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U.S. DEPARTMENT OF ENERGY
Office of Science

How good a magnet can be?

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Contributions from: P. Ferracin, S. Prestemon, G. Sabbi, X. Wang

IMCC 2023

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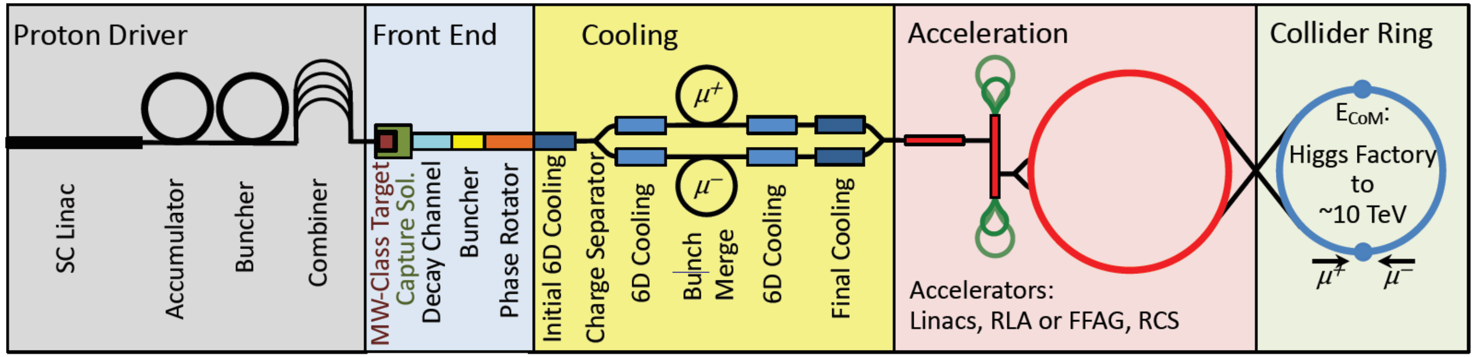
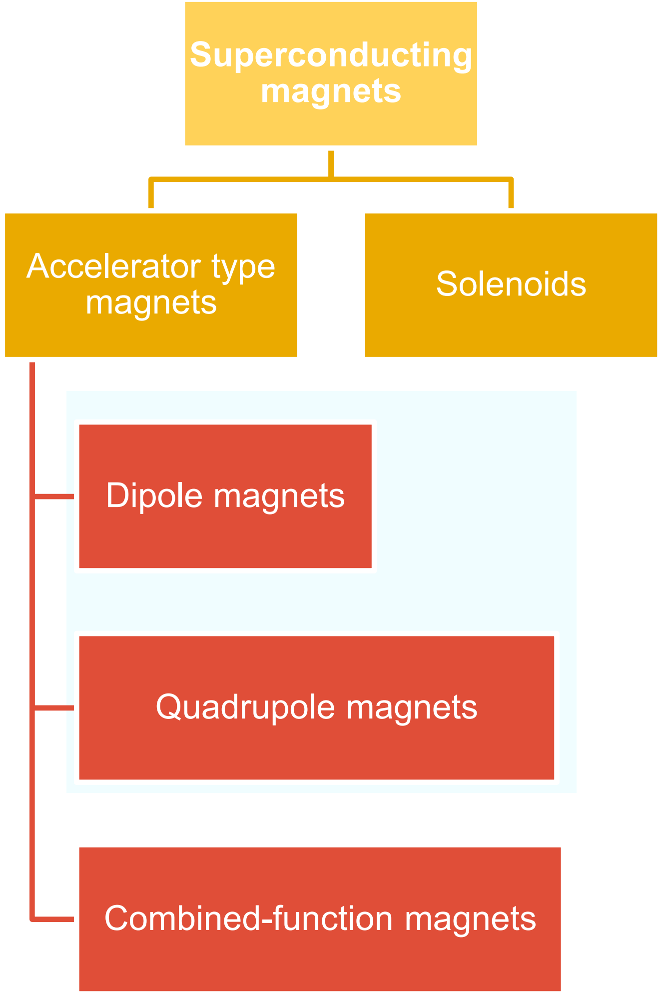
1. Introduction How good a magnet can be?

What are the magnets that we will discuss?



Boscolo, M., Delahaye, J.P. and Palmer, M., 2019. The future prospects of muon colliders and neutrino factories. *Reviews of Accelerator Science and Technology*, *10*(01), pp.189-214



Arc and IR magnet challenges

- Large bore (~ 150mm)
- High field (~ 10 → 20T)
- Large stress in the conductor due to e.m. forces (~ 300…400MPa) if not intercepted (need for stress-management concepts)

1. Introduction How good a magnet can be?

What do we mean by "good"?

- **Magnetic field strength:**
  - The magnitude of the generated magnetic field
- **Magnetic field quality/uniformity:**
  - How close is the real magnetic field to the design/intended values
- **Others:**
  - Cost-effectiveness, *training*, efficiency, operational margin, time dependency, degradation, repeatability, physical configuration, operational temperature, winding, weight, size…

1. Introduction

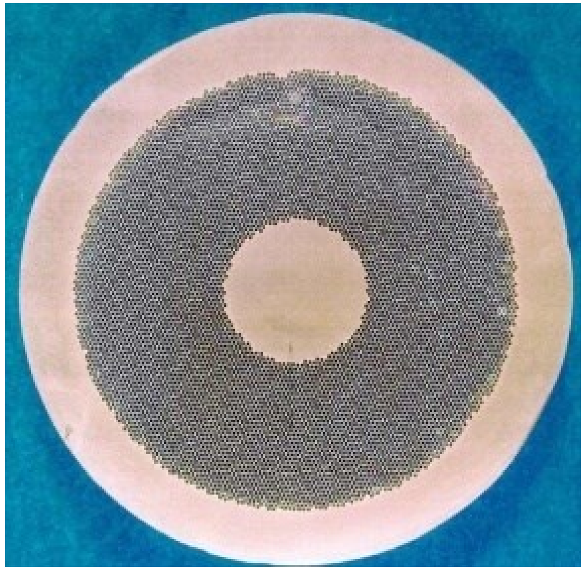
Superconducting materials

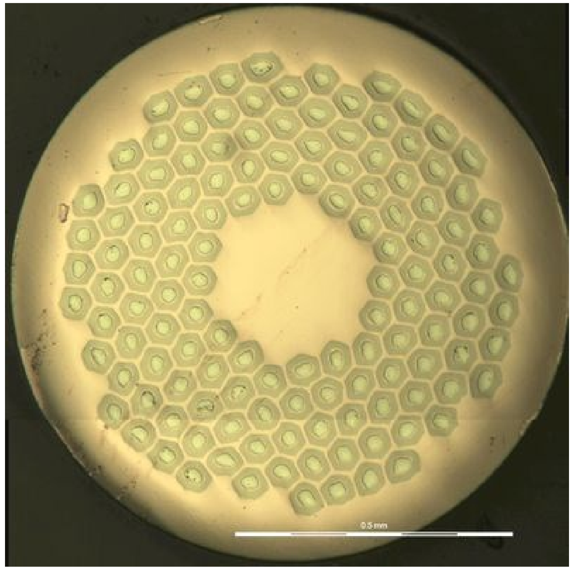
Nb-Ti
Small filaments, ductile and cheap

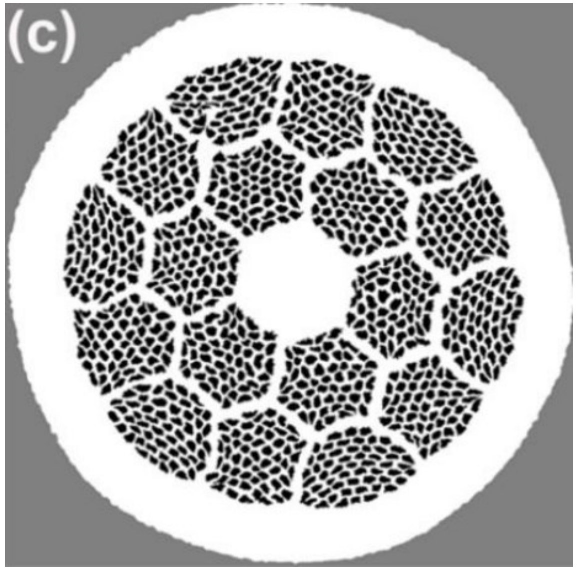
Nb_3Sn
Strain sensitive and brittle, reaction at ~650 °C, larger filaments

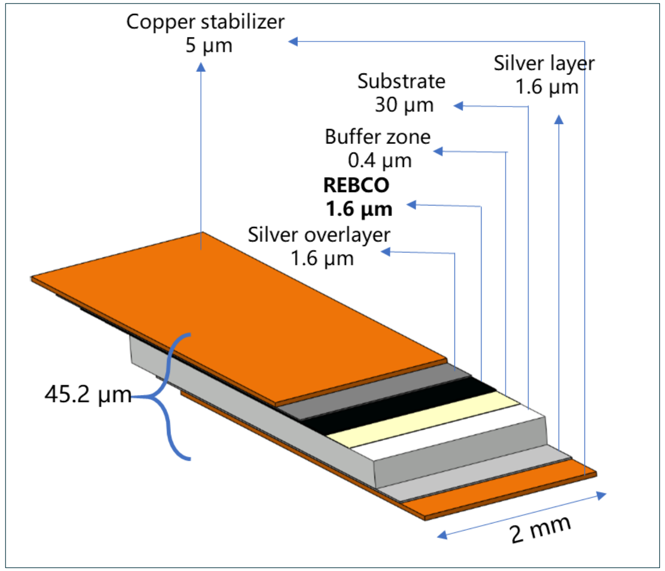
Bi2212
Round strand -> cable, reaction at ~900 °C in O_2 at 50 bar, strain sensitive

REBCO
Tape, no reaction, resistance to stress, strong angle dependence of J_c (much higher with $B_{\parallel}$ than with $B_{\perp}$)



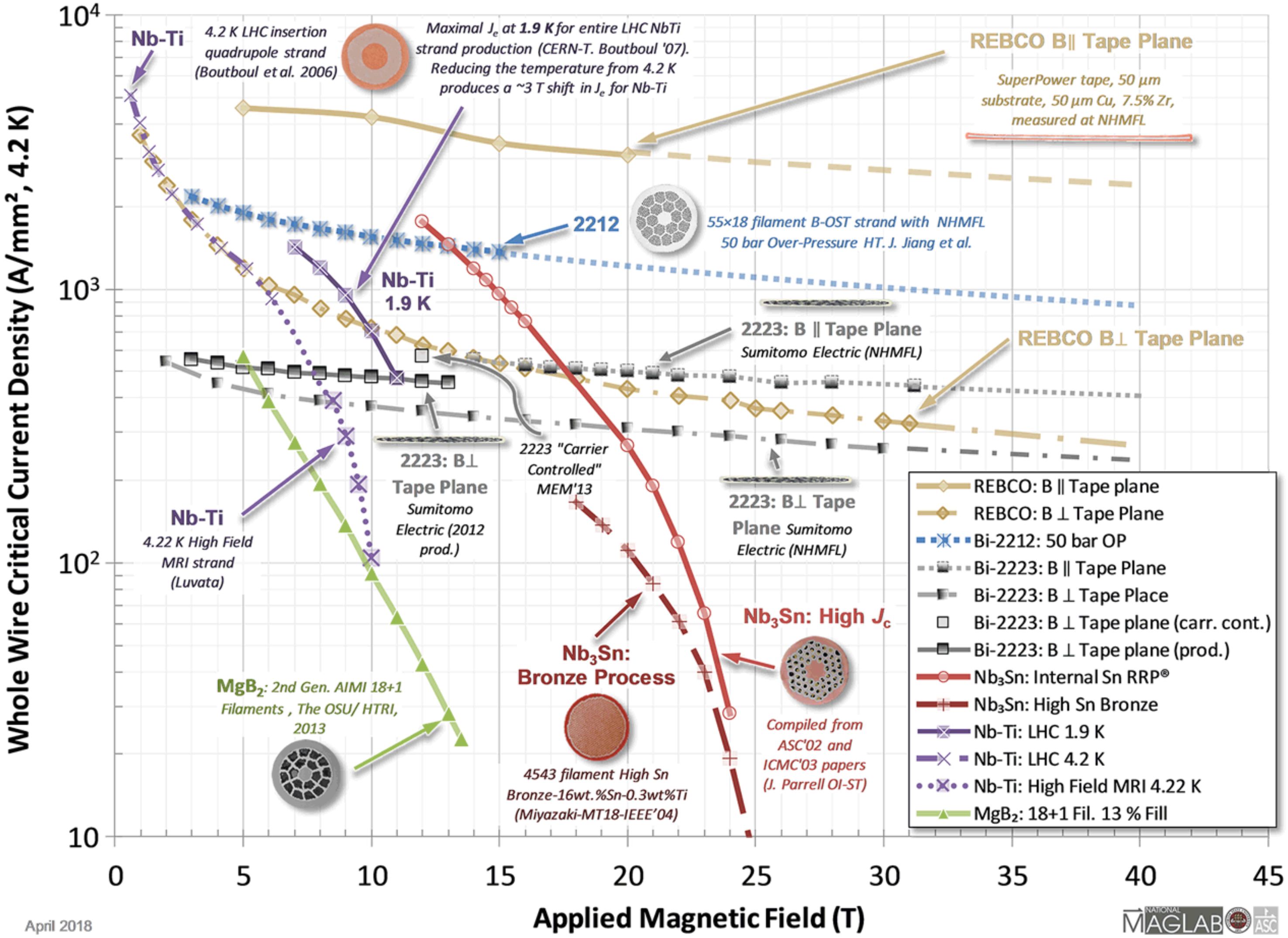






1. Introduction

Superconducting critical surfaces



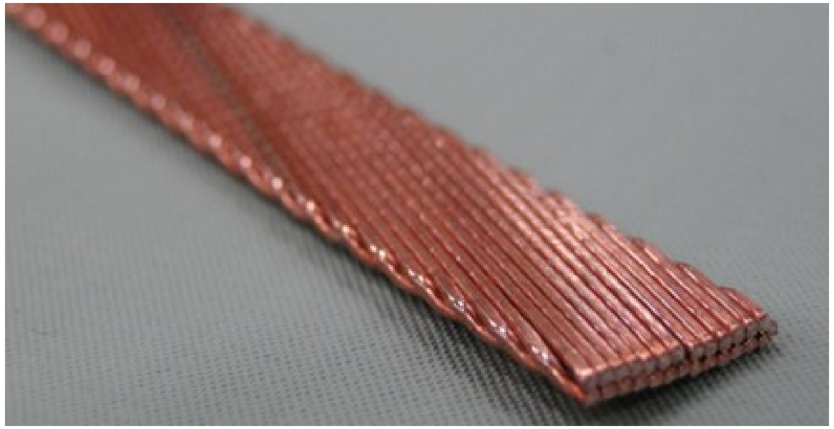
1. Introduction

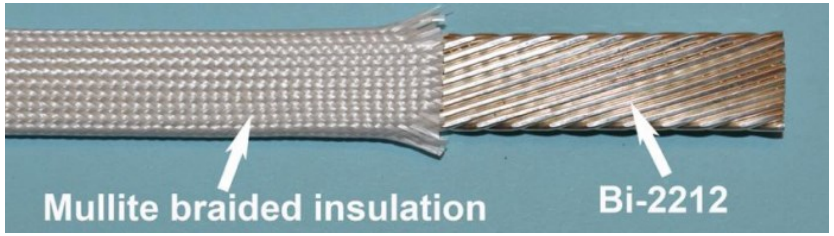
Superconducting cable architectures for superconducting magnets

Multi-wire **Rutherford cable**

Used for **Nb-Ti**, **Nb_3Sn**, and **Bi2212**

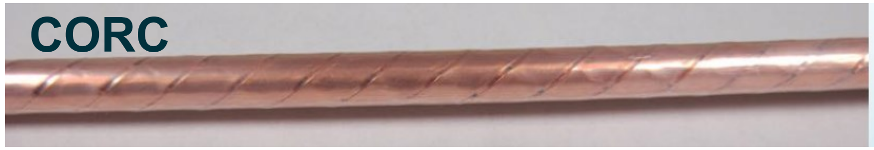
In theory, similar designs, independently of strand material





Tape based architecture

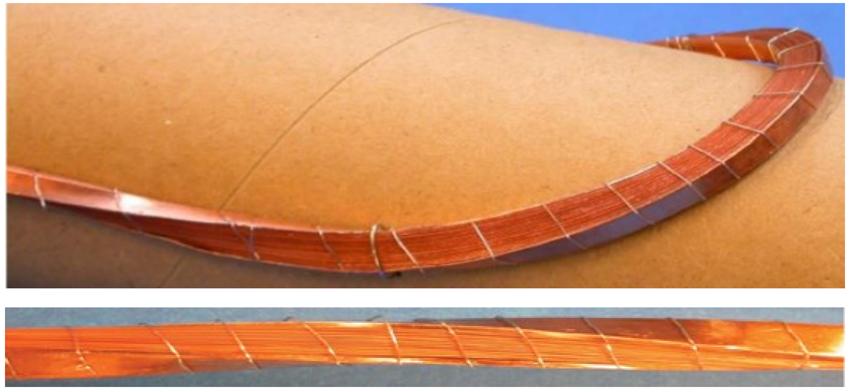
On-going R&D for **REBCO** tapes



1. Introduction

Superconducting cable architectures for superconducting magnets - **REBCO** based

MIT **twisted stacked-tape cable** (TSTC)

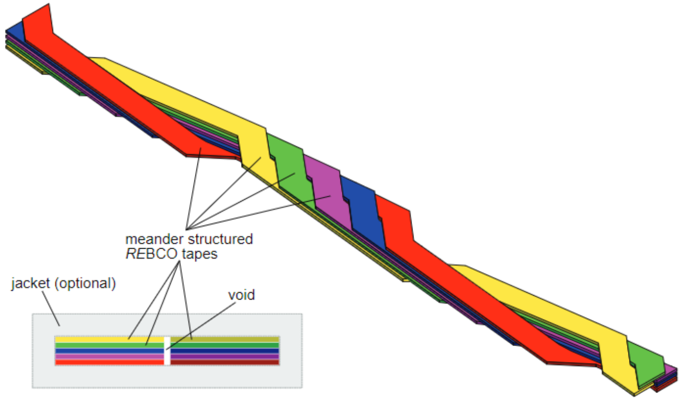


- Concept: Simple and straightforward
- Compact → High engineering current density
- Partial transposition

- Behavior of a tape
  - Bending in certain directions
  - Anisotropic field dependence

Takayasu et al., 2011. *SuST* 25 (1): 014011

REBCO **Roebel cable**



- A design by Ludwig Roebel for low loss copper cables in 1914
- Compact → high engineering current density
- Full transposition along cable direction

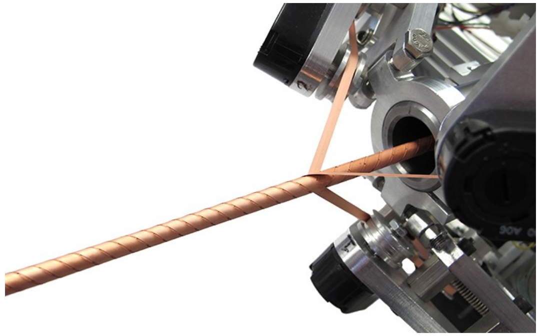
- Punch away conductors
- Behavior of a tape
  - Bending in certain directions
  - Anisotropy

Goldacker et al., 2014. *SuST* 27 (9): 093001
Barth. 2013. *High Temperature Superconductor Cable Concepts for Fusion Magnets*.

1. Introduction

Superconducting cable architectures for superconducting magnets - **REBCO** based

Round wire #1: conductor on round core (**CORC**®)



Advanced Conductor Technologies LLC
www.advancedconductor.com

- Macroscopic round conductor → isotropic in bending direction and magnetics
- Partial transposition
- ~ 30 tapes, 30 micron thick substrate, 3.8 mm diameter,10kA transport current at 4.2 K, self-field

- Lower J_e compared to rectangular cable due to the additional former
- Tape degradation due to bending

Weiss et al., 2020. *SuST* 33 (4): 044001

Round wire #2: Symmetric Tape Round (**STAR**™) wire

http://www.ampeers-llc.com/

- Similar to CORC
- But with few (< 10) and highly customized REBCO tapes
  - Higher flexibility: bending radius < 15 mm
  - Smaller diameter: 1.4 - 2 mm → higher J_e

- Generally carry less current than CORC
- Interesting candidate for cabling

Kar et al., 2020. *SuST* 33 (9): 094001

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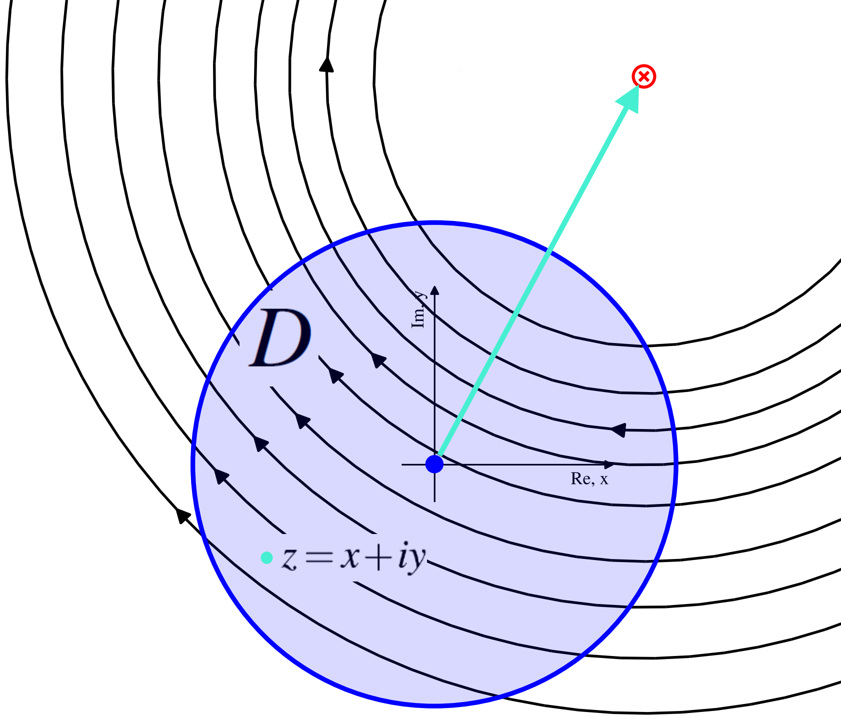
2. Magnetic Field Quality *- Introduction*

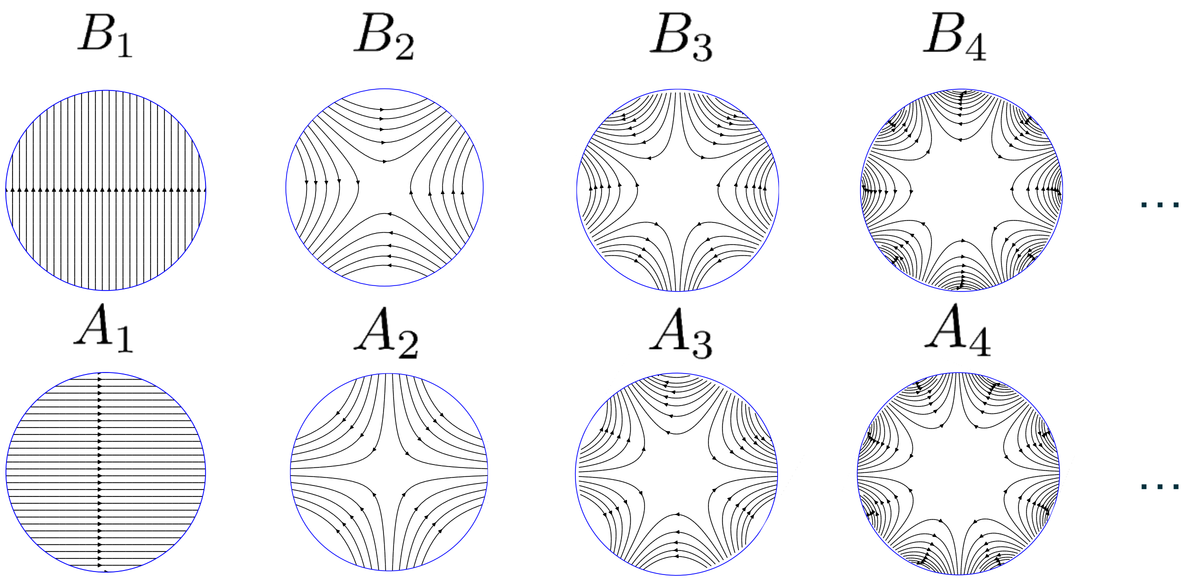
Mathematical definition of field quality for accelerator magnets

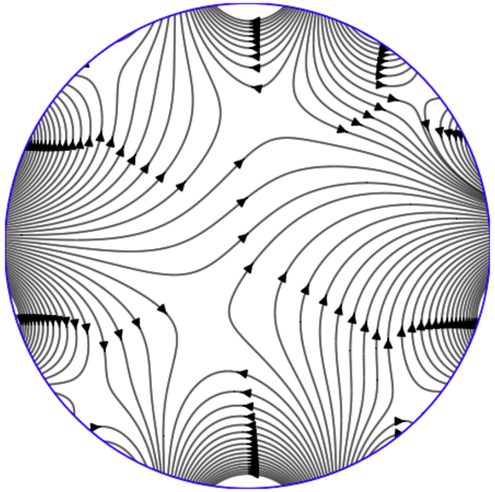
$$\mathbf{B}(z) = \sum_{n=1}^{\infty} C_n \left(\frac{z}{R_{ref}}\right)^{n-1} \quad \text{with} \quad z \in D$$



Definition of **units** $\quad c_n = b_n + i a_n = 10^4 \dfrac{C_n}{B_m}$

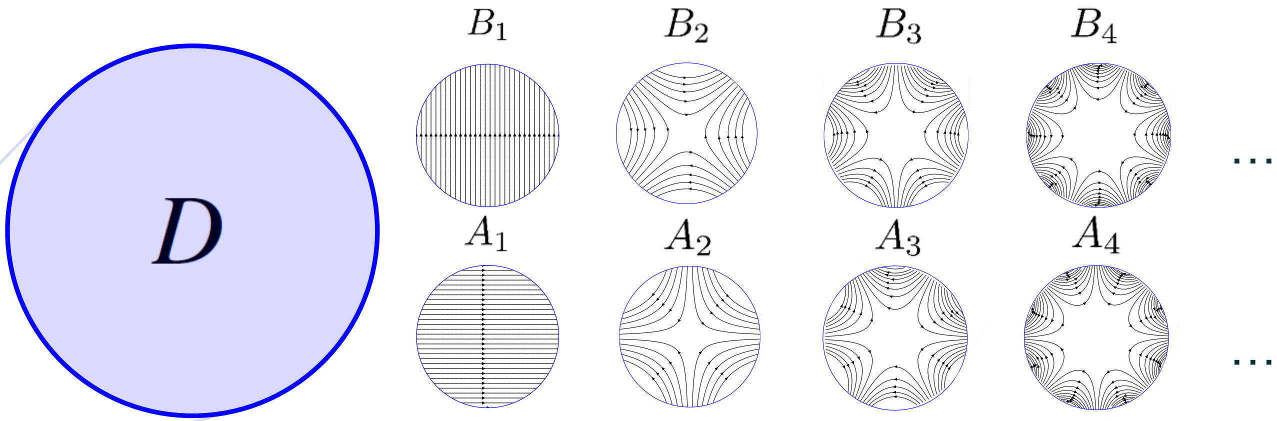
$$C_n = B_n + i A_n$$

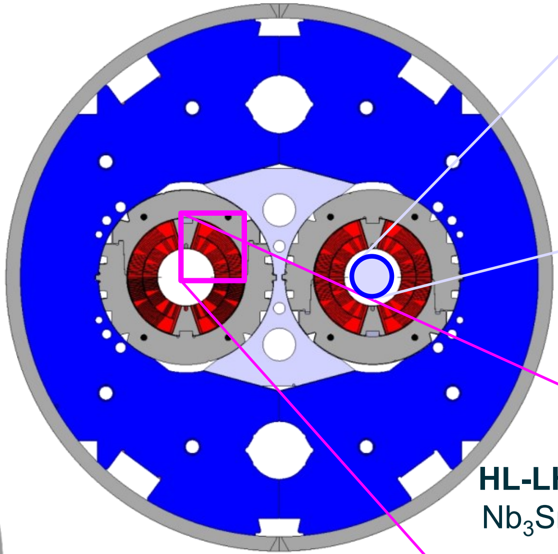




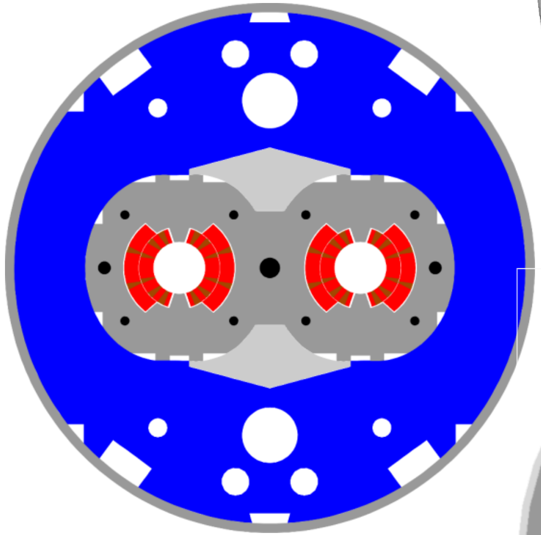
2. Magnetic Field Quality

Geometric field errors

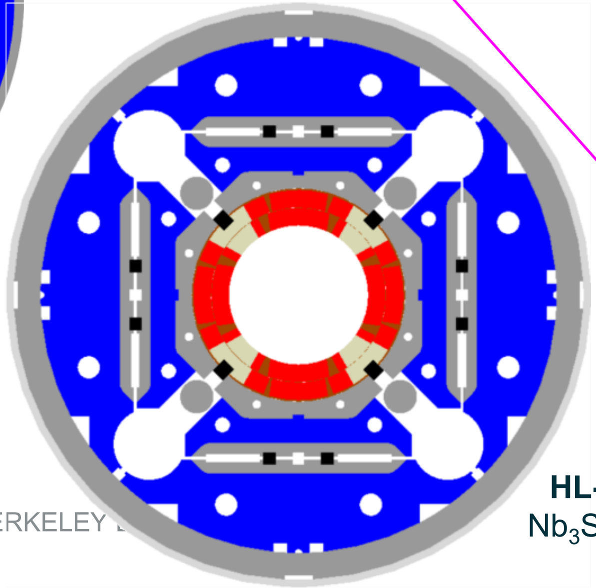




HL-LHC MBH 11 T
Nb_3Sn, B_p = 11.7 T

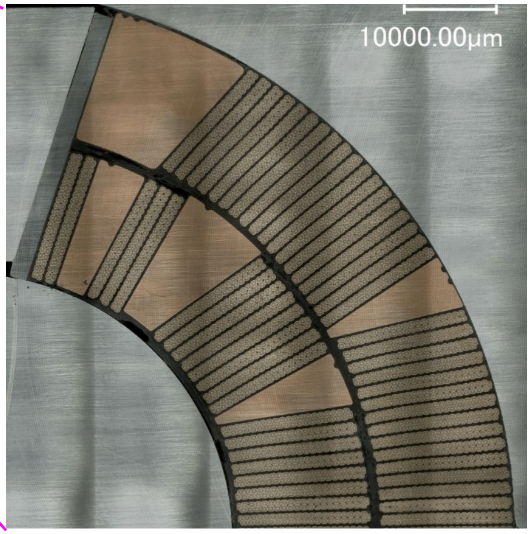


LHC MB
NbTi, B_p = 8.6 T

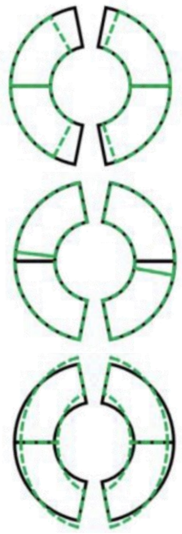


HL-LHC MQXF
Nb_3Sn, B_p = 11.3 T

Position of the strand/conductor/cable within the coil



Global deformation modes due to components' geometrical deviations, assembly, cool down and e.m. forces

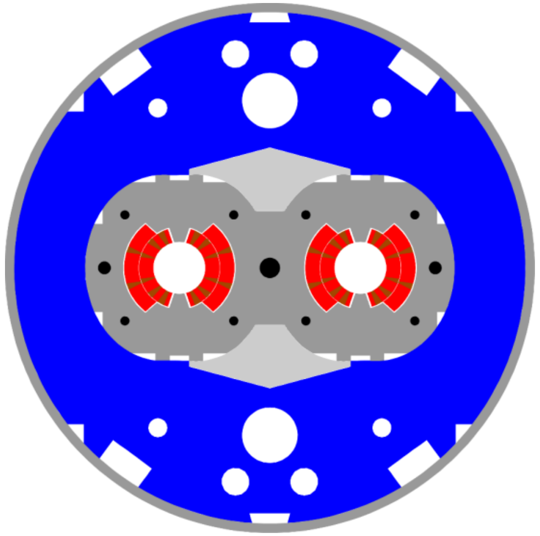


2. Magnetic Field Quality

Geometric field errors – Challenges for specific superconductor material

Nb-Ti

Low stiffness coil in relation to Nb_3Sn impregnated coils



LHC MB

NbTi, B_p = 8.6 T

Nb_3Sn

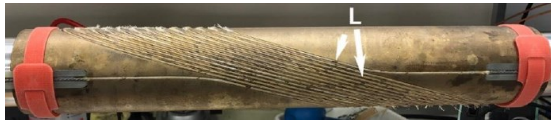
Strain sensitive and brittle, reaction to ~650 °C

During the reaction cycle, Nb_3Sn phase expands in volume. Due to its brittle nature, additional space is needed to limit strain.

Bi2212

Reaction at ~900 °C in O_2 at 50 bar

Due to higher temperatures, the structural elements of the coil might be geometrically distorted.

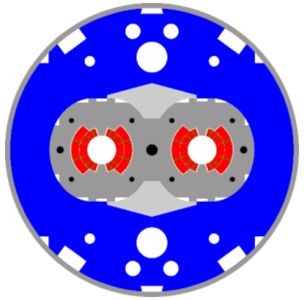


REBCO

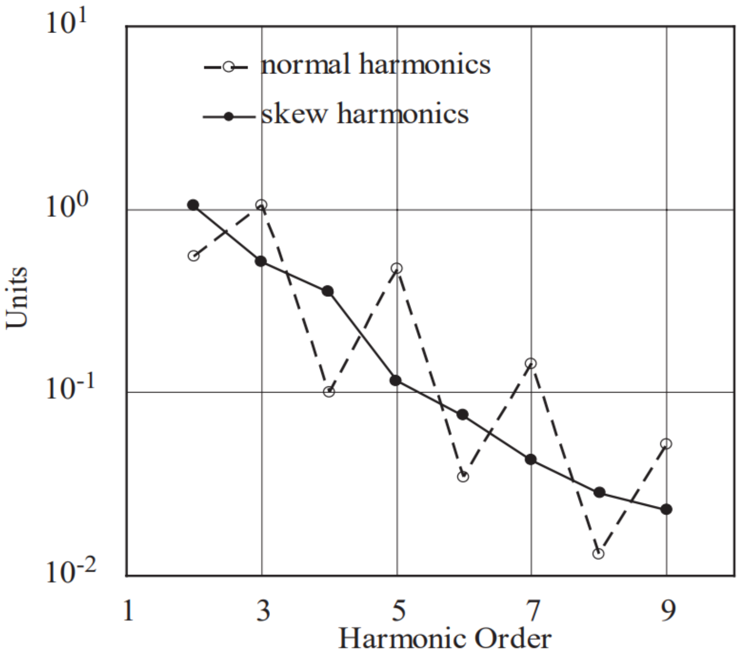
Coils are normally resin impregnated. The geometrical size is very challenging to control precisely.

2. Magnetic Field Quality

Geometric field errors – Arc dipoles – collared structures



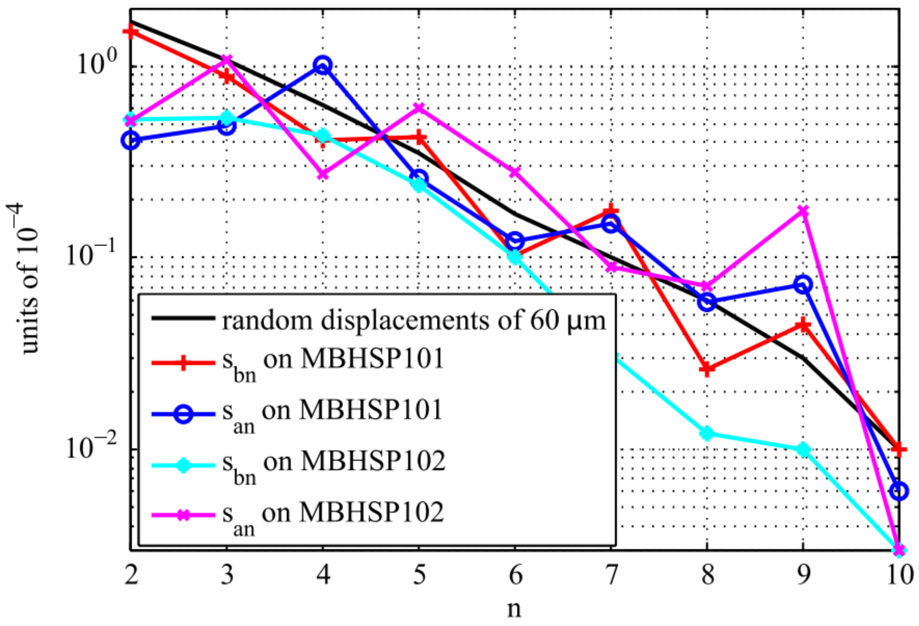
LHC MB
NbTi, B_p = 8.6 T

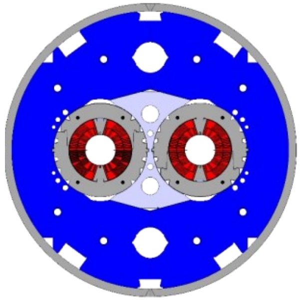


	d_0 [μm]
Tevatron	65
HERA	41
RHIC	16
LHC	25

*First order estimate is **25 microns** for block positioning accuracy in LHC dipole.*

Bellesia, B., Todesco, E. and Santoni, C., 2006. *Random errors in superconducting dipoles*





HL-LHC MBH 11 T
Nb_3Sn, B_p = 11.7 T

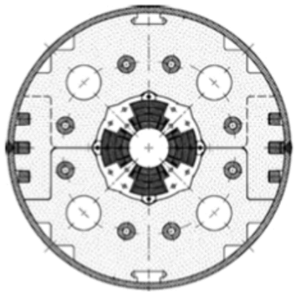
The block positioning accuracy is worst than in NbTi LHC dipole (~ x2)

Fiscarelli, L. et al.., 2016. Magnetic measurements and analysis of the first 11-T Nb 3 Sn dipole models developed at CERN for HL-LHC. *IEEE Transactions on Applied Superconductivity*, *26*(4), pp.1-5.

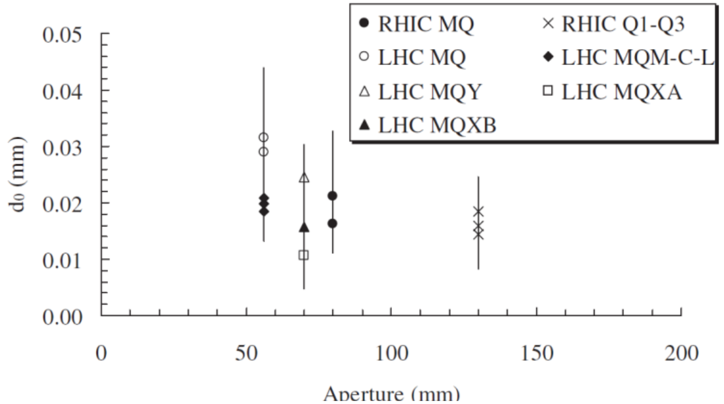
Fiscarelli, L., et al., 2016. Magnetic measurements and analysis of the first 11-T Nb3Sn 2-in-1 model for HL-LHC. *IEEE Transactions on Applied Superconductivity*, *27*(4), pp.1-4.

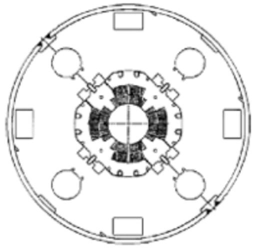
2. Magnetic Field Quality

Geometric field errors – IR quadrupoles

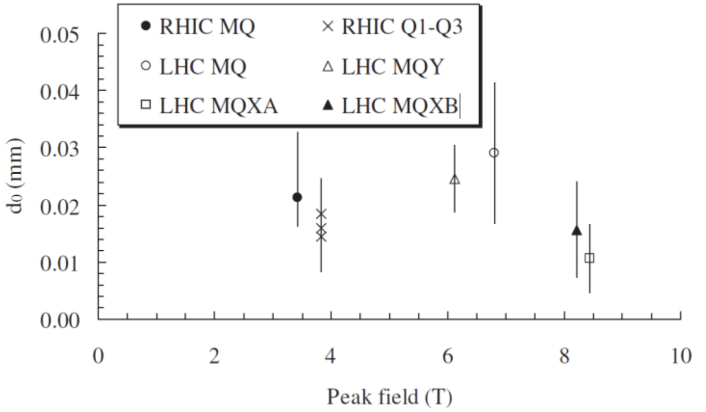


LHC MQXA



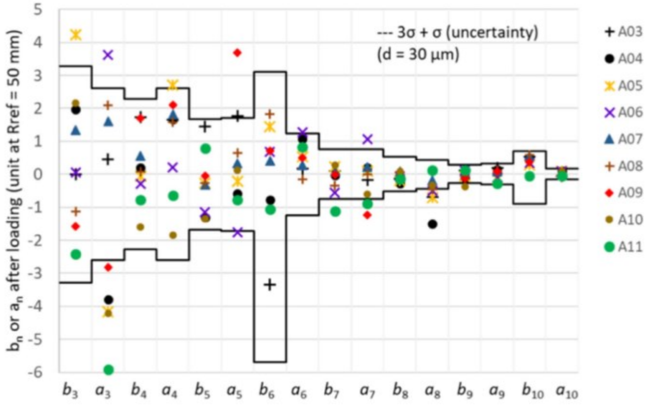


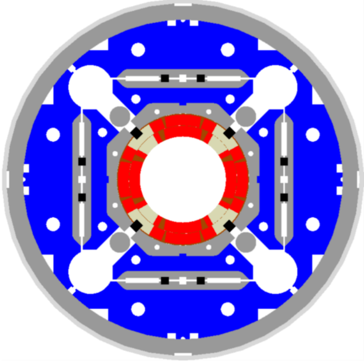
LHC MQXB



*First order estimate is 10-**20 microns** for block positioning accuracy in IR quadrupoles*

Bellesia, B., Koutchouk, J.P. and Todesco, E., 2007. Field quality in low-β superconducting quadrupoles and impact on the beam dynamics for the Large Hadron Collider upgrade. *Physical Review Special Topics-Accelerators and Beams*, *10*(6), p.062401.

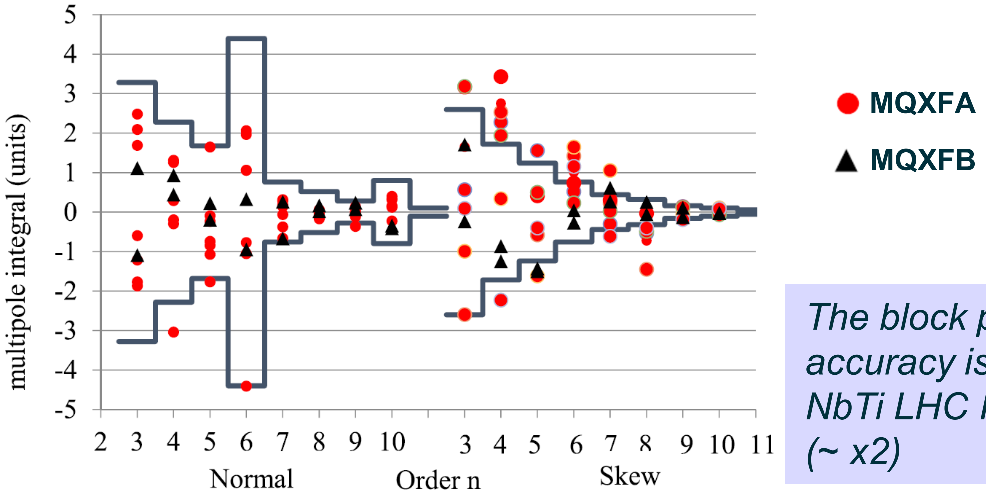




HL-LHC MQXF

Nb_3Sn, B_p = 11.3 T

Cheng, D.W., Ambrosio, G., Ferracin, P., Fajardo, L.G., Prestemon, S.O., Ray, K.L., Sabbi, G.L., Solis, M., Vallone, G. and Wang, X.R., 2023. The challenges and solutions of meeting the assembly specifications for the 4.5 m long MQXFA magnets for the Hi-Luminosity LHC. *IEEE Transactions on Applied Superconductivity*.

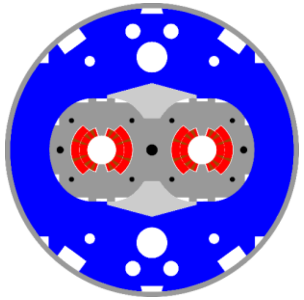


The block positioning accuracy is worst than in NbTi LHC IR quadrupoles (~ x2)

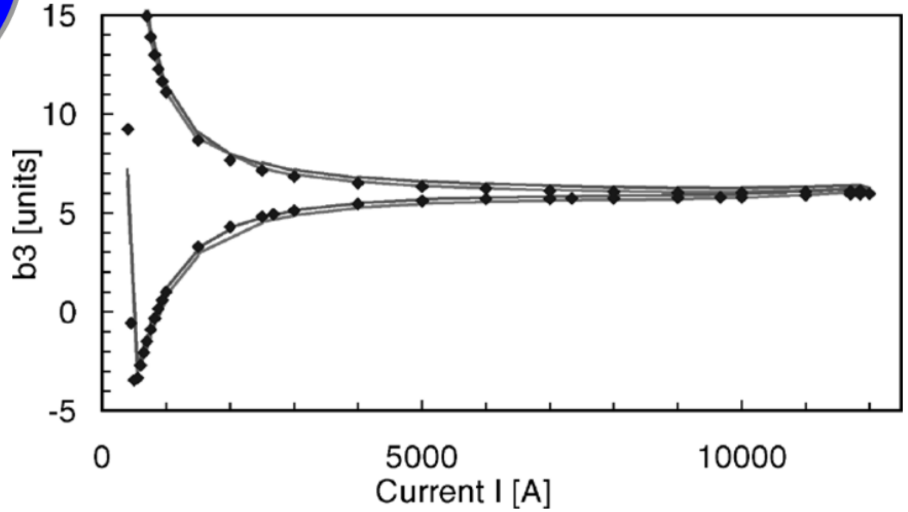
Todesco, E., Bermudez, S.I., Foussat, A., Gautheron, E., Kirby, G., Felice, H., Perez, J.C., Fleiter, J., Barth, C., Milanese, A. and Prin, H., 2023. Status and challenges of the interaction region magnets for HL-LHC. *IEEE Transactions on Applied Superconductivity*.

2. Magnetic Field Quality

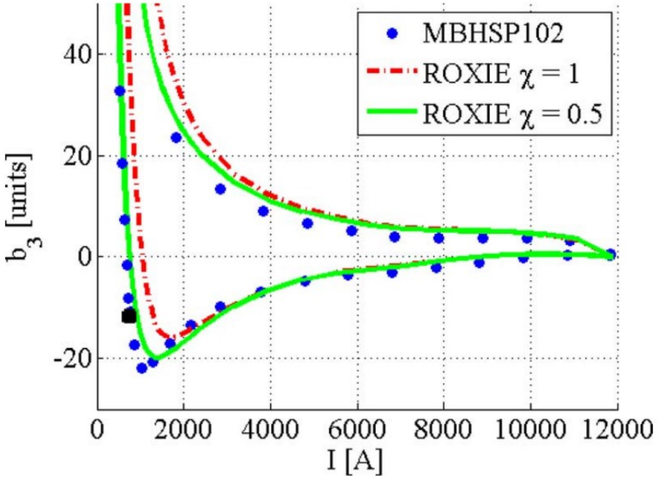
Magnetization effects (persistent currents) – NbTi and Nb_3Sn

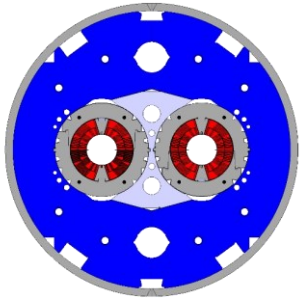


LHC MB
NbTi, B_p = 8.6 T



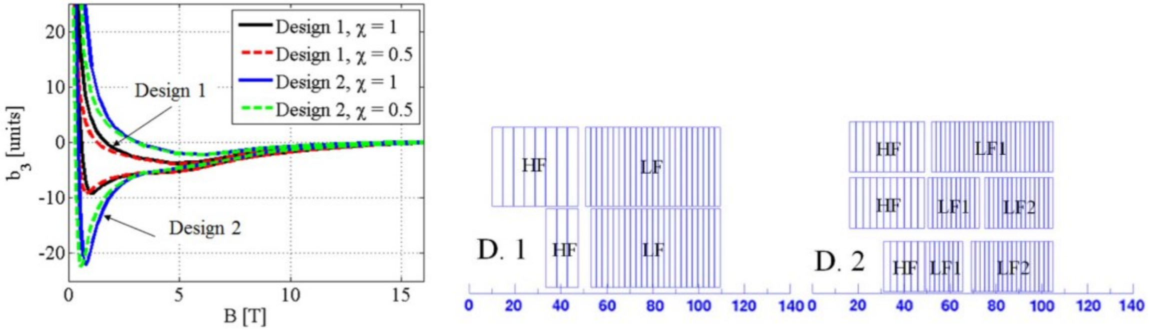
Bellesia, B., Bottura, L., Granata, V., Le Naour, S., Oberli, L., Sanfilippo, S., Santoni, C., Scandale, W., Schwerg, N., Todesco, E. and Vollinger, C., 2005. Trends in cable magnetization and persistent currents during the production of the main dipoles of the Large Hadron Collider. *IEEE transactions on applied superconductivity*, *15*(2), pp.1213-1216.





HL-LHC MBH 11 T
Nb_3Sn, B_p = 11.7 T

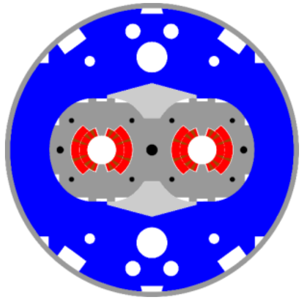
Bermudez, S.I., Bottura, L. and Todesco, E., 2016. Persistent-current magnetization effects in high-field superconducting accelerator magnets. *IEEE Transactions on Applied Superconductivity*, *26*(4), pp.1-5.



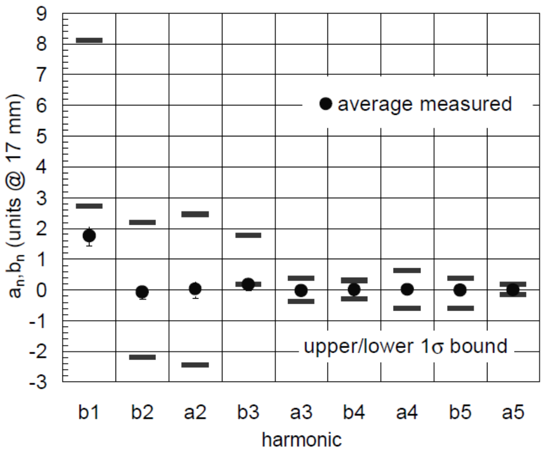
Larger magnetization in Nb3Sn due to coalescing of filaments within sub-element, effective filament size ~45-50 micron in RRP 108/127 at 0.7 mm diameter. However, this can be mitigated with coil design and precycle optimization.

2. Magnetic Field Quality

Magnetization effects (inter-strand coupling currents) – NbTi and Nb_3Sn

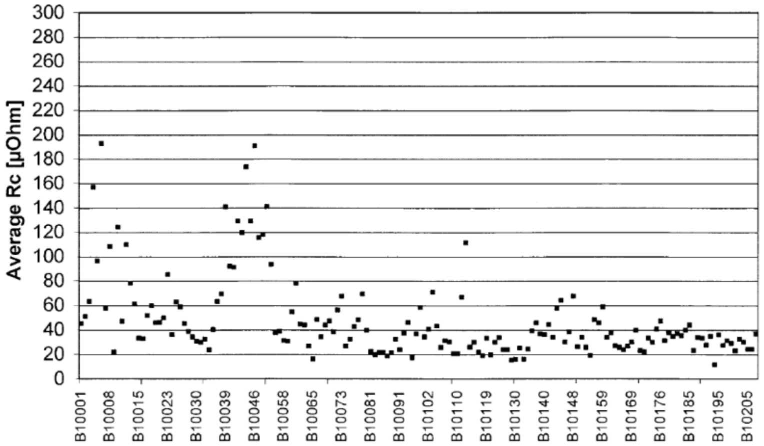


LHC MB
NbTi, B_p = 8.6 T



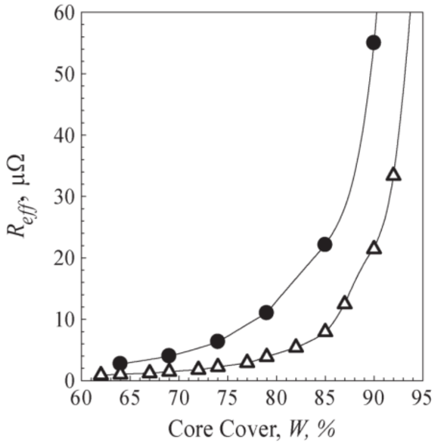
Aleksa, M., Amet, S., Ang, Z., Bottura, L., Buzio, M., Ferracin, P., Pagano, O., Remondino, V., Russenschuck, S., Sanfilippo, S. and Scandale, W., 2002. Measurement and analysis of the field quality of LHC prototype and pre-series superconducting dipoles. *IEEE transactions on applied superconductivity*, *12*(1), pp.247-250.

Small contribution at 10 A/s

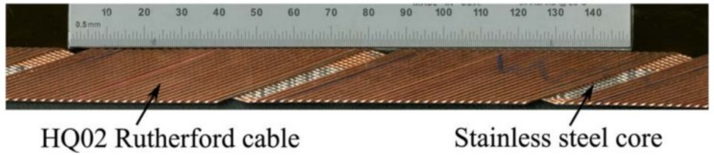


Rossi, L., 2003. The LHC main dipoles and quadrupoles toward series production. *IEEE transactions on applied superconductivity*, *13*(2), pp.1221-1228.

It is possible to reach an inter-strand resistance of 20-40 μΩ (acceptable 15-150 μΩ)



Collings, E.W., Sumption, M.D., Majoros, M., Wang, X. and Dietderich, D.R., 2015. Effects of Core Type, Placement, and Width on the Estimated Interstrand Coupling Properties of QXF-Type Nb 3 Sn Rutherford Cables. *IEEE Transactions on Applied Superconductivity*, *25*(3), pp.1-5.



RUTHERFORD CABLES FOR HQ01e AND HQ02a

Parameter	Unit	HQ01e	HQ02a
Strand number	-	35	
Core material	-	-	SS316L
Nominal strand diameter	mm	0.80	0.778
Cable pitch length	mm	102	95
Bare cable width	mm	15.15	14.77
Bare cable mid thickness	mm	1.437	1.376
Keystone angle	deg.	0.75	0.73
Twist pitch	mm	14±2	

COMPARISON OF THE DYNAMIC HARMONICS AT 13 A/s, 14 kA (UNIT AT R_{ref} = 40 mm). η IS THE COMPENSATION FACTOR

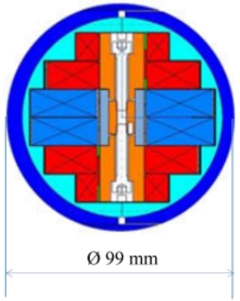
Harmonics	HQ01e	HQ02a	η
b_2	14.60	0.85	0.94
b_3	1.56	-0.12	1.08
b_4	0.43	0.04	0.90
b_5	0.21	-0.00	1.02
b_6	2.09	0.10	0.95
a_3	4.73	0.44	0.91
a_4	0.18	-0.14	1.75
a_5	0.52	0.12	0.77
a_6	-0.26	-0.04	0.84

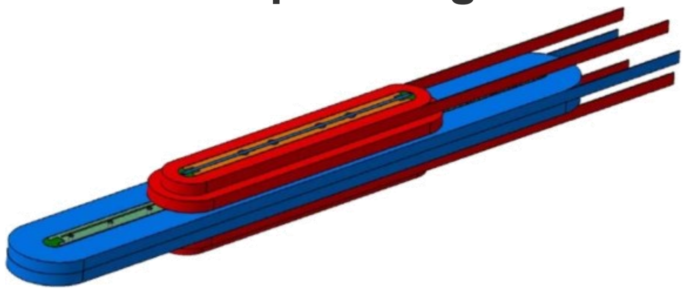
Wang, X., Ambrosio, G., Borgnolutti, F., Buehler, M., Chlachidze, G., Dietderich, D.R., DiMarco, J., Felice, H., Ferracin, P., Ghosh, A. and Godeke, A., 2013. Multipoles Induced by Inter-Strand Coupling Currents in LARP Nb3Sn Quadrupoles. *IEEE transactions on applied superconductivity*, *24*(3), pp.1-7.

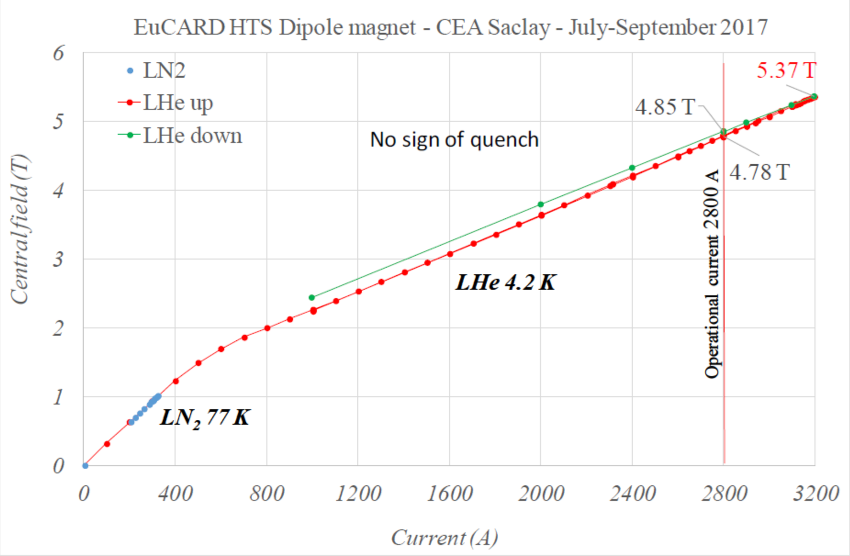
2. Magnetic Field Quality

Magnetization effects in REBCO-based magnets - Roebel examples

EuCARD 5.4-T REBCO Dipole Magnet

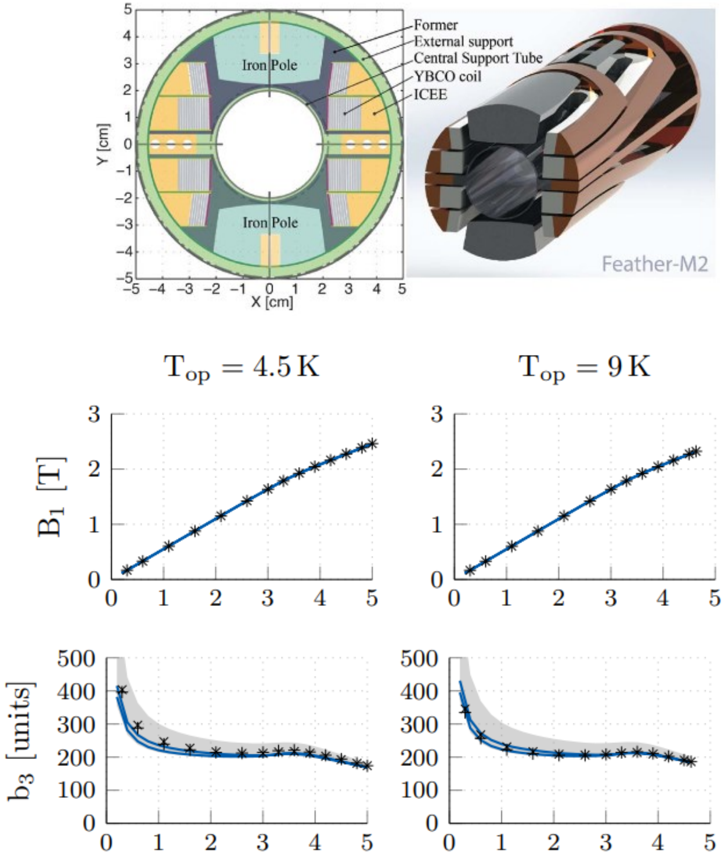






Durante et al. 2018. *IEEE* TAS 28 (3): 4203805

Feather-M2.1-2 REBCO Dipole Magnet

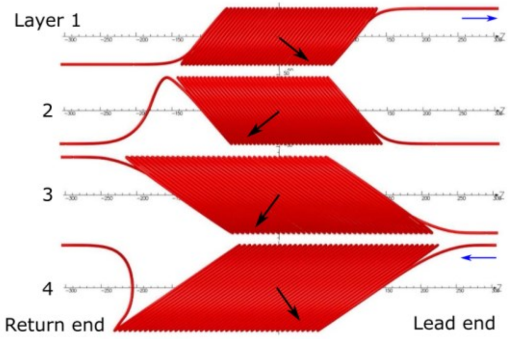


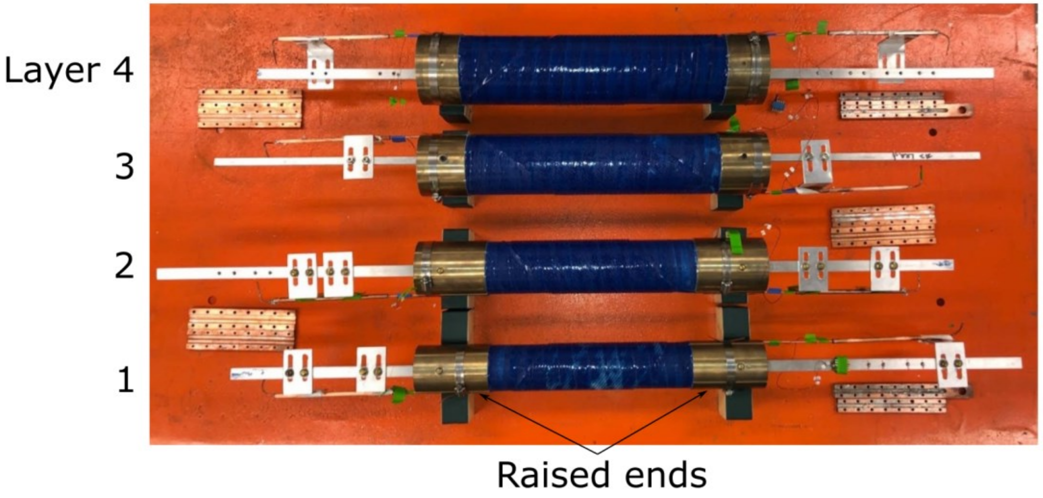
Bortot et al. 2020. SuST

2. Magnetic Field Quality

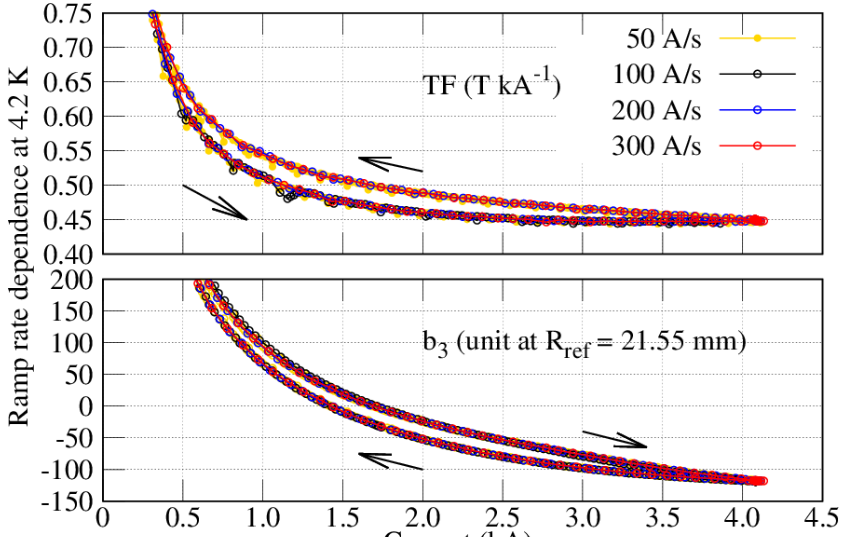
Magnetization effects in REBCO-based magnets - CORC example

C2 CORC CCT dipole magnet

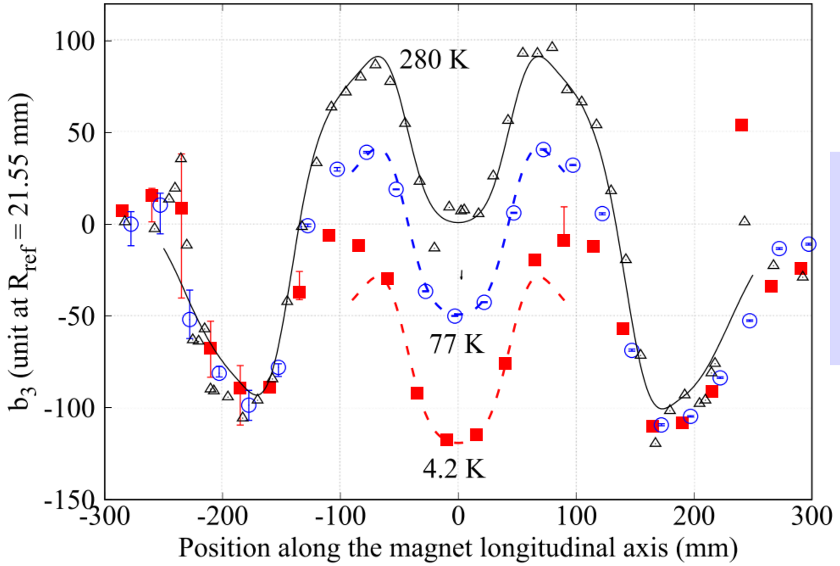




Wang et al., 2020. *SuST*.



Negligible ramp-rate dependence of the dipole transfer function and normal sextupole (b3) measured between 0.3 and 4.1 kA at 4.2 K



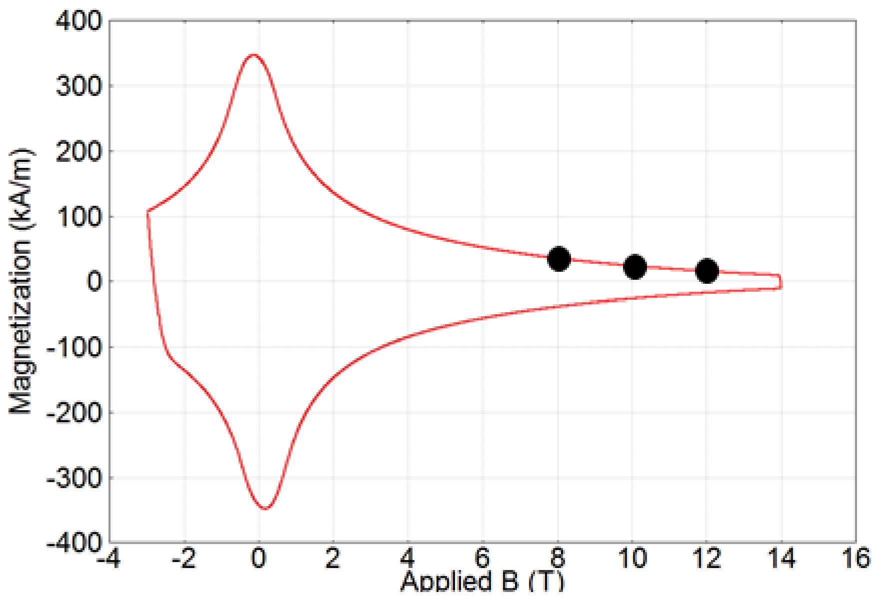
Measured and calculated normal sextupole (b3) along the magnet at 280 K with a current of 5 A (black triangle), 77 K with 200 A (blue circle) and 4.2 K with 4 kA (red square).

2. Magnetic Field Quality

Magnetization effects in REBCO-based magnets – A path to reduced magnetization

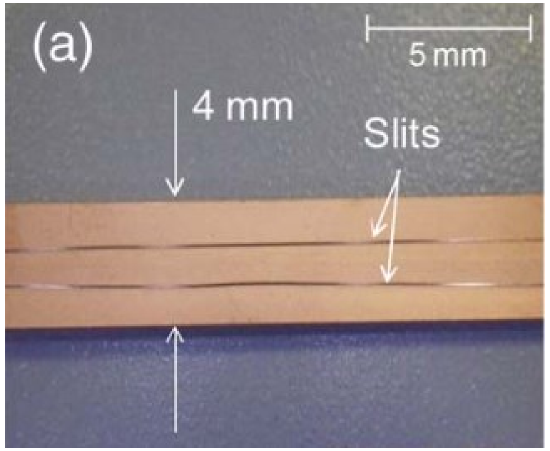
When the field fully penetrates the filament

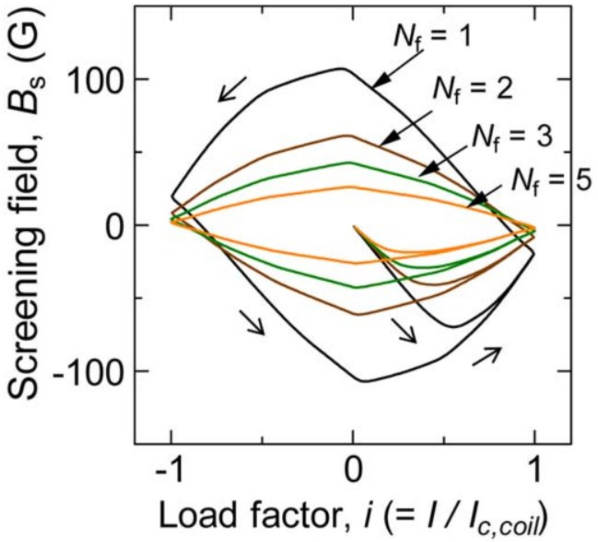
$M \propto J_c\, d$



Smaller size of superconductor can reduce magnetization

→ striation in REBCO tapes





Yanagisawa et al., 2015. *IEEE TAS* 25 (3): 6603705.
Amemiya et al., 2018. *SuST* 31 (2): 025007.
Kesgin et al., 2013. *APL* 103 (25): 252603.
Vojenčiak et al., 2015. *SuST* 28 (10): 104006.

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3. Magnetic Field Strength

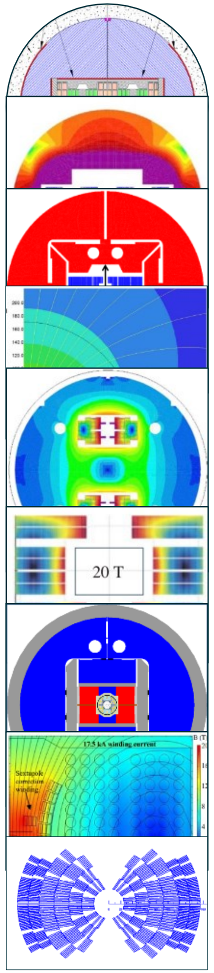
Path towards very high field accelerator magnets

Key factors in the design of future very high-field (>16 T) and large aperture (>100 mm) superconducting magnets:

- Ability to deal with high Lorentz forces and resulting strain-stress in the strain-sensitive conductor (i.e. **stress management structures**).
- **Efficient** use of the conductor to create a certain magnetic field (i.e. required length of conductor for an equivalent integrated field along the beam path). In terms of efficiency, the ability to implement “grading” is also crucial (cost).
- **Effective use of HTS** superconductors (i.e. magnet designs that could leverage all the potential of HTS superconductors without subjecting it to degradation due to required geometrical or manufacturing conditions).
- **Easiness**, **scalability**, and **cost-effective** manufacturing of the coil and magnet.

3. Magnetic Field Strength

Path towards very high field accelerator magnets



- 2005, P. McIntyre, *et al.*, 24 T hybrid for LHC tripler (TAMU)
- 2011, 2014, E. Todesco, *et al.*, 20 T hybrid for LHC upgrade (CERN)
- 2015, G. Sabbi, *et al.*, 20 T hybrid for SPPC China and FCC (LBNL)
- 2015, R. Gupta, *et al.*, 20 T hybrid for LHC upgrade (BNL)
- 2016, Q. Xu, *et al.*, 20 T hybrid for SPPC China (IHEP)
- 2018, J. van Nugteren, *et al.*, 20+ T HTS for LHC upgrade or FCC (CERN)
- 2020, D. Martins Araujo , *et al.*, towards 20 T FRESCA2+Feather (CERN)
- 2021, J.S. Rogers, *et al.*, 18 T hybrid (TAMU)
- 2022, P. Ferracin, *et al.*, 20 T hybrid demonstrator (US MDP)

3. Magnetic Field Strength

Path towards very high field accelerator magnets

Context – US Magnet Development Program

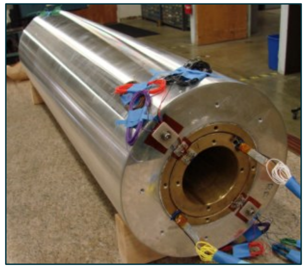
Hybrid LTS-HTS magnets

LBNL Hybrid Test (2023)

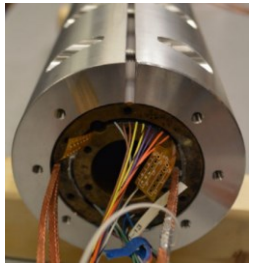
In development

Nb_3Sn Outserts

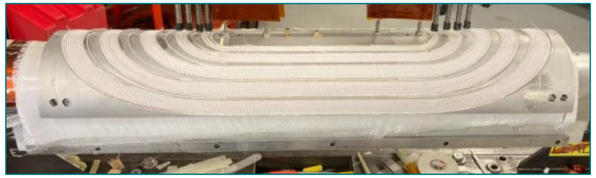
HTS Inserts



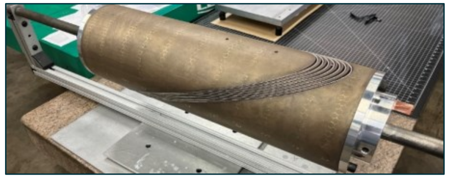
CCT5 as Nb_3Sn outsert
8-9 T in 90 mm aperture



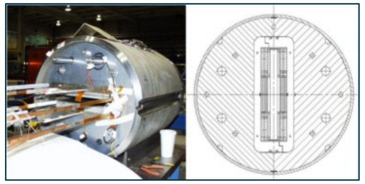
Bin5 as Nb_3Sn insert
1-2 T in 30 mm aperture



FNAL, SMCT
120 mm aperture (11-12 T)



LBNL, CCT6
120 mm aperture (11-12 T)



LBNL, REBCO CORC CCT (5 T)

FNAL, REBCO CORC COMB (~5 T)

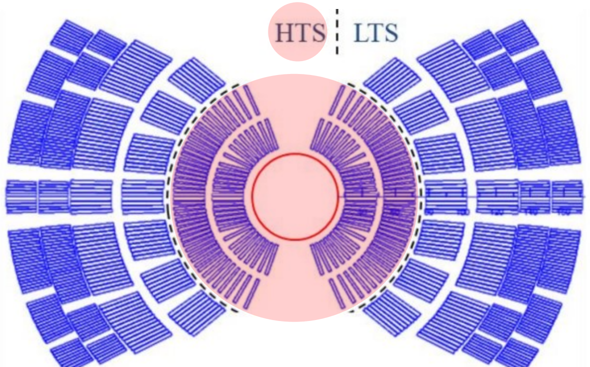
BNL, REBCO CORC CC insert

FNAL Bi2212 SMCT (~3 T)

LBNL, Bi2212 CCT (3-5 T)

Towards 20 T hybrid accelerator magnets

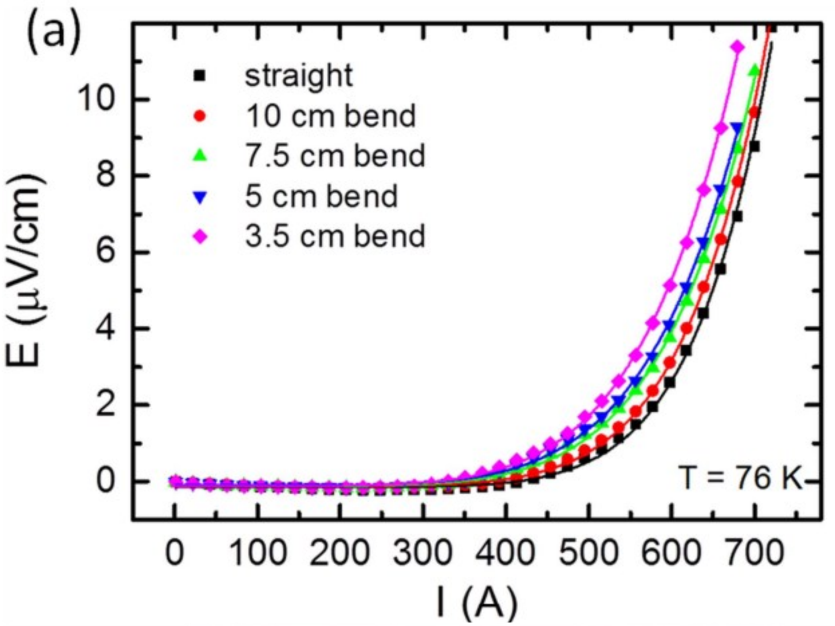
Ferracin, P., et al. "Conceptual design of 20 T hybrid accelerator dipole magnets." *IEEE Transactions on Applied Superconductivity* (2023).



Due to their intrinsic properties and cost, HTS conductors are more effectively used in the innermost layers.

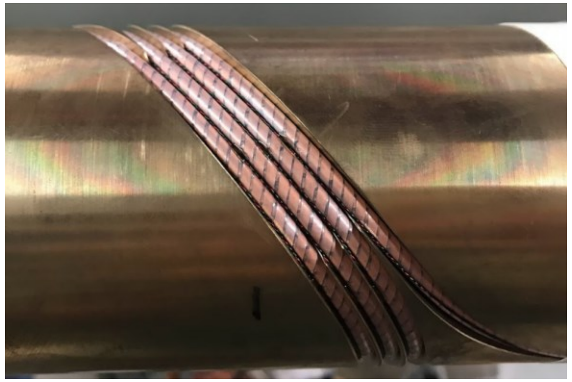
3. Magnetic Field Strength

Context – US Magnet Development Program

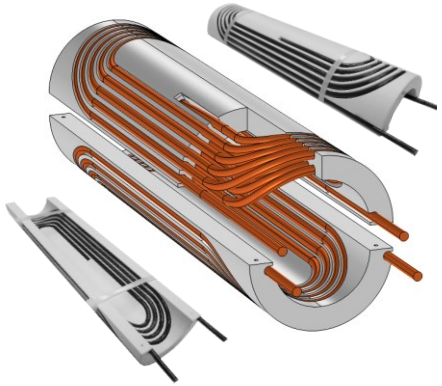


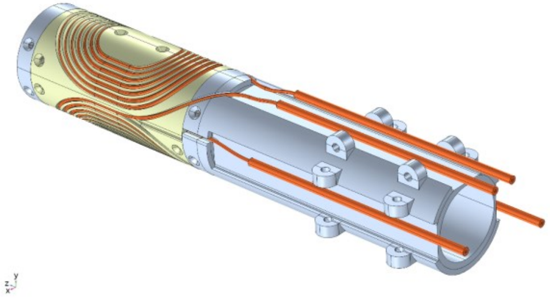
Weiss, Jeremy D., et al. "Introduction of CORC® wires: highly flexible, round high-temperature superconducting wires for magnet and power transmission applications." *Superconductor science and technology* 30.1 (2016): 014002.

CORC



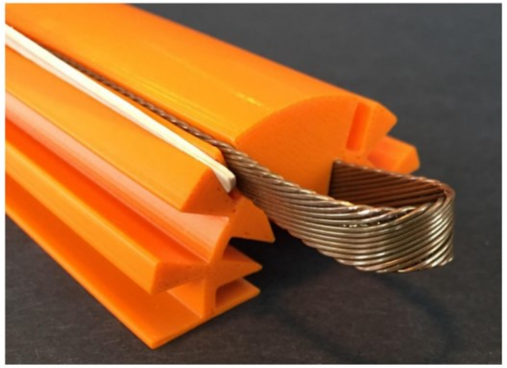
X. Wang (LBNL)

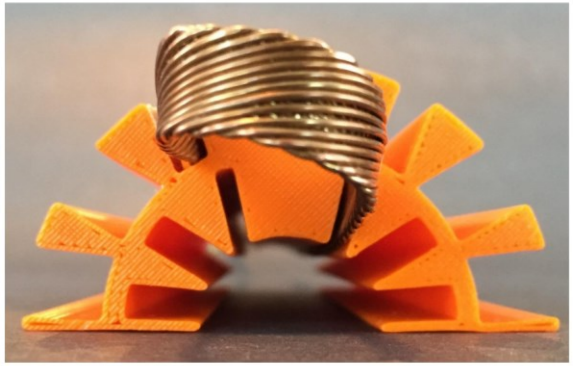




V. Kashikhin (Fermilab)

Bi2212





A. Zlobin *(Fermilab)*

3. Magnetic Field Strength

2024 | **2025** | **2026** | **2027**

***LBNL* HMB1**

Bi2212 CCT Bin5c insert (1.6 T, 30 mm)
Nb_3Sn CCT5 outsert (8-9 T, 90 mm)
Test late 2023

***FNAL* HMB1**

Bi2212 SMCT insert (4 T, 15 mm)
Nb_3Sn SMCT+MDPCT1-inner outsert (14-15 T, 60 mm)
Test in in 2025

***LBNL* HMB2**

Bi2212 CCT Bi-CCT1 (3-5 T, 40 mm)
Nb_3Sn CCT6 outsert (12-13 T, 120 mm)
To be tested in 2026

***LBNL* HMR1**

STAR CCT S1 (~1.2 T, 50 mm)
Nb_3Sn CCT5 outsert (8-9 T, 90 mm)
Test in 2024-2025

***LBNL* HMB3**

Bi2212 CCT Bi-CCT2 (4-7 T, 40 mm)
Nb_3Sn CCT6 outsert (12-13 T, 120 mm)
To be tested in 2027

***FNAL* HMR1**

CORC COMB (~5 T, 100 mm)
Nb_3Sn SMCT outsert (11 T, 120 mm)
Test in 2025

***LBNL* HMR2**

CORC CCT C4 (5 T, 50 mm)
Nb_3Sn CCT6 outsert (12-13 T, 120 mm)
To be tested in 2027

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4. Conclusions

- Field quality
  - Nb_3Sn represents the immediate future for collider magnets up to 16 T. The field quality requirements in accelerator magnets are reachable with this technology:
    - When looking at the Nb_3Sn-based dipoles and quadrupoles produced for the HL-LHC, the accuracy of the positioning of the conductor (i.e. ~ 50 μm) is a factor two higher than LHC NbTi-based magnets (i.e. ~ 25 μm).
    - The size of the filaments in Nb_3Sn conductor is ~ 50 μm (i.e. 10 times higher than LHC NbTi conductor) leading to higher magnetization effects (e.g. field error, losses).
  - HTS conductor represents the path for very high field magnets beyond 16 T:
    - REBCO-based magnets: significant R&D in the conductor and cable architecture is still necessary to mitigate the effects of the large magnetization on field errors and losses.
- Field strength
  - When aiming at very high-field (>16 T) and large aperture (>100 mm) superconducting magnets:
    - HTS conductor with good level of J_e is available but extensive R&D is required in relation to cables and coil fabrication in order to avoid current limitations (e.g. minimum bending radius of CORC).
    - Stress management concepts are necessary to deal with the very high e.m. forces.

Thanks