

Susana Izquierdo Bermudez. 29-04-2014

Quench Modelling Nb₃Sn magnets: Longitudinal quench propagation



11T and QXF are pushing the boundary of protection → we need a good understanding of the dominating physics



Let's try to understand it bit by bit...

Longitudinal quench propagation

Important because it determines the time needed to detect a normal zone

Heat transfer within the coil

Important because it determines the time needed to quench the whole magnet cross section

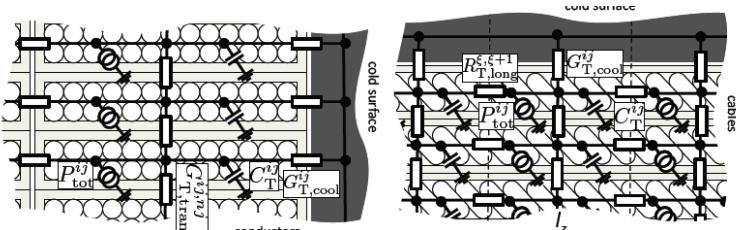
Heat transfer from heater to coil

Important because it defines the time needed to induce a distributed quench

Models overview

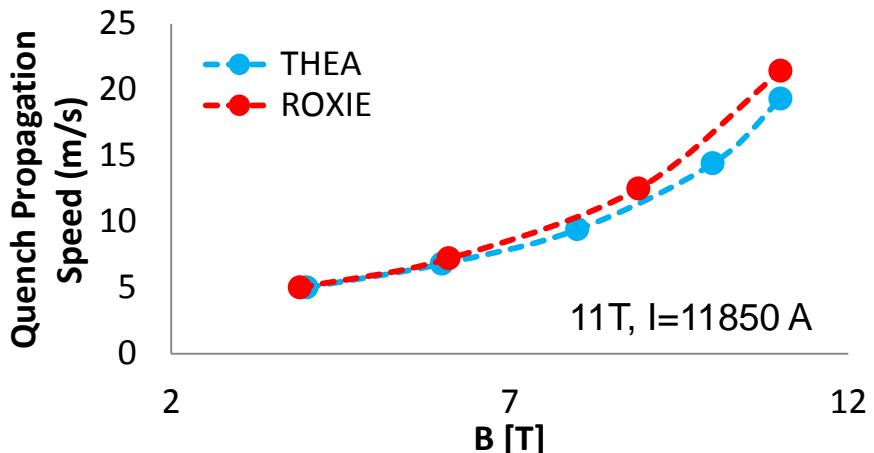
ROXIE QUENCH MODULE [Sch 2010]

Couples magnetic, electrical and thermal.
First order thermal network (2D (XSec) + 1 (z*))



*Requires small element size (<1mm) in the longitudinal direction to converge in terms of longitudinal quench propagation velocity

Under the same assumptions...very close propagation velocity (not the case for $T_{max}!$)

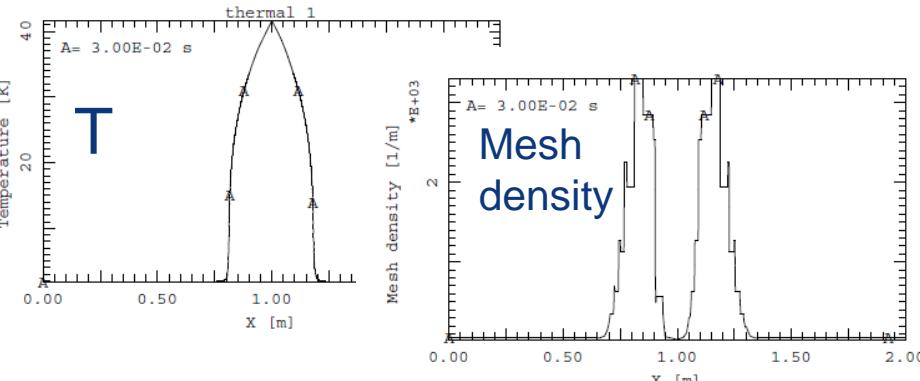


SUPERMAGNET [Bot 2007]

Built by different blocks with an unified interface for data exchange.

THEA [Bot 2010]

Thermal, Hydraulic and Electric analysis of superconducting cables
Adaptive mesh tracking



HEATER [Bot 2010]

FE heat conduction

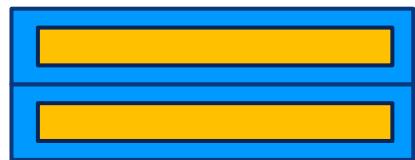
POWER [Bot 2004]

Electric network simulation of magnetic systems

Modelling: Thermal Coupling

$$\rho C_v(T, B) \frac{dT}{dt} = \dot{Q}_{joule} + \nabla \cdot (k_T(T, B) \nabla T)$$

First Order Thermal Coupling



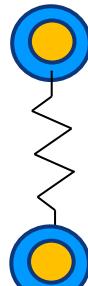
Option 1

$$C_p = C_p_{\text{cond}}$$



Option 2

$$C_p = C_p_{\text{cond}} + C_{\text{ins}}$$



[ROXIE]

Higher Order Thermal Coupling

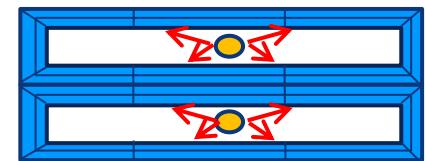
[Gav 1992]



Hybrid model



FE mesh
(insulation)



Conductor

Coupling



Cu+SC



Insulation



Heat capacity

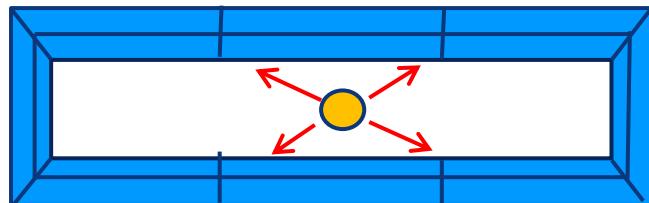


Thermal resistance

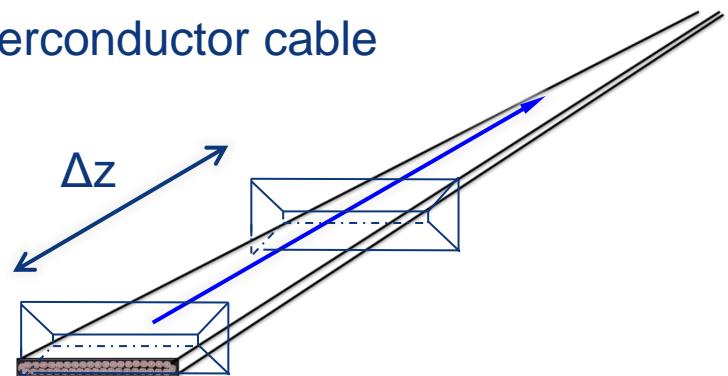
Modelling: coupling heat conduction domains

HEATER : Heat conduction in the insulation is solved in 2D cross sections

THEA: Thermal and Electrical analysis of the superconductor cable



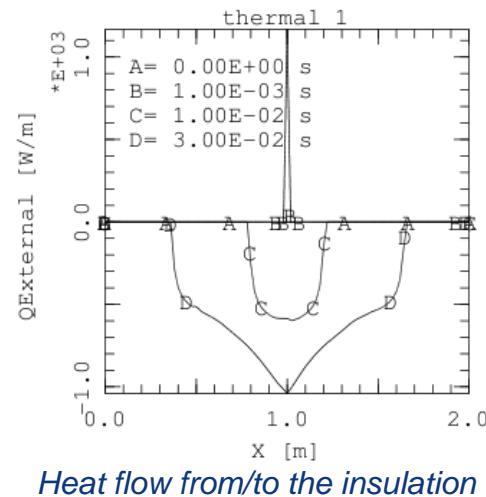
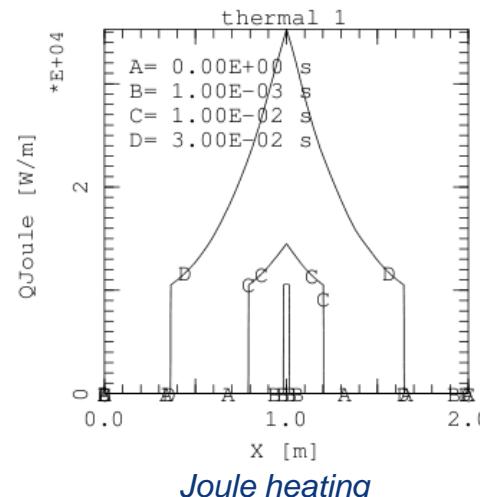
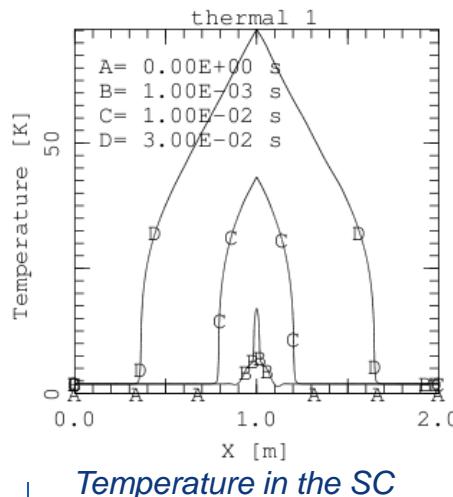
2D quadrilateral elements with 4 nodes
and first order shape function



Explicit coupling → conditionally stable. Small heat capacity and large thermal conductance requires small time steps for the stability of the coupling

Example: HEATER : $\Delta z=20$ mm
THEA : $\Delta z=0.3\text{mm}-100\text{mm}$

$$t_{\text{step}} = [10^{-6} \text{ } 10^{-3}] \text{ s}$$
$$t_{\text{step}} = [10^{-7} \text{ } 10^{-4}] \text{ s}$$



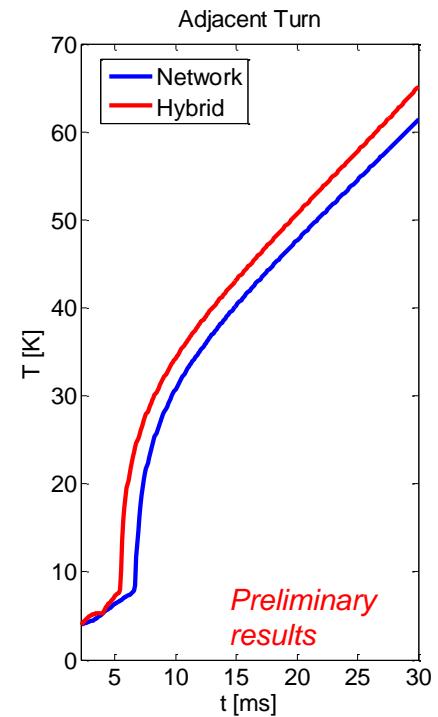
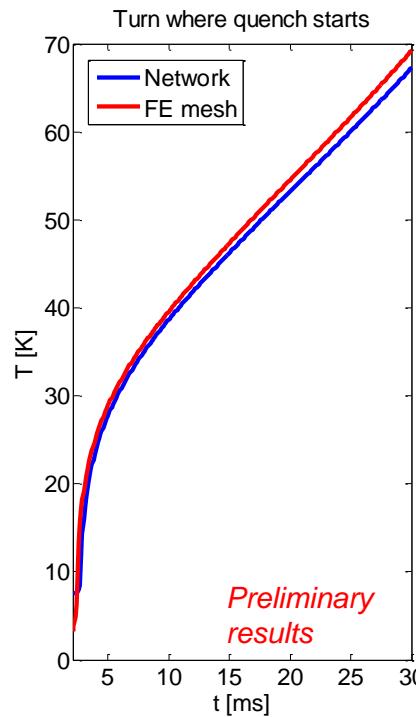
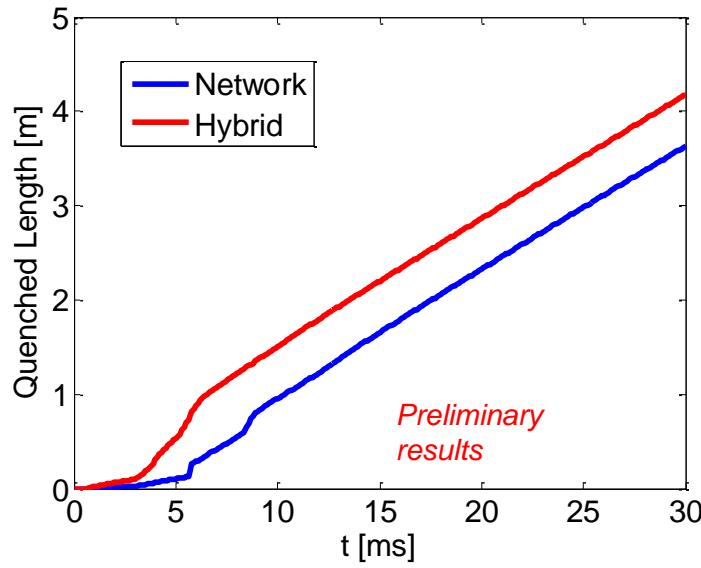
Modelling: Network model vs Hybrid model

11T Cable, $B = 11.3 \text{ T}$, $I = 11850 \text{ A}$

Quenched initiated in the middle turn of a stack of three cable



	Network Model	Hybrid Model	Diff
$T_{\max} @ t=30 \text{ ms [K]}$	66	68	3 %
Turn2Turn propagation (ms)	4	3	25 %
Longitudinal quench propagation velocity (m/s)	23	22	4%



Negligible impact of the thermal coupling method on the longitudinal quench propagation

Validation of the model

Available experimental data

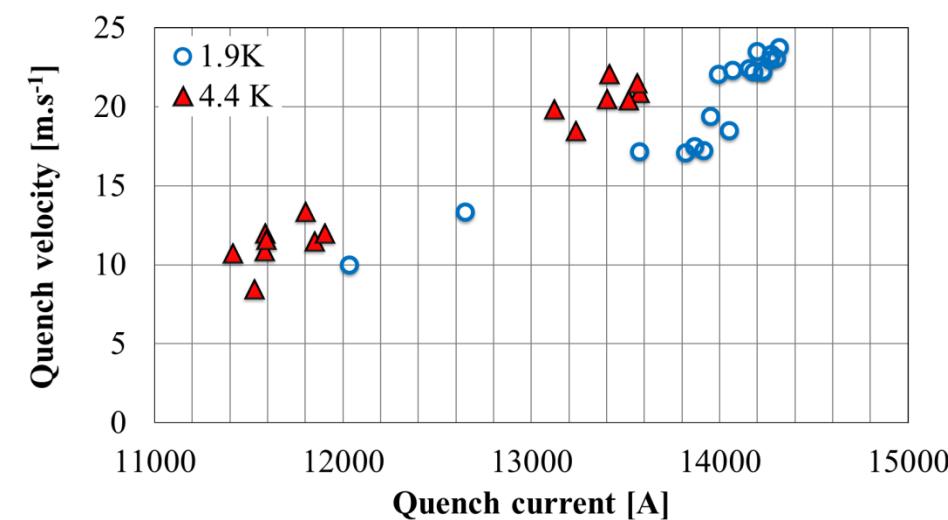
SMC 11T (H. Bajas):

Pole turn @ 1.9 K $I = 12936$ A ($B_p = 11.3$ T)

$v = 27$ m/s

SMC3 (H. Bajas):

Pole turn @ 1.9 K & 4.4 K, $I \approx 11.5\text{-}14.2$ kA



HQ01d (M. Marchevsky)

Training quenches. $I = 14.3$ kA $v = 11.4$ m/s

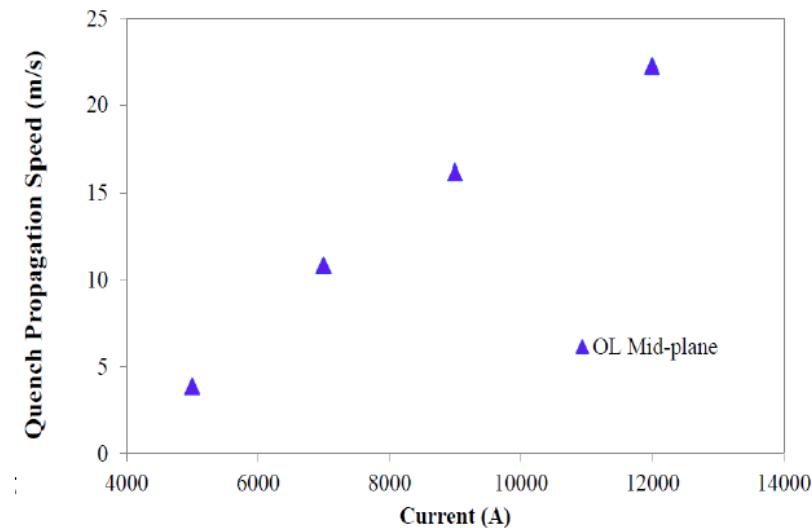
$I = 13.6$ kA $v = 9.4$ m/s

MBHSP01(G. Chlachidze):

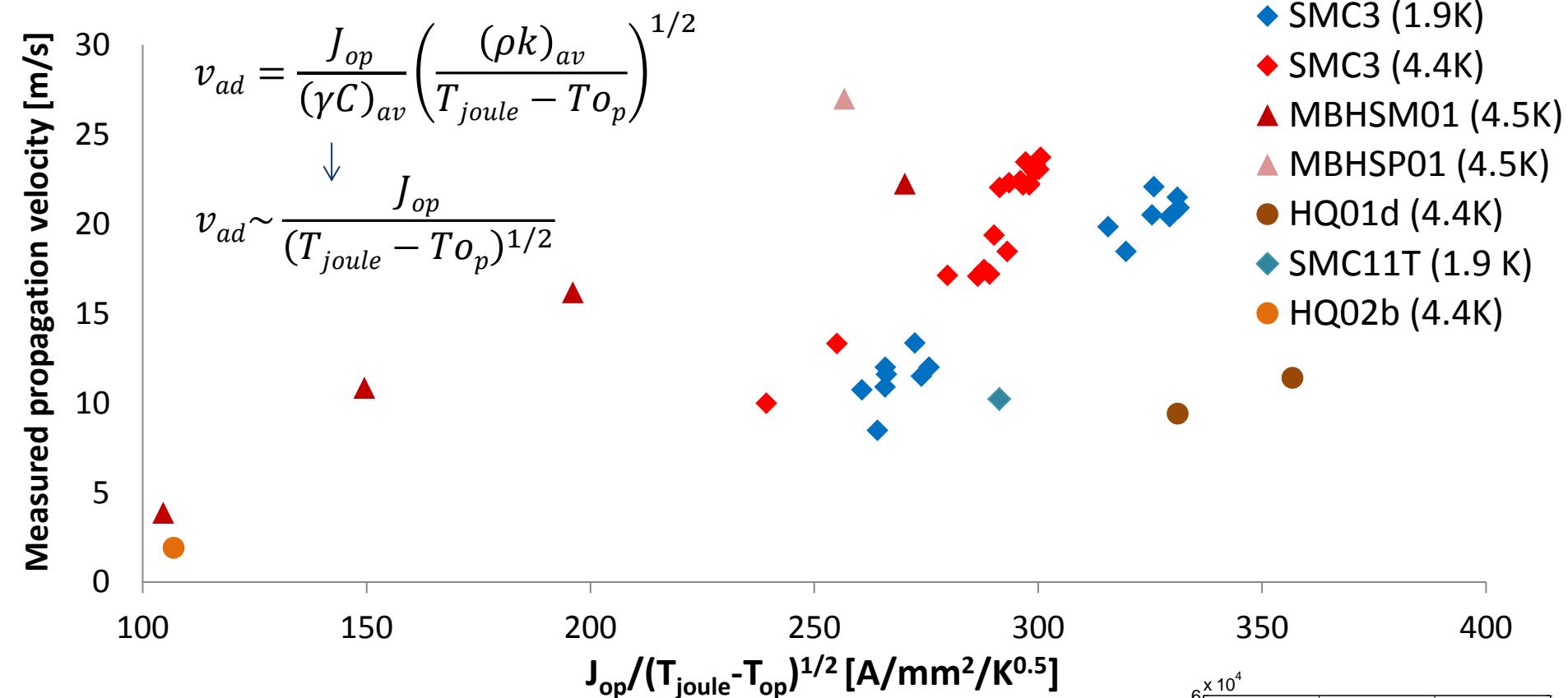
Inner layer pole turn @ 4.5 K $I = 73\%$
 $v \sim 27$ m/s

MBHSM01 (G. Chlachidze):

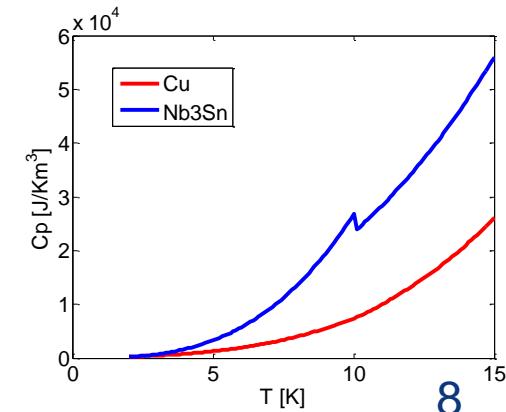
Outer layer mid-plane turn @ 4.5 K
 $I \approx 5\text{-}12$ kA



Experimental data

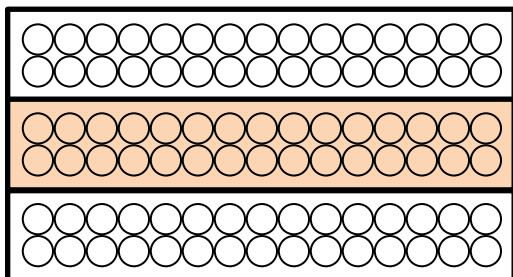


Don't forget that the material properties strongly depend on the temperature and field, and change by several order of magnitudes!

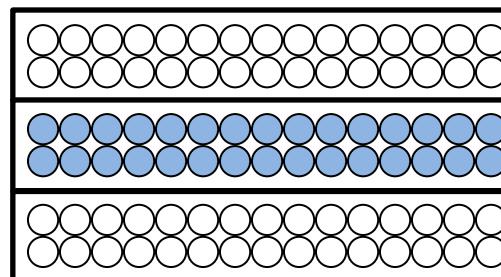


Comparison to SMC measured data

Conductor + insulation

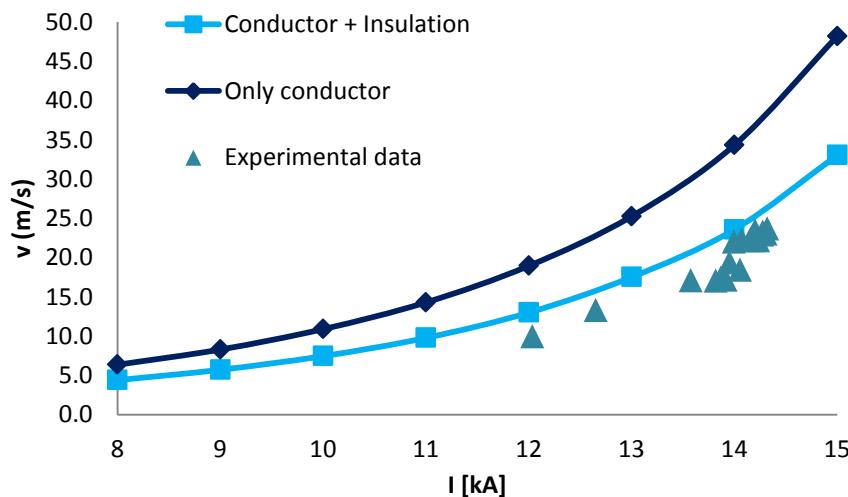


Conductor only

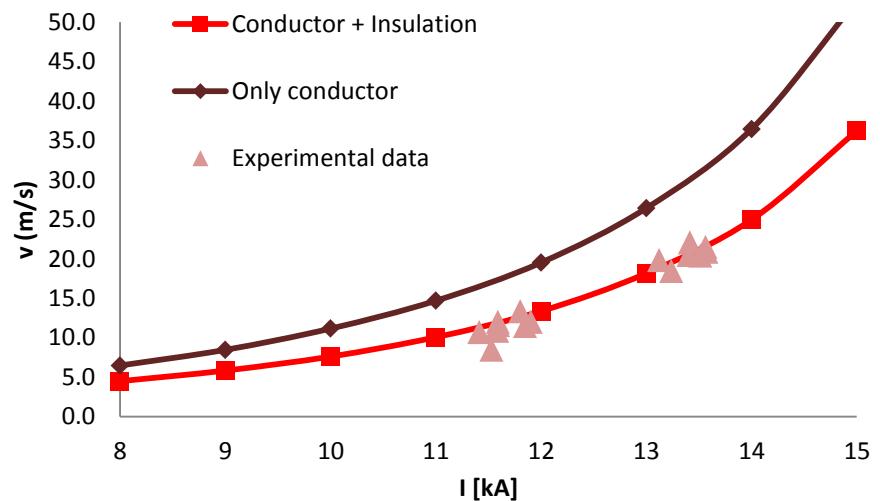


Measured longitudinal propagation velocities in SMC11T and SMC3 are close to numerical data when considering the heat capacity of insulation + conductor.

SMC3 1.9 K



SMC3 4.2 K

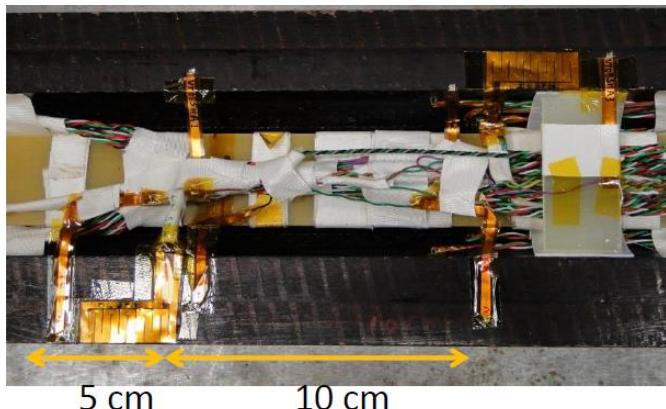


Experimental data H. Bajas

Remark: natural quenches in the high field region

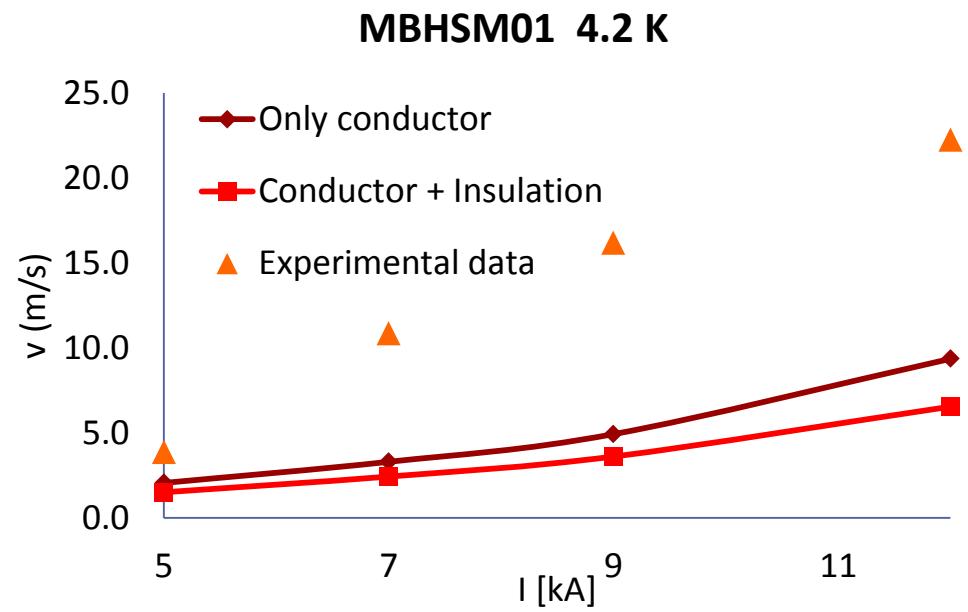
Comparison to 11T measured data

Spot heater test in the outer layer mid-plane turn



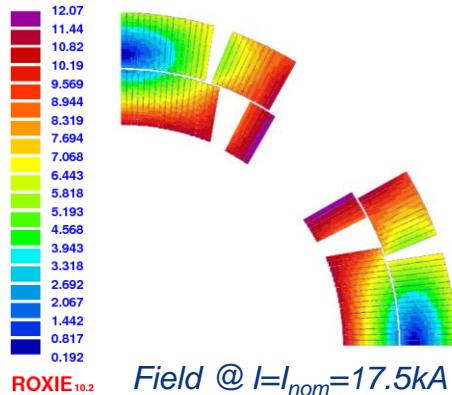
I [kA]	B_{peak} , OL mid-plane [T]
5	2.65
7	3.44
9	4.25
12	5.50

The 11T mirror magnet tested at FNAL shows velocities ~2.5 times larger than the ones predicted by the model

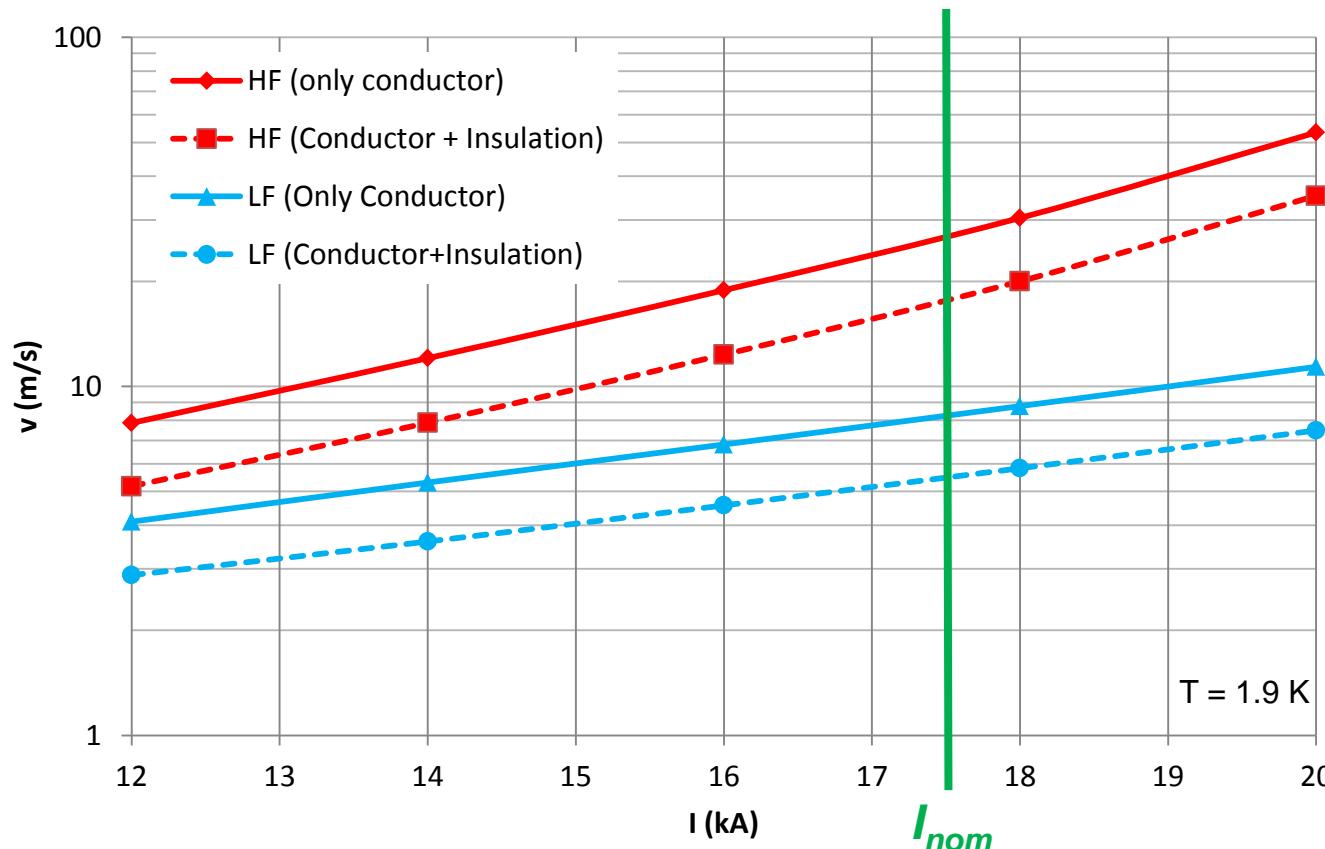


Experimental data G. Chlachidze

Expected long. propagation QXF



I (kA)	Bp [T] (HF: Pole turn IL)	Bp [T] (LF: Mid plane turn OL)
12	8.5	3.4
14	9.8	4.1
16	11.1	4.9
18	12.4	5.7
20	13.7	6.5



REFERENCES

- MATERIAL PROPERTIES
 - [Man 2011] G. Manfreda, Review of ROXIE's Material Properties Database for Quench Simulation
 - [TD Note ----] TD Note 00-041, Material properties for quench simulation
 - [Dav ----] A. Davies, Material properties data for heat transfer modelling in Nb3Sn magnets
- EXPERIMENTAL DATA
 - [Mar 2012] M. Marchevsky. Quench Performance of HQ01, a 120 mm Bore LARP Quadrupole for the LHC Upgrade
- MODELLING
 - [Bot 2004] Power. User's Guide. CryoSoft, Ver. 2.0; 2004
 - [Bot 2007] SuperMagnet. User's Guide. CryoSoft, Ver. 1.0; 2007
 - [Bot 2010] Thea. User's Guide. Cryosoft, Ver. 2.1; 2010
 - [Bot 2010] Heater. User's Guide. Cryosoft, Ver. 2.0; 2010
 - [Bot 2013] L. Bottura, Magnet Quench 101, WAMSDO CERN 2013
 - [Gav 1992] A. Gavrilin, Cryogenics, 32 (1992), 390-393
 - [Rus 2008] S. Russenschuck. Field Computation for Accelerator Magnets
 - [Sch 2010] Numerical Calculation of Transient Field Effects in Quenching Superconducting Magnets. PhD Thesis

Additional slides

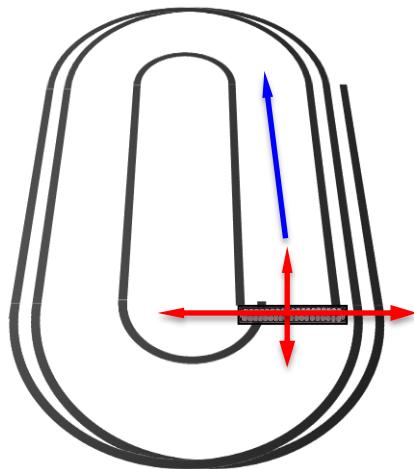
Cable Data

DATA BEFORE REACTION

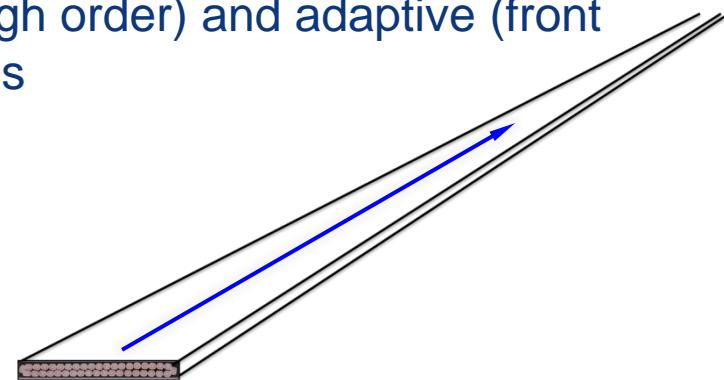
	# strands	Strand diameter	Cu/nCu	Cable width	Bare Cable Mid-Thickness	Insulation thickness
	-	mm	-	mm	mm	mm
SMC3	14	1.25	1.25	9.9	2.2	0.1
SMC 11T	40	0.7	1.25	14.99	1.305	0.15
11T	40	0.7	1.15	14.7	1.25	0.15
HQ	35	0.778	1.13	15.15	1.437	0.1
QXF	40	0.85	1.13	18.15	1.525	0.15

Modelling: length scale

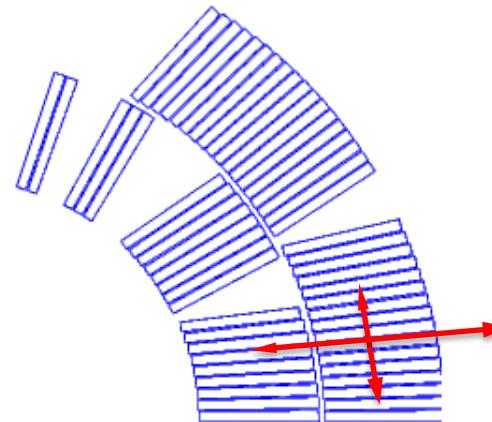
2 Principal directions:
longitudinal and **transverse**



Longitudinal → length scale: hundreds of m
Cable is a continuum “relatively easy” to solve
with accurate (high order) and adaptive (front tracking) methods



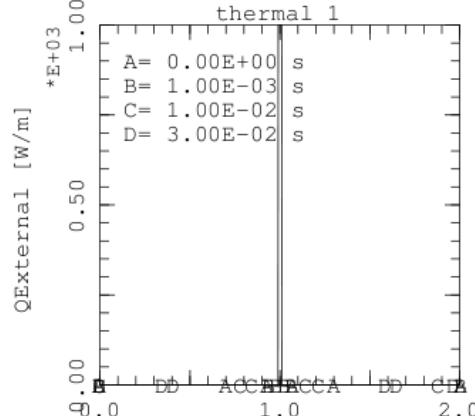
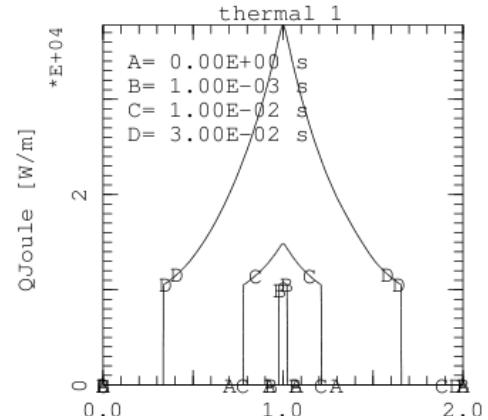
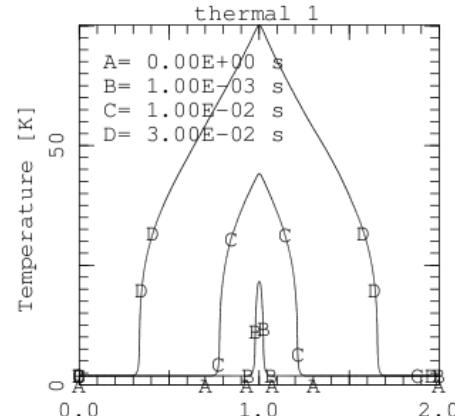
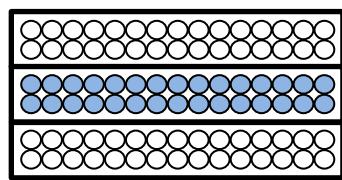
Transverse → length scale: mm
Heat diffusion across the insulation



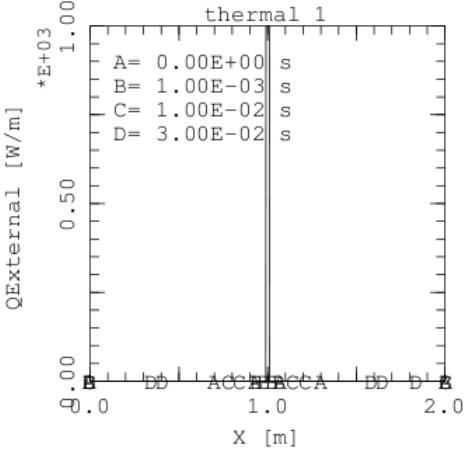
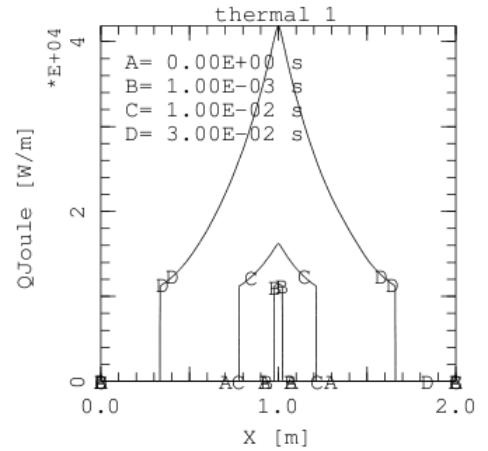
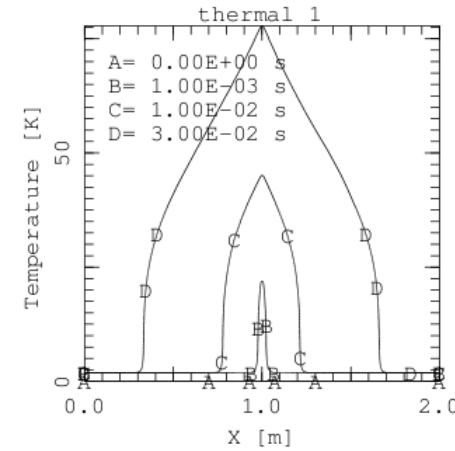
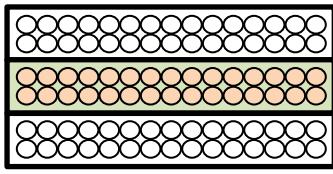
Modelling: time scale

- Heat flow
 - Heat flow from supports and structures 1 s
 - Heat flow in the coil winding 1 s
 - Heat flow along the cable 100 μ s
- Electro-magnetics
 - Steady and transient coil currents 1 s
 - Steady and transient magnetics fields 1 s
 - Current distribution in the cable 1 ms
 - Steady and transient magnetization 10 μ s

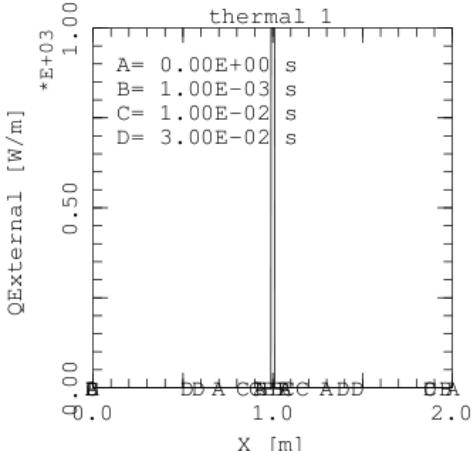
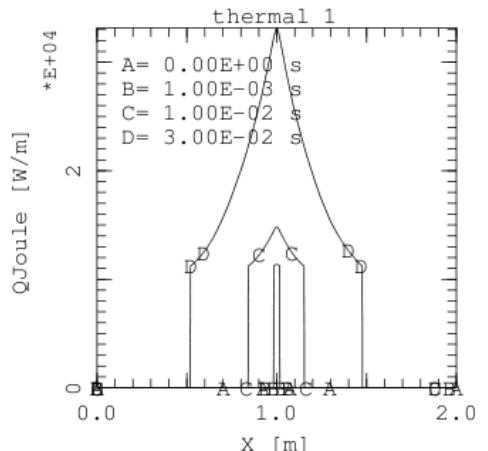
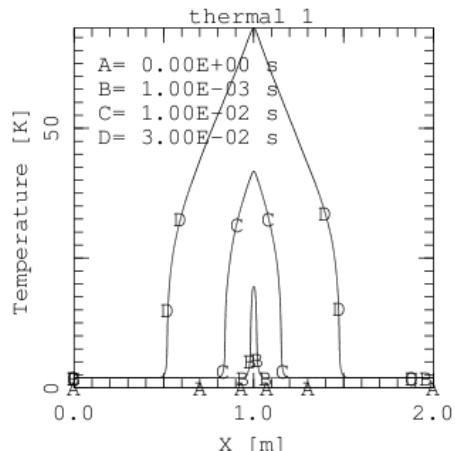
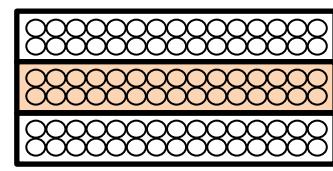
Conductor only



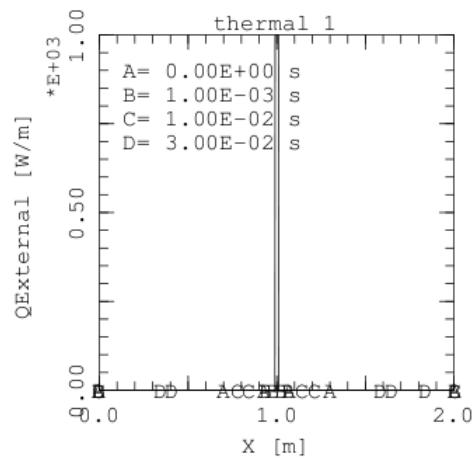
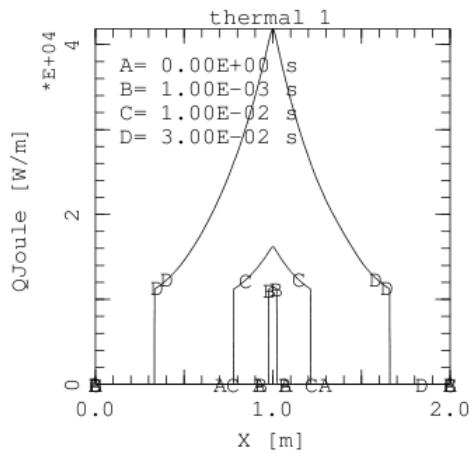
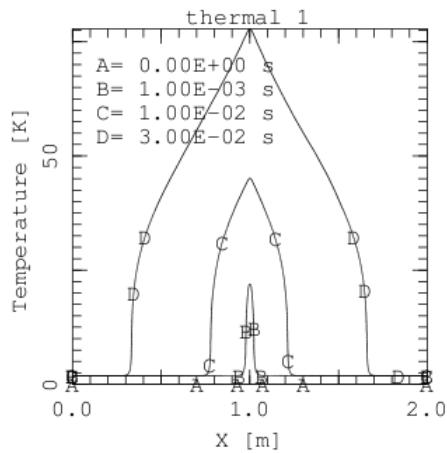
Conductor /insulation



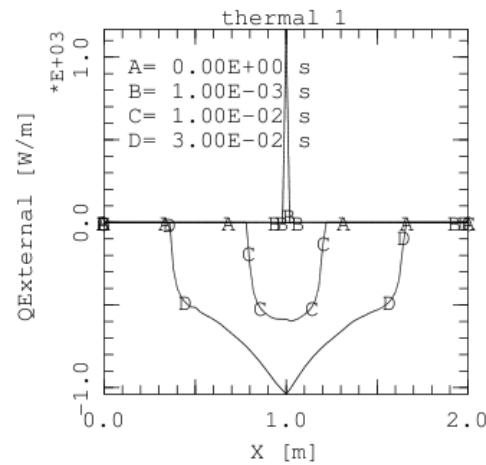
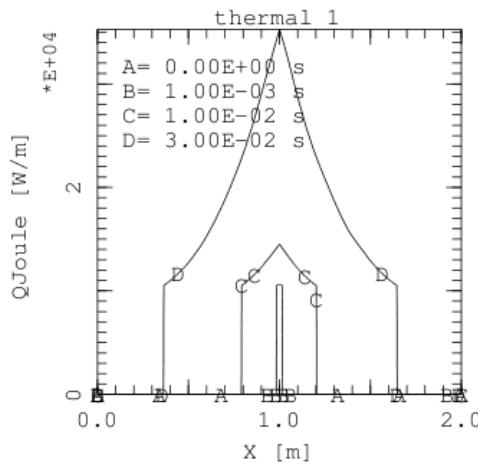
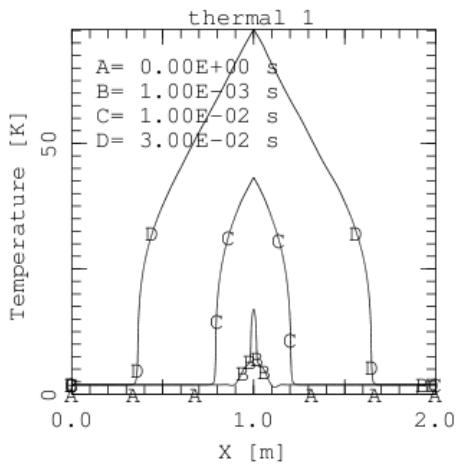
Conductor +insulation



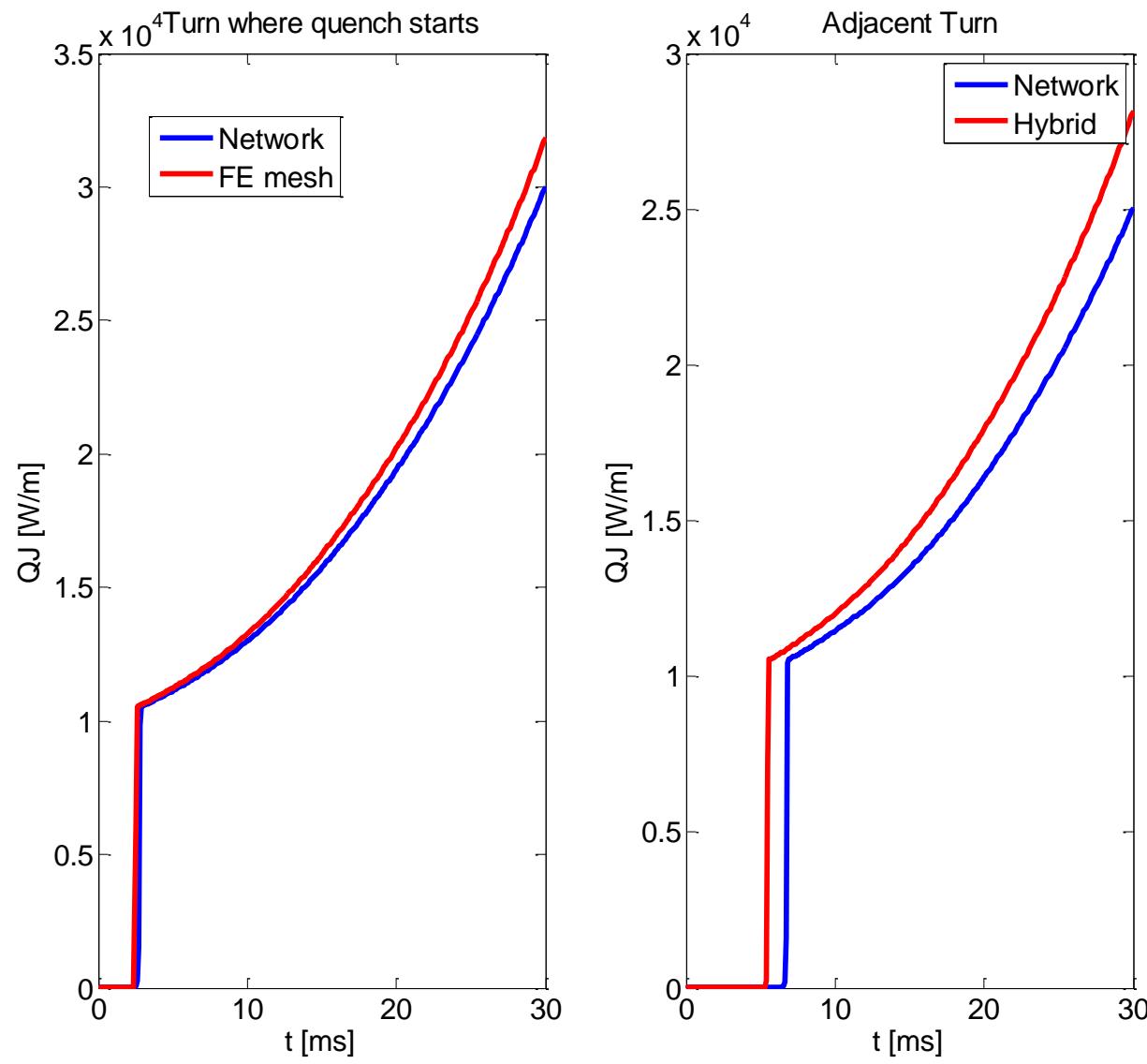
Network



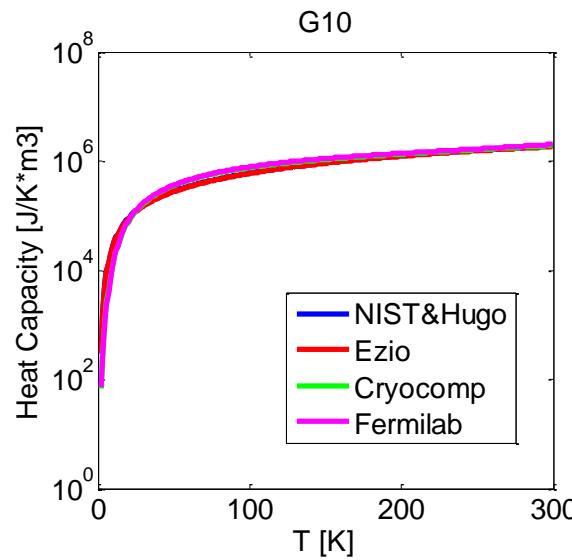
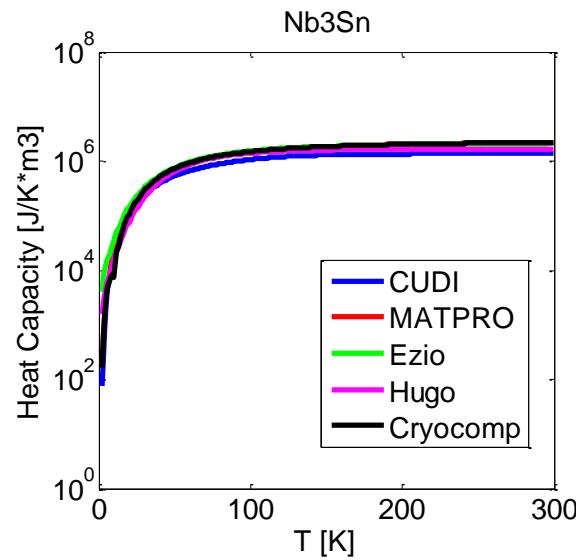
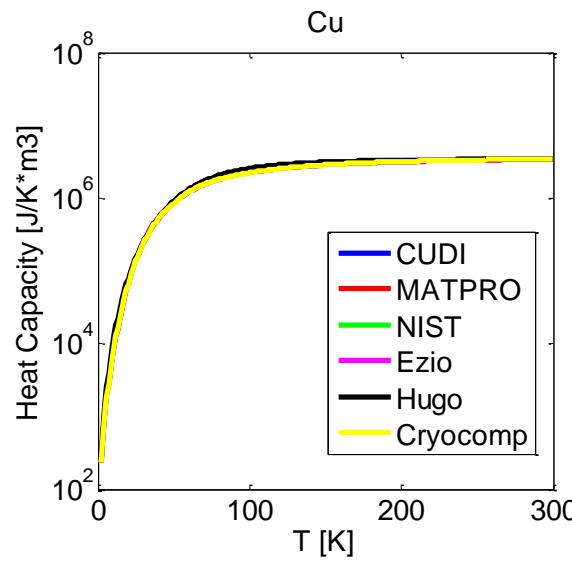
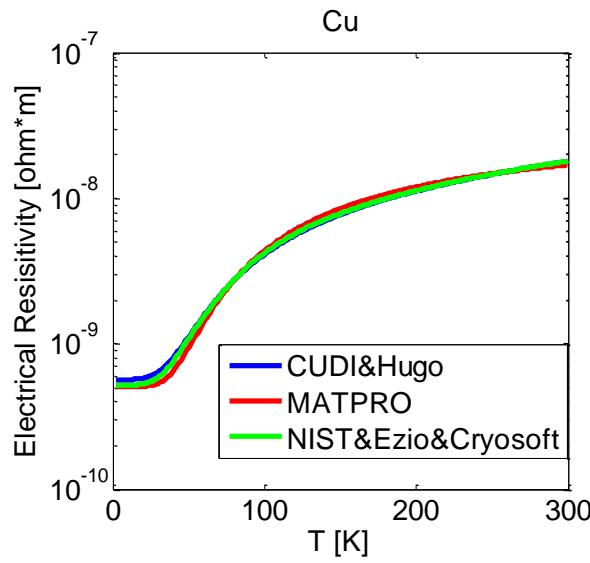
FE mesh



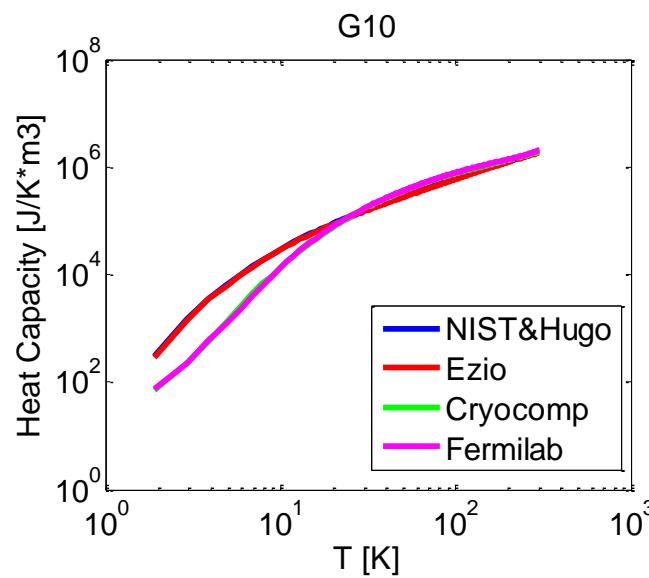
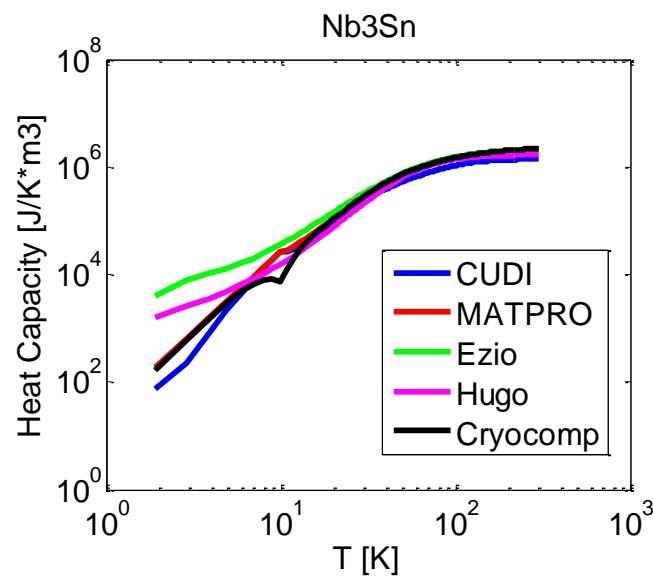
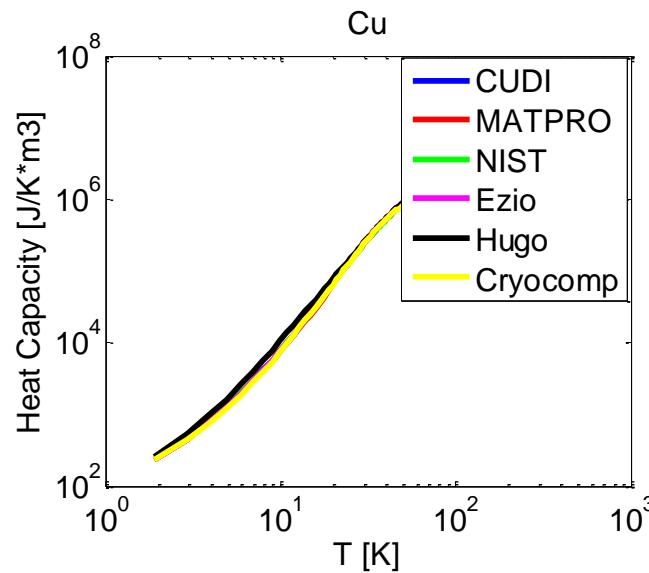
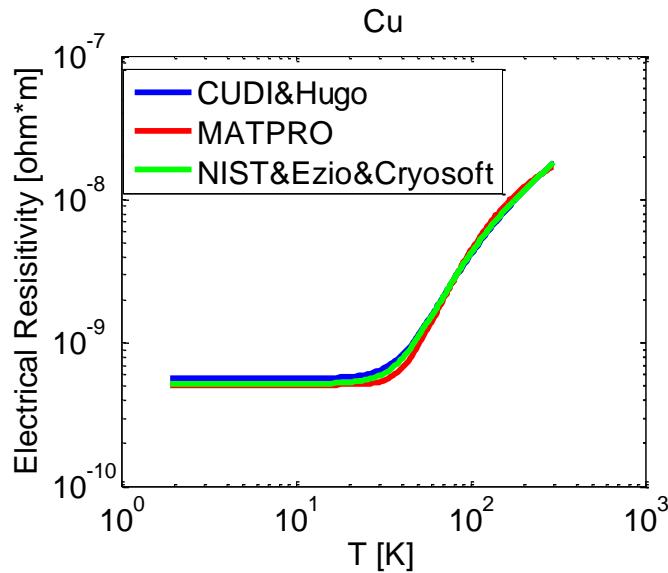
Network vs Mesh. Joule heating



Material Properties



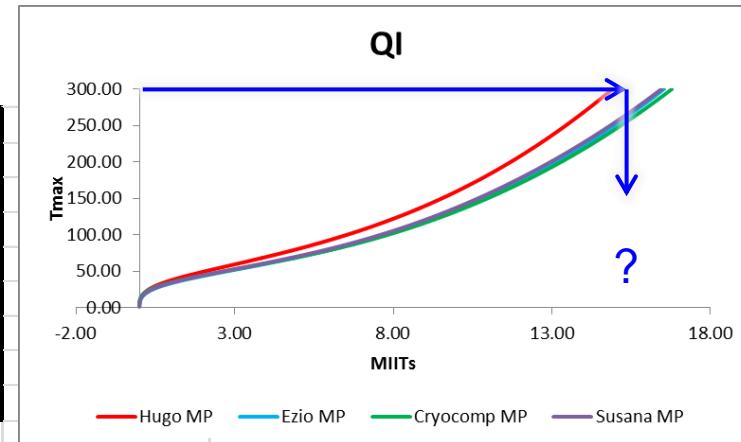
Material Properties



Sensibility to material properties

SMC 11T, B= 12T , RRR=100

Electrical Resistivity		Heat capacity		
Copper	Cu	Nb3Sn	G10	
CUDI (1)	CUDI (1)	CUDI (1)		
MATPRO (2)	MATPRO (2)	MATPRO(2)		
NIST (3)	NIST (3)		NIST (3)	
	Ezio (4)	Ezio (4)	Ezio (4)	
	Hugo (5)	Hugo (5)		
	CRYOCOMP (6)	CRYOCOMP (6)	CRYOCOMP (6)	
			FERMILAB(7)	

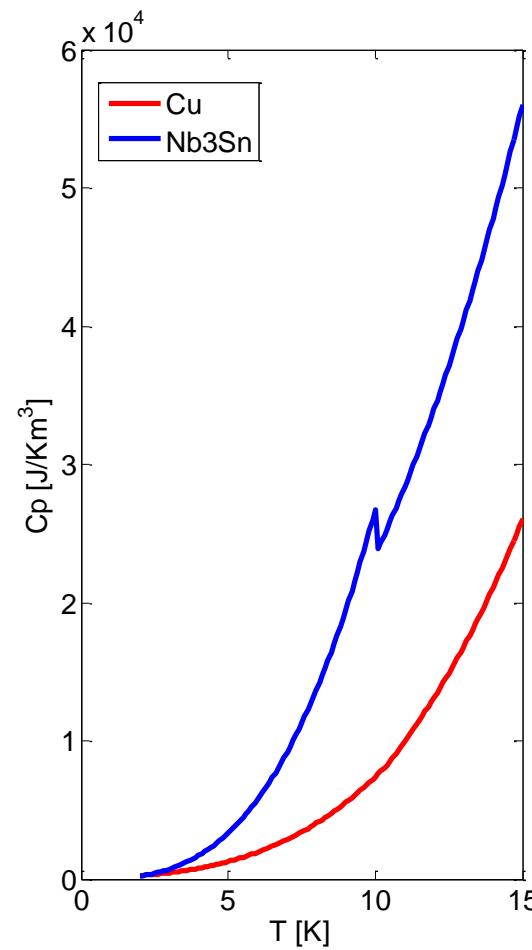
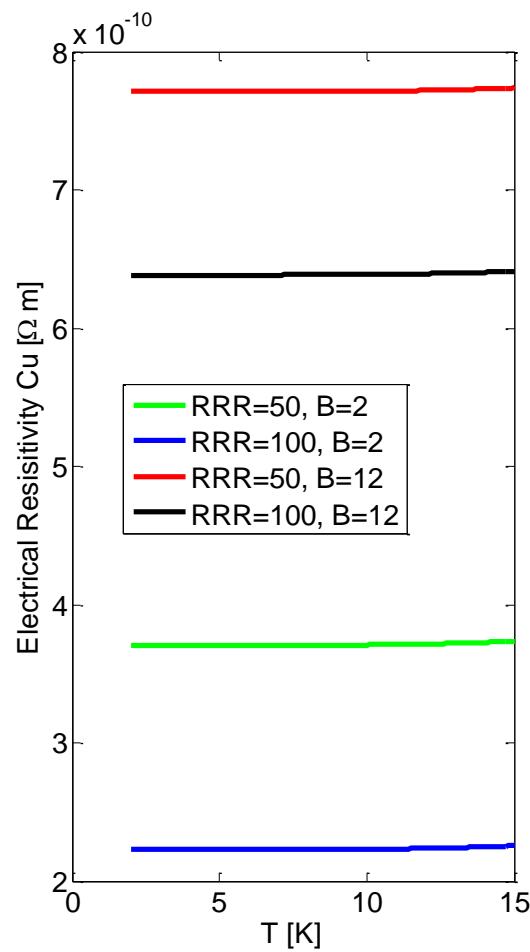


CASE [resCu, CpCu,CpNb3Sn,CpG10]	MIITs for Tmax=300K	delta MIITs	delta MIITs [%]	Comments
1113	13.74			
2113	14.27	0.53	3.86	
3113	15.07	1.33	9.68	
1213	13.74	0	0.00	
1313	13.74	0	0.00	
1413	13.76	0.02	0.15	
1513	14.25	0.51	3.71	
1613	13.65	-0.09	-0.66	
1123	15	1.26	9.17	
1143	15.12	1.38	10.04	
1153	14.4	0.66	4.80	
1163	14.99	1.25	9.10	
1114	13.67	-0.07	-0.51	
1116	14.13	0.39	2.84	
1117	14.25	0.51	3.71	
1553	14.90	1.16	8.44 (HugoMP)	
3666	16.78	3.04	22.11 (Cryocomp MP)	
3444	16.53	2.79	20.33 (Ezio MP)	
3323	16.45	2.71	19.73 (Susana MP)	

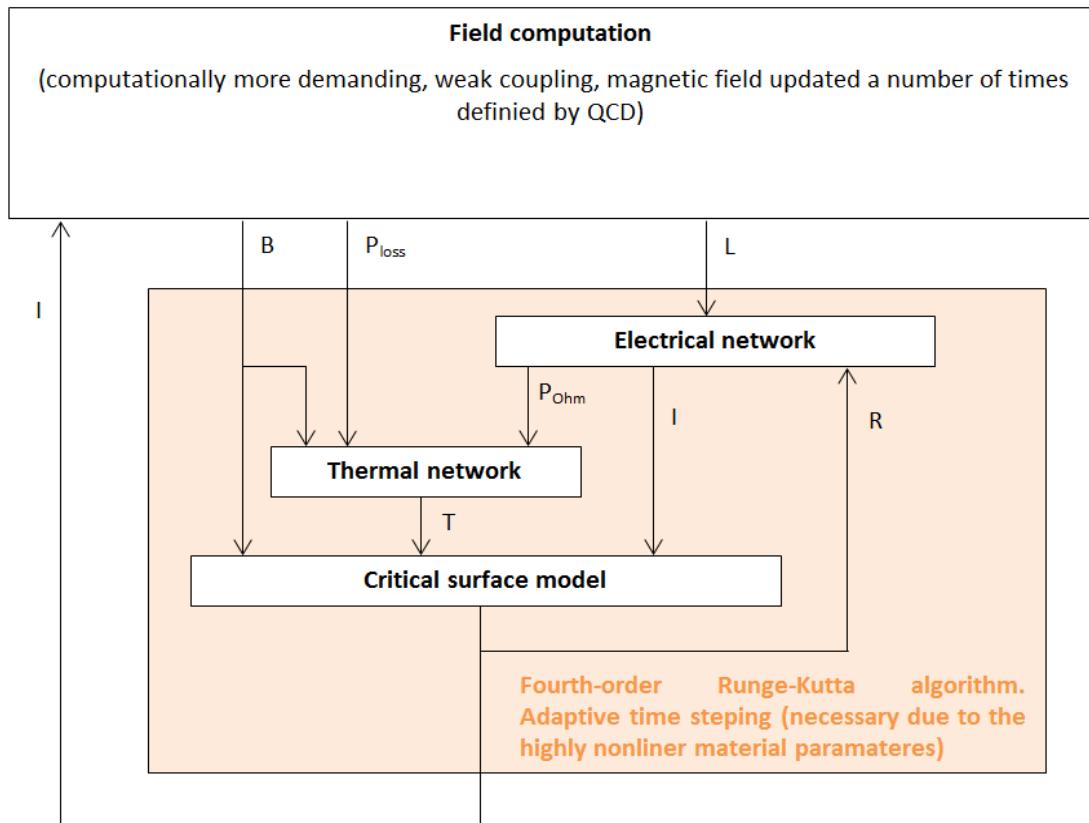
For SMC-11T cable,
MIITs to reach 300 K
under adiabatic
conditions vary from
14 to 17.5 depending
on the material
properties database



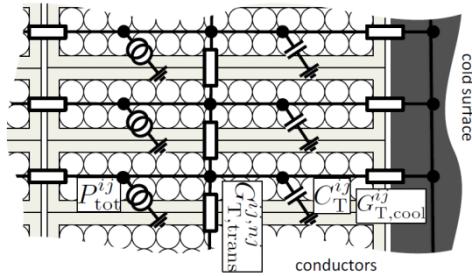
Material Properties Cryosoft [1.9-15 K]



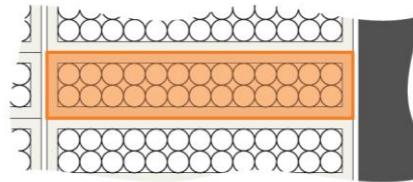
ROXIE Quench Module



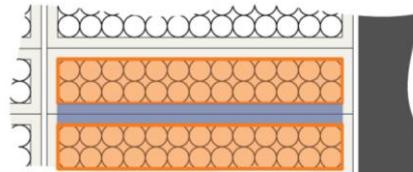
Thermal network:



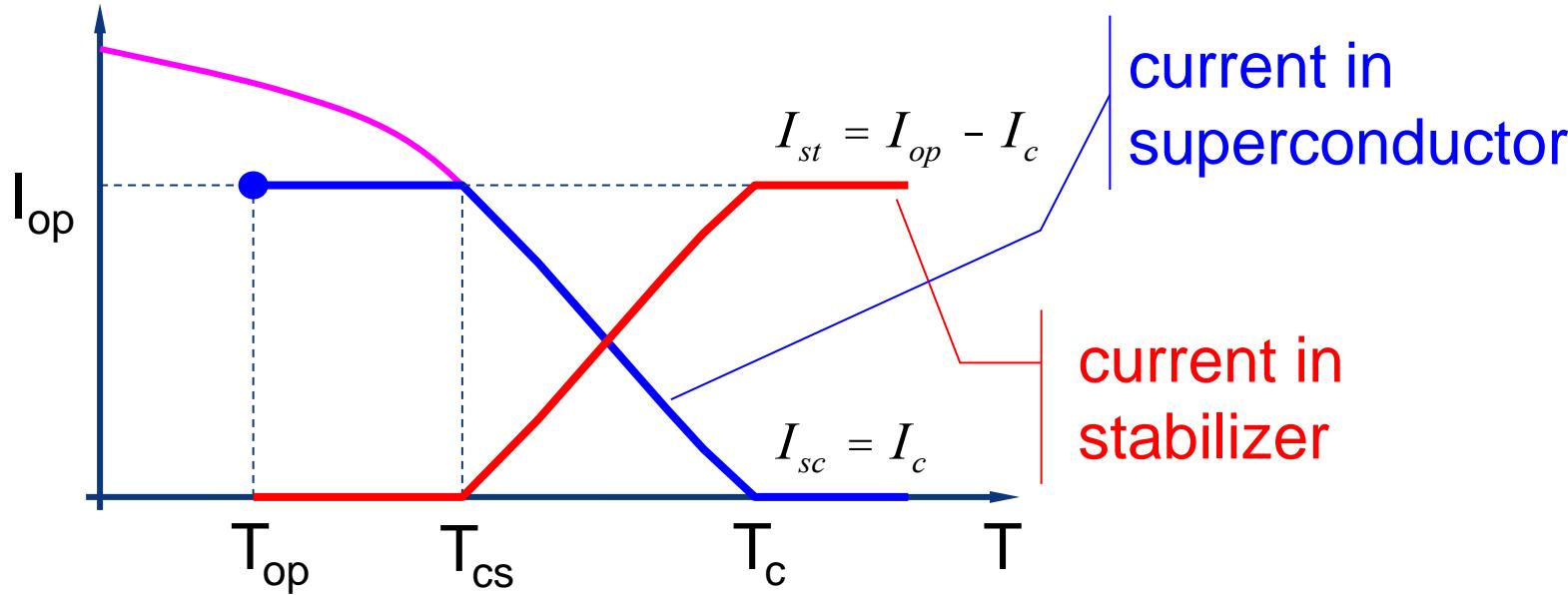
Heat capacity:
includes conductor + insulation



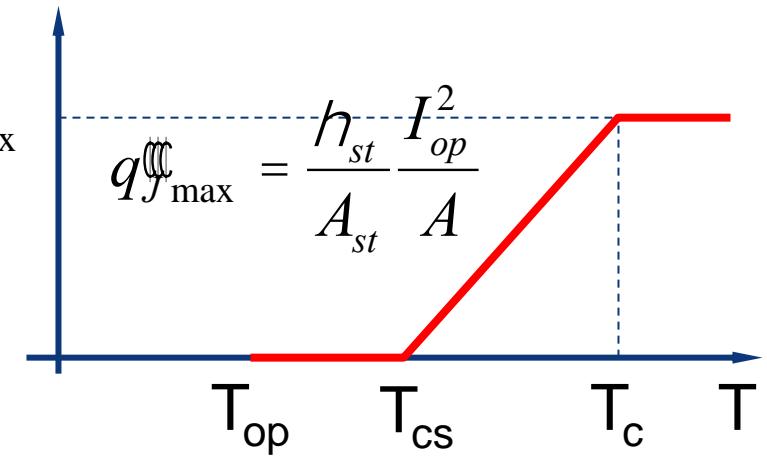
Thermal conductance and heat fluxes:
Conductor without insulation. Uniform temperature in the conductor and linear temperature distribution in between them



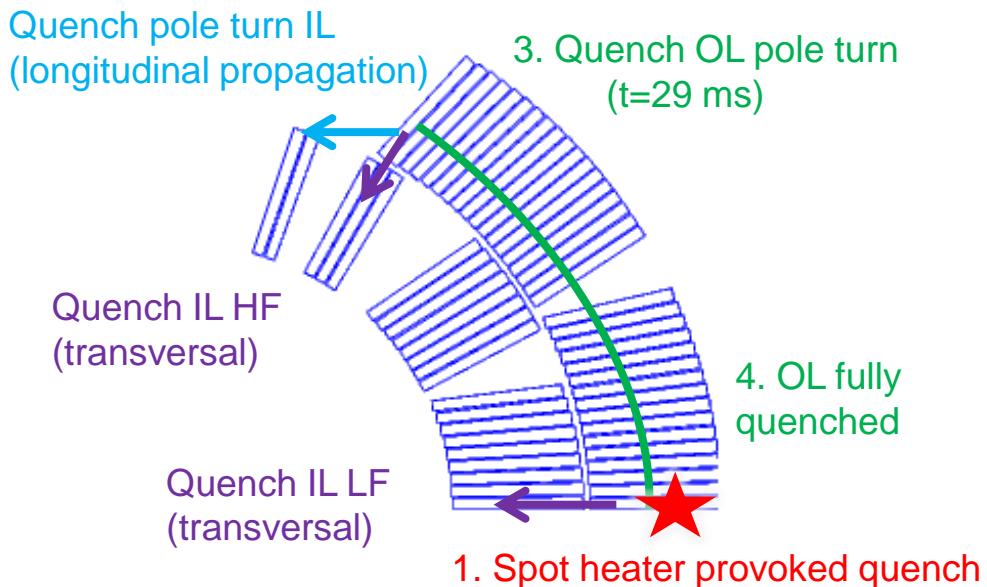
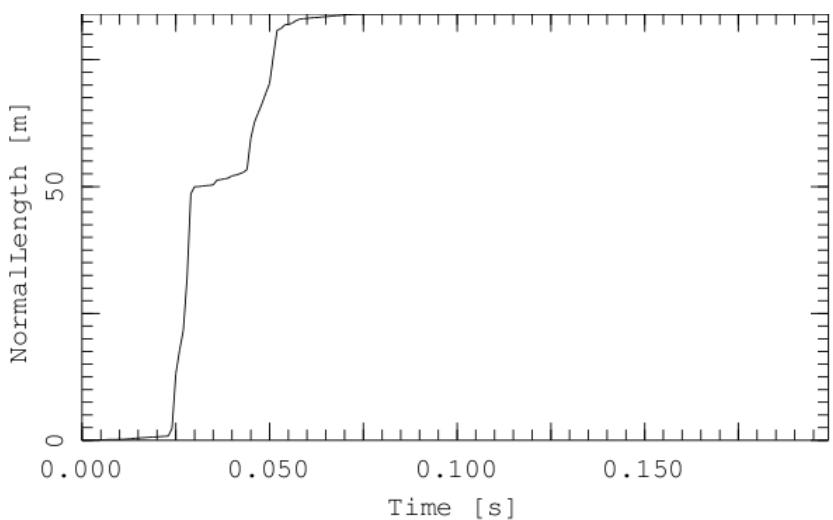
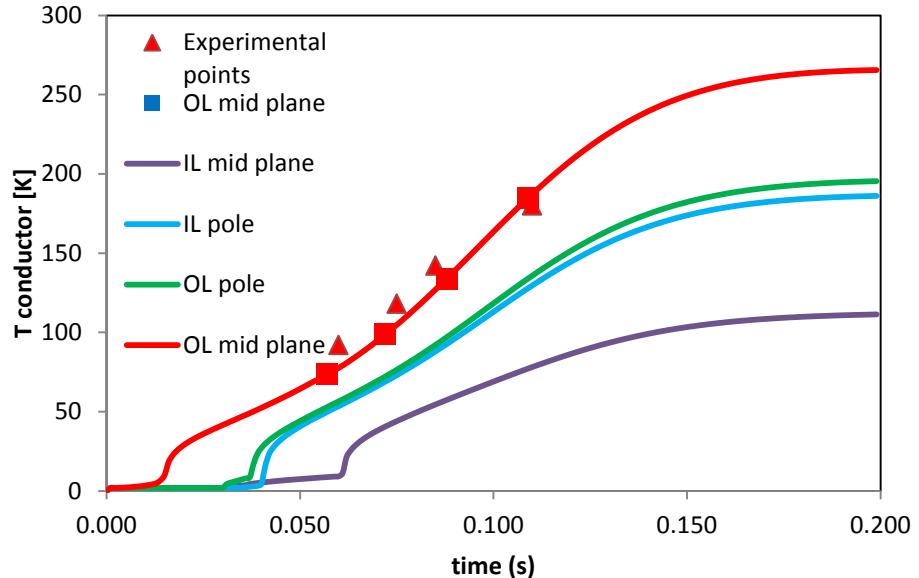
Current sharing and Joule heating



$$q_{\mathcal{J}}^{\mathbb{C}} = \begin{cases} q_{\mathcal{J}}^{\mathbb{C}}_{\max} \frac{T - T_{cs}}{T_c - T_{op}} & \text{for } T < T_{cs} \\ q_{\mathcal{J}}^{\mathbb{C}}_{\max} & \text{for } T_{cs} < T < T_c \\ q_{\mathcal{J}}^{\mathbb{C}}_{\max} & \text{for } T > T_c \end{cases}$$



Higher order thermal coupling for MBHSM01 (Supermagnet)



Looking at the delays ...

- The first conductor that quenches thanks to the quench heaters, quench at the measured delay: 29 ms (heater delay defined accordingly to satisfy this)
- All the OL quenches within ≈ 7 ms
- Quench travels very fast from OL to IL thanks to the longitudinal propagation (≈ 2 ms)
- IL-OL delay due to transversal propagation is ≈ 20 ms in the HF ($B_p=9.5T$) and about ≈ 25 ms in the LF ($B_p=8.5T$)

MBHSM01. Spot heater test

$I = 12 \text{ kA}$

MIITs	T MEASURED	$T_{\text{MAX}} \text{ ANALYTIC}$ (B=5.5 RRR=100)	TMAX FIRST ORDER THERMAL COUPLING (ROXIE)	TMAX HIGHER ORDER THERMAL COUPLING (SUPERMAGNET)
8	92	82	88	74
10	118	105	117	99
12	142	136	156	134
14	180	175	205	185

