Magnet Systems Status

P. Wanderer
LARP Magnet Systems Leader

DOE Annual Review

July 13, 2009

OUTLINE

Magnet names, length, aperture

Overview

Long quads (LQ)

Materials

Large-aperture model quads (HQ) [H = high]

Technology model quads (TQ)

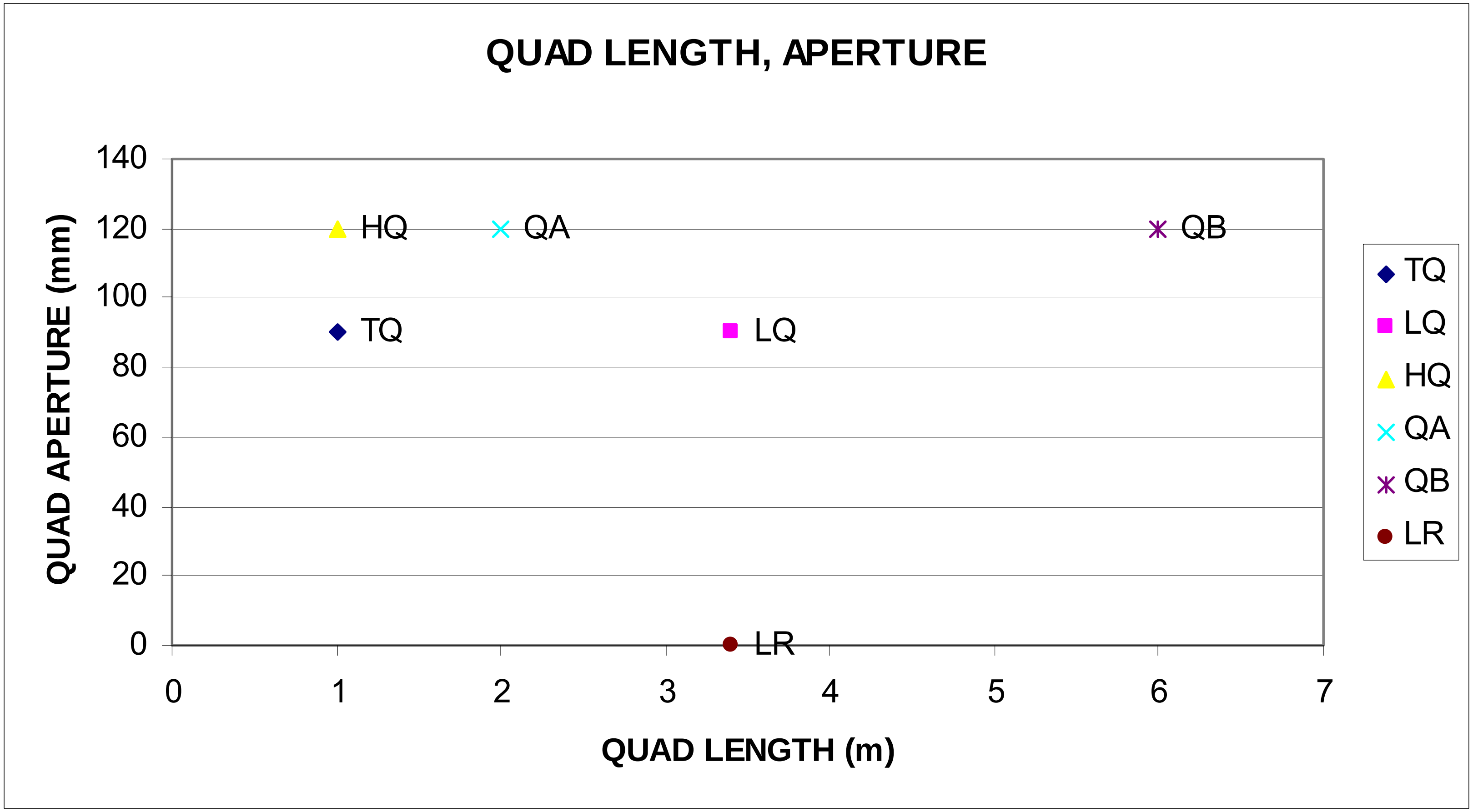
FY10 draft budget

Five-year R&D plan

Response to previous review

Summary

MAGNET NAMES, LENGTH, APERTURE



MAGNET SEQUENCE TABLE

LARP magnet sequence table - V8b - July 2009

Type	Length [m]	Aperture [mm]	Gradient [T/m]	Peak coil Field [T]	Accelerator Qualities	Purpose	Comment
SQ	0.3	110 - 130	>80	>11	Alignment	Conductor, mechanical and quench studies	Complete
LR	4	0	N/A	>11	None	Length scale-up with racetrack coils	Complete
TQ	1	90	>200	>11	G, some FQ	Test bench	As needed
LQ	3.4	90	>200	>11	G, some FQ	Demonstrate Nb3Sn technology in long quads	2009 goal
HQ	1	120	>175	>14	G, FQ, alignment	Short model for QA, QB	High peak field
QA	2	120	> 175	> 14	G, FQ, alignment	Length effects, lifetime, alignment, etc.	make 4 (6)
QB	~ 6	120	> 175	> 14	All	Full-length demo coil(s)	$ from APUL?

OVERVIEW

LARP MAGNET SYSTEM GOALS

- **Near term** (end of CY 2009): Nb_3Sn quadrupole (LQ)
  - 200 T/m
  - 3.4 m
  - 90 mm ∅ (aperture)

- Medium term: demonstrate the technology for use in LHC

- **Long term** (LHC Phase II upgrade, ~ 2020):
  - Nb_3Sn IR quads

AREAS OF WORK

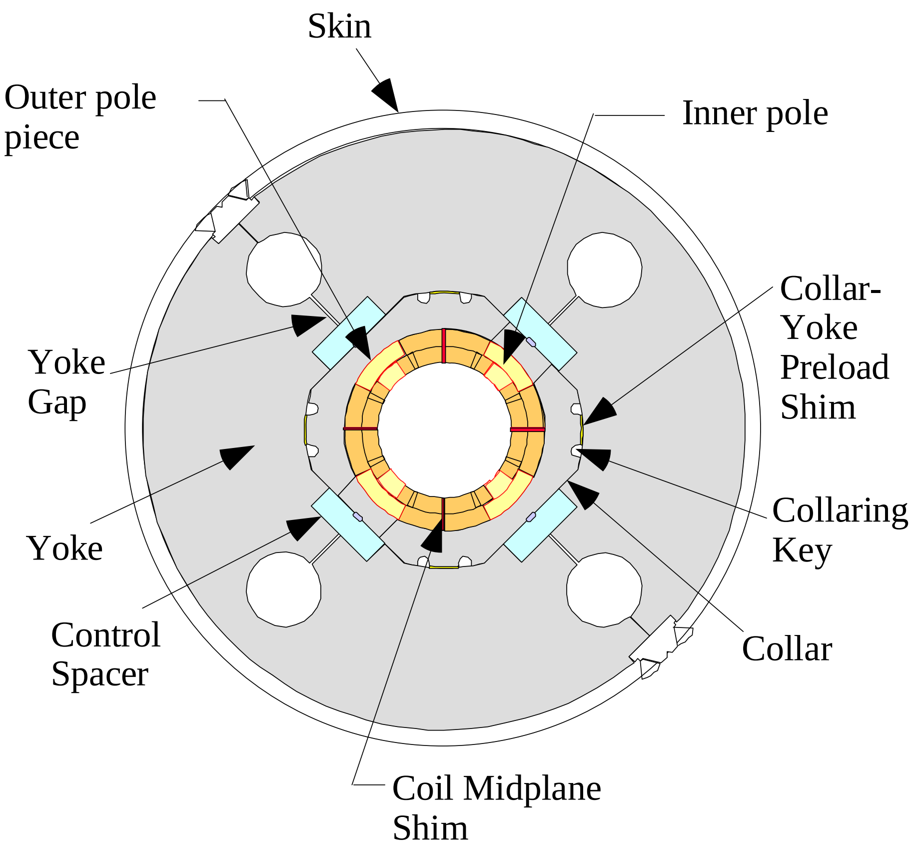
- <u>**Underway for end of 2009: Long quadrupole, LQ:**</u>
  - Coils, support structures – make, assemble, test

- <u>**Results in hand:**</u>
  - **Magnetic mirror quad TQM** (conductor stability demonstration)
    - Funds from Fermilab off-project program
  - **Technology quads** (TQ – 1 m, 90 mm; TQS shell, TQC collar):
    - ~ 90% I_{ss} (200 T/m to 225 T/m)
    - Now: test bench for instability in quench current, axial preload,…
  - **Long racetrack** (LR – 3.6 m, racetrack coils):
    - ~ 96% I_{ss}, 11.5 T field on coil
    - shell structure development

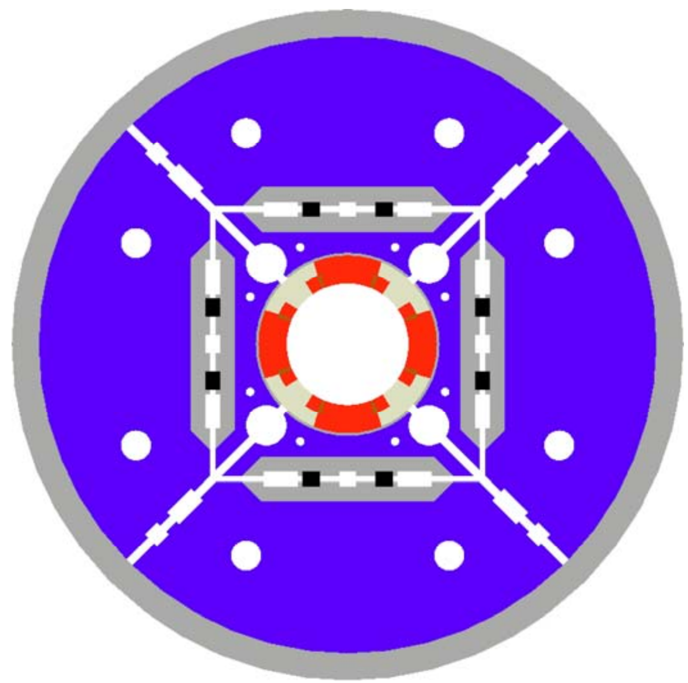
- <u>**Underway:**</u>
  - HQ – ∅ 120 mm, 1 m, cos2θ
  - Materials: stability, properties during reaction
  - TQ – test bench (108/127 conductor, conductor with core)

LONG QUADRUPOLES

LQ SUPPORT STRUCTURES
LQ #1 being assembled in shell structure



Collar



Shell

LQ COIL STATUS

- Coil production methods developed (for now)
  - Fermilab winds, cures all coils;
  - Fermi & BNL react, impregnate
  - 1 m $\rightarrow$ 3.4 m coils **NOT** easy

- Five practice coils – each served multiple purposes
- Coils # 6 through #9 going into LQS01
  - That is, after five practice coils, the next four were ok (although not perfect – careful review before use in LQS01)

LQ COIL AND REACTION FIXTURE

BNL/Fermilab review of
coil-making procedures

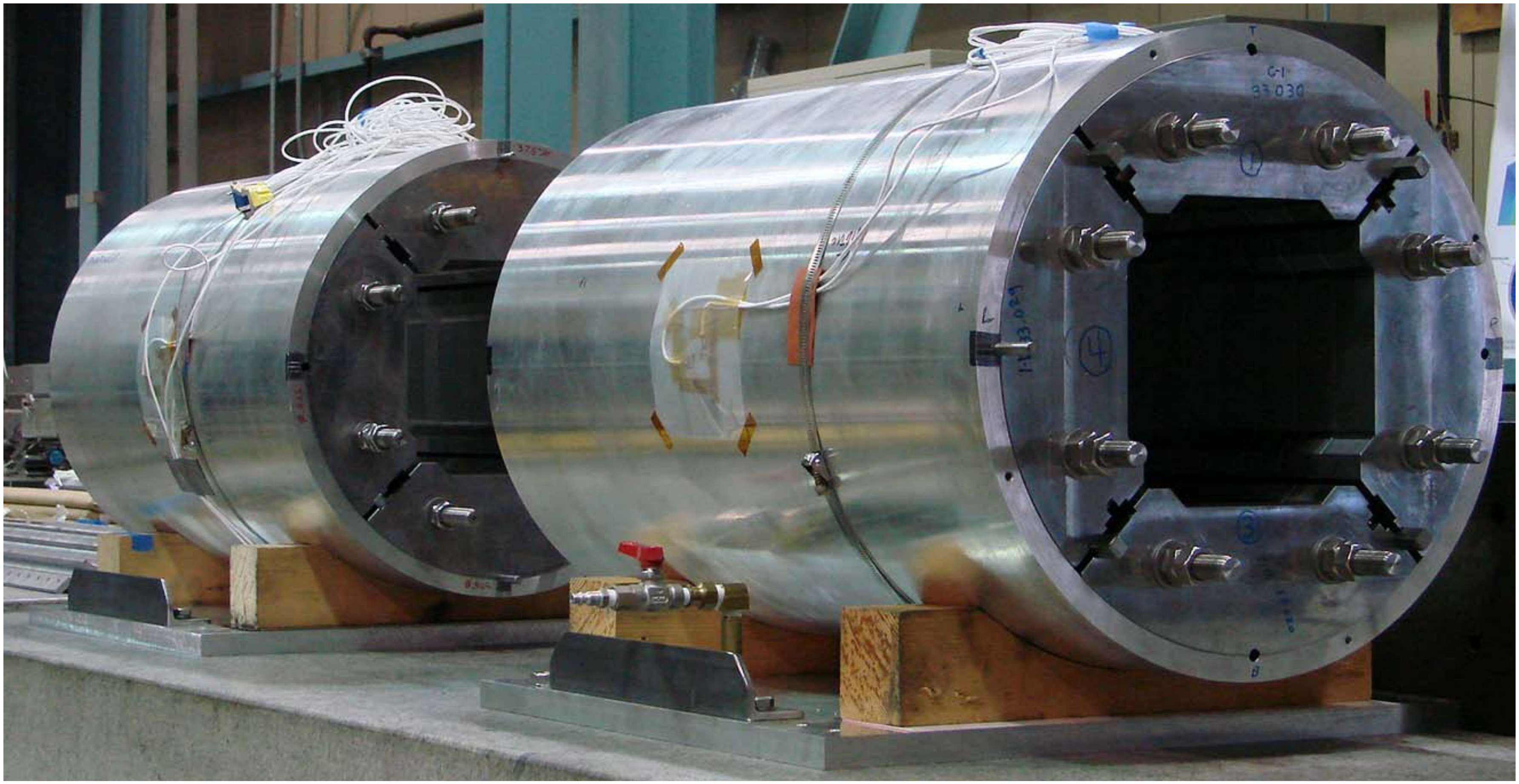
Reaction fixture

SUPPORT STRUCTURE STATUS

- **Shell development:**
  - 1 m shell structure with "dummy" coils (aluminum segments)
    - Assembled
    - Cooled to 77 K – forces measured – agreed with calculations
  - 3.4 m shell structure
    - Assembled 4 "1 m" lengths (no coils) at LBNL → alignment ok
    - Install 3.4 m dummy coils in support structure → ok
    - Cooled to 77 K at Fermilab – forces measured (72 strain gauges) – agreed with calculations

- **Collar: no work underway, no development needed**

Assembly of full-length shell structure
Sections 1 and 2 just before assembly



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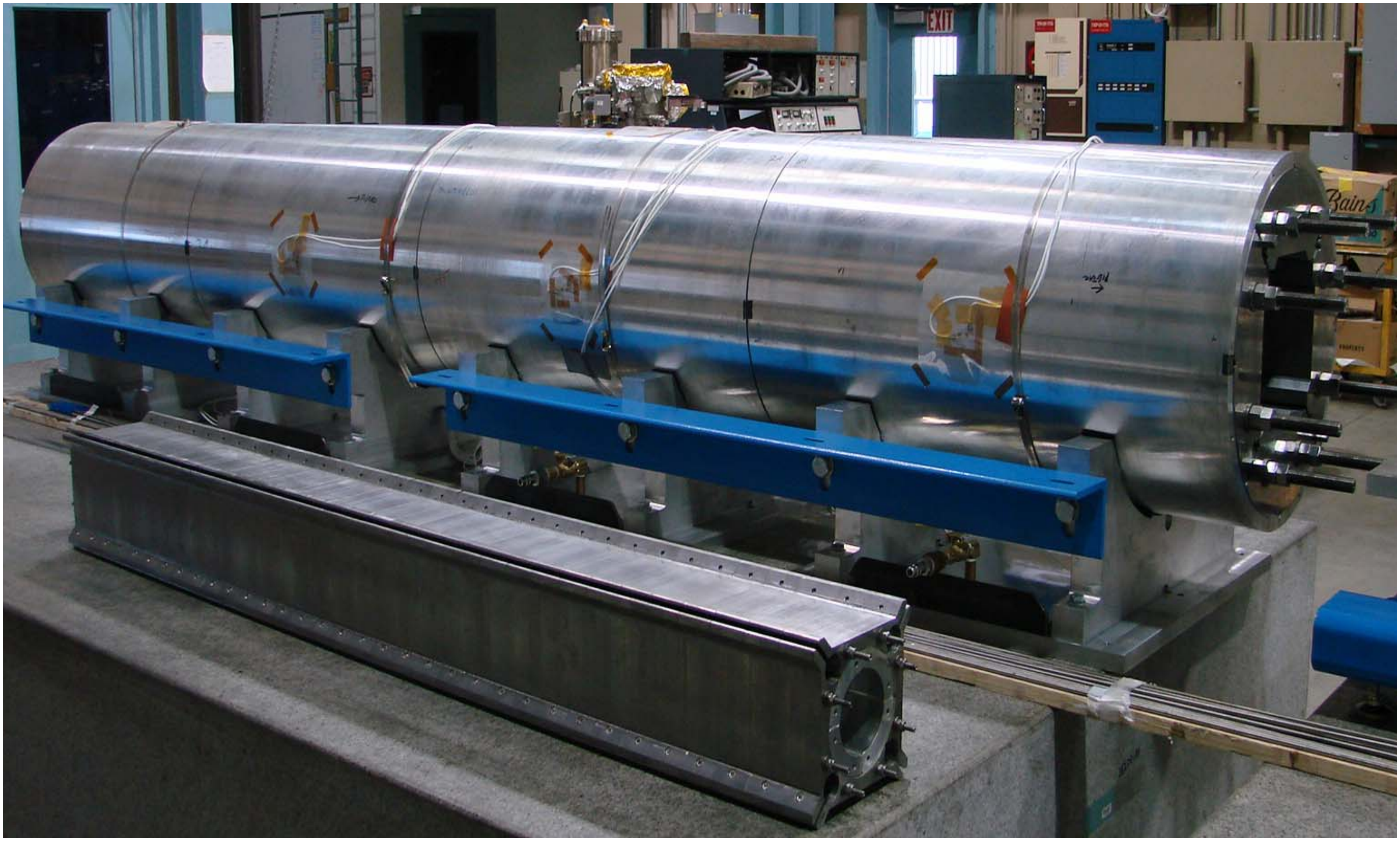
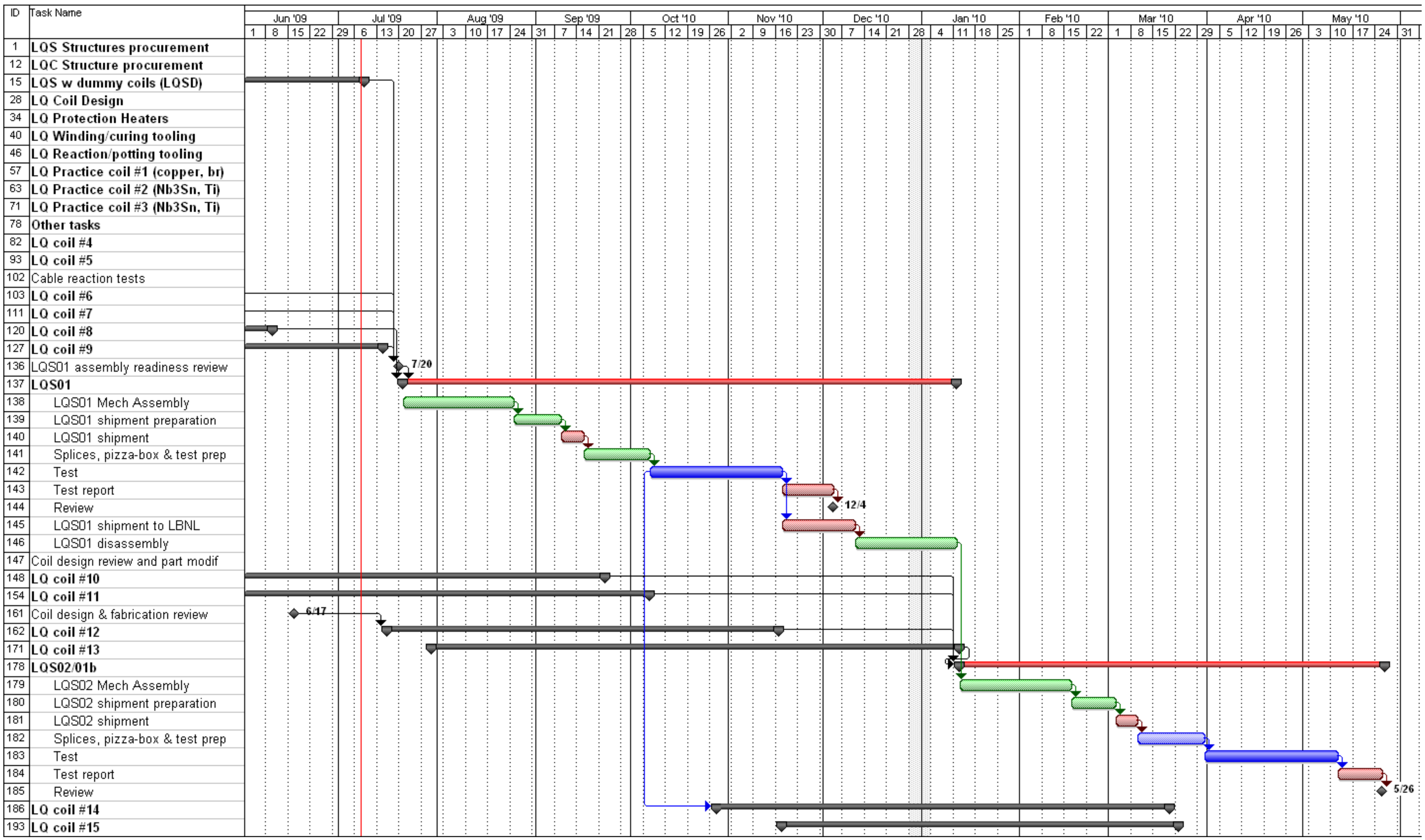
Assembly of full-length structure
3.4 m long yoke-shell sub-assembly



Test of shell support structure with dummy coils at 77K at Fermilab

LQ SCHEDULE


ID Task Name
Jun '09 Jul '09 Aug '09 Sep '09 Oct '10 Nov '10 Dec '10 Jan '10 Feb '10 Mar '10 Apr '10 May '10
1 LQS Structures procurement
12 LQC Structure procurement
15 LQS w dummy coils (LQSD)
28 LQ Coil Design
34 LQ Protection Heaters
40 LQ Winding/curing tooling
46 LQ Reaction/potting tooling
57 LQ Practice coil #1 (copper, br)
63 LQ Practice coil #2 (Nb3Sn, Ti)
71 LQ Practice coil #3 (Nb3Sn, Ti)
78 Other tasks
82 LQ coil #4
93 LQ coil #5
102 Cable reaction tests
103 LQ coil #6
111 LQ coil #7
120 LQ coil #8
127 LQ coil #9
136 LQS01 assembly readiness review
137 LQS01
138 LQS01 Mech Assembly
139 LQS01 shipment preparation
140 LQS01 shipment
141 Splices, pizza-box & test prep
142 Test
143 Test report
144 Review
145 LQS01 shipment to LBNL
146 LQS01 disassembly
147 Coil design review and part modif
148 LQ coil #10
154 LQ coil #11
161 Coil design & fabrication review
162 LQ coil #12
171 LQ coil #13
178 LQS02/01b
179 LQS02 Mech Assembly
180 LQS02 shipment preparation
181 LQS02 shipment
182 Splices, pizza-box & test prep
183 Test
184 Test report
185 Review
186 LQ coil #14
193 LQ coil #15
7/20
12/4
6/17
5/26

LQ SCHEDULE HIGHLIGHTS UPDATE

- Reviews:
  - Support structure tests with dummy coils – April
  - Coils – June
  - Assembly plans – July
  - Test plan - ~ September

- LQS01 assembly begins later this month

- LQS01 test in October

- Options for LQ testing in FY10
  - test with all new 54/61 coils
  - replace one coil, retest (more likely option)

MATERIALS

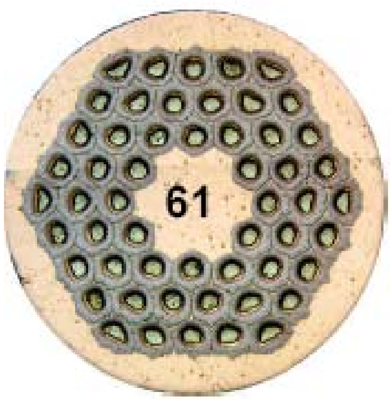
Available strands

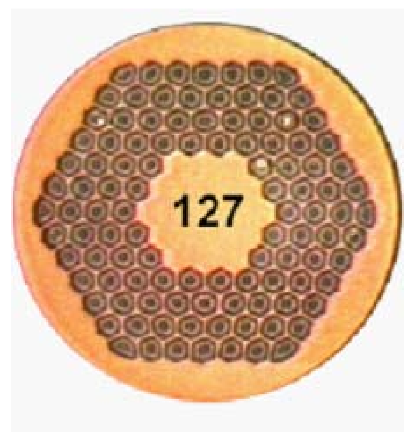
Inventory and orders

Conductor R&D topics

AVAILABLE STRANDS

- OST (Oxford Superconducting Technology) RRP® Nb_3Sn:
  - 54/61 – LARP workhorse – used for racetrack, recent TQ, LQ
    - 54/61 with increased Cu/spacing ⇒ more strain tolerant
  - 108/127 – smaller filaments
    - Successful test in a "mirror" quad (see later slide)
    - Underway: "qualify" in a TQ (1m) – magnet test in July
    - More stable than 54/61 at same strand ∅
    - In HQ (0.8 mm 108/127) same filament ∅ as 0.7 mm 54/61 in TQ





CONDUCTOR INVENTORY

- **LQ** (54/61, 0.7 mm strand diameter, 70 μm filament diameter)
  - 26 kg = UL = unit length cable = 1 LQ coil
  - 12 UL's cable made (coils 4-15), **6 UL cable in inventory**
  - **Strand inventory** is 78 kg (**2-3 UL**)

- **HQ 54/61**: (0.8 mm strand diameter, 80 μm filament diameter)
  - 54/61 (with increased Cu) (18 kg = UL = 1 HQ coil)
  - 5 UL's cable made, **3 UL cable in inventory**

- **HQ 108/127**: (0.8 mm strand diameter, 57 μm filament diameter)
  - 108/127 (with increased Cu)
  - **Strand inventory** is 117 kg (**5 UL**)

CONDUCTOR ORDERS

- Vendor: Oxford Superconducting Technology (NJ)
- 15 months from order to cable available for winding
- Some strand specifications can be changed ~ 6 months after order placed

- 88 kg order in process, due January 2010
  - Decide by September: 54/61 or 108/127?
- 70 kg order, place by end of July → delivery in April
  - 2 UL LQ or 3 UL HQ -- 54/61 or 108/127?

- Magnet Steering Committee to discuss later in July

MATERIALS DEVELOPMENT UNDERWAY

- Conductor studies in strands, cables, magnets, as appropriate
  - Ongoing strand characterization (e.g., HQ cable development)
  - Underfunded by LARP → off-project support (FNAL, BNL)

- Conductor stability (see following slides)
  - Strands
  - Magnets (e.g., TQS02c, TQS03, and TQM [mirror])

- Strain tolerance
  - Strands (NIST)
  - Cables (initial test at NHMFL in May, at CERN this fall)
  - But only one campaign at each place is funded.

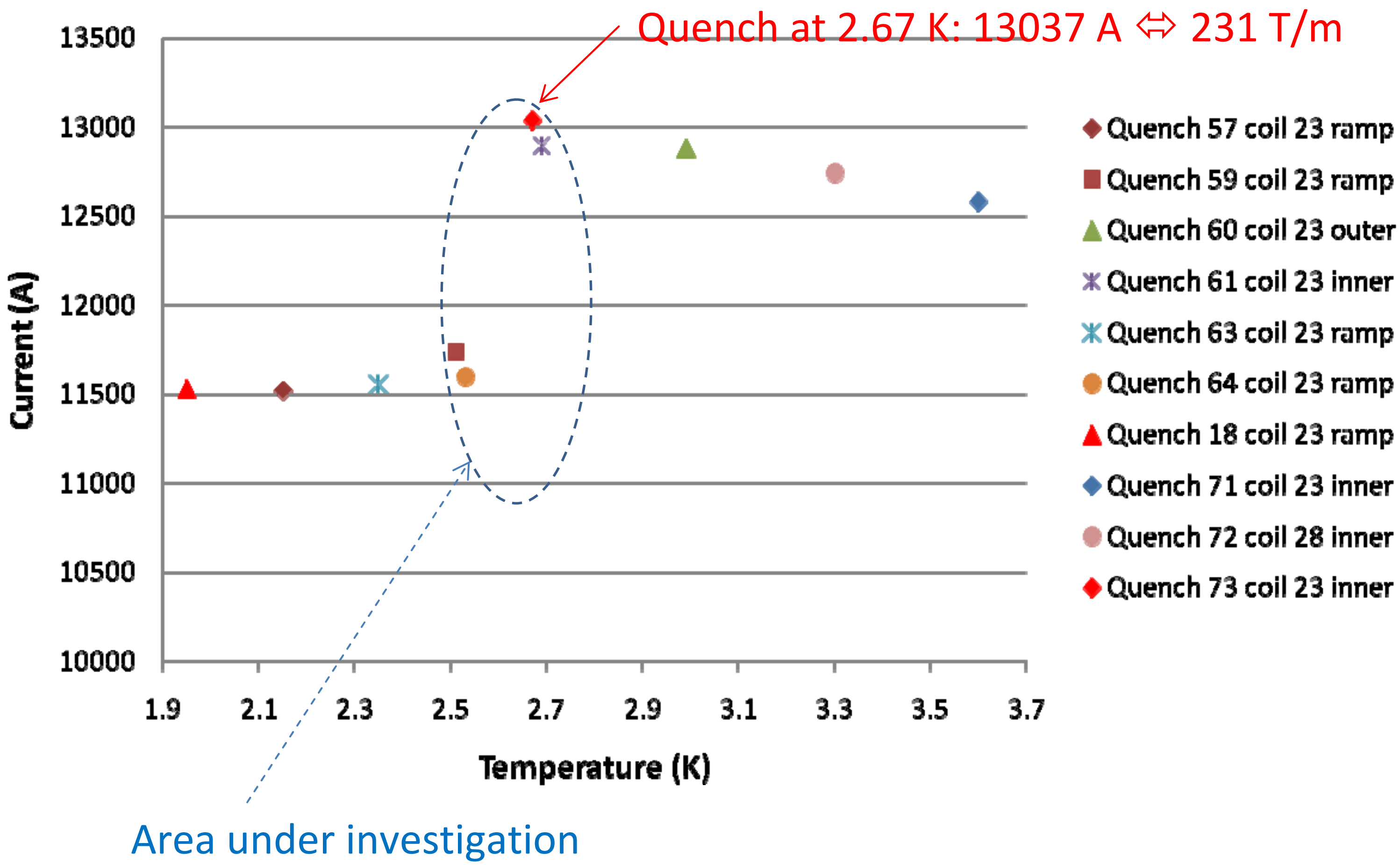
- Cable length at each stage of the reaction process

MAGNET PERFORMANCE AT 1.9 K

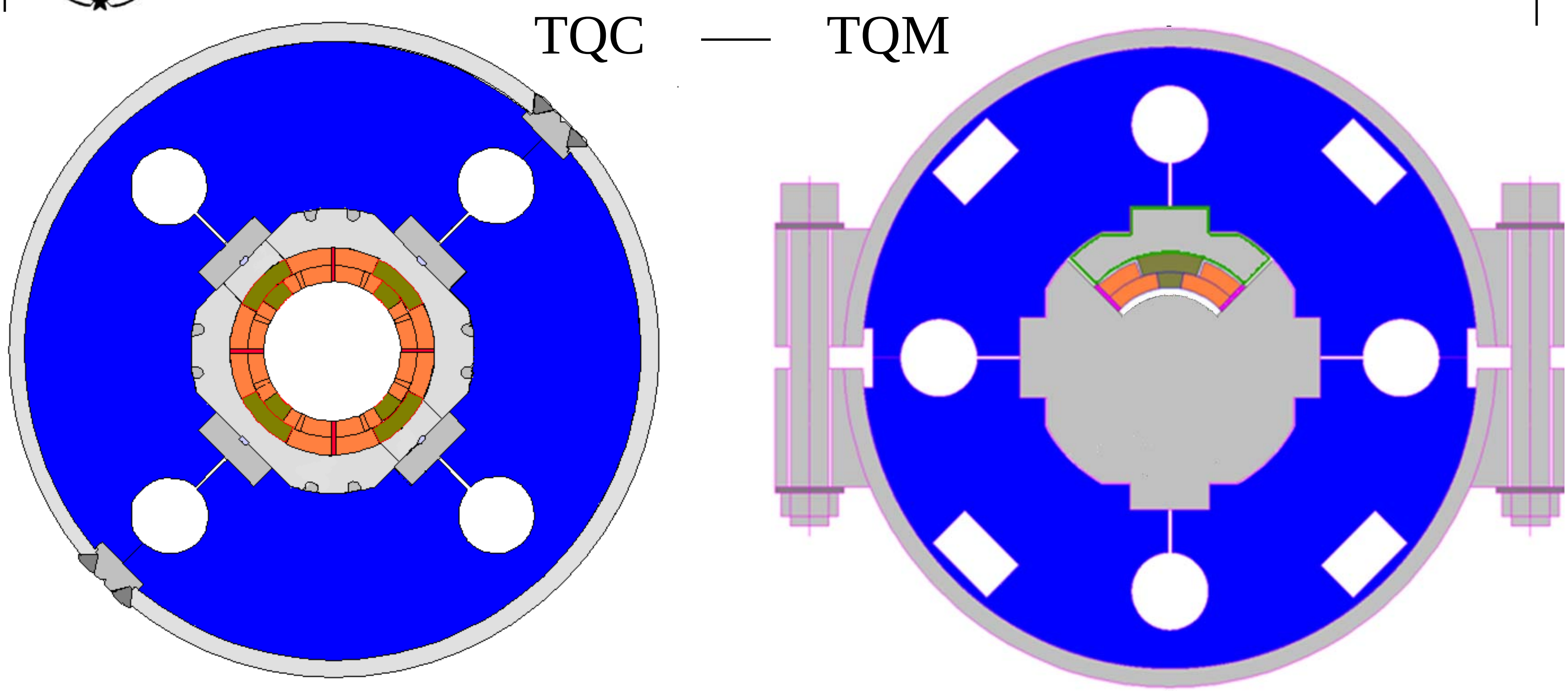
- Critical issue –
  - TQS – 54/61 – quench current *decreased* as temperature lowered below 2.6 K
  - TQM – 108/127 (⇒ smaller filaments than 54/61) – quench current increased as temperature lowered below 2.6 K.
  - TQS – 108/127 – test at CERN later this month

- Remark: HQ likely less sensitive to filament diameter than TQ/LQ, due to a lower load line (G vs. I)

TQS02c training (20 A/s) vs. temperature [RRP 54/61, test at CERN]



Mirror Design – Fermilab, off-project



The quadrupole mirror design TQM is based on the mechanical structure of the LARP technology quadrupole of TQC series.

Three coils, stainless steel collar blocks and preload control spacers were replaced by the magnetic mirror blocks and spacers.

Mirrors Quench Performance – Zlobin et al.

4.5 K:

Standard training behavior and typical ramp rate dependence.

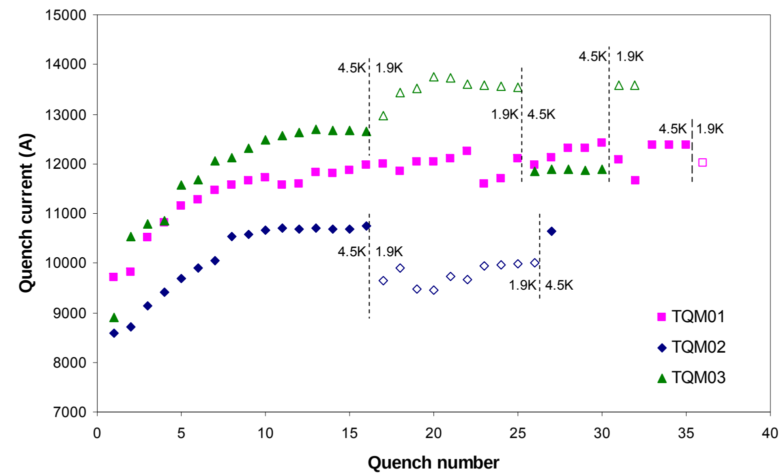
1.9 K:

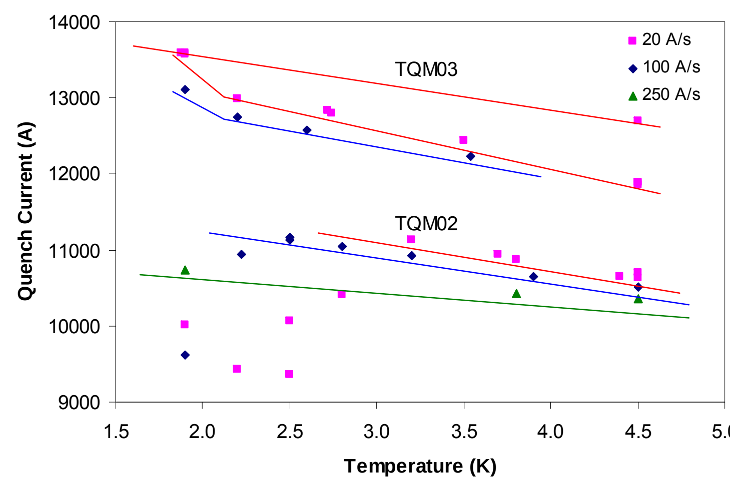
TQ coils made of RRP-54/61 strand show Iq reduction and an erratic quench behavior during training and ramp rate studies.

- unusual increase of the quench current at 200-275 A/s.

The new coil made of more stable RRP-108/127 strand shows the expected Iq increase and regular ramp rate dependence.

This coil reached 98-99% of its SSL.





MATERIALS R&D NOT FUNDED BY LARP

- Eddy current reduction – ESSENTIAL - UNDERWAY
  - Stainless steel ribbon (“core”), 25 μm thick, inside cable
  - Increases resistance between top and bottom of cable ⇒ eddy current reduction
  - 1 coil made, test in magnetic mirror TQM (FNAL off project)

- Epoxy with increased radiation resistance

- Turn-to-turn insulation that can be wrapped around the cable
  - Replaces sleeve – needed for long cable lengths

- Measurement of magnet thermal margin (TQM02 off project)

COIL #35 WITH CORED CABLE

Mirror Quadrupole

Fermilab off-project

Test this fall

LARGE APERTURE QUAD (HQ)

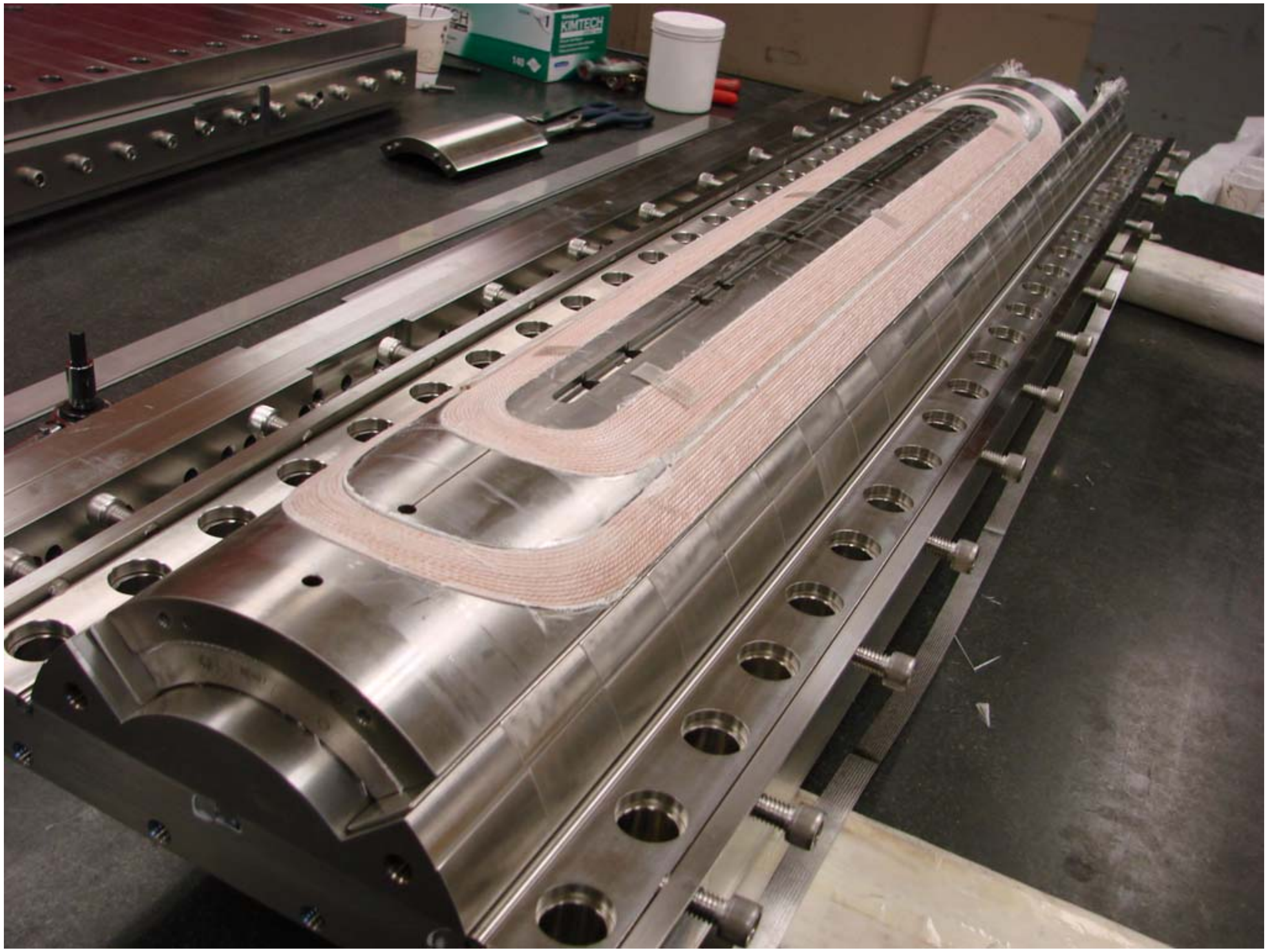
LARGE APERTURE (HQ) - 120 mm

- **Reoptimization TQ → HQ (~1 m):**
  - Strand (0.7 mm → 0.8 mm), 54/61
  - Cable (10 mm → 15 mm, new keystone angle, heat treatment)
  - Coil (90 mm → 120 mm, new coil ends)
  - Support structure (max. o.d. for LHC, include alignment)

HQ COIL STATUS

- Berkeley
  - Cable development (0.8 mm strand ∅)
  - **First practice coil reacted; 2nd practice coil being wound**
- BNL
  - Design reaction, impregnation fixtures
  - Scheduled to react, impregnate coils
- Fermilab
  - Design coil 2D, 3D cross section
  - Supply coil parts, ends & straight section

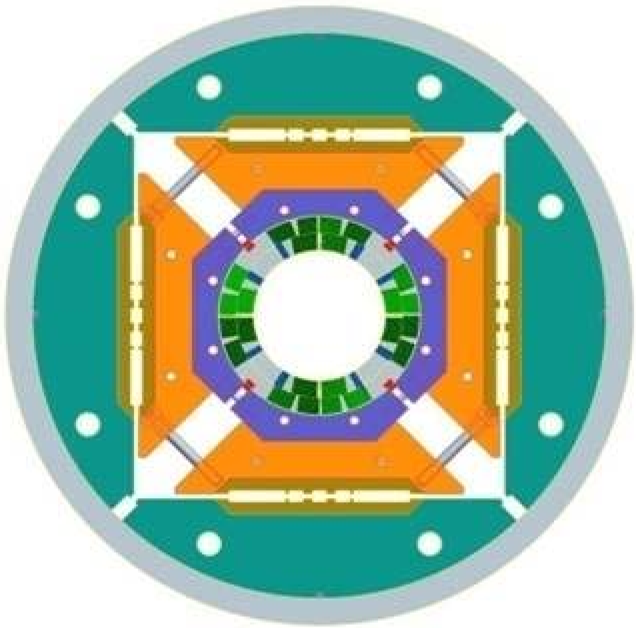
FIRST HQ PRACTICE COIL



HQS – Mechanical Shell based Structure

Components

- Aluminum bolted collars => alignment
    - remains in compression from assembly to operating conditions
- Iron pads and yoke
- Iron master key => alignment
- axial rods => axial preload
- 25 mm aluminum shell => azimuthal preload
    - Coil and collar in compression
- Cooling area



570 mm outer diameter

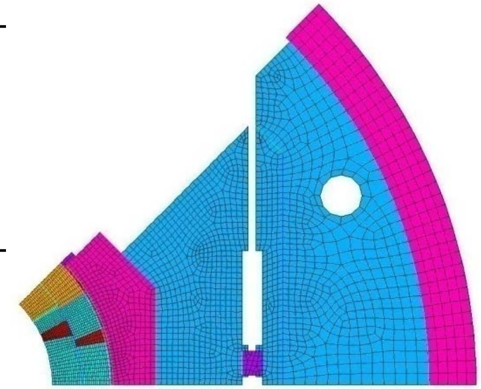
Assembly

- 60 mm bladders located outside the key span
- 38 MPa pressure (600 + 50 microns clearance for 220 T/m)
- Collars, pads and key locations optimize to minimize stress

Short-sample limit in the straight section

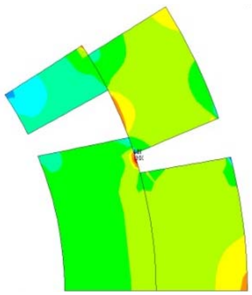
1.9 K / 4.4 K	**Layer 1**			**Layer 2**		
A/mm^2	**2000**	**2500**	**3000**	**2000**	**2500**	**3000**
Imax (kA)	**17.5**/15.98	**18.58**/16.95	**19.45**/17.72	18.14	19.30	20.22
Bmax (T)	**13.72**/12.59	**14.52**/13.3	**15.17**/13.9	13.55	14.34	14.98
Gmax (T/m)	**197/**181	**208**/191	**219**/199			

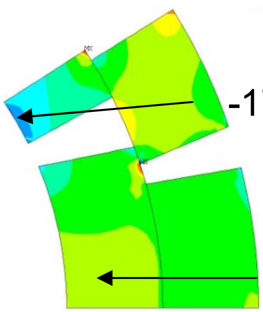
HQ – Mechanical analysis
Azimuthal stress in the coil



	Target 219 T/m
During bladder operation	-90 MPa
With loading key	-82 MPa
At 1.9 K	-177 MPa
With Lorentz forces	-177 / 20 MPa

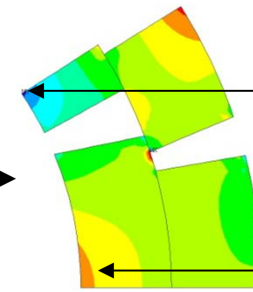
-90 MPa





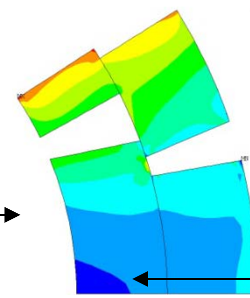
-177 MPa

- 80 MPa



-82 MPa

- 20 MPa



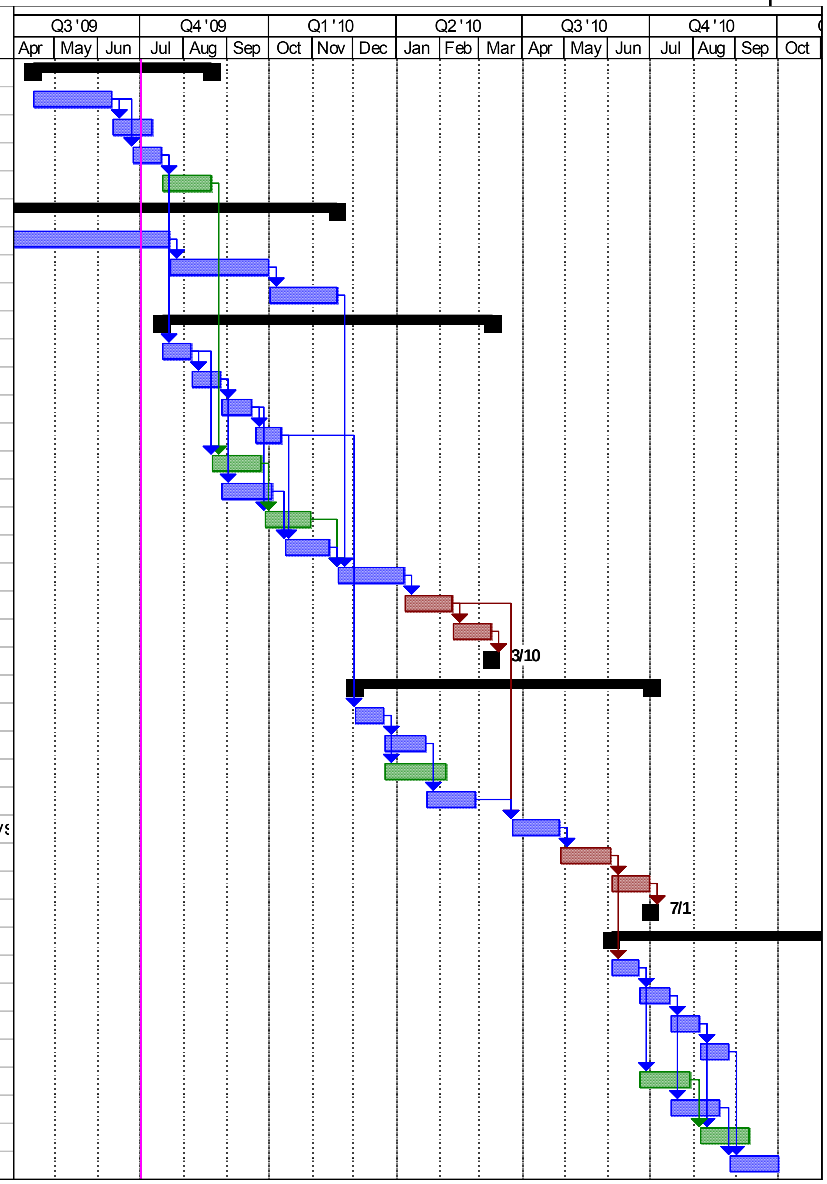
-177 MPa

=> High but acceptable stress at short sample

Courtesy of H. Felice

HQ schedule – Rev. 7/02/2009

ID	Task Name	Start	Finish	Duration	Predecessors
1	**Tooling, Parts, Practice Coils**	**Wed 4/15/09**	**Thu 8/20/09**	**90 days**	
2	Practice winding/curing #1	Wed 4/15/09	Wed 6/10/09	40 days	
3	Practice reaction/potting #1	Thu 6/11/09	Thu 7/9/09	20 days	2
4	Practice winding/curing #2	Thu 6/25/09	Thu 7/16/09	15 days	2FS+10 days
5	Practice reaction/potting #2	Fri 7/17/09	Thu 8/20/09	25 days	4
6	**Structure Design and Fabrication**	**Mon 2/2/09**	**Wed 11/18/09**	**205 days**	
7	Structure Procurement	Mon 2/2/09	Tue 7/21/09	120 days	
8	Structure pre-assembly	Wed 7/22/09	Wed 9/30/09	50 days	7
9	Mechanical model	Thu 10/1/09	Wed 11/18/09	35 days	8
10	**HQ01 Model**	**Fri 7/17/09**	**Wed 3/10/10**	**159 days**	
11	Coil 3 Wind / Cure	Fri 7/17/09	Thu 8/6/09	15 days	4
12	Coil 4 Wind / Cure	Fri 8/7/09	Thu 8/27/09	15 days	11
13	Coil 5 Wind / Cure	Fri 8/28/09	Fri 9/18/09	15 days	12
14	Coil 6 Wind / Cure	Mon 9/21/09	Fri 10/9/09	15 days	13
15	Coil 3 React/Impreg	Fri 8/21/09	Fri 9/25/09	25 days	11,5
16	Coil 4 React/Impreg	Fri 8/28/09	Fri 10/2/09	25 days	12
17	Coil 5 React/Impreg	Mon 9/28/09	Fri 10/30/09	25 days	15,13
18	Coil 6 React/Impreg	Mon 10/12/09	Fri 11/13/09	25 days	14,16
19	Magnet Assembly	Thu 11/19/09	Tue 1/5/10	25 days	18,17,9
20	Test	Wed 1/6/10	Tue 2/9/10	25 days	19
21	Analysis & Reporting	Wed 2/10/10	Tue 3/9/10	20 days	20
22	Review	Wed 3/10/10	Wed 3/10/10	1 day	21
23	**HQ01b Model**	**Wed 12/2/09**	**Thu 7/1/10**	**144 days**	
24	Coil 7 Wind / Cure	Wed 12/2/09	Tue 12/22/09	15 days	14FS+35 days
25	Coil 8 Wind / Cure	Wed 12/23/09	Thu 1/21/10	15 days	24
26	Coil 7 React/Impreg	Wed 12/23/09	Thu 2/4/10	25 days	24
27	Coil 8 React/Impreg	Fri 1/22/10	Thu 2/25/10	25 days	25
28	Magnet Assembly	Wed 3/24/10	Tue 4/27/10	25 days	27,20FS+30 days
29	Test	Wed 4/28/10	Wed 6/2/10	25 days	28
30	Analysis & Reporting	Thu 6/3/10	Wed 6/30/10	20 days	29
31	Review	Thu 7/1/10	Thu 7/1/10	1 day	30
32	**HQ02 Model**	**Thu 6/3/10**	**Thu 1/20/11**	**156 days**	
33	Coil 9 Wind / Cure	Thu 6/3/10	Wed 6/23/10	15 days	29
34	Coil 10 Wind/cure	Thu 6/24/10	Thu 7/15/10	15 days	33
35	Coil 11 Wind / Cure	Fri 7/16/10	Thu 8/5/10	15 days	34
36	Coil 12 Wind / Cure	Fri 8/6/10	Thu 8/26/10	15 days	35
37	Coil 9 React/Impreg	Thu 6/24/10	Thu 7/29/10	25 days	33
38	Coil 10 React/Impreg	Fri 7/16/10	Thu 8/19/10	25 days	34
39	Coil 11 React/Impreg	Fri 8/6/10	Fri 9/10/10	25 days	35,37
40	Coil 12 React/Impreg	Fri 8/27/10	Fri 10/1/10	25 days	36,38



FY10 DRAFT BUDGET

LARP FY10 DRAFT MAGNET BUDGET

July 2, 2009 - V7												
P. Wanderer	Costs are in k$											
							BNL		FNAL		LBNL	
Task	specifics	# items	$/item	item total			labor	materials	labor	materials	labor	materials
LQ	complete LQS01 test, analysis	1	$168	$168			0	0	56	6	106	0
	LQS01b/02 assy, test, disassy	1	$482	$482			0	0	193	16	241	32
	LQ coils #12 - #15	1	$686	$686			220	28	272	78	55	33
	Reports, reviews	1	$90	$90			20	0	40	0	30	0
			LQ total	$1,426	**$1,426**							
HQ	HQ01 build, test	1	$685	$685			15	0	124	23	457	66
	HQ01b (see note), test	1	$1,497	$1,497			258	22	213	141	770	93
			HQ total	$2,182	**$2,182**							
Materials	Cable/insulate UL LQ	2	$28	$55							41	14
	Cable/insulate UL HQ	6	$19	$114							88	26
	EDIA for LQ, HQ cable, insulate	1	$74	$74							74	
	Buy strand 10 UL QA	1	$452	$452			7		6	434	5	
	Strand tests (30 BNL, 25 Fermi)	1	$313	$313			144	22	127	20		
			Mat. Total	$1,008	**$1,008**							
QA	design only				**$400**		$400					
						total	1064	72	1031	718	1867	264
Total FY10 budget					**$5,016**	lab total		1136		1749		2131

FIVE-YEAR R&D PLAN

TECHNOLOGY DEMONSTRATION PROGRAM

- MAGNETS
  - Minimal set of magnets →
    - 1 long (3.4 m), 90 mm aperture quad [LQ]
    - 4 (6) medium-length (2 m), 120 mm aperture [QA]
      - QA = 2 m version of HQ
        - » Because HQ has only 30 cm of straight section

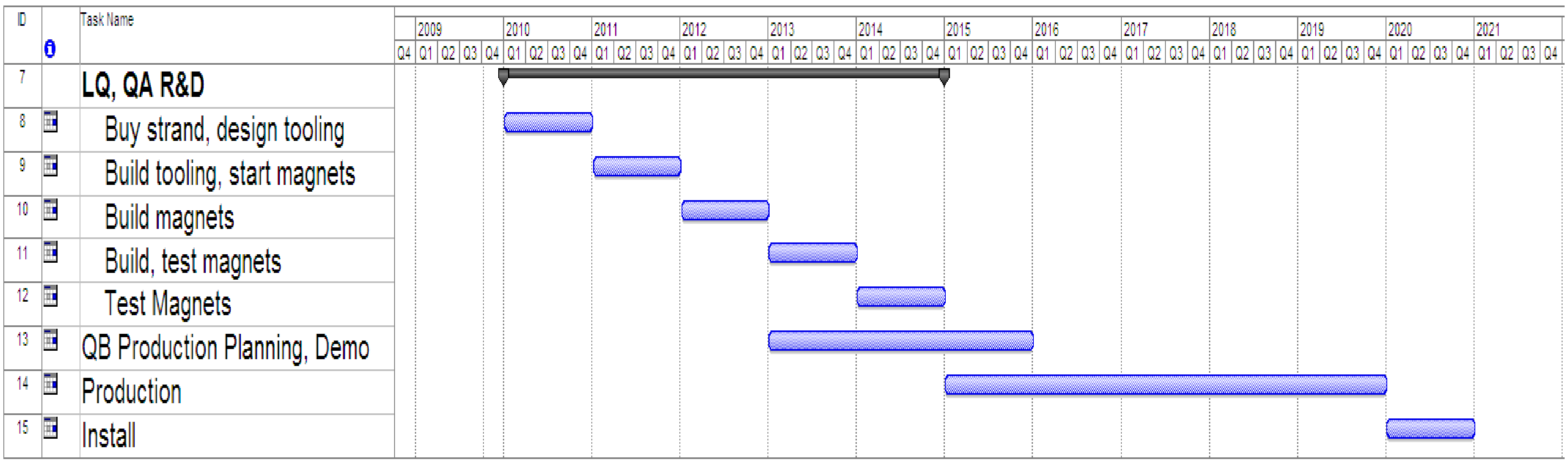
- RELATED R&D
  - Carried out through core programs (i.e., off-project)

FUNDING ASSUMPTIONS

- Guidance: LARP funding decreases $1M/yr
- Assume: $13 M LARP total for FY10
- Assume: Magnet fraction constant, ~ 38%, w/o contingency

- Develop QA budget, schedule using LQ experience
  - No built-in schedule contingency
  - Yield: assume build 5 coils, use 4 in a magnet
  - Two rebuilds included (replace 1 or 2 coils, retest)
  - Schedule requires parallel production lines, three labs
  - QA budget + LQ work + HQ (1 m, 120 mm) development (FY10, FY11) fits into budget (w/o contingency) for FY10-FY14.

TIME FRAME - R&D, PRODUCTION



RECOMMENDATIONS/ACTION ITEMS FROM JUNE 2008 REVIEW

Action Items / Recommendations (1)

- 1. To ensure a reproducible manufacturing process, a single conductor and structure-type should be adopted to determine and quantify the effects of coil variability on magnet performance. This effort should be based on Oxford Type 54/61 conductor and the shelltype structure for testing LQ magnets.
  - *Response: LQS01 = shell; all LQ, HQ coils 54/61 as recommended*
- 2. At this juncture, restrict the use of more advanced conductors (such as Oxford Type 108/127) to tests involving short technology quadrupoles (TQ).
  - *Response: 108/127 only in TQS03, TQM03 (mirror), as recommended*

Action Items / Recommendations (2)

- 3. Complete an accelerator-quality magnet design (HQ) as soon as possible, focusing on operational stability with a 2K temperature margin (with all loads).
  - *Response: As directed, HQ design, with some accelerator-quality features, completed; construction underway*

- 4. Should give priority to MCNPX-type of simulation of radiation effects over the work on decreasing the diameter of strands (Deff).
  - *As directed, no LARP funds for work on strands beyond 108/127. Test of magnet in beam discussed with CERN*

SUMMARY

CONCLUSIONS

- **Good progress toward demonstrating technology:**
  - 200 T/m achieved in 1 m model quads, both support structures
  - 96% I_{ss}, 11.5 T field achieved in 3.6 m racetracks
  - On track to test 3.4 m, 90 mm quad by end of CY 2009
  - Work on larger aperture well underway; test early CY 2010
  - 108/127 – increased stability

- **There is still a lot to do:**
  - Demonstrate 200 T/m in 3.4 m, 90 mm quad
  - Demonstrate full set of properties needed for accelerator use
    - As needed for demonstration, develop/understand/optimize superconducting & mechanical properties of Nb_3Sn materials and magnets

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backup

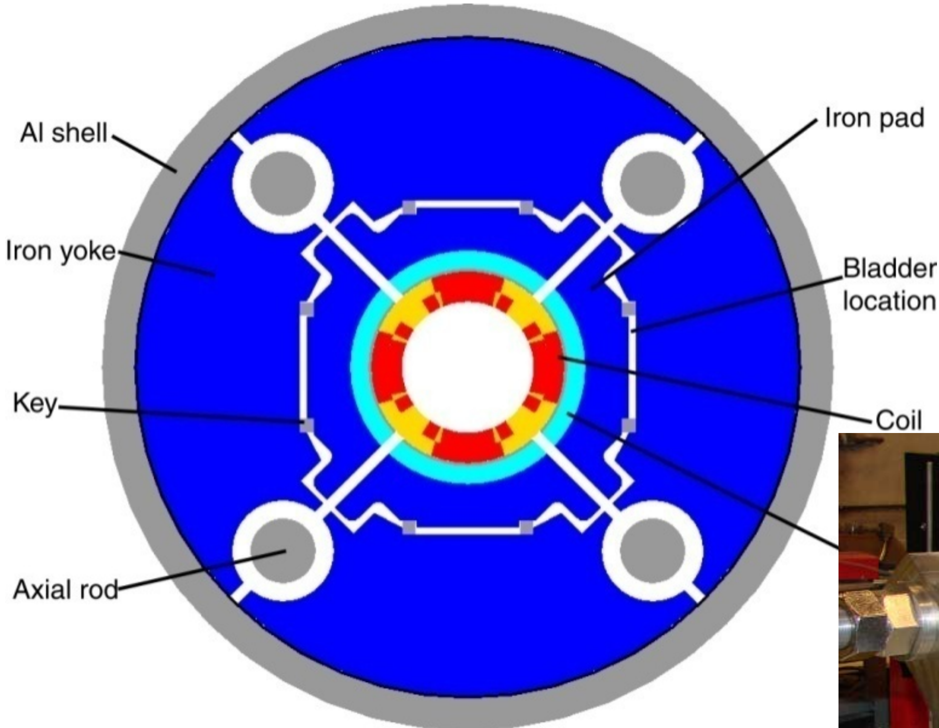
TECHNOLOGY QUADS
1M QUADS – TQS, TQC

Now: test bench for new conductors, etc.

TECHNOLOGY QUAD OVERVIEW

- Recall: length ~ 1 m, aperture 90 mm.
- With good RRP coils and proper assembly, exceed 220 T/m (4.5 K) and reach ~ 90% $I_{ss} \Rightarrow$ gradient goal reached
- Support structures now used for development tests
  - Stability/1.9 K performance versus number of filaments –
    - 54/61 (TQS02c) – results in hand
    - 108/127 (TQS03) – test at CERN July 09

TQ SHELL SUPPORT STRUCTURE



aluminum shell

High axial preload