Potential future developments in superconducting magnets - Nb_3Sn and beyond

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Office of Science

ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION

ATAP

Outline

- Context for high field accelerator magnet R&D
  - Focus on pp collider: P5 and ARD Subpanel
- Current status of the technology
- Challenges
- The future: R&D Roadmap

Many thanks to my colleagues who provided content, in particular S. Caspi, S. Gourlay, D. Dietderich, X. Wang, M. Marchevsky, T. Shen

Higgs discovery has renewed interest in pp colliders

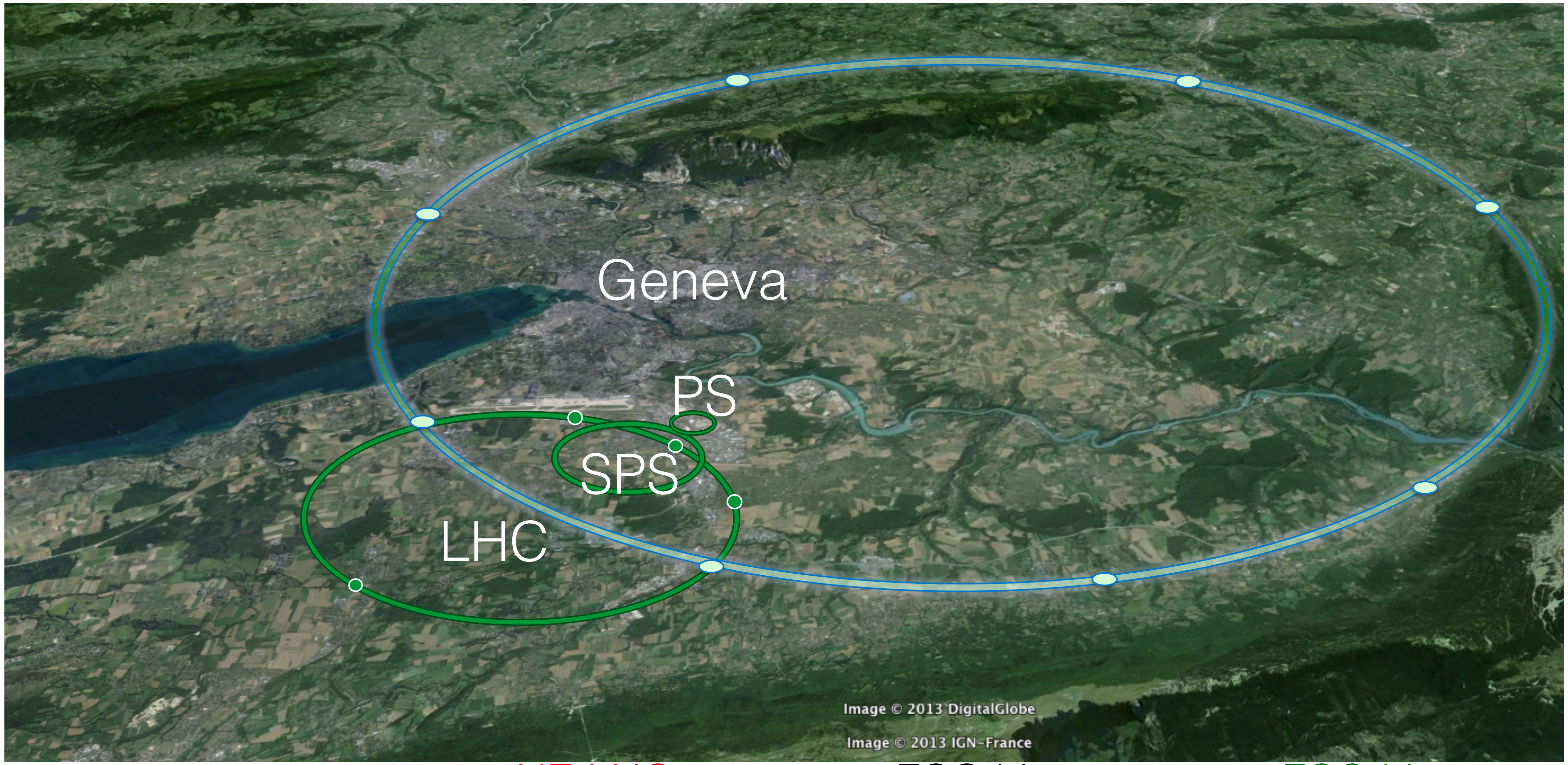
Europe (European Strategy Group) . . .

d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. *CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.*

- 100 TeV scale collider - The largest and most complex accelerator ever built
- Many technical challenges but *cost* will be a significant factor in feasibility

". . . . deliver a conceptual design report (CDR) together with a cost review by 2018, in time for the next update of the European Strategy for Particle Physics."

Ideas beyond the LHC: the FCC's

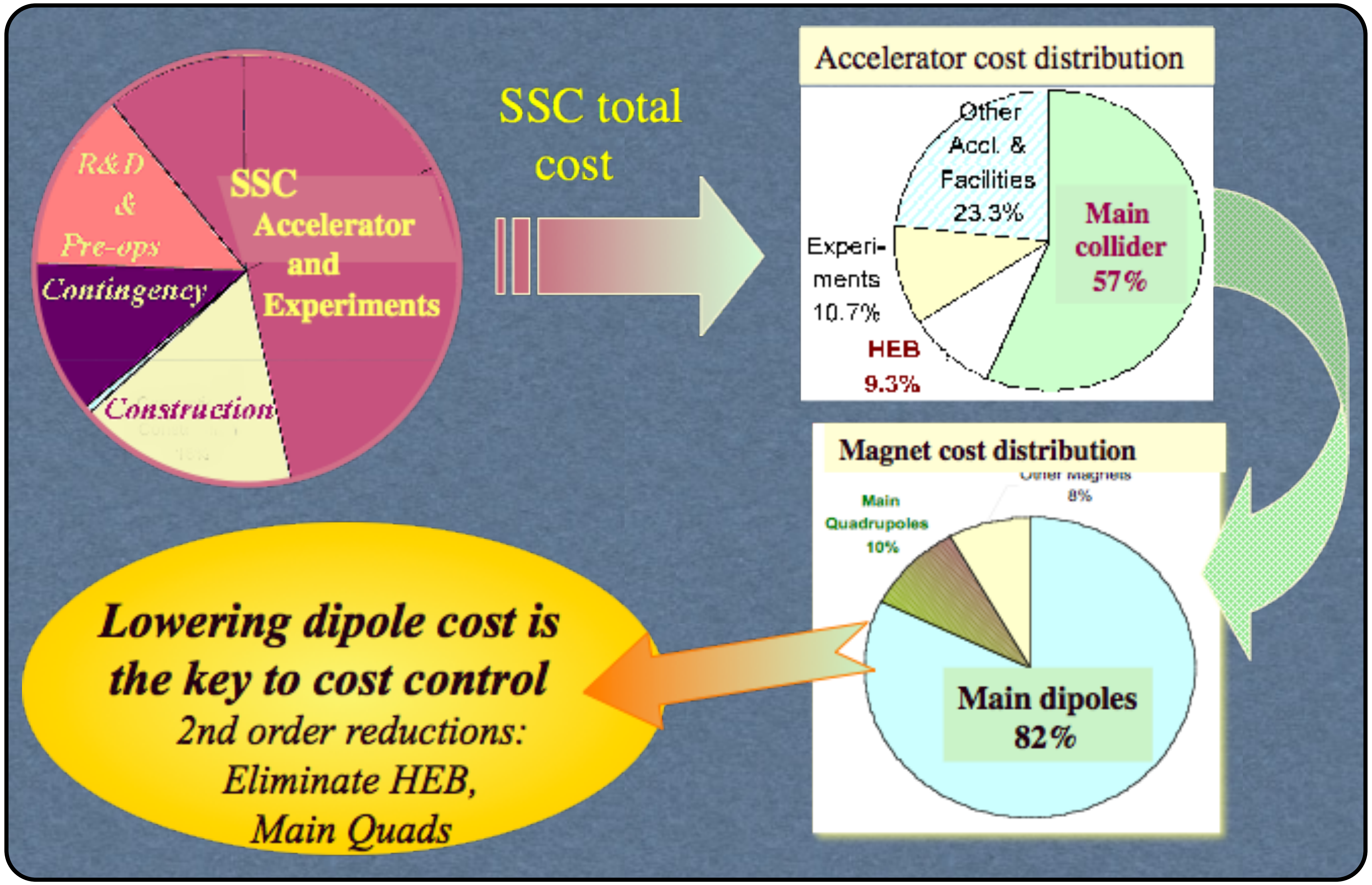


LHC	HE-LHC	FCC-hh	FCC-hh
27 km, 8.33 T	27 km, 20 T	80 km, 20 T	100 km, 16 T
14 TeV (c.o.m.)	33 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)

CEPC-SppC

中国科学院高能物理研究所
Institute of High Energy Physics

Magnets drive accelerator cost



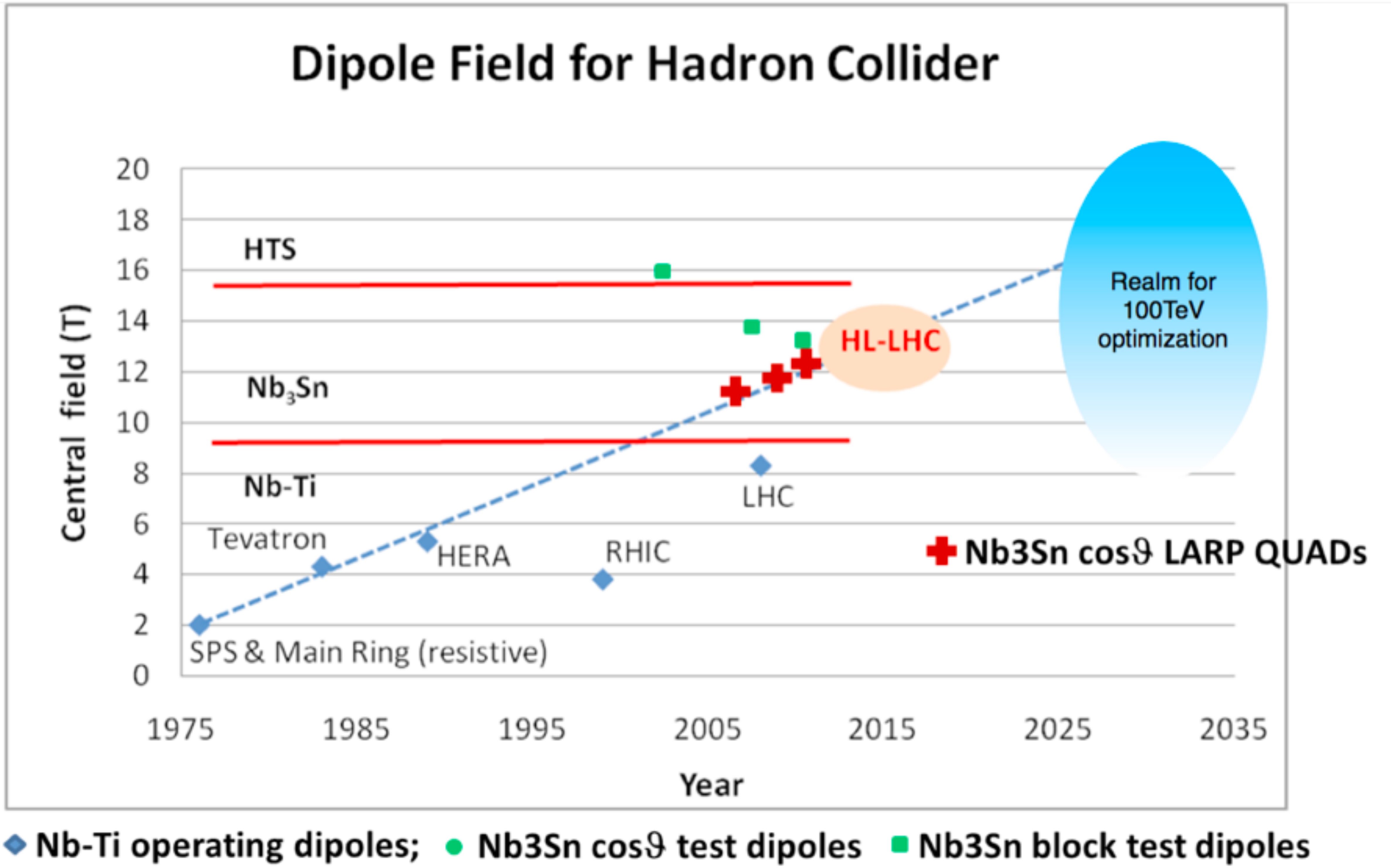
CERN cost estimates*:
$\$_{magnets}/\$_{tot}$

LHC: 57%
HE-LHC:
- 70% (26TeV; Nb_3Sn)
- 77% (33TeV; HTS)

**L. Rossi, "TOE" talk*

W. Barletta

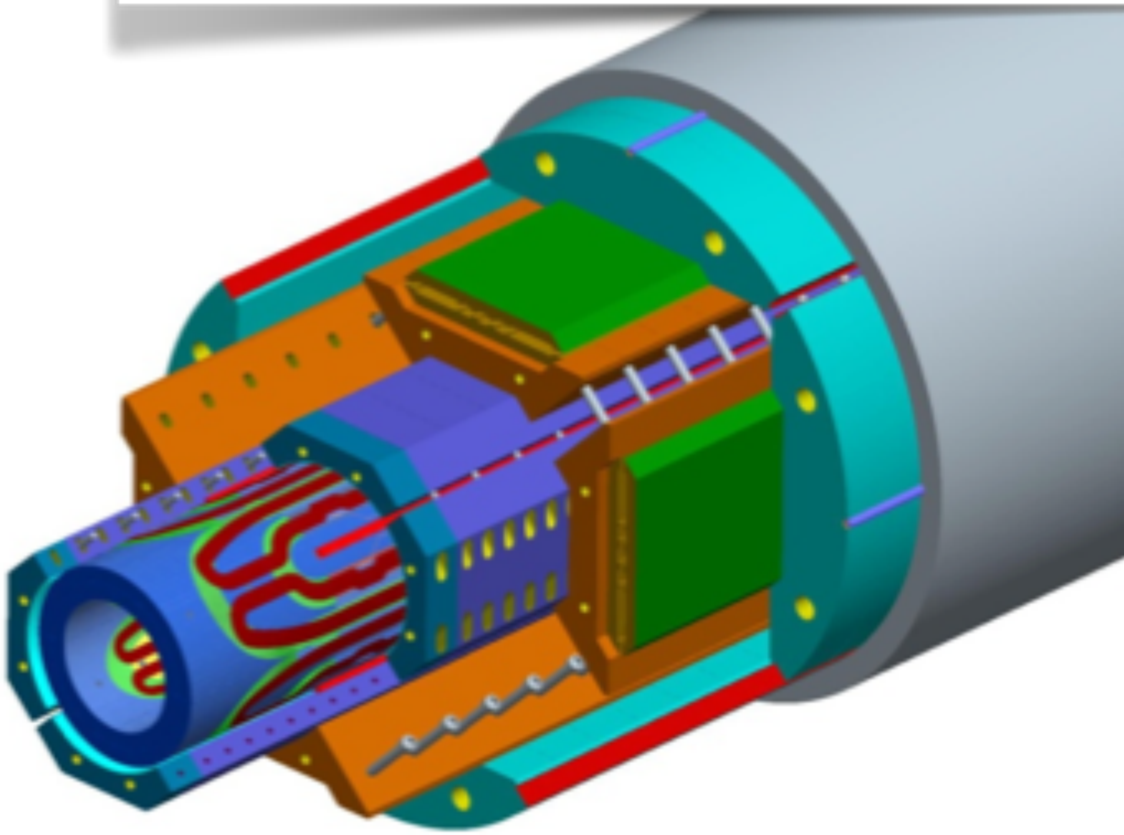
Some progress towards higher field accelerator magnets

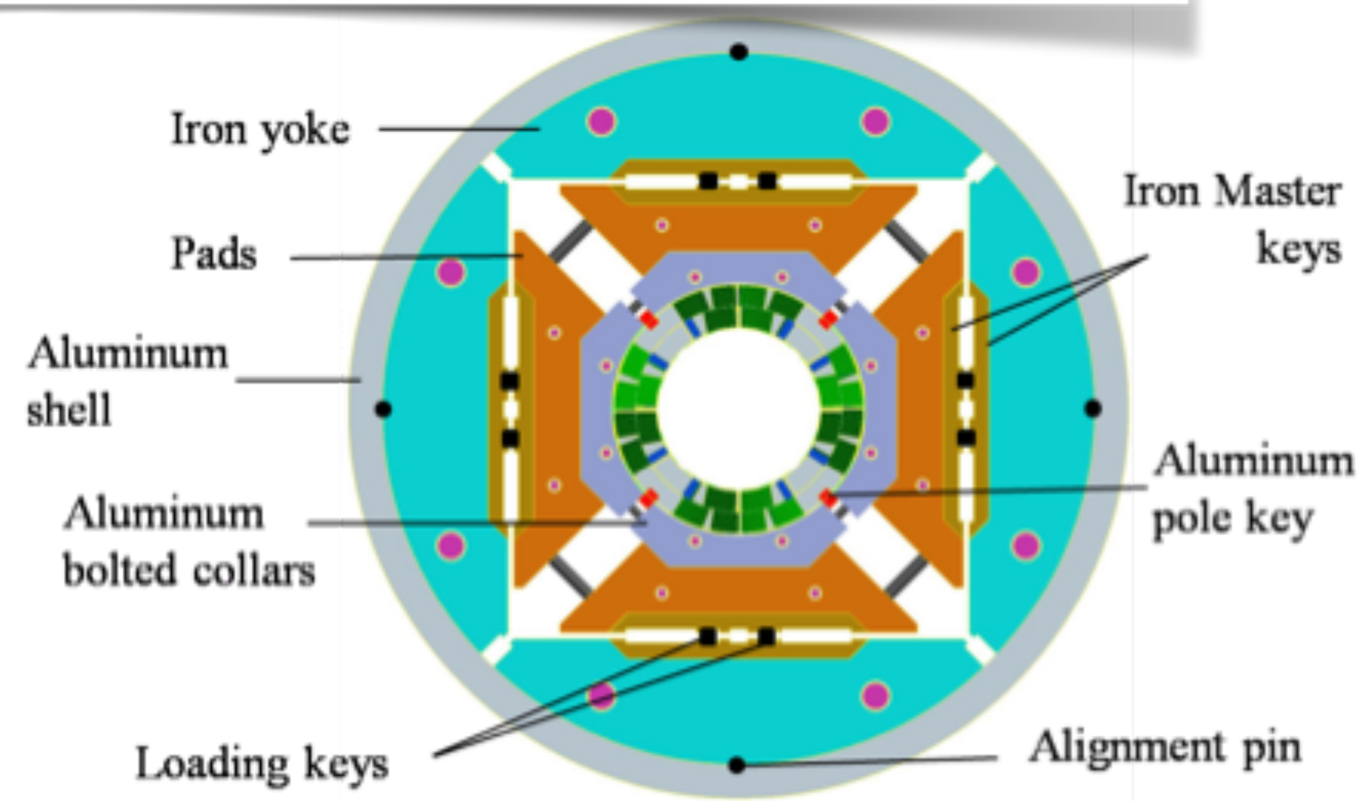


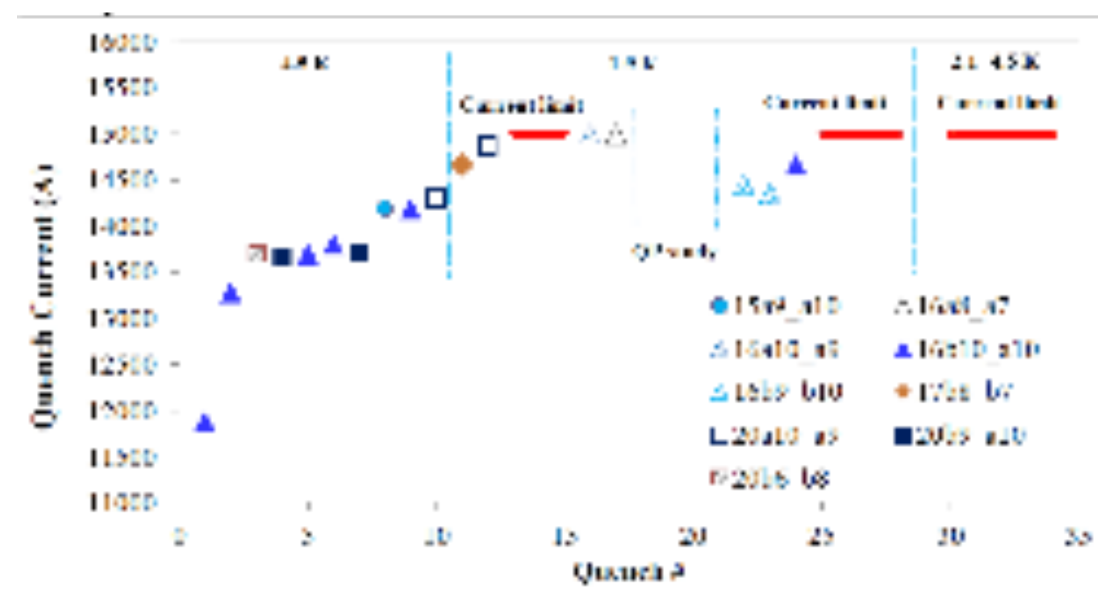
S. Prestemon, LBNL

Nb3Sn technology is being readied by LARP:
HQ ➠QXF ➠ Hi-Lumi upgrade

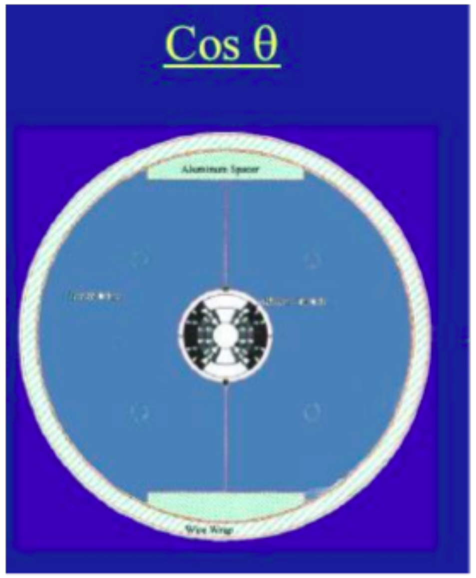
Design, fabrication, and test results from LARP: FNAL, LBNL, BNL

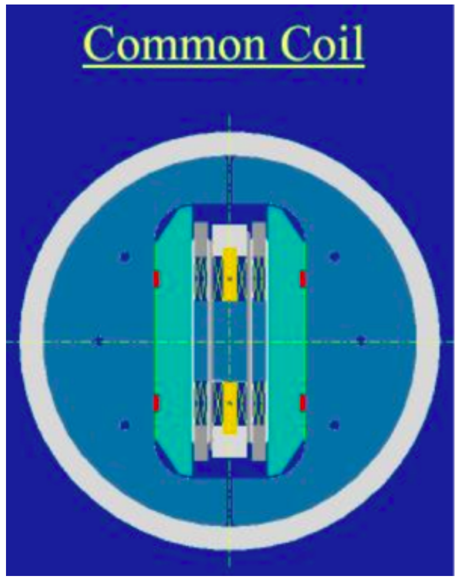


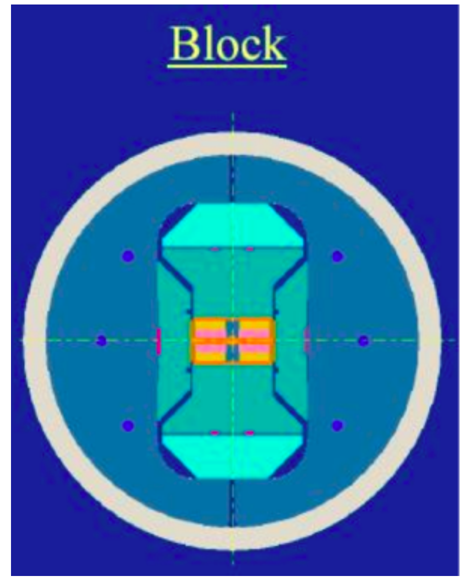




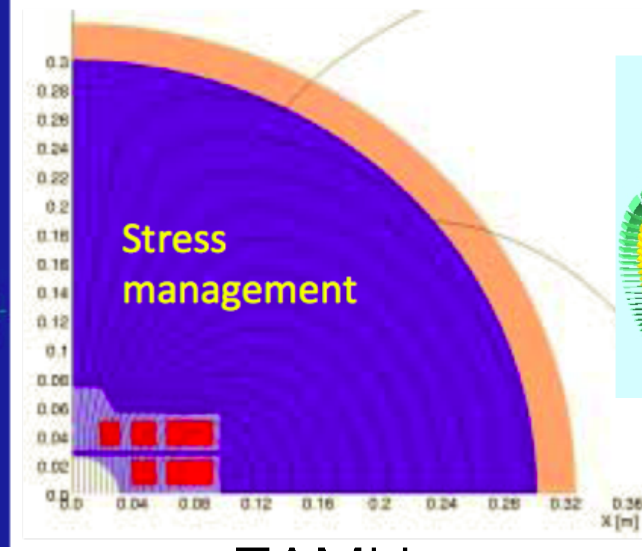
Starting point for magnet technology



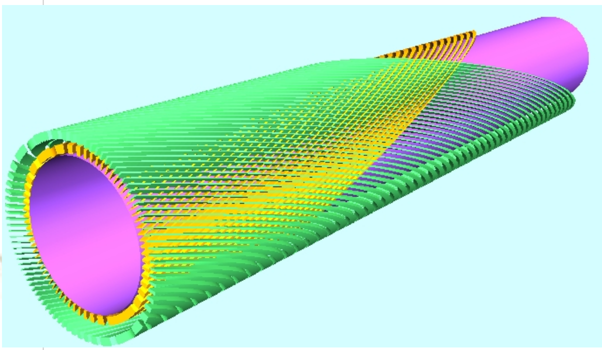




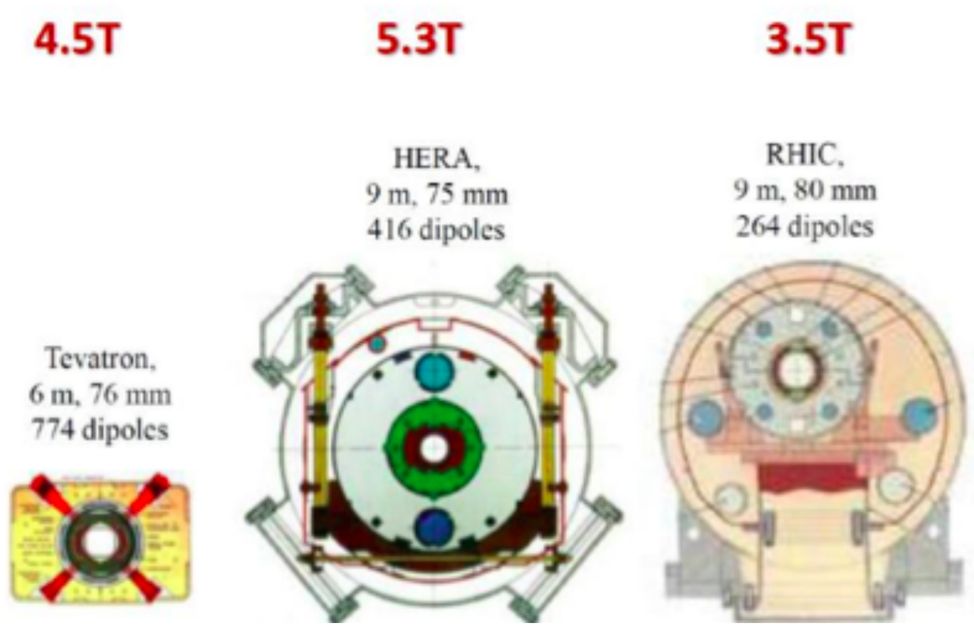
LBNL



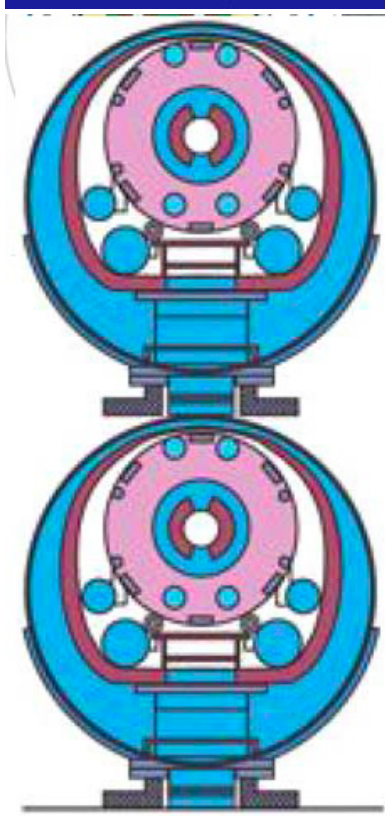
TAMU



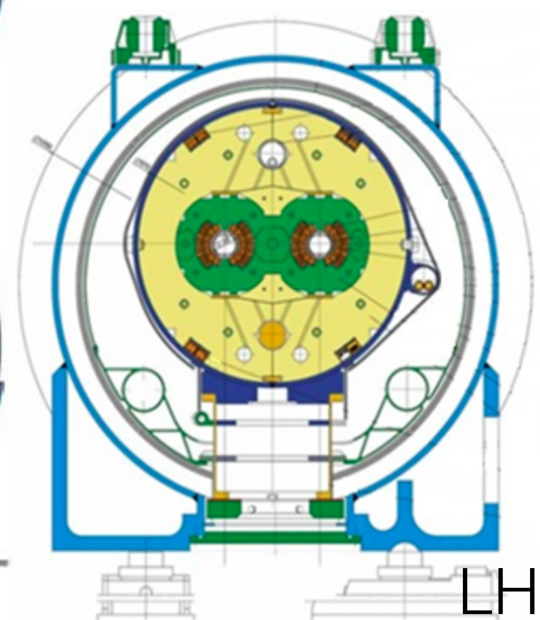
CCT



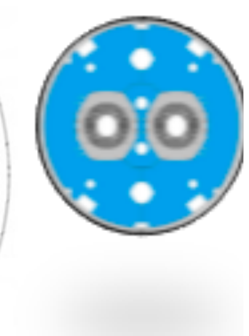
Shiltsev/Zlobin, (FNAL)



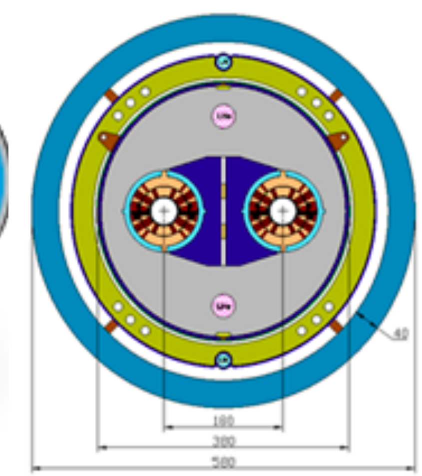
SSC, 50mm
6.6T, 4.3K



LHC, 56mm
8.3T, 1.9K



LHC, 60mm
11T,1.9K
FNAL/CERN



VLHC, 43mm
10T, 4.5K

Grand Challenges aligned with the Subpanel recommendations

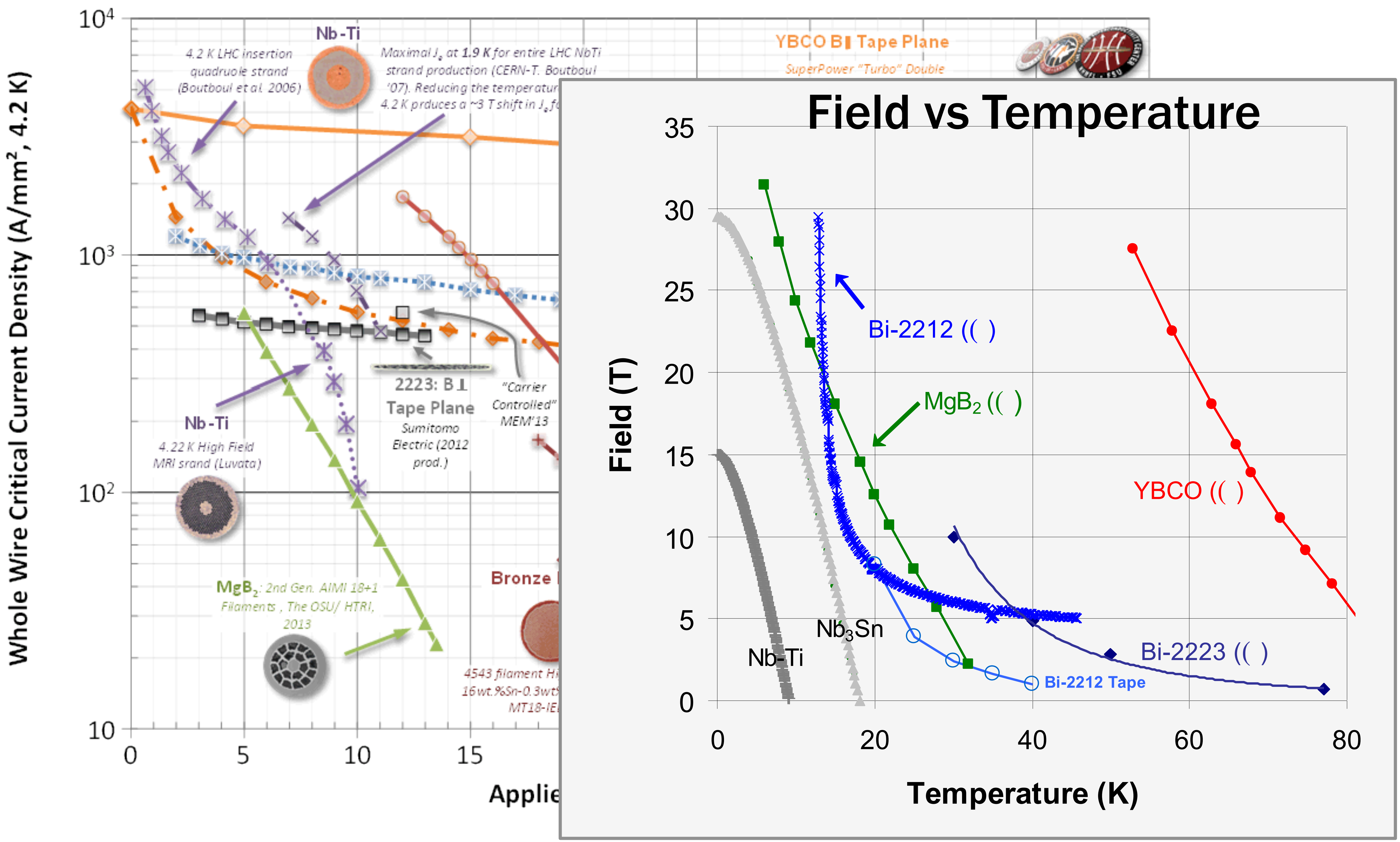
Magnets

- Achieve a field of 16T in a bore of at least 50mm
- Focus on simple, manufacturable designs (the cost goal)
- Understand training of Nb_3Sn magnets and develop ways to reduce or eliminate it
- Produce an HTS (Bi-2212/YBCO) insert with a self-field of > 4T and measure the field quality

Conductor

- Focus on magnets as technology drivers
- Reduce cost and improve performance of Nb_3Sn
- Increase the current density by 30% with a scalable sub-element structure
- Aim for a cost per kg the same as NbTi
- HTS conductor development with clear performance targets

J_e Chart – Peter Lee, Applied Superconductivity Center FSU and NHMFL



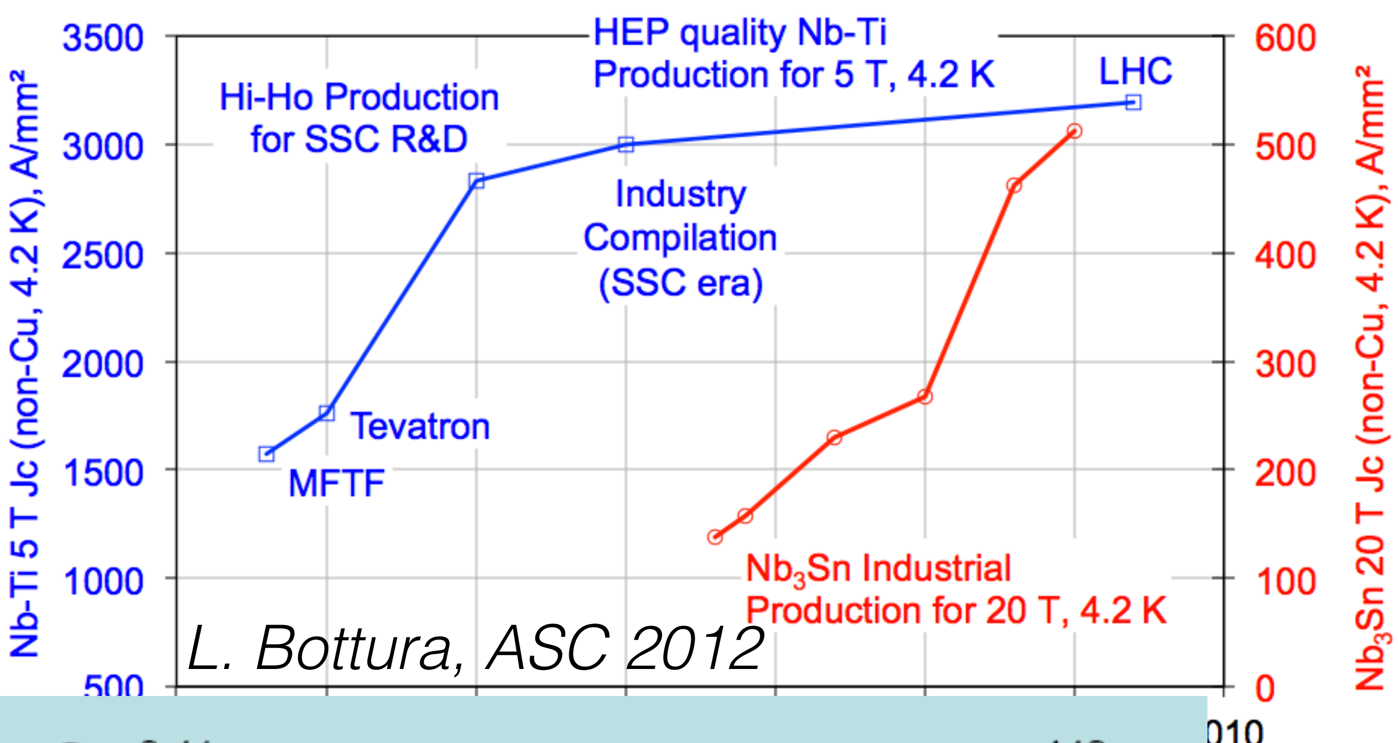
Conductor Comparison

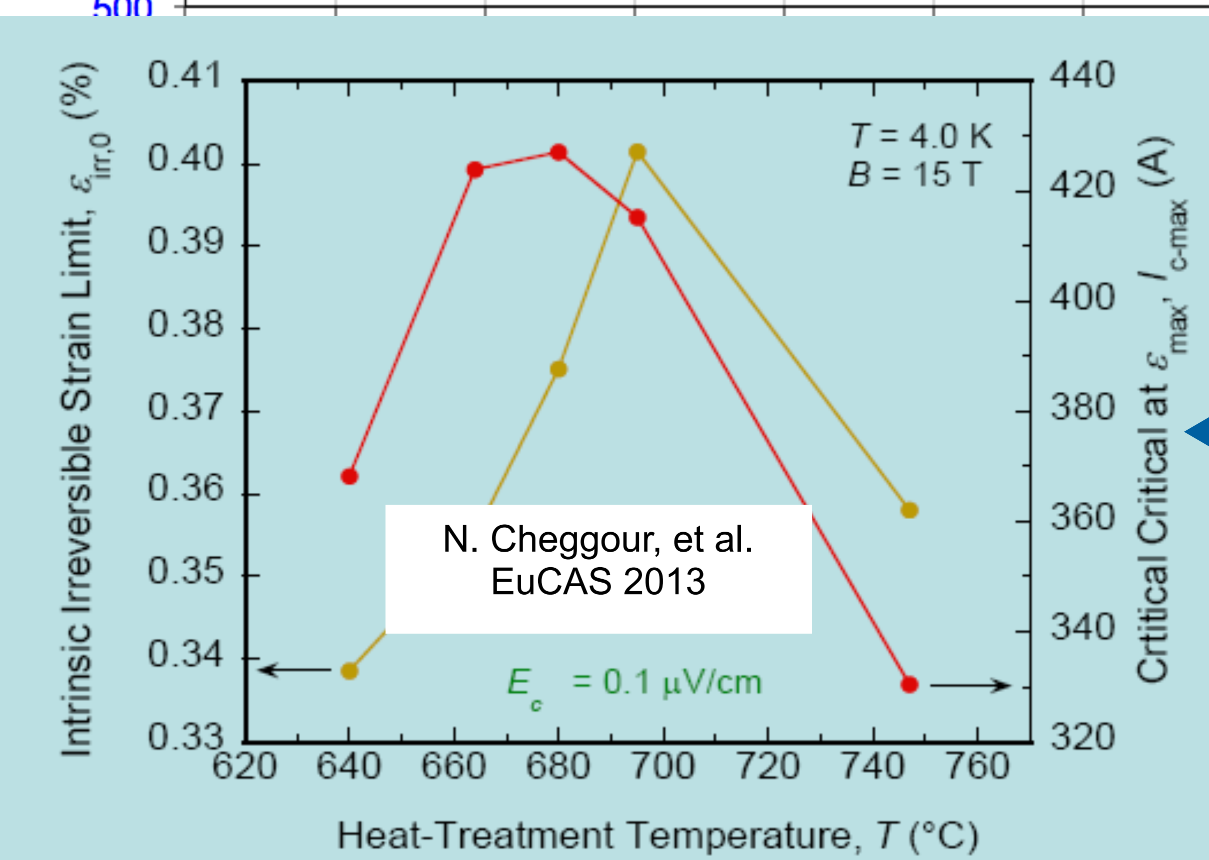
Material	NbTi	Nb_3Sn (Nb_3Al)	Bi-2212	YBCO
Max Field	**10-11 T**	**16-17 T**	**Stress limited**	**Stress limited**
Reaction	**Ductile**	**~675^{0}C in Ar/ Vacuum**	**~890^{0}C in O_2 (+/-2^{0}C)**	**None**
Wire axial compression	**N/A**	**Reversible**	**Irreversible?**	**Reversible**
Transverse stress	**N/A**	**< 200 MPa**	**60 MPa?**	**≥ 150 MPa**[1]
Insulation	**All**	**S/E Glass**	**Ceramic**	**All**
Construction	**G-10, stainless...**	**Bronze/Titanium, Stainless**	**Super alloy**	**All**
Quench propagation	**>20m/s**	**~20 m/s**	**~0.05 m/s? (4.2 K, 8 T)** [2]	**~0.01 m/s? (4.2 K, self-field)** [3]

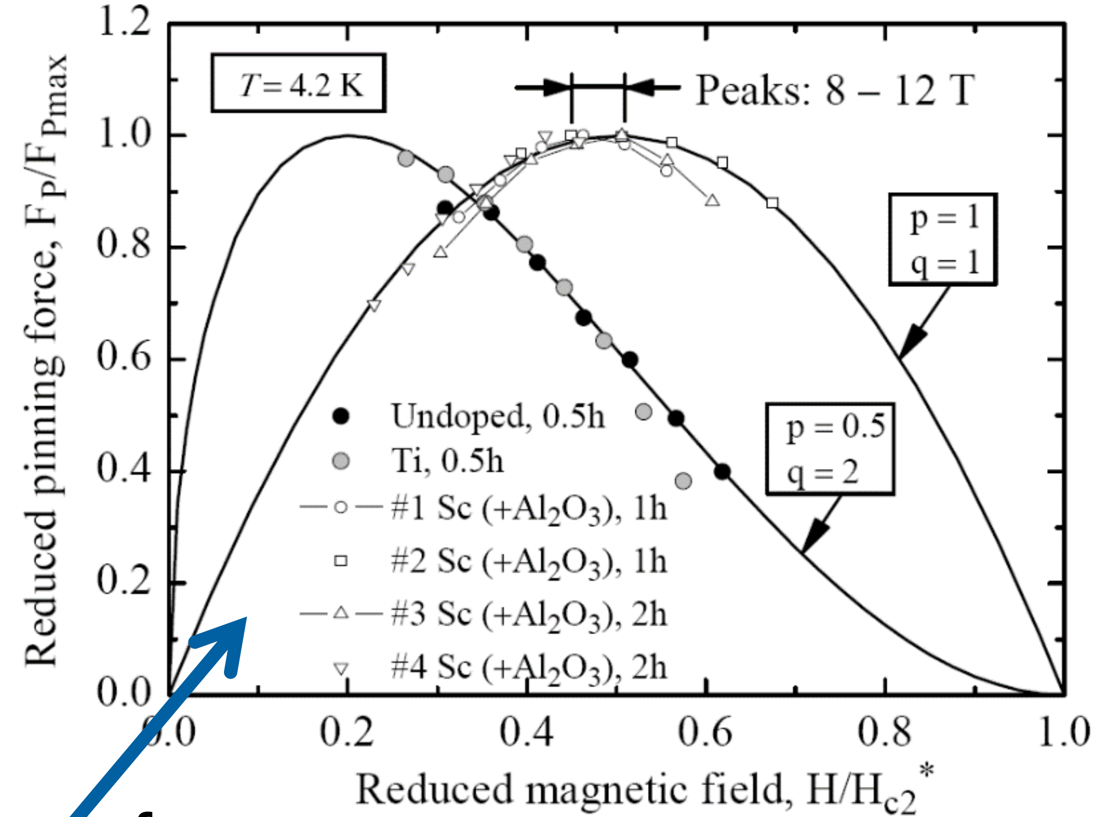
1. Cheggour *et al.*, IEEE TAS (2007) 17(2), pp. 3063 – 3066.
2. Trociewitz *et al.,* SuST 21 (2008) 025015.
3. Song and Schwartz, IEEE TAS (2009) 19(5), pp. 3735 – 3743.

Nb_3Sn has improved significantly – but further gains can be had

Nb_3Sn performance has doubled in ten years; Can we expect more?







Example of potential and challenge

"Engineered Microstructure"

ADMA201404335(201404335)

www.advmat.de

Author Proof

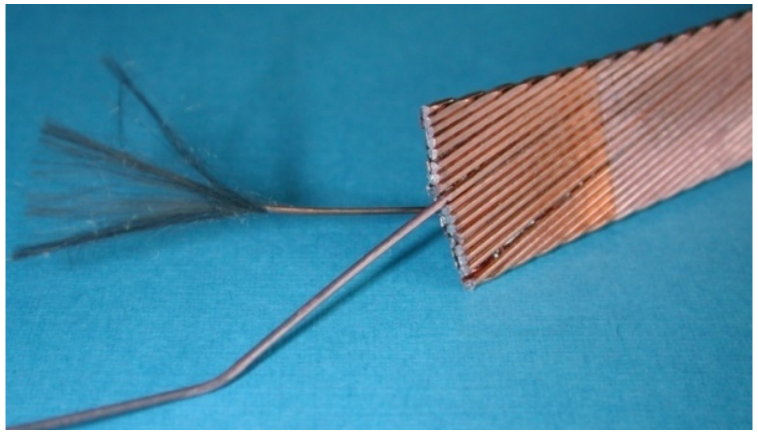
ADVANCED MATERIALS

Internally Oxidized Nb_3Sn Strands with Fine Grain Size and High Critical Current Density

By Xingchen Xu, Michael D. Sumption,* and Xuan Peng

Rutherford Cables remain the preferred approach for high current, low inductance magnets

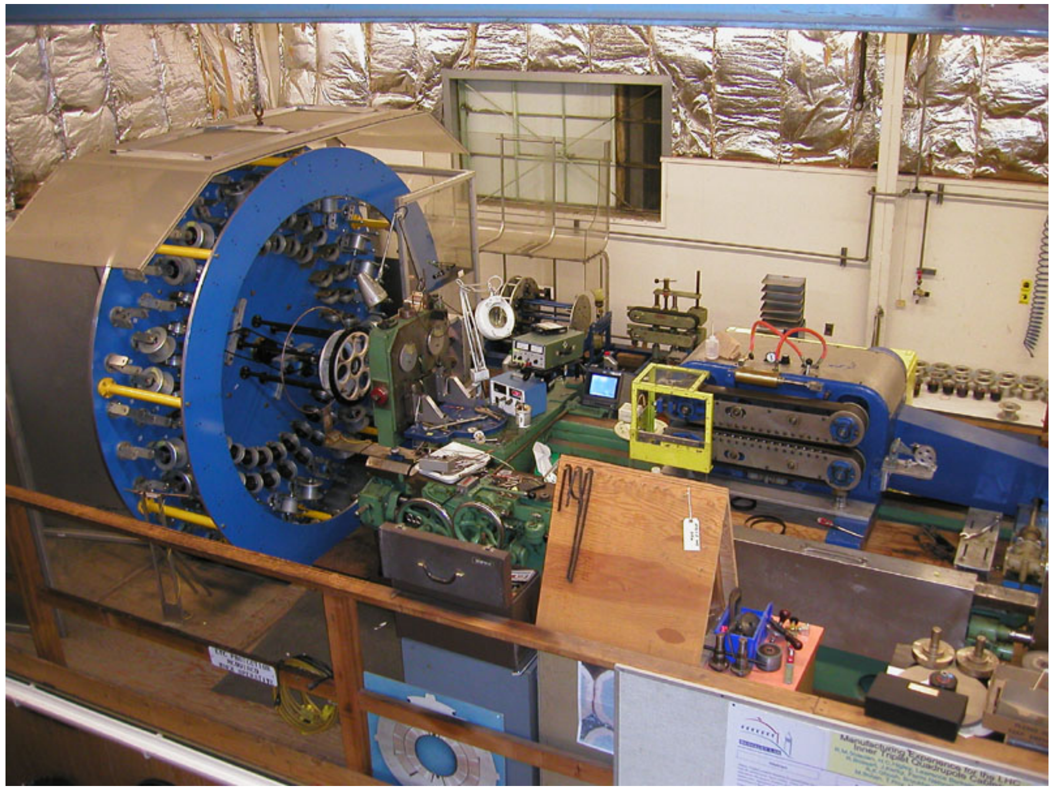
$$PF_{cable} = \frac{N_{wire} \pi d_{wire}^2}{4 w_{cable} t_{cable} \cos\psi_{cable}}$$

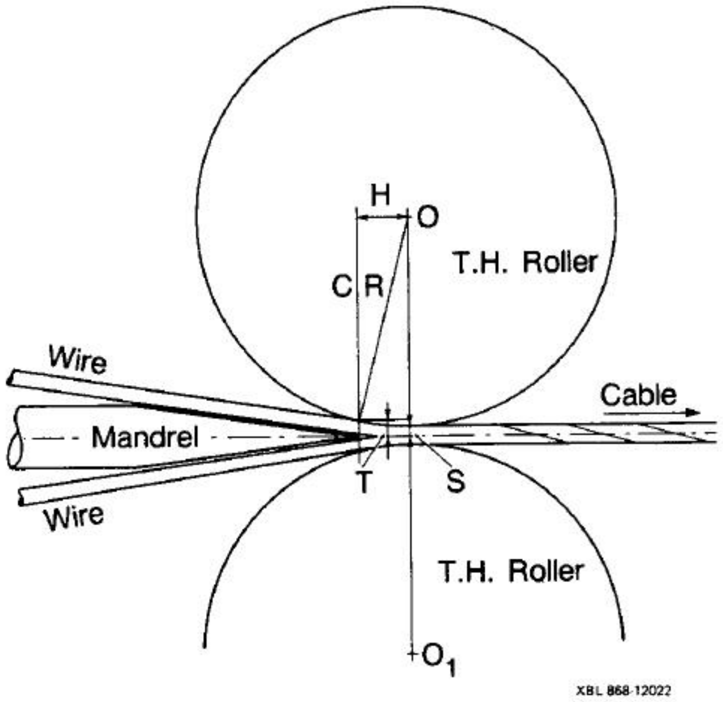


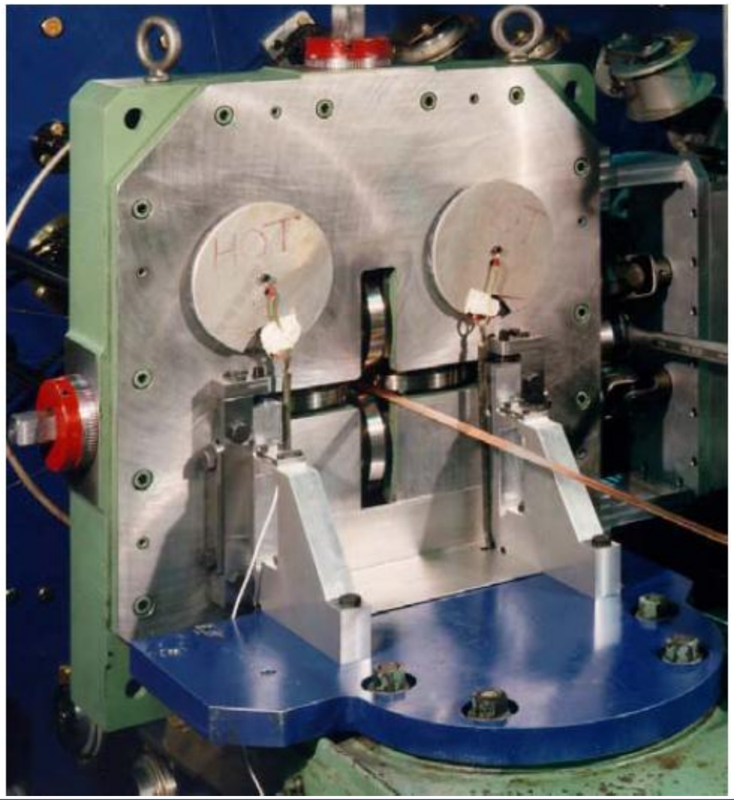
Cable cross-section is rectangular or trapezoidal

Packing Fraction (PF) ranges from 85% - 92%

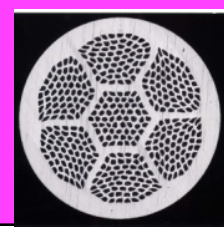
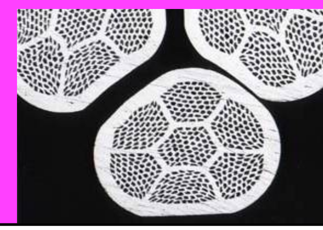
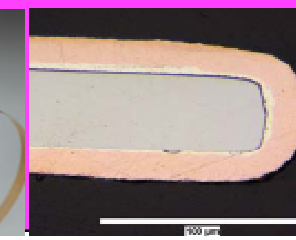
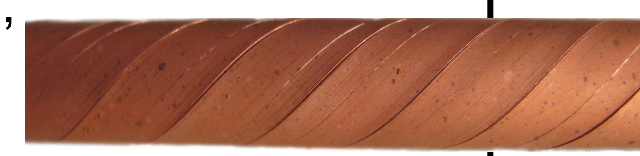
- Too much compaction – damage to filaments
- Too little compaction – mechanically unstable





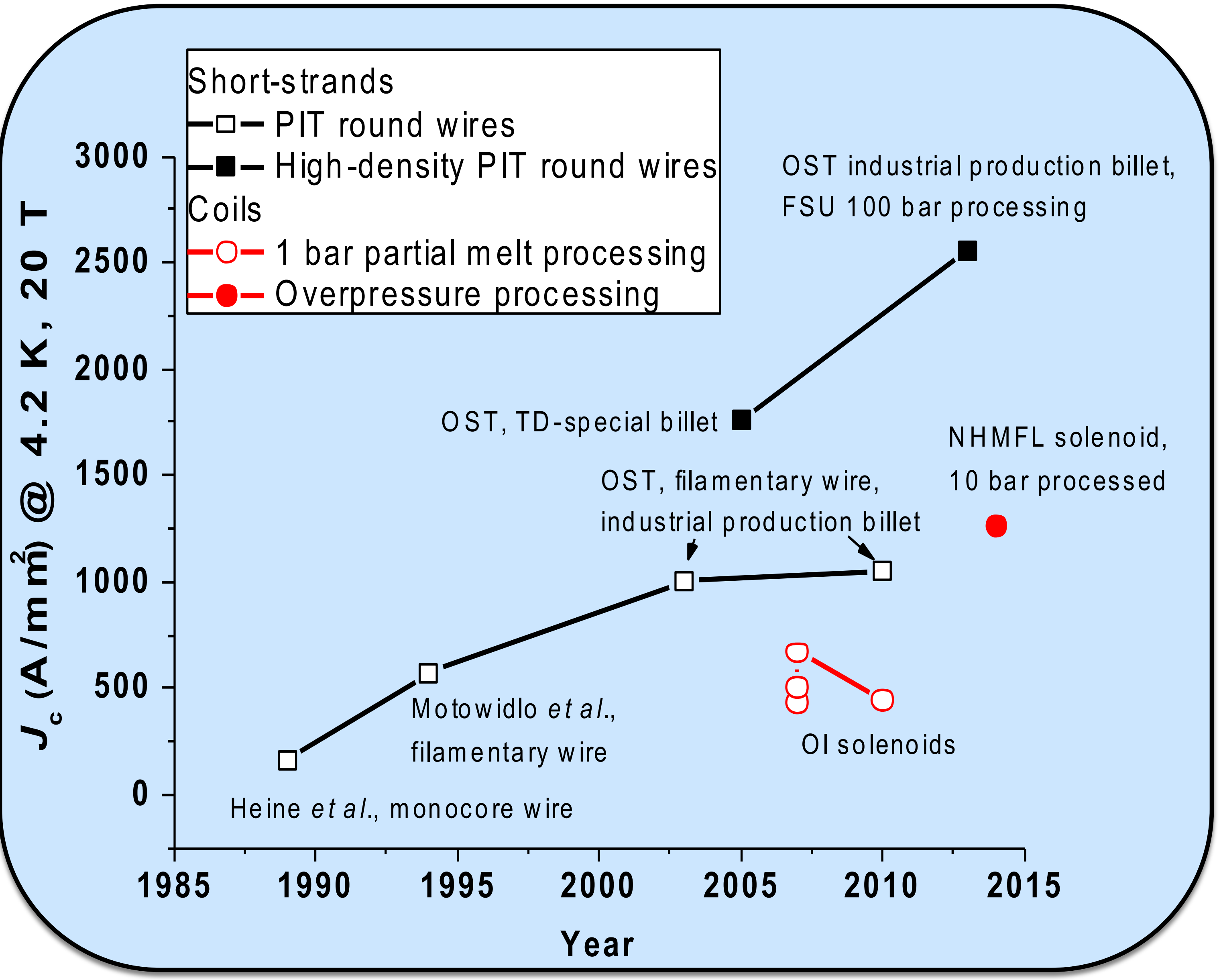


HTS Technology Challenges

	$Bi_2Ca_2CuSr_2O_{8+x}$ (Bi-2212)  	$YBa_2Cu_3O_{7-\delta}$ (YBCO)  
Process	W&R (900C, pure Oxygen) Sensitive to temperature variations; high pressure required for high J_c	W (pre-reacted tape)
Scalability (current)	Can use Rutherford cables (routinely fabricated since ~2000)	Difficult; "Roebel" and "Corc" cable under investigation; 
Winding	Can use existing processes	Challenge: minimum bend radius, no hard-way bends
Dep. on field orientation	Isotropic	Highly anisotropic; being addressed
Strain dependence	Degradation starts at 60 Mpa in present wires; little reversible regime expected	Reversibility improving; transverse pressure limitations

Bi2212 wire J_c history, milestones, and implications

Courtesy Tengming Shen

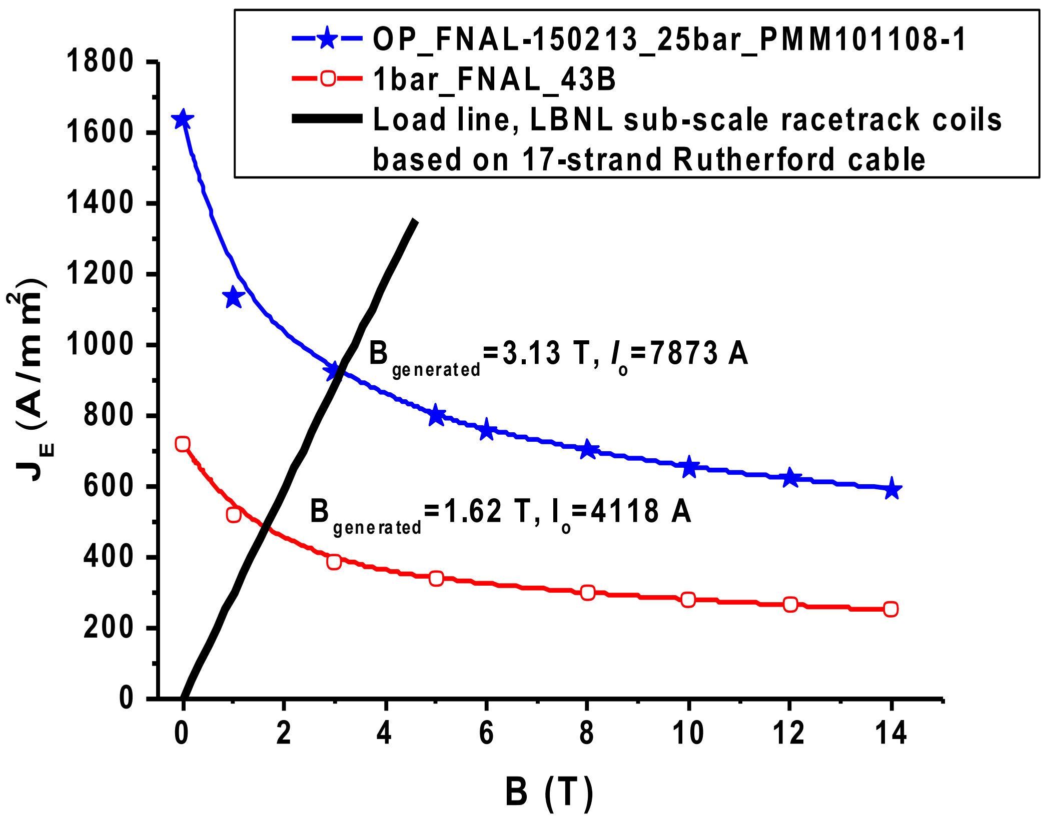


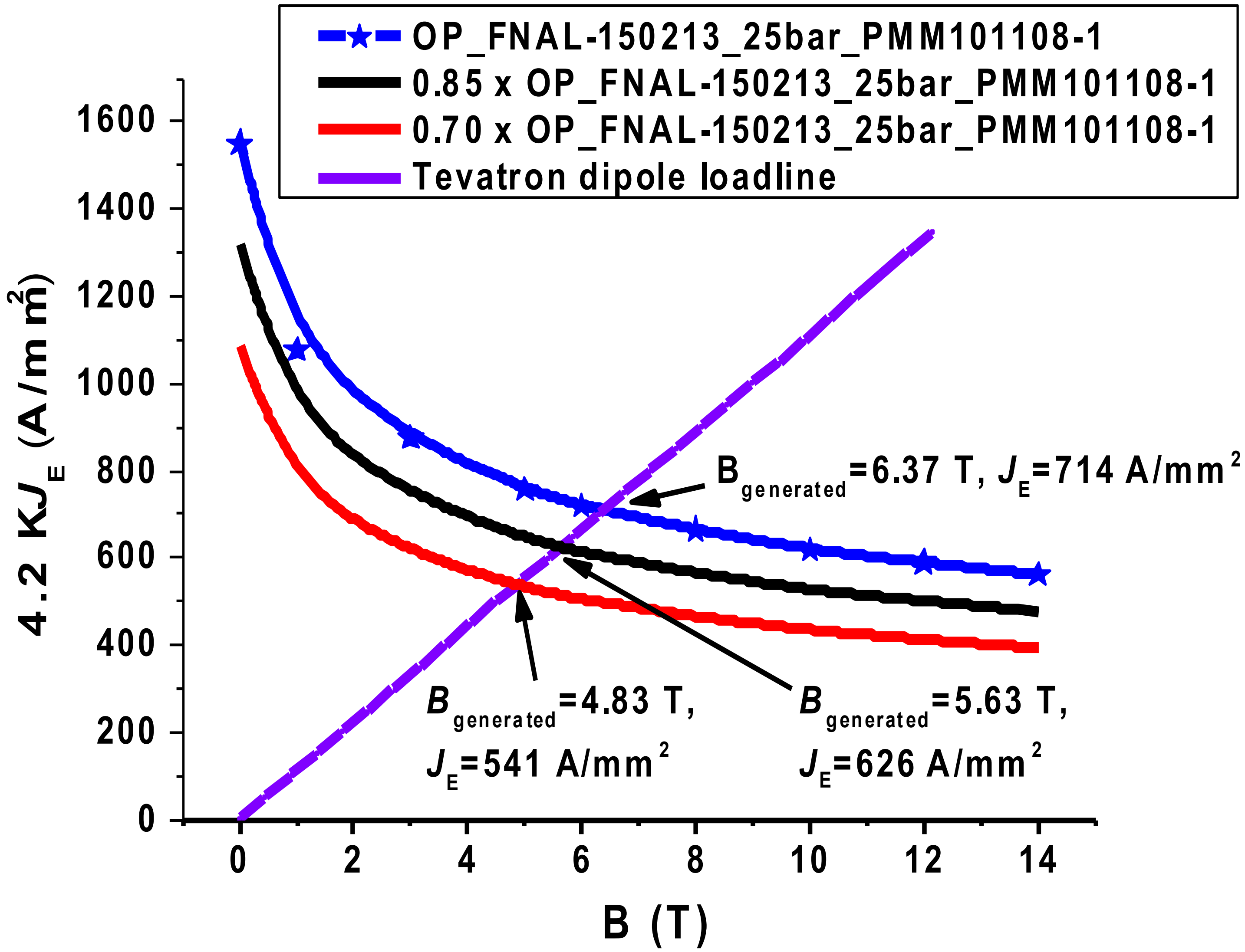
- Getting high J_c in long-length wire is not easy.
  - Overpressure processing in 2012
  - Bi2212 20 T J_c now on par with Nb_3Sn 12 T J_c
- Industry hasn't made significant progress for 10 years
  - Bi2212 now <= Nb_3Sn in 1990
  - Still learning to build solenoids
  - Need to walk the road that Nb_3Sn colleagues have been walking.

Overpressure processing technology provides a new tool for HEP magnet grade 2212 conductors

Courtesy Tengming Shen

Godeke – HTS-SC08: 2600 A, 65% of SSL (with internal gas effects considered) 2 layers-6-turns/layer racetrack coils



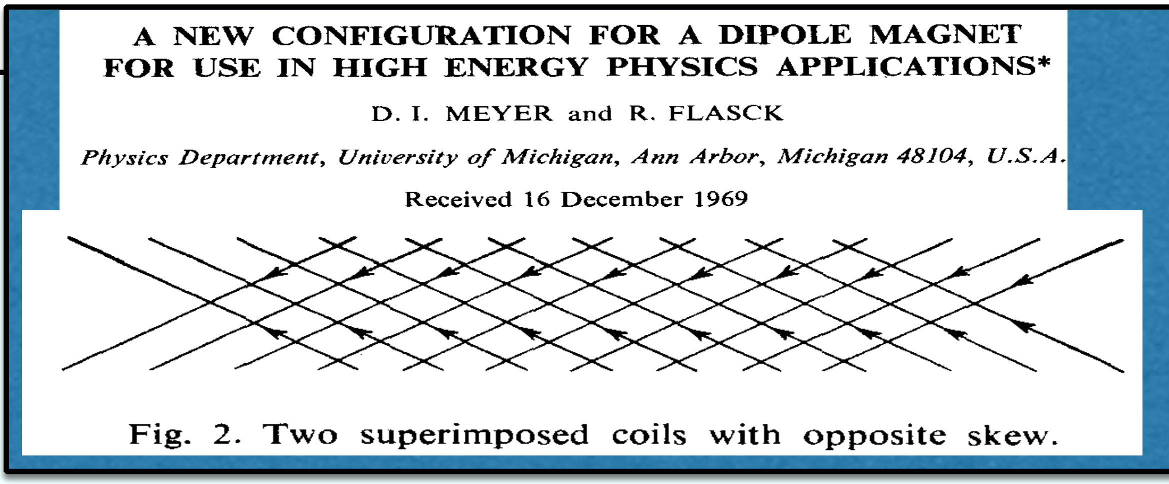


The key elements of a new magnet paradigm

1) Decrease operating margin
2) Minimize or eliminate training
3) Fully utilize grading
4) Flexible choice of bore diameter
5) Manufacturability (reliability and reproducibility)

- **Take baseline technologies to higher level of performance**
  - **The HD magnets are on the asymptote for Nb_3Sn so it will be difficult**
- **Combine with a strong component of high-risk, potentially high payoff disruptive technology**
  - **development that can leapfrog the status quo**
- **A parallel program of supportive R&D**
  - **Advanced materials R&D**
  - **Explore other applications of the new technology that challenge current capabilities**

One example of a New Paradigm, building on established foundations: The Canted Cosine Theta Magnet (CCT)


A NEW CONFIGURATION FOR A DIPOLE MAGNET FOR USE IN HIGH ENERGY PHYSICS APPLICATIONS*

D. I. MEYER and R. FLASCK

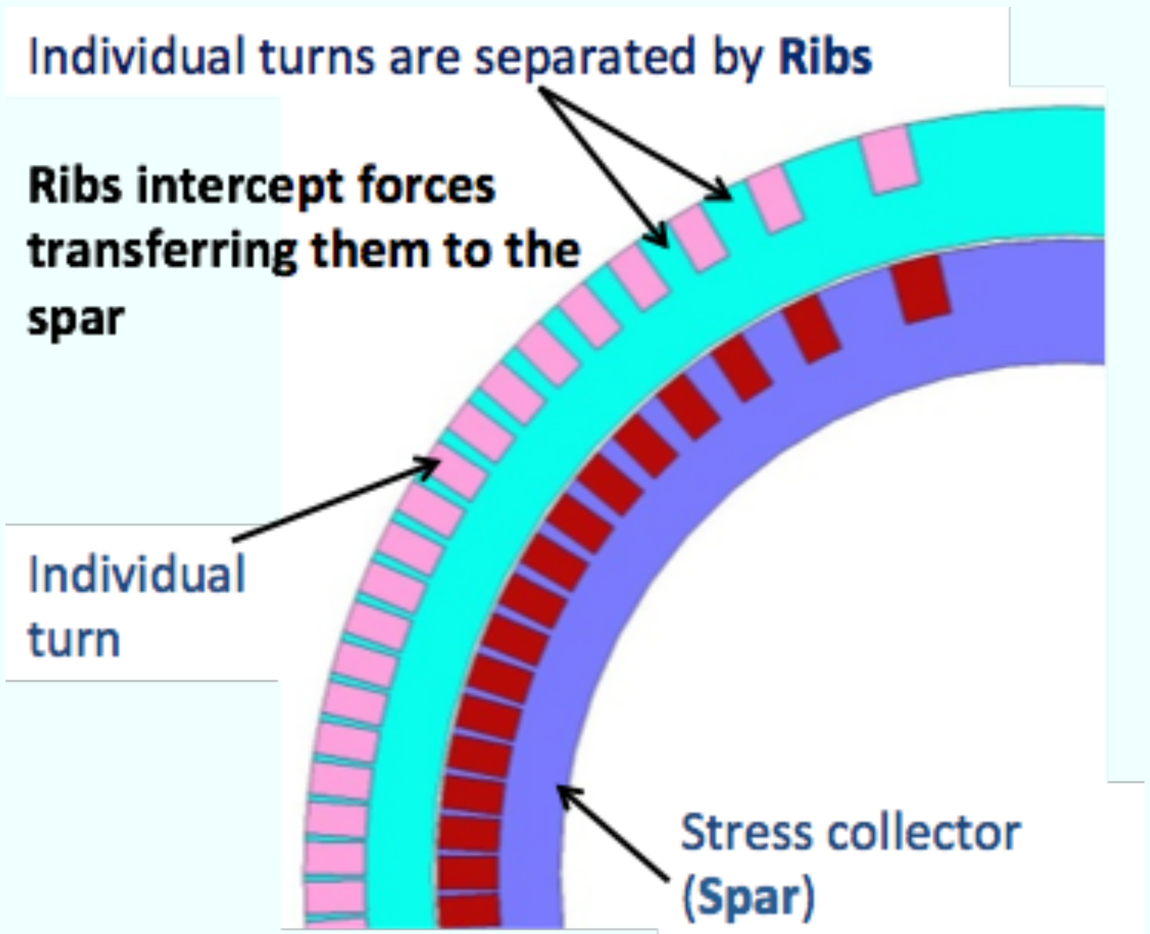
Physics Department, University of Michigan, Ann Arbor, Michigan 48104, U.S.A.

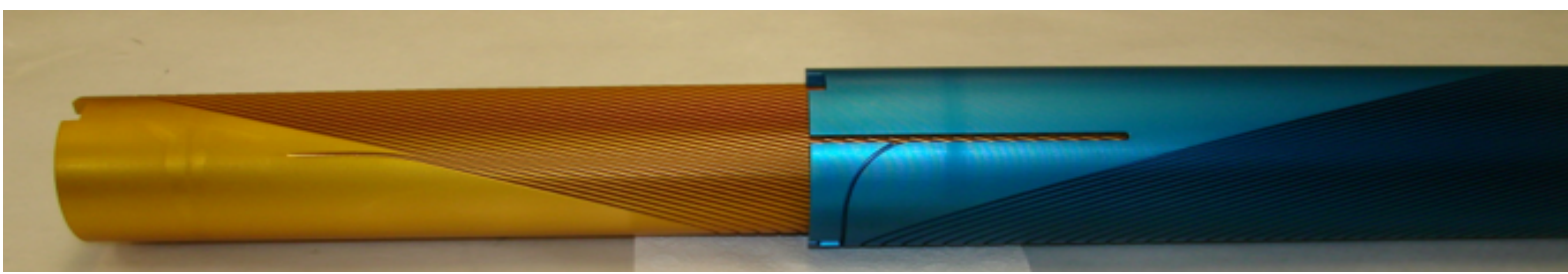
Received 16 December 1969

Fig. 2. Two superimposed coils with opposite skew.

Key characteristics we want:

- *Remove the stress barrier*
- *Incorporate grading for efficiency*
- *Reasonable bore diameter for shielding*
- *Scalable design allowing industrialization*



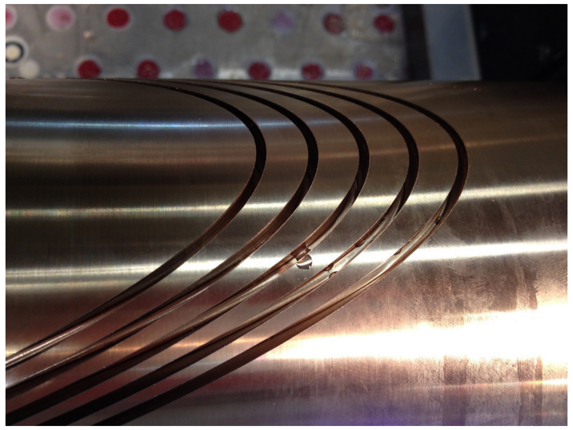


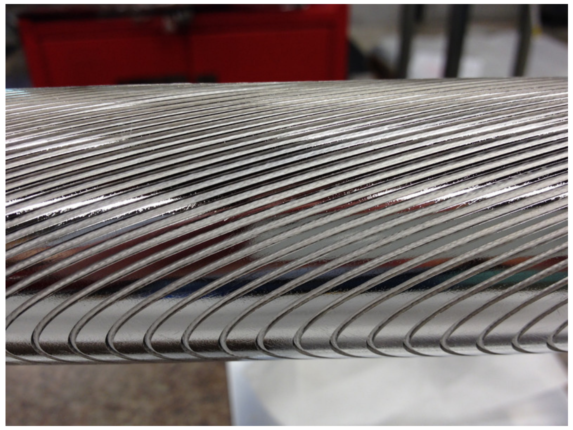
CCT has the potential to meet required characteristics

Stress is captured by rib, transferred to mandrel

No accumulation of stress on the mid plane

No stress issue with larger bore





Every layer can use different cable size

Allows near optimal grading for conductor efficiency

Significant saving in Nb_3Sn over Cos(θ) designs

Conductor mass scales with bore radius only

Excellent field quality ("for free")

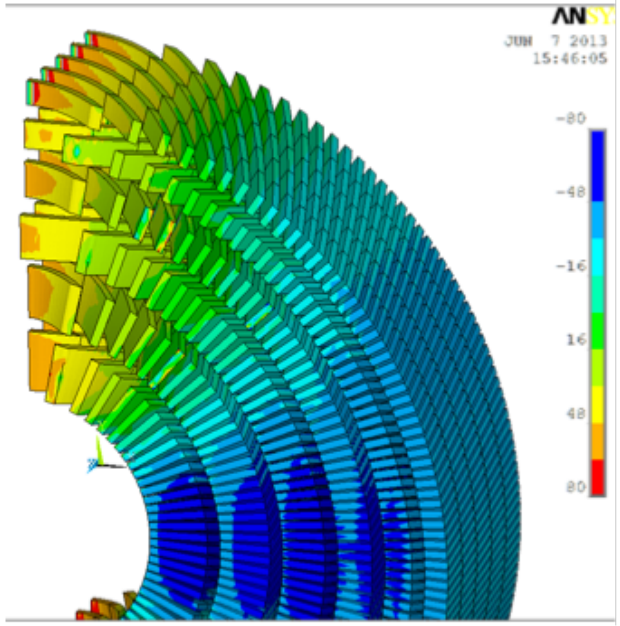
Fabrication:

Minimal external structure

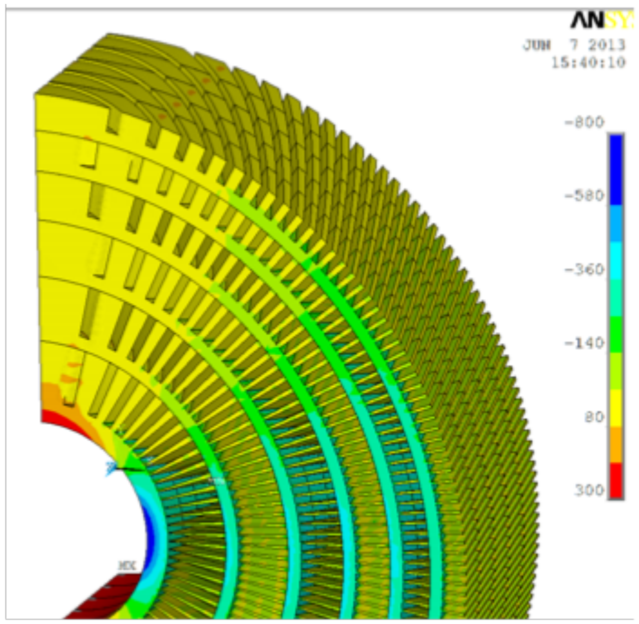
No spacers, end parts, etc.

Simple winding ➪ Industrialization

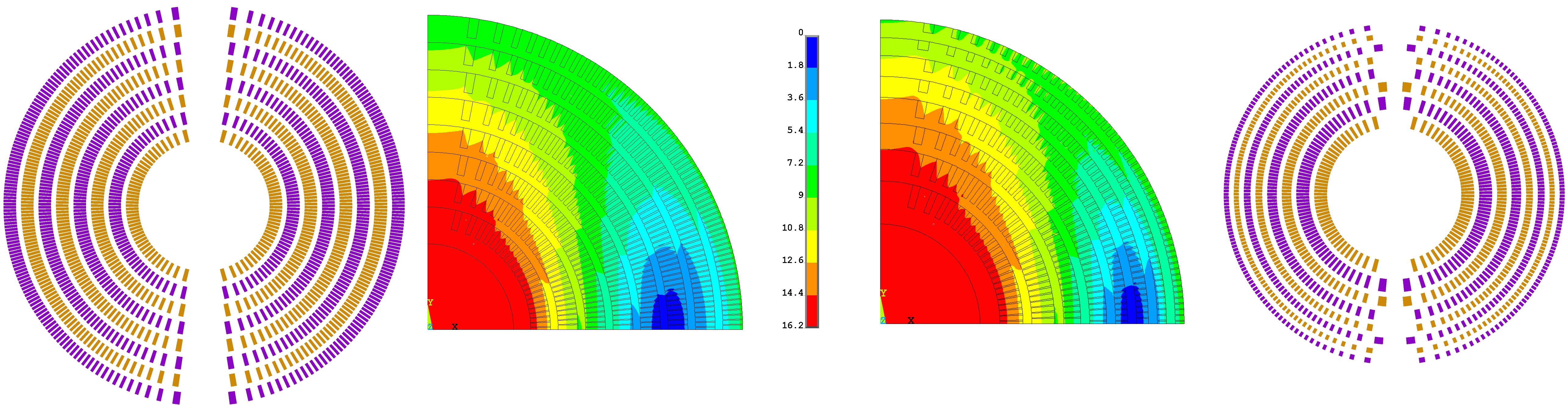
Coil stresses



Structure stresses

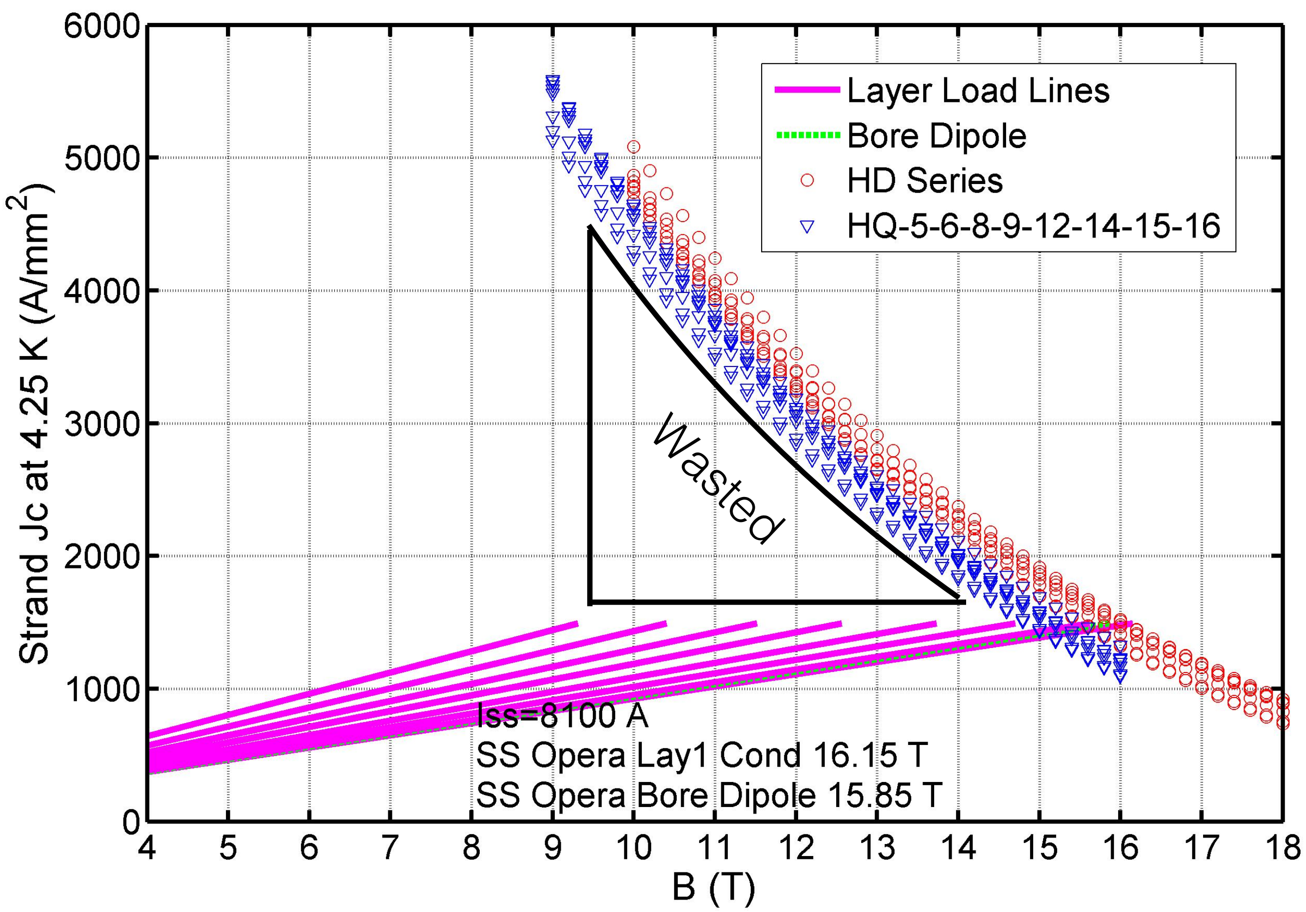


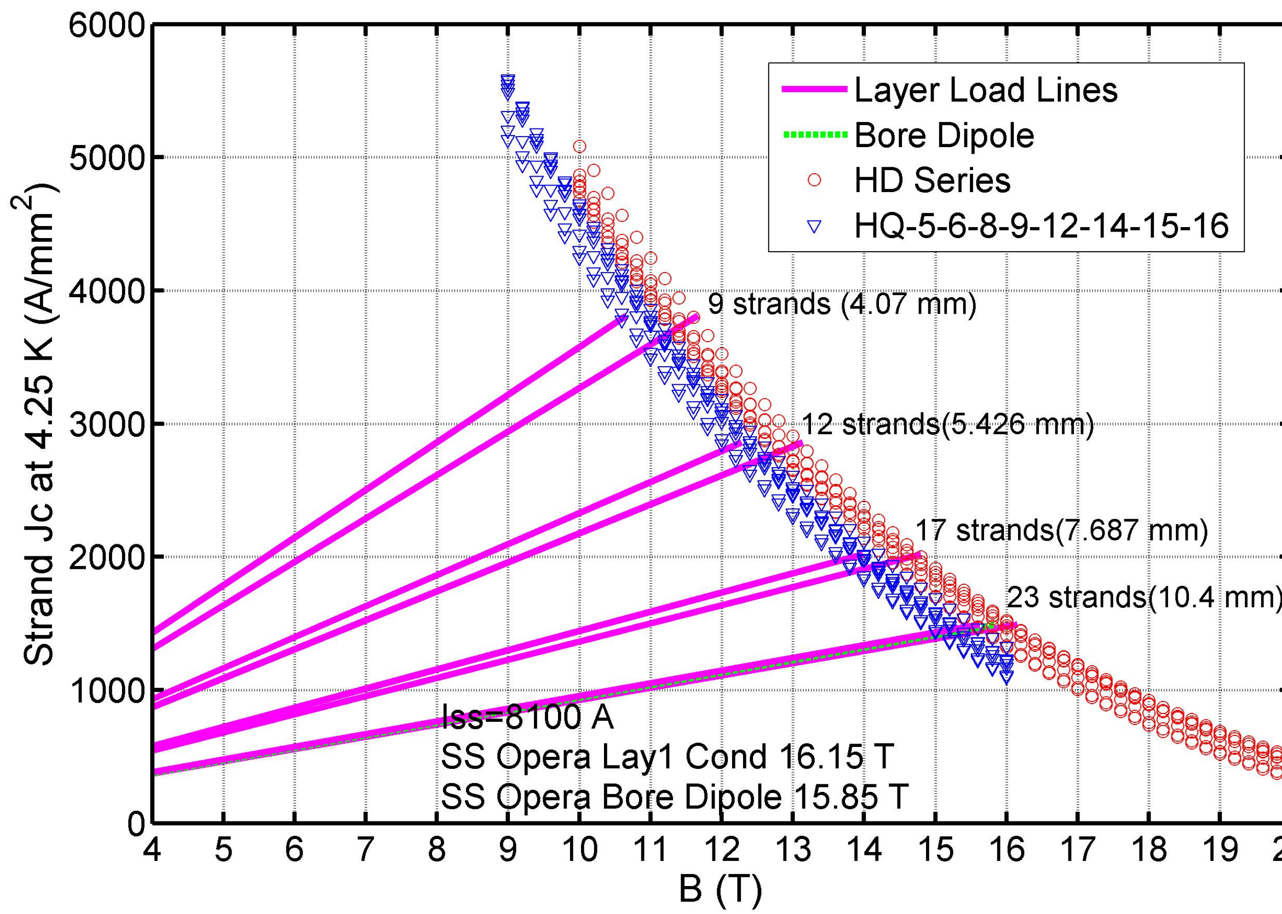
Minimize conductor by “grading”



Un-graded

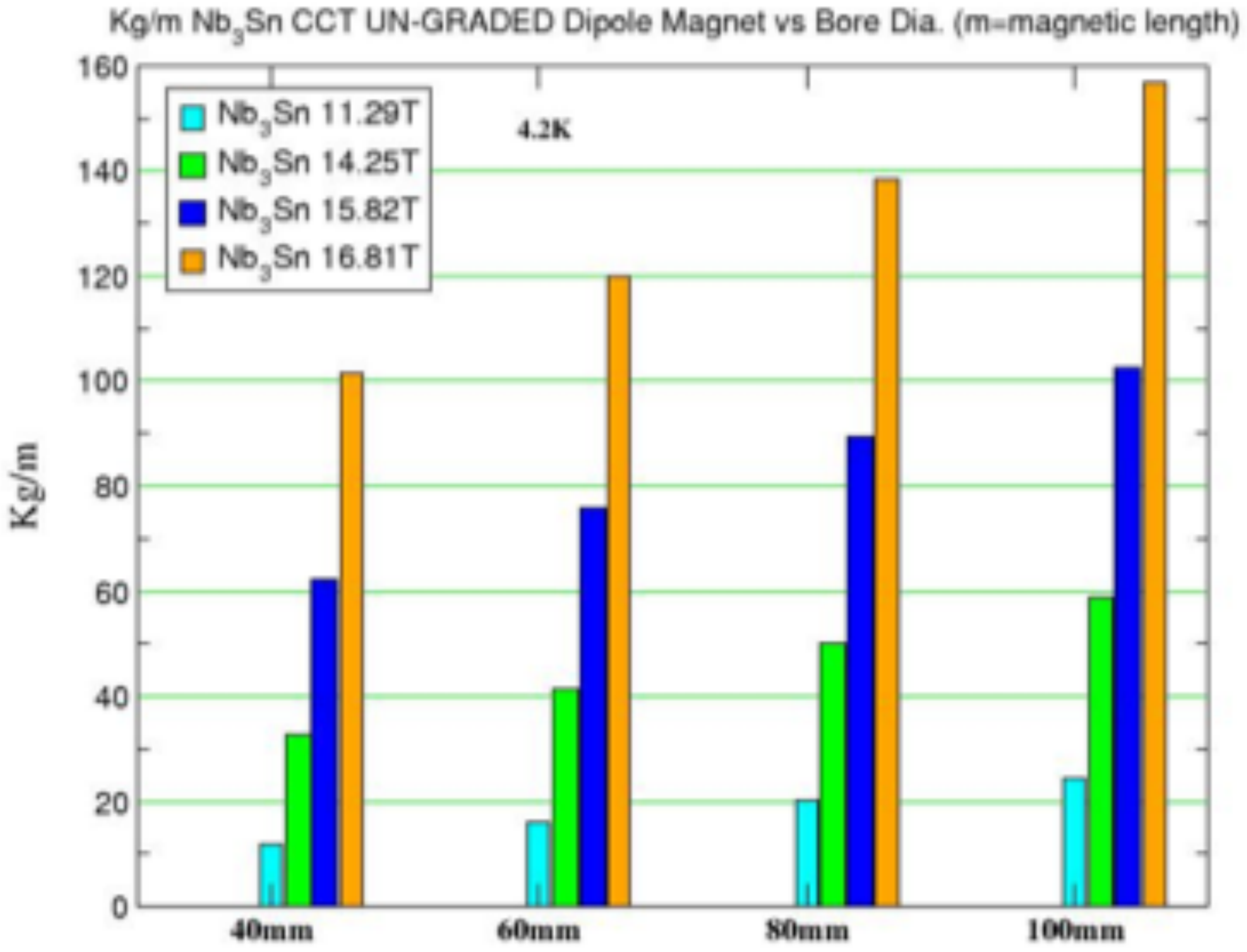
Graded



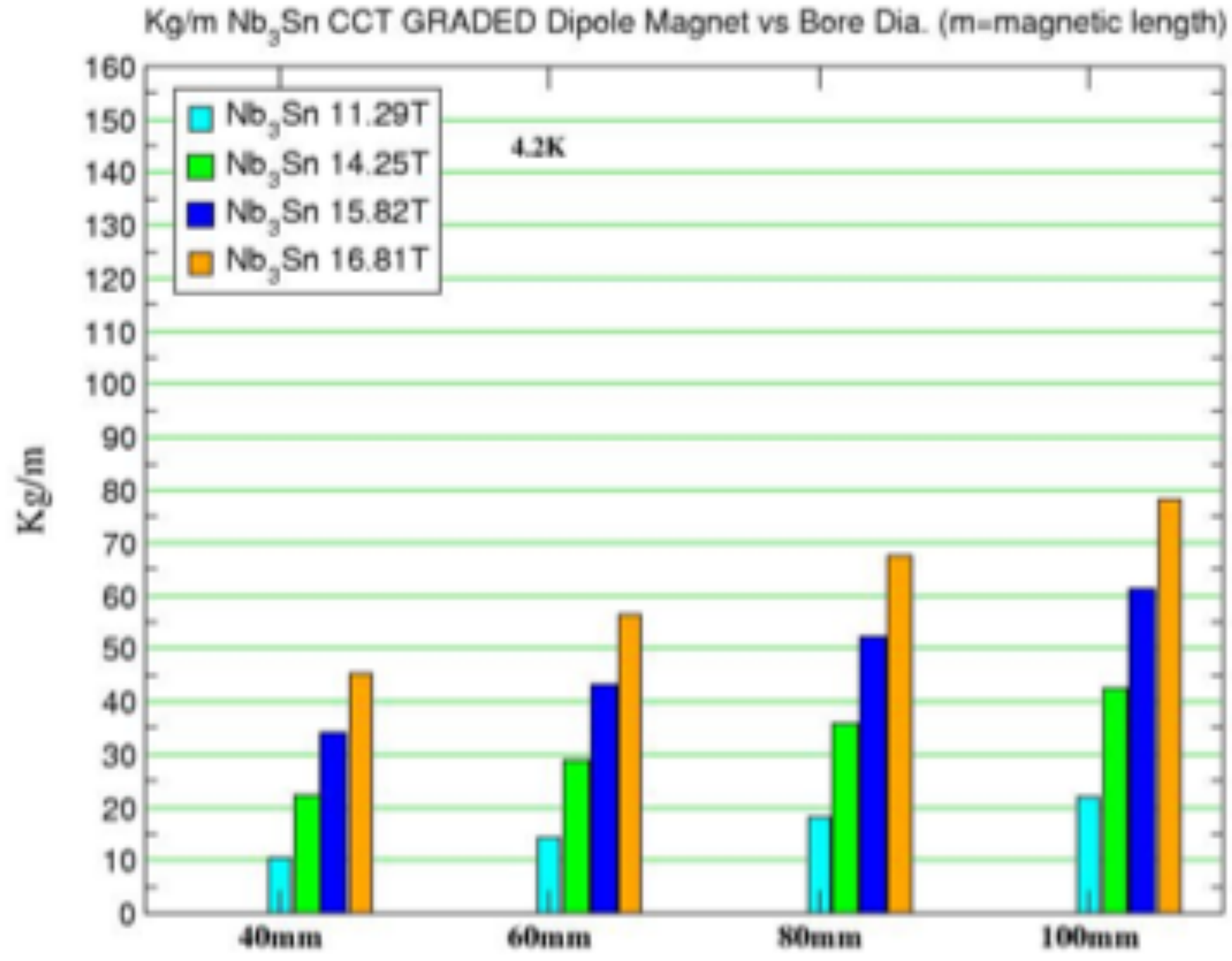


Grading the conductor is critical for large production

Un-graded CCT

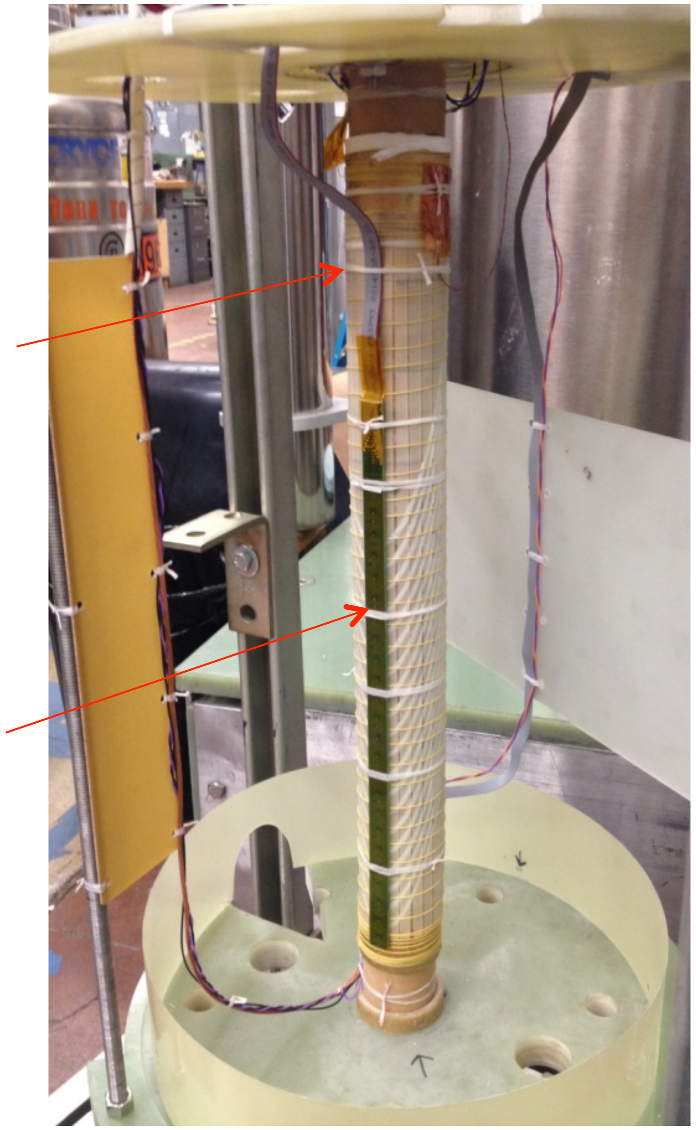


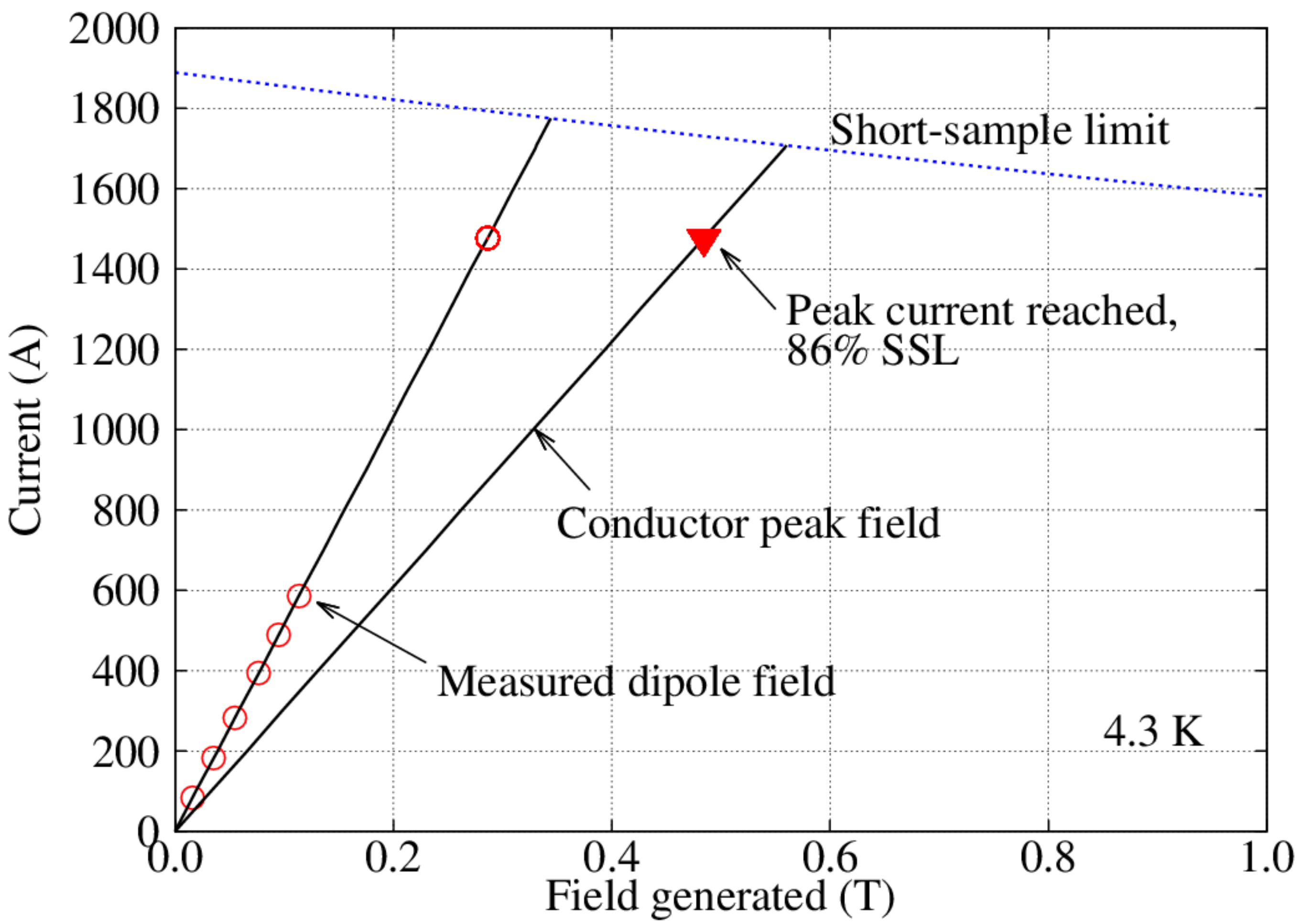
Graded CCT



HTS magnet developments: Bi-2212 insert coil

Courtesy Xiaorong Wang





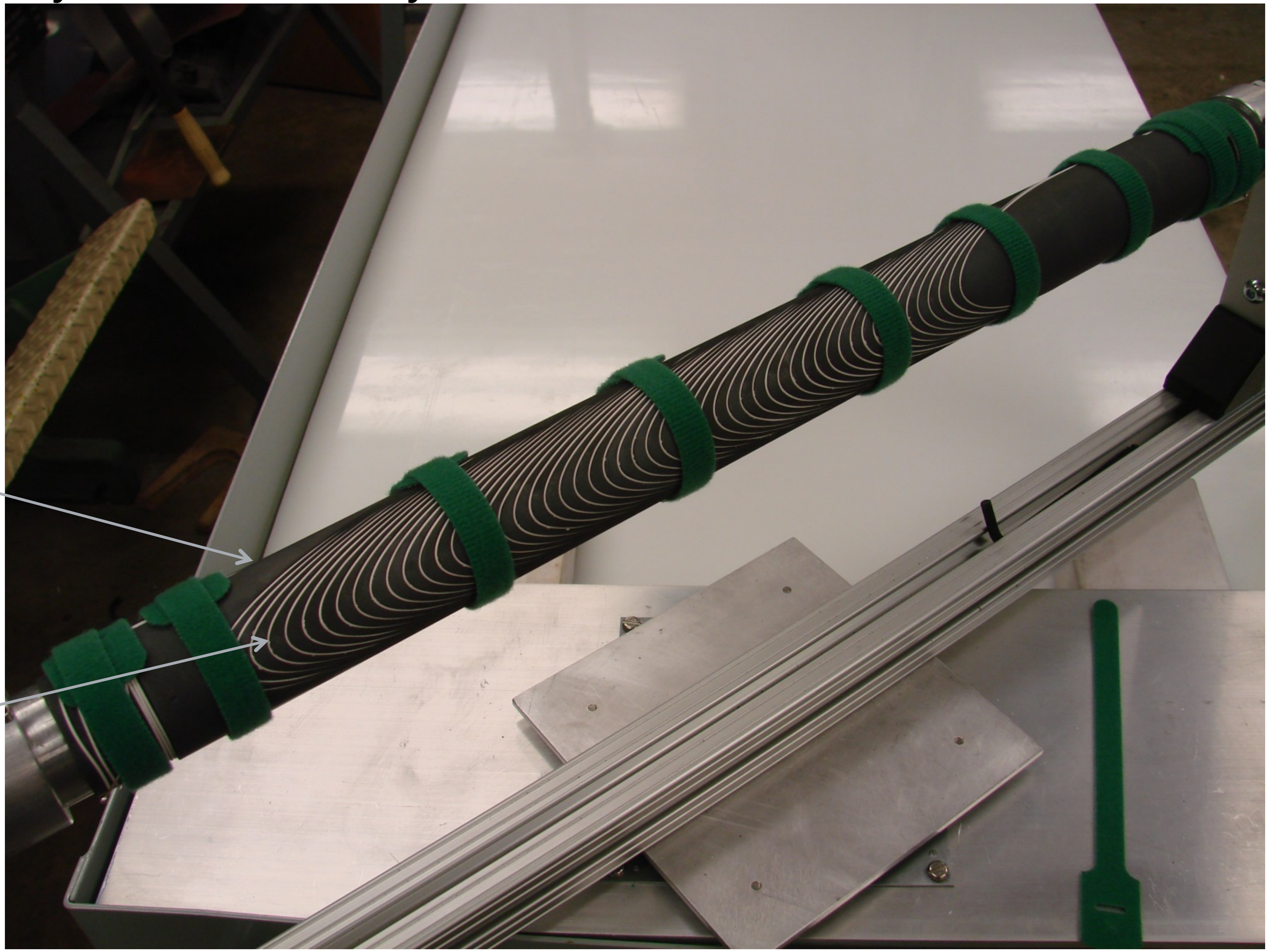
- Inner layer, 6-aroun-1 cable, reacted at 1 bar (OP reaction with FSU in preparation)
- Measured peak current 1477 A, 86% SSL at 4.3 K
- Excellent agreement between measured and calculated dipole field
- Ramped to 1400 A several times without degradation

Single wire CCT for OP HT

Courtesy Xiaorong Wang

NATIONAL MAGLAB

- CDP Oxford wire, TiO_2 insulation applied at NHMFL
- Both layers are ready to be heat treated at NHMFL

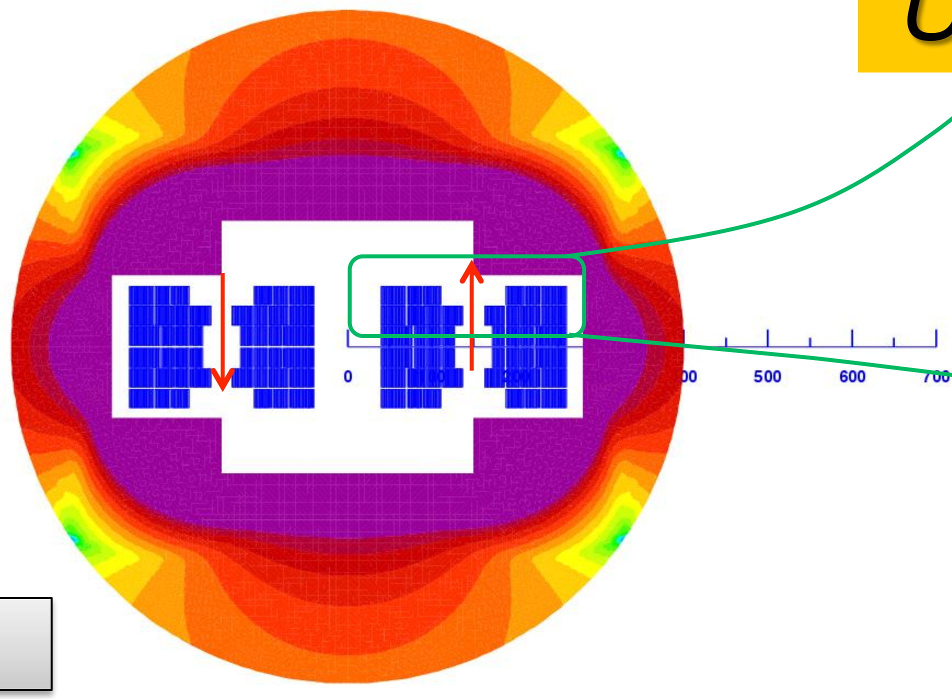


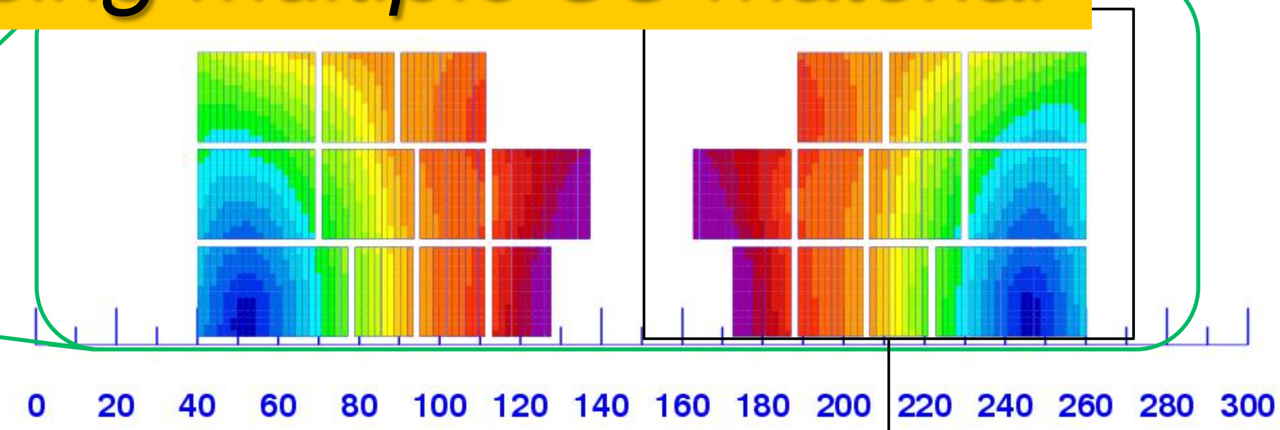
Inconel mandrel

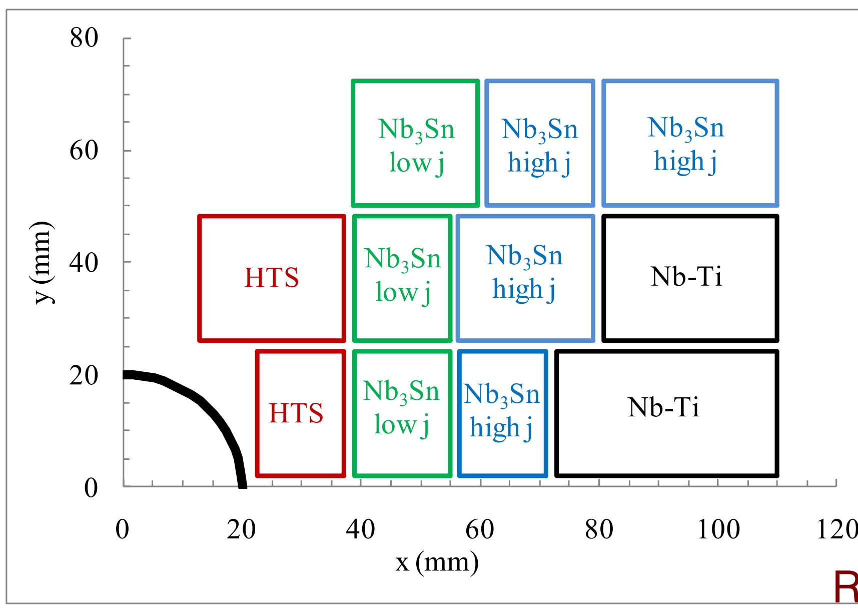
2212 wire with TiO_2 insulation

First consistent conceptual high field design from CERN

Using multiple SC material







L.Rossi

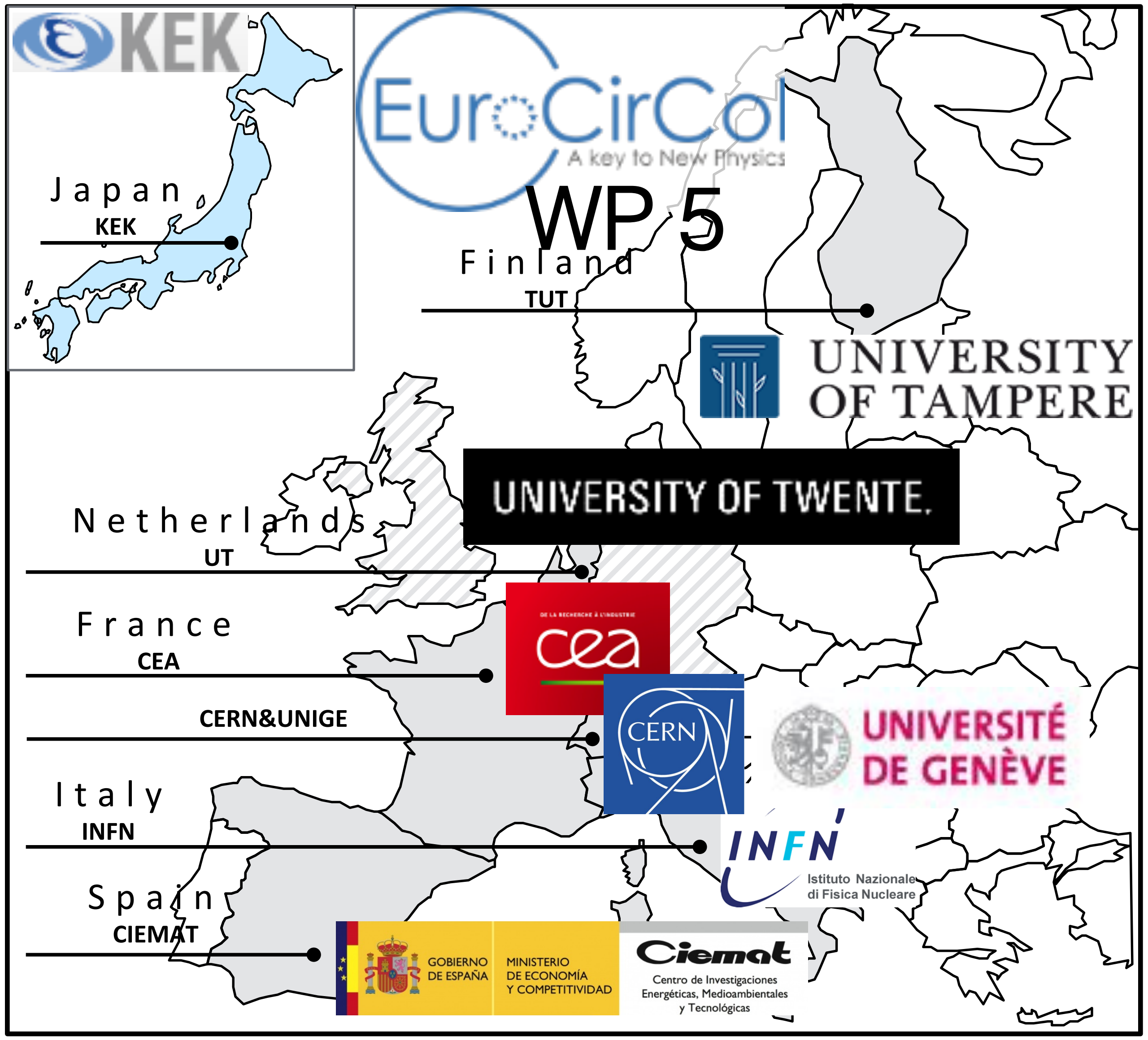
Material	N. turns	Coil fraction	Peak field	$J_{overall}$ (A/mm^2)
Nb-Ti	41	27%	8	380
Nb3Sn (high Jc)	55	37%	13	380
Nb3Sn (Low Jc)	30	20%	15	190
HTS	24	16%	20.5	380

20 T field!

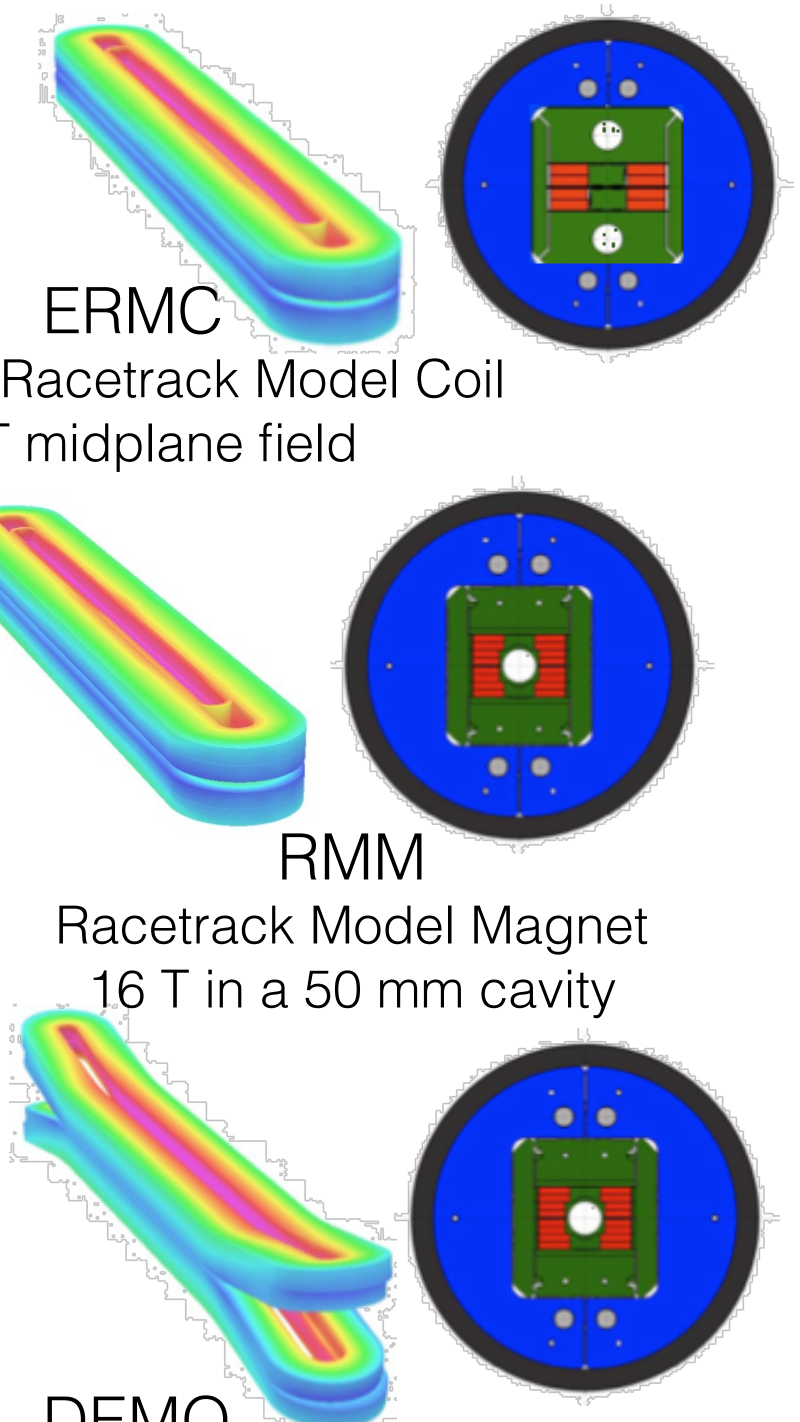
Roy Aleksan
CERN
Feb. 22, 2013

Magnet design: 40 mm bore (depends on injection energy: > 1 Tev)
Approximately 2.5 times more SC than LHC: 3000 tonnes! (~4000 long magnets)
Multiple powering in the same magnet for FQ (and more sectioning for energy)
Only a first attempt: cos? and other shapes needs to be also investigated

CERN/EU program



Design a 16 T accelerator-quality model dipole magnet, operating at 4.5 K with a 10% margin, by 2018



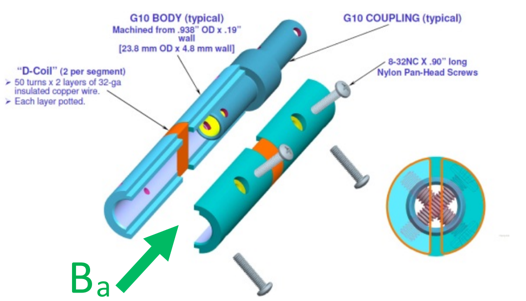
ERMC
Extended Racetrack Model Coil
16 T midplane field

RMM
Racetrack Model Magnet
16 T in a 50 mm cavity

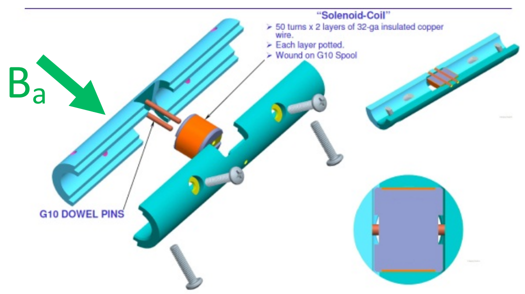
DEMO
Demonstrator Magnet
(blocks and cos-ϕ options under study)

75 km Nb_3Sn wire for short model

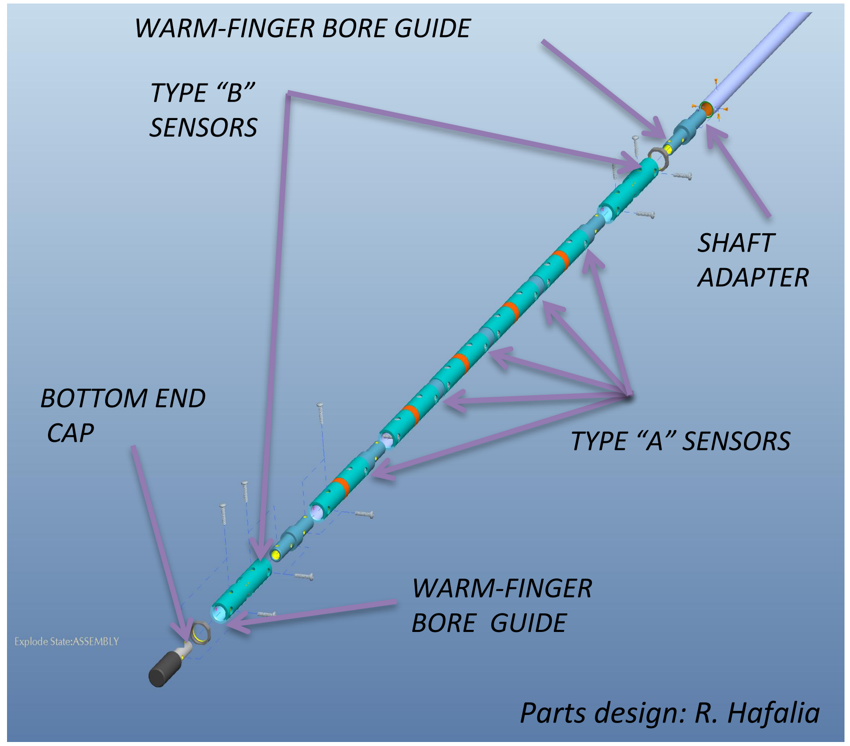
Key to magnet development is state-of-the-art diagnostics

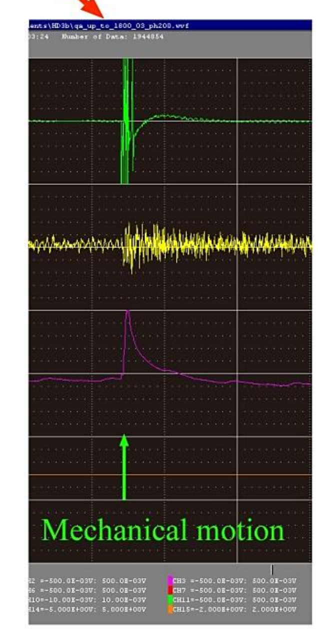


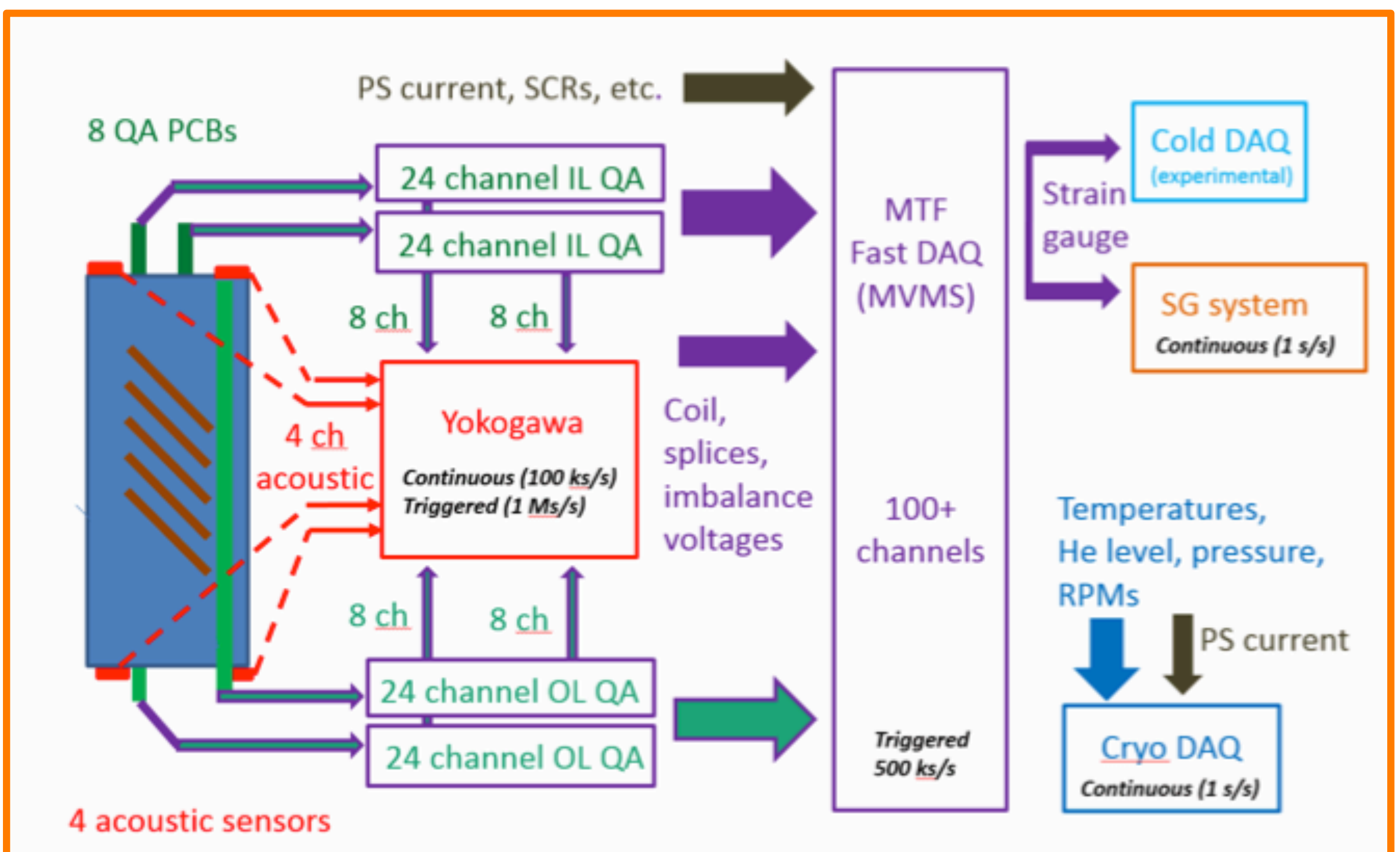
Longitudinal field sensors (“A) for the magnet straight section



Transverse field sensors (“B”) for the magnet ends







Conclusions

- Accelerator quality dipoles with an operating field of 16T are ***feasible***
- Making them ***affordable*** is a challenge and will take time and require more resources than we have now. It will be a world-wide effort.
- HTS has many issues to understand and overcome in order to be a viable option
  - We need to prove feasibility, which could be demonstrated within the next year or two, then we can worry about the cost.

A future high-energy proton-proton collider yielding new breakthrough particle physics requires significant magnet developments