LARP

BNL - FNAL - LBNL - SLAC

LHC Accelerator Research Program Magnet Development

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for the US LARP collaboration

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LARP Program Goals

Coordinates LHC Accelerator Research in the US:

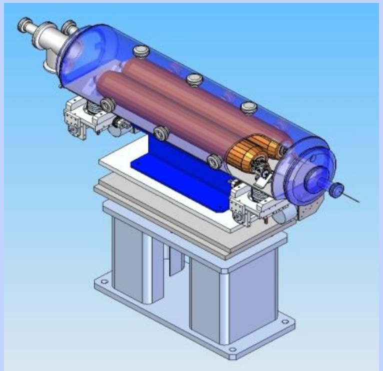
- Started by DOE in 2003, progression from USLHC construction
- Collaboration of four national Labs: BNL, FNAL, LBNL, SLAC
- Funding level: $12-13M/year (FY06-FY11)

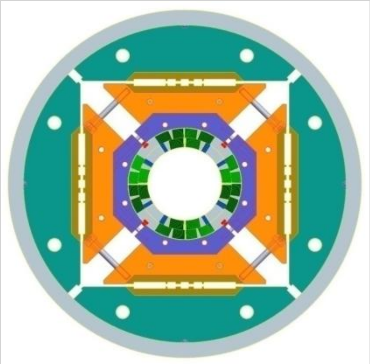
Goals:

- Extend and improve the performance of LHC
  - ➢ *Maximize scientific output in support of the experiments*
- Maintain and develop US Labs capabilities
  - ➢ *Prepare for future projects*
- Research and training for US accelerator physicists and engineers
- Advance US and international collaboration on HEP projects

Overview of LARP Activities

Accelerator Systems	Instrumentation	• Luminosity monitor • Tune tracker, AC dipole • Schottky monitor
	Accelerator Physics	• Electron cloud instability • Beam-beam studies • Crab crossing
	Collimation	• Rotatable collimators
Magnet Systems	Materials	• Strand characterization • Cable development
	Model Quadrupoles	• Technology Quadrupoles • High-field Quadrupoles
	Long Quadrupoles	• Coil fabrication • Structure and assembly • Instrumentation and Test
Program Management	Programmatic Activities	• Toohig Fellowship • Long Term Visitors





Magnet R&D Program

- Goal: **Develop Nb_3Sn quadrupoles for the LHC luminosity upgrade**
- Potential to operate at higher field and/or larger temperature margin
- Follows Nb_3Sn development and demonstration by CDP & US Labs

LARP is a focused R&D program with specific scope & objectives:

- Application: High Luminosity LHC
- Timescale: ~2014
- Budget: ~7M$/year
- Magnet type: Large aperture IR Quadrupole
- Conductor: Nb_3Sn

- Specific focus has been a key element of program success
- Considerable progress to date, much work is still required

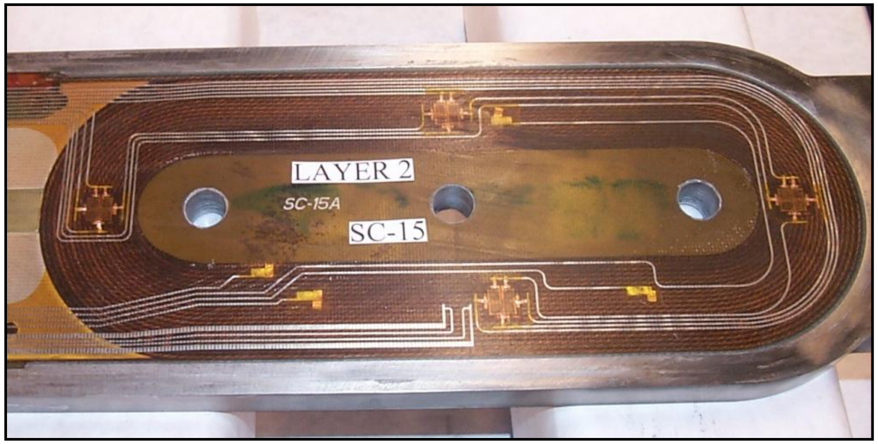
Nb_3Sn Challenges

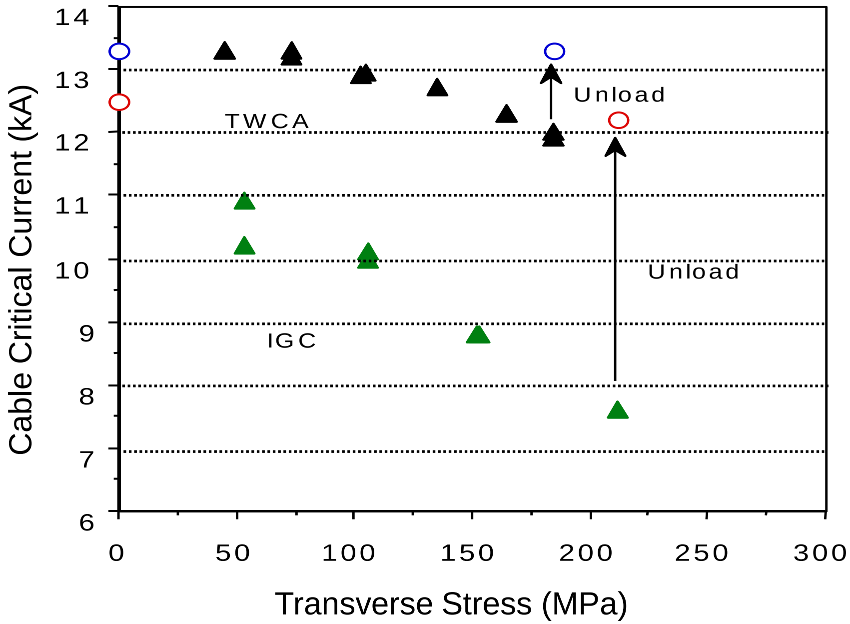
<u>Brittleness</u>:

- React coils after winding
- Epoxy impregnation

<u>Strain sensitivity</u>:

- Mechanical design and analysis to prevent degradation under high stress





Material	NbTi	Nb_3Sn
Dipole Limit	~ 10 T	~ 17 T
Reaction	Ductile	~ 675^{0}C
Insulation	Polymide	S/E Glass
Coil parts	G-10	Stainless
Axial Strain	N/A	~ 0.3 %
Transverse stress	N/A	~ 200 MPa

Program Components

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

   Ongoing

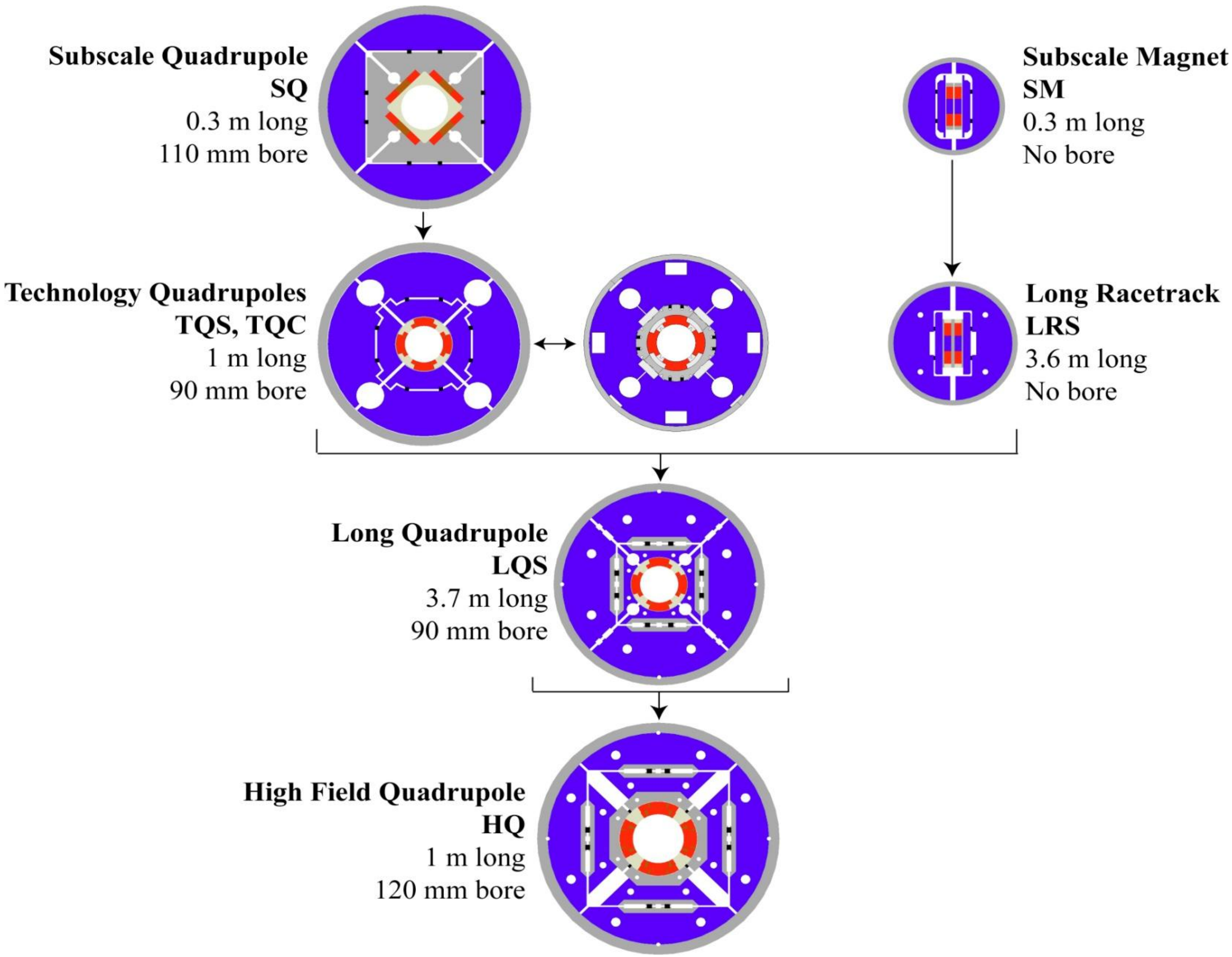
2. Technology development with Racetrack Coils:
   - *Subscale Quadrupole (SQ)*
   - *Long Racetrack (LR)*

   Completed

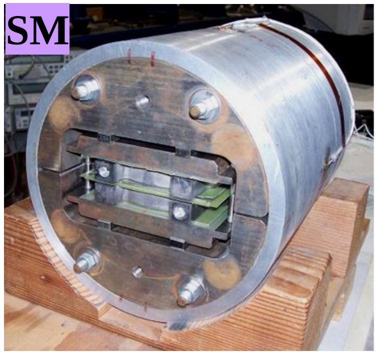
3. Cos 2θ Quadrupoles with 90 mm aperture:
   - *Technology Quadrupole (TQ)* — *Completed*
   - *Long Quadrupole (LQ)* — *~75%*

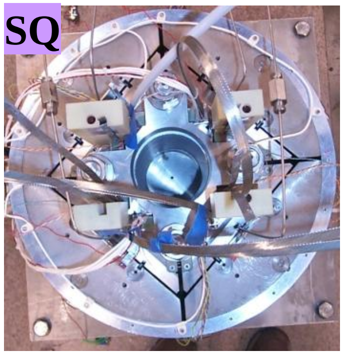
4. Cos 2θ Quadrupoles with 120 mm aperture:
   - *High-Field Quadrupole (HQ)* — *~30%*
   - *Long High-Field Quadrupole (LHQ)* — *Starting*

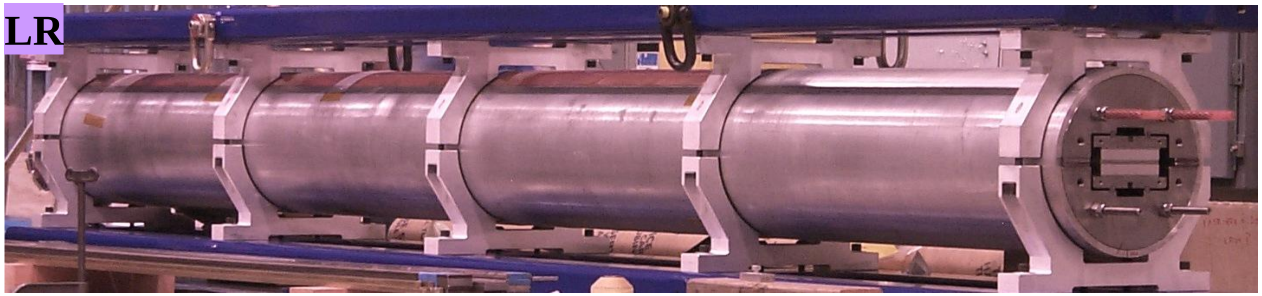
Magnet Development Chart

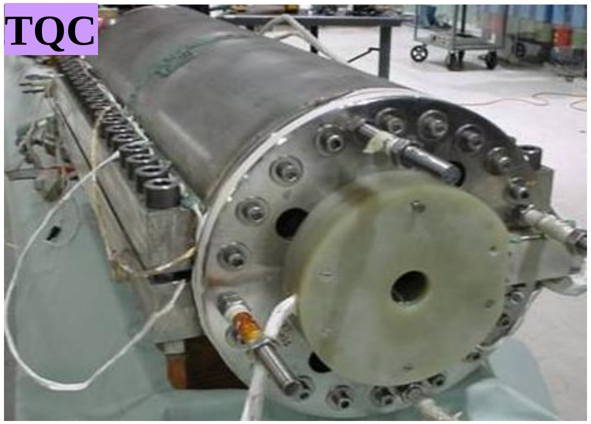


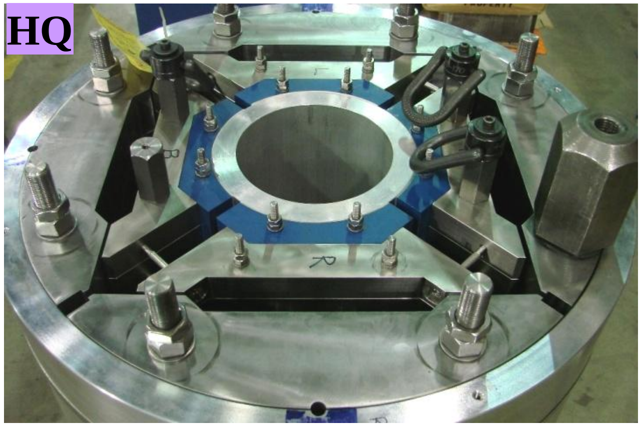
Magnet Series











A fully integrated program: HQ example

• Cable design and fabrication	LBNL
• Magnetic design & analysis	FNAL, LBNL
• Mechanical design & analysis	LBNL
• Coil parts design and procurement	FNAL
• Instrumentation & quench protection	LBNL
• Winding and curing tooling design	LBNL, FNAL
• Reaction and potting tooling design	BNL
• Coil winding and curing	LBNL
• Coil reaction and potting	BNL, LBNL
• Coil handling and shipping tooling	BNL
• Structures (baseline, revised, mirror)	LBNL, BNL, FNAL
• Assembly (baseline, revised, mirror)	LBNL, BNL, FNAL
• Magnet test	LBNL, CERN, FNAL
• Accelerator Integration	BNL, LBNL, FNAL

Magnet Tests in the last 12 months

Dec. 2009 LQS01a (first Long Quadrupole) - FNAL
- *Achieved target gradient of 200 T/m*

Dec. 2009 TQS03c (high stress) - CERN
- *88% SSL w/200 MPa average coil stress*

Feb. 2010 TQS03e (cycling) - CERN
- *No degradation after 1000 cycles*

May 2010 HQS01a (first High-Field Quadrupole) - LBNL
- *>155 T/m @4.5K, already above NbTi limit @1.9K*

June 2010 HQS01b (revised coil-structure shims) - LBNL
- *First Quench >150 T/m (78%); insulation failure*

July 2010 LQS01b (revised coil-structure shims) - FNAL
- *Rapid training to >220 T/m @4.5K; retained at 1.9K*

Oct. 2010 HQS0c (two new coils) - LBNL
- *Underway – Insulation integrity checks*

Progress on Key Technical Issues (1/5)

Strand design and fabrication:

+ Solid performance from RRP 54/61 in LR, TQ, LQ, HQ models
+ New RRP 108/127 shows improved stability and robustness
- Only one vendor and production cycle is 12 (15) months
- Piece length (esp. 108/127) not yet sufficient for efficient production

Cable design and fabrication:

+ Three cable designs developed (LR, TQ/LQ, HQ)
+ More than 7 km of cable fabricated with minimal losses
- Control of inter-strand resistance not yet incorporated in magnets

Conductor performance:

+ Demonstrated capability of achieve full conductor potential
+ Demonstrated excellent tolerance to high stress levels
+ Stability margins always sufficient to reach performance goals

Progress on Key Technical Issues (2/5)

Quench performance and training:

+ Achieved high gradient - TQ: 238 T/m, LQ: 225 T/m, HQ:156 T/m
+ Fast training in optimized models (SQ, LR, TQ, LQ, HQ)
+ Steady progress through systematic analysis and correction

Magnetic and mechanical design:

+ Complete FEA modeling capabilities and high quality data
  Performance issues can be quickly understood and corrected
+ Further optimization underway for integration and production

Stress limits:

+ Satisfactory performance up to ~250 MPa peak, ~200 MPa average
+ No degradation in TQ after 1000 cycles

Progress on Key Technical Issues (3/5)

Coil fabrication technology:

+ Steady improvement in tooling and procedures
+ Distributed coil fabrication shows flexibility, robustness
  However: insulation failure in recent HQ test
+ Successful length scale-up in LR and LQ
  However: full coil modeling framework is not yet available

Quench protection:

+ Key parameters are well understood
  Propagation, detection & heater delays, peak temperatures
+ Steady improvements in modeling and heater fabrication
- Protection is intrinsically challenging
- Quench process in superfluid He may compromise heaters

Progress on Key Technical Issues (4/5)

Alignment and field quality:

- No coil alignment in LR, TQ, LQ models
  Neither during fabrication nor at assembly/excitation

+ Coil alignment features introduced in HQ models
  Shows good mechanical performance while engaging keys

- Dynamic effects are not yet controlled
  Cables with cores will be introduced in HQ models

Accelerator integration:

+ Studies underway to further optimize alignment, field quality, cooling, heat transfer, radiation damage etc.

- Much work left to do in this area

Working with CERN on design requirements and options
Opportunities for collaboration with EuCARD, KEK, CERN etc.

Progress on Key Technical Issues (5/5)

Radiation and thermal management:

+ Thermal margins are intrinsically high compared to NbTi
- Heat transfer is limited due to epoxy impregnation
- Epoxy is also the weak point in terms of radiation damage
+ Field/aperture margin can be effectively used for absorbers

Production issues:

+ Demonstrated distributed production, extensive shipping
- Insulation failures observed in recent HQ tests

  Need more focus on reliability vs. performance
+ Insulation options for long cables are under development
+ Timeline from specifications to test is similar to NbTi
- Current infrastructure is limited to 4 m coil length

Next steps: 90 mm Long Quadrupoles

- Fully reproduce performance of the TQ short models
  - *Higher gradient (220 T/m in TQS02, 240 T/m in TQS03)*
  - *Fast training (plateau in 5-10 quenches, no retraining)*
- Systematic analysis of coil length effects
  - *Detailed modeling of the reaction process*
  - *Understand/optimize coil strain state after reaction*
- Design and process optimization for construction
  - *Coil size control/reproducibility*
  - *Protection heater design, esp. for inner layer*
  - *One-side loading with 4 m keys/bladders*
  - *Cable insulation techniques for production*

Next steps: 120 mm High Field Quadrupoles

Present focus: address electrical insulation issues in HQ

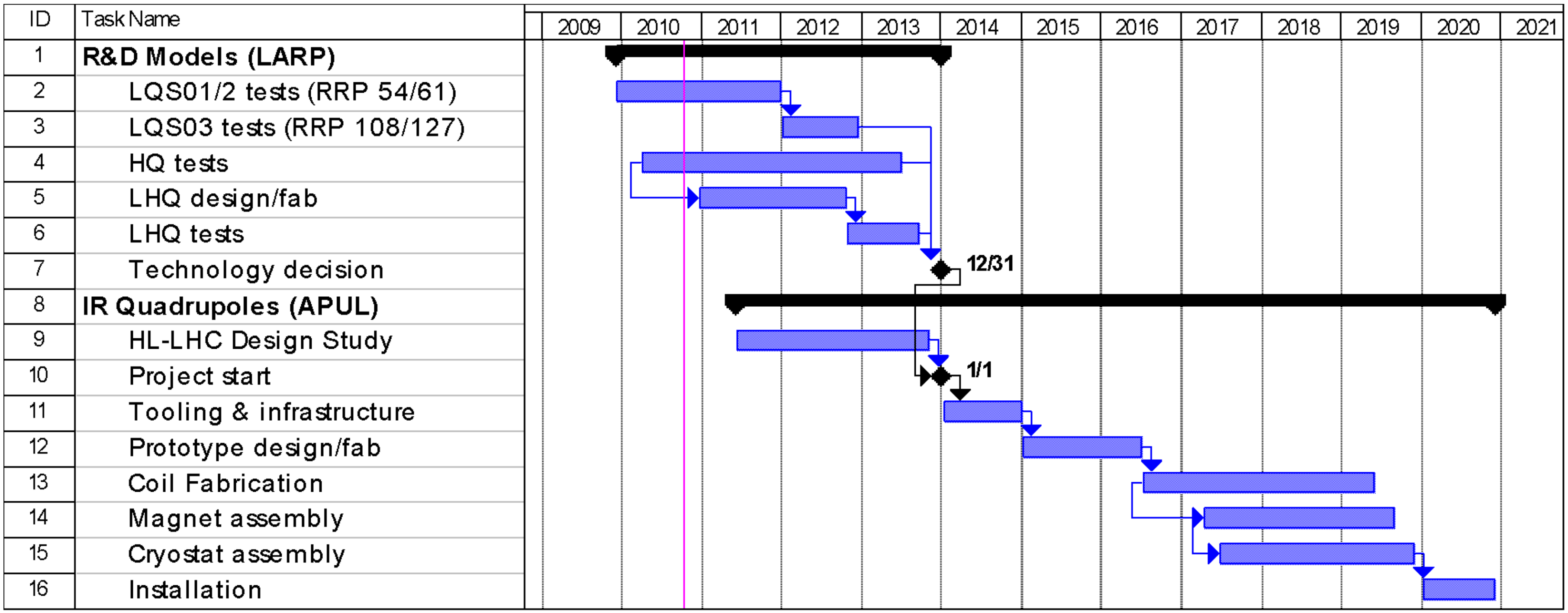
- Progress on results analysis and identification of root cause, other contributing factors and possible solutions
- Near term: enhanced QA and selection of coils
- Long term: design modifications for improved robustness

Short model R&D:

- Performance limits, training, pre-load optimization
- Quench protection and thermal studies
- Cored cables to control dynamic effects
- Structure optimization for production and accelerator integration
- Field quality characterization and optimization

Scale-up to Long HQ model as a technology demonstrator for HL-LHC

From LARP R&D to HL-LHC Construction



- Assuming technology decision at the end of 2013 and installation in 2012
- 3 years for coil fabrication requires 2 production lines of full length coils
- 64 full length coils required i.e. one new coil completed every ~2 weeks

LARP R&D relevant to HE-LHC

LARP

- IR Quadrupole development
- HE-LHC dipoles will require Nb_3Sn technology
  - *Cabling and insulation of long ULs*
  - *Long coil fabrication, mechanical structures*
  - *Instrumentation and analysis*
  - *Field quality, quench protection*
- From cold mass development to accelerator integration:
  - Cooling, helium containment, alignment
- Development of radiation tolerant components
- Capability to organize/integrate R&D effort across Laboratories
- Initial feedback on series production and operation issues:
  - Infrastructure, production steps/times/cost
  - Reliability, failure rates in production/operations

HE-LHC R&D outside the scope of LARP

- HTS materials development
- HTS (Bi-2212) coil fabrication technology
  - ➢ chemical compatibility, reaction process
- Cabling, in particular for YBCO tapes
- High field dipole designs:
  - ➢ Small aperture, block geometry
  - ➢ Two-in-one layout
- Hybrid Nb_3Sn/HTS coils:
  - ➢ internal splices or independent powering
  - ➢ nested assembly and mechanical support
- Scale up to dipole length (additional factor of 2-3)
  - Coil fabrication, sagitta, quench protection
- Technology transfer, large scale production

Summary

- A large knowledge base is available after 5 years of fully integrated effort involving three US Labs and CERN
- Demonstrated all fundamental aspects of Nb_3Sn technology:
  - *Steady progress in understanding and addressing R&D issues*
- R&D effort should now focus on increased reliability, accelerator integration and production-oriented processes
  - *Recent HQ insulation failure is a timely reminder*
- HL-LHC is a key step for all future high-field applications
  - *First demonstration represents a significant opportunity and risk*
  - *Strong synergy on technical and production issues*
- Next few years will be critical and much work is still left to do
  - *Integrate effort with CERN, EuCARD, KEK, US Labs*