Models and Experimental Results from the Wide Aperture Nb-Ti Magnets MQXC, D1 and Q4

Glyn A Kirby
CERN

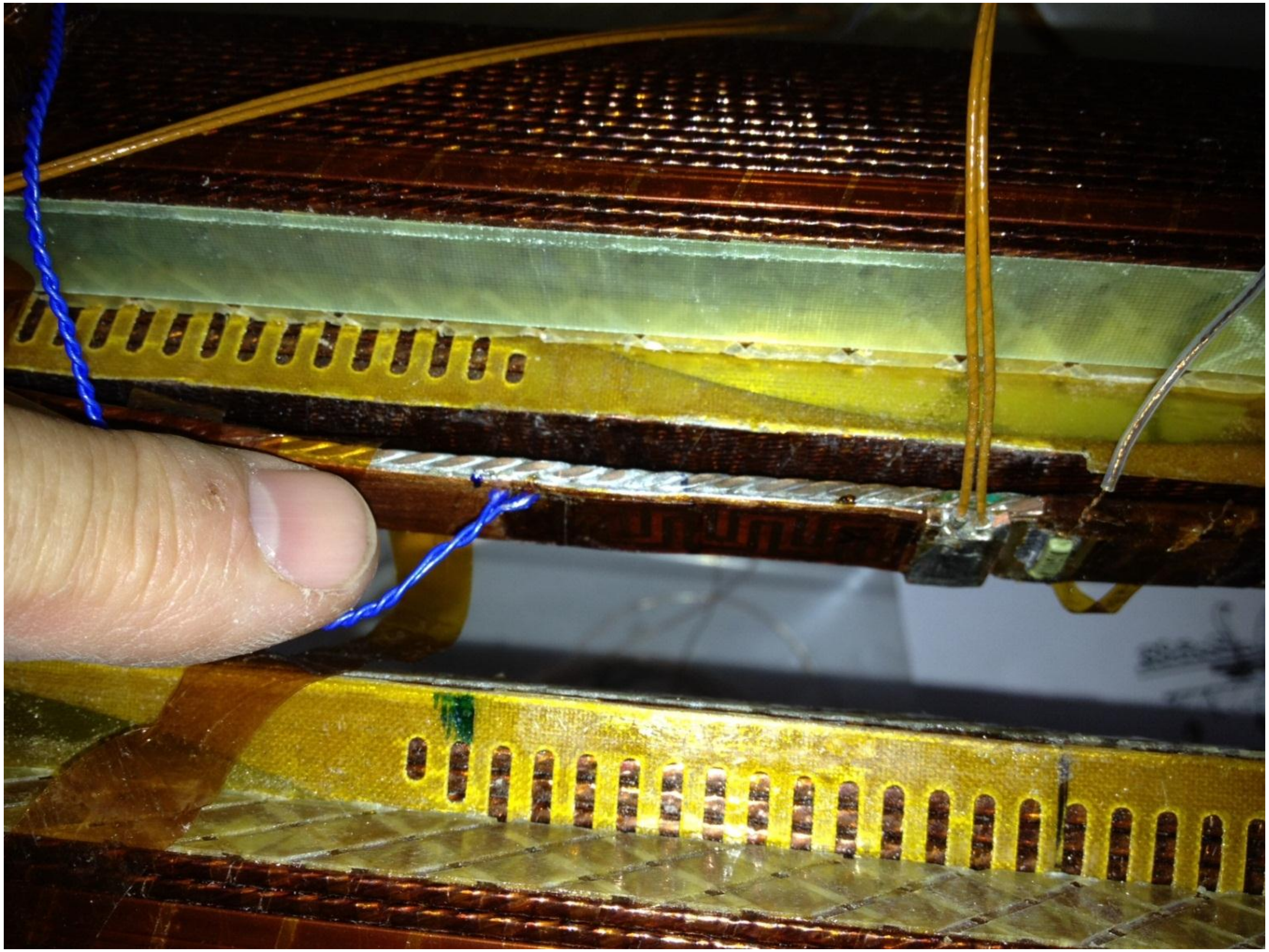
Outline

- MQXC instrumentation some details
- Some cold test results
- Microsoft Excel overview Quench calculation
- Summary conclusions to MQXC test
- Applying to DI & Q4

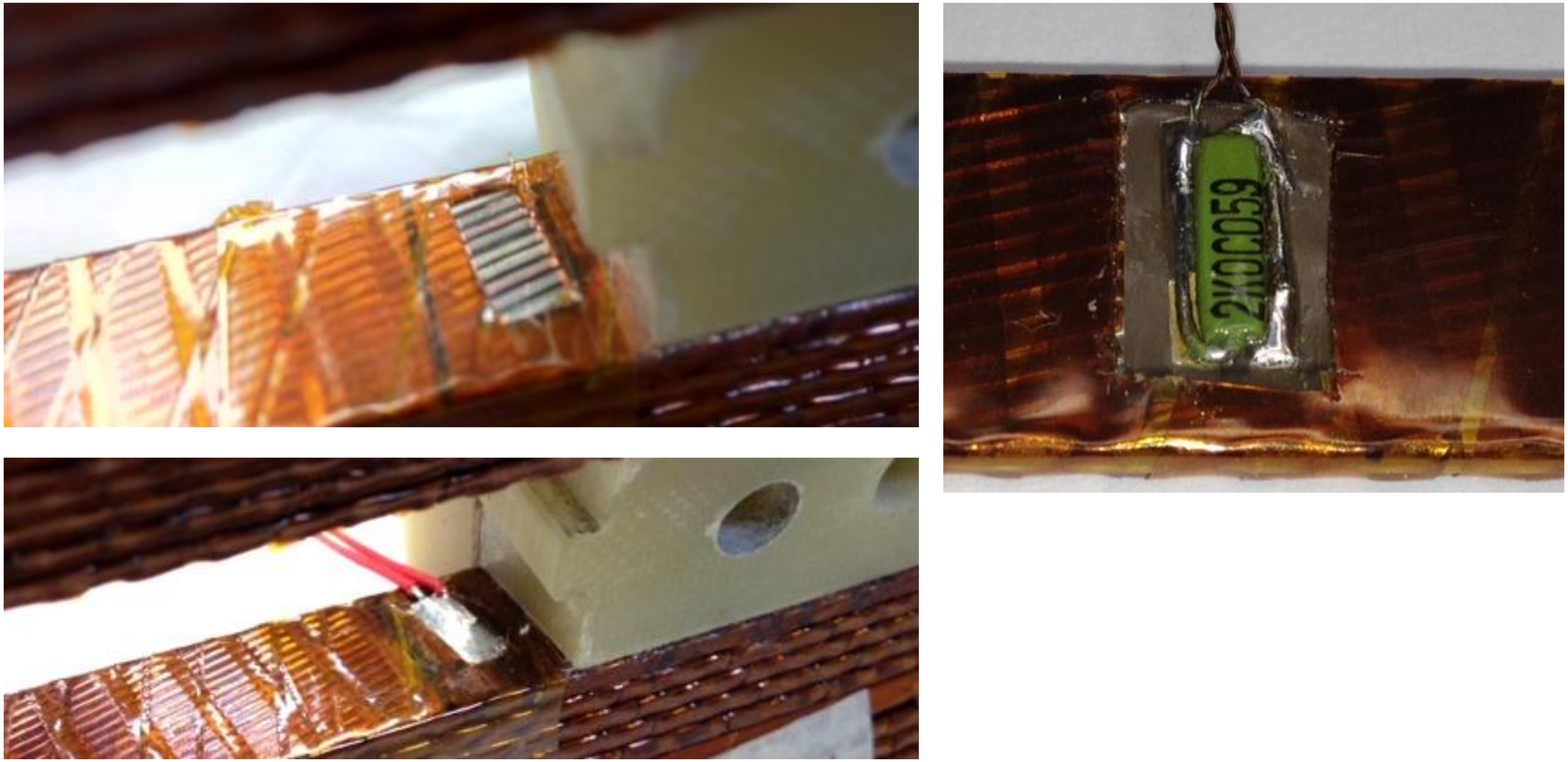
MQXC High Heat Extraction Design

Open cable insulation, ground insulation

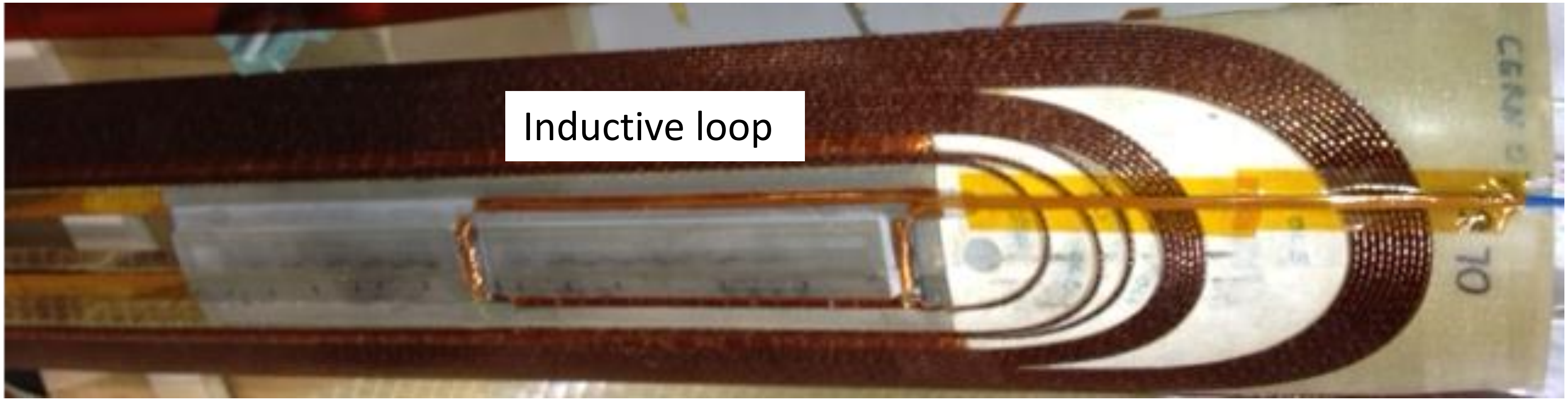
Spot Heater, Voltage Tap's, & CCS temp sensor

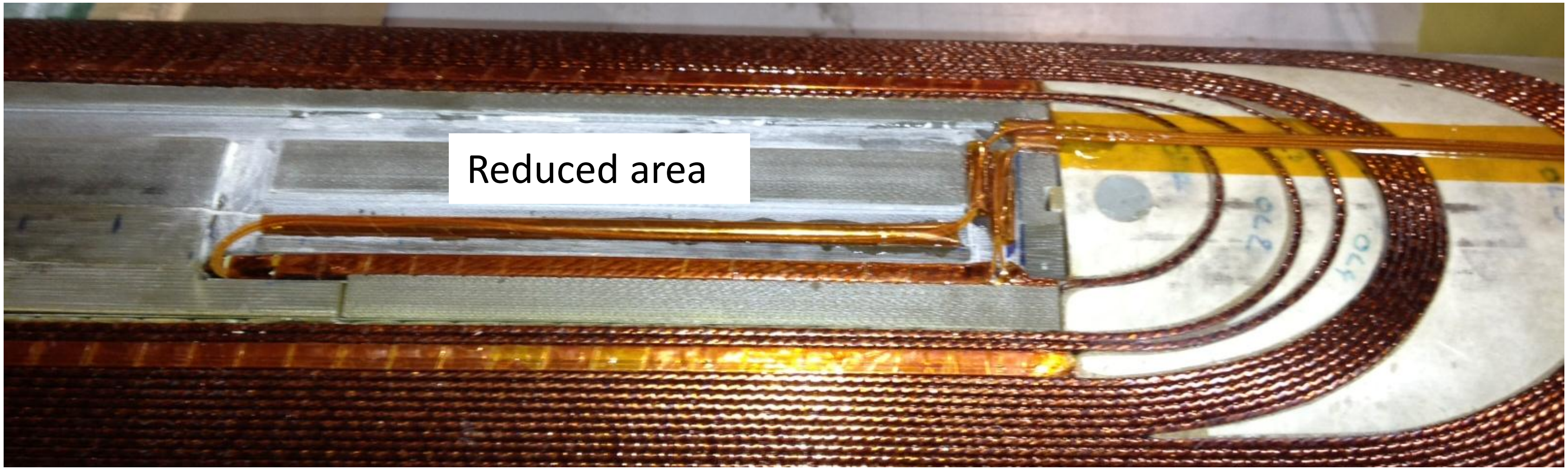


Voltage tap & CCS sensor mounting

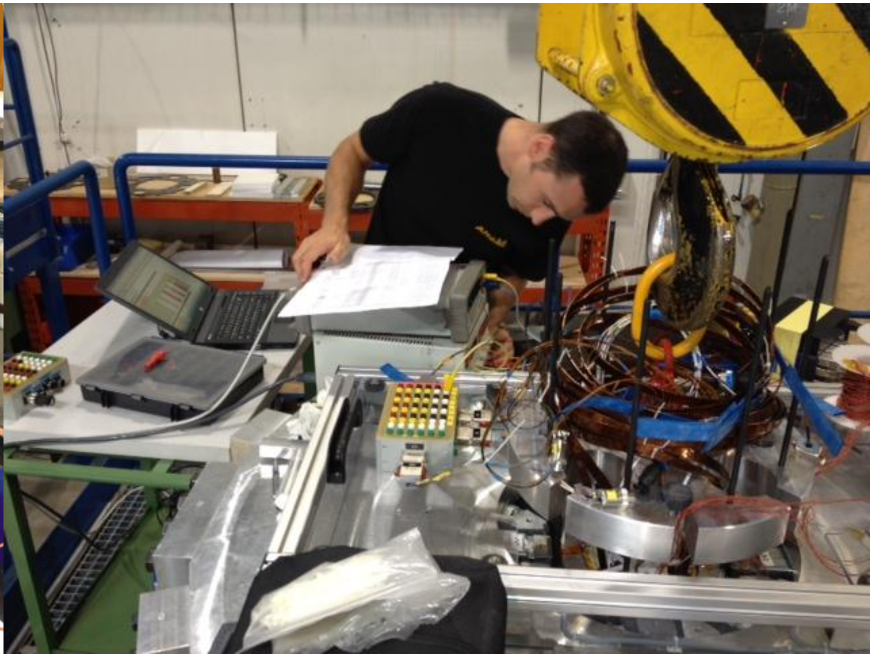


Joint voltage tap exit wiring
the bad and the better





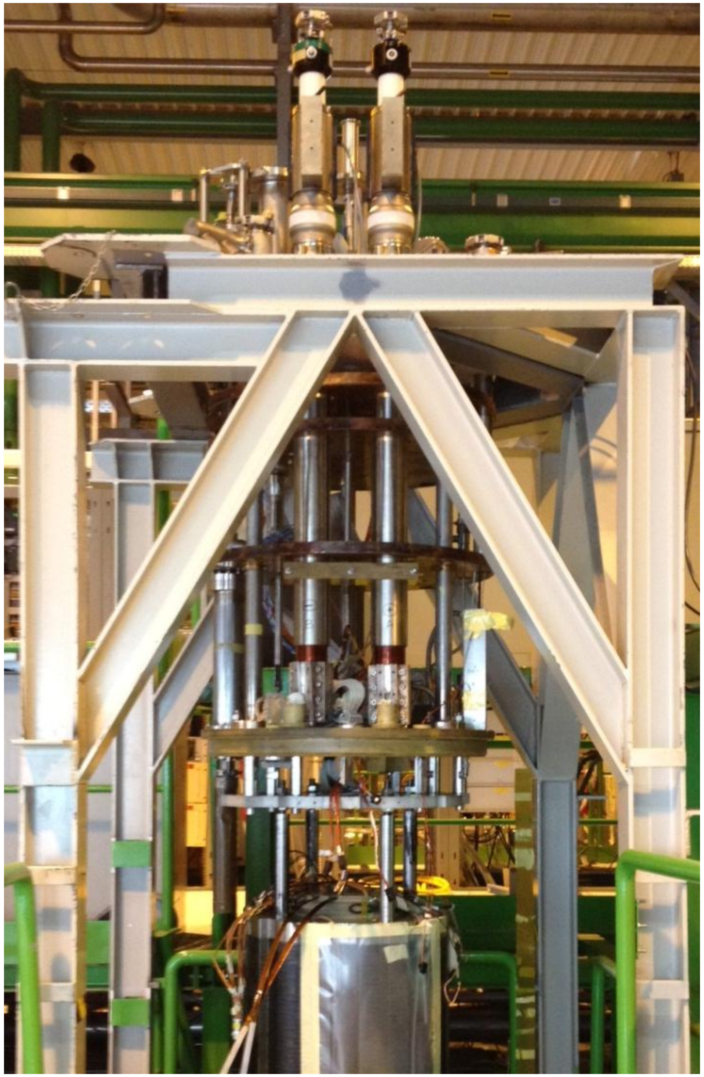
Electrical checks



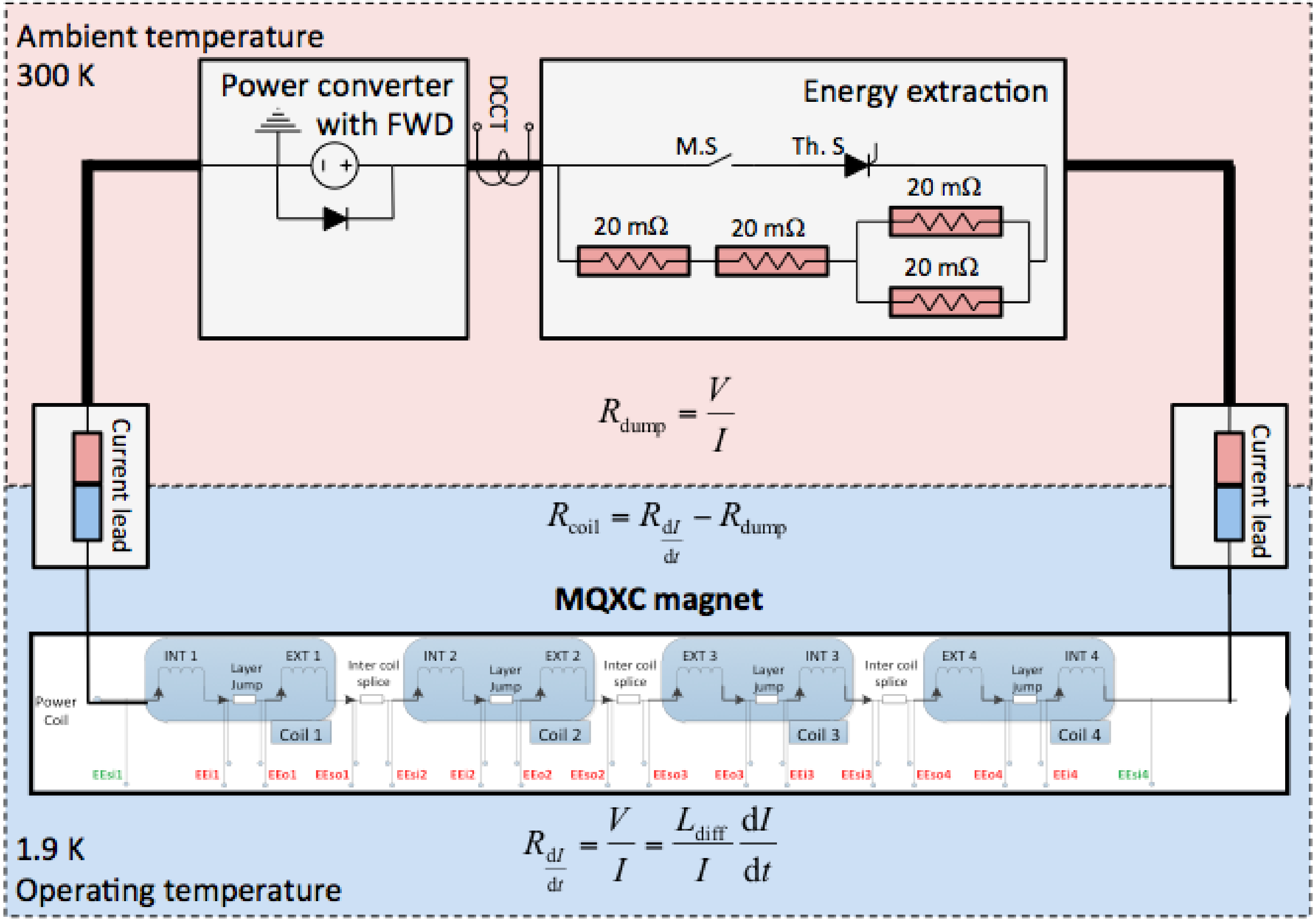
We performed electrical checks at each stage of production
.

1KV pulse test looking for shorts in the coils.
5KV ground insulation tests.
Resistance and inductance of coils
Insulation between all circuits.
Quench heater firing at full 850V, 80A

Cryostat Internal Wiring



SM18 test Circuit

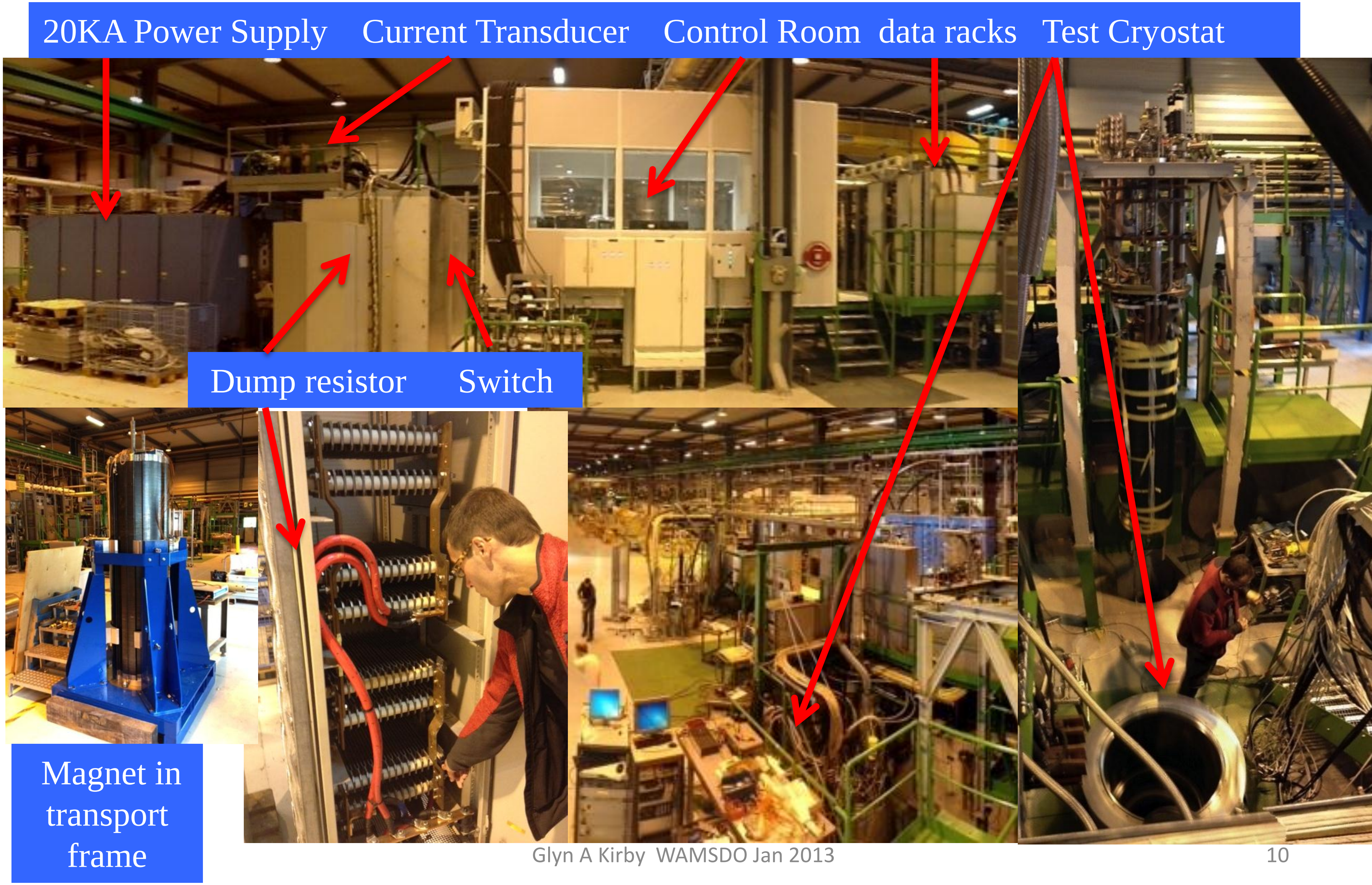


$$R_{\text{dump}} = \frac{V}{I}$$

$$R_{\text{coil}} = R_{\frac{dI}{dt}} - R_{\text{dump}}$$

$$R_{\frac{dI}{dt}} = \frac{V}{I} = \frac{L_{\text{diff}}}{I}\frac{\mathrm{d}I}{\mathrm{d}t}$$

Test lab. For Model magnets at CERN

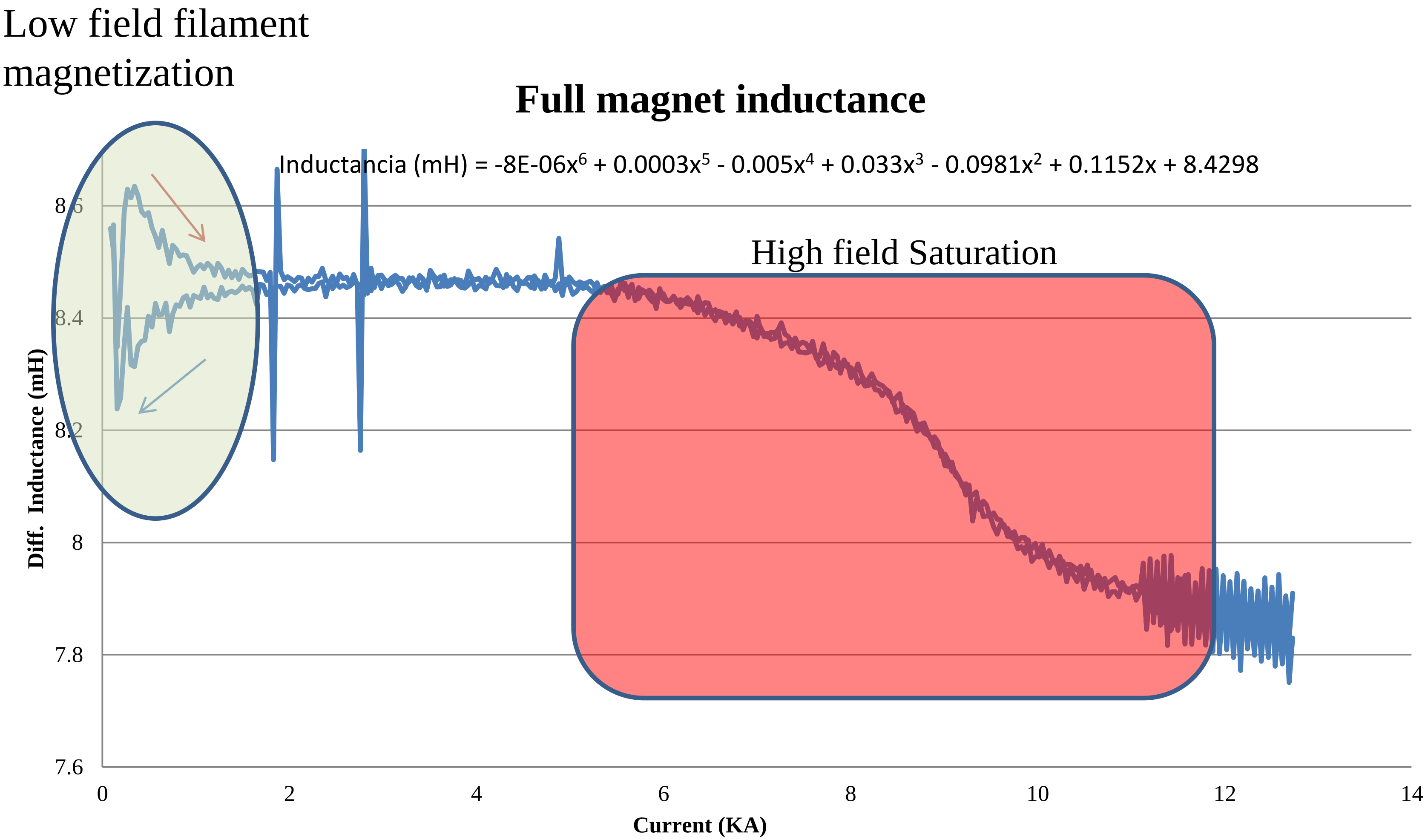


20KA Power Supply Current Transducer Control Room data racks Test Cryostat

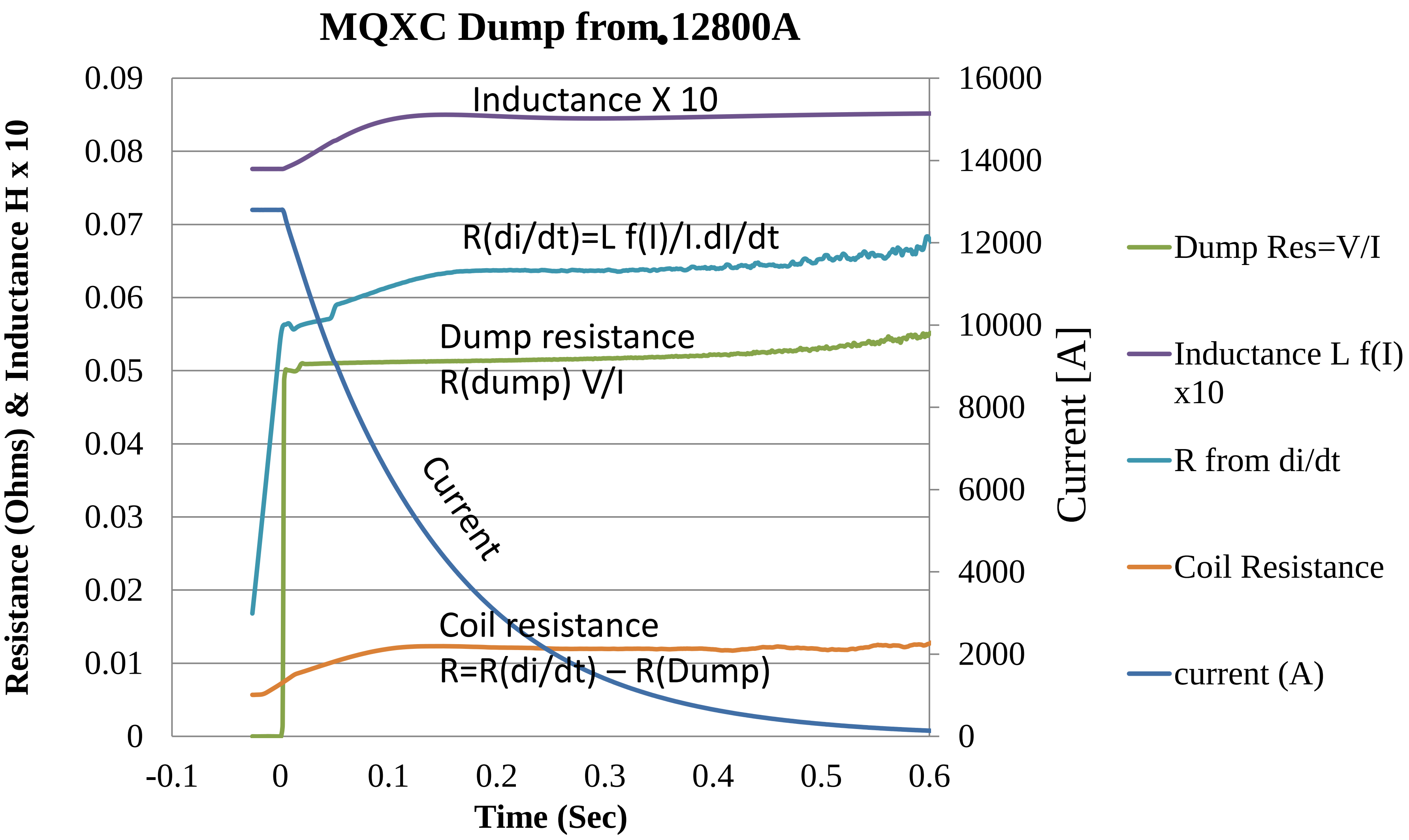
Dump resistor Switch

Magnet in transport frame

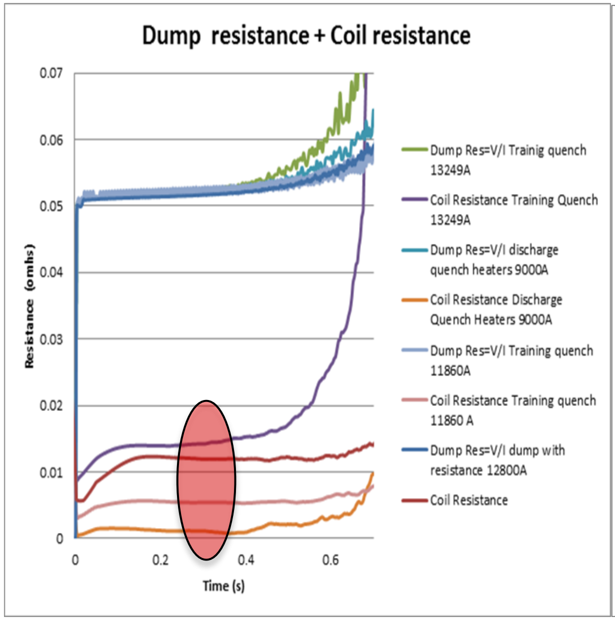
Differential Inductance f(current)

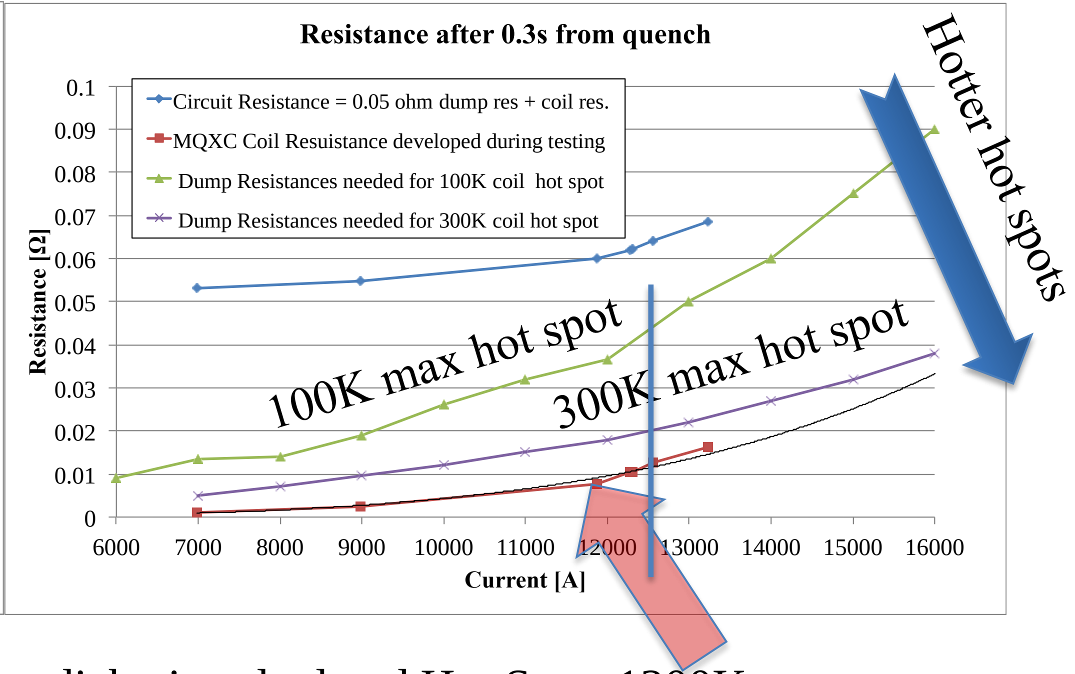


Dump 12.8 kA no Quench heaters test



Dump and Coil Resistance during Quench or Discharge.





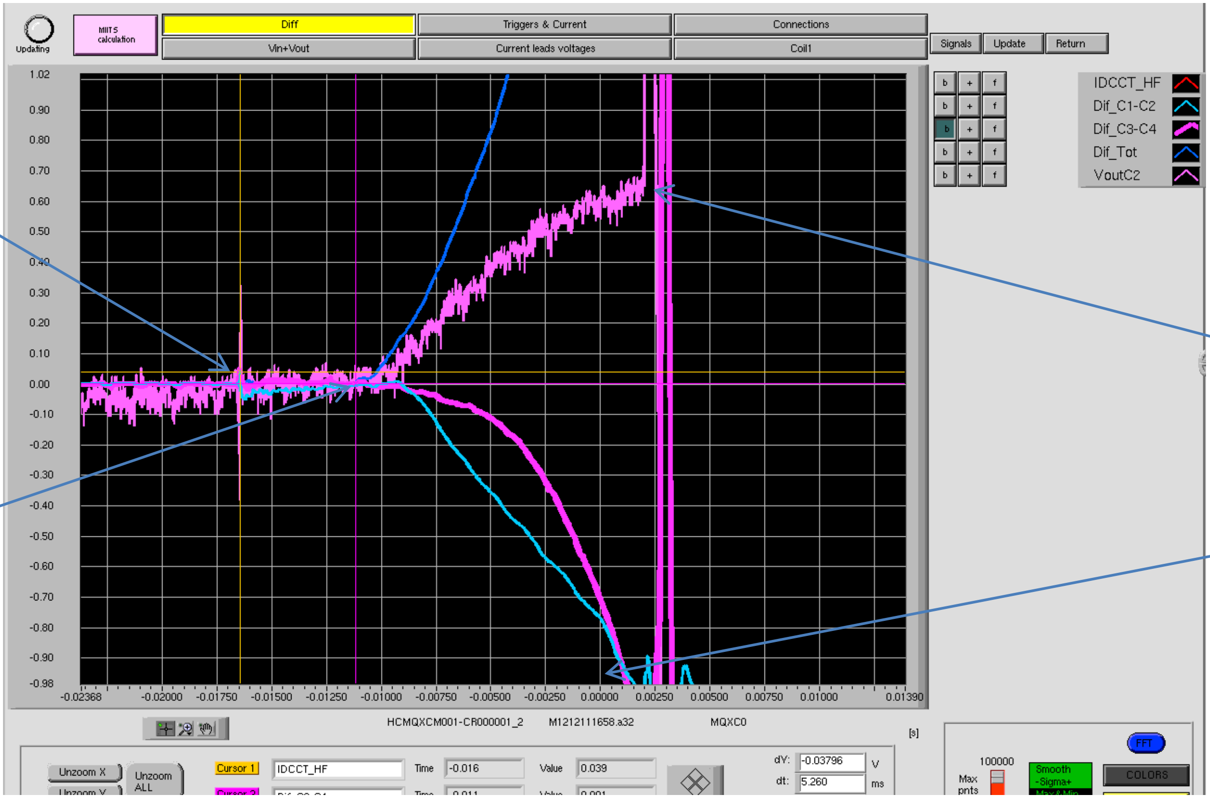
Without Dump adiabatic calculated Hot Spot 1200K

Two curves are plotted, giving the circuit resistance needed to limit the hot spot temp. One limiting the cable hot spot to 300K and the second limiting, HS. to 100K. With a 0.012 s detection delay.

We see from the tests that the internal coil resistance is insufficient at all currents to protect the magnet.

With 60% quenched cable we could protect the magnet!

TIMES USED IN A QUENCH



HCMQXCM001-CR000001_2 M1212111658.a32 MQXC0

Cursor 1 IDCCT_HF Time -0.016 Value 0.039

dY: -0.03796 V

dt: 5.260 ms

t firing heaters

t quench

t aperture switch

t trigger

t firing heaters – t quench = **heaters delay** in this example 5,26mS.

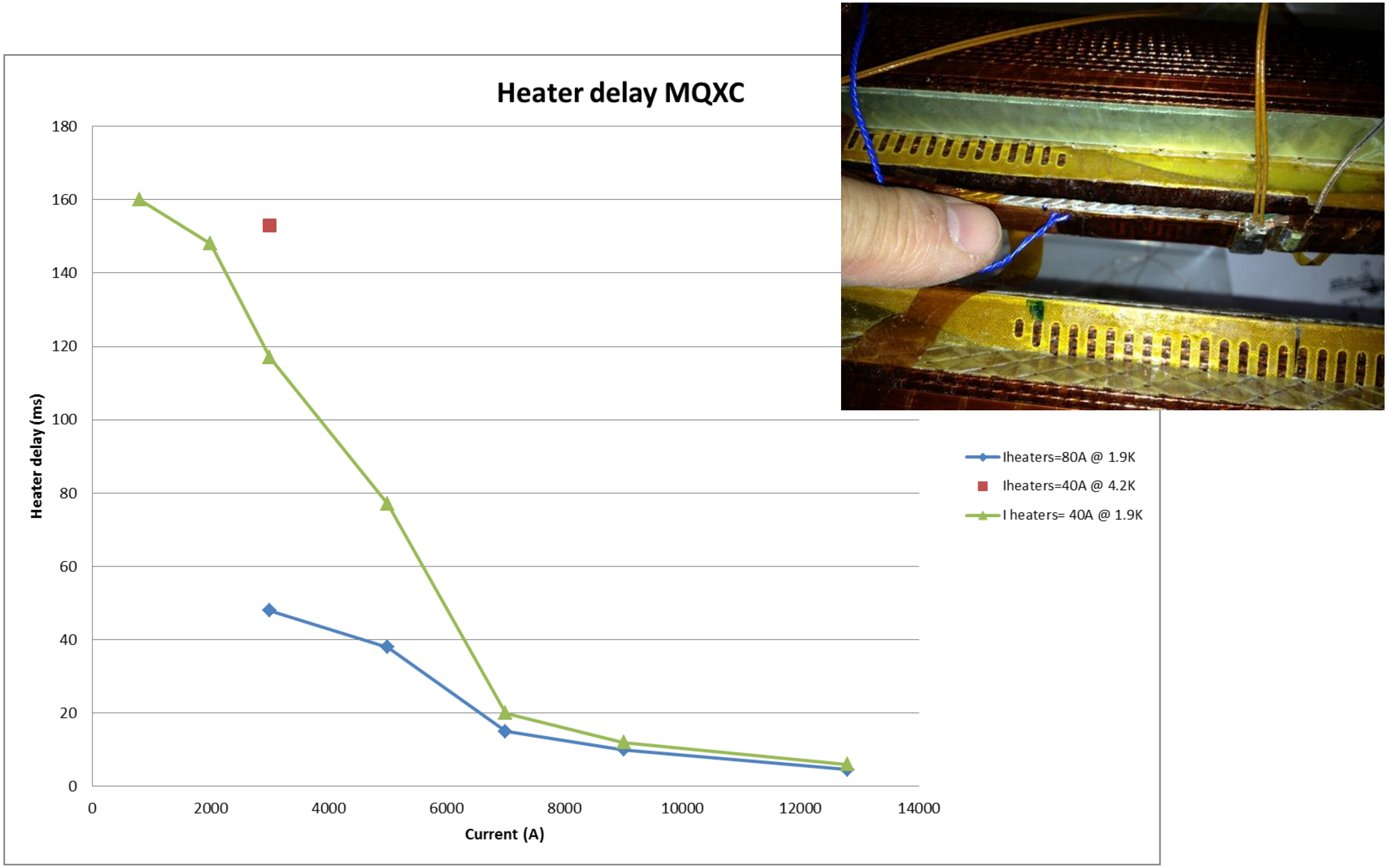
In this case threshold in the difference is 50mV (std 100mV) with a delay of 10ms, and it’s this signal which triggers the QPS.

t quench is the time used for calculation of MIIT’S.

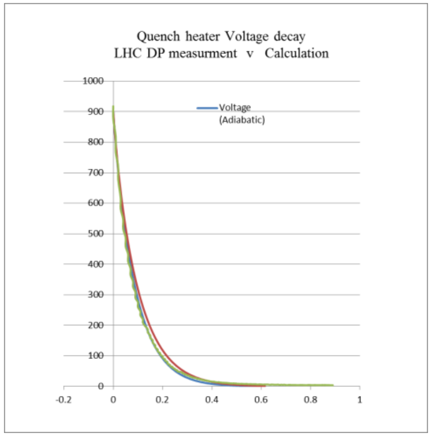
t trigger is always 0s.

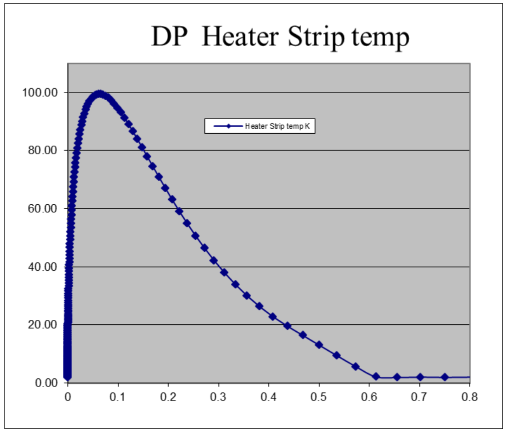
t aperture switch is around 2 to 3ms after the trigger.

Heater delays for 40A and 80A

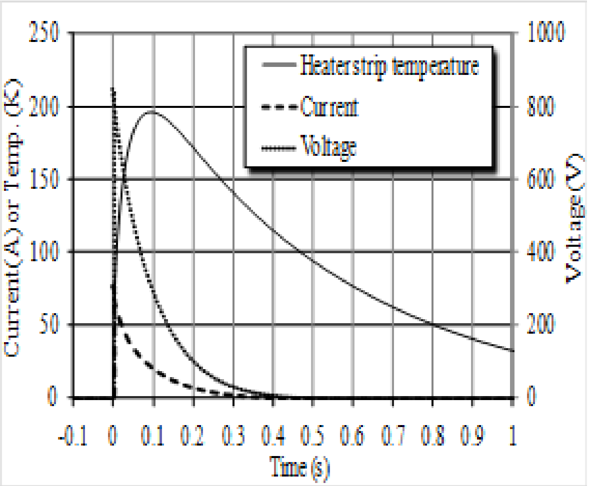


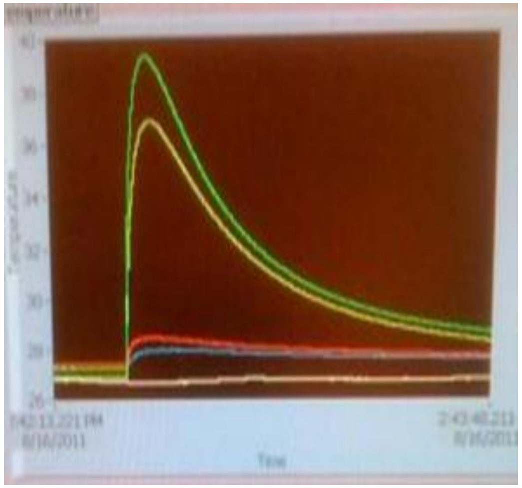
Quench heater power





MQXC quench heaters hotter and faster by 10% then HLC DP





Room temperature testing & 77K

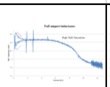
Excel Quench Calculation

cable (1) inner		
length cable l(m)=	155	m
Cu/SC ratio	1.65	
Number of strands =	28	
diameter of strand	1.065	mm
CSA of cable (m^2) =	2.49E-05	m^2
CSA Cu of cable (m^2) =	1.55E-05	m^2
Cu Volume (m^3) =	2.41E+03	cm^3
NbTi Volume (m^3) =	1.46E-03	m^3
RRR	230	

Quadrupole Magnet		
inner cable type 1 # turns	2	
cable type 2 # turns	1.5	
Magnet length	9.5	m
Inductance / m / aperture	5.22	mH/m
Inductance total	49.59	mH
Current	12800	Amps
Bore dia	120	mm
grat T/m	118.7351	T/m
max field f(G,Bore)	7.1241061	Tesla
Dump Resistor	0.13	Ohms
Dump delay	0.016	Sec
QH delay (S)	0.016	sec

start intaval time steps	0.0001
intival multiplyer	1.1

Current I=A e-(R/L)t

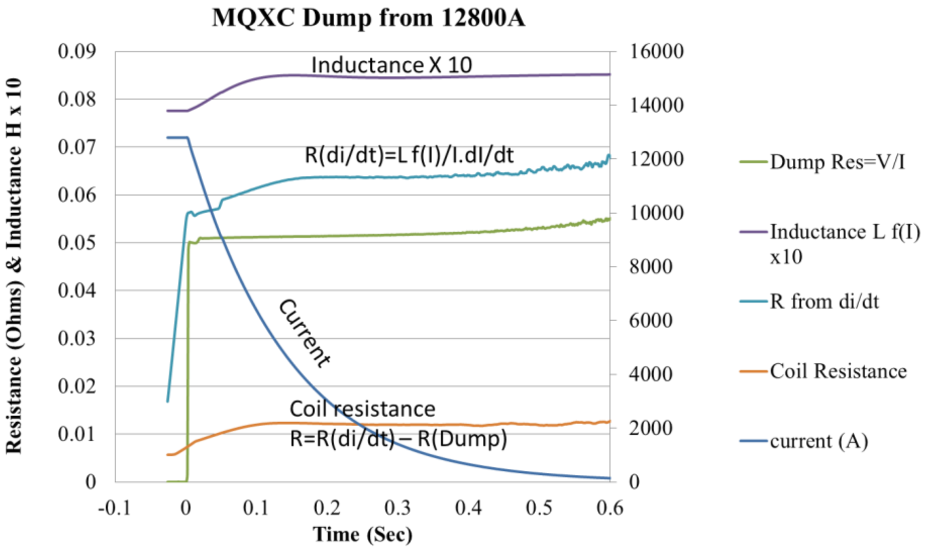
							Cable 1								
delay switch for dump resistor	Delay switch cable 2	Delay switch cable 1	Time t(s)	Current I(A)	 inductance f(currrent)	Field B(T) f(current)	Av Temp Cable 1 T(K)	CU (resistively) ρ cable 1 f(T,B)	NbTi (resistively) ρ cable 1 f(T,B)	Coil resistance R(Ω) f(ρ,I,CSA) cable 1	Power J/s Cable 1 (P= I^2*R) X dt =ω J	Cp copper f(T) J/cm^3	Cp NbTi f(T) J/m^3	total Cp X volume f(Cu to Sc ratio)	Temp change due to resistive heating ΔT = ω/m.cp
0	0.0859107	0.064433	0	12800	0.00775251	7.12410615	10	4.1E-10	6.1207E-07	1.63E-04	2.6642026	0.0077101	25680	56.09748772	0.047492369
0	0.0859107	0.064433	0.0001	12800	0.00775251	7.124100784	10.04749	4.1E-10	6.12089E-07	0.000162614	0.2664263	0.0078105	25958.84685	56.74670239	0.004695009
0	0.0859107	0.064433	0.0001	12800	0.00775251	7.124100247	10.05219	4.1E-10	6.12091E-07	0.000162614	0.2930695	0.0078205	25986.53409	56.81121255	0.005158657
0	0.0859107	0.064433	0.0001	12800	0.00775251	7.124099657	10.05735	4.1E-10	6.12093E-07	0.000162615	0.3223773	0.0078314	26016.98068	56.88216196	0.005667458

Cable 2								
Av Temp Cable 2 T(K)	CU (resistively) ρ cable 2 f(T,B)	NbTi (resistively) ρ cable 1 f(T,B)	Coil resistance R(Ω) f(ρ,I,CSA) cable 2	Power J/s Cable 2 (P= I^2*R) X dt =ω j	Cp copper f(T) J/cm^3	Cp NbTi f(T) J/m^3	total Cp f(Cu to Sc ratio)	Temp change due to resistive heating ΔT = ω/m.cp
11	4.05843E-10	6.1248E-07	2.11E-04	3.45523632	0.010086	32036.4	39.26051	0.08800793
11.09	4.05869E-10	6.1251E-07	2.11E-04	0.34554546	0.0103232	32646.2	40.074808	0.00862251
11.09663	4.05872E-10	6.1252E-07	2.11E-04	0.38010239	0.0103467	32706.4	40.155318	0.00946580

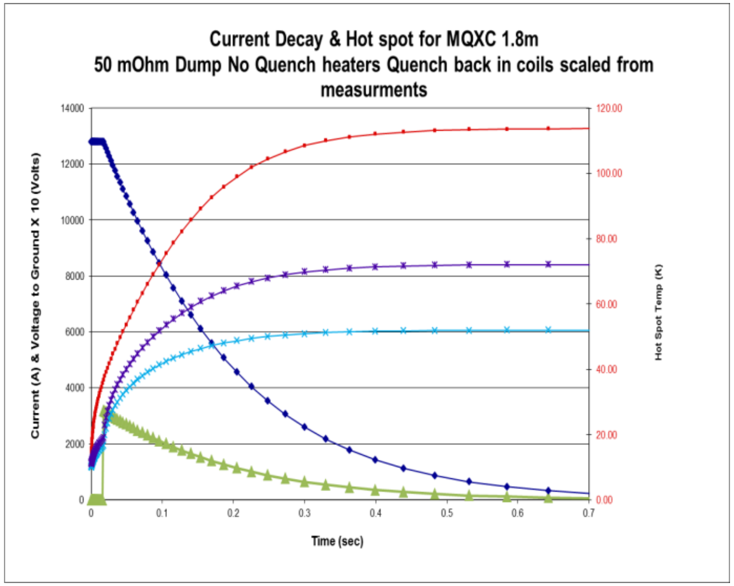
Small time steps
Temperature dependent material properties
RRR, Av Magneto resistance, PSU delay, dump delay, No cooling (0.6sec.), inductance f(current)
Hot spot, Av coil temp., Voltages,

	Total																	
coil resistance inner + outer	Total Coil resistance 1+2& dump R(Ω) f(R1, R2, dump R))	Energy dumped in coil	Energy dumped in dump resistor	MIITS	Apert Volt [V] L*dI/dt	volts I*R	Total Voltage IR-Ldi/dt	Dump Res * Current Voltage over dump	Hot spot Temp Cable 2 T(K)	CU (resistively) ρ cable 2 f(T,B)	NbTi (resistively) ρ cable 2 f(T,B)	Coil resistance R(Ω) f(ρ,I,CSA) cable 2	Power J/s Cable 2 (P= I^2*R) X dt =ω j	Cp copper f(T) J/cm^3	Cp NbTi f(T) J/m^3	total Cp f(Cu to Sc ratio)	change due to resistive heating ΔT = ω/m.cp
3.74E-04	3.74E-04	6.12E+00	0.00E+00	0.016384				0	10.00	4.05597E-10	6.1207E-07	2.95E-05	0.483439501	0.007710121	25680	0.265601	1.820171
3.74E-04	3.74E-04	6.12E-01	2.13E+03	0.0180224	4.8	4.8	0.0	0	11.82	4.06121E-10	6.1281E-07	2.95E-05	0.048406371	0.012491177	38053.27	0.407136	0.118895
3.74E-04	3.74E-04	6.73E-01	2.13E+02	0.0198246	4.8	4.8	0.0	0	11.94	4.06168E-10	6.1286E-07	2.95E-05	0.053253156	0.012877506	38989.14	0.418156	0.127352
3.74E-04	3.74E-04	7.40E-01	2.34E+02	0.0218071	4.8	4.8	0.0	0	12.07	4.0622E-10	6.1291E-07	2.96E-05	0.058586008	0.013302417	40010.01	0.430221	0.136177

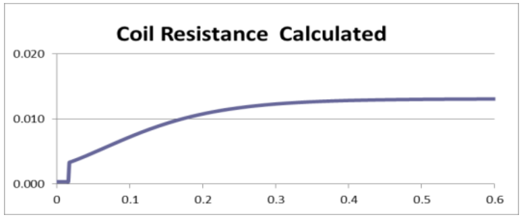
Measurement v Calculation



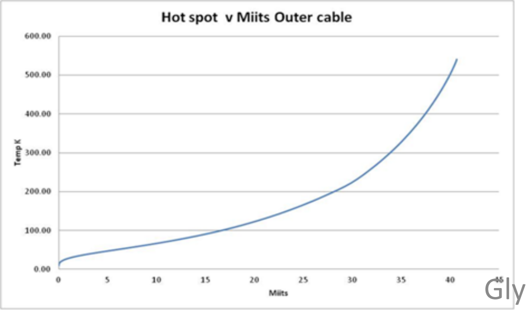
MQXC Dump from 12800A



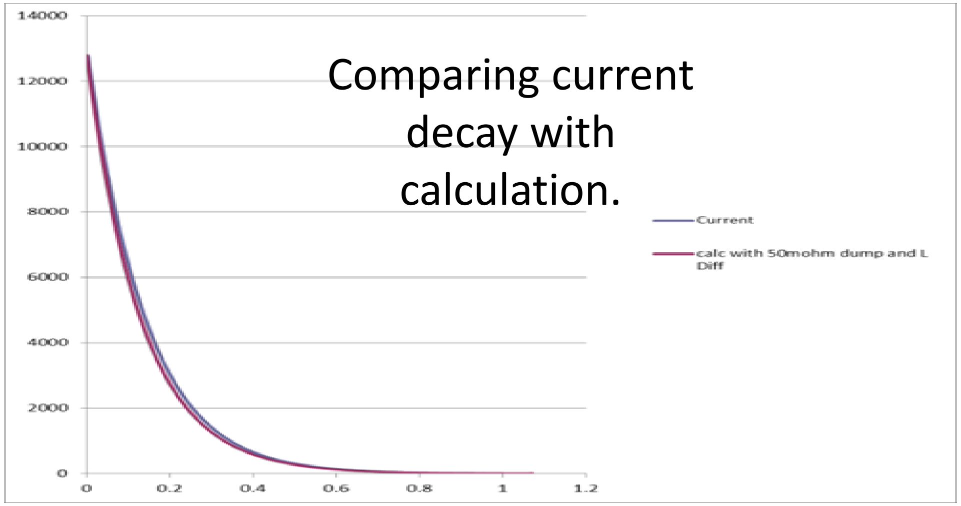
Current Decay & Hot spot for MQXC 1.8m
50 mOhm Dump No Quench heaters Quench back in coils scaled from measurments



Coil Resistance Calculated

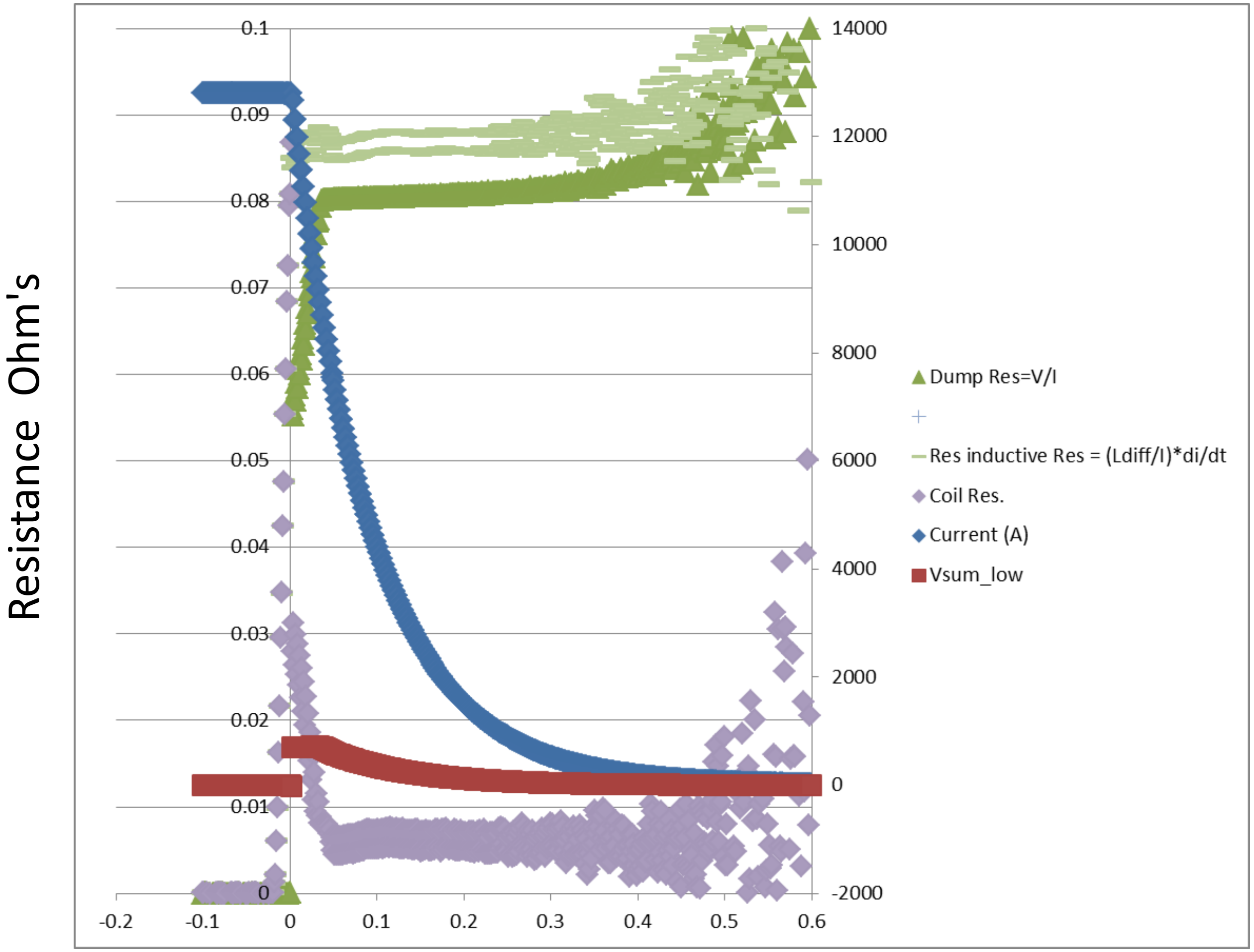


Hot spot v Miits Outer cable



Comparing current decay with calculation.

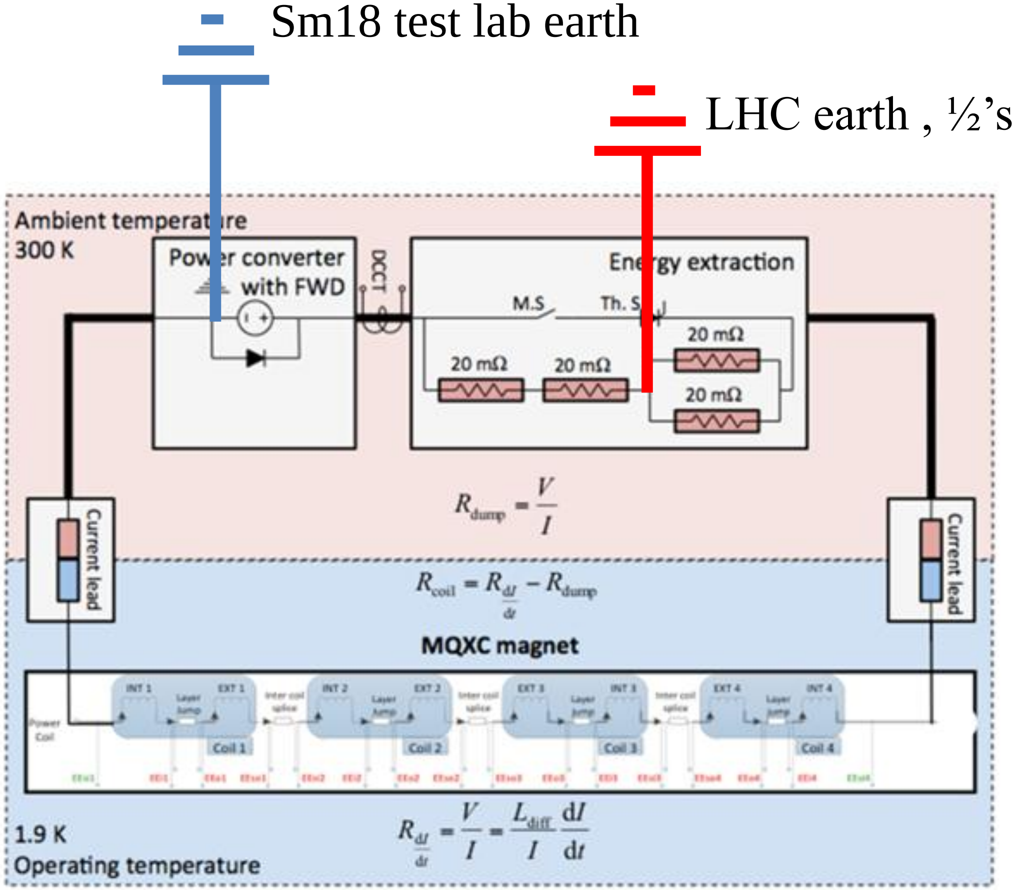
12.8KA 80 mOhm dump 80A in quench heaters, test results.

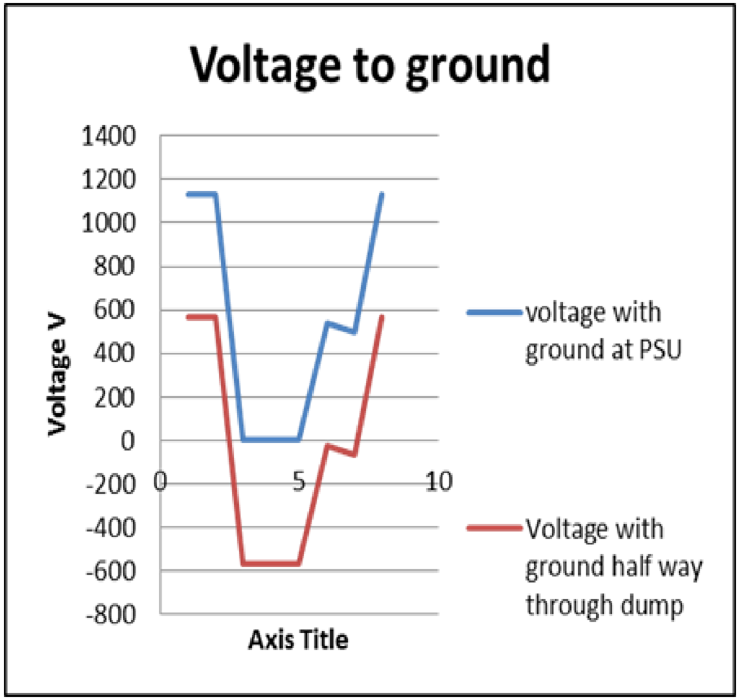


Position of Circuit Earth

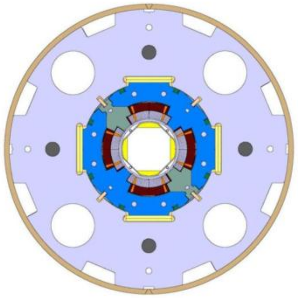
Sm18 test lab earth

LHC earth , ½’s magnet voltage to ground

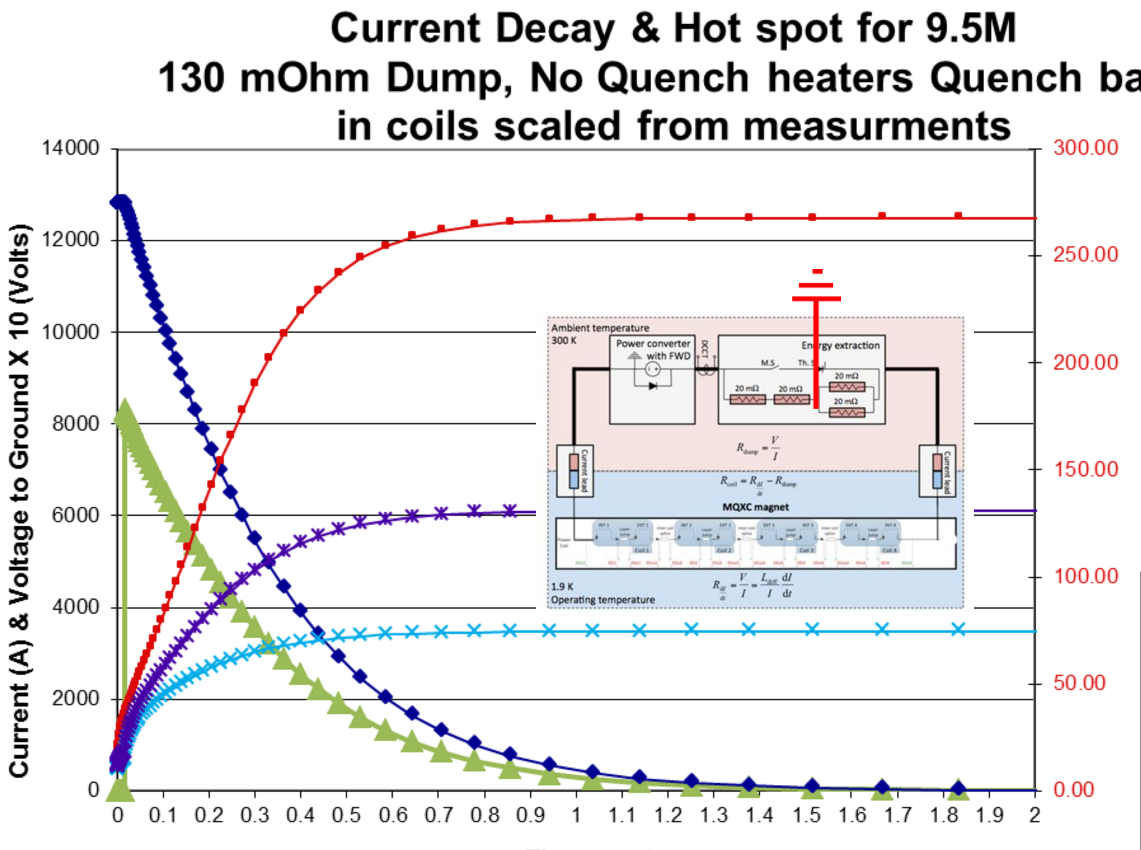


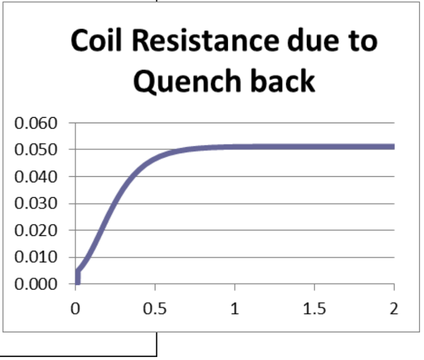


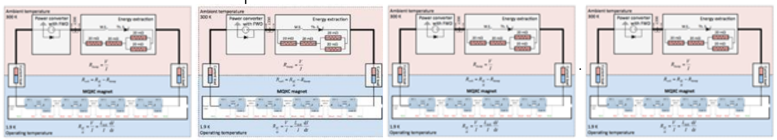
In LHC we will place the earth in the center of the dump and half the voltage to ground!



MQXC Nb-Ti 120 T/m,120 Aperture LHC luminosity Upgrade 9.5m long magnet possible circuit protection



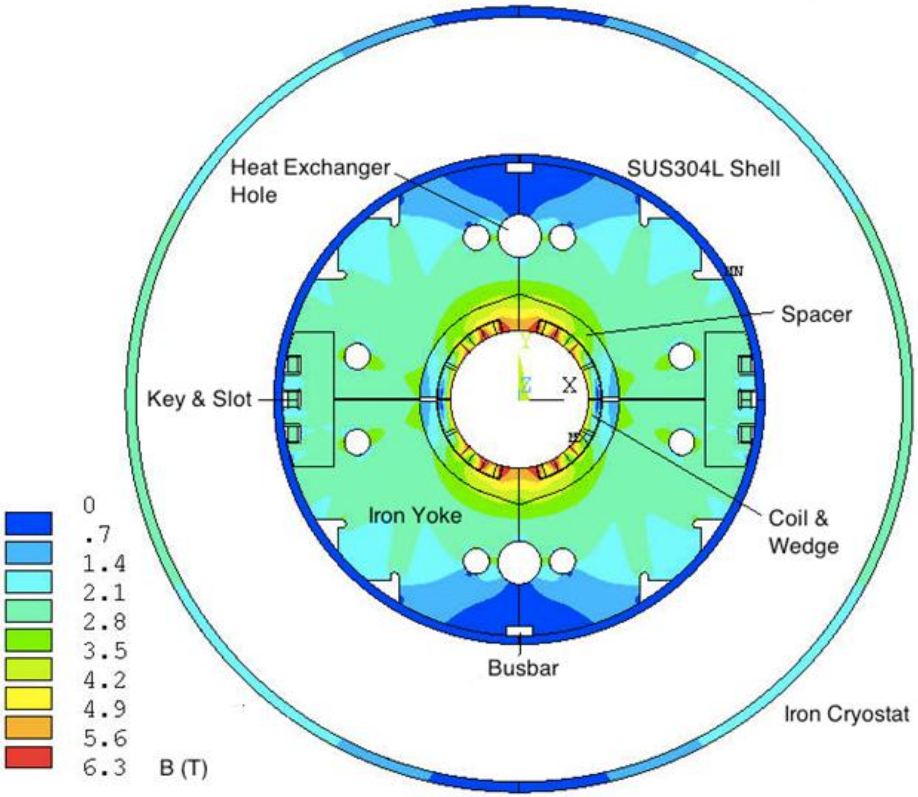


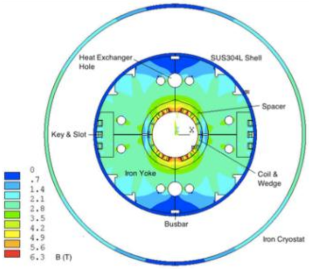


D1 Study at KEK

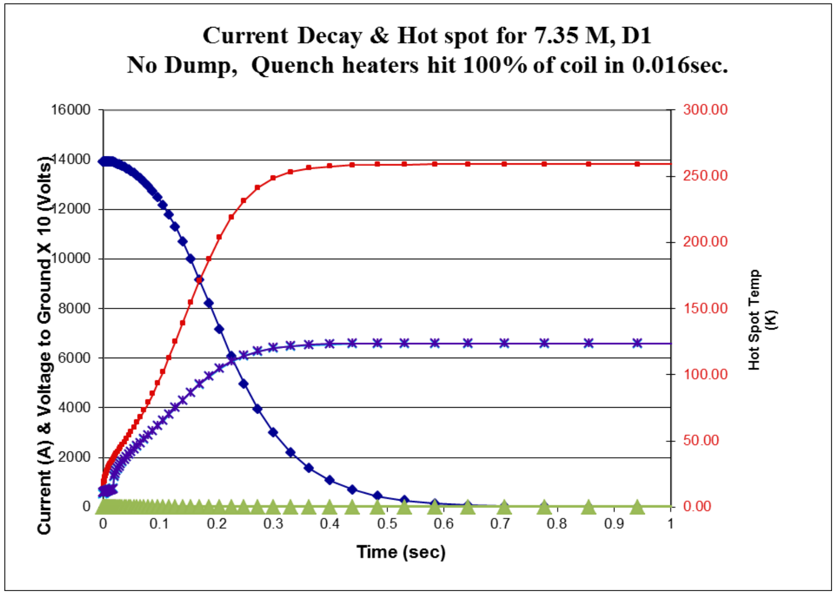
Thanks to Qingjin Xu from KEK for providing the parameter list and cross section.

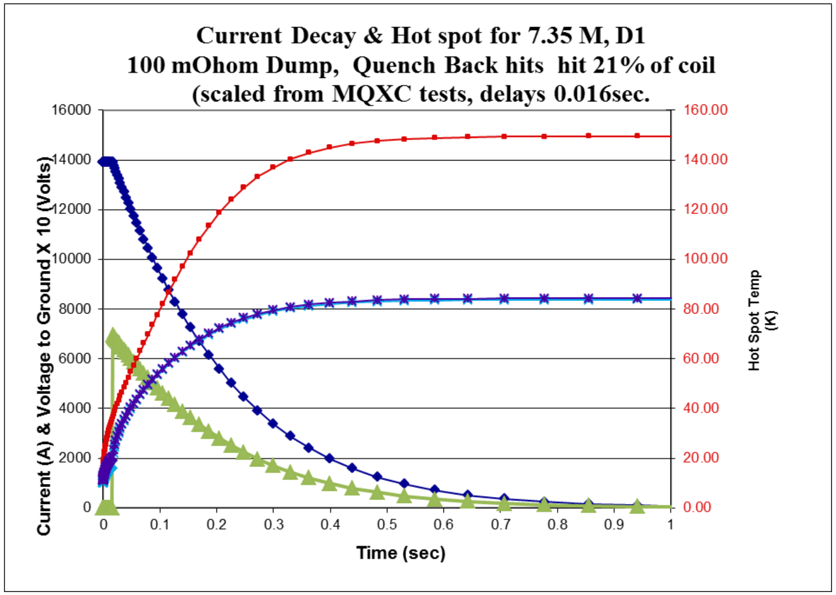
	LHC outer cable	LHC inner cable	20 mm cable & inner strand
Bore diameter	160 mm	160 mm	160 mm
Nominal field (dipole)	**5.23 T**	**5.44 T**	**5.90 T**
Magnetic length	**7.65 m**	**7.35 m**	**6.78 m**
Operating current	**11 kA**	**13.9 kA**	**15.8 kA**
Injection current	~ 0.7 kA	~ 0.9 kA	~ 1 kA
Field homogeneity	<0.01% (R_{ref}=50 mm)	<0.01% (R_{ref}=50 mm)	<0.01% (R_{ref}=50 mm)
Peak field in the coil	6.1 T	6.5 T	6.9 T
Load line ratio	70% @ 1.9 K / 91% @ 4.2 K	70% @ 1.9 K / 91% @ 4.2 K	70% @ 1.9 K / 91% @ 4.2 K
Inductance (low / nominal field)	6.58 / 5.91 mH/m	4.6 / 3.1 mH/m	4.5 / 3 mH/m
Stored energy	**331 kJ/m**	**361 kJ/m**	**447 kJ/m**
Peak field/central field	1.17	1.2	1.16
Lorenz force X/Y (1st quadrant)	**1.4/0.6 MN/m**	**1.6/0.7 MN/m**	**1.9/0.8 MN/m**
Outer dia. of iron yoke	550 mm	550 mm	550 mm
Inner dia. of iron yoke	232 mm	232 mm	232 mm
Strand diameter	0.825 mm	1.065 mm	1.065 mm
Cu/Non-Cu ratio	1.95	1.65	1.65
Cable dimension / insulation	**15.1* 1.48mm^2** / 0.16 mm (radial) 0.145 (azimuthal)	**15.1* 1.9 mm^2** / 0.16 mm (radial) 0.145 (azimuthal)	**20* 1.9mm^2** / 0.16 mm (radial) 0.145 (azimuthal)
No. of strands	36	28	37
Keystone angle	0.9 °	1.24 °	1.15 °
Superconductor current density	1710 A/mm^2	1495 A/mm^2	1290 A/mm^2
Total length of the cable	**752 m (Coil length ~8 m)**	**600 m (Coil length ~7.7 m)**	**554 m (Coil length ~7.1 m)**





D1 quench protection



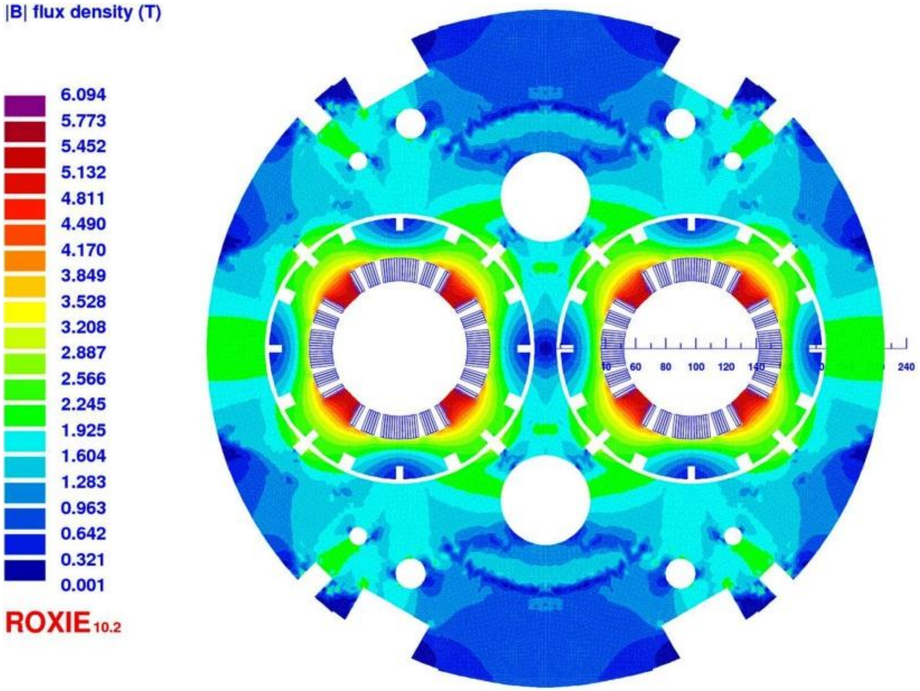


Conclusion:
If D1 needs to use the open (MQXC) insulation to extract more heat and we use the cooling measured by the MQXC test , an individual dump with
100 mohm's can protect the magnet ~700V to ground . And no quench heaters.

Quench heaters will be difficult to implement!   If we only hit 50% (I predict 40%) of the coil with the QH , with no dump the hot spot it too high at 450K with 50% and 540K with 40%!

Q4 study at CEA

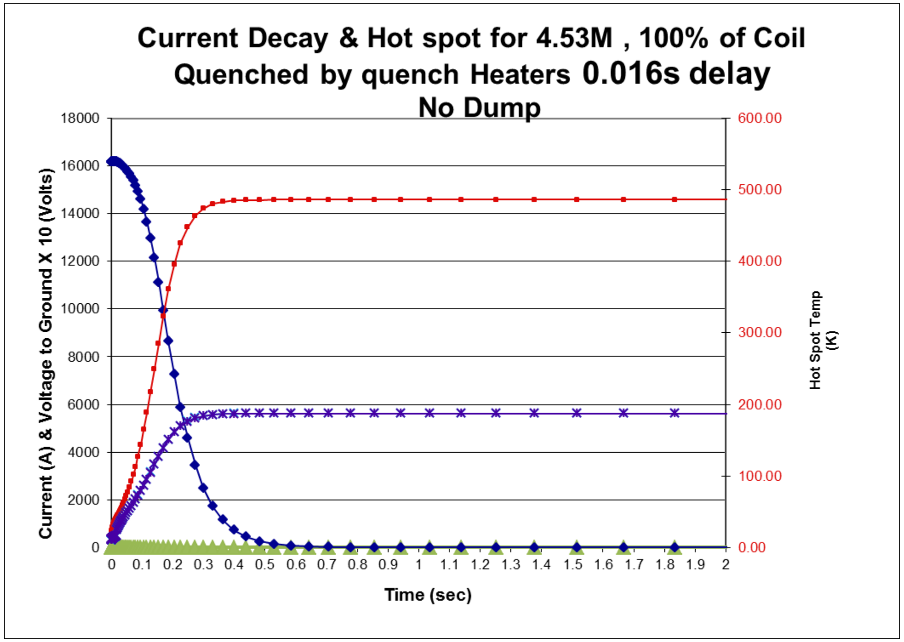
Current	Gradient	Peak field	Mag. length	Diff. Inductance	Stored energy	Multipoles (Units)								
(A)	(T/m)	(T)	(m)	(mH/m)	(kJ/m)	b1	b3	b4	b5	b6	b7	b10	b14	b18
440	**6.37**	**0.32**	**5.33**	**4.92**	**0.477**	**-0.32**	**-0.03**	**0.24**	**0.00**	**-0.34**	**0.00**	**0.01**	**2.19**	**-0.58**
500	7.23	0.36	5.33	4.92	0.615	-0.32	-0.03	0.24	0.00	-0.34	0.00	0.01	2.19	-0.58
1000	14.5	0.73	5.33	4.92	2.46	-0.32	-0.03	0.24	0.00	-0.34	0.00	0.01	2.19	-0.58
1500	21.7	1.1	5.33	4.92	5.535	-0.32	-0.03	0.24	0.00	-0.34	0.00	0.01	2.19	-0.58
2000	28.9	1.46	5.33	4.92	9.839	-0.32	-0.03	0.24	0.00	-0.34	0.00	0.01	2.19	-0.58
2500	36.2	1.83	5.33	4.92	15.37	-0.32	-0.03	0.24	0.00	-0.34	0.00	0.01	2.19	-0.58
3000	43.4	2.19	5.33	4.92	22.14	-0.32	-0.04	0.24	0.00	-0.34	0.00	0.01	2.19	-0.58
3500	50.6	2.56	5.33	4.92	30.13	-0.32	-0.04	0.24	0.00	-0.34	0.00	0.01	2.19	-0.58
4000	57.9	2.93	5.33	4.92	39.36	-0.33	-0.04	0.24	0.00	-0.34	0.00	0.01	2.19	-0.58
4500	65.1	3.29	5.33	4.92	49.81	-0.33	-0.04	0.23	0.00	-0.34	0.00	0.01	2.19	-0.58
5000	72.3	3.66	5.33	4.92	61.49	-0.34	-0.04	0.23	0.00	-0.33	0.00	0.01	2.19	-0.58
5500	79.6	4.02	5.33	4.92	74.41	-0.36	-0.04	0.23	0.00	-0.30	0.00	0.00	2.19	-0.58
6000	86.8	4.39	5.33	4.91	88.55	-0.36	-0.04	0.23	-0.01	-0.26	0.00	0.00	2.19	-0.58
6500	94	4.75	5.33	4.9	103.9	-0.37	-0.04	0.23	-0.01	-0.16	0.00	0.00	2.19	-0.58
7000	101.2	5.12	5.33	4.89	120.5	-0.43	-0.05	0.23	-0.01	-0.01	0.00	0.00	2.19	-0.59
7043	**102**	**5.15**	5.33	**4.89**	**122**	**-0.44**	**-0.05**	**0.23**	**-0.01**	**0.00**	**0.00**	**0.00**	**2.19**	**-0.59**
7500	108.4	5.48	5.33	4.87	138.3	-0.43	-0.04	0.23	-0.01	0.19	0.00	0.00	2.19	-0.59
8000	115.5	5.84	5.33	4.84	157.3	-0.44	-0.03	0.22	-0.02	0.47	0.00	-0.01	2.19	-0.59

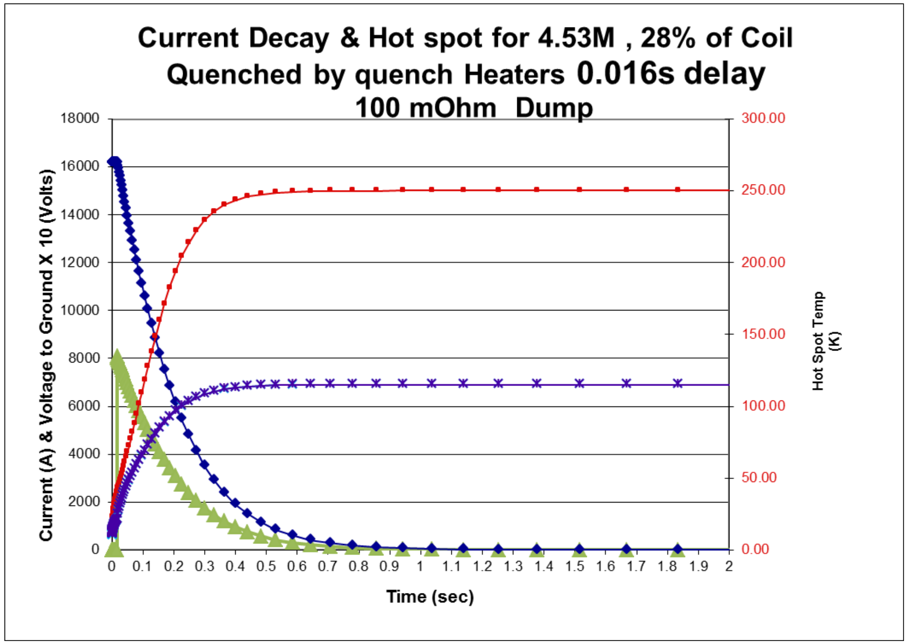


Thanks to Michel Segreti from CEA for the magnet data and cross section.

All the data for most of the magnets are in
www.cern.ch/hilumi/wp3

Q4 quench





100% Quench Heaters still too hot?!

Large aperture / inductance ,
low conductor volume,
High current.

Need Dump! With 100 mOhm's , we see ~ 800V to ground. Hot spot of 250K.

Summing up

- High heat extraction is in conflict with quench protection.
- Can be solved by using external dump resistors.
- D1 and Q4 have High heat loads. So care is needed. Development and model magnet needed.
- Some new ideas are being tested.

Thanks to the MQXC teams

- Cooperating labs: CERN, CEA Saclay FR
- Conceptual Design Team.
- Drawing Design Team.
- Heat deposited in magnet.
- Cable insulation at CERN bat180.
- Polymer lab.
- Chemical etching lab.
- The senior technicians and their assembly. teams.
- Electrical testing teams. 180 and 927.
- Field measurement team.
- Sm18 cold test team.
- The student and visitors that helped.
- Component suppliers.

The End