US LHC Accelerator Research Program

bnl - fnal- lbnl - slac

Status of Magnet R&D

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LARP Magnet Systems Leader

CERN-US annual meeting

January 13, 2009

Geneva

OUTLINE

- Overview
- Long quads (LQ)
- Large-aperture model quads (HQ)
- Materials
- Technology model quads (TQ)
- A loook ahead
- Summary

OVERVIEW

LARP MAGNET SYSTEM GOALS

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

- **Long term** (LHC Phase II upgrade, ~ 2015):
  - Nb_3Sn IR quads

AREAS OF WORK

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

- **Results in hand:**
  - **Technology quads** (TQ – 1 m, 90 mm; TQS shell, TQC collar):
    - ~ 90% I_{ss} (200 T/m to 225 T/m)
    - 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

- **Underway:**
  - HQ – ∅ 120 mm, 1 m, cos2θ
  - Materials: stability, properties during reaction
  - TQ – test bench (new conductor)

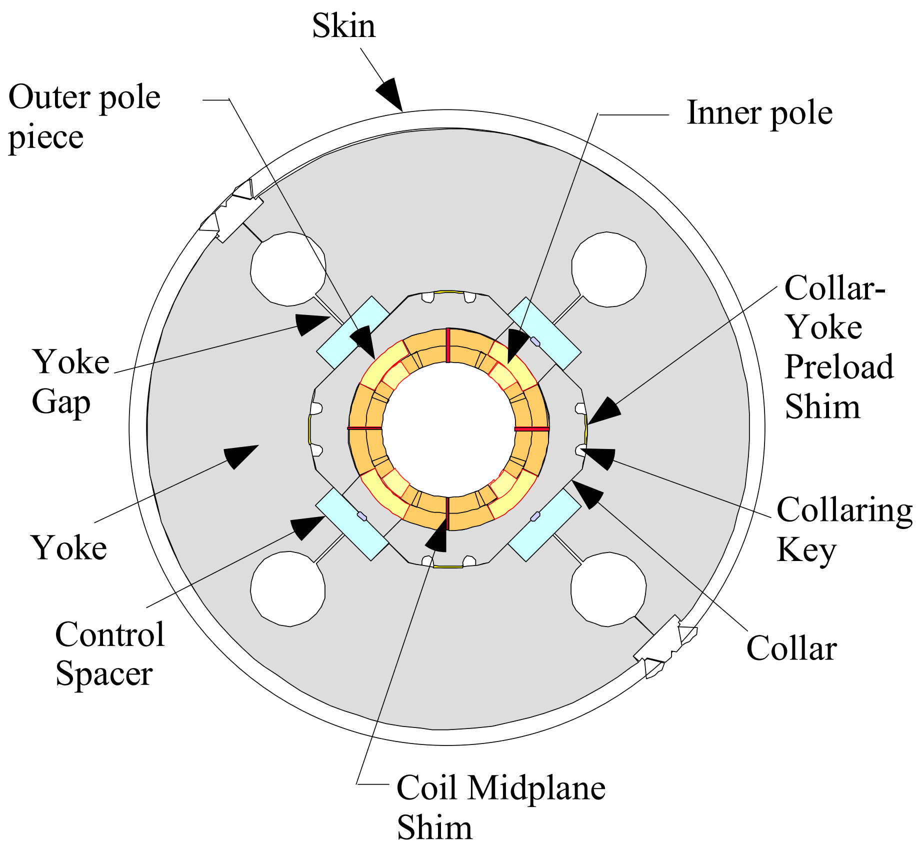
LARP Magnet Sequence Table

LARP magnet sequence table - V7b - January 2009

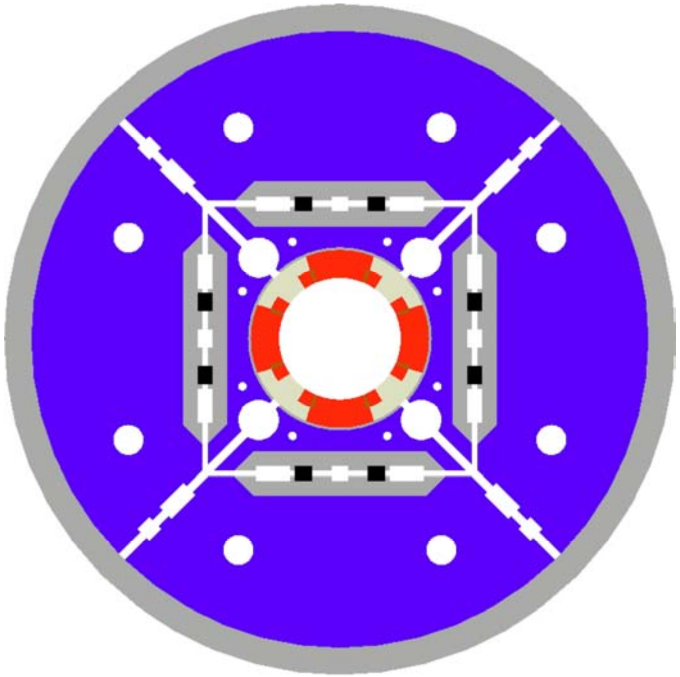
Type	Length [m]	Aperture [mm]	Gradient [T/m]	Peak coil Field [T]	Accelerator Qualities	Purpose	Comment
SQ	0.3	110 - 130	>80	>11	Alignment	Conductor, mechanical and quench studies	Complete
LR	4	0	N/A	>11	None	Length scale-up with racetrack coils	Complete
TQ	1	90	>200	>11	Mag. measurements	Test bed for conductor & LQ	Ongoing
LQ	4	90	>200	>11	Suport structure	Demonstrate Nb3Sn technology in long quads	2009 goal
HQ	1	120	>175	>14	Field Q & alignment	Short model for QA	High peak field
QA	~ 4	120	120	~ 10	All	Length effects, lifetime, alignment, etc.	
QB	tbd	tbd	tbd	tbd	All	Phase 2 upgrade magnet	

LONG QUADRUPOLES

LQ COIL, SUPPORT STRUCTURES



Collar



Shell

LQ COIL STATUS

Development of coil production methods complete (for now)

One nasty problem overcome – loading of Ti poles after reaction

-- essential info from expert at CERN

Numerous other issues

1 m → 3.8 m coils not easy

Production of the first 4 coils for LQS01 underway

[Fermilab winds, cures all coils; both labs react, impreg.]

Fermilab: #6 – ready for impregnation; #8 – wound, cured

BNL: #7 – reaction complete; #9 – ship cured coil to BNL soon

Schedule: Coil #9 (4^{TH} for LQS01) shipped to Berkeley in April

LQ COIL AND REACTION FIXTURE

Reacted coil – lead prep

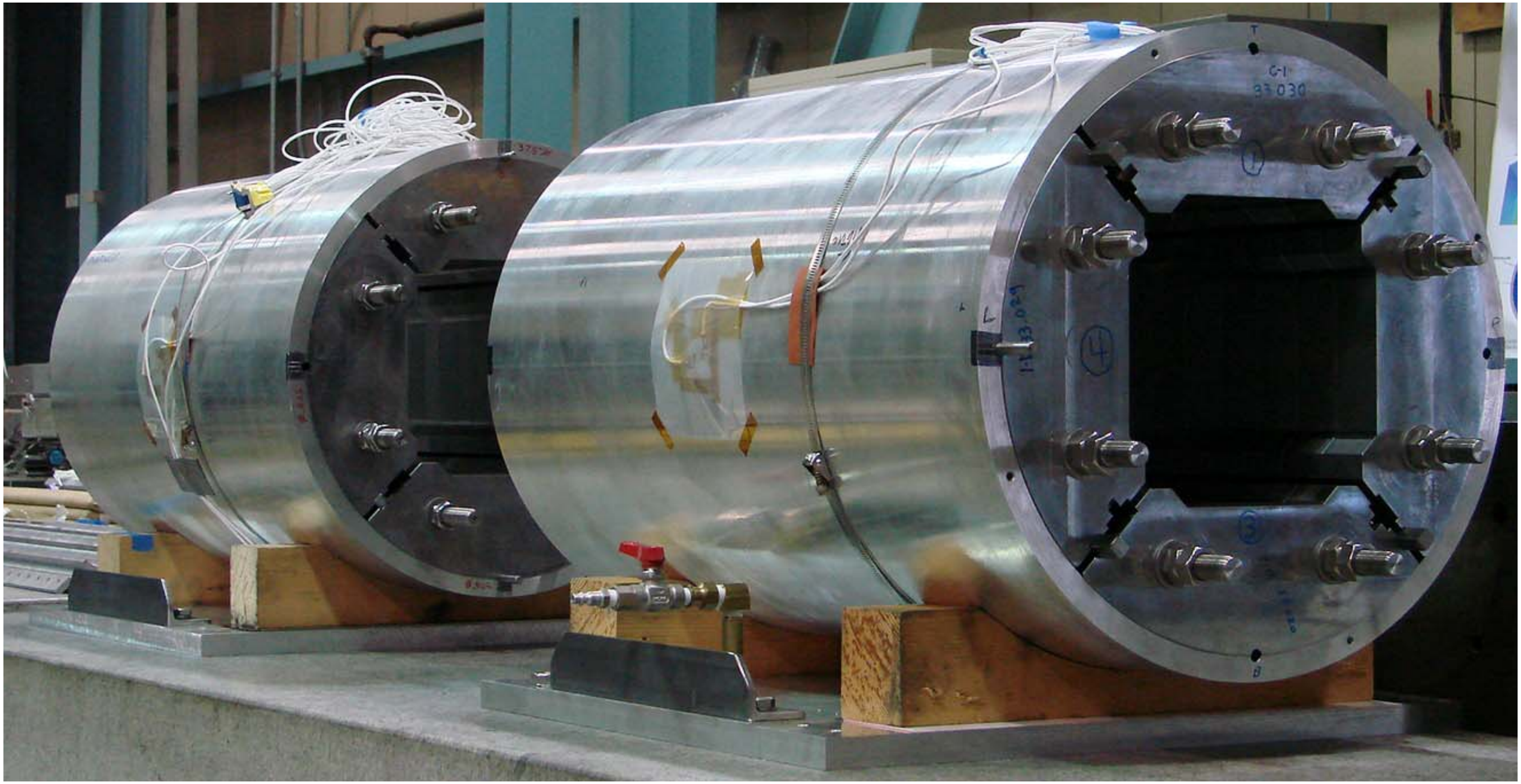
Reaction fixture

SUPPORT STRUCTURE STATUS

- **Collar: components purchased (no development needed)**

- **Shell development:**
  - 1 m shell structure with "dummy" coils (aluminum segments)
    - Assembled
    - Cooled to 77 K – forces measured – agreed with calculations
  - 3.8 m shell structure
    - Assembled 4 "1 m" lengths (no coils) → alignment ok
    - Install 3.8 m dummy coils in support structure → ok
    - Next: 77 K cooldown at Fermilab, attached to warm-cold interface and support -- February

Assembly of full-length structure
Section 1 and 2 before joining operation



3.2 m long coil-pack sub-assembly

LQS trial assembly #1, dummy coils, room temp.

- Successful trial assembly – all goals achieved:
  - Strain gauges on dummy coils, shell, axial support rods
  - No major problems
  - Axial preload works to at least 10% > design
  - Azimuthal preloads of shell, dummy coil consistent
  - Azim. preload will be increased to reach design goal by adding 75 μm shims to keys during next trial assembly

LQ SCHEDULE HIGHLIGHTS

- LQS01 assembly begins in May
  - Handling of 3.8 m practice coils begins earlier
- LQS01 test in September
- Options for LQ testing in FY10
  - shell support with all new coils
  - replace one coil, retest in shell structure
  - collar support structure (LQC)

LARGE APERTURE QUAD (HQ)

HQ DESIGN STUDY: 134 mm → 110 mm → 120 mm

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

- **Testing planned for end of CY09.**

HQ STATUS

- BNL
  - Drawings for reaction, impregnation fixtures submitted to BNL shops
- Fermilab
  - Coil design completed
  - Drawings for coil end parts released for quotes
- Berkeley
  - Cable development completed (0.8 mm strand ∅)
  - Most of the tooling for coil winding and curing is in-house, now being assembled

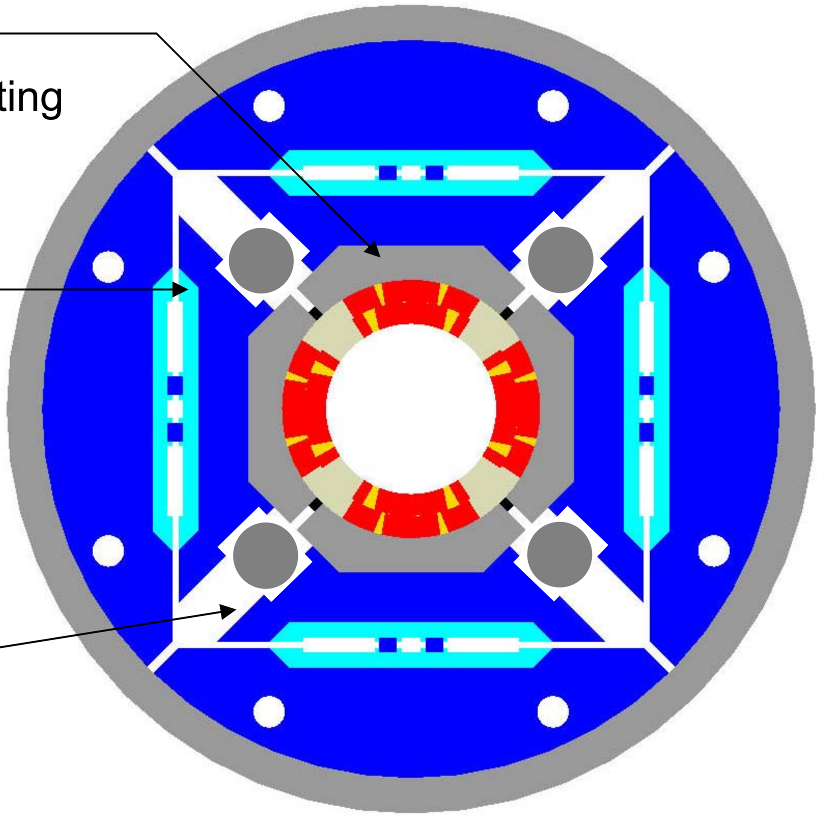
HQS – Mechanical Shell based Structure

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

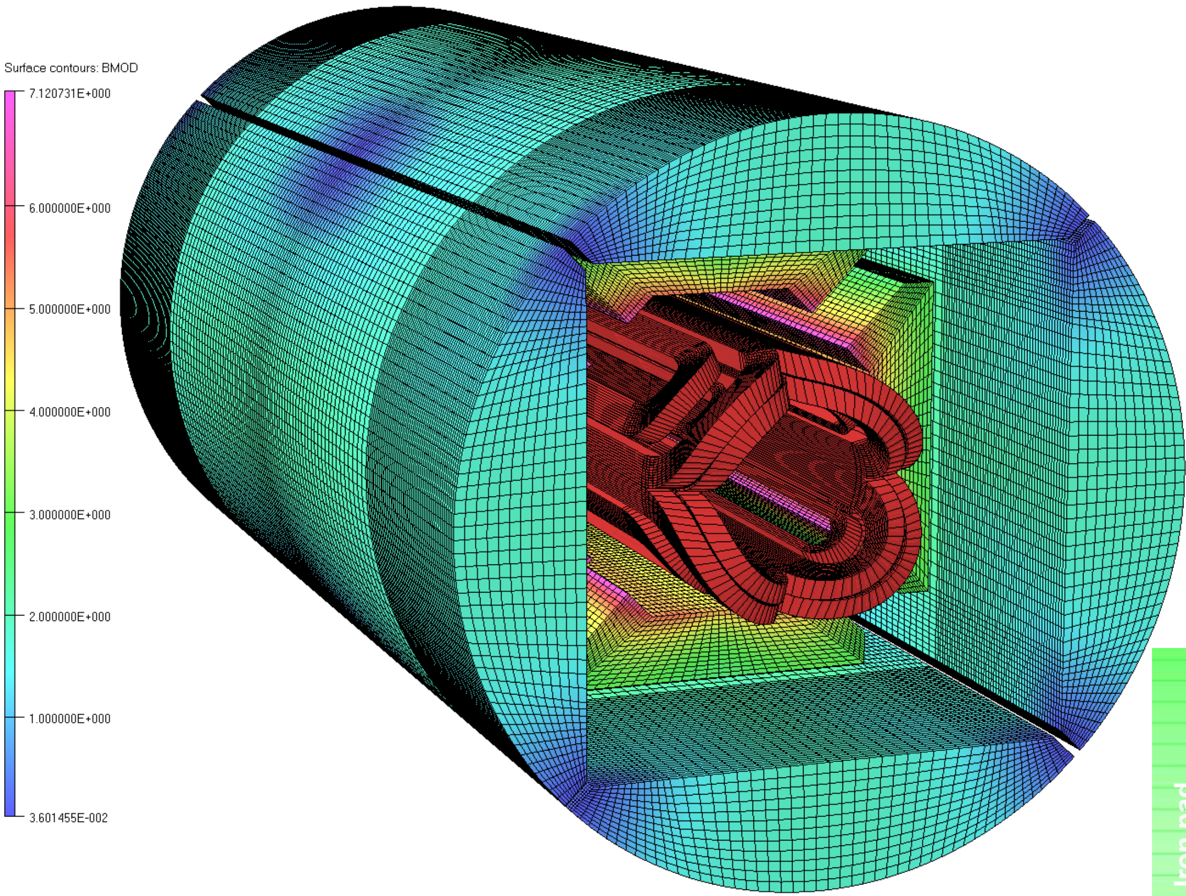
Assembly

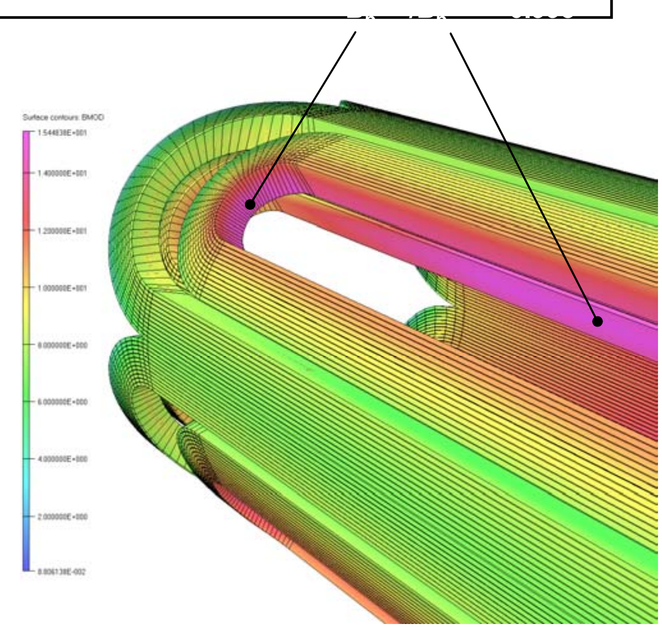
- 60 mm bladders located outside the key span
- 38 MPa pressure (600 + 50 microns clearance for 220 T/m)
- Collars, pads and key locations optimize to minimize stress

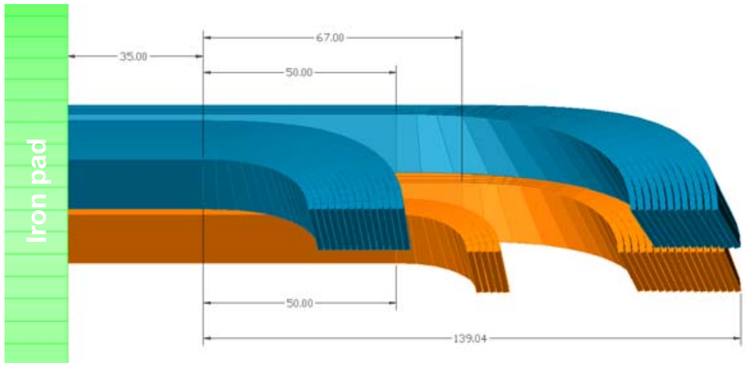


570 mm outer diameter

3D analysis - Tosca







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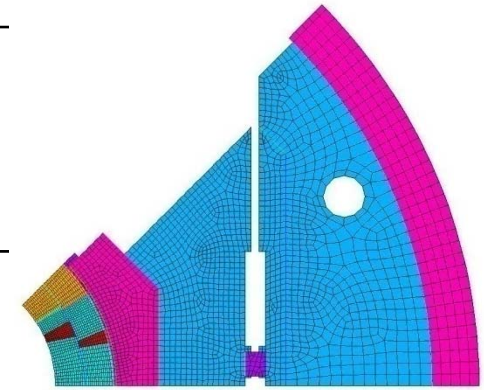
Short-sample limit in the straight section

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			

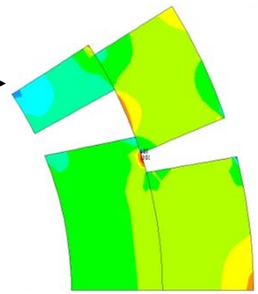
Critical temperature T_c (120 T/m) = 10.7 K

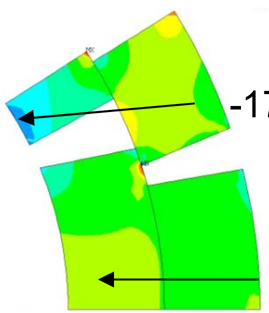
HQ – Mechanical analysis
Azimuthal stress in the coil



	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

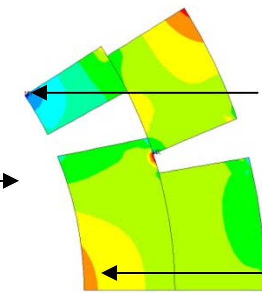
-90 MPa





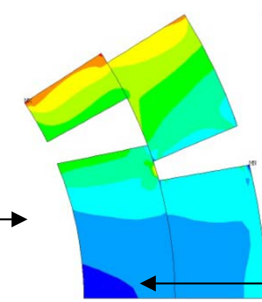
-177 MPa

- 80 MPa



-82 MPa

- 20 MPa



-177 MPa

=> High but acceptable stress at short sample

Courtesy of H. Felice

MATERIALS

Available strands

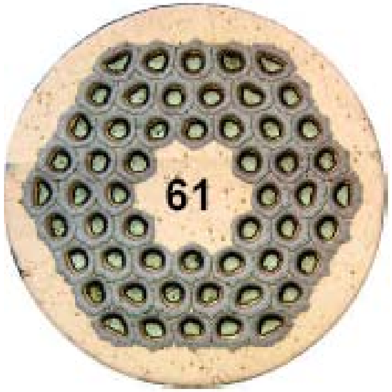
Magnet instability at low temp.

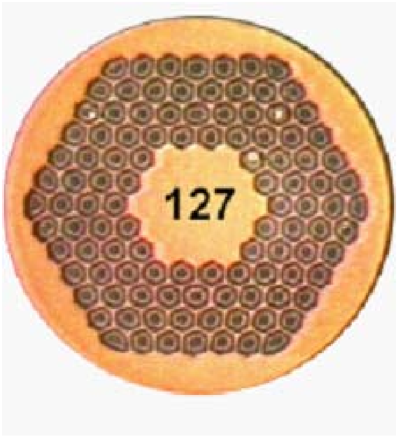
Other work

[Conductor pipeline – ok]

AVAILABLE STRANDS

- OST RRP® Nb_3Sn:
  - 54/61 – LARP workhorse – used for LR, recent TQ, LQ
  - 108/127 – recently became a standard product
    - Underway: "qualify" in a TQ (1m) – coils now being made
    - More stable (see below) than 54/61 at same strand ∅
    - In HQ (0.8 mm 108/127) same filament ∅ as 0.7 mm 54/61 in TQ





CONDUCTOR/MAGNET INSTABILITY

TQ QUENCH PERFORMANCE LOWER, ERRATIC AT 1.9 K

- Source of instability:
  - conductor only?
  - conductor + magnet construction (i.e., conductor damage)?
- Temperature threshold ~2.5 K
  - I_q decreases (13 kA → 11.6 kA) at ~2.5K

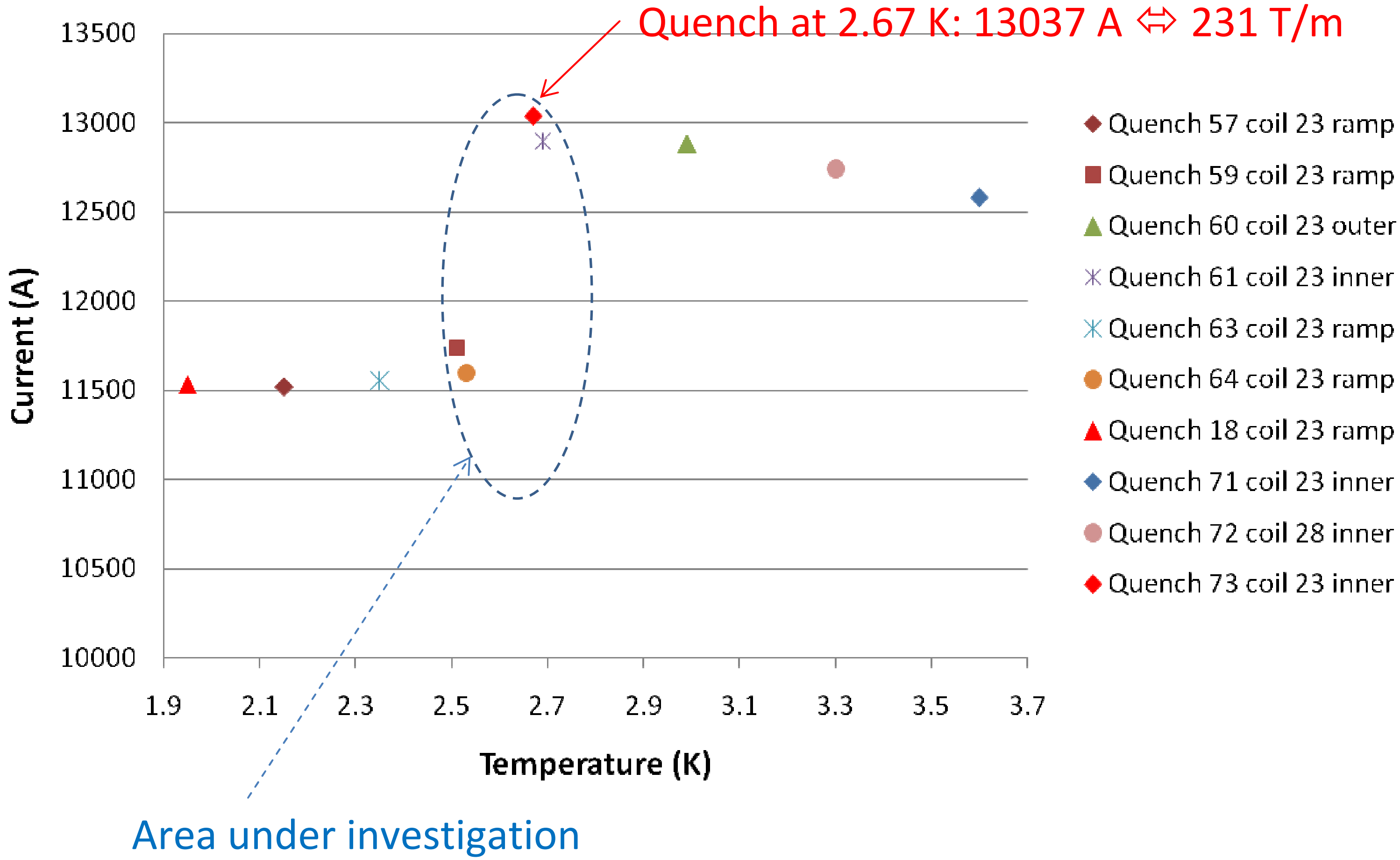
STRAND TESTS

- Instability at medium field (6 T)
  - "self field" instability differentiated from low field "flux jump" instability (which we know how to avoid)
- Instability onset between 2K and 2.5 K (Lambda point 2.17 K)

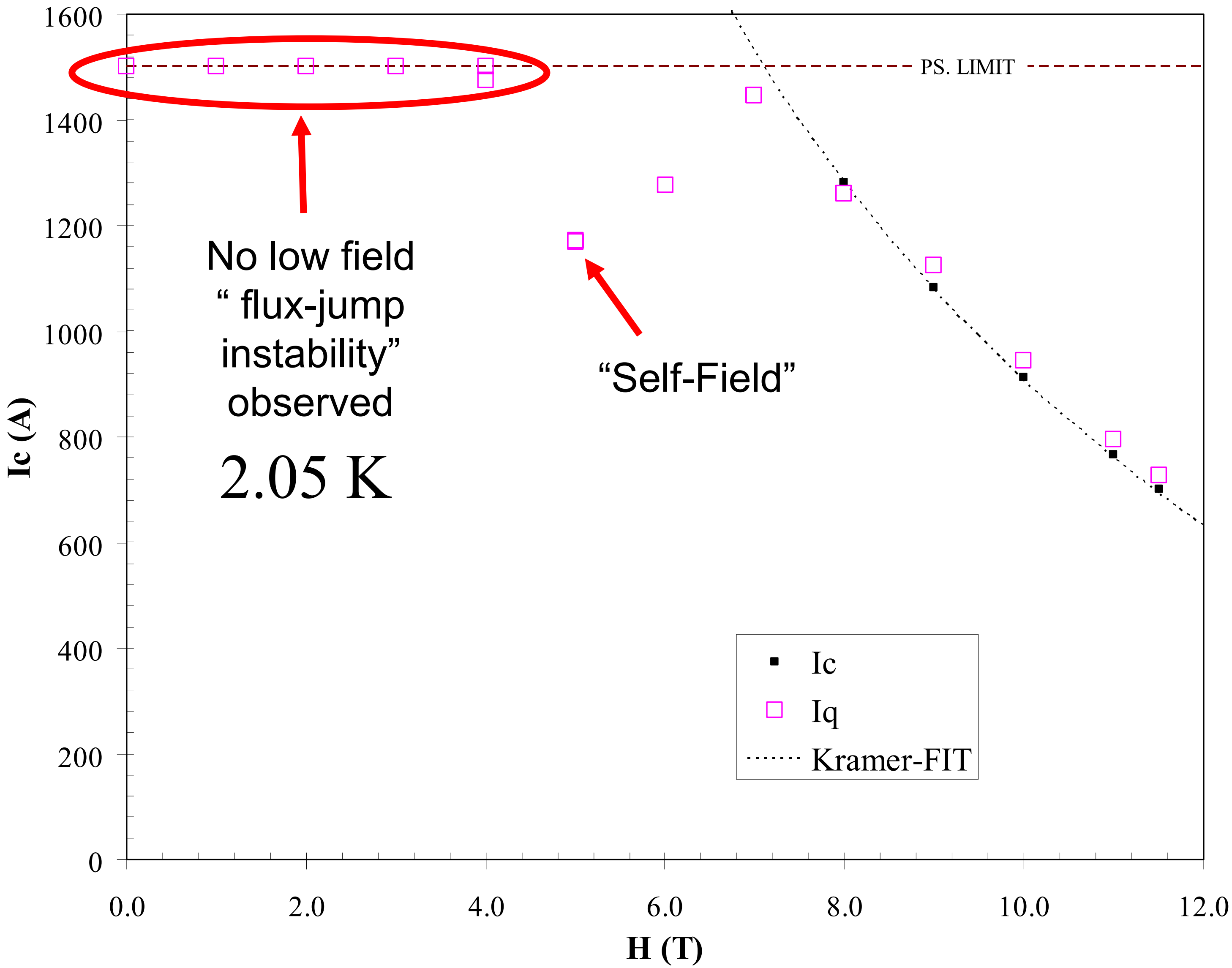
AN ACTIVE AREA OF STUDY …

[Note: HQ load line < TQ load line ⇒ instabilities in HQ < TQ]

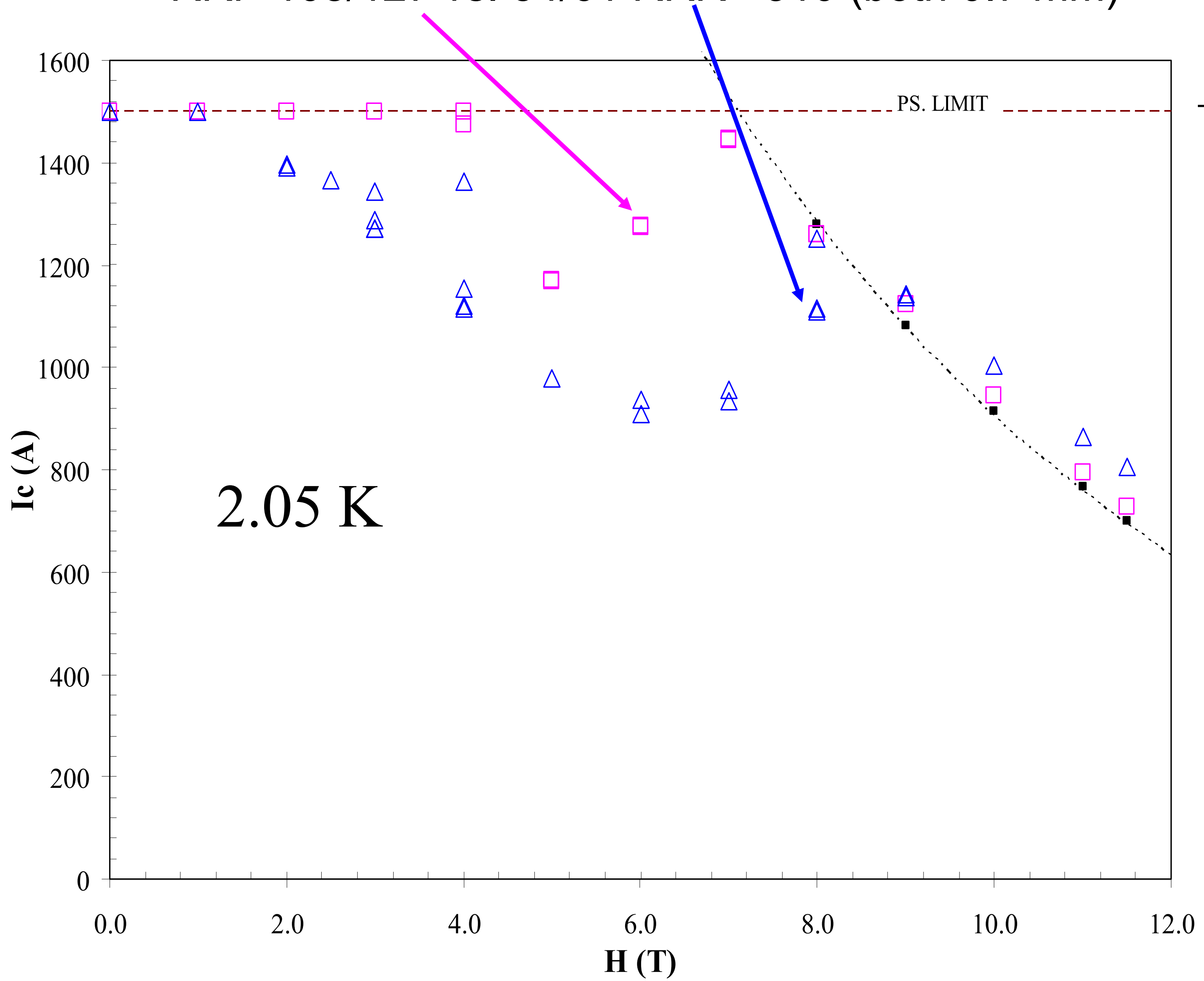
TQS02c training (20 A/s) vs. temperature [RRP 54/61, test at CERN]



RRP 108/127 0.7 mm 640C/48h RRR~ 310 (high)



RRP 108/127 vs. 54/61 RRR~ 310 (both 0.7 mm)

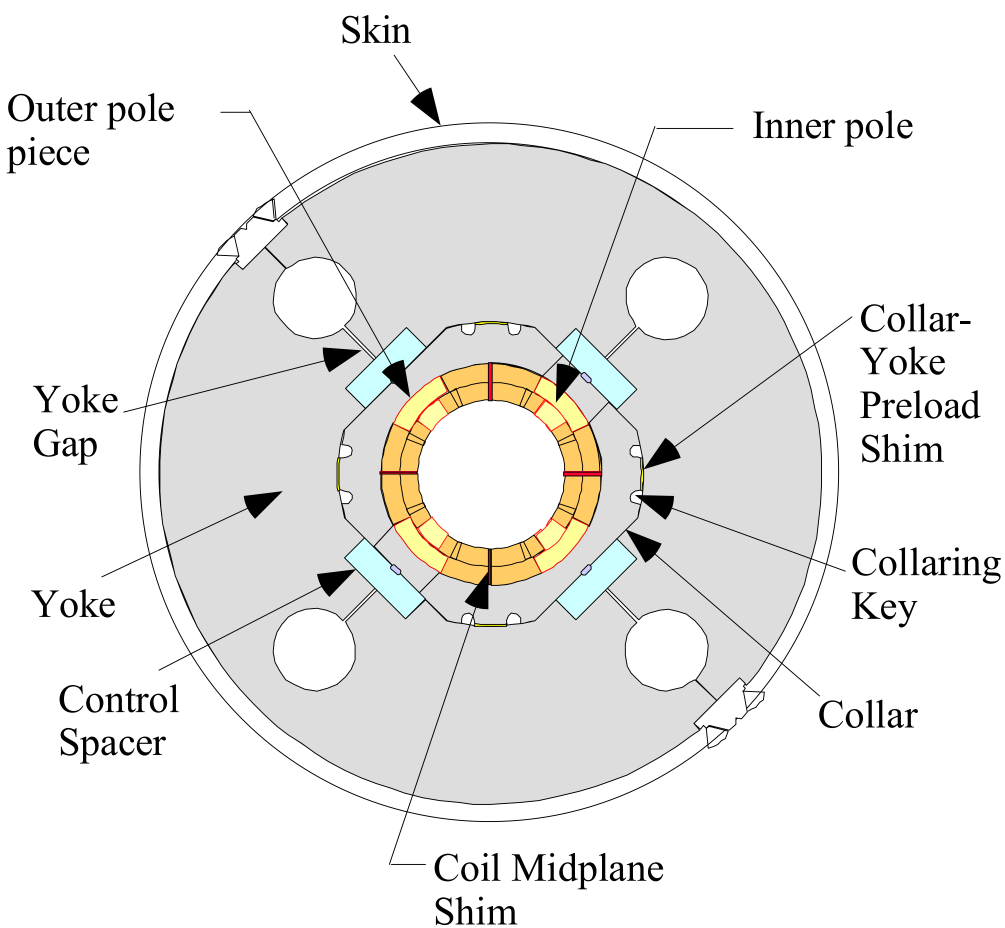


OTHER MATERIALS WORK

- **Cable** R&D Underway:
  - Measure cable length change at each stage of reaction
  - Measure cable J_c versus stress transverse to plane of cable
    - NHMFL in Florida (Jan.) – vary preload while cold, 4.2 K
    - CERN FRESCA (summer 09), 4.2 K and 1.9 K [also: stability]
- Strand degradation (rolling) vs. cable degradation
- "Self-field" instability model (Bordini, Rossi) fits some strand measurements
- **Needed, not yet funded:**
  - Manufacture "cored" cable (25 μm stainless steel strip inside cable, to increase interstrand resistance R_I), test in TQ for reduced ramp rate effects on gradient, harmonics
  - Measure thermal margin in cable, magnet

TECHNOLOGY QUADS
1M QUADS - TQS, TQC

TQ/LQ COLLAR SUPPORT STRUCTURE

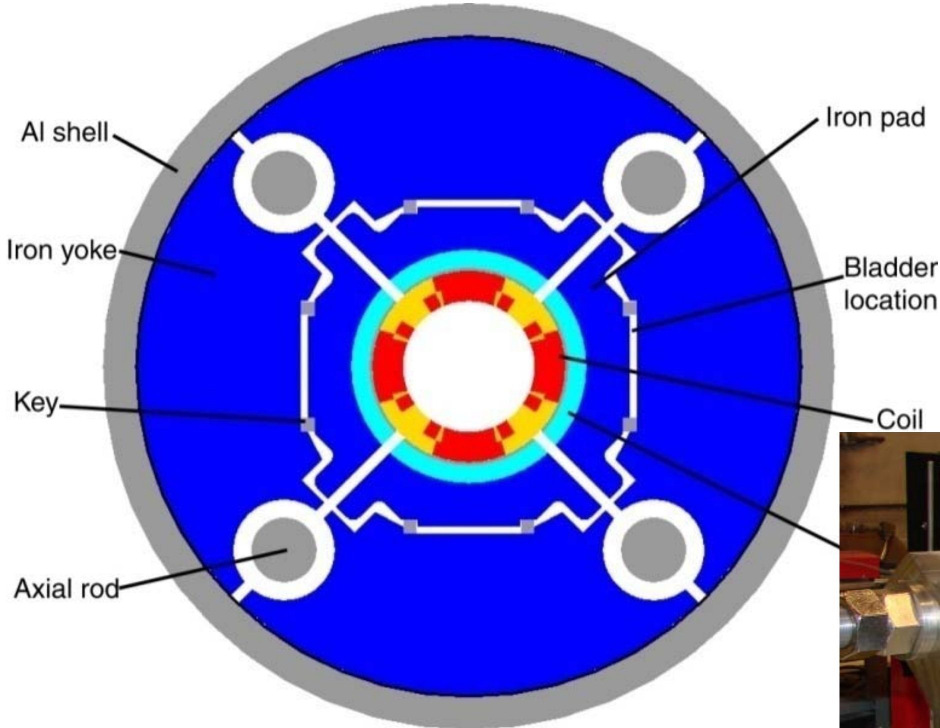


"No" axial preload – i.e.,

"no gap"

Stainless steel shell

TQ SHELL SUPPORT STRUCTURE



aluminum shell

High axial preload

CONCLUSIONS FROM TQ CONSTRUCTION & TESTING

- Thorough review of TQ data by videoconference (Sept., Oct.)
  - Talks by Bossert, Caspi, Chlachidze, Felice, Ferracin

- Firm Conclusions:
  - With good RRP coils and proper assembly, exceed 200 T/m (4.5 K) and reach ~ 90% I_{ss}
  - Same coils used in both structures reached ~ same fraction I_{ss} (caveat: TQC02e testing limited by leads)
  - 1.9 K (superfluid):
    - MJR performs as expected (i.e., I_q increases)
    - RRP erratic, I_q generally lower than at 4.5 K
  - Some of the causes that limit magnet quench performance

MORE TQ CONCLUSIONS

- Conclusions:
  - Poles must be bonded to coils
  - Etc. (other "minor" construction features)
  - Some of the causes that limit magnet performance

- Not yet settled:
  - Source of 1.9 K RRP erratic quench performance
  - Either end preload (high or "snug") ok
    - TQS02d reached 97% of previous quench plateau with end support reduced to ~ 76% of that of the previous assembly

A LOOK AHEAD

NEEDED TO DEMONSTRATE "ACCELERATOR QUALITY"

- **Model HQ magnets (~ 1 m) to study/demonstrate:**
  - Quench performance, margin w. r. to operating field
  - Field quality (mean, rms, uncertainty in mean, cross section iteration – 2D and ends, alignment) – 6 magnets for initial cross section, 6 magnets for final (iterated) cross section.
  - Lifetime (multiple thermal cycles, at least two magnets)
  - Additional coil production tooling
  - Additional support structure(s), test facility
- **QA (long version of HQ)**
  - Field quality as above (6 magnets)
  - Lifetime as above (operation in cryostat)
  - "Medium" level of instrumentation
  - Additional coil production tooling, support structure
  - Operation in test beam at CERN

PLANNING

- Have info on staff, calendar time, materials to make TQ, LQ, HQ (some)

- Iterate initial list of magnets, goals with LARP Magnet Steering Committee, CERN

- Draft plan available in March, presented at CM12 in April. Five-year plan presented at DOE Annual Review in June.

- Remark: At some point, funding would shift from LARP to APUL (Accelerator Project for the Upgrade of the LHC).

- To keep in mind: When will CERN decide that CERN will need to build magnets for the Phase 2 upgrade?

SUMMARY

CONCLUSIONS

- **Good progress toward establishing 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 3.6 m quad by end of CY 2009
  - Work on larger aperture well underway; test end CY 2009

- **There is still a lot to do:**
  - Demonstrate 200 T/m in 3.6 m, 90 mm quad
  - Develop/understand/optimize superconducting & mechanical properties of Nb_3Sn materials and magnets
  - Demonstrate full set of properties needed for accelerator use
  - Establish engineering phase space (aperture, gradient, etc.)

ACKNOWLEDGEMENTS

- U.S. DoE High Energy Physics for consistent support of LARP and the Conductor Development Program
- "Core" magnet R&D programs at Fermilab, Berkeley, Brookhaven for timely assistance
- CERN for support of assemblies and tests of 1 m quads
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