FERMILAB PROGRAM RESULTS AND NEXT STEPS

LARP Collaboration Meeting 14
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OUTLINE

- Introduction
- Single Nb_3Sn quadrupole coil test in a “magnetic mirror” structure
  - Effect of coil pre-stress on magnet performance
  - Complementary to study performed by LARP (TQS03)
- Development and test of a quadrupole magnet with “dipole style” collars
  - Reduction of assembly time and of the risk of coil damage
- Future plans

INTRODUCTION

Fermilab, along with other US National Laboratories, is developing a new generation of accelerator magnets based on Nb_3Sn super-conductor

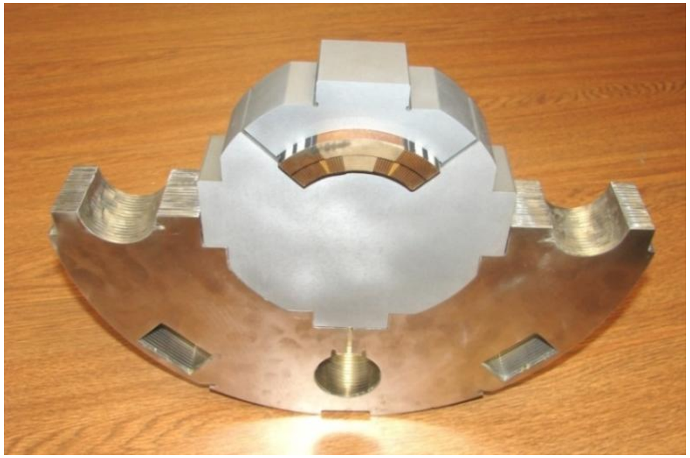
- Study and optimization of Nb_3Sn strands and cables, insulation
- Fabrication of coils and other components with various design and processing features
- Fabrication and test of a series of model magnets
- Nb_3Sn coil technology scale-up

Recent technology developments within Fermilab's base High Field Magnet (HFM) program include

- Quadrupole mirror structure to test single quadrupole coils in a real magnetic field environment
- Assembly and test of a Technology Quadrupole (TQC) with a dipole style collar design and coil alignment

TQ MIRROR STRUCTURE

- The "Magnetic Mirror" concept was developed for the HFM dipole and now expanded to include the 90-120-mm quadrupoles
  - Long mirror dipoles (LM01, LM02) were built and successfully tested for the Nb_3Sn coil technology scale-up
- Design details and first test results were presented at LARP Collaboration Meeting 13 (Port Jefferson, November 2009) by Rodger Bossert
  - http://larpdocs.fnal.gov/LARP-public/DocDB/DisplayMeeting?conferenceid=69
- Specific coil and cable features can be tested and optimized efficiently, in a short time period
  - Re-assembly turnaround time is about 3 weeks
  - 2.5 months required for construction of a mirror magnet with a new coil (compare to ~ 6 months for a quadrupole magnet)



- Simplified structure – coil to coil interactions not present – an intermediate step to speed up overall magnet development time

TQ MIRROR DESIGN FEATURES AND HISTORY

Mirror	COIL #	STRAND	CABLE	INSULATION	COIL POLE
TQM01	19	RRP 54/61	LBNL	S2-Glass Sleeve	Bronze
TQM02	17	RRP 54/61	LBNL	S2-Glass Sleeve	Bronze
TQM03: a, b, c	34	RRP 108/127	FNAL	E-Glass Tape	Titanium

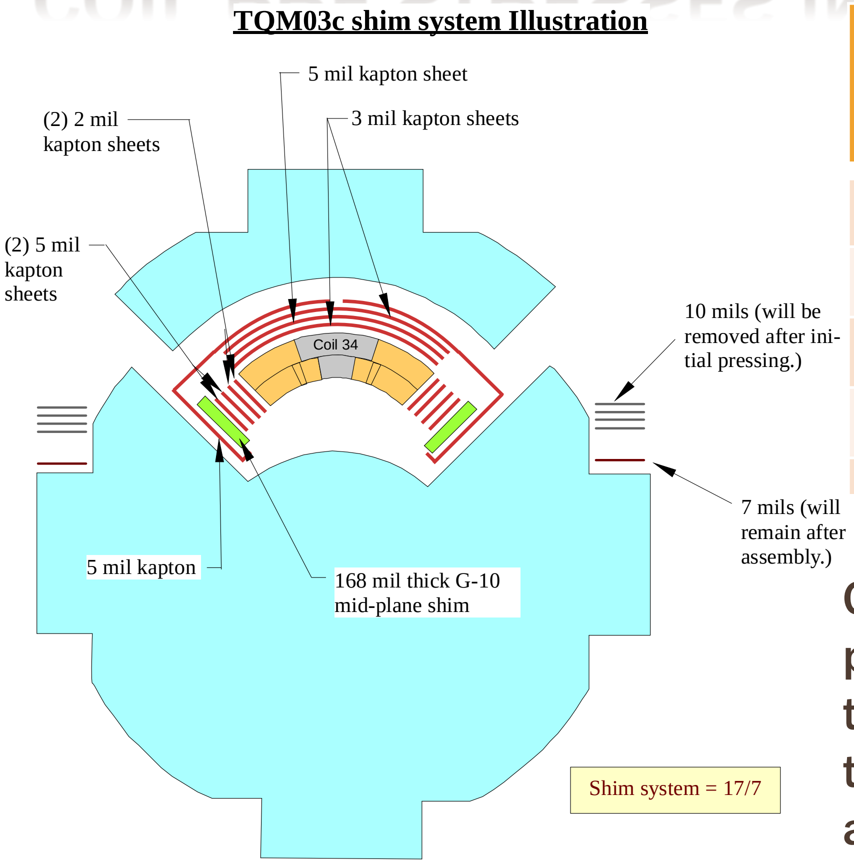
TQM01 and TQM02 mirror magnets were tested in Jan.-April 2009

- Test results were presented at CEC/ICMC and MT-21 in 2009
- Coil quench performance in the mirror structure found consistent with the performance in TQS and TQC models

TQM03 magnets tested in Jun.-Aug. 2009 and Feb.2010

- 3 variations with different coil pre-loads
- Cable based on RRP-108/127 strand was fabricated at Fermilab
- E-Glass tape was used for cable insulation instead of expensive S2-Glass sleeve

COIL PRE-STRESSES IN QUADRUPOLE MIRROR

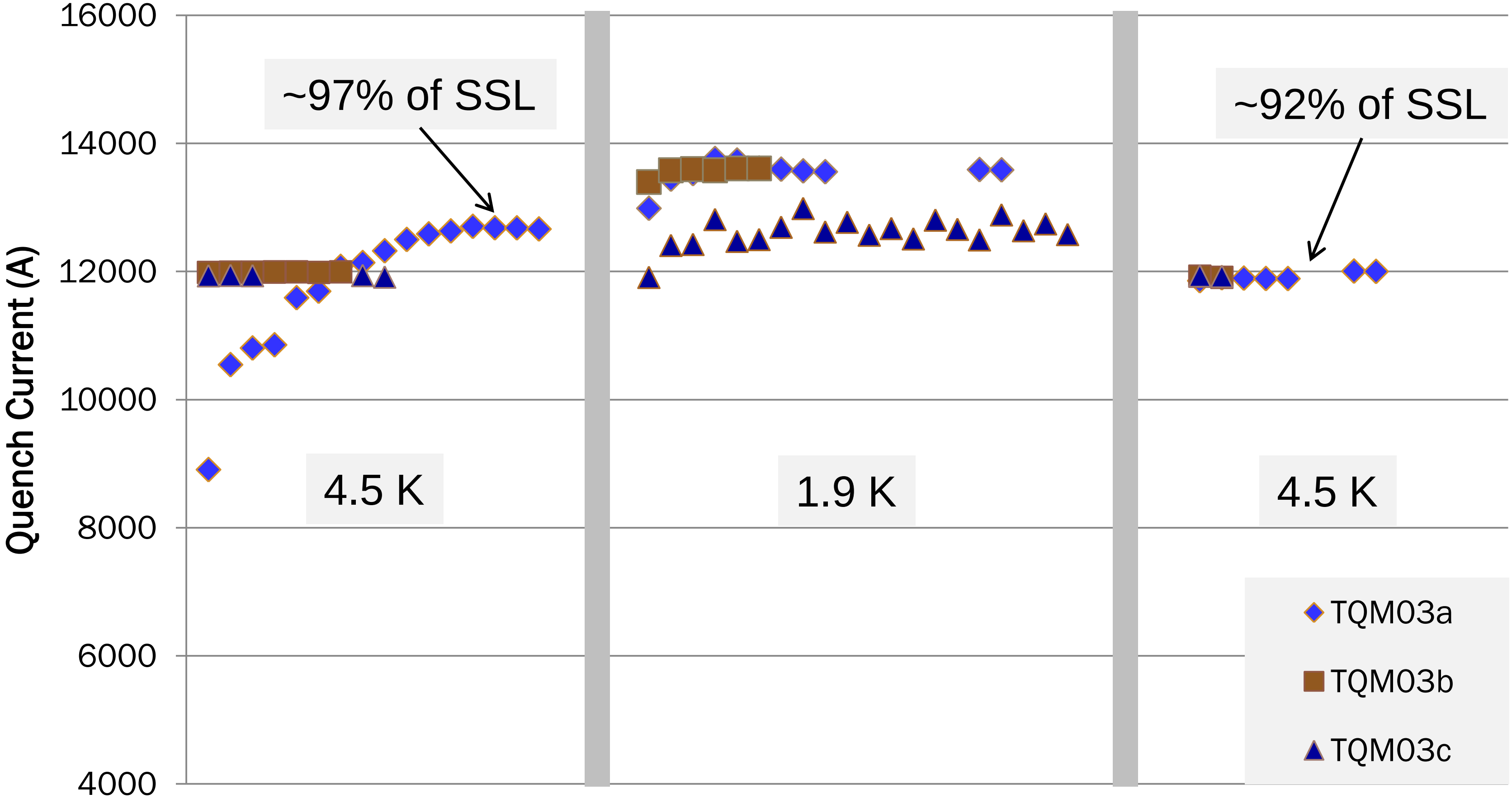


MIRROR	Measured warm stress (MPa)	Air Gap (mils)	Predicted Cold stress (MPa)
TQM01	100	4	90
TQM02	100	6	110
TQM03a	100	5	100
TQM03b	105	8	145
TQM03c	135	10	185

Gauges bonded directly to coils confirmed pre-loads at room temperature, however these gauges are not compensated at LHe temperatures. Therefore, cold pre-loads are assumed from FEM analysis

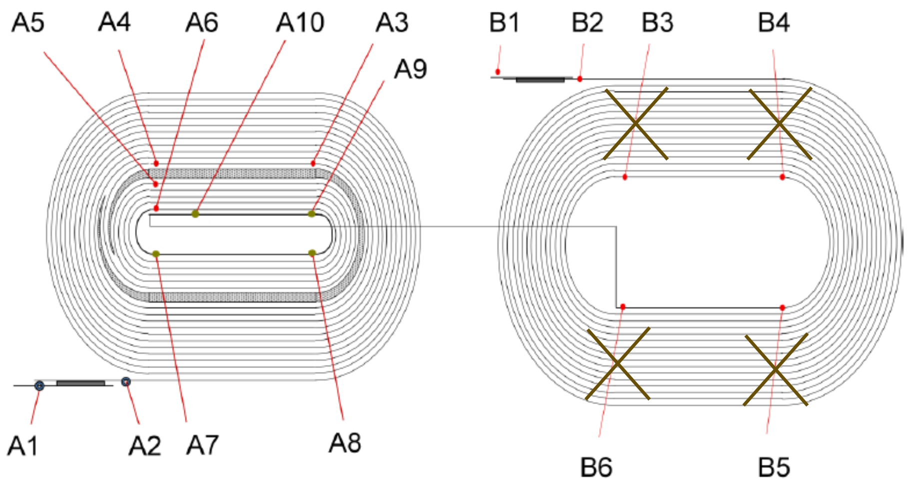
Next mirror magnet (TQM04) will be equipped with gauges connected in a full-bridge configuration on Titanium pole and will be compared to analysis

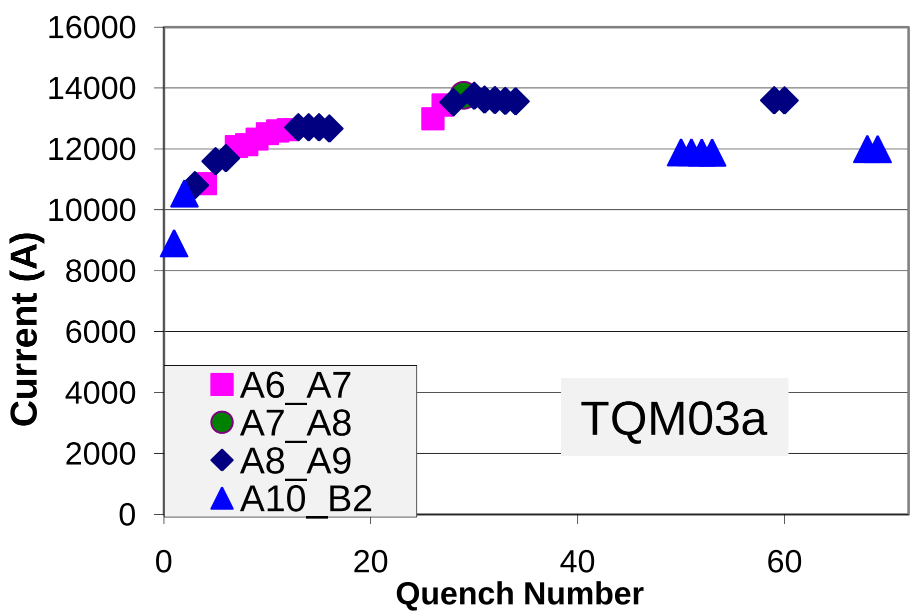
TQM03 QUENCH TRAINING

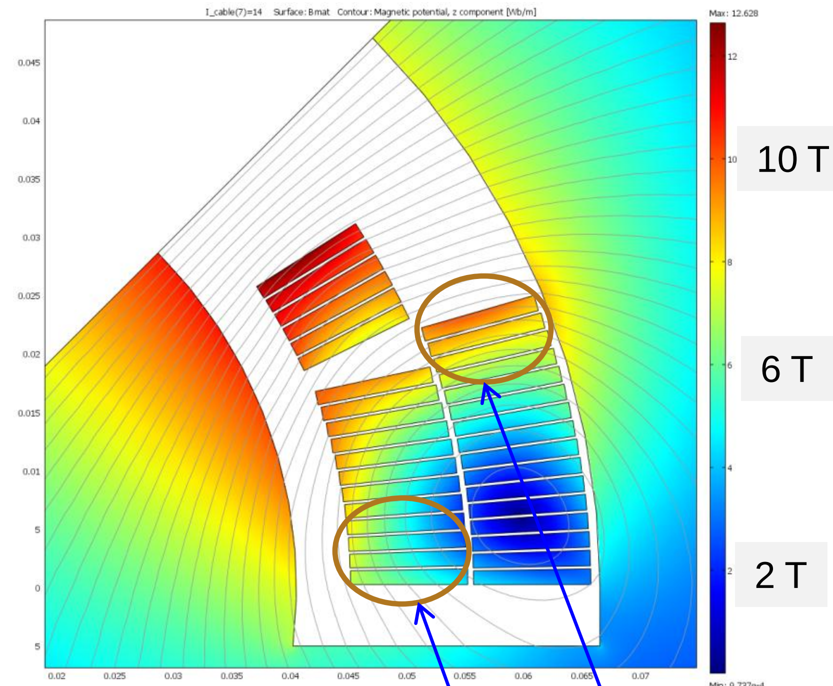


SSL at 4.5K ~ 13.0 kA
1.9K ~ 14.4 kA

QUENCH LOCATIONS





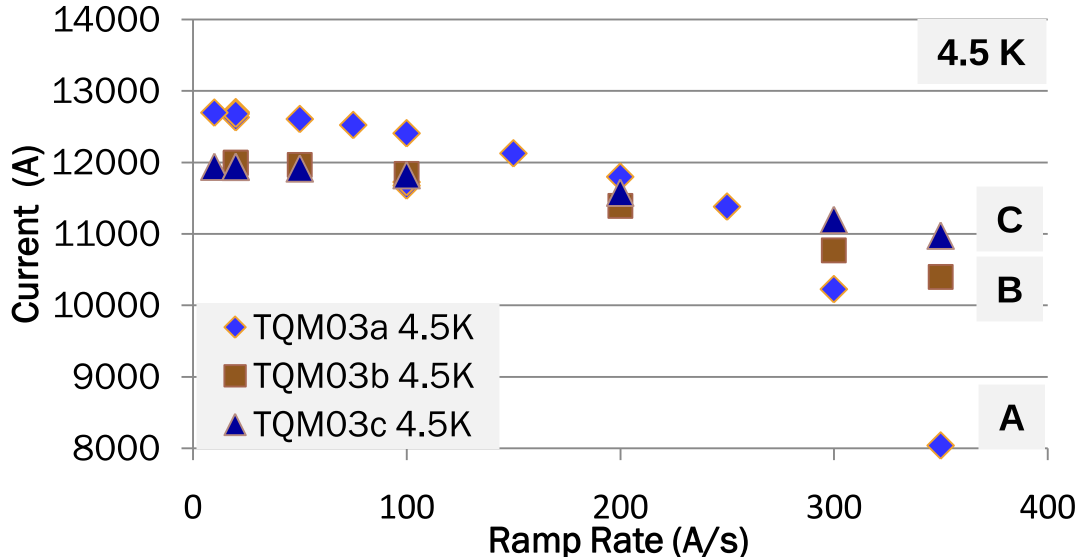


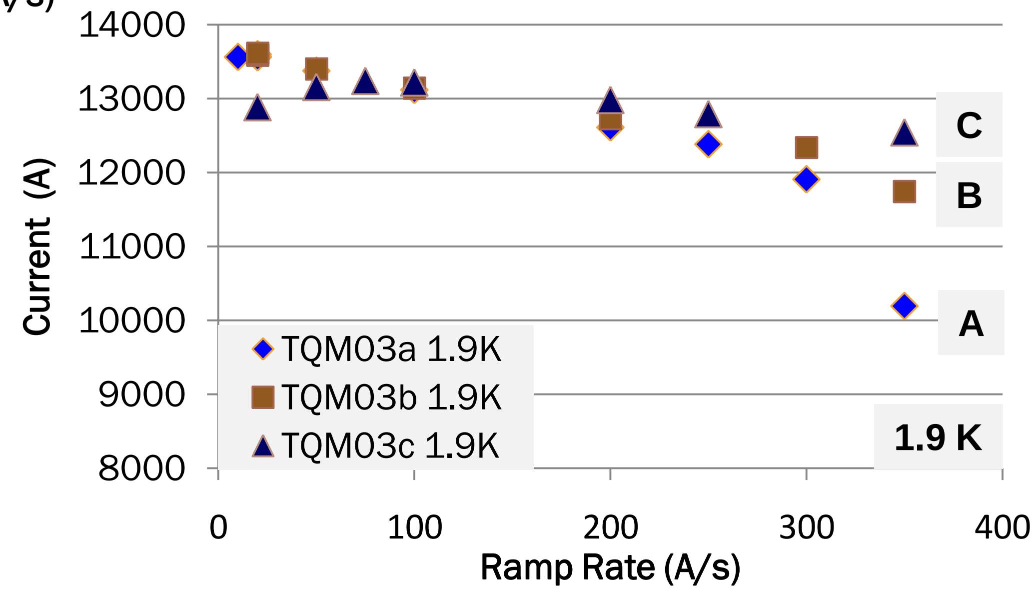
Coil cross section with flux density distribution in mirror magnet at 14 kA

<u>TQM03b</u> - all quenches in A10_B2

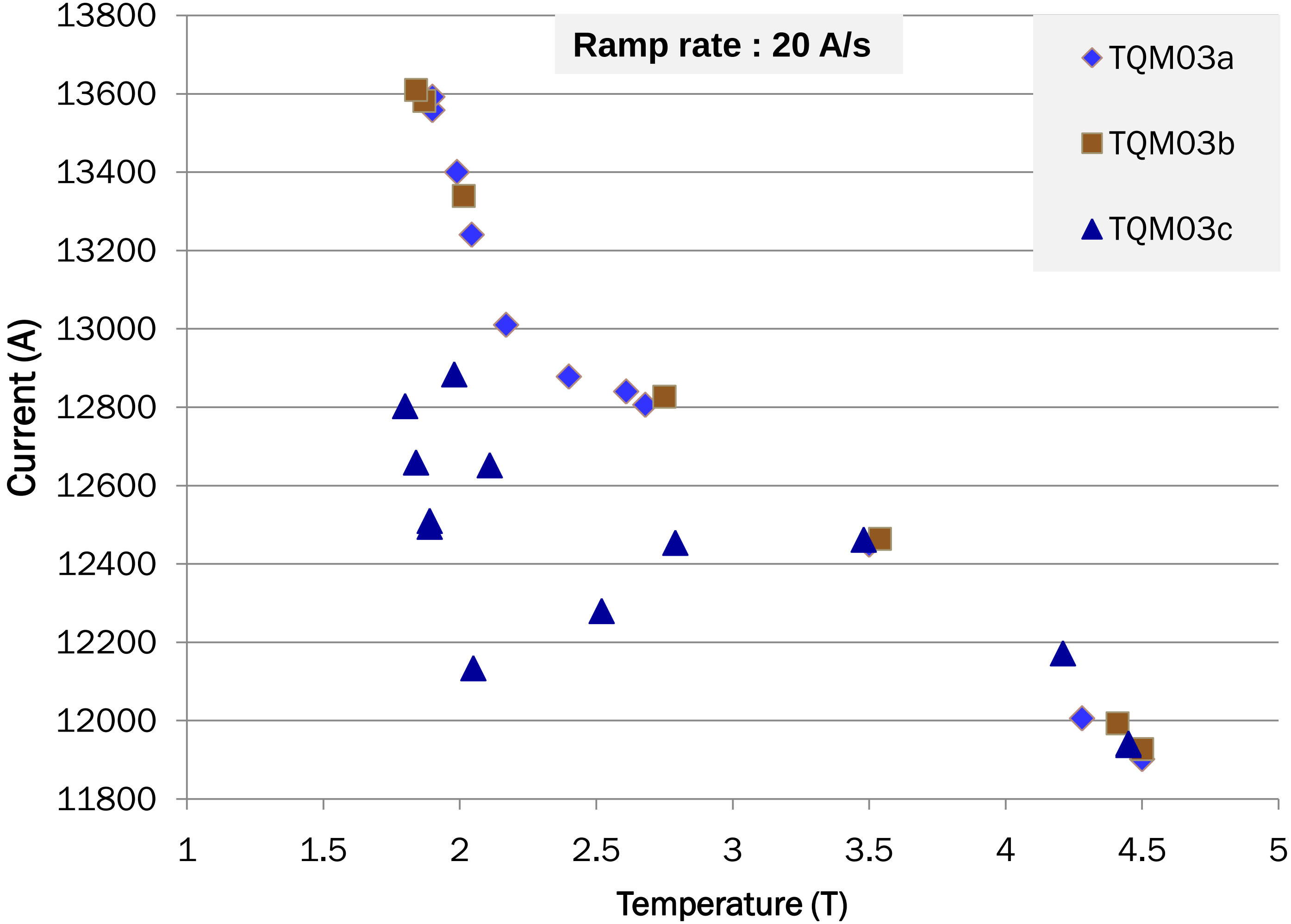
<u>TQM03c</u> - 4.5 K quenches in A10_B2
1.9 K quenches in A2_A3

TQM03 RAMP RATE DEPENDENCE





TQM03 TEMPERATURE DEPENDENCE



SUMMARY OF TQM03 MODELS

A “magnetic mirror” structure for quadrupole coil evaluation has been developed and successfully employed in testing at Fermilab

Coil with Nb_3Sn RRP-108/127 strand and new cable insulation (E-Glass tape) demonstrated excellent quench performance and improved stability at 1.9 K

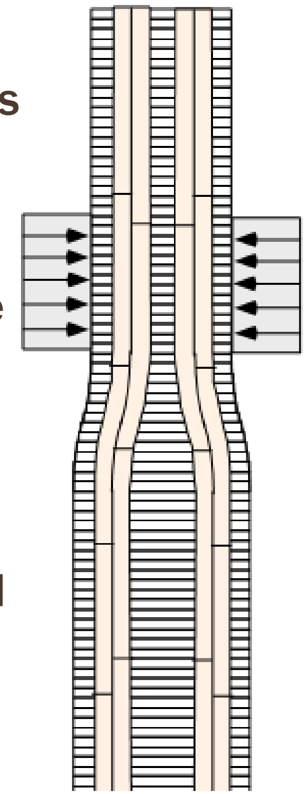
- RRP 108/127 is now LARP baseline strand
- E-glass insulation is considered for long LQ coils

Coil pre-stress up to ~185 MPa does not introduce significant degradation in conductor I_c (consistent with TQS03 test data). However noticeable degradation of conductor stability at 1.9 K was observed (TQM03c)

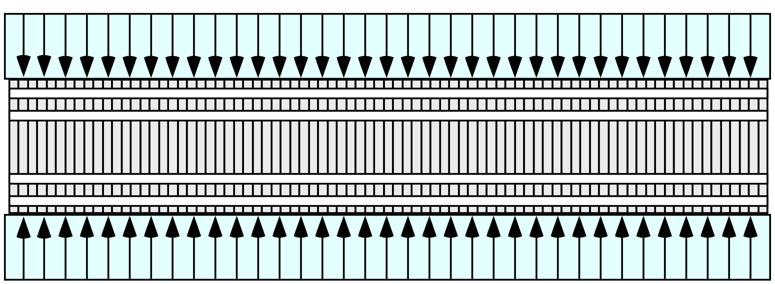
Next : New Nb_3Sn coil (RRP 108/127) with cored conductor is ready for test in mirror structure (TQM04)

TQC MAGNET WITH DIPOLE STYLE COLLARS

- Feasibility of quadrupole support structure and collaring procedure based on traditional quadrupole-style collar have been demonstrated in several TQC model magnets
  - Requires additional horizontal to vertical handling of the coils
  - Collaring using short vertical 4-jaw press with partial coil compression along the length
  - Time consuming process with many (~6-8) passes and some risk of damage to coils



- Dipole style collar design
  - Collaring using full-length horizontal press
  - Collaring in a single pass reducing coil degradation risks and construction time

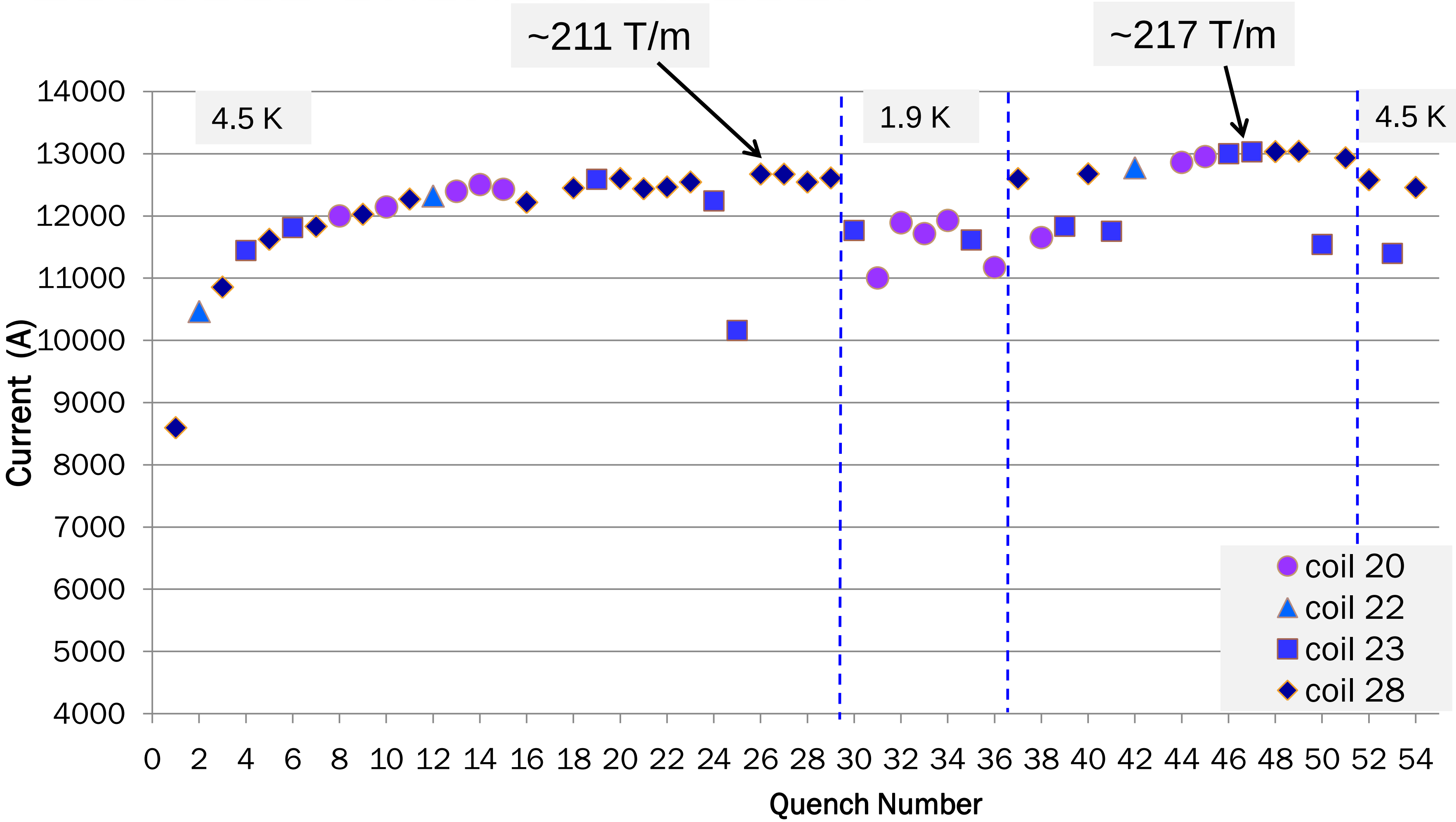


TQC02EB TEST AT FERMILAB

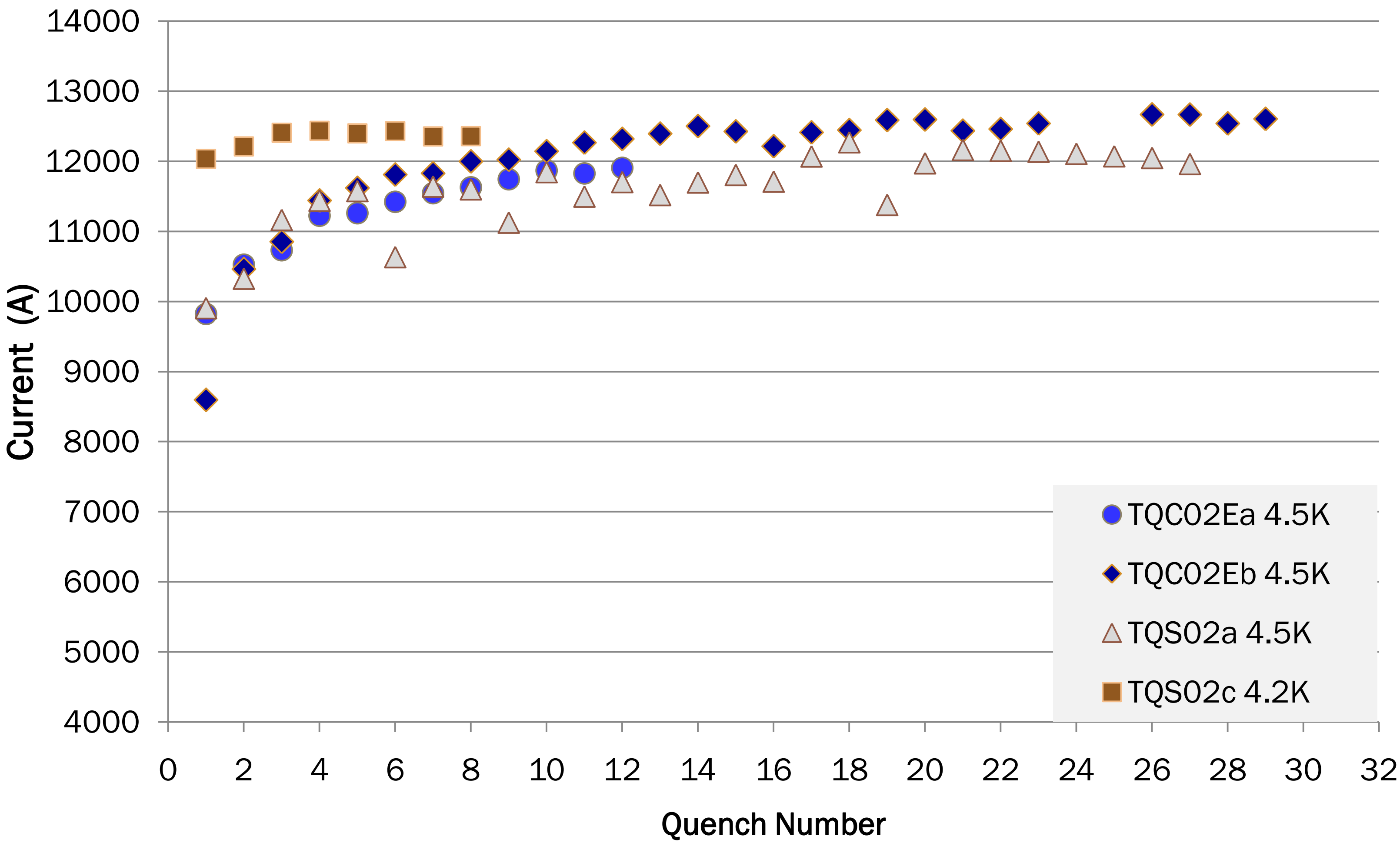
- Magnet was built with Nb_3Sn coils (RRP 54/61) already tested in both shell and collar structures
  - 4 variations of TQS02 magnet were tested at Fermilab and CERN
  - TQC02Ea with coils 20,21,22 and 23 previously tested at Fermilab
- Standard shim configuration with a target stress of ~120 MPa at 4.5 K
- First time dipole style collars are used in TQC magnet
- Coil alignment key installed

- Test at 4.5 K and 1.9 K included magnet training, ramp rate and temperature dependence study

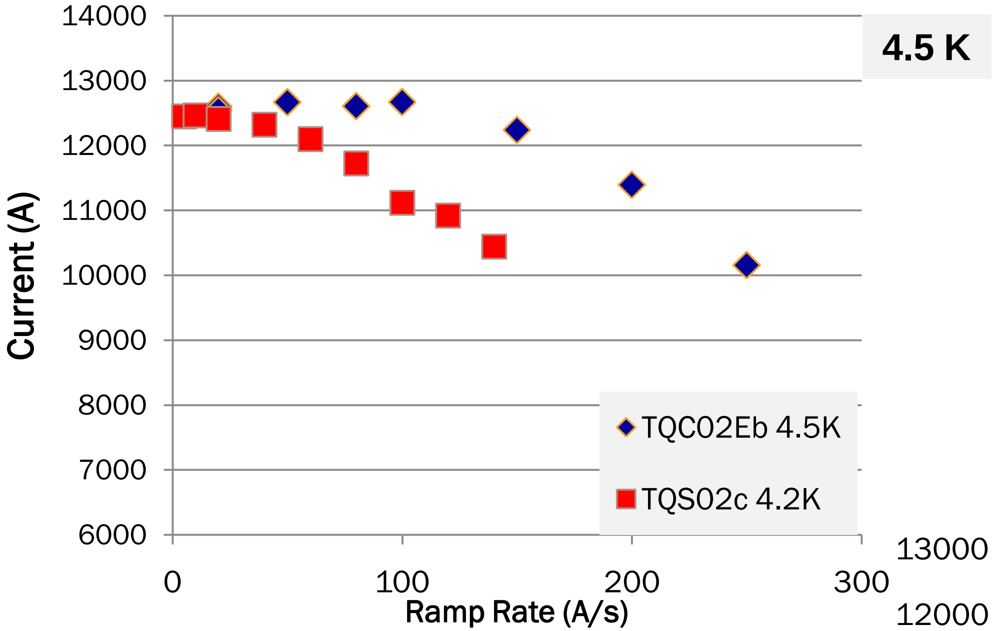
TQC02EB QUENCH HISTORY

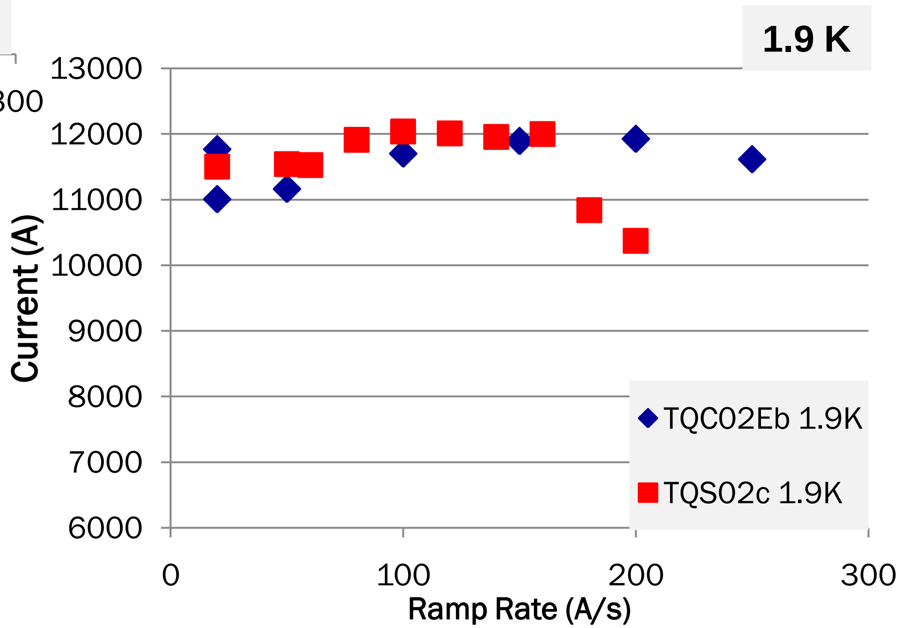


TQC02E AND TQS02 PERFORMANCE AT 4.5 K

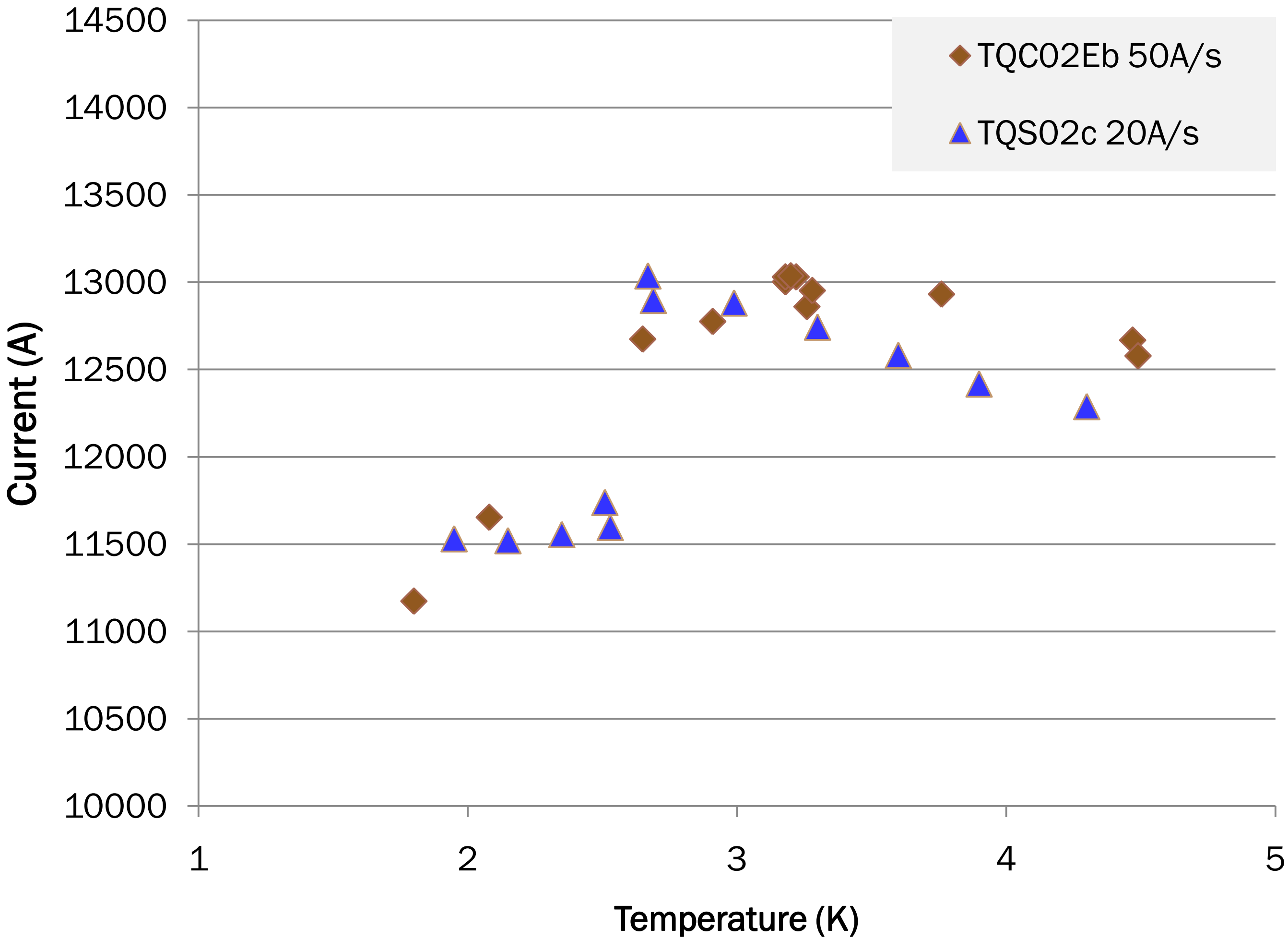


TQC02EB RAMP RATE DEPENDENCE





TQC02EB TEMPERATURE DEPENDENCE



SUMMARY ON TQC02EB TEST

The first Technology Quadrupole with a dipole style collar design - TQC02Eb - was built and tested successfully at Fermilab

TQC02Eb reached ~211 T/m field gradient at 4.5 K and ~217 T/m at 3.2K temperature

Coil quench performance in magnets of shell (TQS02) or collar (TQC02E) structure is consistent

- Multiple handling and test cycles demonstrates that the TQ Nb_3Sn coil design is robust

Magnetic field measurements do not show any significant distortions related to the dipole style collar design in TQC02Eb

CONCLUSIONS AND FUTURE PLANS

The quadrupole mirror structure, developed at Fermilab, has confirmed the expected technical performance and high efficiency

The mirror concept can be easily adapted to test long LQ or 120-mm diameter HQ coils

Future Plans:

- A Nb_3Sn coil (RRP 108/127) with stainless steel cored conductor is ready for test in the mirror structure (TQM04)
  - Standard S2-Glass sleeve insulation
  - Titanium pole pieces
- Work on a long mirror structure for LQM01 in progress
  - Mirror structure is available
  - Fabrication of long coil with Nb_3Sn 114/127 strand and E-Glass insulation has started
  - Cold test expected in September 2010
- Mirror structure for HQ coil test is available
  - Choice of coil and schedule under discussion
- Test of TQ coil impregnated with liquid polyimide (MATRIMID) – TQM05 (planned for FY 2011)

CONCLUSIONS AND FUTURE PLANS

Dipole style collar design and collaring process were developed and successfully tested at Fermilab using TQ coils

- Performance consistent with the test results from shell structure magnets (TQS02a/c) or collared structure magnet with a quadrupole style collar (TQC02Ea)
- Dipole style collar configuration can easily be adopted for long structures

- Next steps:
  - Test of Nb_3Sn coils made of RRP-108/127 strand using dipole style collars (expecting TQS03 coils in May)
  - Test of 4-m long quadrupole based on dipole style collars (recycle LARP LQ coils, planned for FY 2011)

BACKUP SLIDES

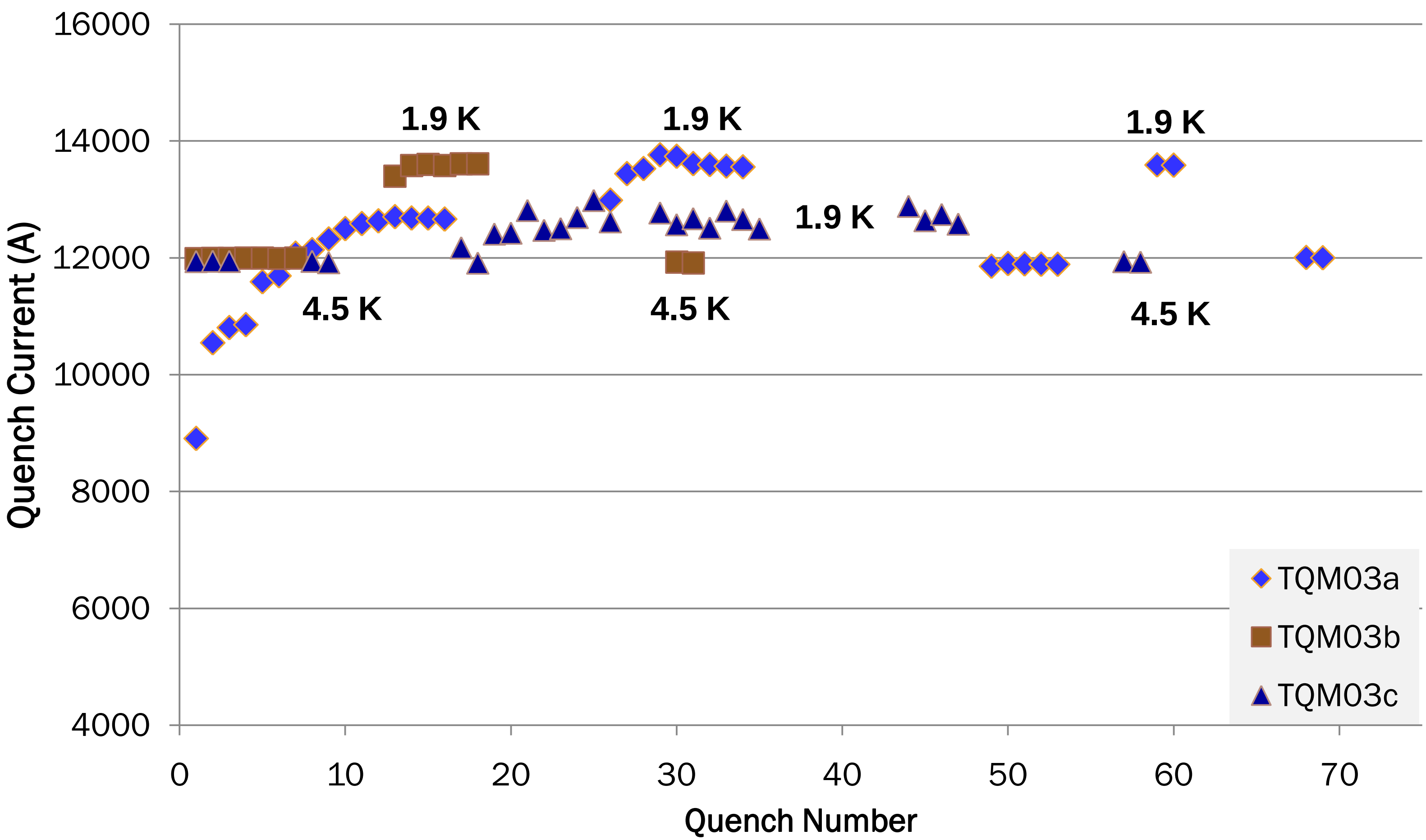
Magnetic Design - SSL

The estimated magnet quench currents based on the “reference” current density of 2800 A/mm^2 at 4.5 K and 1.9 K are shown below. This SSL is based on the mirror magnetic features and the presentation by Paolo Ferracin, “TQ Performance Overview” on Sept. 8, 2008 at the TQ discussion teleconference.

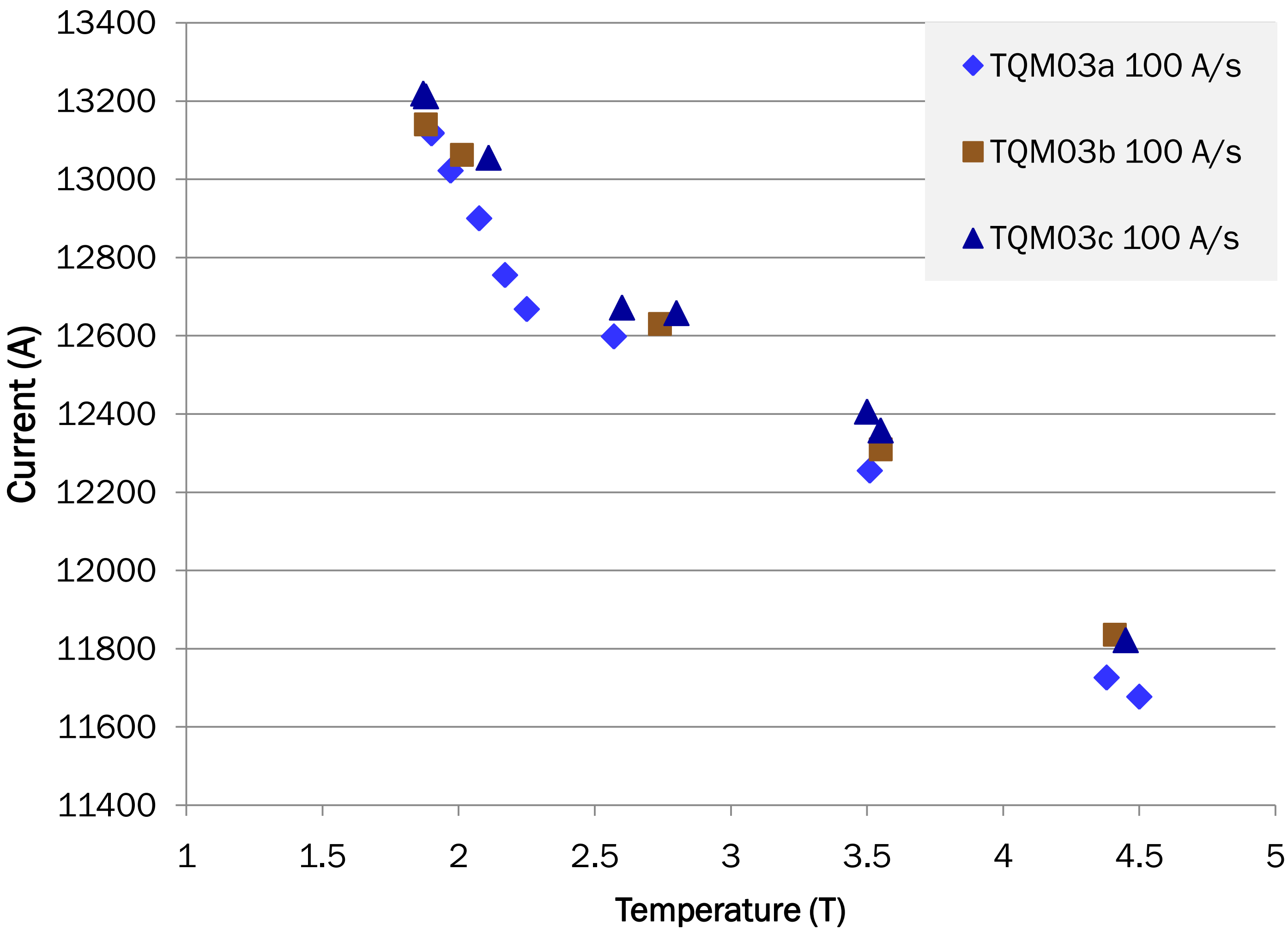
SSL in TQS, TQC and TQM structures compared.

Magnet	Iss (kA)	Iss (kA)
	4.3K-4.5K	1.9K
TQM01 (2800 A/mm^2)	13.0	14.4
TQS02 (2800 A/mm^2)	13.8	15.1
TQC02 (2800 A/mm^2)	13.9	15.1

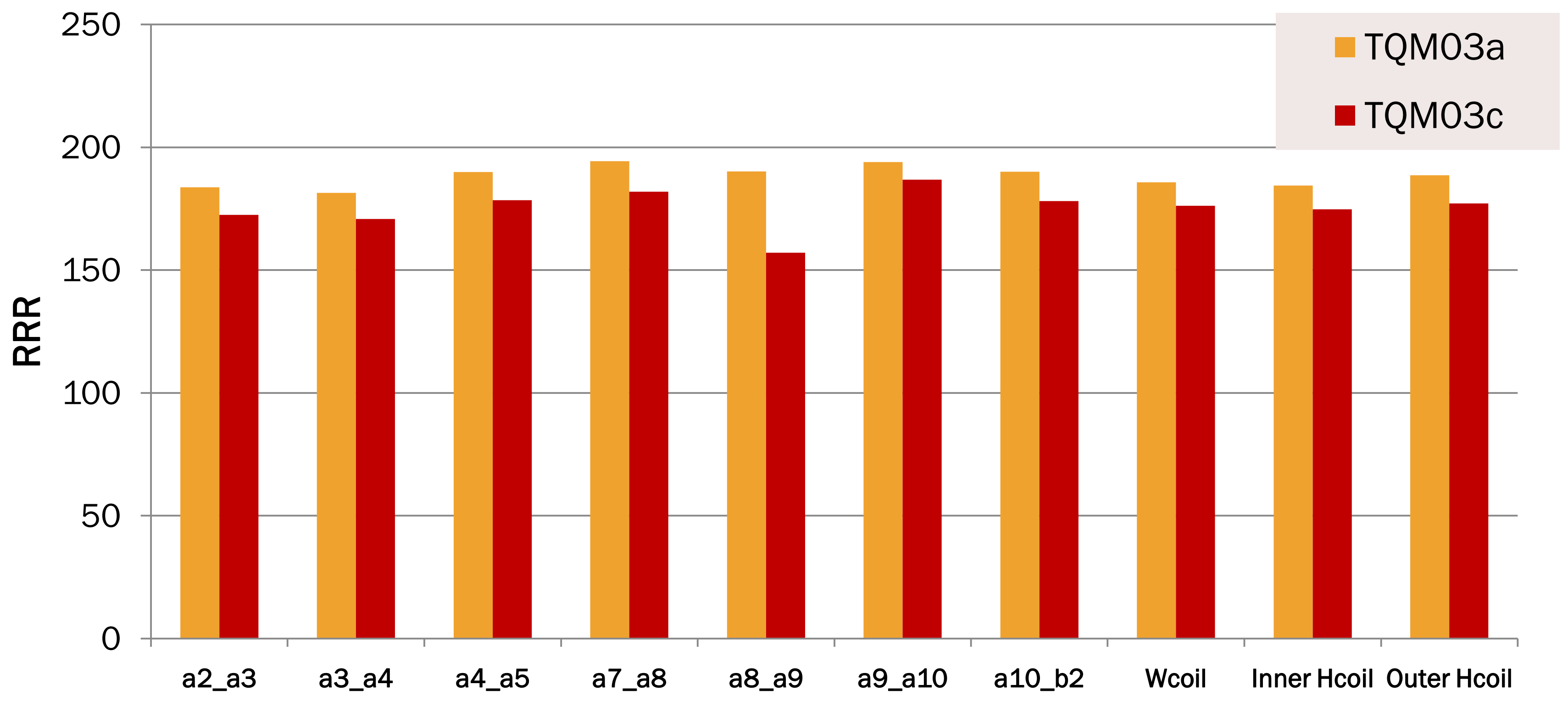
TQM03 QUENCH TRAINING



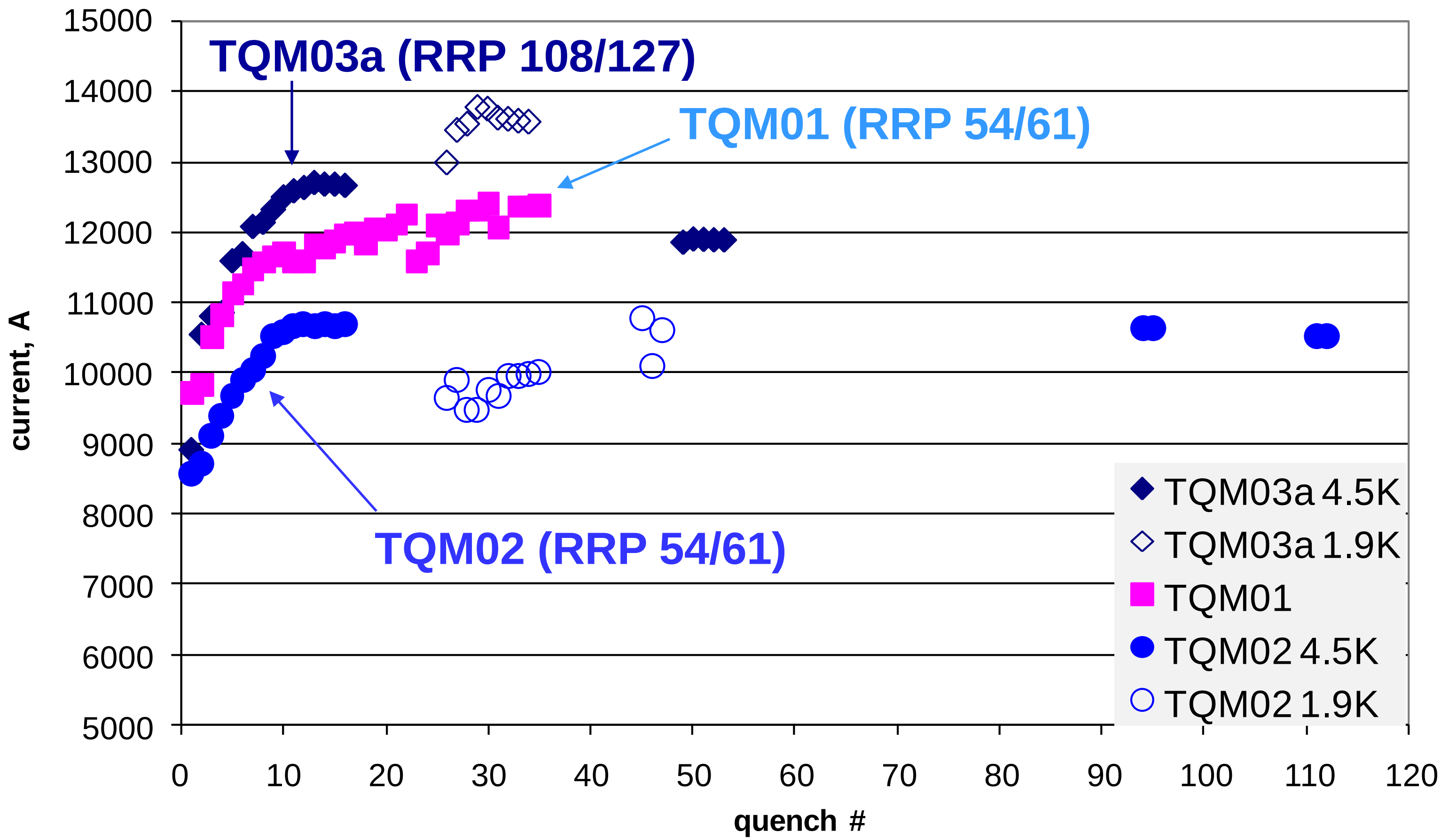
TQM03 TEMPERATURE DEPENDENCE



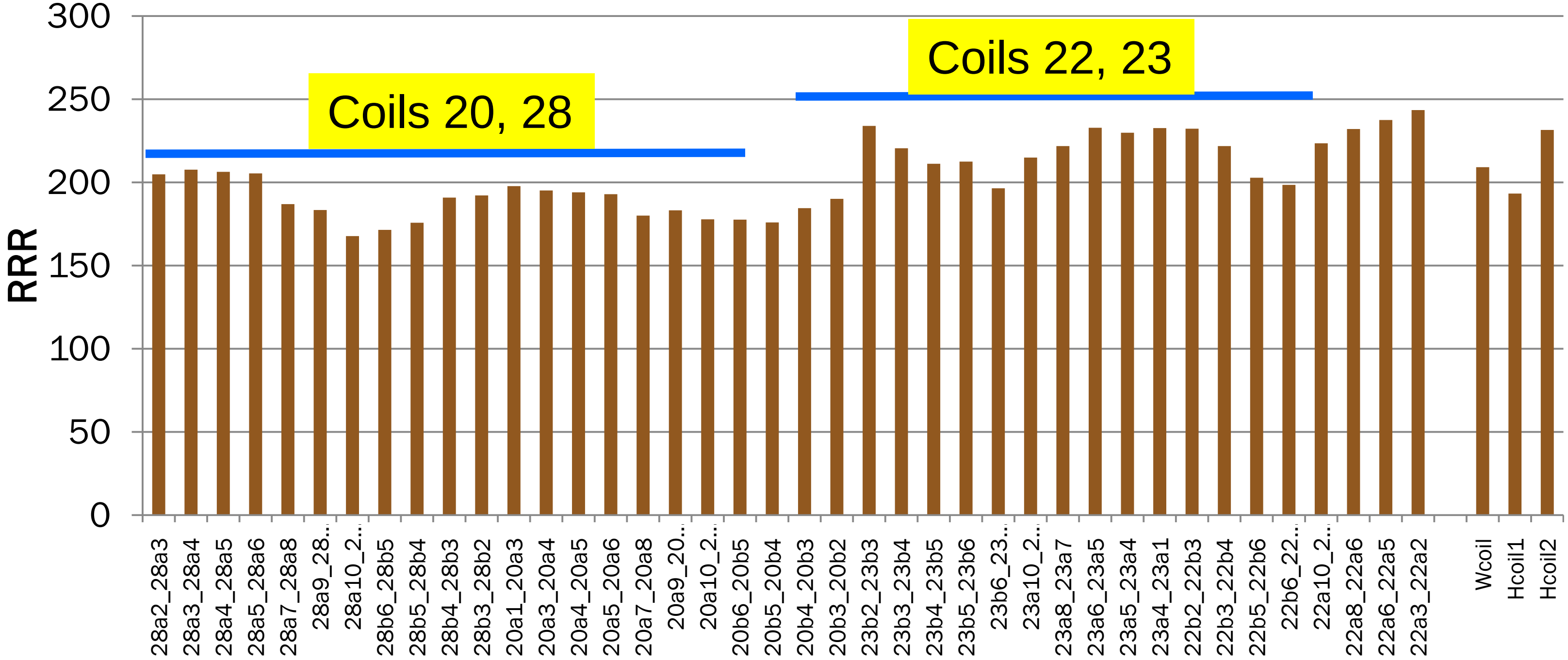
TQM03 RRR DATA



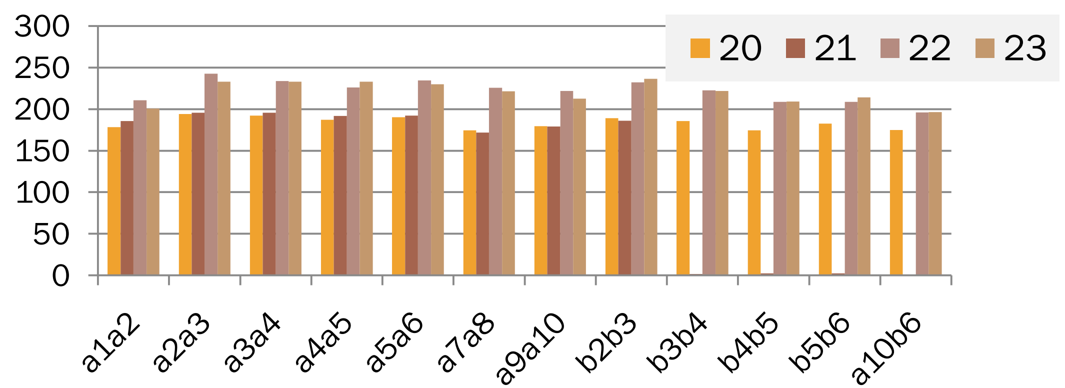
TQM01/02/03 MIRRORS



TQC02EB: RRR DATA



TQC02E RRR



MAGNETIC MEASUREMENTS AT 4.5 K

Measured gradient 111 T/m at 6500 A. Reference radius ~ 1inch
TF = 17.1 T/m/kA

n	TQC			TQS		
	calc	measured		calc	measured	
		01	02E		01	02
b_3	-	2.01	1.07	-	-1.46	2.98
b_4	-	-1.90	-2.92	-	-0.52	1.31
b_5	-	0.58	-2.11	-	3.06	-1.45
b_6	0.90	1.71	2.72	5.00	5.40	6.23
b_7	-	0.07	-0.37	-	0.07	0.05
b_8	-	0.01	0.12	-	-0.11	-0.13
b_9	-	0.04	0.08	-	0.02	0.10
b_{10}	0.00	-0.06	-0.02	-0.04	0.02	-0.05
a_3	-	-1.72	1.17	-	4.41	0.66
a_4	-	0.62	1.47	-	-1.99	0.82
a_5	-	-1.33	-3.31	-	0.71	-1.50
a_6	-	-0.10	0.59	-	-0.37	0.12
a_7	-	0.10	-0.09	-	-0.11	-0.01
a_8	-	-0.03	-0.19	-	-0.18	-0.10
a_9	-	0.08	0.11	-	-0.02	0.02
a_{10}	-	0.00	-0.08	-	0.00	-0.08

TQC02Eb averaged body harmonics

	b	a
3	-3.57	4.71
4	-3.34	-0.29
5	0.20	-0.76
6	-0.62	0.05
7	0.03	0.10
8	-0.07	0.10
9	0.06	-0.02
10	0.01	0.02