NATIONAL HIGH MAGNETIC FIELD LABORATORY

Comprehensive quench analysis of the NHMFL 32T all-superconducting magnet system (REBCO inner magnet + LTS outer magnet).

Andy Gavrilin

National High Magnetic Field Laboratory (NHMFL), Florida State University

Tallahassee, Florida, USA

Contributions by:

H.W. Weijers, W. D. Markiewicz (models development, analyses results interpretation),

D.K. Hilton, U.P. Trociewitz, D.C. Larbalestier (practical fit functions for critical current)

D.V. Abraimov, A. Xu, J. Jaroszynski (critical current and related measurements)

P.D. Noyes (input data on electric circuits and measurement details in quench tests)

Z.L. Johnson (coil structure and layout interpretation)

J. Lu, H. Bai (AC loss & LHe issues)

CHATS on Applied Superconductivity of 2015

University of Bologna, Bologna, Italy

September 15, 2015

NATIONAL HIGH MAGNETIC FIELD LABORATORY

Outline

1. Quench analysis - focusing on the quench simulation methodology:

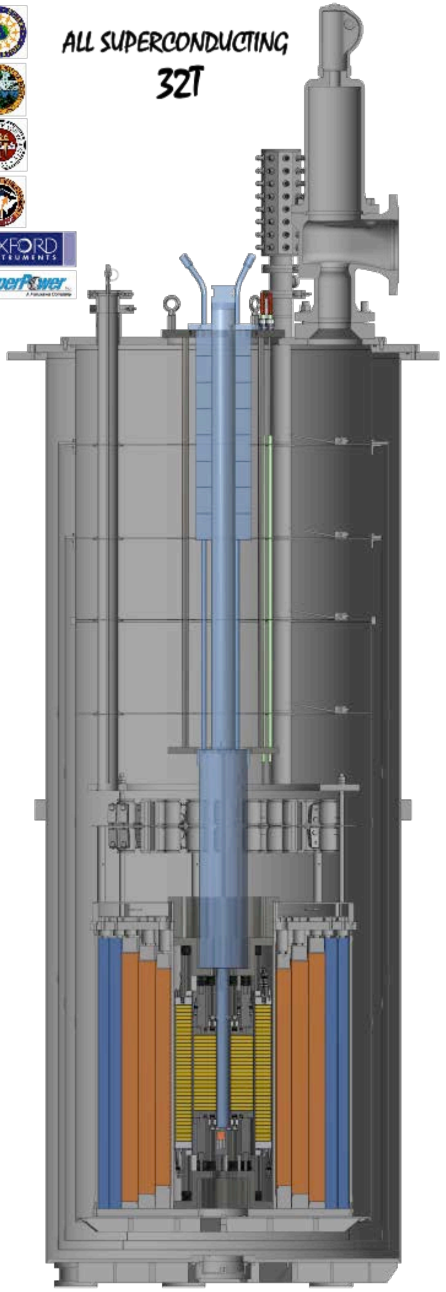
- Important details of our approach

- HTS: new features to be included and challenges to be addressed as compared to LTS magnets.

(Likely, the approach can be of use to any magnets wound with REBCO tapes and some other HTS conductors?)

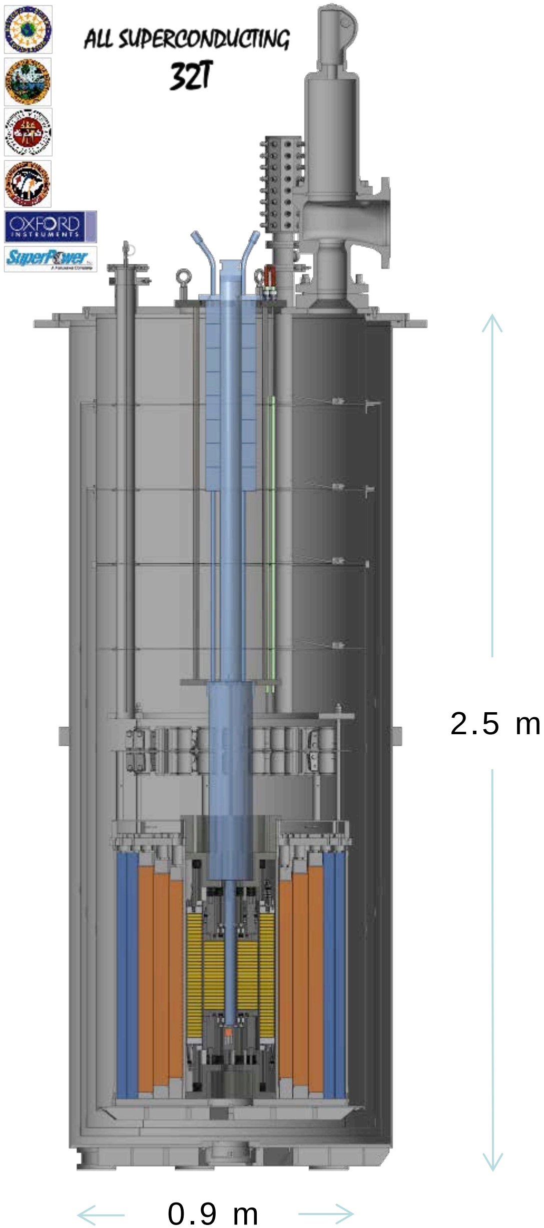
2. Importance of the analysis input data understanding adjustment and correct use: how to not substitute the reality.

3. Some results and lessons to learn.



NATIONAL HIGH MAGNETIC FIELD LABORATORY

The NHMFL 32T all-superconducting magnet system.



It is a big user magnet:

Total inductance 254 H

Stored energy 8.6 MJ

Collaboration of

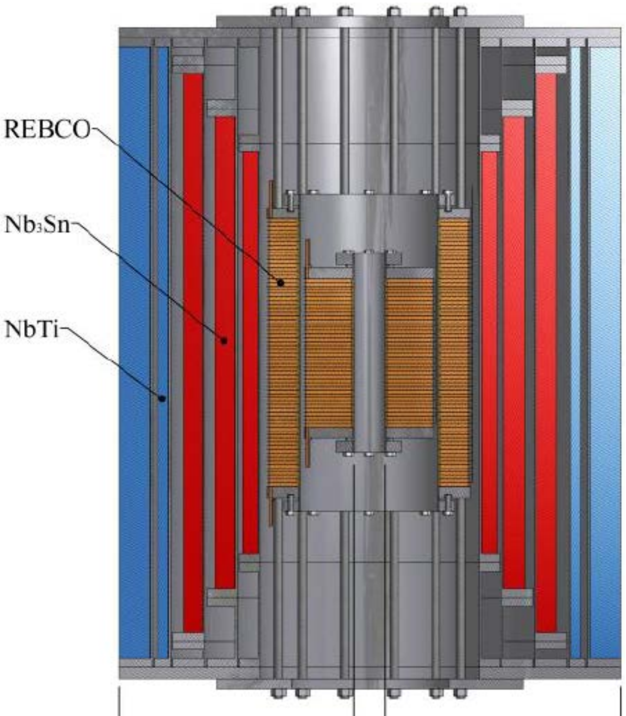
the NHMFL (inner HTS magnet “insert”),

Oxford Instruments, Inc. (outer LTS magnet “outsert”), and

SuperPower Inc. (REBCO superconductors)

A SuperPower ~4.12-mm wide YBCO tape cross-section (the hastelloy substrate and copper matrix are visible)

The 32T magnet design details



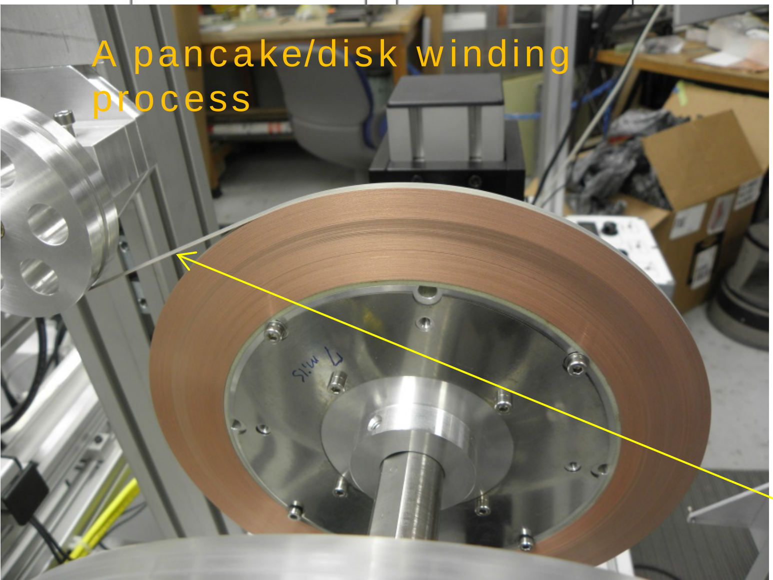
It is a hybrid: a combination of HTS and LTS magnets *to be considered together* (was not done before):

A 15 T / 250 mm bore LTS multi-coil outer magnet (the real configuration is not shown) – *LTS outsert*
&
a 17 T / 32 mm bore REBCO tape-wound 2-coil inner magnet – *HTS insert .*

All at 4.2K.

Two power supplies: one – for the insert, another – for the outsert, i.e., there are 2 electrically independent, but inductively coupled circuits. Both the insert & outsert are actively protected with heaters.

Each coil of the HTS insert consists of double-pancakes (*modules*): 20 in the inner coil (“coil 1”) + 36 in the outer coil (“coil 2”), i.e., 40 pancakes/disks in coil1 and 72 pancakes/disks in coil 2. The coils are connected in series.



The REBCO conductor/tape cross-section

New features and challenges to address

Why to model a quench event in such a magnet is challenging?

1. Both the insert and the outsert are to be considered together.

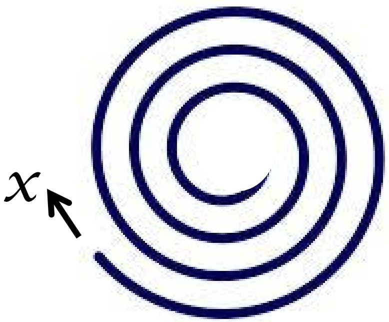
2. There are new features to be understood and addressed w.r.t. the insert (an HTS REBCO conductor wound magnet) quench behaviour as compared to that of an LTS magnet, and they will be detailed, but now - about the approach of principle to a quench modelling of the HTS magnet (insert) ...

NATIONAL HIGH MAGNETIC FIELD LABORATORY

Thermal problem. Model equation: heat conductance with a source term.

$$\left(A_{Cu}C_{Cu} + A_{SC}C_{SC} + A_{ins}\left(C_{ins} + f\gamma_p^{He}C_p^{He}\right)\right)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(A_t\kappa_t\frac{\partial T}{\partial x}\right) +$$

$$+\left[A_tQ_J + A_tQ_{AC}\right] + \sum_{i=1}^{4}\frac{P_i}{\delta_i}\kappa_i^{(ins)}(\bar{T}_i)\left(T^{(i)} - T\right) + P_{1(2)}Q_{heater},\ [W/m]$$



Schematic of a pancake ("disk")

x - the coordinate along the spiral path of superconducting tape within a given pancake.

$T = T(x,t)$ – the tape temperature;

the tape cross-section area: $A_t = A_{Cu} + A_{SC}$

A_{Cu} – the tape copper matrix cross-section area;

A_{SC} – the cross-section area of other materials of the tape, incl. hastelloy substrate, etc.;

the insulated tape heat capacity:

$$A_{Cu}C_{Cu}(T) + A_{SC}C_{SC}(T) + A_{ins}(C_{ins}(T) + f\gamma_p^{He}(T)C_p^{He}(T)),\ [J/(m\ \ K)],$$

also includes the heat capacity of helium in the winding at constant pressure,

f is the helium proportion of the insulation in terms of volume.

The helium density $\gamma_p^{He}(T)$ is considered temperature dependent to mimic the helium vaporization process.

Thermal problem. Model equation: heat conductance with a source term.

$$\left(A_{Cu}C_{Cu} + A_{SC}C_{SC} + A_{ins}(C_{ins} + f\gamma_p^{He}C_p^{He})\right)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(A_t\kappa_t\frac{\partial T}{\partial x}\right) +$$

$$+\left[A_tQ_J + A_tQ_{AC}\right] + \sum_{i=1}^{4}\frac{P_i}{\delta_i}\kappa_i^{(ins)}(\overline{T}_i)\left(T^{(i)} - T\right) + P_{1(2)}Q_{heater},\ [W/m]$$

The tape effective longitudinal thermal conductivity:

$$A_t\kappa_t = A_t\kappa_t(T, B);\ B = B(x,t);$$

The heating power density (index and Joule heating, and AC loss (in the superconducting areas) if any):

$$A_tQ_J + A_tQ_{AC} =$$

$$= A_tQ_J(T(x,t), I(t), B(x,t)) + A_tQ_{AC}(T(x,t), B(x,t), \dot{B}(x,t), I(t))$$

Detailed time-varying distributions of the magnetic field components within the coils are required.

MAGNETIC NATIONAL HIGH FIELD LABORATORY

Thermal problem. Model equation.

$$\left(A_{Cu}C_{Cu}+A_{SC}C_{SC}+A_{ins}\left(C_{ins}+f\gamma_p^{He}C_p^{He}\right)\right)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(A_t\kappa_t\frac{\partial T}{\partial x}\right)+$$

$$+\left[A_tQ_J+A_tQ_{AC}\right]+\sum_{i=1}^{4}\frac{P_i}{\delta_i}\kappa_i^{(ins)}(\overline{T}_i)\left(T^{(i)}-T\right)+P_{1(2)}Q_{heater},\ [W/m]$$

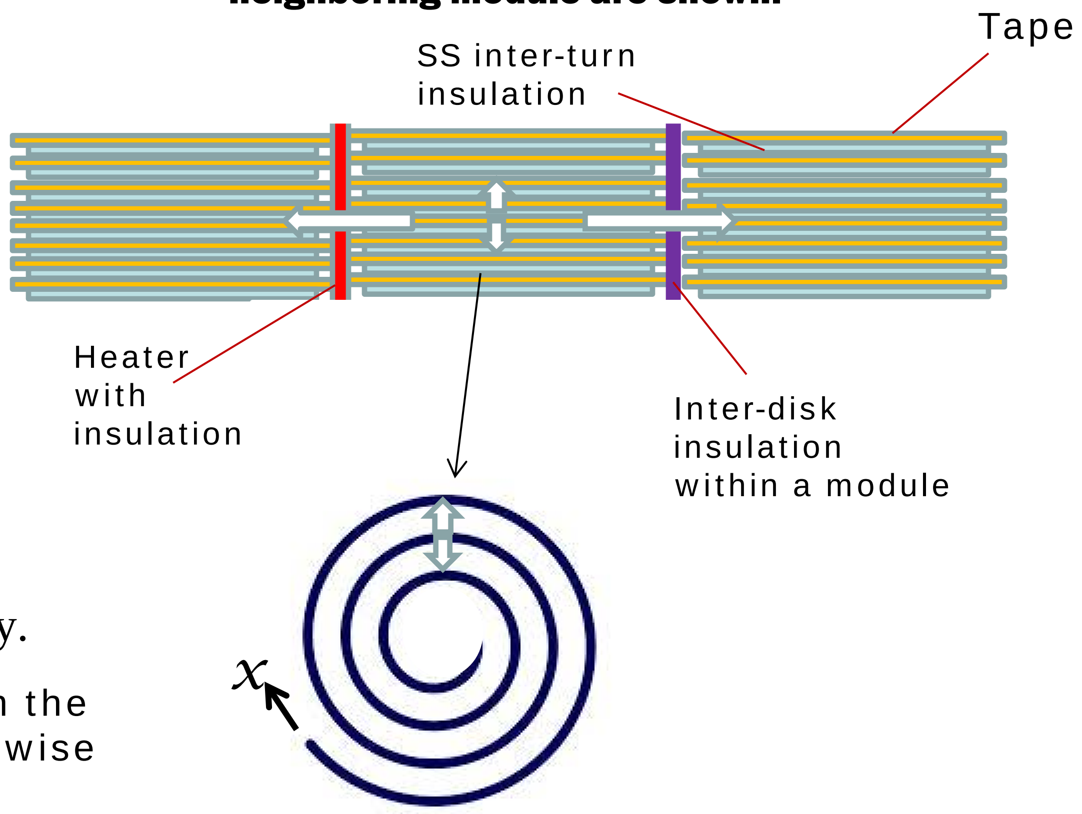
The transverse thermal axial (disk - to - disk) and radial (turn - to - turn, within a disk) links :

$$\sum_{i=1}^{4}\frac{P_i}{\delta_i/\kappa_i^{(ins)}(\overline{T}_i)+R_C^{(i)}}(T^{(i)}-T)$$

$R_C^{(i)}$ is the thermal contact resistance characterizing the quality of contact between the superconducting tape copper matrix and the insulation.

$Q_{heater}(x,t)$ is the heat flux density from the quench protection heaters if any.

Schematic of winding cross-section (fragment). One module and a half of neighboring module are shown.



The outsert modelling is based upon the same equations, albeit for the layer-wise geometry.
Finally, circuit equations are included.

Thermal problem. Model equation: heat conductance with a source term.

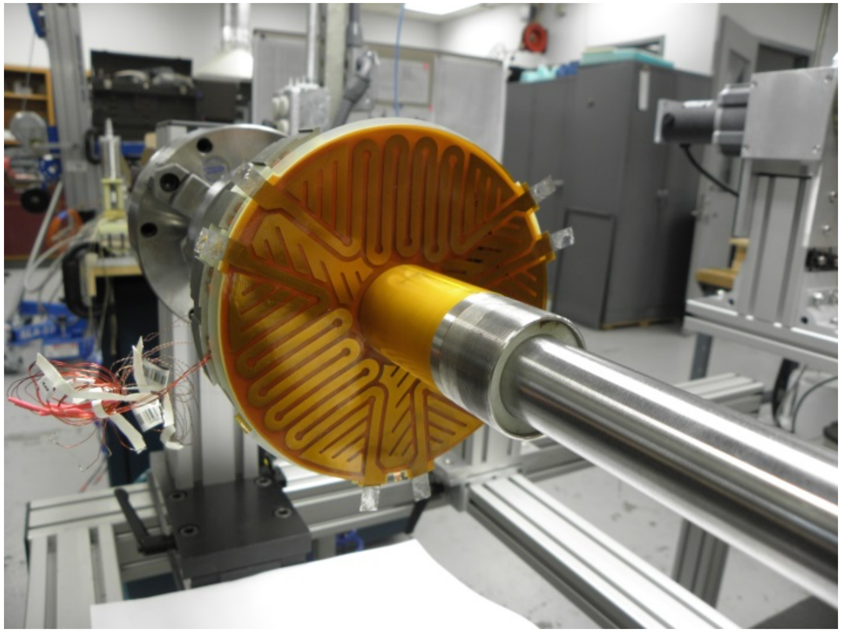
$$\left(A_{Cu}C_{Cu} + A_{SC}C_{SC} + A_{ins}(C_{ins} + f\gamma_p^{He}C_p^{He})\right)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(A_t\kappa_t\frac{\partial T}{\partial x}\right) +$$

$$+\left[A_tQ_J + A_tQ_{AC}\right] + \sum_{i=1}^{4}\frac{P_i}{\delta_i}\kappa_i^{(ins)}(\bar{T}_i)\left(T^{(i)} - T\right) + P_{1(2)}Q_{heater}, \; [W/m]$$

The tape effective longitudinal thermal conductivity:

$$A_t\kappa_t = A_t\kappa_t(T,B);\; B = B(x,t);$$

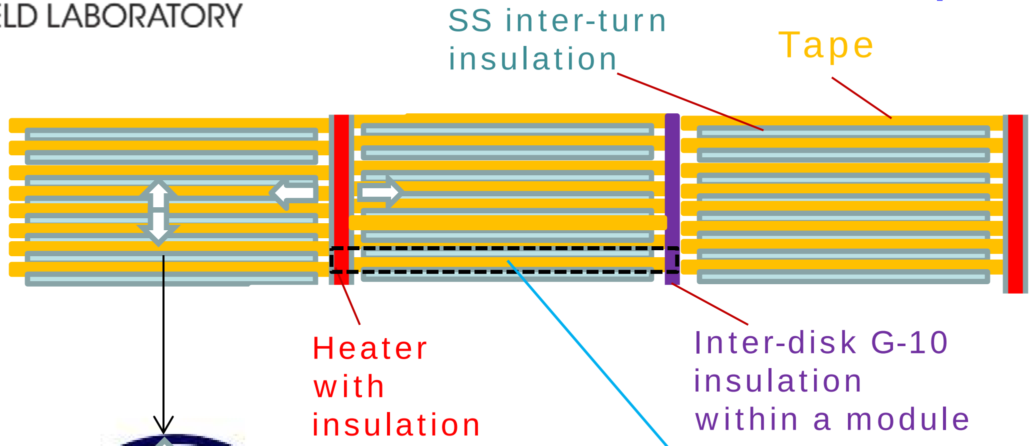
We may disregard the longitudinal heat conductance, if the distributed heaters are used.



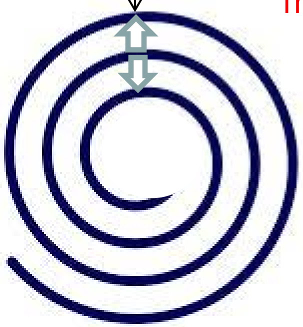
A 3-element distributed protection heater is attached to a pancake of the insert coil 1 (the inner coil).

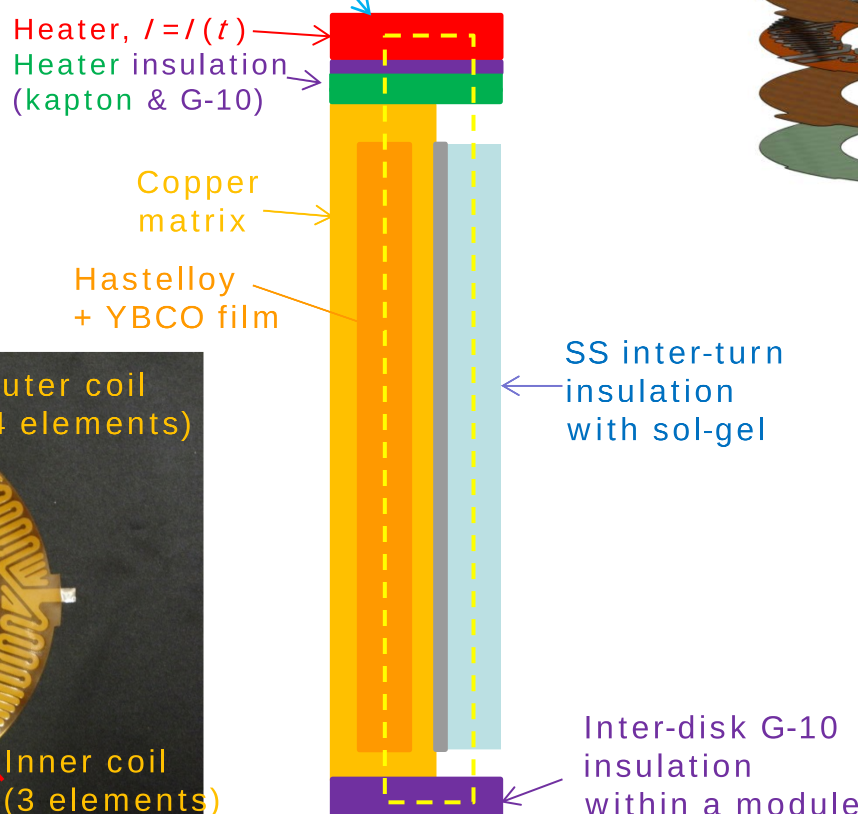
How we model the quench heaters' operation

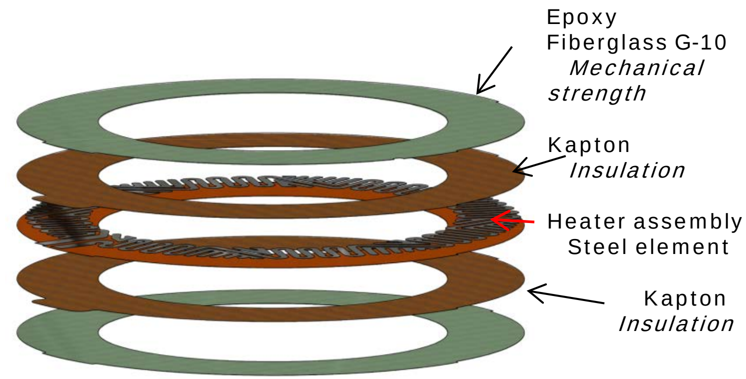
The heaters are supposed to create promptly a large enough normal zone (with appropriately large resistance) without overheating their insulation and the coils.

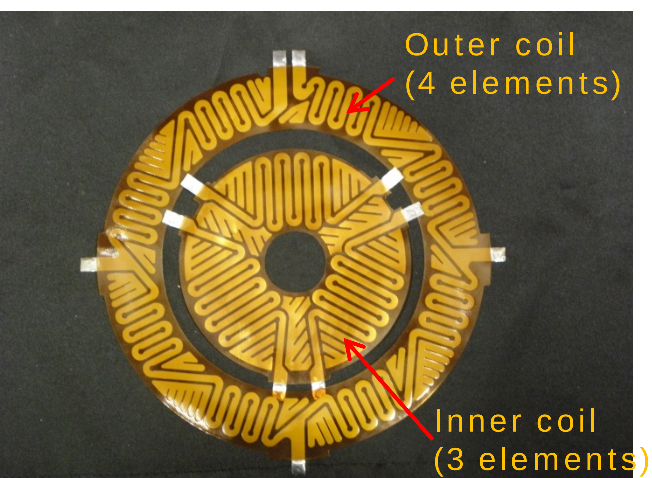


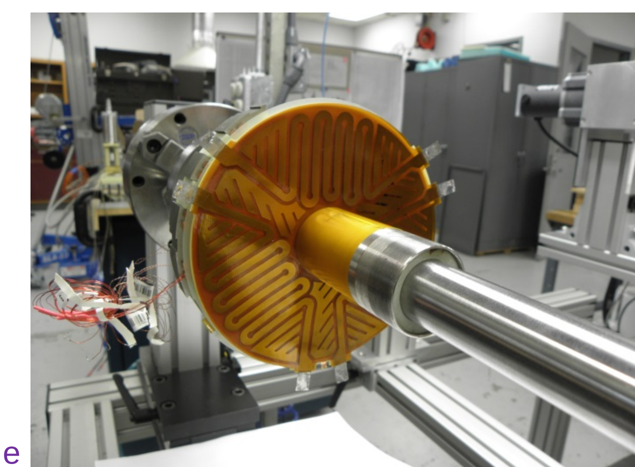
Schematic of winding cross-section (fragment). One module and a half of neighboring module are shown.





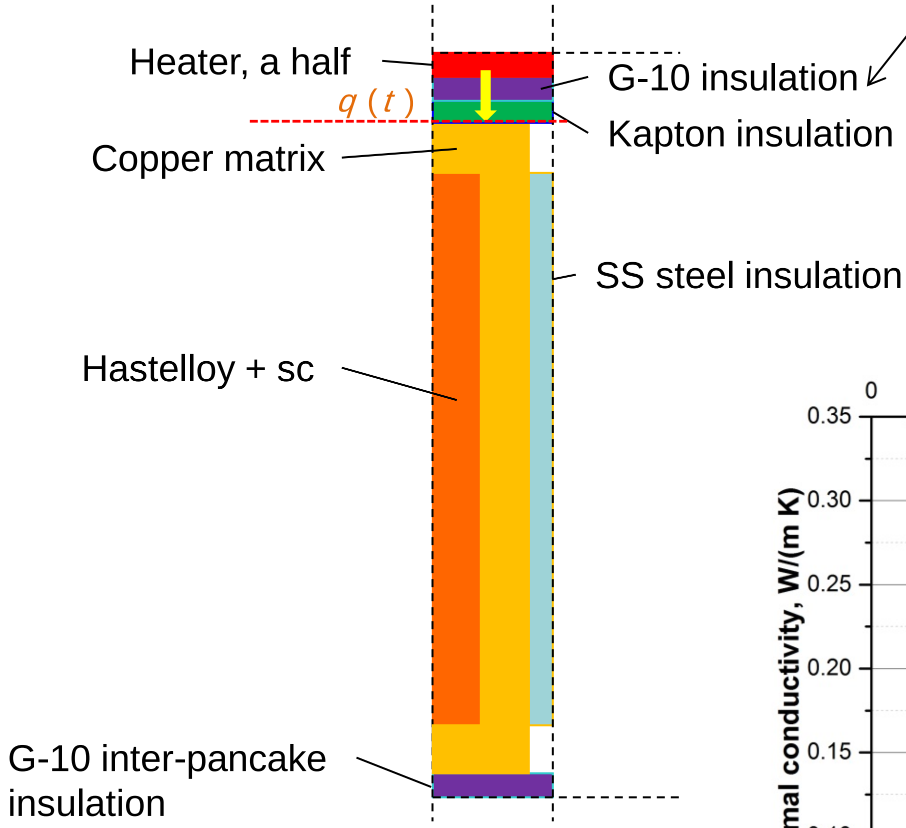






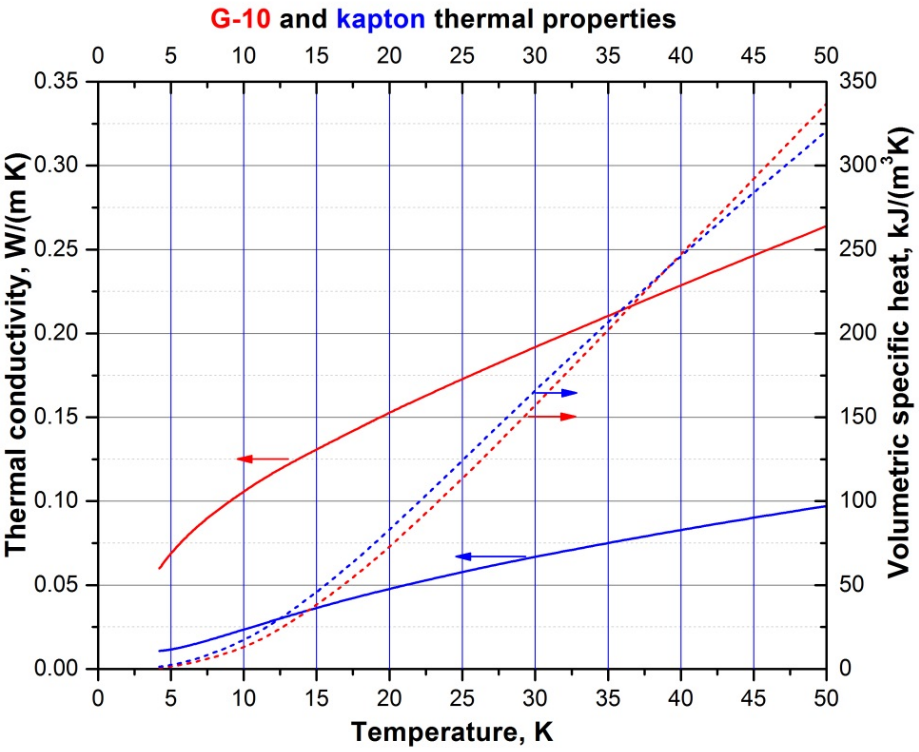
Analytical unit cell.

Symmetry BC along the black dashed lines

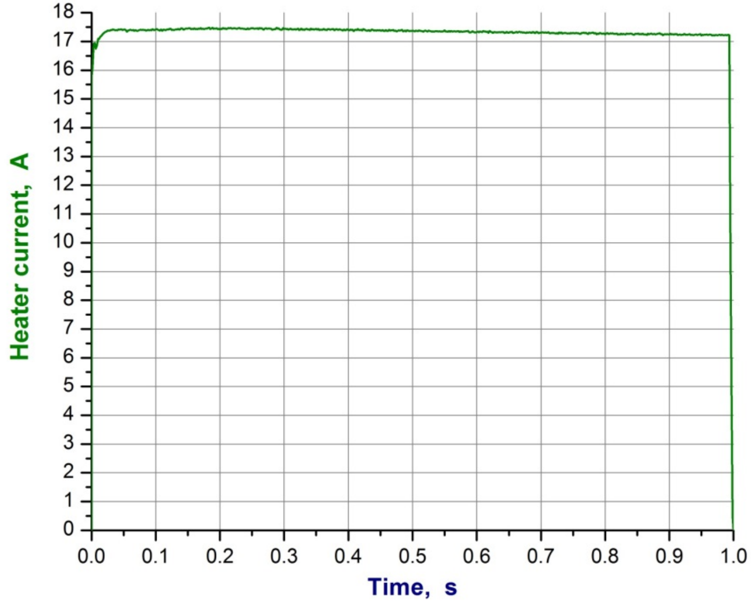


~30 combinations of G-10 and kapton thicknesses were tried.

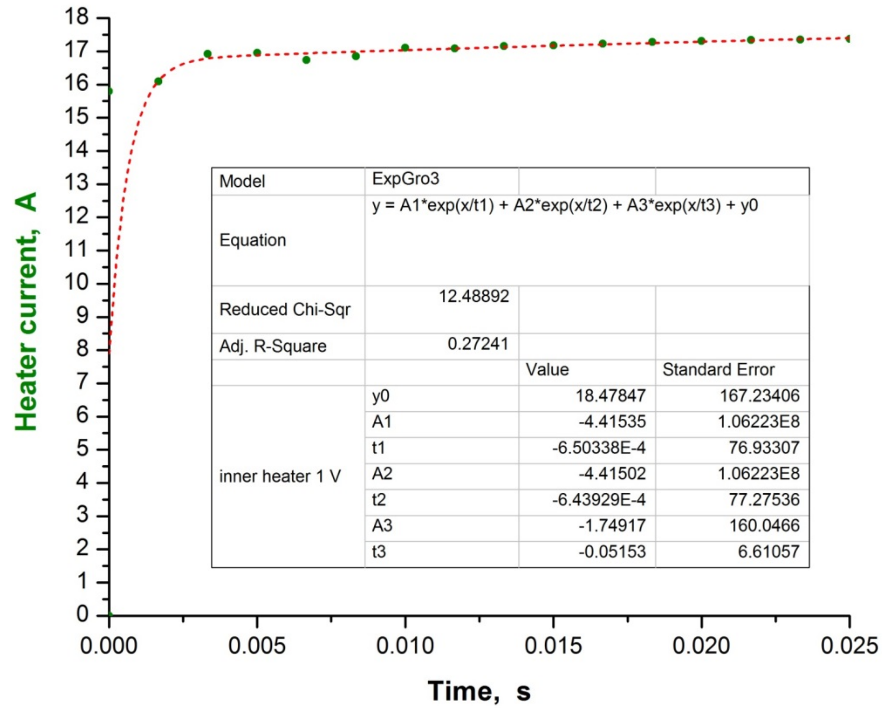
A 2D transient non-liner heat conductance equation with a heat term is solved to obtain the heat flux per unit area of the pancake side surface (at the heater insulation – copper matrix interface). The 2D mesh is fine to model the transient heat transfer precisely.



Protection heater current trace as the input

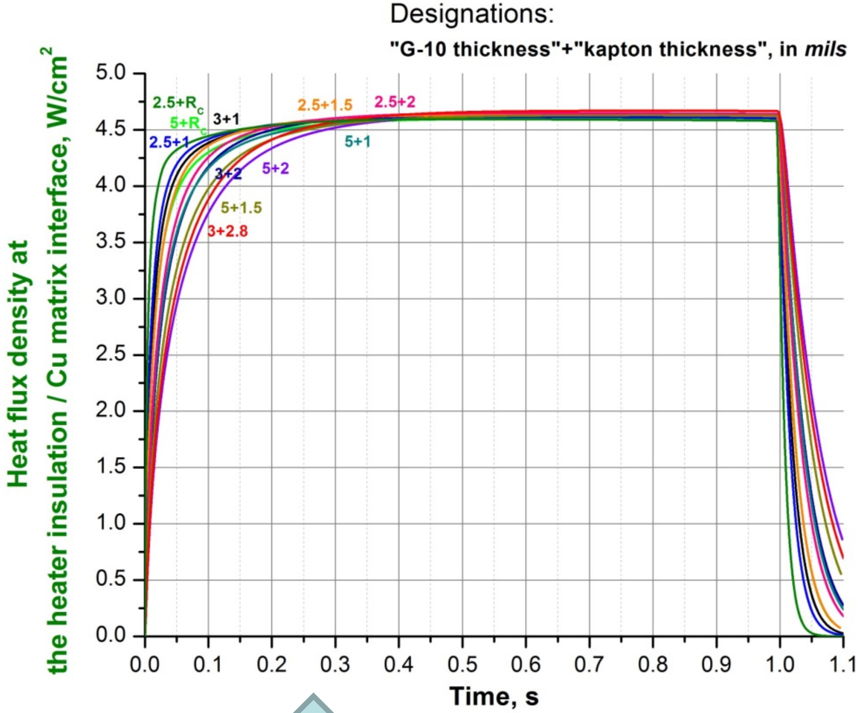


A current pulse in the heater. -
A capacitor bank is used.
Duration of typical pulse is 1 second.

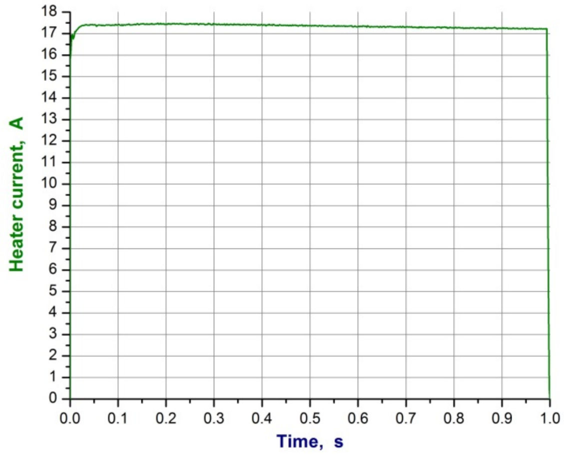


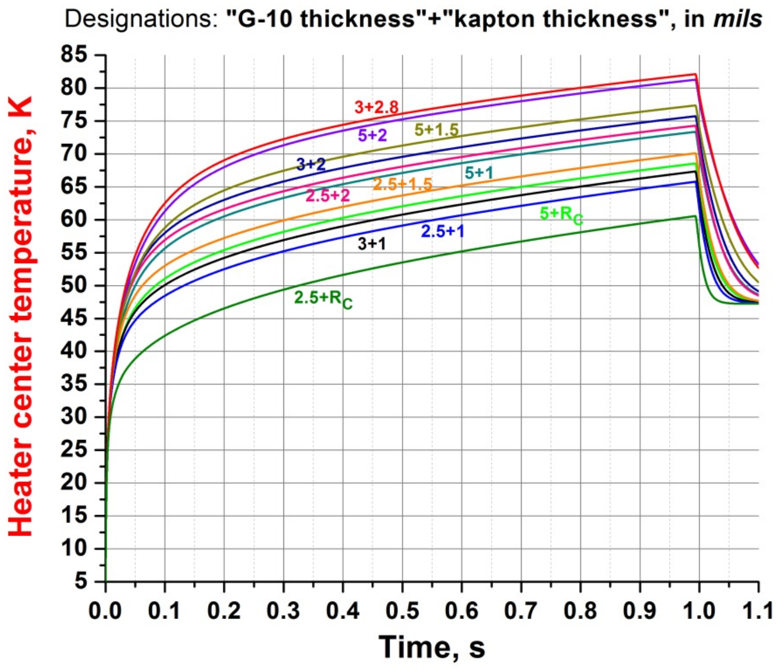
Model	ExpGro3		
Equation	y = A1*exp(x/t1) + A2*exp(x/t2) + A3*exp(x/t3) + y0		
Reduced Chi-Sqr	12.48892		
Adj. R-Square	0.27241		
		Value	Standard Error
inner heater 1 V	y0	18.47847	167.23406
	A1	-4.41535	1.06223E8
	t1	-6.50338E-4	76.93307
	A2	-4.41502	1.06223E8
	t2	-6.43929E-4	77.27536
	A3	-1.74917	160.0466
	t3	-0.05153	6.61057

Evolution of heat flux into the winding.



The heat flux is actually the same with various combinations of heater insulation layers. Temperature rise/drop of heater element compensates for increased/decreased thermal impedance.

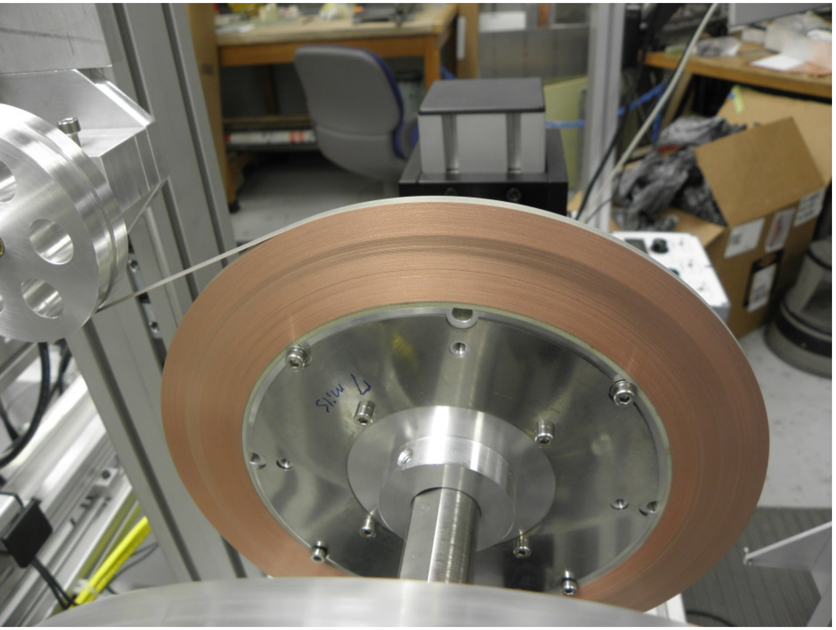


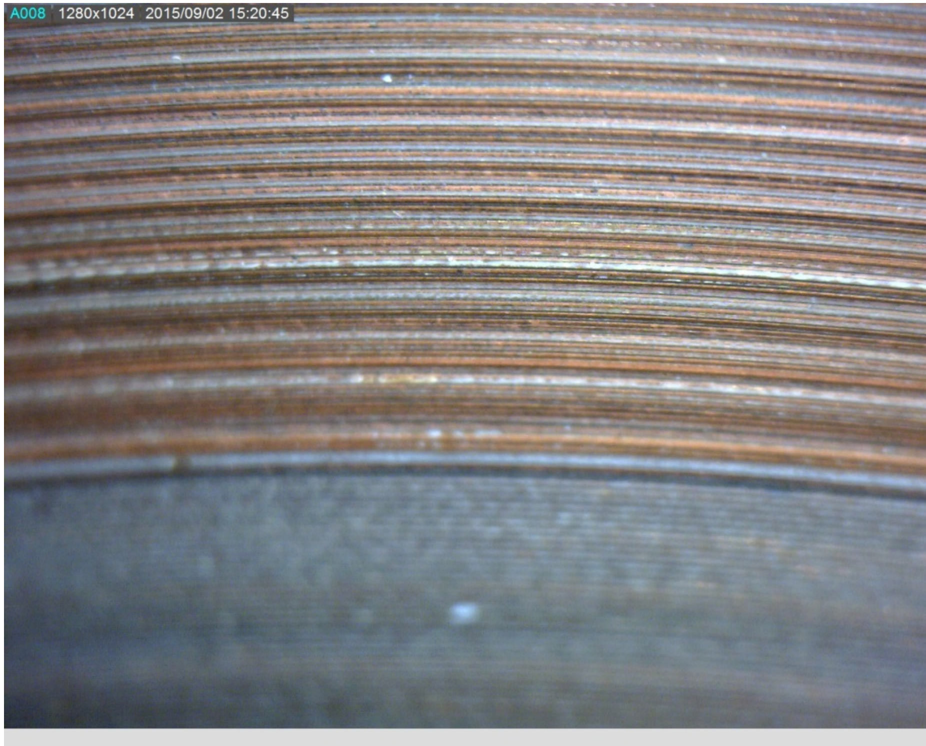


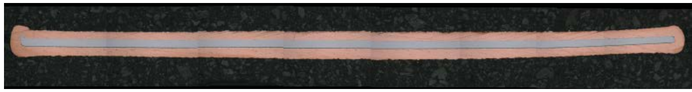
NATIONAL HIGH MAGNETIC FIELD LABORATORY

New features and challenges to address

1. The insert coils are not impregnated:
- Full contact of heaters with the pancakes is not guaranteed







The edge (side surface) of pancake is not flat, because
- the tape edge is not flat
- the tape cross-section area is not a rectangular
- the tape width varies.

As a result, the real size of contact spot between the heater and the pancake is unknown, and there might be small multiple spots.

How to deal with this? - Our approach that works: we need to determine/specify a fraction of full contact spot/area. 50%, 75%, 30% ? It is what we were to figure out. Also, we were supposed to specify the contact pattern (# of spots and their distribution).

NATIONAL HIGH MAGNETIC FIELD LABORATORY

New features and challenges to address

1. The insert coils are not impregnated: some LHe in the insert coil winding is guaranteed.

The calculations show that the amount of LHe in the winding (characterized by the volume fraction f) is too small and vaporizes quickly. Thus, its effect on the characteristics of quench is very small if not negligible, if the winding hydraulic impedance is large and no natural convection can occur.

$$\left(A_{Cu}C_{Cu} + A_{SC}C_{SC} + A_{ins}(C_{ins} + f\gamma_p^{He}C_p^{He})\right)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(A_t\kappa_t\frac{\partial T}{\partial x}\right) +$$

$$+\left[A_tQ_J + A_tQ_{AC}\right] + \sum_{i=1}^{4}\frac{P_i}{\delta_i}\kappa_i^{(ins)}(\overline{T_i})\left(T^{(i)} - T\right) + P_{1(2)}Q_{heater},\ [W/m]$$

x - the coordinate along the spiral path of superconducting tape within a given pancake.

$T = T(x,t)$ – the tape temperature;

the tape cross-section area: $A_t = A_{Cu} + A_{SC}$

A_{Cu} – the tape copper matrix cross-section area;

A_{SC} – the cross-section area of other materials of the tape, incl. hastelloy substrate, etc.;

the insulated tape heat capacity:

$$A_{Cu}C_{Cu}(T) + A_{SC}C_{SC}(T) + A_{ins}(C_{ins}(T) + f\gamma_p^{He}(T)C_p^{He}(T)),\ [J/(m\ \ K)],$$

also includes the heat capacity of helium in the winding at constant pressure,

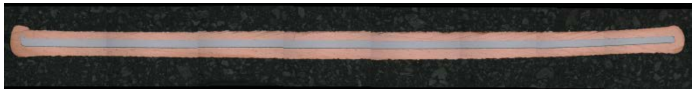
f is the helium proportion of the insulation in terms of volume.

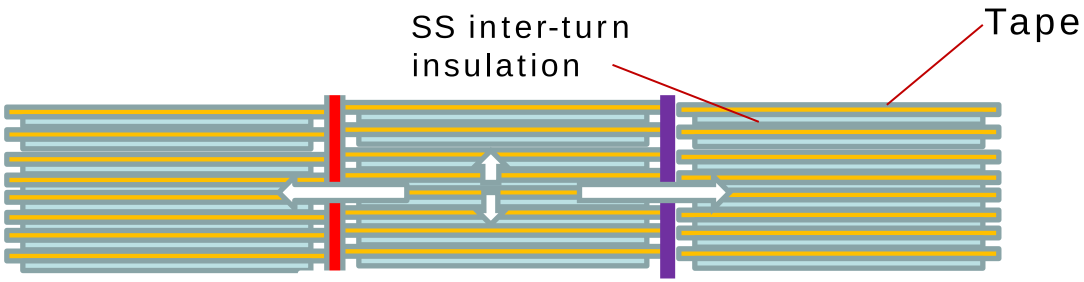
The helium density $\gamma_p^{He}(T)$ is considered temperature dependent to mimic the helium vaporization process.

New features and challenges to address

1. The insert coils are not impregnated:
- Uncertainty with the transverse/turn-to-turn heat conductance within pancakes and with the axial/pancake-to-pancake heat conductance as well.

The tape is not flat.
The stainless steel insulation is sol-gel both-side covered.





The transverse thermal axial (disk-to-disk) and radial (turn-to-turn, within a disk) links:

$$\sum_{i=1}^{4}\frac{P_i}{\delta_i/\kappa_i^{(ins)}(\bar{T}_i)+R_C^{(i)}}\left(T^{(i)}-T\right)$$

$R_C^{(i)}$ is the thermal contact resistance characterizing the quality of contact between the superconducting tape copper matrix and the insulation.

$$\left(A_{Cu}C_{Cu}+A_{SC}C_{SC}+A_{ins}\left(C_{ins}+f\gamma_p^{He}C_p^{He}\right)\right)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(A_t\kappa_t\frac{\partial T}{\partial x}\right)+$$

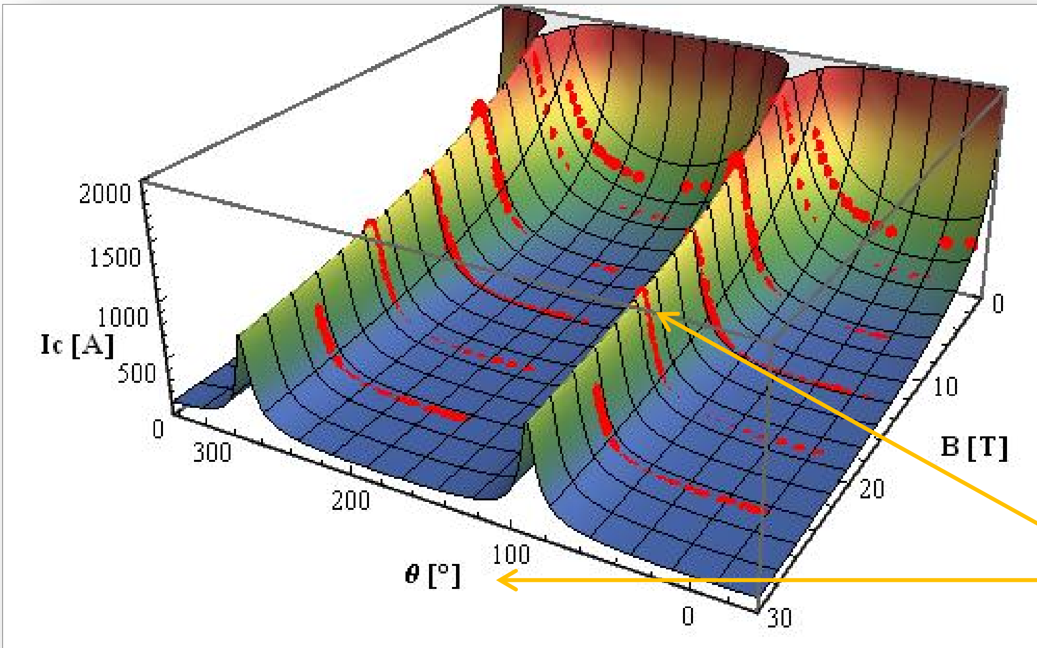
$$+\left[A_tQ_J+A_tQ_{AC}\right]+\sum_{i=1}^{4}\frac{P_i}{\delta_i}\kappa_i^{(ins)}(\bar{T}_i)\left(T^{(i)}-T\right)+P_{1(2)}Q_{heater},\ [W/m]$$

The contact resistance is supposed to be rather large....

New features and challenges to address. Ic-value.

2. The REBCO critical current dependence on the field and temperature is much more complicated; there exists the dependence on the field angle as well:

- Need to examine and use the measured critical current dependencies carefully.
- Need to calculate precisely the field angle distributions within the insert coils.
- Huge sensitivity of the critical current value to the tape orientation in space in the parallel field (small tilt angles make a difference) that affects the protection heaters efficiency and quench behavior



Numerous measurements of the critical current were made, and a practical fit function was suggested (@ 4.2K) (**D.K. Hilton, A.V. Gavrilin and U.P. Trociewitz, "Practical fit functions for transport critical current versus field magnitude and angle data from (RE)BCO coated conductors at fixed low temperatures and in high magnetic fields", Superconductor Science and Technology, Volume 28 , Number 7, 2015**).

As can be inferred from the dependence, the critical current value is extremely sensitive to the field angle value in the vicinity of peak.

$$I_c(B,\theta) = \frac{b_0}{(B+\beta_0)^{\alpha_0}} + \frac{b_1}{(B+\beta_1)^{\alpha_1}}\left[\omega_1^2(B)\cos^2(\theta-\varphi_1)+\sin^2(\theta-\varphi_1)\right]^{-1/2}$$

NATIONAL HIGH MAGNETIC FIELD LABORATORY

Critical current calculation. Temperature dependence.

SP-26_x-B-T_Ic_Data_Fits.pdf - Adobe Acrobat Pro

Measurements and Nonlinear Least-Squares Fits of Transport Critical Current of BZO-Doped SCS-4050-AP Tape (SP-26) vs. Magnetic Flux Density and Angle at Fixed Low Temperatures

National High Magnetic Field Laboratory
D. K. Hilton, U. P. Trociewitz, D. V. Abraimov, J. J. Jaroszynski, A. Xu, H. W. Weijers, D. C. Larbalestier

Nonlinear Fit Model:

$$I_c(B,\theta) = \frac{b_0}{(B+\beta_0)^{\alpha_0}} + \frac{b_1}{(B+\beta_1)^{\alpha_1}}\left[\omega_1^2(B)\cos^2(\theta-\varphi_1)+\sin^2(\theta-\varphi_1)\right]^{-1/2}$$

Ridge Width Function:

$$\omega_1(B) = c_1\left[B+\left(\frac{1}{c_1}\right)^{1/\varepsilon_1}\right]^{\varepsilon_1}$$

Table 1. Nonlinear Fit Parameters vs. Measurement Temperature.

T [K]	α_0 [-]	α_1 [-]	b_0 [-]	b_1 [-]	β_0 [T]	β_1 [T]	φ_1 [°]	c_1 [-]	ε_1 [-]	N* [-]
4.2	1.29746	0.809120	8870.39	18456.2	13.8	13.8	-0.180370	2.15	0.600	458
10	-	-	-	-	-	-	-	-	-	-
20	1.22463	-0.118386	1984.79	808.573	1.63	1.63	0.045741	2.11	0.833	784
30	1.55834	-0.412436	4783.15	311.800	2.78	2.78	0.670420	5.10	0.800	1022
40	0.794303	-0.468420	583.391	198.420	0.600	0.600	-0.375648	26.09	0.500	1076

** Number of data points per fit.*
- Measurements at T = 10 K pending.

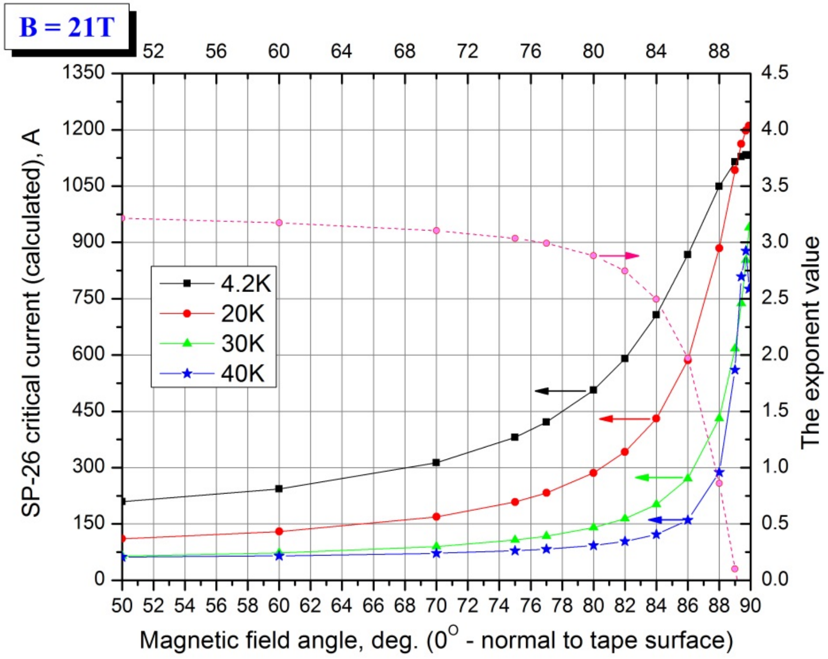
To include the temperature dependence, the critical current was measured at several temperatures and the fit function coefficients were found for each temperature. The critical current values at other temperatures are calculated by means of interpolation and extrapolation.

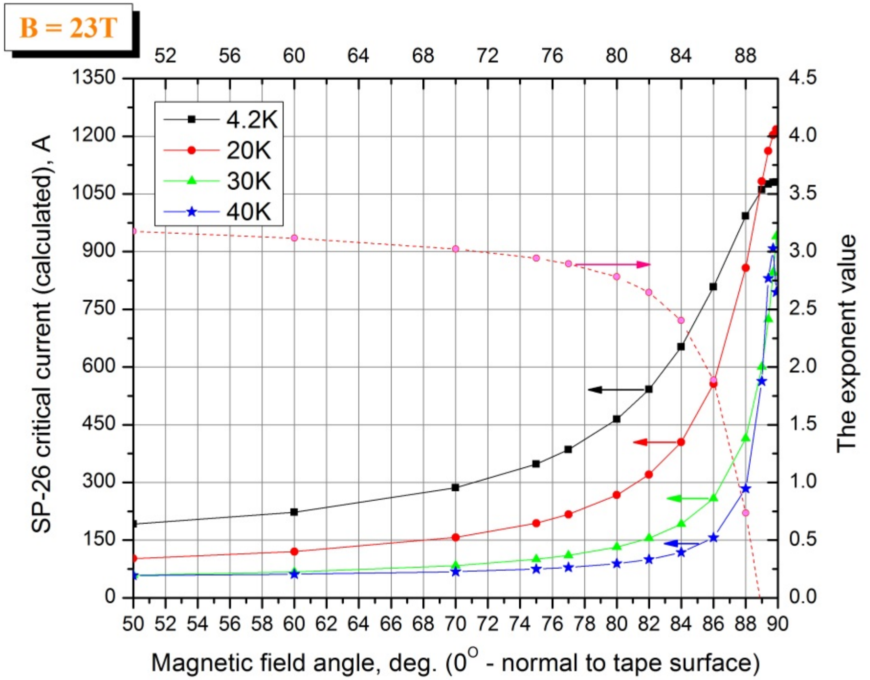
New features and challenges to address. Ic-value.

2. The REBCO critical current dependence on the field and temperature is much more complicated; there exists the dependence on the field angle as well:

- Need to examine and use the measured critical current dependencies carefully.

The measured and fitted data in high fields:





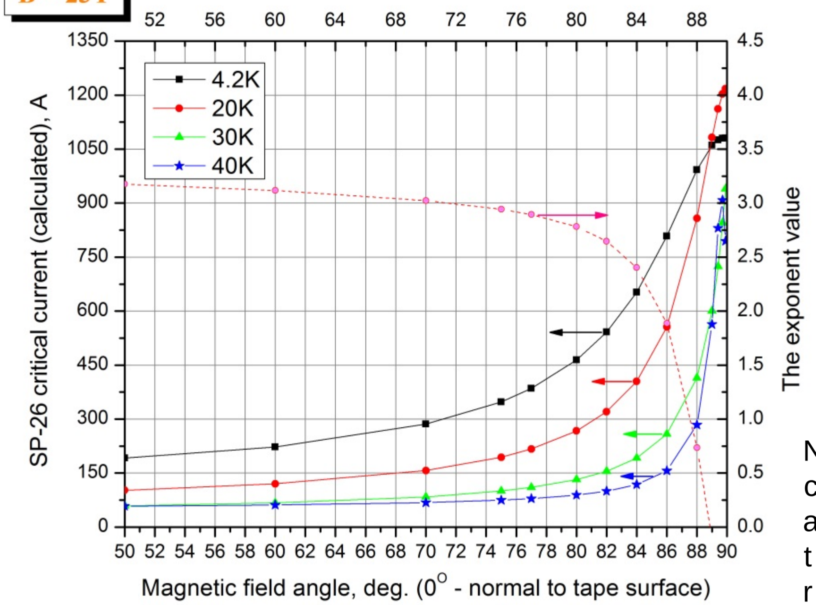
At 4.2K, to measure the Ic-values precisely in the almost parallel field is very difficult: the measurement error is too large, and, to be specific, at the field angles, say, > 77 deg. the dependence looks questionable and at angles > 88K – incorrect (indeed, Ic(4.2K) < Ic(20K) ?!).

At the same time, the measurement errors at higher temperatures are very small (e.g., @ 20K).

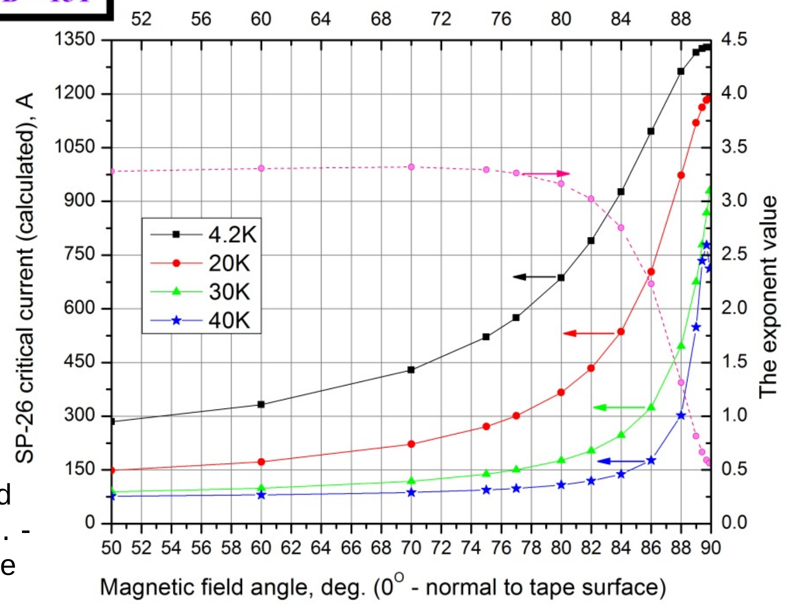
How to “repair” the dependence at 4.2K and large field angles?

Ic data @ 4.2K to be adjusted

B = 23T

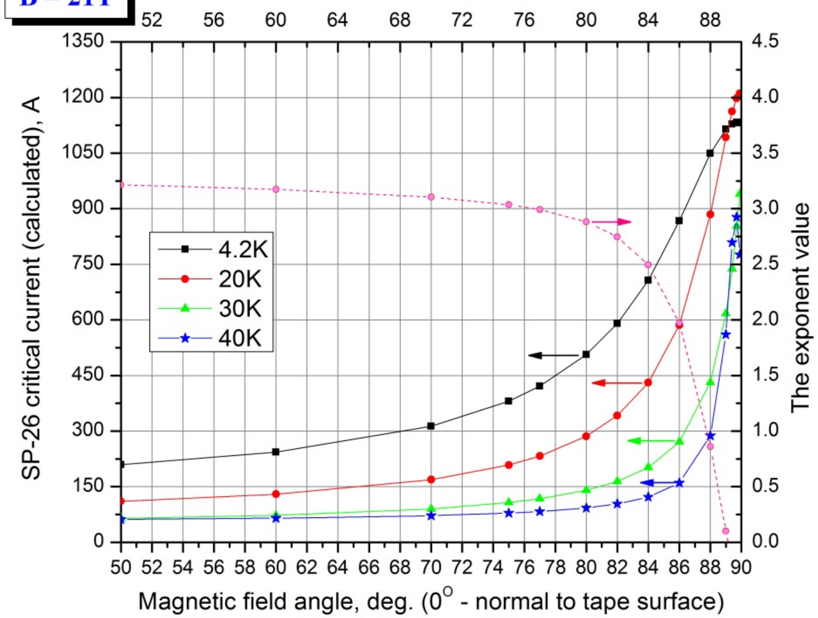


B = 15T



N-value is not constant at field angles > 77 deg. - the questionable range.

B = 21T



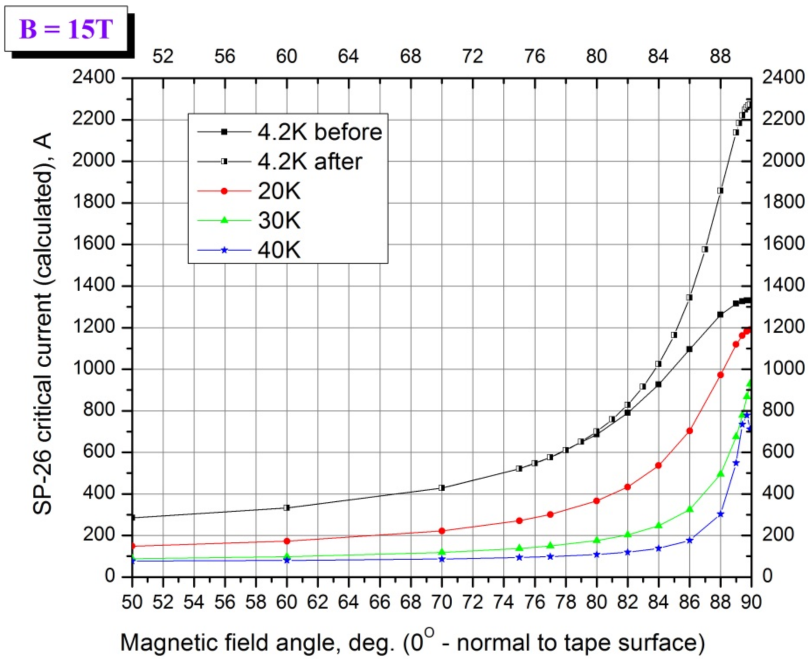
$$I_C(T) = I_{C0}\left(1 - T/T_C\right)^N$$

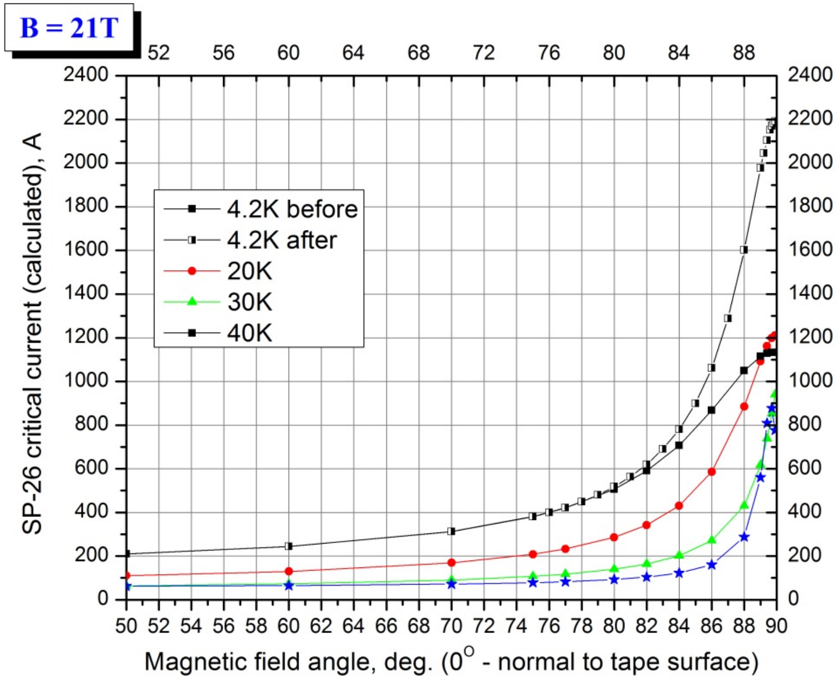
For a number of the field magnitude & field angle values, one can find the exponent values by solving the set of equations :

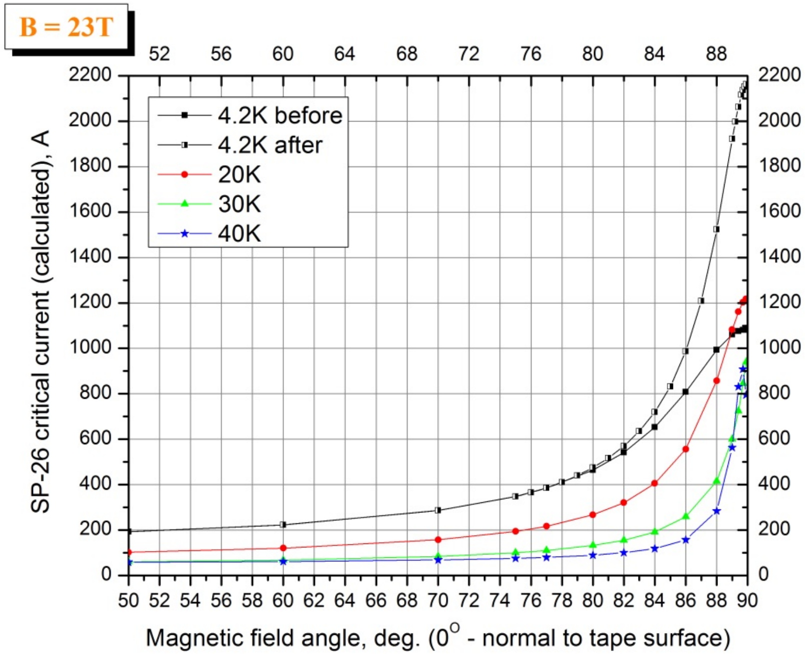
$$I_C(20) = I_{C0}\left(1 - 20/T_C\right)^N$$

$$I_C(4.2) = I_{C0}\left(1 - 4.2/T_C\right)^N \Rightarrow N = \frac{\log\left(\dfrac{I_C(4.2)}{I_C(20)}\right)}{\log\left(\dfrac{T_C - 4.2}{T_C - 20}\right)}$$

Ic input data @ 4.2K after correction







Making this correction to obtain a more realistic ***I*c**-dependence @ 4.2K and the large field angles:

$$I_C(4.2,\theta,B) = I_C(20,\theta,B)\left(\frac{T_C-4.2}{T_C-20}\right)^{N(B)} \quad ,\theta > 77^O$$

$$\textit{The N} - \textit{value @ } \theta = 77^O \textit{ is taken.}$$

NATIONAL HIGH MAGNETIC FIELD LABORATORY

New features and challenges to address

3. The process of superconducting-normal transition in a REBCO tape differs from that in a LTSuperconductor. A new model is required.

The index and Joule power density is calculated using the following model:

If $I < I_C(B,T,\theta)$, $A_t Q_J = I\ E$, where $E = E_0 \left[\frac{I}{I_C} \right]^{n(B,T,I)}$.

the critical current criterion is $1\ \mu V/cm$ ($E_0 = 1\ \mu V/cm$), A_t – *the tape cross – section area*.

If $I \geq I_C(B,T,\theta)$ and $\frac{\partial E}{\partial I} \approx \frac{E - E_0}{I - I_C} < \rho_{Cu} / A_{Cu}$, then $A_t Q_J = I\ E$;

else (i.e., $\frac{\partial E}{\partial I} \geq \rho_{Cu} / A_{Cu}$):

$A_t Q_J = I\ (I - I_C)\ \rho_{Cu} / A_{Cu}$ if $I_C > 0$, and $A_t Q_J = I^2\ \rho_{Cu} / A_{Cu}$ if $I_C = 0$ (*transition is complete*).

The resistive voltage of a pancake (disk) $V_D(t) = \int_o^l E(t,x)\,dx$,

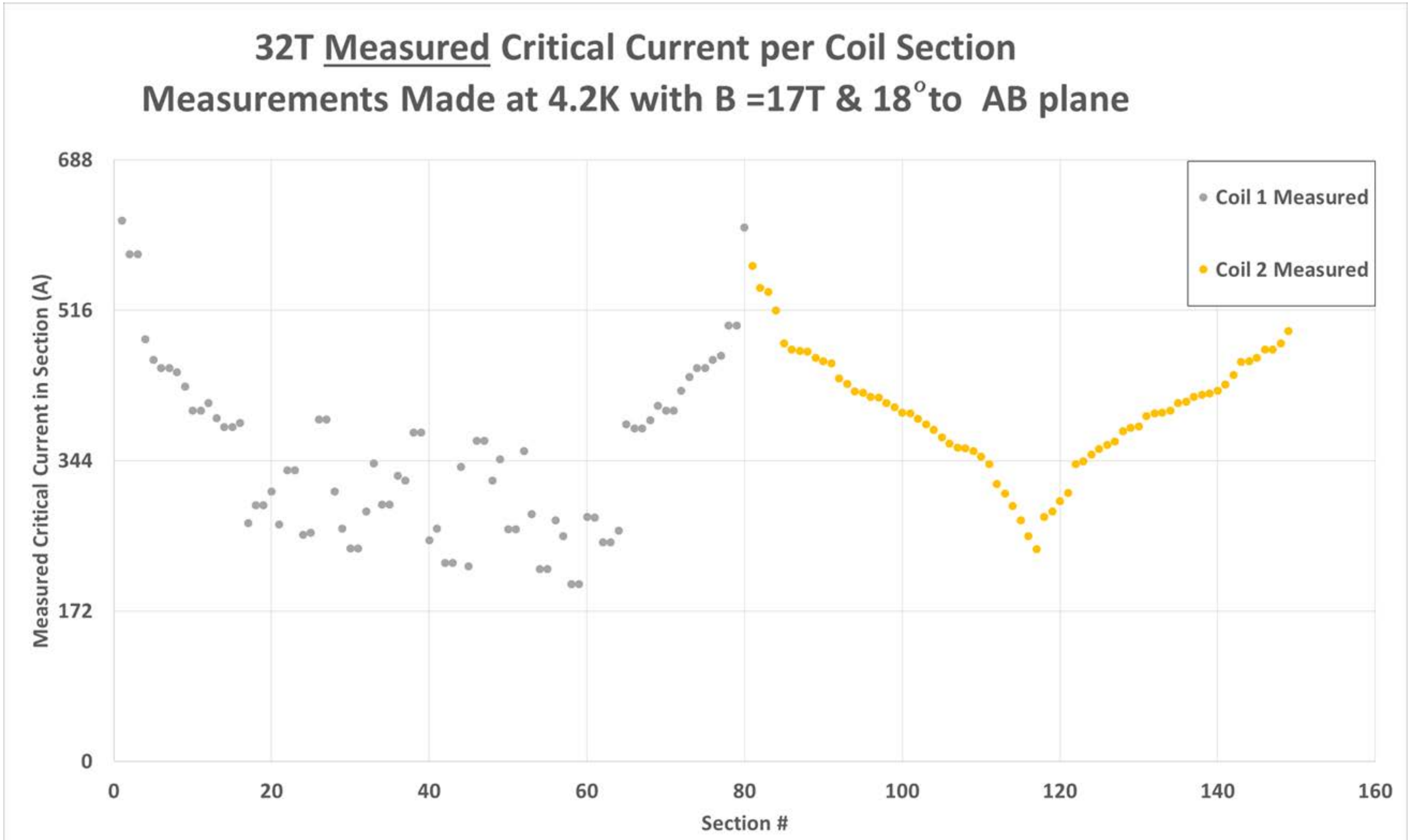
where l is the tape length within a given pancake;

the coil resistance $V_C(t) = \sum_{k=1}^{K} V_D^{(k)}(t)$, where K is the total number of pancakes in the coil.

New features and challenges to address. Layout.

4. *Each* pancake is wound of *2 different pieces* of conductor (with different current carrying capacity):

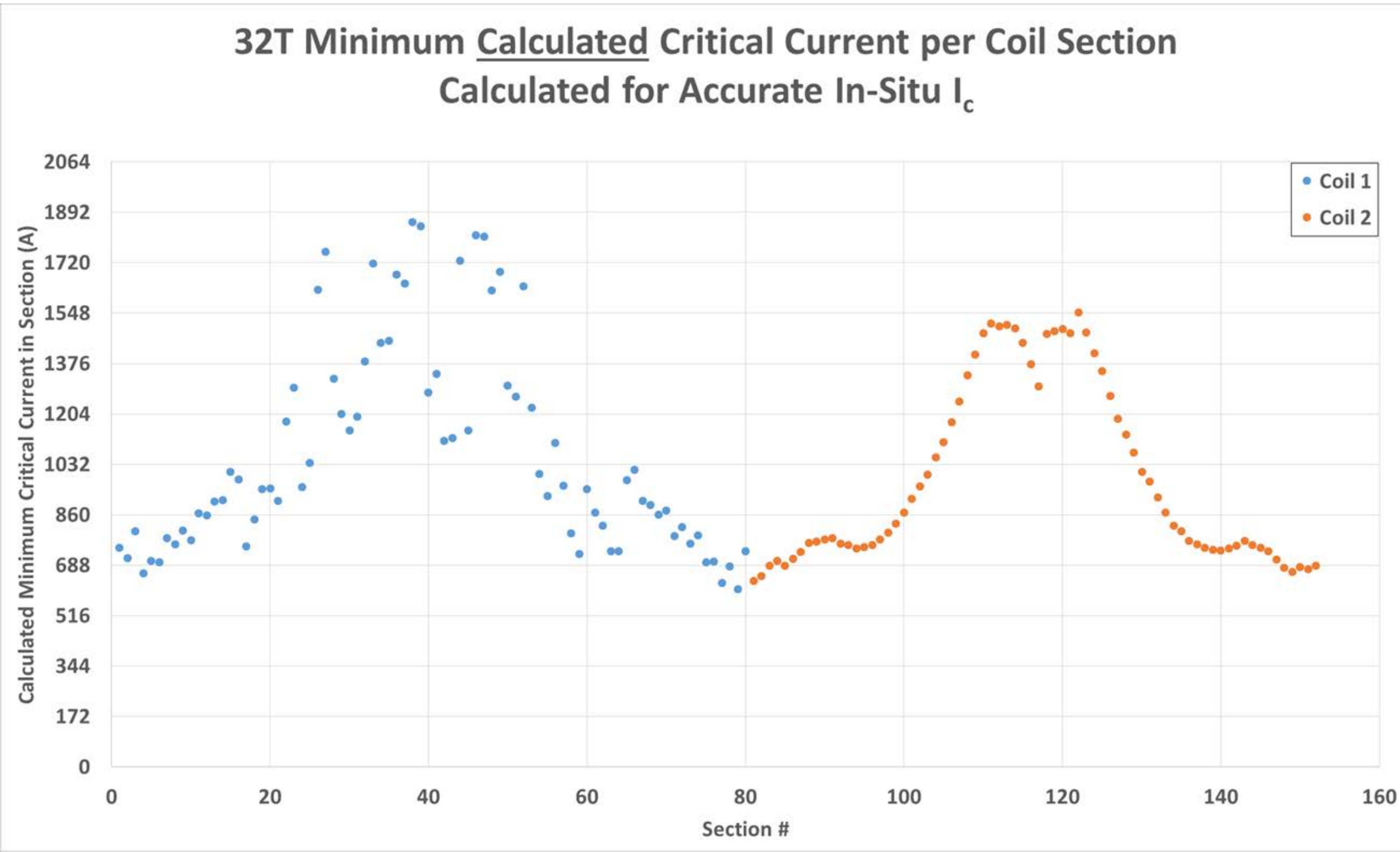
- All the pieces have different width, thickness, and current carrying capacity, Ic (the Ic-density is assumed to be the same, but the amount of superconductor – to be different).
- Thus, the actual layout of conductor should be included : different sections of each pancake have different # of turns, thickness and different current carrying capacity.
- All this affects the insert geometry, field distribution, heaters efficiency, and thus quench behavior.



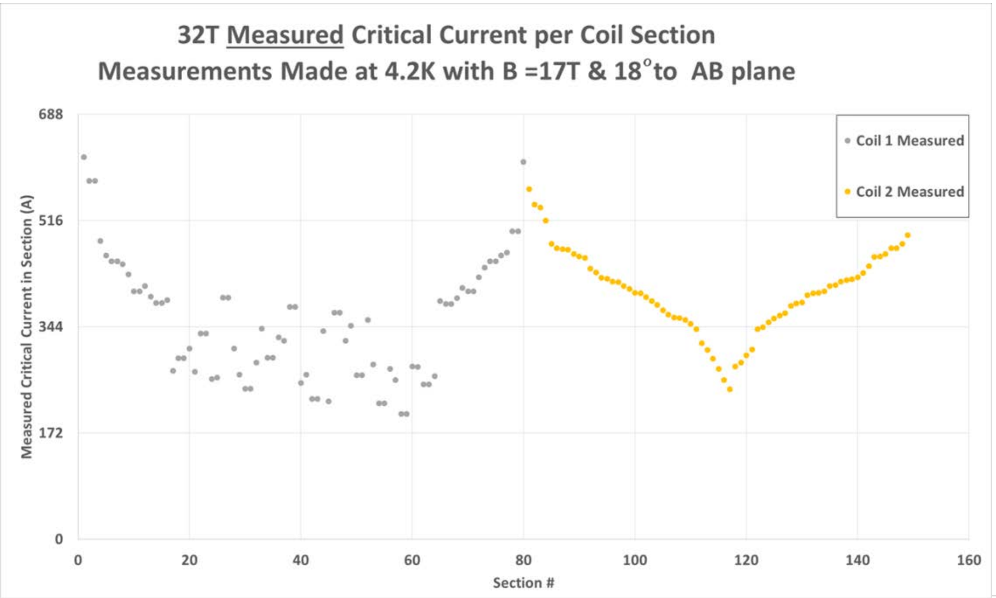
New features and challenges to address. Layout.

4. *Each* pancake is wound of *2 different pieces* of conductor (with different current carrying capacity):

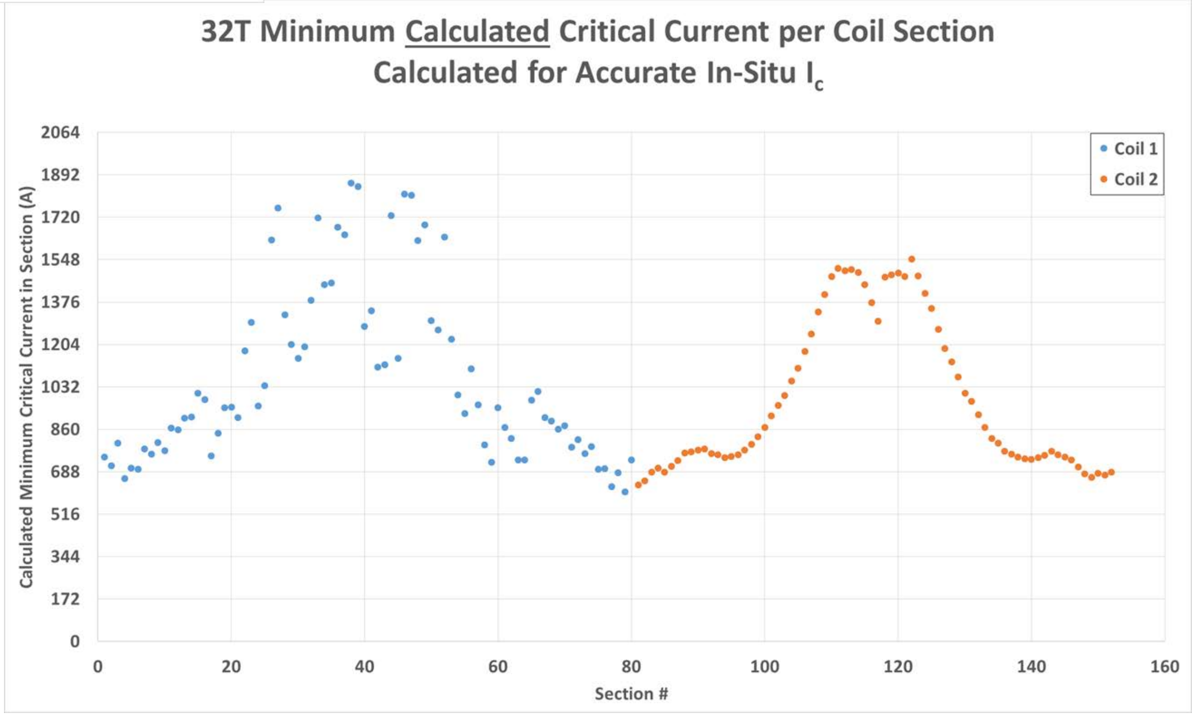
- All the pieces have different width, thickness and current carrying capacity.
- Thus, the actual layout of conductor should be included : different sections of each pancake have different # of turns, thickness and different current carrying capacity.
- All this affects the insert geometry, field distribution, heaters efficiency, and thus quench behavior.



New features and challenges to address. Layout.



Despite the fact that the least-quality tapes are used for the internal modules, to quench them by the heaters will not be easy.



New features and challenges to address

5. AC loss in a REBCO tape wound coil is very different from that in an LTS coil and uncertain. How and when should one include the AC loss?

- Results of the magnetization loss calculations based upon the magnetization measurements on short sample and results of AC loss measurements on prototype coils are very different. The latter show that the AC loss are rather low.

- Fortunately, if the protection heaters are used, then the AC loss effect is supposed to be small to influence on the quench behavior noticeably.

6. Shielding currents:
- Is this effect really important w.r.t. quench modelling? If so, when and to what extent?

- In a high external magnetic field (e.g., from the LTS outsert), the shielding current effect is small and can be neglected in a REBCO coil quench simulations. If there is no strong external magnetic field, then the shielding current effect should be included, albeit depending on a number of factors.

- In fact, the shielding current effect results in a decreasing of the field angles in the coil interior (makes the field distribution flatter) and in the angle increasing at the ends.

- We have a simple model to include the shielding currents appropriately, but the calculation may turn out to be time-consuming.

- The shielding current effect on a magnet quench behavior depends dramatically on the magnet configuration/geometry/shape.

- The effect may improve the field uniformity in the magnet bore.

NATIONAL HIGH MAGNETIC FIELD LABORATORY

The quench analysis input data adjustment

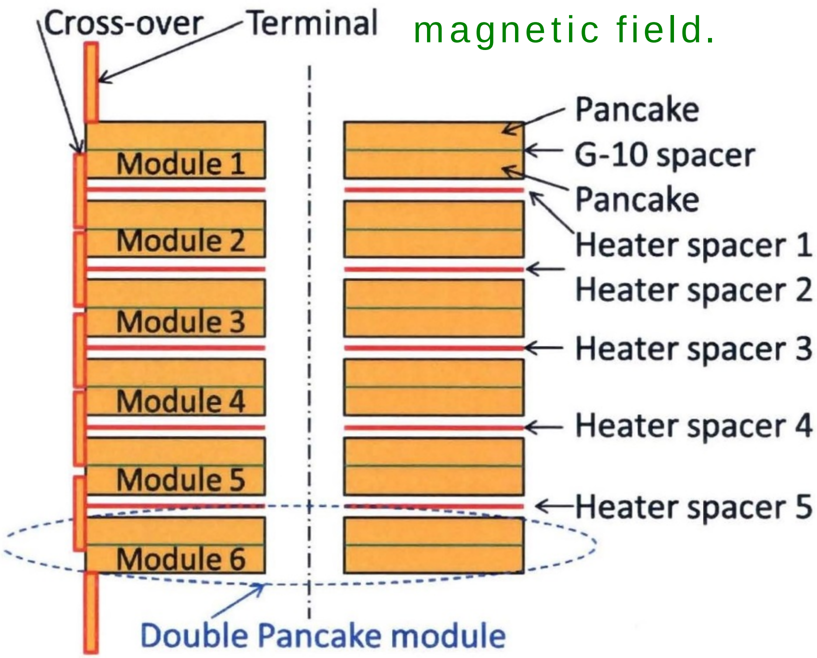
Thus, what input data should be chosen/found and adjusted?

- The contact spot fraction of the protection heaters
- The thermal contact resistance in the radial direction (between the tape and the stainless steel strip)
- And one more parameter ....

We used quench tests of our prototypes for the approach (and quench code) verification.

Quench code verification. Prototype coil quench test.

Coil "20/70" – the insert inner coil short prototype: 6 modules versus 20 in the inner coil of 32 T insert, albeit the same inner and outer radii. Much extra instrumentation. Quench tested in 15T background magnetic field.

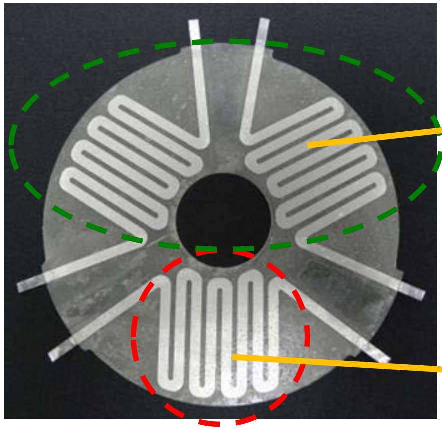


Quench tests: the coil was quenched with the use of a number of scenarios. Fast discharge on the nz resistance.

The goal: to compare the calculation results and the measurements:

- current decay
- voltages
- quenching times of modules

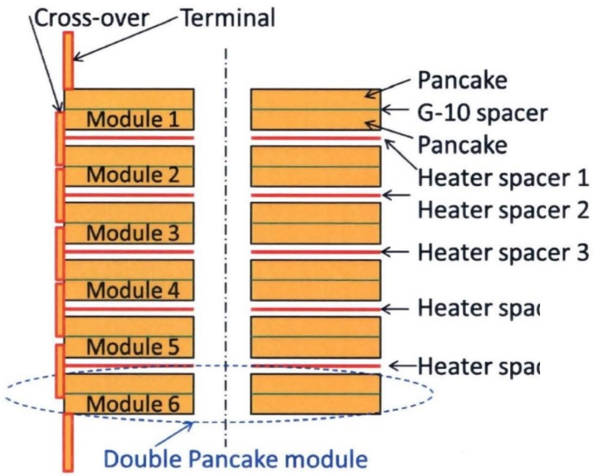
so as to adjust the input data to be used for the 32T magnet.



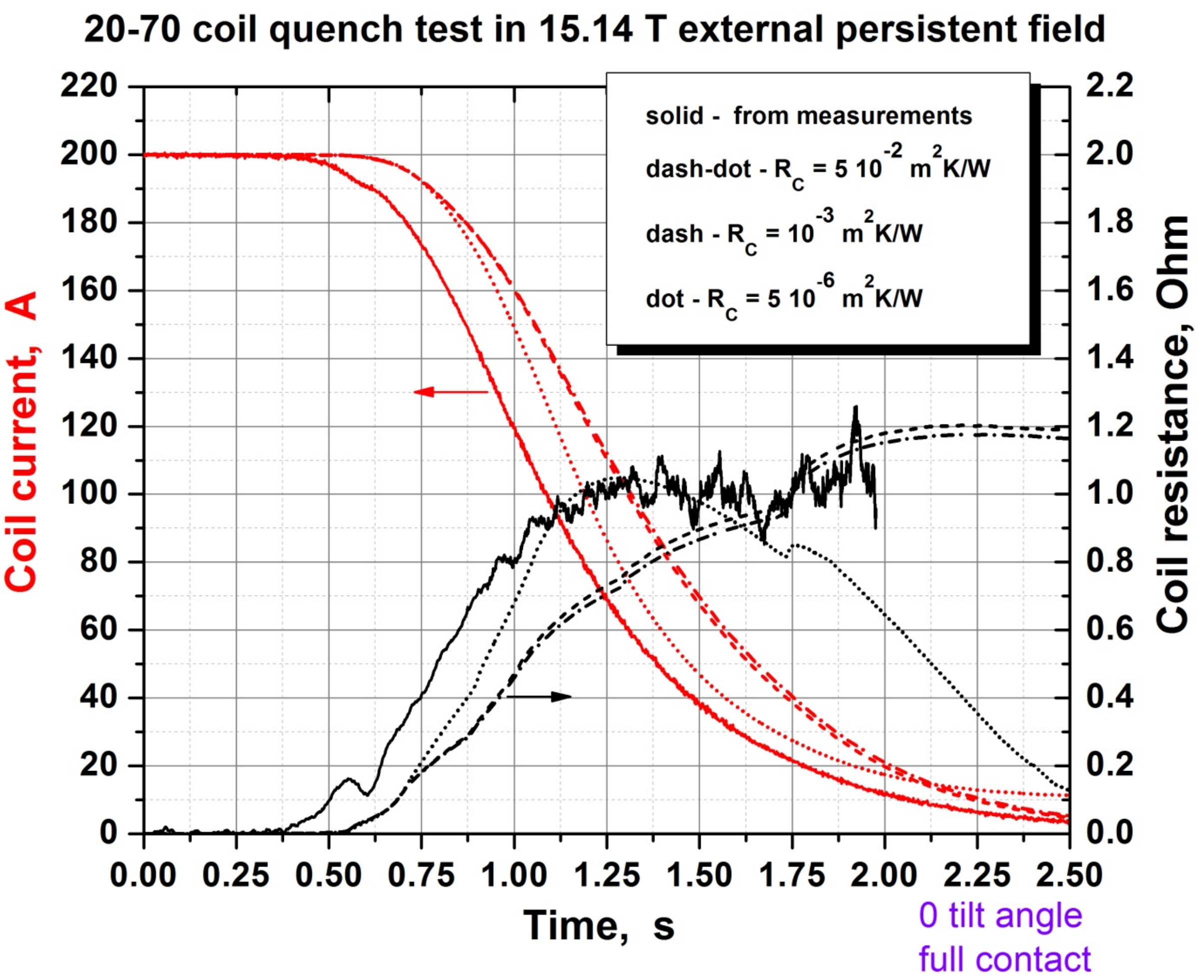
Elements for quench protection

Element for quench initiation

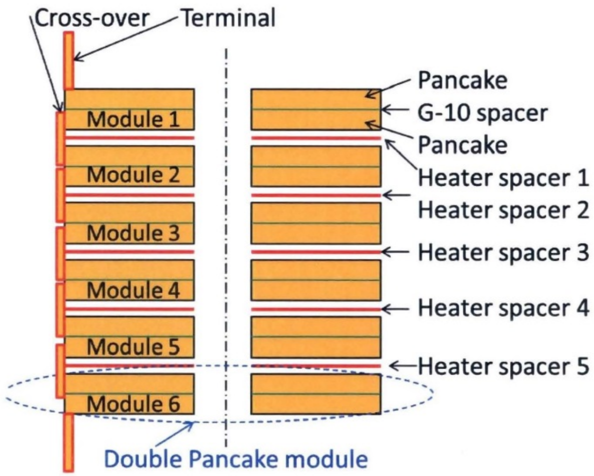
Quench code verification. Fast discharge.



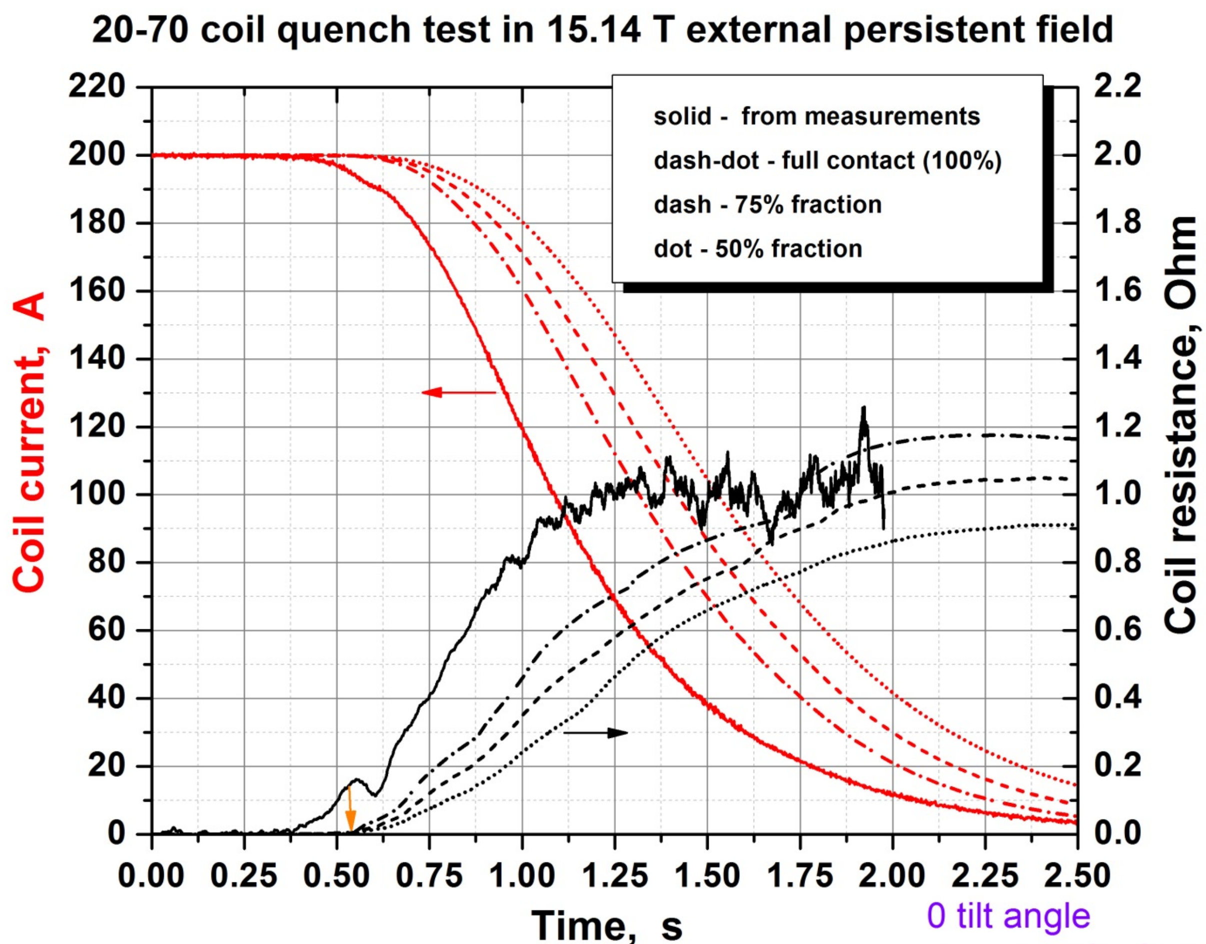
1. Let us try to adjust the thermal contact resistance first (turn-to-turn, within a pancake). The contact resistance is supposed to be rather high, and the best agreement seems to be reached at Rc = 0.05 sq.m K/W. Let us use this value, although as calculated the quench start is still delayed and the calculated coil maximum ohmic resistance remains too high.



Quench code verification. Fast discharge.



Let us try to adjust the contact spot fraction value (between the pancake and heater). The required coil ohmic resistance maximum is reached at 75% contact fraction, but the quench delayed start is still observed in the calculation and the coil ohmic resistance increasing rate is below the measured one. Let us stay with 75%.

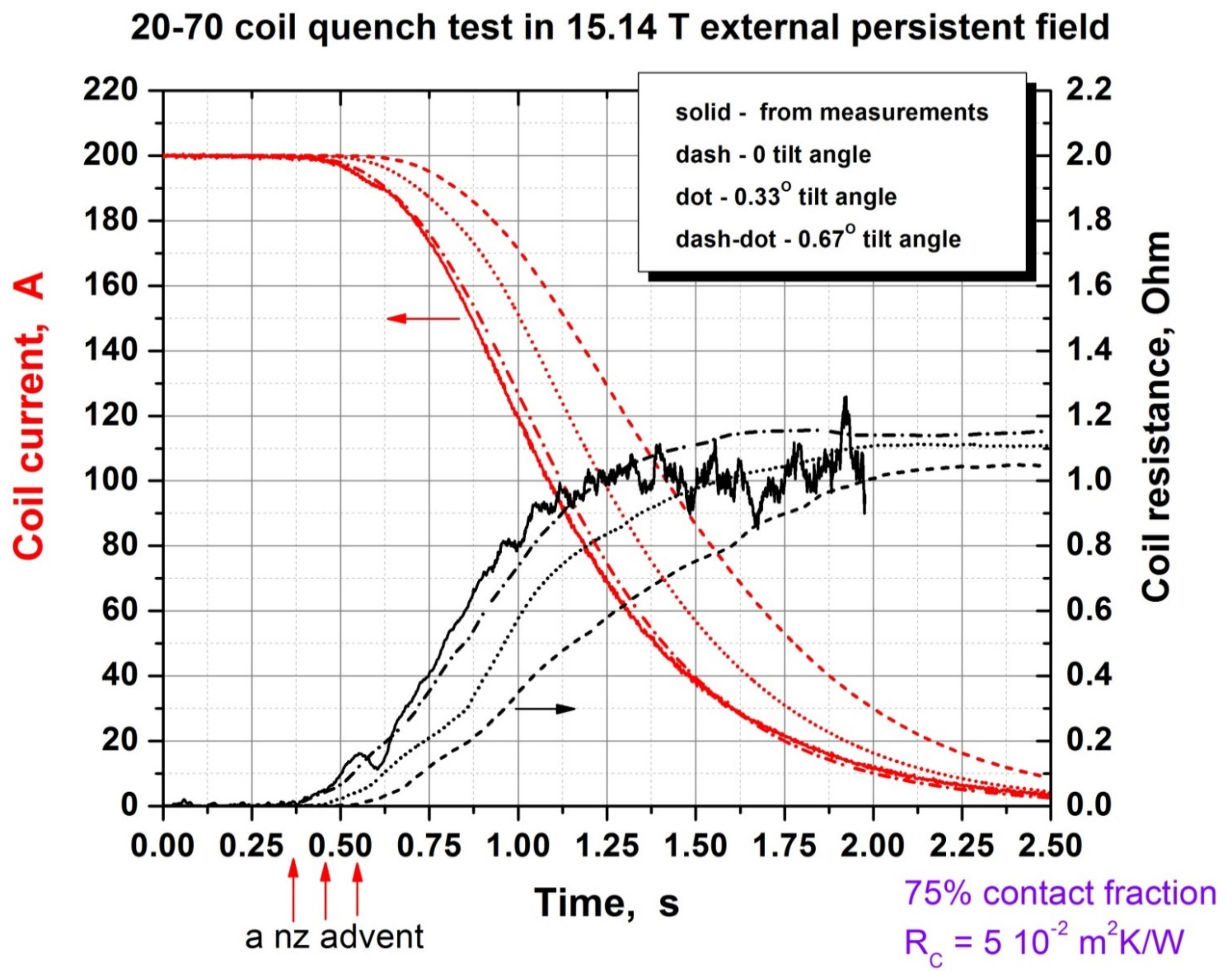


0 tilt angle

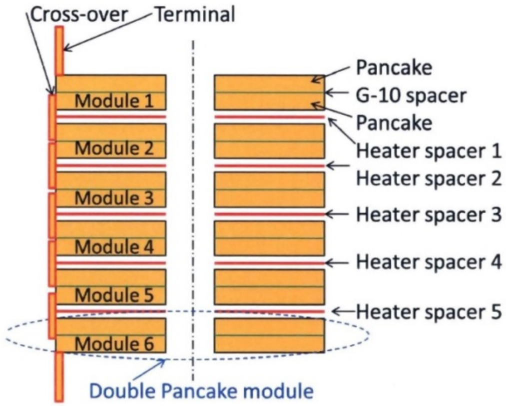
$R_C = 5\ 10^{-2}\ m^2K/W$

Quench code verification. Fast discharge.

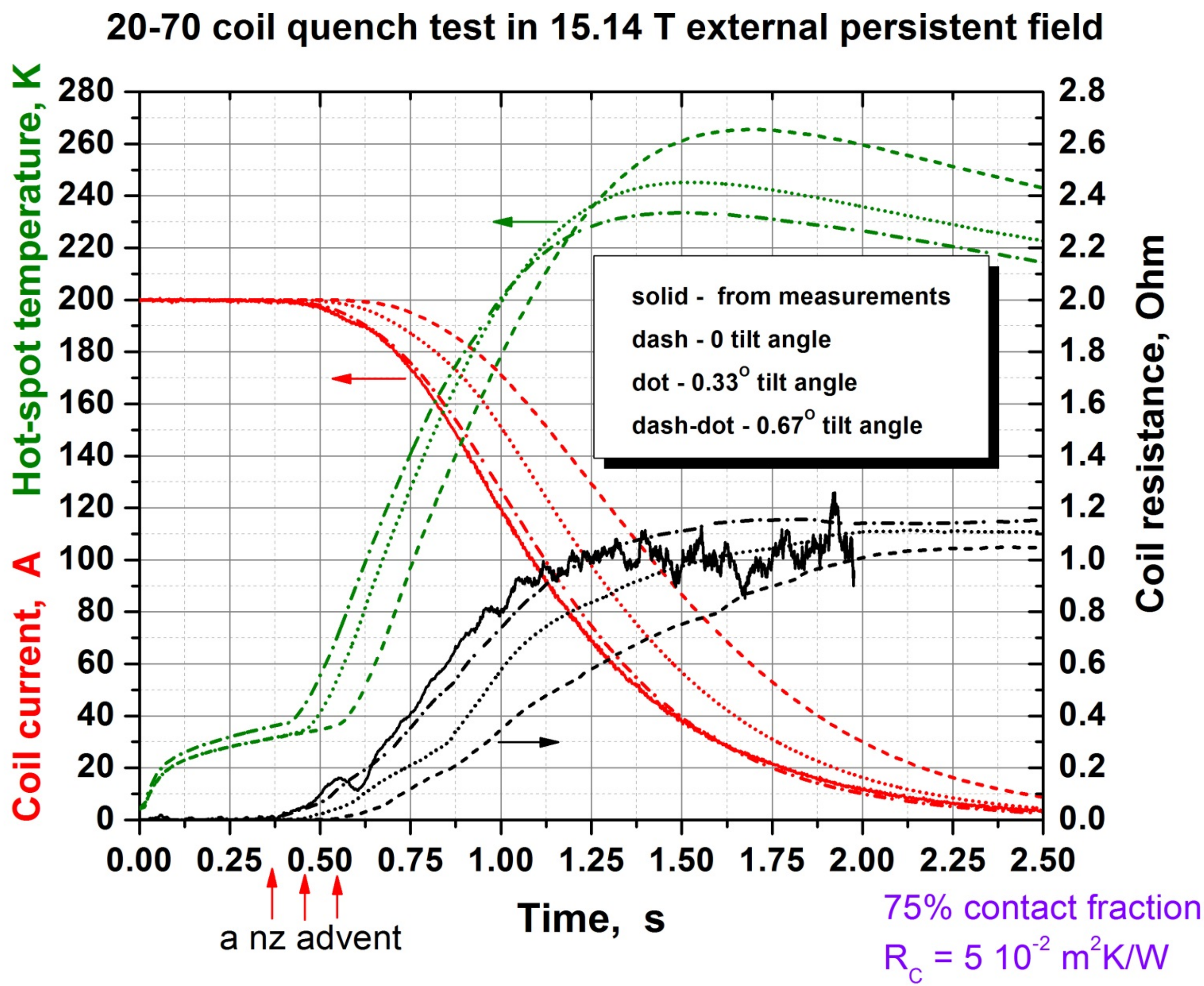
The final adjustment: the average tilt angle of the turns is supposed to be found (it cannot be zero as was assumed in the previous simulations! – there cannot be fully horizontal orientation of REBCO layers, because the tape cross-section is not perfectly rectangular). The calculated quenching time, the slopes, the coil ohmic resistance magnitude are in good agreement with the measurements, if the tilt angles are assumed to be around 0.7 deg. (very small and so quite realistic & understandable – why not?). - The heaters can quench a larger # of pancakes at non-zero tilt angles and do it faster. Let us use this tilt angle further.



Quench code verification. Fast discharge.



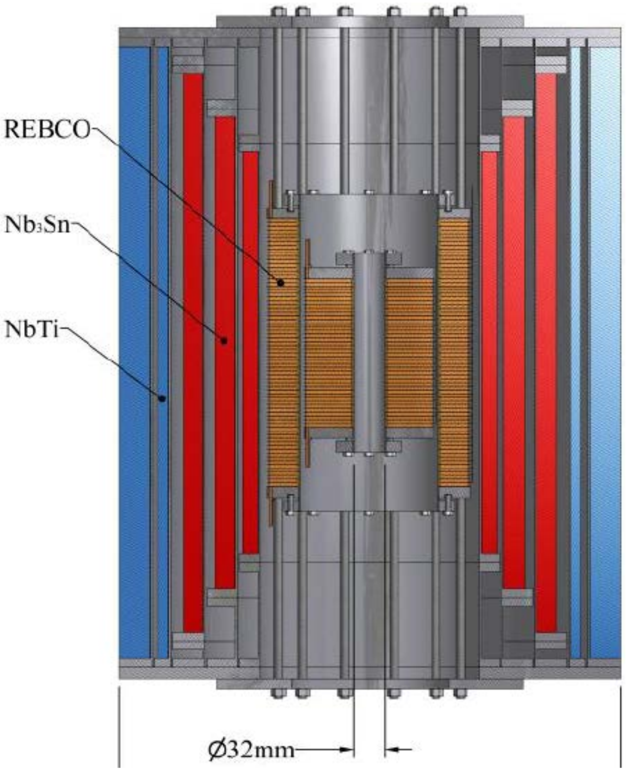
The effect of input data on the temperature is significant even in a small coil. It will be dramatic in a large, multi-coil system.



Quench code verification.

It was not the only verification. We tested a 2-coil prototype in the real outsert and computer simulated the tests. The results are being processed.

The entire 32T magnet quench simulations



A 15 T / 250 mm bore LTS multi-coil magnet (the real configuration is not shown) – *LTS outsert*
&
a 17 T / 32 mm bore REBCO tape-wound 2-coil magnet – *HTS insert .*

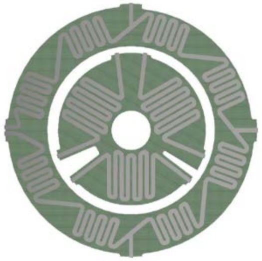
Two power supplies: one – for the insert, another – for the outsert, i.e., there are 2 electrically independent, but inductively coupled circuits.

Each coil of the HTS insert consists of double-pancakes (*modules*): 20 in the inner coil ("coil 1") + 36 in the outer coil ("coil 2"). The coils are connected in series.

Quench protection of the insert:

- Distributed quench protection heaters between the modules.

- Dump resistance .



The outsert is also actively and passively protected.

What is the quench code used for? – To adjust parameters of the quench detection and protection systems so as to get more control over quench events if any.

The simulations continue…..

Thank you !