U.S. MAGNET DEVELOPMENT PROGRAM

Design limits for accelerator magnets

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First Collaboration Meeting of the Muon Collider Study
CERN, Switzerland
October 11-14, 2022

Acknowledgements/References

- Nb-Ti and Nb_3Sn
  - **E. Todesco**, “Masterclass - Design of superconducting magnets for particle accelerators”, https://indico.cern.ch/category/12408/
  - **P. Ferracin, M. Marchevsky, E. Todesco, S. Prestemon**, “Superconducting accelerator magnets”, www.uspas.fnal.gov.
  - **L. Rossi and Ezio Todesco**, “Electromagnetic design of superconducting dipoles and quadrupoles….”, *Phys. Rev. ST Accel. Beams 9 (2006) 102401 and Phys. Rev. ST Accel. Beams 10 (2007) 112401.*
  - **P. Fessia**, *et al.*, “Parametric Analysis of Forces and Stresses in Superconducting Dipoles (and quadrupole)”, *IEEE Trans. Appl. Supercond. Vol. 19, No. 3, June 2009 1203 (Vol. 19, No. 3, June 2009 1203).*
  - **E. Rochepault**, *et al.*, “The Use of Grading in Nb3Sn High-Field Block-Coil Dipoles”, *IEEE Trans. Appl. Supercond. Vol. 31, No. 4, June 2021 4001510*
  - **D. Schoerling**, *et al.*, “The 16 T Dipole Development Program for FCC and HE-LHC”, *IEEE Trans. Appl. Supercond. Vol. 19, No. 3, June 2009 1203.*
  - **Clement Genot**, *et al.*, “FCC-hh Conceptual Designs and Windability of the Main Quadrupoles”, *IEEE Trans. Appl. Supercond. Vol. 31, No. 2, March 2021, 4000107.*
  - “Nb_3Sn Accelerator Magnets”, edited by D. Schoerling and A. Zlobin, Springer Open, 2019.
  - “WAMSDO: Workshop on Accelerator Magnet Superconductors, Design and Optimization”, edited by E. Todesco, CERN-2013-006
  - “High-Luminosity Large Hadron Collider (HL-LHC): Technical design report”, CERN-2020-010.

Acknowledgements/References

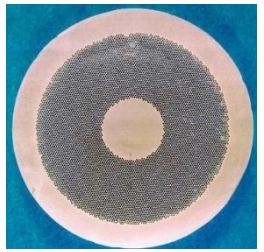
- Nb_3Sn limits and beyond (HTS)
  - Work from the US MDP working group on “20T hybrid dipoles”
    - “Towards 20 T Hybrid Accelerator Dipole Magnets”, *IEEE Trans. Appl. Supercond. Vol. 32, No. 6, Septemeber 2022, 4000906.*
  - US MDP
    - **S. Prestemon**, *et al*. “A Strategic Approach to Advance Magnet Technology for Next Generation Colliders”, submitted to the *Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)*
  - European Strategy for Particle Physics - Accelerator R&D Roadmap
    - **P. Védrine**, *et al.,* “High field magnets”

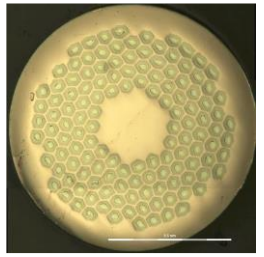
Outline

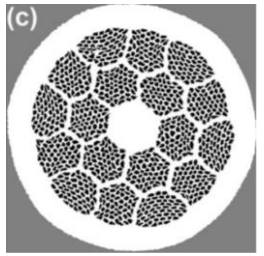
- Introduction on superconducting materials and field levels
- Performance limits
  - Field
  - Stress
  - Quench protection
- Cost
- Conclusions

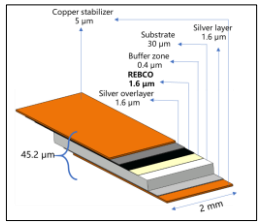
Introduction
Superconducting materials

- Nb-Ti
  - The “workhorse”, small filaments, ductile and cheap
- Nb_3Sn
  - Strain sensitive and brittle, reaction to ~650 °C, larger filaments
- Bi2212
  - Round strand -> cable, reaction to ~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 $B_{\perp}$)





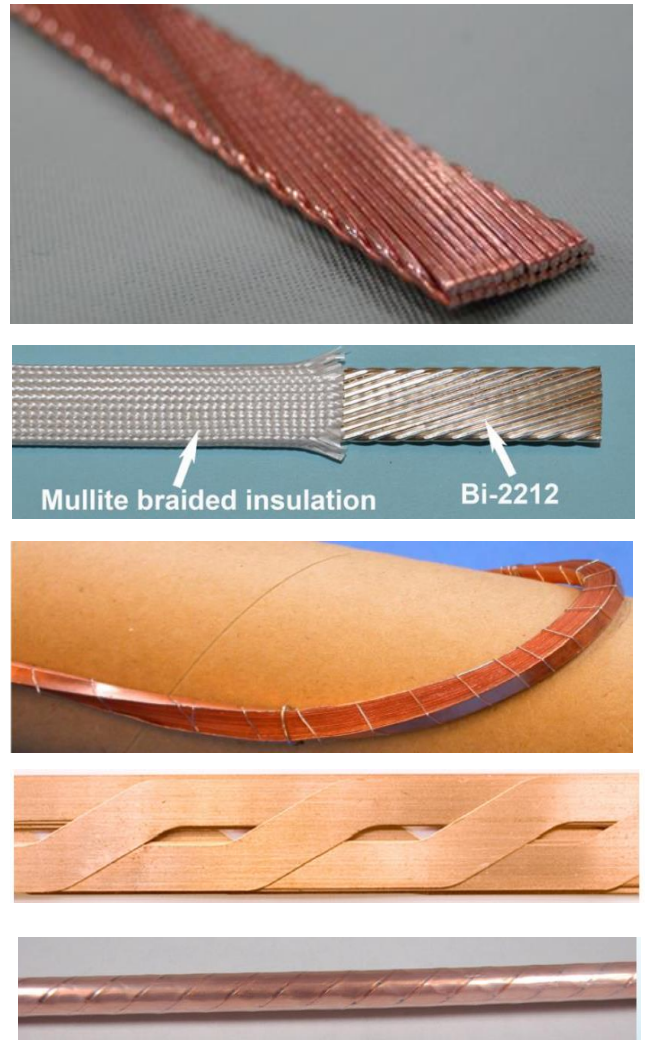




Introduction
Superconducting cables

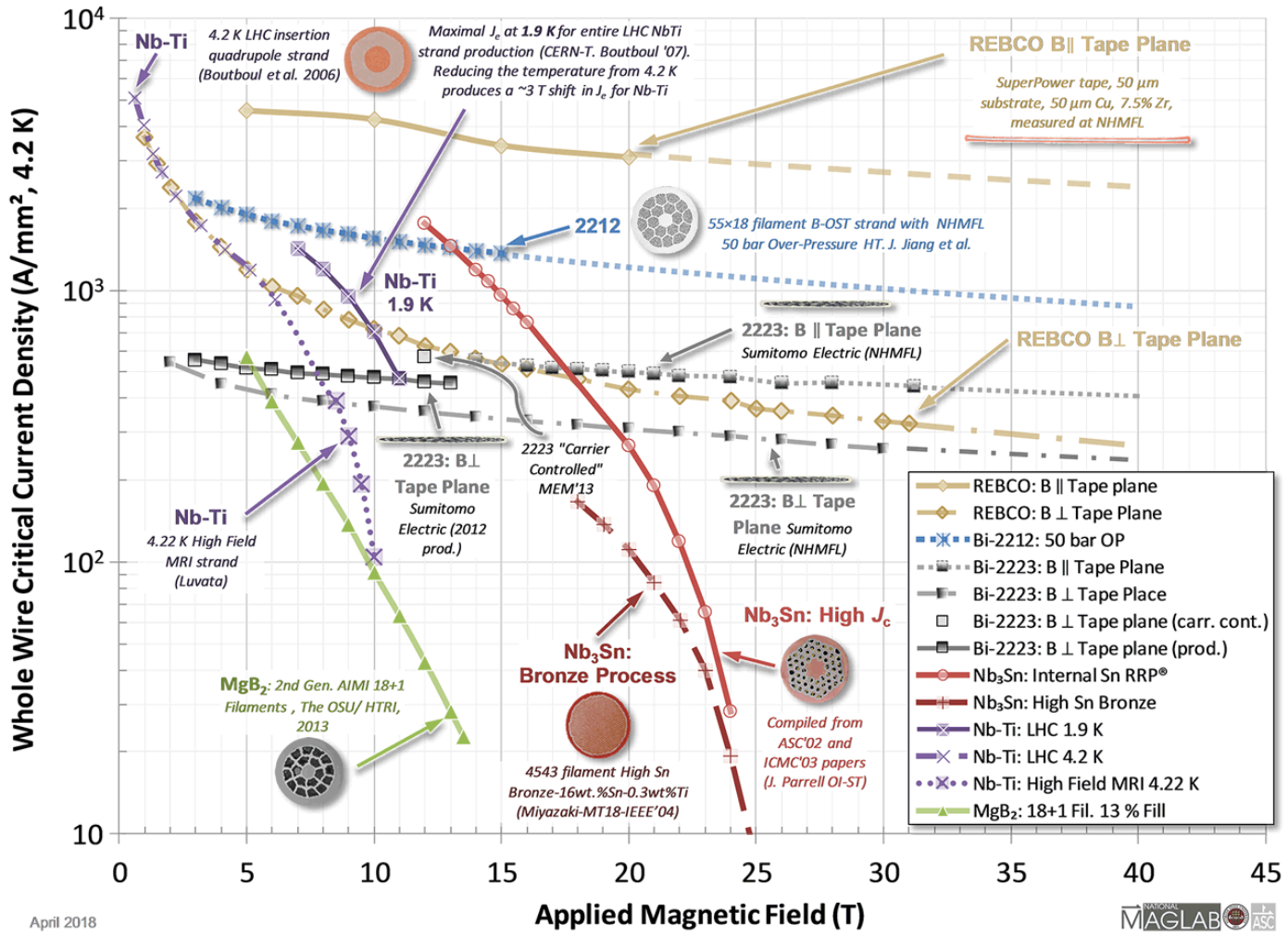
- Multi-wire Rutherford cable
  - Used for Nb-Ti, Nb_3Sn, and Bi2212
    - In theory, similar designs, independently on strand material
    - Compaction progressively reduces from Nb-Ti to Bi2212

- Significant R&D on cables with REBCO tapes
  - Twisted stacks
  - Roeble
  - CORC

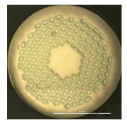


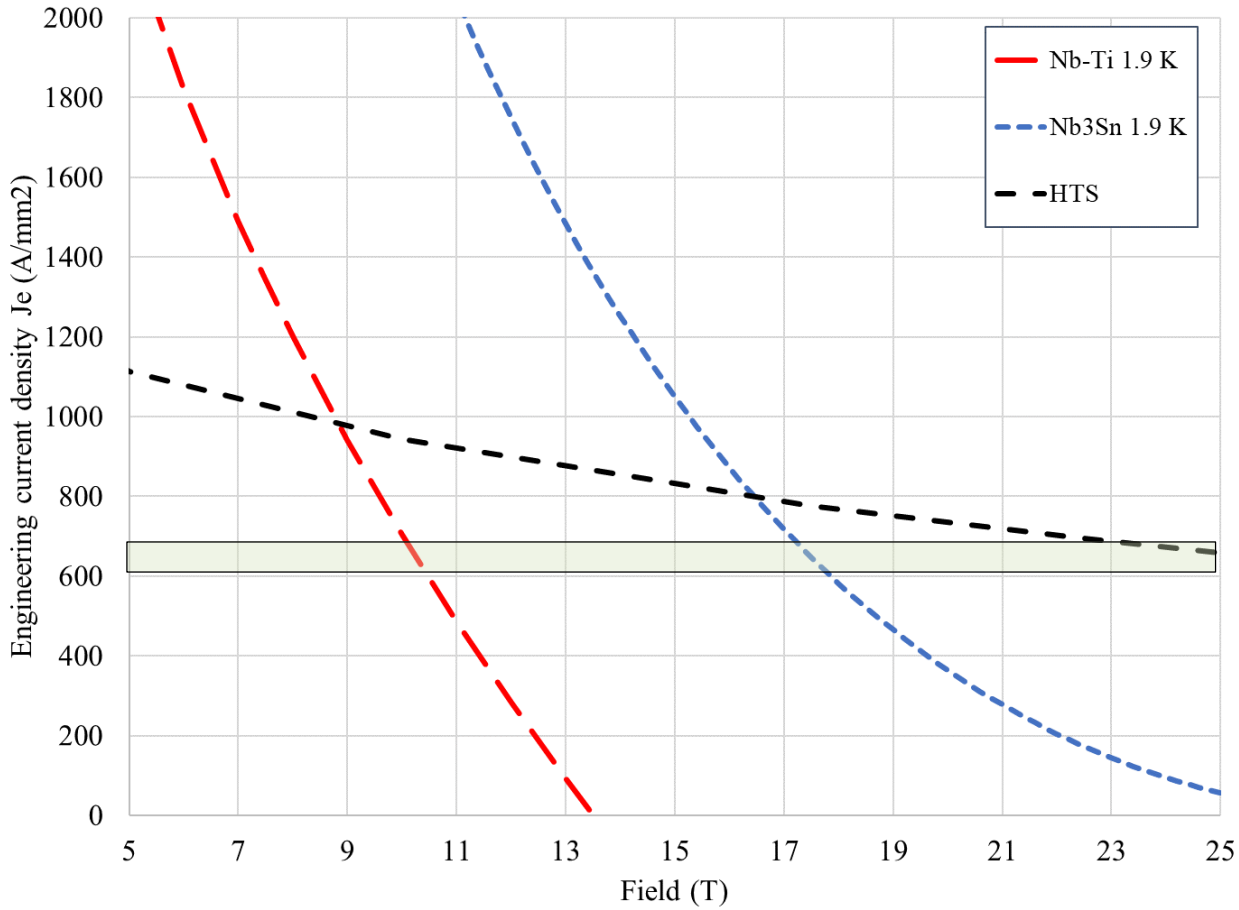
D. Uglietti, *et al.,* "A review of commercial high temperature superconducting materials for large magnets: from wires and tapes to cables and conductors", ***2019 Supercond. Sci. Technol. 32 053001***

Introduction
Superconductor critical curves



Superconductor critical curves: a simpler version

- $J_e = J_{engineering} = I_{strand} / A_{strand}$ 
  - Typical values for acc. magnets in operational conditions
    - ~ 600-700 A/mm
- "Realistic" superconducting properties
  - At J_e of 600-700 A/mm
    - Nb-Ti at ~10 T
    - Nb_3Sn at ~17 T
    - Bi2212 at 23-25 T
    - REBCO: compared to Bi2212, lower properties in ⊥ direction, but much better //

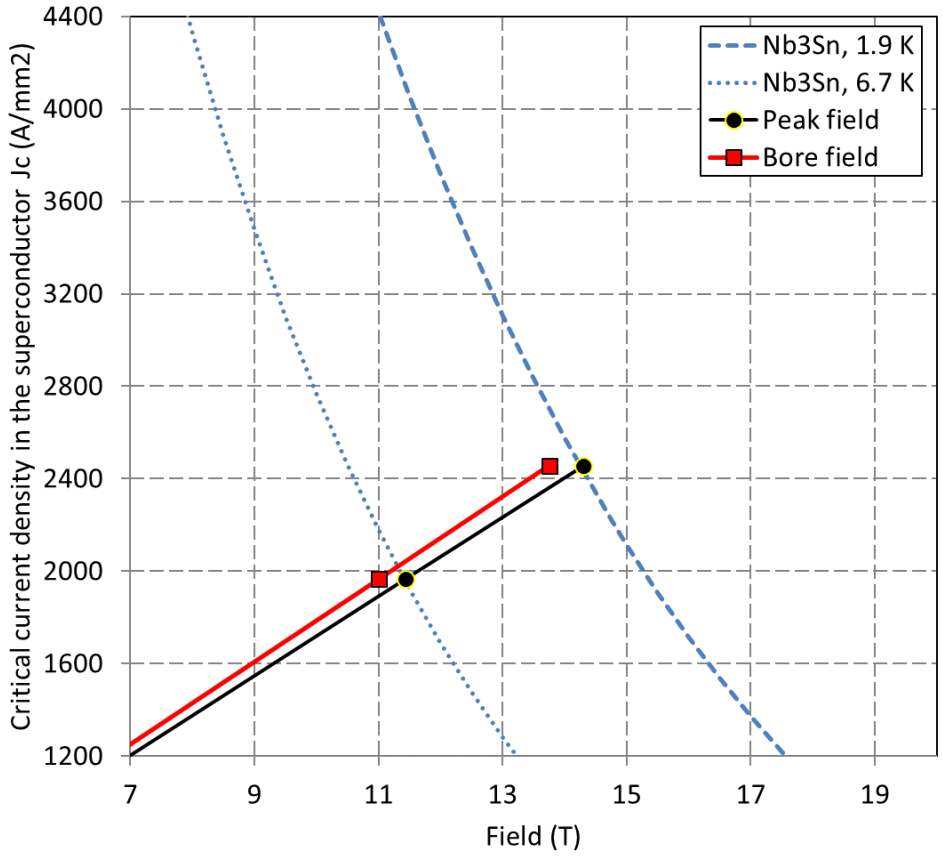


Outline

- Introduction on superconducting materials and field levels
- Performance limits
  - Field
  - Stress
  - Quench protection
- Cost
- Conclusions

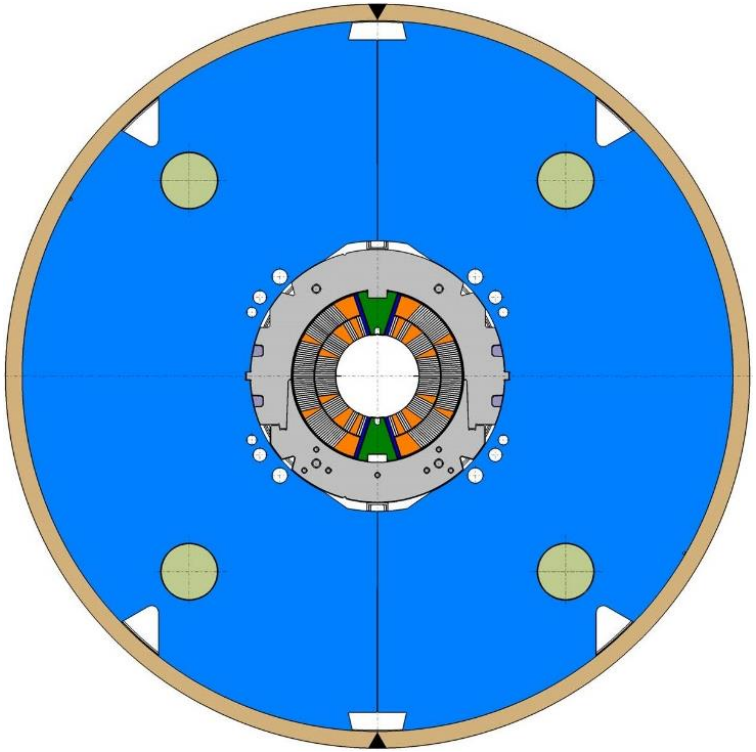
Field limits

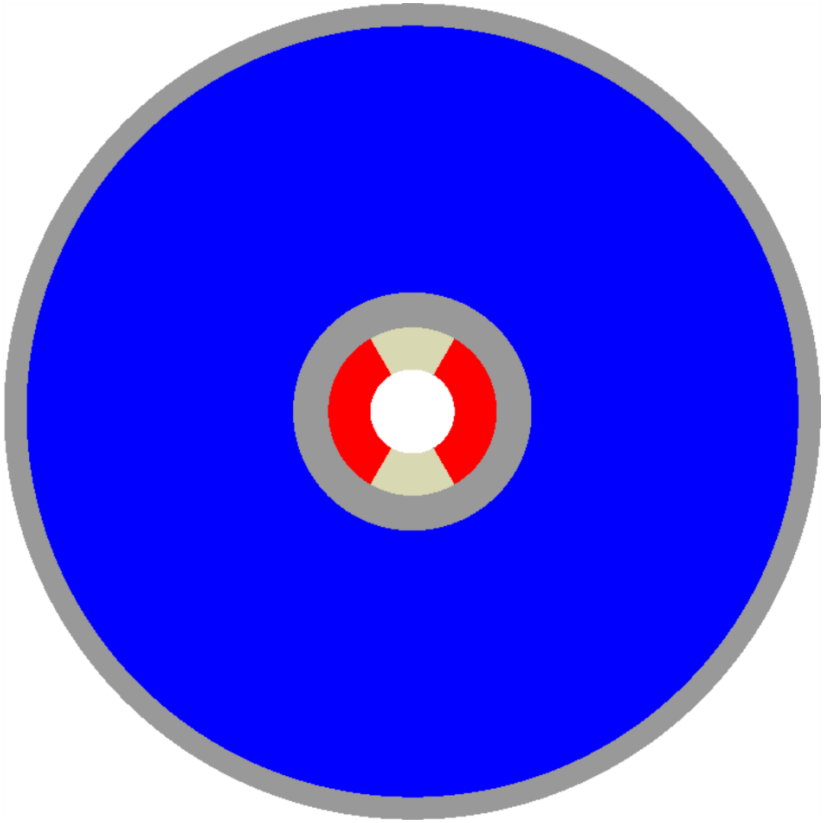
- Two important caveats before looking at the limits:
  - Bore field vs coil field: usually ~4-5% lost
  - Magnet usually operate at a certain "distance" from the critical surface
    - $I_{op} < I_{max}$ (or $I_{short\ sample}$)
    - Along the load-line, the I_{op}/I_{max} ratio is typically in the 70-90 % level
      - LHC (Nb-Ti): 87 %
      - HL-LHC (Nb_3Sn): 77%
    - Load-line margin is T margin
      - 80% with Nb3Sn → 4-5 K
    - One of the most critical (and discussed) decision at the beginning of the design
      - Strongly related to cost and performance



Field limits

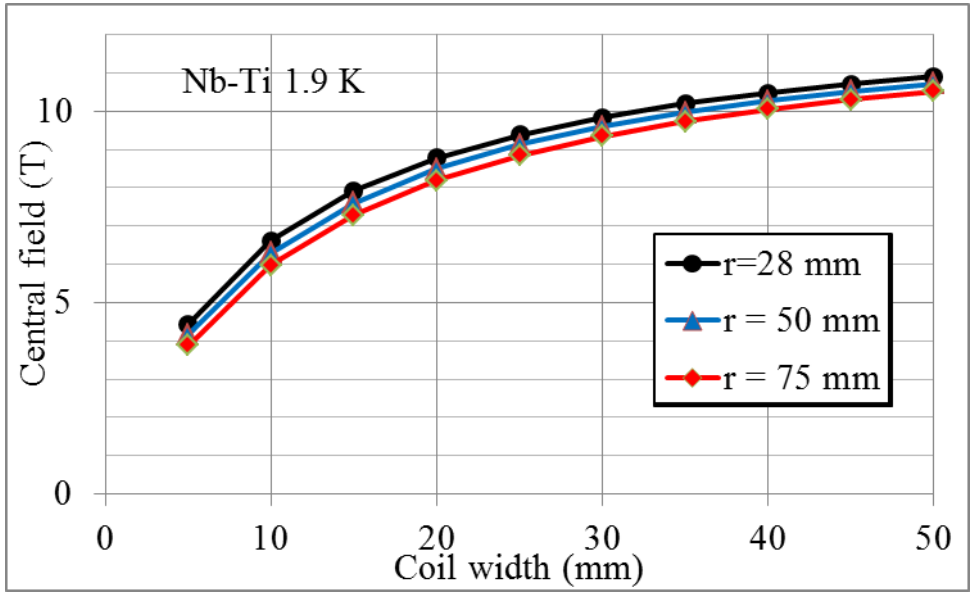
- Estimates of the limits obtained with “sector coils”
  - Both analytically and numerically

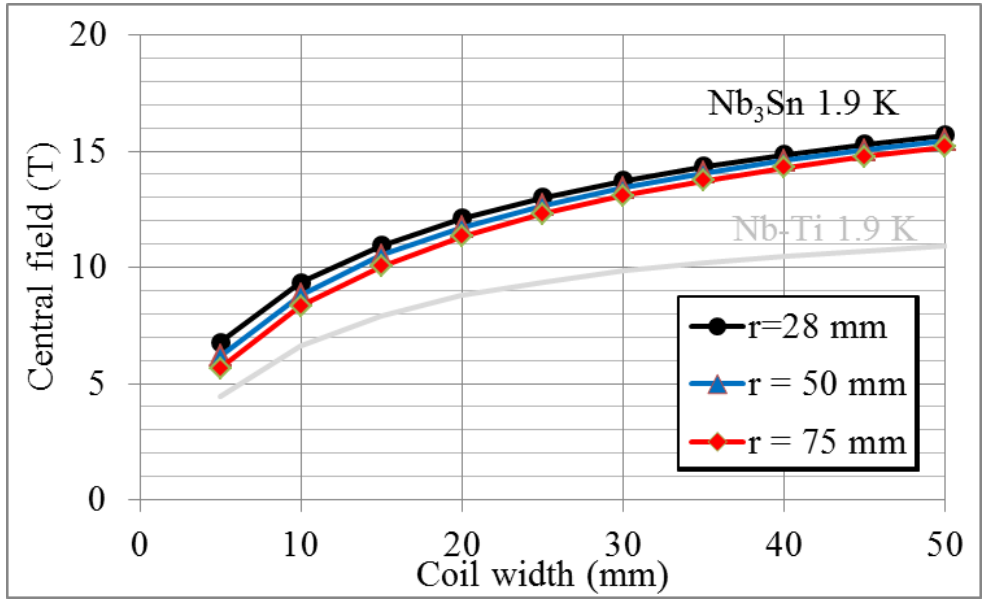




Field limits: Nb-Ti and Nb_3Sn dipole magnet

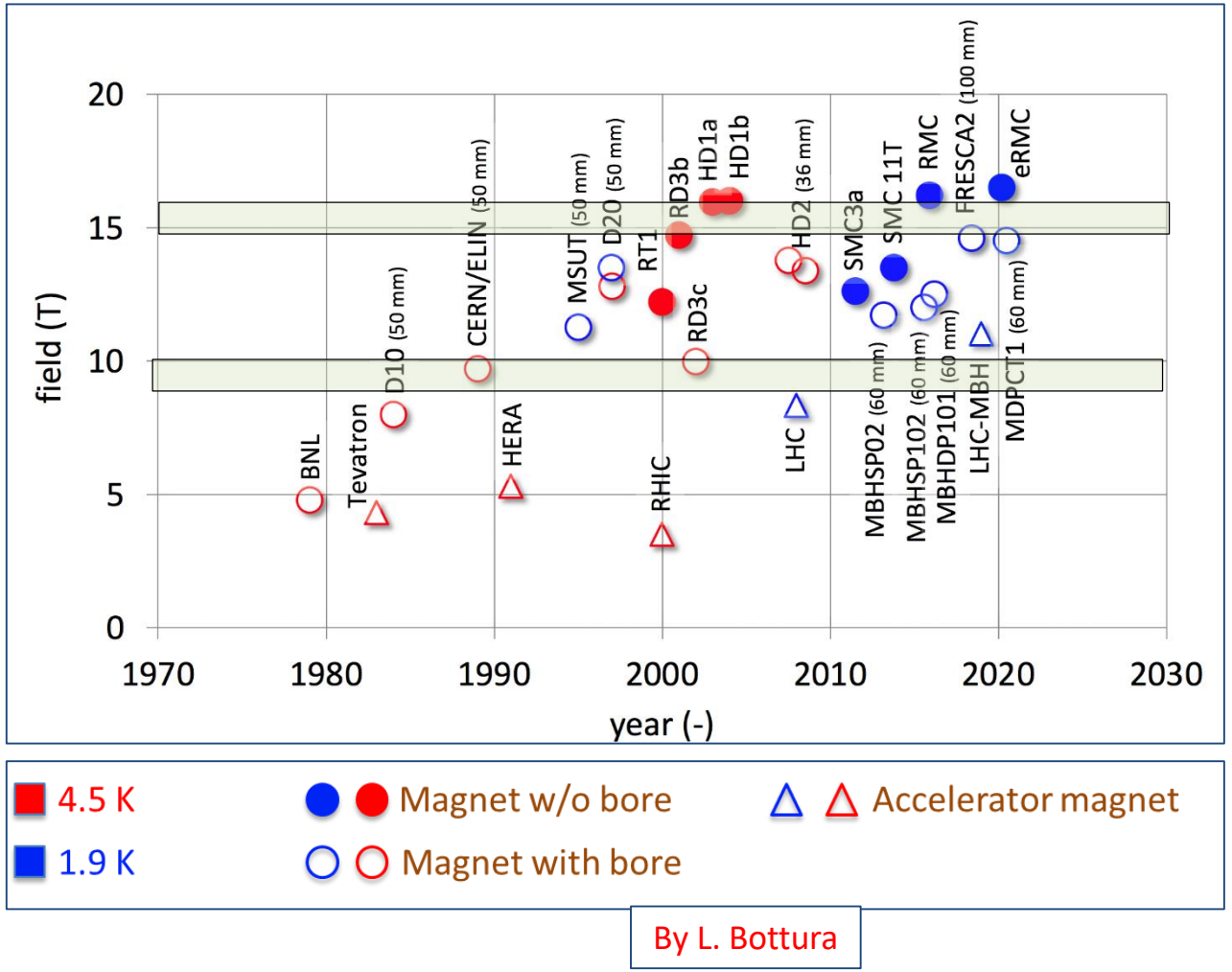
- In general, the larger the coils, the higher the field, but up to a point
- Practical limits: 9-10 T for Nb-Ti, 15-16 T for Nb_3Sn





L. Rossi and E. Todesco, "Electromagnetic design of superconducting dipoles based on sector coils", ***Phys. Rev. ST Accel. Beams 9 (2006) 102401***

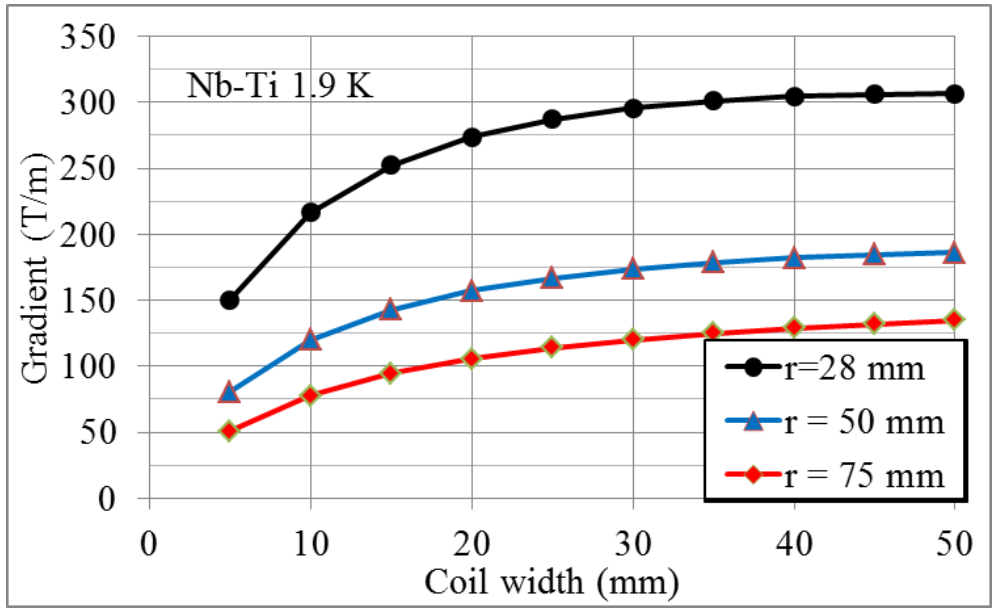
Field limits: Nb-Ti and Nb_3Sn dipole magnet

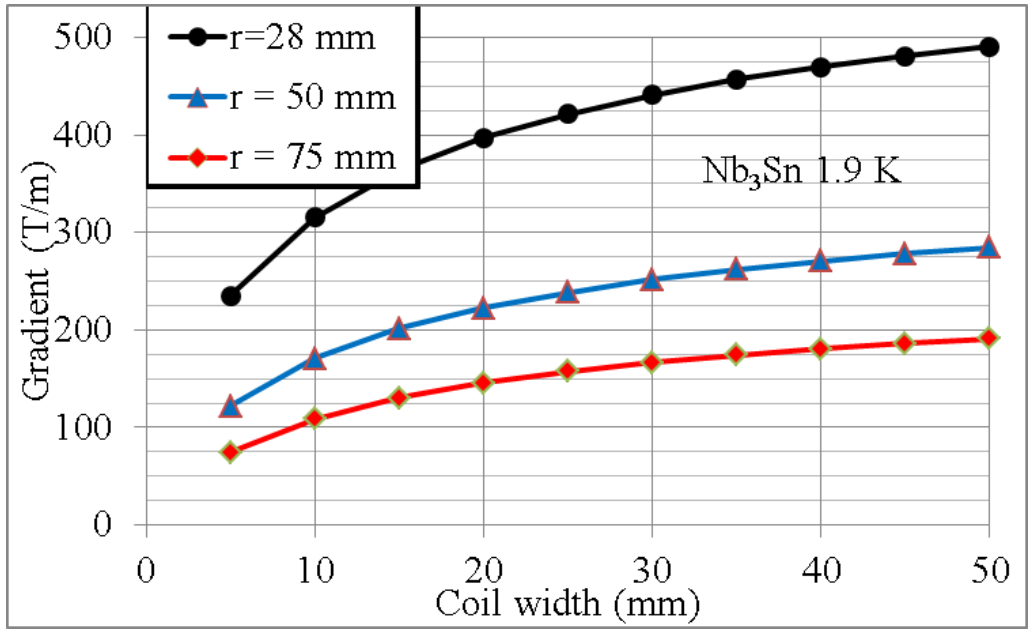


By L. Bottura

Field limits: Nb-Ti and Nb_3Sn quad. magnet

- Quadrupole: gradients saturate for large coils
  - Unlike dipoles, no point in making coils extremely wide

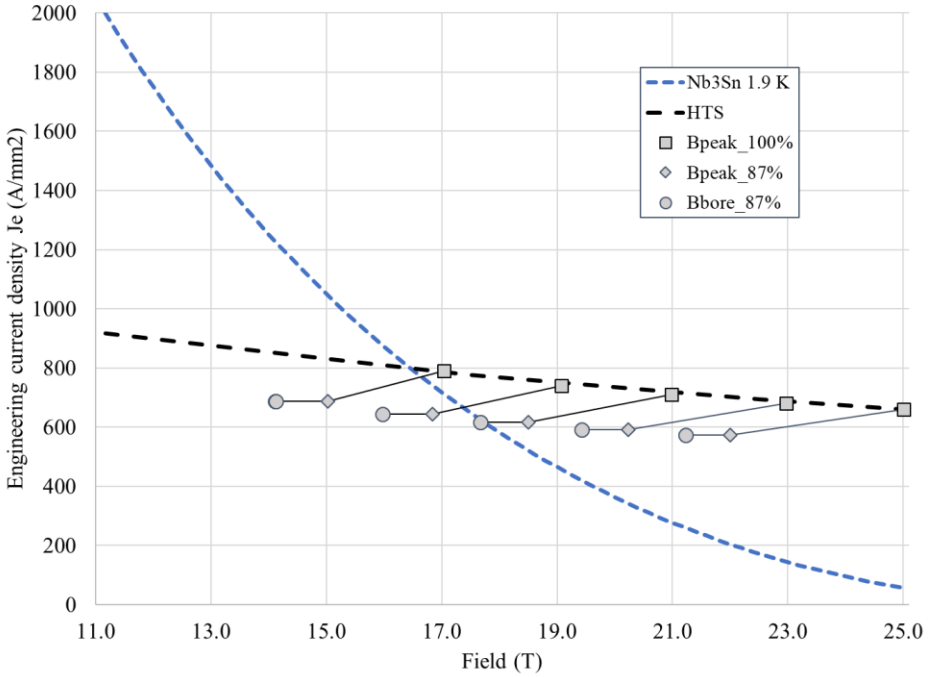


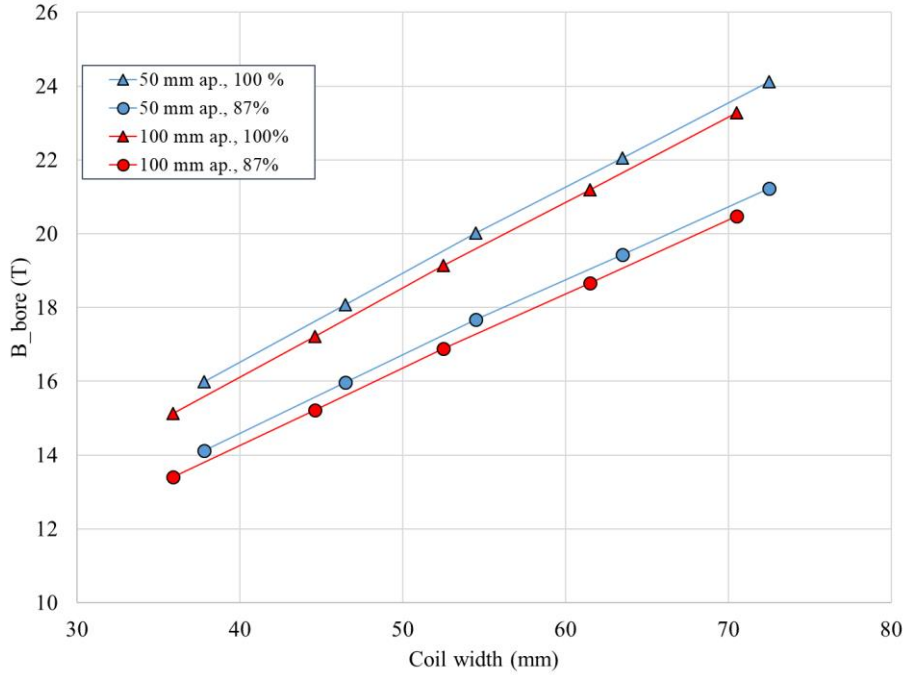


L. Rossi, E. Todesco, "Electromagnetic design of superconducting quadrupoles", ***Phys. Rev. ST Accel. Beams 10 (2007) 112401.***

Field limits beyond Nb_3Sn: HTS

- Let's assume, optimistically, I_{op}/I_{max} ratio of 87% level, and again, sector coils
  - More linear behavior, due to the "flat" HTS critical curve
  - No significant dependence on aperture
  - For 20 T bore field, coil 70+ mm wide (for the LHC and HL-LHC is about 30 mm)





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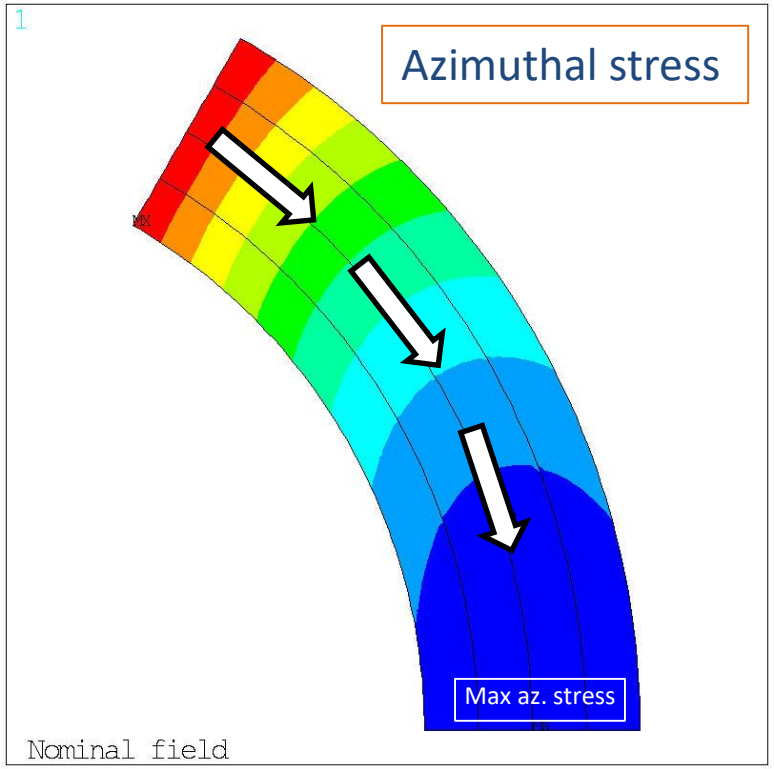
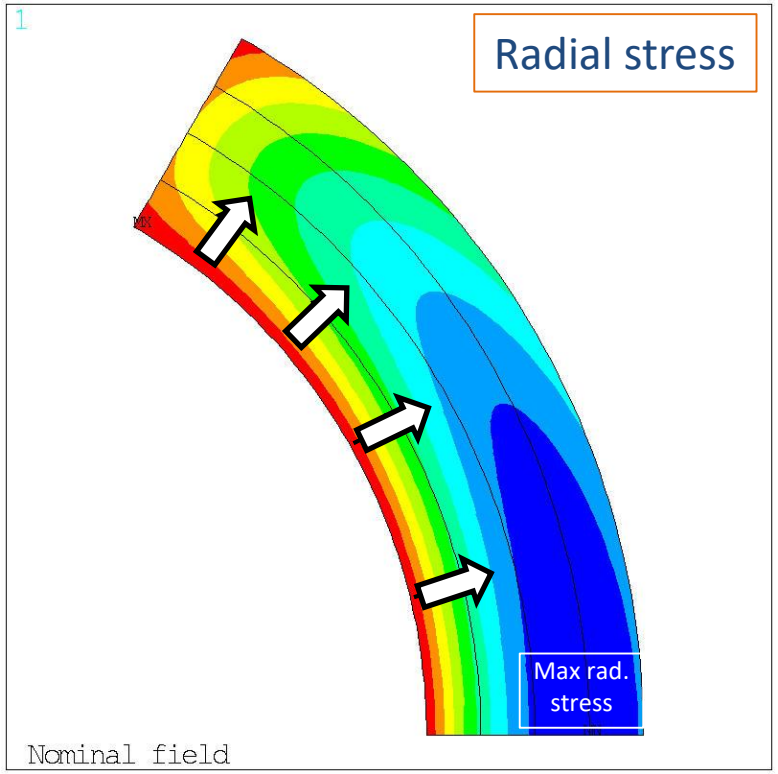
Stress limits

- Stress in superconducting coils
  - Accumulation of azimuthal and radial electro-magnetic forces





Stress limits

- Nb-Ti: ~150 MPa
  - Mainly to avoid polyimide insulation damage
- Nb_3Sn: ~150 MPa
  - Exact level still under investigation

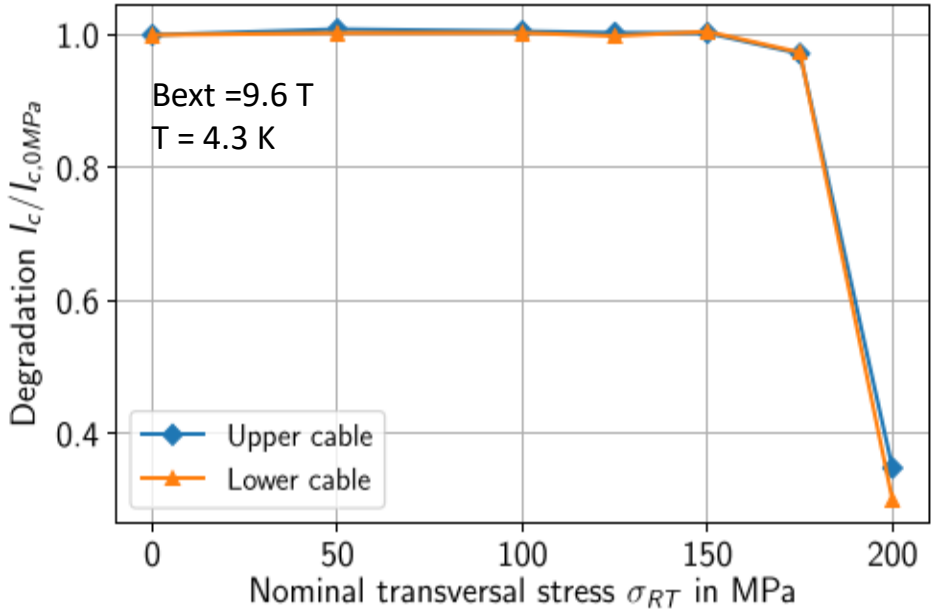
P. Ebermann, *et al.*, ***2018 Supercond. Sci. Technol. 31 065009***

- Bi2212: ~120 MPa
  - Again, to be determined

D.R. Dietderich, *et al.*, ***Physica C 341-348 (2000) 2599-2600***

- REBCO
  - In general tape is extremely robust, but cable less
  - In US MDP, a indicative value of 120 MPa was assumed

D.C. van der Laan, *et al.*, ***2019 Supercond. Sci. Technol. 32 010002***



Stress limits: Nb-Ti and Nb_3Sn dipole magnets

- Dipole: "*in order to respect the limit of 150 MPa at the short sample limit, apertures radii 30 mm are advisable, unless a large coil is adopted*"
- Quad: "*the stress in aperture radii smaller than 60 mm is below 150 MPa,*"

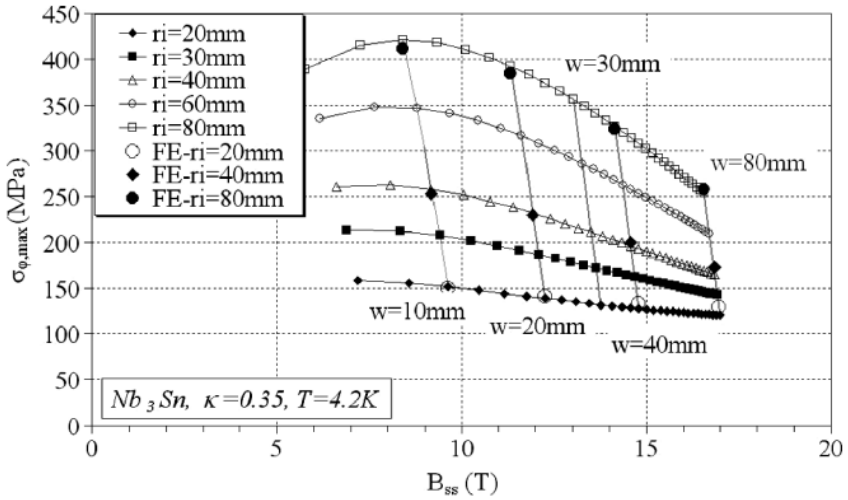


Fig. 4. Maximum compressive stress on coil mid plane $\sigma_{\varphi,max}$ vs. bore field B_0 at short sample condition for a Nb_3Sn cable and comparison with numerical results.

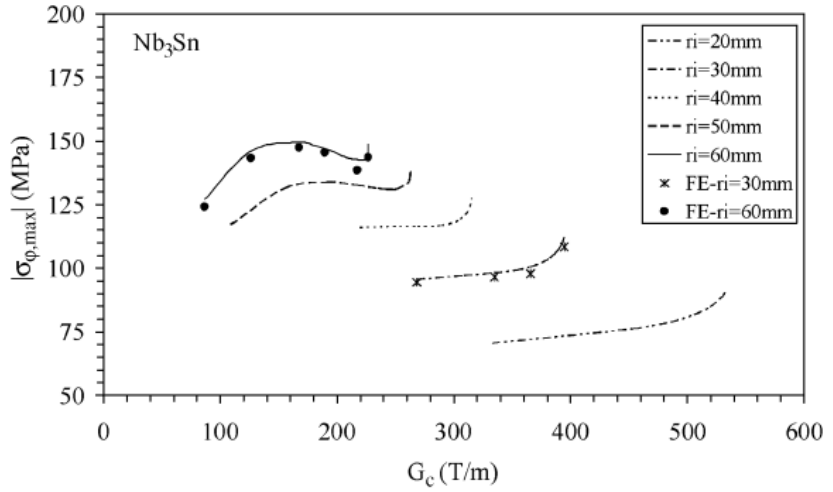
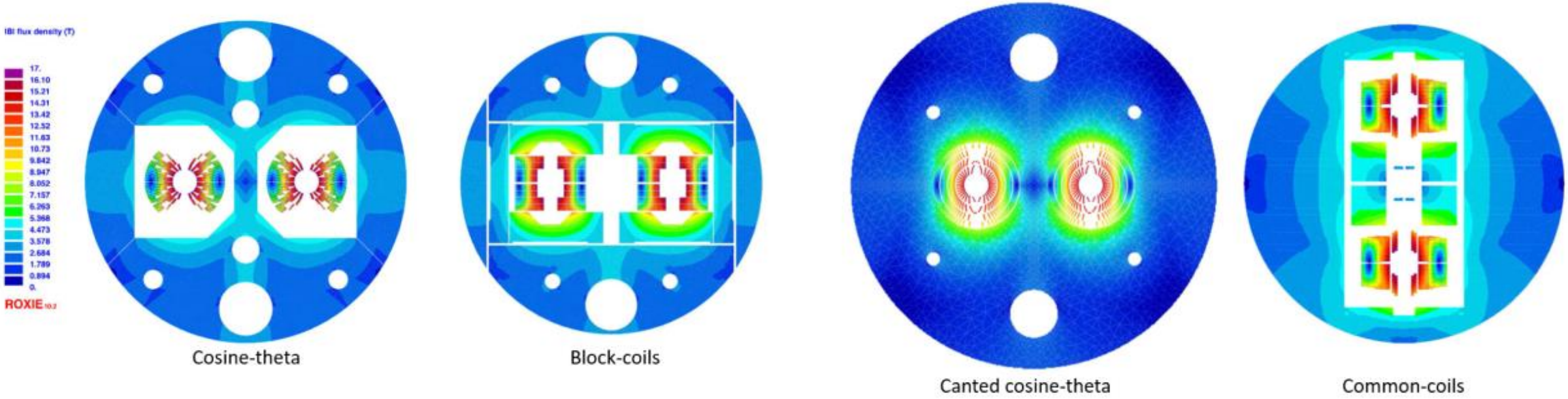


Fig. 5. Maximum azimuthal compressive stress on coil mid plane for different coil layouts considering a Nb_3Sn cable (constant aperture radius). $T = 4.2$ K.

P. Fessia, *et al.*, "Parametric Analysis of Forces and Stresses in Superconducting Dipoles (and quadrupole)", ***IEEE Trans. Appl. Supercond. Vol. 19, No. 3, June 2009 1203 (Vol. 19, No. 3, June 2009 1203).***

Stress limits: Nb-Ti and Nb_3Sn dipole magnets

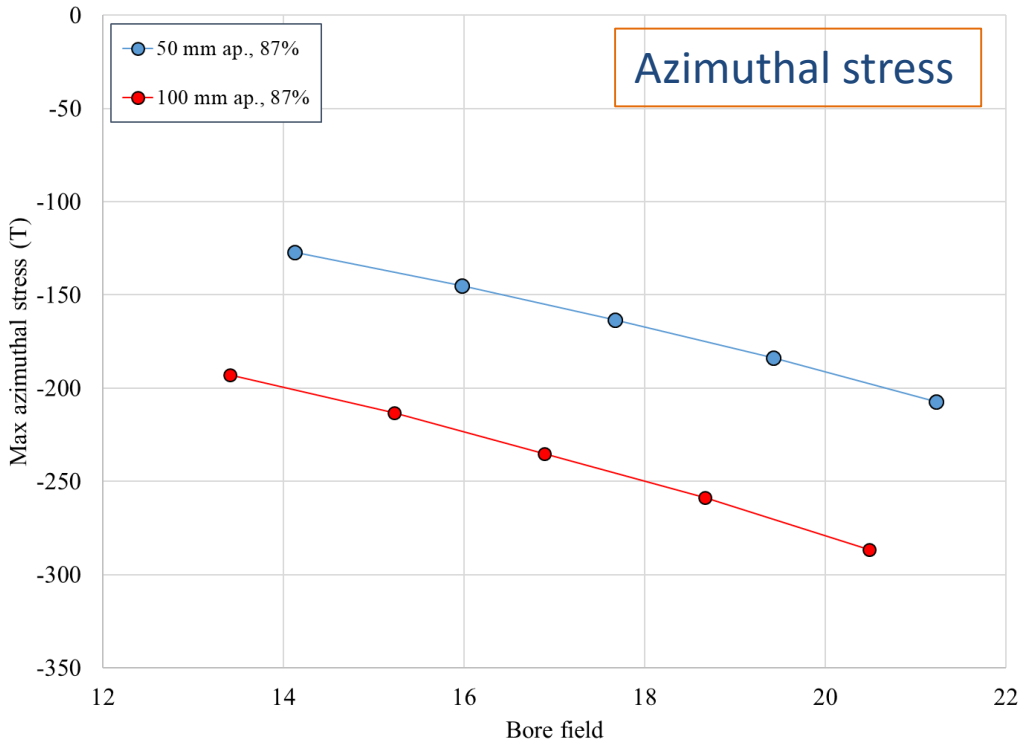
- For FCC design studies, "It is assumed in the magnet design that the insulated cable can be submitted to pressures of up to 150 MPa at ambient temperature and 200 MPa when cold, without experiencing an irreversible degradation"

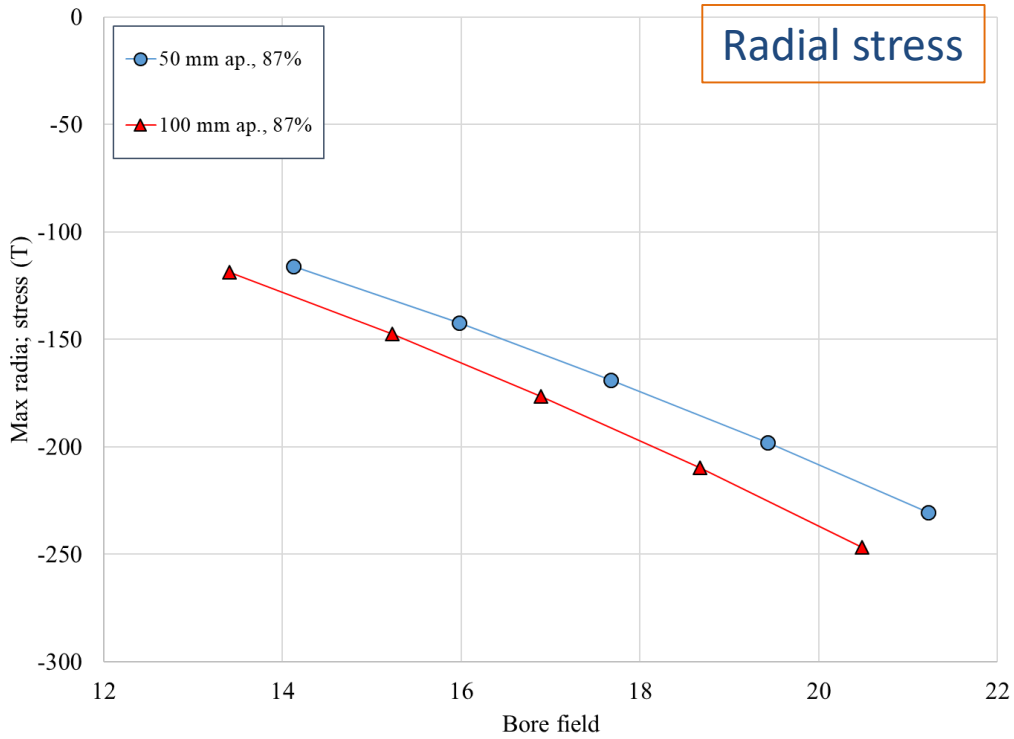


D. Schoerling, *et al.*, "The 16 T Dipole Development Program for FCC and HE-LHC", ***IEEE Trans. Appl. Supercond. Vol. 19, No. 3, June 2009 1203.***

Stress limits beyond Nb_3Sn: HTS

- In general, azimuthal and radial stress in the 150 MPa level at 16 T, 50 mm ap.
- Then, azimuthal more dependent on aperture, radial on B

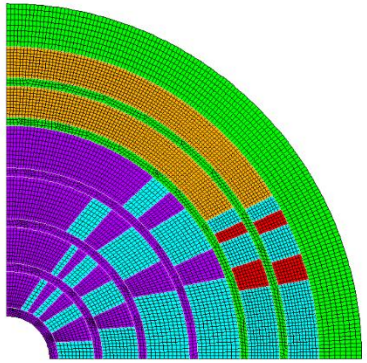




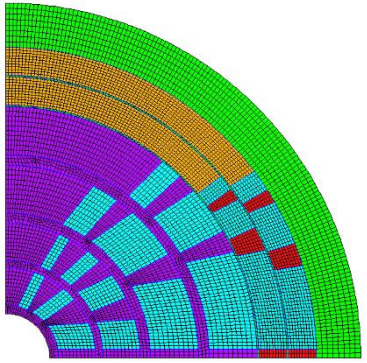
Stress limits beyond Nb_3Sn: HTS

- What about beyond 16 T? Stress management

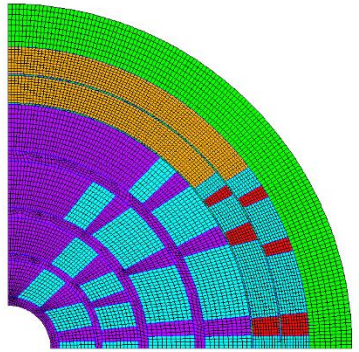
By G. Vallone and V. Marinozzi



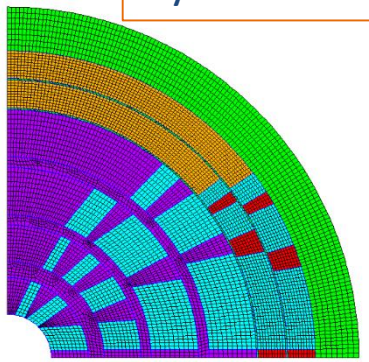
Test 1



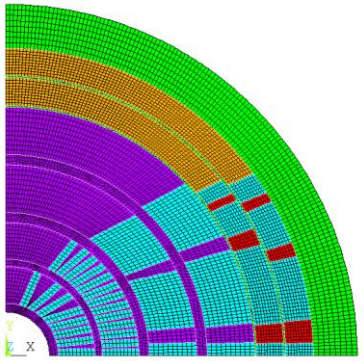
Mid Plane Rib



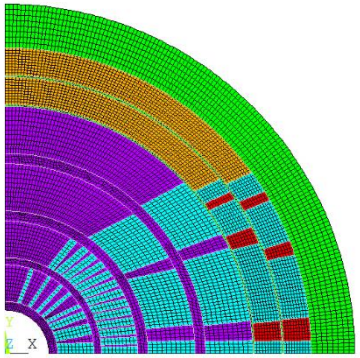
Aligned Wedges



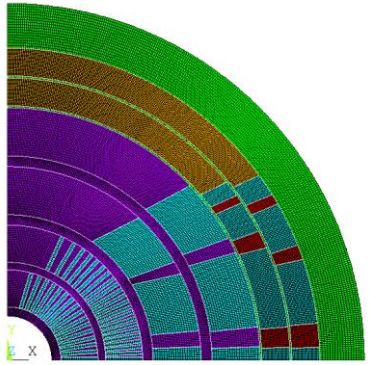
Shared Mandrel



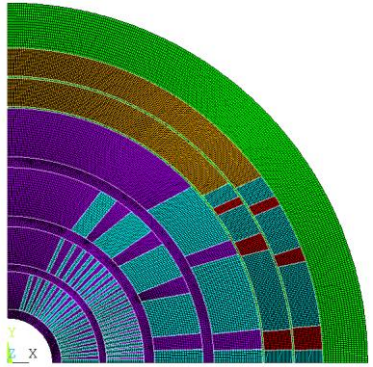
Coil 1
2 Turns



Layer 1
3/2/1 Turns



Coil 1
CCT / 1 Turn



Layer 3
5 Blocks

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- Introduction on superconducting materials and field levels
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Quench protection

- Protection systems to limit the T_{hot_spot} to below…..???
  - Usually ~300 K
  - For Nb_3Sn, no degradation observed up to 350-400 K
    - For HL-LHC, with no protection system failures, T_{hot_spot} set to ~250 K

G. Ambrosio, "Maximum allowable temperature during quench in Nb3Sn accelerator magnets", WAMSDO Workshop, **CERN–2013–006, 21 November 2013.**

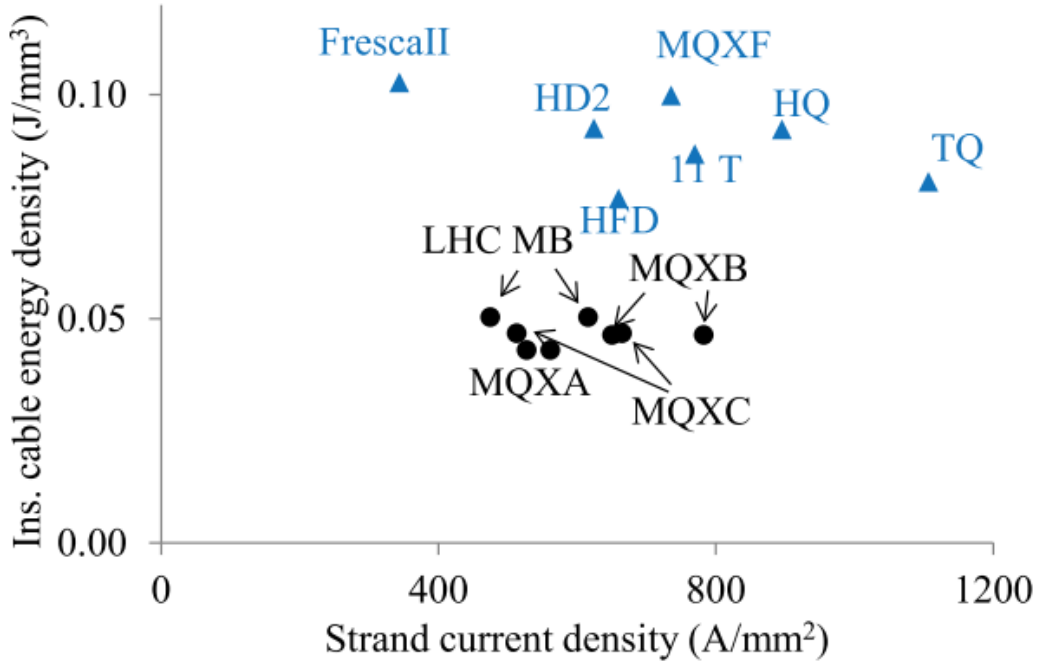
- For HTS, similar numbers (~400 K), but detection still an issue

Liyang Ye, "Quench degradation limit of multifilamentary Bi2212 round wires", ***2016 Supercond. Sci. Technol. 29 035010.***

X. Wang, "Critical current degradation of short YBCO coated conductor due to an unprotected quench", ***2011 Supercond. Sci. Technol. 24 035006.***

Quench protection: Nb-Ti and Nb_3Sn magnets

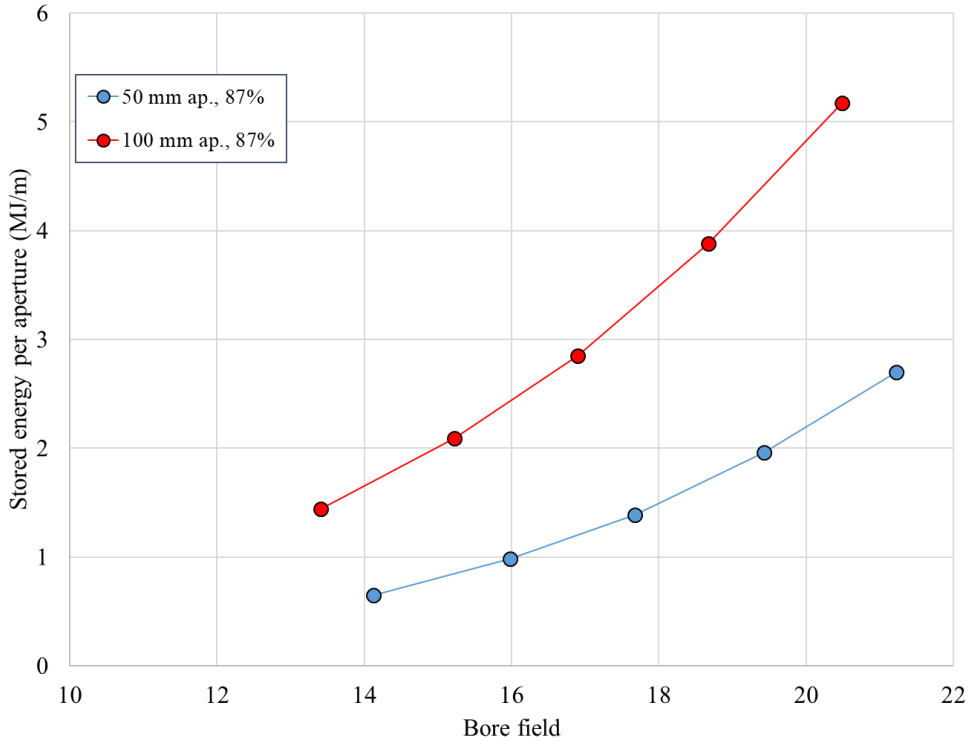
- Among different parameters... stored energy and insulated cable stored energy density (0.05 J/mm^3 for Nb-Ti and 0.10 for HL-LHC)

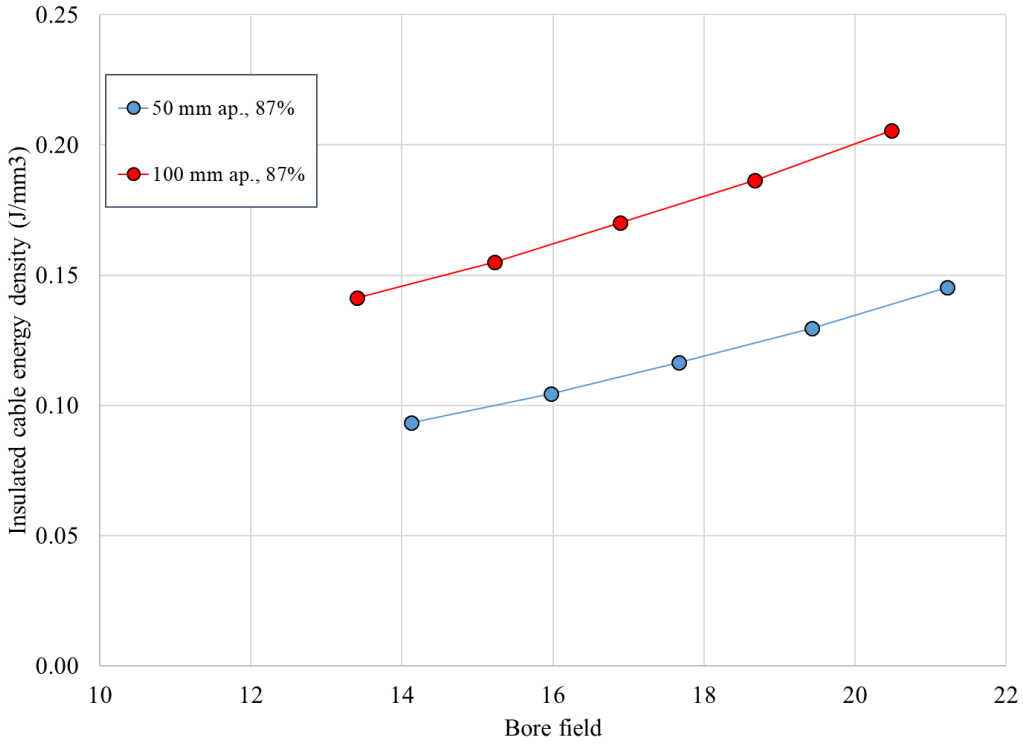


E. Todesco, "Quench limits in the next generation magnets", WAMSDO Workshop, **CERN–2013–006, 21 November 2013.**

Quench protection beyond Nb_3Sn: HTS

- Stored energies twice as big as HL-LHC and FCC levels (1-1.5 MJ/m) and even more for large apertures
- But energy densities only 50% larger than HL-LHC



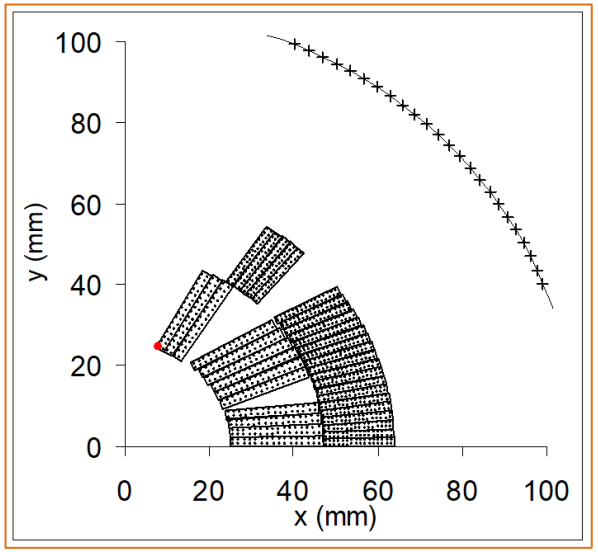


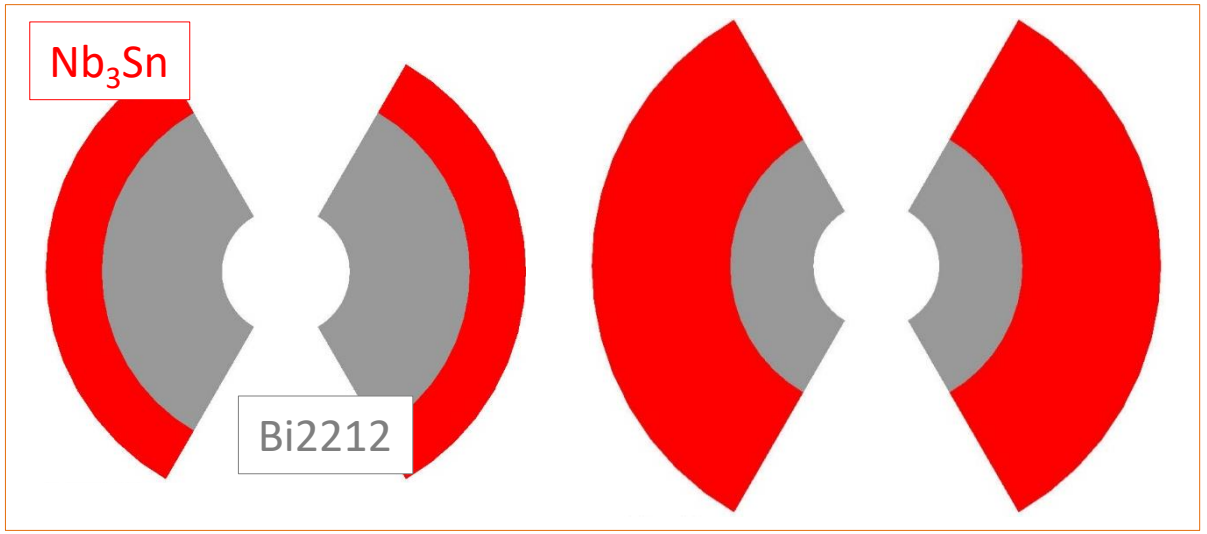
Outline

- Introduction on superconducting materials and field levels
- Performance limits
  - Field
  - Stress
  - Quench protection
- Cost
- Conclusions

Cost

- Very rough rule of thumb (to be updated…)
  - Nb-Ti → factor of 5+ → Nb_3Sn → factor of 5+ → HTS
- Strong incentive to reduce quantity of superconductor
  - More efficient magnets, less margin, more J_e
    - But then, potential issues with stress and QP
  - Grading and anti-grading (in 20 T hybrid magnets)





Outline

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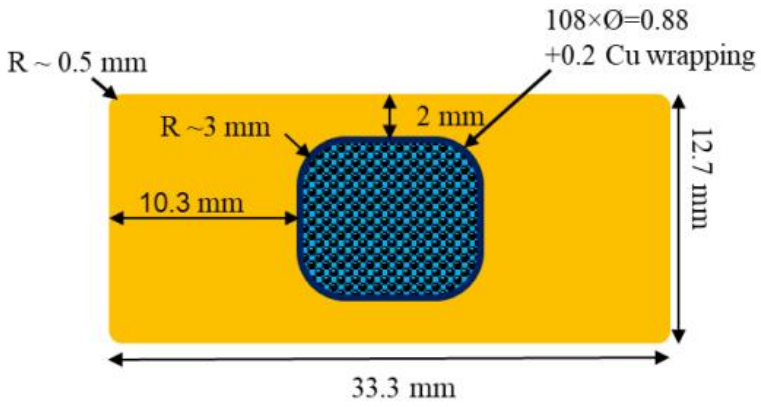
Conclusions

- "Simplified" coil design allows a preliminary numerical and analytical investigation of future magnets and their limits
- If we look at very high field (>16 T) and very large aperture (>100 mm aperture)
  - HTS conductor with good level of J_e is available; R&D required towards cables and coil fabrication
    - For example: bending radius for REBCO, heat treatment control for Bi2212
  - Very high stresses in coil are generated by the e.m. forces
    - Both azimuthal (aperture!) and radial (field!)
    - Some sort of stress management necessary
  - Quench protection for HTS and hybrid magnets still with many unknowns
  - Cost: hybrid is an attractive option under investigation
    - R&D on going on stresses, quench protection, integration of coils with different materials….

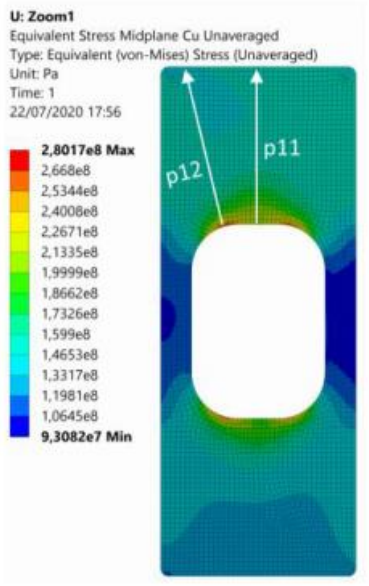
Appendix

Madmax: a large-aperture NbTi dipole

Superconductor	NbTi
Operatin Temperature	1.8 K
Load line margin	10 %
Temperature margin	1 K
Hot spot temperature	100 K
J_E	50 A/mm^2
Bore field	8.8 T
Peak field	9.9 T
Stored energy	482 MJ

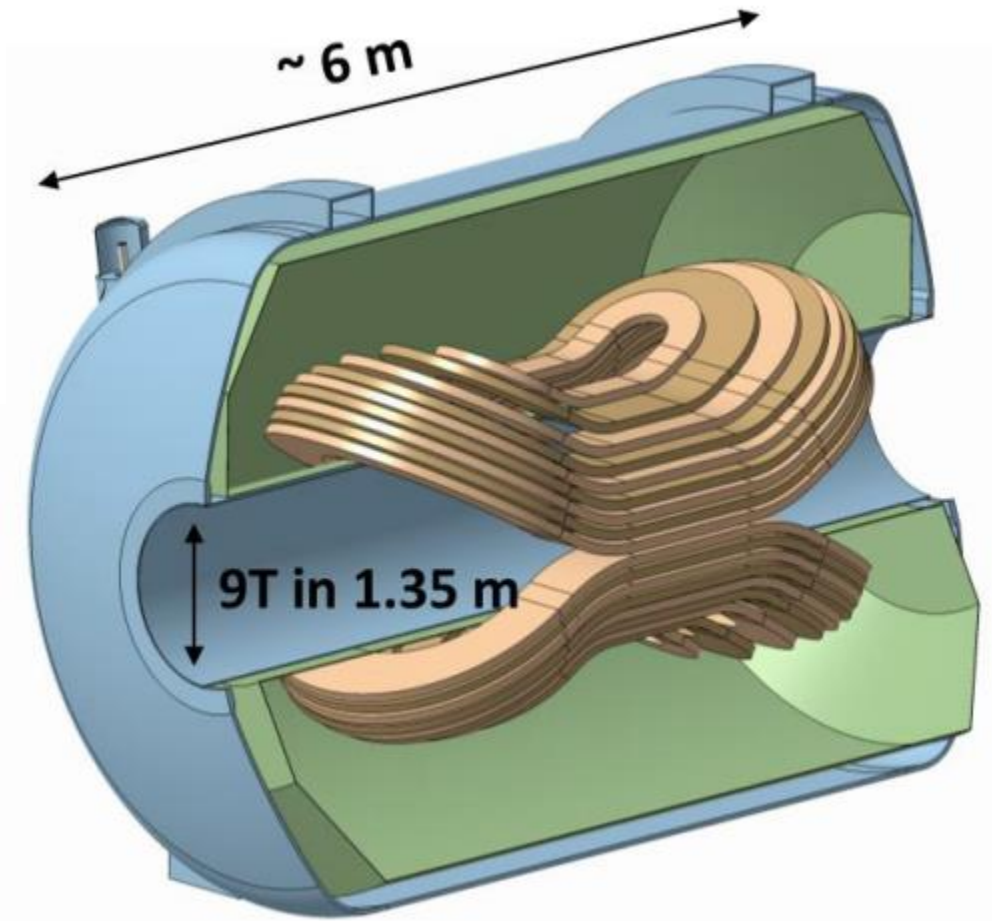


Conductor design



Stress at the limit of materials :

- 180 MPa in NbTi
- ~300 MPa in Cu
- ~500 MPa in Steel



W. Abdel Maksoud, "Madmax: Large Dipole Dectector for Dark Matter", ***CERN Workshop 2022***