R&D for High Field Magnets

GianLuca Sabbi
Lawrence Berkeley National Laboratory
Superconducting Magnet Program

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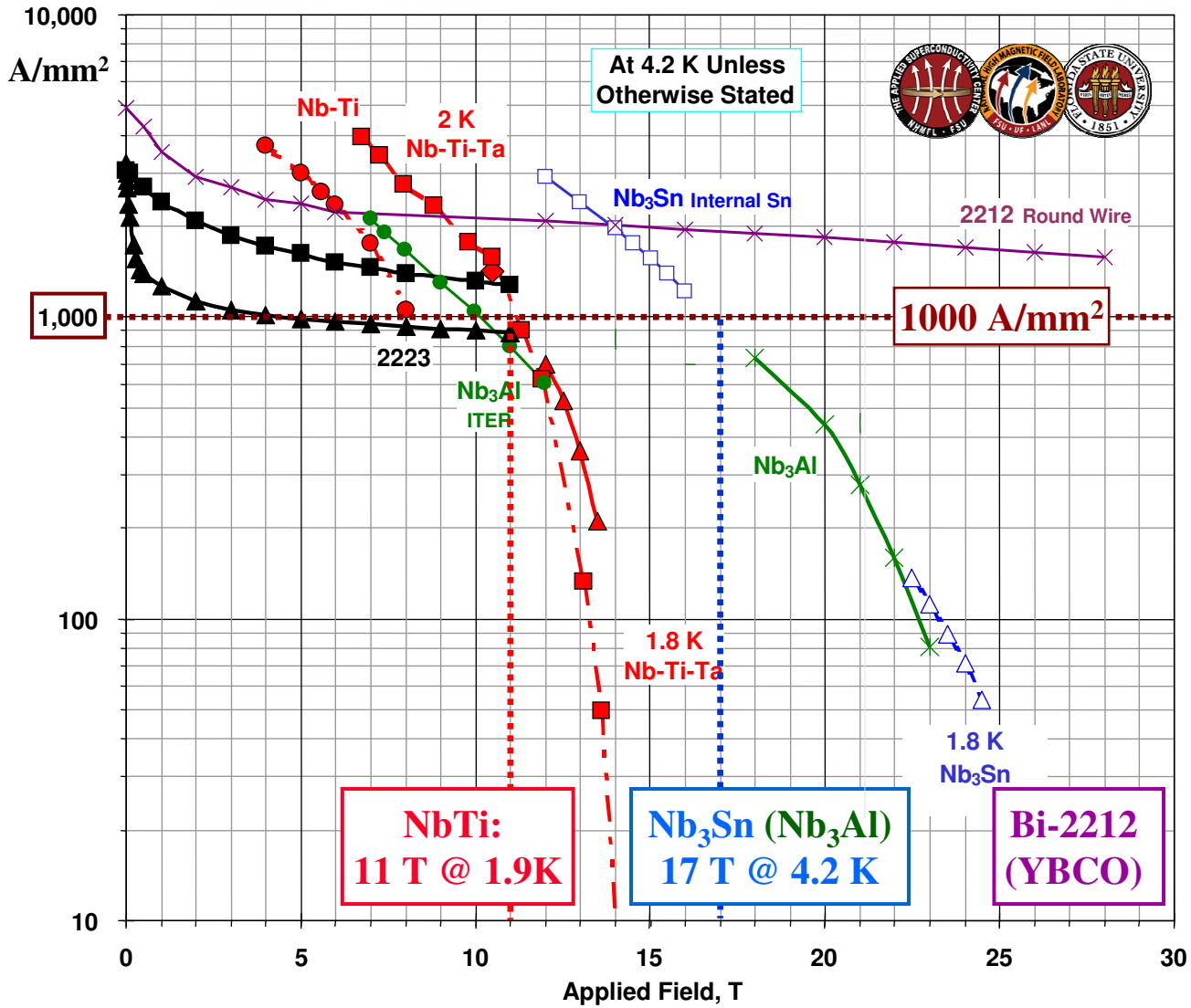
Conductor Options



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

High Field Applications & Challenges

Enabling technology *for the highest energy colliders:*

LHC: • IR quadrupoles & dipoles – large aperture, high radiation
• "14→28 TeV is great, 14→42 even better" *(SLHC meeting)*

MC: • 10-15 T dipoles, very high radiation (collider ring)
• 30+ T solenoids (final stages of muon cooling)

Main challenges:

- Control of large forces and stresses
- High field superconductors are brittle and strain sensitive

R&D components:

- Development of cable and coil fabrication technology
- New concepts for mechanical support and magnet assembly
- Advances in modeling capabilities and diagnostic techniques

Infrastructure and Technology Development

BNL	React-and-Wind technology; HTS, special magnets
CEA	Nb_3Sn Quadrupole, sub-scale structure, new insulation
CERN	Nb_3Sn dipole coils and structures, magnet testing
FNAL	Cos-θ dipoles, long coil technology, HTS solenoids
KEK	Nb_3Al coil technology, sub-scale models
LBNL	Very High Field Dipoles (Nb_3Sn, HTS); advanced cables
NHMFL	Very High Field Solenoids, HTS coil technology
TAMU	Stress intercepts for dipoles, new materials/insulation
UT	Cos-θ dipoles, PIT conductor

A Worldwide Collaboration Network

LARP (MagSys)
- Participants: BNL, FNAL, LBNL + CERN
- Goal: fully qualified quadrupoles for SLHC (Phase 2 upgrade)

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

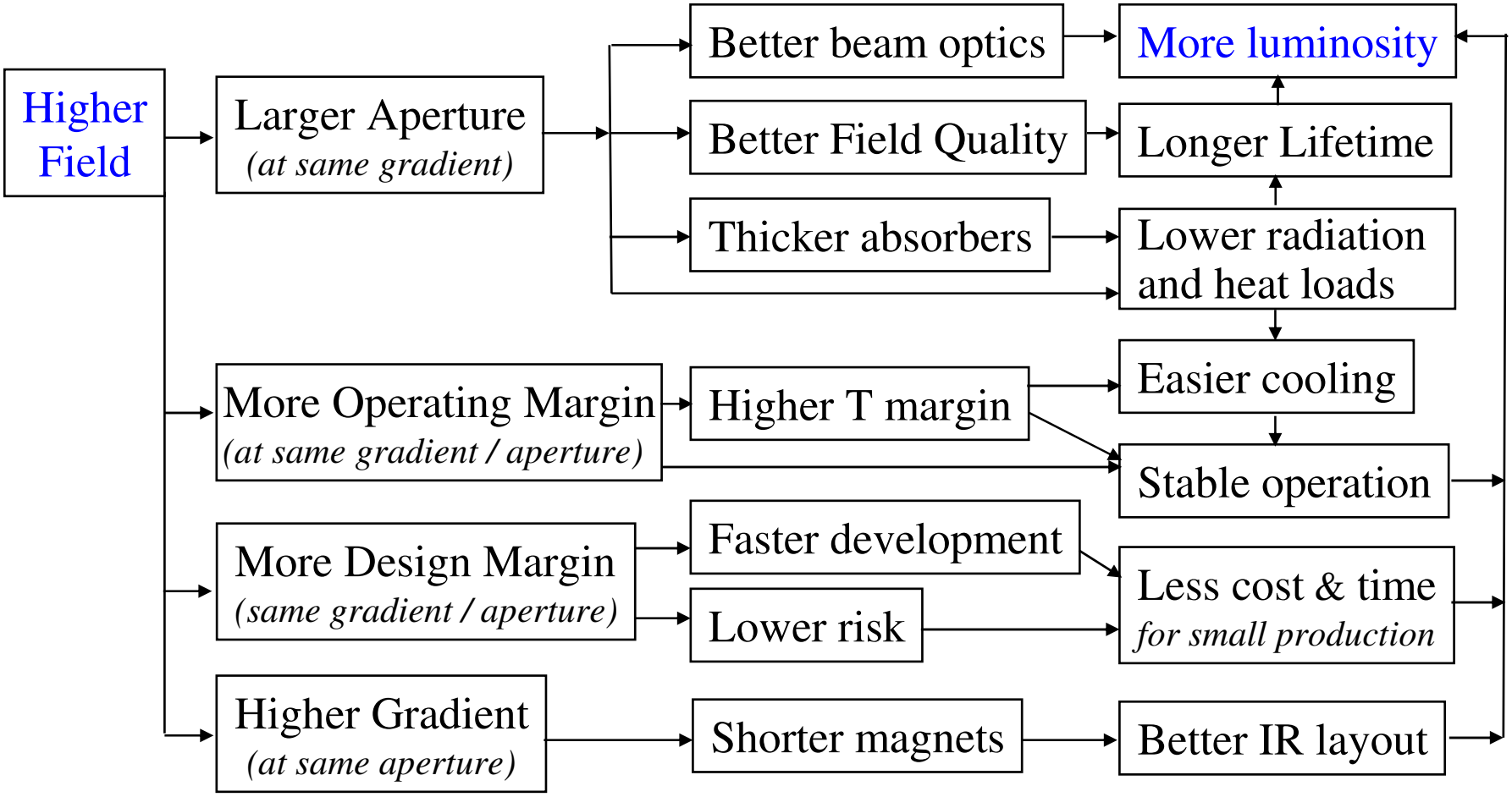
EUCARD (HFM)
- Participants: CERN, CEA, CNRS, COLUMBUS, DESY, EHTS, FZK, INFN, PWR, SOTON, STFC, TUT, UNIGE
- Goal: high field Nb_3Sn dipole model & very high field (HTS) insert

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

Quadrupoles for the LHC Phase 2 Upgrade

High field technology provides design options to maximize luminosity



LARP Sub-scale Quadrupoles (2005-06)

Design features:

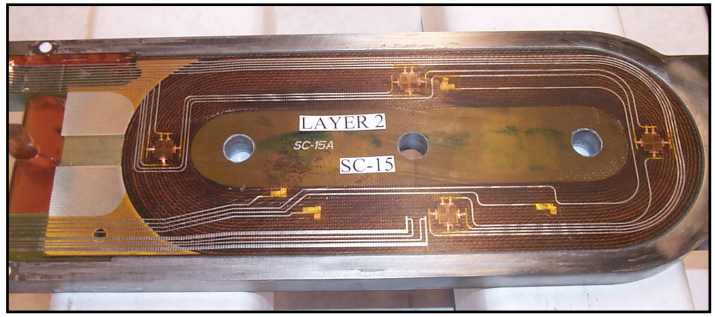
- Based on LBNL "SM" design
- Four racetrack coils, square bore
- Aperture 130 mm, Length 30 cm

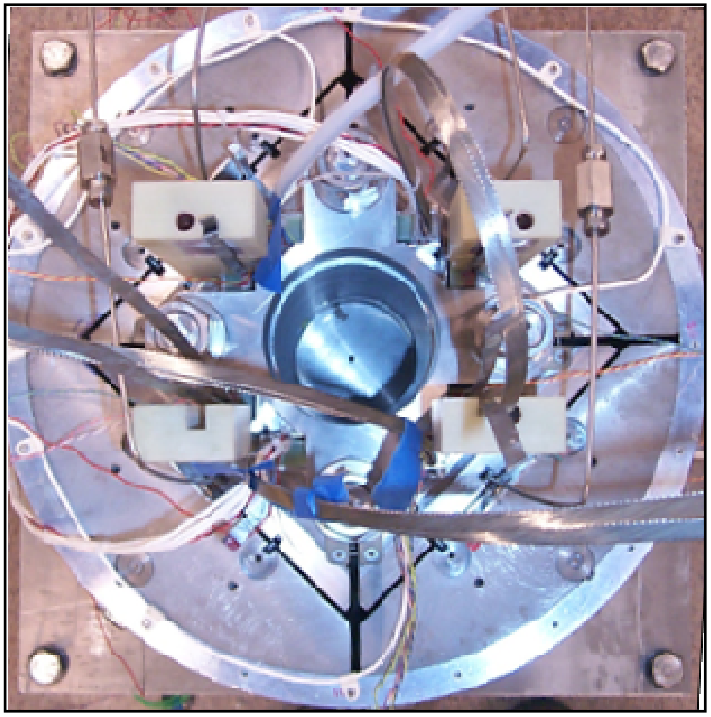
R&D Goals:

- *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**

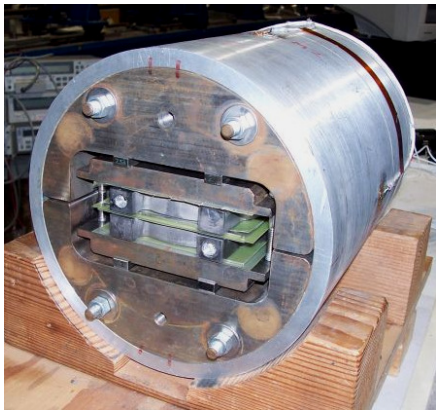




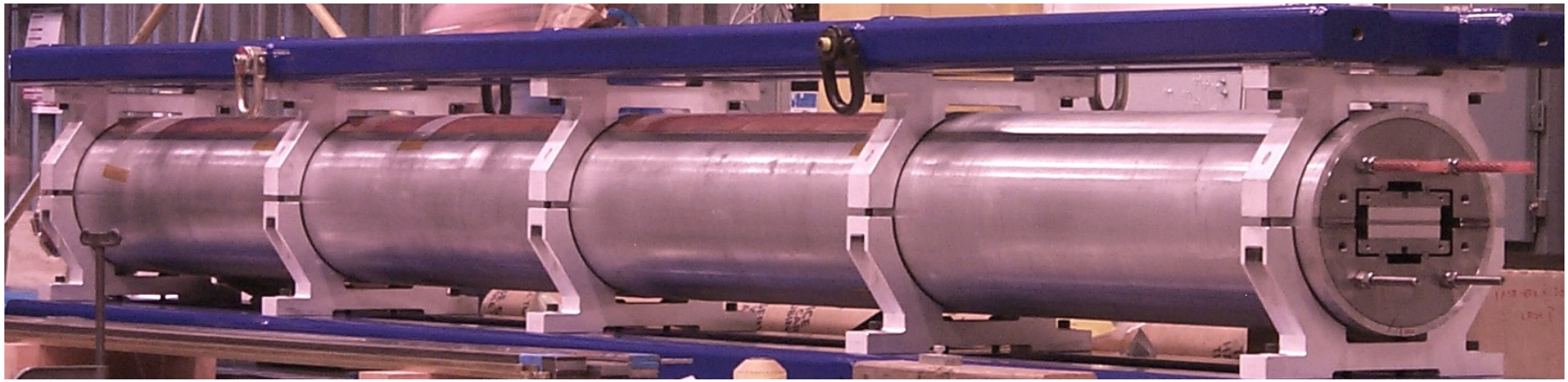
LARP Long Racetrack (2006-08)

- 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*
- *FNAL: contributions to design and coordination*

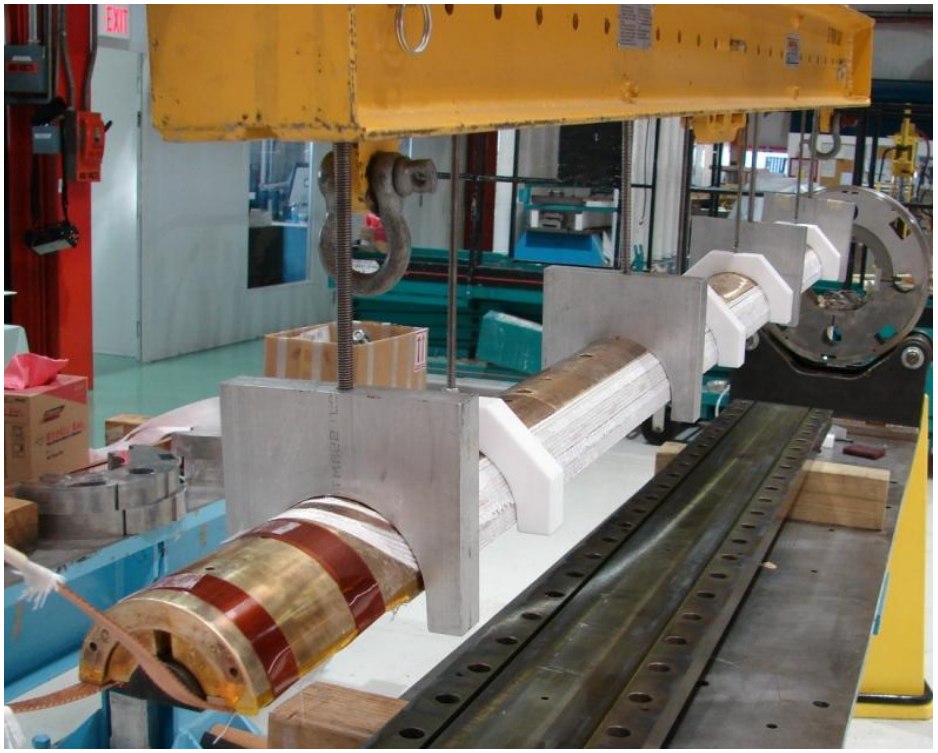


- Fast training: LRS01 first quench at 84% of SSL
- LRS02 achieved 11.5 T, **96% of short sample limit**



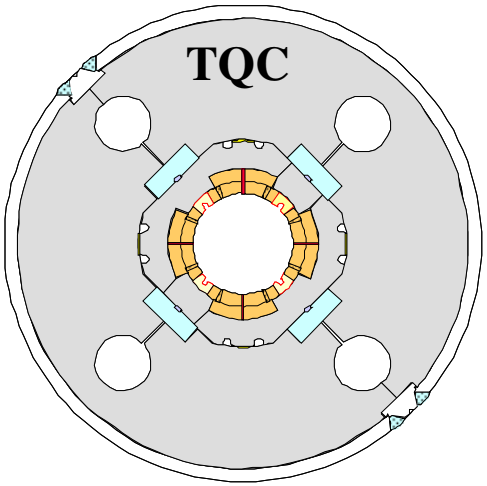
Fermilab Mirror Dipole (2006-08)

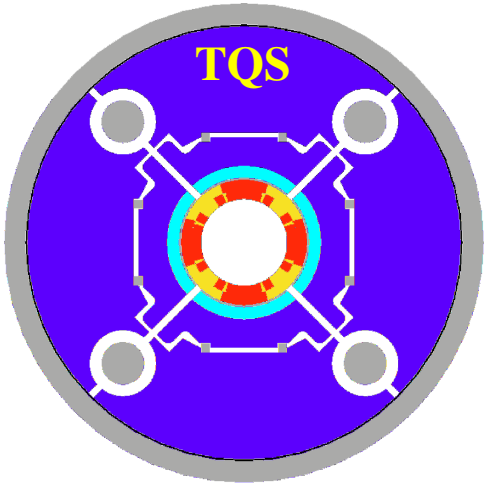
- Three steps were performed: 1m, 2m and 4m models
- First length scale-up of Nb_3Sn cosθ coil technology
- Experience applied toward LARP models



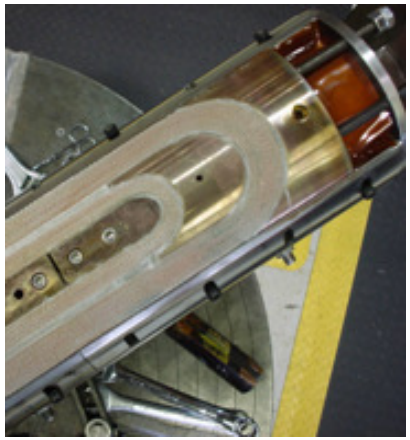
LARP Technology Quadrupoles (2005-08)

- 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 Summary

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

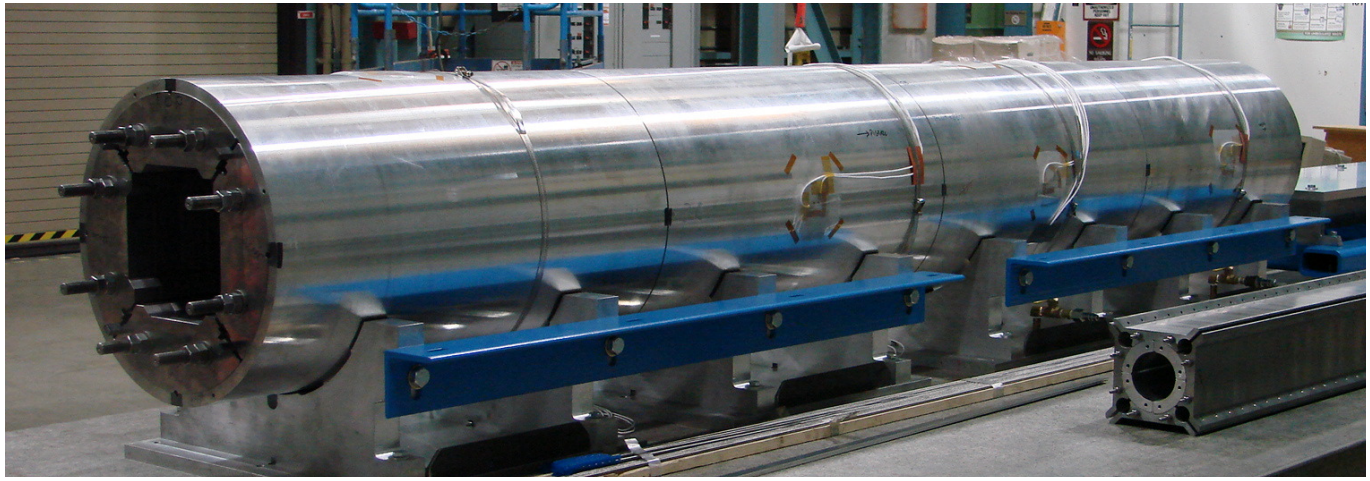
Optimized models surpassed the 200 T/m target gradient with good margin

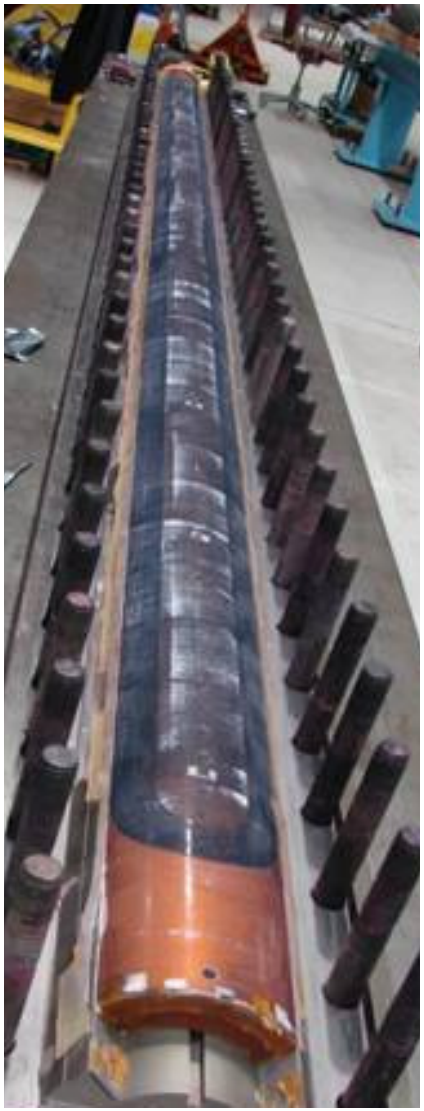
Present focus: Long Quadrupole (LQ)

Scale up of TQ design from 1 m to 3.6 m

- Coil design and fabrication: FNAL & BNL
- Structure design and fabrication: LBNL
- Magnet assembly: LBNL
- Magnet test: FNAL

Two LQS tests are planned for 2009

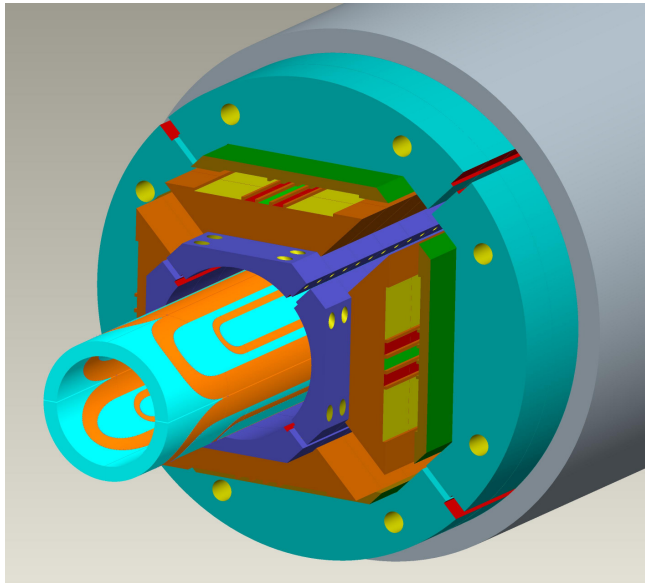




Next Step: 120 mm Quadrupoles

Completed:

- *Cable optimization & test winding (LBNL)*
- *Coil cross-section and end design (FNAL)*
- *Winding/curing tooling design (LBNL)*



In progress:

- *Reaction/potting tooling design (BNL)*
- *Coil parts procurements (FNAL)*
- *Support structure design (LBNL)*

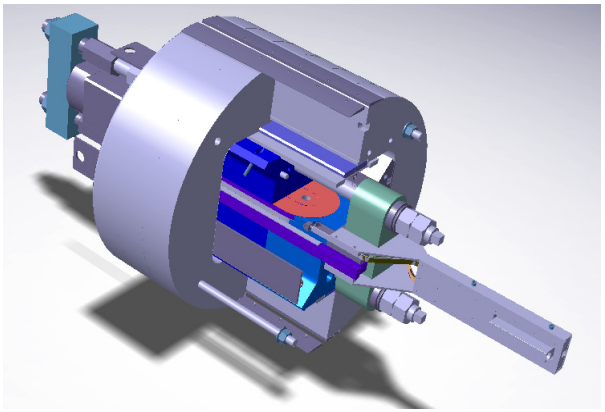
Plans:

- *Test 1 m models (HQ) in 2009-10, 4 m models (QA) in 2011-12*
- *Aiming at full qualification based on Phase 1 upgrade requirements*
- *Conductor-limited gradient is about twice the Phase 1 requirement*
- *Will provide performance reference for Phase 2 upgrade design*

HFM Developments in Europe and Japan

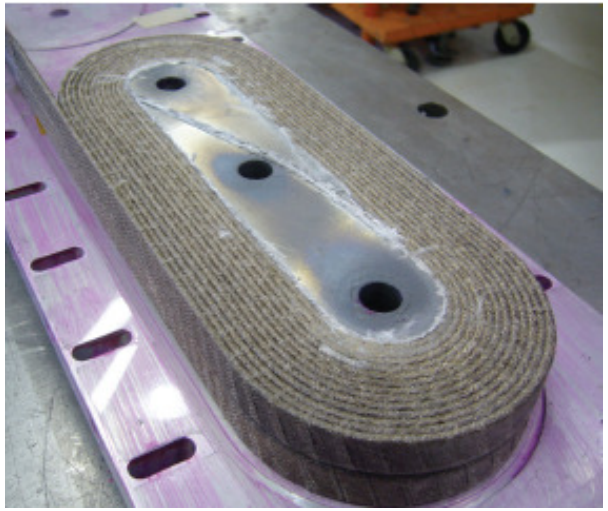
1. Short Model Coil (SMC) Program

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



2. Assembly & Test of TQ models

- *Best results achieved in CERN tests*

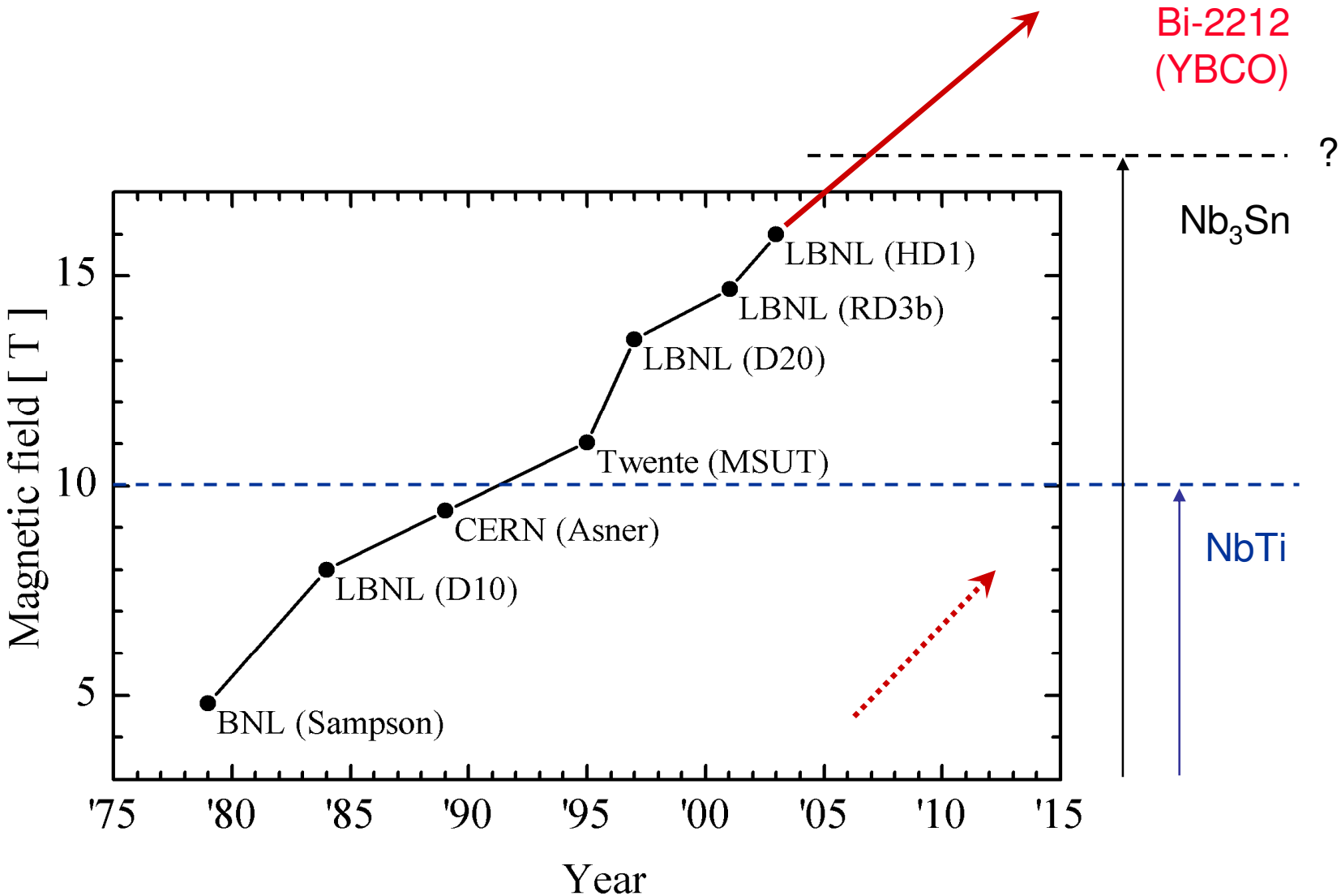


3. Nb_3Al Magnet Development

- *KEK, NIMS: conductor development*
- *FNAL: cable and coil fabrication*
- *First model coil reached short sample*

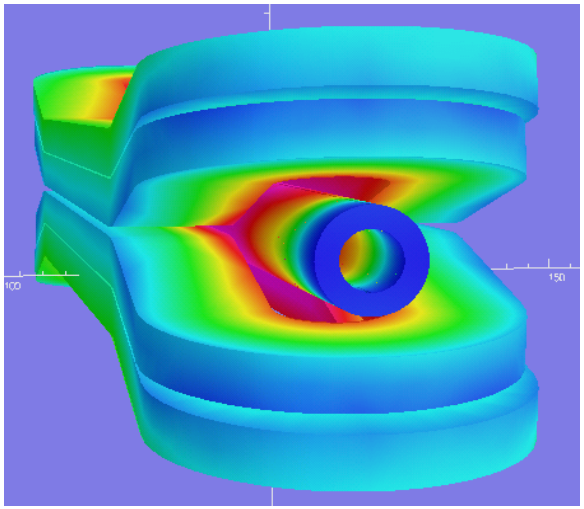
Efficient start of new R&D efforts by collaboration with ongoing programs

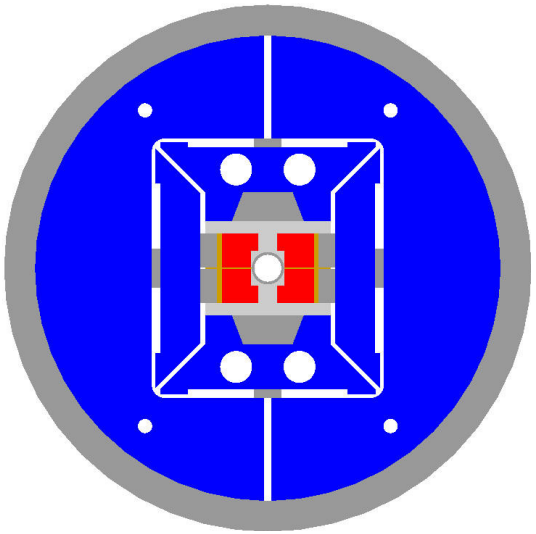
High Field Dipoles

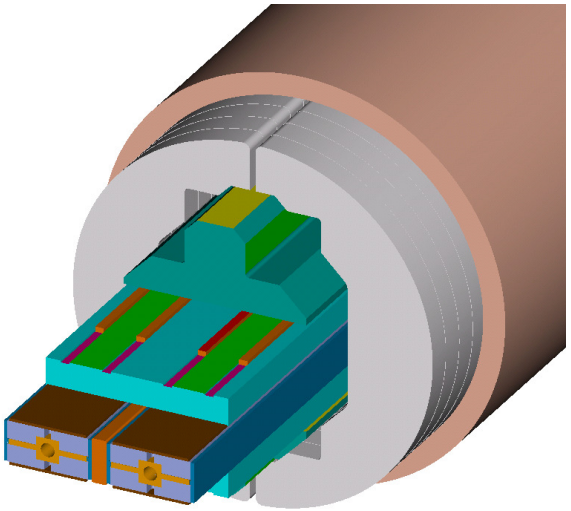


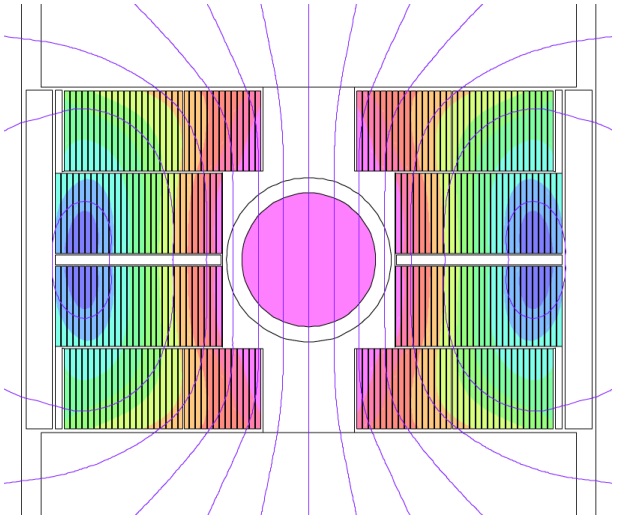
HD2 Design

- Target dipole field: **15 T** (15.8 T coil field)
- Clear bore 36-42 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

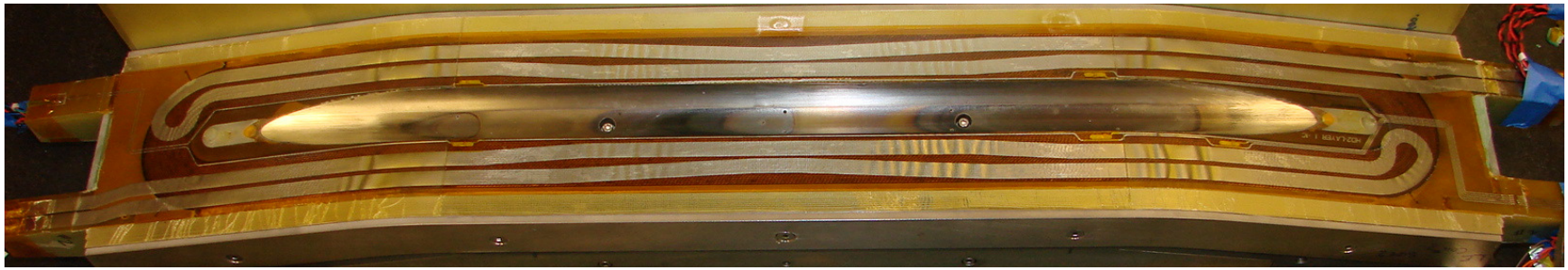


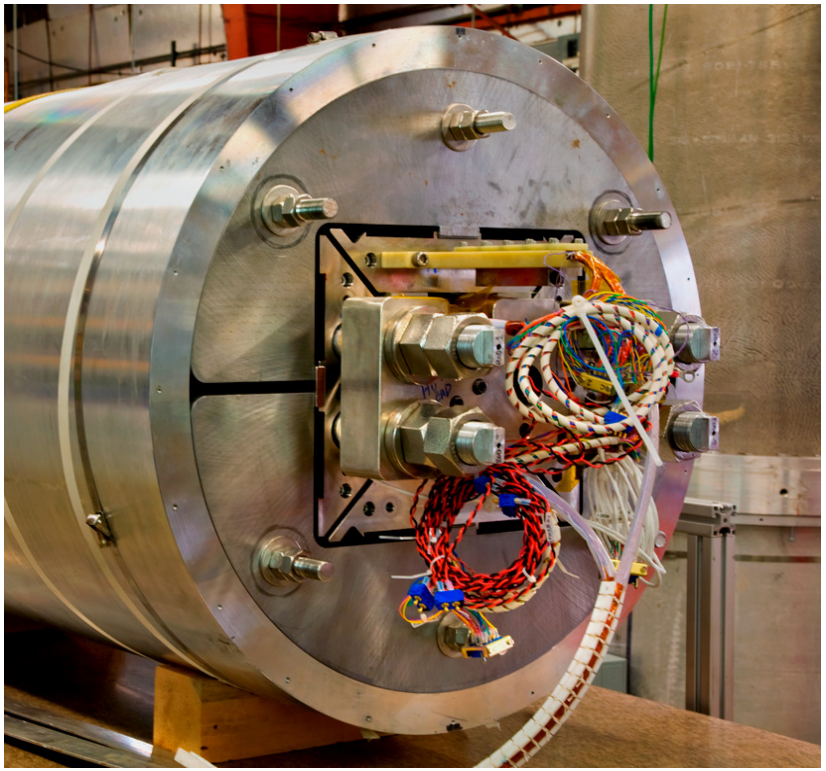


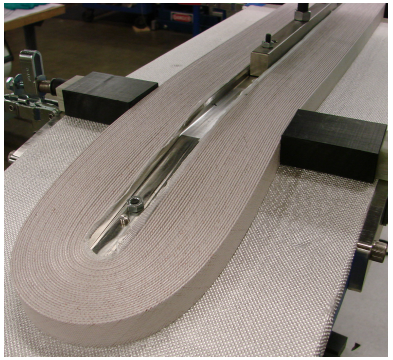


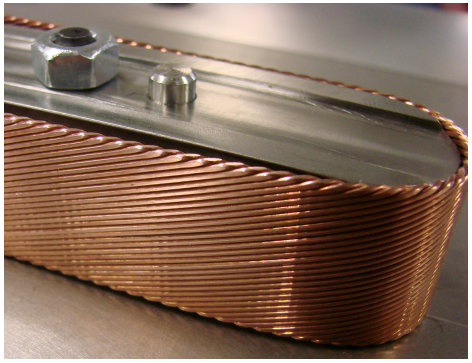


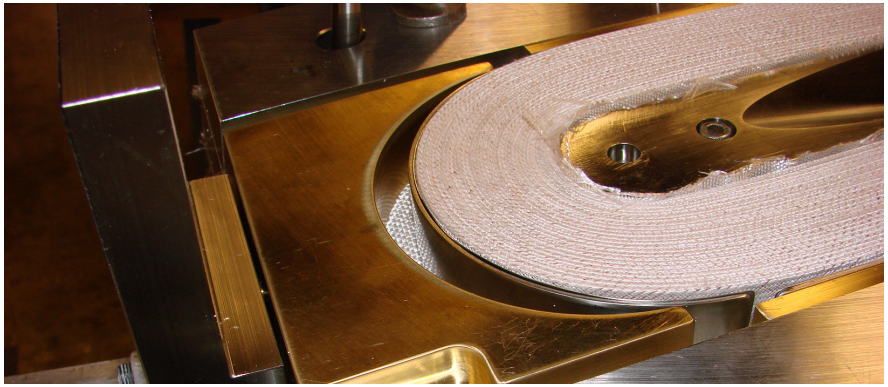
HD2 Components & Assembly



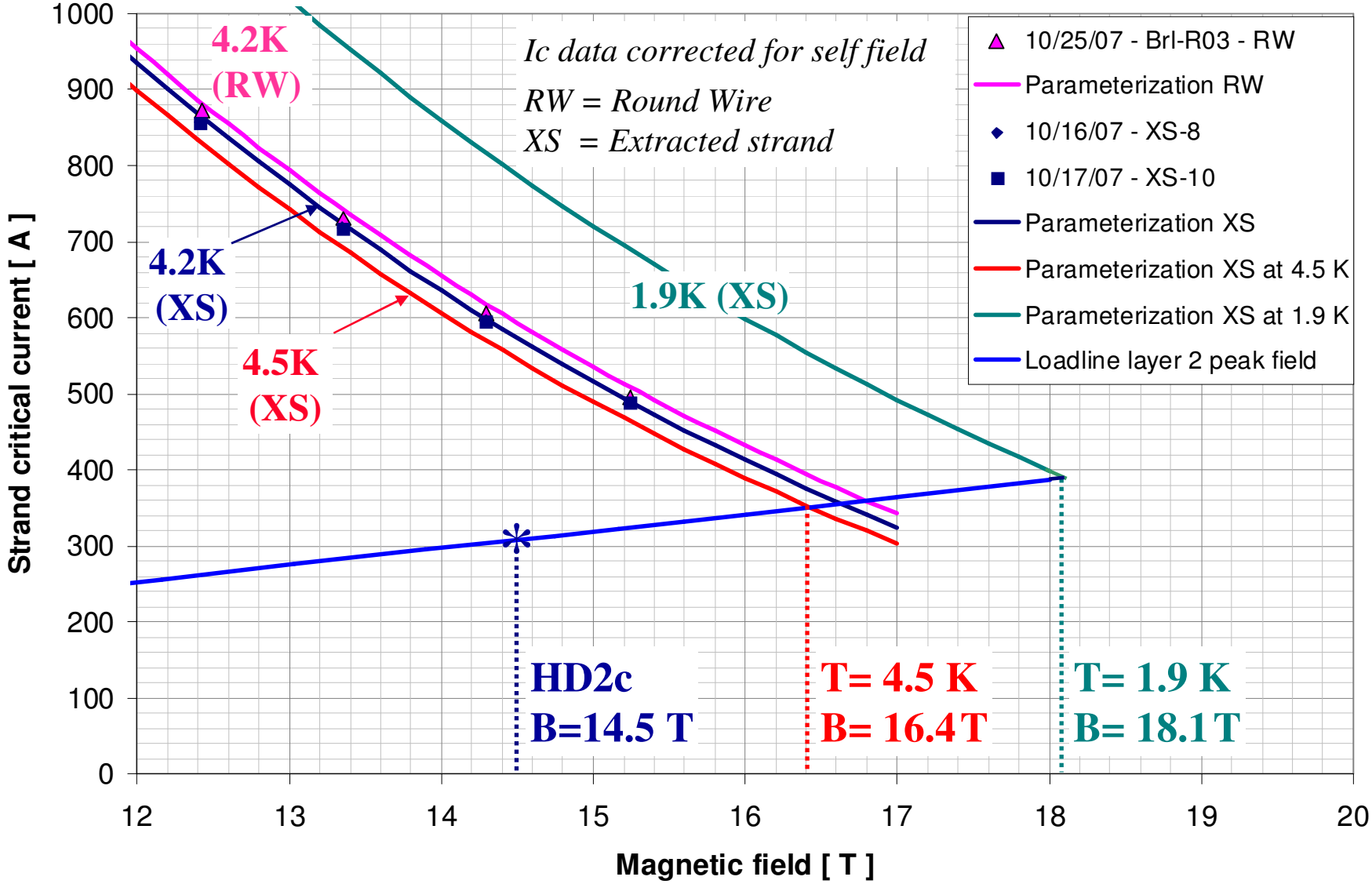




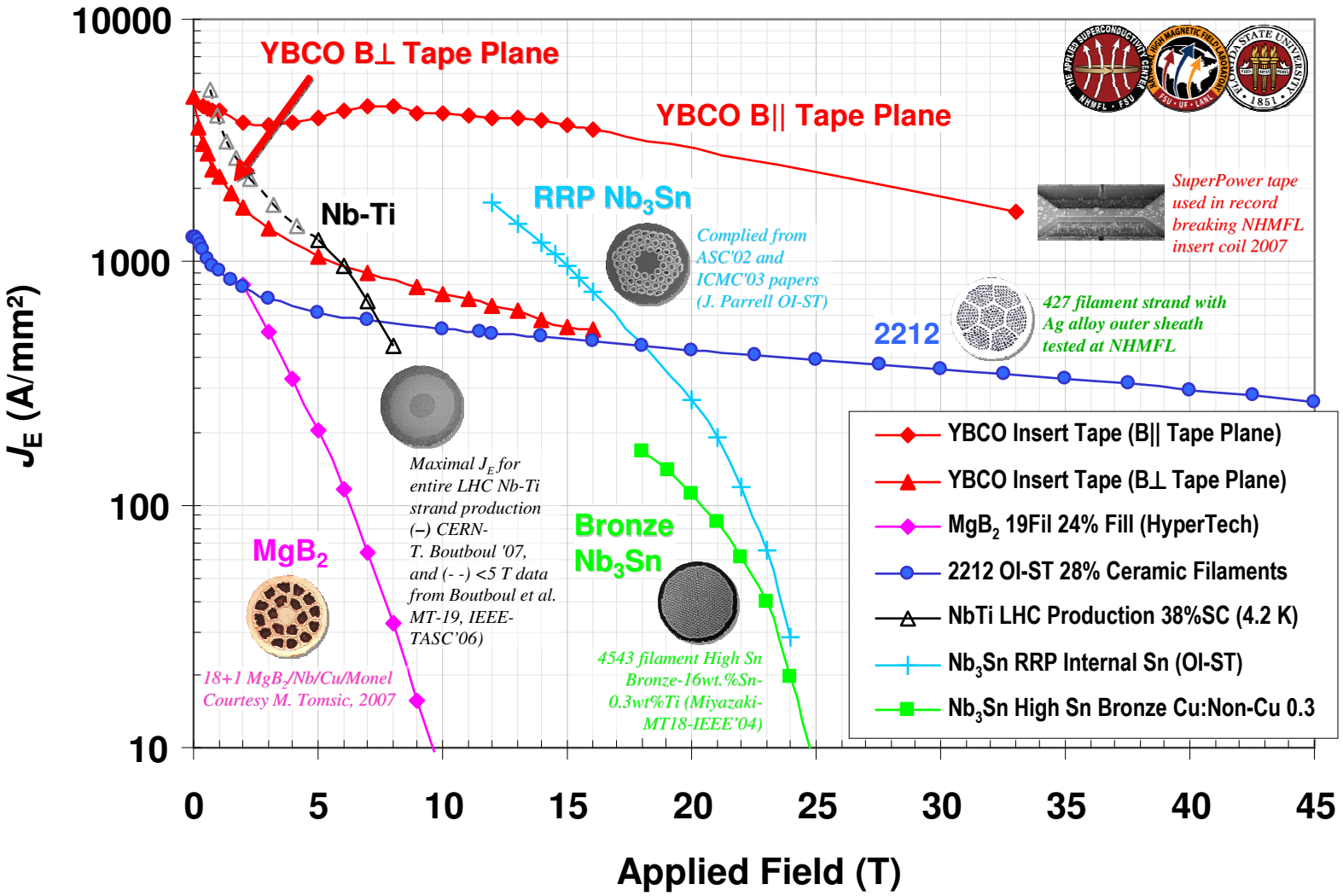




HD2c Peak Field vs. Conductor Limit



Beyond ~18 T: HFS (Bi-2212 & YBCO)



HTS Challenges

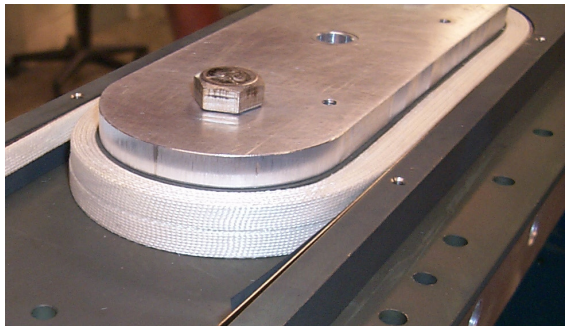
- YBCO: only in tape form, not suitable for high current cables
- Bi-2212 react-and-wind: excessive degradation during winding
- Bi-2212 wind-and-react: reaction temp, materials compatibility

Material	NbTi	Nb_3Sn	Bi-2212
Dipole Limit	10-11 T	16-17 T	Stress limited
Reaction	Ductile	~675^{0}C in Air/Vacuum	~890^{0}C in O_2 (±2^{0}C)
Axial compression	N/A	Reversible	Irreversible?
Transverse stress	N/A	< 200 MPa	60 MPa?
Insulation	Polymide	S/E Glass	Ceramic
Construction	G-10, stainless...	Bronze, Stainless	Super alloy
Quench velocity	>20m/s	~20 m/s	0.1 m/s?

HTS Coil Technology Development

Dipole coils (MC, DLHC): react & wind at BNL, TAMU; wind & react at LBNL

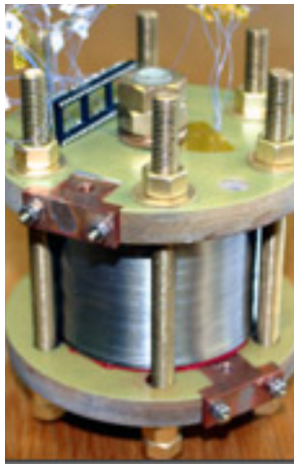




Solenoid insert coils (MC cooling channel): **Record fields obtained at NHMFL**

Year	Material	B_{HTS} [T]	B_{Total} [T]	J_e [A/mm^2]
2003	Bi2212	5	25	100
2007	YBCO	**7.8**	26.8	259
2008	Bi2212	1.1	32.1	80
2008	YBCO	2.8	**33.8**	359

Bi2212 by OST; YBCO by Superpower



Summary

- Strong, efficient collaboration network among magnet programs
- Demonstrated all fundamental aspects of Nb_3Sn technology:
  - *Conductor & structure performance, length scale-up*
- Complete engineering toolbox, fast fabrication turnaround
- On track to fully qualify a Nb_3Sn quadrupole for the LHC IR
- Demonstrated a 14 T dipole with accelerator quality features
- Exciting developments for very high field dipoles and solenoids

Acknowledgement

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