Beam loss induced quenches

(The latest estimates of quench limits)

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Outline

- Motivation
- Thermodynamics of magnet structure
  - Magnet characteristic
  - Heat transport in the magnets
  - Characteristic of superconducting cables and coils
  - Free volume calculation
- Network Model
  - Electrical equivalent
  - Superconducting cable and coil models
  - Results of the simulation
- Validation of the model
  - Measurements in SM 18
  - Evaluation of the network model quality
- „Beam loss" simulation
- Summary and outlook

Motivation

- Quench is transition of the superconductor from the superconducting to the normal state. Such a transition invariably occurs if one of the three parameters: temperature, magnetic field or current density, exceeds a critical value.
- Quench limit calculation in terms of external energy deposition is vital for accelerators making use of superconducting magnets
- These studies are important for the LHC operation and efficiency of magnet protection system
- BLM calibration
- Design and operation of collimators

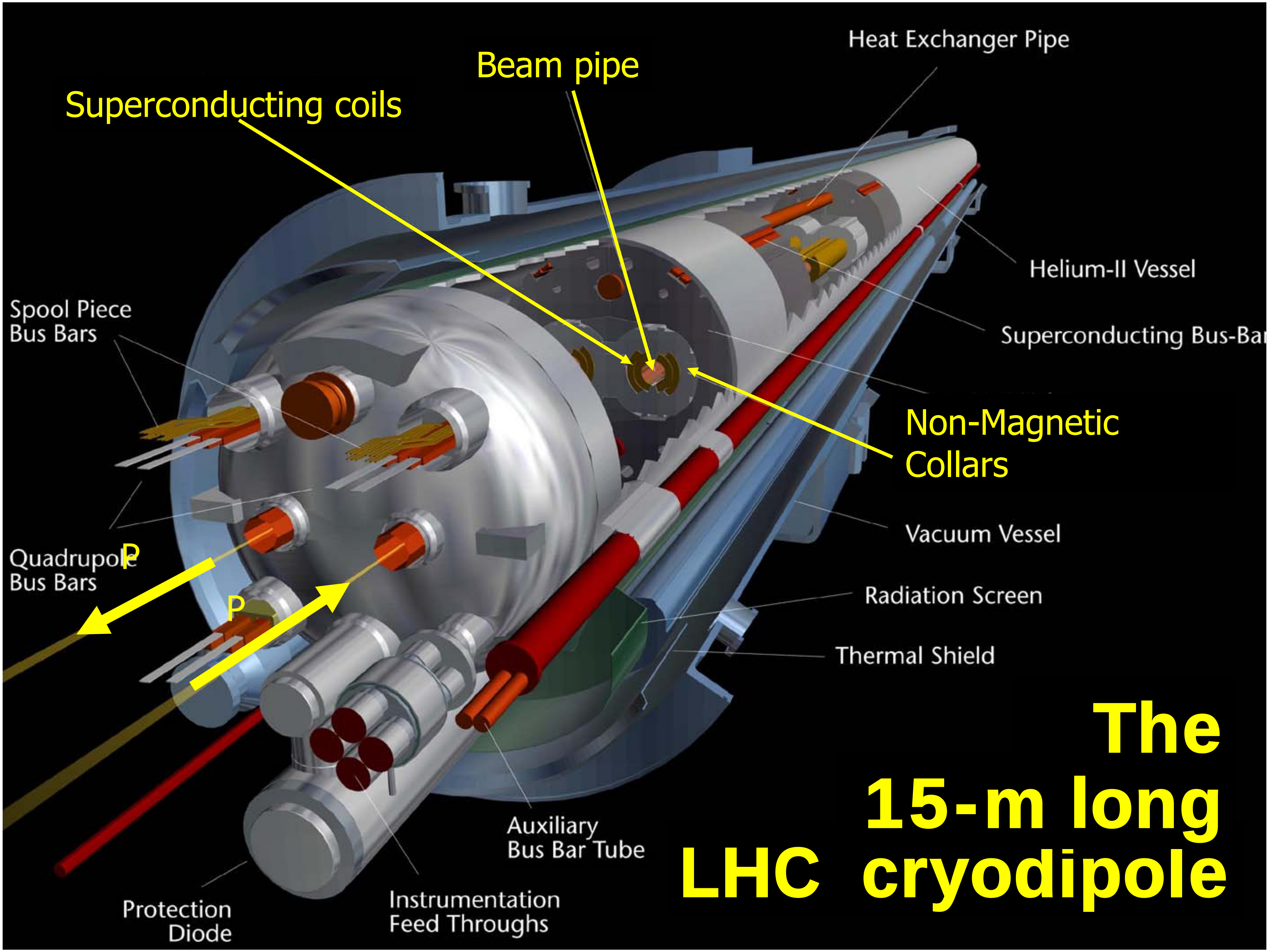
Thermodynamics of magnet structure

Magnet characteristic

Heat transport in the magnets

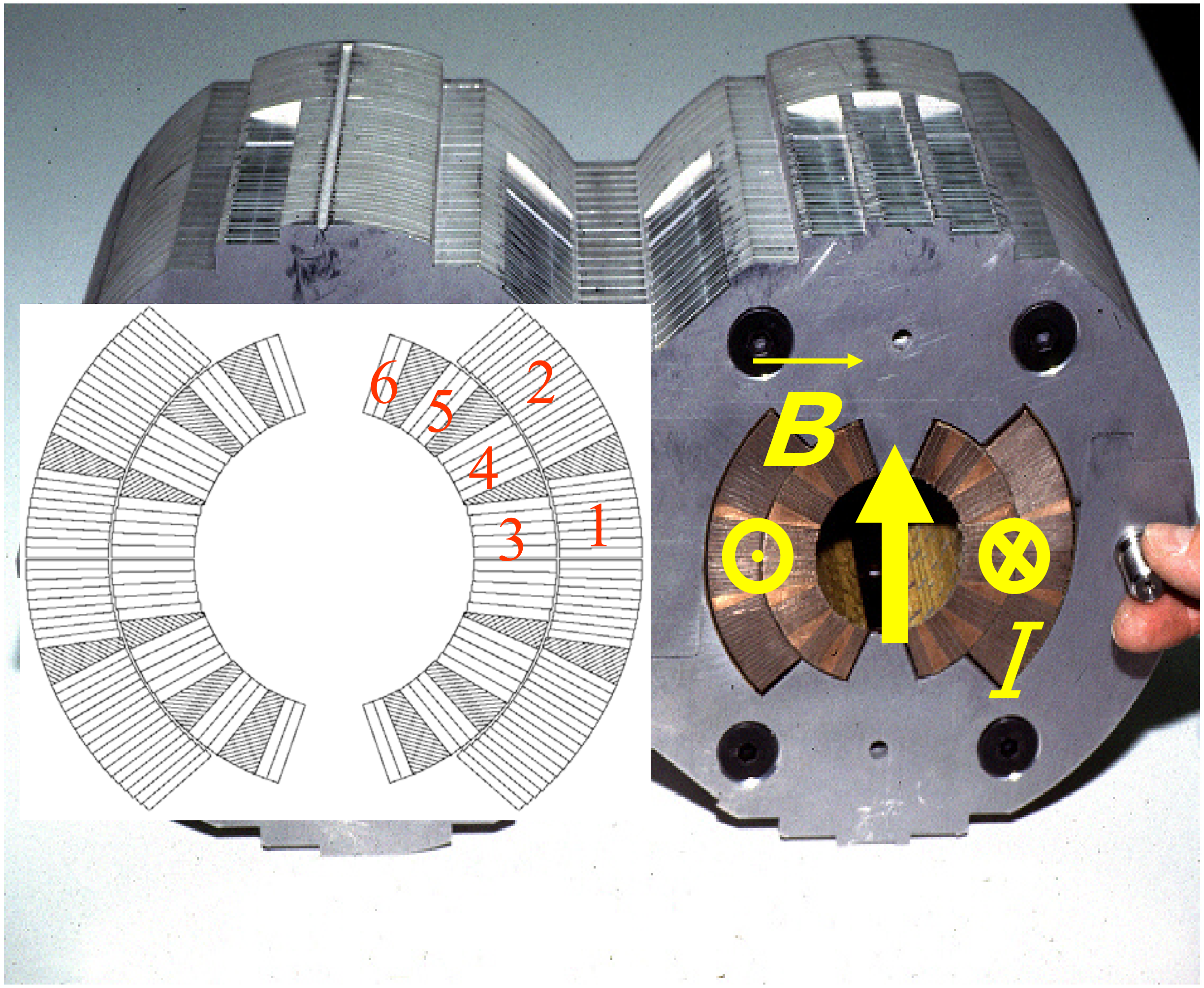
Characteristic of cables and coils

Free volume calculation



The 15-m long LHC cryodipole

Magnets chracteristic
LHC dipole magnets cross section



Thermodynamics of magnet structure

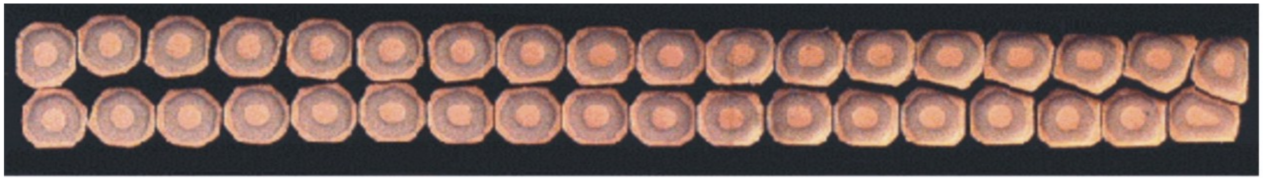
Magnet characteristic

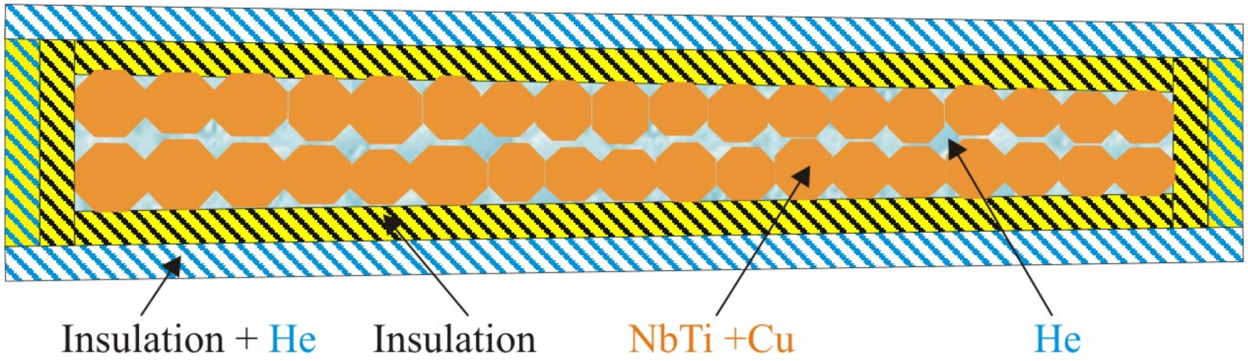
Heat transport in the magnets

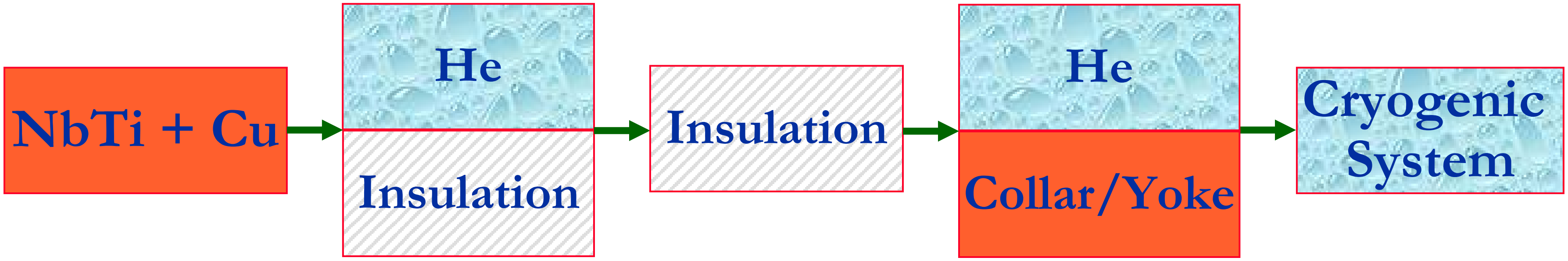
Characteristic of cables and coils

Free volume calculation

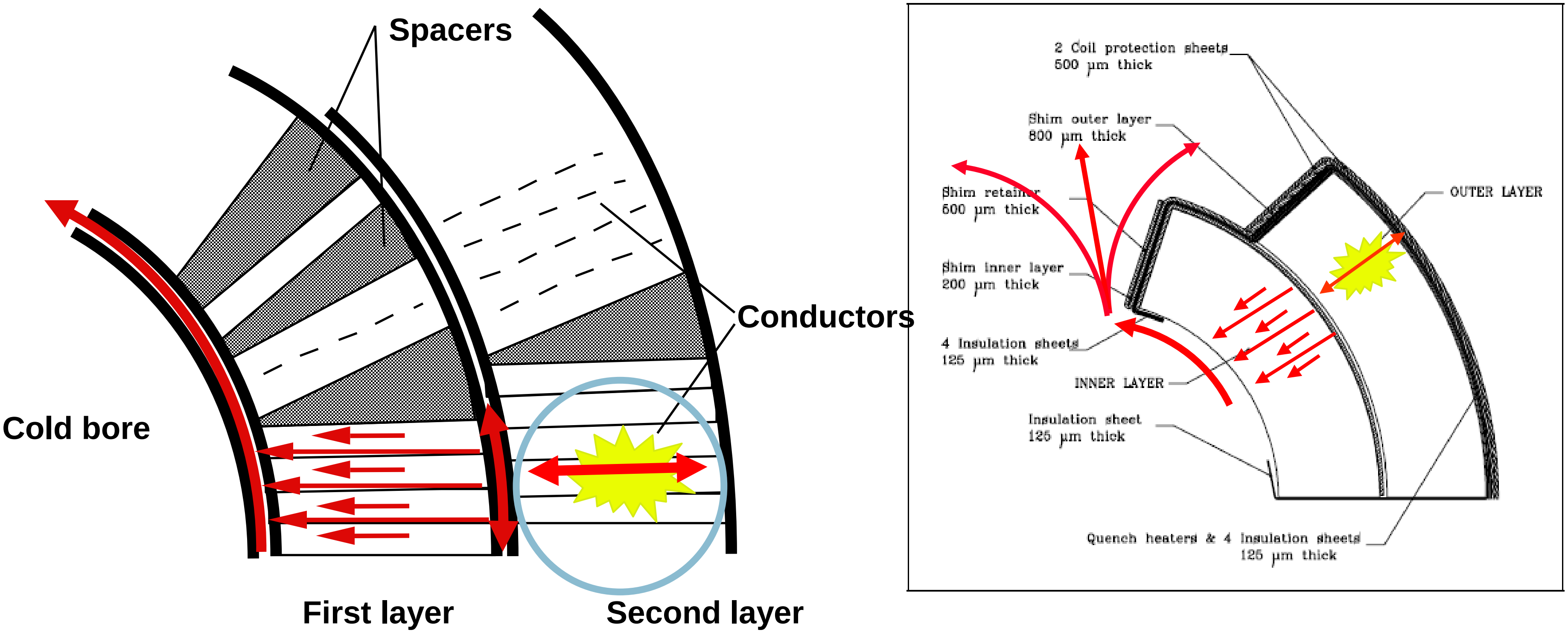
Steady state heat transport in the magnet







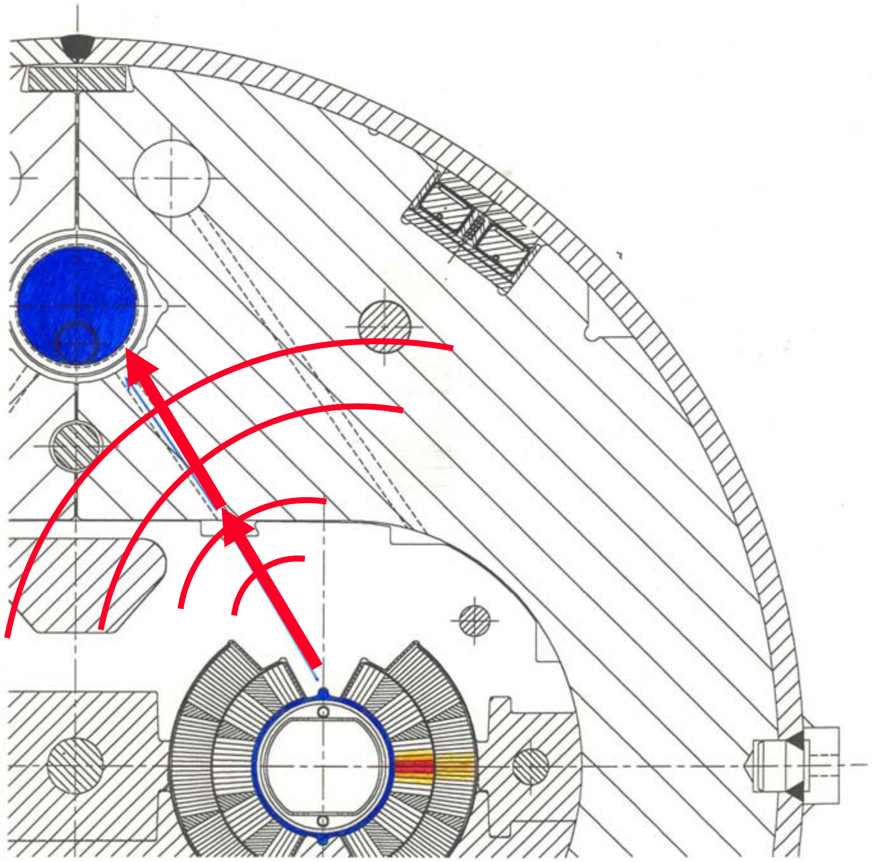
Steady state heat transport in the magnet



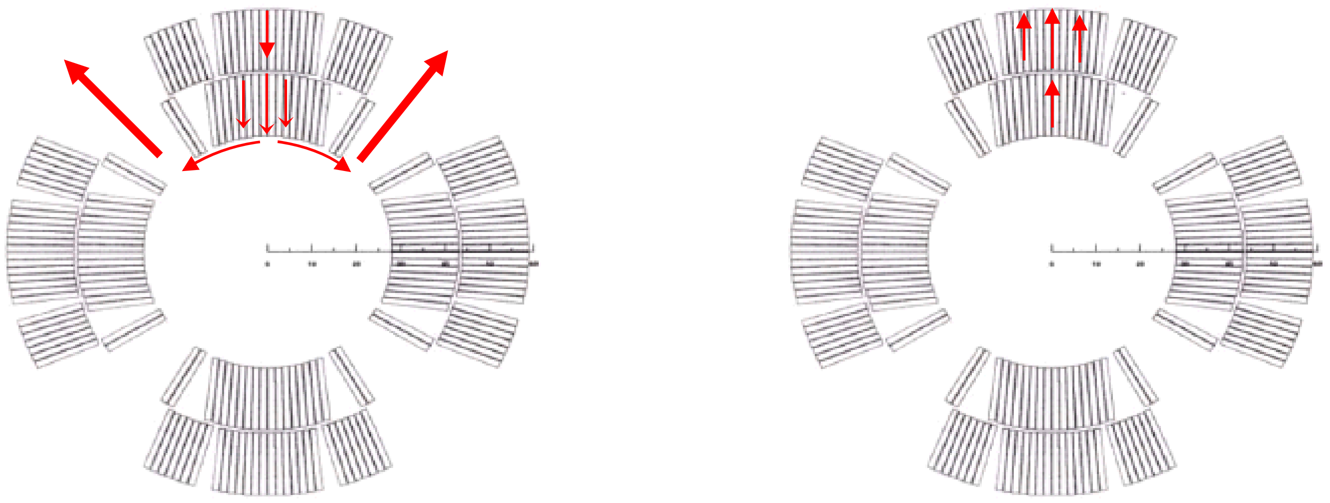
A heat transfer in the main dipole. Arrows indicate the radial path of the heat transfer in the magnet.

Heat transfer in the magnets

- ◆ Heat transfer from the conductor to the cold source define the temperature margin
- ◆ Electrical insulation is the largest thermal barrier at 1.9 K against cooling



Heat transfer in the magnets



A simple sketch of the heat transfer in the quadrupole

at T=1.9 K (left) and T=4.5K(right).

Thermodynamics of magnet structure

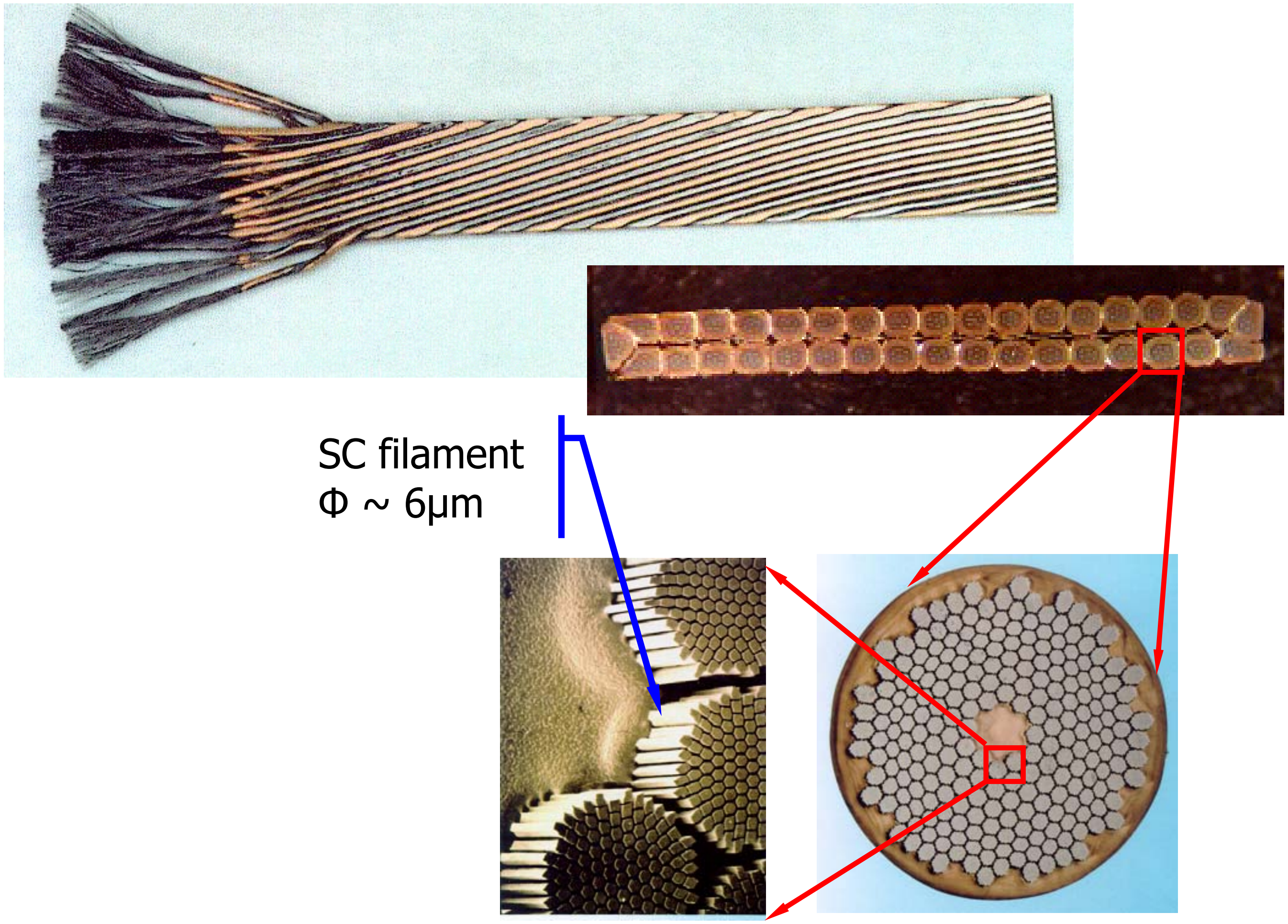
Magnet characteristic

Heat transport in the magnets

Characteristic of cables and coils

Free volume calculation

Superconducting cable



SC filament
Φ ~ 6µm

SC cables characteristic

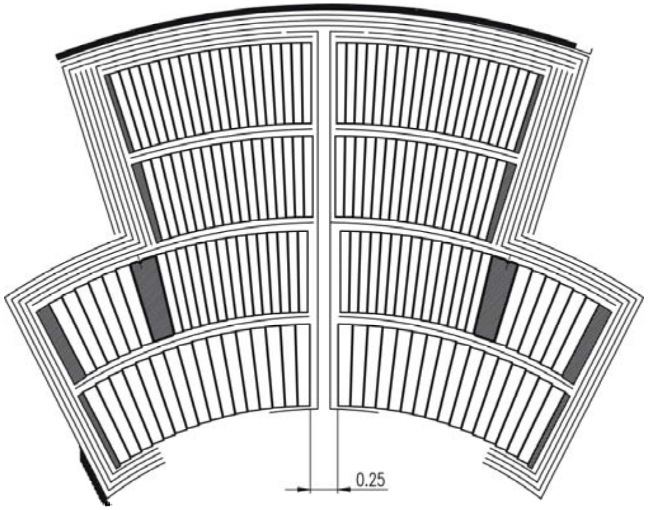
Strand type	diameter (mm)	A-strand(mm^2)	r=Cu/Sc
1	1.065	0.891	1.65
2	0.825	0.535	1.95
5	0.480	0.181	1.75
6	0.740	0.430	1.25

Cable type	Strand type	#strands	A-cable (mm2)	Cu (mm2)	NbTi (mm2)
1	1	28	24.94	15.53	9.41
2 & 3	2	36	19.24	12.72	6.52
4 & 7	5	36	6.51	4.15	2.37
5	5	34	6.15	3.91	2.24
6	6	22	9.46	5.26	4.20
corr-1			0.11	0.09	0.02
corr-2			0.21	0.17	0.04
corr-3			0.69	0.42	0.26
corr-4			1.30	0.80	0.50

Cable characteristic

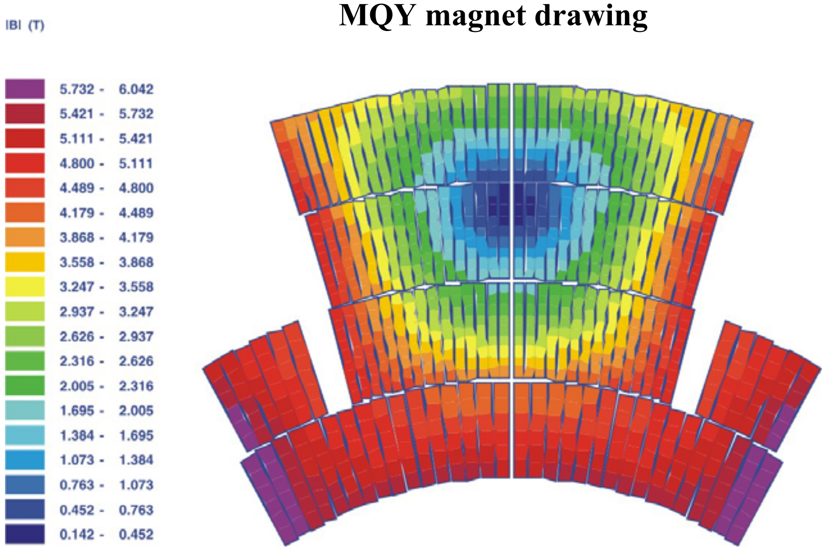
	Units	Cable 1	Cable 2	Cable 3	Cable 4	Cable 5	Cable 6	Cable 7
Strand diameter	mm	1.065	0.825	0.825	0.48	0.48	0.74	0.48
Number of strands		28	36	36	36	34	22	36
Average r=Cu/NbTi		1.65	1.95	1.95	1.75	1.75	1.25	1.75
Keystone angle	deg	1.25	0.9	0.9	0.91	0.9	1.72	0.91
Cable width (bare)	mm	15.1	15.1	15.1	8.8	8.3	8.3	8.8
Cable mid-thickness (bare)	mm	1.9	1.48	1.48	0.84	0.845	1.275	0.84
Cable inner thickness (bare)	mm	1.7353	1.3614	1.3614	0.7701	0.7798	1.1504	0.7701
Cable outer thickness (bare)	mm	2.0647	1.5986	1.5986	0.9099	0.9102	1.3996	0.9099
Transposition pitch	mm	115.00	100.00	100.00	66.00	66.00	66.00	66.00
Radial insulation thickness	mm	0.15	0.15	0.13	0.08	0.08	0.08	0.08
Azimuthal insulation thickness	mm	0.12	0.13	0.11	0.08	0.08	0.08	0.08
Cable width (ins.)	mm	15.4	15.4	15.36	8.96	8.46	8.46	8.96
Cable thickness (ins.)	mm	2.14	1.74	1.70	1.00	1.005	1.435	1.00
Cable inner thickness (ins.)	mm	1.9720	1.6190	1.5794	0.9288	0.9386	1.3080	0.9288
Cable outer thickness (ins.)	mm	2.3080	1.8610	1.8206	1.0712	1.0714	1.5620	1.0712
Cable length	m	460	740	740	740	775	710	540

MQY coil



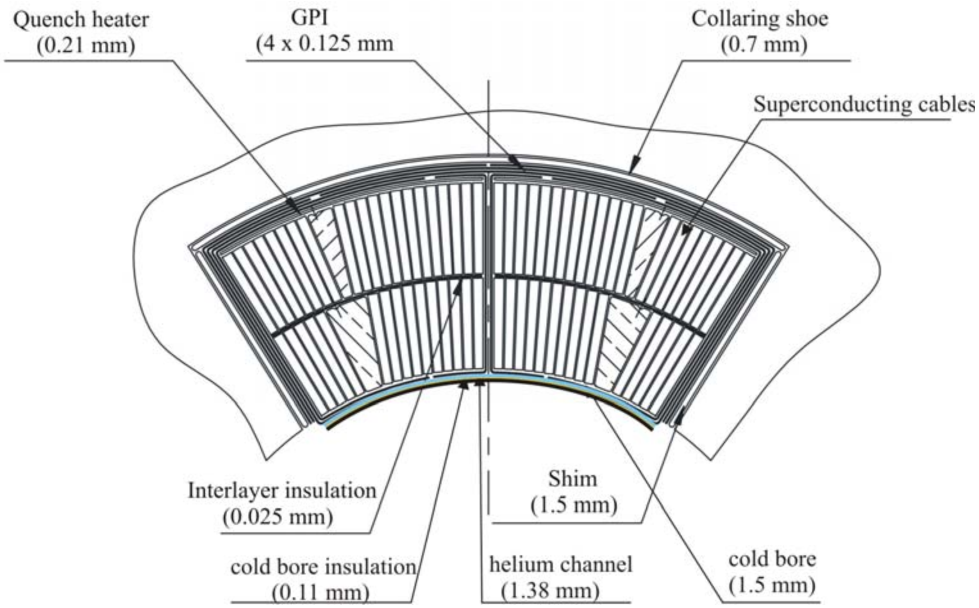
MQY magnet drawing

Photo of the MQY magnet cross-section

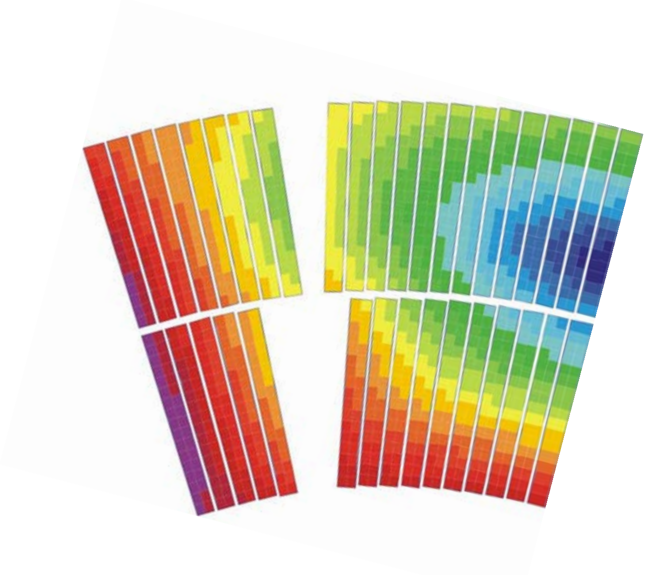


MQY magnetic field distribution

MQM coil



MQM magnet drawing



MQM magnetic field distribution

Thermodynamics of magnet structure

Magnet characteristic

Heat transport in the magnets

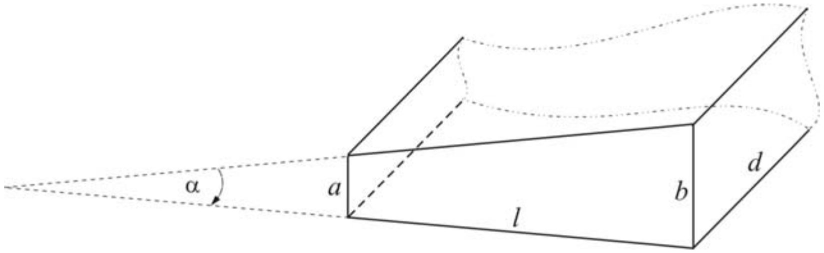
Characteristic of cables and coils

Free volume calculation

Free volume calculations

Free volume is a space inside insulated superconducting cable which can be penetrated by the helium.

The calculation of free volume is based on the difference of the volume calculated from the cable dimensions and volume calculated from the mass and density



Superconducting cable sketch

$$V_1 = \frac{a+b}{2} \cdot l_1 \cdot \cos\left(\alpha / 2\right) \cdot d$$

where
a – is the cable inner thickness,
b – is the cable outer thickness,
l – is the cable width,
a – is the keystone angle,
d – is the cable (sample) length,

$$V_2 = \frac{m_{NbTi}}{\rho_{NbTi}} + \frac{m_{Cu}}{\rho_{Cu}}$$

where
mNbTi – is the NbTi alloy mass,
mCu – is the Cu mass,
rNbTi - is the NbTi alloy density,
rCu - is the Cu density.

Including insulation

$$V_2 = \frac{m_{NbTi}}{\rho_{NbTi}} + \frac{m_{Cu}}{\rho_{Cu}} + \frac{m_{ins}}{\rho_{ins}}$$

Free volume calculation - DATA

	Units	ρ_{Cu}	ρ_{NbTi}	ρ_{Apical}
Density	g/mm^3	0.00893	0.006138	0.00142

	Units	Cable 1	Cable 2	Cable 3	Cable 4	Cable 5	Cable 6	Cable 7
Insulation thickness layer 1	mm	0.0508	0.0508	0.0508	0.025	0.025	0.025	0.025
Insulation thickness layer 2	mm	0.0508	0.0508	0.0375	0.025	0.025	0.025	0.025
Insulation thickness layer 3	mm	0.0686	0.0686	0.0558	0.056	0.056	0.056	0.056

	Units	Cable1	Cable2 & 3	Cable4 & 7	Cable5	Cable6
Sample length	mm	69.3	67.3	68.9	61.9	60.8
Sample weight	g	13.9128	10.7318	3.6242	3.0816	4.4095
$m_{NbTi}=m_{tot}/(r*\rho_{Cu}/\rho_{NbTi}+1)$	g	4.0914	2.7969	1.0220	0.8690	1.5644
$m_{Cu}=m_{tot}-m_{NbTi}$	g	9.8214	7.9349	2.6022	2.2126	2.8451
$m_{Apical}=\rho_{Apical}*V_{Apical}$	g	0.537	0.509	0.184	0.157	0.162

Free volume: RESULTS

	Units	Cable1	Cable2 & Cable3	Cable4 & Cable7	Cable5	Cable6
Volume0* (strand) (bare)	mm^2	25.789	20.103	6.742	6.344	9.757
Volume1* (m,ρ) (bare)	mm^2	25.489	19.974	6.646	6.290	9.432
Volume2* (α,h,l) (bare)	mm^2	28.688	22.347	7.392	7.013	10.581
Free Volume* (bare)	mm^2	**3.199**	**2.373**	**0.746**	**0.723**	**1.149**
Free Volume (bare)	%	**11.152**	**10.621**	**10.090**	**10.313**	**10.860**

	Units	Cable1	Cable2	Cable3	Cable4 & 7	Cable5	Cable6
Volume1 *(m,ρ) (insulation)	mm^2	30.949	25.301	25.301	8.531	8.080	11.304
Volume2 *(α,h,l) (insulation)	mm^2	32.954	26.795	26.795	8.960	8.502	12.139
Free Volume (insulation)	mm^2	**2.005**	**1.494**	**1.494**	**0.429**	**0.422**	**0.834**
Free Volume (insulation)	%	**6.085±0.2**	**5.576±0.15**	**6.231±0.16**	**4.789±0.18**	**4.966±0.29**	**6.873±0.18**

* - Normalized Free Volume = Volume is divided by length of the sample

Network Model

Electrical equivalent

Model of the superconducting cable and coils

Results of the simulations with PSpice

Electrical equivalent

The analogy of the equivalent thermal circuit

Thermal circuit			Electrical Circuit		
T	[K]	Temperature	**V**	[V]	Voltage
Q	[J]	Heat	**Q**	[C]	Charge
q	[W]	Heat transfer rate	**i**	[A]	Current
κ	[W/Km]	Thermal Conductivity	**σ**	[1/Ωm]	Electrical Conductivity
R^{Θ}	[K/W]	Thermal Resistance	**R**	[V/A]	Resistance
C^{Θ}	[J/K]	Thermal Capacitance	**C**	[C/V]	Capacitance

The analogy between electrical and thermal circuit can be expressed as:

-steady-state condition *Temperature rise* ⇔ *Voltage difference*

$$\Delta T = qR^{\Theta} \quad \Leftrightarrow \quad \Delta V = iR$$

-transient condition *Heat diffusion* ⇔ *RC transmission line*

$$\nabla^2 T = R^{\Theta} C^{\Theta} \frac{\partial T}{\partial t} \quad \Leftrightarrow \quad \nabla^2 V = RC \frac{\partial V}{\partial t}$$

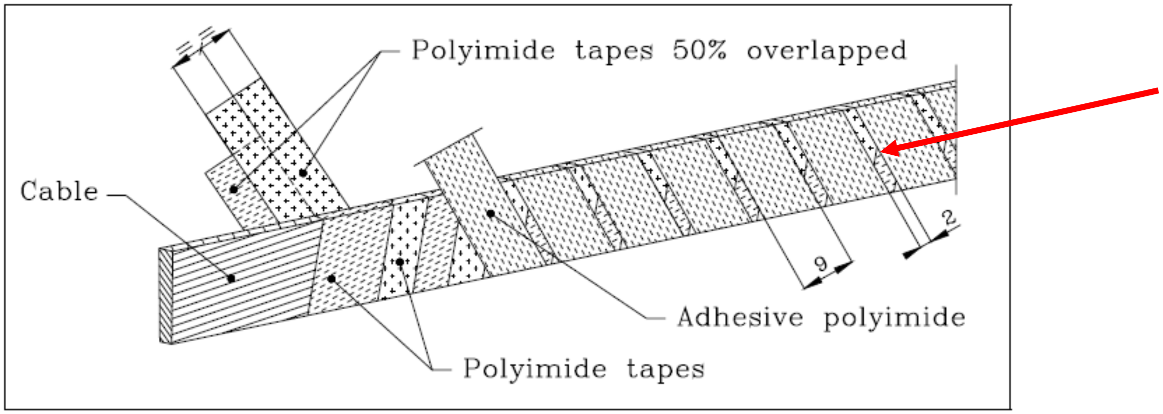
Network Model

Electrical equivalent

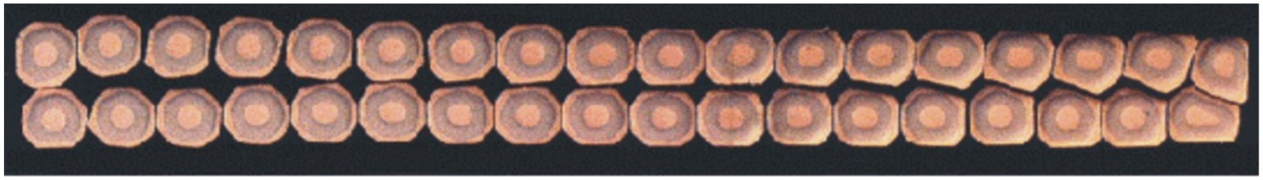
Model of the superconducting cable and coils

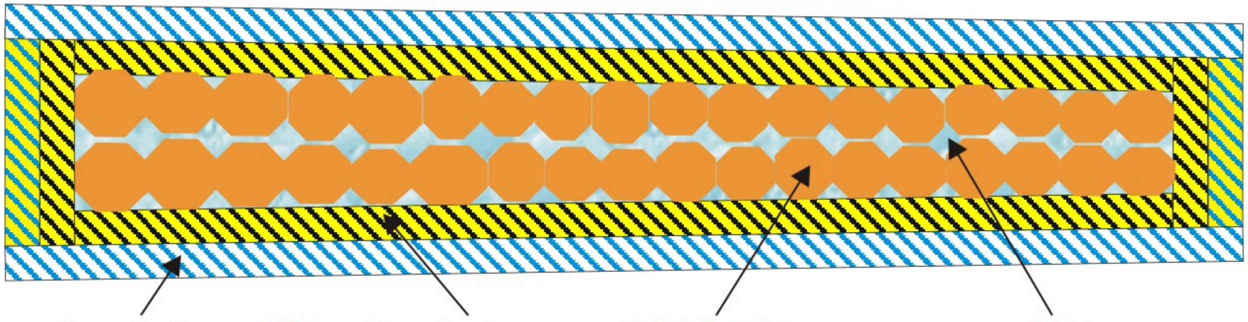
Results of the simulations with PSpice

“WET” superconducting cable modeling



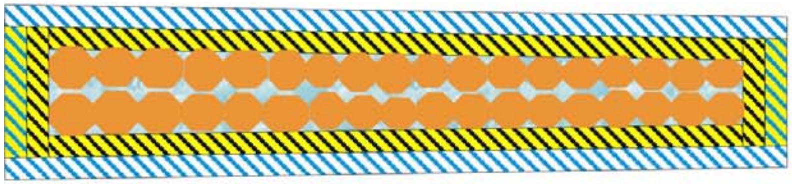
µ-channel



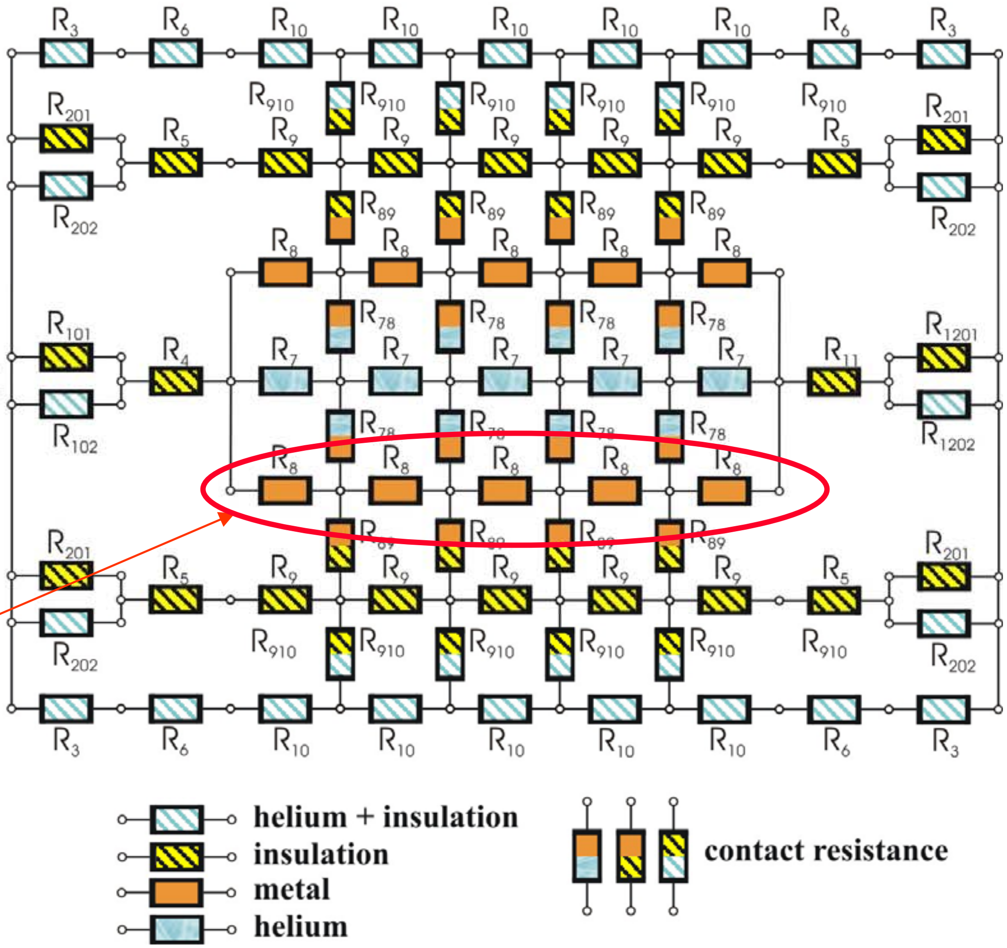


Cable modeling

Cable



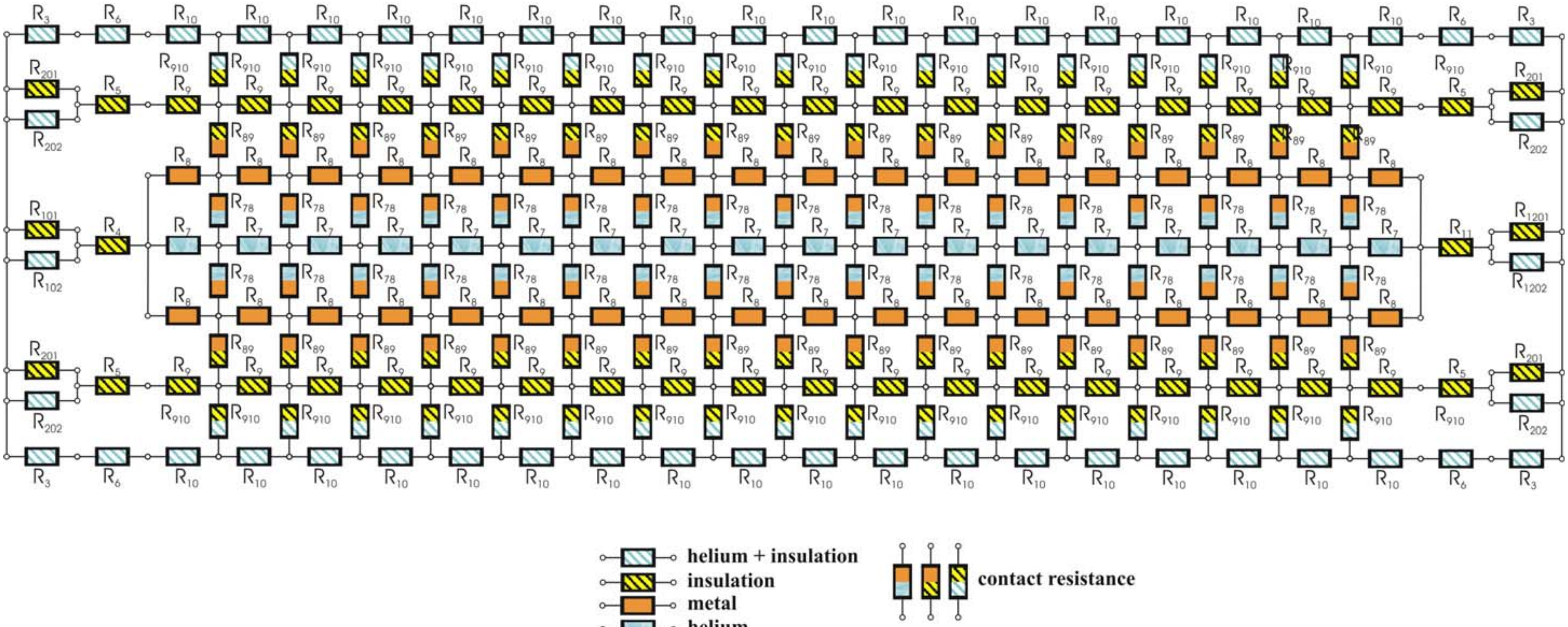
Network model of the cable



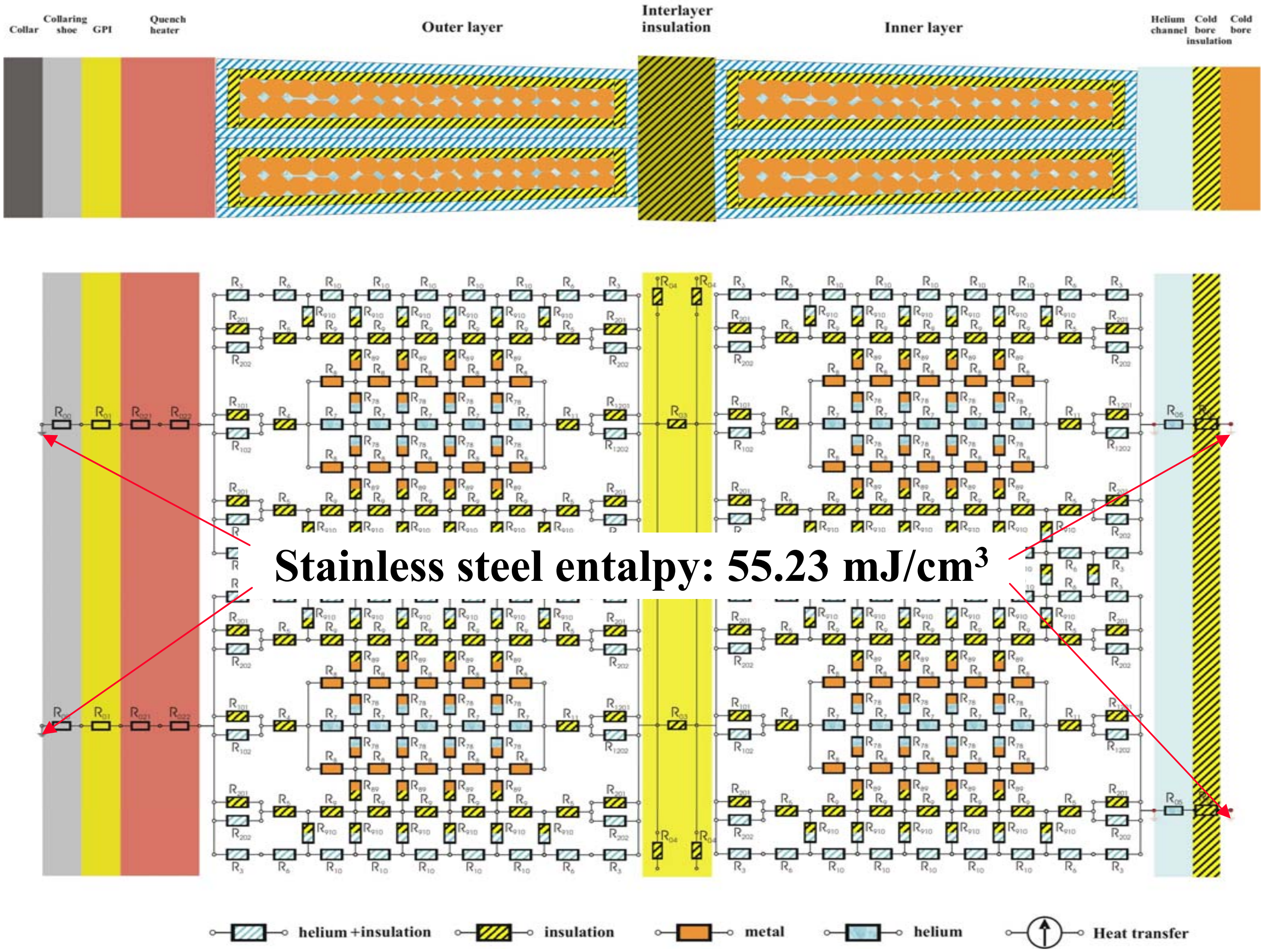
5 block discretization

Cable model – 36 strands

Network model of the cable - 36 strands model



Coil modeling



Stainless steel entalpy: 55.23 mJ/cm^3

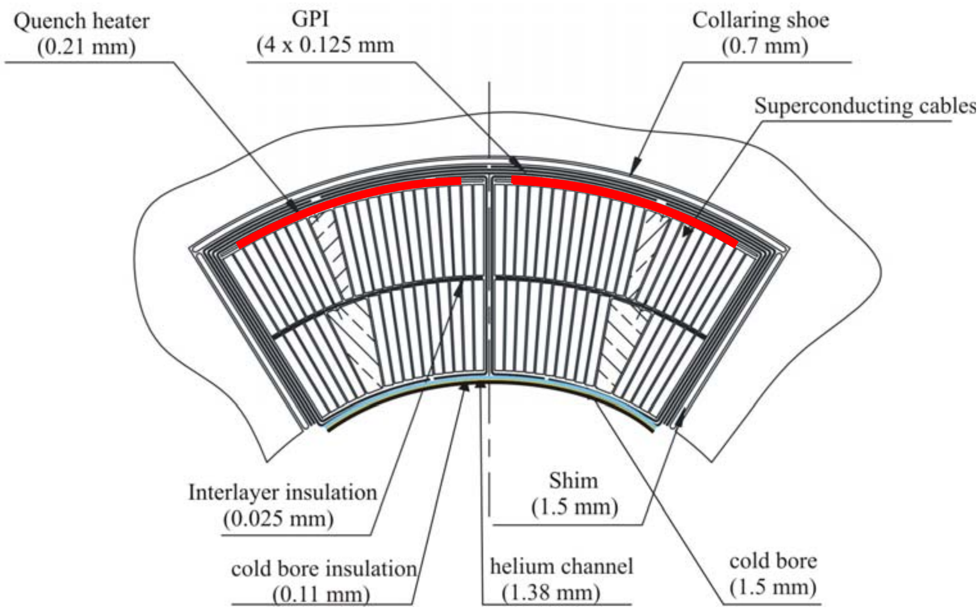
Network Model

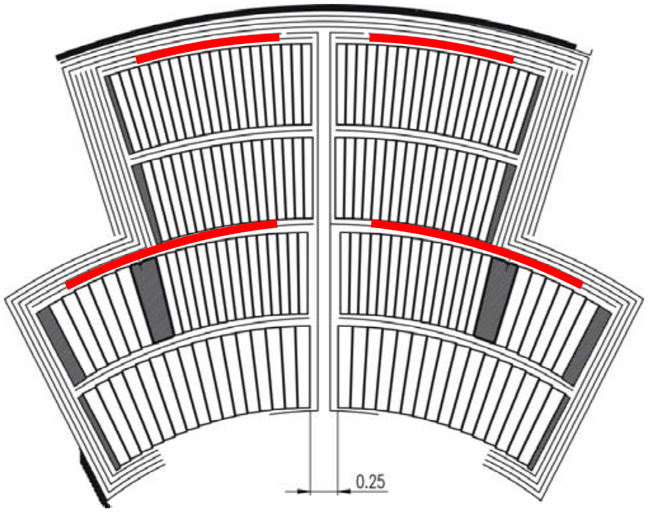
Electrical equivalent

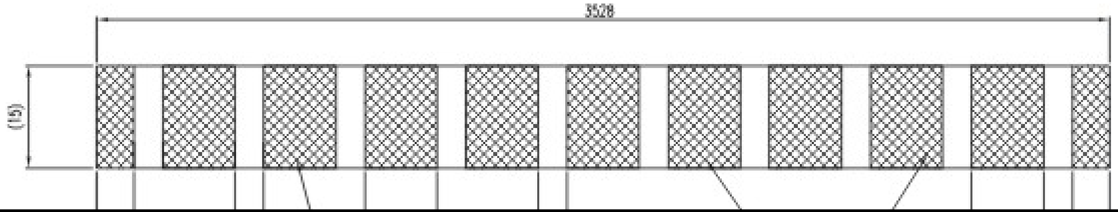
Model of the superconducting cable and coils

Results of the simulations with PSpice

Quench heater as a heat source

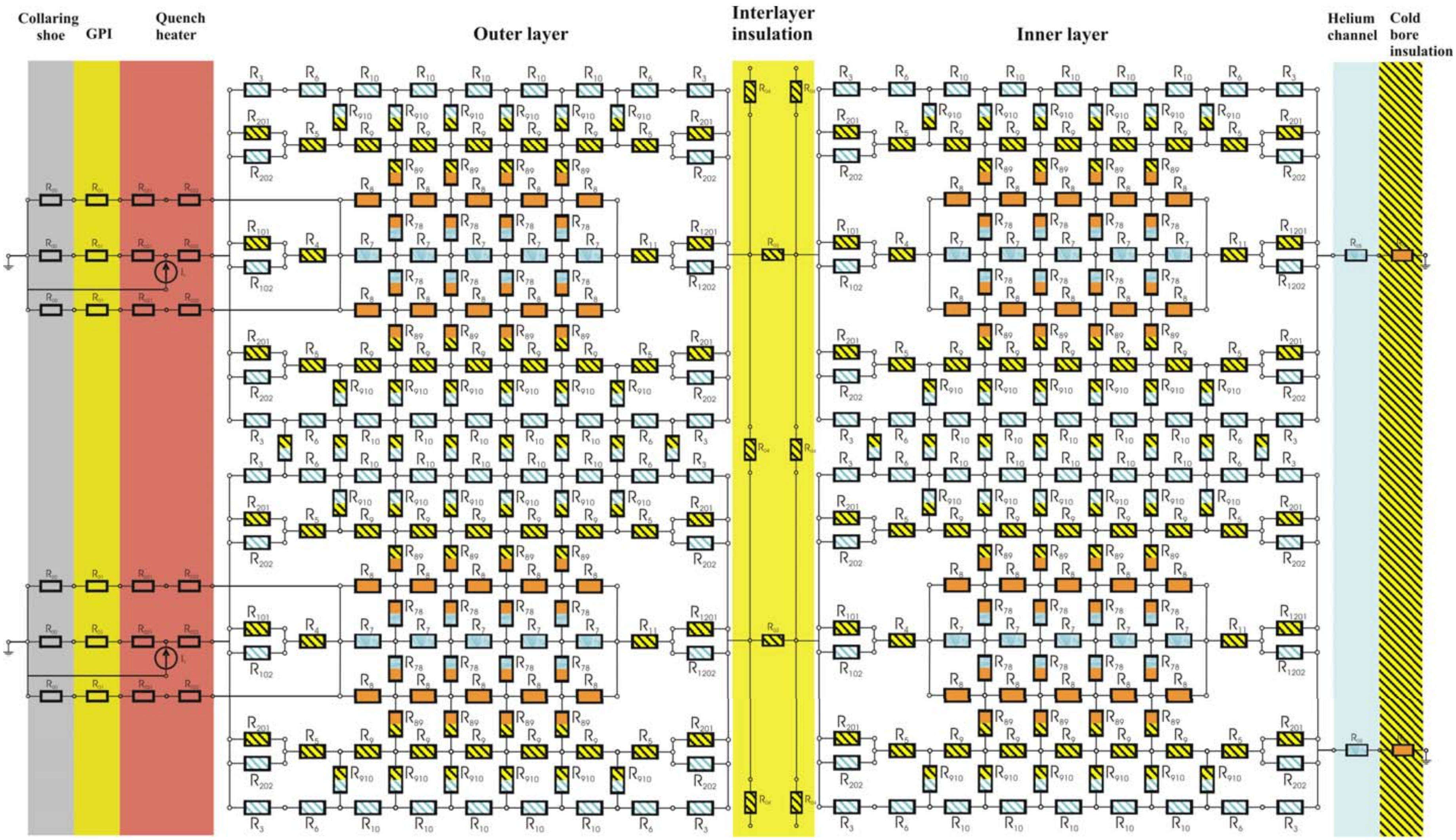




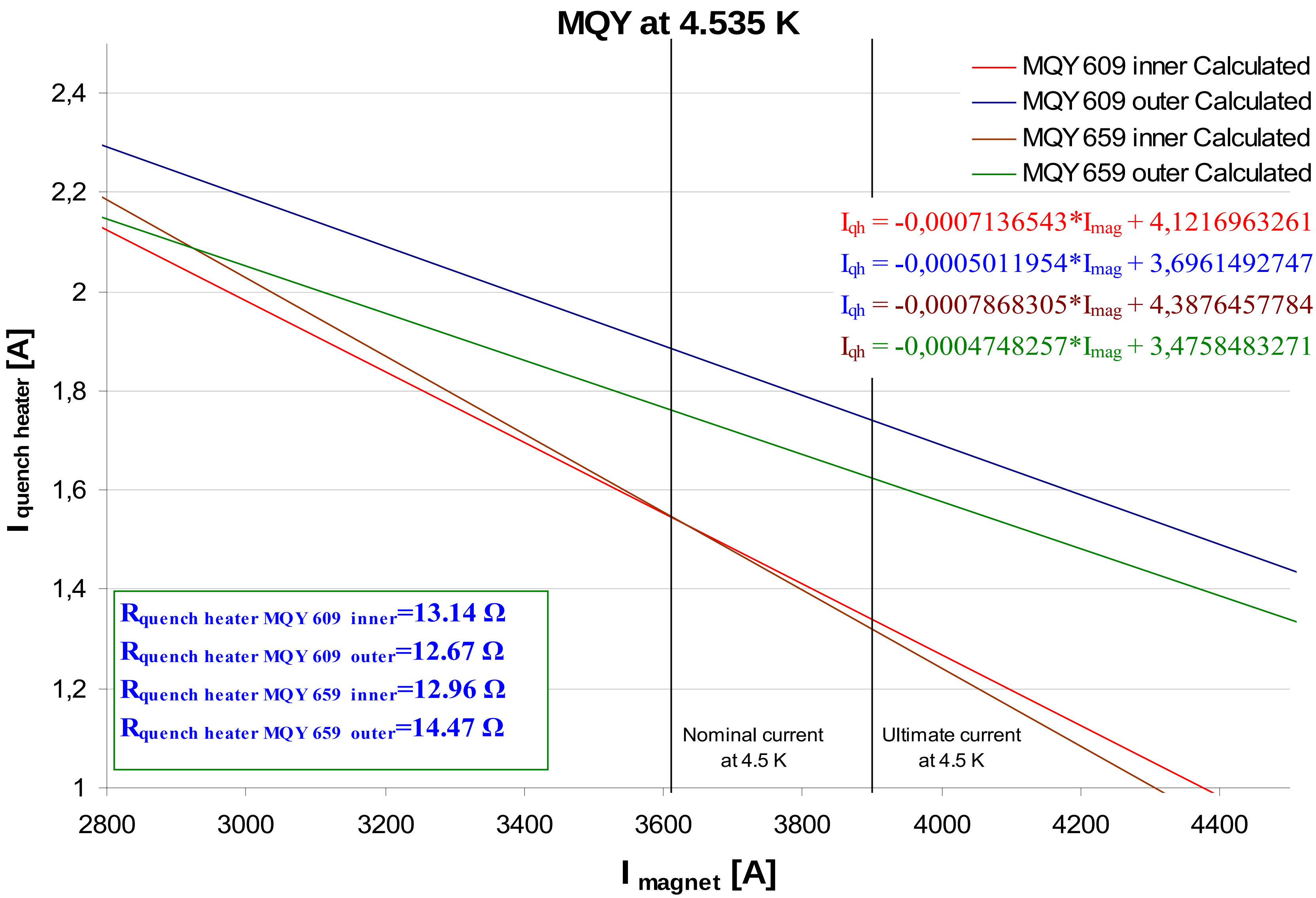


Magnet type	Length [mm]	Width [mm]	Thickness [mm]	Stainless Steel / Copper ratio [mm/mm]
MQM	3511	21	0.025	120/170
MQMC	2506	21	0.025	125/100
MQML	4916	21	0.025	140/350
MQY - outer	3528	15	0.025	100/250
MQY - inner	3528	21	0.025	130/190

Network model - simulation



Results of the simulations



$I_{qh} = -0,0007136543*I_{mag} + 4,1216963261$

$I_{qh} = -0,0005011954*I_{mag} + 3,6961492747$

$I_{qh} = -0,0007868305*I_{mag} + 4,3876457784$

$I_{qh} = -0,0004748257*I_{mag} + 3,4758483271$

$R_{quench\ heater\ MQY\ 609\ inner}=13.14\ \Omega$

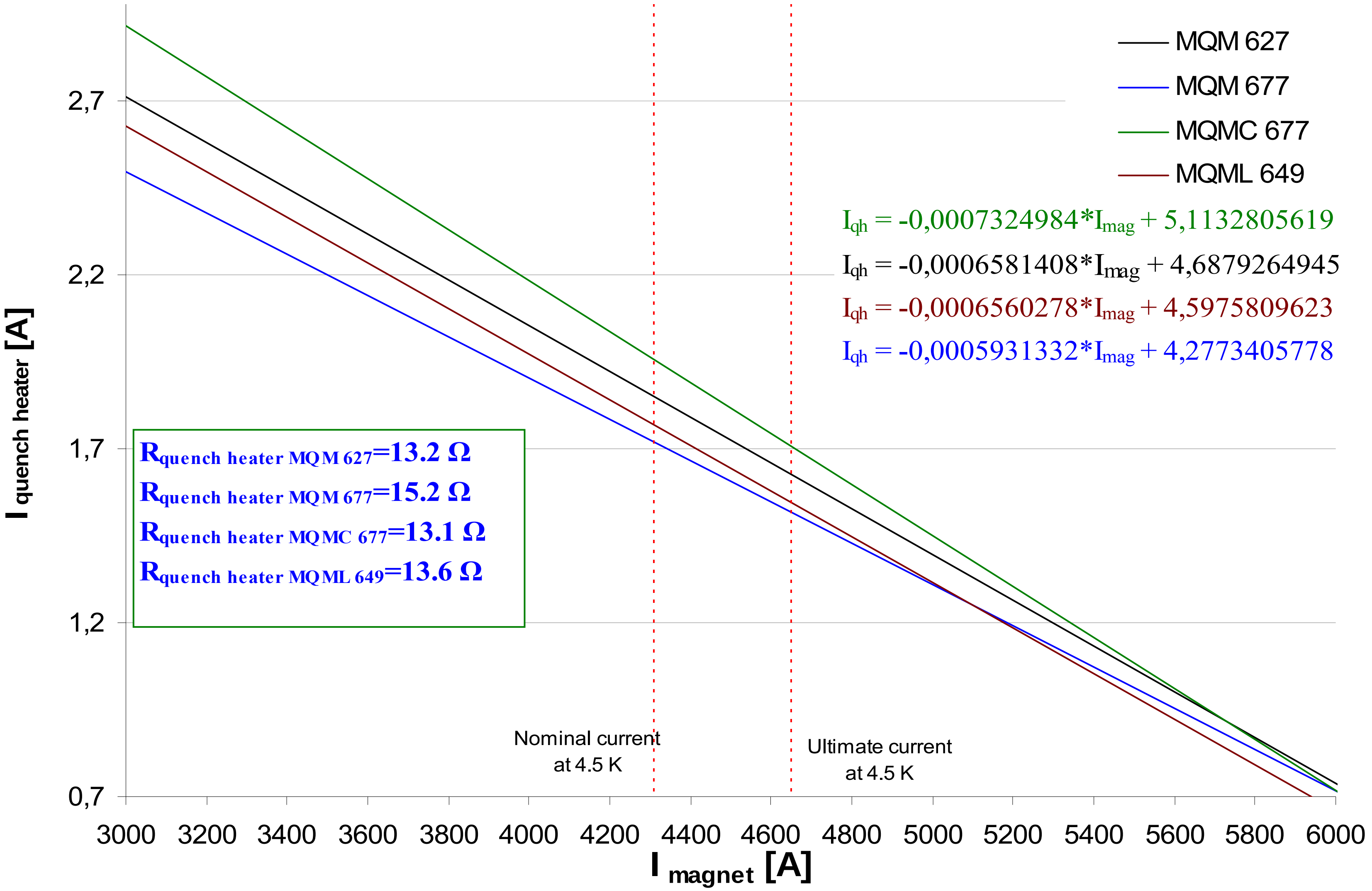
$R_{quench\ heater\ MQY\ 609\ outer}=12.67\ \Omega$

$R_{quench\ heater\ MQY\ 659\ inner}=12.96\ \Omega$

$R_{quench\ heater\ MQY\ 659\ outer}=14.47\ \Omega$

Results of the simulation

3 families of MQM magnets including real parameters of their quench heaters



$I_{qh} = -0{,}0007324984*I_{mag} + 5{,}1132805619$

$I_{qh} = -0{,}0006581408*I_{mag} + 4{,}6879264945$

$I_{qh} = -0{,}0006560278*I_{mag} + 4{,}5975809623$

$I_{qh} = -0{,}0005931332*I_{mag} + 4{,}2773405778$

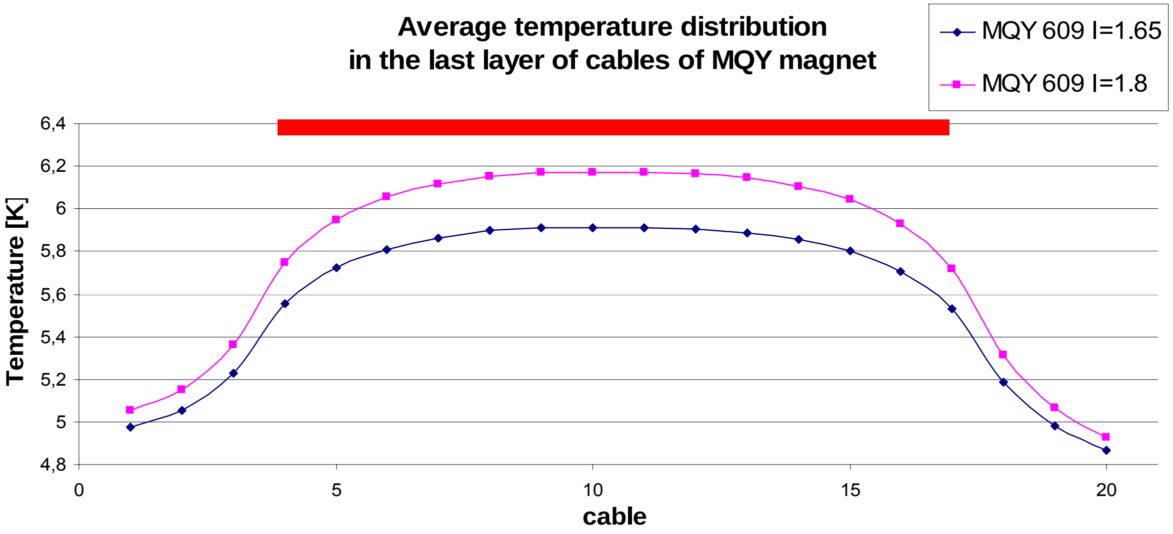
$R_{\text{quench heater MQM 627}}=13.2\ \Omega$

$R_{\text{quench heater MQM 677}}=15.2\ \Omega$

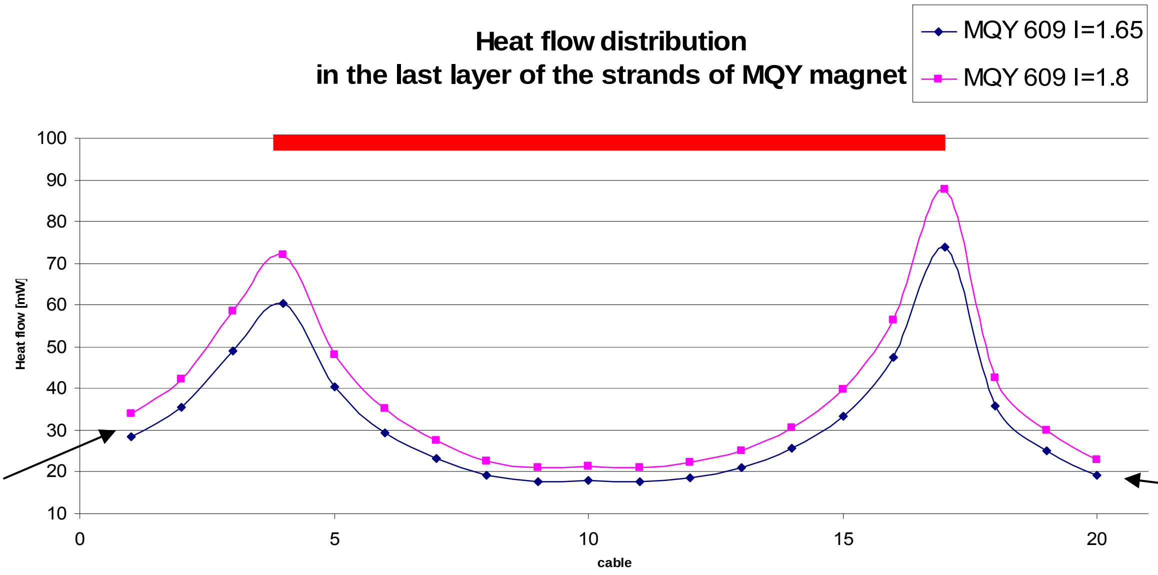
$R_{\text{quench heater MQMC 677}}=13.1\ \Omega$

$R_{\text{quench heater MQML 649}}=13.6\ \Omega$

Temperature and heat flow distribution



🟥 Quench heater



Midplane

collar

Validation of the model

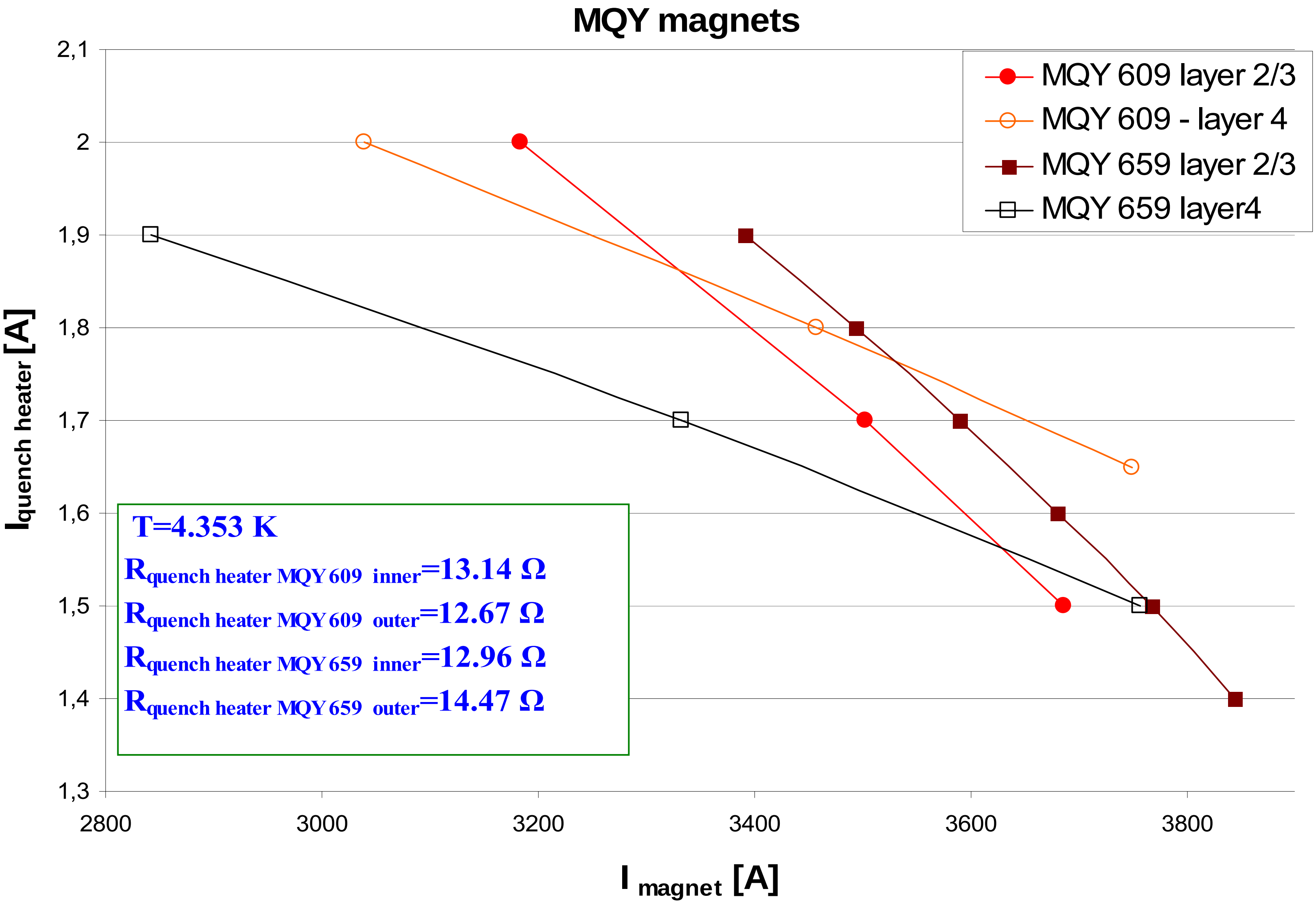
Measurements in SM18

Evaluation of the network model quality

Measurements in SM 18

- Two methods of measurement
  - I_{coil} =const, increase of I_{QH} with a step of 0.1 A
  - I_{QH} =const, wait 300 second for staeady state, then ramp of I_{coil}
- Second method is better for steady state heat transport
- 3 MQM's and 2 MQY's at 4.535K have been tested

Measurements in SM18



T=4.353 K

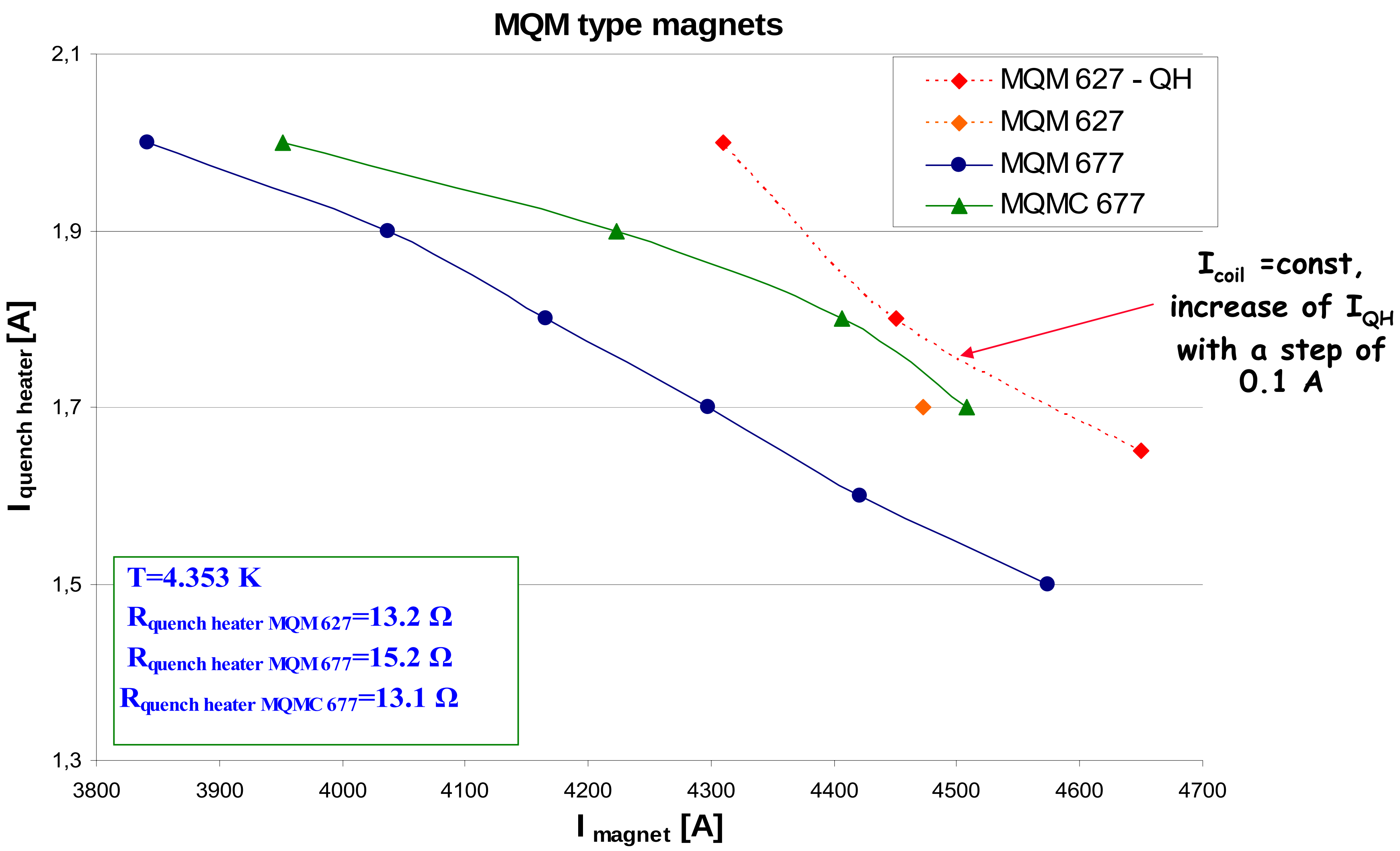
$R_{\text{quench heater MQY 609 inner}}=13.14\ \Omega$

$R_{\text{quench heater MQY 609 outer}}=12.67\ \Omega$

$R_{\text{quench heater MQY 659 inner}}=12.96\ \Omega$

$R_{\text{quench heater MQY 659 outer}}=14.47\ \Omega$

Resluts of the measurements


MQM type magnets

T=4.353 K

$R_{\text{quench heater MQM 627}}=13.2\ \Omega$

$R_{\text{quench heater MQM 677}}=15.2\ \Omega$

$R_{\text{quench heater MQMC 677}}=13.1\ \Omega$

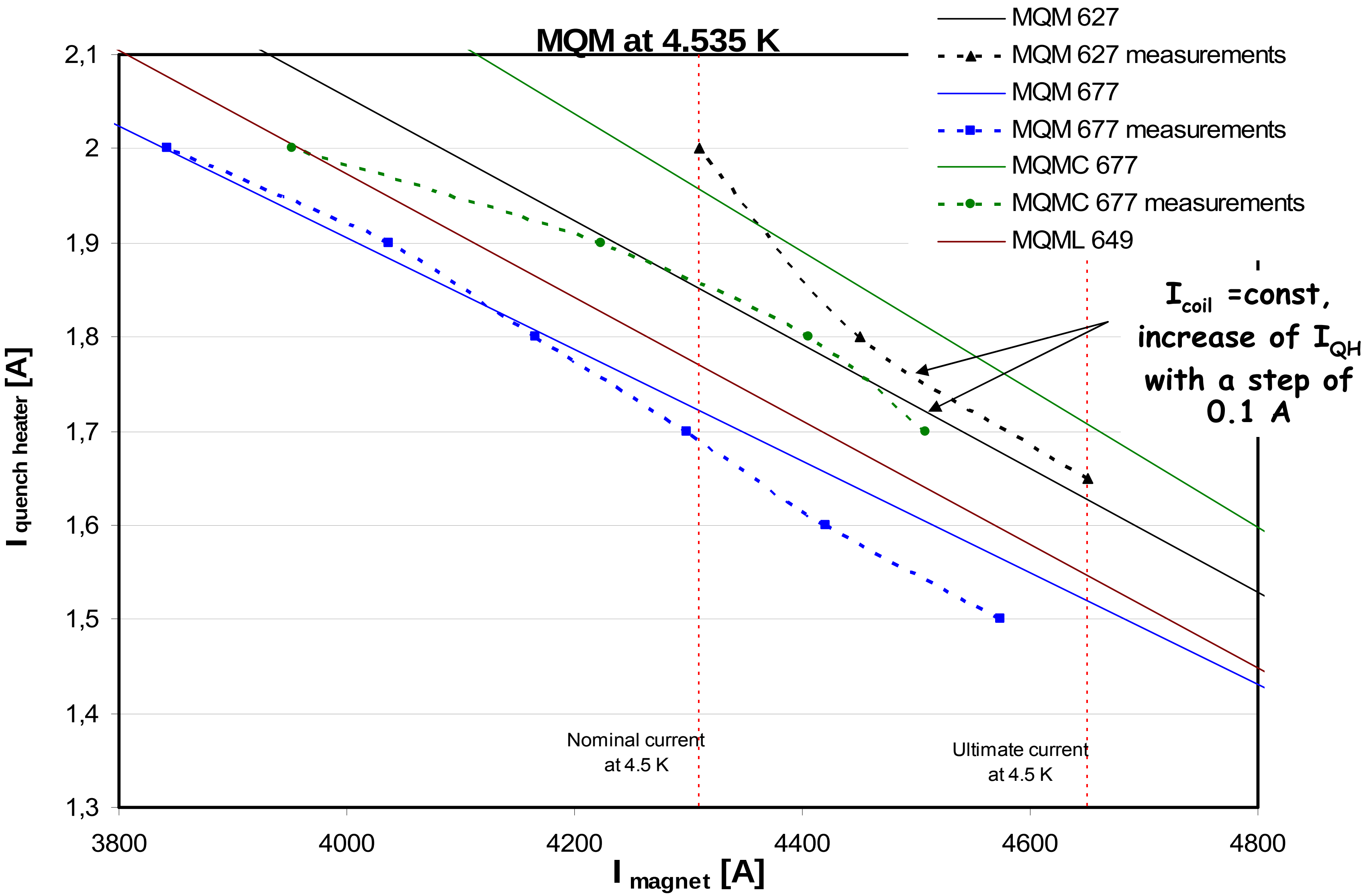
I_{coil} =const, increase of I_{QH} with a step of 0.1 A

Validation of the model

Measurements in SM18

Evaluation of the network model quality

Evaluation of the model quality

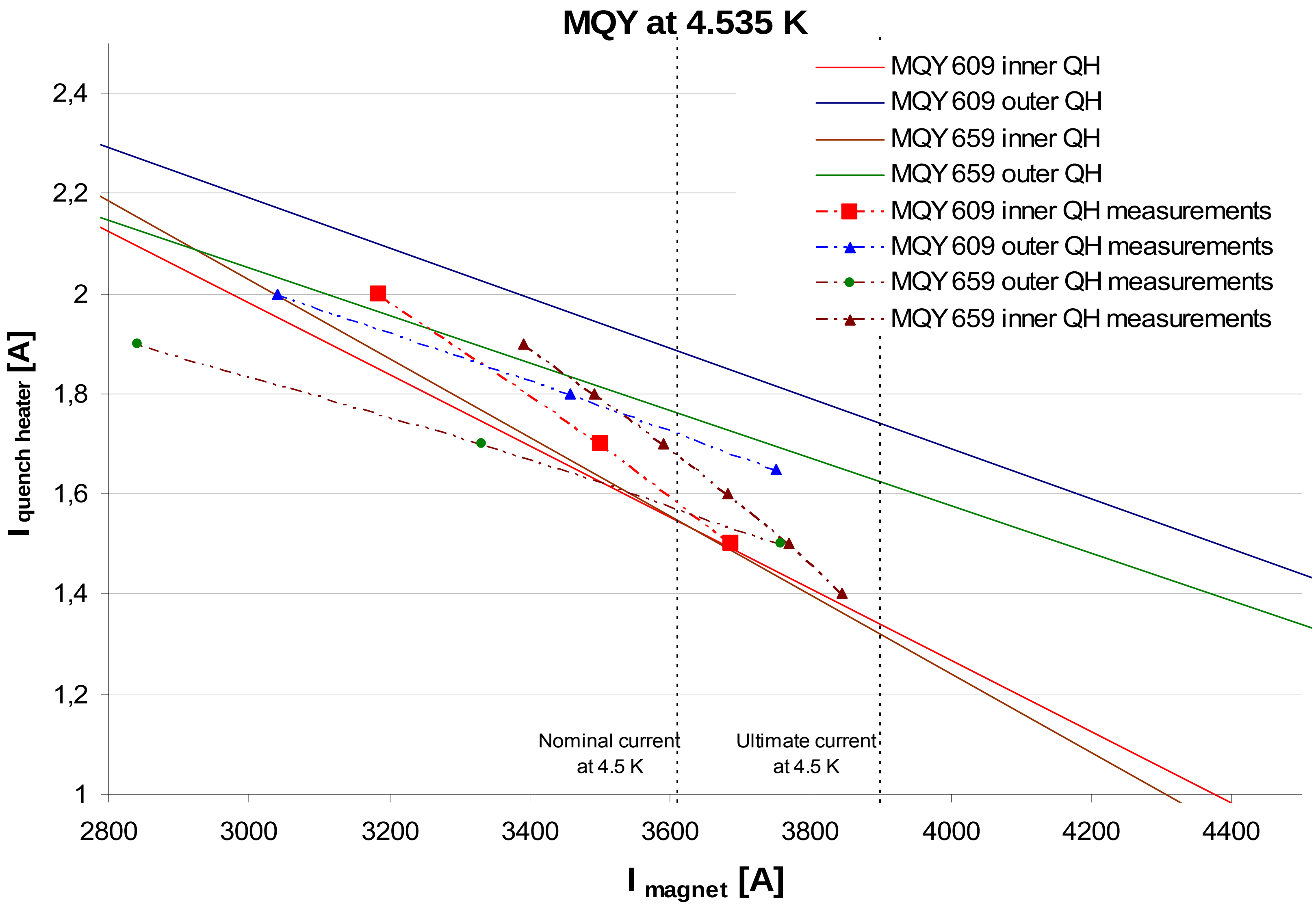


I_{coil} =const, increase of I_{QH} with a step of 0.1 A

Evaluation of the model quality

Magnet type	Temperature margin ΔT [K]	$I_{\text{quench heater}}$ [A]	I_{magnet} [A] calculated	I_{magnet} [A] measured	ΔI_{magnet} [A]	ΔI_{magnet} [%]
MQM 627	1,019	1,65	4609	4650	-41	**-0,89**
	1,213	1,8	4398	4450	-52	**-1,18**
	1,498	2	4080	4310	-230	**-5,64**
	1,082	1,7	4541	4472	69	**1,52**
MQM 677	0,9704	1,5	4661	4574	87	**1,87**
	1,104	1,6	4517	4421	96	**2,13**
	1,246	1,7	4361	4298	63	**1,44**
	1,397	1,8	4194	4166	28	**0,67**
	1,557	1,9	4013	4037	-24	**-0,60**
	1,725	2	3820	3842	-22	**-0,58**
MQMC 677	0,976	1,7	4655	4508	147	**3,16**
	1,094	1,9	4528	4406	122	**2,69**
	1,219	1,9	4391	4223	168	**3,83**
	1,35	2	4246	3952	294	**6,92**

Evaluation of the model quality



Evaluation of the model quality

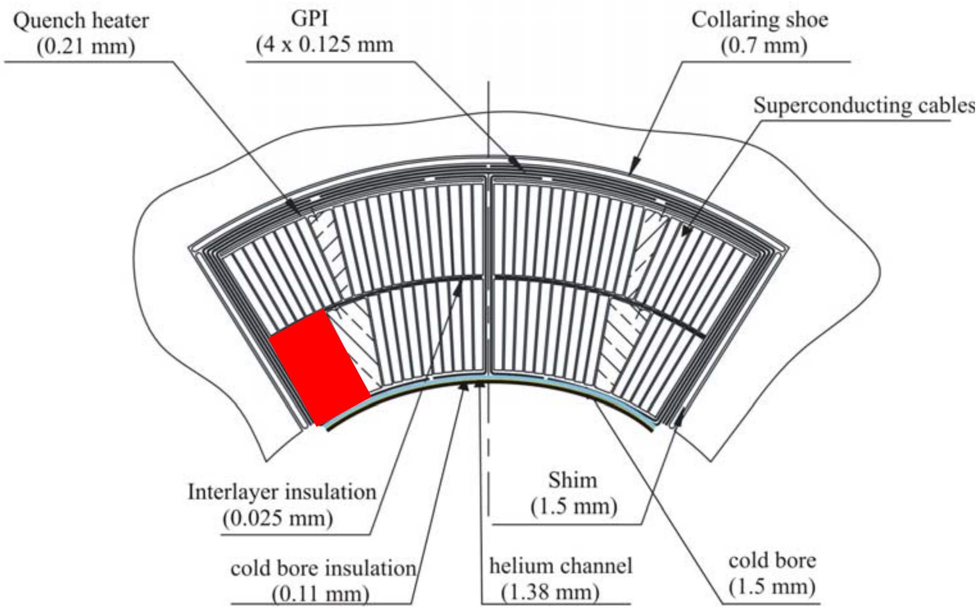
Magnet type	Temperature margin ΔT [K]	$I_{\text{quench heater}}$ [A]	I_{magnet} [A]		ΔI_{magnet} [A]	ΔI_{magnet} [%]
			calculated	measured		
MQY 609 outer	1,571	1,65	4073	3750	323	**7,93**
	1,8803	1,8	3799	3457	342	**9,00**
	2,279	2	3378	3040	338	**10,01**
MQY 609 inner	0,983	1,5	3661	3686	-25	**-0,68**
	1,1994	1,7	3413	3502	-89	**-2,61**
	1,5612	2	2966	3184	-218	**-7,35**
MQY 659 outer	1,5645	1,5	4417	3757	660	**14,94**
	1,9913	1,7	3766	3332	434	**11,52**
	2,4468	1,9	3307	2842	465	**14,06**
MQY 659 inner	0,7926	1,4	3780	3844	-64	**-1,69**
	0,8848	1,5	3672	3768	-96	**-2,61**
	0,989	1,6	3556	3681	-125	**-3,52**
	1,0966	1,7	3429	3590	-161	**-4,70**
	1,2098	1,8	3293	3493	-200	**-6,07**
	1,3273	1,9	3146	3391	-245	**-7,79**

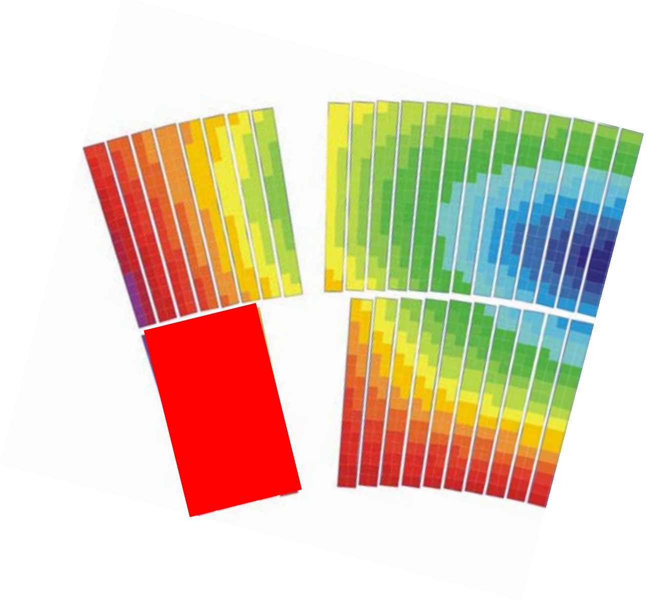
„Beam loss" simulations

„Beam loss” simulations

- Quench limit for the „real” beam loss depends on the beam loss profiles
- heat flow distribution in the coil will be different compare to the „quench heater” simulations
- A simple simulation of beam loss are presented in the next slides
- The first result for typical „beam loss profile” in MQM magnet

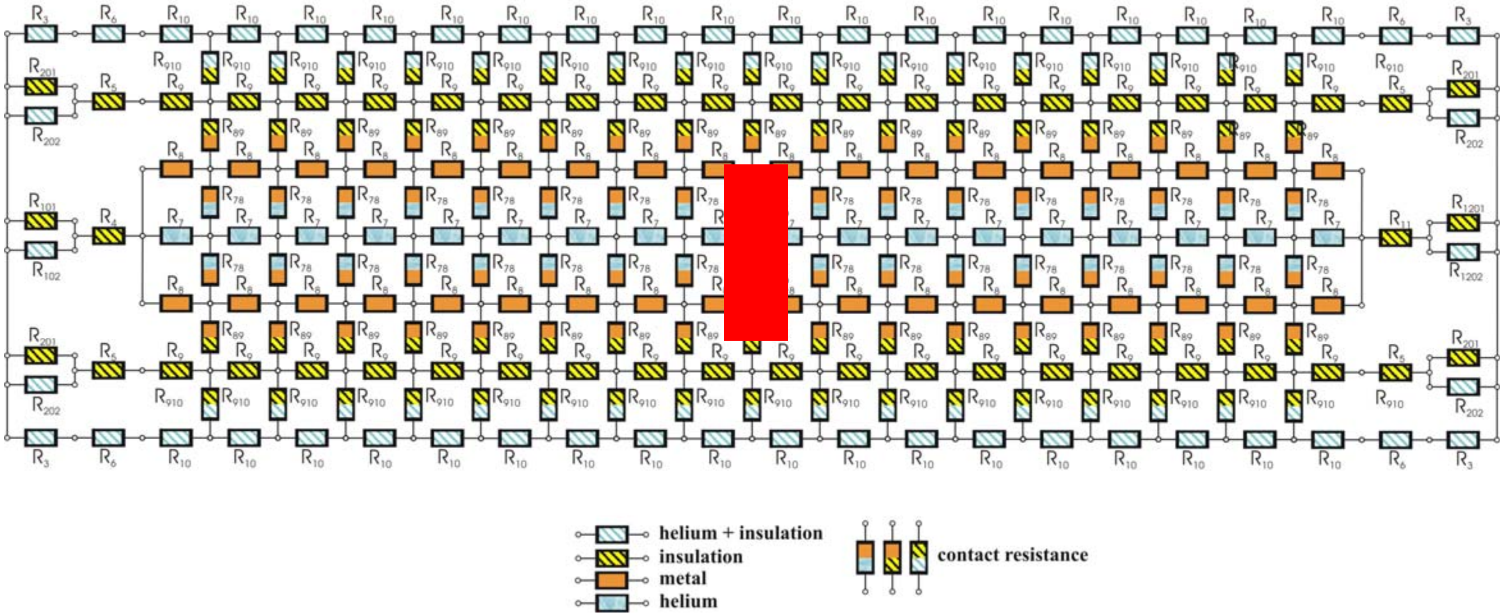
„Beam loss” simulation MQM magnet





„Beam loss" simulation
MQM magnet

Network model of the cable - 36 strands model

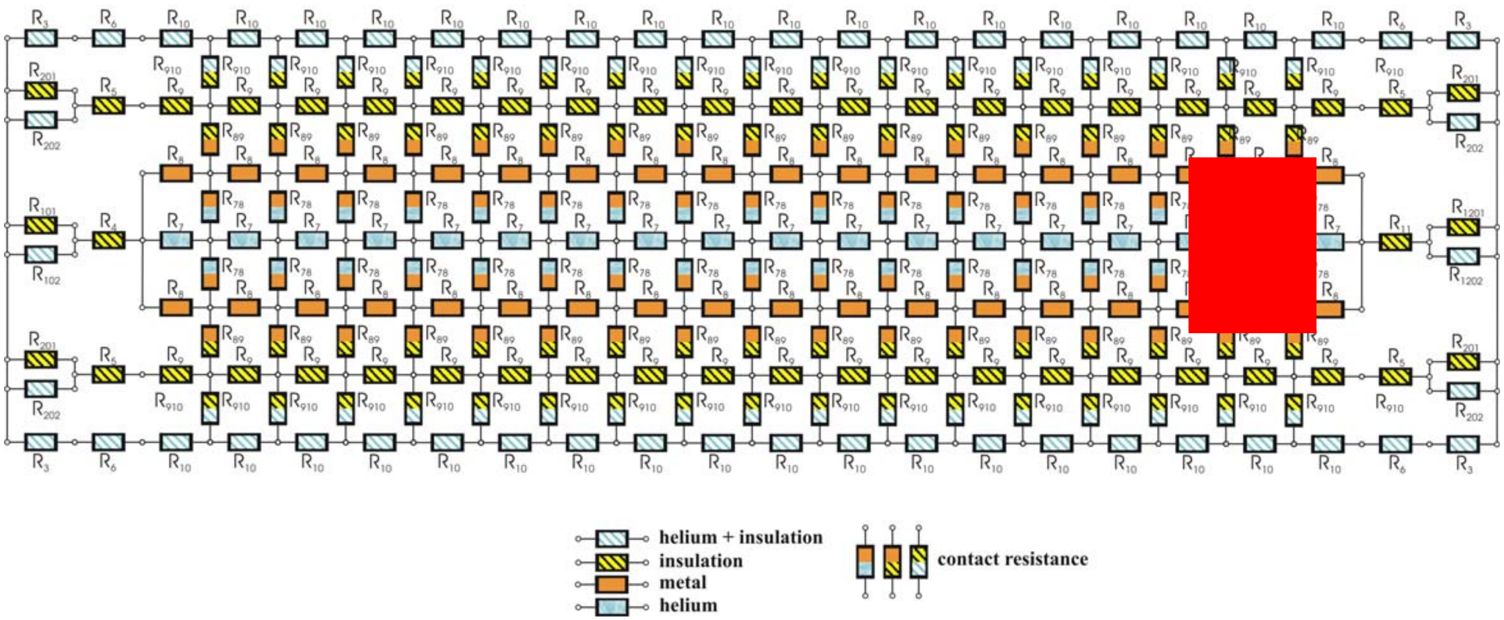


Simulation settings:

- heat source in the middle of the cable
- heating 5 cables with a one source of 0.6 W
- temperature margin $\Delta T = 0.8$ K

MQM quench limit for nominal current (4310 A) ~ 8 [mW/cm^3]

„Beam loss” simulation
MQM magnet



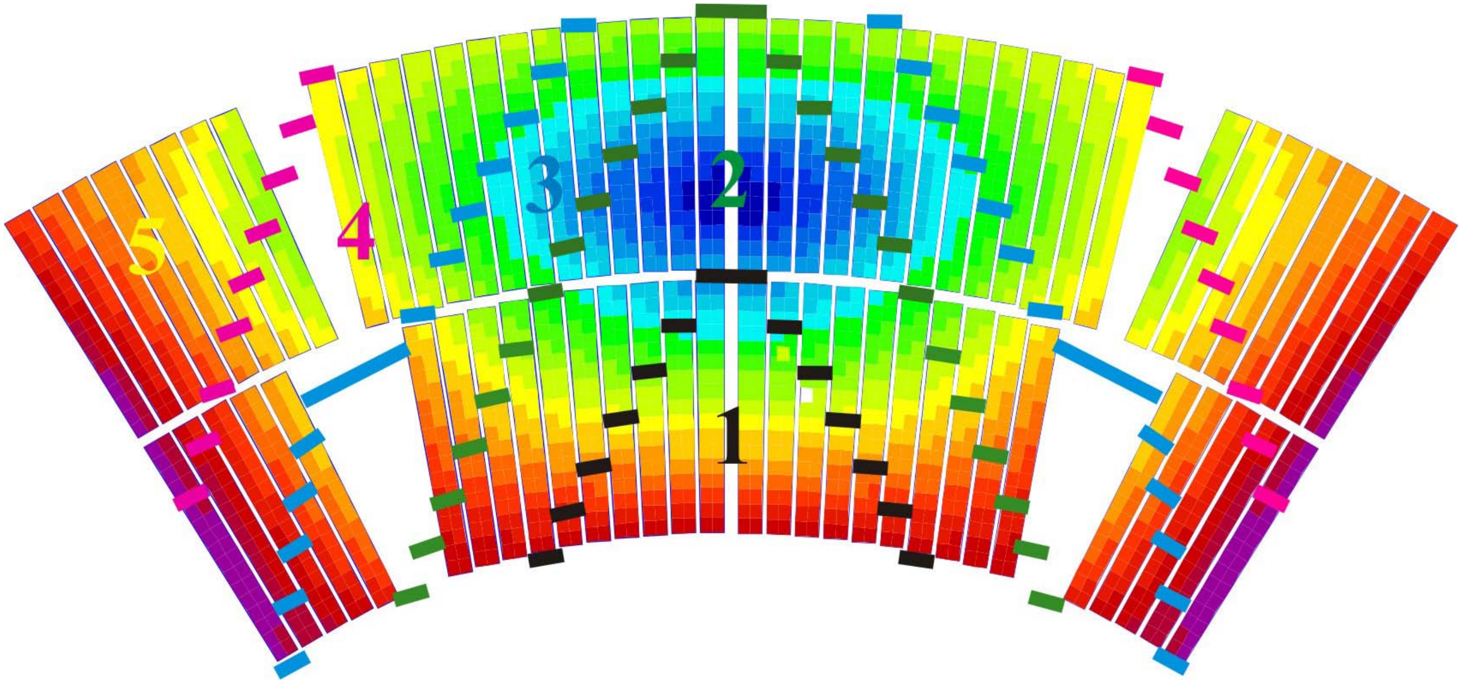
Network model of the cable - 36 strands model

Simulation settings:

- heat source in the middle of the cable
- heating 5 cables with a 10 sources of 0.6 W each
- temperature margin $\Delta T = 0.8$ K

MQM quench limit for nominal current (4310 A) ~ 15 [mW/cm^3]

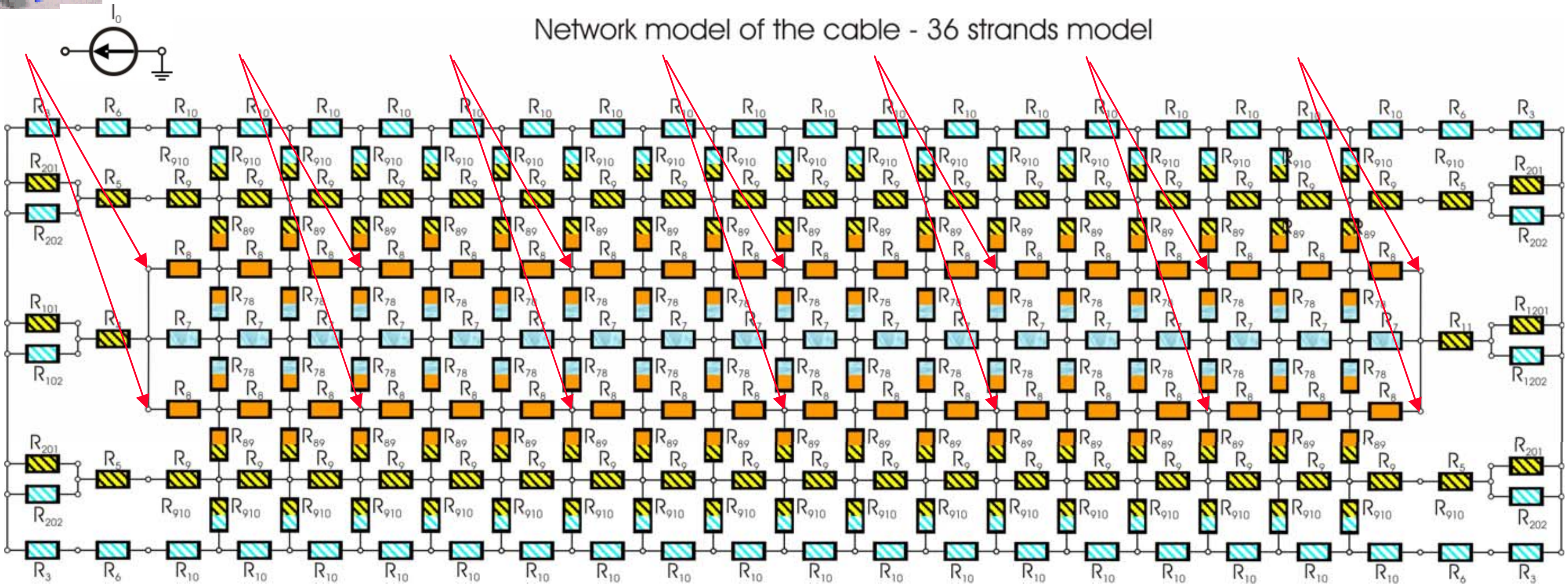
„Beam loss" profile in MQM magnet



◆ Beam loss profile with 5 region of heat deposition scalled (weighted) as follow:

1. 1.0
2. 1.0/3.0
3. 0.4/3.0
4. 0.1/3.0
5. 0.03/3.0

„Beam loss" simulation



MQM quench limit for nominal current (4310 A) ⇒ *6 [mW/cm^3]*

MQM quench limit for ultimate current (4650 A) ⇒ *4 [mW/cm^3]*

MQM quench limit for nominal current (4310 A) and naive homogeneous heat deposit in profile 3, 4 and 5 ⇒ *3 [mW/cm^3]*

MQY quench limit for nominal current (3610 A) and only "first layer heat deposit" ⇒ *10 [mW/cm^3]*

Conclusions

- The network model has been presented
- All vital parameters have been collected or calculated
- Model is validated with measurements at 4.5 K
- First results from model are promising
- Beam loss simulations with GEANT 4 are on going
- It is necessary validate model at 1.9 K
- Model developement – transient losses simulations
- Non-linear object in the model – outer layer of MQY magnet
- Now starting work on model of MQTL magnet
- We are open to discussion