Quench Protection Issues in Nb3Sn Accelerators Magnets

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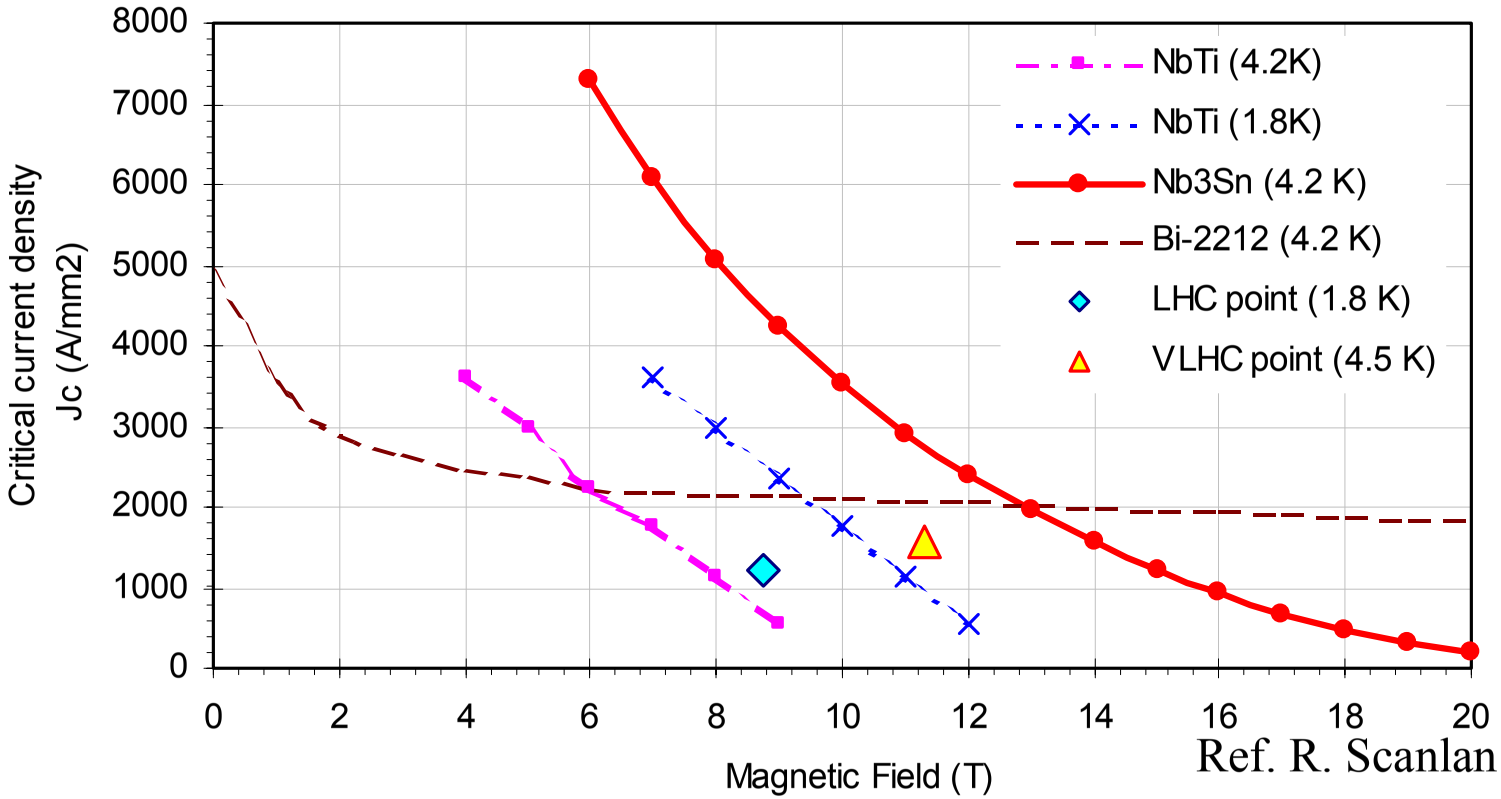
Outline

1. **Quench Protection Studies**
   - Simulations of the quench
   - Peak temperature issue
2. **Material Properties and Quench Parameters**
   - Thermal conductivity
   - Quench integrals
   - Quench velocities and Quench heater studies
3. **Thermal Shock experiments**
   - Cable quench test and simulations
   - Small Nb_3Sn magnet quench test

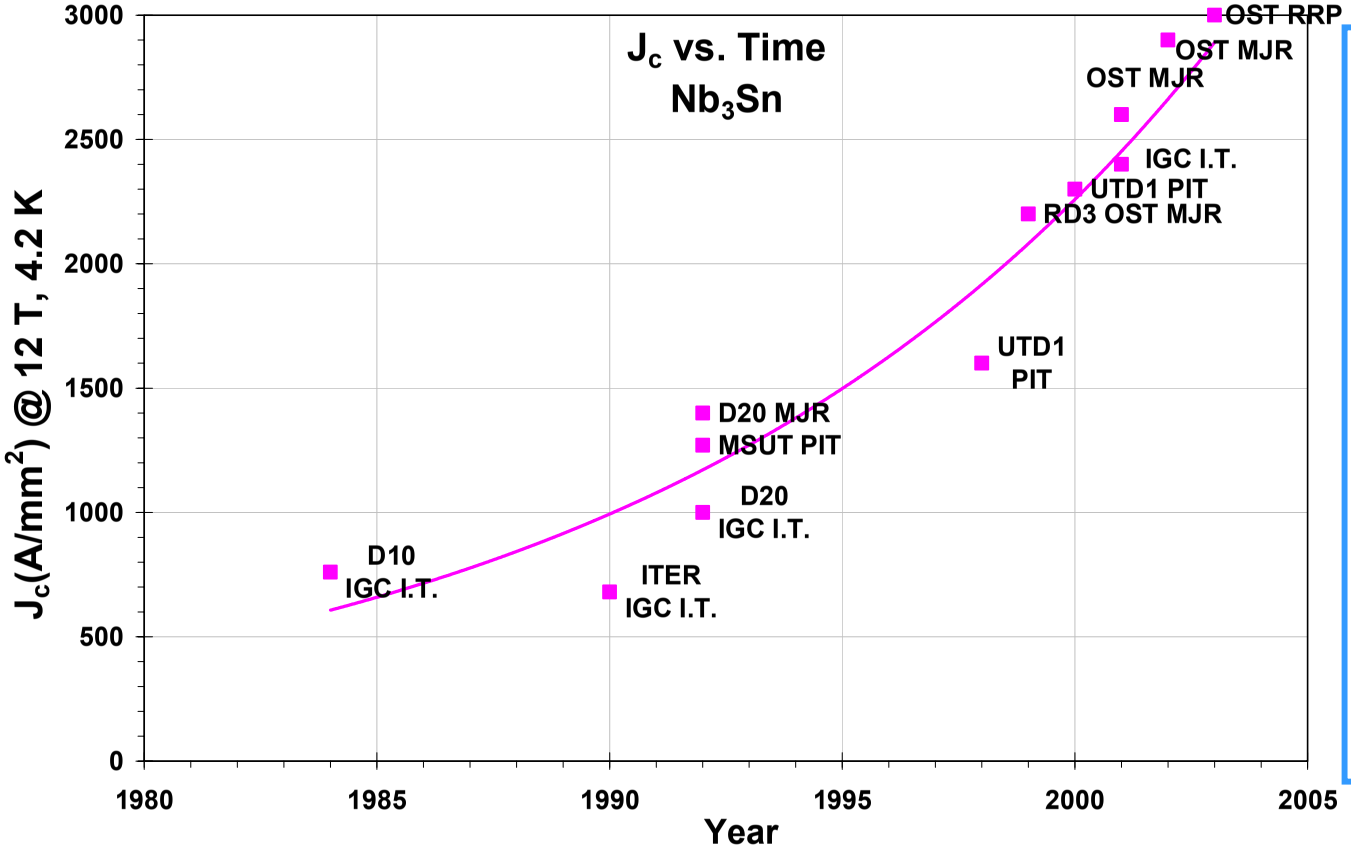
Accelerator development

Accelerator		E (TeV)		R (km)	B_0 (T)	Magnet	cooling	Year	
Tevatron	Fermilab	2	c.m. p-p_{bar}	1	4.5	NbTi	LHe I	‘83	Operating
HERA	DESY	0.9	p -target	1	5.5	“	“	‘91	Prot.-elect.
RHIC	BNL	0.2	c.m.	1.2	3.5	“	“	‘99	Heavy ions
SSC	SSCL	40	c.m. p-p	14	6.6	“	“	‘93	Dismissed
LHC	CERN	14	“	4	8.3	“	He II, 1.9 K	2007	Scheduled
VLHC-1	Fermilab	40	“	35	2	superferric	LHe, 4.5 K	2015	HEPAP recc.
VLHC-2	“	175	“	“	11	Nb_3Sn	“	2030	?



Ref. R. Scanlan

Nb_3Sn Conductor Development



US/HEP Conductor Development Program

Goals

- cost-effective
- high-performance

Collaborations

- National Laboratories
- Universities
- Industry

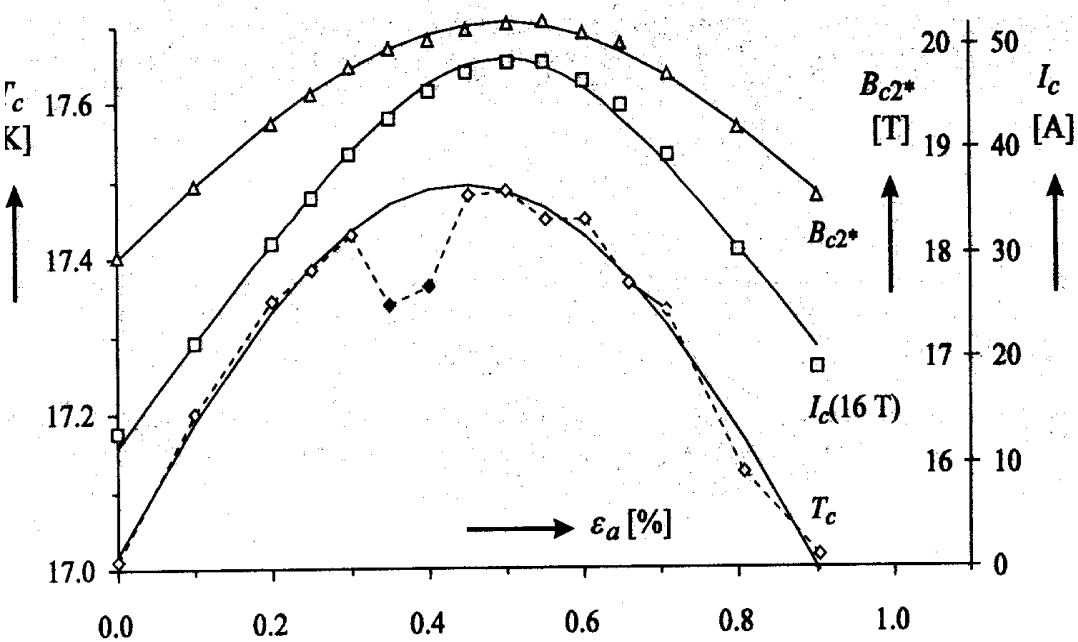
Parameter	Goal	Progress
Jc (A/mm^2)	3000	2600-2900
Deff (μm)	< 40	100-120 (MJR, IT); 50 PIT
Piece length (km)	> 10	0.25-1.5 (MJR); 0.25-1 (high Jc IT)
Heat treatment (hr)	< 400	148
Cost ($/kA-m at 12 T)	< 1.50	5.50 (Int. Sn); 7.75 (MJR)

Nb_3Sn Strain Dependence

Nb_3Sn is a very brittle material after reaction:

- Bare Nb_3Sn filaments break at ~**0.2%** uniaxial tensile strain.
- In composite strands, irreversible I_c degradation starts at ~**0.5%**

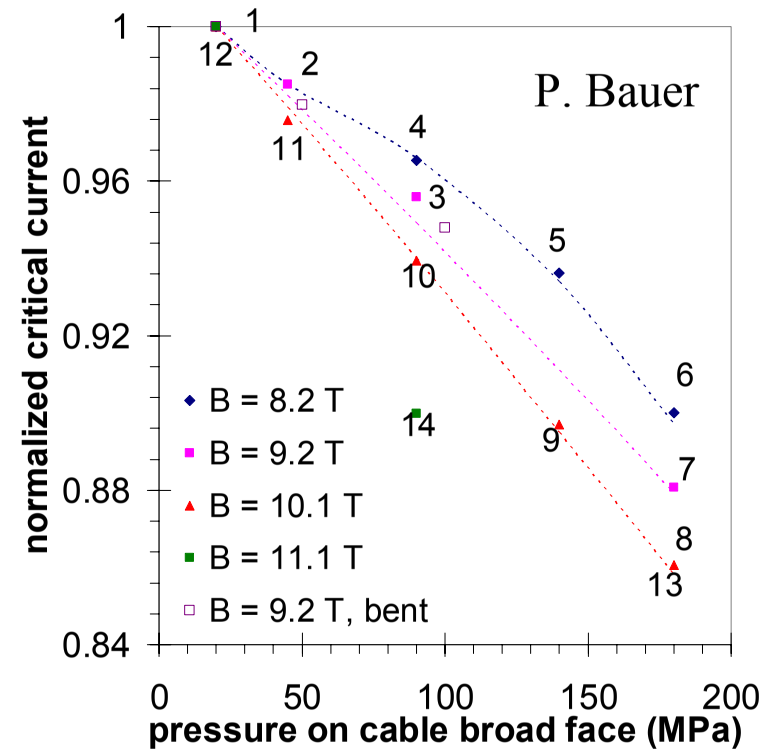
Degradation of the critical parameters with applied strain



A. Den Ouden, thesis, Univ. of Twente

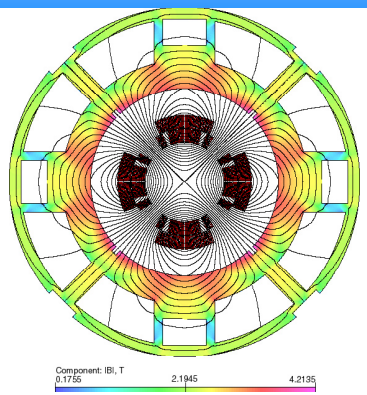
The maximum Ic corresponds to the minimum intrinsic strain

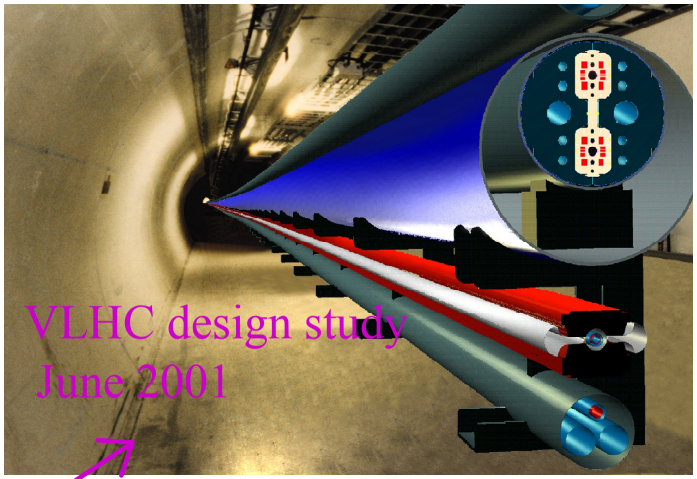
Few studies on cables: max. pressure on broad face for impregnated cables ~150 MPa



Nb_3Sn magnets for accelerators

- LHC upgrade
  - Luminosity upgrade
    - Quadrupoles at IR
    - Separation dipoles at IR
  - Energy Upgrade: arc magnets

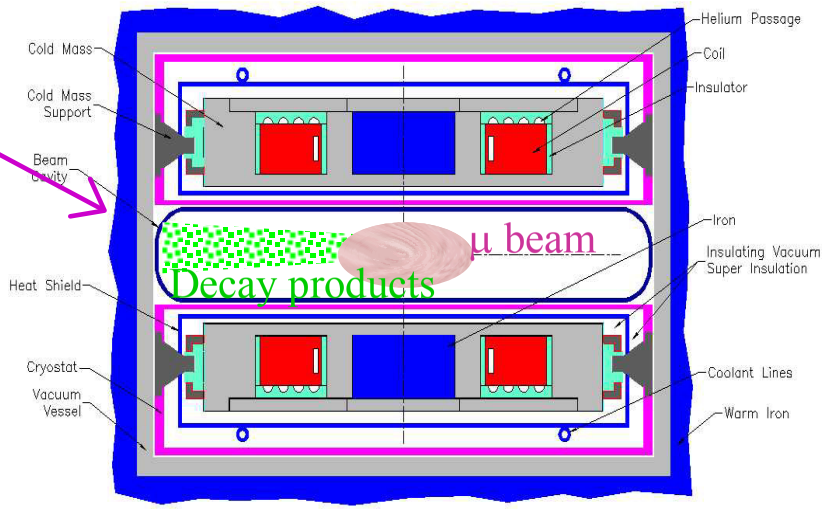




- Tesla: quad for final focus
- Very Large Hadron Collider (VLHC)
- Muon Collider, ν factory

(high T margin for high radiation doses)

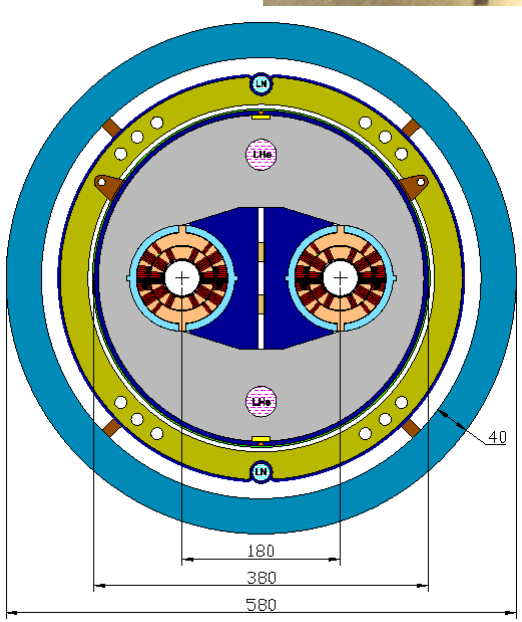
- …

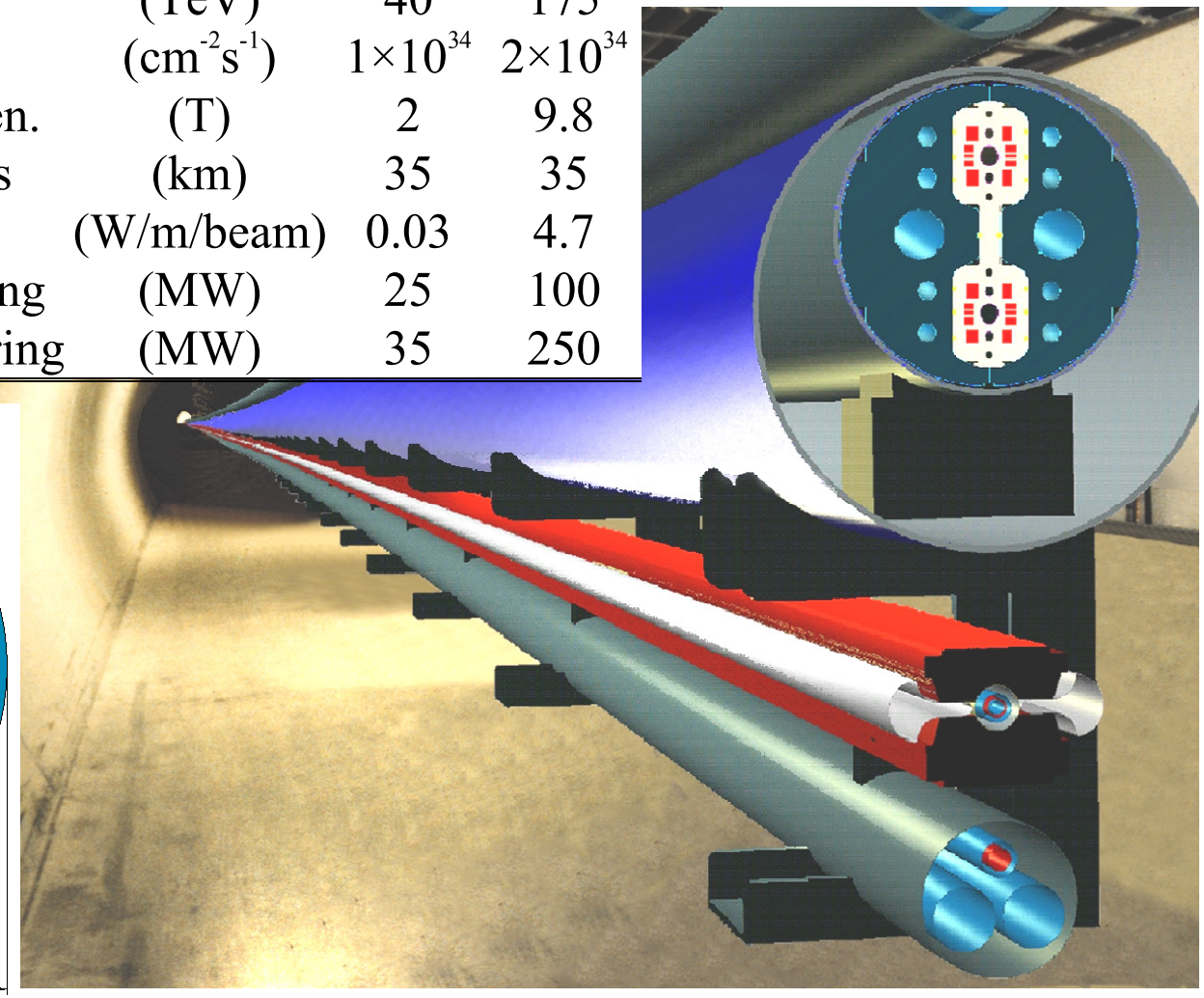


VLHC Design Study

		Stage 1	Stage 2
Total Circumference	(km)	233	233
Center-of-Mass Energy	(TeV)	40	175
Peak luminosity	($cm^{-2}s^{-1}$)	1×10^{34}	2×10^{34}
Dipole field at collision en.	(T)	2	9.8
Average arc bend radius	(km)	35	35
Synchrotron radiation	(W/m/beam)	0.03	4.7
Average power use per ring	(MW)	25	100
Total installed power per ring	(MW)	35	250

Very Large Hadron Collider





VLHC FNAL magnets

Magnet parameters and comparison with LHC main dipole magnets

	Com. Coil	cosθ	LHC dipole
Bore Field/Peak Field (T)	10/11.3	10/10.5	8.3
Operating Current - I_o (kA)	23.5	21.3	11.8
Inductance (mH/m)	2×1.5	2×1.07	2×3.7
Stored Energy (kJ/m)	2×414	2×243	2×245
Length (m)	16	16	14.5
Cable Cross Section (mm^2)	31	29.3	24/28
Cu/non Cu	1.05	1.2	1.6/1.9
J_{Cu} (A/mm^2)	1987	1734	709

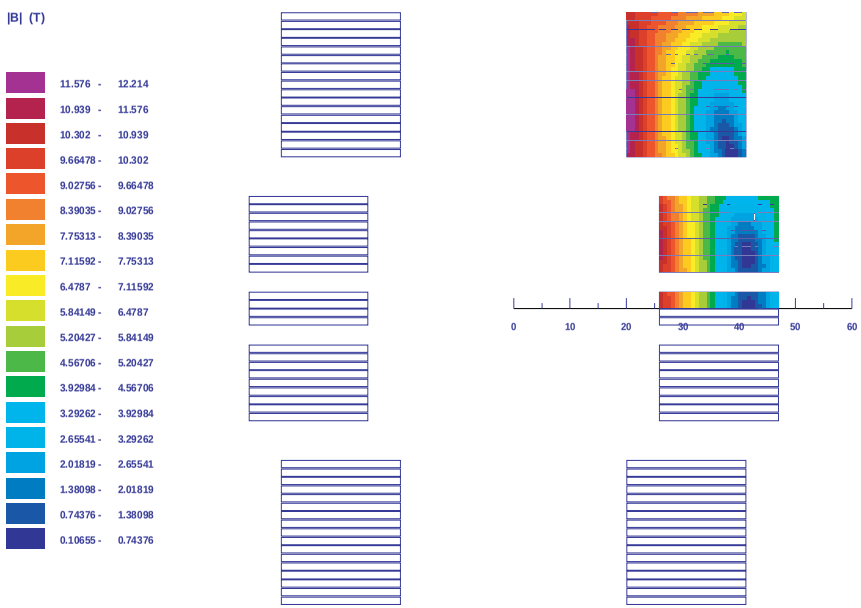
<u>With no active protection</u>

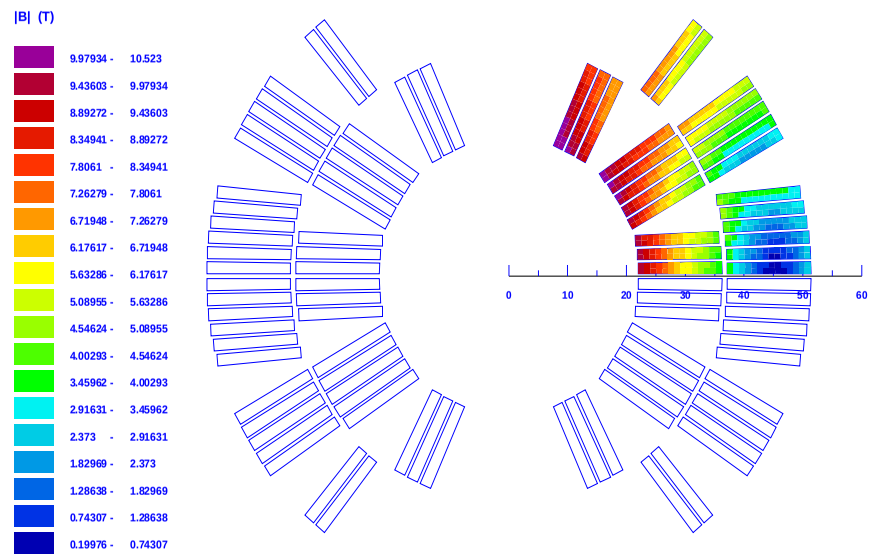
Power/volume = ρJ_{Cu}^2 =

$\cong 6\cdot 10^{-10}\Omega m\cdot 10^{18} A^2/m^4$=

= 600 MW/m^3 melts

metals in a few sec!





Common Quench Protection Strategy

1- <u>Quench detection</u> as fast as possible for accelerator magnets:

- Voltage taps detecting resistive growth
- Noise rejection with bridge circuit
- Signal processing (software)

2- <u>Current disconnection</u>

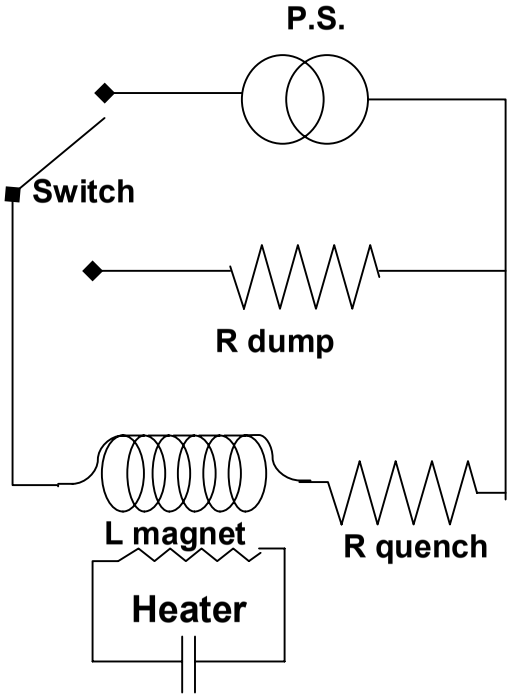
- Switch
- PS shut-down

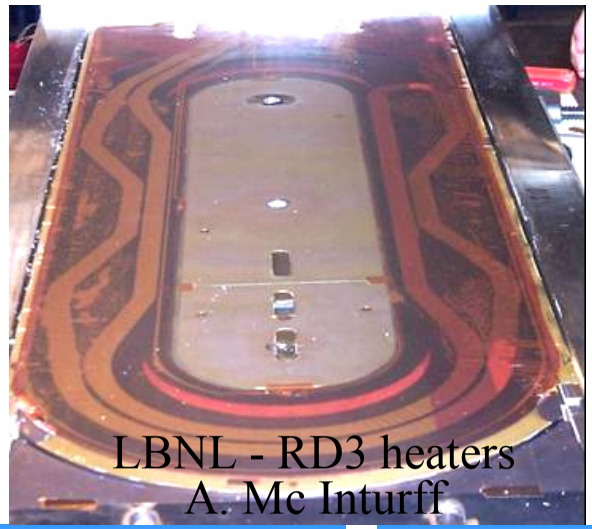
3- <u>Stored energy extraction</u>

- Extract stored energy into an external dump resistor

4- <u>Spread energy into the winding</u>

- Natural quench propagation – only for small magnets
- Quench heaters
- "Quench-back" (quench induced by fast current decay)





LBNL - RD3 heaters
A. Mc Inturff

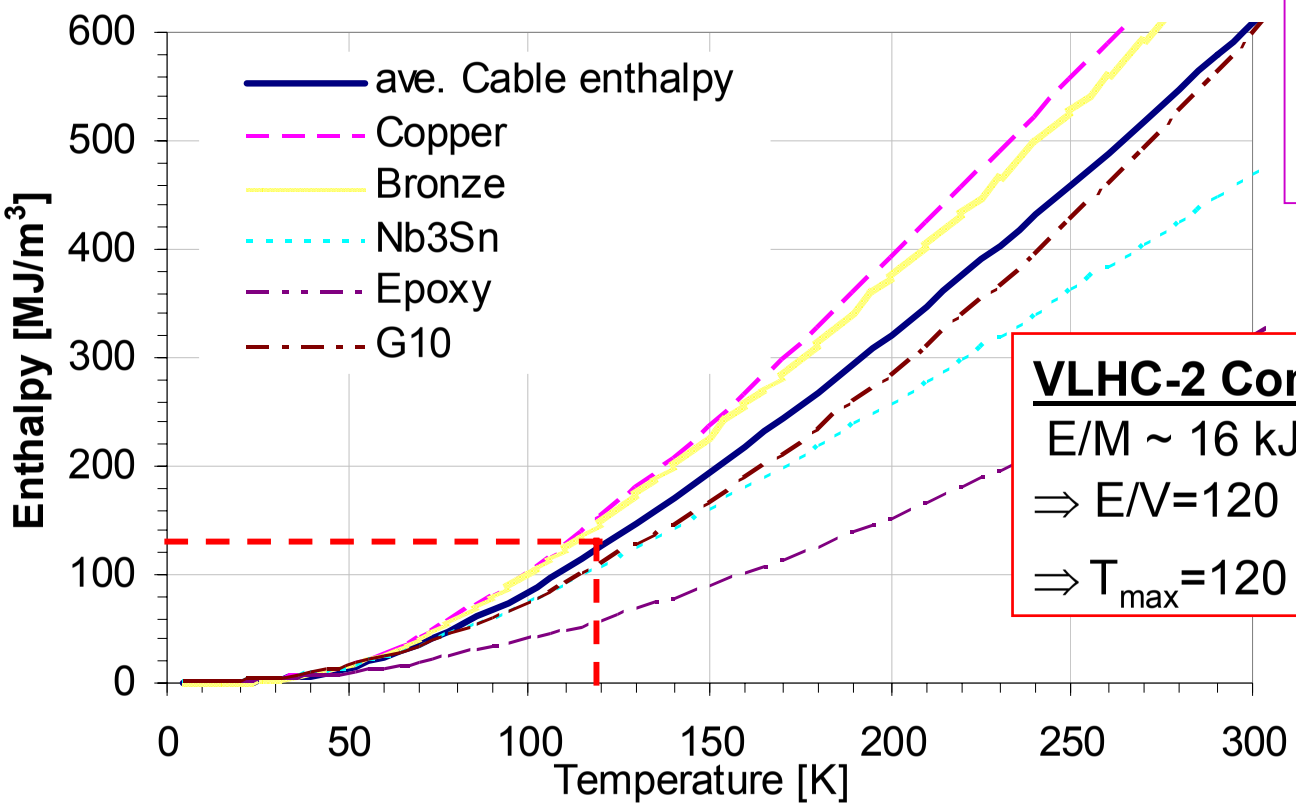
Protection of Large Magnets

$V_{max} = I_0 \cdot R_{Dump}$; R_{Dump} chosen to have $V_{max} < 1$ kV

=> R_{Dump} is fixed with the current, cannot increase with magnet size

=> Spread energy into the coils as uniform as possible with heaters

Example:



For $I_0 = 20$ kA

$\Rightarrow R_{Dump} = 50\ m\Omega$

$\Rightarrow V_{max} \cdot I_0 = 20$ MW

$\Rightarrow E_{dump} = 2$ MJ in 0.1s

VLHC-2 Common Coil

E/M ~ 16 kJ/kg

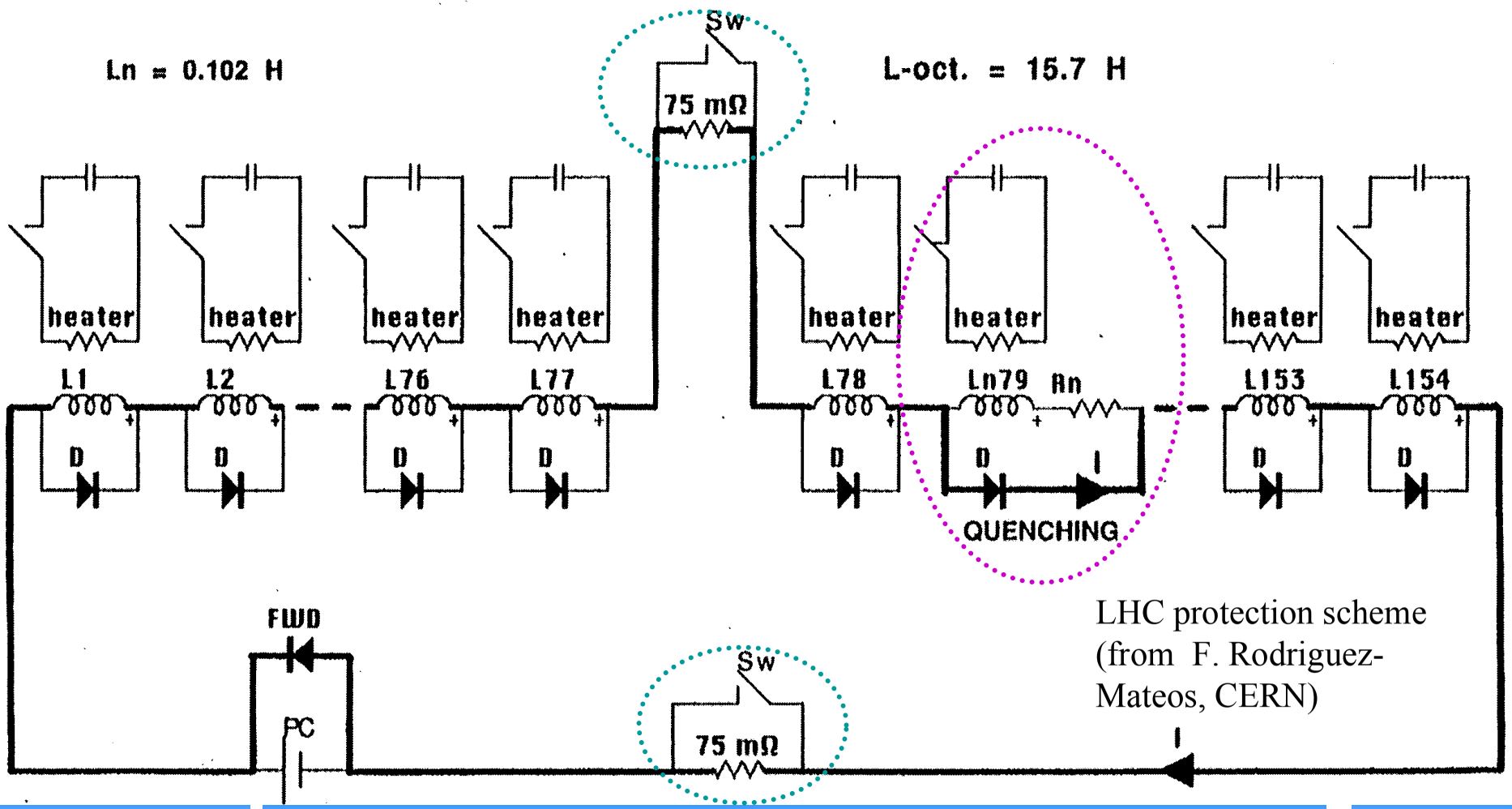
$\Rightarrow$ E/V=120 MJ/m^3

$\Rightarrow T_{max}$=120 K

Quench protection in a string

Bypassing the quenching magnet (through external thyristors or cold diodes)

⇒ Two current circuit: **1- Magnet string + dump resistors** ($\tau \sim 100$ sec)
2- Quenched magnet + diode ($\tau \sim 100$ ms)



LHC protection scheme (from F. Rodriguez-Mateos, CERN)

Hot Spot Temperature

Adiabatic heat balance equation

Joule heating per unit volume

$$\rho(T) \quad J(t)^2 \, dt = c_P(T) \, dT$$

Temperature rise

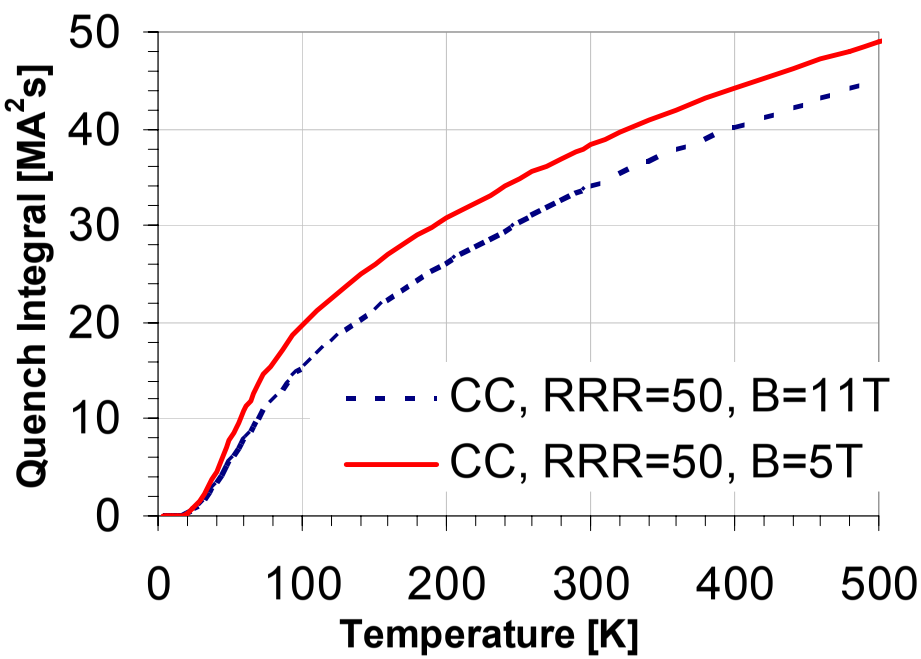
Definition:

The *QI* is the square current integrated in time [MIIts = MA^2s]

$$QI(T_{peak}) = \int_0^{\infty} I^2(t)\,dt = A^2 \int_{To}^{Tpeak} \frac{c_P(T)}{\rho(T)}\,dT$$

Current decay Material properties

Magnets with the same coil composition, refer to the same MIIts curve, a way to predict the hot spot temperature.



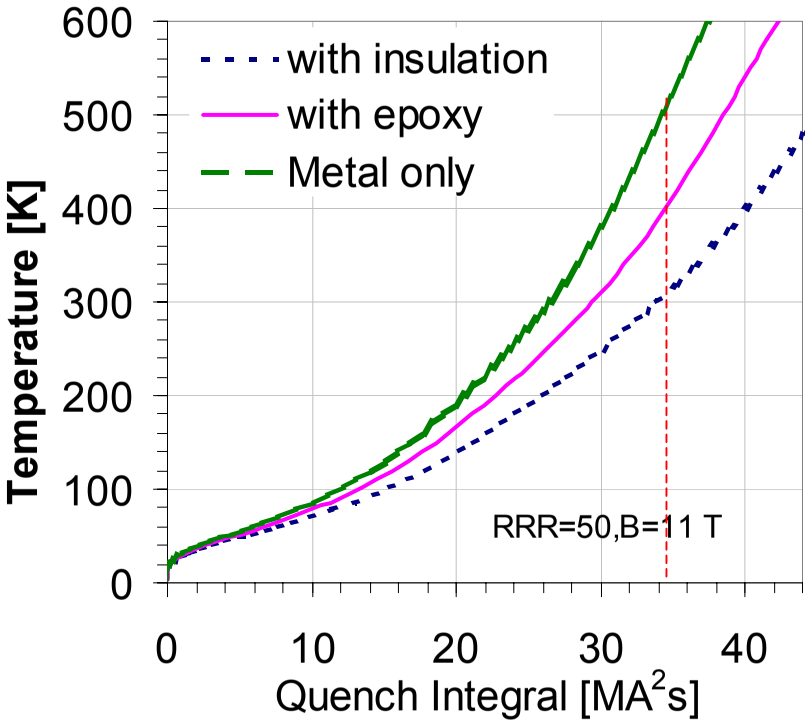
To reduce T_{peak}:

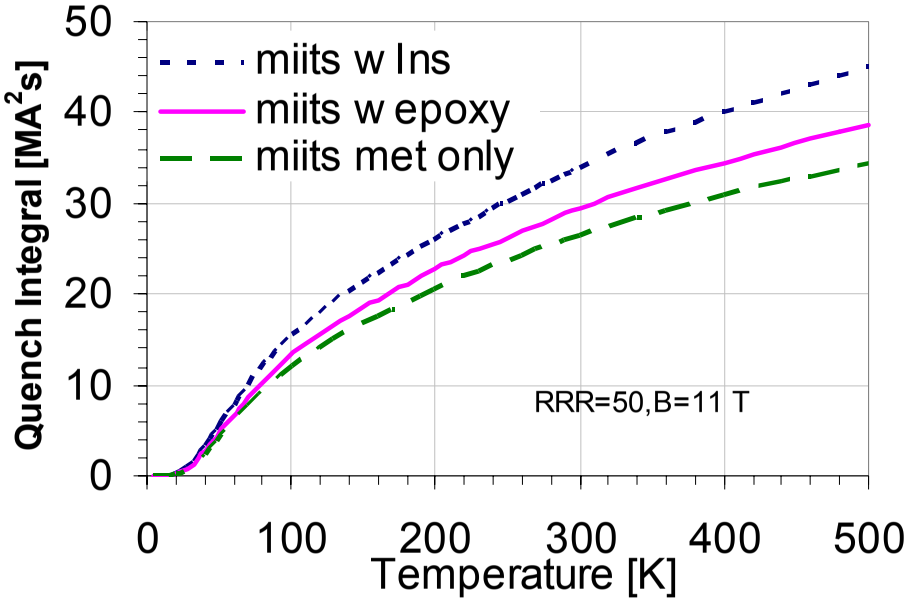
- Decrease J (larger cable, more copper)
- Lower resistivity
- Fast current ramp down (early quench detection and fast heater action)

Hot Spot Temperature

- Adiabatic equation (no heat exchange with Helium ; no heat conduction) => conservative peak temperature estimation ?
- The insulation can absorb heat (~ as LHe for NbTi magnets)
- Heat diffusion into 0.1 mm insulation

Diffusivity Material	D (m^2/s) at 4 K	D (m^2/s) at 300 K	Δt (ms) at 4 K	Δt (ms) at 300 K
G10	$9 \cdot 10^{-5}$	$3 \cdot 10^{-7}$	0.1	33
Epoxy	$6 \cdot 10^{-5}$	10^{-6}	0.2	10



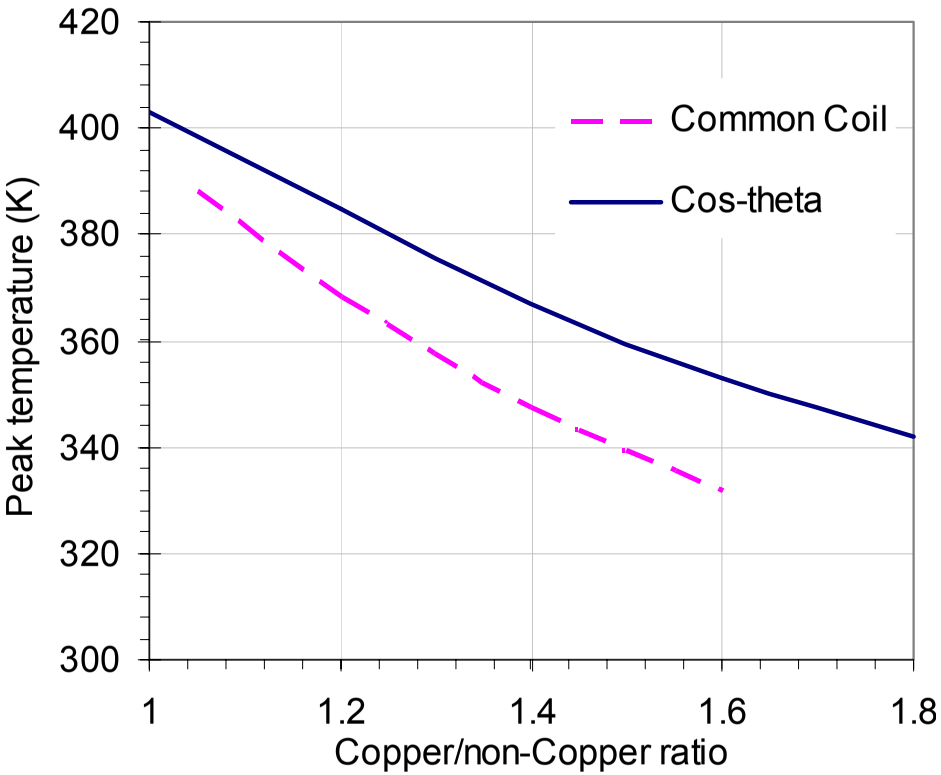


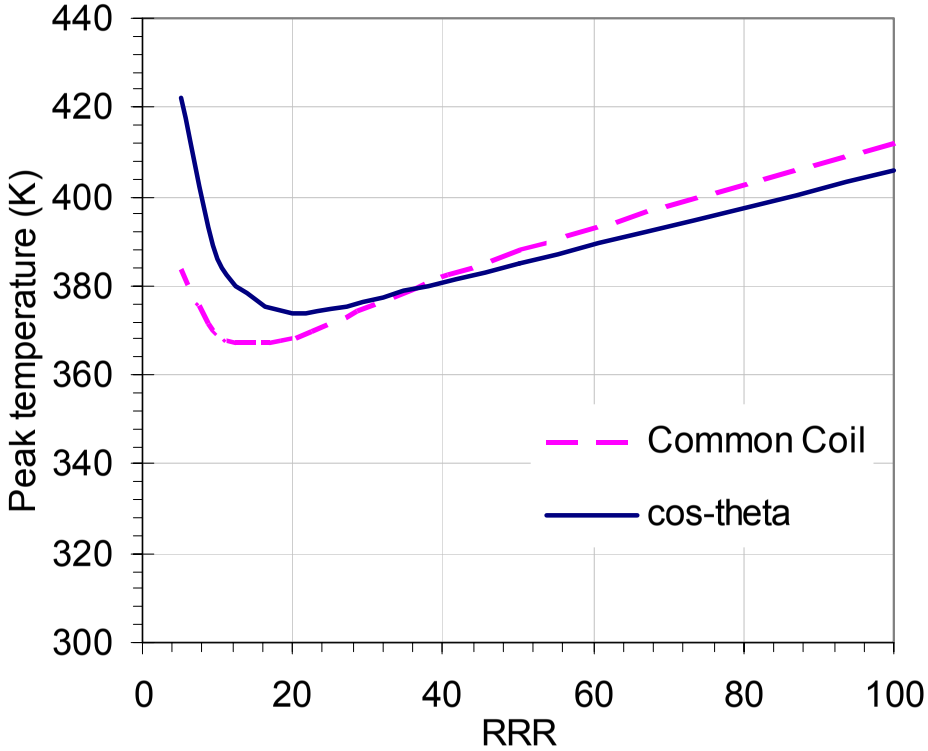
Quench Simulations

1. with numerical codes
   - VLHC-2 magnets
   - Protection requirements
2. Analytical model
   - Generic Nb_3Sn accelerator magnet
   - Peak temperature trends varying several parameters
3. FE model
   - Cable quench experiment
   - Detailed temperature distribution (T gradients)

VLHC Quench Protection

Conductor parameters: copper content and RRR





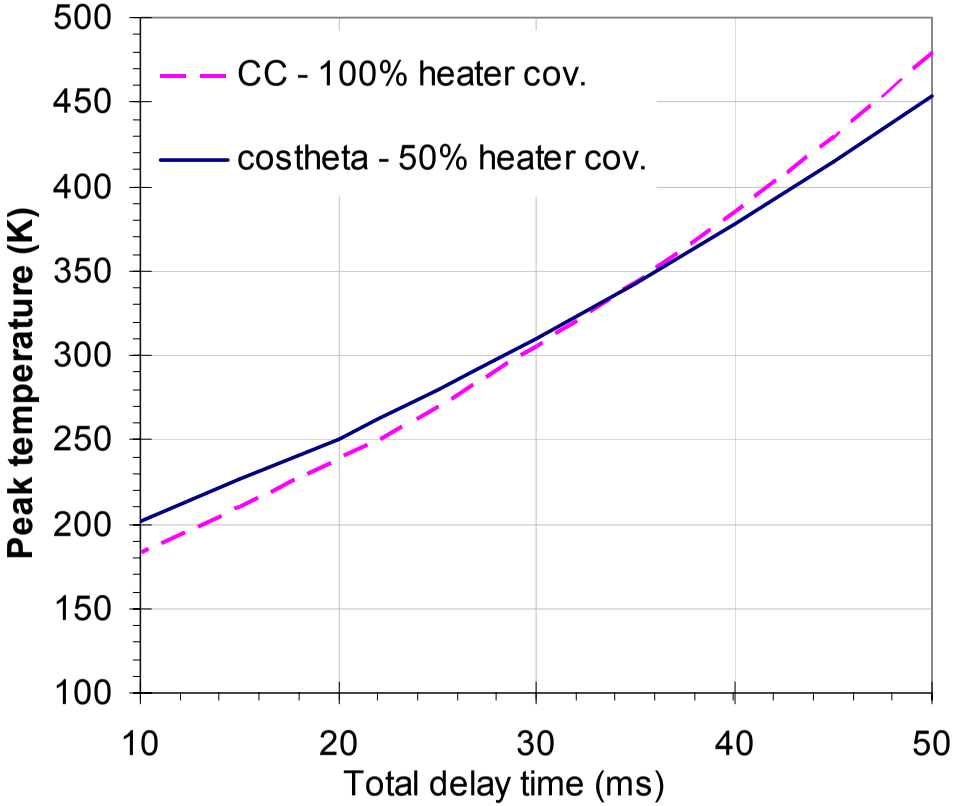
<u>The resistance affects the quench process in two antagonistic ways:</u>

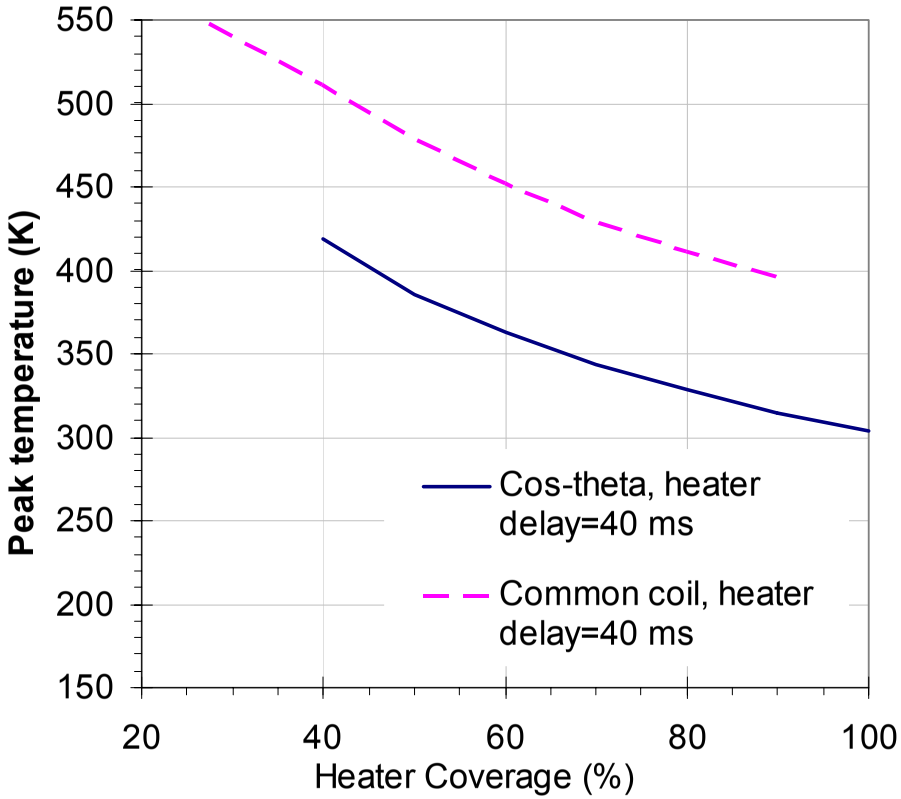
1- the lower the resistance the lower the heat generation at the hot spot;

2- the lower the overall resistance of the magnet, the longer the decay time.

VLHC Quench Protection

We need an active protection system: heater efficiency





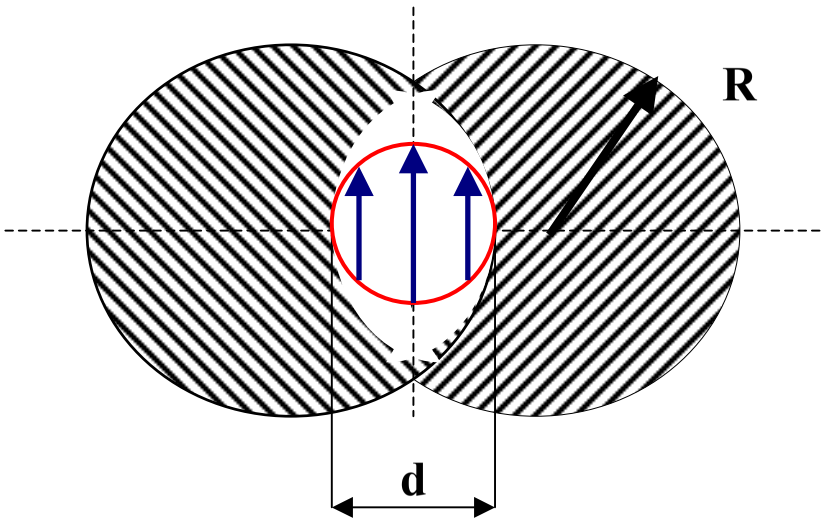
Voltage :

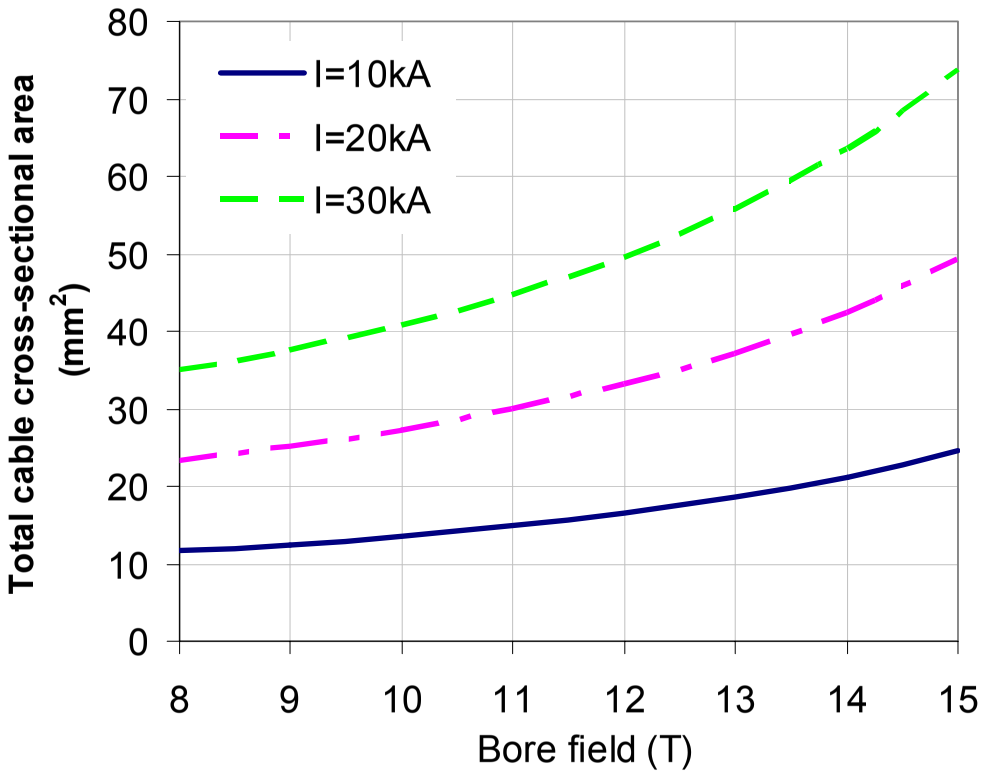
For $V_{max} < 1$ kV, the cosθ/common coil magnets require 50/70% heater coverage.
V depends also on the symmetry of the heater strips.
Heater failure has to be avoided, to avoid high T, V and high thermal stress.

General HFM Quench Study

An analytical calculation of trends, varying magnet parameters, such as …

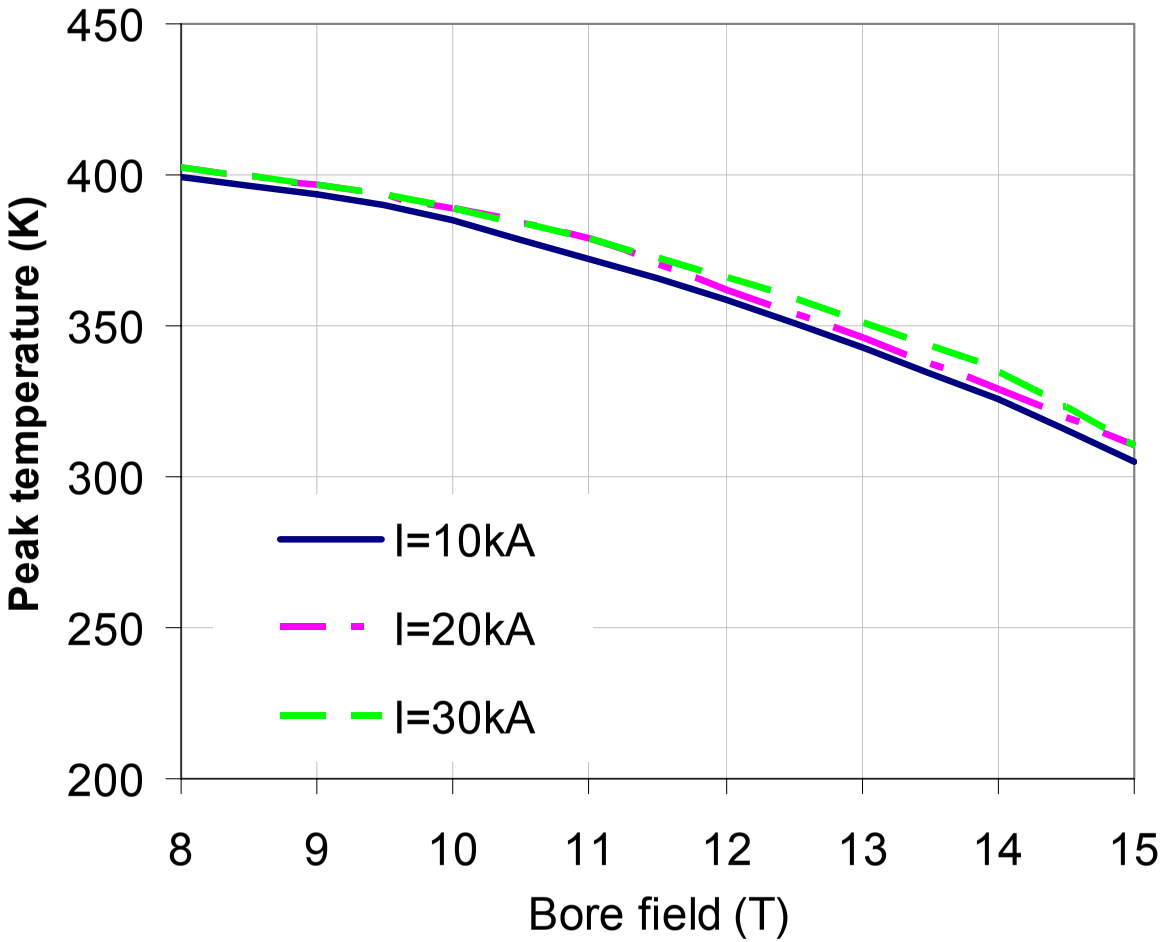
… when fixed	*Value*	*Unit*
Bore field	10	T
Oper. current	20	kA
Total delay time	30	ms
Bore diameter	40	mm
J_{CU}	2	kA/mm^2
J_c at 12 T	3	kA/mm^2
Magnet length	15	m
Heater coverage	50	% area





Peak Temperature Trends

Increasing the field and keeping all the other parameters fixed (I, J_{CU},…)



1- T_{peak} does NOT depend on the current

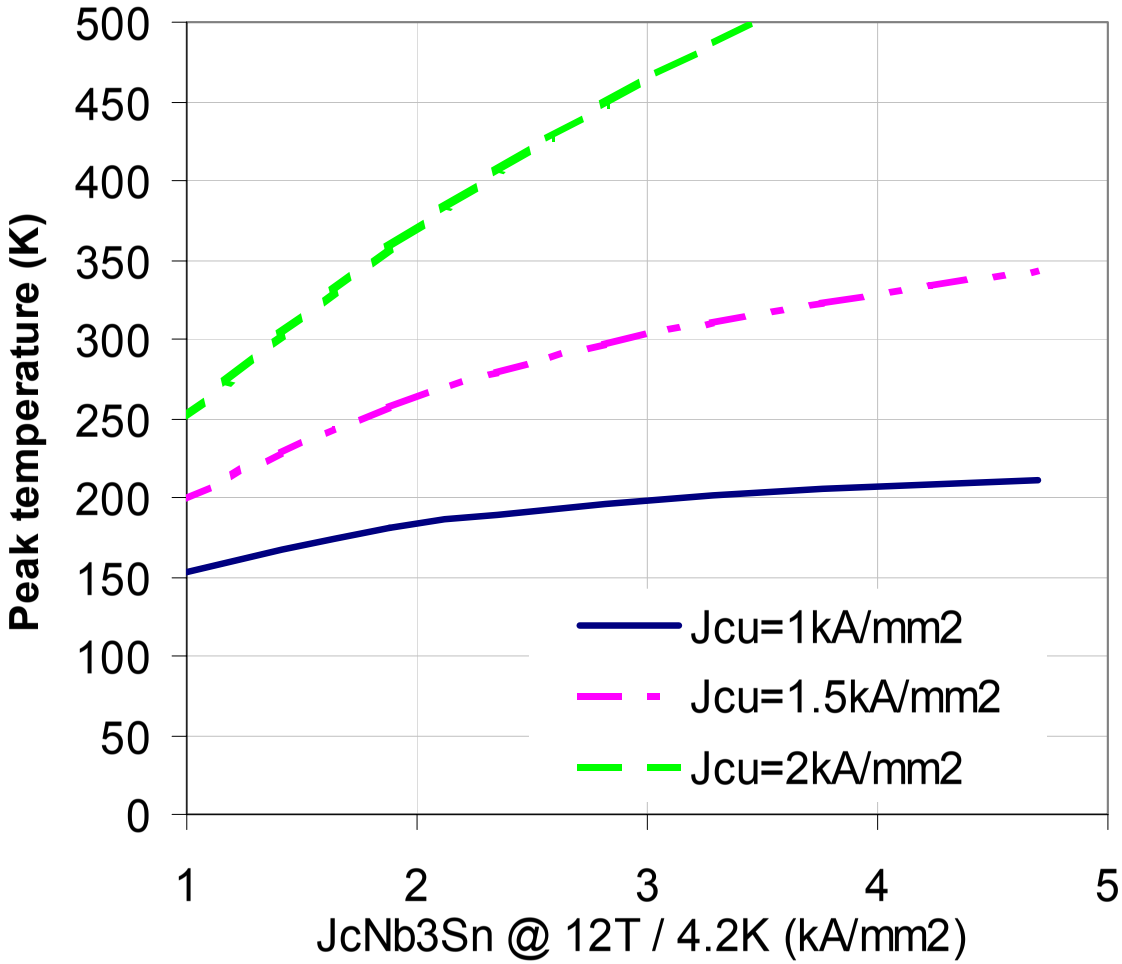
2- T_{peak} does NOT increase with field

→ Increase number of turns and cable size

→ Increase both total stored energy and coil volume

Peak Temperature Trends

- T_{peak} increase steeply with J_{CU}
- T_{peak} increase with J_c, (especially at high J_{cu})

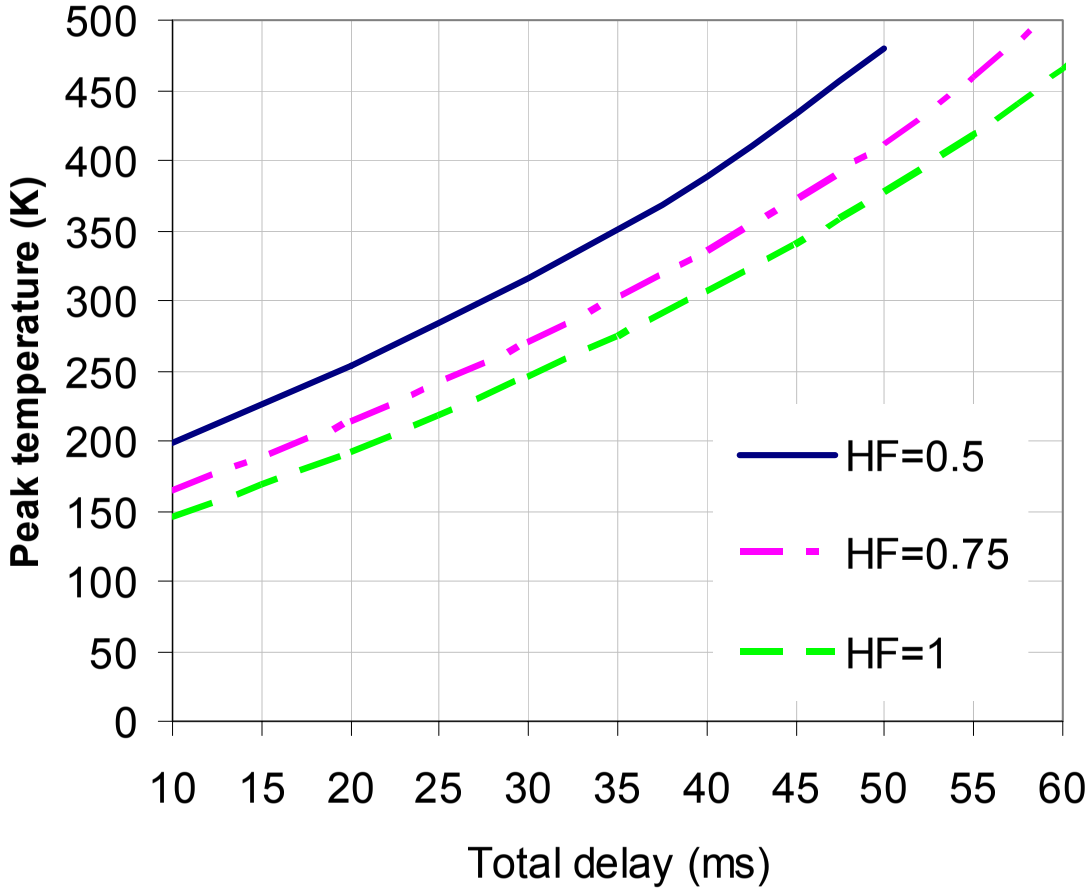


T_{peak} increase with J_c
- because of the loss of c_P
- reduced inductance (less turns), partly counteracts the c_P loss

Peak Temperature Trends

Heater efficiency:

- 10 ms increase in time delay results in a ~25% increase in T_{peak}
- Heater coverage > 50% conflicts with redundancy!



Peak temperature limit

High peak Temperatures in long magnets **(> 300 K)**

⇒High temperature gradients

⇒ High thermal stress

⇒ Theoretical studies

⇒ FE quench simulation

⇒ Mechanical analysis

⇒ Experimental program

⇒ Cable quench experiment

⇒ Small Nb_3Sn magnet: "thermal shock test"

⇒ Material properties and quench parameters studies

Peak temperature limit ?

- 500 K: solder melting point
- 400 K: epoxy glass-transition
- Conductor damage
- epoxy failures

Thermal conductivity

Measurements of thermal conductivity of impregnated coils with different cable insulation schemes

- **Stability**; especially for radiation, AC losses …
- **Quench protection:**

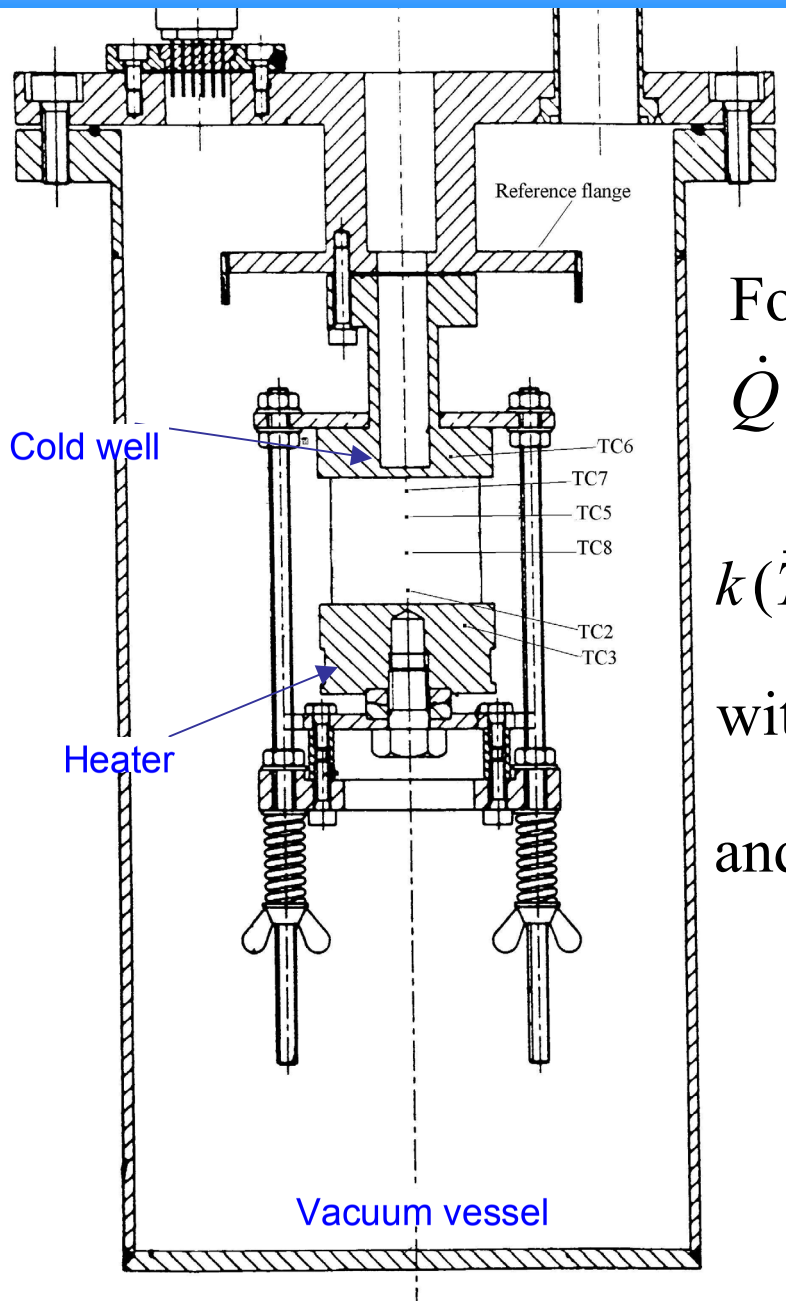
  - to reduce hot spot T

  - to reduce thermal gradients and hence stresses

Collaboration with LASA lab (INFN lab near Milan)

L. Rossi G. Volpini, V. Previtali, and D. Pedrini

Measurement set up



Fourier-Biot law:

$$\dot{Q} = -k \cdot S \cdot dT/dl$$

$$k(\overline{T}) = \frac{P \cdot l}{S \cdot \Delta T};$$

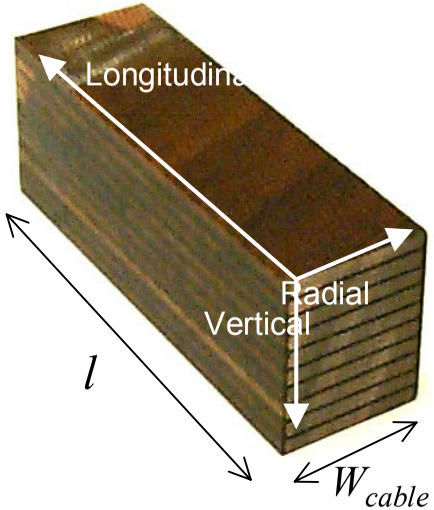
with : $\Delta T = T_2 - T_1$

and $\overline{T} = \frac{T_1 + T_2}{2}$

Thermocouples:
KP/Au-0.07 at % Fe

Samples

Sample#	1	2	3	4 & 5
Insulation material	Fiberglass (E-glass)	Kapton+ Pre-preg	Only epoxy	Ceramic fibers
Ins. thickness	0.2 mm	0.23 mm	-	0.35 mm
Strand diameter	0.7 mm	0.7 mm	0.7 mm	1 mm
Cu/non-Cu	1.4	0.87	0.87	0.92
Packing factor	0.87	0.87	0.87	0.9
Cable thickness	1.2 mm	1.2 mm	1.2 mm	1.8 mm



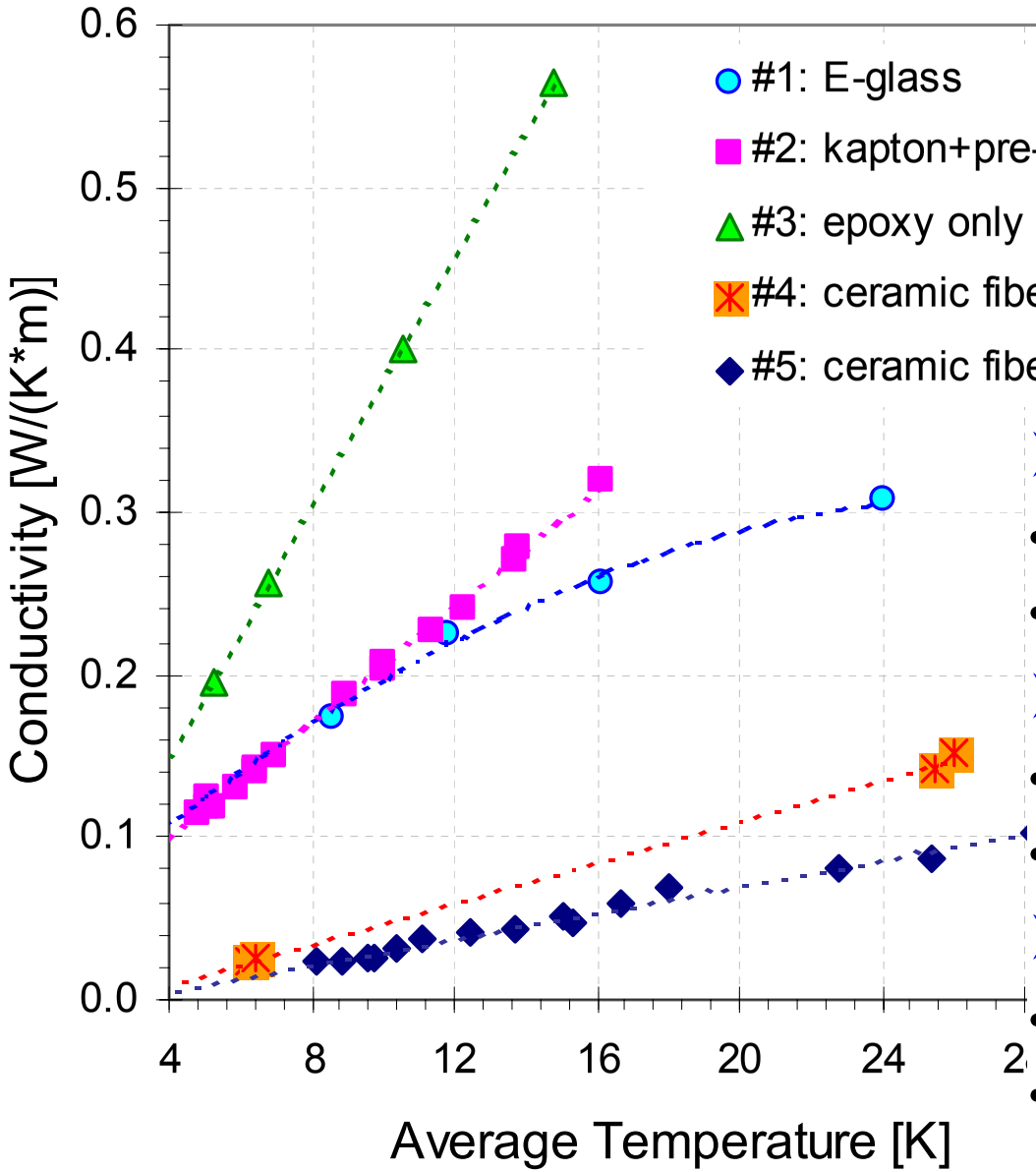
Racetrack magnets samples

1) fiberglass tape wrapped around each cable with 30 % overlap.
2) 1 layer of Kapton (76 μm-thick), + 1 pre-impregnated fiberglass layer.
3) same cable, but epoxy-impregnated without any insulating material.

Cos-theta magnet samples

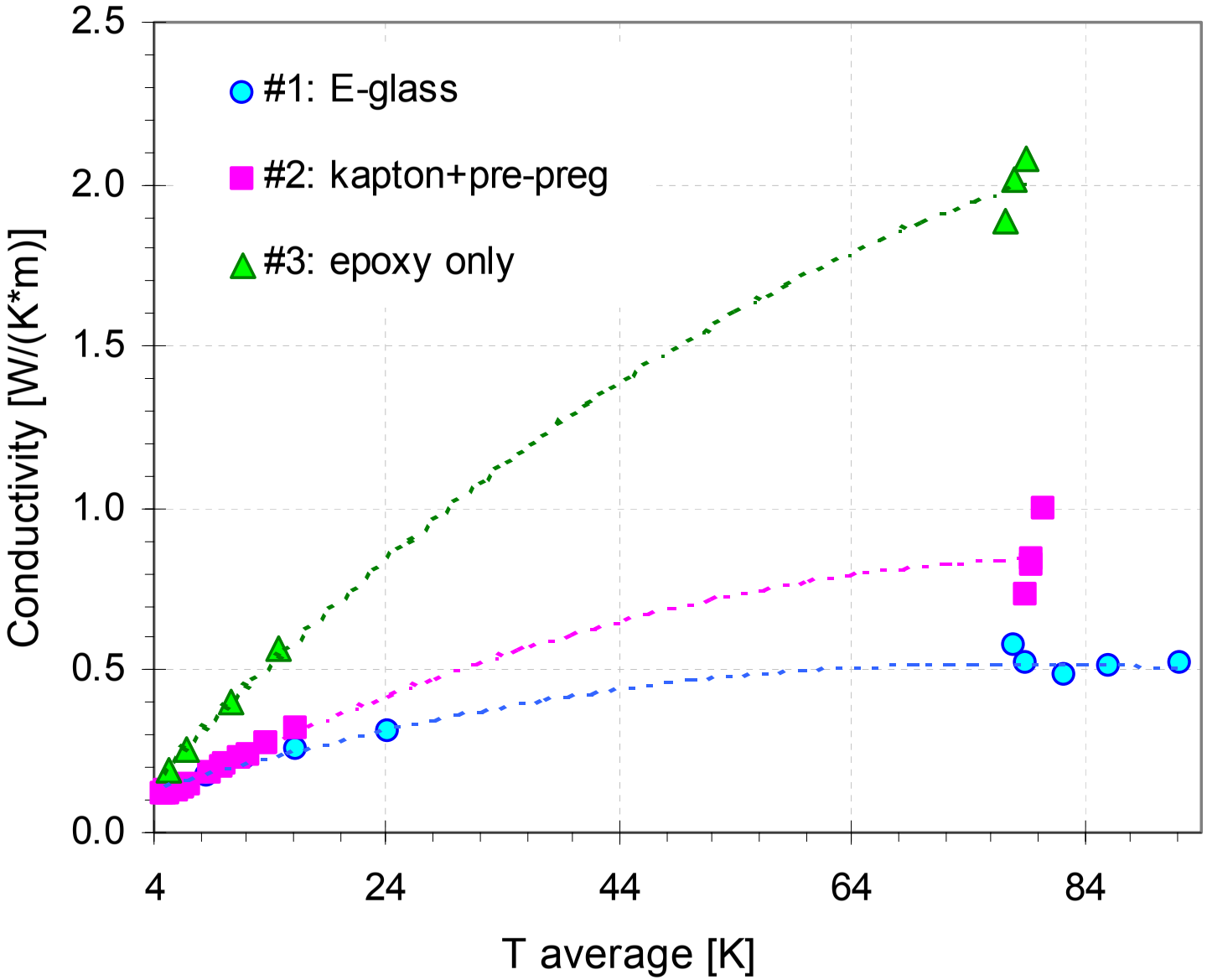
4,5) cable wrapped with ceramic fibers tape (40% overlap), wetted with ceramic binder (CTD-1002x), cured at 80 °C for 20', and heat treated to form Nb_3Sn.

Results with LHe



- **Sample 1 and 2**
  - close k at T < 12 K;
  - Extrapol. @4.2 K k~0.1 $\left(\frac{W}{K \cdot m}\right)$
- **Sample 3** (epoxy only)
  - higher k;
  - Extrapol. @4.2 K k ~0.16 $\left(\frac{W}{K \cdot m}\right)$
- **Samples 4 and 5** (ceramic)
  - low k ~0.03 W/(K-m), @6-8 K
  - No extrapol. to lower T

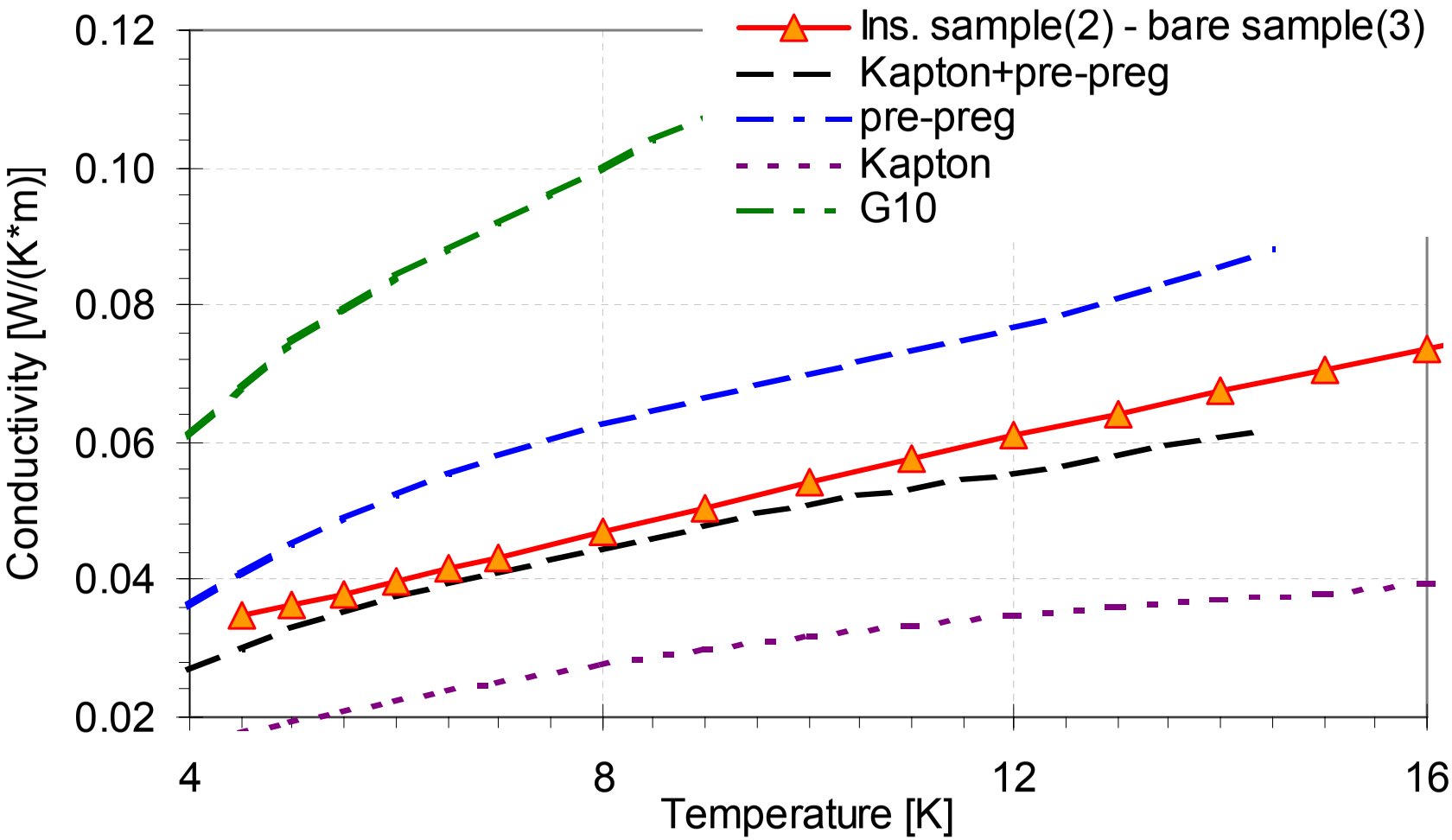
Results with LN



Kapton + pre-preg

Thermal resistance of insulating layer calculated from samples 2 & 3:

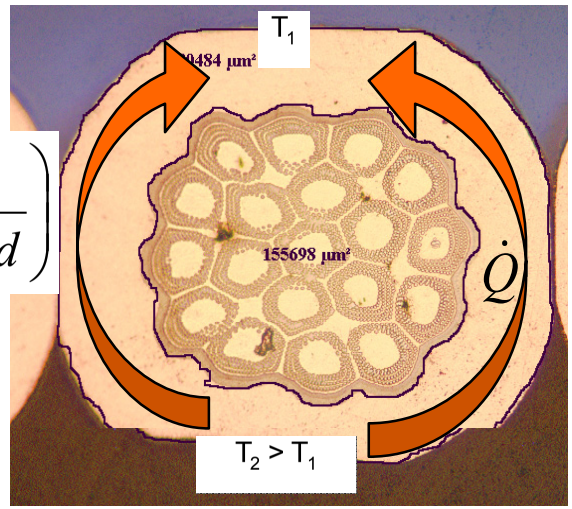
$$R_{th}(\text{Ins.}) = R_{th}(\text{ins. Stack}) - R_{th}(\text{bare Stack})$$

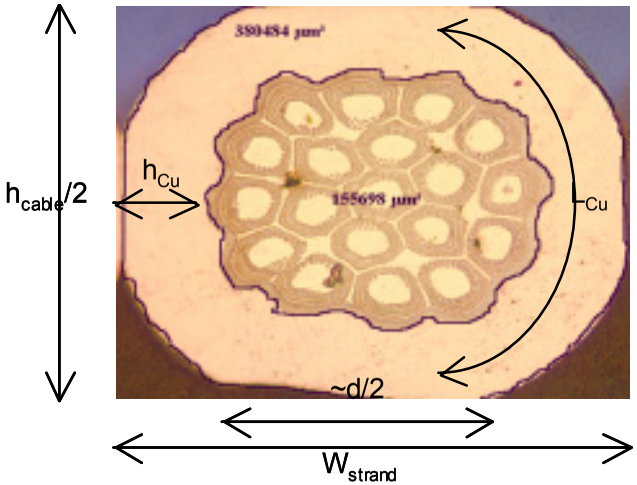


Cable modeling

- Single strand

$$k_{strand} = k_{Cu} \cdot \frac{h_{cable}/2}{W_{strand}} \cdot \left(\frac{2h_{Cu}d}{2h_{Cu}^{2} + L_{Cu}d} \right)$$



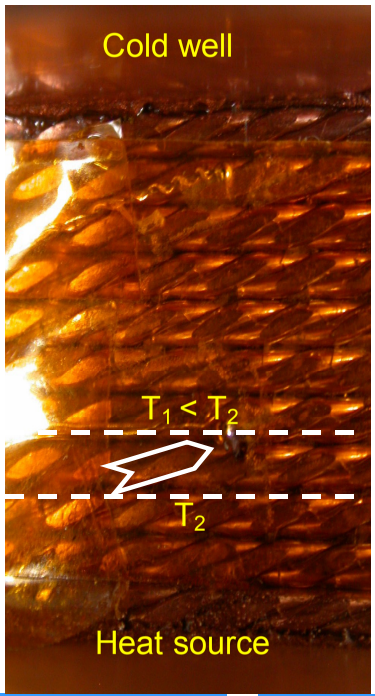


- Contact between strands

$$\begin{cases} C_{contact}(T) = \alpha \cdot T^{n} & \text{for } T < T_r = 16\,\text{K} \quad (\text{W/K}) \\ C_{contact}(T) = C_{300} \cdot e^{-1/\beta \cdot T} & \text{for } T > T_r \quad (\text{W/K}) \end{cases}$$

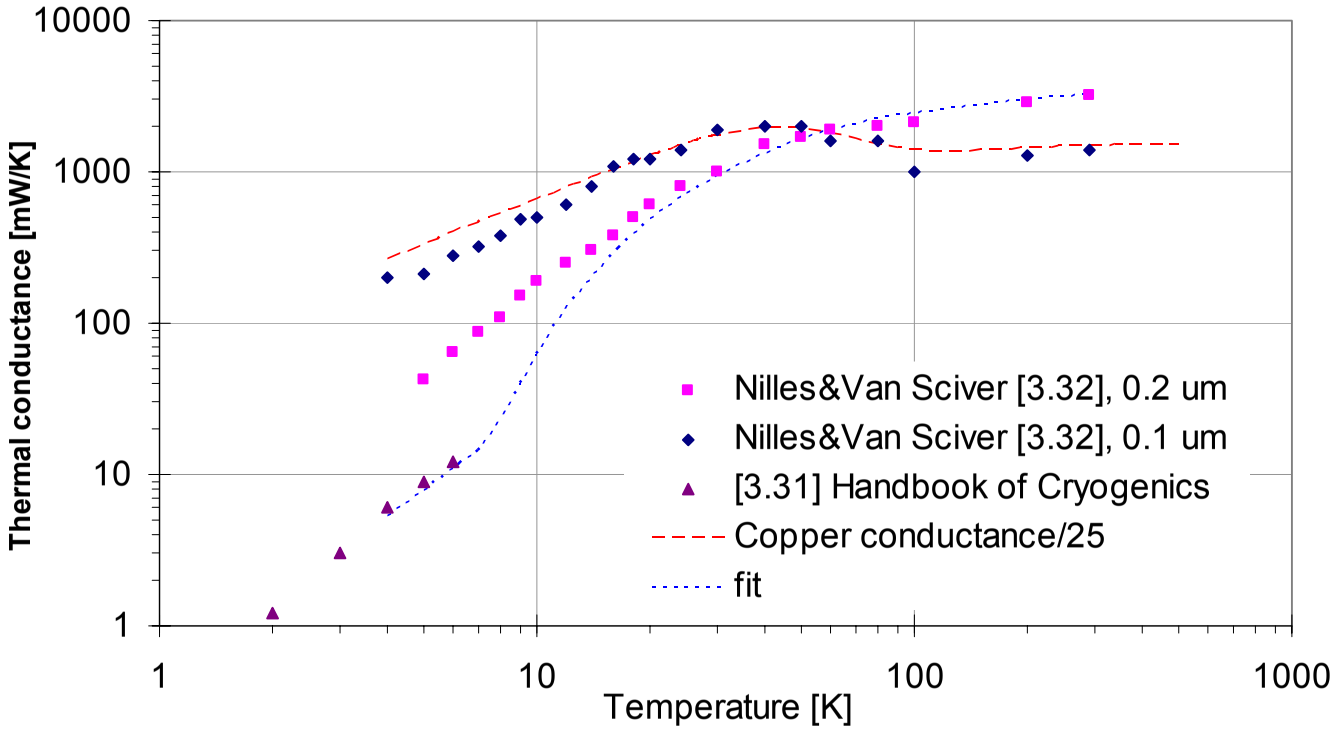
- Transposition of the strands

$$k_{pitch} = k_{long} \frac{h_{cable}^{2}}{L_{pitch} \cdot L_{transp}}$$



Cable modeling

Thermal contact resistance between copper surfaces

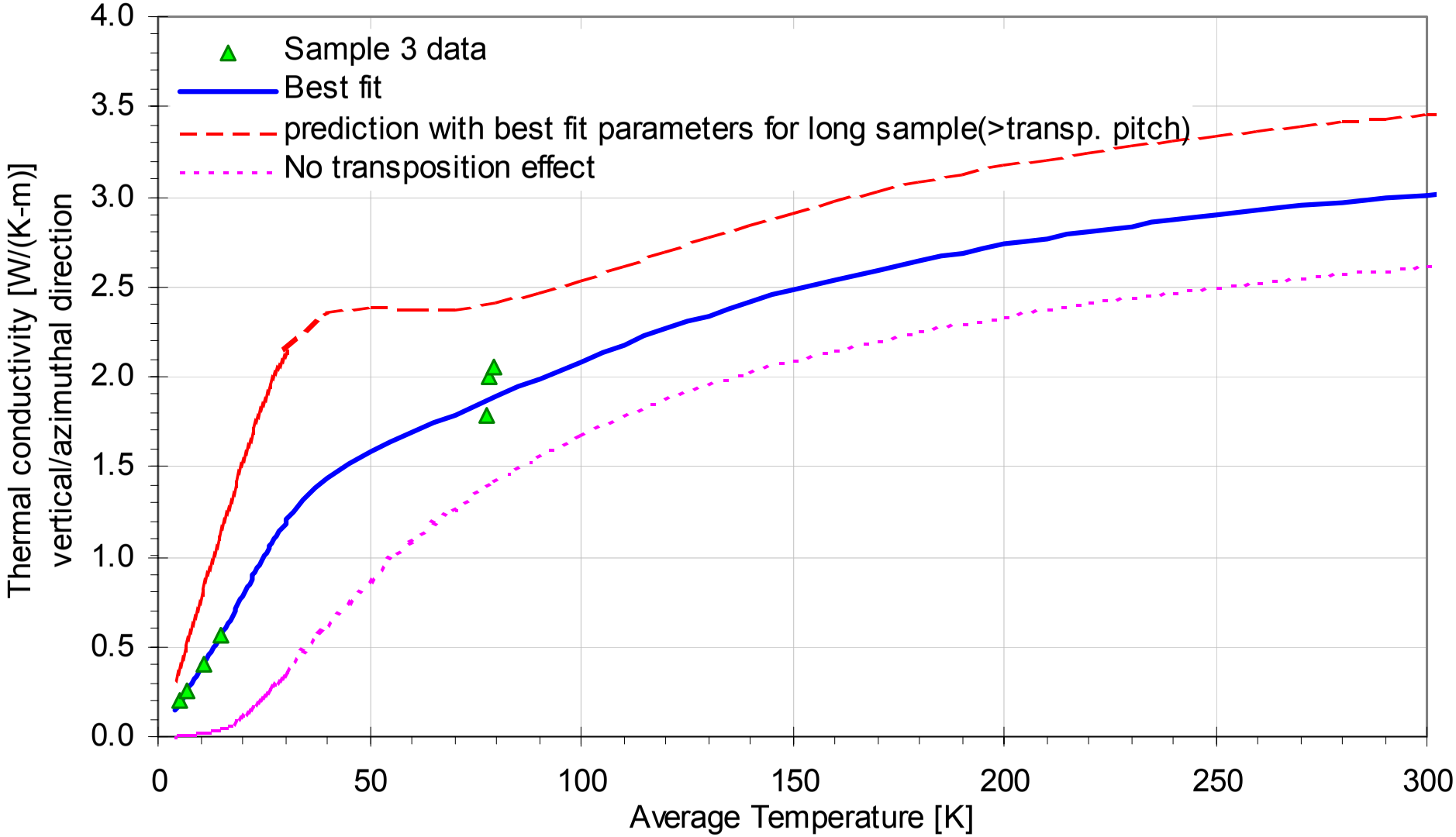


Insulating coatings of the strands:

- Samples 1, 2, 3: React&Wind technology (for **racetrack magnet)**, includes synthetic **oil**, in order to prevent sintering of the two layers of strands during reaction.
- sample 4 & 5 (**cos-theta** magnet procedure): coating of the strands may come from the **ceramic binder** (SEM analysis and ramp rate dependence).

Cable modeling results

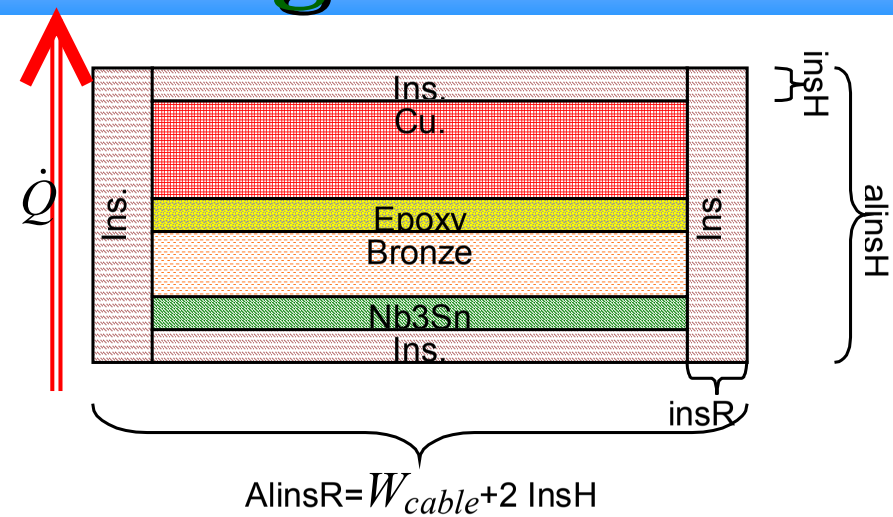
Total conductivity = $k_{sample} = k_{cable} + k_{pitch} \cdot l/L_{pitch}$

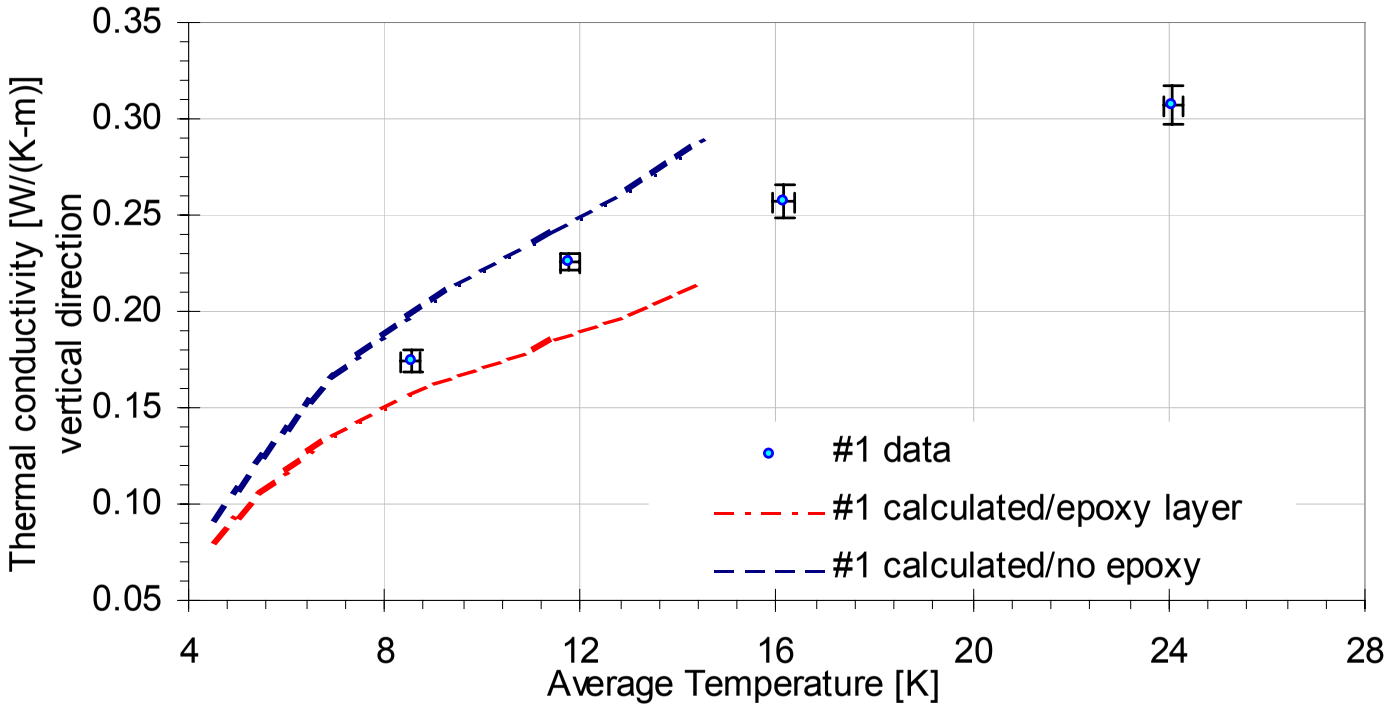


Cable modeling

Overall thermal conductivity

$$C_{sample}^{QLASA} = C_{insR} + \frac{W_{cable} \cdot l}{\sum_i h_i / k_i} \quad (\mathrm{W/K})$$

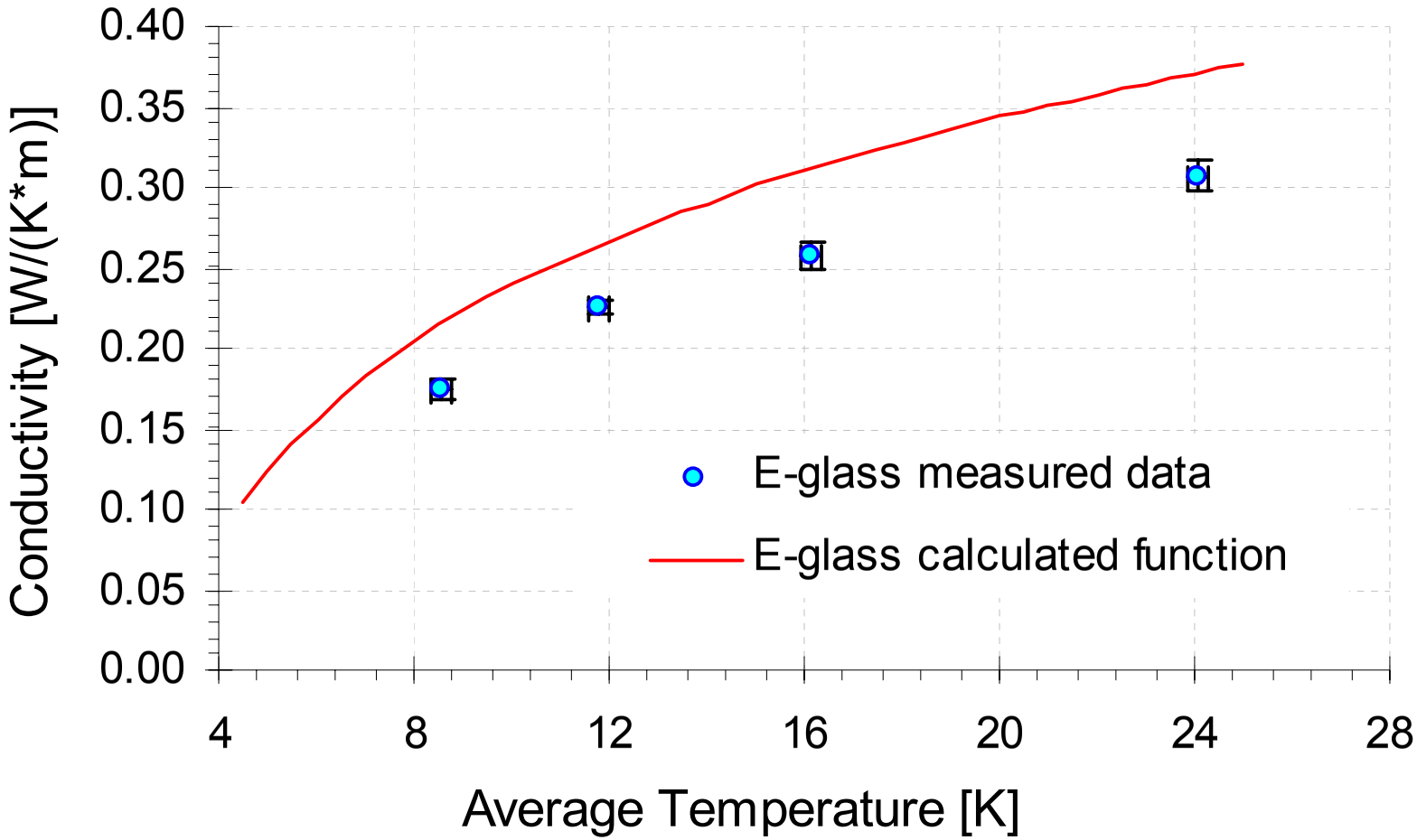




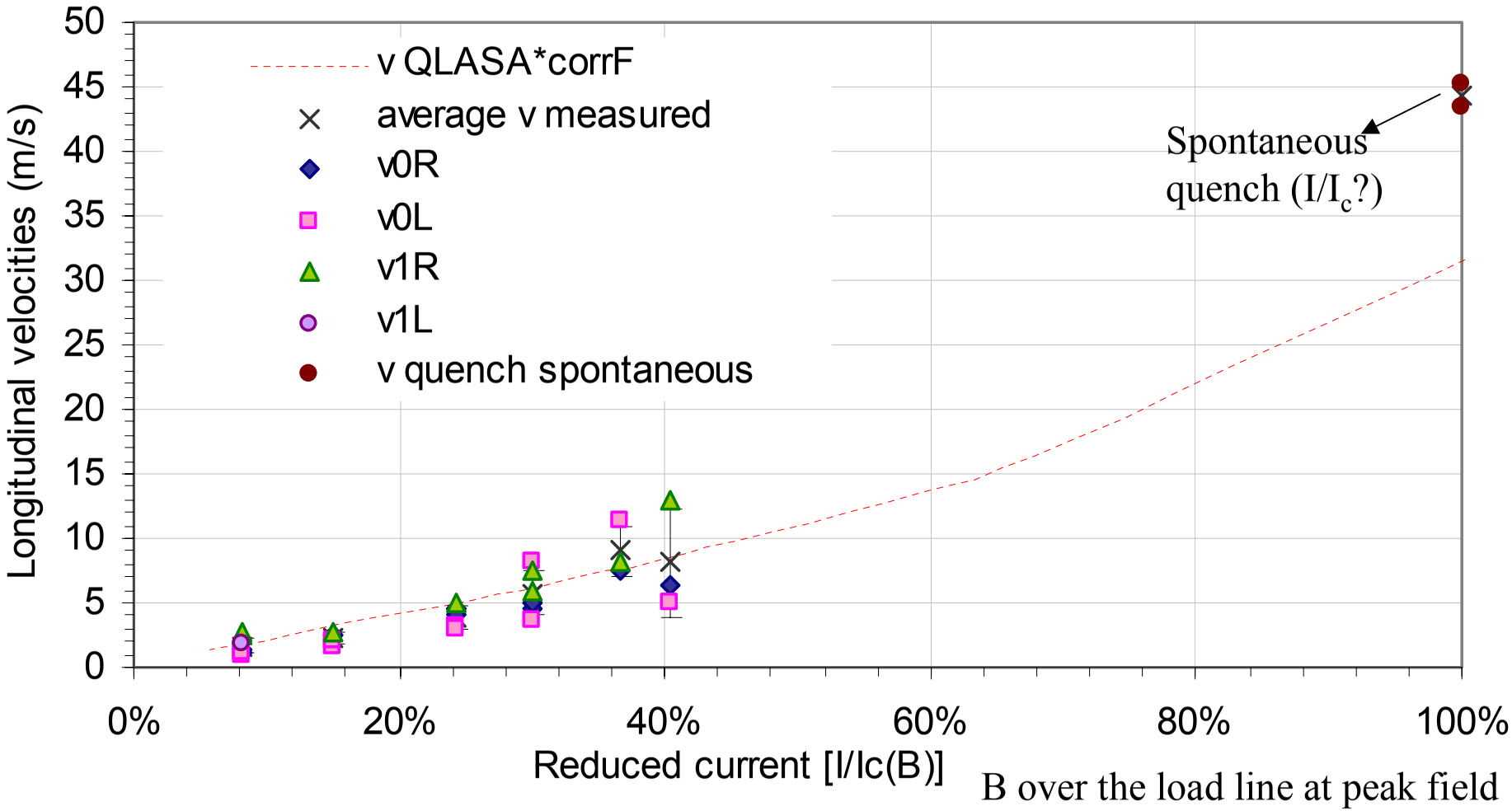
Overall thermal conductivity

measured data (sample 1: E-glass insulation)

Calculations with G10 insulation

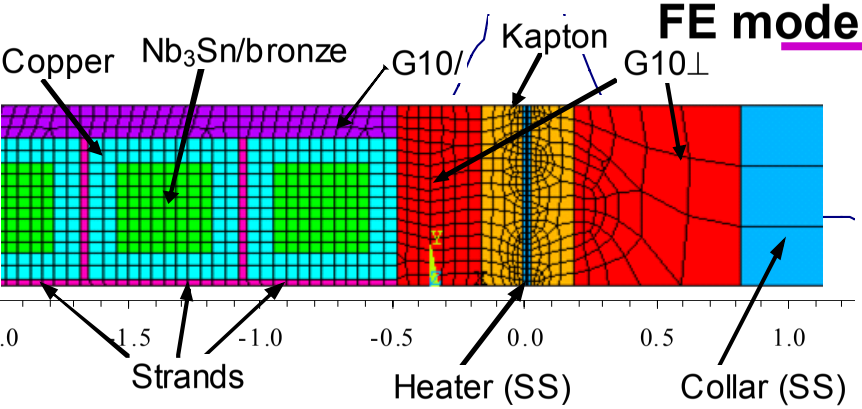


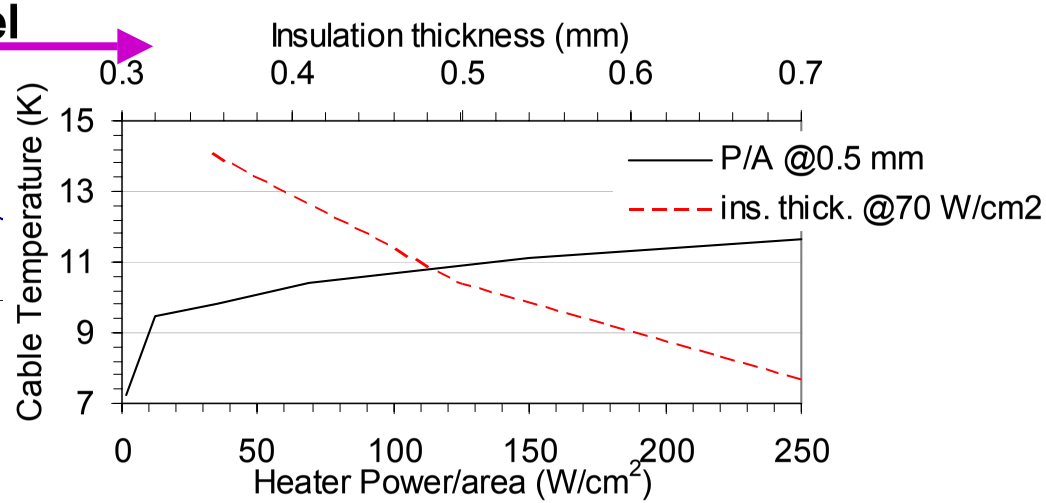
Quench velocities

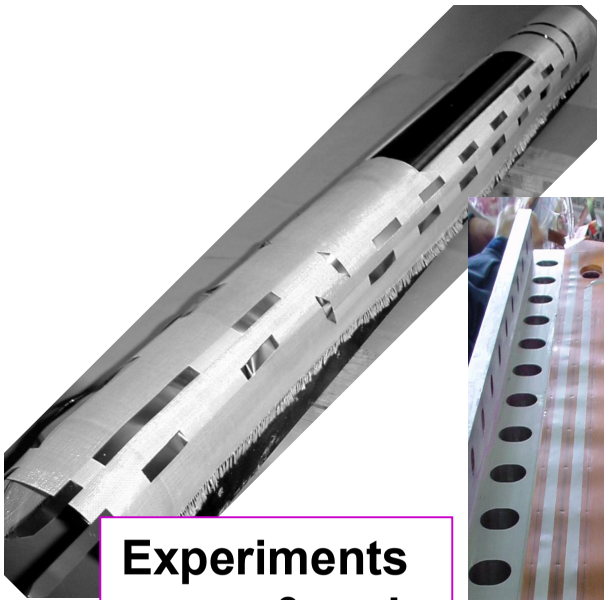


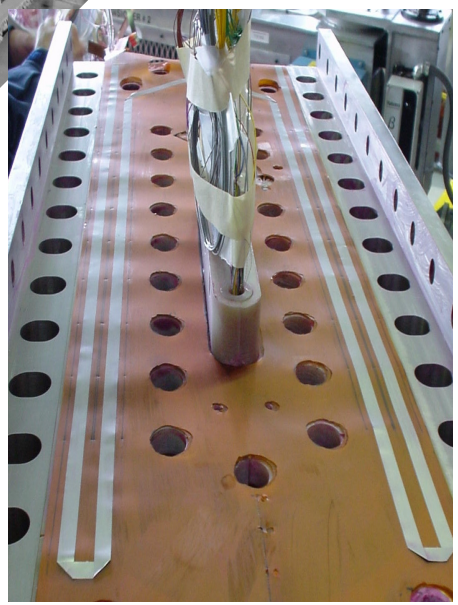
correction factor of 1.5

Quench Heater Studies

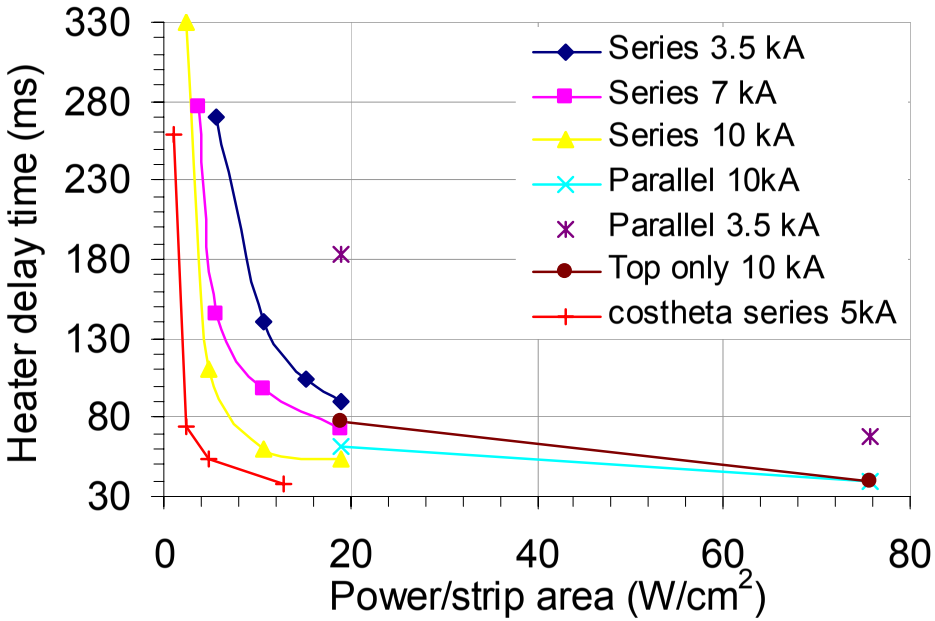








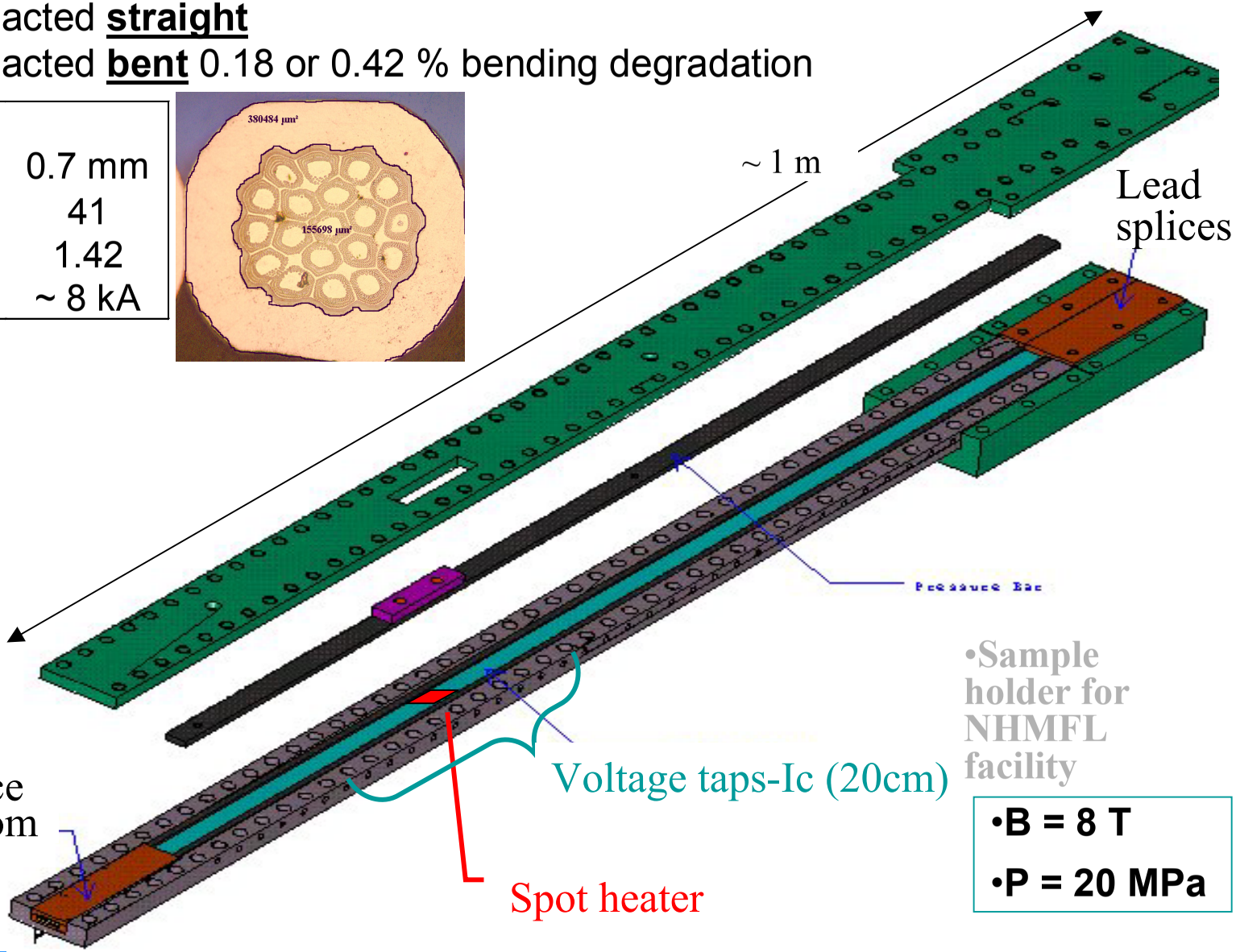
Experiments on cosθ and racetrack magnets



Quench Test on Cables

- **Sample 1**: reacted **straight**
- **Sample 2**: reacted **bent** 0.18 or 0.42 % bending degradation

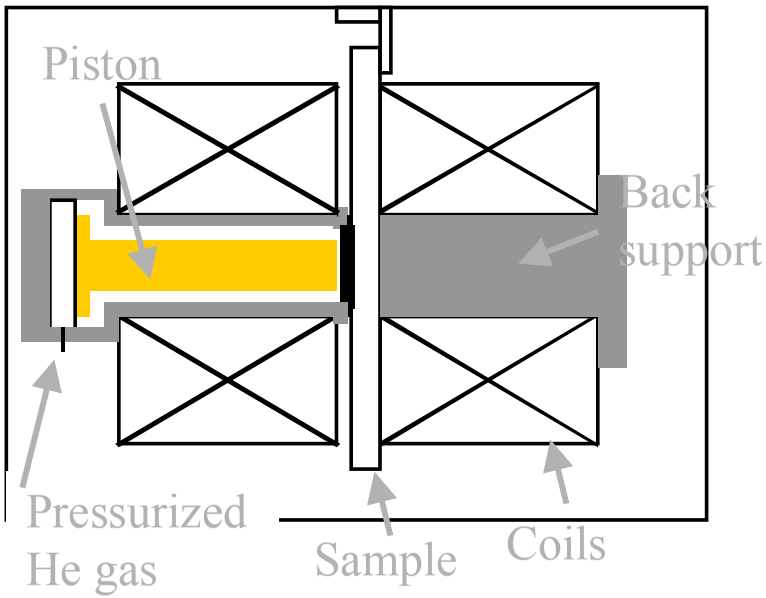
ITER Cable	
Strand ∅	0.7 mm
# strands	41
Cu/NCu	1.42
Ic @ (8T,4.2K)	~ 8 kA

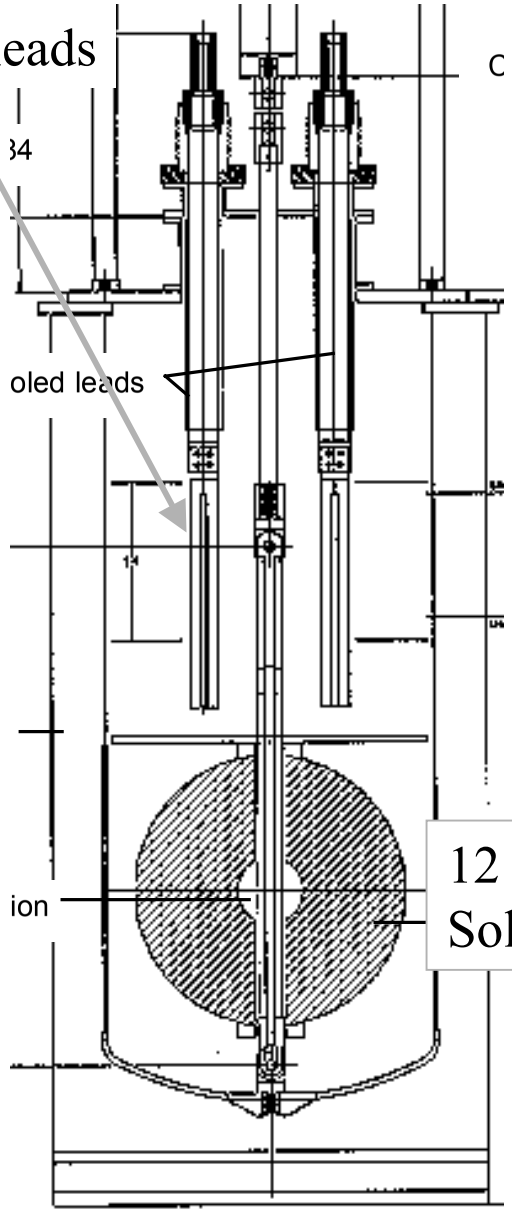


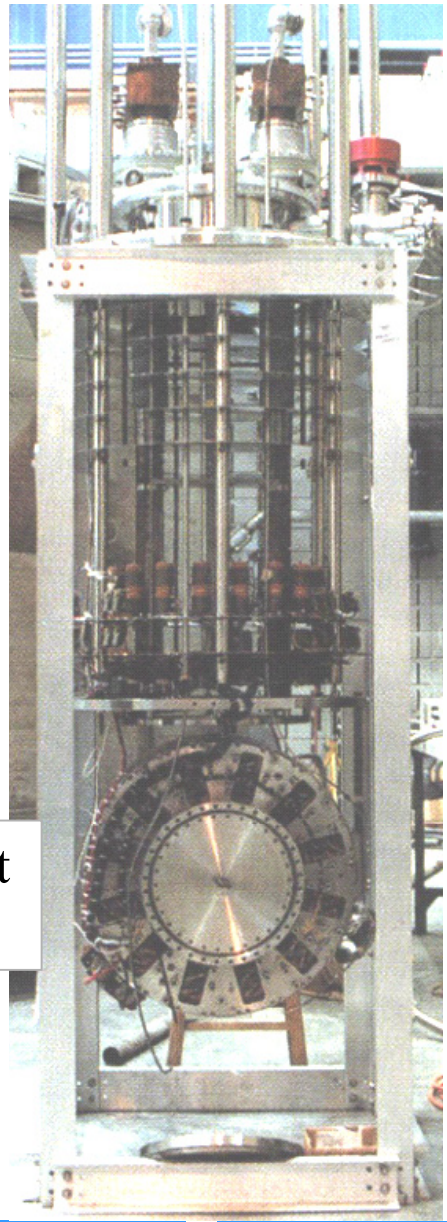
- Sample holder for NHMFL facility

- **B = 8 T**
- **P = 20 MPa**

Cable Test Facility

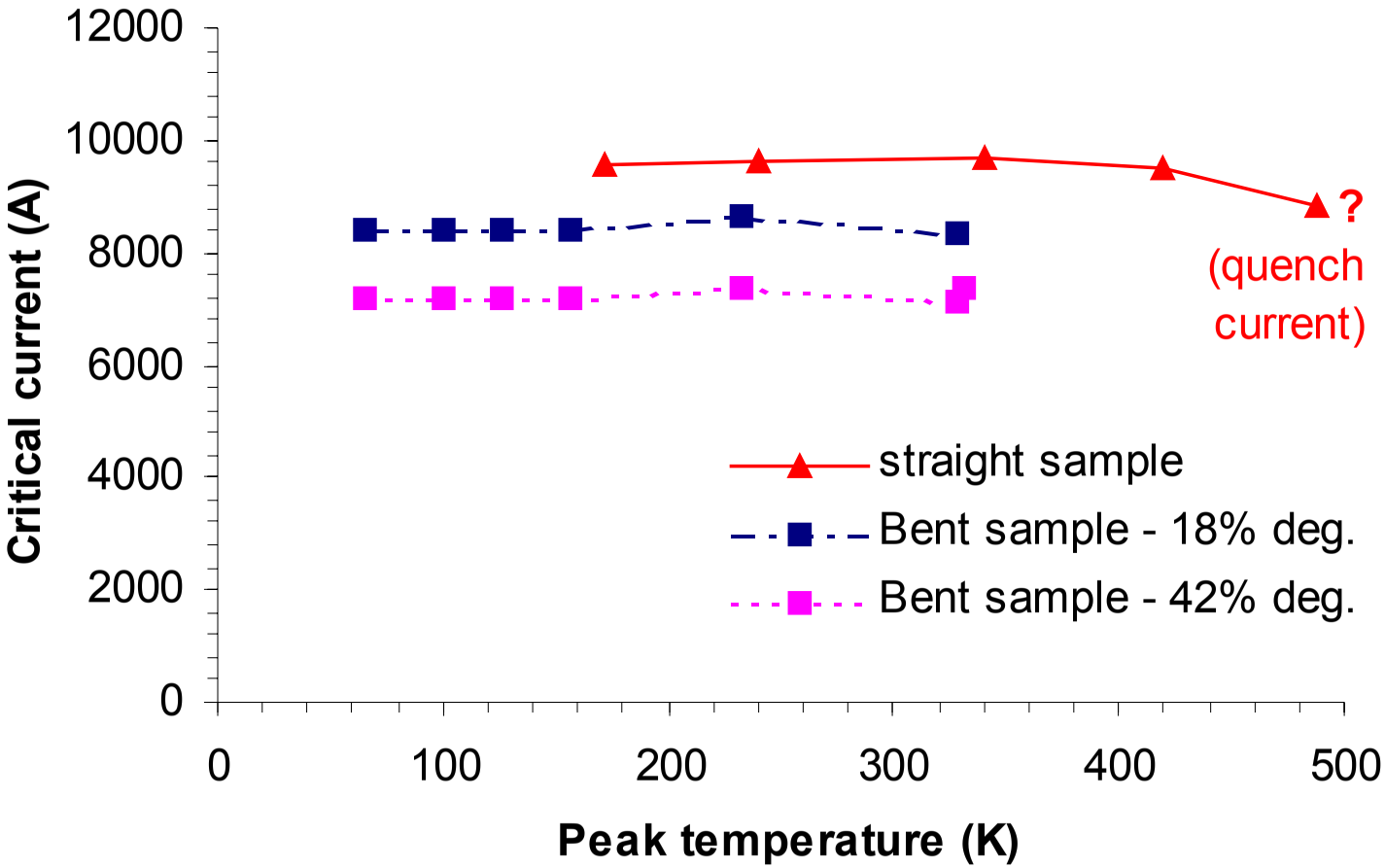


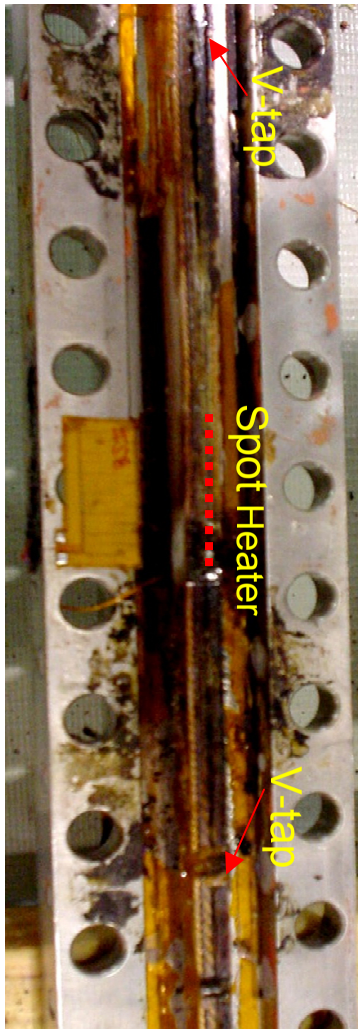




Experiment results

- No degradation up to ~ **400 K** (straight sample)
- No degradation up to ~ **300 K** (bent sample)

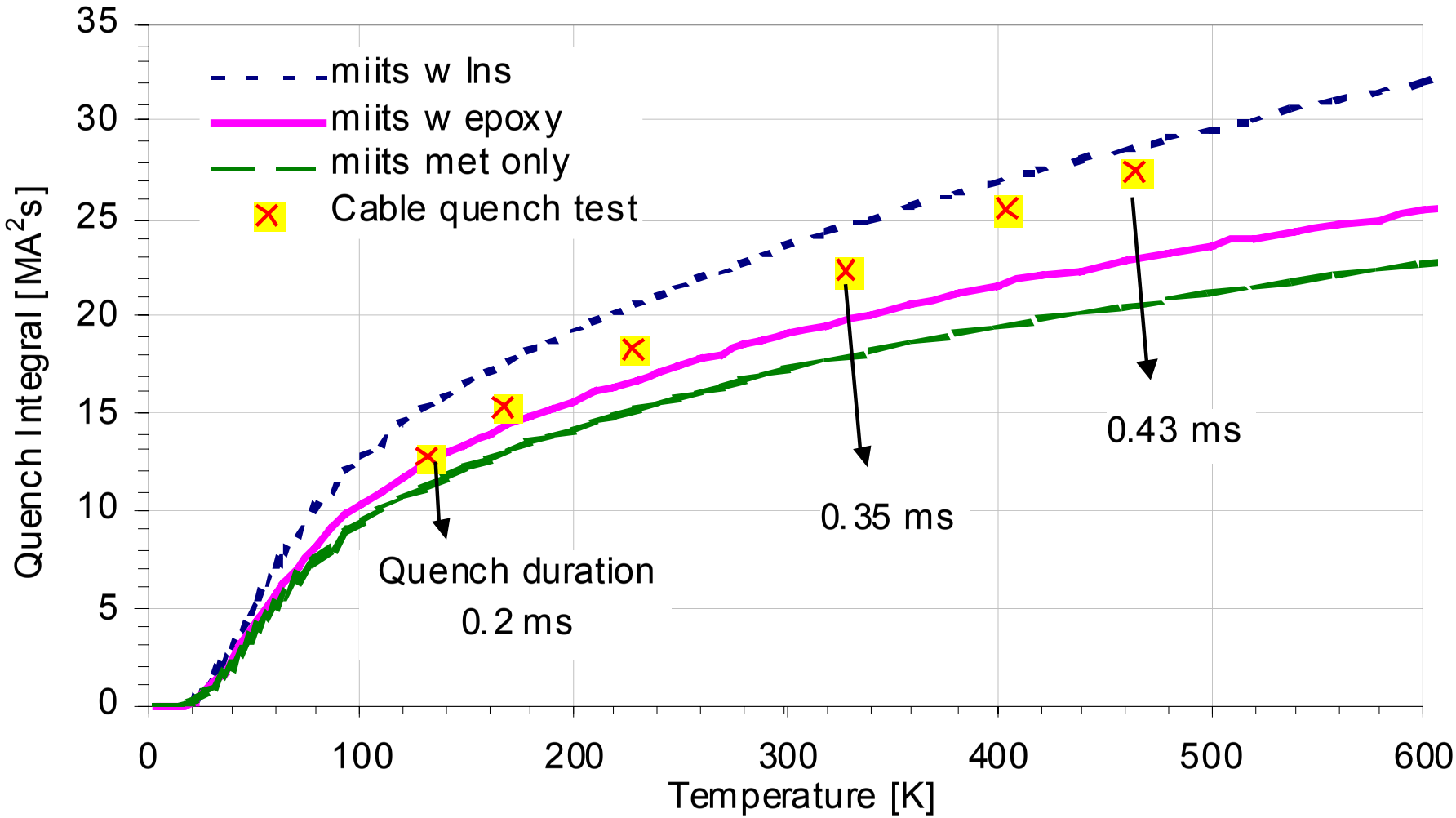




Burn marks on the sample that reached ~500 K

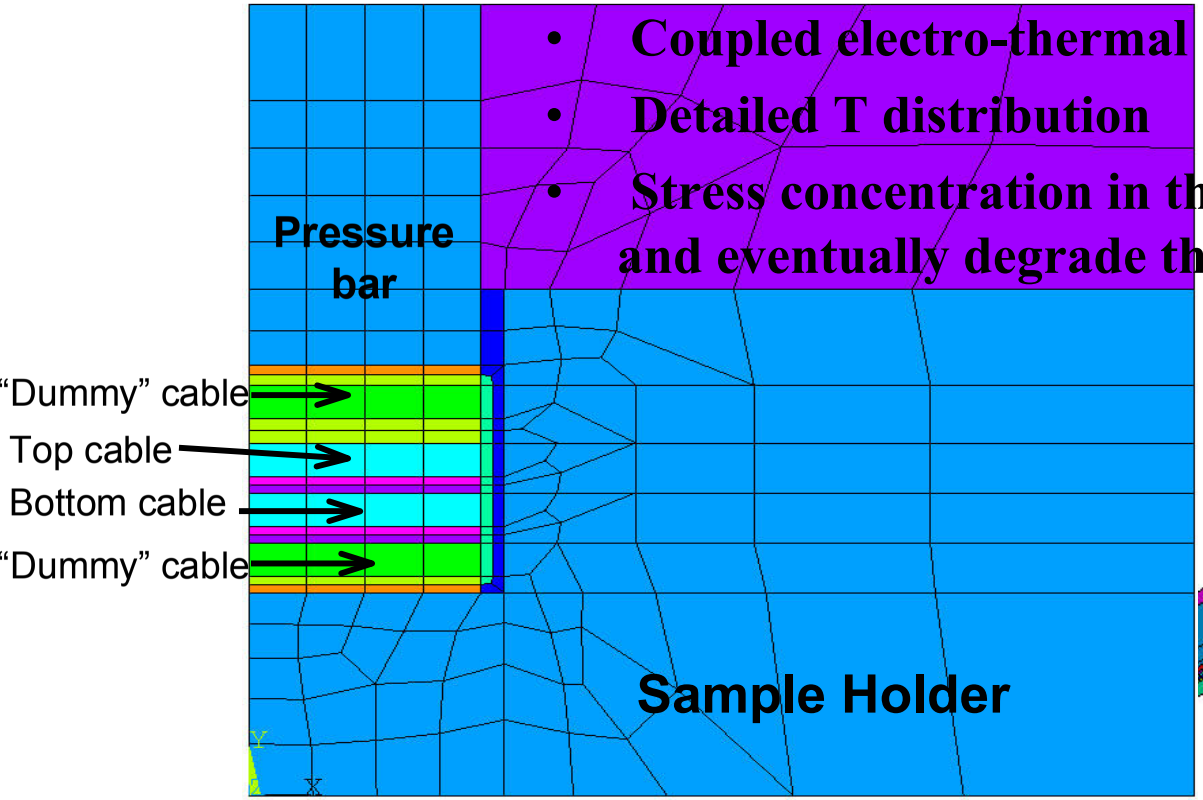
Adiabatic model

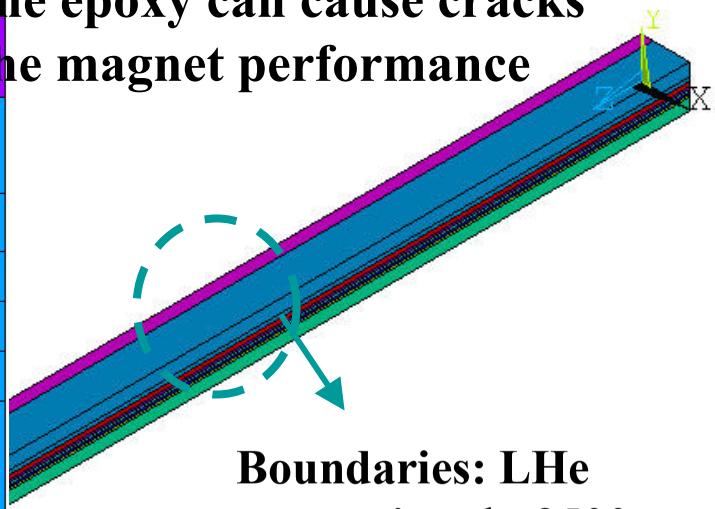
Quench Integral includes ~ 0.1 mm cable insulation



Sample Holder FE Model

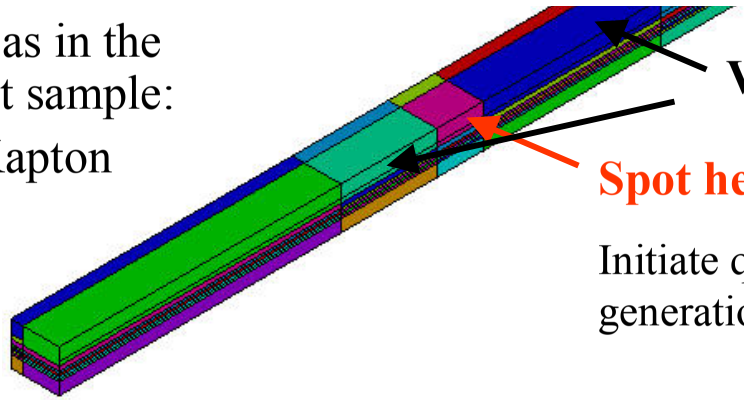
- Coupled electro-thermal simulation of the quench
- Detailed T distribution
- Stress concentration in the epoxy can cause cracks and eventually degrade the magnet performance





Boundaries: LHe convection; h=2500

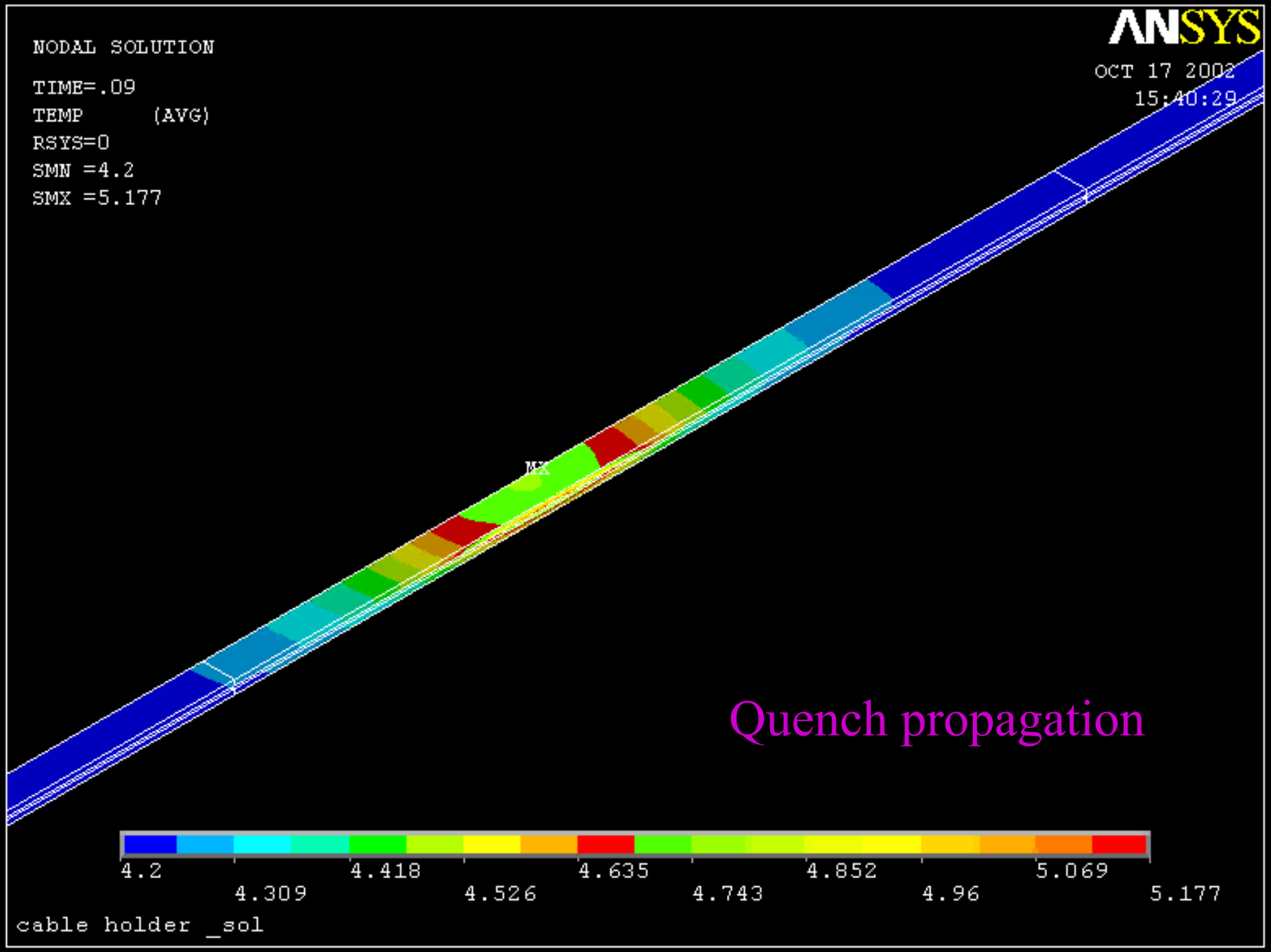
Insulation as in the straight sample:
= G10 + Kapton



V tap regions

Spot heater region:

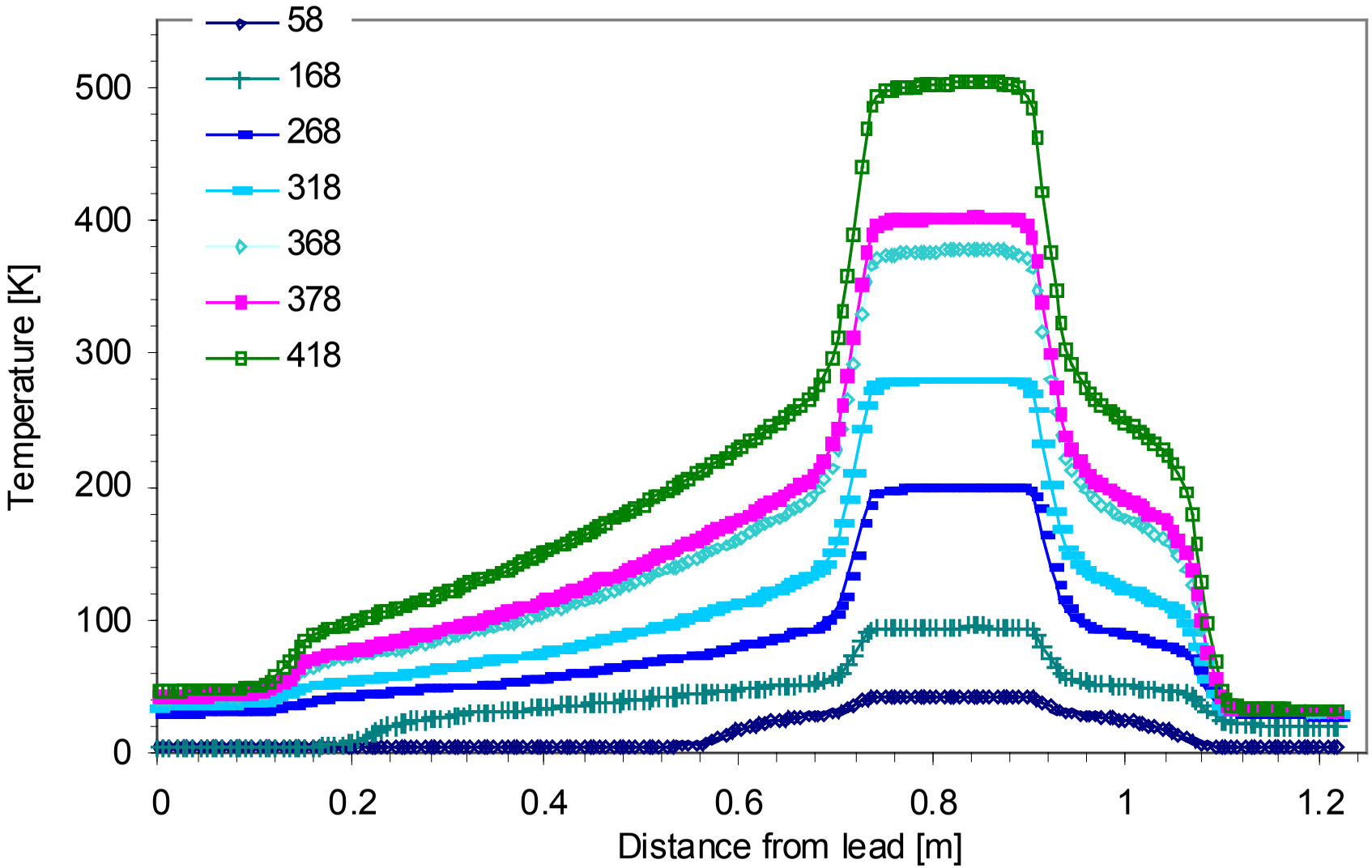
Initiate quench with heat generation in heater



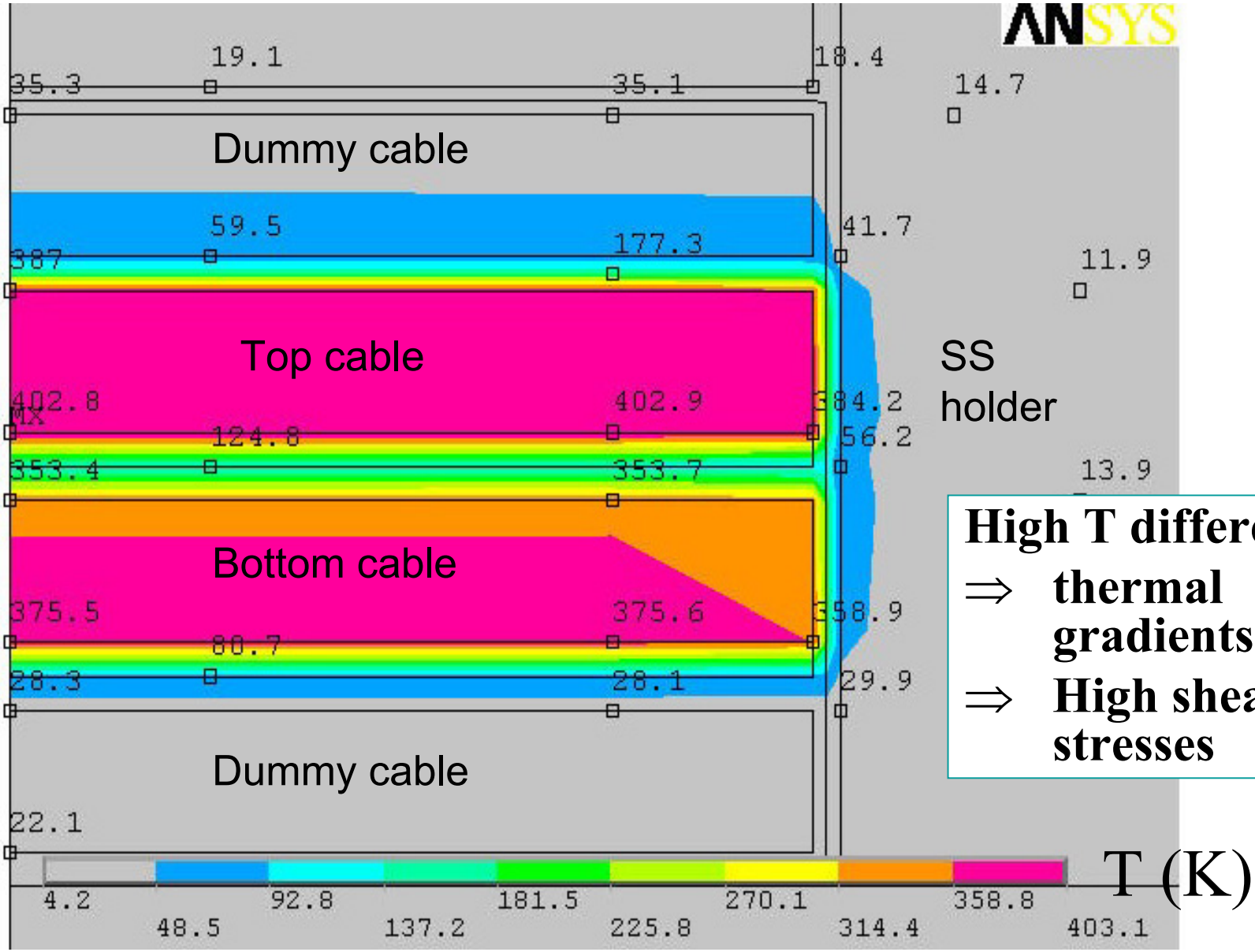
Quench propagation

FE Quench Simulation

T profile at different times (ms) after the quench start



FE model results



High T differences

⇒ **thermal gradients**

⇒ **High shear stresses**

Stress Analysis

Total strain contributions at T_{peak} = 400 K :

- Pre-compression of Nb_3Sn filaments **ε_{int}= -0.14%**
  - due to different thermal contraction of the materials inside the strand (from T_{reac}= 650ºC to 4.2 K is ε_m = -0.28 %)
  - at 400 K ~50 % of ε_m (estimated by thermal contraction coefficients, bronze/SC area, and elasticity moduli)
- Thermal expansion strain **ε_{therm} = -0.46 %** (Stress = 167 MPa)
  - With ANSYS T profile **ε_{therm} = -0.22 %**

⇒ Total intrinsic strain ε_{tot}

- Applied Pressure (piston) **σ_y= 20 MPa**

Main	x	y	z
ε_{tot}	-0.6	-0.06	-0.36
σ	-102	-20	-60

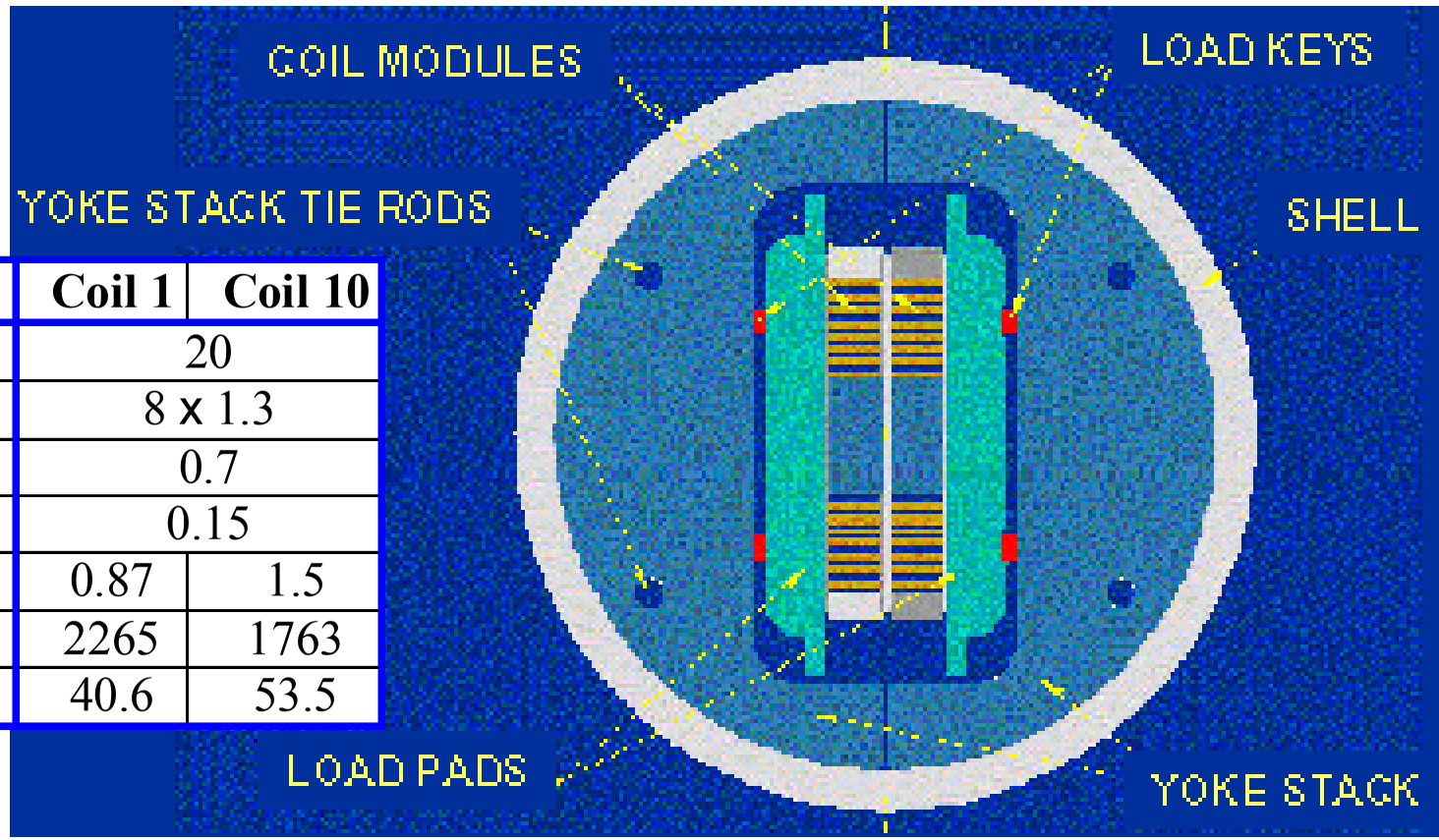
Shear	σ_y=20 MPa	
$\gamma 2$	0.55	%
$\tau 2$	41	MPa

Neglected other applied strains
- Pre-stress
- Lorentz forces
- Bending strain (for React&Wind)

Thermal Shock Test

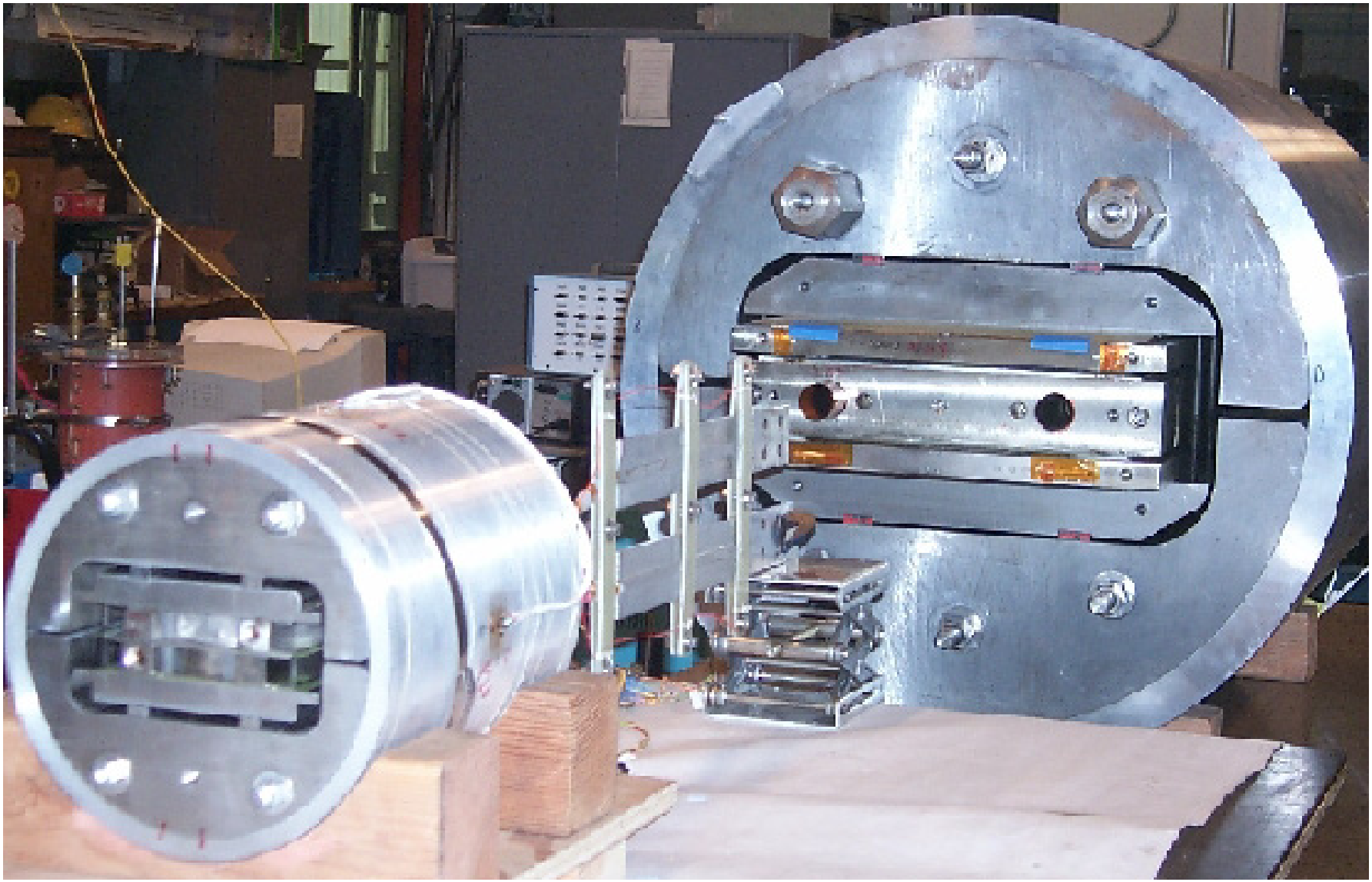
- two "double pancake" racetrack coils
- "state-of-the-art" conductor MJR
- Sub-sized cable
- Field: 10–11 T
- I_{MAX} = 9.1 kA
- L = 0.4 mH

LBL Sub-sized Magnet



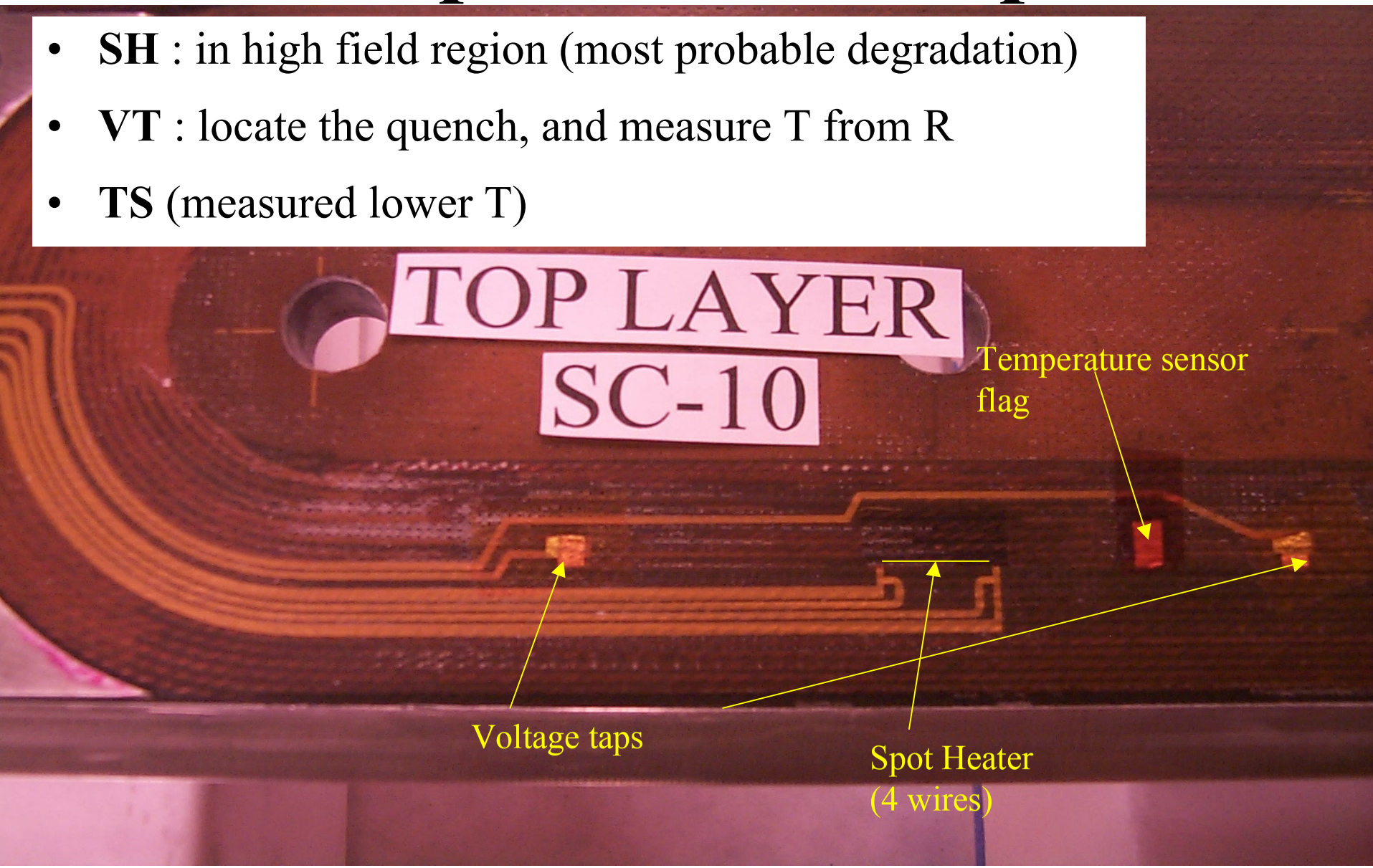
Parameters	Coil 1	Coil 10
N of strands	20	
Cable (mm)	8 x 1.3	
Strand d (mm)	0.7	
Insulation (mm)	0.15	
Cu:SC	0.87	1.5
J_C (A/mm^2)	2265	1763
Cu RRR	40.6	53.5

Subsized & RD3 Magnets

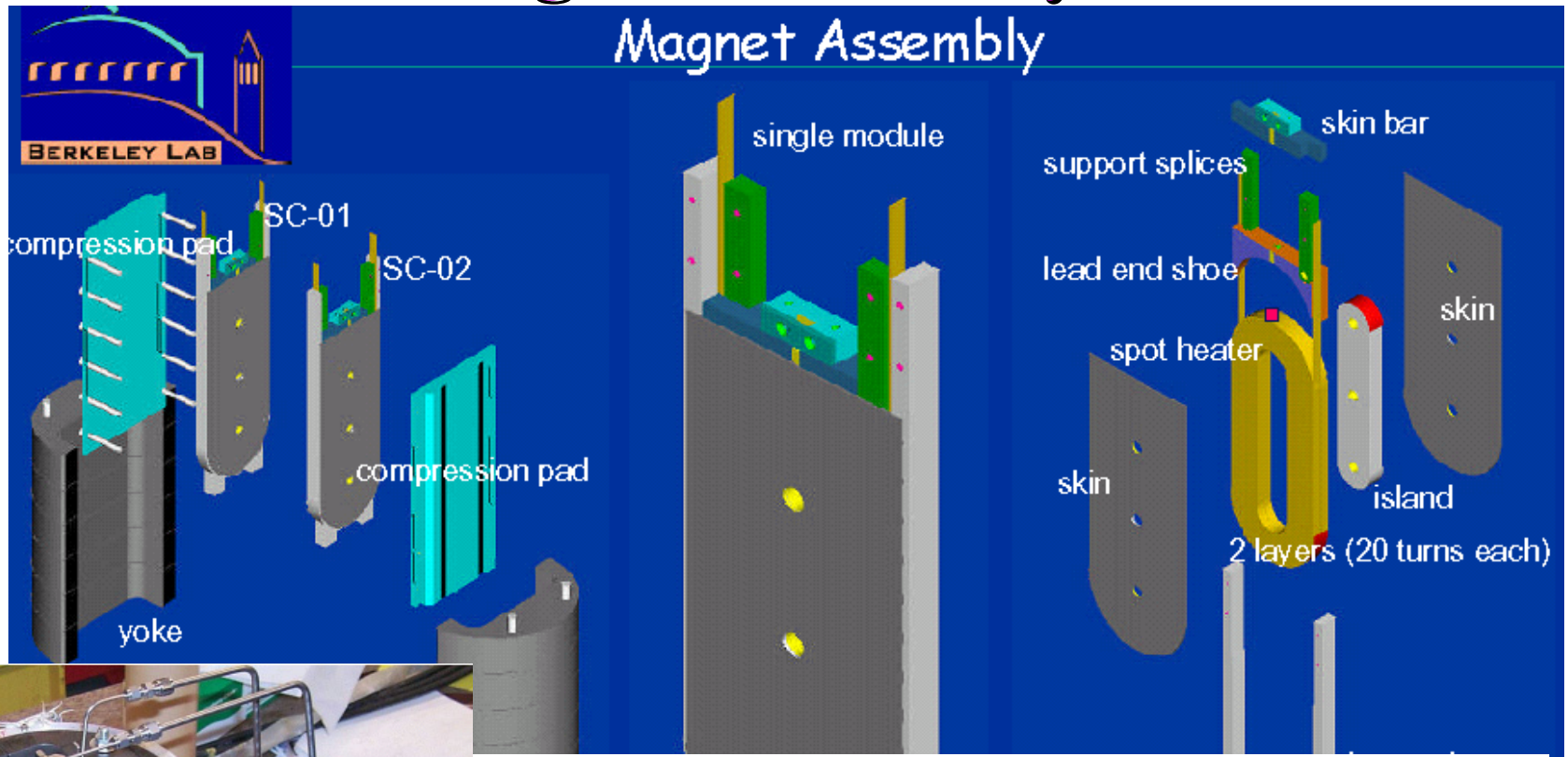


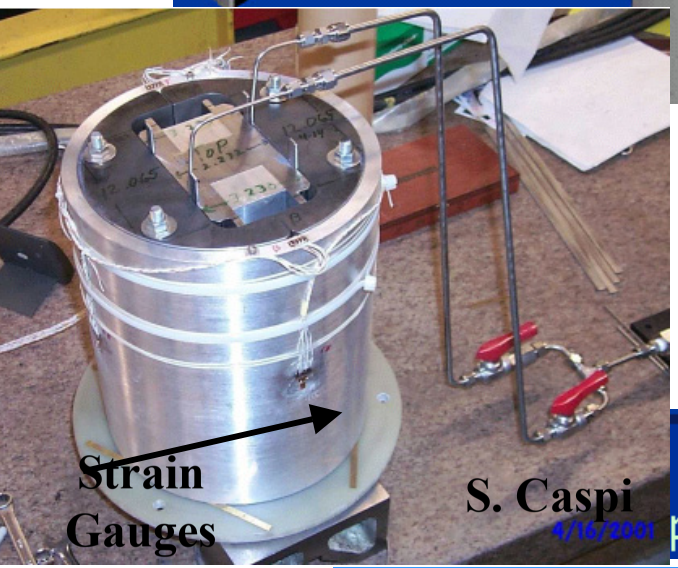
Experiment set up

- **SH** : in high field region (most probable degradation)
- **VT** : locate the quench, and measure T from R
- **TS** (measured lower T)



Magnet Assembly





- **SS skins replaced by G10 spacers**
- **spacers inserted between the coils**
  - ⇒increase inductance, decrease quench back effect
- **low pre-stress => fast training**

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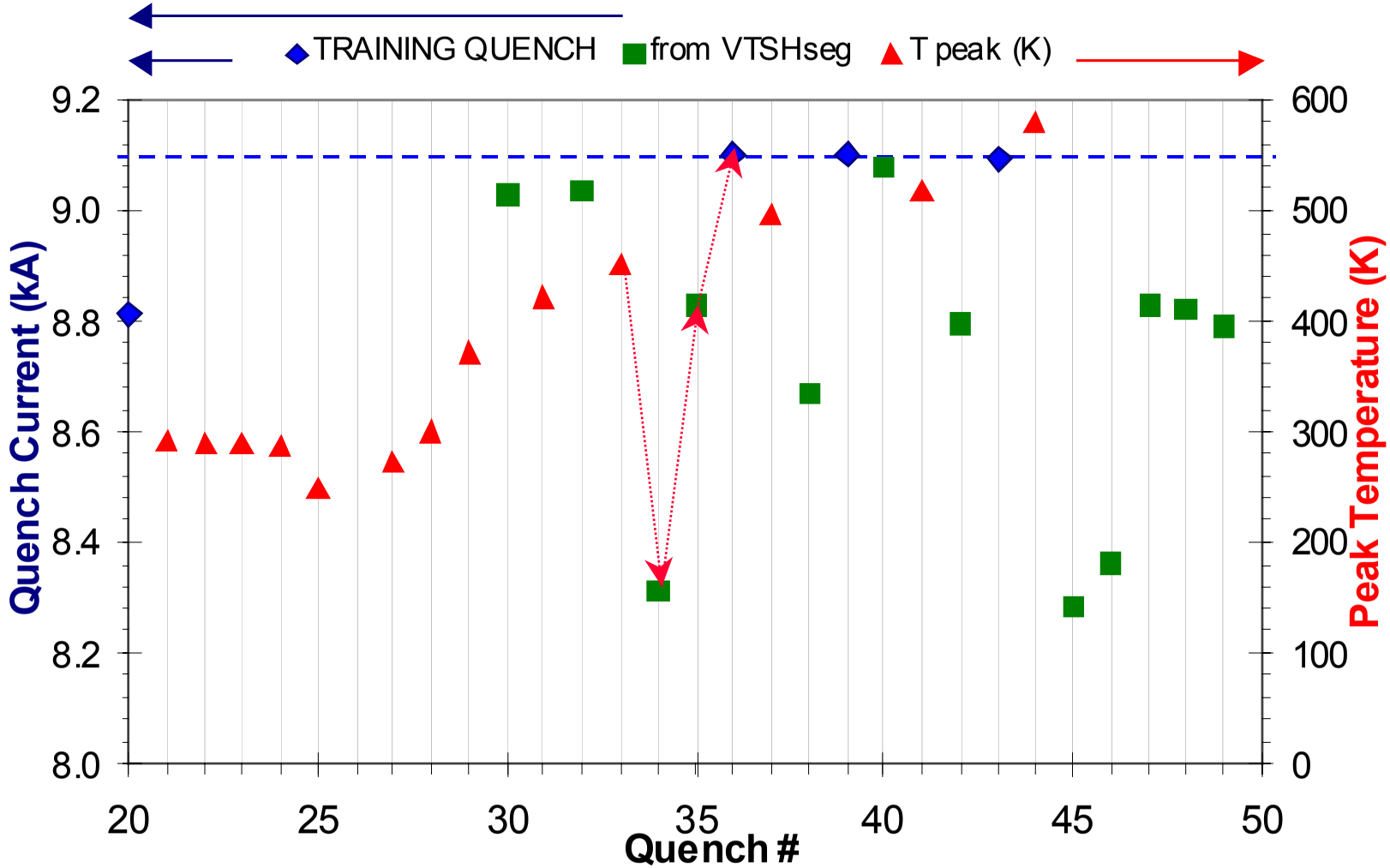
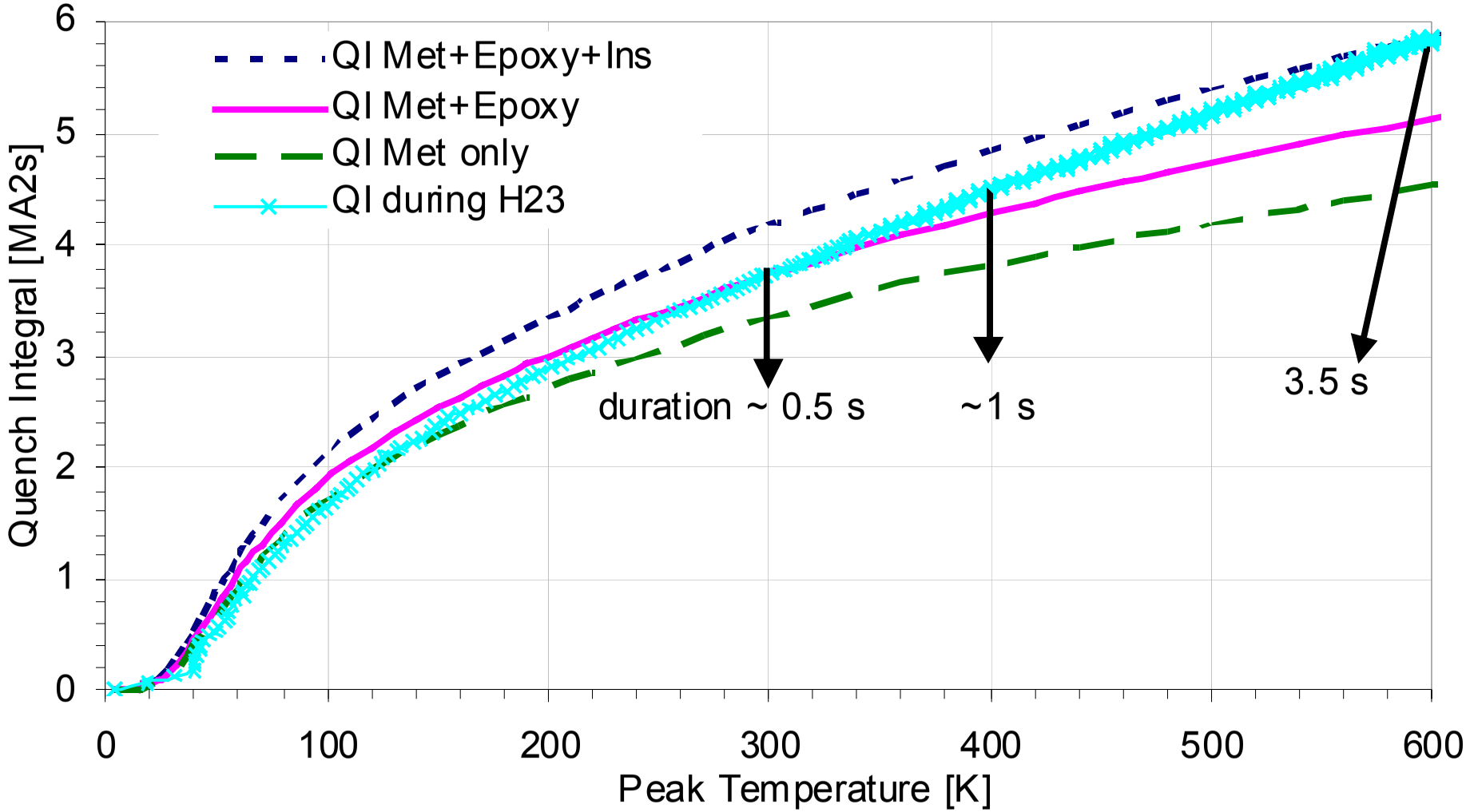
perconducting Magnet Program

Test Results

- Detraining after T > 430 K
- Signs of irreversible degradation (I/I_{max} ~ 3%) after T > 580 K.



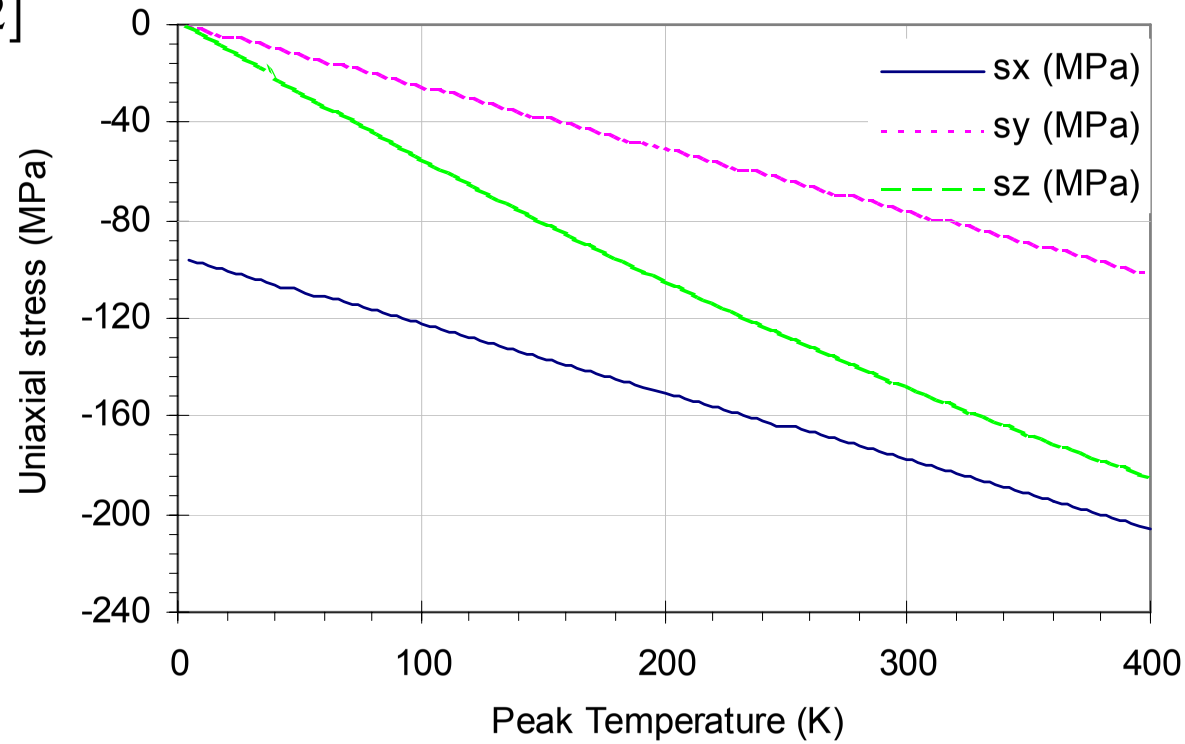
Quench Integral



⇒ ~0.1 mm of insulation needs to be included in the thermal balance

Stress analysis

$$\sigma_x(T) = E_x\left[\varepsilon_{0x} + c_x(T - T_{bath})/2\right]$$
$$\sigma_y(T) = E_y c_y(T - T_{bath})/2$$
$$\sigma_z(T) = E_z(T) c_z(T - T_{bath})`$$



Up to 400 K

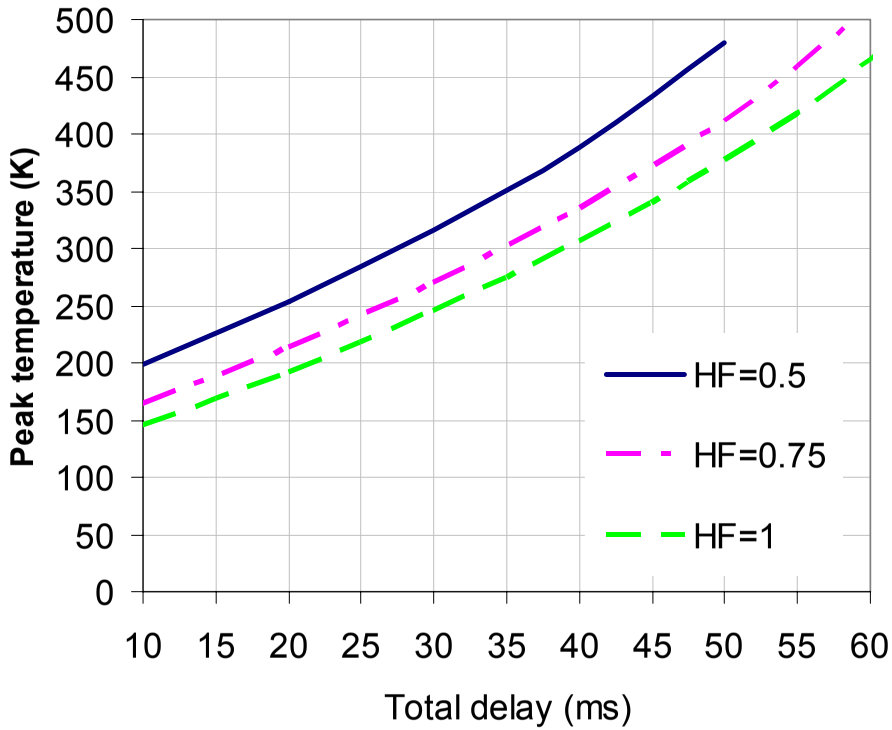
- Stresses and strains below irreversible limits
- Shear stress ~ epoxy strength (~40 MPa)

	x	y	z
ε (%)	-0.21	-0.27	-0.42
ε_{tot} (%)	-0.36		-0.57
σ (MPa)	-206	-111	-169
τ (MPa)	$\tau_{x,y} = 47$	$\tau_{y,z} = 29$	$\tau_{x,z} = 18$
Irreversib.	σ=-150/-200 MPa	σ=-150/-200 MPa	ε_{tot}<-0.7%

Conclusions -1

- **Quench simulations** showed T_{peak} > 300 K in long Nb_3Sn magnets
- to reduce T_{peak}, without compromising conductor efficiency and cost by increasing Cu fraction and magnet size, it is necessary to increase quench heater coverage and efficiency

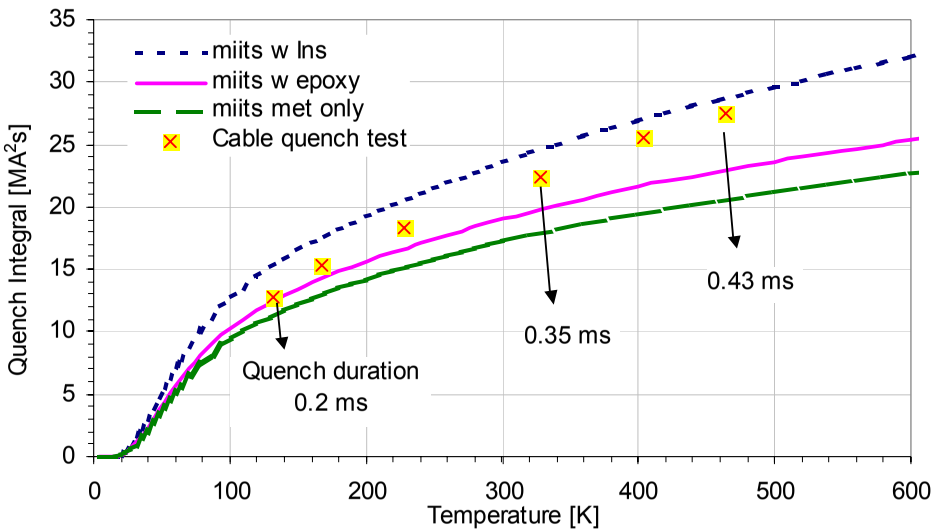
VLHC magnet	cosθ	Com.Coil
Cu/Ncu	1.2	1
RRR	~50	~50
Heater Coverage (%)	50	100
Total Heater Time Delay(ms)	<40	<10+30
QI @ 400 K (MA^2s)	43	42
QI @ 40 ms ($I=I_0$) (MA^2s)	18	22
Heater insulation (mm)	<0.5	<0.5
Heater Power (W/cm^2)	>130	>130
Peak Temperature (K)	380	390
Bulk Temperature (K)	140	120
Max Volt to Ground (V)	900	255
Current Decay Time (ms)	120	100

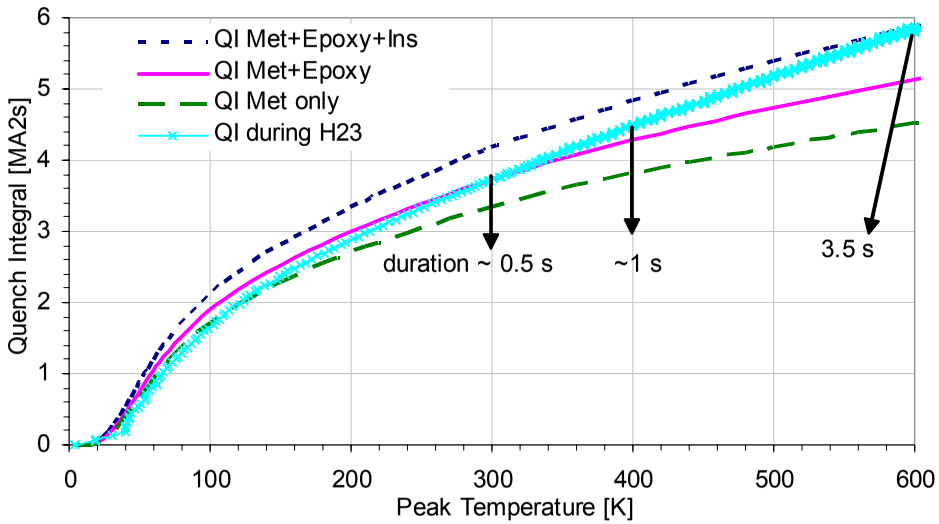


Conclusions -2

Contribution of insulation to thermal balance during quench

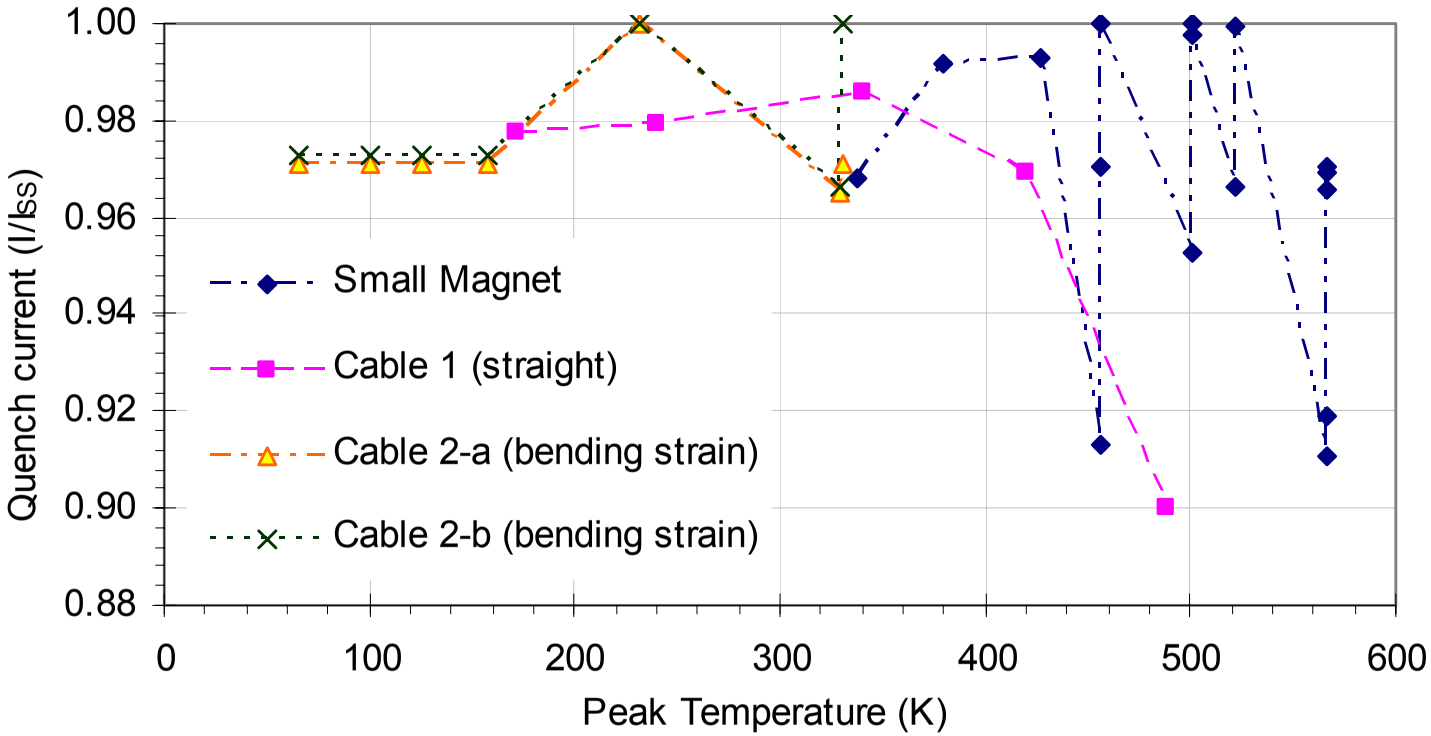
- Measured *QI* agree with the insulated cable curve at ~ T ≥ 300 K, and with the pure metal curve at lower T
- Consistent with diffusivity times: more "adiabatic", (less insulating material participating in the process) at the beginning of the quench
- Best quench simulation through complete FE model
- Adiabatic simulations with ~0.1 mm-insulation at high T.





Conclusions -3

- "Thermal shock" experiments indicate that T_{peak} up to 400 K do **not** compromise the magnet performance, if the stresses and strains in the conductor remain below its limits.
- At about 430 K, the epoxy resin undergoes a reversible glass transition, which can temporary weaken the insulation.



Outlook

The quench on Nb_3Sn magnet studies should continue with

- FE analyses of the thermo-mechanical response of a magnet during quench
- Material R&D, including
  - strip heaters insulation (sol-gel?)
  - Coil mechanical limits including I_c degradation under pressure thin edge of the cable and shear strength
- Thermal shock Tests on Nb_3Sn magnets with different designs

Acknowledgments:

Fermilab Technical Division

NHMFL Magnet Division

LBNL Supercon Magnet group