High Field Magnet Developments
- For Future Accelerators -

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KEK

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Acknowledgement

- BNL: R. Gupta
- CERN: L. Bottura, G. de Rijk, M. Karppinen, L. Rossi, E. Todesco
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- KEK: M. Iio, X. Jin, T. Ogitsu, K. Sasaki, M. Sugano, Q. Xu, A. Yamamoto
- LBNL: G. Sabbi

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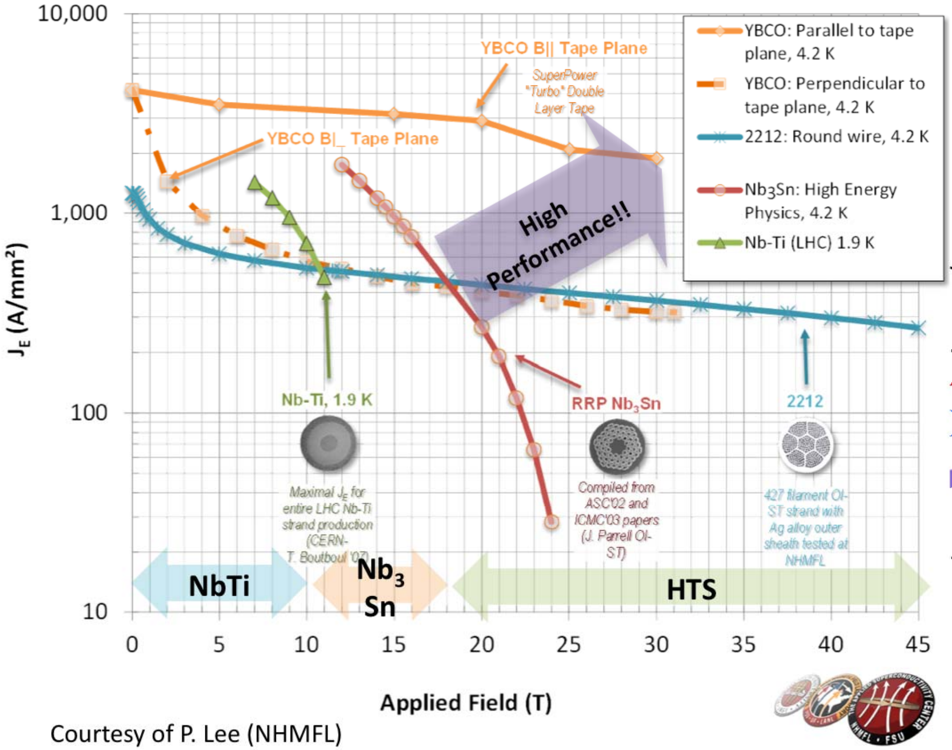
- Introduction
  - Advanced Superconductors for HFM
- Nb_3Sn HFM Development
  - Previous R&D
  - Present Developments
- R&D with Nb_3Al
- R&D with HTS
- Summary

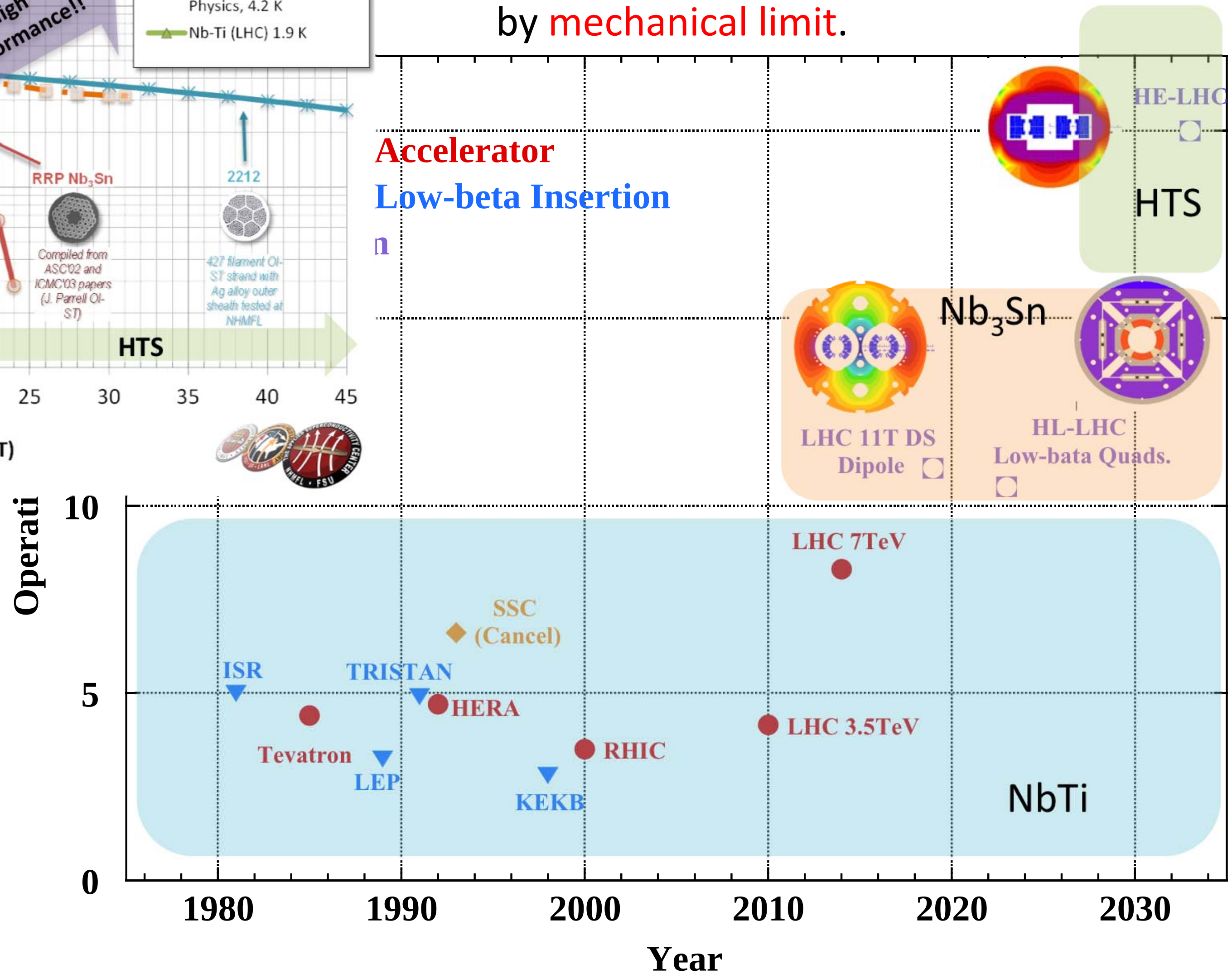
SC Magnets in Accelerators

Muon Collider 40T ???

- Superconductor determines the magnet technology, performance limit.
- HFM performance limit is NOT only determined by J_c, but also (or mainly) by mechanical limit.

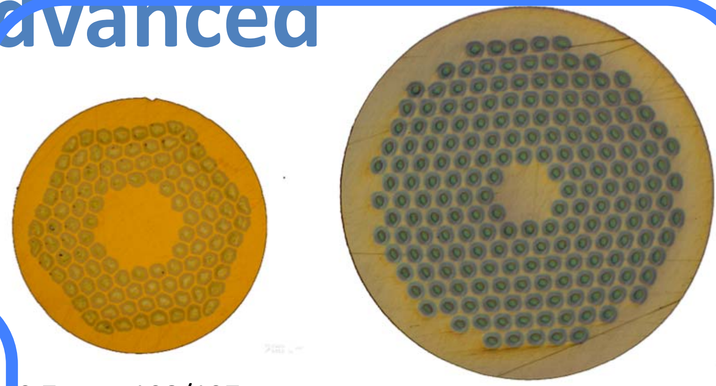


Courtesy of P. Lee (NHMFL)
http://magnet.fsu.edu/~lee/plot/plot.htm



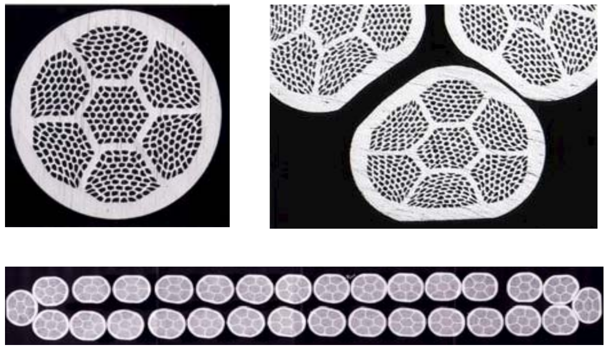
High Field Magnets with Advanced Superconductors

- NbTi: Robust, ductile alloy. Workhorse, but applicable up to 10 T.
- Nb_3Sn: Staged heat treatment ~650 °C, and then becoming brittle. Impregnated coil. Up to ~15 T.
  - US: OST RRP. Support by DOE, US-LARP.
  - Europe: Bruker PIT. Support by NED, EuCARD.
  - J_c of 2500~3000 A/mm^2 at 4.2 K, 12 T. RRR >100.
  - D_{eff} 30~50 μm >> 5-7 μm in NbTi
- HTS conductors: Up to ~45 T or higher!!
  - Bi-2212: Round wire available. Precise heat treatment (~890°C) in oxygen gas. Leak of molten Bi2212. Mechanically weak Ag matrix.
  - ReBCO tape: Very high J_e, but anisotropic. No heat treatment at coil fabrication. High longitudinal tensile strength of Hastelloy substrate, but debonding and cleavage by stresses in other directions.
  - Fundamental R&D is necessary. Limited unit length, costly.

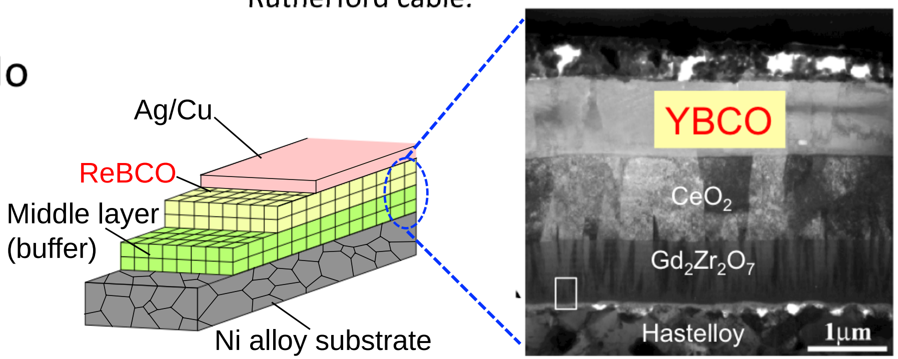


0.7 mm, 108/127 stack RRP from OST

1 mm, 192 tubes PIT from Bruker EAS



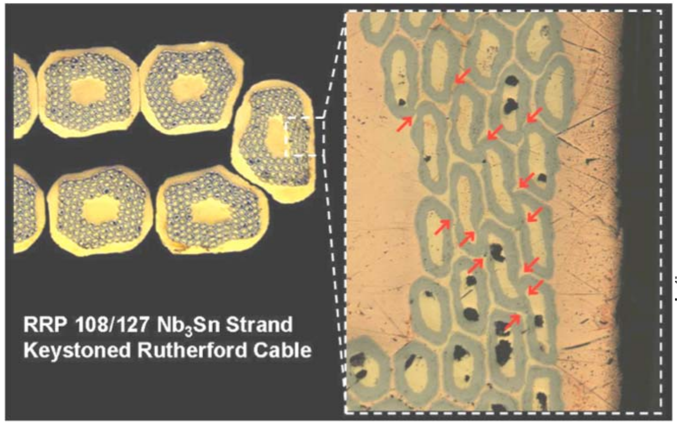
Bi-2212 round wire and Rutherford cable.



Schematic and cross section of YBCO coated conductor.

Courtesy of L. Bottura (CERN), G. Sabbi(LBNL), M. Sugano(KEK).

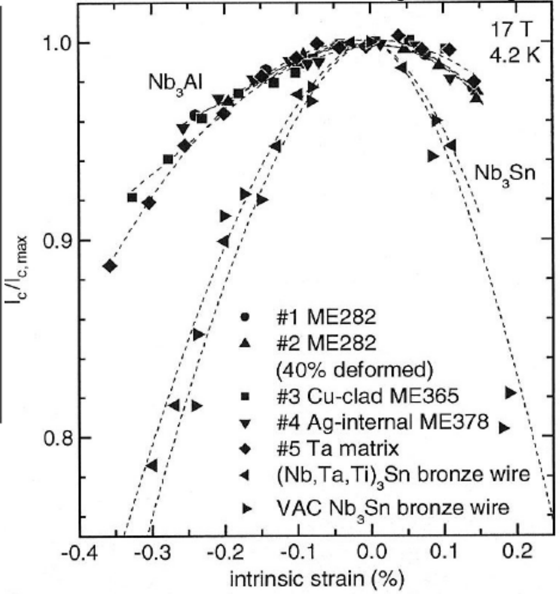
Mechanical Weakness in Advanced Superconductors



Courtesy of E. Barzi (Fermilab)

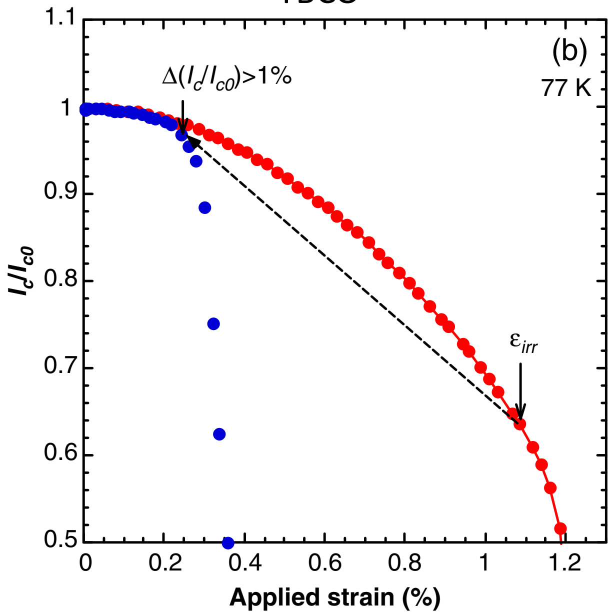
Strain sensitivity of J_c

A15 compounds (Nb_3Sn, Nb_3Al)



Supercond. Sci. Technol. 18 (2005) p. 284.

YBCO



M. Sugano et al., Supercond. Sci. Technol. 21 (2010) 085013.

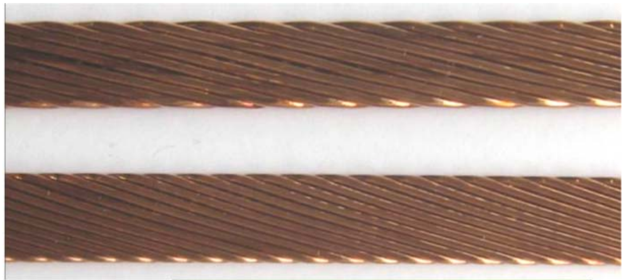
- Deformation, damage in cabling (Nb_3Sn, Nb_3Al, Bi2212)
  - Sub-elements: elongation, merger, breakage.
  - Tin leak at HT (Nb_3Sn).
- Strain dependence of Jc.
- Cracking of filament.
  - irreversible degradation.
  - stress history

Handling of stress issues is crucial in HFM.
For Nb_3Sn HFM, coil stress designed below the target limit of 200 MPa.

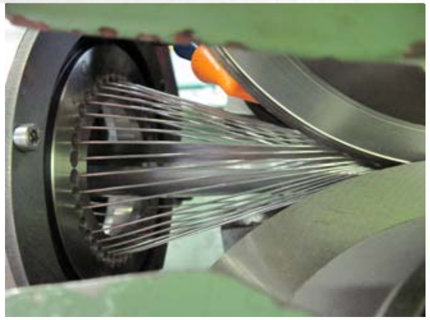
Cabling of Nb_3Sn Wires for HFM

Courtesy of L. Bottura and G. de Rijk (CERN)

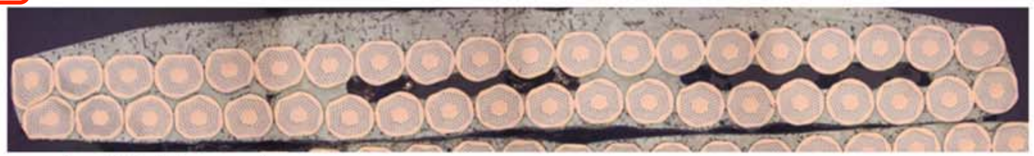
- Cabling tests were performed on several variants of strands/cable sizes to explore the space of parameters, and among others: dimensions, compaction, twist pitch, cabling angle and cabling force, …
- Cabling degradation was reduced from 45 % (worst case) to *negligible* (within the scatter of measurements of extracted strands)



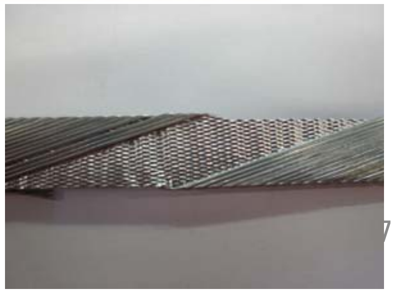
SMC Dipole cable – 14 strands (1.25 mm) and
18 Strands (1 mm), Width = 10 mm, Twist Pitch = 60 mm
Average I_C degradation 0 … 4 %



Fresca 2 Dipole cable – 40 Strands (1 mm)
Width = 20.9 mm, Twist Pitch = 120 … 140 mm
Average I_C degradation < 15 %



DS Dipole cable – 40 Strands (0.7 mm)
Width = 14.7 … 15.1 mm, Twist Pitch = 100 mm, 0.8° keystone
Average I_C degradation < 3 %

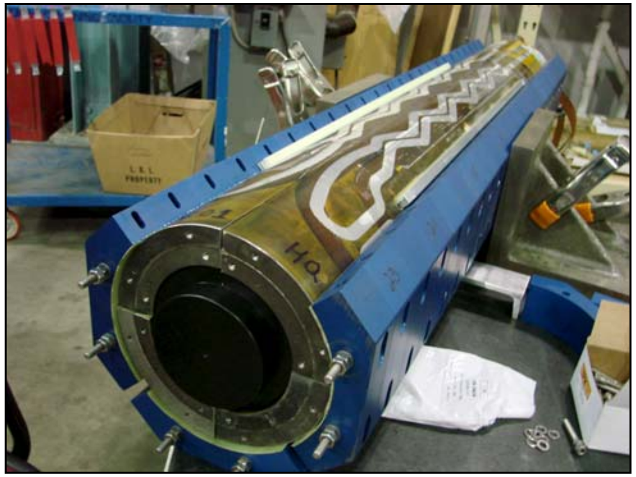


- New technology: cored cable to reduce eddy current effects.

Nb_3Sn Magnet Technology

Superconductor	NbTi	Nb_3Sn	Remarks
Field Limit	~10 T @ 1.9 K	~17 T @ 4.2 K	
Fabrication	Winding (ductile)	Winding & React	very brittle
Heat treatment	~150 °C for Cure	~650 °C	thermal contraction, anisotropic transformation
Insulation	Polyimide, epoxy prepreg.	S/E glass, ceramic	not robust
Coil Parts	GFRP (G10)	Stainless steel, Ti alloy	need of ground insulation
Axial strain limit	-	~0.3 %	J_c degradation, damage
Lateral stress limit	-	~200 MPa	J_c degradation, damage

- Heat Reaction at ~650 °C after coil winding
  - dedicated mechanical design and analysis for brittle Nb_3Sn coil: strain, stress.
  - inorganic insulation.
  - vacuum impregnation: essential for electrical insulation, mechanical reinforcement.



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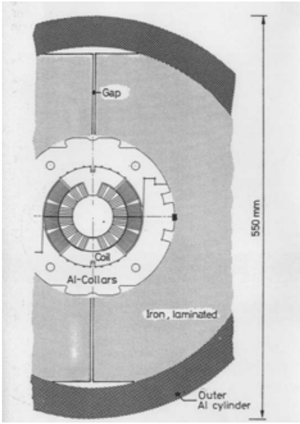
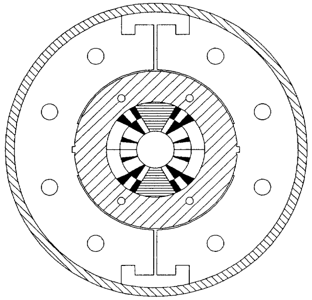
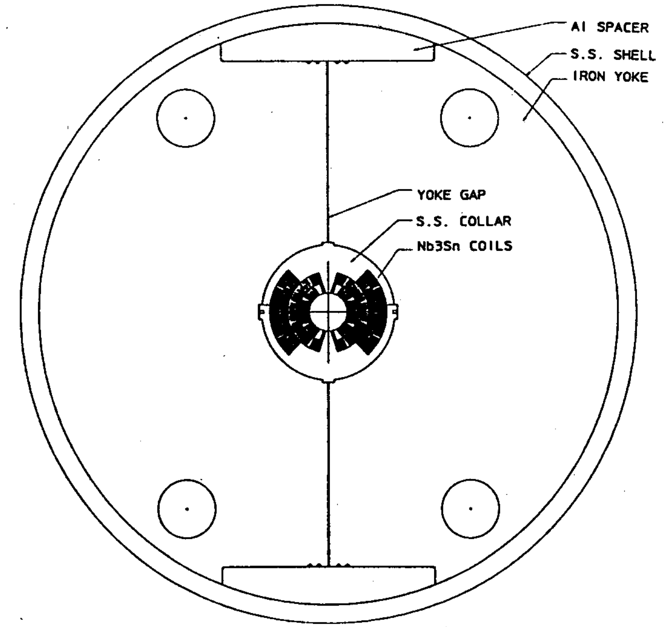
Nb_3Sn cosθ HFM in the 1990s

"Wind & React" technology







•CERN/Elin (1989).
•9.5 T at 4.2 K.
•50 mm bore.
•17 mm wide cable,
•2 layer coil.
•Al collar and shell.

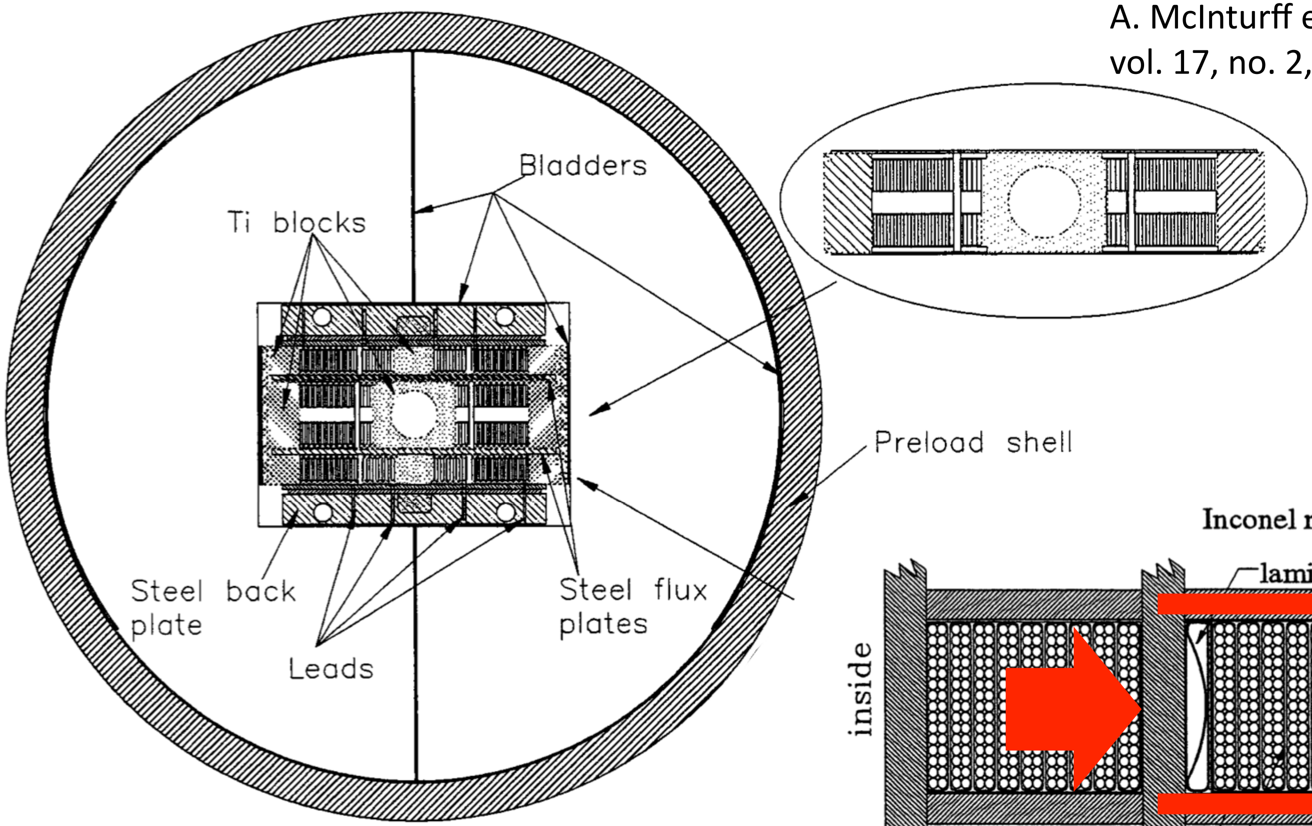
•MSUT by Twente Univ. (1995)
•11.03 T at 4.4 K
•50 mm bore.
•2 layer coil.
•SUS pole insert,
•Warm shrinkage fit of Al round collar.

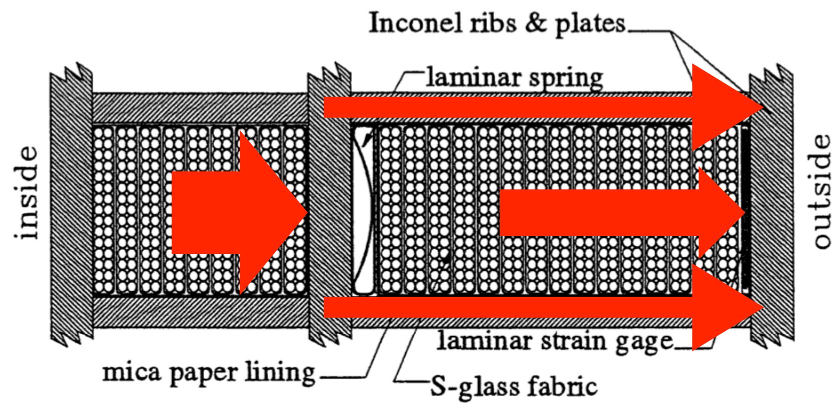
•D20 by LBNL (1997)
•12.8 T (13.5 T) at 4.2 K (1.8 K)
•50 mm bore.
•4 layer coil.

•A. Asner, et al., Proc. of 11th Inter. Conf. on Magnet Technology (MT11), Tsukuba, pp. 36-41, 1992.
•A. den Ouden et al., IEEE Trans. Appl. Supercond., vol. 7, no. 2, pp. 733-738, 1997.
•A.D. McInturff et al., Proceedings of PAC97, pp. 3212-3214, 1998.

TAMU2: "Stress Management Strategy"

A. McInturff et al., IEEE Trans. Appl. Supercond., vol. 17, no. 2, pp. 1157-1160, 2007.



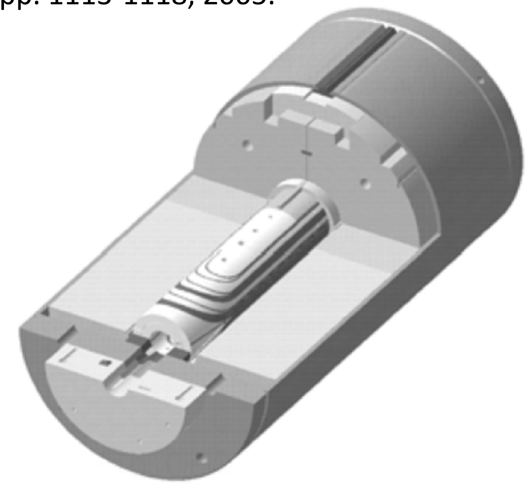


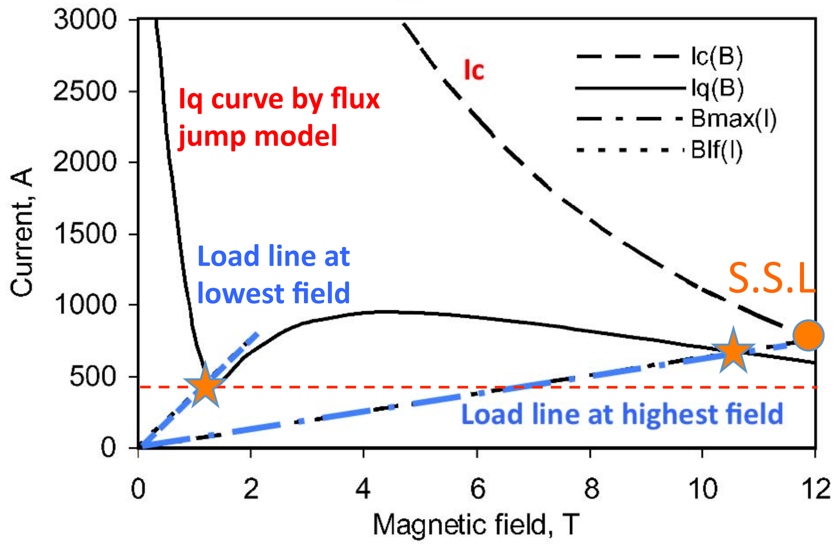
- •A unique approach to manage high stress in the block-type dipole coil by Texas A&M Univ.
- •The coil blocks are individually supported by rigid matrix structure of ribs and plates.
- •The accumulation of Lorenz force can be limited within the single coil block.
- •Laminar spring for stress decoupling.
- •Max. design field of 6.8 T in mirror configuration.
- •Quench current reached 95 % of the short sample limit (~6.5T).

Achievement: HFDA

- Fermilab started HFM program in 1998 aiming VLHC.
- HFDA model dipoles: cost effective magnets applicable for the future industrialization of full-scale magnets.
- Initial HFDA02-04 reached only 7 T. Frequent quenches at low field region. Extensive analysis;
  - low field instability of the Nb_3Sn wire due to;
    - higher J_c,
    - larger filament D_{eff}.
  - Also, issue of large persistent current effects in field quality.
  - Furthermore, recent study revealed that low RRR (< 100) compromises the stability.
- **Important suggestion for later HFM developments.**
- HFDA05 with more stable PIT conductor reached the short sample limit (10 T) at 4.5K.

A. Zlobin et al., IEEE Trans. Appl. Supercond., vol. 15, no. 2, pp. 1113-1118, 2005.

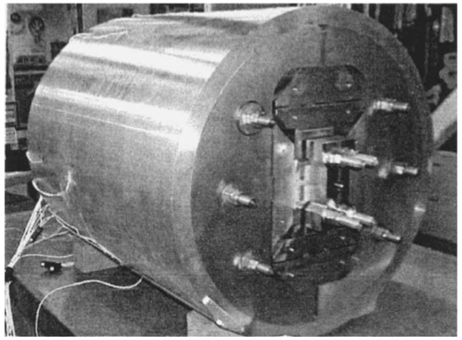




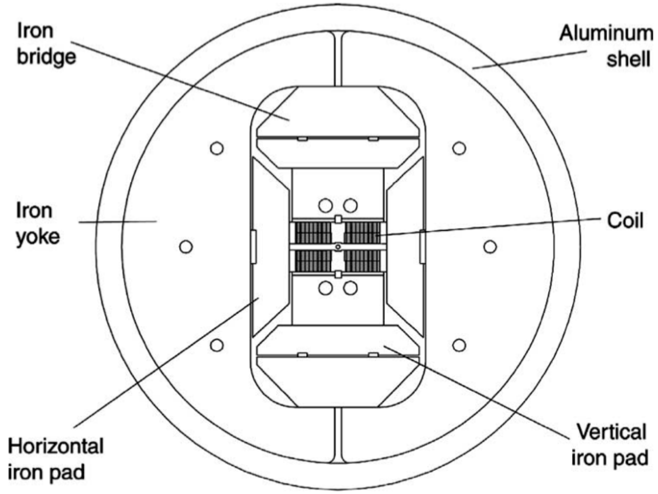
Quench performance limited by either load lines…

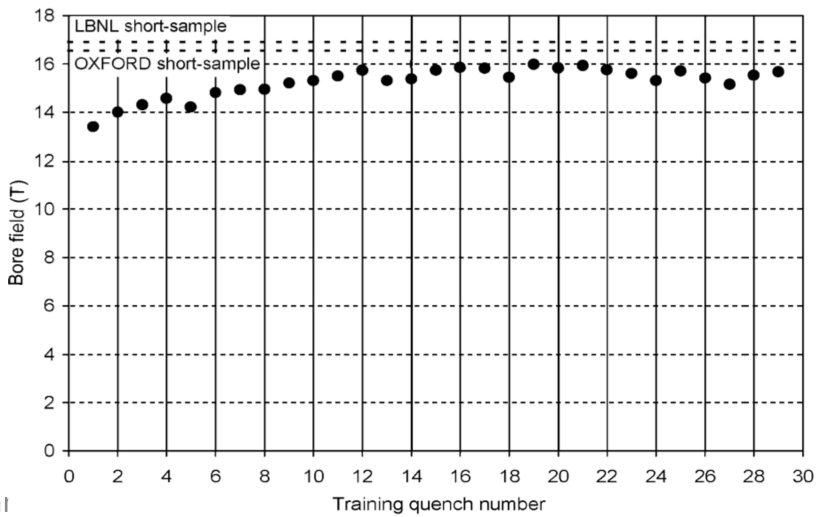
Control, adjustment of J_c, D_{eff}, RRR in "Accelerator Quality" Nb_3Sn wire.

Achievement: 16 T SC Dipole



- A number of HFM model developed by LBNL.
- A significant milestone: 16 T SC Dipole (w/ a clear bore of 8 mm) in 2003.
- 2 Nb_3Sn double-pancake racetrack coils (W&R).
  - HT: 650°C, epoxy vacuum impregnation.
- 36 strands Rutherford cable.
  - OST-RRP Nb_3Sn strand,
  - J_c=1450 A/mm^2 at 15T, 4.2K.
- Proof of "Bladder & Key" technology.
- Mechanical support by outer aluminum shell (OD 740mm) and axial aluminum rod.
  - stress increase during cool down,
  - radial stress control by shell thickness, keys.
- Precursor development, followed by low-beta quadrupoles for the LHC luminosity upgrade.





A.F. Lietzke et al., IEEE Trans. Appl. Supercond., vol. 14, no. 2, 2004, 345-348

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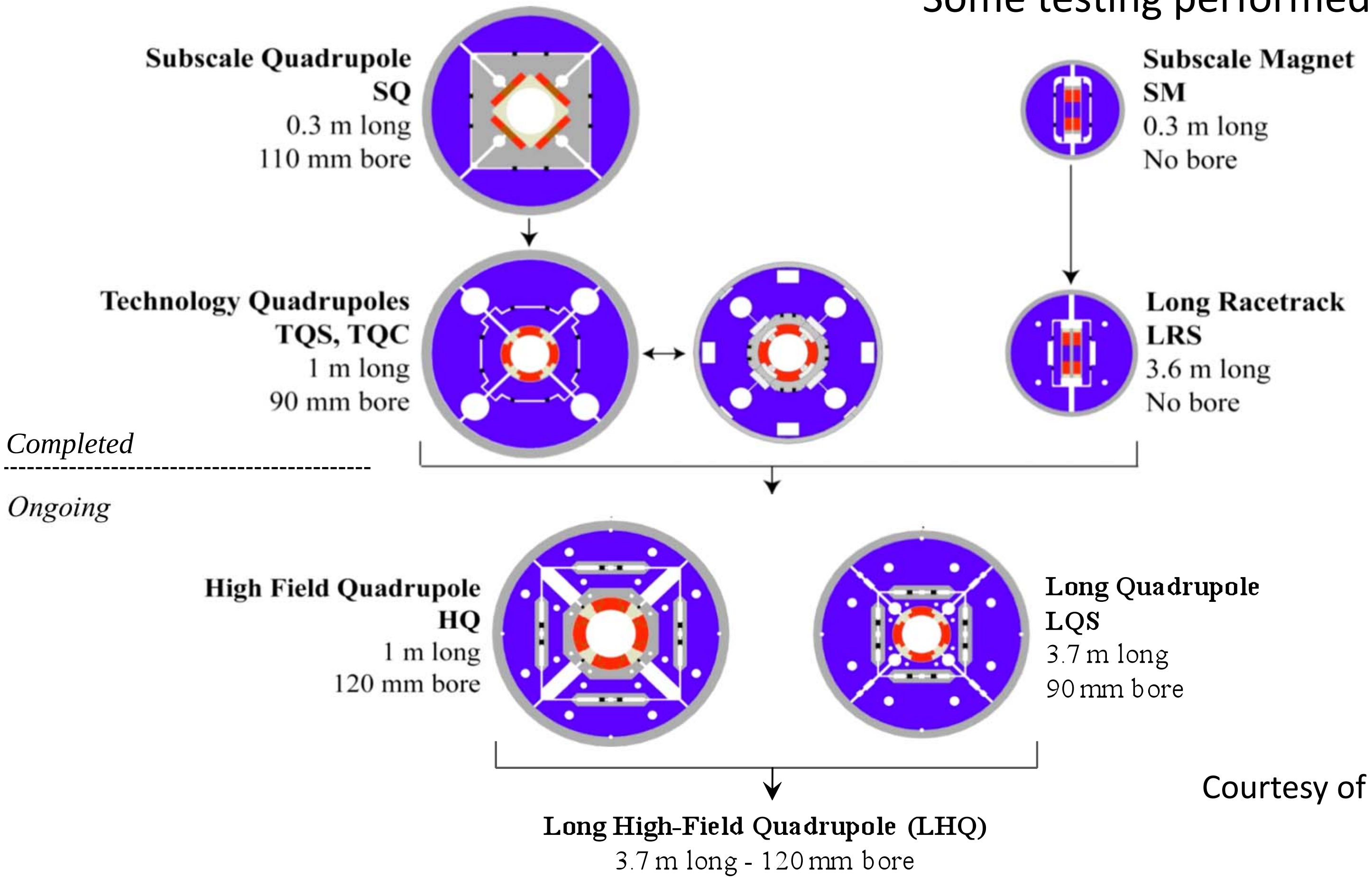
HFM Development by US-LARP

- Started by DOE in 2003, expected to be completed around 2014.
- Progression from the US LHC Accelerator Research Project.
- Collaboration of four national Labs: BNL, FNAL, LBNL, SLAC.

Major focus: development of Nb_3Sn IR Quadrupoles for HL-LHC

*Some testing performed at CERN.



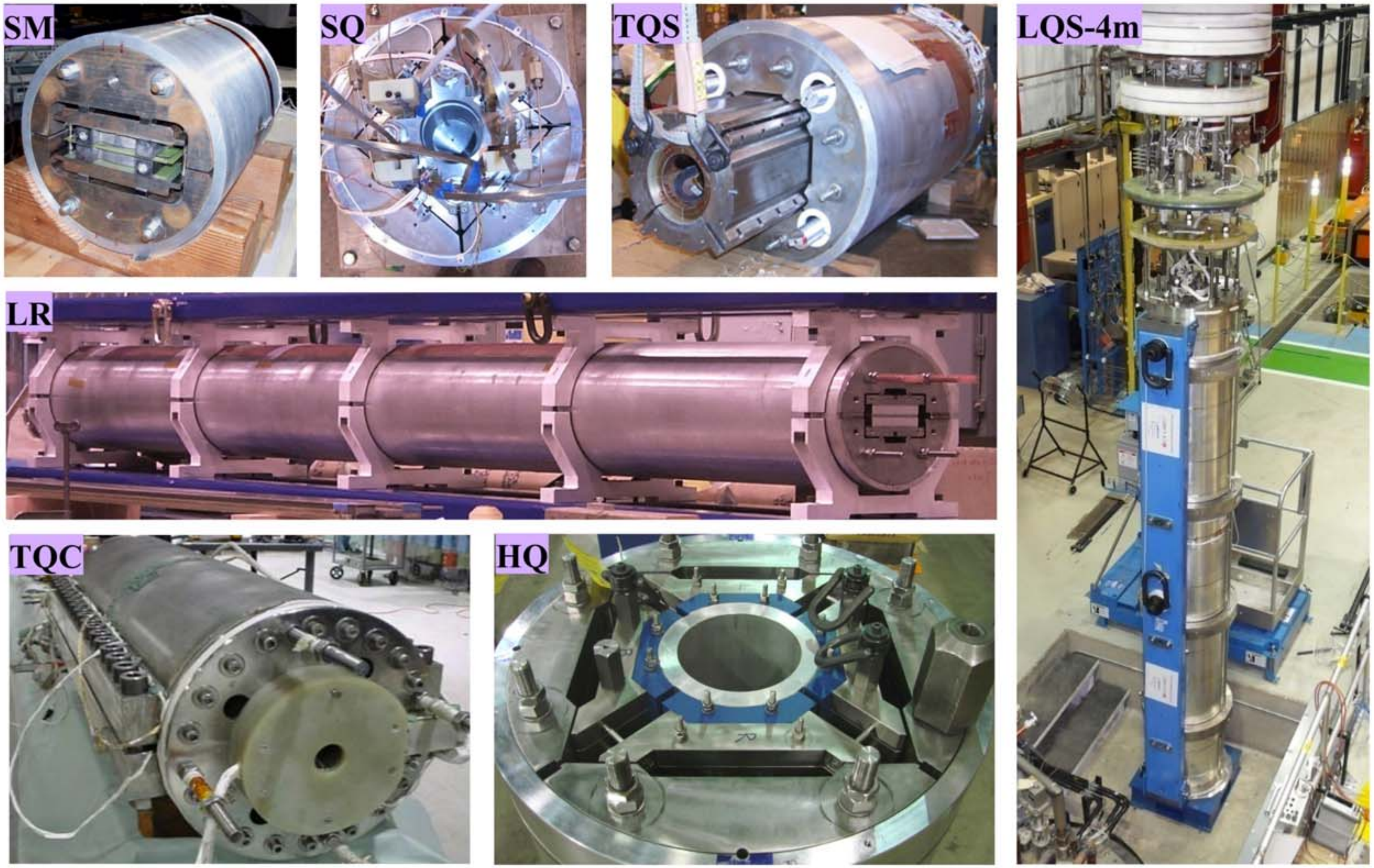
Courtesy of G. Sabbi (LBNL)

HFM Development by US-LARP

Courtesy of G. Sabbi (LBNL)

LARP

LARP Magnets

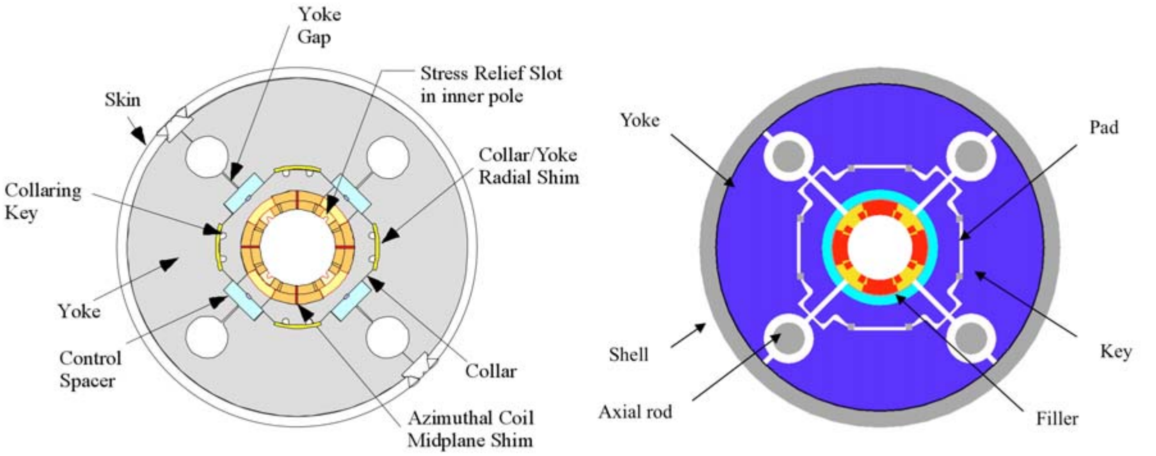


HFM Development by US-LARP

Courtesy of G. Sabbi (LBNL)

LARP

TQC and TQS Designs



TQC (Collar)

TQS (Shell)

- Stainless steel collars and skin
- Control spacers to limit pre-load
- Full pre-load at room temperature
- End support plates, low pre-load

- Aluminum shell over iron yoke
- Assembly with bladders and keys
- Full preload after cool-down
- Rods/plates for high axial pre-load

Technical objective: develop technology base for the Long Quadrupole

- Evaluation of conductor and cable performance
- Development and optimization of coil fabrication procedures
- Comparison of mechanical design concepts & support structures

Magnet parameters:

- 1 m length, ***90 mm aperture***, cos2θ coil geometry

Goal: predictable and reproducible performance above 200 T/m (10-11T)

HFM Development by US-LARP

Courtesy of G. Sabbi (LBNL)

LARP

TQ Quench Performance 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	74	151	196	86	200	1.9K, *100A/s*
TQC01b	142	177	88	179	200	92	200	1.9K
TQC02E	177	201	90	198	198	81	201	4.4K
TQC02a	124	156	70	145	165	68	169	1.9K, *50 A/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	222	4.4K

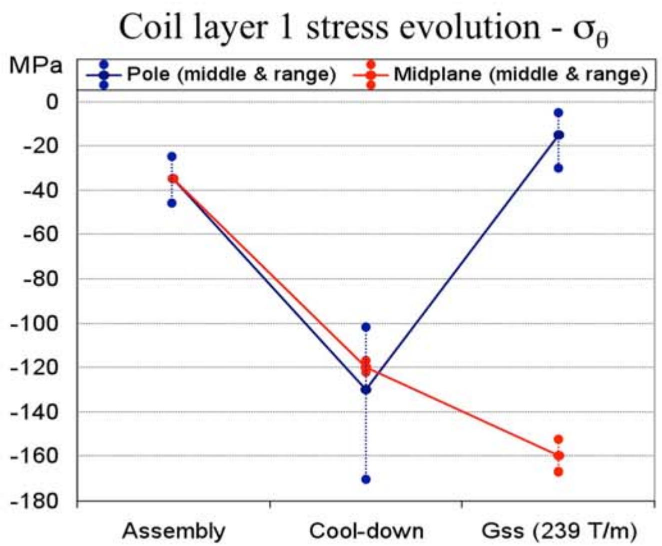
(*) Highest Quench value includes all Training, Ramp Rate & Intermediate Temperature Quenches

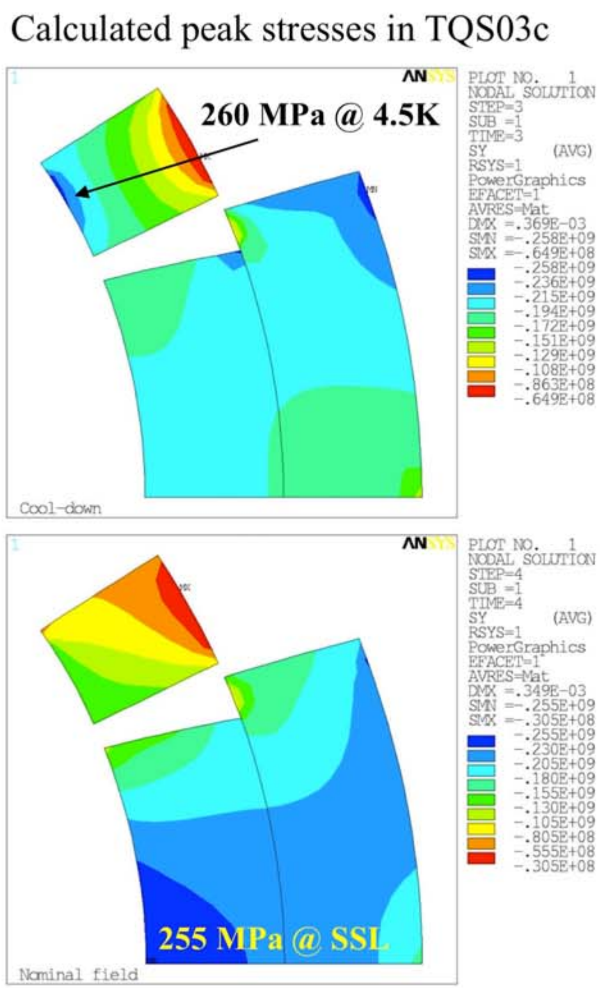
- Both TQC and TQS achieved target gradient of 200 T/m.
- The highest record was 237 T/m (B_{peak} ~12 T) at 1.9 K in TQS03.

HFM Development by US-LARP

Courtesy of G. Sabbi (LBNL)

TQ Studies: Stress Limits





Systematic investigation in TQS03:

Excitation test for 3 stress cases.

- TQS03a: 120 MPa at pole, 93% SSL
- TQS03b: 160 MPa at pole, 91% SSL
- TQS03c: 200 MPa at pole, 88% SSL

Peak stresses are considerably higher →

Considerably widens design window

Tolerable up to 260 MPa in the coil.

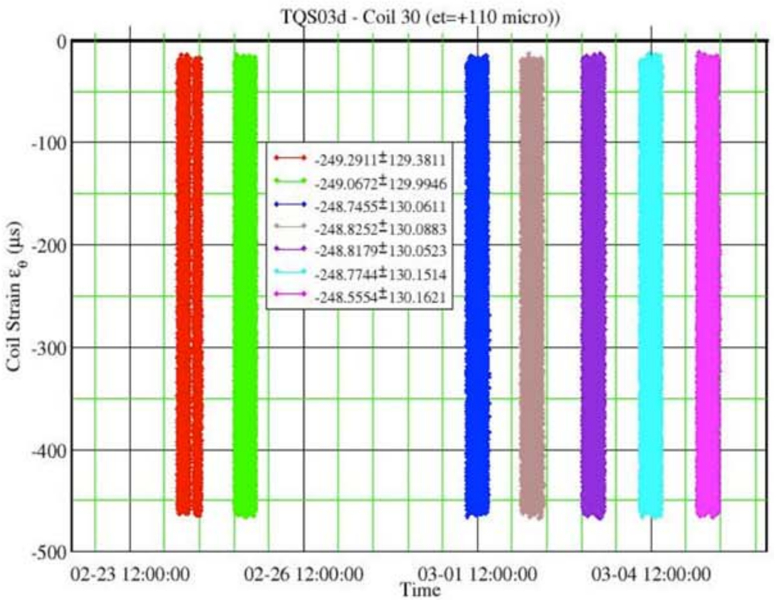
HFM Development by US-LARP

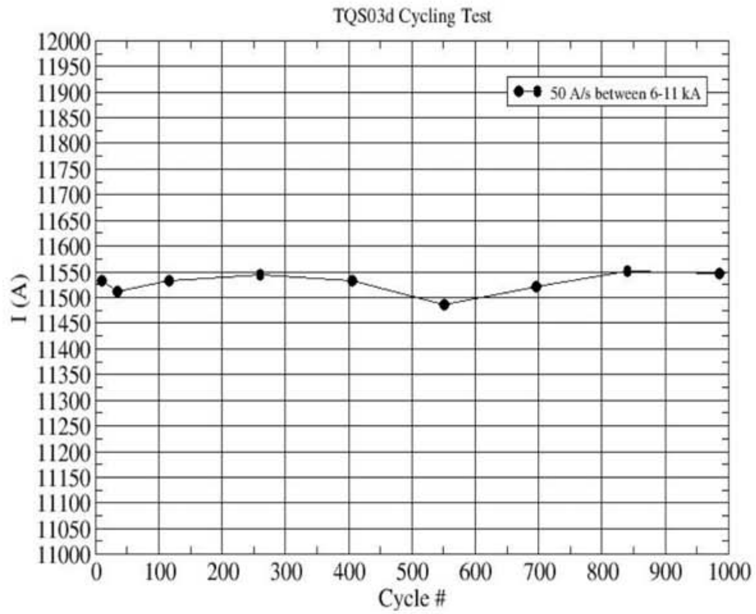
Courtesy of G. Sabbi (LBNL)

LARP

TQS03d Cycling Test

- Reduced coil stress to TQS03b levels (160 MPa average)
  - *Pre-loading operation and test performed at CERN*
- Did not recover TQS03b quench current (permanent degradation)
- Performed 1000 cycles with control quenches every ~150 cycles
- No change in mechanical parameters or quench levels



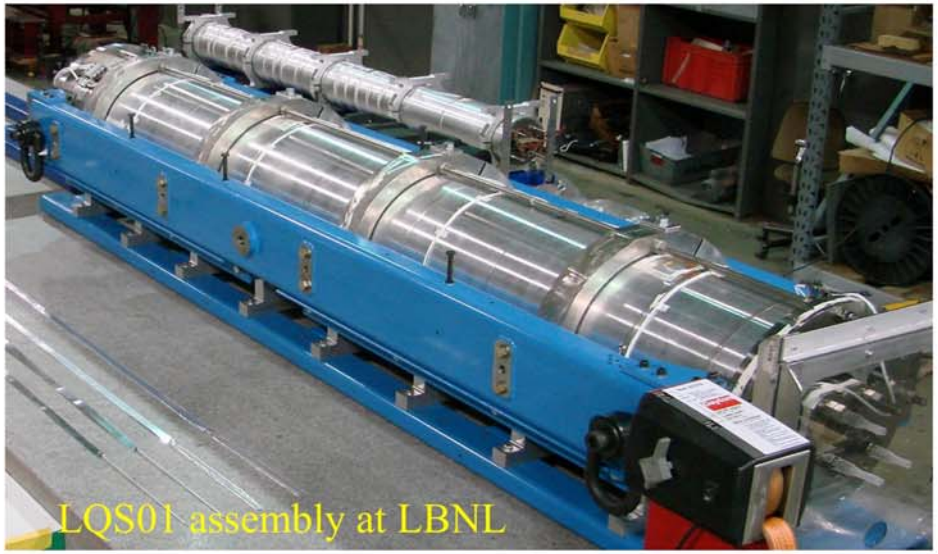


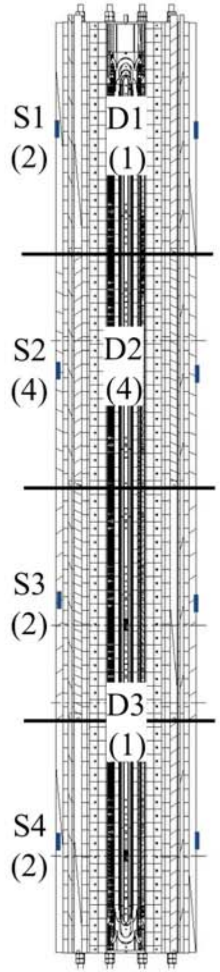
HFM Development by US-LARP

Courtesy of G. Sabbi (LBNL)

Long Quadrupole (LQ)

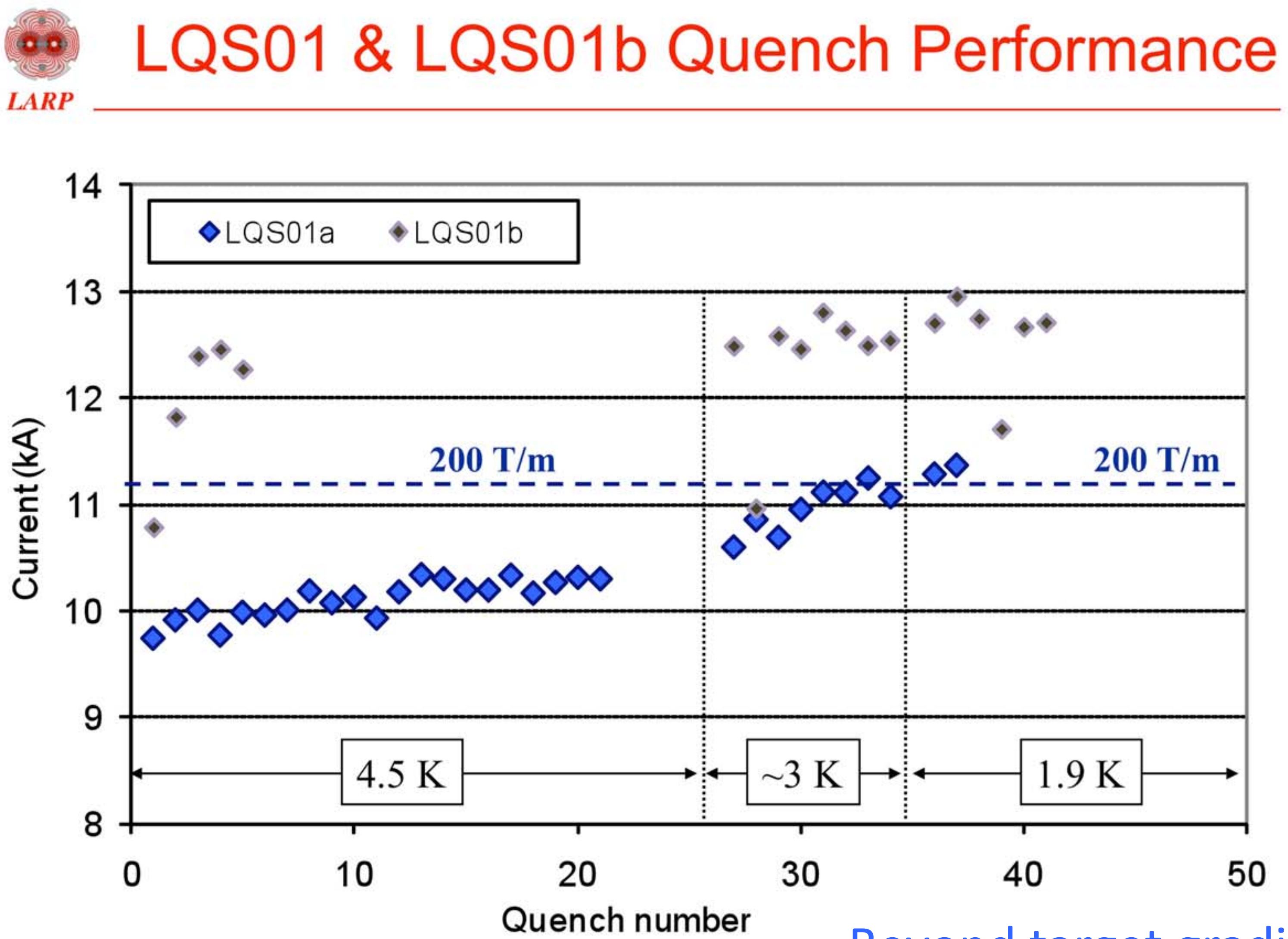
- TQ length scale-up from 1 m to 4 m
- Coil Fabrication: FNAL+BNL+LBNL
- Mechanical structure and assembly: LBNL
- Test: FNAL
- Target gradient **200 T/m**





HFM Development by US-LARP

Courtesy of G. Sabbi (LBNL)



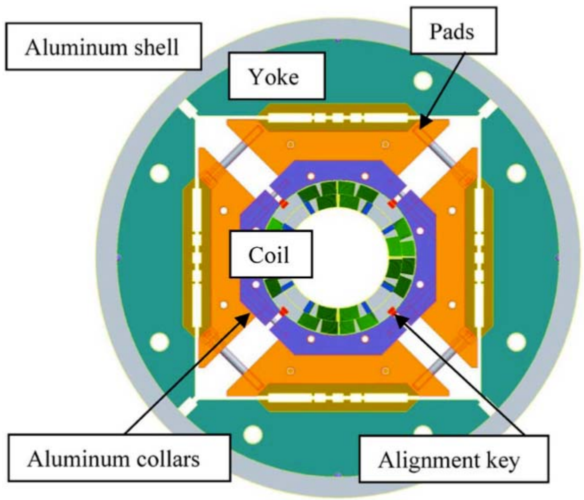
Beyond target gradient...

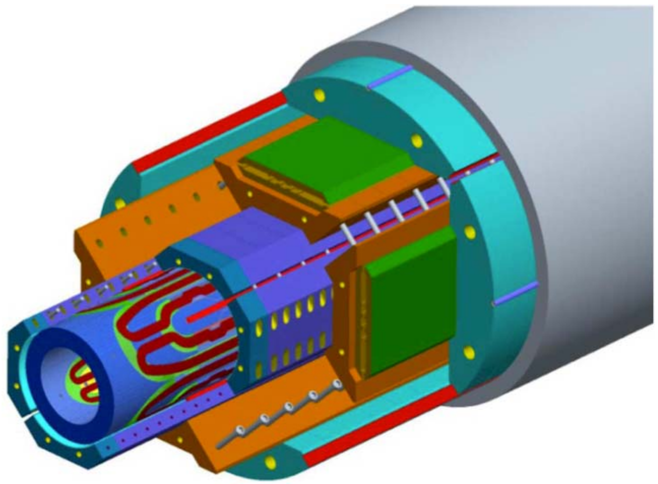
HFM Development by US-LARP

[HQ model design parameters]

Courtesy of G. Sabbi (LBNL)

- 120 mm aperture, same as NbTi MQXC model.
- 2 layer Nb_3Sn cos2θ coils (20/26 turns).
- Mechanical structure: Based on TQS (outer aluminum shell w/ bladder& key).
- Alignment feature by Al collars with alignment keys.
- Rutherford cable (w15.1mm, t 1.44mm) with 35 RRP 108/127 strands. Insulation 0.09 mm.
- Max. gradient: 195 (214) T/m at 4.2K (1.9K).
- Peak field: 13.7 (14.9) T at 4.2K (1.9K).
- Total Fx, Fy (octant): 3.38, -5.03 MN/m.
- Stored Energy: 1.1 MJ/m.





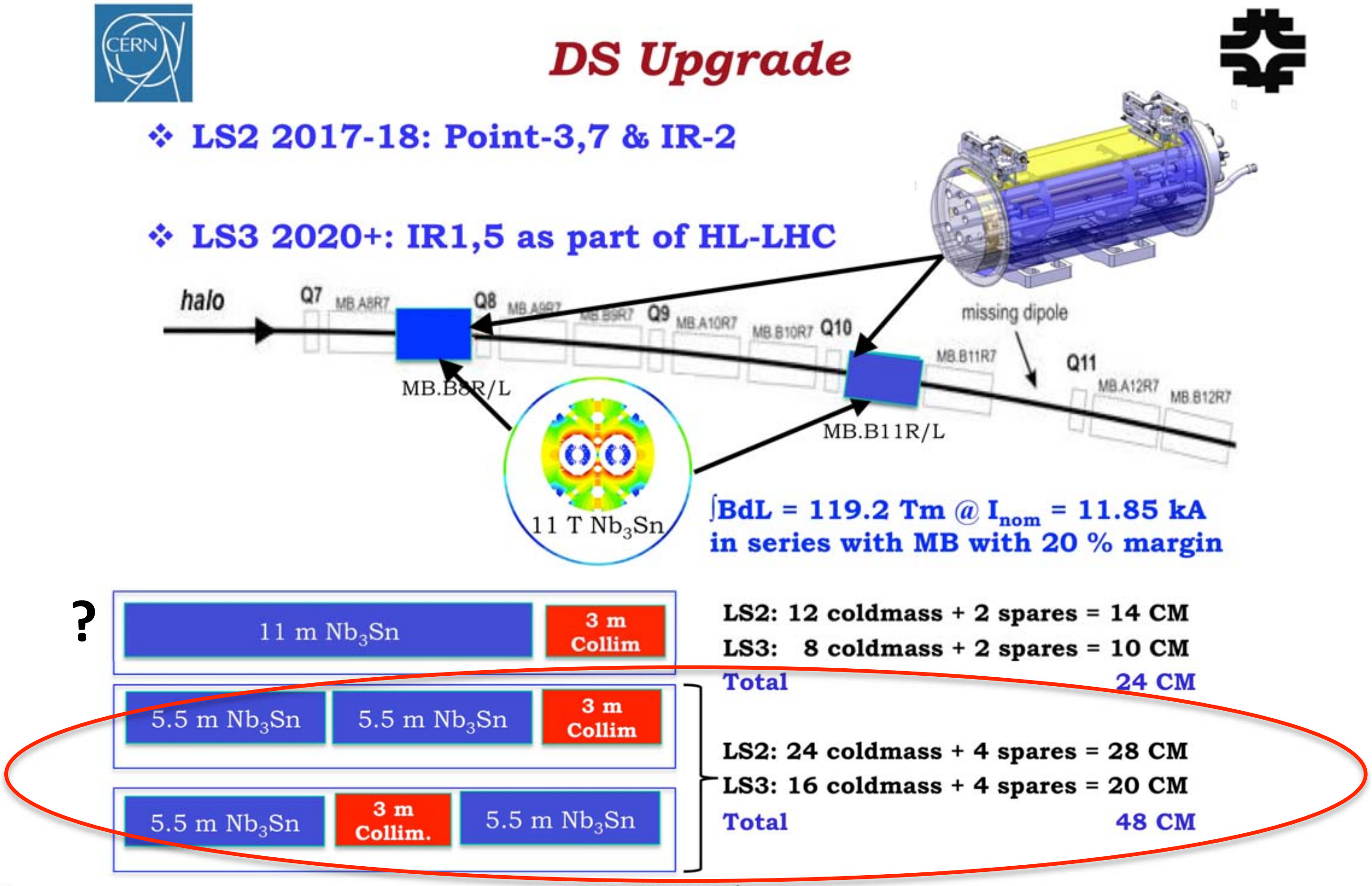
[Status]

- Quench: 157 T/m (HQ01a) > NbTi limit!!
  170 T/m (HQ01d)
- Suffering frequent electrical breaking.
  - coil high compaction, mismatched end spacer design.
  - Extensive analysis, modification in design and fabrication.
- Field quality
  - OK for geometry and iron saturation.
  - Large persistent current effect, in particular, at injection region.
  - Frequent flux jump, dynamic behavior...

Development of 11T Dipole for LHC Upgrade

Courtesy of A. Zlobin (Fermilab) and M. Karppinen (CERN)

- New collimators will be necessary to secure the main dipoles (MB) in the LHC DS regions.
  - Need the longitudinal space for the collimator.
  - Replacement of the current MB by new Nb_3Sn 11 T dipoles.
- Collaboration with CERN and Fermilab.

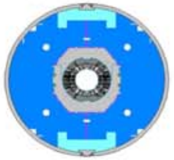
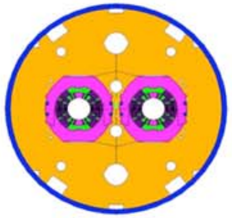


Development of 11T Dipole for LHC Upgrade

Courtesy of A. Zlobin (Fermilab) and M. Karppinen (CERN)

11 T Nb_3Sn Dipole for LHC Upgrade

- **Nb_3Sn dipole for LHC upgrade (with CERN)**
  - **11 T at 11.85 kA, compatible with LHC lattice and main systems to replace 8.35 T MB**
  - **2012: 2-m long single-aperture demonstrator**
  - **2013: 2-m long twin-aperture demonstrators**
  - **2014: 5.5-m long twin-aperture prototype**

Parameter	Single-aperture 	Twin-aperture 
Aperture	60 mm	
Yoke outer diameter	400 mm	550 mm
Nominal bore field @11.85 kA	10.86 T	11.25 T
Short-sample bore field at 1.9 K	13.6 T	13.9 T
Margin B_{nom}/B_{max} at 1.9 K	0.80	0.81
Stored energy at 11.85 kA	473 kJ/m	969 kJ/m
F_x per quadrant at 11.85 kA	2.89 MN/m	3.16 MN/m
F_y per quadrant at 11.85 kA	-1.57 MN/m	-1.59 MN/m

IPAC2012: TUOAC03, THPPD043, THPPD044

40-strand keystoned cable

Fresca2 dipole by EuCARD WP7

Courtesy of G. de Rijk (CERN)

- HFM development by 12 European institutes, following NED in the CARE project.
- Replacement of 10 T NbTi dipole in the Fresca cable test station at CERN.

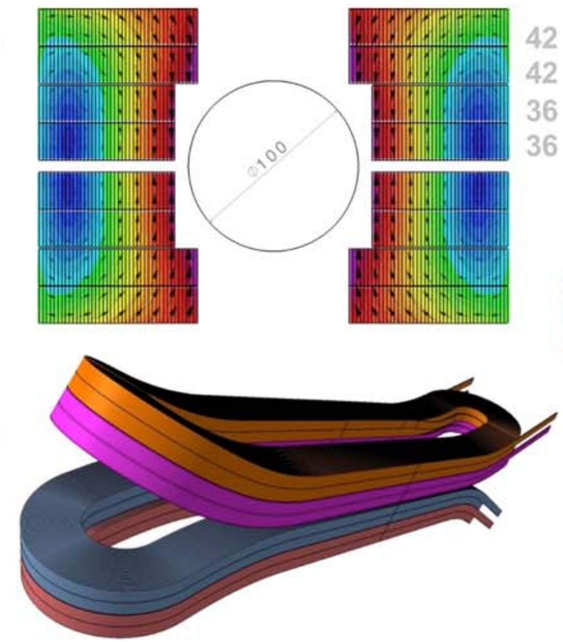
Challenging construction with several new concepts:

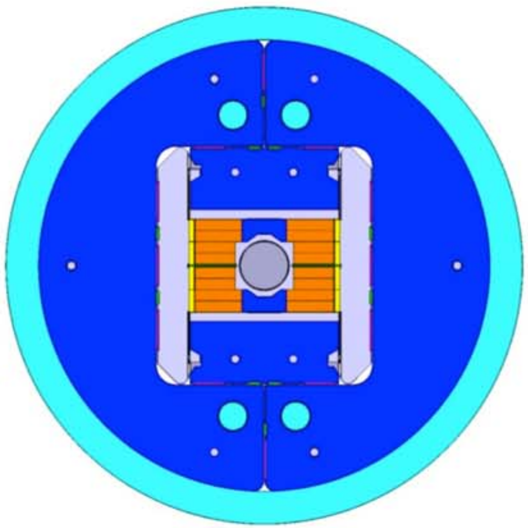
- Block coil geometry with flared ends
- Shell-bladder and key structure

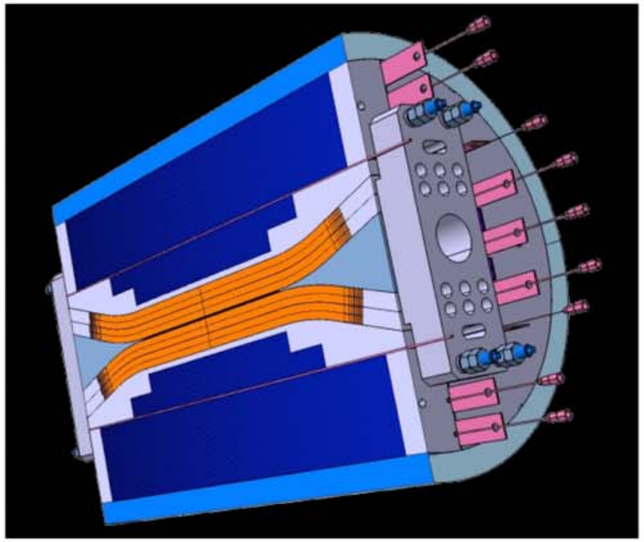
(inspired by the HD2 of LBNL)

- 156 turns per pole
- Iron post
- B_{center} = 13.0 T
- I_{13T} = 10.7 kA
- B_{peak} = 13.2 T
- E_{mag} = 3.6 MJ/m
- L = 47mH/m

- Diameter Aperture = 100 mm
- L coils = 1.5 m
- L straight section = 700 mm
- L yoke = 1.6 m
- Diameter magnet = 1.03 m







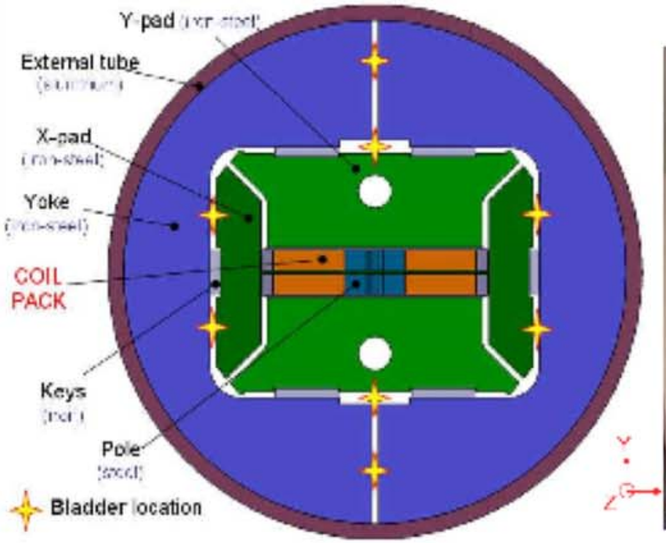
Courtesy Attilio Milanese, Pierre Manil

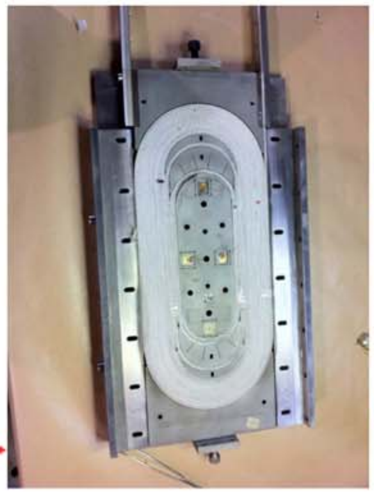
* The 1st coil is planned to be tested by April 2013.

SMC for HFM Technology Development

Coherent R&D with Fresca2 dipole development.

- An CEA-Saclay / CERN / SRFC-RAL / LBNL collaboration
- Test Nb_3Sn cables in a magnet-like setup (Jc, stress sensitivity, etc)
- Cost effective training of the manufacturing of Nb_3Sn coils
- First coils set (SMC1) tested in Oct 2010: low performance at 40 % Jc
- Second coil (SMC3) set tested in June 2011: performance 85%-95% Jc
  - Confirmed in a second test
- The Fresca2 cable with final insulation scheme will be certified in SMC before a full scale coil will be made → Validation by new "RMC" coil.

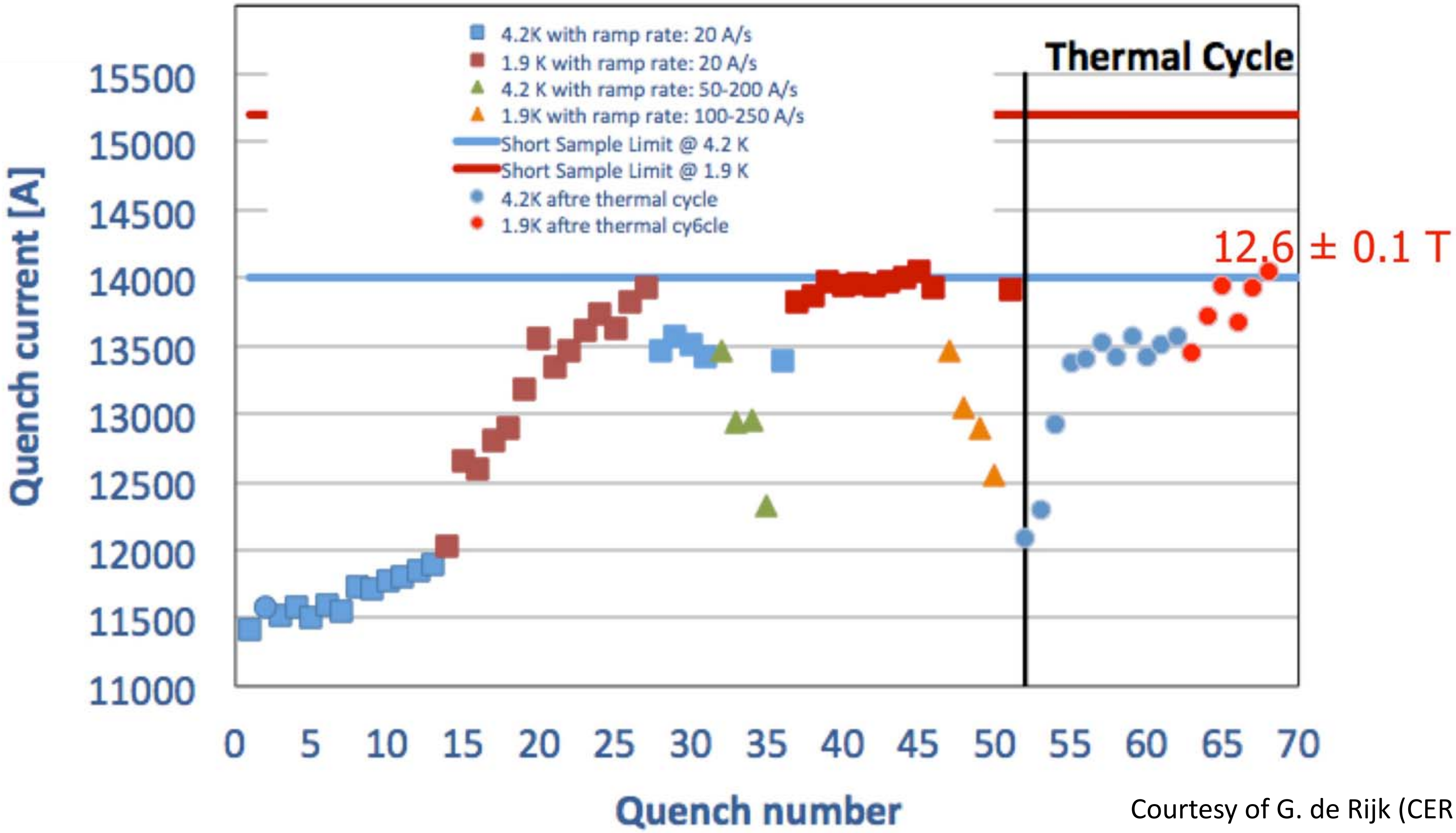




Courtesy of G. de Rijk (CERN)

SMC for HFM Technology Development

Short Model Coil performance (SMC-3, June & Aug 2011)



Courtesy of G. de Rijk (CERN)

- Achieving the short sample limit at 4.2 K.
- Validation of design concept, fabrication process.

Contents

- Introduction
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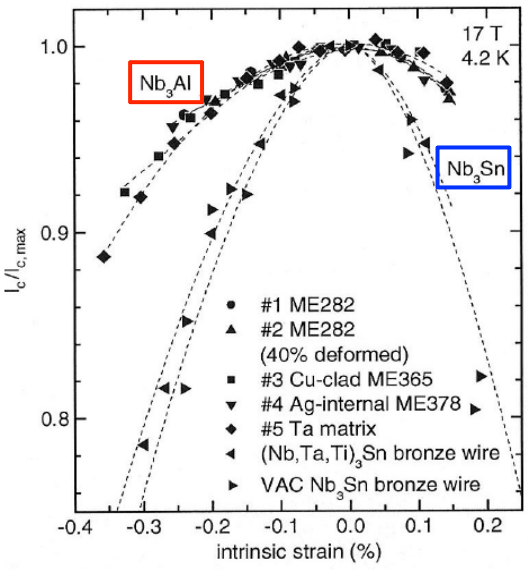
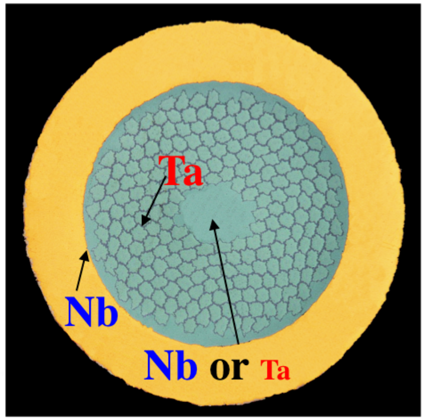
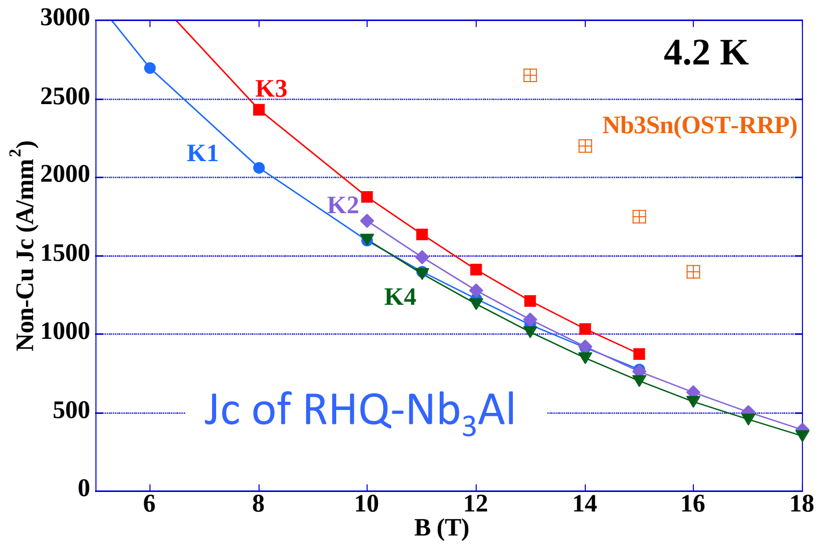
RHQT-Nb_3Al by KEK, NIMS, and Hitachi Cable

- Development of Rapid Heating, Quenching and Transformation (RHQT) processed Nb_3Al superconductor for accelerator magnet application with a support from CERN.
- Less stress/strain sensitivity of Jc than Nb_3Sn.
  - Possible candidate for HFM application: accelerator, fusion device.
- But, stress free J_c is still about a half of Nb_3Sn RRP wire.
- Frequent wire breaking of Ta matrix wire was a major technical issue for industrialization.
  - Recent improvement in Cu-matrix wire developed by NIMS.



Supercond. Sci. Technol. 18 (2005) p. 284.
by N. Banno et al.

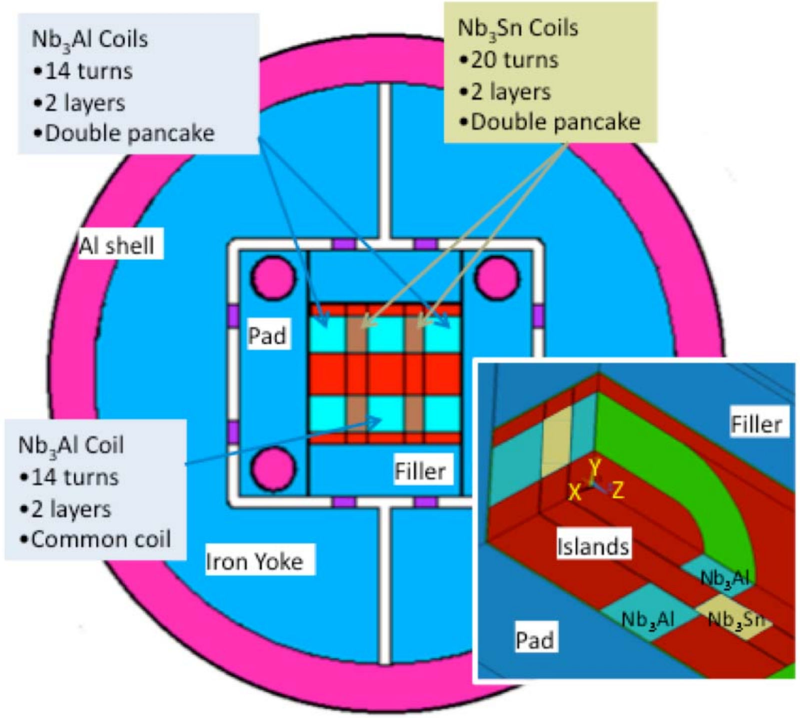


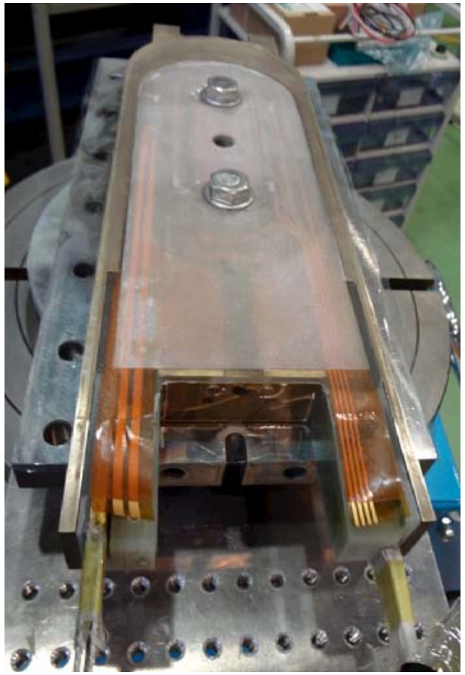


13 T Nb_3Al/Nb_3Sn Hybrid Sub-scale Magnet

- To demonstrate feasibility of Nb_3Al cable.
- Key design points
  - The common coil concept, and the shell structure,
  - 3 Nb_3Al coils & 2 LBL-Nb_3Sn coils to increase peak field.

*Technology Transfer from LBNL.
*Cabling at Fermilab.

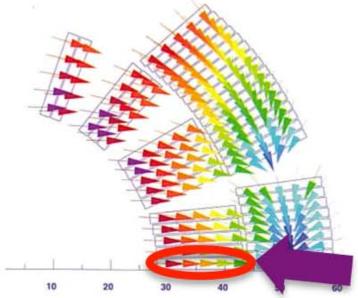


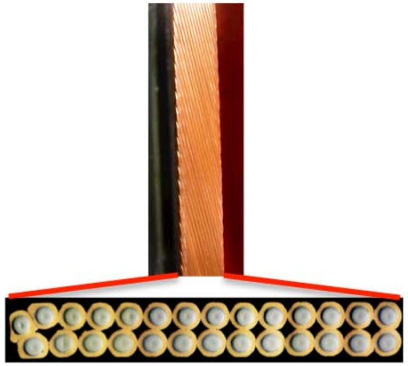


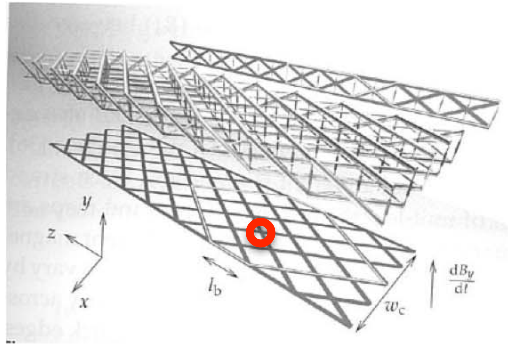
•Two RHQ-Nb3Al coils are ready for assembly.
•Testing in 2-Nb_3Al & 2-Nb_3Sn coils configuration will be performed in 2012.

Item	Value
Operation current	11.8 kA
Peak field in coils	12.8 T
Stored energy	67.5 kJ
Inductance	0.97 mH
Magnet Length	740 mm
Shell Dia.	580 or 680 mm
Nb3Al Coil	3coils (14 turns, 2 layer)
Nb3Al Cable	w: 13.96 mm, t: 1.84 mm, 28 strands
Nb3Al Cable Insulation	40 % overwrapping with alumina fiber tape (t 0.14 mm)
Nb3Sn Coil	2 coils (20 turns, 2 layer)

Stress/Strain Issues in High Field Magnet



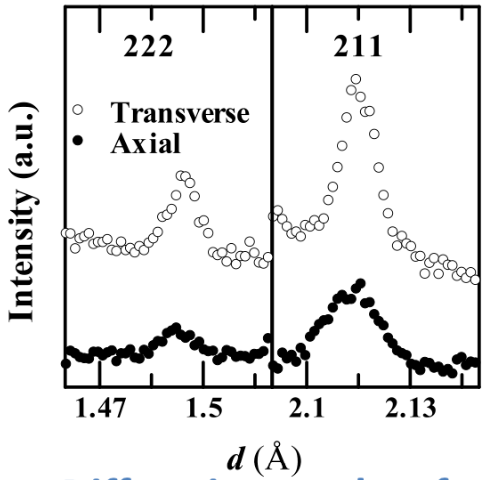




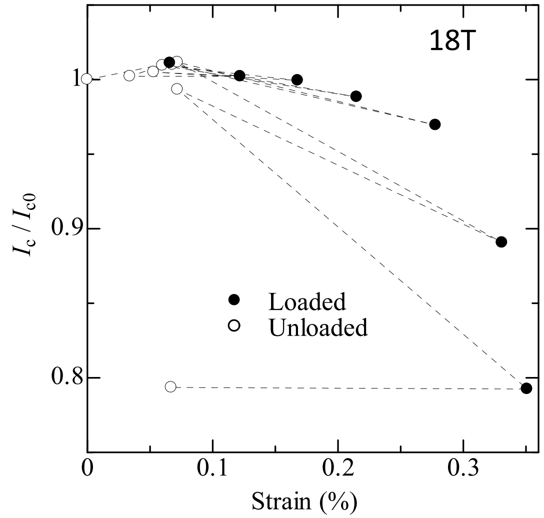
- Local strain at **cross over** of Rutherford-type A15 SC cable?
- Effect of mechanical reinforcement by resin impregnation?

<< Final Goal

- Neutron diffractometer at J-PARC MLF BL-19 (TAKUMI).
- A cryogenic load frame (4 K, 50 kN) has been developed by KEK & JAEA.



- Diffraction peaks of RHQ-Nb_3Al at 4 K for strain analysis.



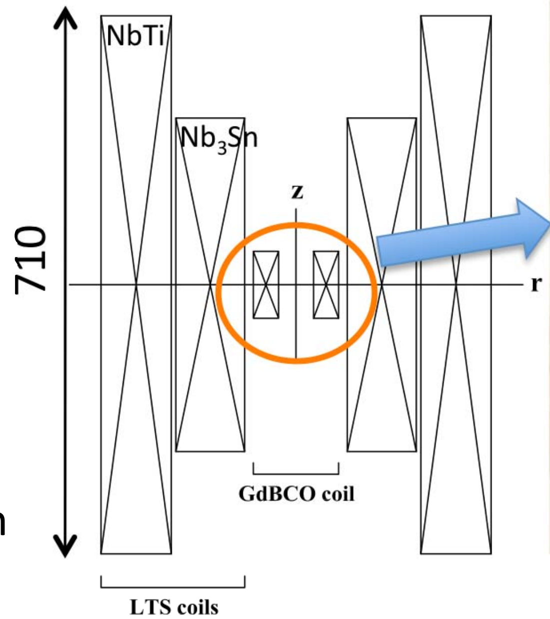
- Jc dependence on tensile strain for RHQ-Nb_3Al. Irreversible damage at 0.3 %.

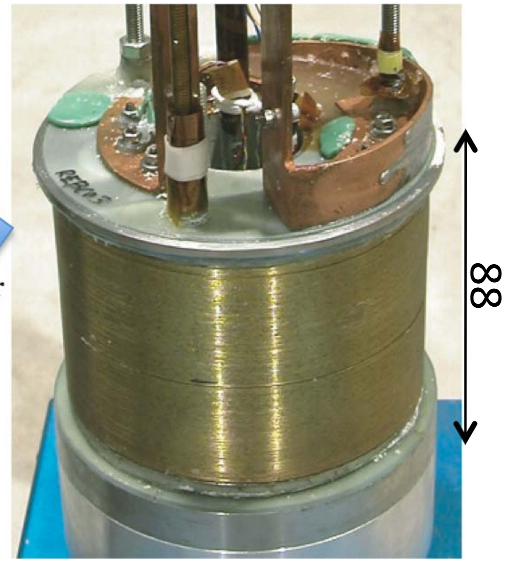
Contents

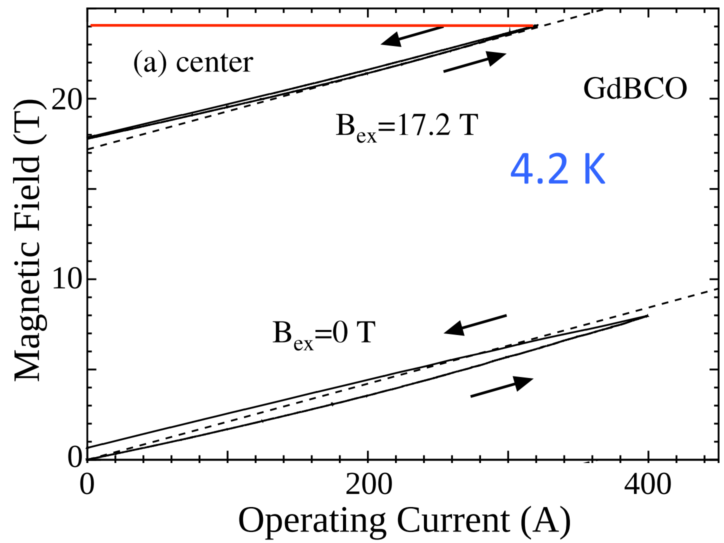
Achievement: 24 T SC Solenoid

- The world highest 24 T SC HFM (solenoid) by NIMS in 2011.
  - LTS + HTS coils
- HTS coil insert: 6.8 T at 480 A/mm^2,
  - GdBaCuO coated conductor (5 mm wide, 0.15 mm thick, 500 m long) by Fujikura Ltd.
  - L=88 mm, Clear bore diam.= 40 mm
  - Max. hoop stress (*BJR*) = 450 MPa.
  - A conductor joint in the coil.
- LTS external coils: 17.2 T
  - Nb_3Sn 8.2 T & NbTi 9.0 T
- Initial HTS trial coils suffered cleavages.
  - Improvement of mechanical design to avoid stress concentration.
  - Epoxy impregnation NG!!
  - Paraffin wax impregnation

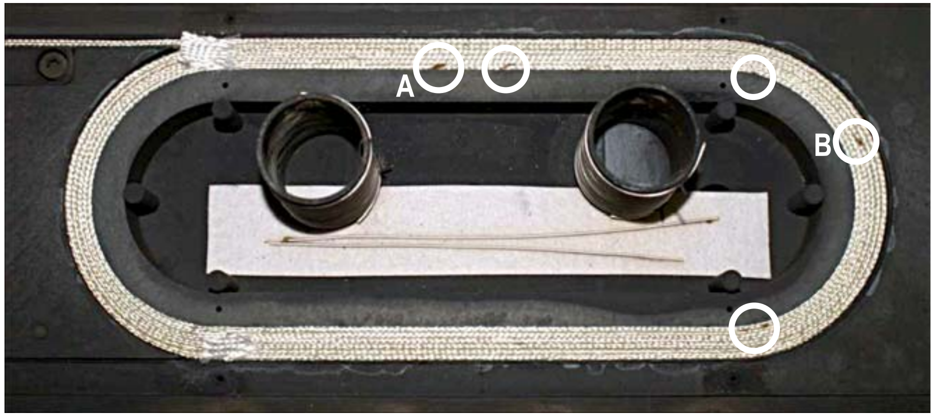
S. Matsumoto et al., Supercond. Sci. Technol. 25 (2012) 025017.

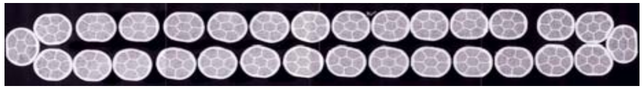




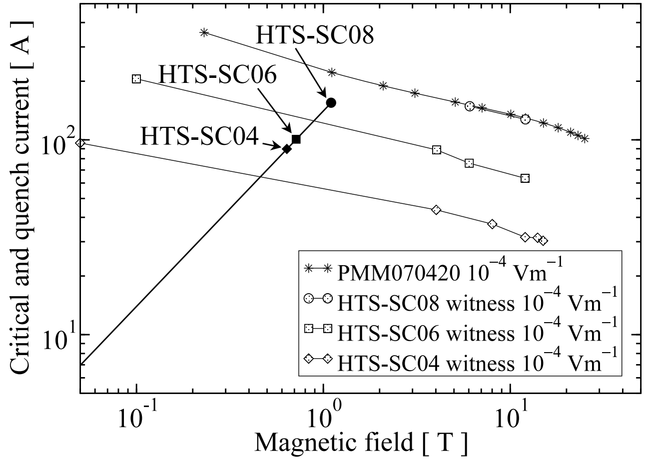


R&D w/ Bi2212 coil by LBNL





A. Godeke et al., Supercond. Sci. Technol., vol. 23, 034022, 2010.

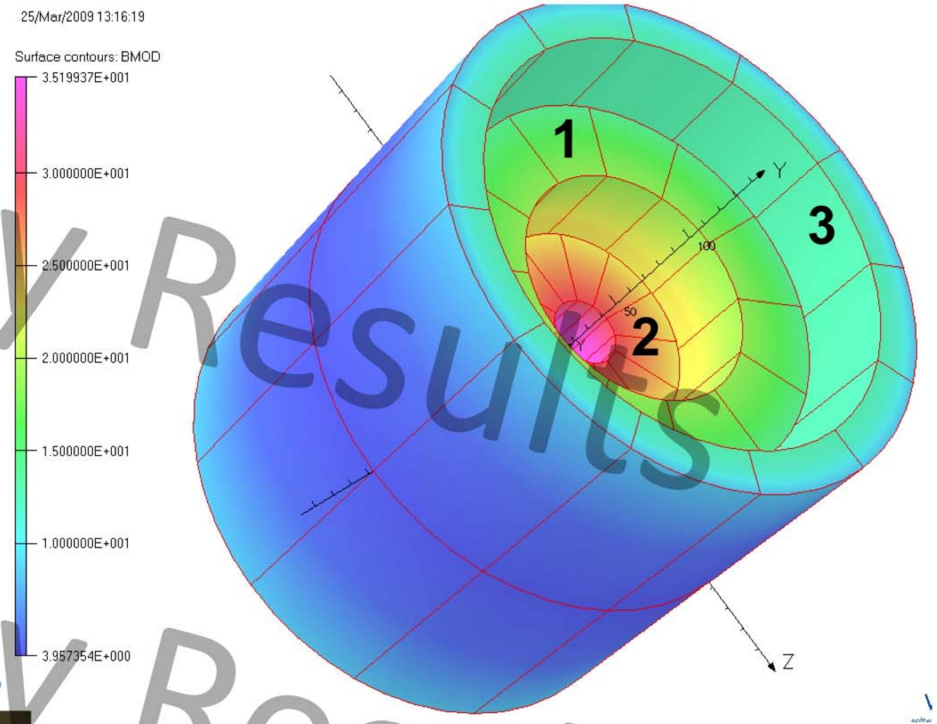


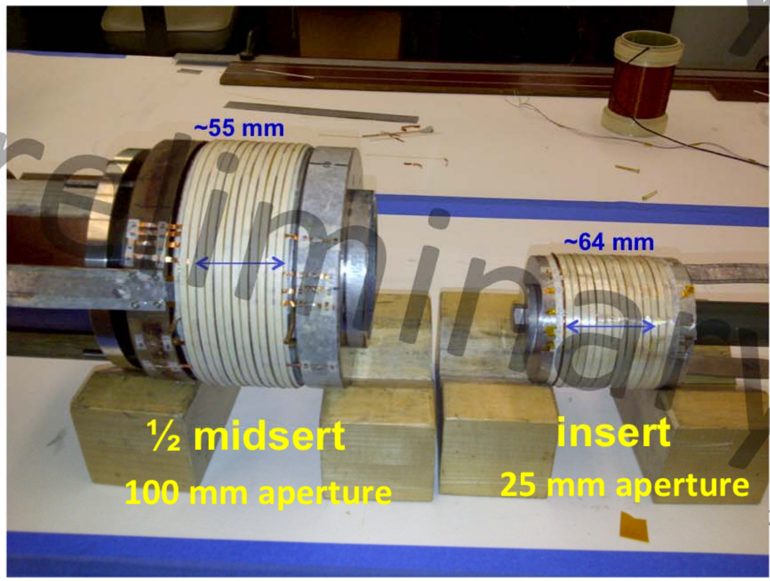
- Start W&R magnet technology early to be ready for material improvements
  - Technology:
    - Rutherford cabling: started at LBNL circa 2000.
    - Insulation: Quartz fiber, Al_2O_3-SiO_2 mullite sleeve.
    - Tooling
- Demonstration of W&R Bi-2212 technology for accelerator magnets.
  - Compatibility studies to suppress leakage;
    - INCONEL600 construction material and Al_2O_3–SiO_2 braided sleeve insulation.
  - Bi-2212 coil performance of ~70% of the witness sample with the marginal leakage
    - potential to carry around 1.7 kA at 15 T.

YBCO coil R&D for MAP by BNL

Courtesy of
R. Gupta (BNL)

- Ionization cooling in Muon Accelerator Program (MAP) needs very high field solenoids (35-40 T).
- Development of a series of YBCO (SuperPower) coils;
  1. 10 T HTS solenoid (midsert)
  2. 12 T HTS solenoid (insert)
  3. 12 T Nb3Sn (outsert)
- **> 20 T solenoid with ALL HTS coils (1&2).**
- **> 35 T solenoid with ALL SC coils (1,2&3).**

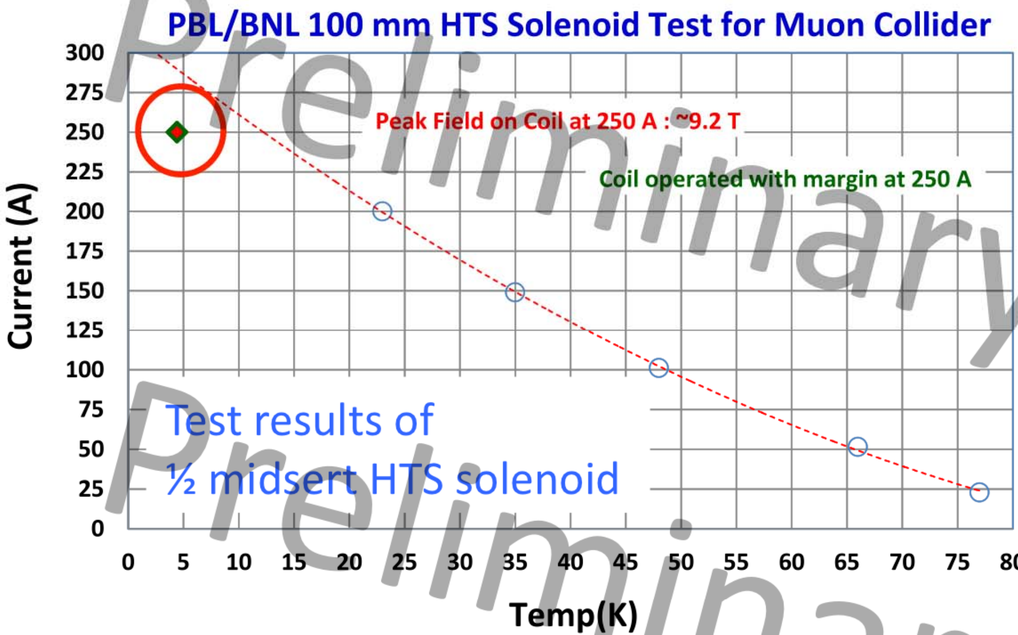


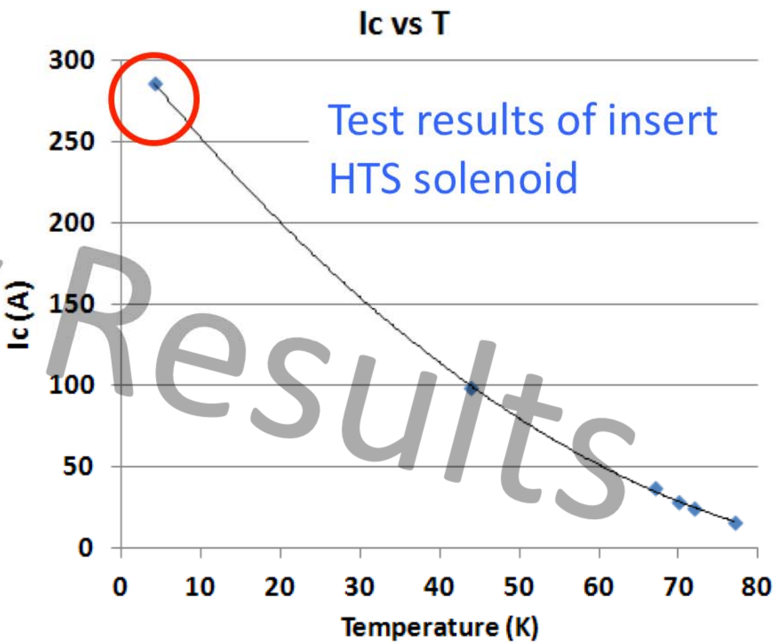


Conductor:
High strength 2G HTS (YBCO) from SuperPower with ~45 μm Copper.

Test results

Courtesy of
R. Gupta (BNL)





- ½ midsert HTS solenoid reached 250 A:
  - **6.4 T on axis, 9.2T on coil.**
  - World first test of large aperture high field 2G HTS magnet, and also one that uses over 1 km (1.2 km) wire.
- Excitation of insert HTS solenoid was stopped at 285 A.
  - **> 15 T on axis, > 16 T on coil. overall J beyond 500 A/mm^2.**
  - 50 % higher than the previous record!!
- Next plan;
  - Testing of full midsert HTS solenoid, and then ALL HTS solenoid (midsert + insert) > 20 T
  - Development of Nb_3Sn outsert and then ALL SC solenoid (out., mid. + insert) > 35 T

R&D of HTS Accelerator Magnet in Japan

***Effort by JST program.**

R&D project of accelerator magnet
using HTS, mainly, coated conductors

Name of project	Research and development of fundamental technologies for accelerator magnets using high T_c superconductors
Objective	•R&D of fundamental technologies for accelerator magnets using HTS •Constructing and testing prototype magnet
Funding program	Strategic Promotion of Innovative Research and Development Program by JST
Project manager	Naoyuki Amemiya (Kyoto University)
Participating institutions	Kyoto University, Toshiba, KEK, NIRS, JAEA
Period	Stage I: 01/2010 – 03/2012 Stage II: 04/2012 – 03/2016 Stage III: 04/2016 – 03/2019

- **Application: Carbon cancer therapy, ADSR**
- **Accelerator: FFAG**
- **B: < 10T**

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Summary

- Significant efforts have been made to develop Nb_3Sn High Field Accelerator Magnets beyond 10 T to overcome many technological issues.
- The LHC upgrade (2018? ~) would be the first case where the Nb_3Sn HFM would be operated in the *"real"* accelerator. To realize this, the following items should be addressed;
  - thorough understanding and control of field quality,
  - reliable quench protection scheme (High Field Magnet = High Energy Magnet),
  - radiation hardness, in particular, for the low-beta quadrupoles.
- HTS has a significant potential to realize HFM beyond 20 T. Nevertheless, substantial R&D is still necessary for both conductor and magnet technology.
  - mechanical robustness,
  - magnetization, AC loss,
  - establishment of quench detection and protection,
  - unit length, cost, etc...