Superconducting accelerator magnets beyond 15 T: design, technology, and performance issues

Alexander V. Zlobin

BNL colloquium

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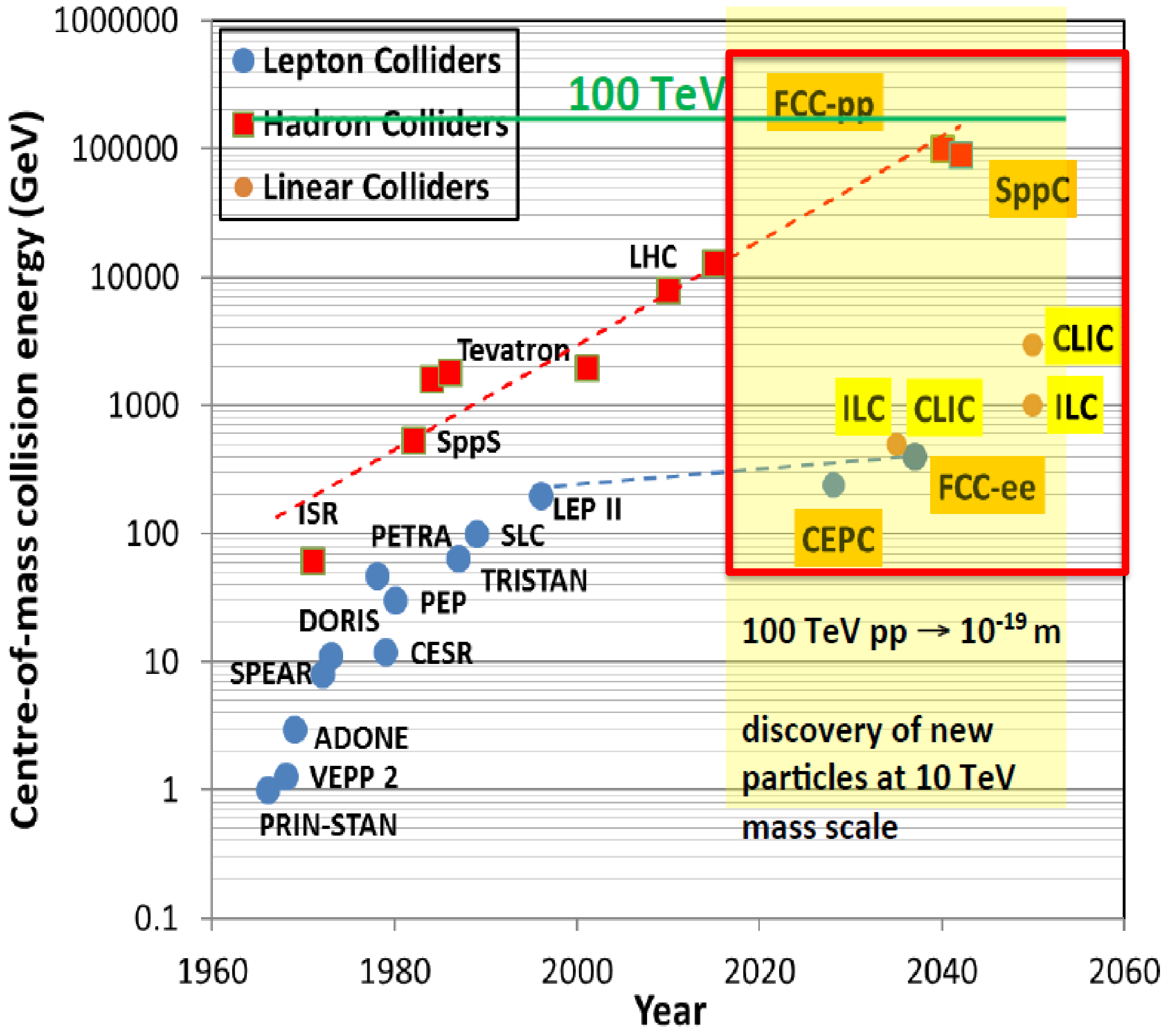
Outline

- HFM needs for post-LHC machines
- Superconducting accelerator magnets up to 15 T
  - Nb-Ti/Nb_3Sn accelerator magnets
  - Nb_3Sn magnets results and open issues
  - Training, degradation, stress management
  - Nb_3Sn wire and cable improvement
- Towards 20 T magnets
  - Hybrid approach
  - HTS inserts
- Summary and conclusions

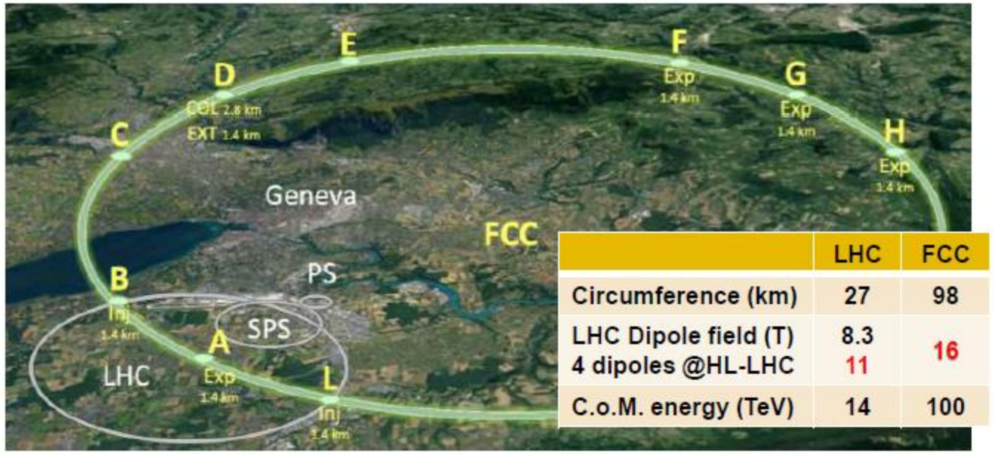
Post-LHC HEP facilities



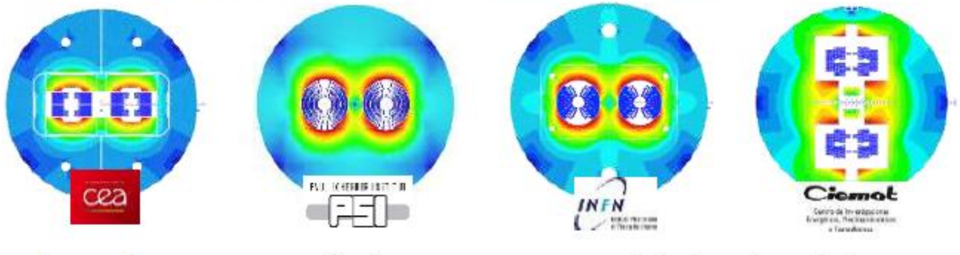
- Historical tendency:
  - Hadron colliders for discovery physics
  - Lepton colliders for precise physics
- New, higher-energy machines are discussed by the international HEP community to explore physics beyond the standard model
  - Snomass'21
- High-field SC magnets are key elements of post-LHC colliders
  - Circular collider energy *E* is limited by the strength of bending dipole magnets *B* and machine radius *R*: $E \sim R \cdot B$
  - For both linear and circular machines, their maximum luminosity is determined by the strength of final focus quadrupoles.

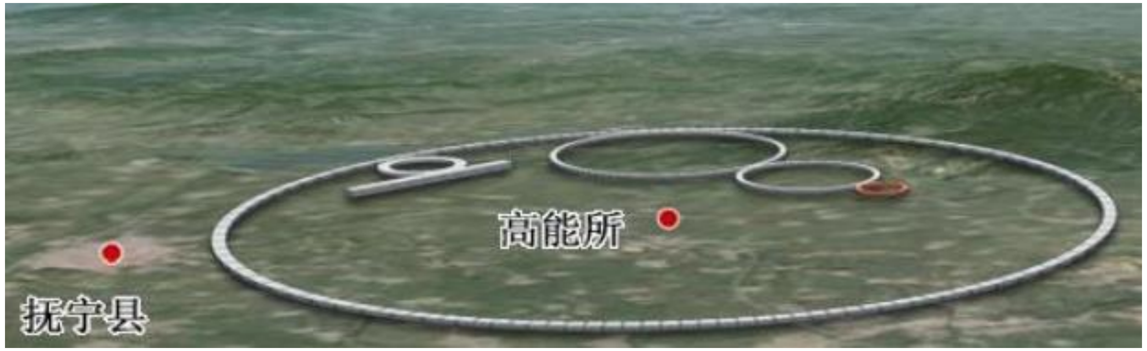
High-field SC magnets in post-LHC colliders

- **FCC:**
  - FCC in Europe, 100 TeV
  - 50-mm aperture, 16 T Nb_3Sn dipoles
  - various designs

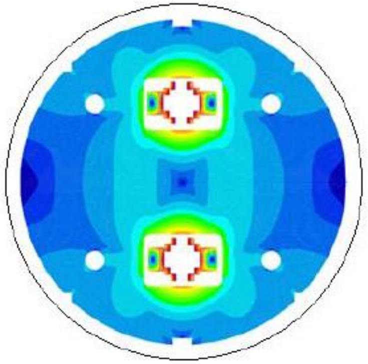


	LHC	FCC
Circumference (km)	27	98
LHC Dipole field (T) 4 dipoles @HL-LHC	8.3 11	16
C.o.M. energy (TeV)	14	100

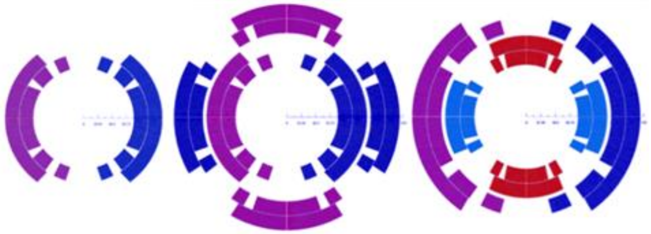




- **SppC:**
  - SppC in China, 75-150 TeV
  - 40-50 mm aperture
  - B=12 (24) T dipoles
  - common coil design
  - IBS - baseline
  - Nb_3Sn/REBCO – backup



- **Muon Collider (MAP):**
  - 150-200 mm aperture
  - Nb_3Sn coils at 4.5 K
  - B_{op}~8-9 T and G_{op}~80 T/m with ~20%
  - B_{max}~17 T – practical Nb_3Sn technology limit



Superconductivity in accelerator magnets

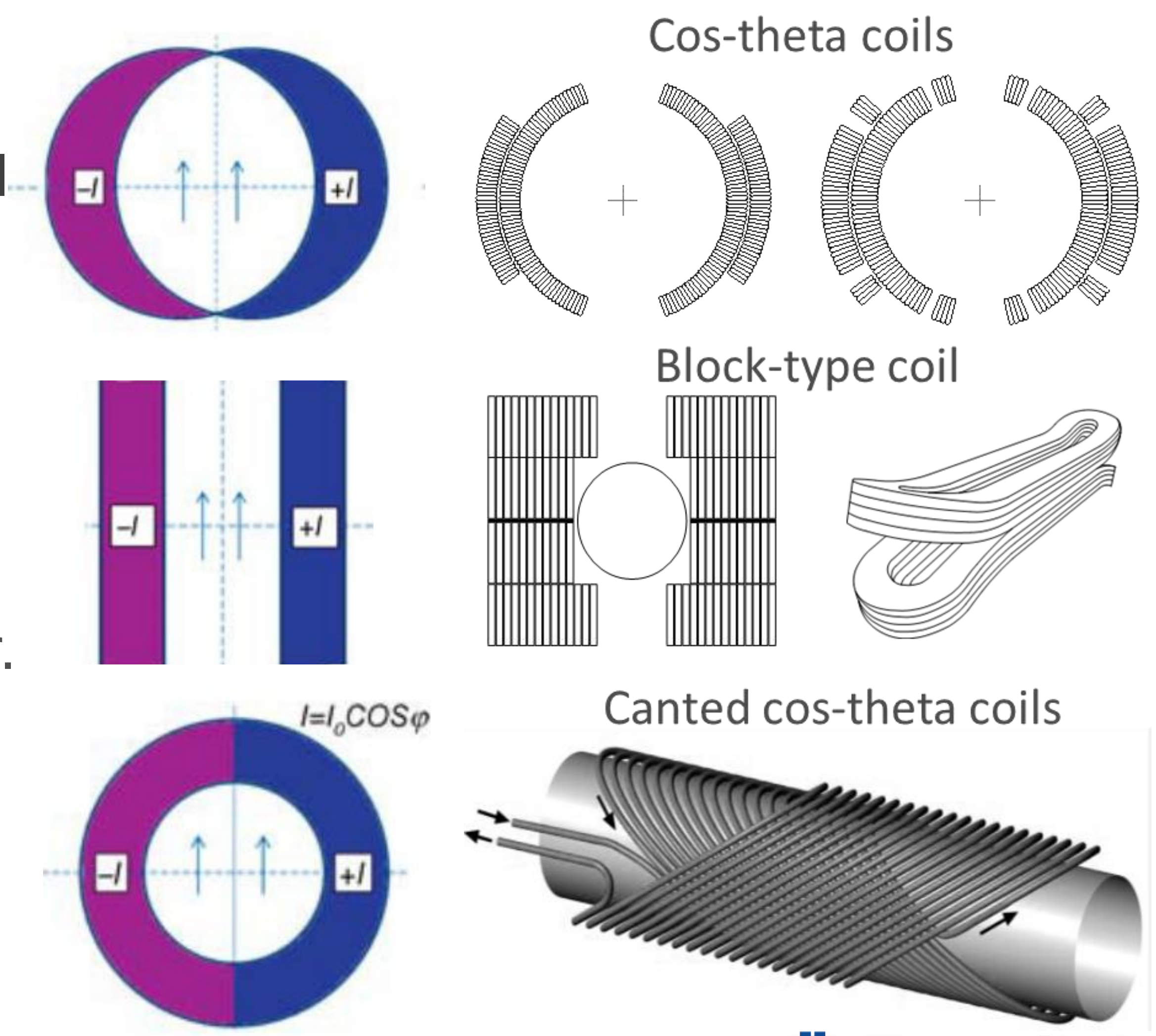
- Magnetic fields of various configurations are generated by electrical currents.
- Dipole field B_D and field gradient G_Q are proportional to current density J_e in coil and coil width w

$$B_D = -\frac{\sqrt{3}\mu_0}{\pi} J_e w$$

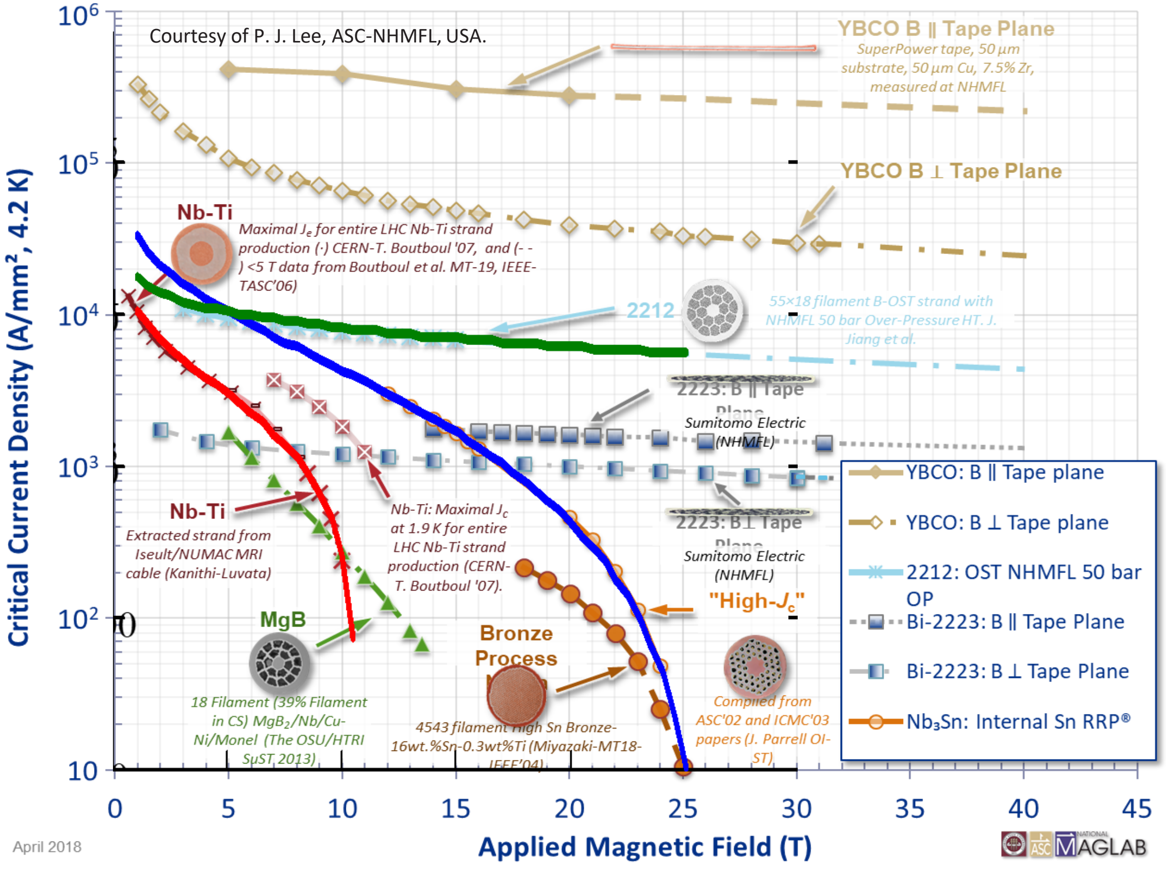
$$G_Q = -\frac{\sqrt{3}\mu_0}{\pi} J_e \ln\left(1 + \frac{w}{r}\right)$$

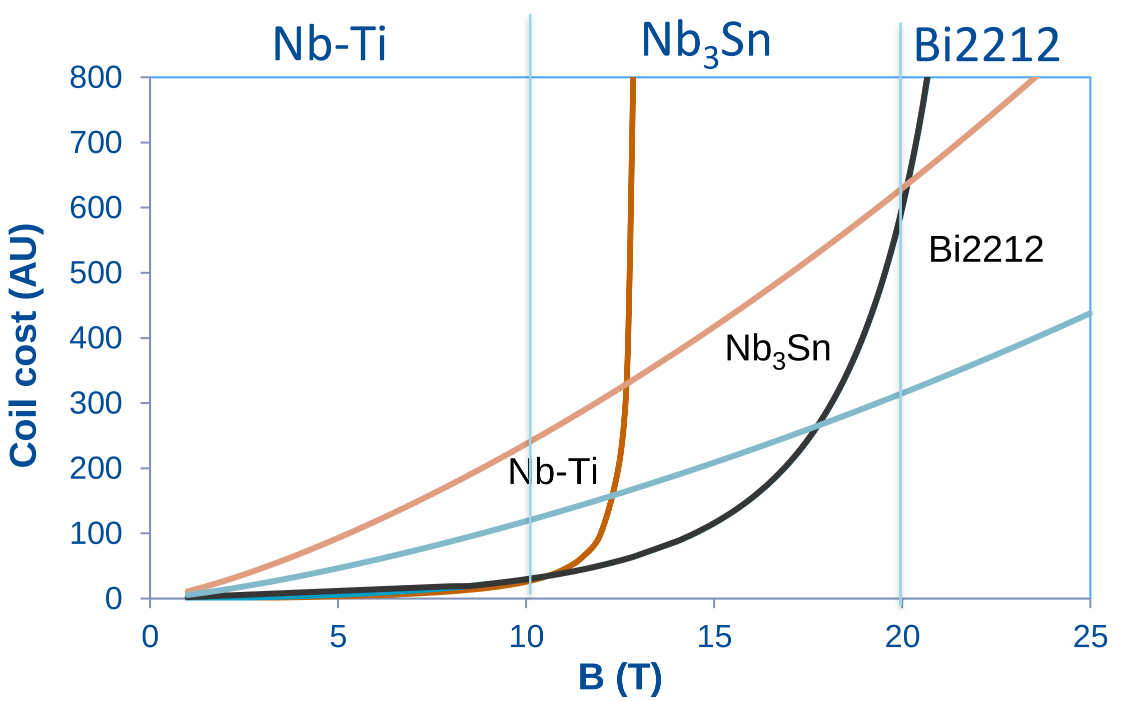
- The current density in coil J_e is a key parameter.
- Due to higher current density, SC magnets are stronger and more compact and, thus, provide better machine performance parameters and lower operation costs.

Dipole field configuration.



Practical superconductors and magnet optimal field ranges

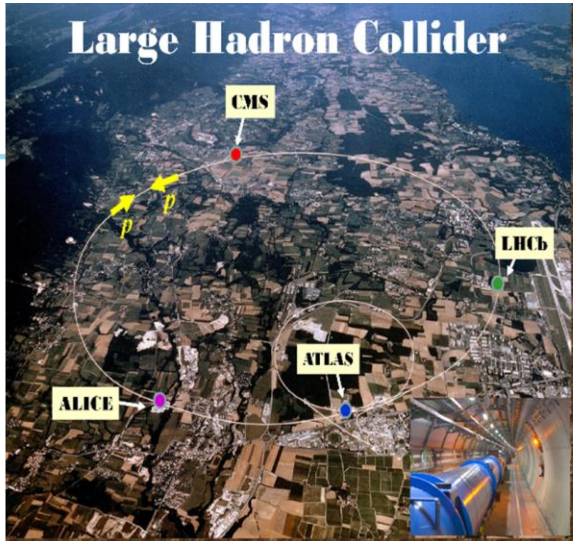




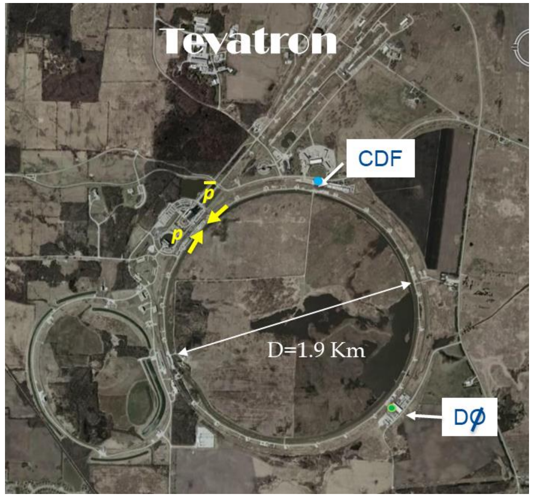
Practical SC materials for SC magnets include *appropriate critical parameters, their reproducibility in long lengths, mass production and affordable cost*.

Boundaries are not fixed, they depend on superconductor and magnet technology costs.

Nb-Ti accelerator magnets



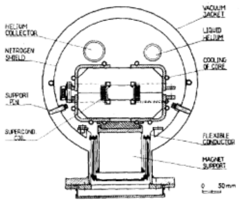
- All the present circular machines use Nb-Ti magnets.
  - operation field range from 2 T (Nuklotron) to 8.3 T (LHC)
  - operation temperatures 1.9-4.5 K
- Generic R&D
  - cable, structure, field quality, quench protection, technology
- Large production experience
  - Laboratory (Tevatron, Nuklotron)
  - Industry (HERA, RHIC, LHC)
- Reliable long-term operation in real machines



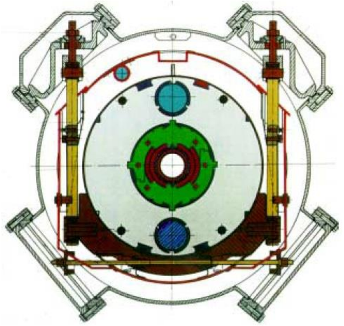
Technology R&D

Tevatron, B=4.5 T, 6 m, 76 mm

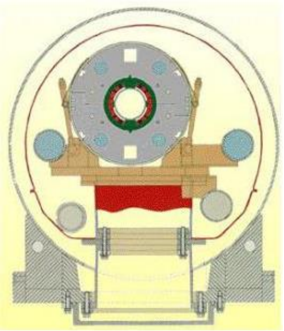
Nuklotron, B=2 T, 1.5 m, 90x42 mm^2



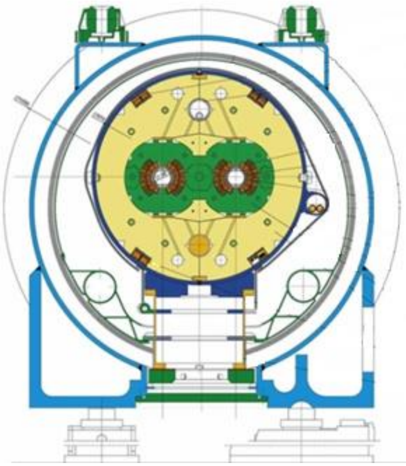
HERA, B=4.7 T,9 m, 75 mm



RHIC, B=3.5 T, 9 m, 80 mm



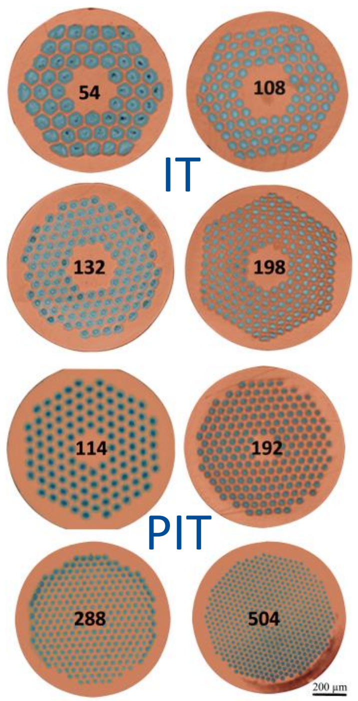
LHC, B=8.3 T, 15 m, 56 mm

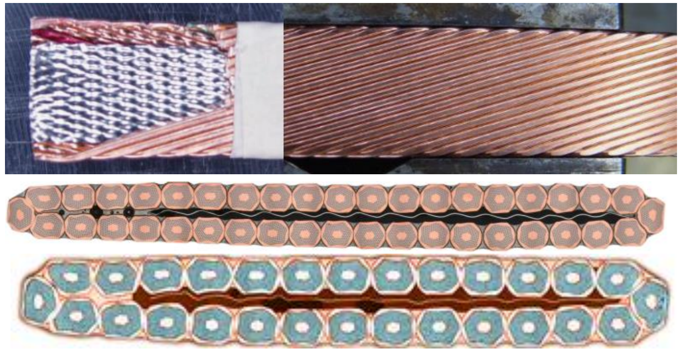


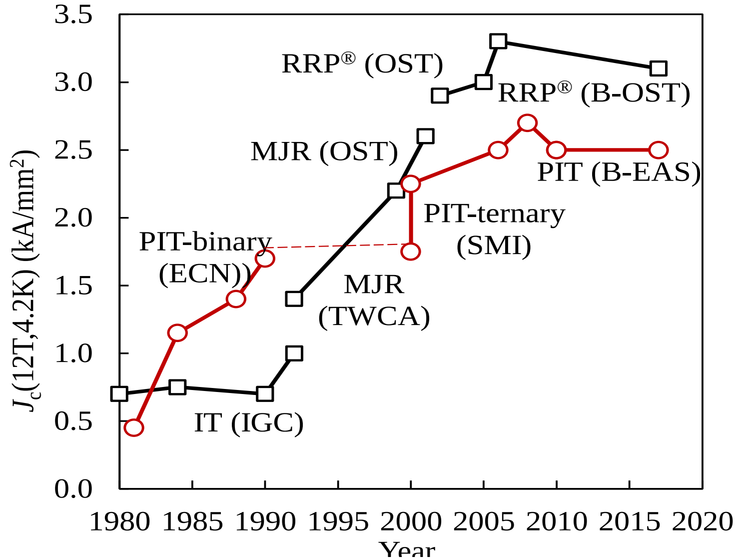
1960s → 1970s → 1980s → 1990s → 2000s

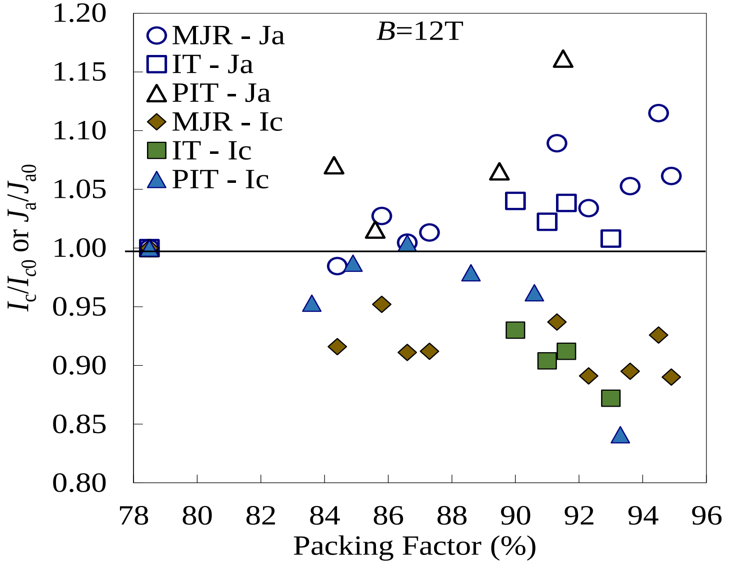
Beyond Nb-Ti magnet technology: Nb_3Sn wires and cables

- Nb_3Sn composite wire
  - Bronze, IT and PIT
  - Cu matrix, RRR~250
  - OD=0.5-1.0 mm
  - D_{eff}~23-85 mcm
  - SC after HT reaction, brittle, flux jumps, large M
- Rutherford cable
  - N<60, PF~85-87%
  - SS core
  - I_c degradation <5%
  - I_c sensitivity to P_{tr}



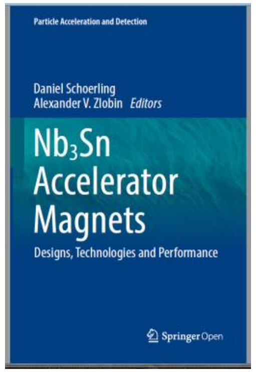


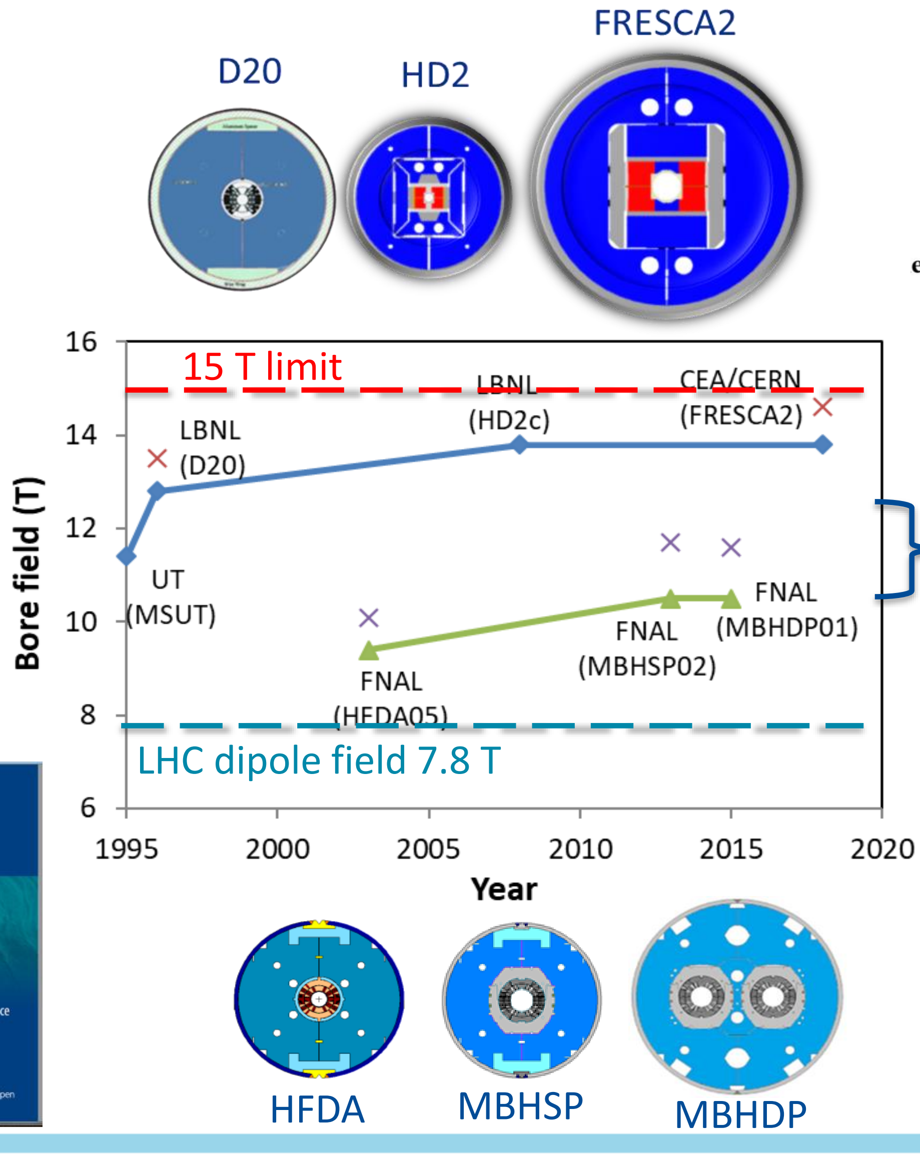




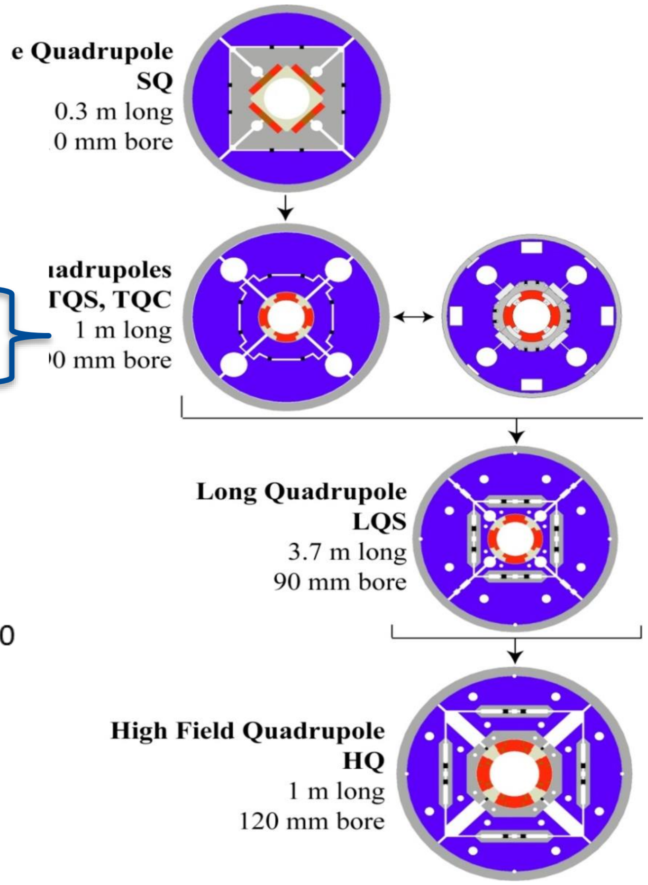
Nb_3Sn accelerator magnet R&D

- Nb_3Sn magnet R&D since 1960s
- Most serious progress since 1990
  - Nb_3Sn magnet performance exceeded Nb-Ti magnets
- Nb_3Sn magnet R&D summary
  - W&R and R&W technologies
  - Cos-theta & block coils
  - Various mechanical structures
  - **High fields up to 14.5 T**
  - Accelerator field quality
  - Reliable quench protection
  - Performance reproducibility
  - Technology scale up





US-LARP
BNL, FNAL, LBNL
(2005-2015)



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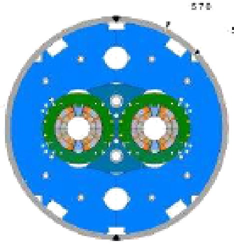
Nb_3Sn technology in the LHC (HL-LHC)

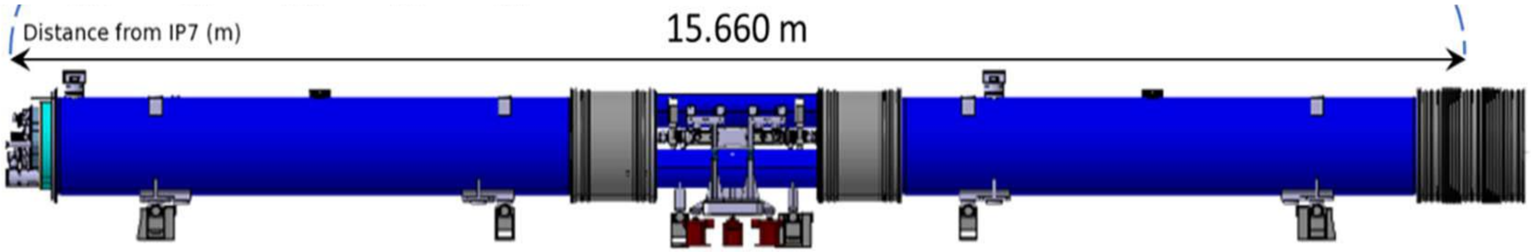
- LS1? –11 T dipole assembly near IP7
  - total length of Nb_3Sn magnets ~40 m

6 Arc dipole magnets

6.752 m length, 11.23 T bore field,

11.8 T peak at 11.85 kA





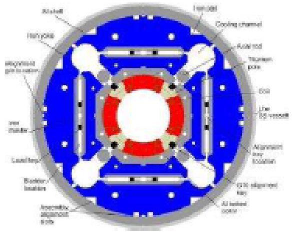
- LS2 – 4 triplets around IP1 (ATLAS) and IP5 (CMS)
  - total length of Nb_3Sn magnets ~150 m

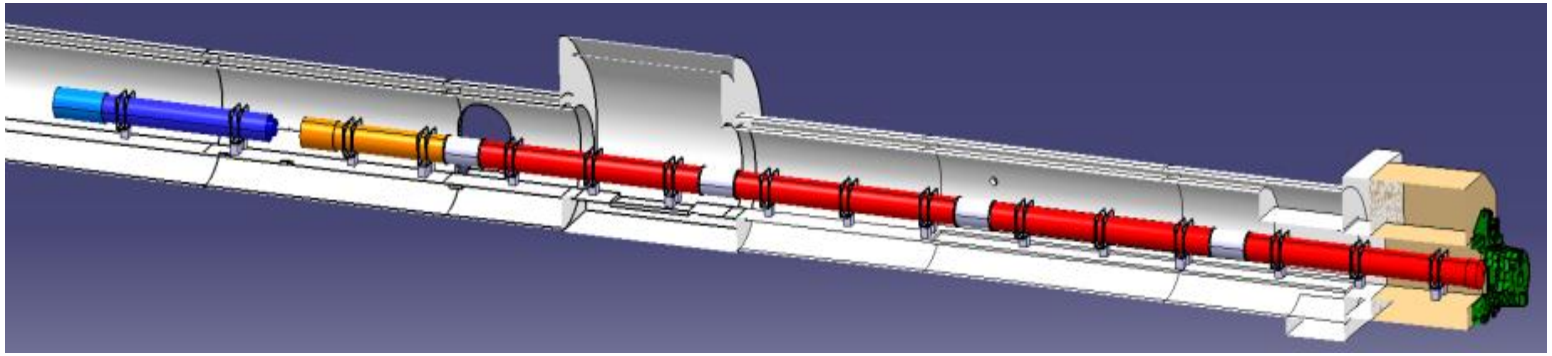
10 IR quadrupole magnets

7.15 m length, 132.6 T/m gradient

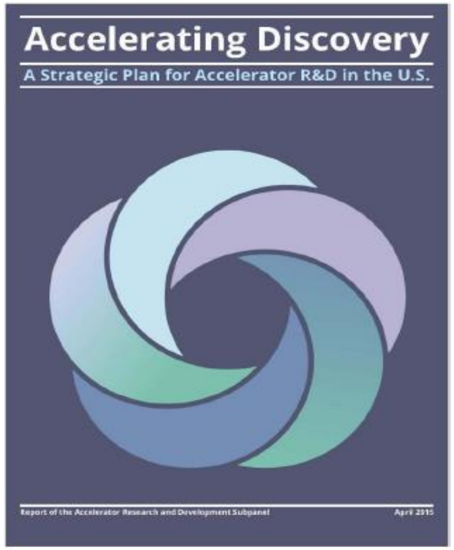
11.4 T peak at 16.47 kA

20 IR quad magnets, 4.2 m length, produced in the US

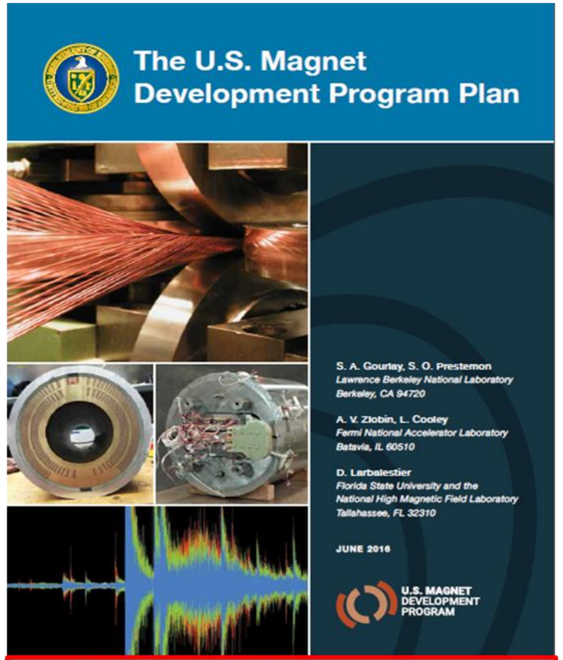




Towards 15 T dipole field



- In 2015 Fermilab in response to recommendations of the Particle Physics Project Prioritization Panel (P5) and HEPAP Accelerator R&D subpanel has initiated a program *to demonstrate the 15 T field in a Nb_3Sn accelerator dipole*
- In 2016, US-DOE Office of High Energy Physics created the national Magnet Development Program (MDP) to integrate accelerator magnet R&D in the U.S. and coordinate it with the international effort
  - the project became a key task of the USMDP
- In 2017 this effort received support also by the EuroCirCol program, making it a truly international endeavor.



BERKELEY LAB Fermilab NATIONAL MAGLAB ASC

EuroCirCol
A key to New Physics

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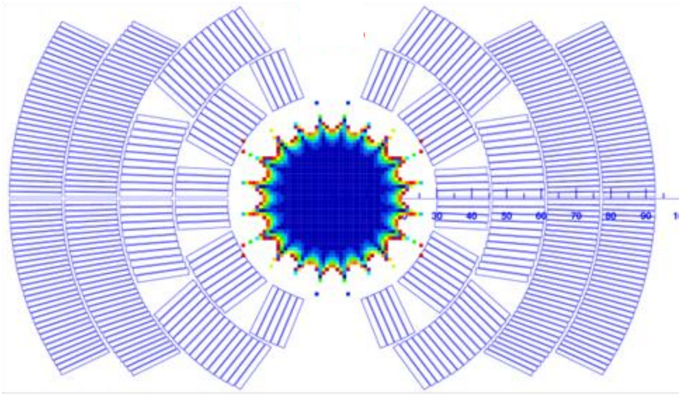
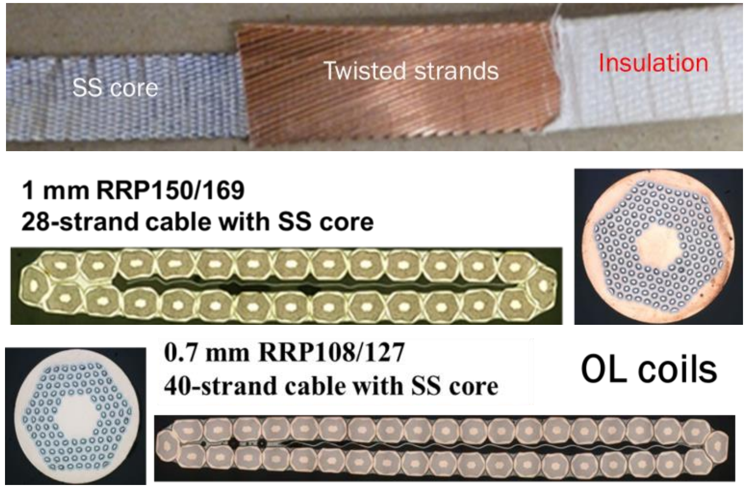
15 T Dipole Demonstrator (MDPCT)

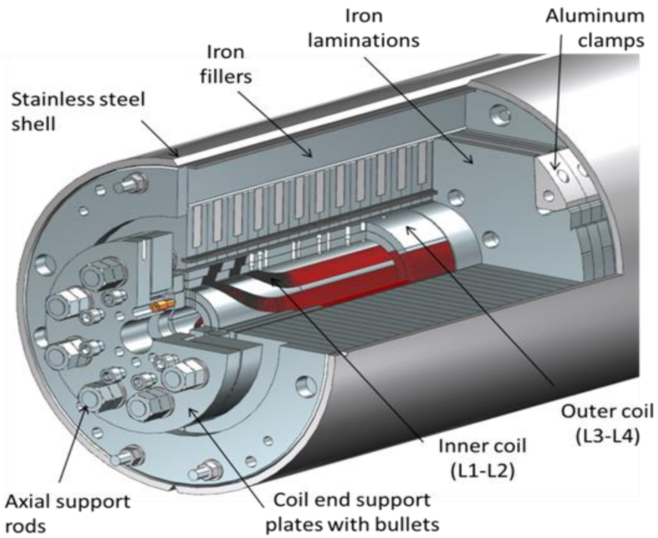
Optimized 60-mm graded coil:

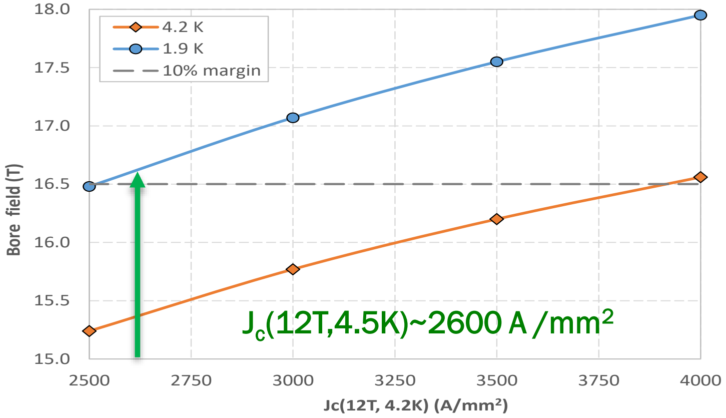


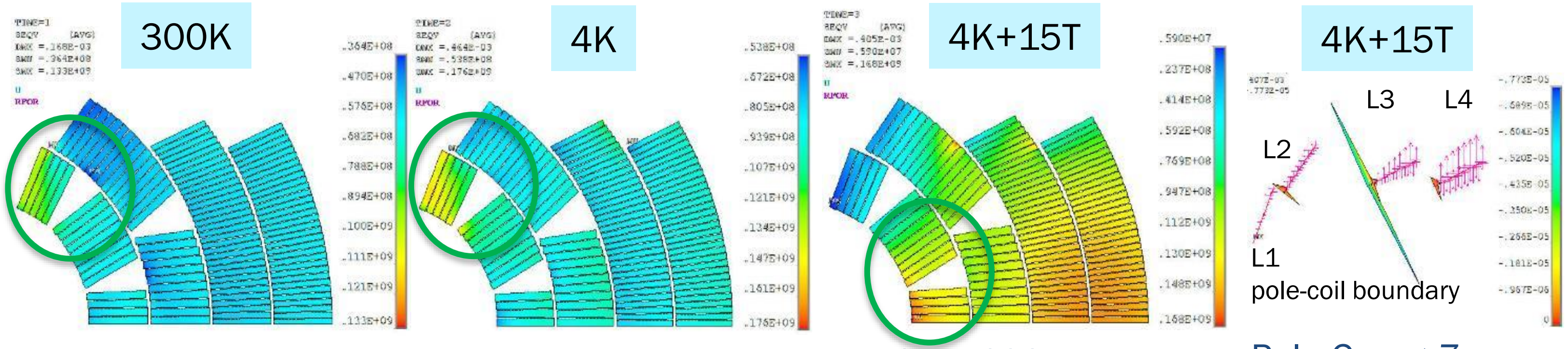
Nb_3Sn strands and cables:



Innovative mechanical structure:







S_{eqv}=133 MPa S_{eqv}=176 MPa S_{eqv}=168 MPa Pole Gap < 7 μm

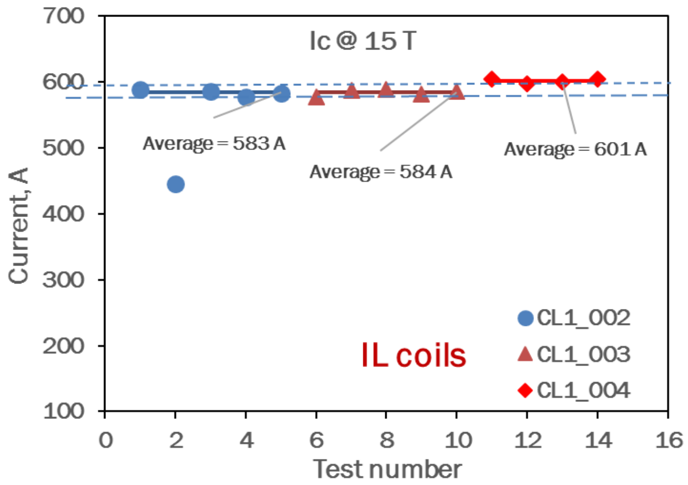
Conductor limit: B_{ap}=15.3(16.7)T @ 4.5(1.9)K

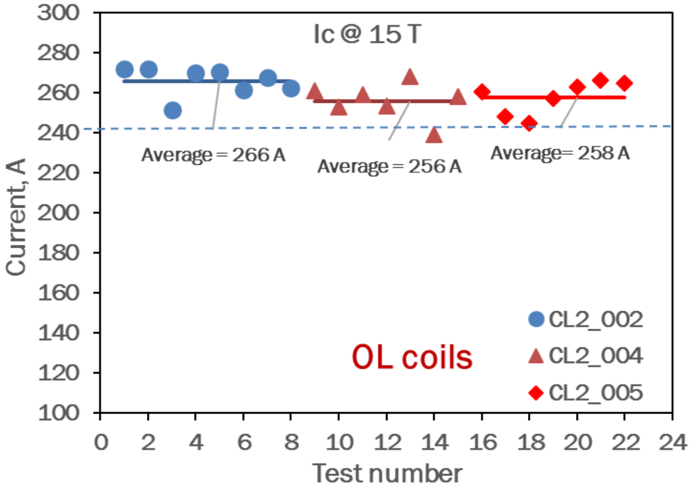
Mechanical limit: B_{ap}~15T S_{eqv}<180MPa

Coil fabrication and parameter control

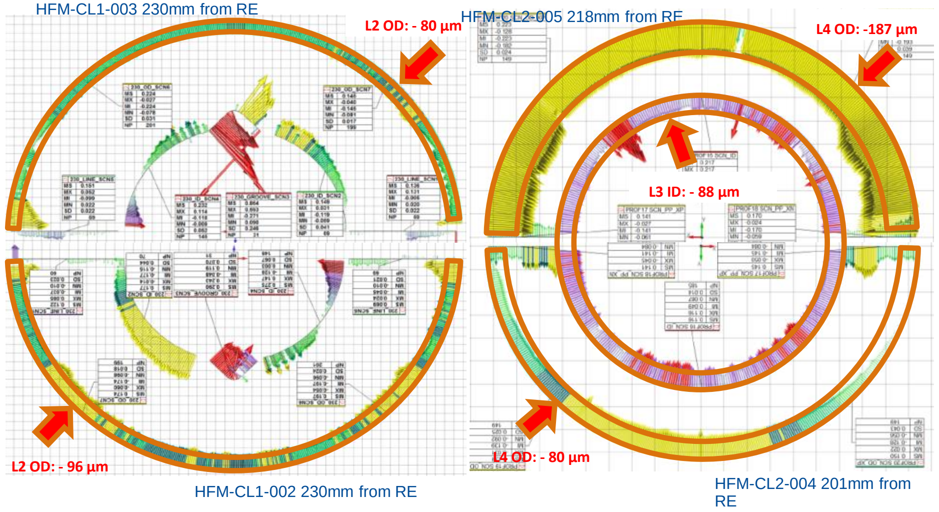
Coil fabrication steps

Witness sample test





Coil size control



- *Inner and outer coils are not glued*
- *L2-L3 interface accurately matched*

- Witness sample data are close to target I_c
- Good data reproducibility

Short sample limit*:15.2 T at 4.5 K and 16.8 T at 1.9 K*

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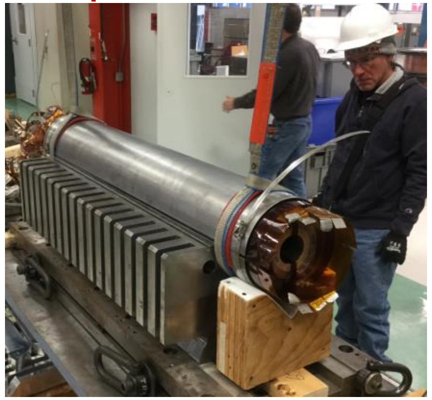
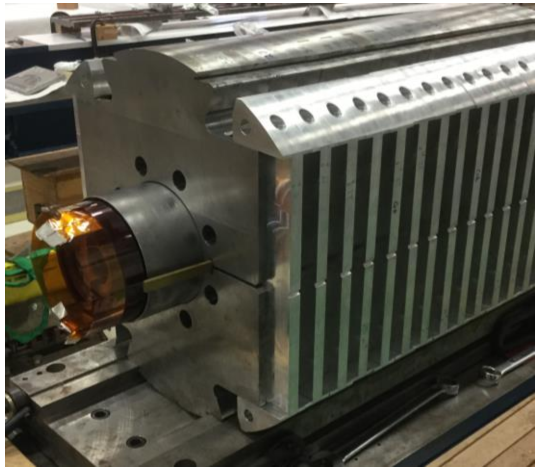
Magnet assembly and 1st test (June 2019)

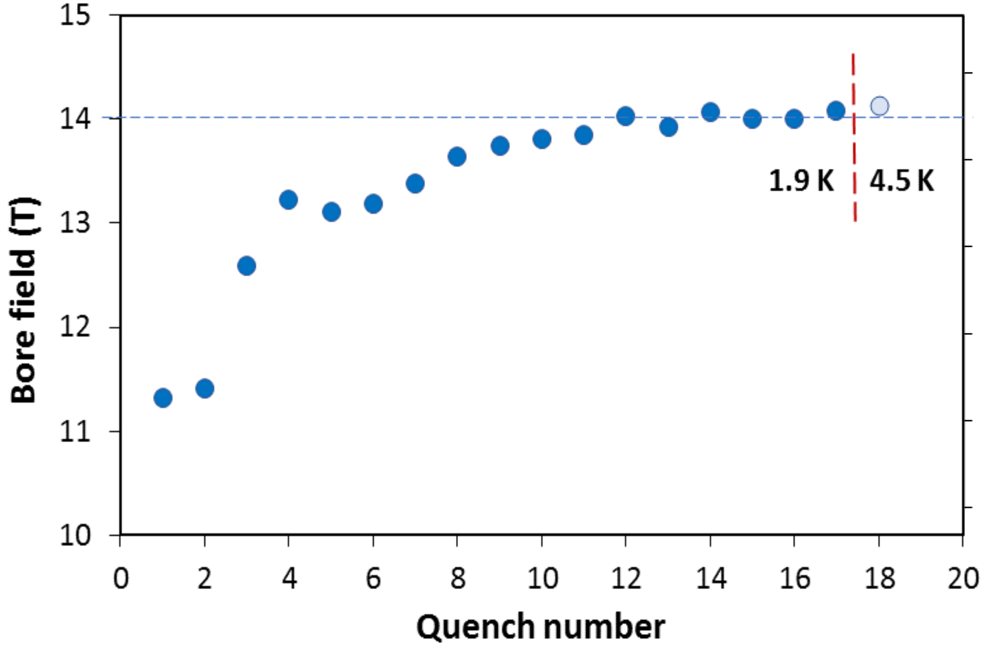
Magnet assembly

Conservative coil pre-stress, σ_{max} at all steps <150 MPa, sufficient to achieve 14 T





Magnet training at 1.9 K



- 11 quenches to plateau
- IL: 2 in coil 2
- OL: 8 in coil 4 and 7 in coil 5

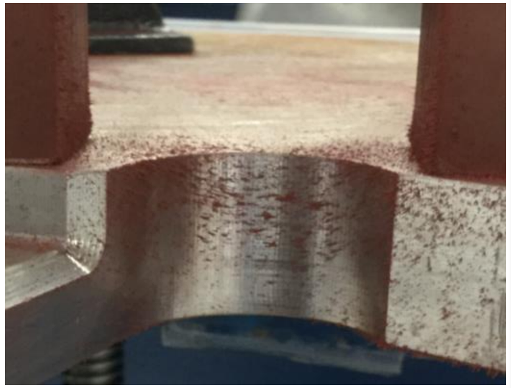
Last quench at 4.5 K:

B_{meas} = 14.13±0.02 T, B_{calc} = 14.112 T

MDPCT1 disassembly, inspection, modifications and reassembly

Al clamp test with die penetration technique

Iron lamination test with magnetic powder



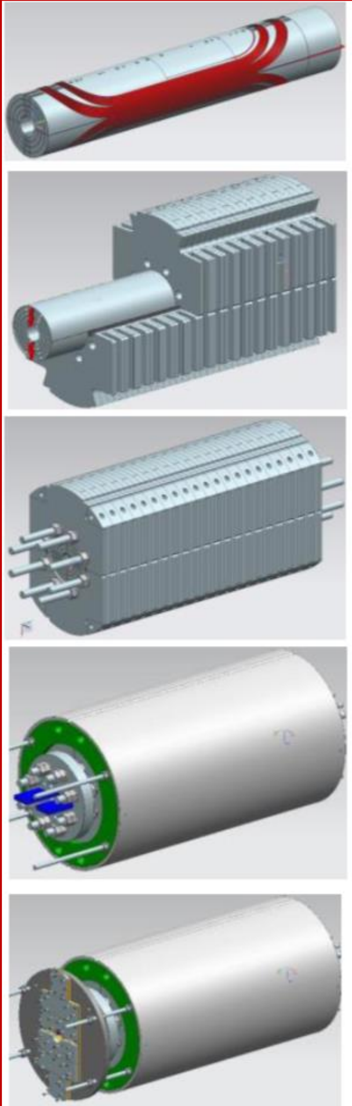
Coil inspection:

L1/L2:

- no coil/pole separation in straight section and ends

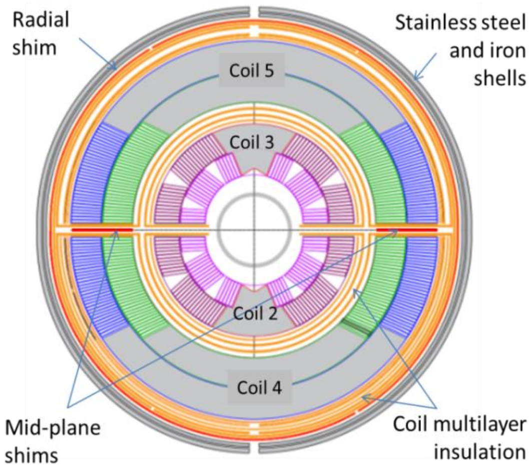
L3/L4:

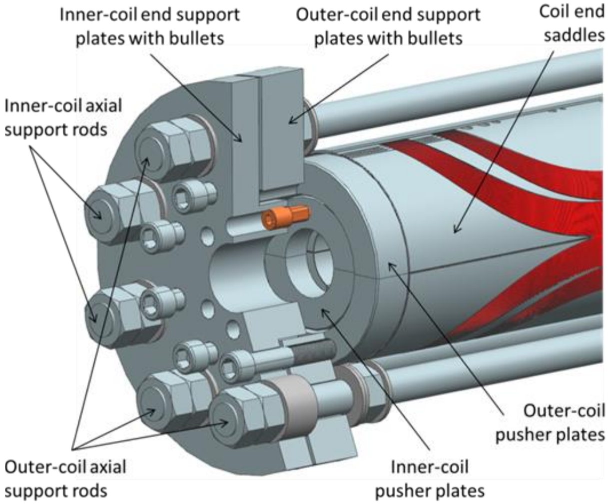
- lost SG and VTs
- coil/pole separation in ends



Improvements:

- Outer coil VTs repaired
- The coil azimuthal pre-load increased by ~20 MPa to achieve the test goal of 15 T
- The end plates modified to improve the coil axial support
- Separate 50-mm and 32-mm end plates for IL and OL coils





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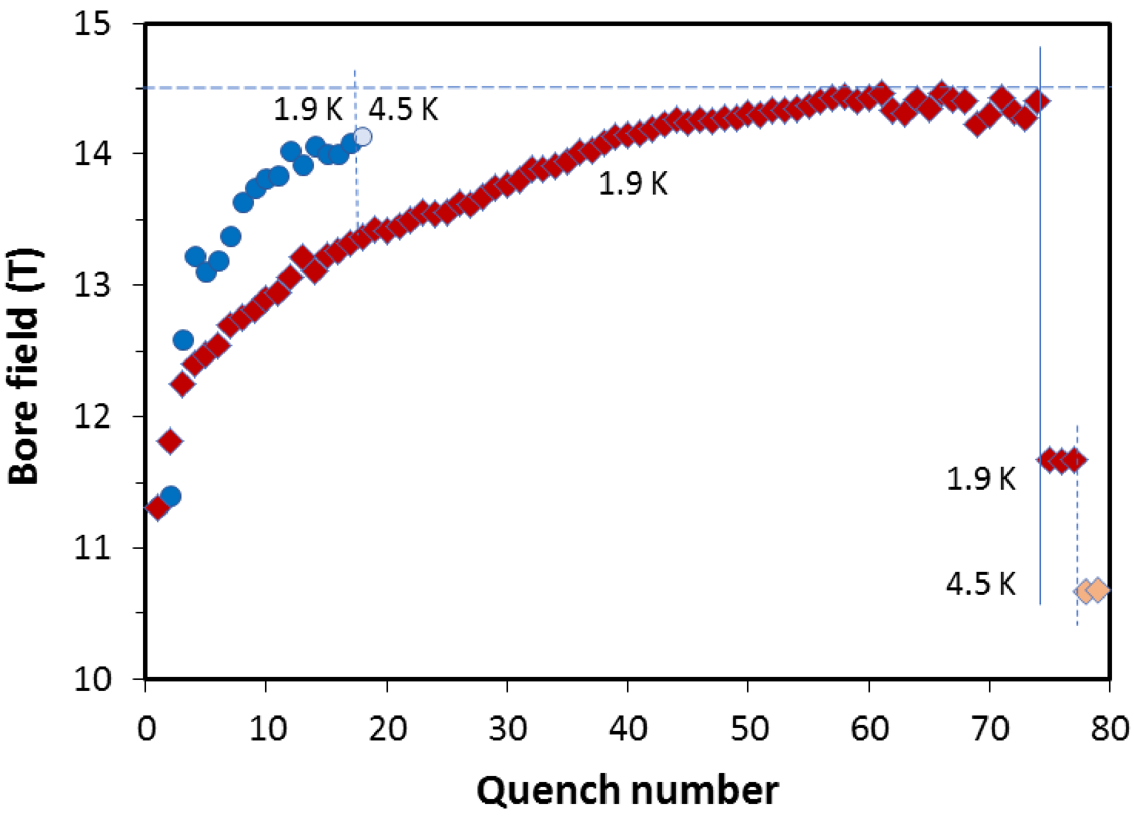
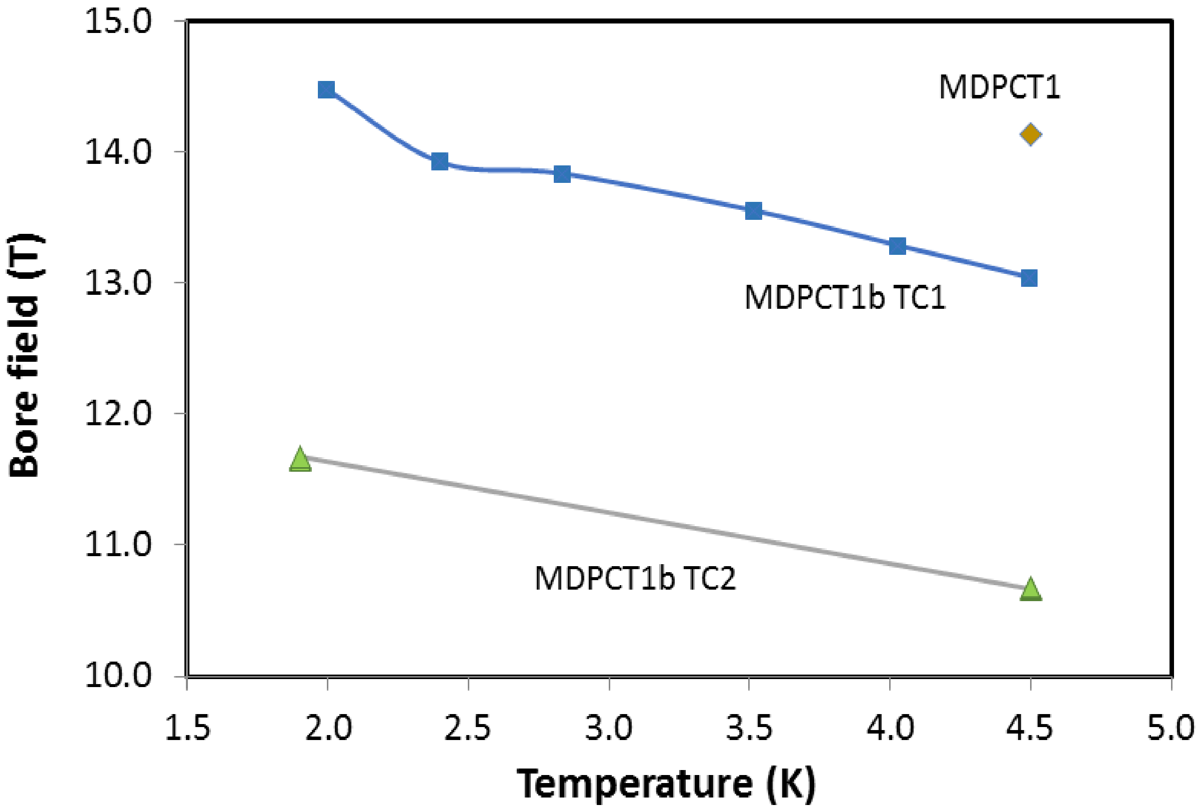
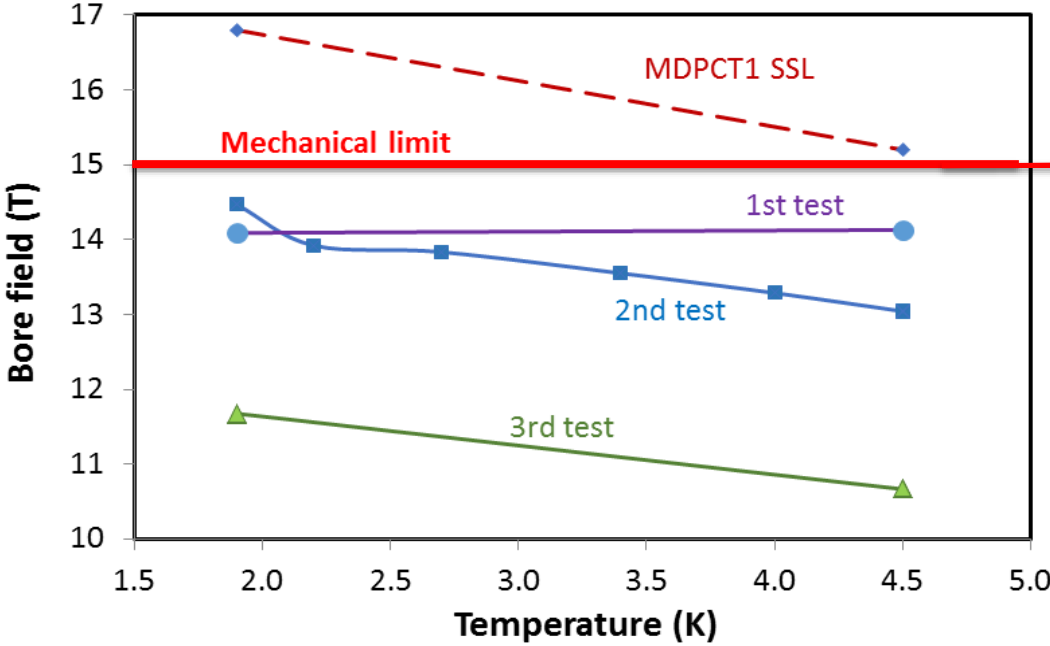
MDPCT1b Quench Performance in TC1 and TC2

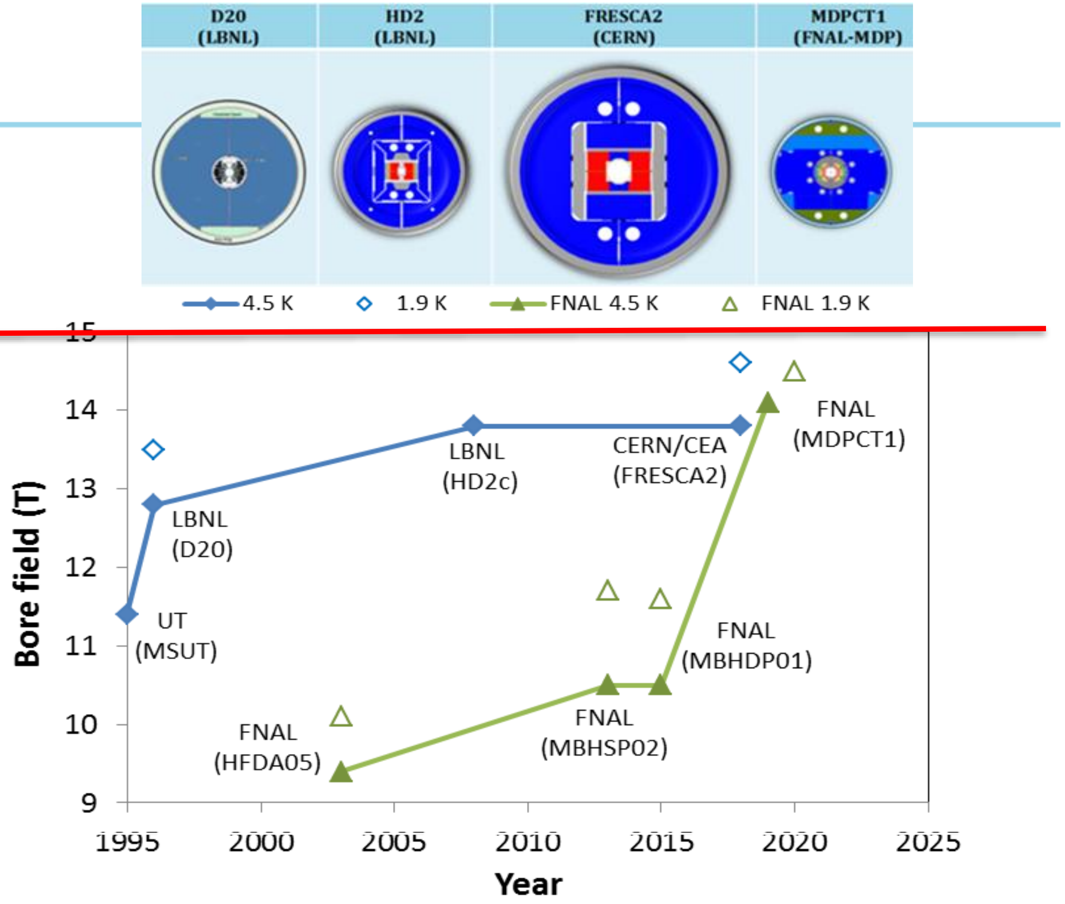




- *MDPCT1b reached its conductor limit at both temperatures*
- *Performance degradation wrt 1st and 2nd tests*

MDPCT program summary





The goals of MDPCT1 program achieved

- graded 4-layer coil, innovative support structure, magnet technologies developed
- magnet performance parameters tested
- B_{max}=14.5 T @1.9 K is 97% of the program goal

The field levels achieved in MDPCT1 at 4.5 K and 1.9 K (with FRESCA2 result at 1.9 K) set *new world records for Nb_3Sn accelerator magnets.*

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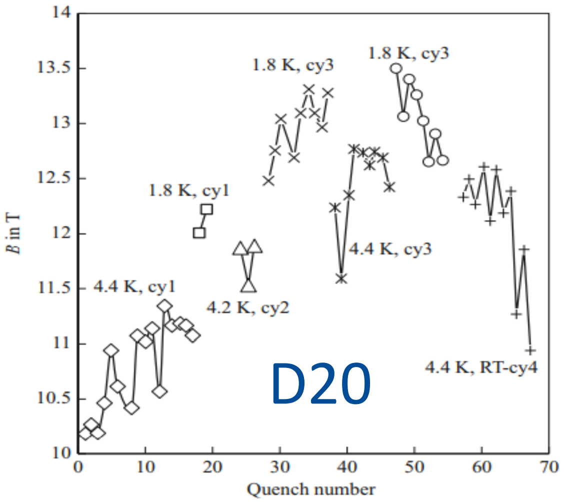
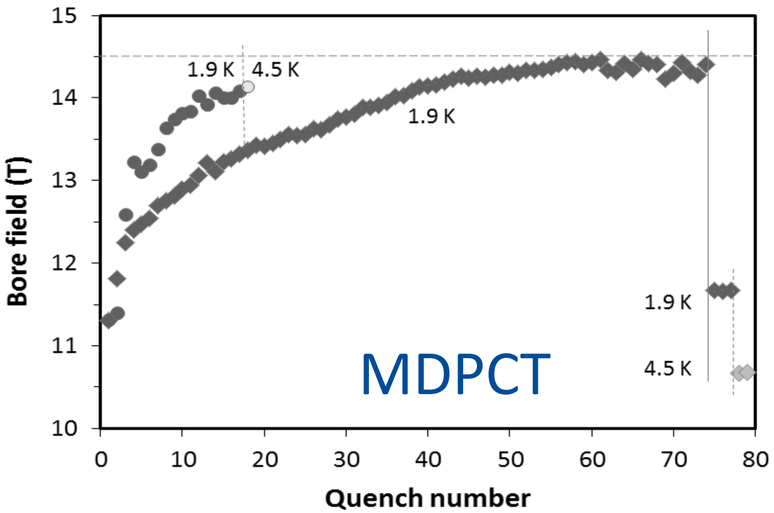
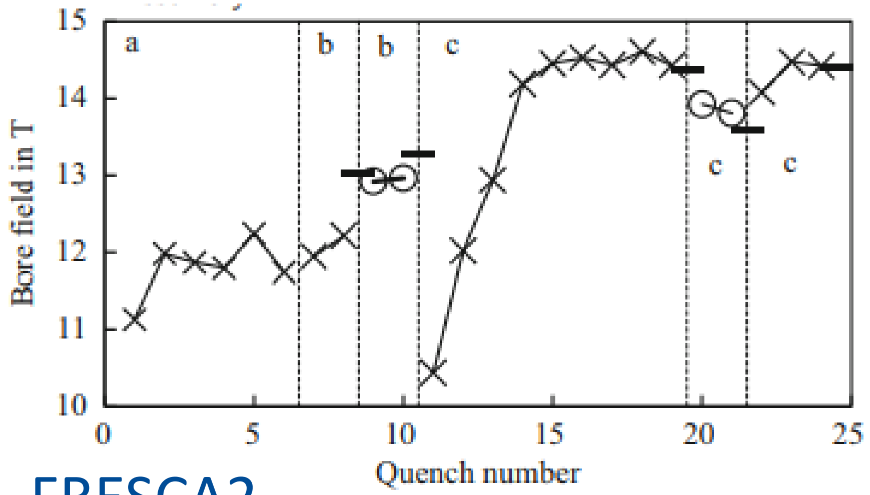
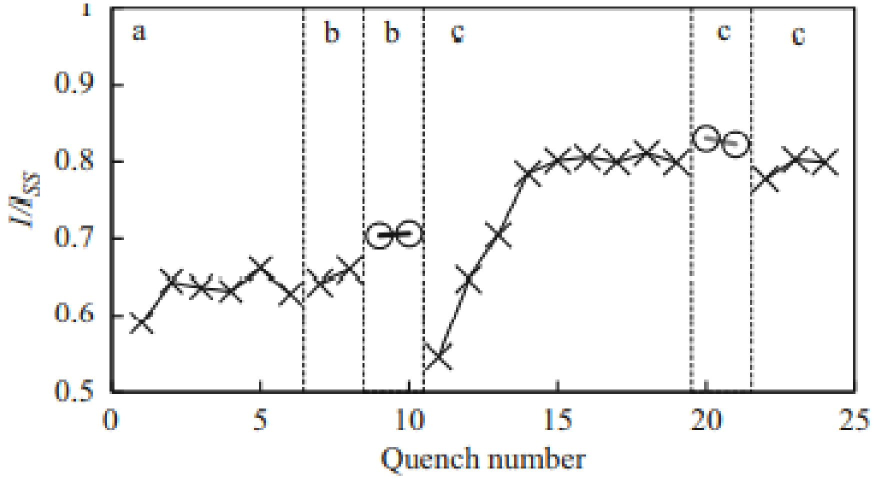
Nb_3Sn magnet training and degradation

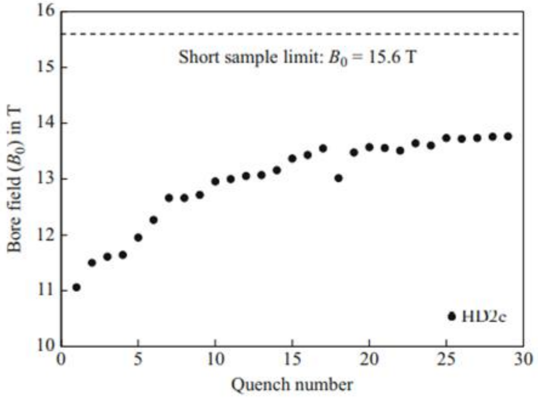




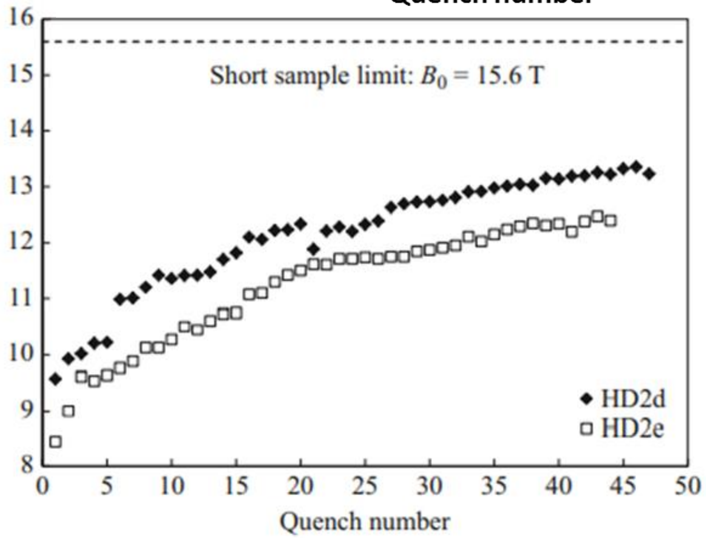


FRESCA2





HD2



Long training and de-training, large degradation => *stress management for both body and ends*

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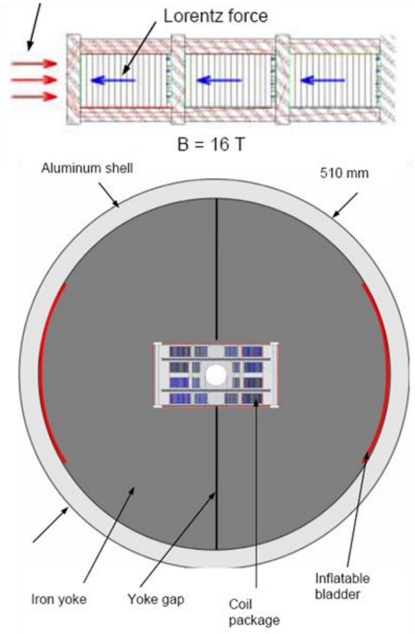
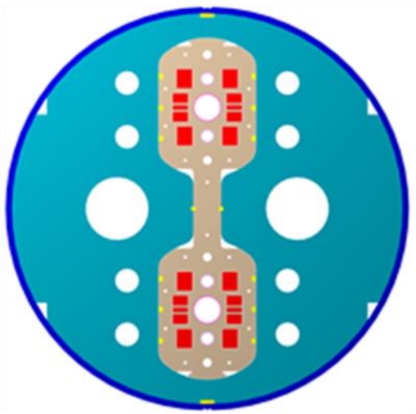
Stress management concepts

- Each coil block or individual turn is placed in its own compartment and supported separately
- Lorentz force on multiple coil blocks does not accumulate, but it is transmitted to the magnet frame by the ribs to plates
- Stress management can avoid or limit I_c degradation - reduces coil packing factor

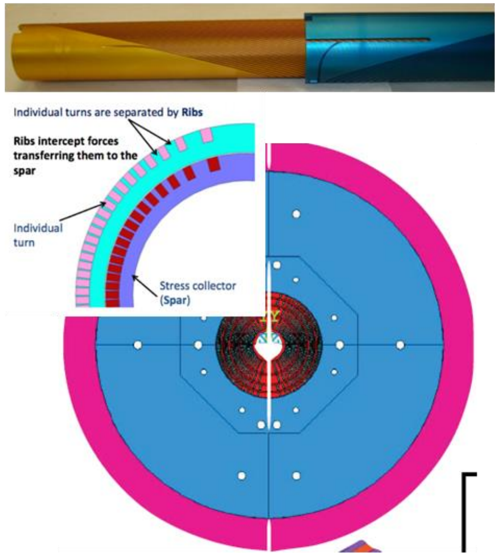
TAMU (Texas A&M)



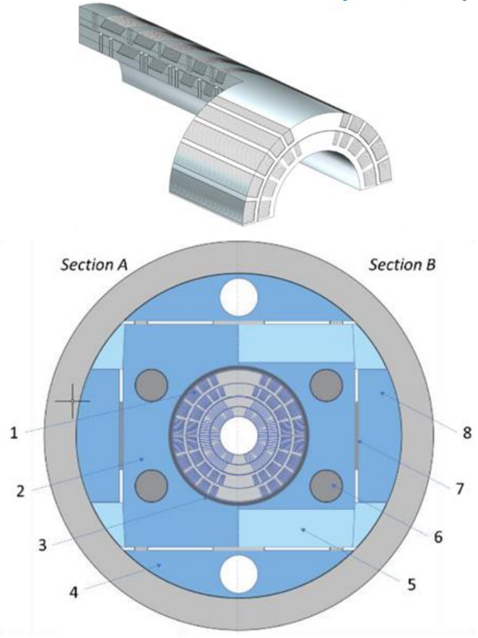
HFDC (R&W)
40 mm 10 T dipole



Canted Cos Theta (LBNL)



Cos Theta SM(FNAL)



CCT coil to solve training/degradation (LBNL)

Two-layer CCT coil

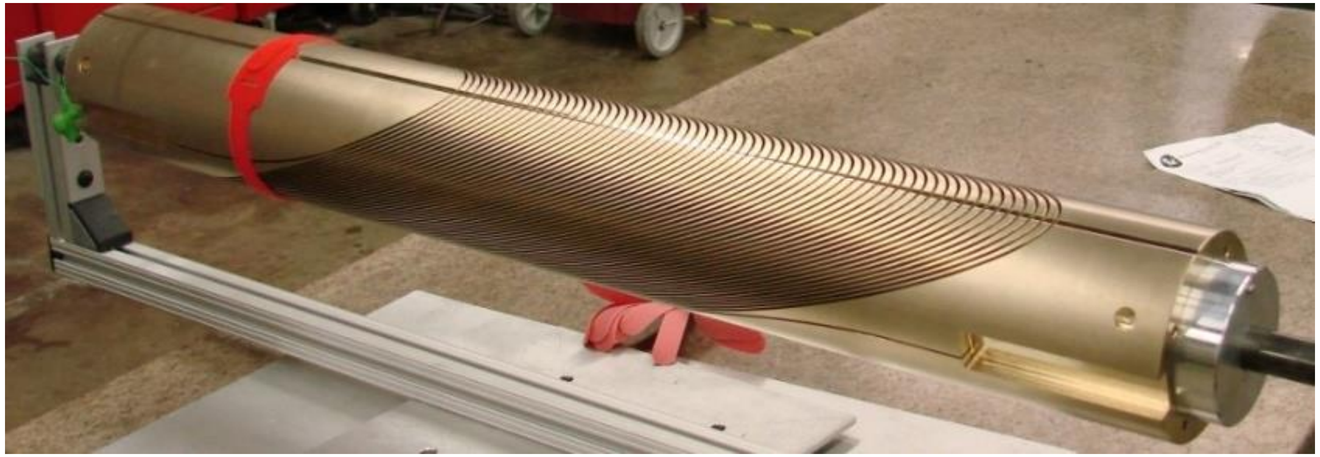
- 90-mm aperture CCT models, 10 T
- 50-mm aperture subscale models, ~6 T

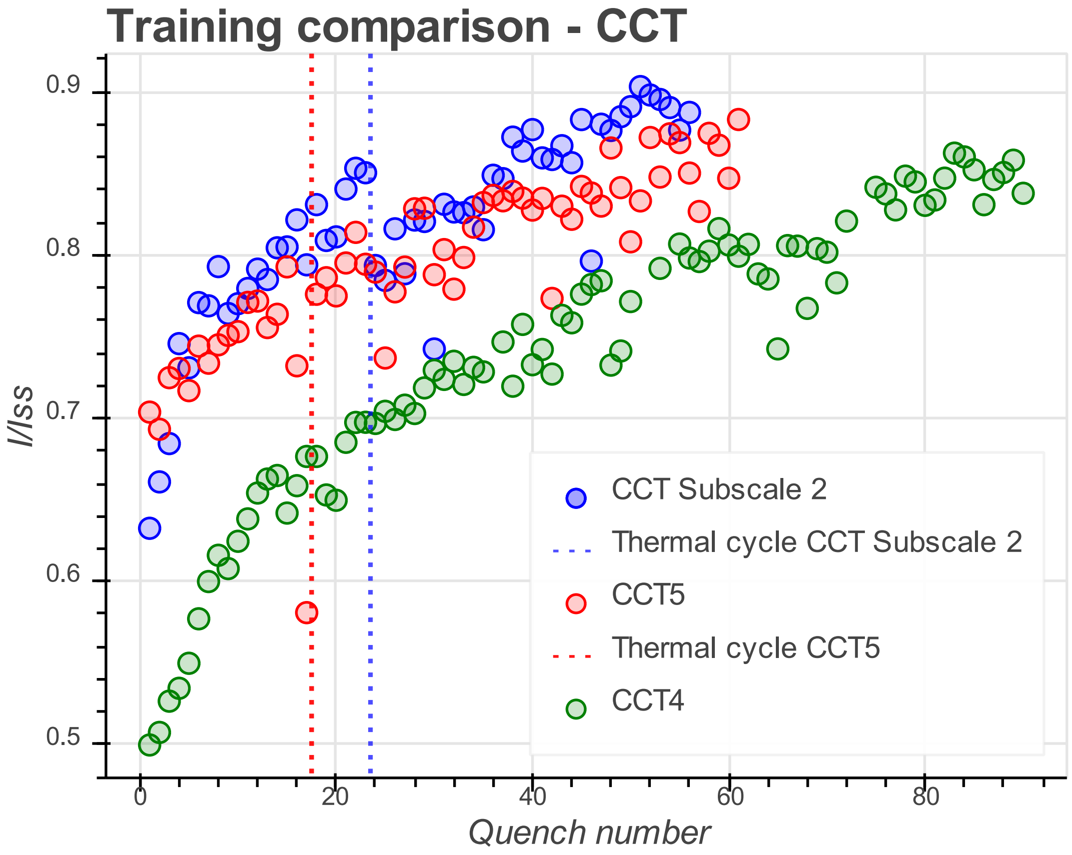
CCT4

- Coils and shell impregnated together
- CTD101K epoxy

CCT5

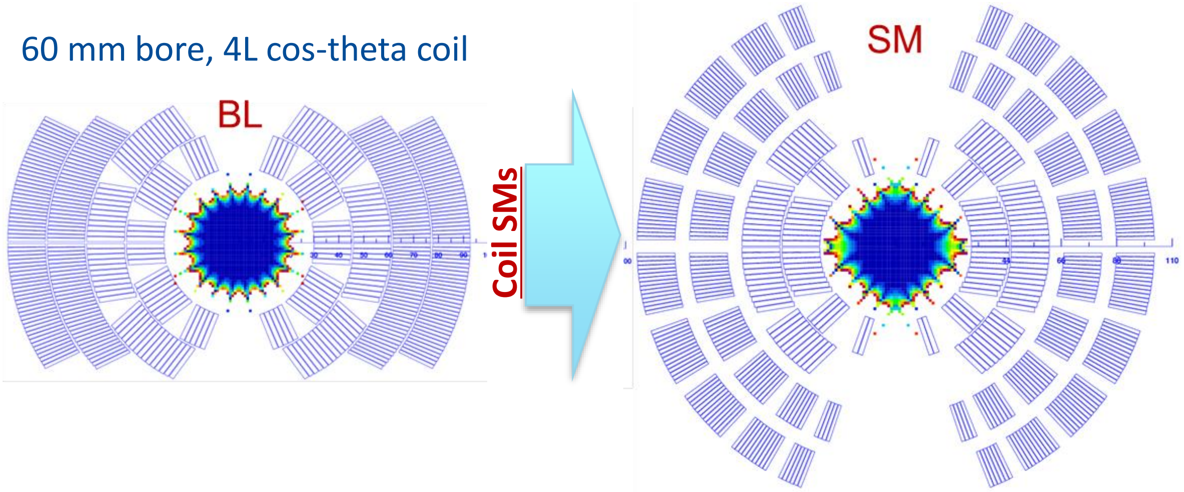
- Bend-and-Shim assembly of individually impregnated coils
- Mix61 epoxy from FSU

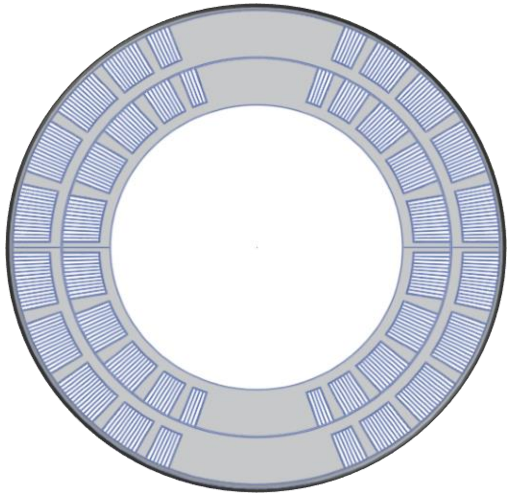


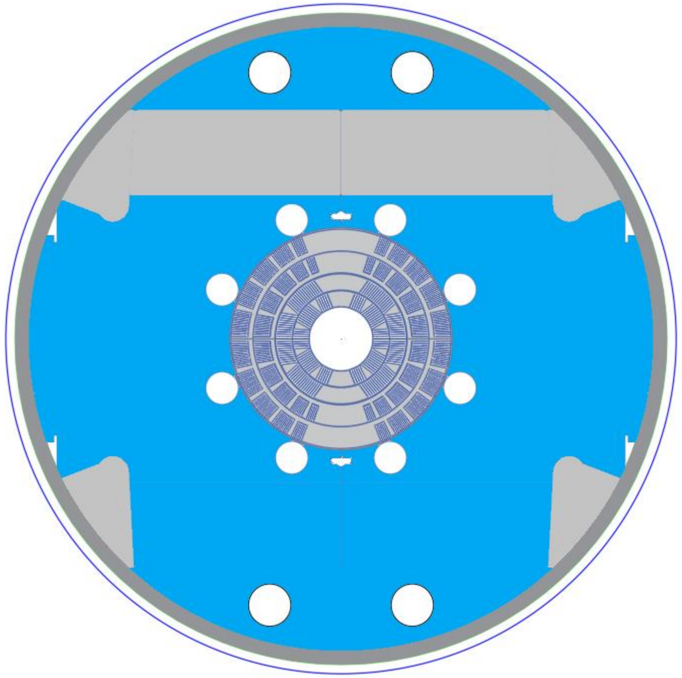


17 T Nb_3Sn dipole with coil stress management (FNAL)

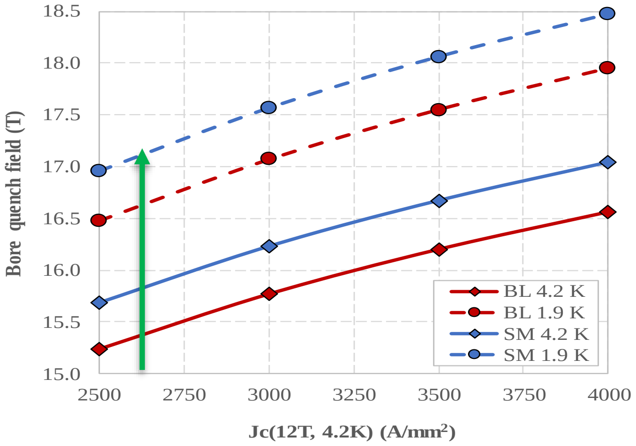
60 mm bore, 4L cos-theta coil

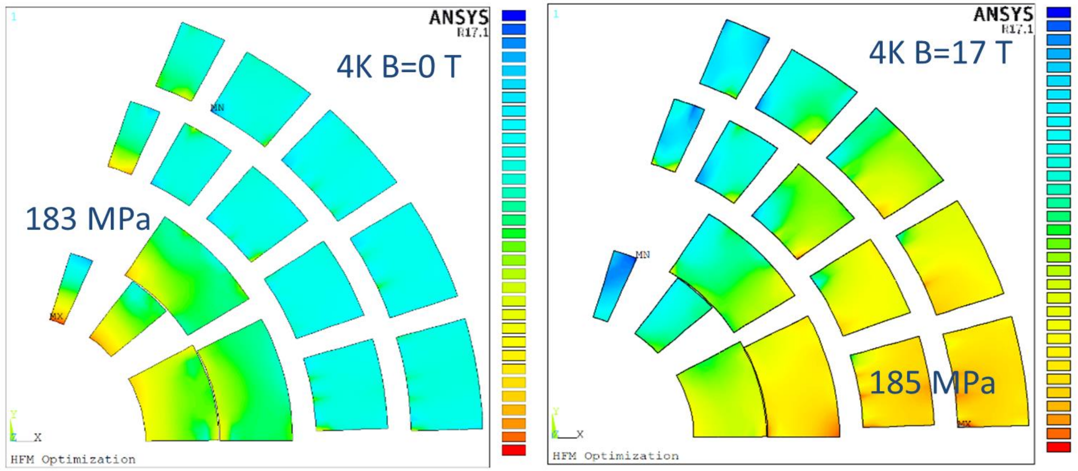






Modified and reinforced MDPCT structure





Conductor limit: B_{ap}=16.7(17.1)T @ 4.5(1.9)K

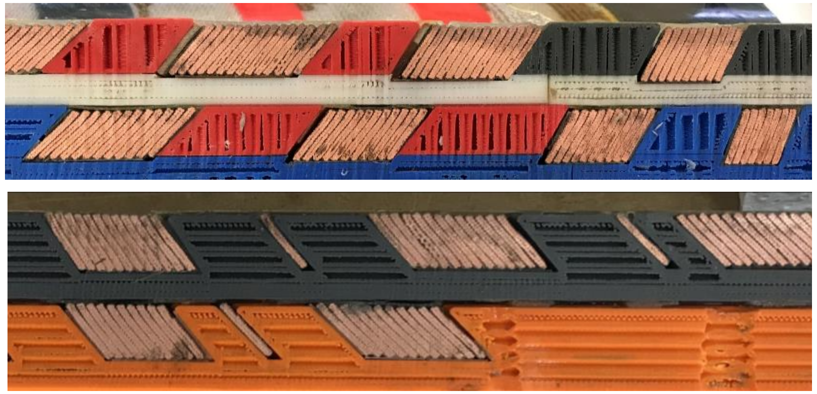
Mechanical limit: B_{ap}~17T S_{eqv}<185MPa

Fermilab

Cos-theta Stress Management coil technology

More efficient coil fabrication process

Better turn positioning and support, minimum epoxy

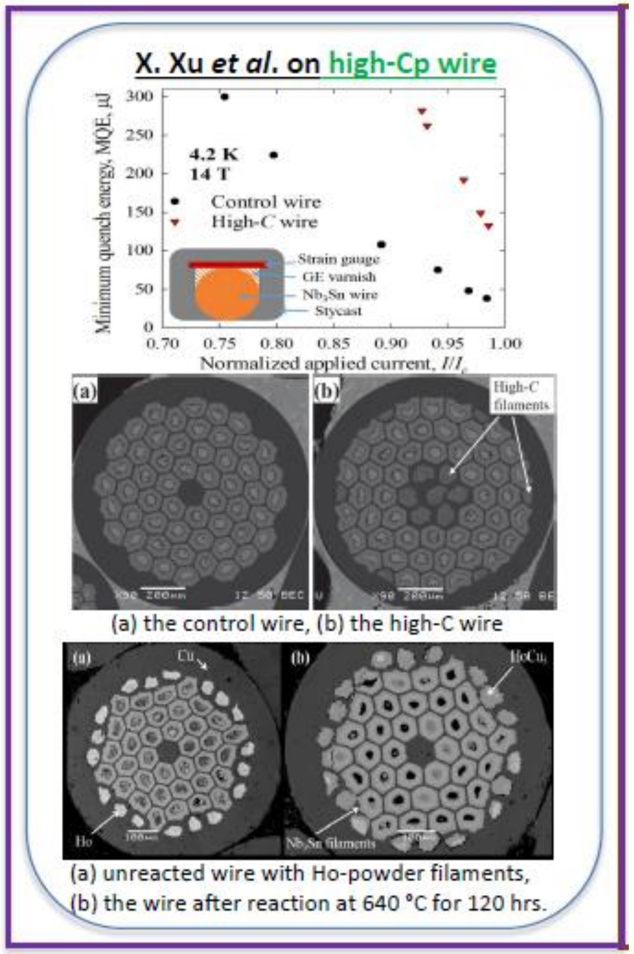


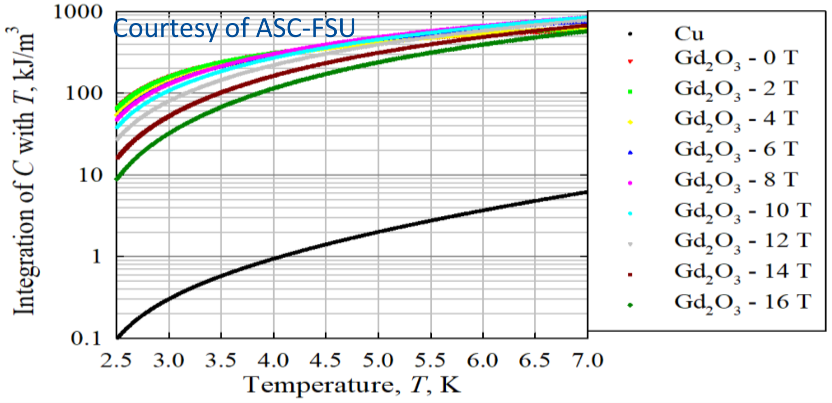
Part procurement at GEA

- 316 stainless steel
- acceptable accuracy
- significant reduction of fabrication time and cost

Increase Nb_3Sn wire/cable C_p to reduce magnet training

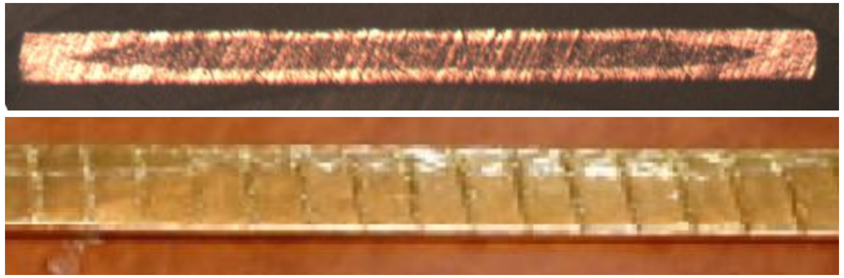
- Increase wire/cable C_p to reduce magnet training





E. Barzi *et al.* on high-Cp cable

Increase cable C_p up to tenfold using a 10-12 mm wide and 70-100 μm thick Cu tape doped with Gd_2O_3 powders at 30% volume.

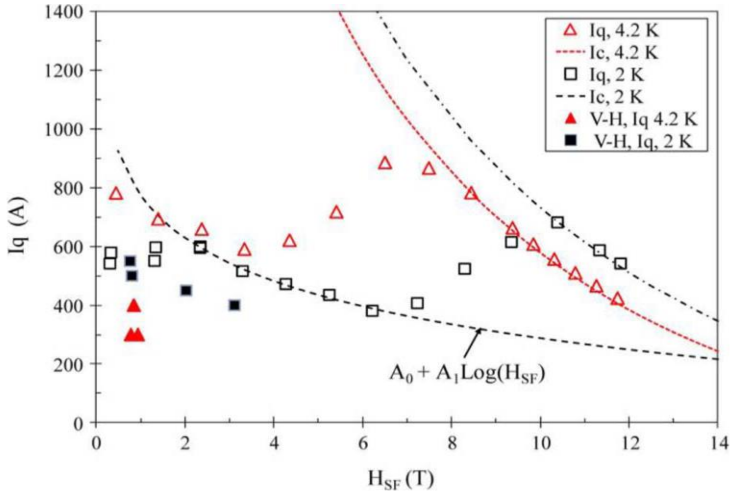


- Stability wrt flux jumps

$$\frac{\mu_0 J_c^2 d_{eff}^2}{4\gamma C (T_c - T_b)} < 3$$

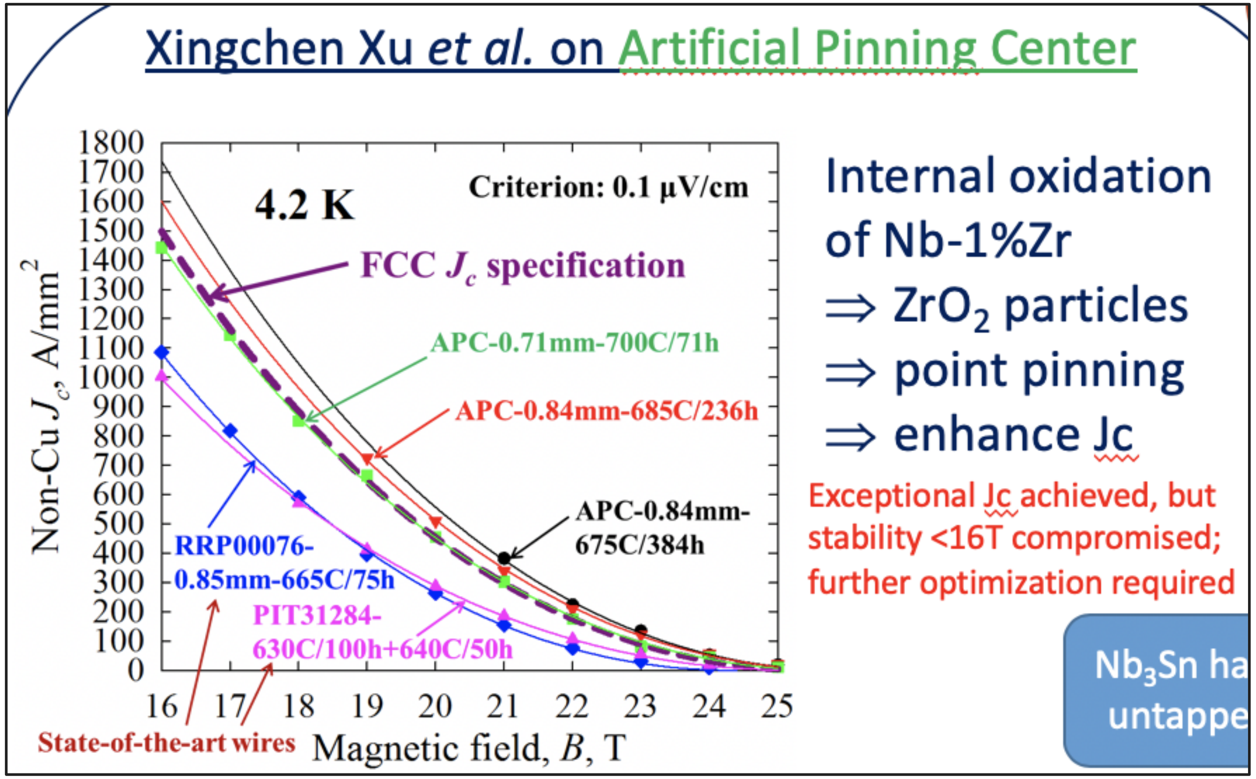
  - d_{eff} is limited by conductor technology,
  - increase C_p
- Stability wrt external perturbations (magnet training)

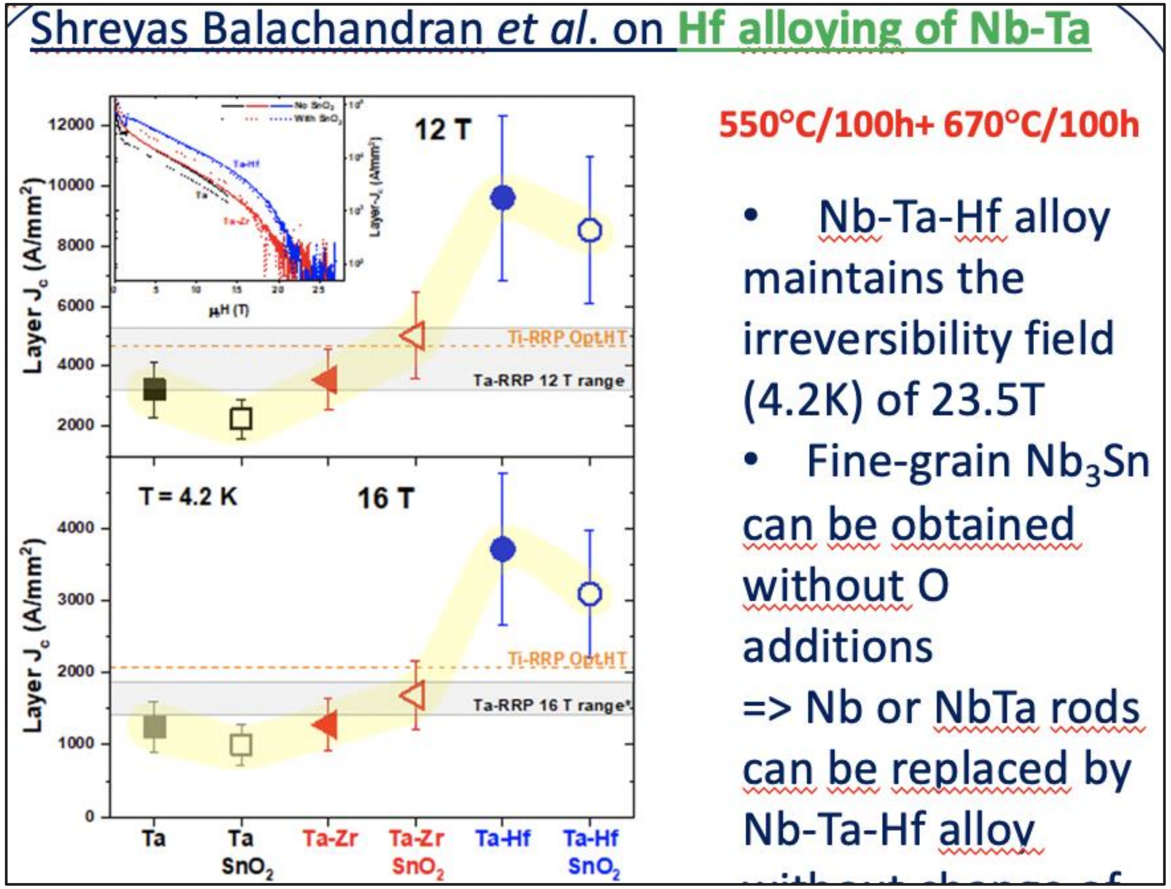
$$\Delta Q \sim C_p \Delta T$$



Increase wire J_c to optimize magnet efficiency and cost

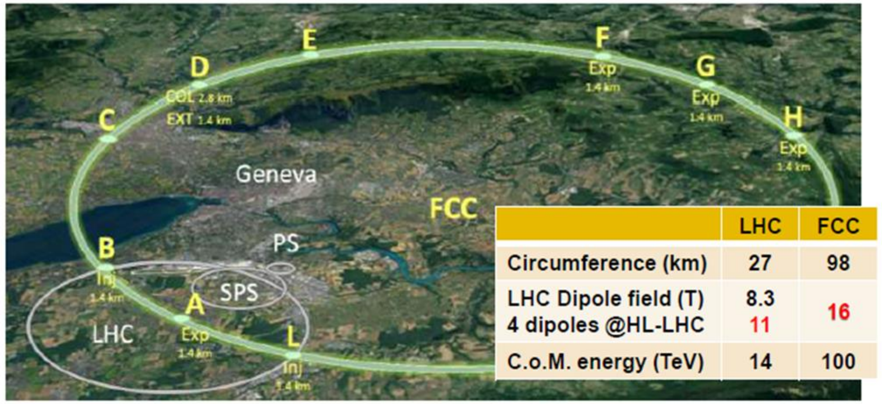
- Two approaches to improve flux pinning
  - APC
  - Hf alloying



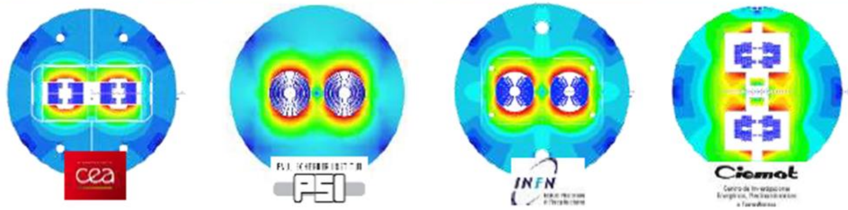


Fermilab

Nb_3Sn magnet R&D in Europe (courtesy L. Bottura)

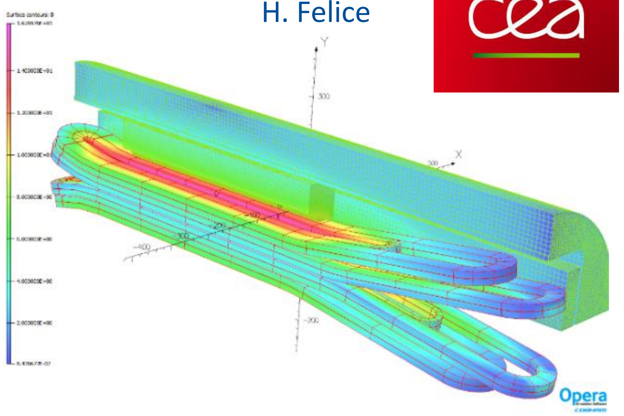


	LHC	FCC
Circumference (km)	27	98
LHC Dipole field (T) 4 dipoles @HL-LHC	8.3 11	16
C.o.M. energy (TeV)	14	100

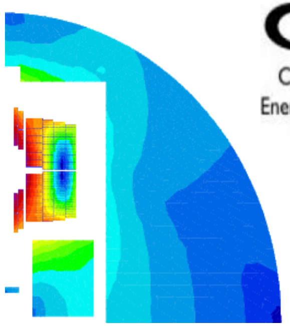


Conceptual design of **16 T** *block* model dipole for FCC

Focus on manufacturing SMC (*process validation*), design and manufacturing of a graded R2D2 (12 T)



Courtesy of H. Felice



Courtesy of F. Toral

Conceptual design of a **16 T** *common coil* dipole model for FCC

EuroCirCol
A key to New Physics

FCC hh ee he

CCT technology development towards a **16T** dipole for FCC

CD1 magnet test is on-going in LBNL (11.1 kA/6.1 T reached !)

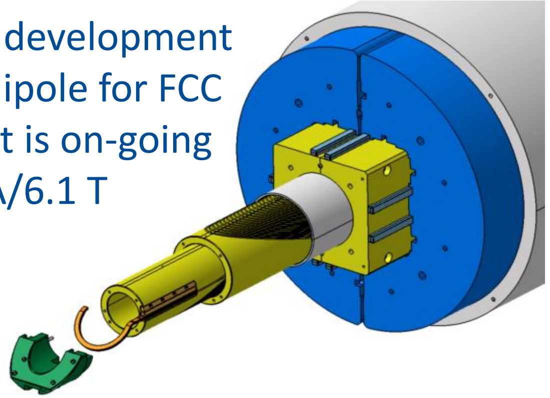
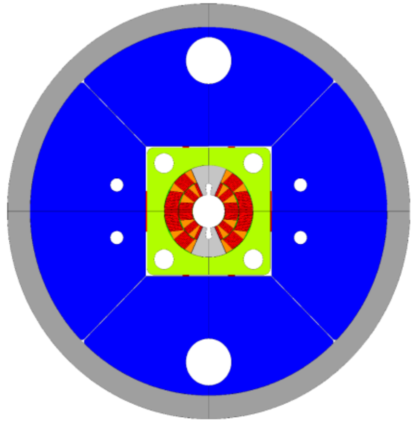


CHART
Swiss Accelerator Research and Technology

Courtesy of B.Auchmann

PAUL SCHERRER INSTITUT

Courtesy of S. Farinon

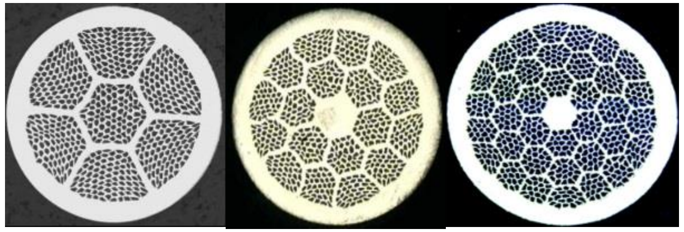


Conceptual design of a **16 T** *cos-theta* model dipole for FCC

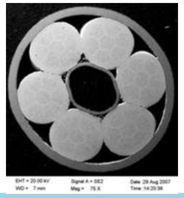
Focus on design and manufacturing a cos-theta, two-layers dipole (12 T)

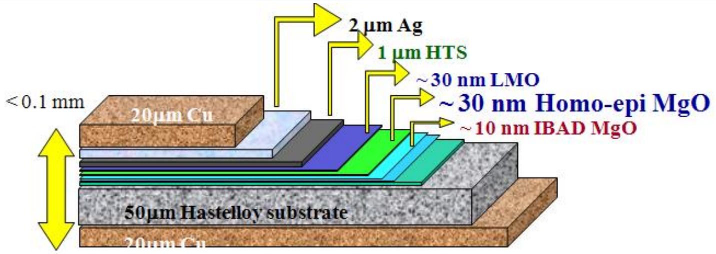
- Coils manufactured at ASG (Genova),
- Magnet assembly at INFN-LASA (Milano)

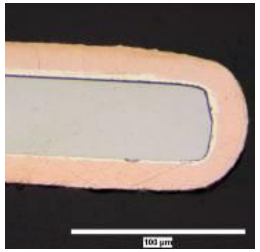
HTS Magnets: Strand and Cable R&D



- $Bi_2Sr_2CaCu_2O_x$ => Bi-2212
- 0.7-1.0 mm wire with Ag matrix
- SC fraction ~25-30%
- Traditional PIT process (OST)
  - Unit length >1 km
- Complex heat treatment in O_2
- Brittle after heat treatment
- Isotropic properties





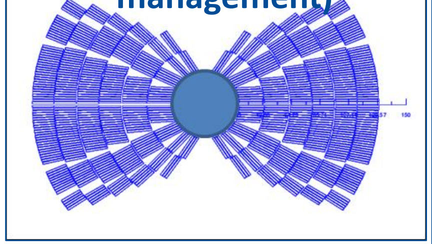


- $YBa_2Cu_3O_y$ => YBCO-123
- 4-12 mm wide tape with Cu stabilizer
- YBCO fraction ~1%
- Complex multilayer deposition process and final Cu electroplating (SP)
  - Unit length ~500-1000 m
- No final heat treatment
- Brittle but withstand substantial load
- Anisotropic

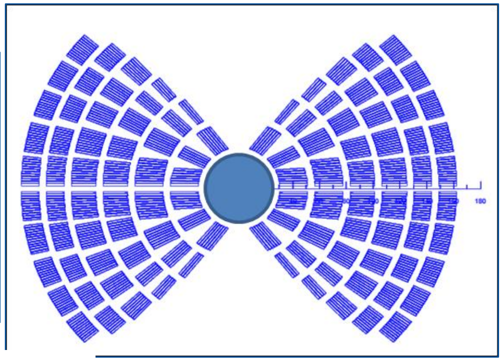
Towards 20 T hybrid dipole (US-MDP)

- Due to relatively high HTS cost and lower J_c at low B, *a hybrid approach is a cost-effective option*.
- Preliminary magnetic analysis of different hybrid design options

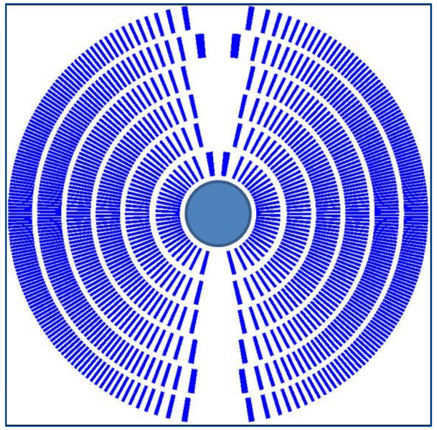
CT (reference, no stress management)



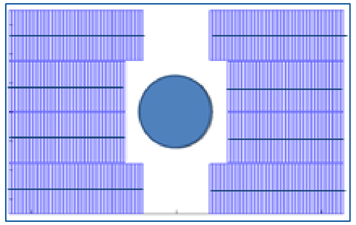
SMCT



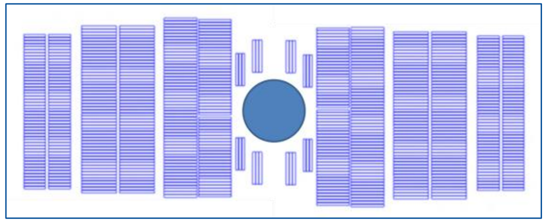
CCT

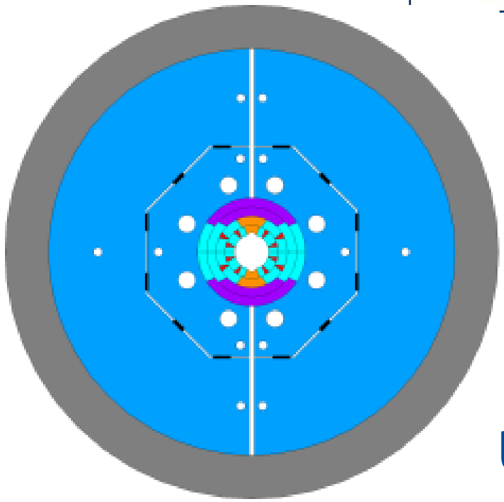


Block (no stress manag.)



Common coil (no stress manag.)



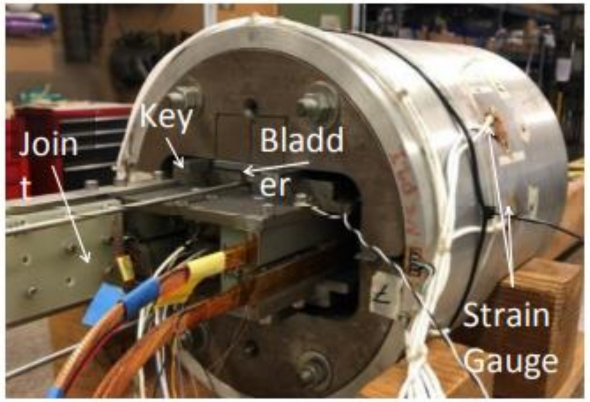


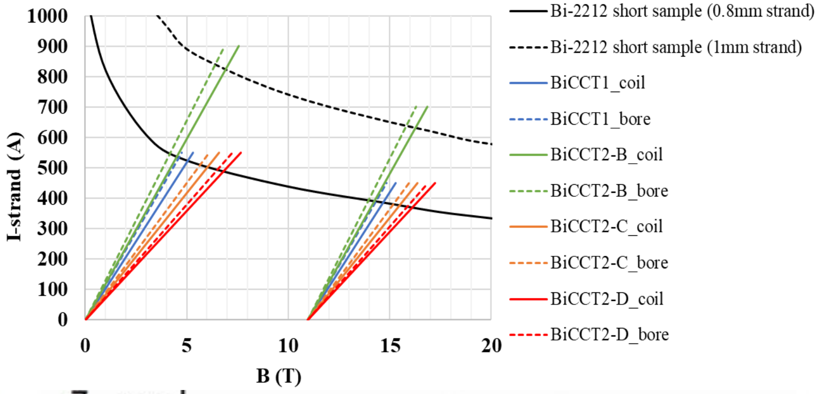
Utility structure design optimization

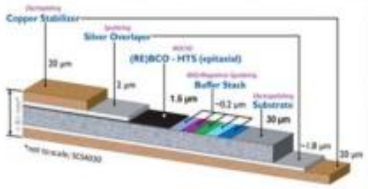
HTS inserts (LBNL)

Bi2212 – multi-filamentary round wire

- **Nano-spray combustion powder technology**
- **J_e(15T)- 1365 A/mm²**
- **Bi2212 now *exceeds RRP J_E at 11T!***





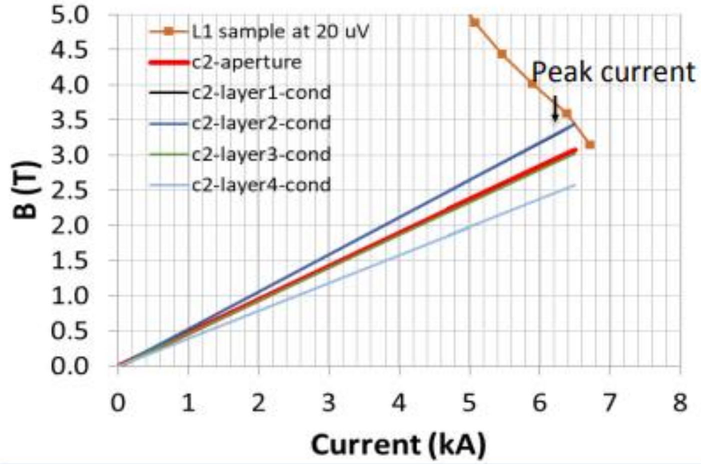


REBCO tape

SuperPower Inc.
A Furukawa Company

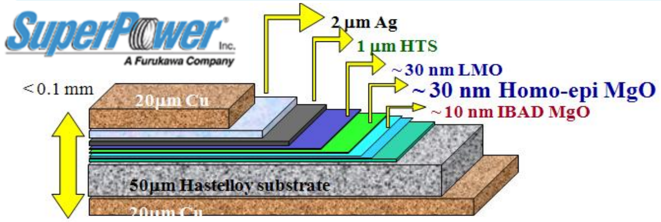
Advanced Conductor Technologies LLC
www.advancedconductor.com

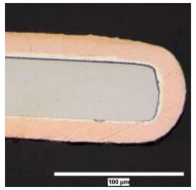
- **C2 reached 2.9 T, 98% of the expected value**
- **Reproducible V(I) transition between ramps**



- Today: 220 A/mm² at 21 T, 4.2 K, 30 mm bend radius
- Goal: Minimum J_e(21 T, 4.2 K) at 3.7 mm wire diam.: 540 A/mm² at 15 mm bend radius

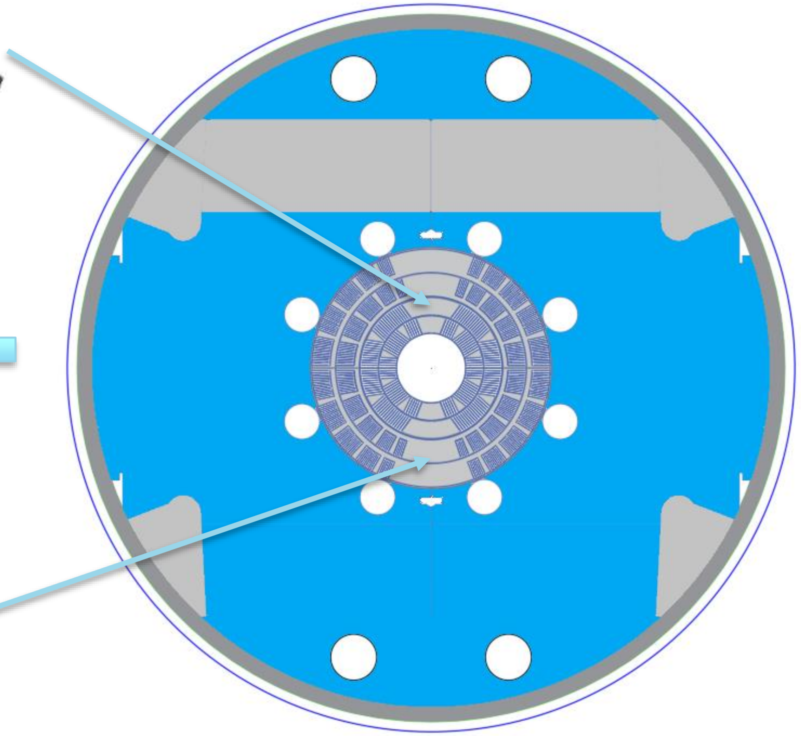
HTS coil inserts (FNAL)

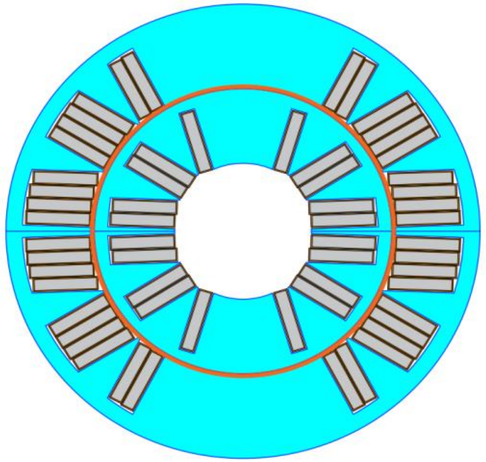




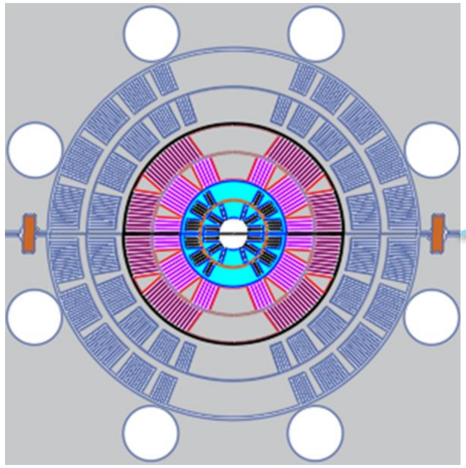
REBCO CORC
100/119mm ID/OD insert

Modified and reinforced 15 T dipole (MDPCT) structure





Bi2212 17/59 mm ID/OD insert

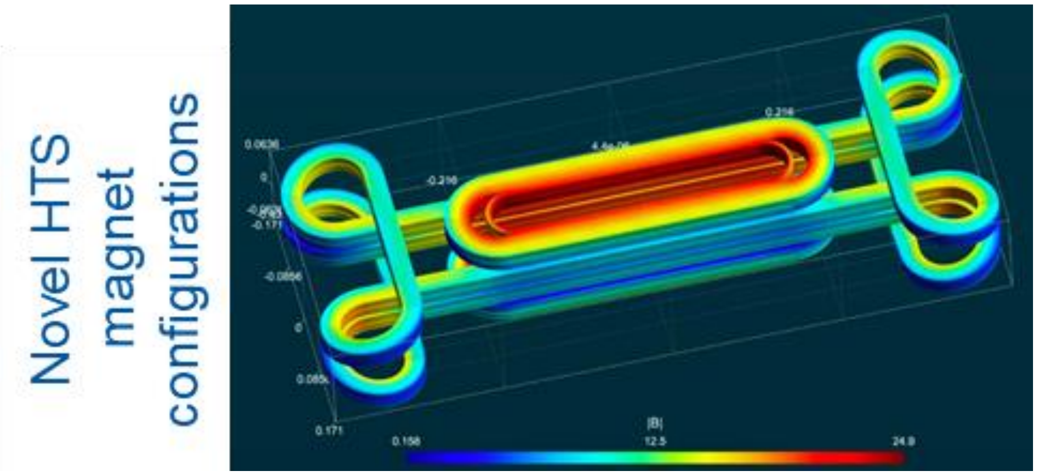


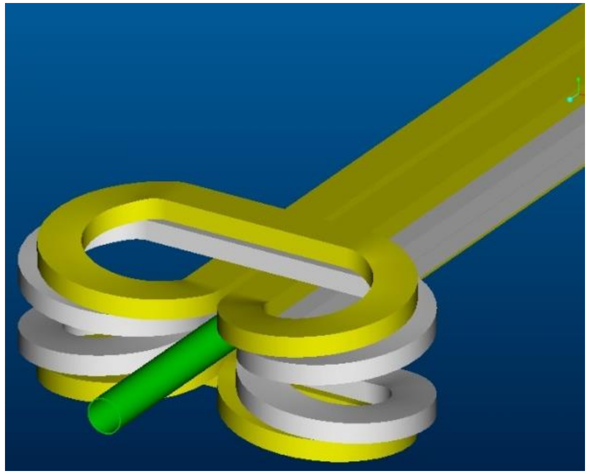
Bi2212 insert inside 17 T Nb_3Sn dipole coil

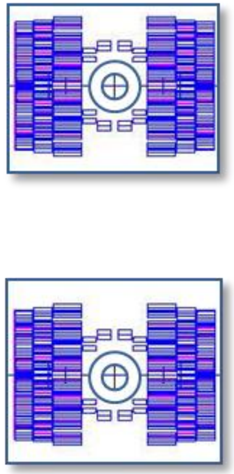
Expected performance:

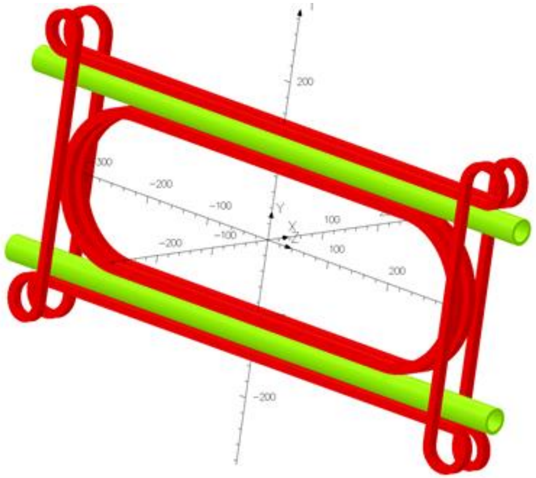
- 4L HD REBCO: B_{max} ~ 13 T
- 6L HD Bi2212: B_{max} ~ 19 T

HTS program (BNL)









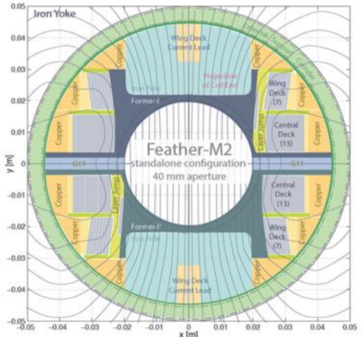
- No reverse or hard way bend (primarily a tilt)
- Conductor friendly design – less strain, less axial length of ends
- Useful for block coil designs (including FCC and FES test dipole

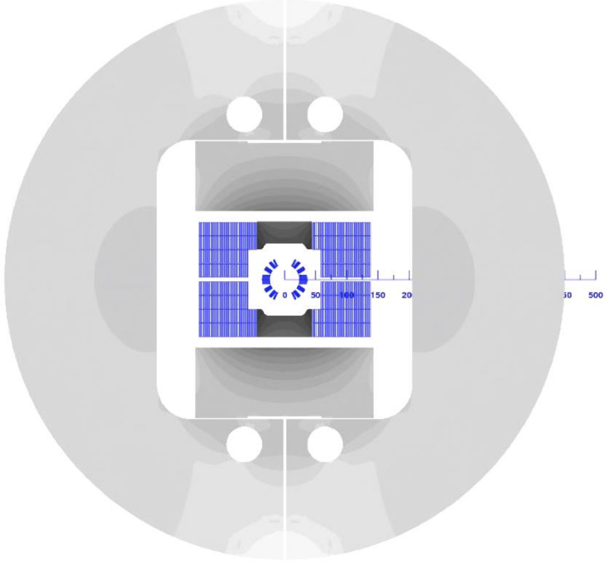
- Conceptual design of the block coil single-aperture dipole based on the overpass/underpass design clearing the bore tube
- common coil design with narrower cable used for pole coils over and under the beam tube
- an OPERA model of the pole coils of a common coil with one overpass/underpass coil and one racetrack coil

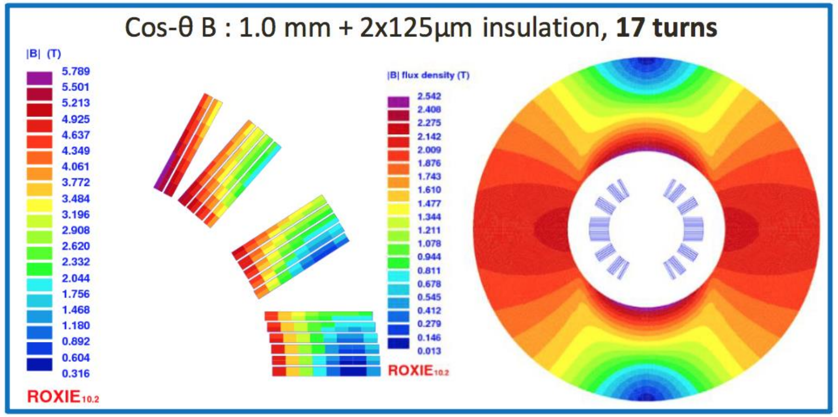
HTS inserts in EU (EUCARD2)

- 5 T dipole: B_p~ 5.5 + 14.5 T, *w*=11 mm, *j*=800 A/mm^2 (FEATHER)
  - block design with flared end
  - Roebel cable
- First model with lower performance cable
  - Reached 3.1 T corresponding to *j*=480 A/mm^2
- Second model with full performance cable to be built in 2019

- 3.5 T dipole: B_p~ 4.1+14.5 T, *w*=12 mm, *j*=560 A/mm^2 (COS THETA)
  - cos-theta design
  - Roebel cable
  - 5 T in stand alone, with : B_p= 5.8 T, *j*=800 A/mm^2
- Construction ongoing in CEA Saclay







Summary and conclusions

- Accelerator magnet technology has made significant progress in the past decades
  - Nb-Ti magnets provided success of Tevatron, HERA, RHIC, LHC and baseline for EIC
  - Nb_3Sn magnets with nominal fields up to 12 T are being produced for the LHC (HL-LHC)
- Attempts to go beyond 15 T towards the limit of Nb_3Sn accelerator magnets continued
  - coil stress management and conductor performance improvements are the key for success
- To go beyond the Nb_3Sn technology limit towards 20 T and higher fields, hybrid approach with Nb_3Sn and HTS coils looks economically and technically justified
  - the work on Nb_3Sn outserts and HTS inserts based on different conductors, coil designs and technologies is progressing well in the U.S. (MDP) and EU (EuCARD2)
  - HTS performance improvement, cost reduction and production capabilities need permanent attention and investments
- HFM designs and technologies, being developed for hadron colliders, are also important for many other application, e.g. Muon Collider Storage Rings, Electron-Ion Colliders, SC undulators for Light Sources, various Test Facilities, etc.
  - important topic for discussions and coordination during Snowmass’21 process

Acknowledgment

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