BNL - FNAL - LBNL - SLAC

Technology Quadrupole Series (TQ)

LARP DOE Review

June 12-14, 2006

Gian Luca Sabbi

TQ Goals, Implementation & Parameters

Objective: develop the technology base, in preparation for LQ & HQ:

- evaluate conductor and cable performance
- develop and select coil fabrication procedures
- compare mechanical design concepts and support structures
- optimized models: ***achieve 200 T/m after training & thermal cycle***

Two series of models, same coil design, different mechanical support:

- TQC models: collar & stainless steel shell; low axial pre-load
- TQS models: aluminum shell over iron yoke; high axial pre-load

Magnet parameters:

- 1 m length, 90 mm aperture, 11-13 T coil peak field
- Nominal gradient 200 T/m; maximum gradient 215-265 T/m

FY06 Tasks and Budget

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FY06 WBS & Budget (k$)		FNAL	LBNL	Total
Model Magnet R&D	Sabbi	1334	1063	2397
2.2.1.1 TQS (Technology Quad Shell)	Caspi	392	784	1176
2.2.1.2 TQC (Technology Quad Collar)	Bossert	942	279	1221

Technology Quad Shell – TQS:

- TQS01 (TQS baseline)
- TQS01b (replace one coil)
- TQS01c (increase pre-load)
- TQS02 (new coils - RRP)

Technology Quad Collar – TQC:

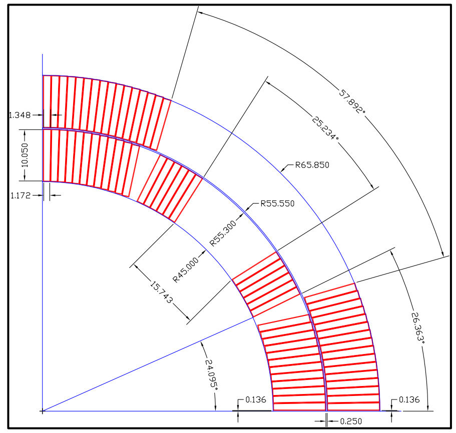
- TQC01 (TQC baseline)
- TQC01b (change collars)
- TQC02 (new coils - RRP)

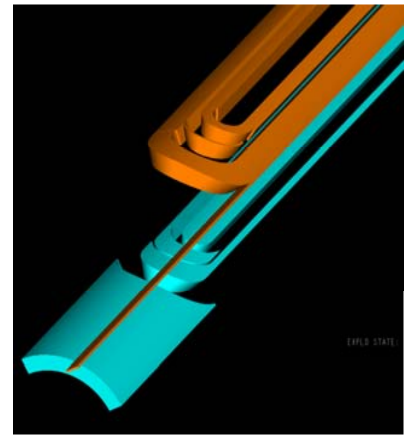
TQS01, TQC01 and TQS01b/c will be completed in FY06
TQC01b/c, TQC02 and TQS02 will be completed in FY07

Coil Design and Fabrication

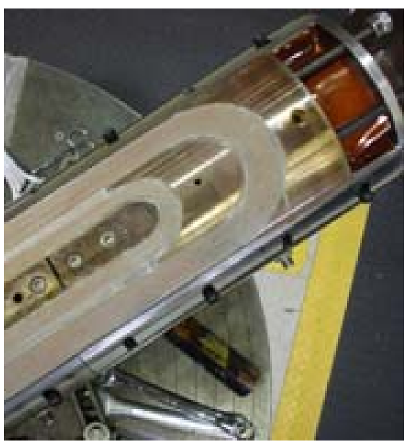
Design features:

- Double-layer, shell-type
- One wedge/octant (inner layer)
- TQ01: OST-MJR strand, 0.7 mm
- TQ02: OST-RRP strand, 0.7 mm
- 27-strand, 10.05 mm width
- Insulation: S-2 glass sleeve



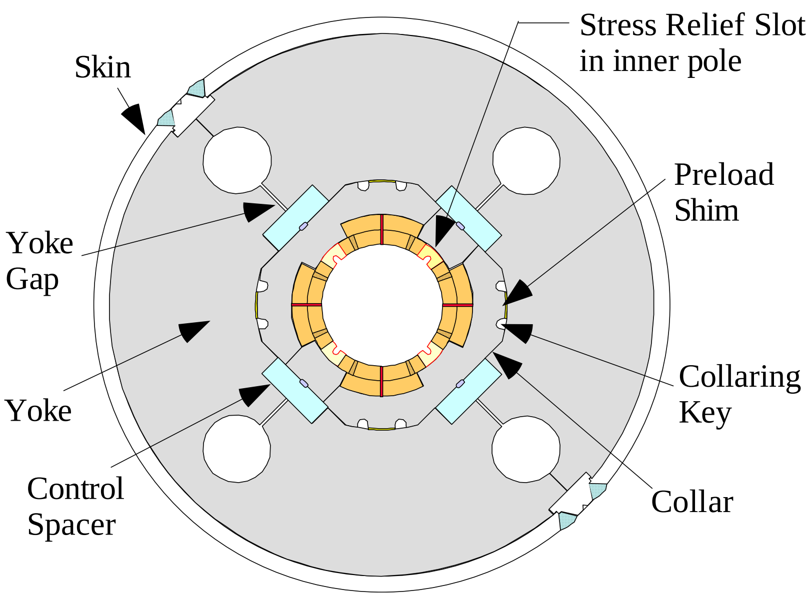


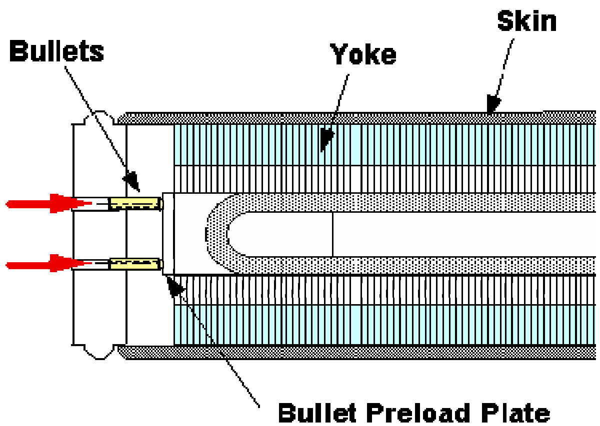
Winding & curing (FNAL - all coils)



Reaction & potting (LBNL - all coils)

TQC Mechanical Support Concept

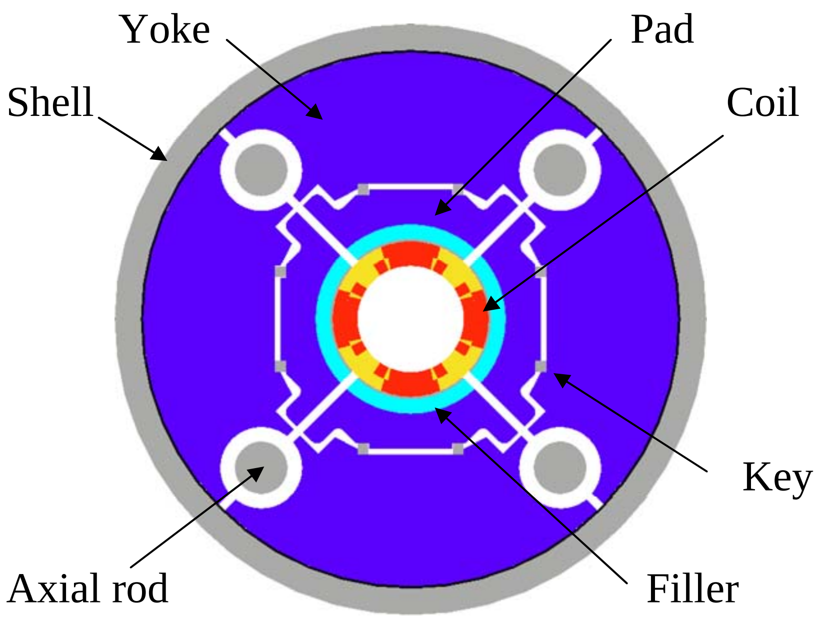


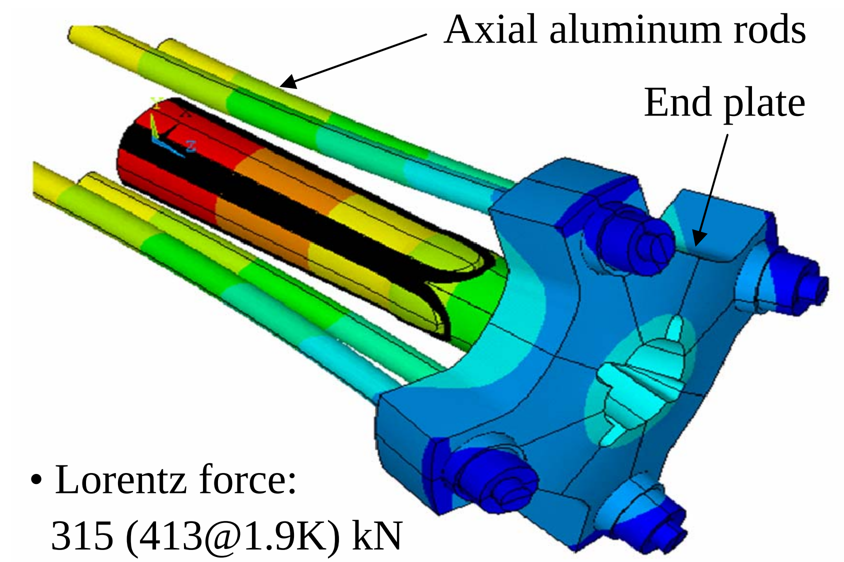


- **Baseline: tabbed collars in body, round collars in ends**
- **Axial force of 14 kN applied by bullets and end plates**
- **Coil end to bullet plate contact is expected at all times**

- Support structure is derived from MQXB Quad and FNAL Nb_3Sn dipoles
- Stainless steel collars and shell (12 mm thick) share transverse pre-load
- End plates and bullets provide rigid boundary for axial Lorentz forces
- Stress relief slot in the inner layer pole to limit coil stress at cool-down
- Control spacers for collared coil alignment and yoke motion control

TQS Mechanical Support Concept





- Lorentz force: 315 (413@1.9K) kN
- Applied axial pre-load: **800 kN**

- Support structure is derived from LBNL SM, RD and HD dipole series
- Aluminum shell over iron yoke for large pre-stress increase at cool-down
- Aluminum rods provide large axial pre-load to eliminate end gaps
- Assembly based on bladders and keys, easy to adjust pre-load conditions
- Issues: coil alignment/field quality (SQ-TQ), length scale-up (LR)

TQ Performance References & Range

J_c = 2 kA/mm²
(12 T, 4.2 K)
MJR strand
Conservative HT
"First models"

Magnet	T_{op} [K]	G_{ss} [T/m]	$B_{ss}^{(body)}$ [T]	I_{ss} [kA]
TQS	4.2	222	11.4	12.5
	1.9	239	12.3	13.6
TQC	4.2	215	11.2	13.0
	1.9	233	12.1	14.1

J_c = 3 kA/mm²
(12 T, 4.2 K)
RRP strand
Aggressive HT
"Final models"

Magnet	T_{op} [K]	G_{ss} [T/m]	$B_{ss}^{(body)}$ [T]	I_{ss} [kA]
TQS	4.2	245	12.6	13.9
	1.9	264	13.5	15.1
TQC	4.2	239	12.4	14.4
	1.9	255	13.2	15.5

- I_c data from extracted strands determine common performance reference for TQS/TQC
- Issue: relatively wide range of extracted strand I_c (TQ01: 1862-1984 A/mm² @12T, 4.2K)
- *Reference magnet performance limits* for a given test run are adjusted for measured T_{bath}
- Actual *conductor-limited quench levels* may be lower due to other degradation effects

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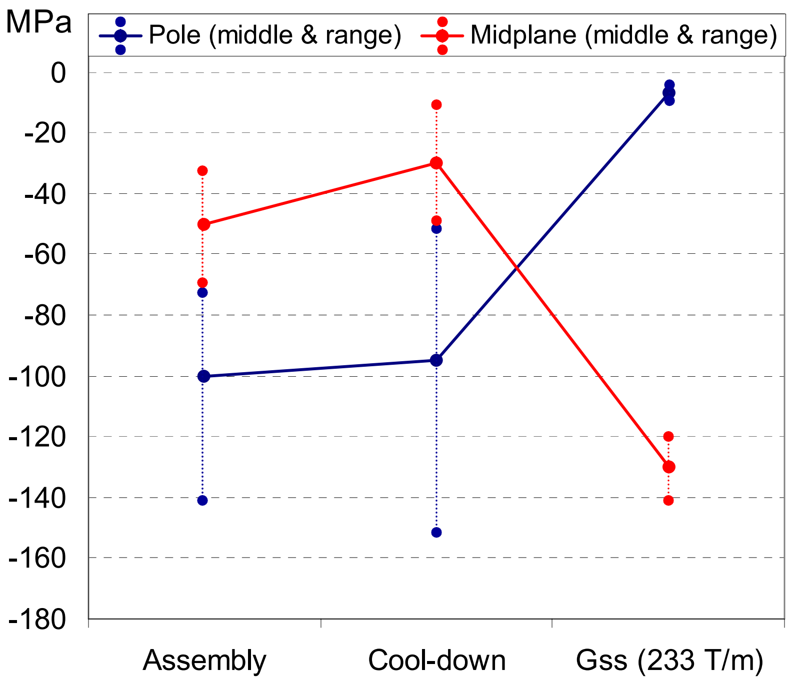
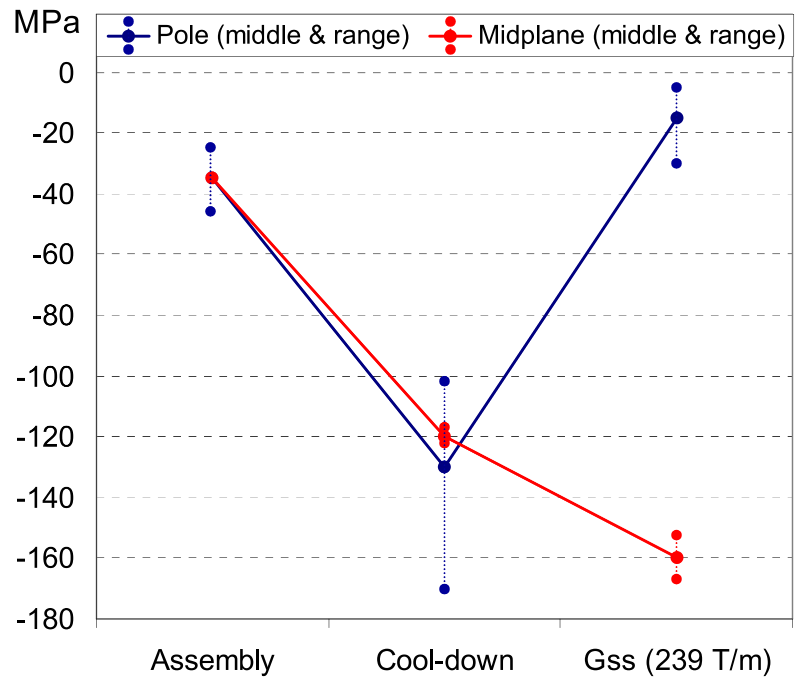
Coil Stress Comparison (2D FEA)

TQC Layer 1 stress - σ_θ

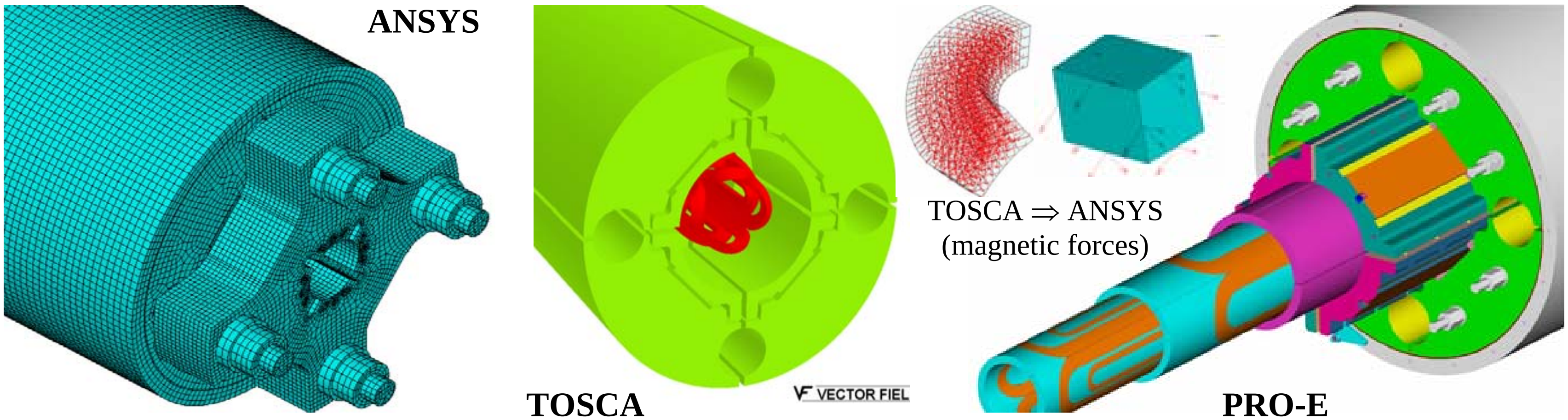


TQS Layer 1 stress - σ_θ

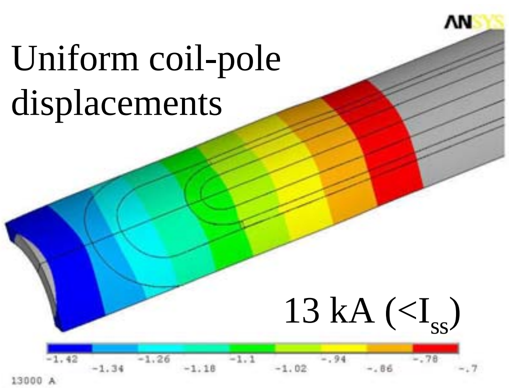


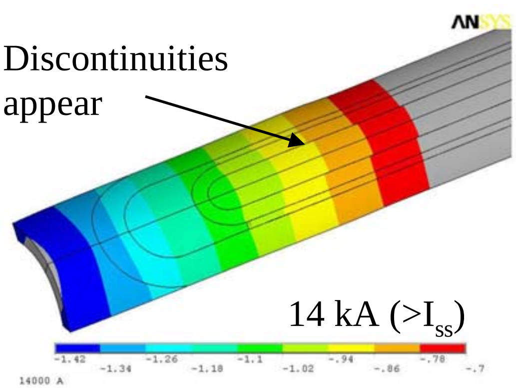
- Main differences: warm pre-load, cool-down effect, stress uniformity (pole to mid-plane)
- Peak stresses are high & no consensus on degradation limits → cable testing required
- Peak stress ~20 MPa difference: stress-relief slot, different G_{ss} & pole stress range at G_{ss}
- Mechanical review recommendations: perform cable tests; add pole-stress relief in TQS
- Detailed FEA shows that 3D effects have a significant impact on actual coil stresses

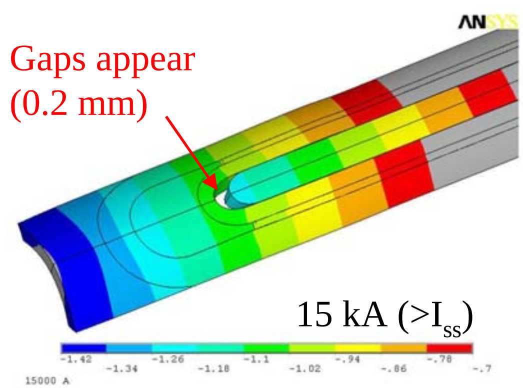
TQS 3D FEA



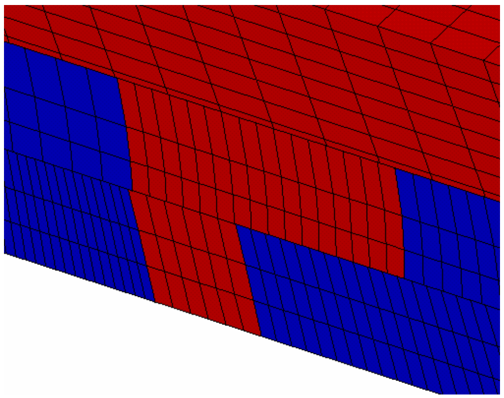
- Interfaces for integrated use of CAD, mechanical and electro-magnetic packages
- Studies of the effects of friction among interfaces (coil-pole, coil-pads, yoke-shell)
- Design goal: *maintain contact between coil and structure at all steps and locations*





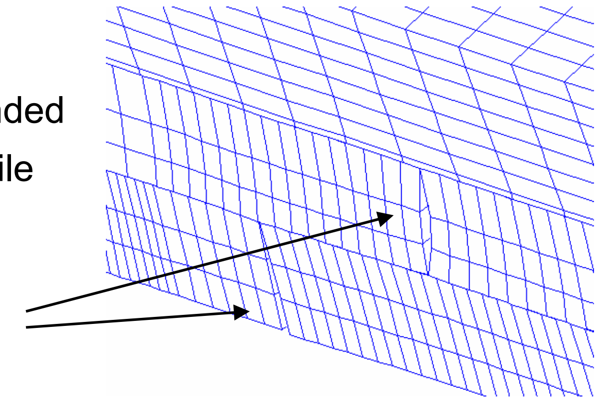


TQC 3D FEA

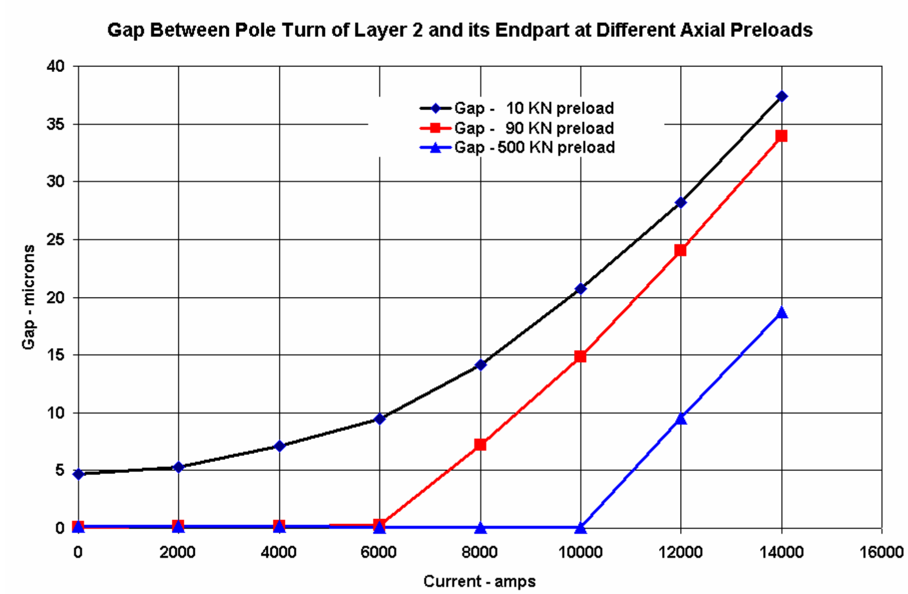


<u>Modeling of epoxy bonding</u>:

- The coils and parts are initially bonded
- Bonded interface releases for tensile stress beyond 30 MPa
- Interface elements with stresses above σ_t are removed allowing surfaces to separate



- Lorentz forces are calculated using a ANSYS magnetic model (SOURC36 elements) and then transferred to the nodes of a structural model (SOLID45 elements) with same mesh
- Calculated effects (end gaps) depend on collar and iron axial stiffness, and slip-or-stick assumptions at interfaces (collar/iron/skin)



TQC Mechanical Models and Assembly

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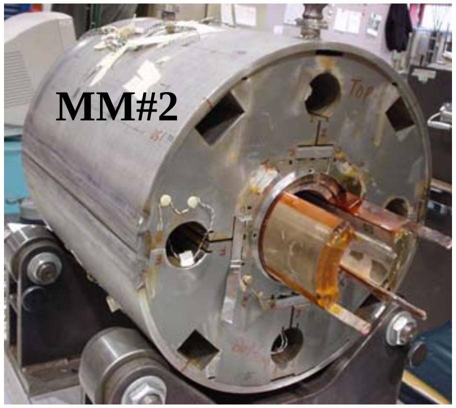
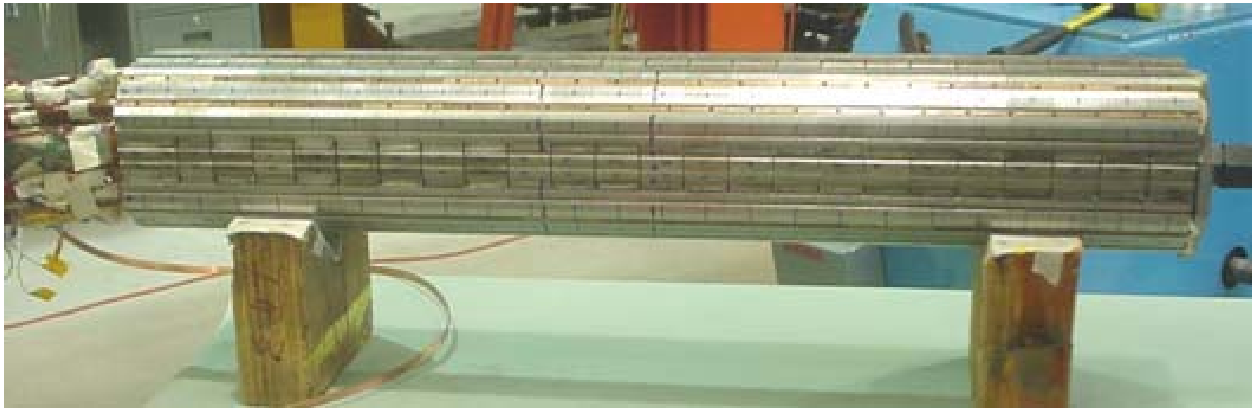
Five TQC mechanical models were built and tested between October 2005 and April 2006

Goals:
- Understand coil size, effect of mid-plane shims and collar-yoke shims
- Check FEA analysis predictions for assembly and cool-down pre-loads
- Optimize collaring and yoke welding process for brittle Nb_3Sn coils

Results:
- Full-round collars are used until coil preload with tabbed collars is understood
- Required collaring pre-load of 70 MPa is obtained with 3 mil mid-plane shims
- Welding operation provides acceptable force to control spacers
- TQC01 coils has been instrumented, assembled, insulated, collared and keyed
- Harmonic measurements have been completed, currently setting up for yoking





TQS Mechanical models and Assembly

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- MM#1: first check of quad assembly steps, LN cool-down (dummy coil, no axial rods)
- MM#2: full assembly and LN cool-down test (practice coils, shell/rods gauges)
- MM#3: full assembly and controlled cool-down (real coils, full set of gauges)

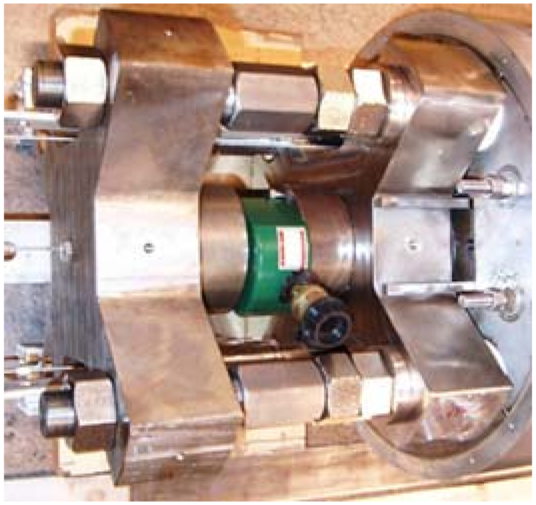
Findings:

- Developed assembly procedure and measured cool-down effects for shell and rods
- Strain gauges on bronze pole provided useful data on stress conditions, homogeneity
- Friction among structural elements plays crucial role: improved FEA models

Coil-pad and yoke-shell sub-assembly

Transverse pre-load

Axial pre-load



TQS01 Performance Analysis

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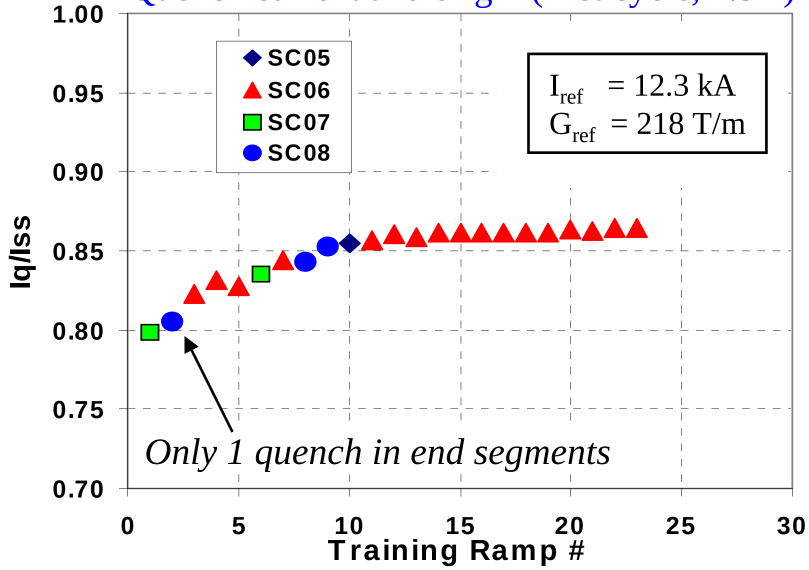
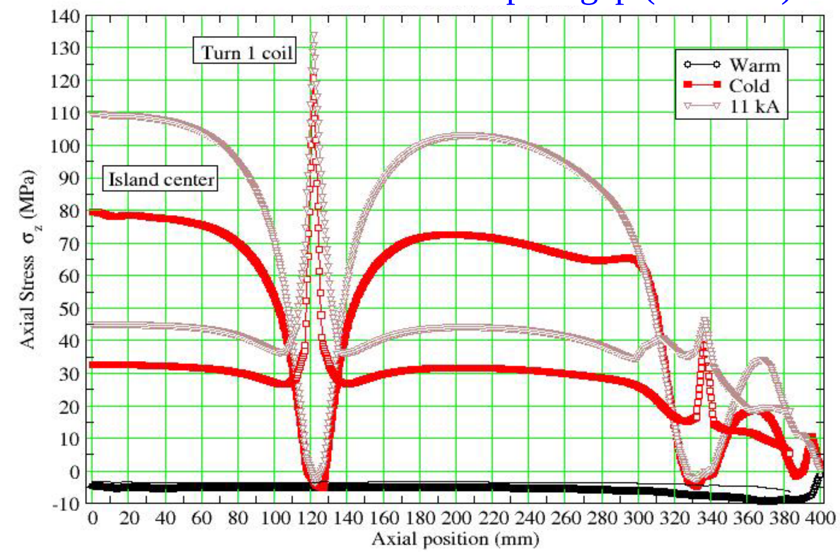
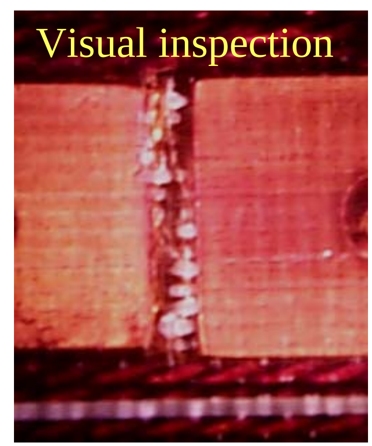
Quench current and origin (first cycle, 4.5K)



Calculated axial stress at pole gap (3D FEA)





Analysis findings:

- Performance limit in the "pole-gap" area of coil 6
- FEA results: coil axial tension spike in gap area
- Post-test inspection shows epoxy tearing (all coils)

Corrective actions:

- TQS01b: replace coil 6 and check reproducibility
- TQC02: eliminate co-planar gaps in the two layers
- TQS02: change materials for pole and/or structure

Progress since DOE Technical Review

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- **Coil fabrication:**
  - TQS01 + TQC01 production coils and 2 spare coils completed
  - Further optimization is needed, but no major design changes
- **Mechanical design:**
  - Mechanical review: designs are consistent with Nb_3Sn experience & FEA
  - Constantly improving FEA models based on prototype measurements
  - Already starting to converge towards an optimal set of design features
- **Feedback from TQS01 test:**
  - First quench > 0.80 I_{ss}; I_{max}= 0.87 I_{ss}; second cycle starts at 84%
  - Axial support: minimal end quenching, no degradation (up to 87% level)
  - ***Excellent result for first prototype of a challenging, new design***
- **Next steps:**
  - Complete TQC01 assembly and replace limiting coil in TQS01
  - TQC01 & TQS01b tests in July-August
  - TQC02 coil fabrication starting in June, TQS02 starts in September

Preliminary FY07 Plan

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MSC Guidance:

- Model magnet R&D effort continues at FY06 funding levels
- Meet TQ milestones to support critical decisions for LQ
- Design/procure LQ tooling and start practice coil fabrication
- Start HQ engineering design and tooling design

Preliminary TQ plan:

Model	Features	FY07 activities	Budget
TQC01b	Re-assemble & test with tabbed collars	Test	55
TQC01c	Adjust pre-load configuration	Fabricate & test	205
TQC02	New conductor, structure optimization	Fabricate & test	359
TQS02	New conductor, structure optimization	Fabricate & test	430
TQ03	LQ reference or TQ02 backup	Fabricate coils	800

Basis for the FY07 Plan

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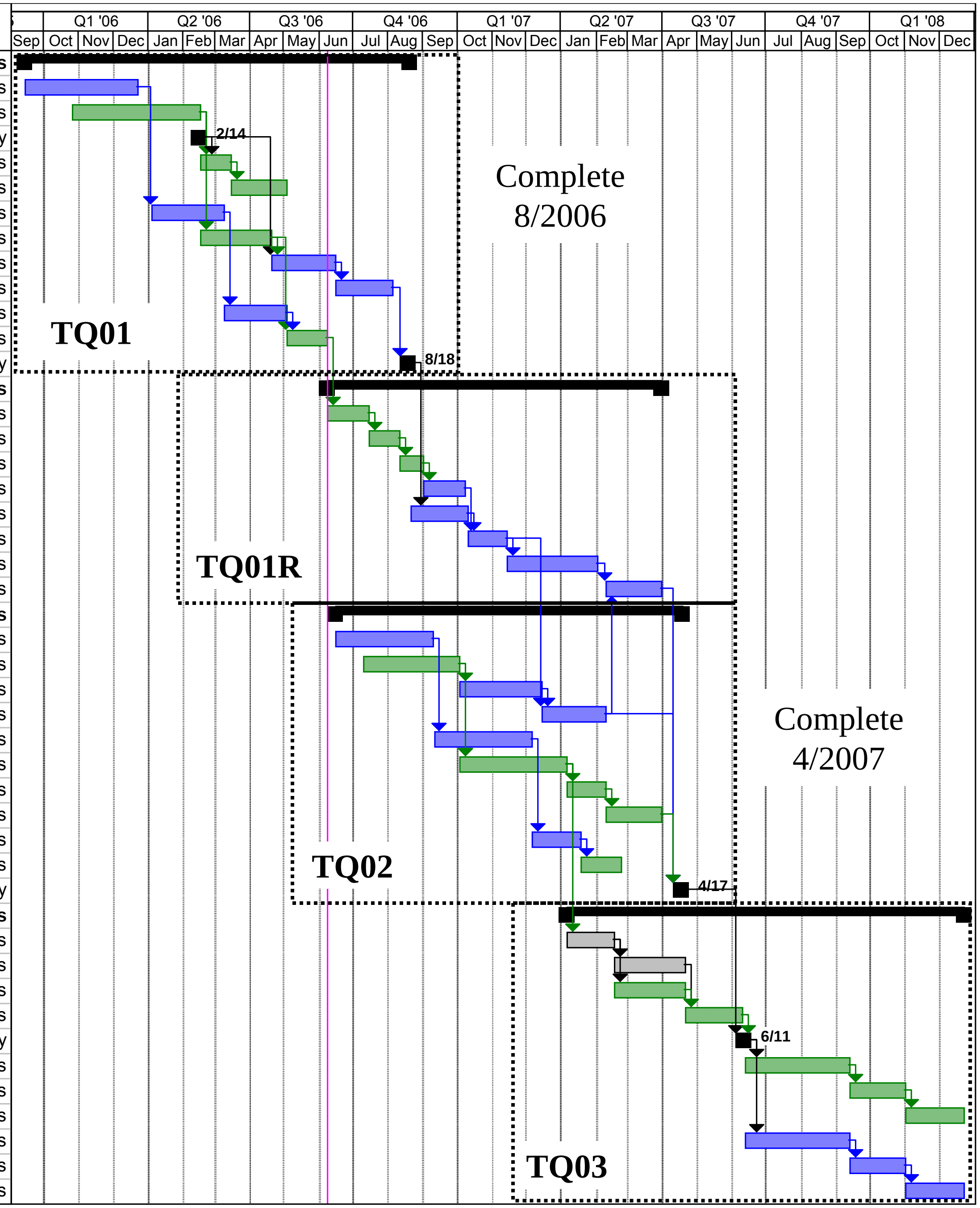
- **Schedule information from TQS01 an TQC01**
  - More accurate information on sub-task requirements
- **Feedback from TQS01 test**
  - First quench above 80% of 4.5 K short sample; max quench at 87%
  - Maximum gradient achieved (197 T/m @ 3.2K) is close to TQ reference
  - Test results and FEA analysis indicate a clear optimization strategy
  - We are on track to meet the LARP Magnet R&D objectives
- **TQS01 & TQC01 coil fabrication approach was successful**
  - Good quality and consistency of fabricated coils
  - Efficient use of resources and facilities; program and team integration
- **TQS01 test information is available before start of TQC02 winding**
  - Optimization: pole piece design near gaps and layer transition; end parts
- **Recommendations from TQ the mechanical review**
  - Extract maximum information at each step; explore variants

TQ Plan – Updated June 12, 2006

Q1-06 Q2-06 Q3-06 Q4-06 Q1-07 Q2-07 Q3-07 Q4-07 Q1-08

ID	Task Name	Start	Finish	Duration
1	**TQS01 & TQC01**	**Tue 9/13/05**	**Fri 8/18/06**	**231 days**
2	TQS01 winding/curing	Tue 9/13/05	Wed 12/21/05	70 days
3	TQS01 reaction/potting	Tue 10/25/05	Tue 2/14/06	70 days
4	TQ01 mech. design review	Tue 2/14/06	Tue 2/14/06	1 day
5	TQS01 assembly	Wed 2/15/06	Tue 3/14/06	20 days
6	TQS01 test	Wed 3/15/06	Tue 5/2/06	35 days
7	TQC01 winding/curing	Tue 1/3/06	Tue 3/7/06	45 days
8	TQC01 reaction/potting	Wed 2/15/06	Tue 4/18/06	45 days
9	TQC01 assembly	Wed 4/19/06	Wed 6/14/06	40 days
10	TQC01 test	Thu 6/15/06	Thu 8/3/06	35 days
11	TQ01 spares winding/curing	Wed 3/8/06	Tue 5/2/06	40 days
12	TQ01 spares reaction/potting	Wed 5/3/06	Wed 6/7/06	25 days
13	TQ1 evaluation review	Fri 8/18/06	Fri 8/18/06	1 day
14	**TQ01 Optimization**	**Thu 6/8/06**	**Thu 3/29/07**	**201 days**
15	TQS01b assembly	Thu 6/8/06	Thu 7/13/06	25 days
16	TQS01b test	Fri 7/14/06	Thu 8/10/06	20 days
17	TQS01c assembly & shipping	Fri 8/11/06	Thu 8/31/06	15 days
18	TQS01c test	Fri 9/1/06	Fri 10/6/06	25 days
19	TQC01b Assembly	Mon 8/21/06	Mon 10/9/06	35 days
20	TQC01b test	Tue 10/10/06	Mon 11/13/06	25 days
21	TQC01c Assembly	Tue 11/14/06	Thu 2/1/07	50 days
22	TQC01c test	Fri 2/9/07	Thu 3/29/07	35 days
23	**TQC02 & TQS02**	**Thu 6/15/06**	**Tue 4/17/07**	**209 days**
24	TQC02 winding/curing	Thu 6/15/06	Fri 9/8/06	60 days
25	TQC02 reaction/potting	Mon 7/10/06	Mon 10/2/06	60 days
26	TQC02 assembly	Tue 10/3/06	Wed 12/13/06	50 days
27	TQC02 test	Thu 12/14/06	Thu 2/8/07	35 days
28	TQS02 winding/curing	Mon 9/11/06	Tue 12/5/06	60 days
29	TQS02 reaction/potting	Tue 10/3/06	Thu 1/4/07	60 days
30	TQS02 assembly	Fri 1/5/07	Thu 2/8/07	25 days
31	TQS02 test	Fri 2/9/07	Thu 3/29/07	35 days
32	TQ02 spares winding/curing	Wed 12/6/06	Wed 1/17/07	25 days
33	TQ02 spares reaction/potting	Thu 1/18/07	Wed 2/21/07	25 days
34	TQ2 evaluation review	Tue 4/17/07	Tue 4/17/07	1 day
35	**TQS03 & TQC03**	**Fri 1/5/07**	**Fri 12/21/07**	**246 days**
36	Coil optimization	Fri 1/5/07	Thu 2/15/07	30 days
37	Tooling, parts	Fri 2/16/07	Thu 4/19/07	45 days
38	Cable fabrication/insulation	Fri 2/16/07	Thu 4/19/07	45 days
39	Practice coils	Fri 4/20/07	Fri 6/8/07	35 days
40	TQ03 readiness review	Mon 6/11/07	Mon 6/11/07	1 day
41	TQS03 coil fabrication	Tue 6/12/07	Wed 9/12/07	65 days
42	TQS03 Assembly	Thu 9/13/07	Wed 10/31/07	35 days
43	TQS03 test	Thu 11/1/07	Fri 12/21/07	35 days
44	TQC03 coil fabrication	Tue 6/12/07	Wed 9/12/07	65 days
45	TQC03 Assembly	Thu 9/13/07	Wed 10/31/07	35 days
46	TQC03 test	Thu 11/1/07	Fri 12/21/07	35 days



TQ Milestones FY06-08

02/2006	Mechanical Design	• Compare design objectives & FEA results • Evaluate results from mechanical models • Assess readiness to assemble/test magnets
08/2006	TQ01 evaluation	• Evaluate TQ01 coil fabrication results • Compare test results with expectations • Demonstrate control of strand stability (for MJR) • Provide a basis for the LQ coil design
04/2007	TQ02 evaluation	• Evaluate conductor performance (for RRP) • Evaluate mechanical design optimization results • Provide a basis for LQ structure design • Assess if TQ goals have been achieved
01/2008	TQ03 evaluation	• Assess if TQ goals have been achieved (backup for TQ02) *and/or* • Validate LQ design, analysis and fabrication • Define performance reference for LQ

TQ Evaluation Criteria

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- Technology demonstration and characterization:
  - *consistently achieve G>200 T/m after training and thermal cycle*
  - *evaluate the mechanical performance of different models*
  - *determine the required design margins (fraction of short sample)*
- Selection of optimal design features and fabrication methods:
  - LQ models:
    - *Provide the optimized coil design and tooling for LQ*
    - *Feedback on coil fabrication methods (integrate with LR)*
    - *Input for structure selection (integrate with DS)*
  - HQ models:
    - *Design methods, coil technology, possibly re-use coils*
    - *Input for structure selection (integrate with DS)*

Summary

- Some delay, but overall good progress on TQ models
- Excellent result from first TQS prototype: a solid basis to build on
- Good understanding of prototype performance and limitations
- Established a reference and developed strategy for optimization
- First TQC prototype is near completion – test in July

- Updated R&D plan takes into account the new information
- TQ goal #1: provide a basis for the LQ coil design
- TQ goal #2: provide a basis for the LQ structure design
- Modularity of TQ tooling should allow smooth transition to LQ
- TQ also provides a basis for HQ design and fabrication