Nb_3Sn Magnets for the LHC Upgrades

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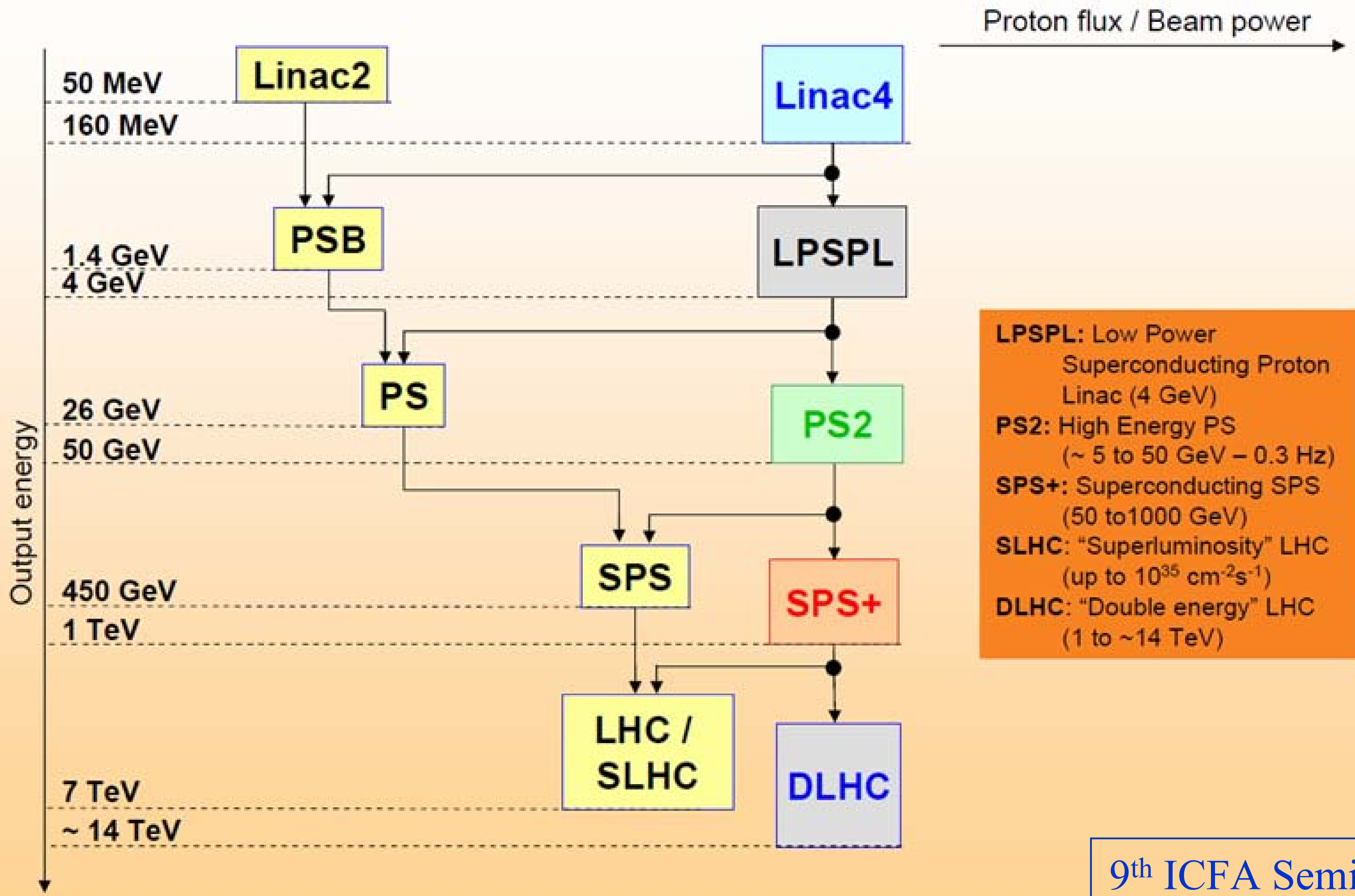
Upgrade components

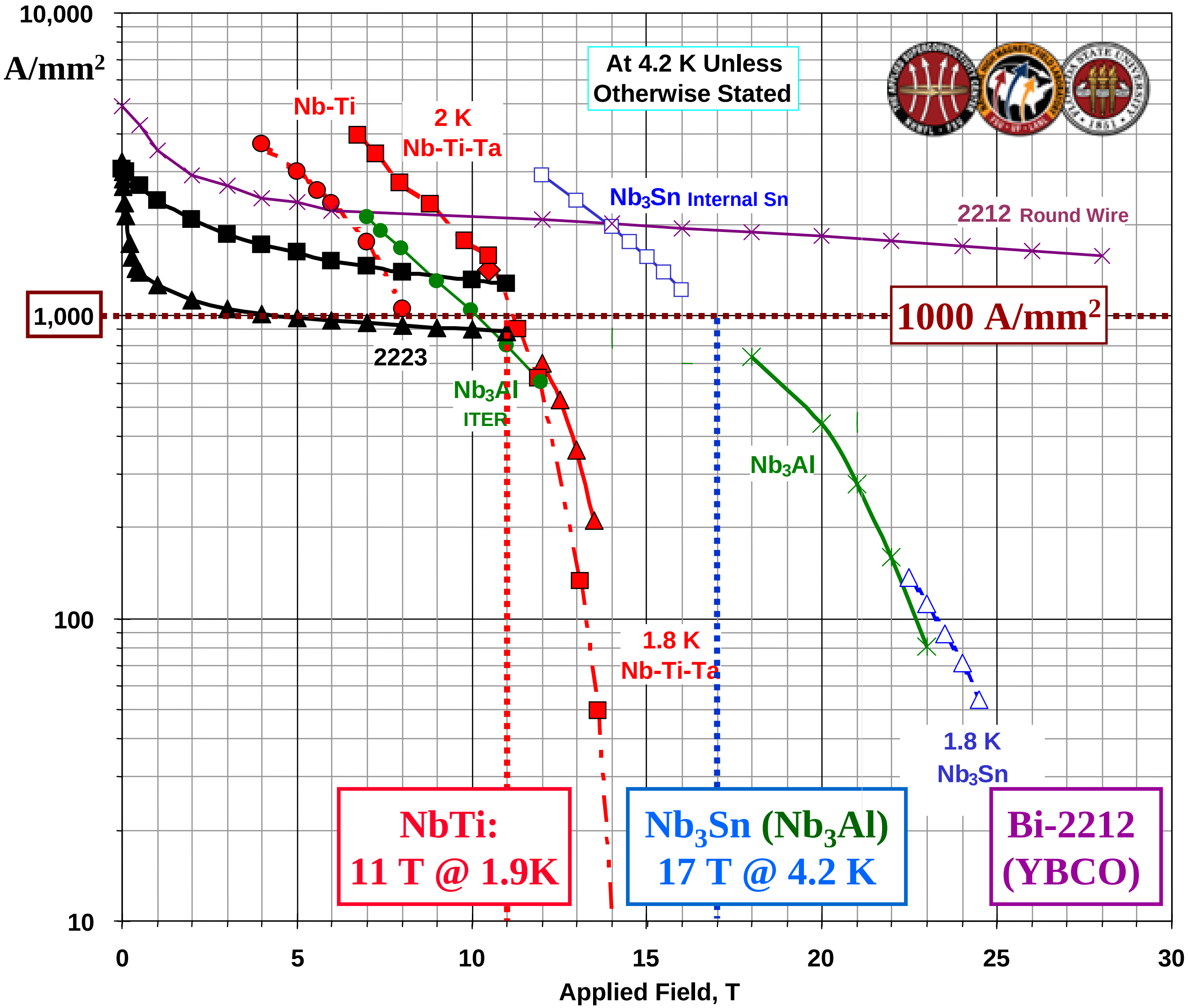


LPSPL: Low Power Superconducting Proton Linac (4 GeV)
PS2: High Energy PS (~ 5 to 50 GeV – 0.3 Hz)
SPS+: Superconducting SPS (50 to1000 GeV)
SLHC: "Superluminosity" LHC (up to 10^{35} $cm^{-2}s^{-1}$)
DLHC: "Double energy" LHC (1 to ~14 TeV)

L. Evans – EDMS Document 974861

9th ICFA Seminar
SLAC, Oct. 2008

Technology Options



Superconductor critical currents for 100 m length capable material (round wires)

- Nb-Ti: Example of Best Industrial Scale Heat Treated Composites ~1990 (compilation)
- Nb-Ti(Fe): 1.9 K, Full-scale multifilamentary billet for FNAL/LHC (OS-STG) ASC'98
- Nb-44wt.%Ti-15wt.%Ta: at 1.8 K, monofil. high field optimized, unpubl. Lee et al. (UW-ASC) '96
- Nb-37Ti-22Ta: at 2.05 K, 210 fil. strand, 400 h total HT, Chernyi et al. (Kharkov), ASC2000
- Nb_3Sn: Bronze route VAC 62000 filament, non-Cu 0.1μW·m 1.8 K J_c, VAC/NHMFL data courtesy M. Thoener.
- Nb_3Sn: Non-Cu J_c Internal Sn OI-ST RRP #6555-A, 0.8mm, LTSW 2002
- Nb_3Al: Nb stabilized 2-stage JR process (Hitachi,TML-NRIM,IMR-TU), Fukuda et al. ICMC/ICEC '96
- Nb_3Al: JAERI strand for ITER TF coil
- Bi-2212: non-Ag J_c, 427 fil. round wire, Ag/SC=3 (Hasegawa ASC2000+MT17-2001)
- Bi 2223: Rolled 85 Fil. Tape (AmSC) B||, UW'6/96
- Bi 2223: Rolled 85 Fil. Tape (AmSC) B|_, UW'6/96

Credit: Peter Lee
Applied Superconductivity Center, FSU/NHMFL

Magnet R&D Collaboration Network

LARP (MagSys)
- Participants: BNL, FNAL, LBNL + CERN
- Goal: fully qualified Nb_3Sn quadrupoles for SLHC

CARE (NED)
- Participants: CCLRC, CEA, CERN, CIEMAT, INFN, UT, WTU
- Goal: basic R&D on conductor, insulation, design, quench protection

EUCARD (HFM)
- Participants: CERN, CEA, CNRS, COLUMBUS, DESY, EHTS, FZK, INFN, PWR, SOTON, STFC, TUT, UNIGE
- Goal: high field Nb_3Sn dipole model & very high field (HTS) insert

***Inter-Laboratory collaborations on specific topics*:**

- CERN, RAL, CEA, LBNL on Short Model Coil development
- KEK, NIMS, FNAL on Nb_3Al model coils
- LBNL, KEK on Nb_3Sn coil, structure and assembly methods
- KEK & CERN on Nb_3Al technology for the LHC upgrades
- CERN & CEA, UT, LBNL/LARP on magnet testing
- LBNL & FNAL, BNL, CERN, UT, TAMU on cable development

Luminosity Upgrade (SLHC)

Physics goals:

- *Improve measurements of new phenomena seen at the LHC*
- *Detect/search low rate phenomena inaccessible at nominal LHC*
- *Increase mass range for limits/discovery by ~30%*

Implementation in 2 phases:

- *Phase 1 ($L= 2\cdot10^{34}\ cm^{-2}sec^{-1}$): ~2014*
- *Phase 2 ($L=10\cdot10^{34}\ cm^{-2}sec^{-1}$): ~2017*

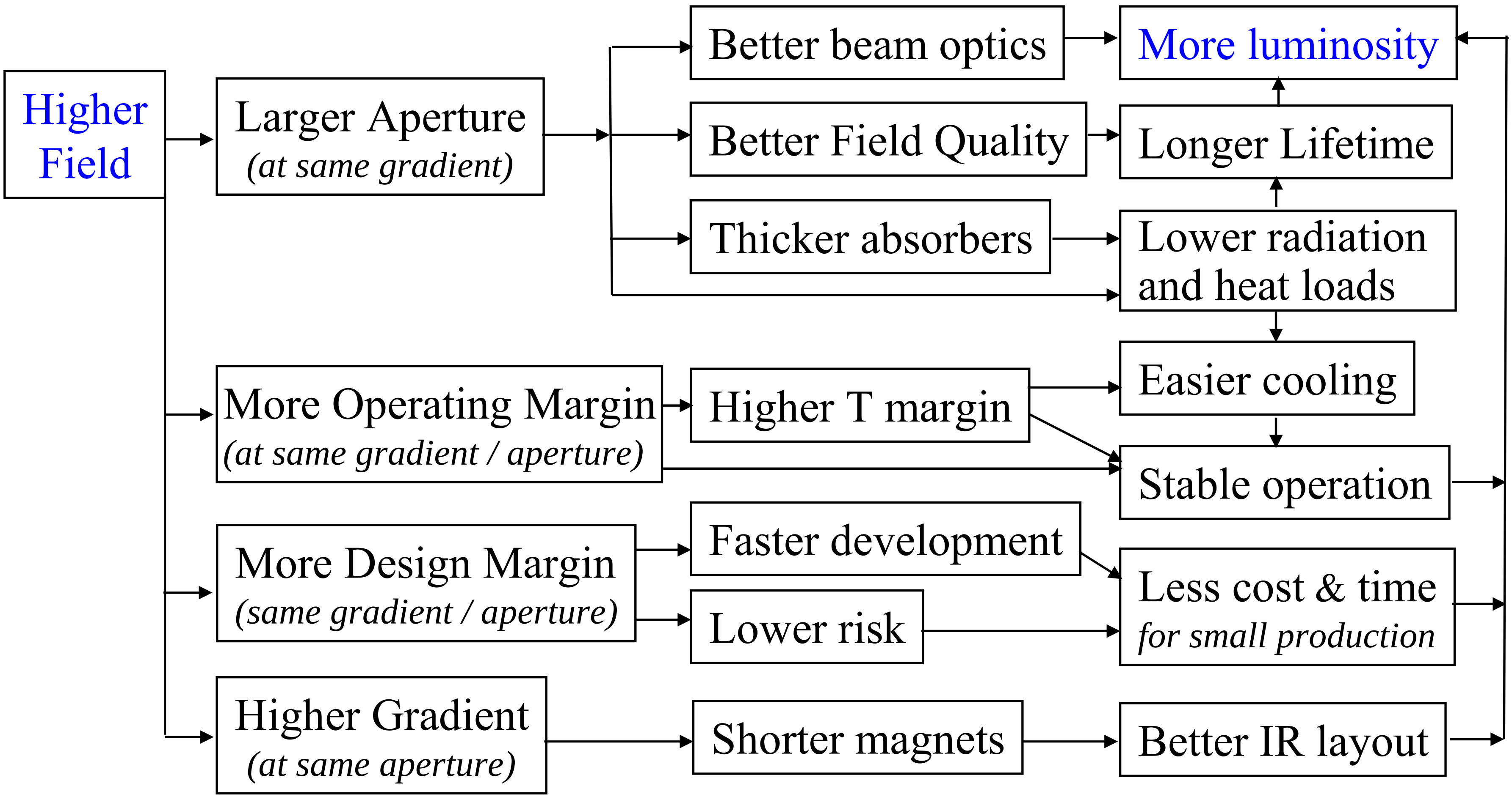
Required accelerator upgrades include new IR magnets:

- *Directly increase luminosity through stronger focusing*
  $\Rightarrow$ *decrease* β^*
- *Provide design options for overall system optimization/integration*
  $\Rightarrow$ *collimation, optics, vacuum, cryogenics*
- *Be compatible with high luminosity operation*
  $\Rightarrow$ *Radiation lifetime, thermal margins*

Major detector upgrades are also required to take full advantage of SLHC

Quadrupole Upgrade Roadmap

High field technology provides design options to maximize luminosity



LARP Magnet Program Components

1. Materials R&D:
   - *Strand specification and procurement*
   - *Cable fabrication, insulation and qualification*
   - *Heat treatment optimization*

   Ongoing

2. Technology development with Racetrack Coils:
   - *Subscale Quadrupole (SQ)*
   - *Long Racetrack (LR)*

   Completed

3. Cos 2θ Quadrupoles with 90 mm aperture:
   - *Technology Quadrupole (TQ)*
   - *Long Quadrupole (LQ)*

   ~80%

4. Cos 2θ Quadrupoles with 120 mm aperture:
   - *High-Field Quadrupole (HQ)*
   - *Accelerator Quadrupole (QA)*

   ~10%

Sub-scale Quadrupole (SQ)

Design features:

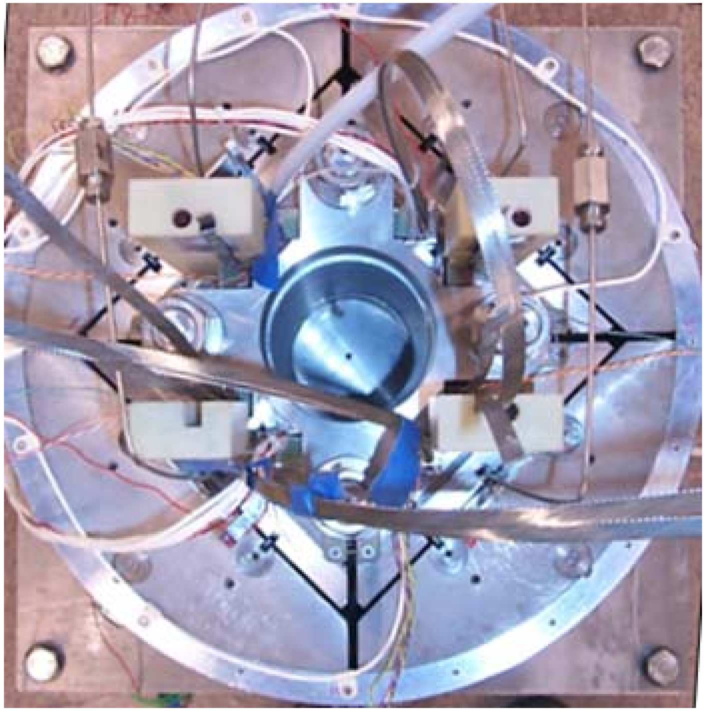
- Based on LBNL "SM" design
- Four racetrack coils, square bore
- Aperture 130 mm, Length 30 cm

R&D Goals:

- *Conductor performance verification*
- *First shell-based quadrupole structure*
- *FEA models verification*
- *Quench propagation analysis*

Results:

- Two models tested at LBNL & FNAL
- SQ02: **98% of SSL at 4.5K & 1.9K**

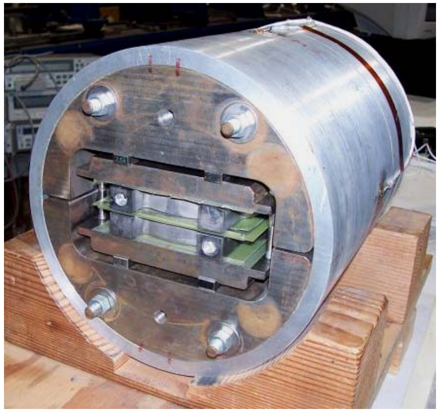


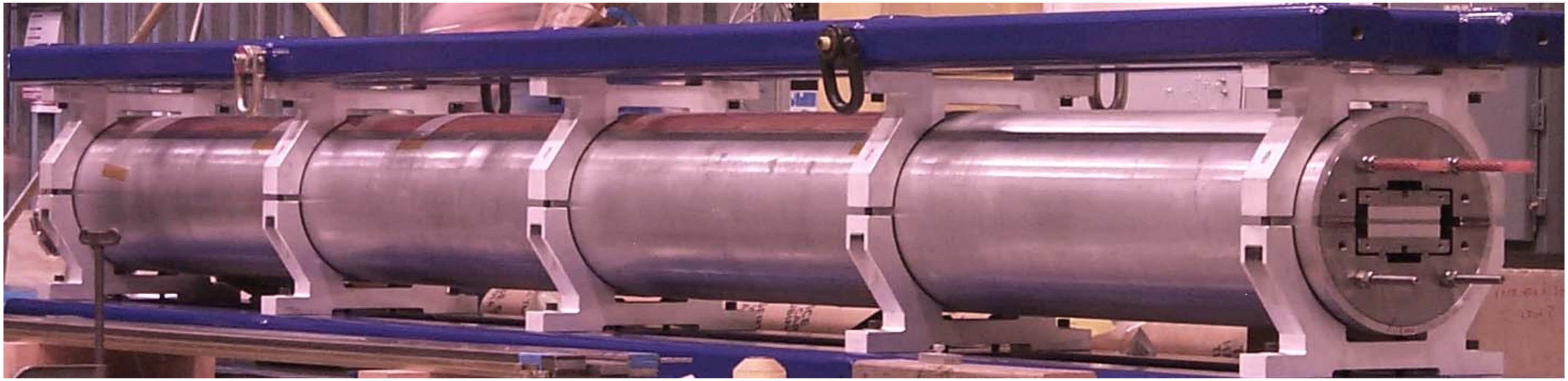
Long Racetrack (LR)

- Scale up LBNL SM coil and structure: 30 cm to 4 m
- Coil R&D: Cable, handling, reaction, impregnation
- Structure R&D: friction effects, magnet assembly

- *BNL: coil fabrication, magnet assembly and test*
- *LBNL: magnet design, structure fabrication/assembly*

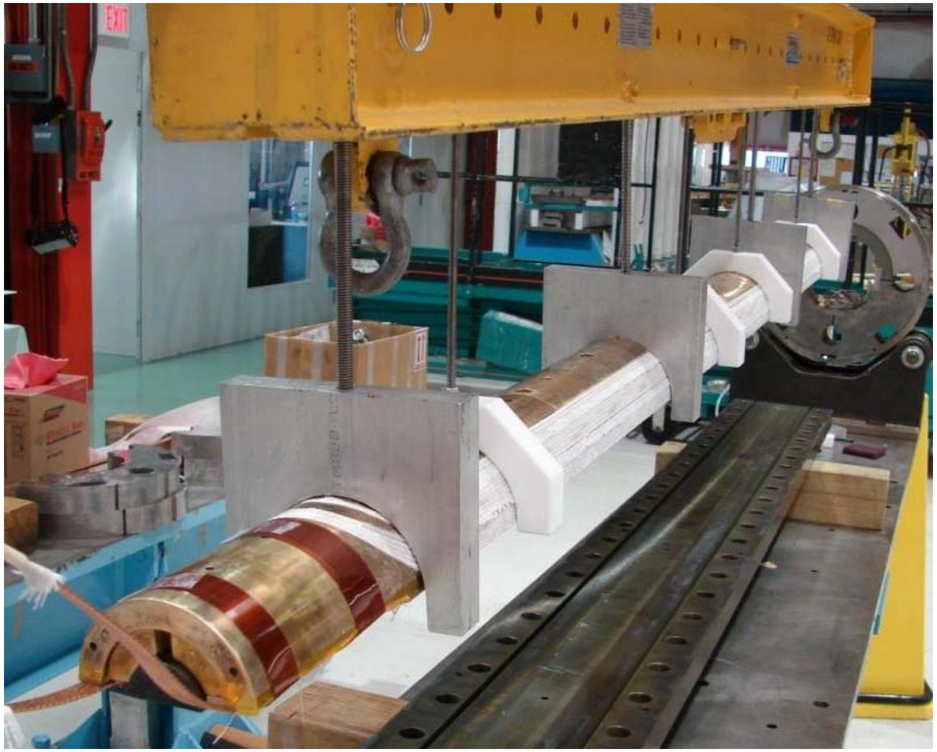
- Fast training: LRS01 first quench at 84% of SSL
- LRS02 achieved 11.5 T, **96% of short sample limit**





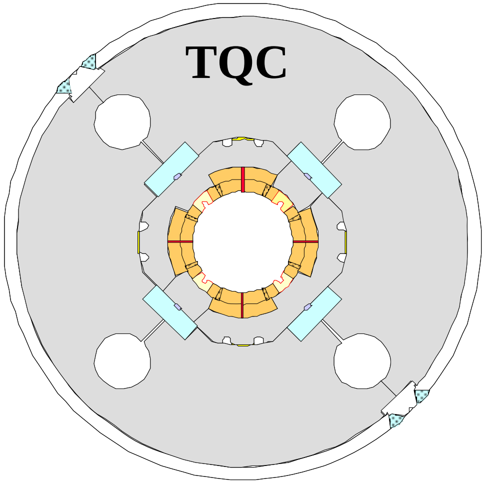
Mirror Dipoles and Quadrupoles

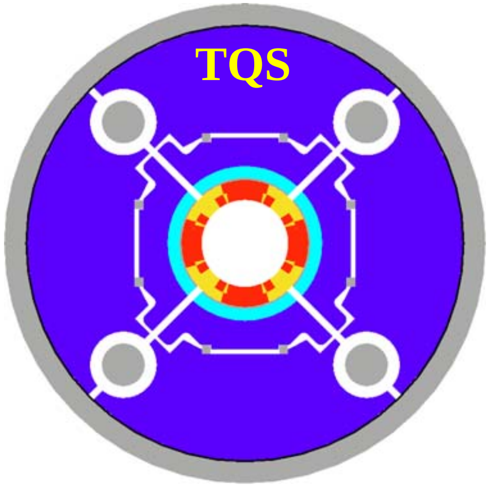
- Fermilab dipole models: 1m, 2m and 4m
- First length scale-up of Nb_3Sn cosθ coil technology
- Experience applied toward LARP models
- Quadrupole version to test single LARP coils



LARP Technology Quadrupole (TQ)

- Double-layer, shell-type coil
- 90 mm aperture, 1 m length
- Two support structures:
  - *TQS (shell based)*
  - *TQC (collar based)*
- Target gradient **200 T/m**





Winding & curing (FNAL - all coils)

Reaction & potting (LBNL - all coils)

TQ Results

Model	First Training at 4.4K			First Training at 1.9K			Highest Quench*	
	G_{Start} (T/m)	G_{Max} (T/m)	G_{max}/G_{ss} (%)	G_{Start} (T/m)	G_{Max} (T/m)	G_{max}/G_{ss} (%)	G_{Max} (T/m)	G_{Max} quench conditions
TQC01a	131	154	72	151	196	87	200	1.9K, *100A/s*
TQC01b	142	178	86	179	200	90	200	1.9K
TQC02E	177	201	87	198	199	79	201	4.4K
TQC02a	124	157	68	145	164	65	169	1.9K, *50 A/s*
TQC02b	141	173	85	158	173	78	175	*3.6K, 50A/s*
TQS01a	180	193	89	n/a	n/a	n/a	200	*3.2K*
TQS01b	168	182	84	n/a	n/a	n/a	182	4.4K
TQS01c	159	176	81	176	191	82	191	1.9K
TQS02a	182	219	92	214	221	85	222	*2.2K*
TQS02b	190	200	84	196	205	79	205	1.9K
TQS02c	216	222	93	205	209	80	231	2.7K

Optimized models surpassed the 200 T/m target gradient with >10% margin

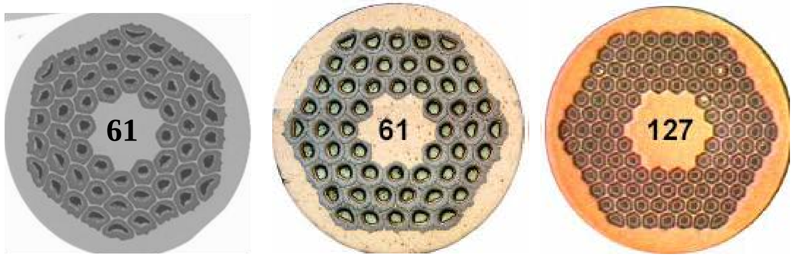
TQ Summary and Next Steps

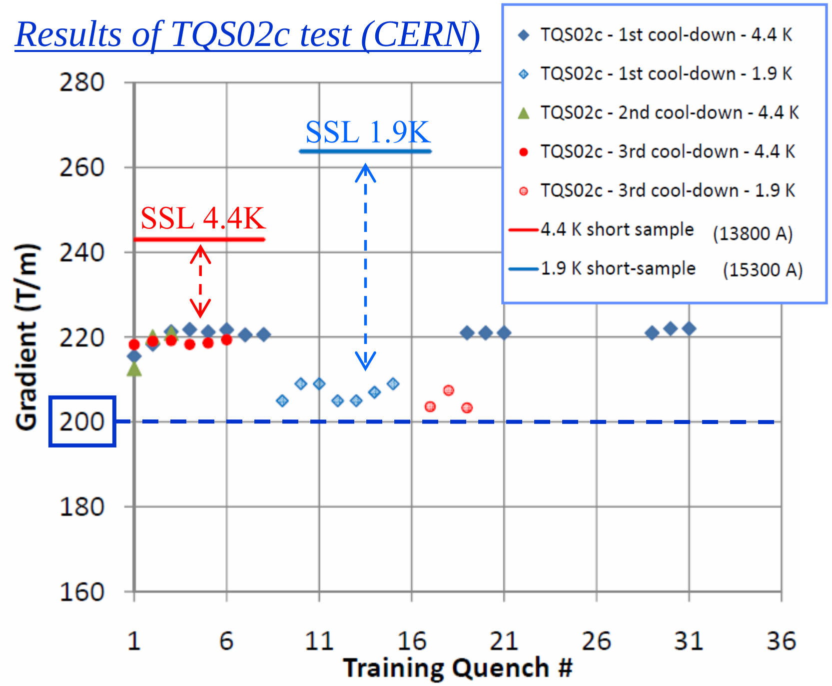
LARP

Achievements:

- *Three coil series using different wire design* ➡
- *A total of 12 quadrupole models were tested*
- *More than 30 coils fabricated*
- *Distributed coil production (FNAL, LBNL)*
- *Two models assembled and tested at CERN*
- *Magnetic, mechanical, quench studies*
- *Optimized models surpassed 220 T/m*
- *First quench >200 T/m in optimized models*

TQ01	TQ02	TQ03
OST-MJR 54/61	*OST-RRP 54/61*	*OST-RRP 108/127*





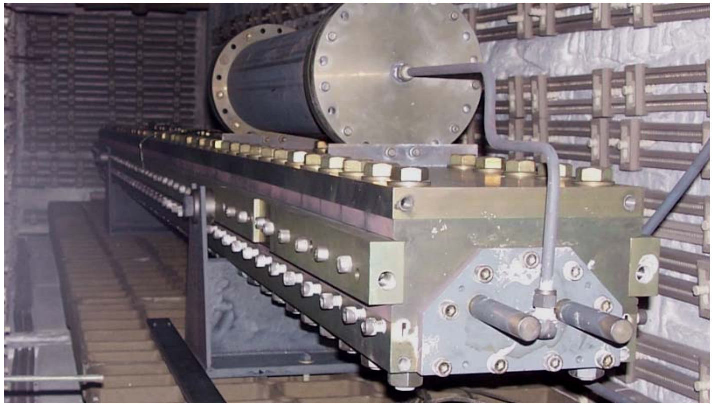
Issues and Next Steps:

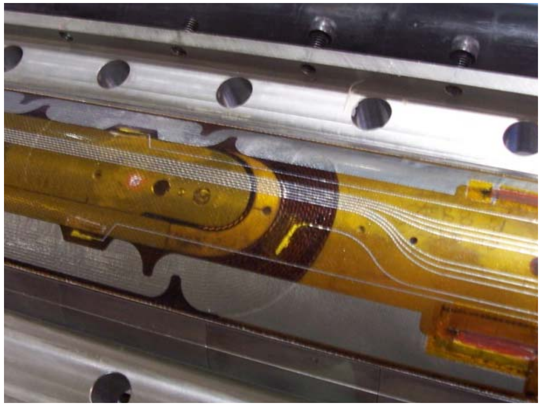
- *Coil variability resulting in local degradation*
- *Coil selection required to achieve best results*
- *Local degradation leads to instability at 1.9K*
- *Need to improve coil fabrication, wire design*

Present focus: Long Quadrupole (LQ)

<u>Scale up of TQ design from 1 m to 3.6 m length</u>

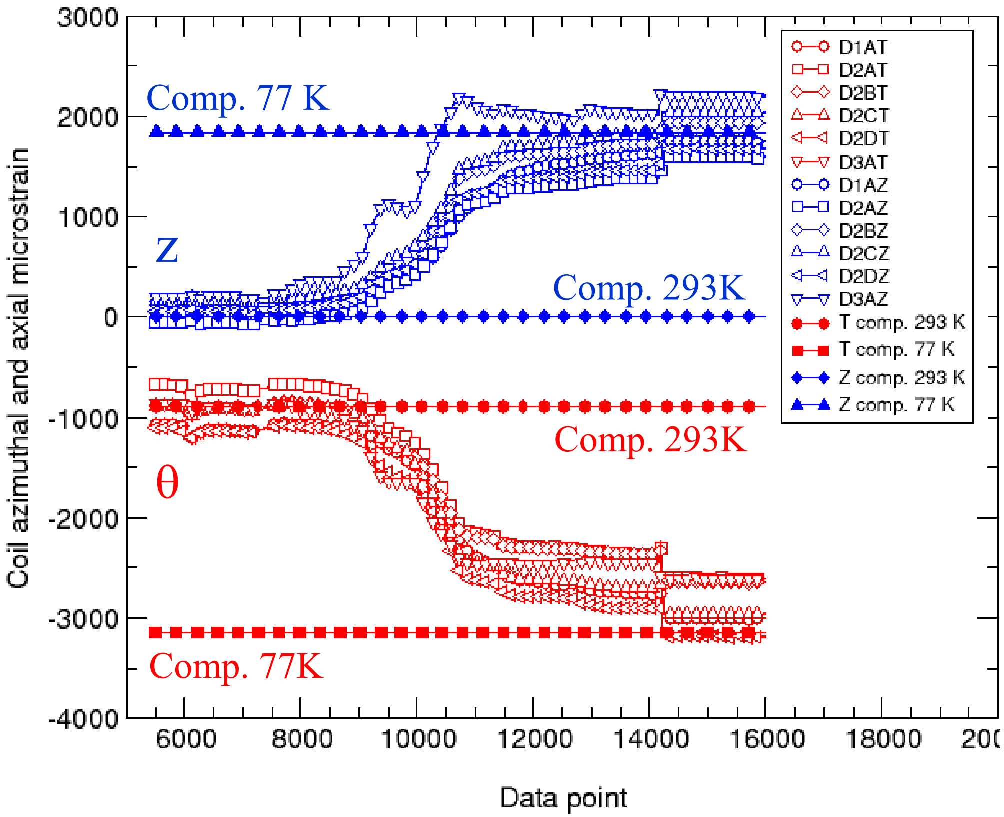
- *Coil parts, winding and curing: FNAL*
- *Coil reaction and potting: FNAL & BNL*
- *Instrumentation traces, strain gauges: LBNL*
- *Collar structure fabrication/assembly: FNAL*
- *Shell structure fabrication/assembly: LBNL*
- *Magnet test: FNAL*

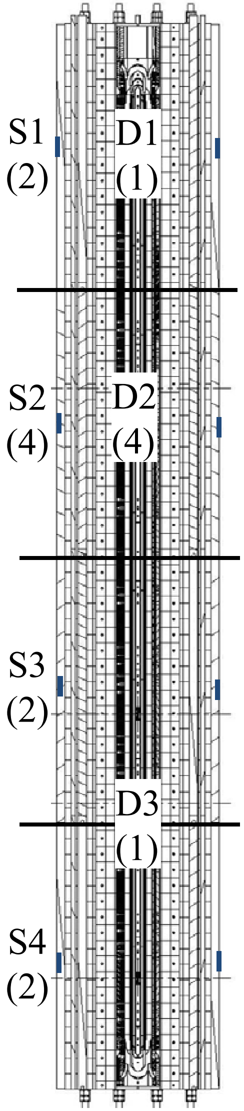




LQSD Mechanical Model

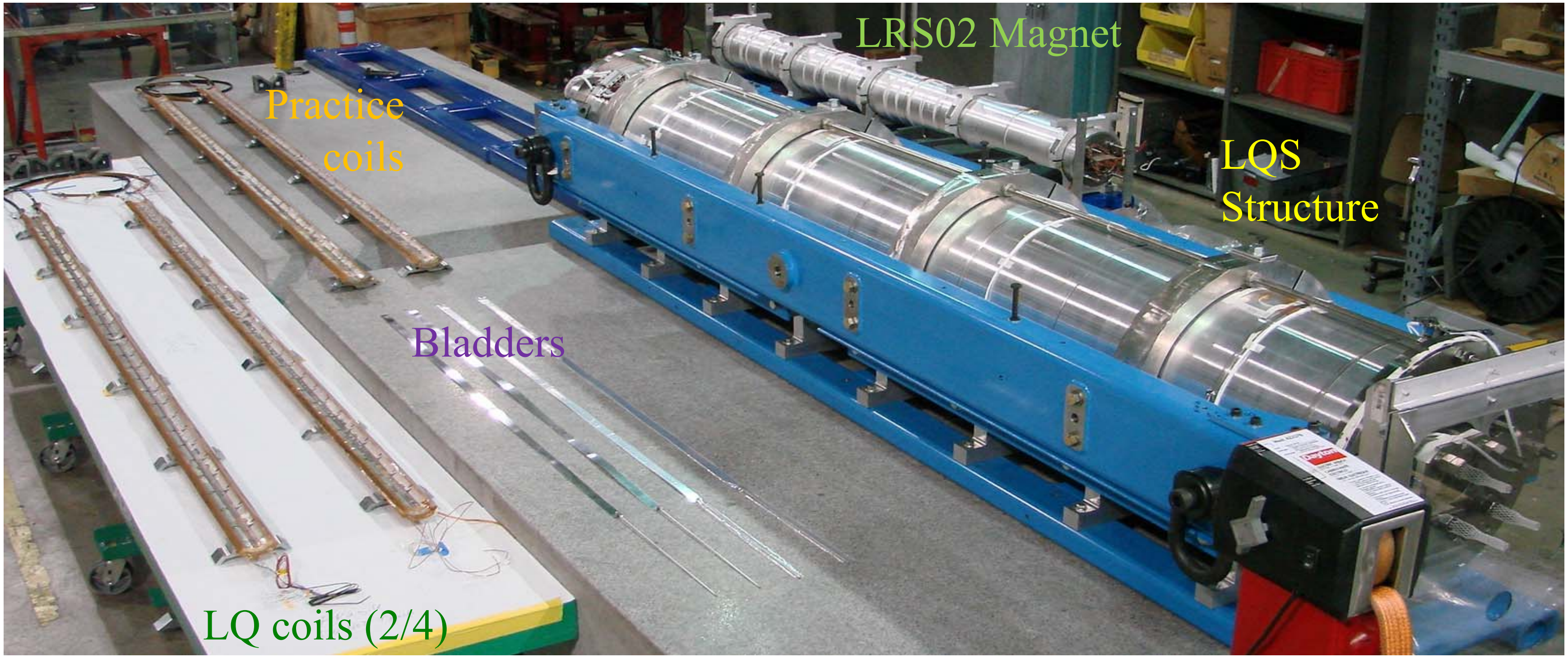
- LQS assembly w/instrumented Dummy coils
- Verify design calculations, qualify structure
- *Practice transport, test setup, cool-down*





LQ Status and Plans

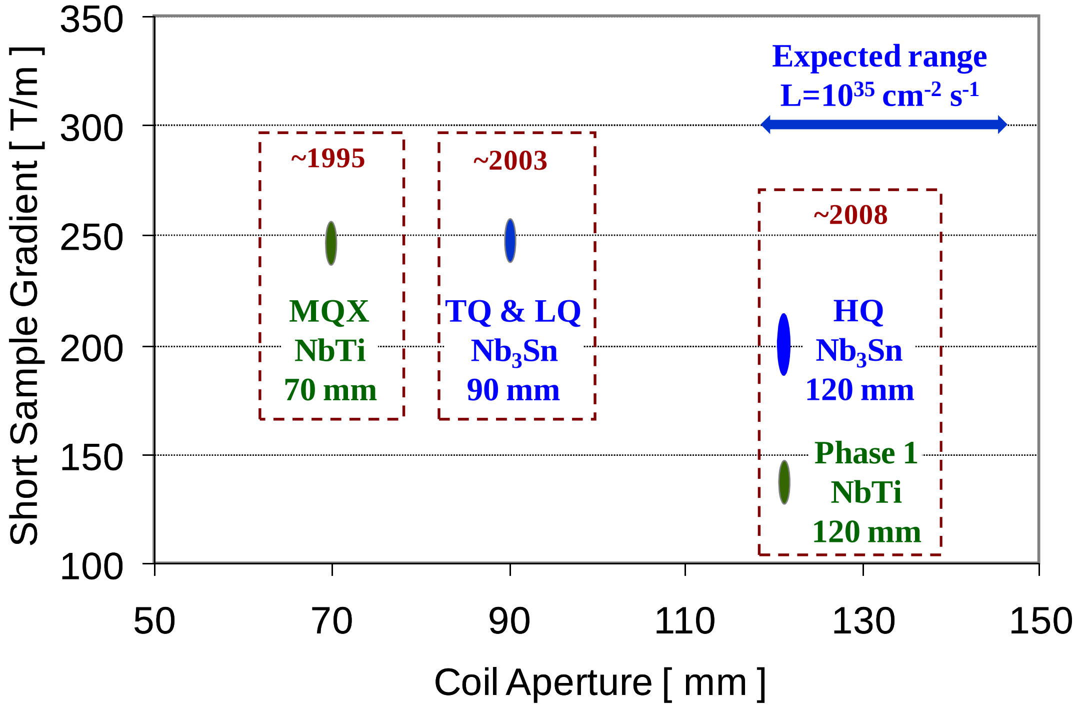
- April 2009 review following cool-down test confirmed LQS Structure Readiness
- Four coils received (2 practice coils); last 2 LQS01 coils to be received in May
- Coil instrumentation & LQS01 assembly in June-July; test in September-October
- *Additional coil fabrication and magnet tests are planned for FY10*



Next Phase: 120 mm Quadrupoles

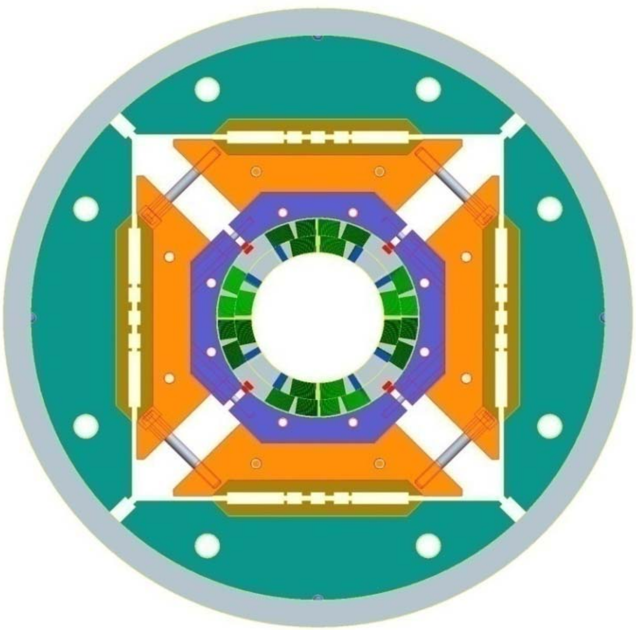
- IR Studies show *large aperture quads required* for L=10^{35} cm^{-2} sec^{-1}
- Phase 1 (L=2 10^{34} $cm^{-2}sec^{-1}$) will use NbTi Quads with *120 mm aperture*
- The *same aperture* was chosen for the next series of Nb_3Sn models (HQ)

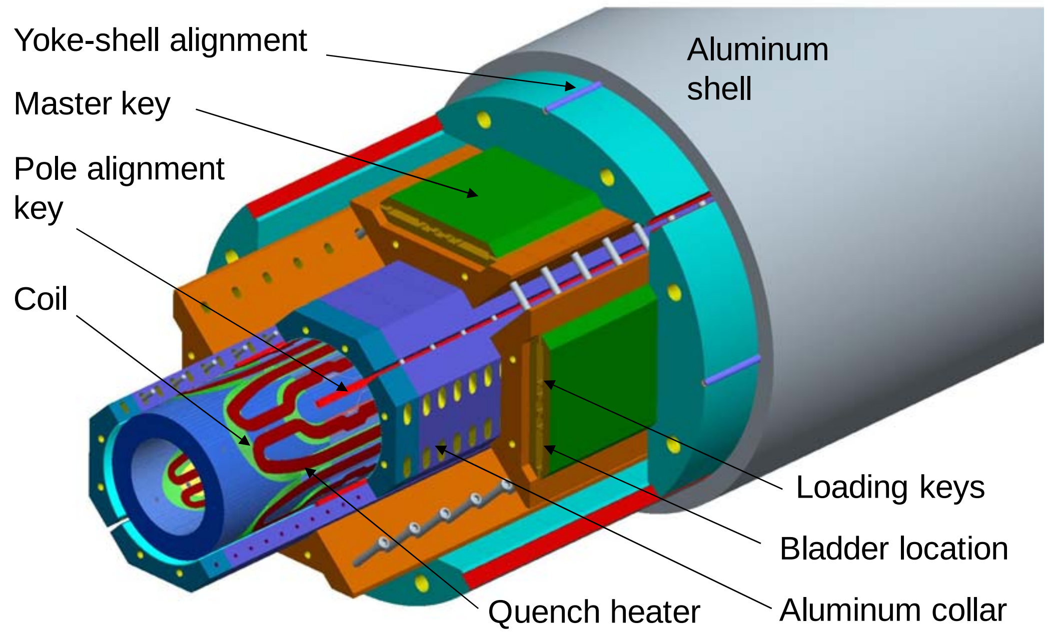
Aiming at:
- Full qualification based on Phase 1 upgrade specifications
- Providing performance reference for Phase 2 upgrade design



HQ Design Features and Parameters

- Coil peak field of 15.2 T at 219 T/m (1.9K un-degraded short sample)
- 190 MPa coil stress at SSL *(150 MPa if preloaded for 180 T/m)*
- Stress minimization is primary goal at all design steps (from x-section)
- Coil and yoke designed for small geometric and saturation harmonics
- Full alignment during coil fabrication, magnet assembly and powering

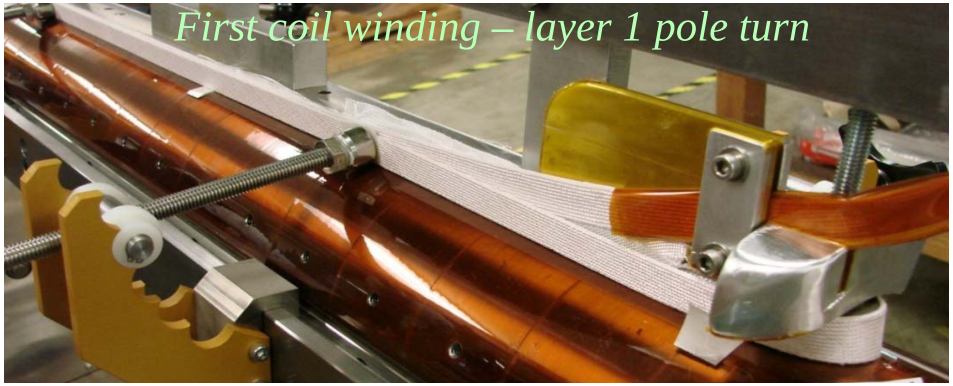




HQ Status and Plans

Status:
- Developed 15 mm wide cable, test windings w/RP parts (LBNL)
- Designed and procured stainless steel coil parts (FNAL)
- Designed and procured winding/curing tooling (LBNL)
- Designed reaction tooling (BNL); procurement underway (LBNL)
- Design and procurement of support structure is underway (LBNL)
- Winding of the first (practice) coil has started (LBNL)

Test winding w/RP parts



First coil winding – layer 1 pole turn

Plans:
- First HQ magnet test expected in early 2010
- Several 1 meter models will be needed to optimize the design
- *Next*: 2 meter models (QA) for field quality study/optimization

Energy Upgrade (DLHC)

Motivation for a 14 TeV → 28 TeV upgrade:

- *Direct enhancement of physics reach by a factor of two in mass*
- *No major detector upgrades required*

The better upgrade path depends on where and what the new physics is:

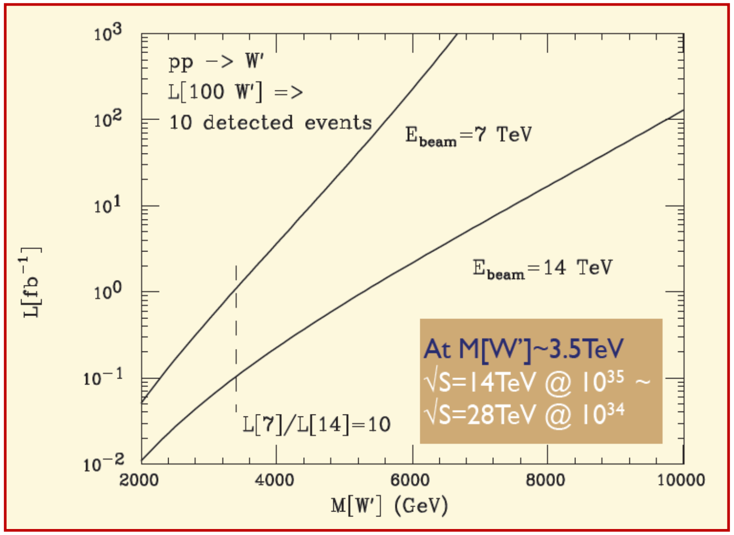
- *Low mass: 10xLum better that $2xE_{beam}$*
- *High mass: increase of E_{beam} is essential*

Strong physics interest in energy upgrade:

"14→28 TeV is great, 14→28 is even better"

(M. Mangano, SLHC kick-off meeting)

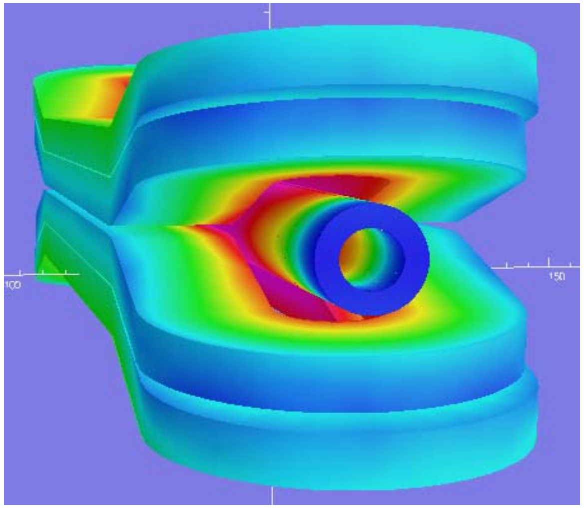
M. Mangano, HHH Workshop, Arcidosso

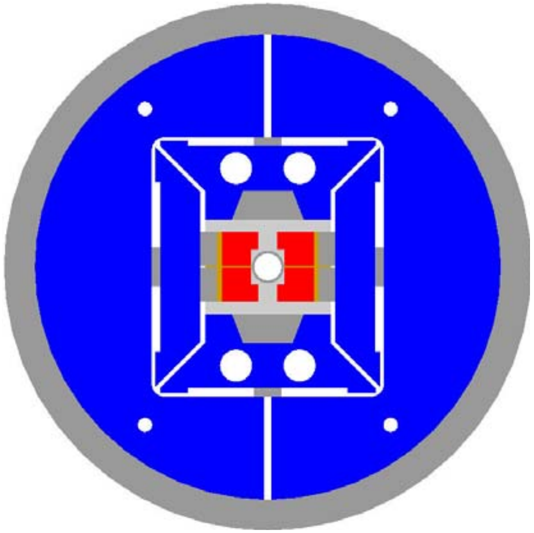


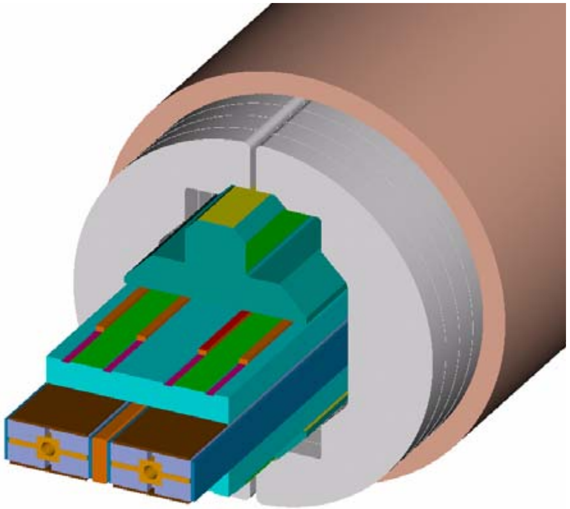
However, energy upgrade is extremely difficult from the accelerator standpoint
Many issues, but key R&D challenge is developing the high field dipoles

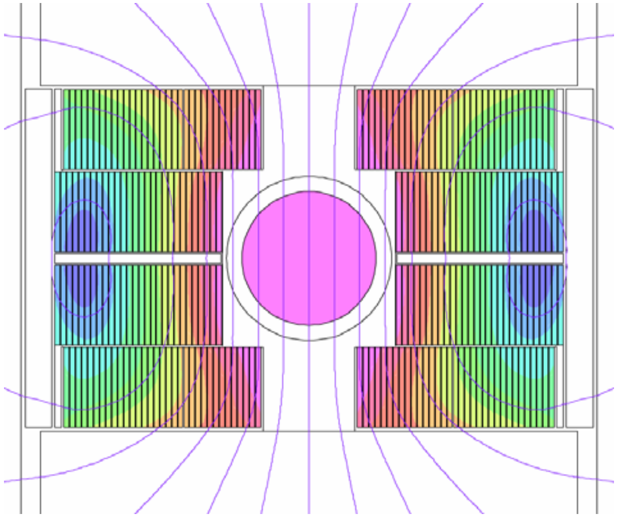
HD2 Design

- Target dipole field: 15 T
- Target aperture: 40-43 mm
- Coil design: block-dipole with flared ends
- Designed for accelerator field quality
- Suitable for 2-in-1 layout
- Can be used for high field cable testing

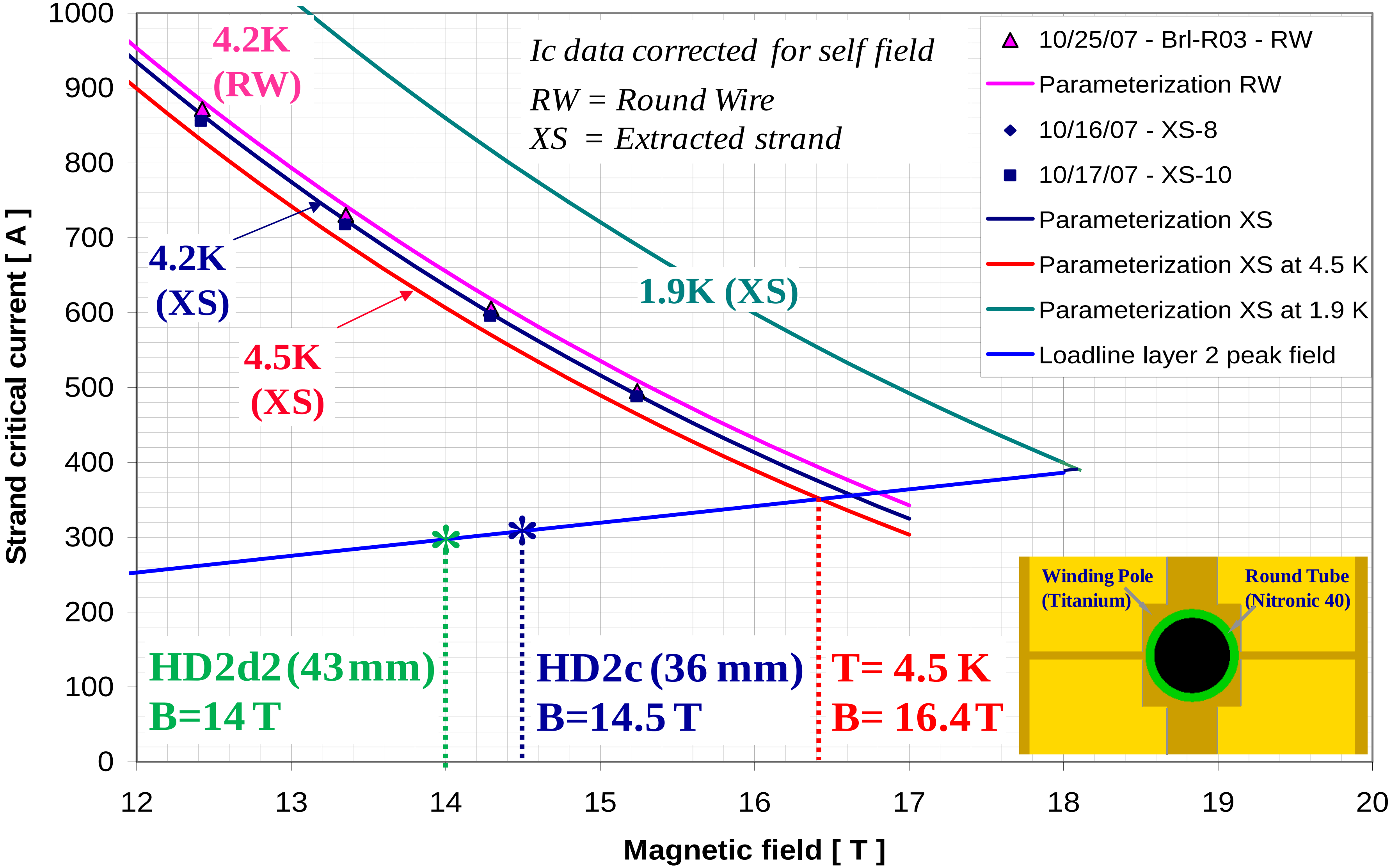




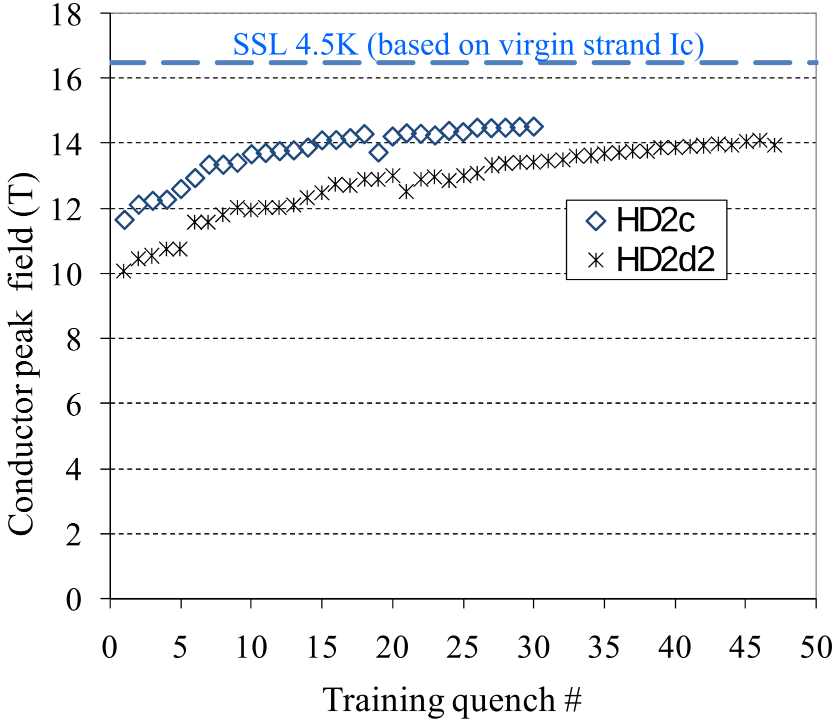


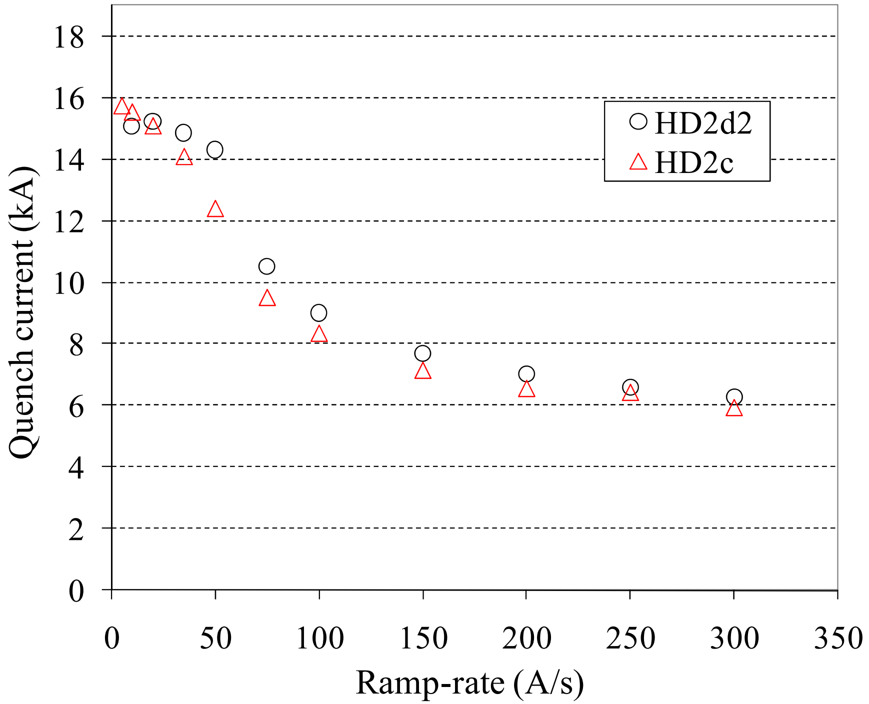


HD2 Field and Aperture



HD2 Training & Ramp Rate Quenches





Next Steps in Dipole Development

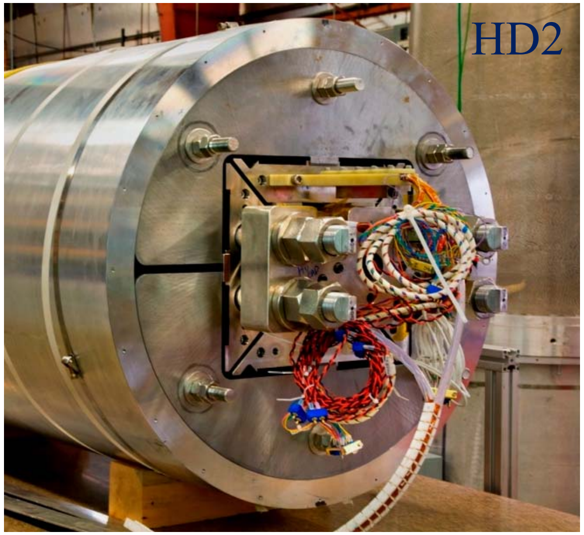
HD2 optimization: 15 T & field quality

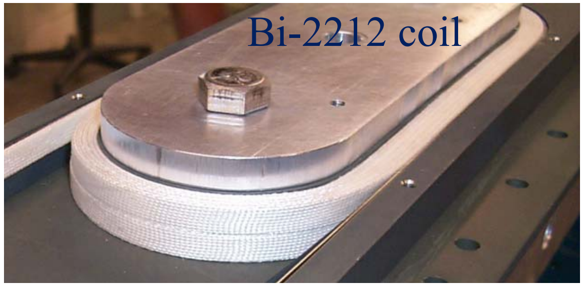
- Eliminate localized quenches in L1 pole turn
- Determine stress limits, optimal pre-load
- Test at 1.9K (requires facility upgrades)
- Field quality optimization:
    - *geometric harmonics (tolerances)*
    - *persistent currents (magnetic shims)*
    - *end region design (axial shift L1/L2)*

Fabrication of new coils planned for next year

16 T and beyond: HTS technology

- Conductor options: Bi-2212 and YBCO
- Technology development with sub-scale coils
- Fabrication of hybrid Nb_3Sn/HTS dipoles

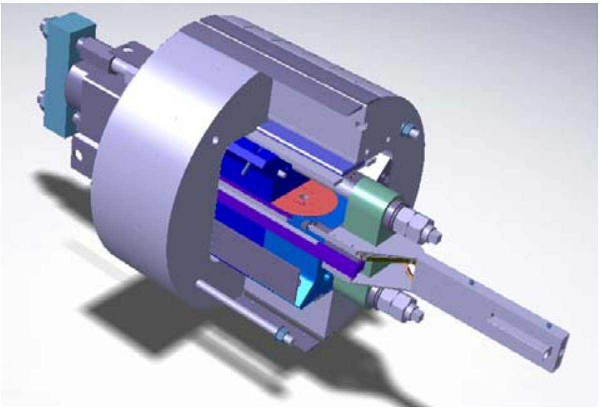




Magnet Programs in Europe and Japan

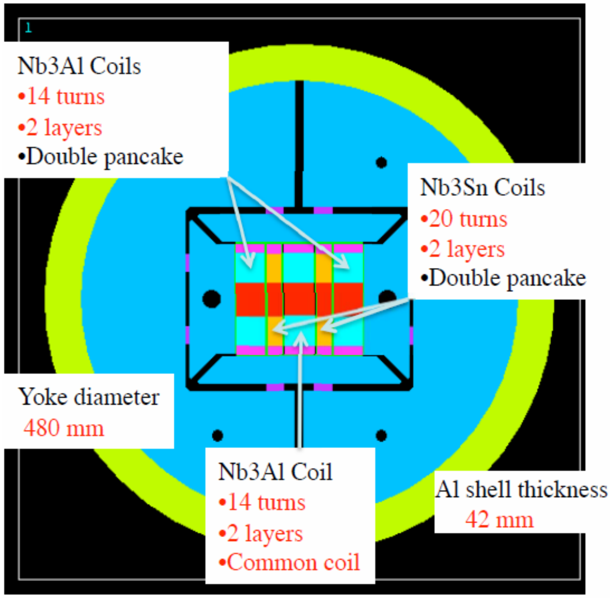
1. Short Model Coil (SMC) Program

- *CERN, STFC/RAL, CEA and LBNL*
- *Demonstrate NED cable and insulation*
- *Gain coil manufacturing experience*



2. Hybrid (Nb_3Al) Sub-scale Magnet

- *NIMS, KEK: Nb_3Al conductor R&D*
- *FNAL: Nb_3Al coil fabrication and test*
- *KEK, LBNL: Mech. structure, Nb_3Sn coil*
- *KEK: radiation and thermal studies*



Efficient start of new R&D efforts by collaboration with ongoing programs

EuCard-WP8 Program

- Work Package 8:
  Superconducting High Field Magnets for higher luminosities and energies
- Comprises the following Tasks:
  - *Task1: Coordination and Communication.*
  - *Task 2: Support studies*
  - *Task 3: High field model*
  - *Task 4: Very high field dipole insert*
  - *Task 5: High Tc superconducting link*
  - *Task 6: Superconducting wiggler for ANKA*
  - *Task 7: Short period helical superconducting undulator*
- WP8 is a CERN, CEA, CNRS, COLUMBUS, DESY, EHTS, FZK, INFN, PWR, SOTON, STFC, TUT, UNIGE collaboration
- Project time span: 2009-2012
- Coordinated with individual Lab programs

Summary

- Strong, efficient collaboration network among magnet programs
- Demonstrated the fundamental aspects of Nb_3Sn technology:
  - *Conductor & structure performance, length scale-up*
- Complete engineering toolbox and fabrication capabilities
- On track to qualify a 120 mm Nb_3Sn quadrupole for the LHC IR
- Developing 15 T dipoles with accelerator quality features
- Started HTS material & technology development for dipoles >16 T

Acknowledgement

BNL CEA CERN FNAL KEK LBNL NHMFL TAMU UT