Comprehensive Modelling Study of Quench Behaviour of the NHMFL 32 T All-Superconducting Magnet System. Input Data and Methodology Aspects.

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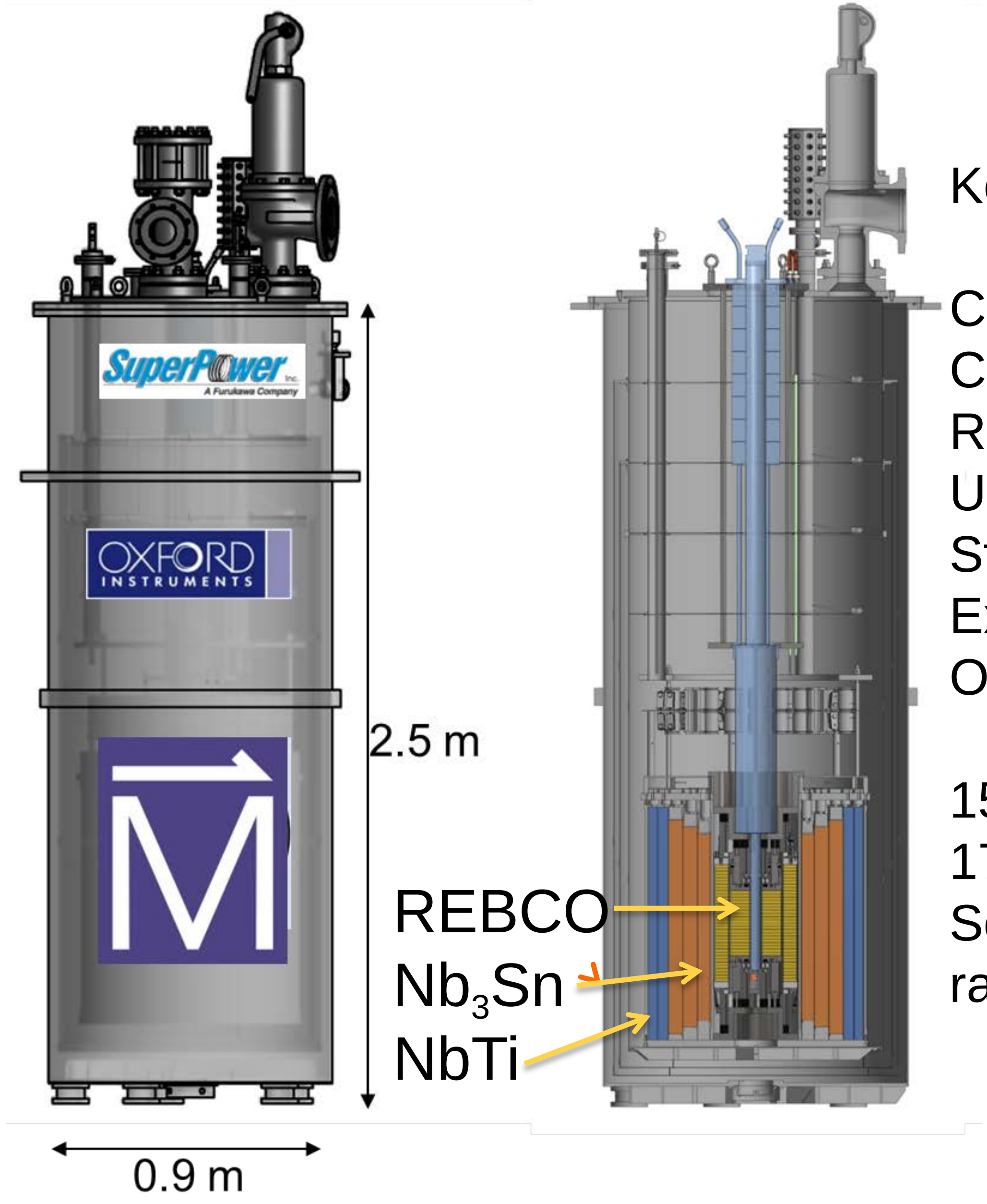
.The 32 T Magnet System



Key parameters:

Center field 32 T
Clear bore 34 mm
Ramp time 1 hour
Uniformity 1 cm DSV 5×10^{-4}
Stored energy 8.3 MJ
Expected cycles/20 years 50,000
Operating temperature 4.2 K

15 T / 250 mm bore LTS magnet
17 T / 34 mm bore REBCO coils
Separately powered, simultaneously ramped

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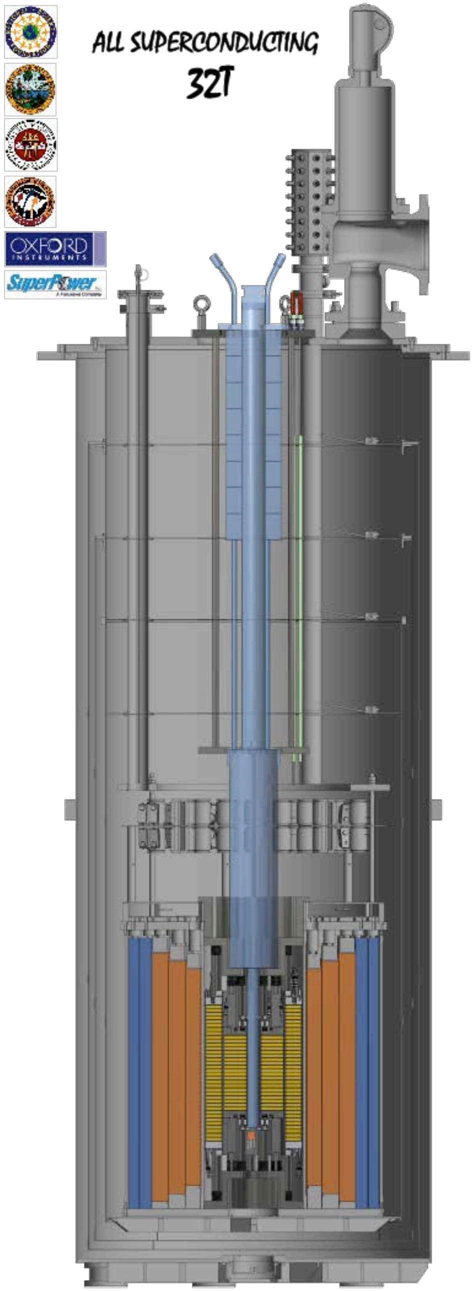
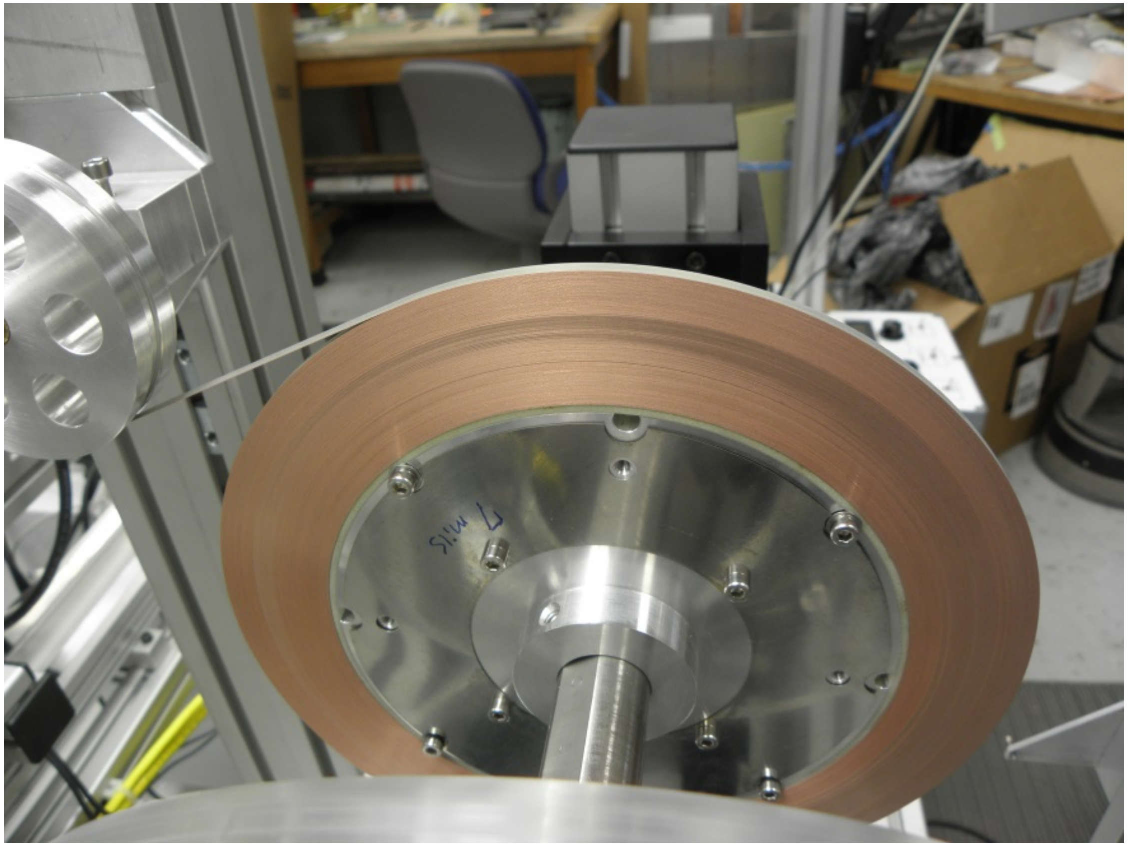
Outline



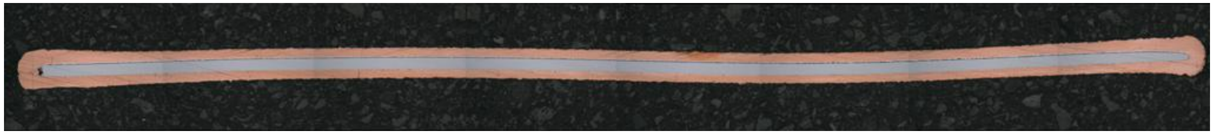
1. Details of a our approach to quench analysis.
2. Comparison with quench test results. What input parameters can affect the simulation results and to what extent?

The 32T magnet insert

Each coil of the HTS insert consists of double-pancakes (*modules*), co-wound with alumina plated stainless steel strips as the inter-turn insulation and reinforcement. The coils are connected in series.



SuperPower REBCO tape



Prototypes versus 32 T

Parameter	Prototypes	32 T
Modules	6+6	20+36
Operating current (default)	200 A	180 A
Field constant	48 mT/A	94 mT/A
B radial max	3.6 / 3.3 T	3.9 / 4.8 T
L	1.6 H	16 H
M with outsert	4 H	22 H
L outsert	194 H	194 H
Max hoop stress	322 / 396 MPa	363 / 378 MPa
Mid-plane stress	-11 / -9 MPa	-21 / -49 MPa

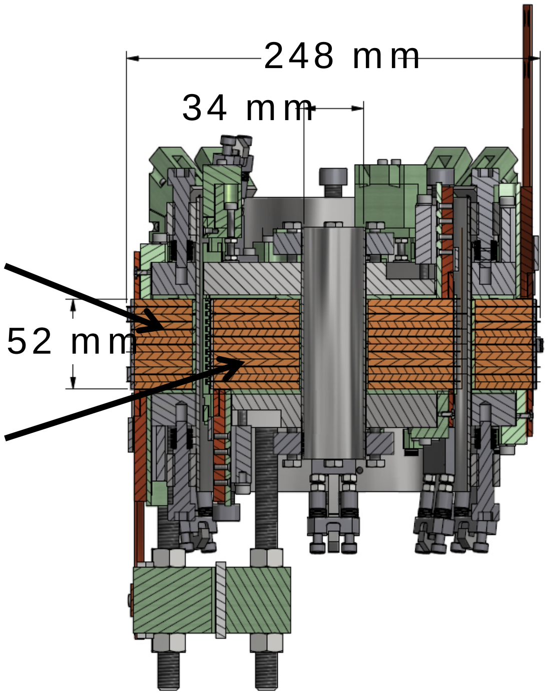
Coil 20/70 or Coil 1 inner) &
Coil 82/116 or Coil 2 (outer)

REBCO Prototypes versus 32 T

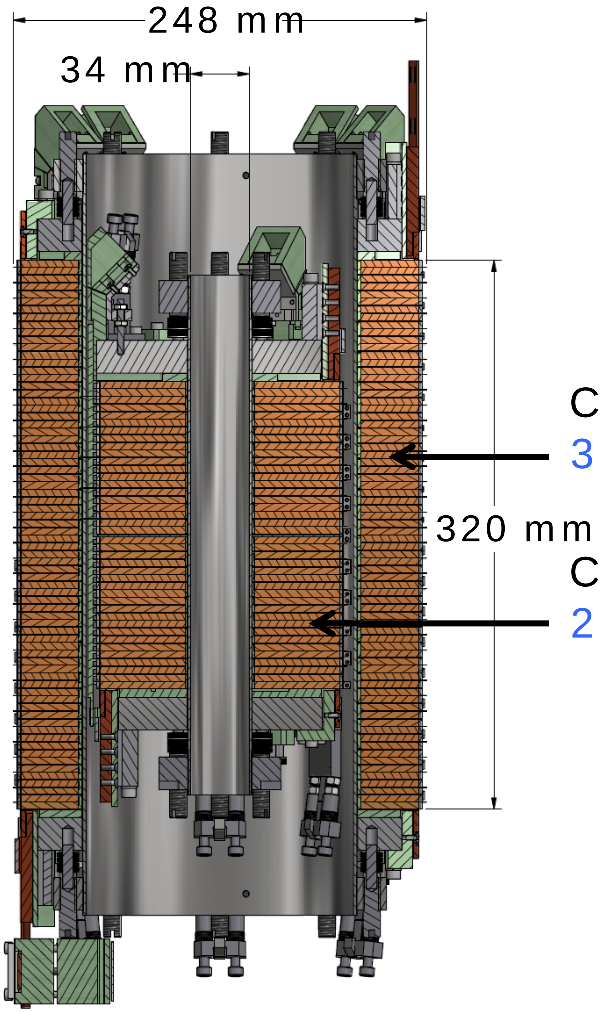
Prototype Coils
(‘Dual Coil Prototype’)

Coil 2
6 modules

Coil 1
6 modules



32 T Inner Coils



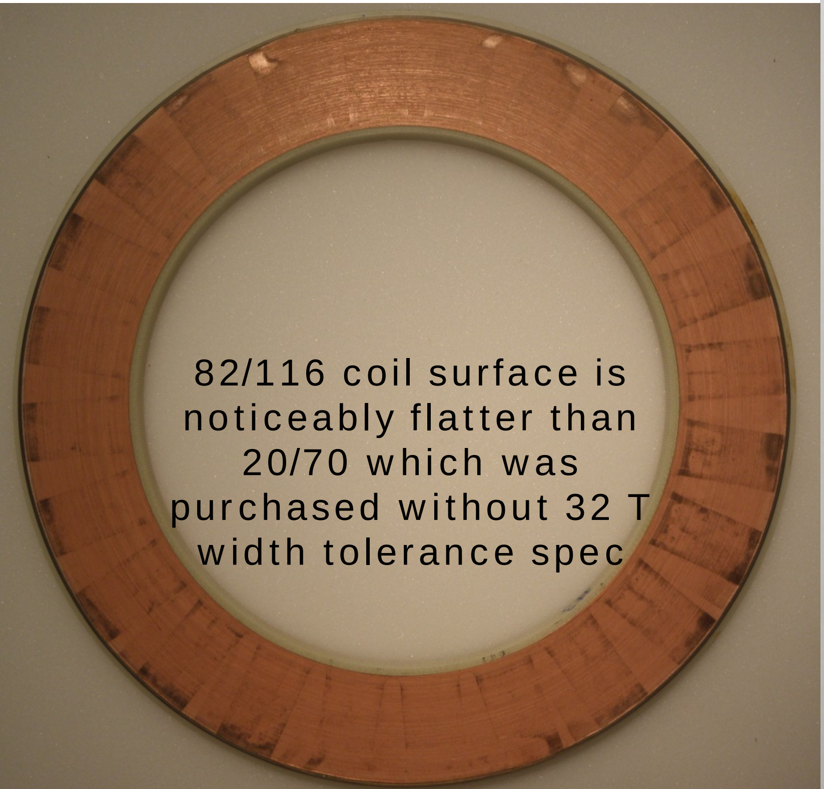
Coil 2
36 modules

Coil 1
20 modules

Module 1 disk 1
Facing Cooling spacer

Imprints of G-10 spacer are visible as (edges of) dark radial bands

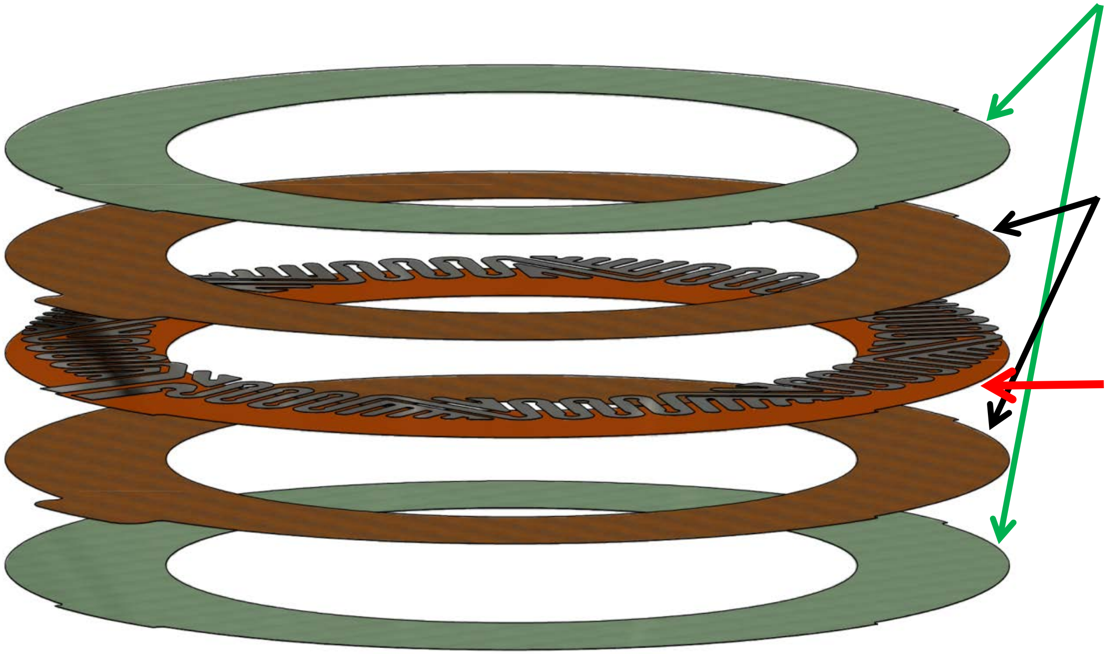
82/116 module



82/116 coil surface is noticeably flatter than 20/70 which was purchased without 32 T width tolerance spec

20/70 module 1

Protection Heater Design



Epoxy Fiberglass G-10

Mechanical strength

Kapton

Insulation

Heater assembly

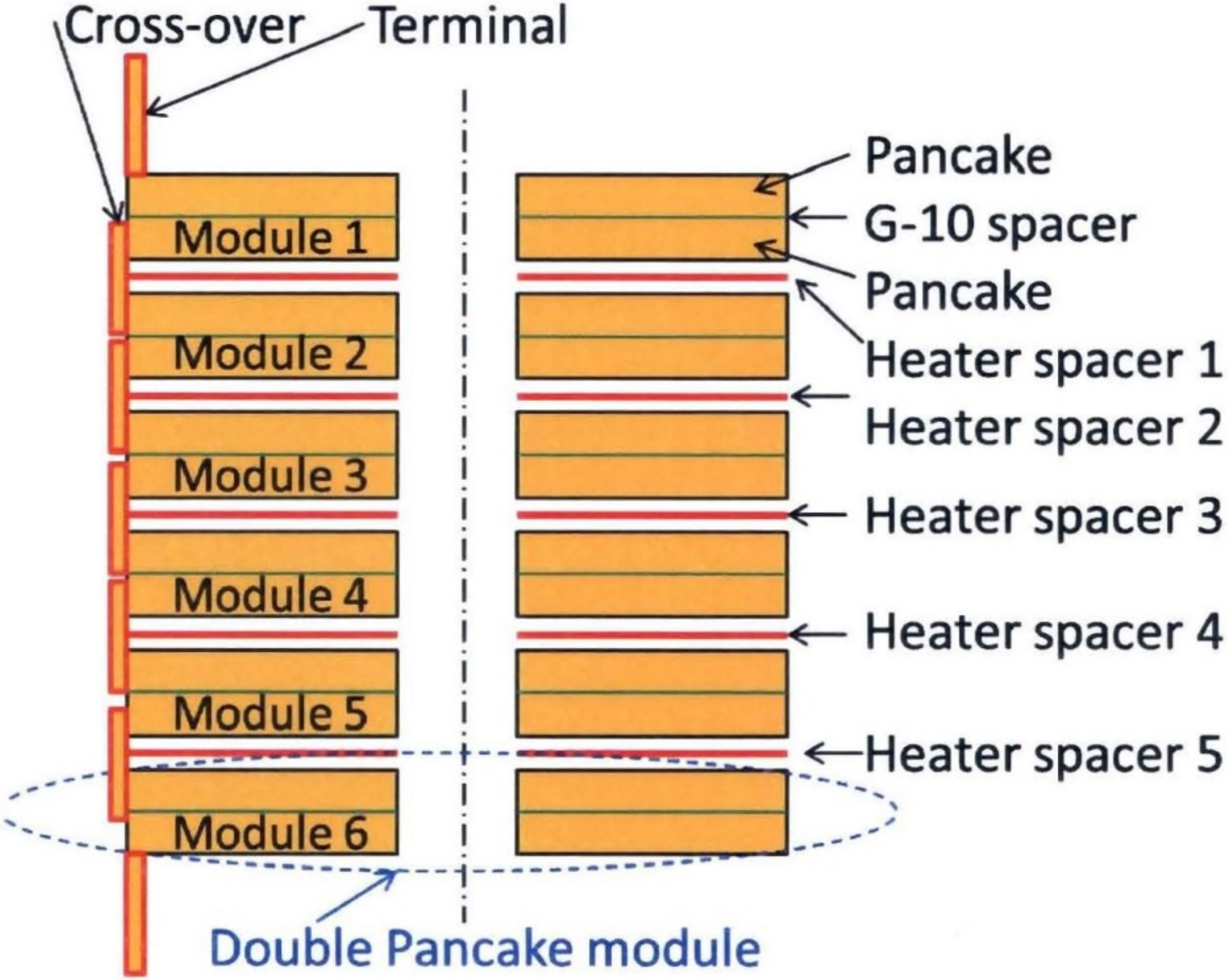
- Steel element

  Power, temperature

- Kapton

  Insulation

Protection Heater Locations



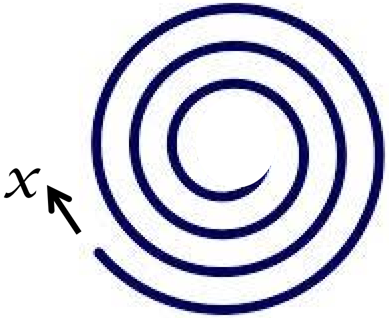
A heater is fired by a current pulse ~ 1 s long.

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

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

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

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



Schematic of a pancake (“disk”)

$T=T(x,t)$ – 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:

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

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.

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

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

The 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.

Thermal problem. Model equation.

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

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

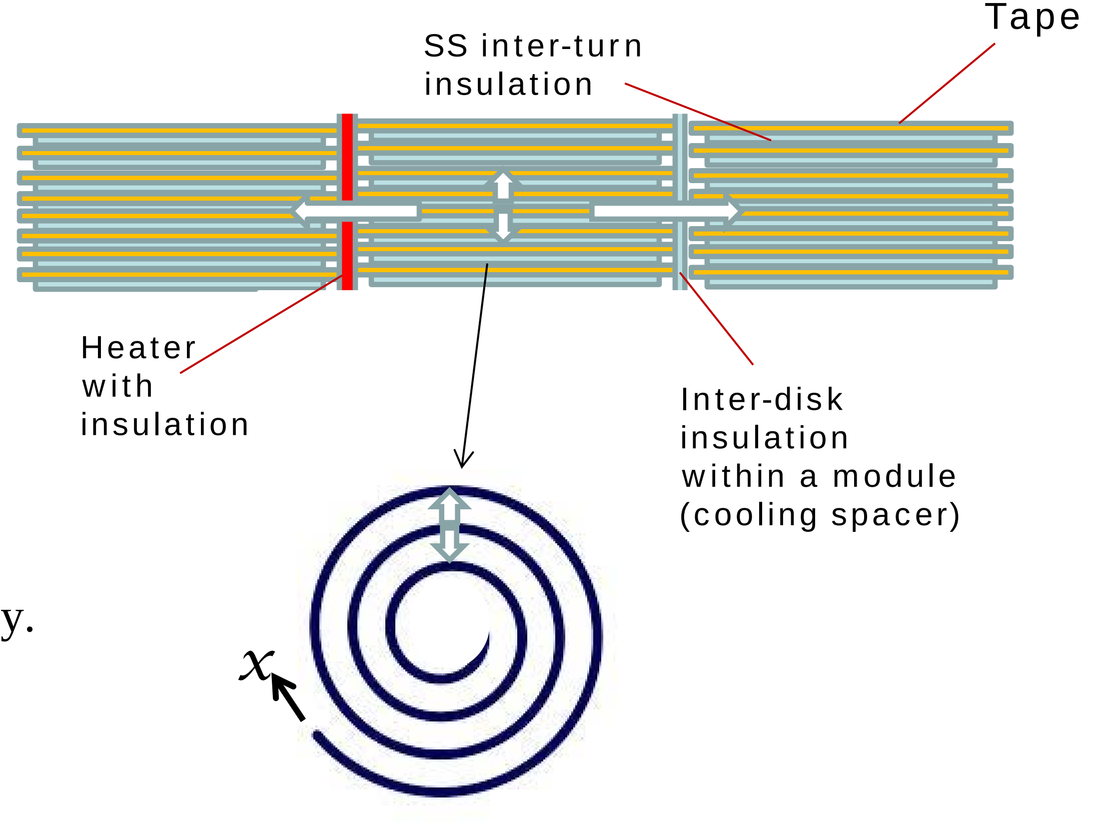
The transverse thermal axial (disk-to-disk) and radial (turn-to-turn, within a disk) links:

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

$R_C^{(i)}$ 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.



Finally, circuit equations are included.

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

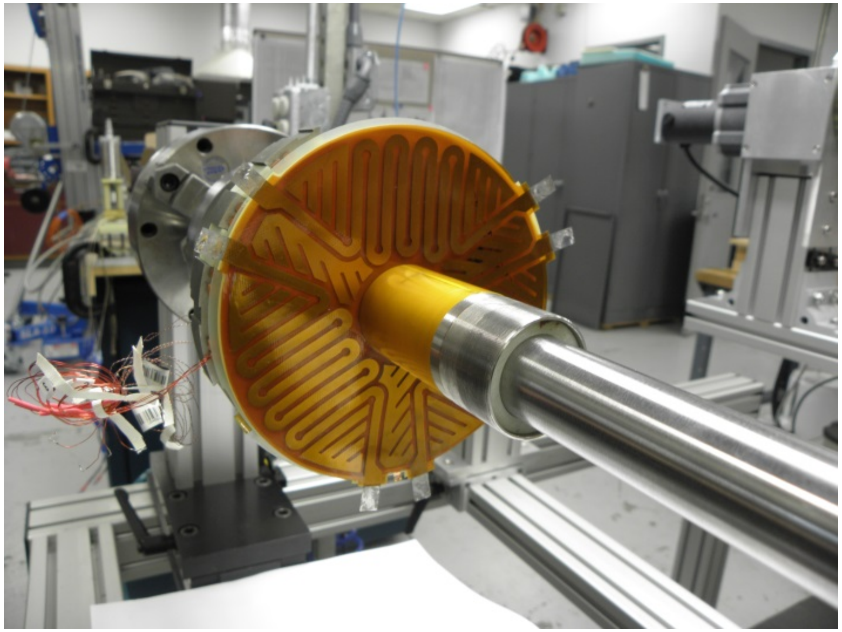
$$\left(A_{Cu}C_{Cu} + A_{SC}C_{SC} + A_{ins}\left(C_{ins} + f\gamma_p^{He}C_p^{He}\right)\right)\frac{\partial T}{\partial t} = \xcancel{\frac{\partial}{\partial x}\left(A_t\kappa_t\frac{\partial T}{\partial x}\right)} +$$

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

The tape effective longitudinal thermal conductivity:

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

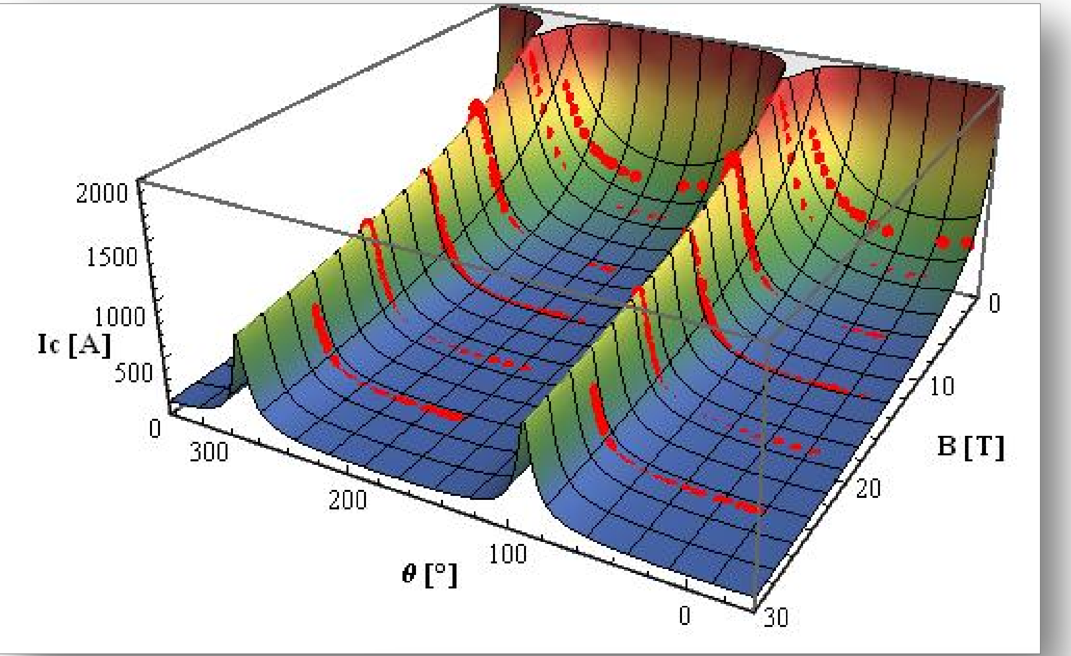
We may disregard the longitudinal heat conductance, if the distributed heaters are used.



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

REBCO tape Ic-value.

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



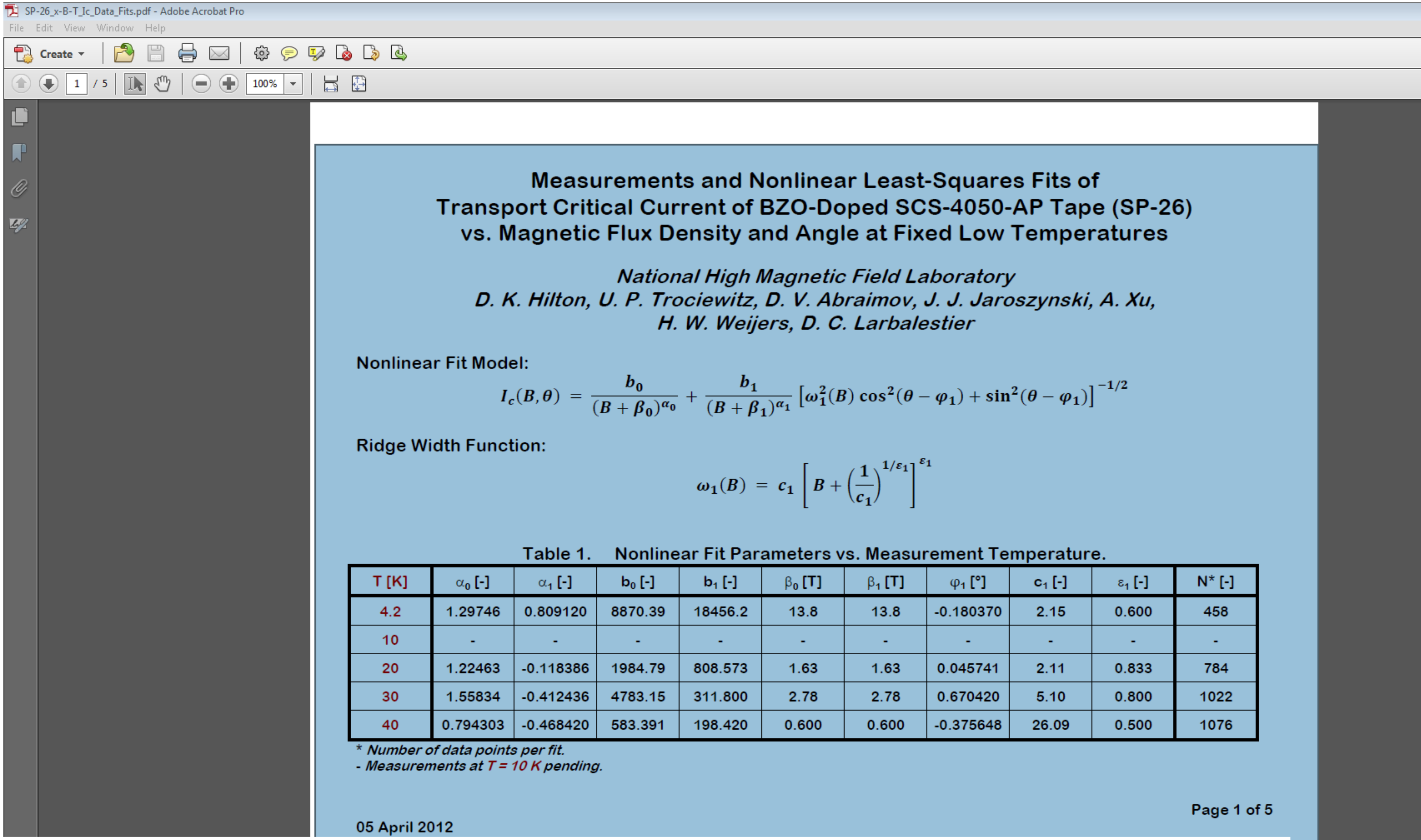
As can be inferred from the dependence, the critical current value is extremely sensitive to the field angle value in the vicinity of peak (90 deg. area).

The fit functions are obtained for a particular tape, SP-26. We apply this dependence to all the tapes, albeit using correction coefficients to match the measured values.

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**):

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

Critical current calculation. Temperature dependence.



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.*

Page 1 of 5

05 April 2012

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.

Superconducting-normal transition modelling

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 $E = E_0 \left[\dfrac{I}{I_C}\right]^{n(T,I)}$, $n(T)$ is measured.

the critical current criterion is $1\ \mu V/cm$ ($E_0 = 1\ \mu V/cm$).

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

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

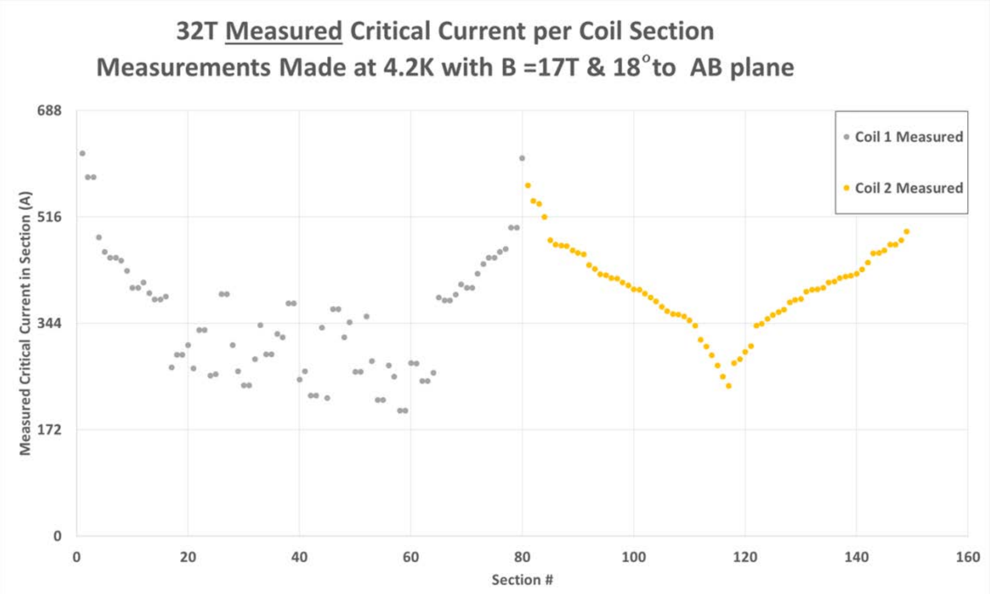
$$A_t Q_J = I\ (I - I_C)\ \rho_{Cu} / A_{Cu}, \text{ if } I_C > 0, \text{ and } A_t Q_J = I^2\ \rho_{Cu} / A_{Cu}, \text{ if } I_C = 0.$$

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 disk;

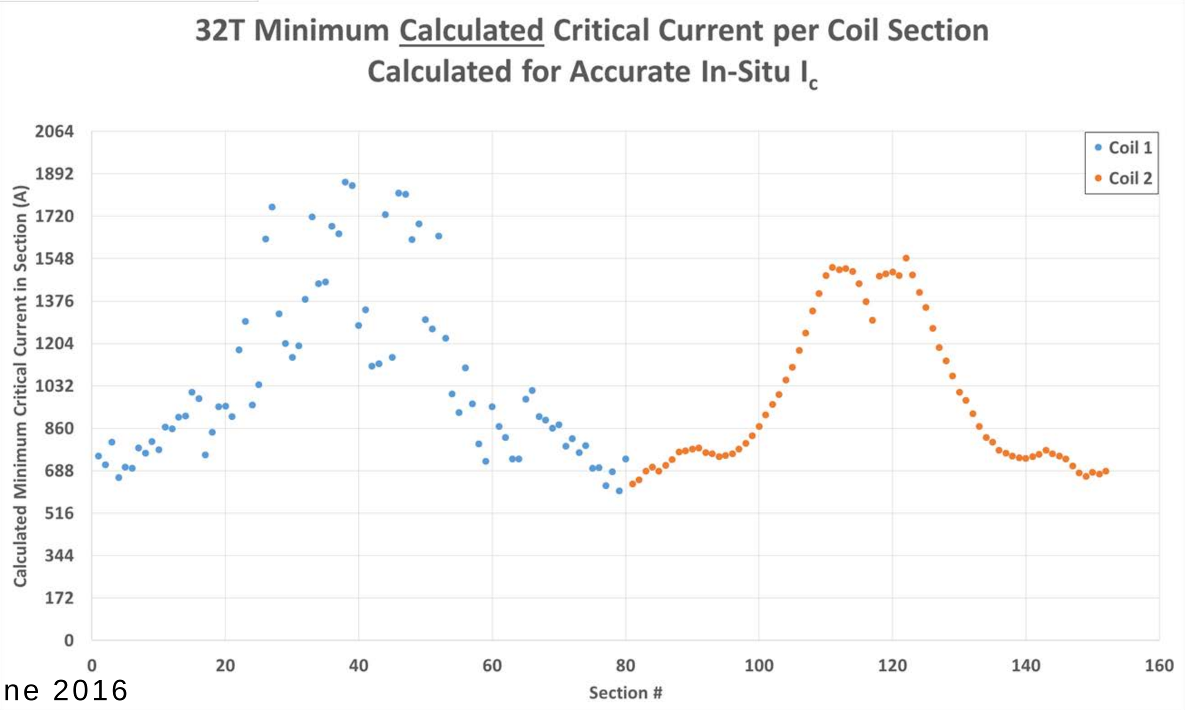
the coil resistance $V_C(t) = \sum_{k=1}^{N} V_D^{(k)}(t)$, where N is the total number of disks in the coil.

Insert Coils Layout. Example.



Different conductors are used to wind pancakes (with rather different Ic-values).

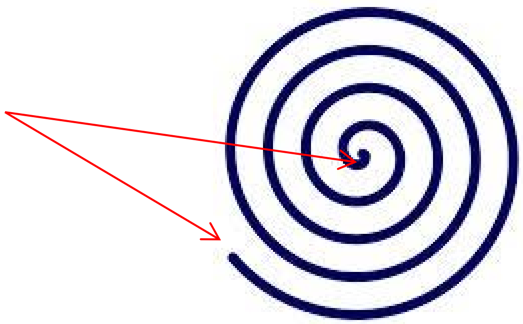
Despite the fact that the least-quality tapes are used for the internal modules, to quench them by the heaters will not be easy.



Insert Coils Layout.

What Ic-values are used?

The superconductor comes in spools. Typically the Ic-value is measured at the ends of each spool in a high field at different angles. We pick the minimal value. Is it a conservative approach? ....



Verification of the approach to **quench analysis**

We tested the dual coil prototype in the actual outsert.

The insert module voltages and the insert current were measured.

Quench test.

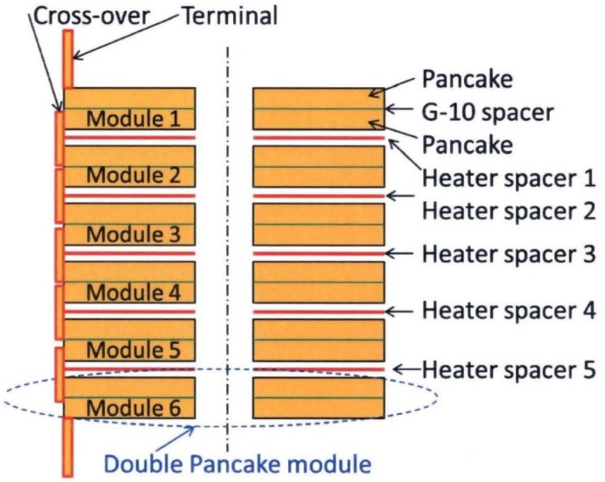
Insert current: 222 A (23T in the insert)

Outsert current: 214 A (12T in the outsert)

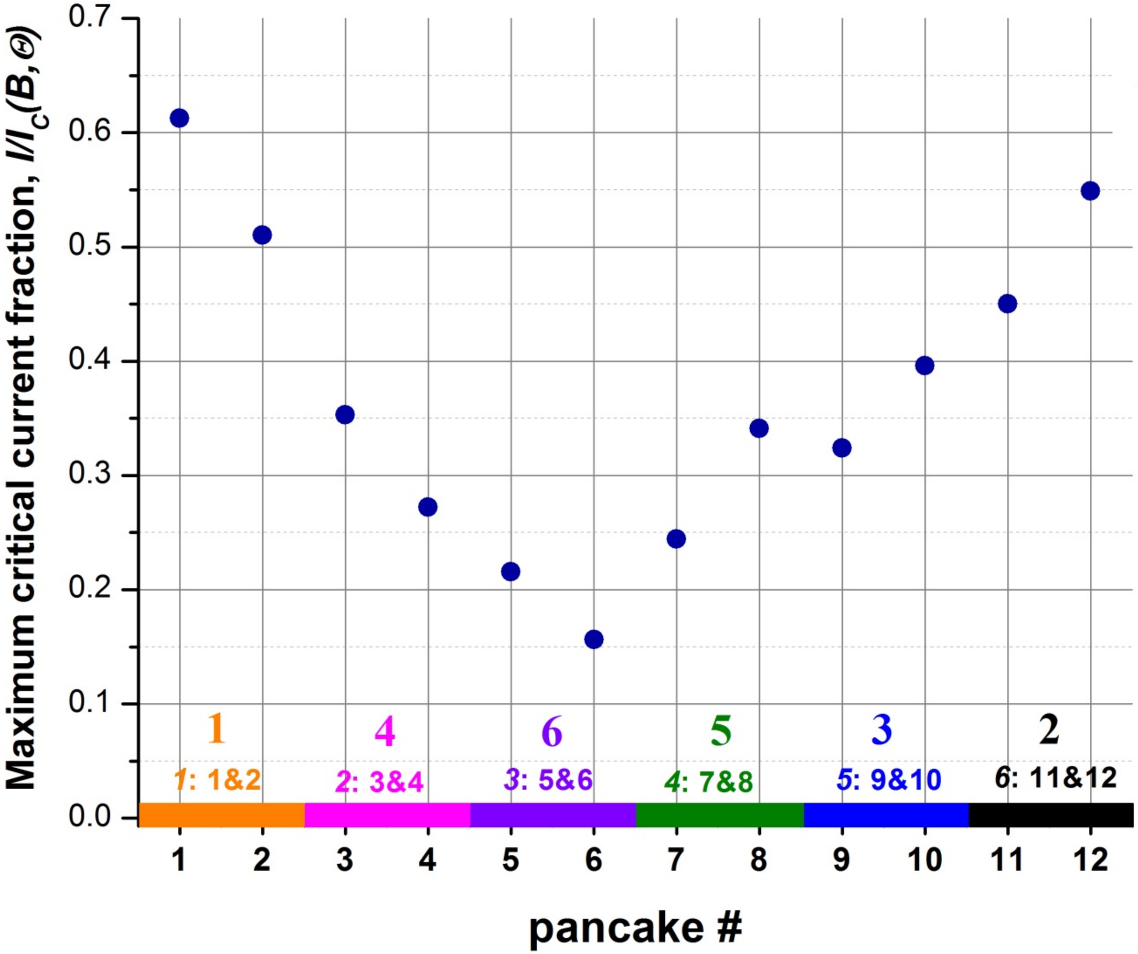
The outsert is actively and passively protected (false positive in detection).

Quench initiation: all the insert heaters are fired simultaneously. ~ 1.2 s long pulse.

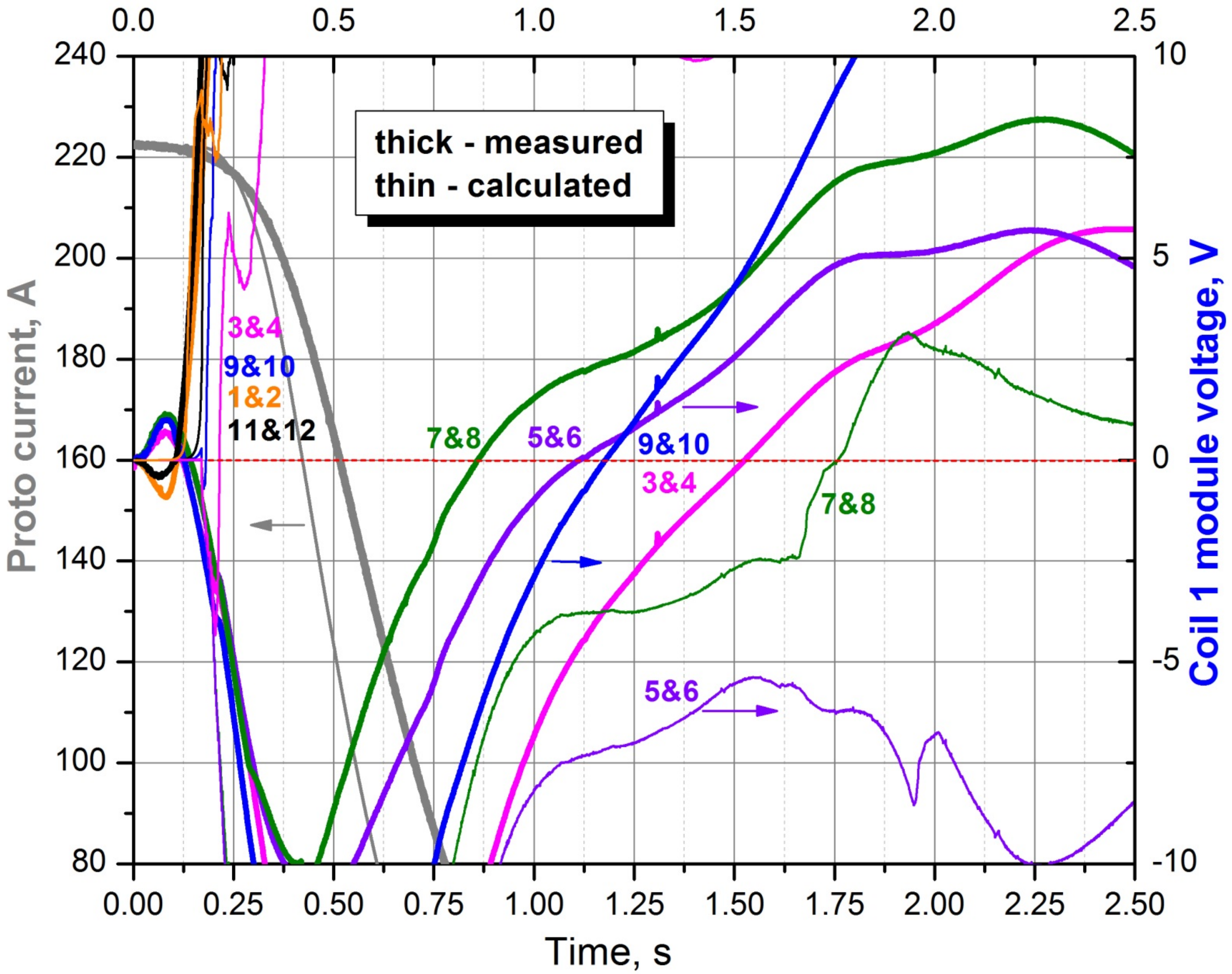
Quench test. The expected sequence of quenching of the modules. Coil 1.



@full currents



Quench test. The real picture (the measured sequence of quenching) & the first-cut simulation. Coil 1.



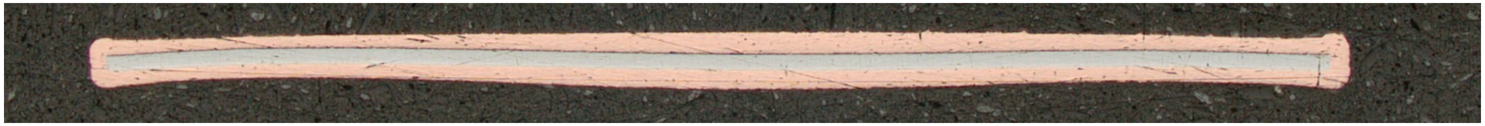
No agreement…

? !

Quench test. The real picture (measurements) & the first-cut simulation. Coil 1.

What is a reason for so huge discrepancy?

1. The turns in the coils are not fully horizontally oriented (tilting, dishing, etc.) due to the fact that the tapes are not flat, and so the tilt angle is not zero (may be ~1 deg. and even larger).



2. The Ic-values we picked are not representative.

Corrections are needed.

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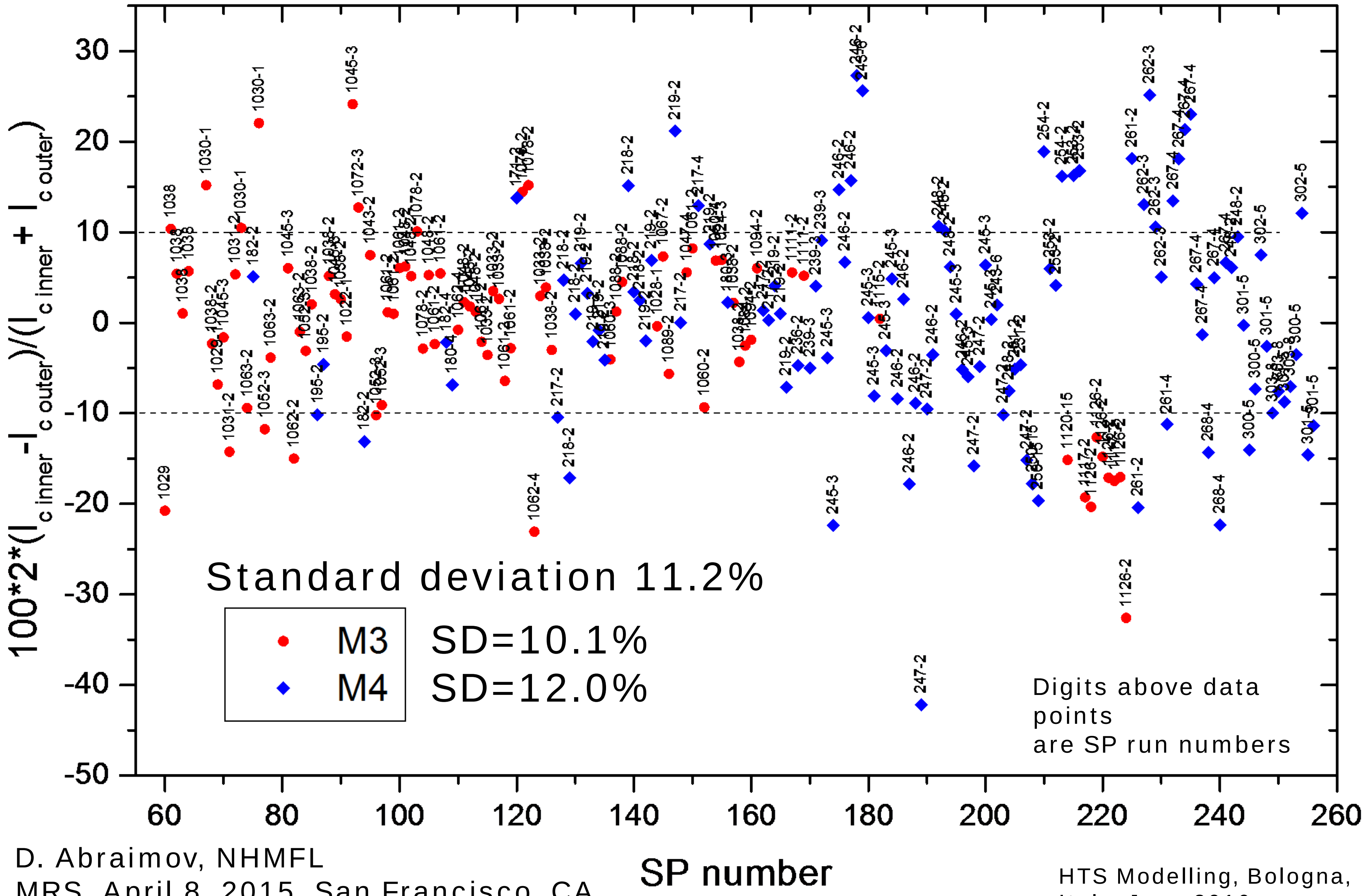
End to end relative variation of I_c(4K; 17T; 18°)

At 4.2K in-field more tapes have relative spread above 10%

M4 tapes have larger relative spread



Standard deviation 11.2%

● M3 SD=10.1%

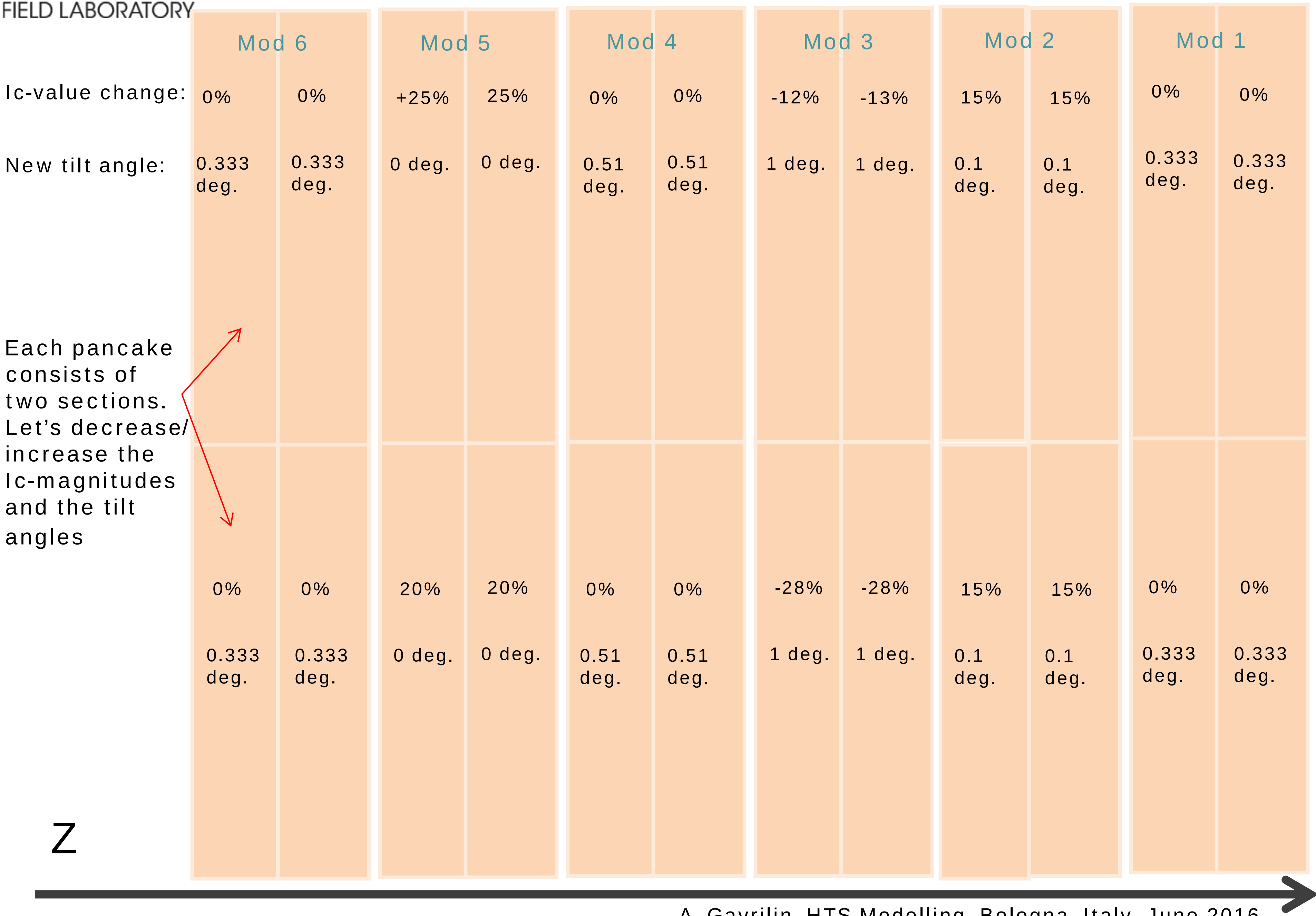
◆ M4 SD=12.0%

Digits above data points are SP run numbers

D. Abraimov, NHMFL
MRS, April 8, 2015, San Francisco, CA

HTS Modelling, Bologna, Italy, June 2016

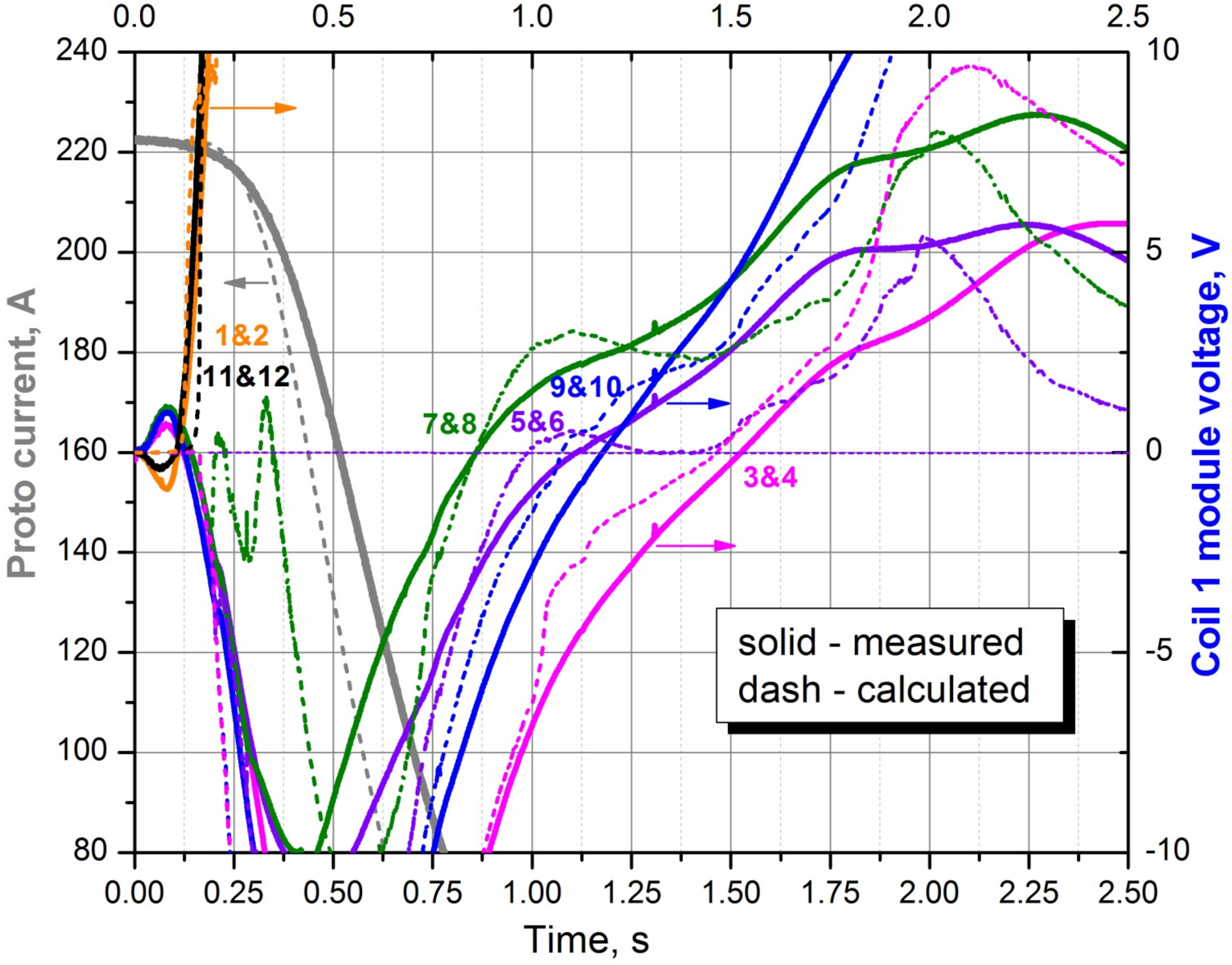
Ic-value and tilt angle corrections. Coil 1.



	Mod 6		Mod 5		Mod 4		Mod 3		Mod 2		Mod 1	
Ic-value change:	0%	0%	+25%	25%	0%	0%	-12%	-13%	15%	15%	0%	0%
New tilt angle:	0.333 deg.	0.333 deg.	0 deg.	0 deg.	0.51 deg.	0.51 deg.	1 deg.	1 deg.	0.1 deg.	0.1 deg.	0.333 deg.	0.333 deg.
	0%	0%	20%	20%	0%	0%	-28%	-28%	15%	15%	0%	0%
	0.333 deg.	0.333 deg.	0 deg.	0 deg.	0.51 deg.	0.51 deg.	1 deg.	1 deg.	0.1 deg.	0.1 deg.	0.333 deg.	0.333 deg.

Each pancake consists of two sections. Let's decrease/ increase the Ic-magnitudes and the tilt angles

Quench test. The real picture (measurements) & the simulation result after the corrections are made. Coil 1.

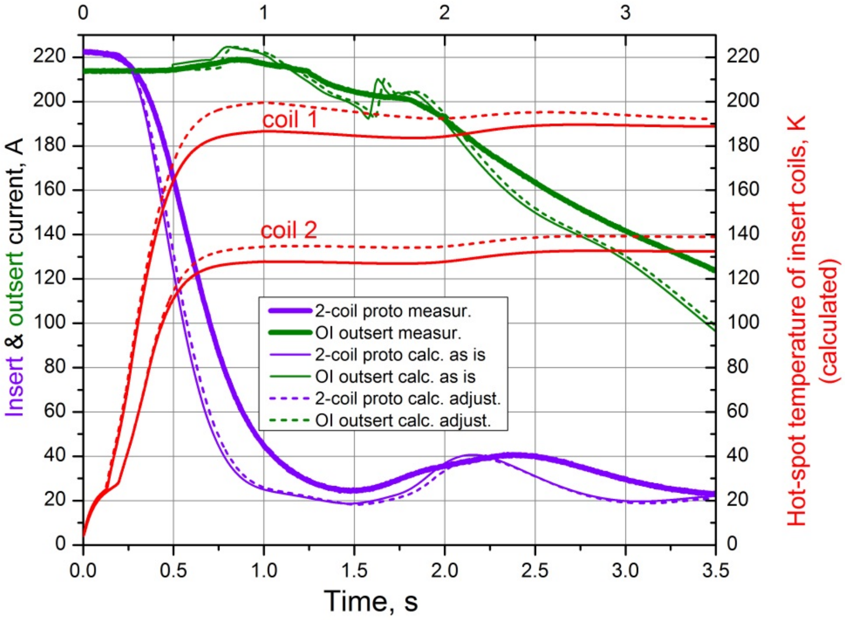


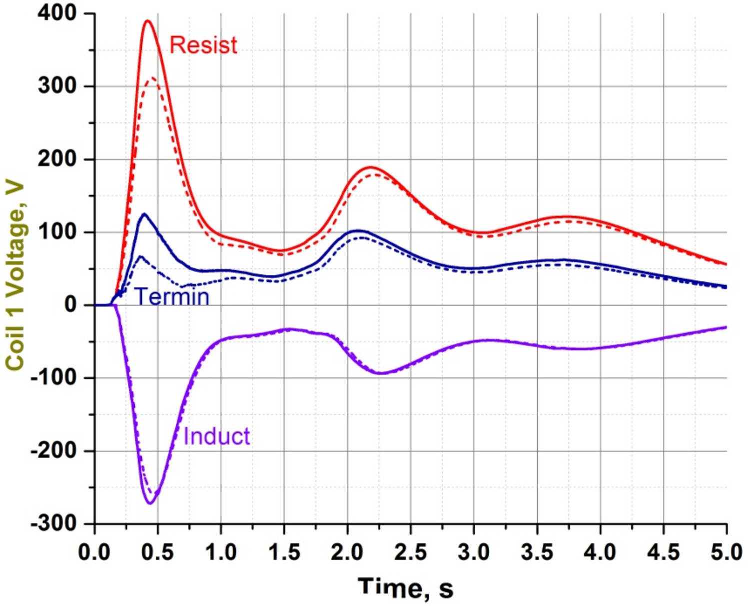
The minor corrections within the limits can change the picture dramatically.

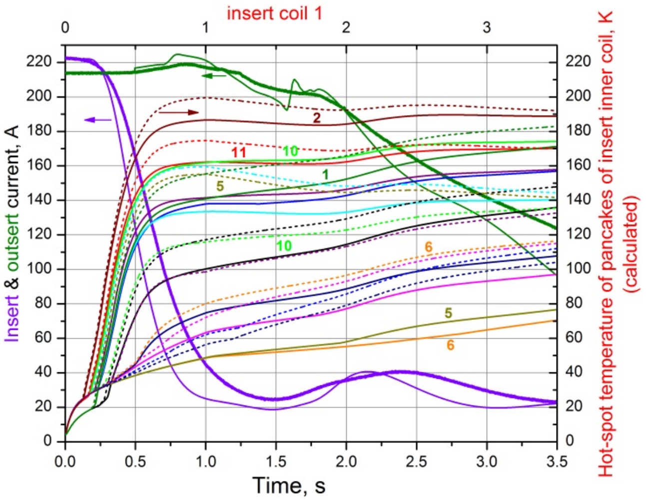
The fitting is not perfect yet, but it shows the phenomenon “in all its glory”.

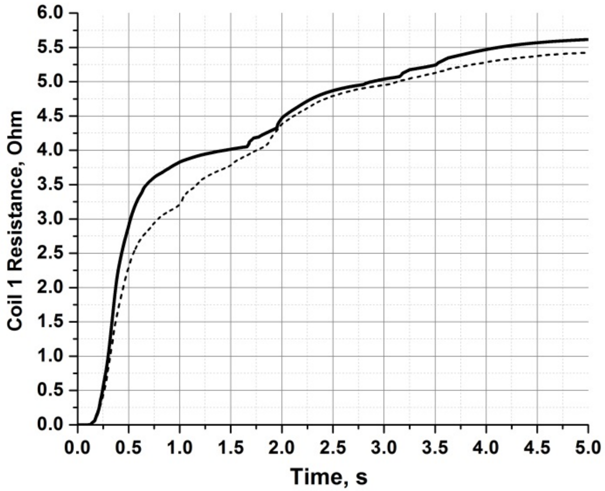
What the corrections change in terms of hot-spot temperature and voltage, which are of primary importance and interest to us?

Quench test. The real picture (measurements) & the simulation result after the corrections are made. Coil 1.









The corrections do not result in changes in the over-all protected-quench behavior in terms of the key characteristics of quench, if the protection is effective.

Conclusive remarks:

1. The REBCO tape Ic fit functions are rather helpful and practical. They describe the Ic-dependencies on the field and field angle adequately.

2. The Ic-values should be measured at several values of high field and field angle and in several locations to have an opportunity to choose correct “effective” values of Ic.

3. Nonetheless, if the active protection is effective, the integral characteristics of quench are not so sensitive to the Ic-values and tilt angles of tapes in the winding (if reasonable measured Ic-values are used and the tilt angles are kept within a realistic range).

4. We are actively using this approach for quench simulation of the 32T magnet, as the approach looks effective.

It seems to be very much it, for now.

Thank you !