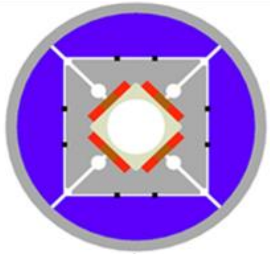
IR Quadrupole R&D Program as a basis for MQXF

GianLuca Sabbi

QXF Design Review
CERN, December 10-12, 2014

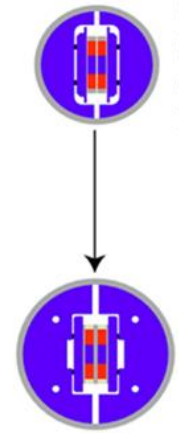
IR Quadrupole R&D Program

Subscale Quadrupole
SQ
0.3 m long
110 mm bore



Technology Development

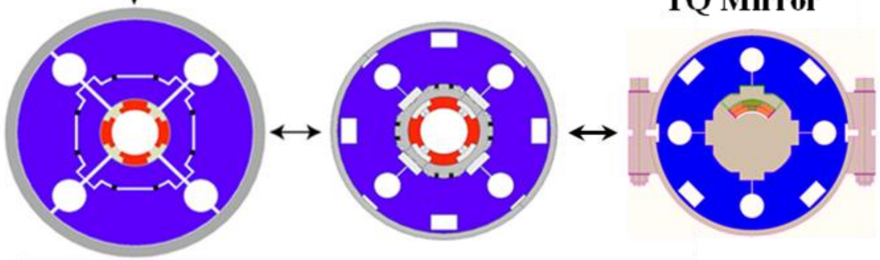
Subscale Magnet
SM
0.3 m long
No bore



Long Racetrack
LRS
3.6 m long
No bore

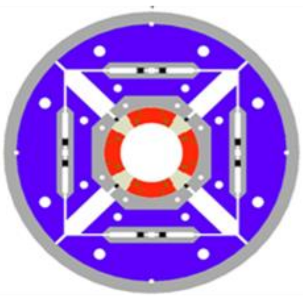
Technology Quadrupoles
TQS, TQC
1 m long
90 mm bore

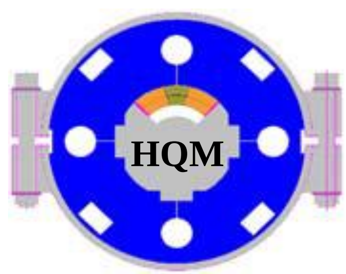
TQ Mirror



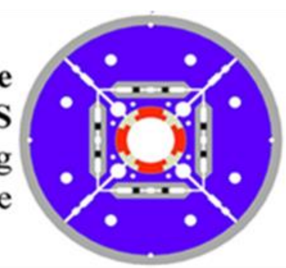
Large aperture quadrupoles | *HQ and LQ Mirrors* | *Long quadrupoles*

High Field Quadrupole
HQ
1.2 m long
120 mm bore





Long Quadrupole
LQS
3.7 m long
90 mm bore

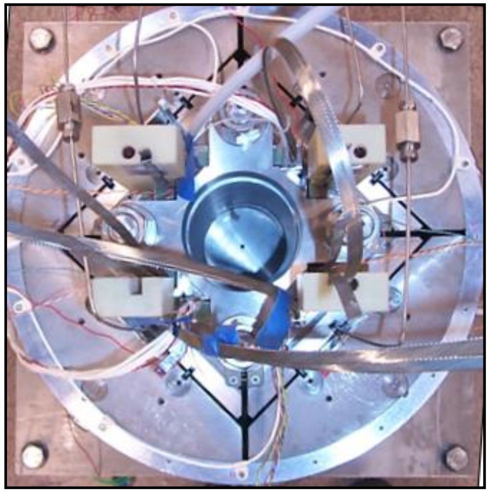


SQ and LR

Based on LBNL “SM” coil design (30 cm long)

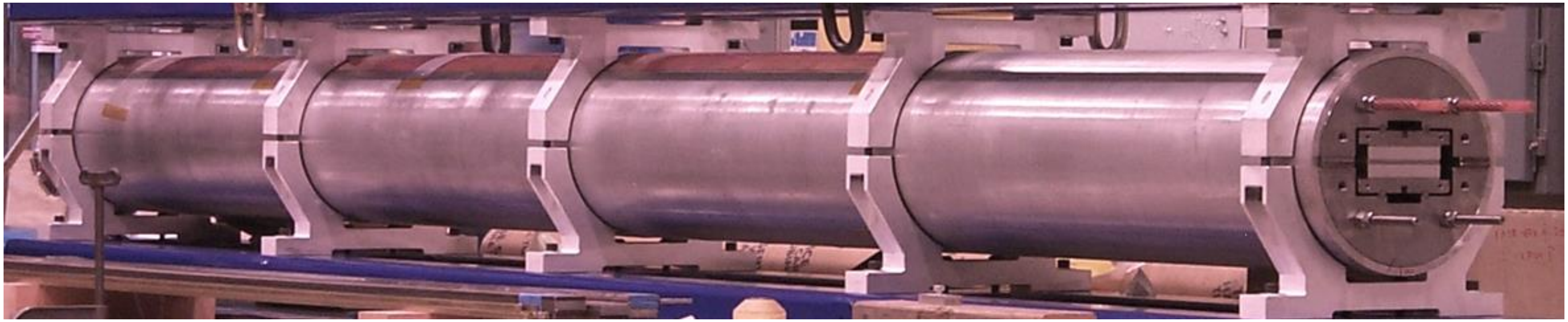
SQ (Sub-scale Quadrupole):

- Four SM coils, 130 mm aperture
- Similar field/current/stress as TQ/LQ
- Extension of shell structure to quadrupole



LR (Long Racetrack):

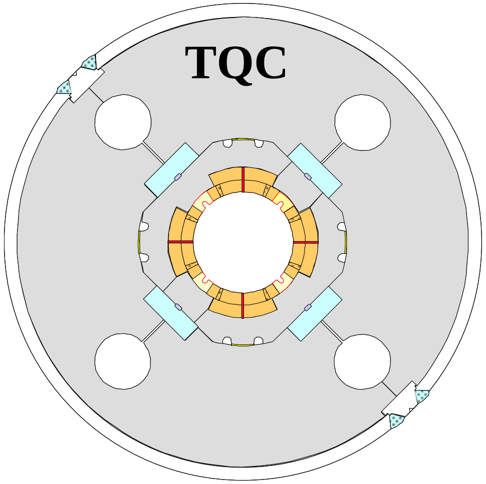
- Scale up of SM coil and structure to 4 m
- Coil R&D: handling, reaction & impregnation
- Structure R&D: friction effects, assembly

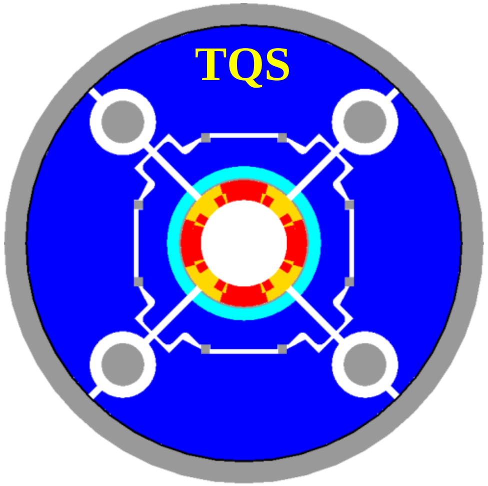


TQ and LQ

Technology Quadrupole:

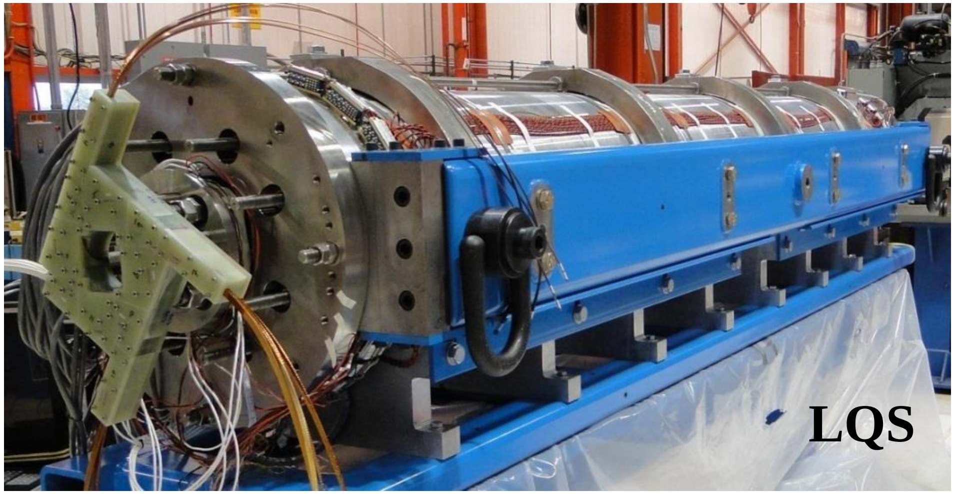
- Double-layer, shell-type coil
- 90 mm aperture, 1 m length
- Two support structures:
  - *TQS (shell based)*
  - *TQC (collar based)*





Long Quadrupole:

- Scale-up to 4 m length
- Same cross-section
- Shell structure only



Target gradient **200 T/m:**

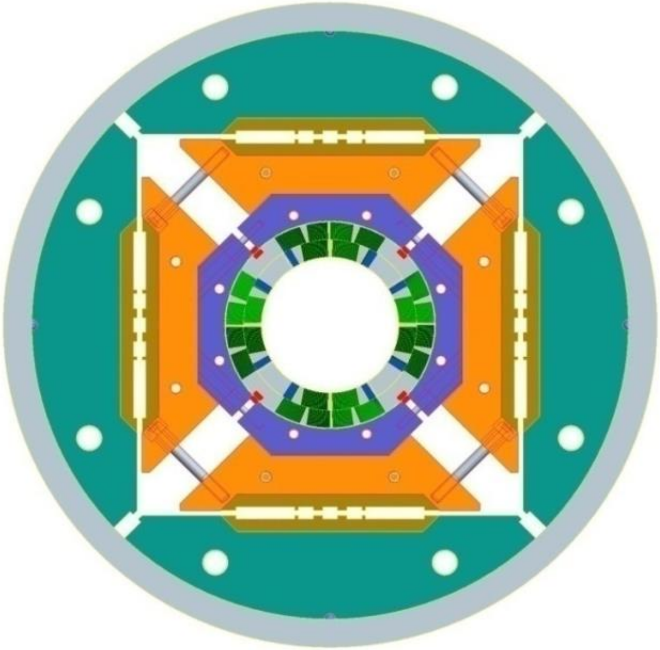
- 83-87% SSL at 4.5K
- 74-79% SSL at 1.9K

HQ and LHQ

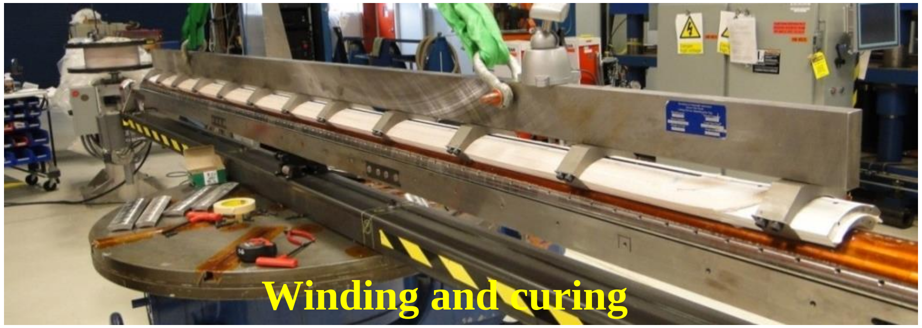
Goals:
- Explore larger apertures (optimal choice for HL-LHC IR)
- Incorporate field quality and full alignment

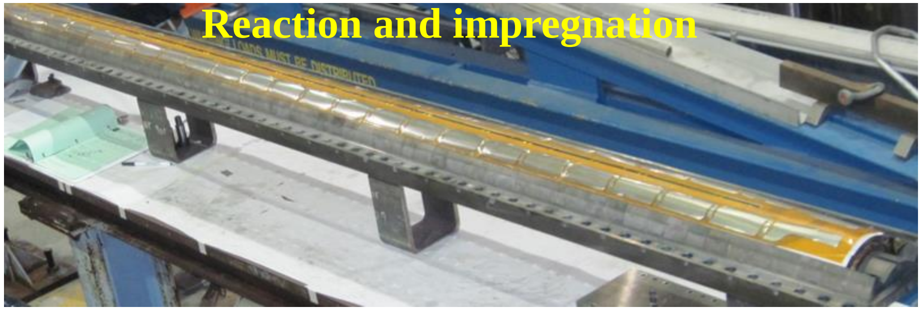
Parameters:
- 120 mm aperture, 15 T peak field at 220 T/m (1.9K)
- *About three times energy and force levels than 90 mm quads*

HQ:1.2 m length quadrupole shell



LHQ: 3.4 m coil scale-up in mirror structure



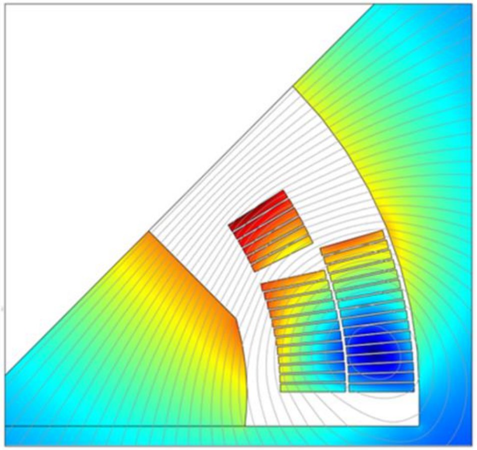


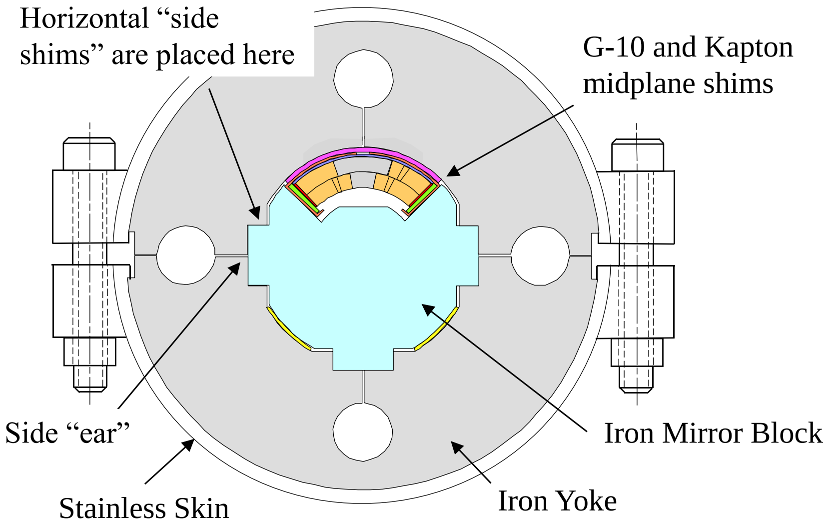
Mirror Structures

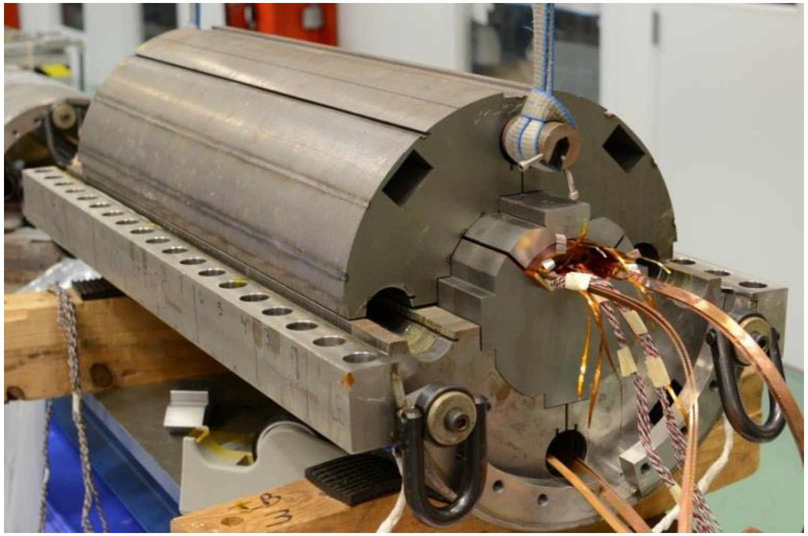
Mirror structure allows to test single coils:

- *Efficient way to study design variations*
- *Fast turnaround and more robust with respect to coil manufacturing variability*

Bolted shell for short models (TQ/HQ) welded shell for long models (LQ/LHQ)







Model Magnet Database

Test facilities: LBNL (11 tests); BNL (2 tests); FNAL (26 tests); CERN (8 tests, entirely funded by CERN)

Series	All new coils			Mix of new and retested coils				All coils previously tested (#)				
SQ**	SQ01	SQ02a						SQ01b	SQ02b	SQ02c		
LR	LRS01							LRS02				
TQC*	TQC01a			TQC02a				TQC01b	TQC02E	TQC02b	TQC03E	
TQS**	TQS01a	TQS02a	TQS03a	TQS01b	TQS02b			TQS01c	TQS02c	TQS03b	TQS03c	TQS03d
TQM*	TQM03a	TQM04a	TQM05					TQM01	TQM02	TQM03b	TQM03c	
LQM*	LQM01											
LQS	LQS01a	LQS02a	LQS03a					LQS01b				
HQM*	HQM01	HQM02	HQM04									
HQ	HQ01a			HQ01b	HQ01c	HQ01d	HQ02a	HQ01e	HQ01e2	HQ02a2	HQ02b	
LHQM	LHQM01											
Total	**19**			**7**				**22**				

(#): includes coil exchanges with previously used coils, full reassembly with same coils, or pre-load adjustments
(*): includes contributions from FNAL GARD program
(**): includes contributions from LBNL GARD program

There is significant additional experience from other programs:

- LBNL high field dipole and subscale dipole program
- FNAL high field dipoles and 11 T program at FNAL and CERN (covered in 11 T review)
- CERN/EU high field magnet development

SQ, LR, LQ & HQ Tests > 95%

Parameter	Unit	SQ02a,b	SQ02b	LRS02	LQM01		HQM04	HQ02a2	HQ02b	
Temperature	K	4.5	1.9	4.5	4.5	1.9	4.5	4.5	4.5	1.9
Fraction of SSL	%	97	98	96	100	99	97	98	95	95
Max. field	T	10.7	11.9	11.5	12.1	13.3	12.8	12.7	12.3	13.5
Max. current	kA	9.5	10.6	10.1	13.1	14.5	15.7	16.1	15.6	17.3
Maximum J_{SC}	kA/mm^2	2.3	2.6	2.4	2.5	2.7	2.1	2.1	2.1	2.3
Coil stress (cold)	MPa	120		30	120		140	180	200	
Coil stress (I_{max})	MPa	70	85	75	130	150	130	170	190	
Strand design		54/61 (MJR)		54/61	114/127		108/127	108/127	108/127	
Strand diam	mm	0.7		0.7	0.7		0.778	0.778	0.778	
No. strands	mm	20		20	27		35	35	35	
Cu/Sc		0.9		0.9	0.95		1.2	1.2	1.2	
Jc (12T, 4.2K)	kA/mm^2	1.9		2.7	2.4		3.0	2.9-3.0	2.9-3.0	
RRR		300		200	180		80	80-140	80-140	
Cored cable		N		N	N		Y	Y	Y	
Coil length	m	0.3		3.6	3.4		1.2	1.2	1.2	

TQ Tests > 95% SSL

Parameter	Unit	TQM01	TQM03a		TQM03b		TQM04a		TQM05	
Temperature	K	4.5	4.5	1.9	4.5	1.9	4.5	1.9	4.5	1.9
Fraction of SSL	%	95	100	98	96	96	100	97	98	98
Max. field	T	11.4	11.7	12.7	11.3	12.4	11.5	12.6	12.1	13.7
Max. current	kA	12.4	12.7	13.7	12.2	13.4	12.5	13.6	13.0	14.7
Maximum J_{SC}	kA/mm^2	2.3	2.7	2.9	2.6	2.8	2.6	2.9	2.4	2.7
Coil stress (cold)	MPa	100	100		130		130		140	
Coil stress (I_{max})	MPa	90	90	110	120	140	140		150	
Strand design		54/61 RRP	108/127		108/127		108/127		54/61 RRP	
Strand diam	mm	0.7	0.7		0.7		0.7		0.7	
No. strands	mm	27	27		27		27		27	
Cu/Sc		0.9	1.2		1.2		1.2		0.9	
Jc (12T, 4.2K)	kA/mm^2	2.9	2.9		2.9		2.8		3.0	
RRR		200	190		190		175		250	
Cored cable		N	N		N		Y		N	
Coil length	m	1	1		1		1		1	

Magnets reliably above 88%

Model magnet	%SSL 4.5K	%SSL 2.2K	%SSL 1.9K	Max Field [T]	Max Stress [MPa]	Wire design	J_C (12T, 4.2K) [kA/mm^2]	Cu/Sc	RRR	Core	Length [m]
SQ02a	97	n.t.	n.t.	10.7	120	54/61 MJR	1.9	0.9	300	N	0.3
SQ02b	97	n.t.	98	11.9	120	54/61 MJR	1.9	0.9	300	N	0.3
LRS01	90	n.t.	n.t.	11.0	75	54/61 RRP	2.7	0.9	200	N	3.6
LRS02	96	n.t.	n.t.	11.5	75	54/61 RRP	2.7	0.9	200	N	3.6
TQS03a	93	n.t.	93	12.2	180	108/127	2.8	1.2	200	N	1.0
TQS03b	91	n.t.	91	12.0	220	108/127	2.8	1.2	200	N	1.0
TQS03c	88	n.t.	88	11.6	250	108/127	2.8	1.2	200	N	1.0
TQS03d	88	n.t.	88	11.6	220	108/127	2.8	1.2	200	N	1.0
TQC03E	88	n.t.	88	11.2	150	108/127	2.8	1.2	200	N	1.0
TQM03a	94	n.t.	96	12.5	110	108/127	2.8	1.2	180	N	1.0
TQM03b	94	n.t.	96	12.5	140	108/127	2.8	1.2	180	N	1.0
TQM04a	97	n.t.	97	12.6	140	108/127	2.8	1.2	180	Y	1.0
TQM05	98	n.t.	98	13.7	150	54/61 RRP	2.9	0.9	250	N	1.0
LQM01	100	n.t.	99	13.3	150	114/127	2.4	0.95	180	N	3.4
HQ02a2	98	89	n.t.	12.7	180	108/127	2.9	1.2	80-140	Y	1.2
HQ02b	95	n.t.	95	13.5	200	108/127	2.9	1.2	80-140	Y	1.2
HQM02	91	89	n.t.	13.2	140	54/61 RRP	3.1	0.9	220	N	1.2
HQM04	97	94	n.t.	13.7	140	108/127	2.9	1.2	80	Y	1.2
LHQM01	90	89	n.t.	13.1	140	108/127	2.9	1.2	100	Y	3.3

Technology Development Tests

Model magnet	%SSL 4.5K	%SSL 1.9K	Wire design	RRR	Length [m]	Notes
SQ01-01b	82-92	n.t.	54/61 (MJR & RRP)	300	0.3	Insufficient mechanical support to the coil ends
SQ02c	-7	-9	54/61 (MJR)	300	0.3	Degradation test to confirm role of end support (comp. SQ02b)
TQS01a	89	n.t.	54/61 (MJR)	200	1.0	Localized quenches at (bronze) pole segmentations
TQS01b	84	n.t.	54/61 (MJR)	200	1.0	Progressive degradation at bronze pole gaps
TQC01a	71	85	54/61 (MJR)	250	1.0	Insufficient mechanical support leading to coil damage
TQC02E	87	77	54/61	200	1.0	Coil defect/damage leading to degradation and instability
TQC02a	67	65	54/61	200	1.0	Coil damage during reaction or collaring with high pre-load
TQC02b	85	78	54/61	200	1.0	Two coils from TQC02a and two from TQC01; lower pre-load
TQS02b	84	79	54/61	200	1.0	Coil defect/damage leading to degradation and instability
TQS02c	93	80	54/61	200	1.0	Coil defect/damage leading to degradation and instability
TQM01	95	short	54/61	200	1.0	Test interrupted due to coil insulation failure & damage
TQM02	84	68	54/61	200	1.0	Coil from TQC02a/b shows degraded/unstable performance
TQM03c	94	-10	108/127	190	1.0	High stress test inducing conductor instability (comp. TQM03b)
LQS01a	80	75	54/61	150	3.4	Mechanical support issues, test interrupted to avoid damage
LQS02a	<70	<70	54/61	200	3.4	Localized damage leading to degradation and instability
HQM01	82	77	54/61	300	1.2	Study of reduced azimuthal compation (-3%) and cored cable
HQ01a	79	n.t.	54/61 & 108/127	300 & 100	1.2	Various issues limiting performance in first-generation HQ coils
HQ01b	77	n.t.	54/61 & 108/127	300 & 100	1.2	Inter-layer short leading to coil damage
HQ01c	70	n.t.	54/61 & 108/127	300 & 100	1.2	Selected a set of coils with good electrical performance
HQ01d	86	n.t.	54/61 & 108/127	300 & 100	1.2	Selected coil set with good electrical and quench performance
HQ02a	91	82	108/127	70-150	1.2	Current limit preventing quench performance characterization

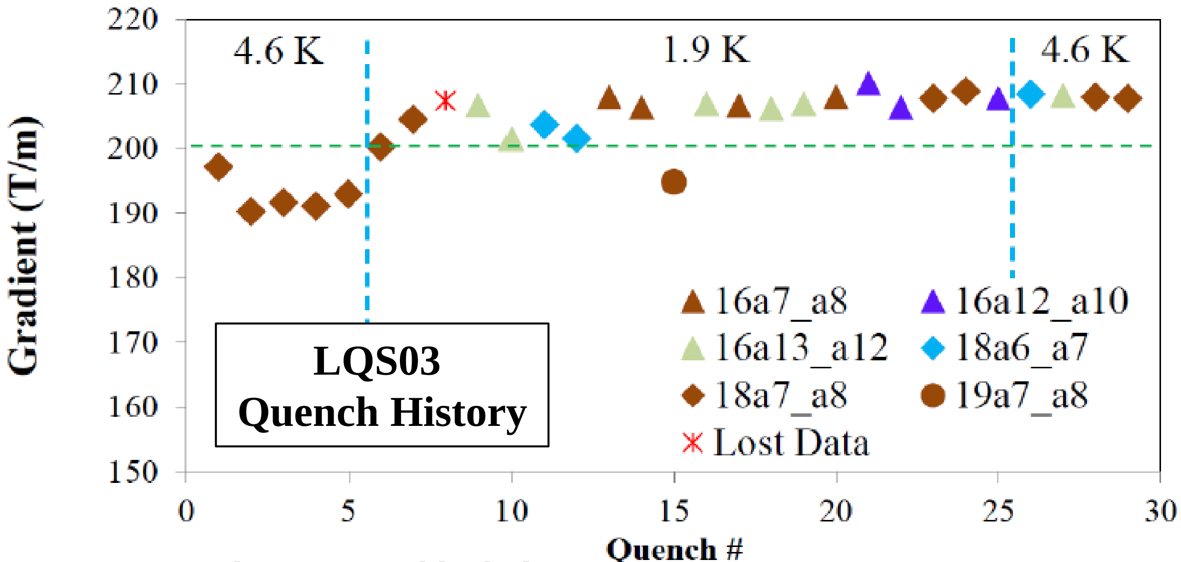
Examples of issues identified and addressed during the R&D program are provided in the following slides

Magnets in the 80-88% range

Model magnet	%SSL 4.5K	%SSL 1.9K	Wire design	Cu/Sc	RRR	Length [m]	Notes
TQC01b	85	87	54/61 MJR	0.9	250	1.0	Optimization phase
TQS01c	81	82	54/61 MJR	0.9	250	1.0	Optimization phase
TQS02a	92	85	54/61	0.9	200	1.0	Optimization phase
LQS01b	90	83	54/61	0.9	150	3.4	Optimization phase
LQS03a	91	82	108/127	1.2	70-150	3.4	Mechanical + low RRR?
HQ01e-e2	85	85	54/61 & 108/127	0.8 & 1.2	190 & 100	1.2	Optimization phase

LQS03a:

- Limited by quenches in multiple segments of 2 coils
- Independent of T
- Possible explanations: insufficient mechanical support, low RRR



G. Ambrosio, G. Chlachidze

Performance issues in HQ01

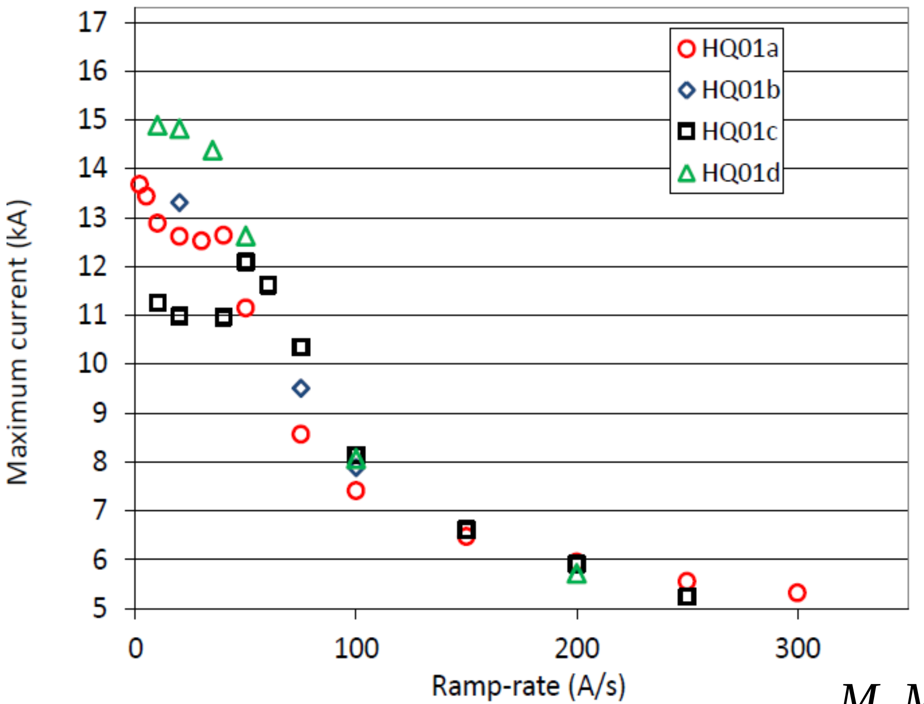
Mechanical issues:

- Ramp rate dependence of first three models is indicative of conductor damage

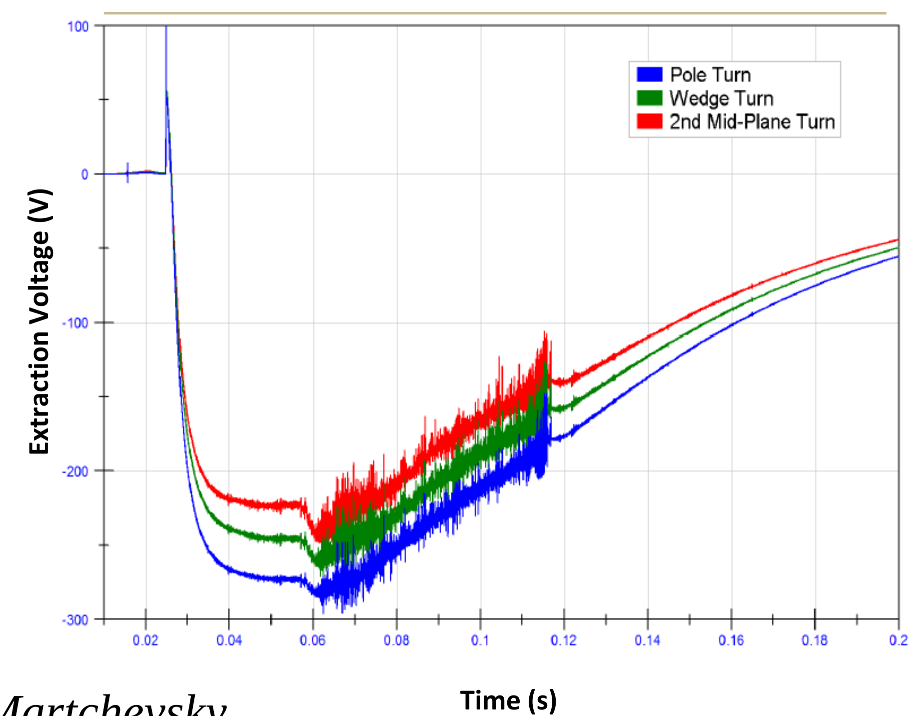
Electrical issues:

- Large number of insulation failures in coils, in particular inter-layer and coil to parts

HQ01a-d Ramp Rate dependence



HQ01b extraction voltage



M. Martchevsky

Design & Process Improvements

Changes in HQ coil design and fabrication to prevent conductor damage and insulation failures observed in first-generation coils:

- **Decreased axial coil strain** by increasing longitudinal gaps between pole pieces
- **Additional room for cable expansion** in reaction using smaller strand
- **Aluminum oxide insulating coatings** for coil parts to prevent shorts
- **Increased insulation thickness** under protection heaters and between coil layers
- **New coil parts design** to account for extra insulation and winding experience
- **More refined/stringent electrical QA** at all stages: coil fabrication, assembly, test

Additional changes implemented to address field quality and production issues:

- **Cored cable** to control eddy currents (for field quality and quench performance)
- **1-pass cable** for more efficient cabling process (also driven by core)
- **Braided insulation** replacing fiberglass sleeve for long unit lengths
- **Ti-doped conductor** to confirm performance for future procurements

Reusing and Replacing Coils

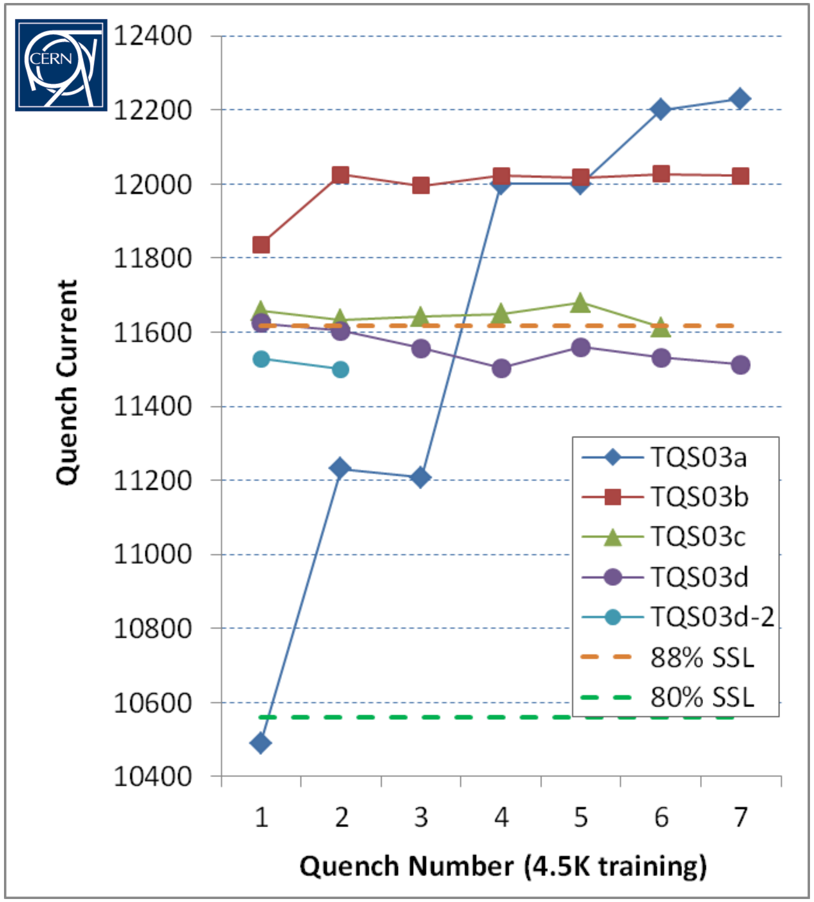
- Demonstrated viability and effectiveness of using coils in multiple assemblies
- For R&D: perform multiple studies with same coils (saves cost and time) or parametric studies (saves cost/time and helps consistency)
- For R&D and production: resolve issues minimizing cost and schedule impact
- An important element of risk mitigation against defective coils

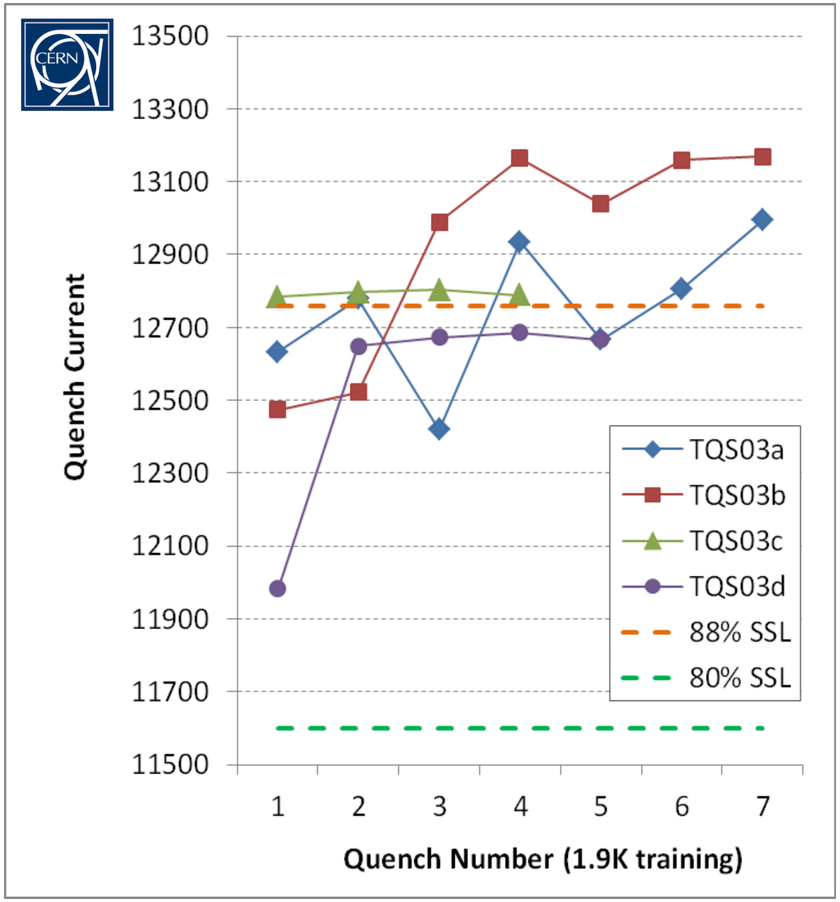
HQ01 example: four tests performed within one year

Model	**Test Dates**	**Coils used***	**%SSL (4.5K)**	**Notes**
HQ01 **a**	**May** 2010	**1-2** **3-4**	79	Replaced coil 3 limiting performance, and coil 2 which was damaged due to insulation failure
HQ01 **b**	**June** 2010	**1** **4-5-6**	77	Extensive damage due to arching in coil 6 (layer to layer short in the end region, pole tip)
HQ01 **c**	**October** 2010	**1** **5-7-8**	70	Selection of a set of electrically robust coils; however, magnet performance limited by coil 1
HQ01 **d**	**April** 2011	**5-7** **8-9**	86	Selection of a set of good performing coils allowing extensive studies (1.9K performance, pre-load control, field quality, quench protection) while developing second generation coils

(*) Coil color coding: 54/61, 108/127

Training/Retraining: TQS03

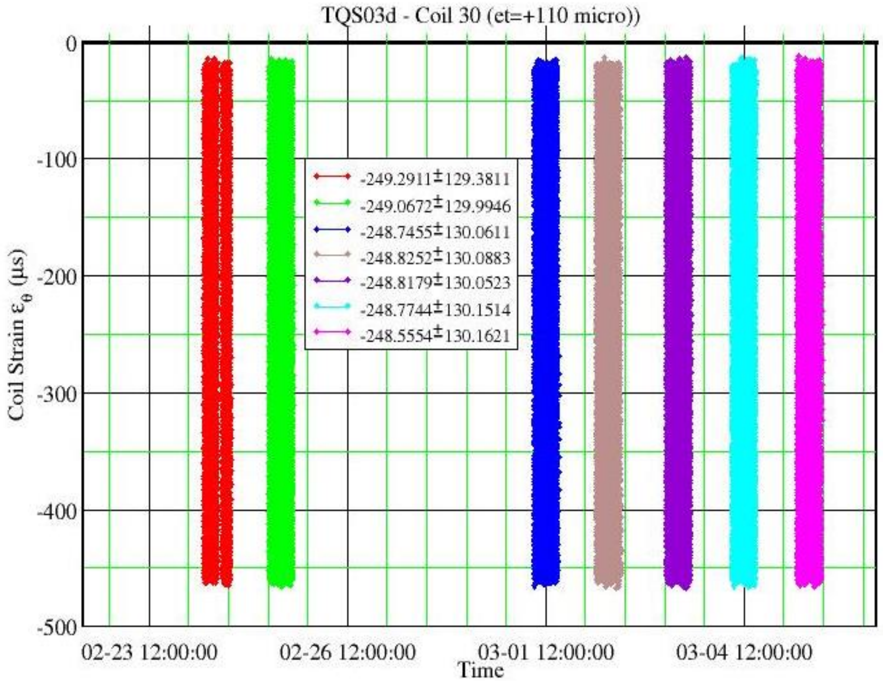


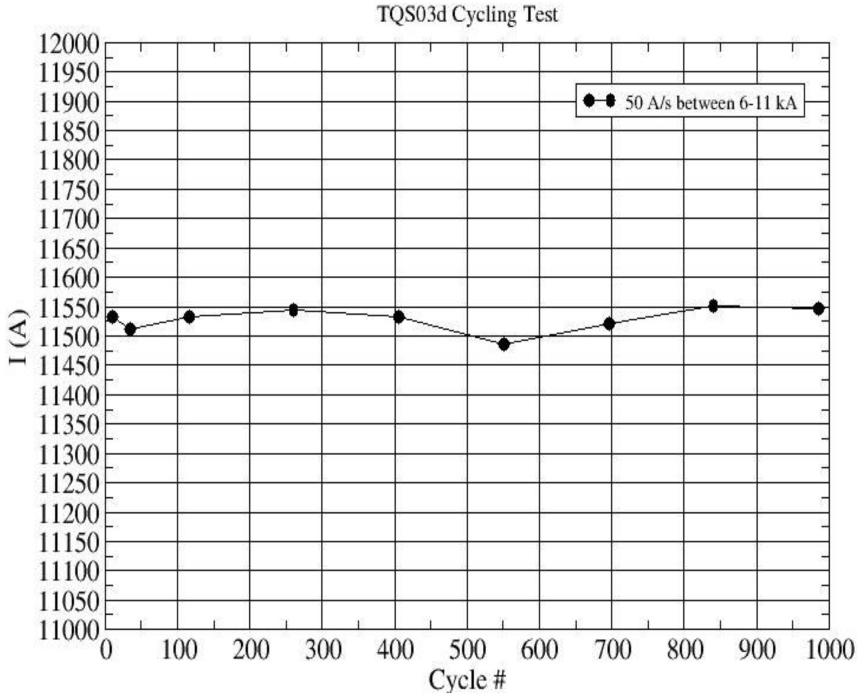


- Balance speed of training and consistent plateau after thermal cycle vs. degradation
- Higher preload (pole ave.120/160/200 MPa) gives lower plateau (93/91/88%) for a/b/c
- Degradation is permanent (TQS03d with lower pre-load does not recover initial level)

TQS03d Cycling Test

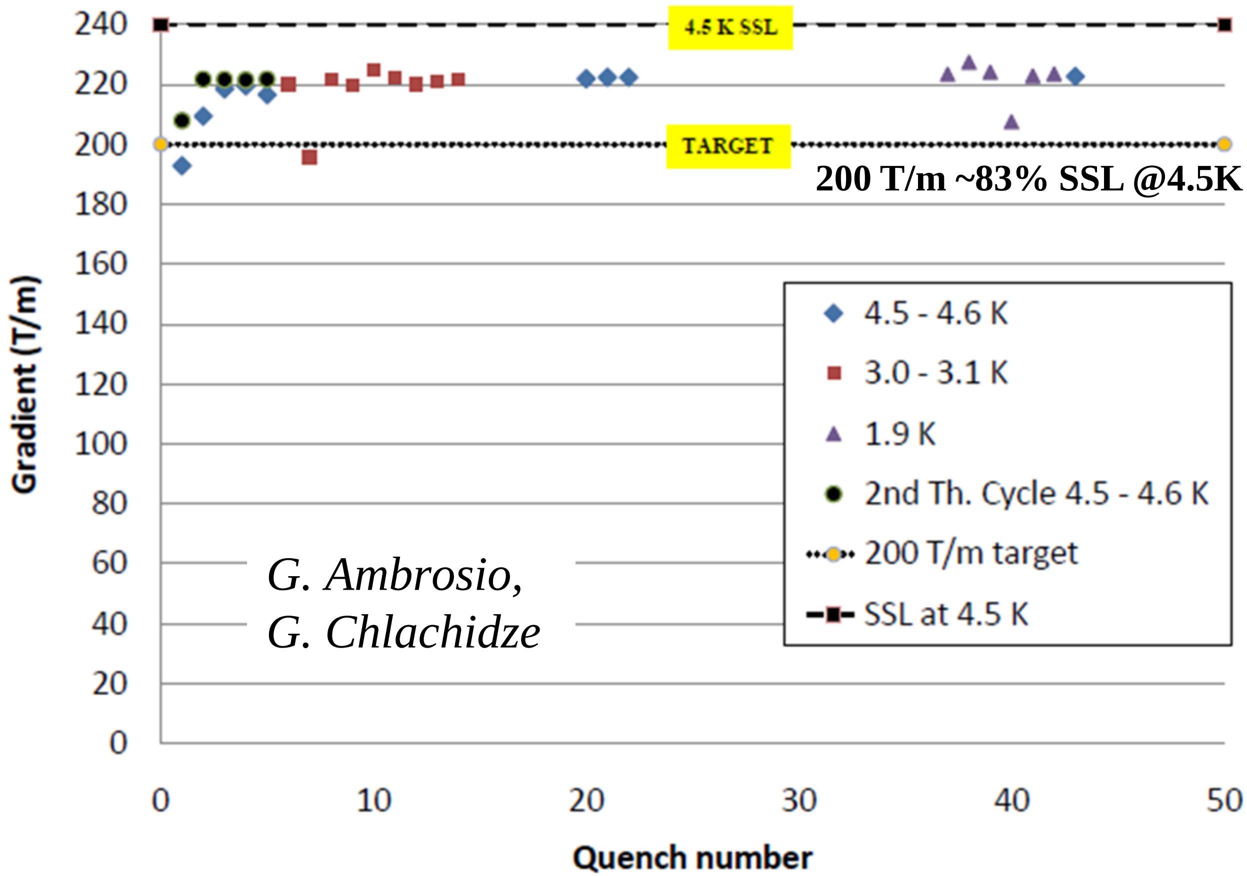
- Follows two high stress tests causing permanent degradation
- Performed 1000 cycles with control quenches every ~150 cycles
- No change in mechanical parameters or quench levels
- Cycling tests were not performed in LQ or HQ





H. Bajas, M. Bajko, S. Caspi, G. DeRijk, H. Felice, P. Ferracin, R. Hafalia, A.Milanese et. al

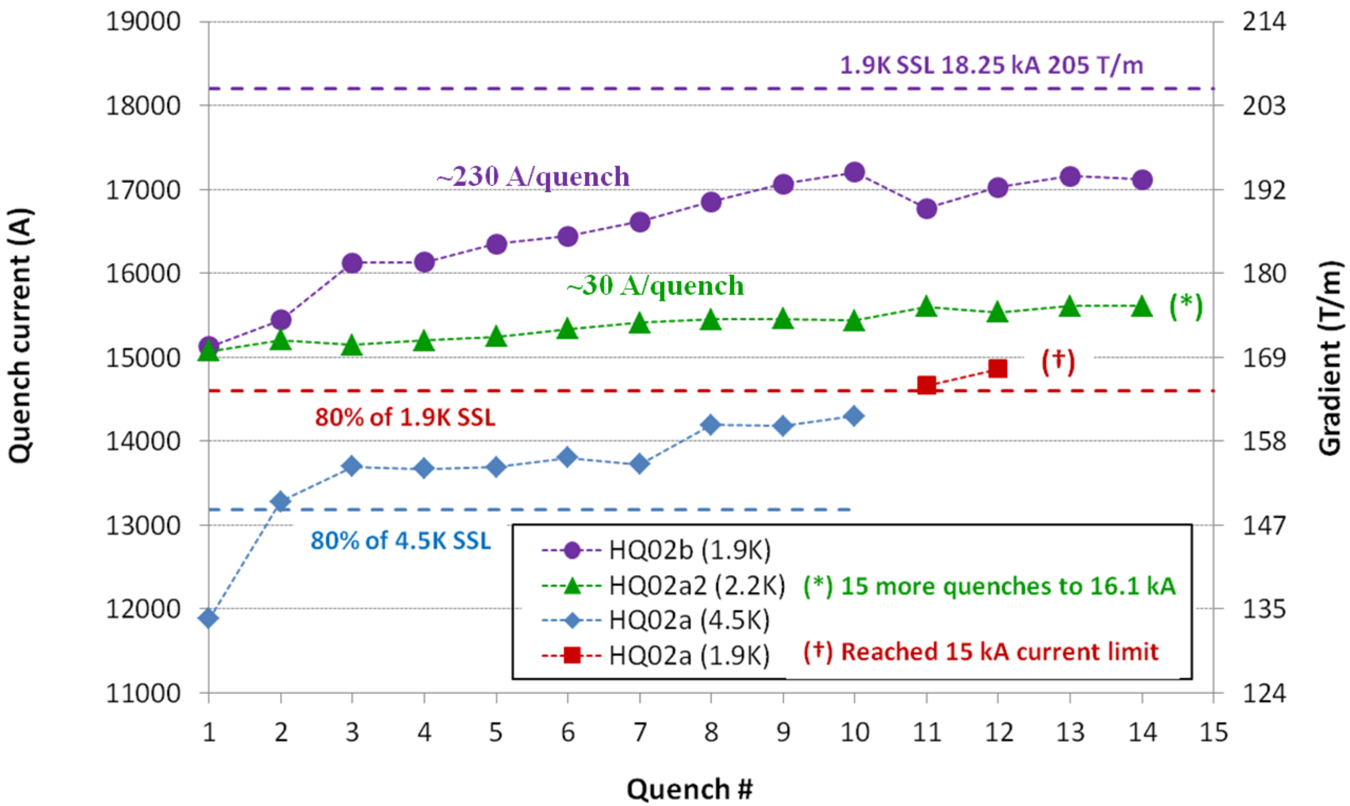
Training/Retraining: LQS01b



- Coils previously tested with long/complex training (but training stopped at 200 T/m)
- Narrow training range in first Thermal cycle → not well suited to assess memory
- Fast training to nominal supersedes the need to rely on memory

Training/Retraining: HQ02

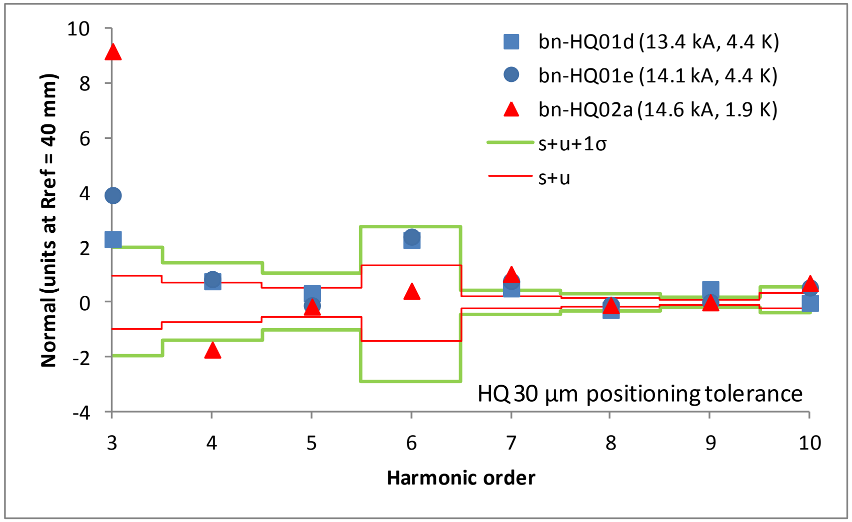
- Fast training to nominal supersedes the need to rely on memory
- HQ02a2 starts from highest current of (not fully trained) HQ02a
- HQ02b: Significant training improvement after pre-load increase

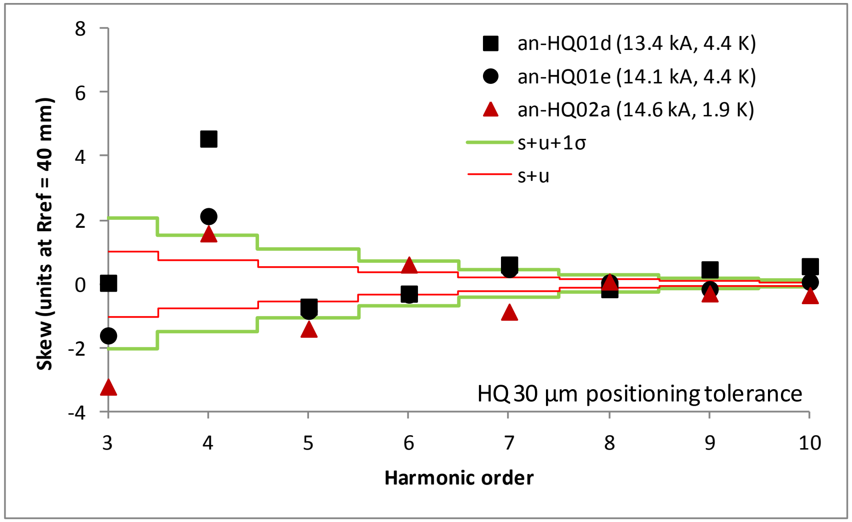


H. Bajas, M. Bajko, G. Chlachidze, M. Martchevsky, F.Borgnolutti, D. Cheng, H. Felice, et al.

Non-allowed Harmonics in HQ

- Some of the sextupole and octupole components are at the upper limits or beyond the range of variability expected from random error analysis
- Both in HQ01 and HQ02, although largest errors are in different harmonics
- Longitudinal scan shows smooth dependence, possibly an end effect

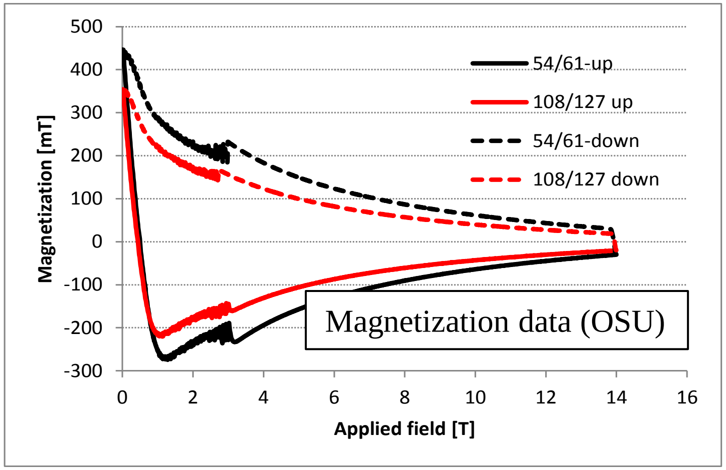


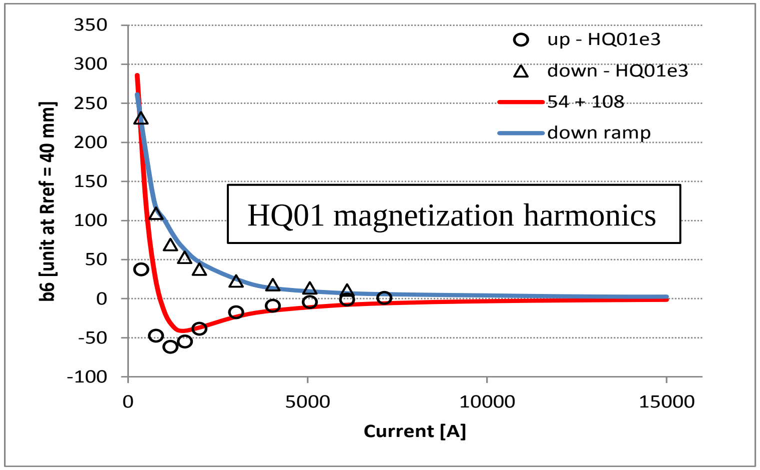


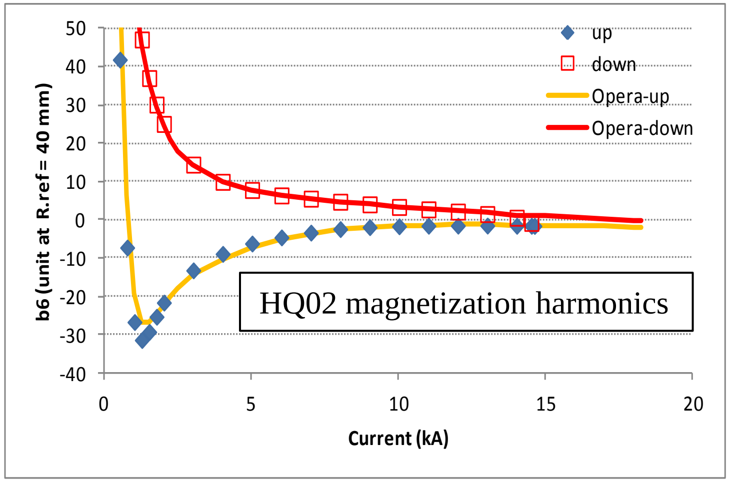
X. Wang, J. DiMarco

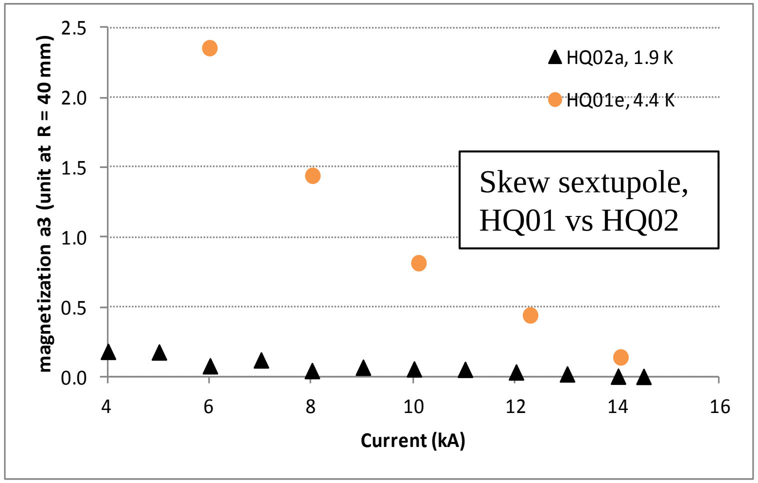
Persistent current harmonics in HQ

Validation of analysis method using HQ01 (54/61+108/127) and HQ02







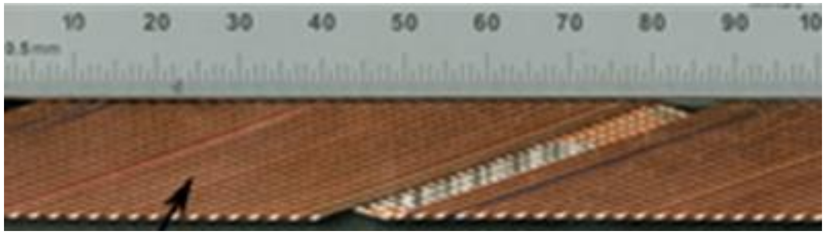


X. Wang

Control of eddy current harmonics

- Large dynamic effects observed in LARP quadrupoles (TQ/LQ, HQ01)
- A thin (25 μm) stainless steel core with partial coverage (8mm, 60%) and biased toward the thick edge was included in HQ02 cables
- Increased the effective R_c from 0.1-0.4 μΩ (HQ01) to 2-4 μΩ (HQ02) with a corresponding decrease of the observed errors

Parameter	Unit	HQ01e	HQ02a
Core material	-	-	SS316L
Strand diameter	mm	0.80	0.778
Cable width	mm	15.15	14.77
Cable mid thickness	mm	1.437	1.376

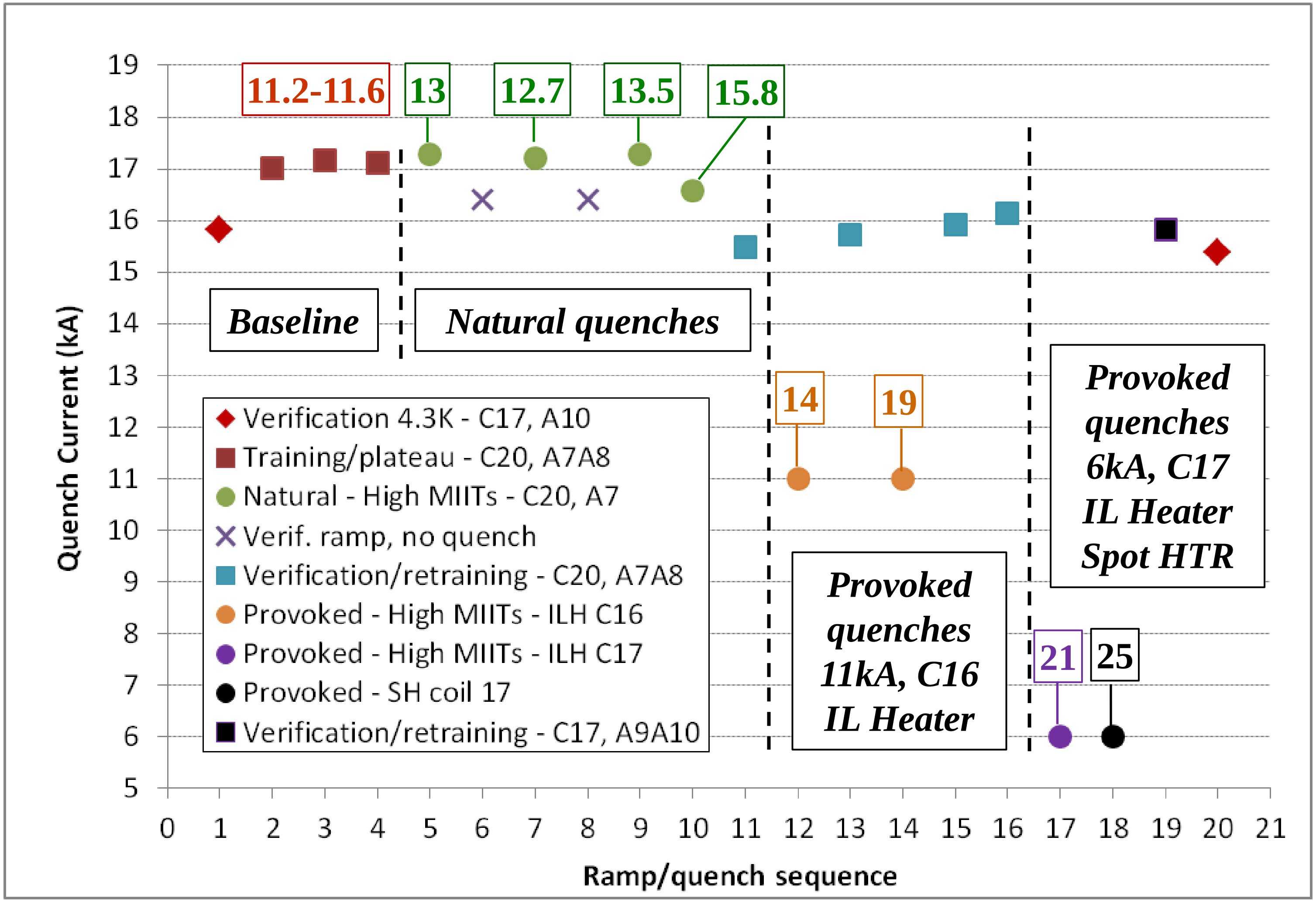


D. Dietderich

Harmonics	HQ01e	HQ02a	Reduction (%)
b_2	14.60	0.85	94
b_3	1.56	-0.12	92
b_4	0.43	0.04	90
b_5	0.21	0.00	98
b_6	2.09	0.10	95
a_3	4.73	0.44	91
a_4	0.18	-0.14	25
a_5	0.52	0.12	77
a_6	-0.26	-0.04	84

J. DiMarco, X. Wang

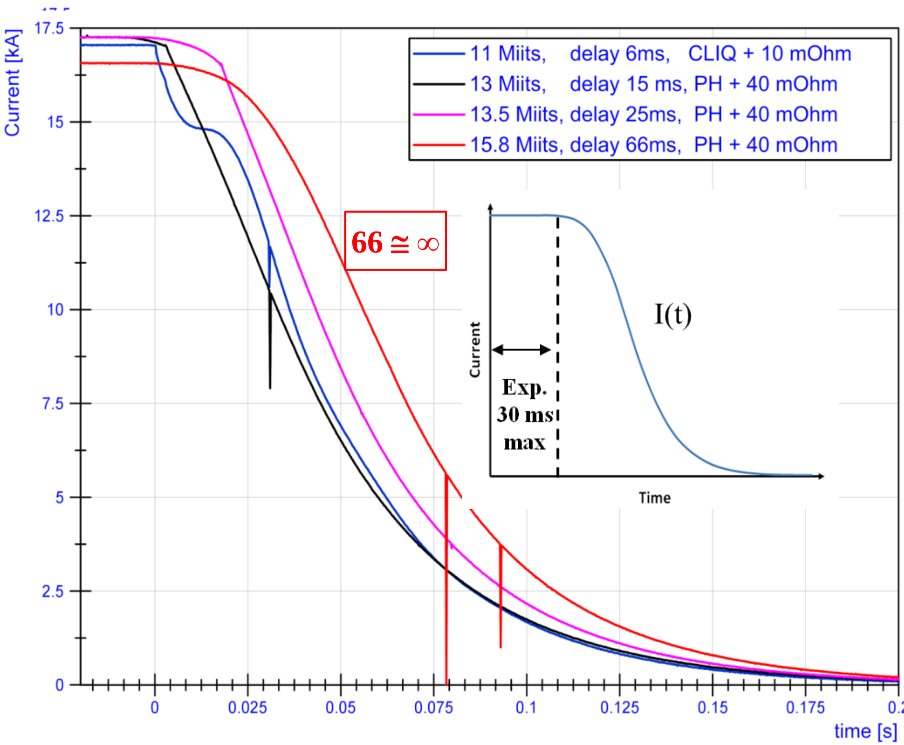
HQ02b Protection Limits Study

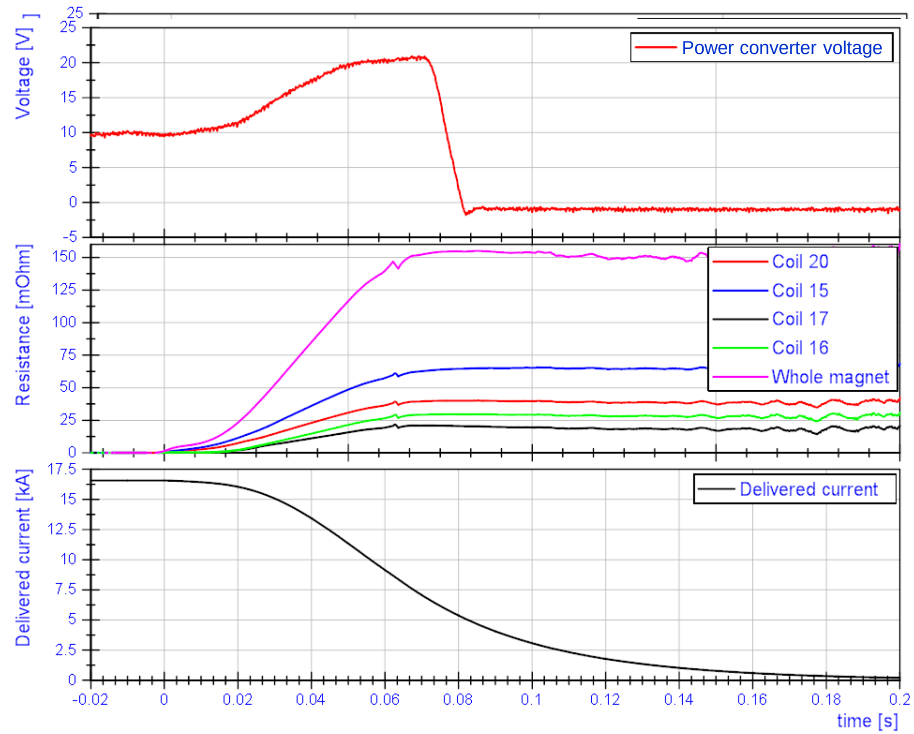


H. Bajas, E. Ravaioli, M. Bajko, G. Ambrosio,G. Chlachidze, M. Martchevsky, E. Todesco et al.

Current decay and Protection limits

- HQ resistance growth without any active protection was much faster than expected
- Limited MIITs despite our attempts to maintain high current – "anti-protection"
- These findings led to improved models and larger estimated margins for QXF
- Similar studies performed in LHQ, with consistent (but less stringent) results





H. Bajas, E. Ravaioli, J. Feuvrier, G. Ambrosio, V. Marinozzi et al.

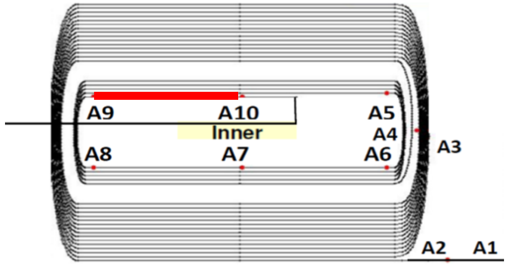
Limits on Maximum Temperature

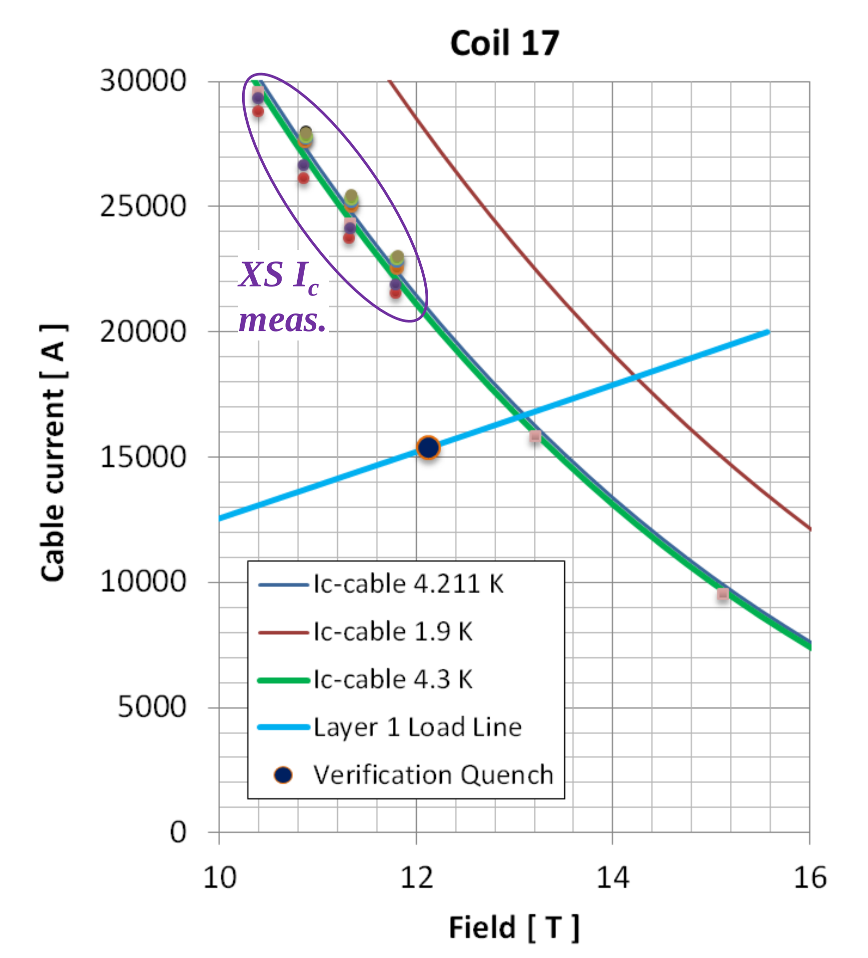
Comparison between 24 MIITs spot heater quench #18 and verification #20 at 4.3K

HQ02b-18	Value
Current	6.0
Coil	17
Segment	A9A10
Field [T]	5.1
Q.I. [MIITs]	24
T_{max} [K]	>350

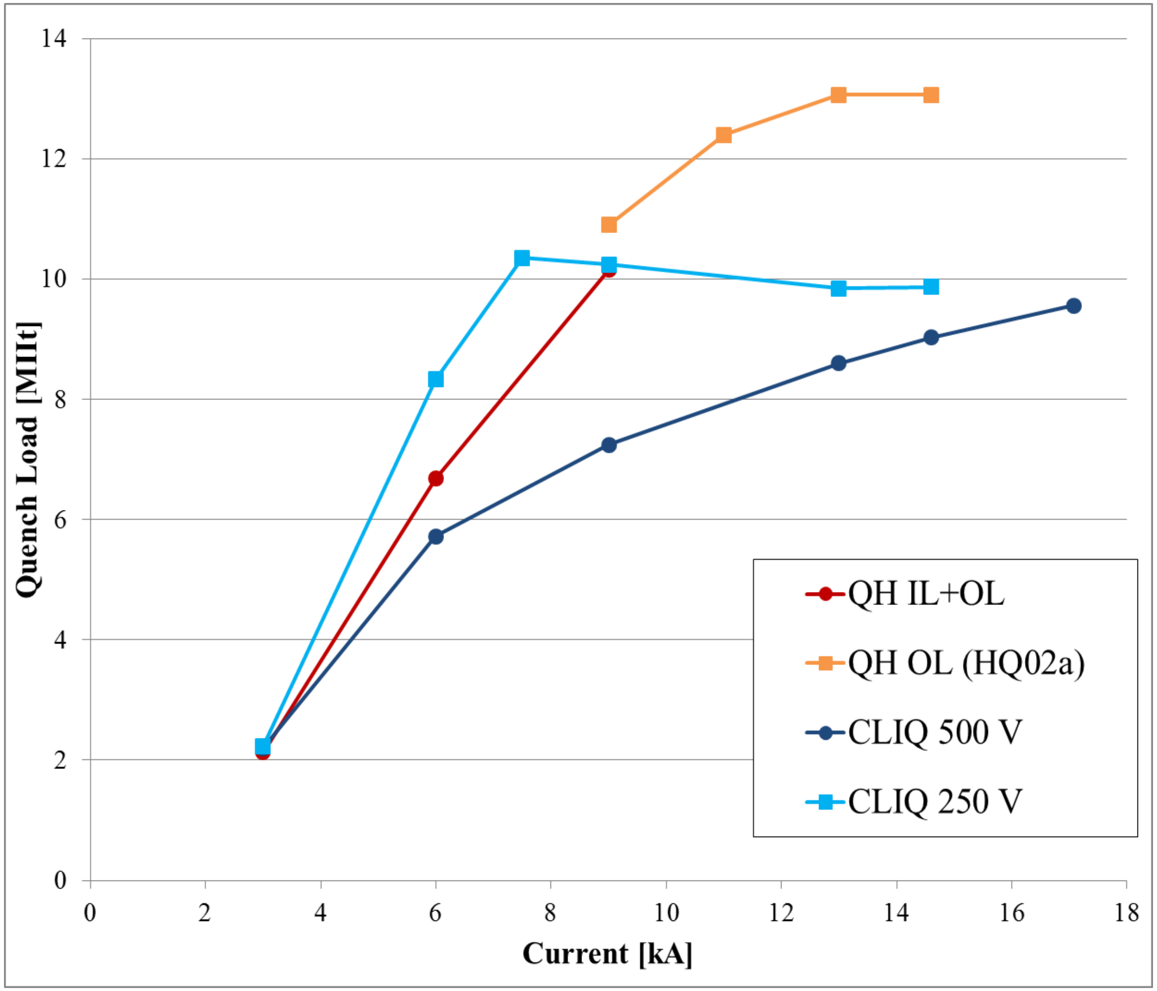
HQ02b-20	Value
Current (kA)	15.38
Coil	17
Quench segment	A9A10
Field A9A10 [T]	12.1
I_q/I_{ss} (4.3K)	0.93
Degradation [%]	<7

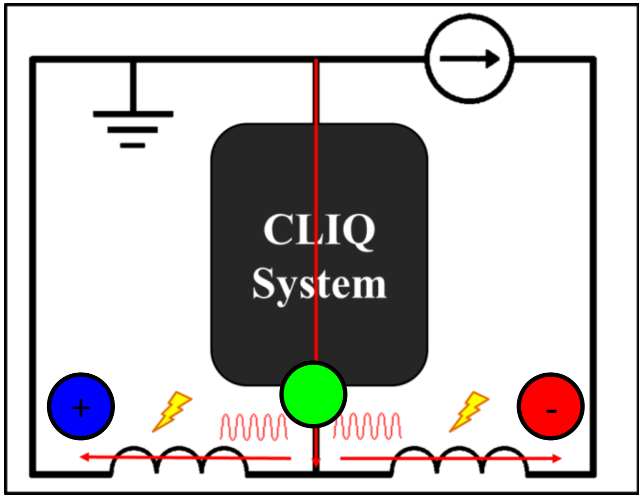
- **Additional retraining and 4.3K verification needed to demonstrate permanent degradation or provide a lower constraint**
- **Significant uncertainty in T_{max} evaluation**

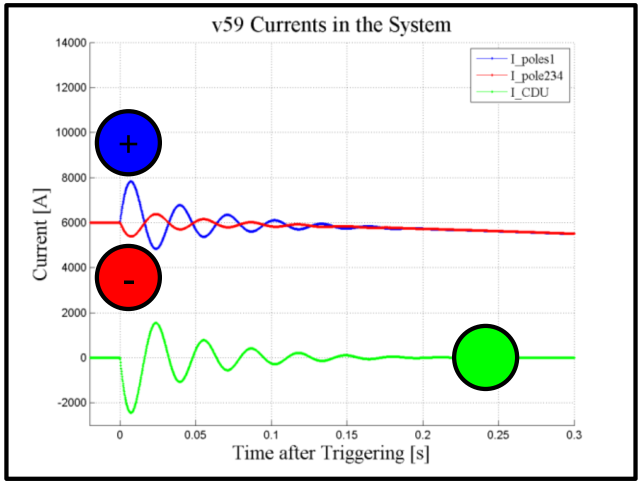




CLIQ Performance in HQ02b







E.Ravaioli, H. Bajas, M. Bajko, V. I. Datskov, V. Desbiolles, J. Feuvrier, G. Kirby, H. H. J. ten Kate et al.

Summary: Quench Performance

- Optimized Nb_3Sn magnets are able to approach the conductor limit over a wide range of performance targets (field/aperture), design features and operational parameters (conductor, coil, structure, stress, etc.)
- A significant number of optimized Nb_3Sn models have demonstrated reliable performance at/above the 88% level
- Extensive development has been required to optimize performance in each new design, including verification and optimization of design options, and specific tests aimed at probing safe parameter windows
- The capability to consistently reproduce >88% performance in a series of models has not been fully demonstrated at this stage
- This risk is mitigated by the capability to repeat the assembly adjusting shims and pre-load, and/or replacing defective coils

Summary: Training, Field Quality

- Optimized quadrupoles have demonstrated fast training and good training memory. However, the R&D program provides only a few directly relevant data points.
- Previously tested coils preserve their training memory also following partial or complete reassembly.
- Higher pre-load generally results in faster training and less retraining, but can lead to permanent degradation. Results indicate that safe preload windows are wider than previously thought, which will benefit series production. Pre-load adjustments are also a possibility if needed in a few cases.
- Ensuring uniformity of properties will be key to ensuring good field quality. This area has not been investigated in detail during the R&D, either in terms of developing processes to ensure uniformity or providing feedback from multiple magnets.
- Persistent current effects are well understood and cored cables have proved very effective in controlling dynamic effects, but previous comment still applies

Summary: Quench Protection

- HQ02 results allow to put constraints on the start of absolute degradation
  - HQ02a: less than 3% below 200K and less than 5% below 250K
  - HQ02b: less than 7% below 380 (420-450) K
- HQ results support the current LARP QXF protection target of 350 K
- Still limited set of data and learning how to improve experiment/analysis
  - HQ03 is the next opportunity to confirm these results and/or place stricter constraints
  - Also need to confirm/improve on maximum temperature assessments
- An important by-product of these studies is the measurement of quench propagation in the absence of active protection
  - Results are being incorporated in QXF quench analysis and protection system design and assessment
- The new CLIQ system has been tested on HQ with very positive results and represents an important new tool to improve margins and redundancy, and provide additional flexibility with respect to quench heaters