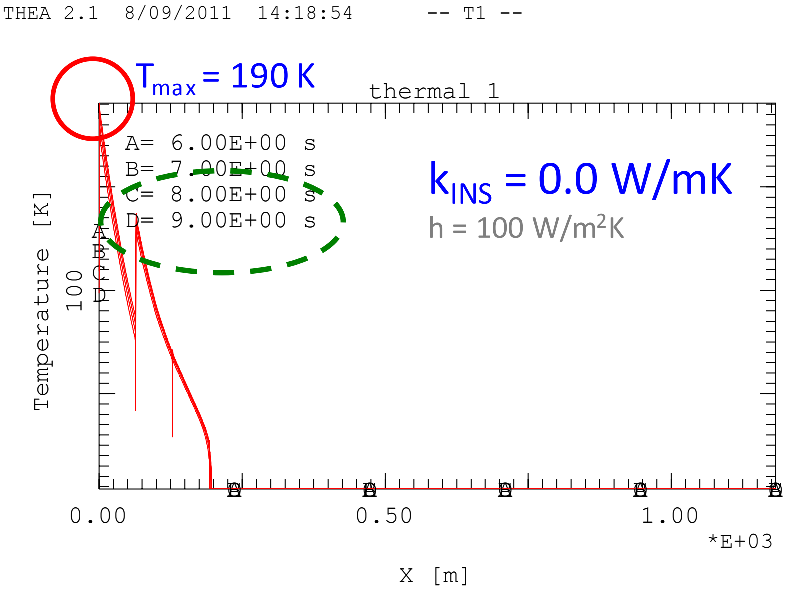
Parametric study #1

T vs X @ 0.10s < t < 5s (Coil #1)

Coil #1

- Less uniform temperature distribution in X for lower k_{INS}

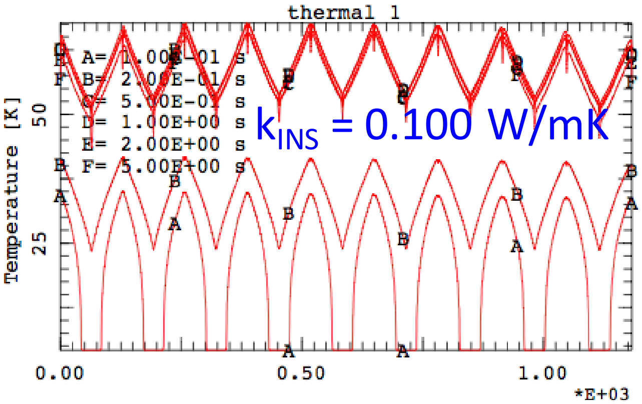
- Hot spot temperature not strongly dependent on k_{INS} (except for k_{INS} = 0)



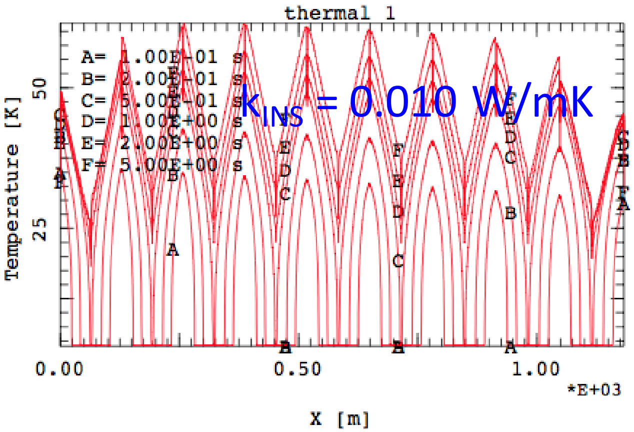
T_{max} = 190 K

k_{INS} = 0.0 W/mK

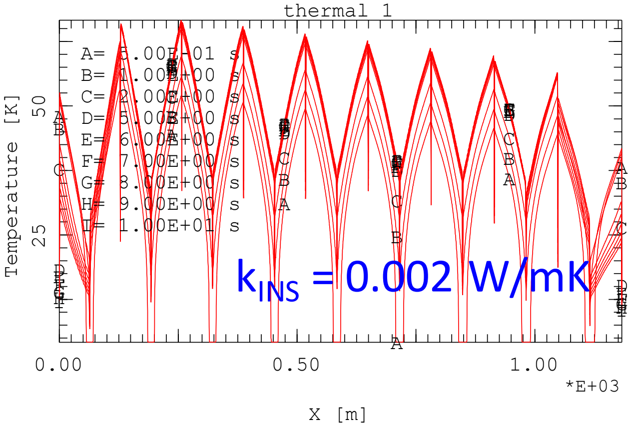
h = 100 W/m^{2}K



k_{INS} = 0.100 W/mK



k_{INS} = 0.010 W/mK



k_{INS} = 0.002 W/mK

Parametric studies

\# 1. Thermal conductivity of insulation

k_{INS} = 0.00 – 0.20 W/mK

reference case: 0.10 W/mK, glass epoxy at 20K

\# 2. Heat transfer coefficient to He bath

h = 0 – 500 W/m^2K

reference case: 100 W/m^2K

\# 3. Protective resistor RD1 and RD2

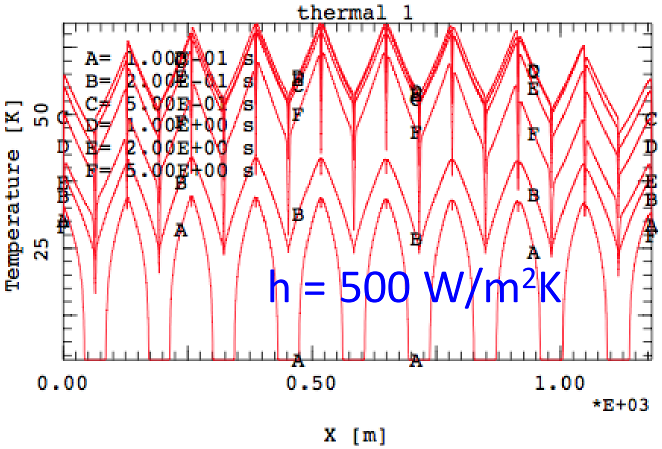
multiplying factor = 1 – 5

reference case: 1 (RD1 = 0.5 Ohm, RD2 = 1.0 Ohm)

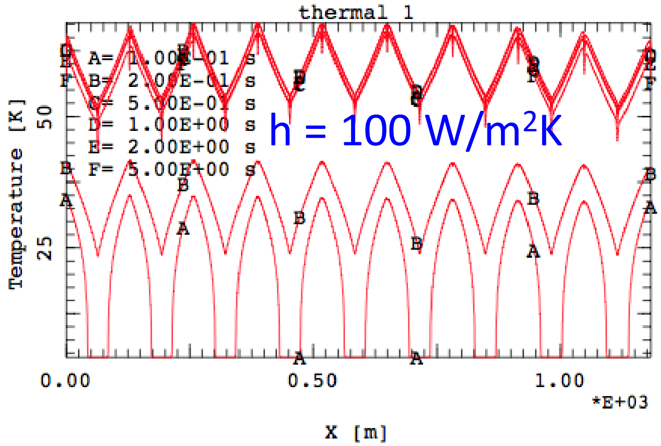
Parametric study #2

T vs X @ 0.1s < t < 5s

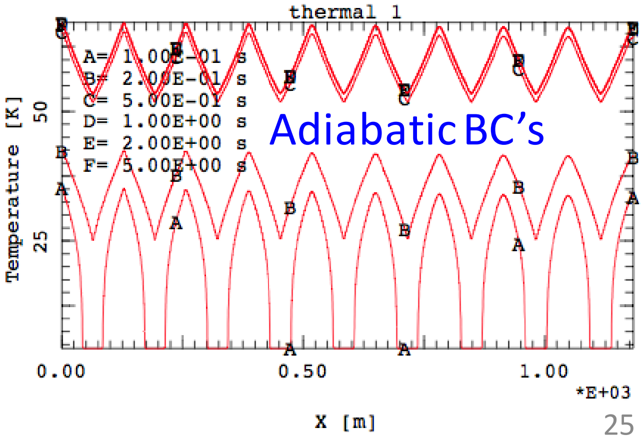
Coil #1



h = 500 W/m^{2}K



h = 100 W/m^{2}K



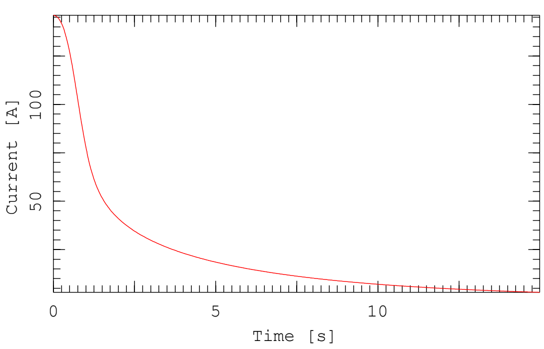
Adiabatic BC's

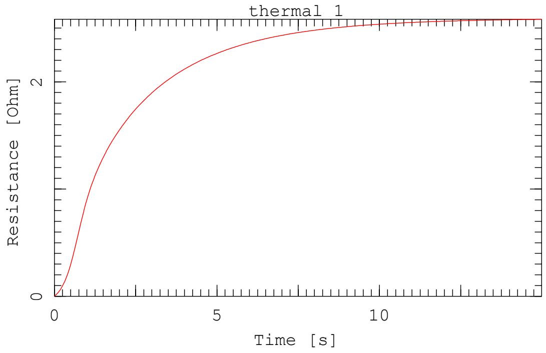
* Less uniform temperature distribution in X for larger h (same qualitative results in Coil #2)

* Hot Spot temperature is independent of h (also in case of adiabatic BC's)

Limiting case

$k_{INS} = 0$ W/mK **and** $h = 0$ W/m^{2}K



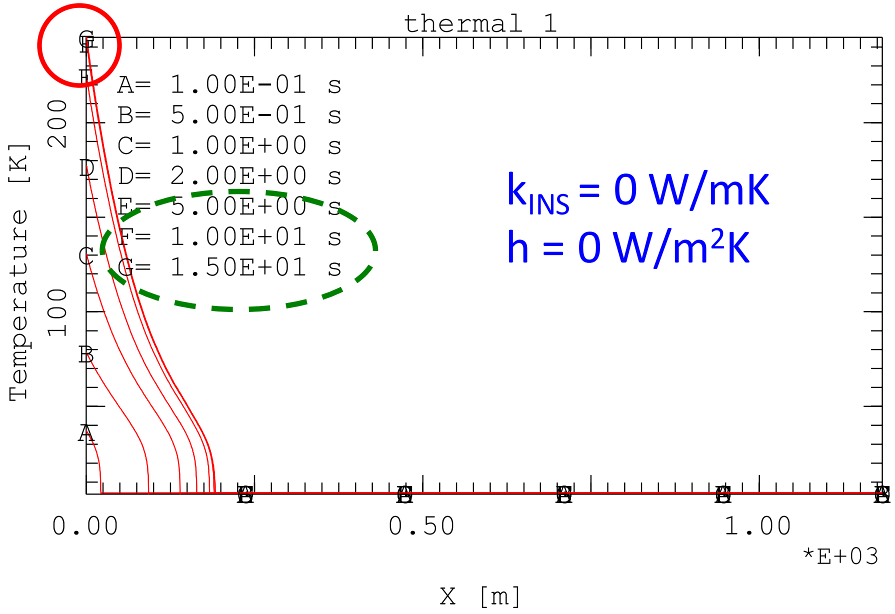


Coil #1

$T_{max} = 250$ K

$T_{max} = 68$ K (Ref. case)

No quench in Coil #2



$k_{INS} = 0$ W/mK

$h = 0$ W/m^{2}K

Parametric studies

\# 1. Thermal conductivity of insulation

k_{INS} = 0.00 – 0.20 W/mK

reference case: 0.10 W/mK, glass epoxy at 20K

\# 2. Heat transfer coefficient to He bath

h = 0 – 500 W/m^2K

reference case: 100 W/m^2K

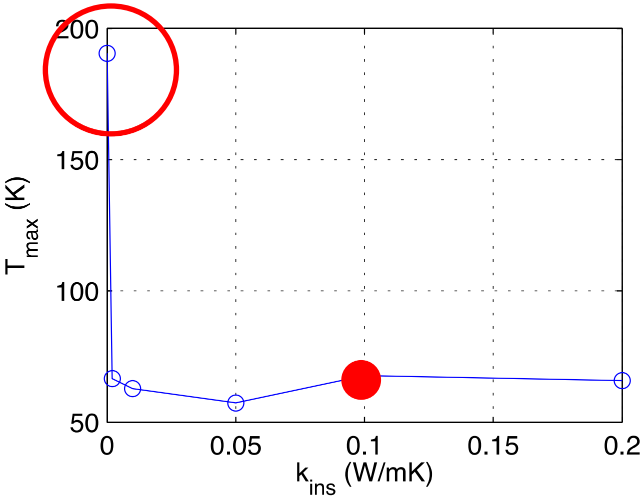
\# 3. Protective resistor RD1 and RD2

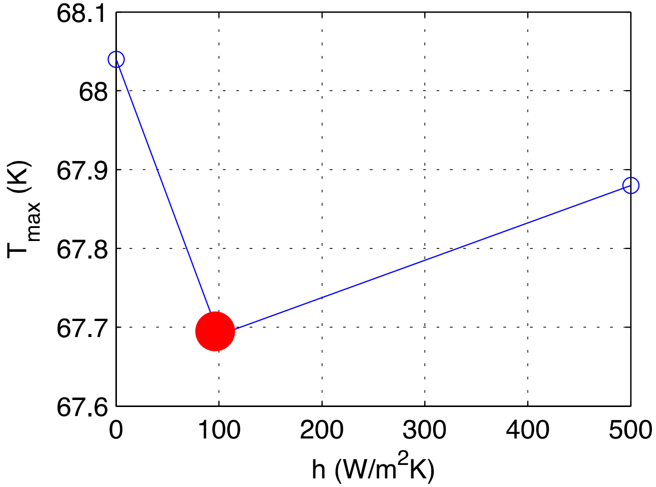
multiplying factor = 1 – 5

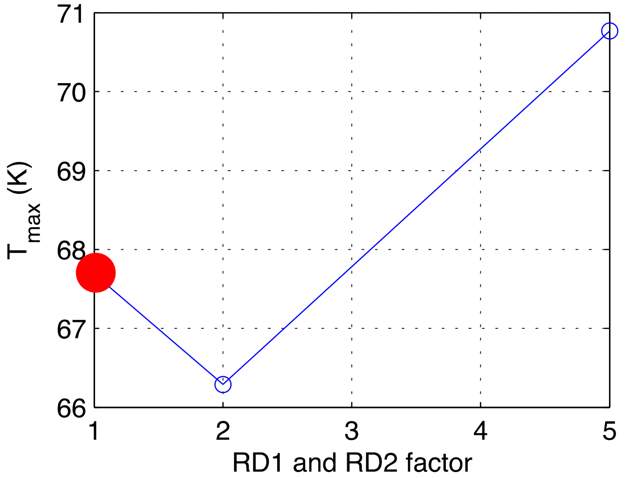
reference case: 1 (RD1 = 0.5 Ohm, RD2 = 1.0 Ohm)

Summary for T_{max} (Coil #1)

Hot spot temperature not strongly dependent on 3 parameters investigated (except $k_{INS} = 0$)



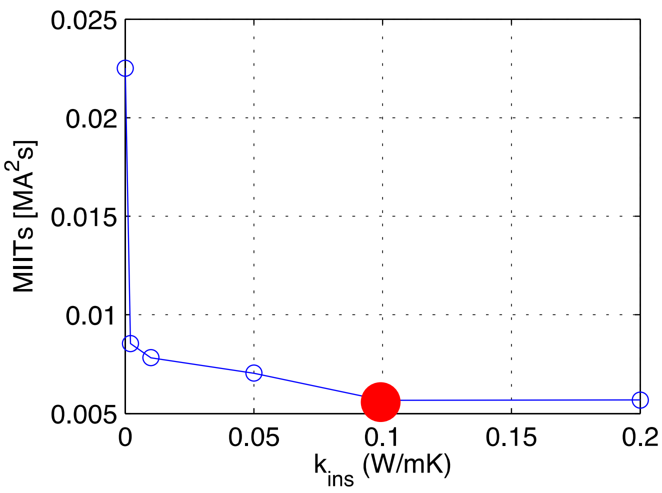


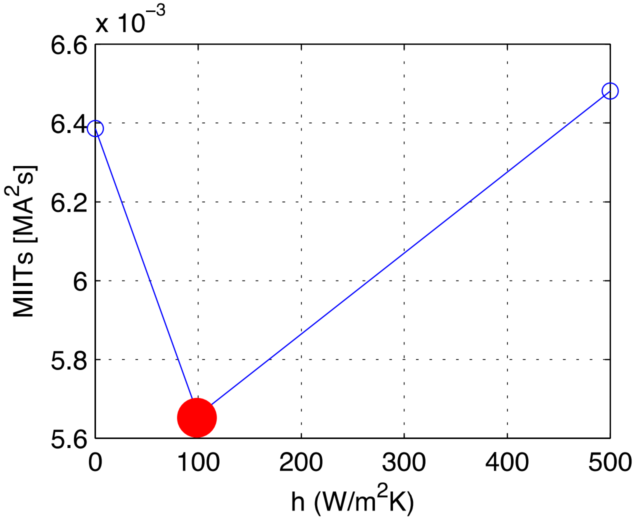


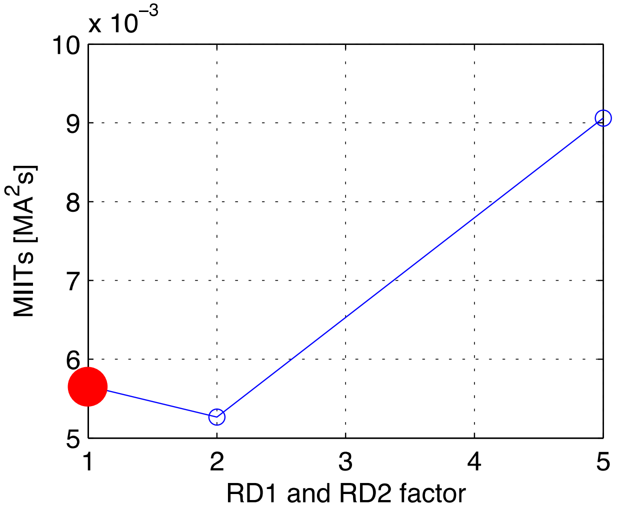
Magnet protection:
Safe conversion of magnetic energy into thermal energy without risk of damaging components, i.e. minimize T_{max}, ΔT_{max} and V_{max}

● Reference case

Summary for **MIITs (Coil #1)**





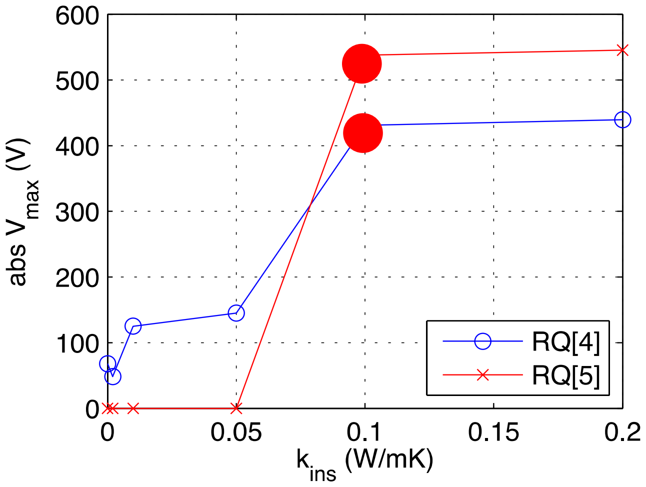


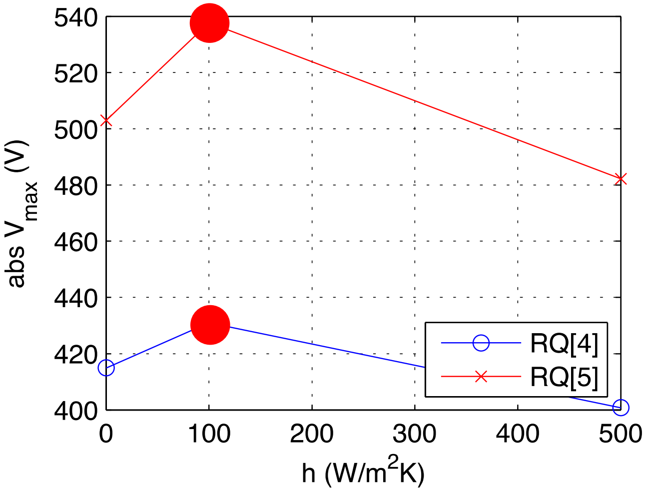
$$MIITs = \int_{t_{quench}}^{\infty} I(t)^2 dt$$

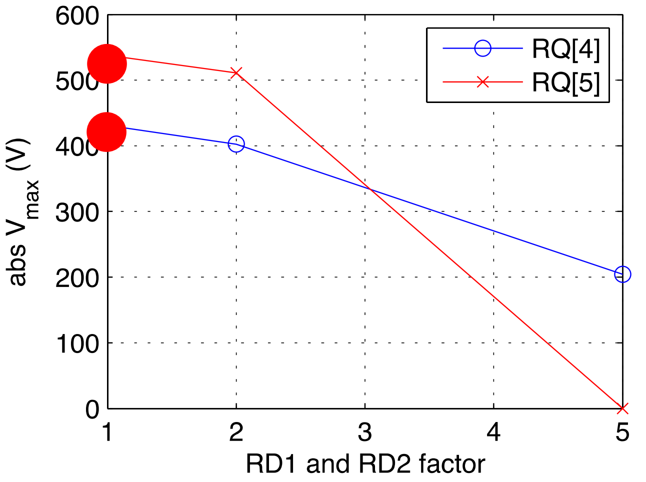
● Reference case

Summary for V_{max} (Coil #1, #2)

Quench voltage







● Reference case

Summary

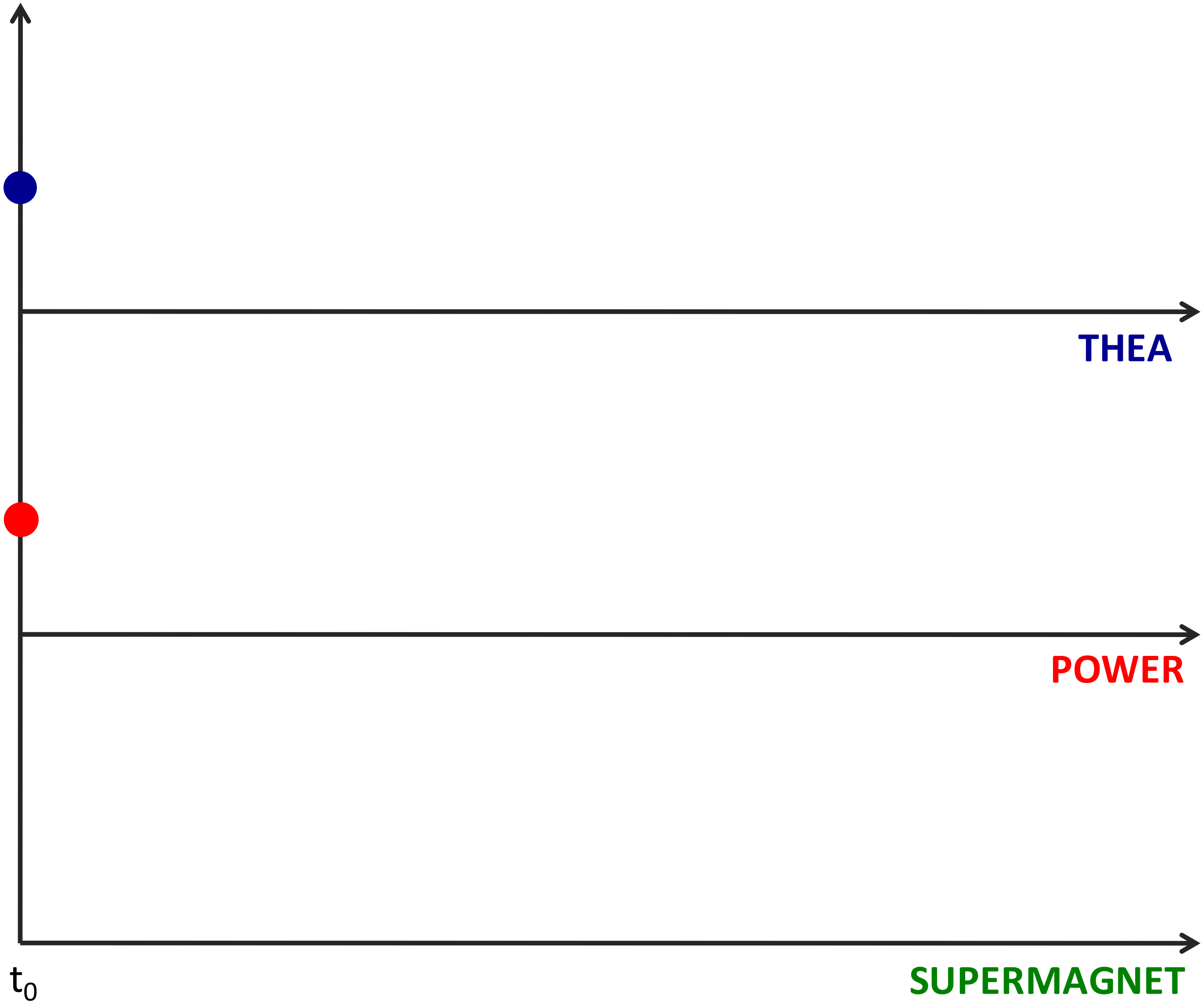
Quench in coupled solenoids is a typical SC magnet design problem, and it can be analyzed using a tailored assembly (SuperMagnet) of selected CryoSoft™ codes (THEA, POWER). The topology is obviously not a limiting factor.

User routines were included in the THEA code to take into account the transversal heat transfer and propagation. The quenching coil resistance was used in a circuital model with lumped parameters (POWER). Other features (e.g. variable magnetic field) can be included easily.

Modeling provides access to hidden parameters (e.g. internal voltage) and parametric analysis in a homogeneous and self-consistent framework

Thank you for your attention

SUPERMAGNET model



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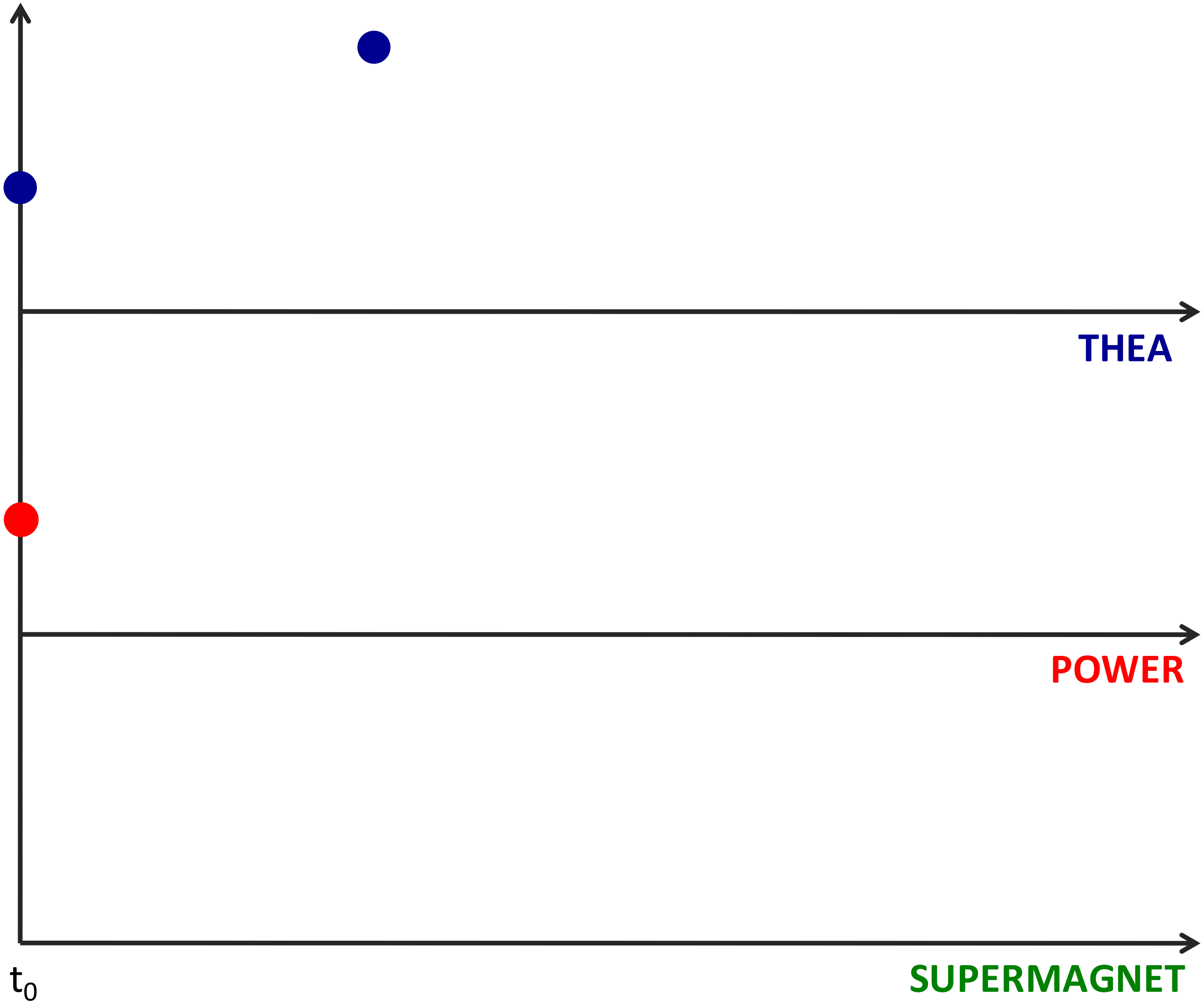

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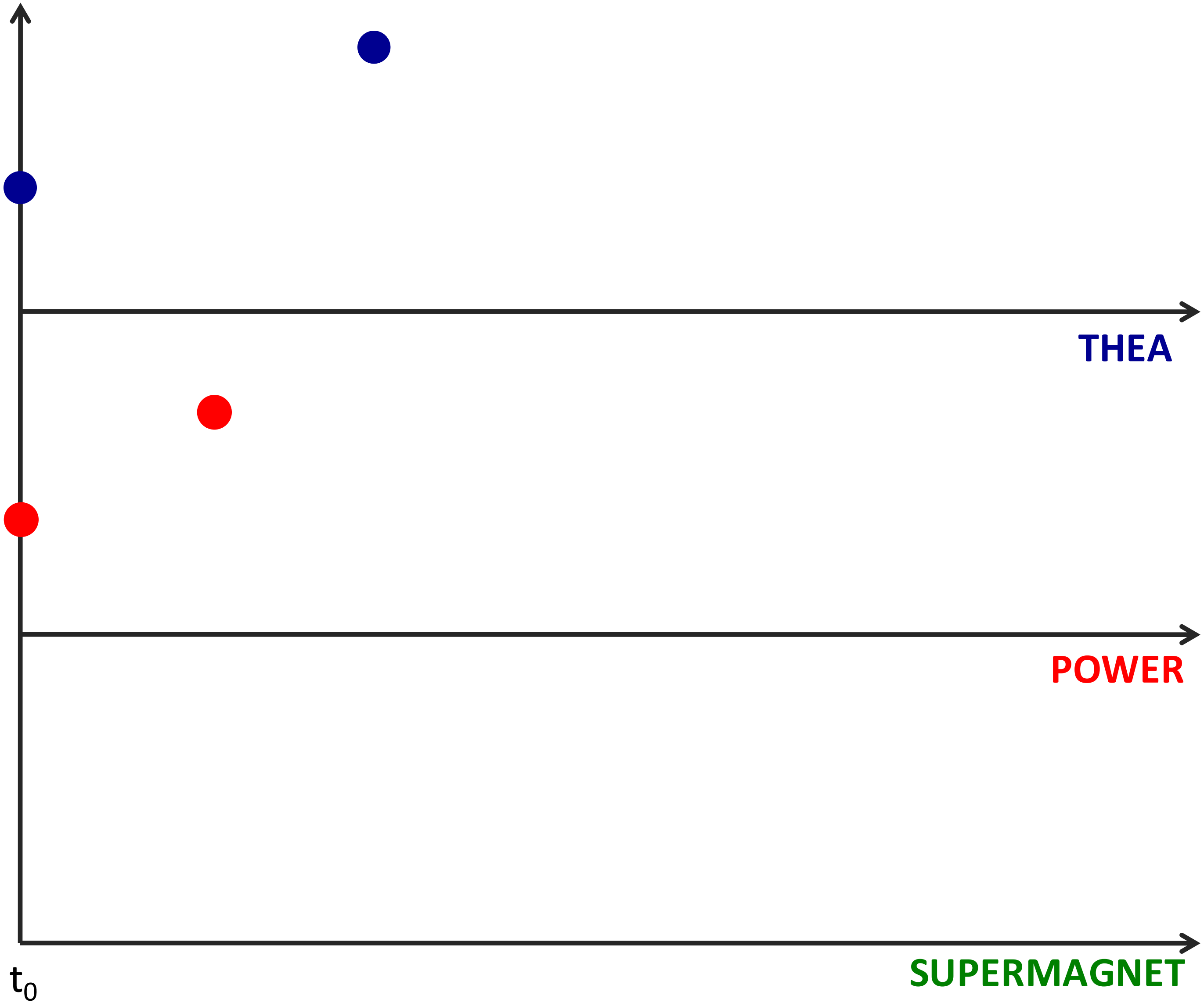

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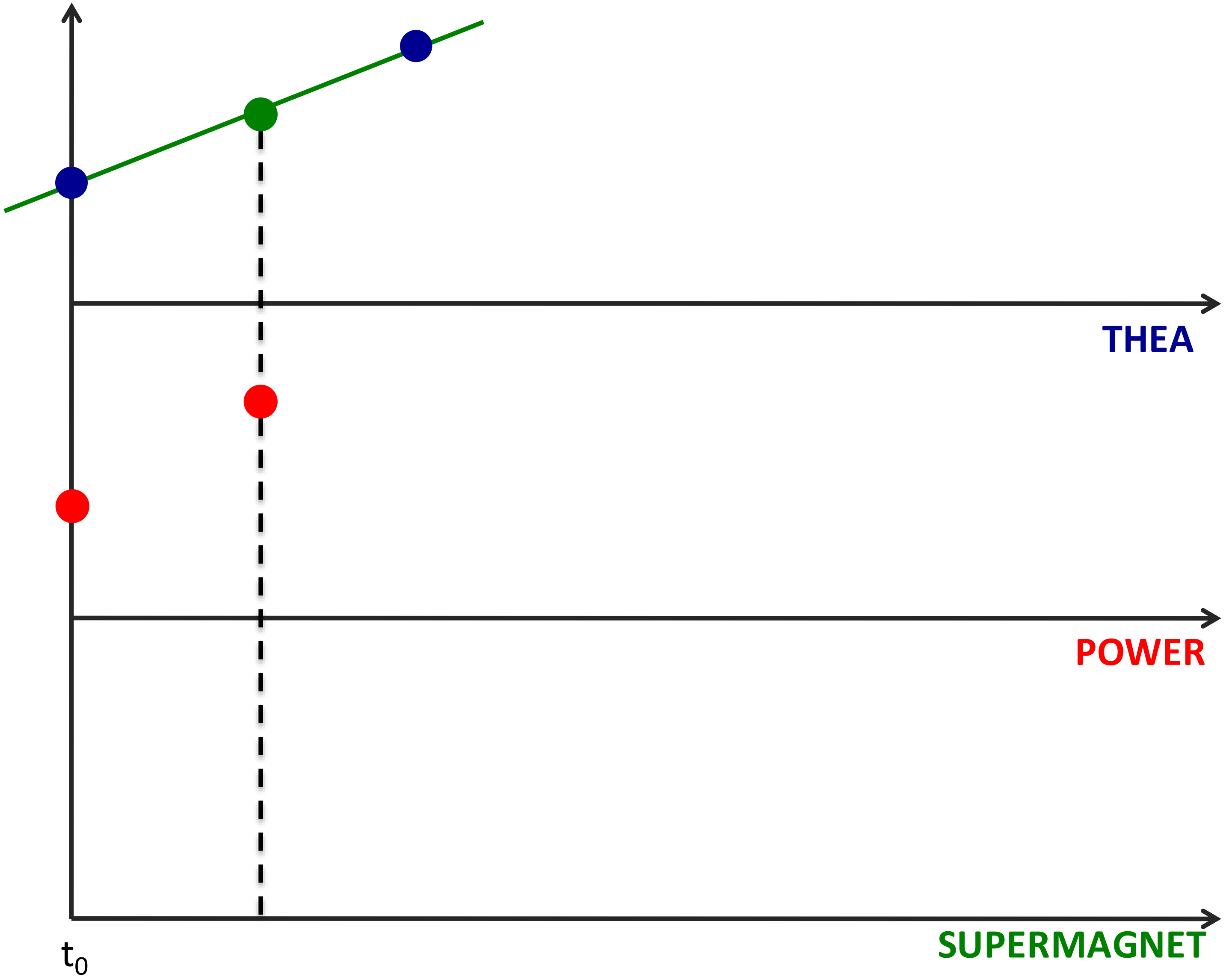

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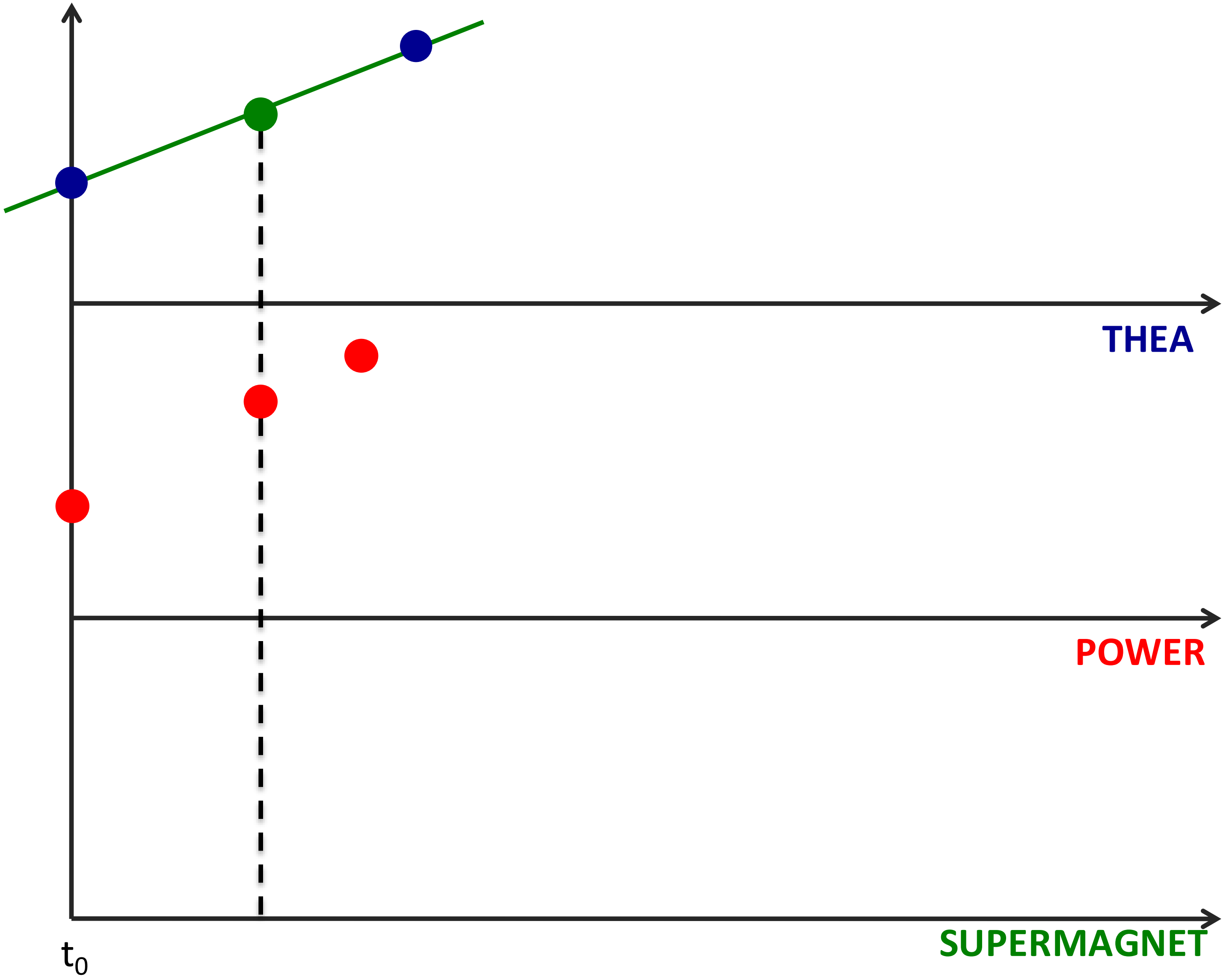

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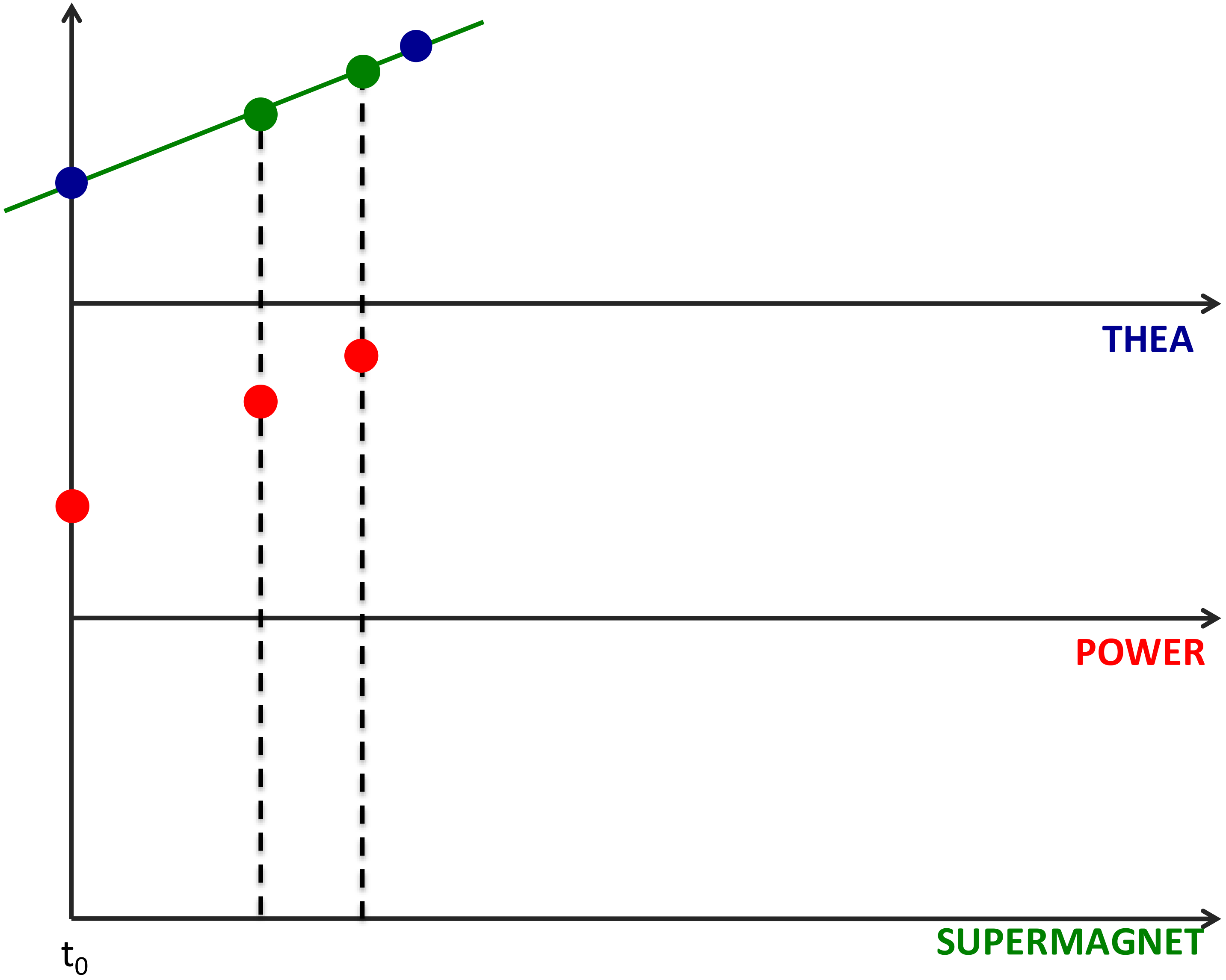

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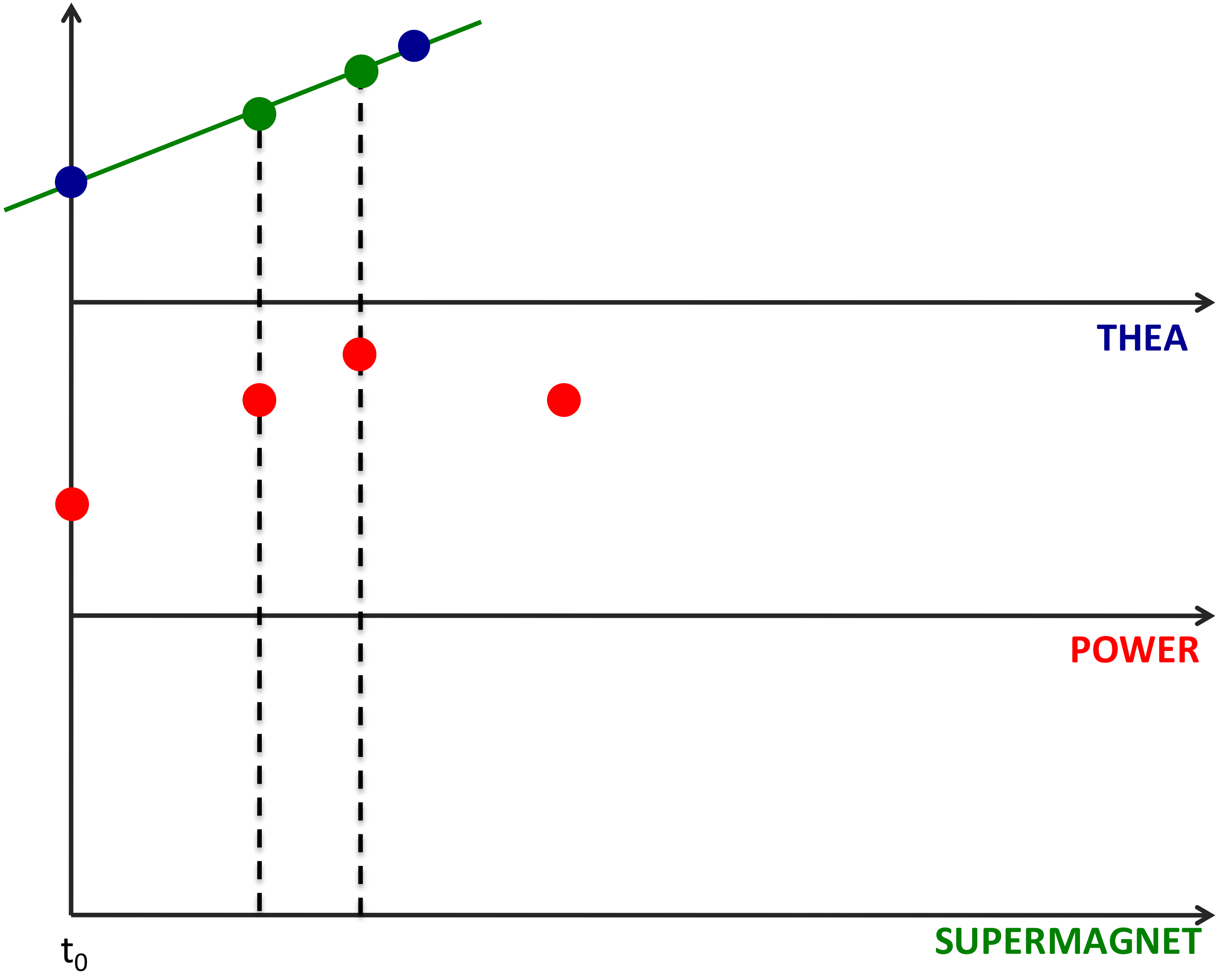

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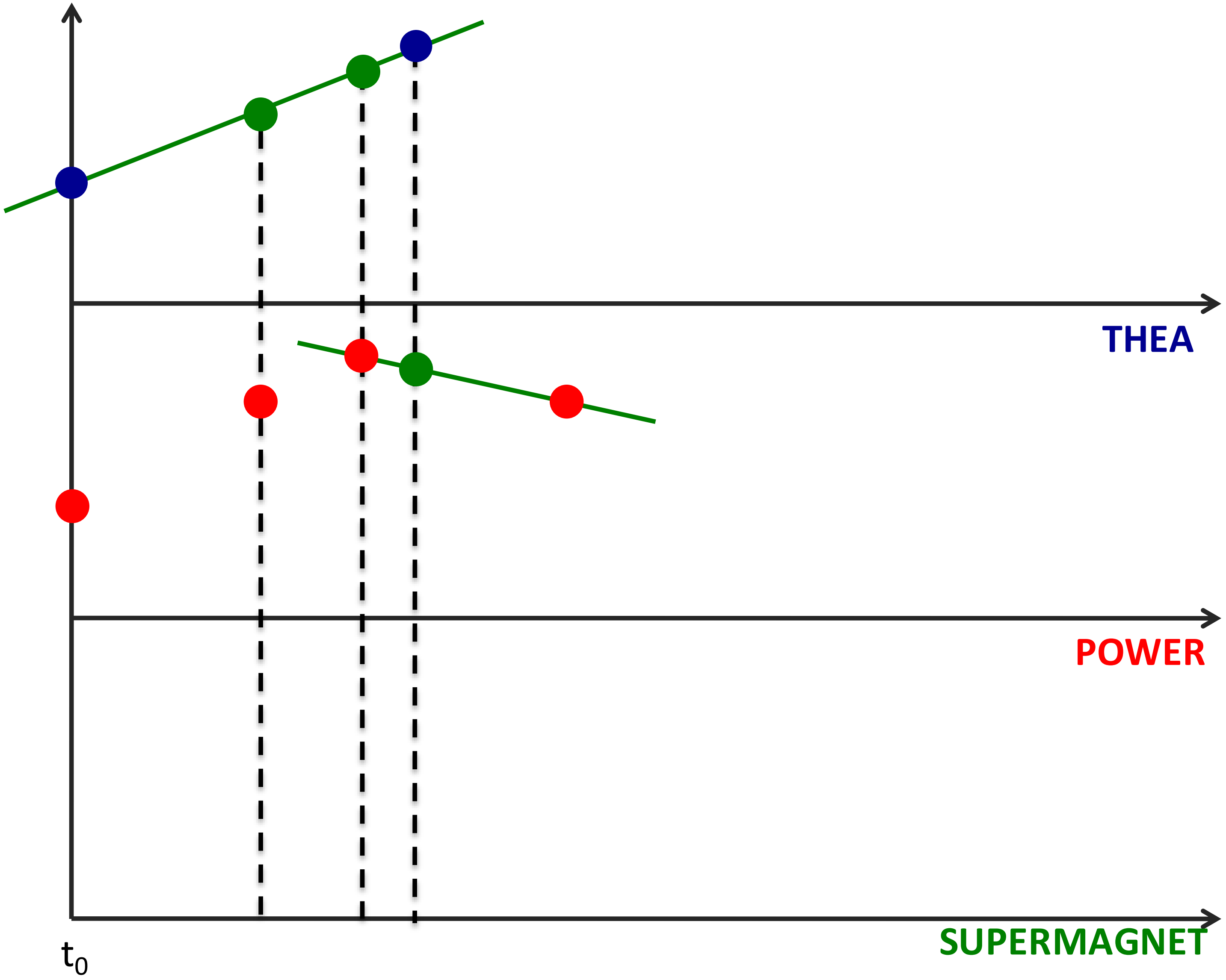

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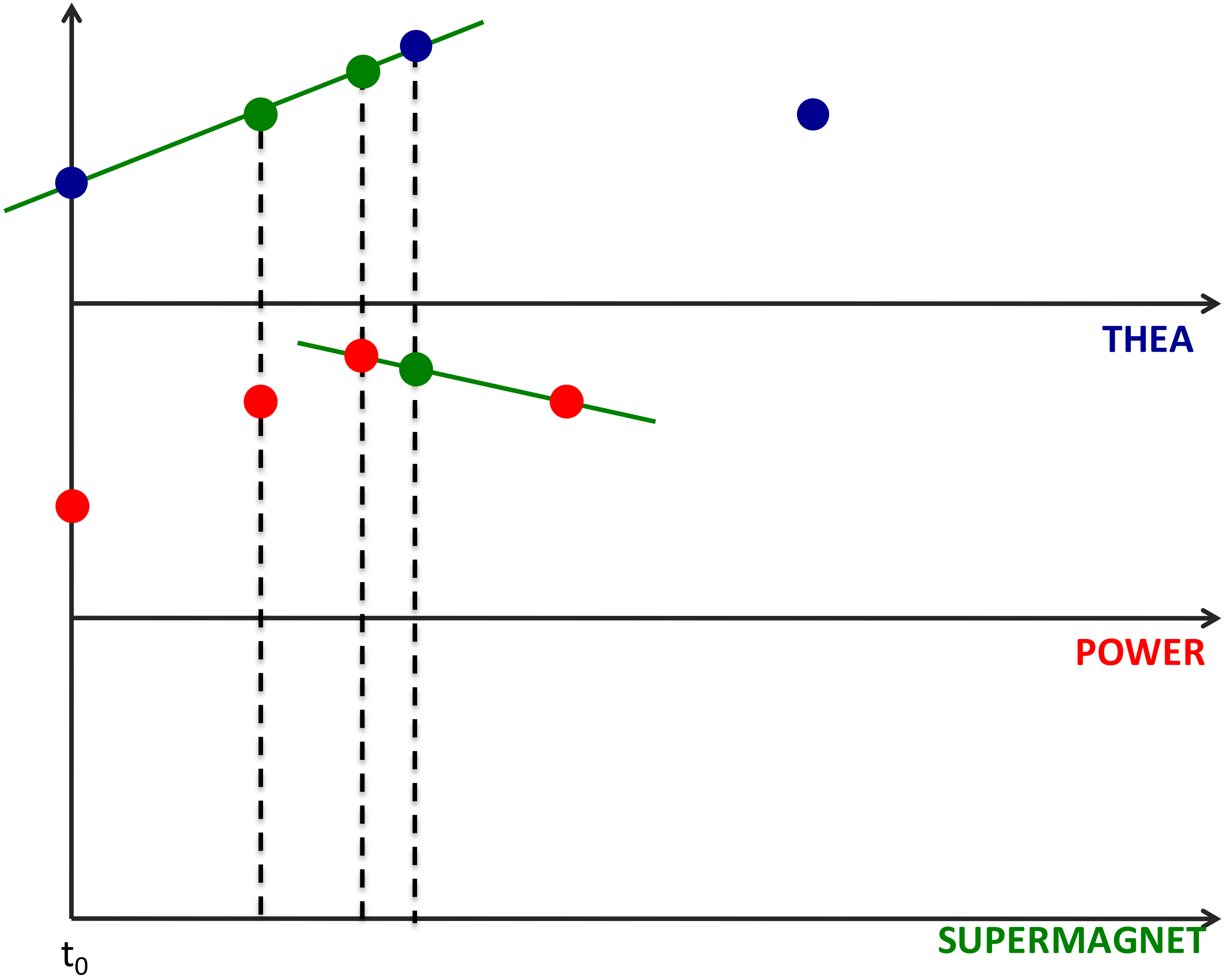

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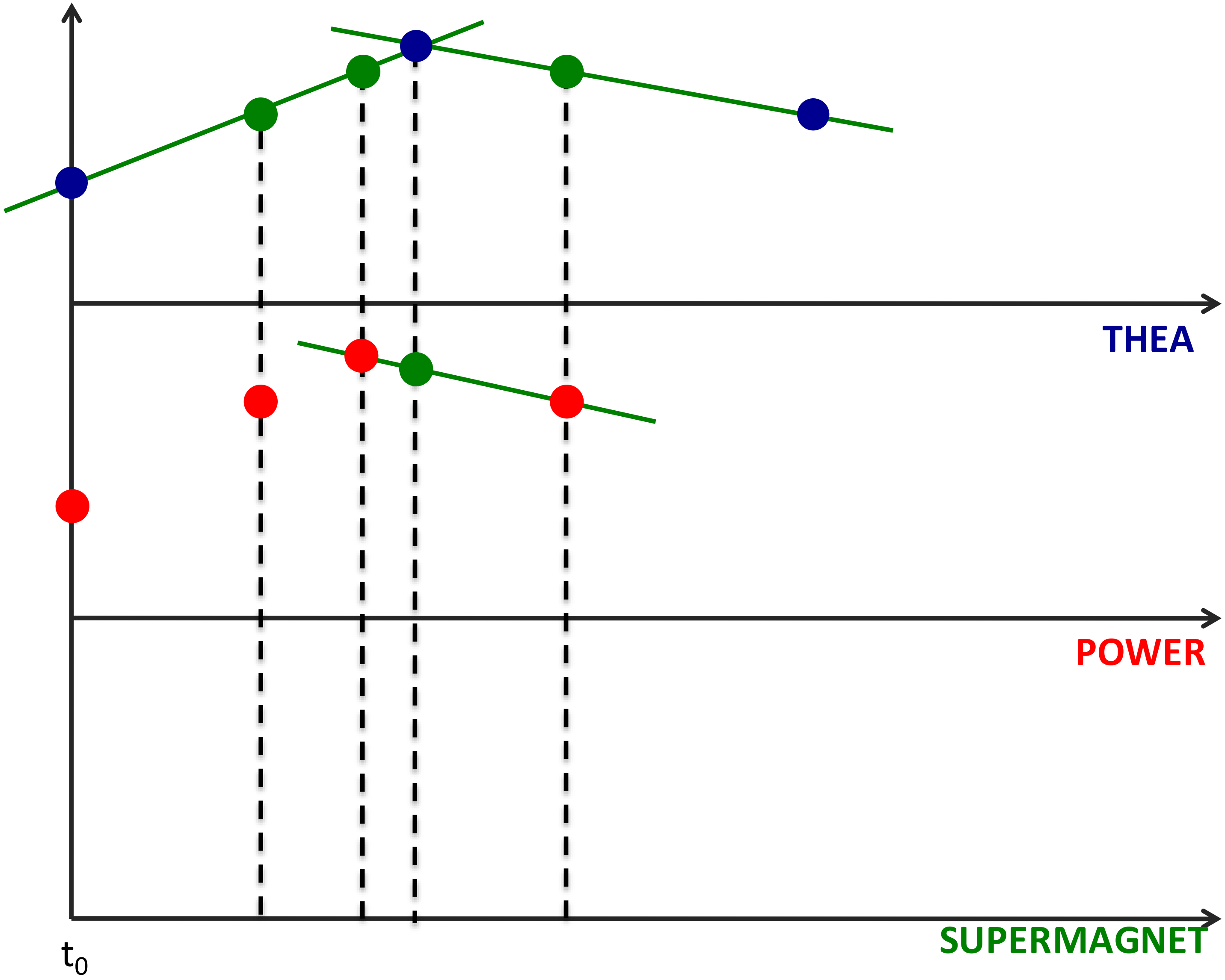

SUPERMAGNET model