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R&D Roadmap Towards 16 T Nb_3Sn Dipole Magnets Ready for Industrial Production

Bruce Strauss

12 February 2013

FCC Design Study

Geneva, CH

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Two weeks ago an email message appeared in my in box from Luca Bottura with the subject line: "…time for a chat?"

This was followed by a very cordial email from Michael Benedikt and Frank Zimmerman that suggested the title on the previous slide. One of the paragraphs in the email began as:

"We were hoping that this talk would address the follow points:

- **Proposal for challenging but realistic goals for FCC magnet R&D in the 4 – 5 year period of the conceptual design study.**

- **Present status of Nb_3Sn and HTS technologies.**

- **Lessons learned from past experience.**

- **FCC as a global project in the longer term: a suggestion for worldwide region based magnet R&D, from magnet models to large scale production.**

- **Potential impact on society.**

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50 years after Kammerlingh Onnes

It was 50 years after Kammerlingh Onnes discovery, in the spring of 1961, when I was a first year student at M.I.T. that Professor John Wulff came into my first materials science class and announced: "Gentlemen, mark this date in your note books. Bell Labs announced …"

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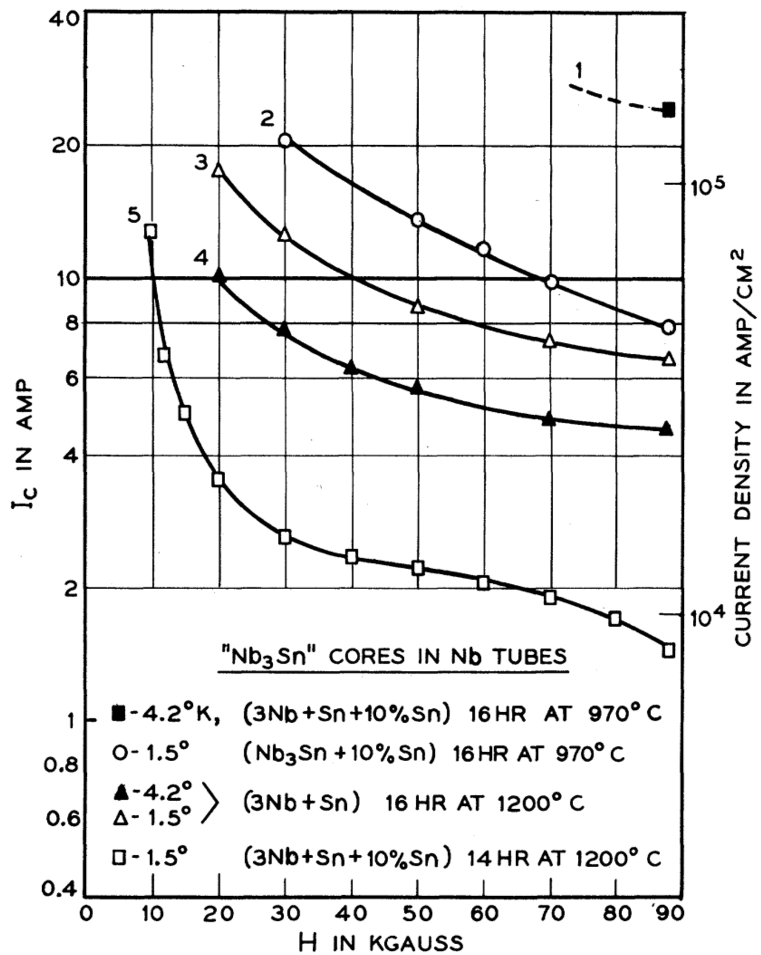
Experimental verification 1961

SUPERCONDUCTIVITY IN Nb_3Sn AT HIGH CURRENT DENSITY IN A MAGNETIC FIELD OF 88 kgauss

J. E. Kunzler, E. Buehler, F. S. L. Hsu, and J. H. Wernick
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received January 9, 1961)

We have observed superconductivity in Nb_3Sn at average current densities exceeding 100 000 amperes/cm² in magnetic fields as large as 88 kgauss. The nature of the variation of the critical current (the maximum current at a given field for which there is no energy dissipation) with magnetic field shows that superconductivity extends to still higher fields. Existing theory does not account for these observations. In addition to some remarkable implications concerning superconductivity, these observations suggest the feasibility of constructing superconducting solenoid magnets capable of fields approaching 100 kgauss, such as are desired as laboratory facilities and for containing plasmas for nuclear fusion reactions.[1,2]

The highest values of critical magnetic fields previously reported for high current densities



Phys Rev Letters 6, 89 (1961), submitted January 9, published February 1, 1961!

Cryogenic Stability-1965

Stekly Equation:

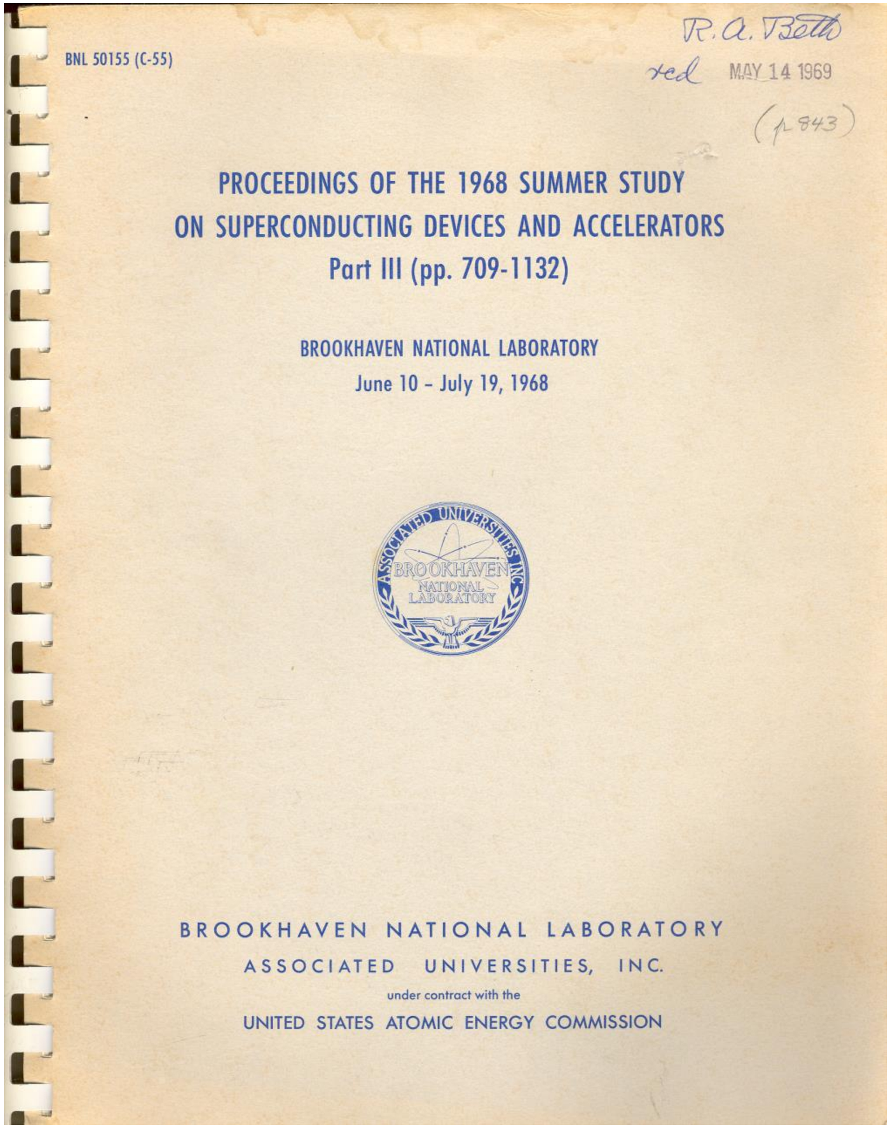
$$\alpha = \frac{\lambda^2 J_c^2 \rho A}{(1-\lambda)Ph(\theta c-\theta 0)} < 1$$

This led to:

- **AVCO 12 inch MHD Magnet**
- **BNL 7 foot bubble chamber**
- **ANL 12 foot bubble chamber**
- **FNAL 15 foot bubble chamber**

Woodstock - 1968

- **1968 Brookhaven Summer Study**
  - **46th Anniversary this year**


BNL 50155 (C-55)

MAY 14 1969

PROCEEDINGS OF THE 1968 SUMMER STUDY
ON SUPERCONDUCTING DEVICES AND ACCELERATORS
Part III (pp. 709-1132)

BROOKHAVEN NATIONAL LABORATORY
June 10 – July 19, 1968

ASSOCIATED UNIVERSITIES, INC. BROOKHAVEN NATIONAL LABORATORY

BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
under contract with the
UNITED STATES ATOMIC ENERGY COMMISSION

http://www.bnl.gov/magnets/Staff/Gupta/

And another Criterion…

"Buy it by the ton."

Paul Reardon, Fermilab

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Summary: Early Milestones

Event	Year	Who and Where
High Field Nb_3Sn	1961	Bell Telephone Labs
ANL 25 cm BC Magnet	1965	Argonne National Lab
Cryostatic Stability Concept	1965	Avco Everett Research Lab
12 inch MHD Dipole Magnet	1966	Avco Everett Research Lab
Intrinsic Stability Concept	1968	RAL, AVCO
12 ft & 7 ft H_2 Bubble Chambers	1968	Argonne & Brookhaven
High Quality M.F. NbTi	1970-80	Industry
Hollow Conductor	1972	CERN
Ramped Magnet Development	1972 to present	Tevatron, HERA, RHIC, SSC, LHC
M.F. Nb_3Sn	1976 to present	Industry
MRI	1982	Industry

After Steve St. Lorant, SLAC

Events and Change—1997 to 2002

- Construction of the LHC at CERN
- MSUT at Twente and D20 at LBNL
- US leaves ITER
- At DOE we wondered what to about the three magnet groups at national labs

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“Superconductivity is absolutely the worst technology to use unless, of course, you have no other choice.”

Dave Sutter, DOE

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Events and Change—1997 to 2002

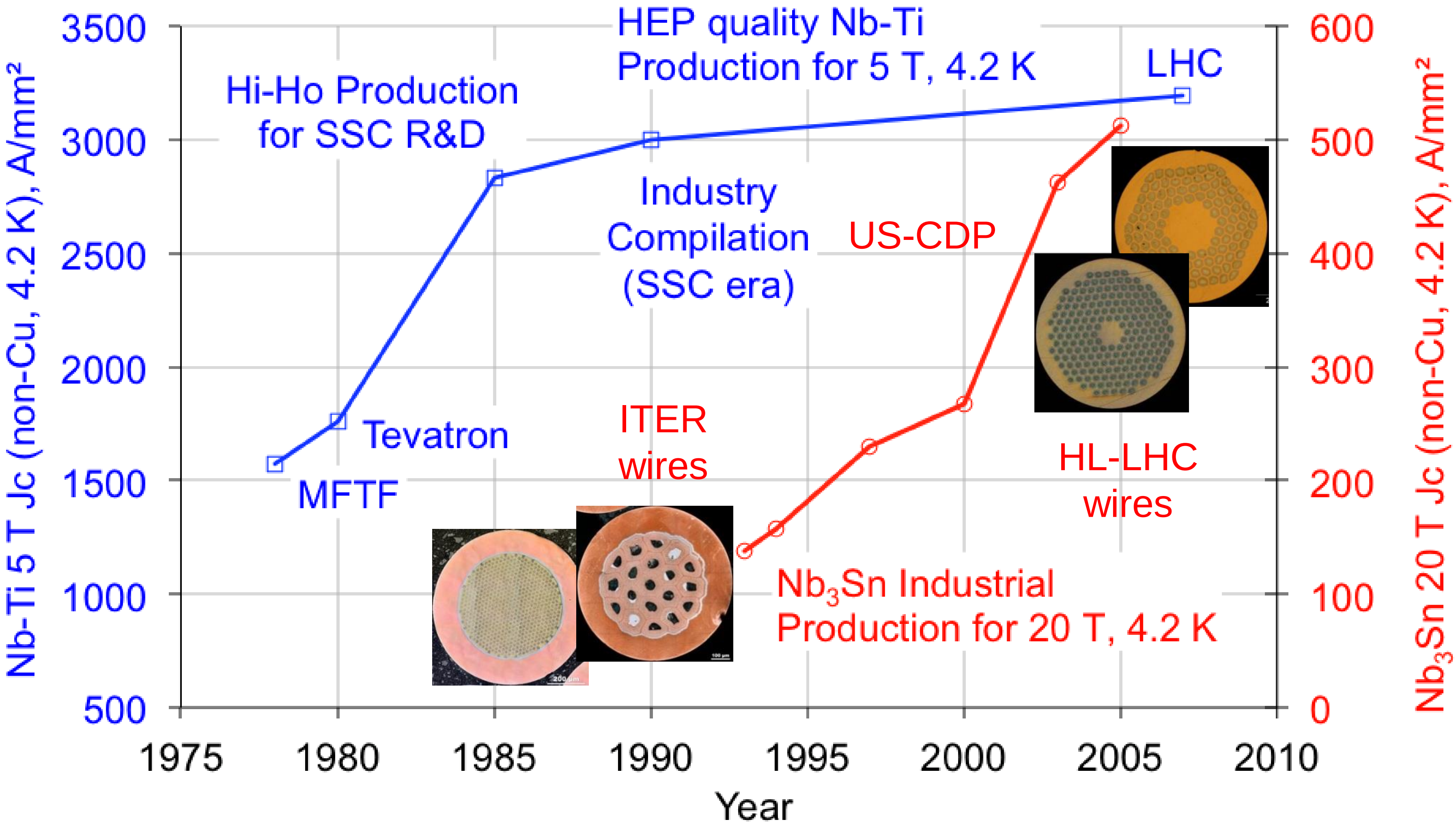
- **Construction of the LHC at CERN**
- **MSUT at Twente and D20 at LBNL**
- **US leaves ITER**
- **At DOE we wondered what to about three magnet groups at national labs**

- **Sutter gets $500,000/year from John O'Fallon for industrial development of Nb_3Sn.**
- **Conductor Development Group is formed.**
- **Nb_3Sn magnet development starts with ITER strand.**
- **Sutter remarks…**

A Convert…

"…20 tesla or bust!"
Dave Sutter, DOE

At 52, LTS's have reached ~~maturity~~ splendor



Data by courtesy of J. Parrell (OST)

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ITER Conductor Statistics

TF Coils	Nb_3Sn	826 Tonnes
CS Coils	Nb_3Sn	739 Tonnes
PF Coils	NbTi	1225 Tonnes

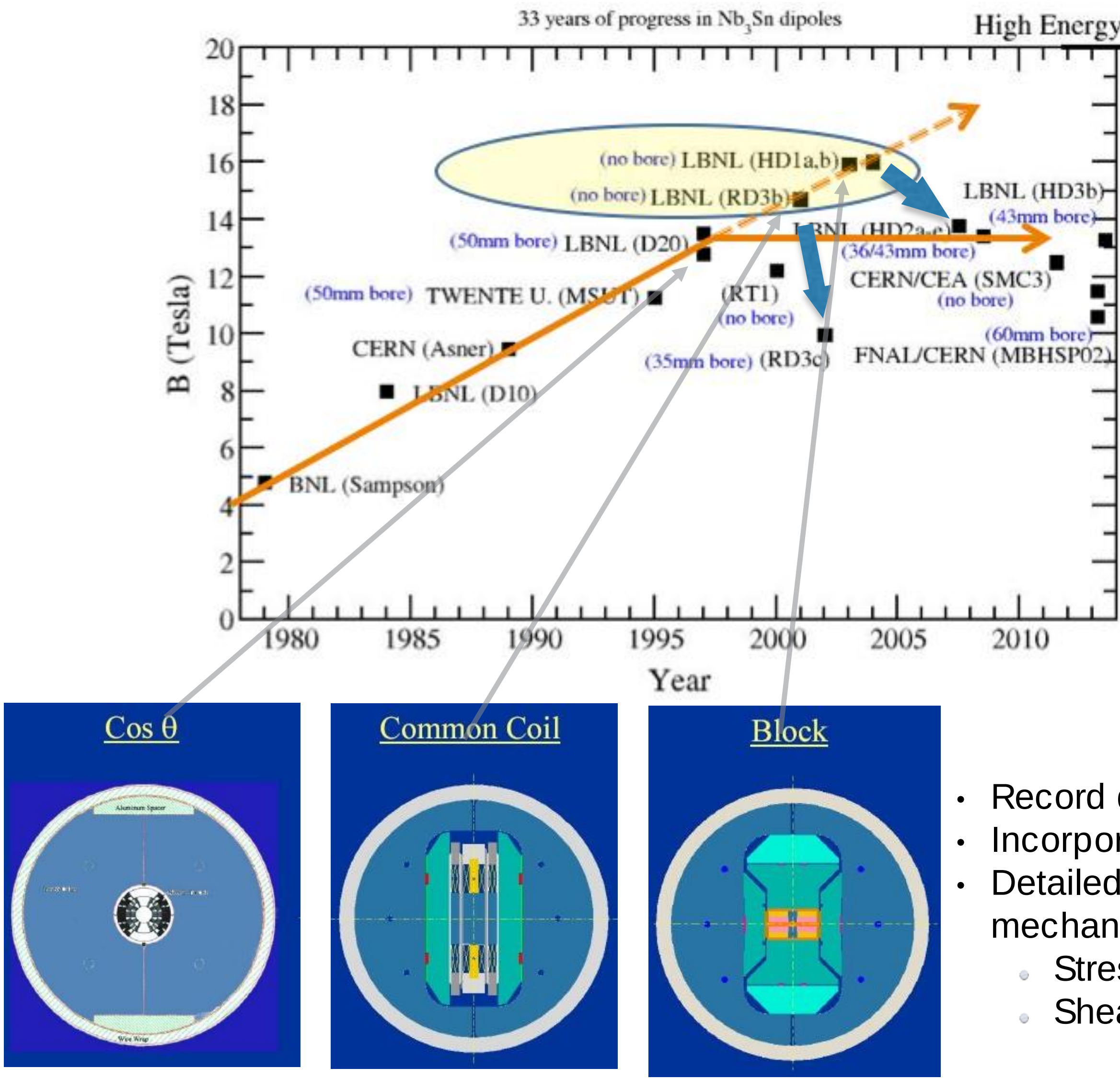
Taking Stock

As a result of the DOE programs in AARD, CDP and LARP:

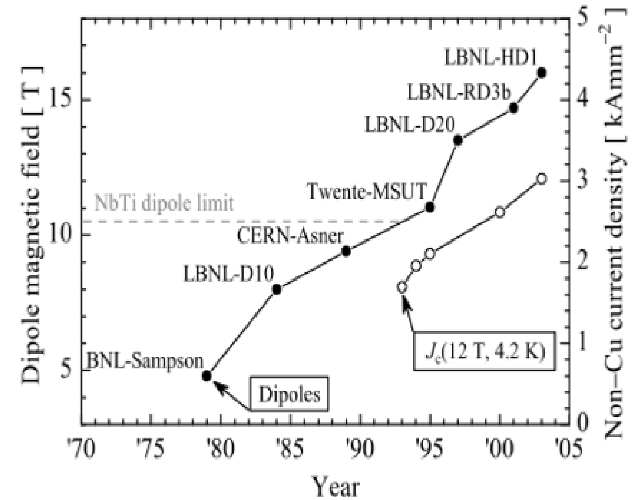
- **J_c of Nb_3Sn doubles**
  - **D_{eff} minimized**
  - **RRR optimized**
  - **Scaling**
    - **ITER**
  - **Asymptotic improvements presently**

- **A series of dipole and quadrupole magnets constructed**
  - **Peak field appears to have hit an asymptote**

LBNL holds Nb_3Sn dipole magnet records in 3 configurations
… but are hitting a wall at ~14T *with a realistic bore*
⇨ *Need a new paradigm*



D20 RD HD



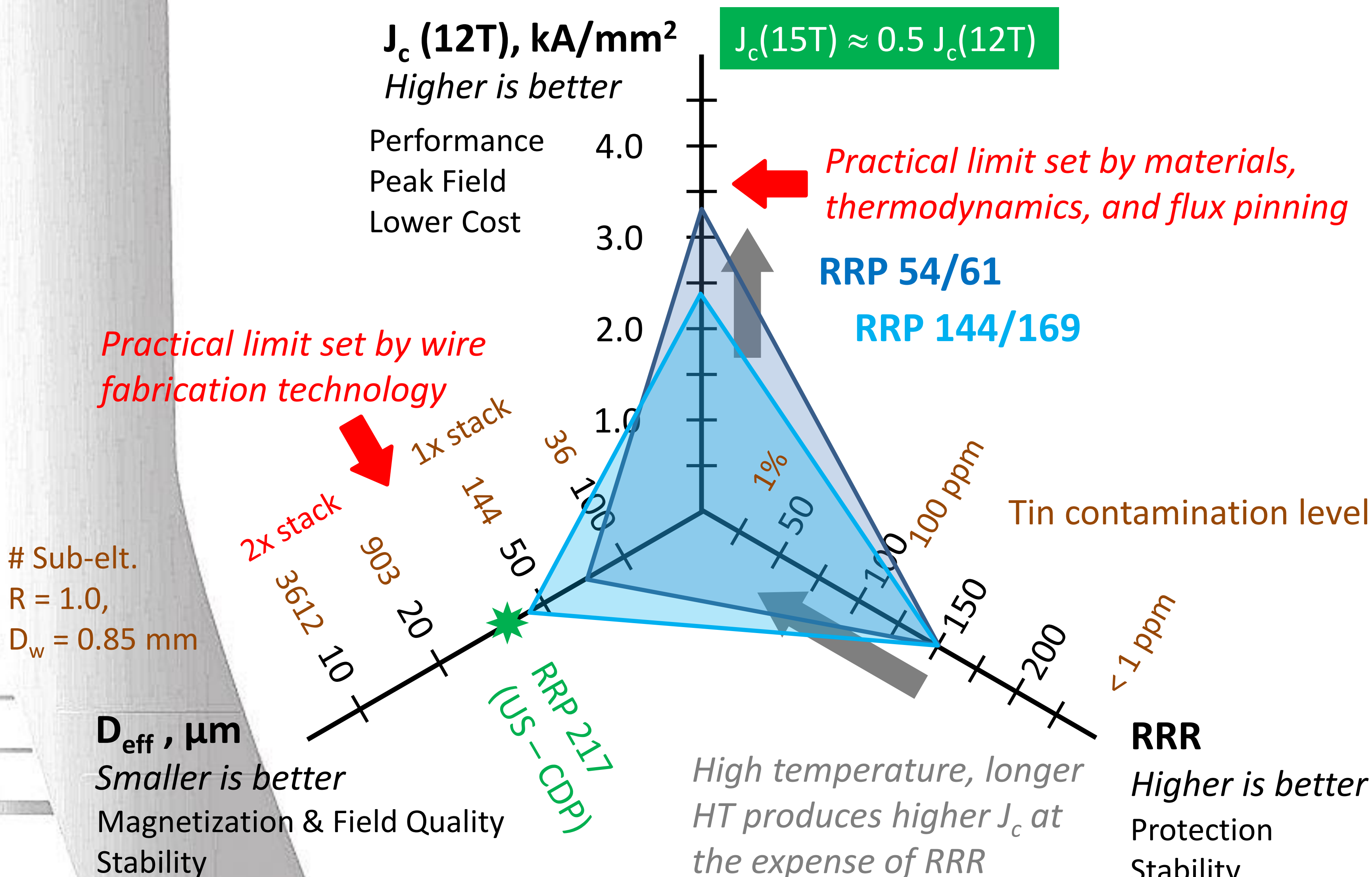
Field performance is correlated with Conductor performance

- Record dipole fields>~14T in each configuration
- Incorporating bore reduces peak field attained
- Detailed investigation suggests limitation is mechanical:
  - Stresses approach 200MPa (Nb_3Sn limit)
  - Shear stresses / interface stress issues

Courtesy of Soren Prestemon (LBL)

Nb_3Sn CONDUCTOR DEVELOPMENT – 3 PARAMETER OPTIMIZATION?

ADAPTED FROM BOTTURA MT-23 AND LARBALESTIER P5 PRESENTATIONS



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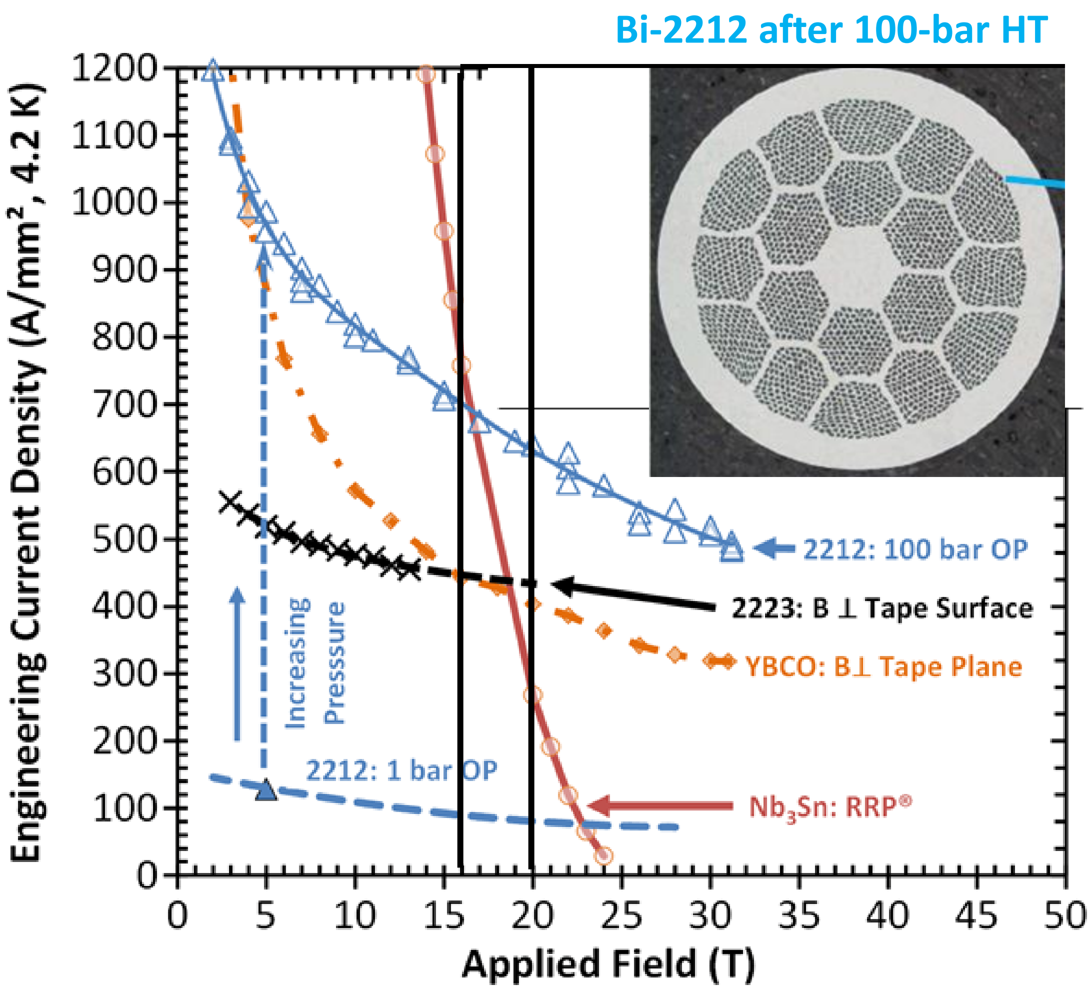
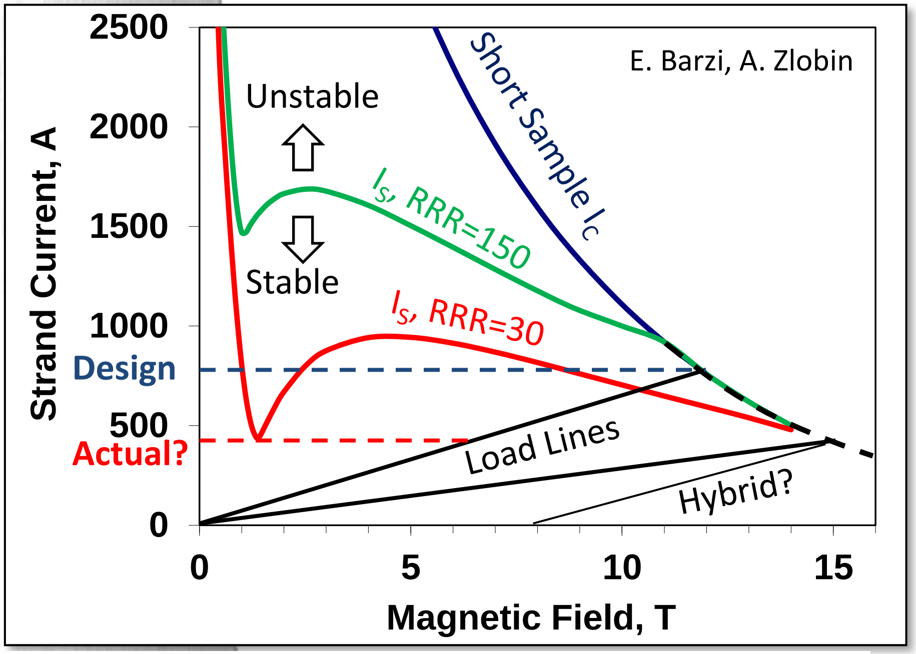
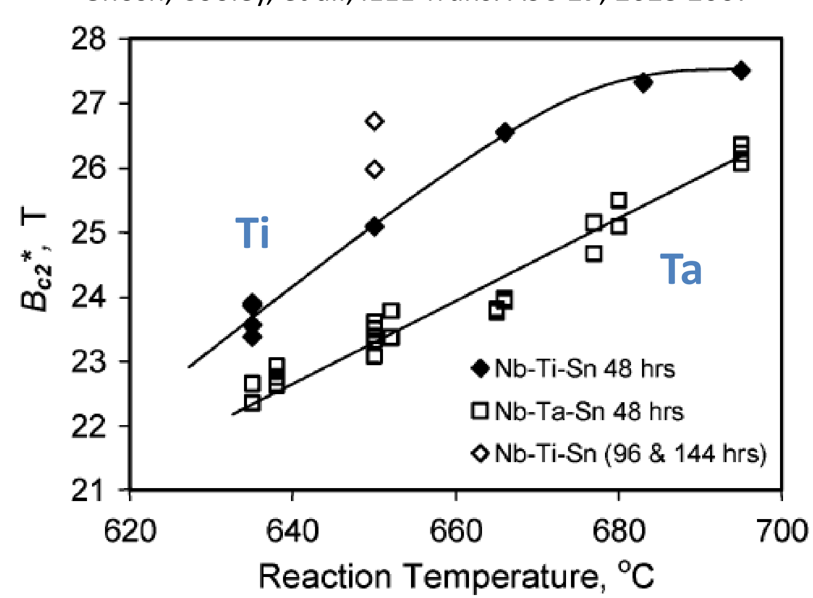
Fermilab


Bi-2212 after 100-bar HT
Engineering Current Density (A/mm², 4.2 K)
Applied Field (T)
2212: 100 bar OP
2223: B ⊥ Tape Surface
YBCO: B⊥ Tape Plane
Increasing Presssure
2212: 1 bar OP
Nb3Sn: RRP®
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
0
5
10
15
20
25
30
35
40
45
50

Nb_3Sn for 15+ Tesla implies 2 fundamental changes for R&D



Ghosh, Cooley, et al., *IEEE Trans. ASC* **17**, 2623 2007



A magnet operating along a load line to 15 T should ***not be as sensitive to RRR*** *compared to a magnet operating to 12 T. Low RRR might be tolerated*

A hybrid magnet might also keep the Nb_3Sn coil at fields above any flux-jump threshold

Implication: Strive for highest J_c at 15 T, defer RRR specification later

J_c(15 T) is more sensitive to irreversibility field than J_c(12 T). ***Optimization of B_{c2}* becomes important.*** *Here,* ***Ti responds more quickly than Ta*** *in RRP.*

High temperature reactions are needed *to produce high irreversibility field.*

Strain dependence of J_c also requires consideration of keeping B_{c2} high*

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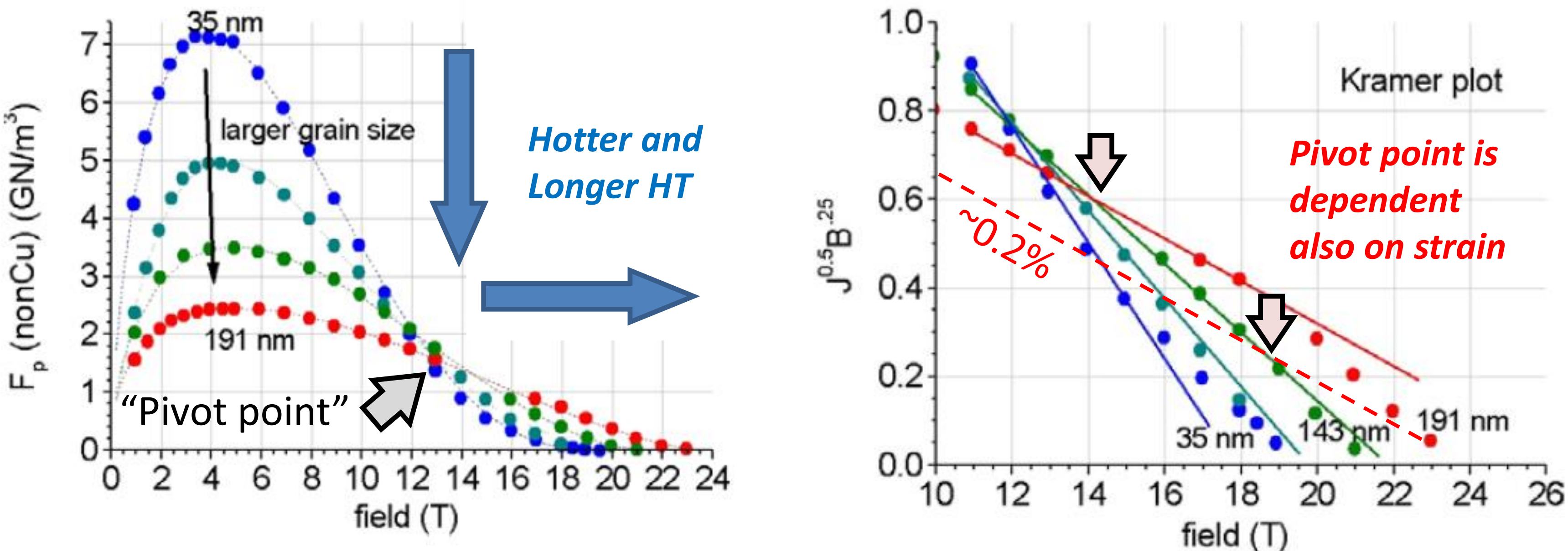
Optimization of Nb_3Sn conductors for 15+ Tesla – The Pivot

*General behavior depicted below; Figures from Flükiger et al., SuST **21** 054015 2006*



Properties at 15+ T are much more sensitive to alloying and B_{c2} than properties at 12 T!! Conductor optimization should balance:*

- *Selection of **alloying** elements (Ti, Ta, Ti+Ta)*
- *Control of **grain size vs. HT temperature and time***
  - ***Ti alloying is very important because high B_{c2}* can be attained at ~ 650 °C, i.e. without blowing up grain size***
- *Understanding of the **strain state in magnets***
  - *Will parameters chosen from strand studies hold up?*

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CHALLENGING BUT REALISTIC GOALS BETWEEN NOW AND 2018

- CDP is engaging OST with a **217-stack RRP** strand. **Goal: make this "3,000 class" conductor.** Options to increase the sub-element number any further for RRP have *high risk*:
  - ◊ Smaller sub-elt. in present billet has risk of crossed pieces and breakage
  - ◊ Tooling for > 500 sub-elt. billet does not exist; present "large" billets (e.g. for LARP) are just now being put into production
  - ◊ A double-stack billet has not been attempted
- Optimize J_c (15-18 T): **Goal: Achieve J_c > 2,000 A/mm² at 15 T, 4.2 K.**
  - ◊ This will be a different optimization than for 12 T. In particular **B_{c2}* may replace RRR** as a second parameter of attention
  - ◊ Understand "knobs" better: strain, alloying, microstructure vs. HT
  - ◊ Measurement facilities at 15-20 T will be needed
- **Goal: Demonstrate OP-processed Bi-2212 inserts**, or other designs compatible with circular colliders
  - ◊ 16 T magnets with appropriate margin approaches 20 T at SSL.
  - ◊ Reduce the cost and increase the scale of OP Bi-2212

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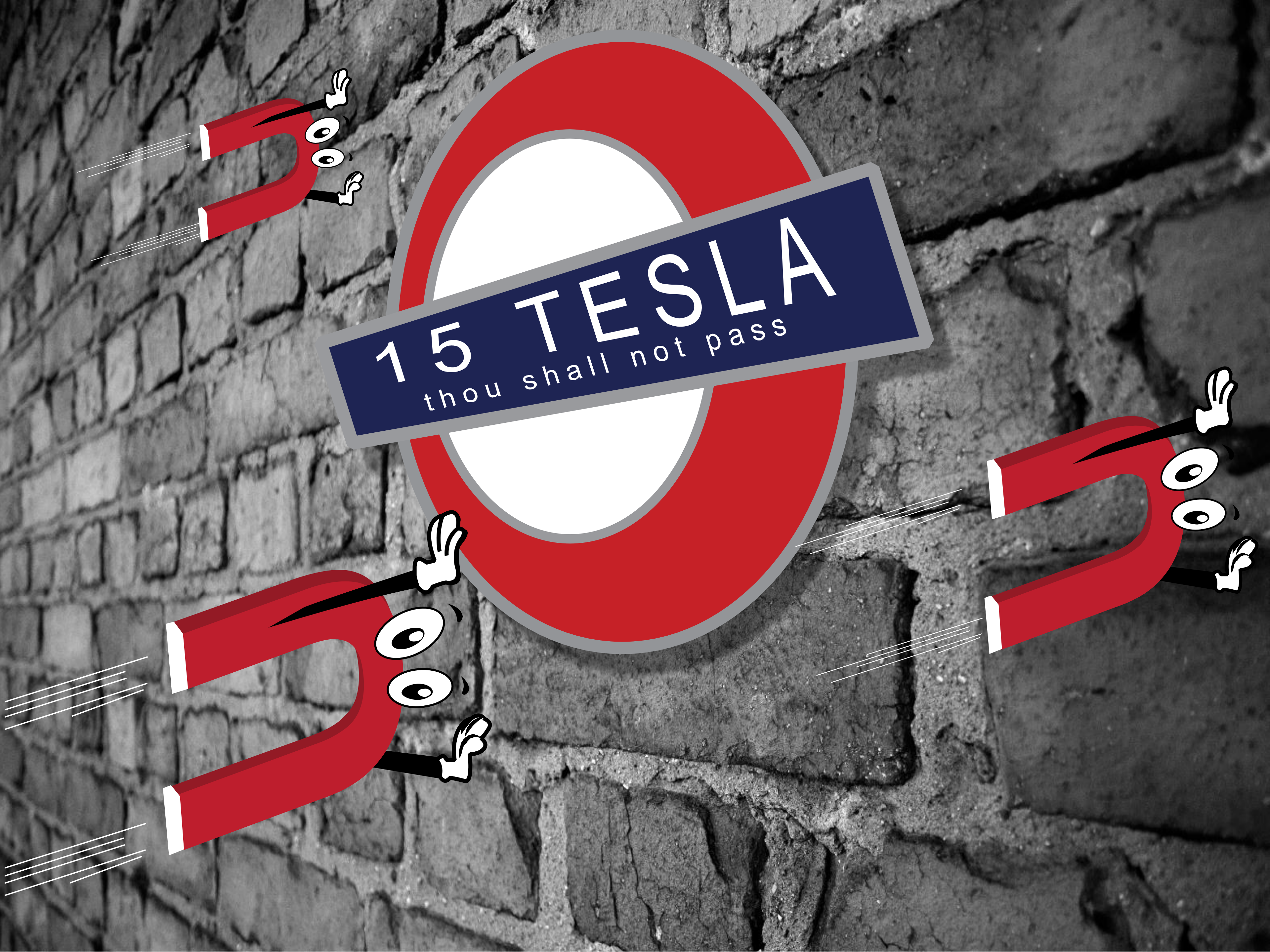
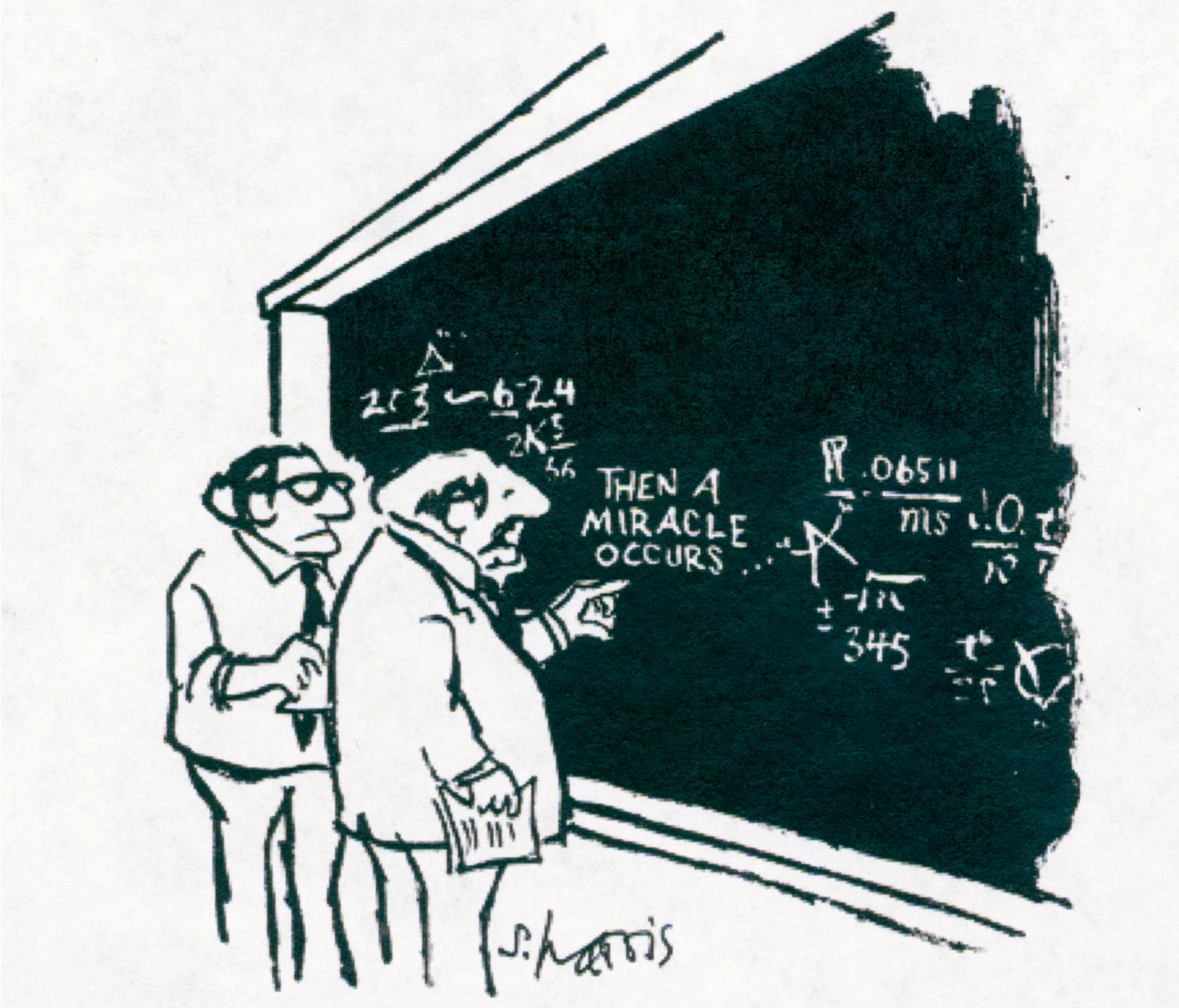

15 TESLA
thou shall not pass



“I think you should be more explicit here in step two.”


FOR
SALE
Superconducting
Unobtainium-Uo

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Where to go from here?

- **Reassess magnet design**
  - Canted Coil
  - Cosine θ
  - Race Track
  - ANSYS friend or foe
- **Quench Engineering**
- **Splice Engineering**
- **Manufacturing**
- **Other conductors?...**
  - HTS friend or foe

1986, the 75th Anniversary…Change!

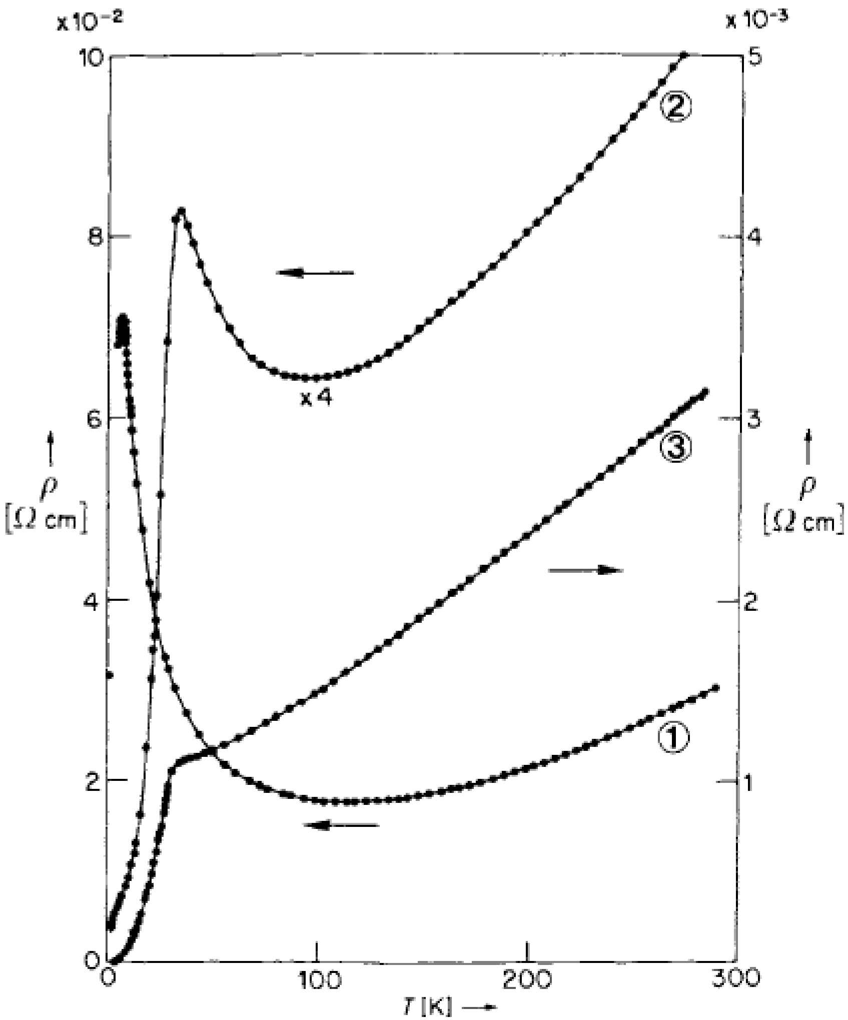
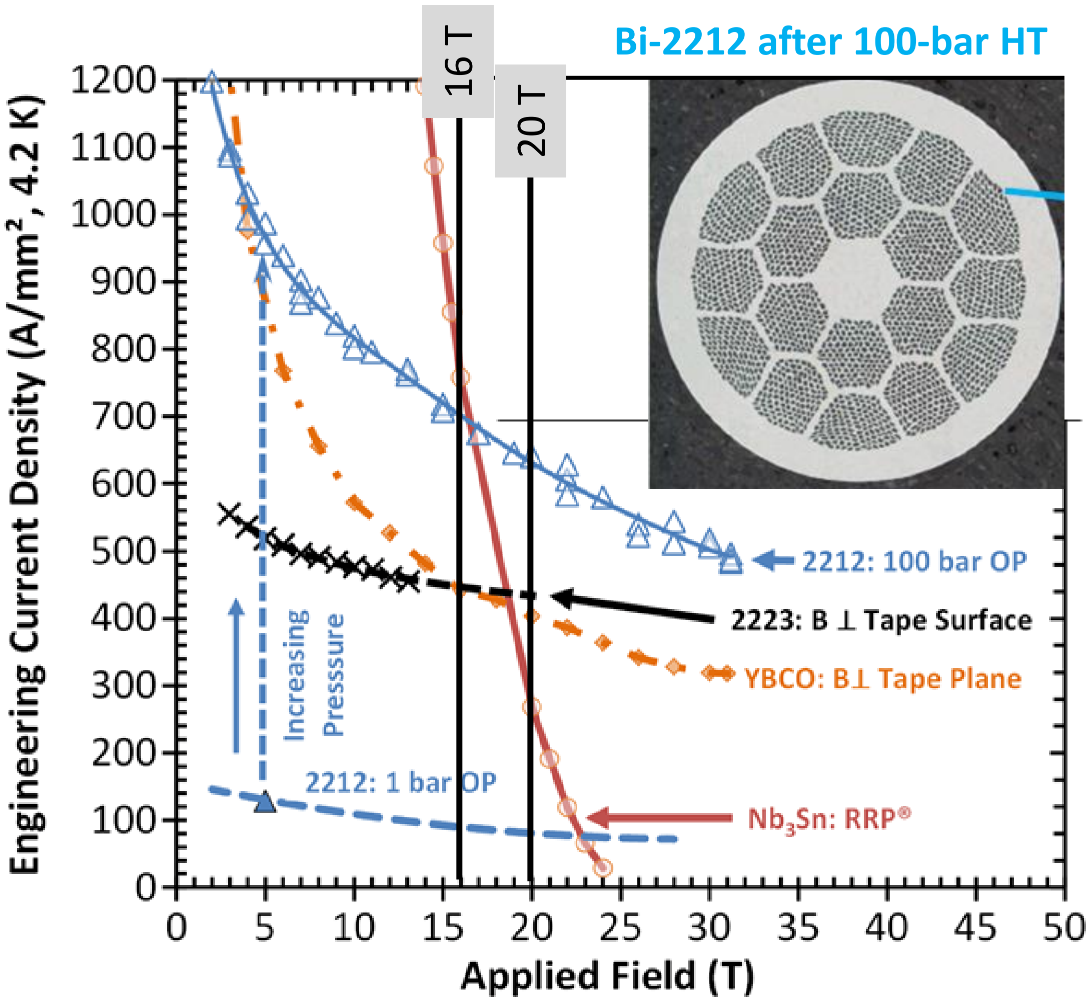


Fig. 1.9. Resistivity as a function of temperature for La_2CuO_{4-y} : Ba samples with three different Ba : La ratios. Curves ①, ②, and ③ correspond to ratios of 0.03, 0.06, and 0.07, respectively (adapted from [1.20]).

- POSSIBLE HIGH-TC SUPERCONDUCTIVITY IN THE BA-LA-CU-O SYSTEM
  BEDNORZ JG, MULLER KA
  Z FUR PHYSIK B-CONDENSED MATTER 64, 189-193 1986 ,
  Times Cited: 7,656

- Superconductivity induced by doping carriers into an insulating anti-ferromagnetic state
- Non-Fermi liquid behavior, but strong correlations that still prevent any generally accepted model for superconductivity in the cuprates

The jump from 16 to 20 T requires HTS



Breakthrough = Breakout

- **Multiple** over-pressure furnaces are being commissioned in the U.S.
- OP processing of **cables** and **small coils** is planned FY14
- Thanks to EUCARD2, Nexans has re-started **raw material** production
- Larger objects: Cos Θ and solenoid magnets fit in cylindrical pressure vessels
- **Fully dense strand** makes J_c more directly connected to changes in composition, microstructure etc. → **Optimization!**

HTS
MAGNETS
ARE . . .

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National Academies Report

Regional, all superconducting high field magnet facilities.

Prepublication Copy—Subject to Further Editorial Correction

High Magnetic Field Science and Its Application in the United States: Current Status and Future Directions

Committee to Assess the Current Status and Future Direction of High Magnetic Field Science in the United States

Board on Physics and Astronomy
Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
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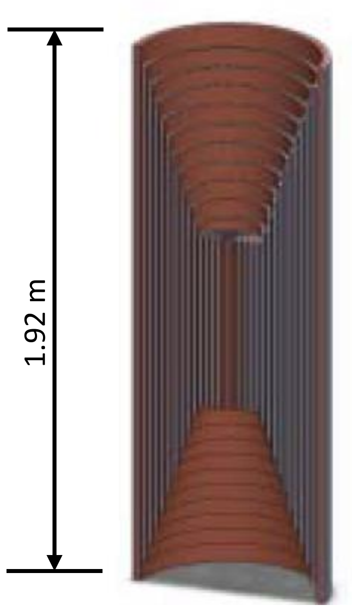
Washington, D.C.
www.nap.edu

60 T Concepts

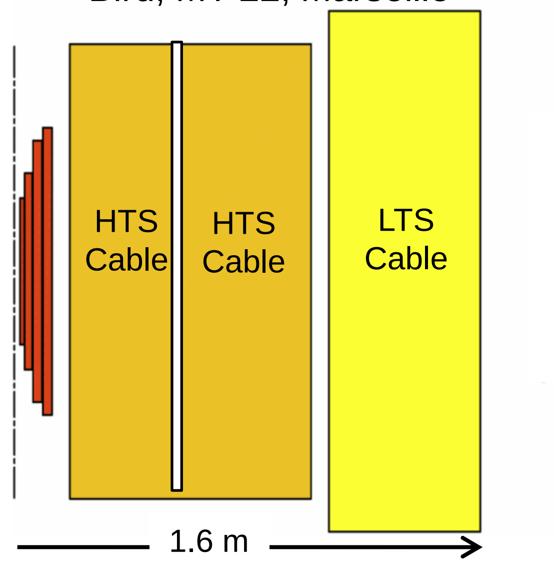
ReBCO

Iwasa, MT 23, Boston



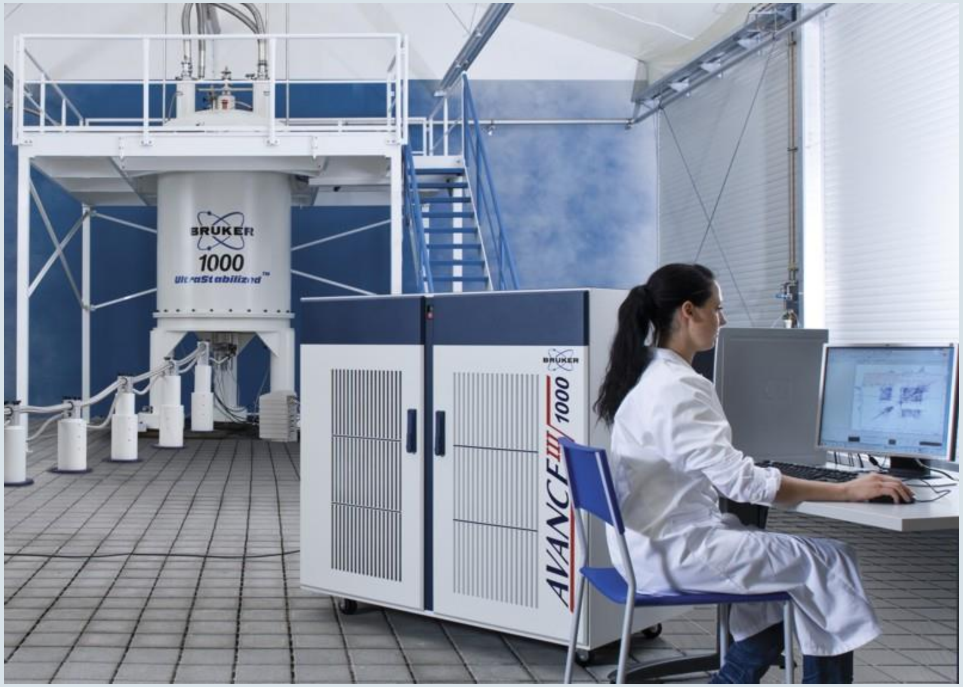
Hybrid

Bird, MT 22, Marseille



Next challenge:
High field NMR beyond 1GHz

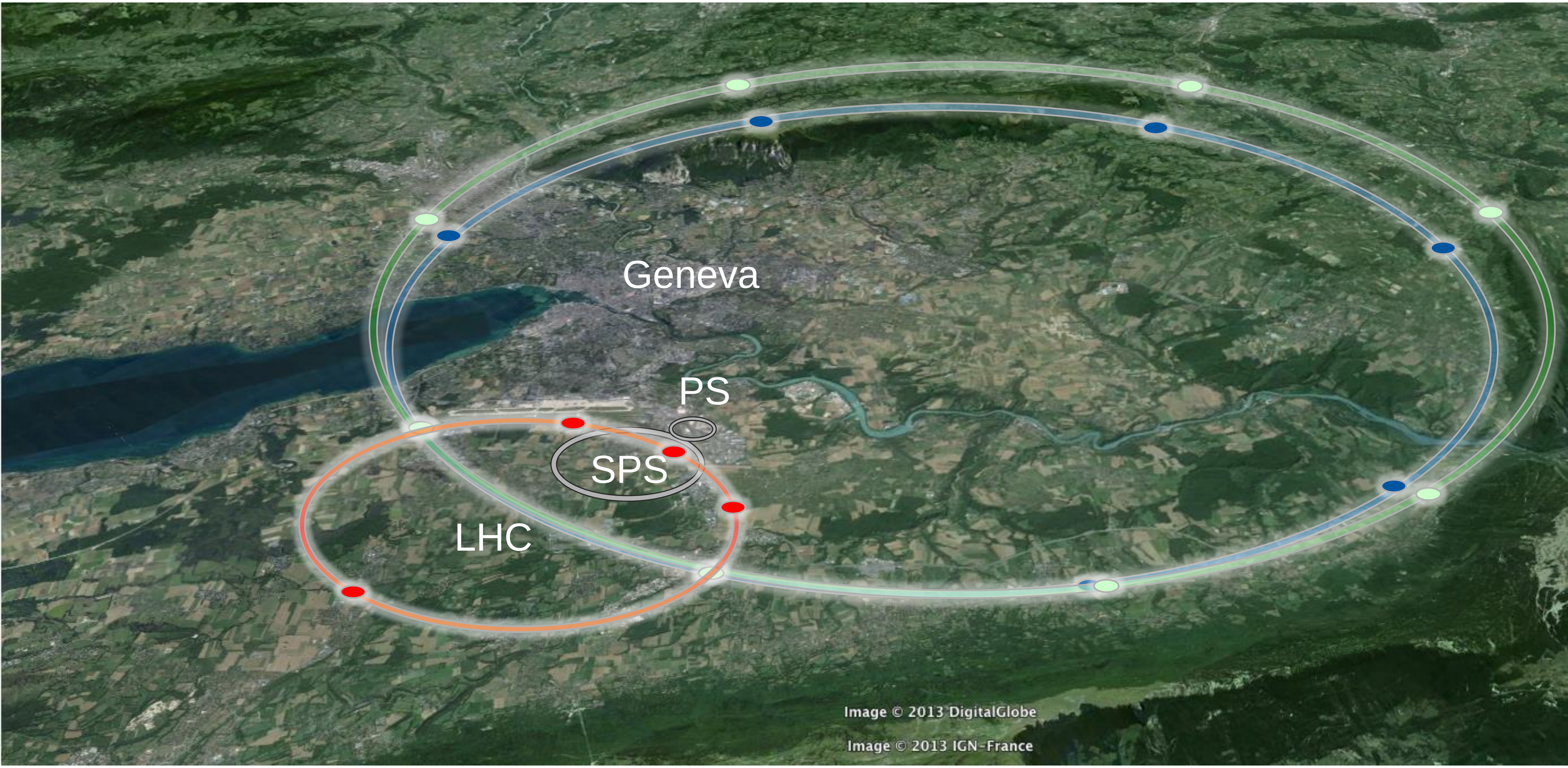
Worlds first, standard high homogeneity 1GHz NMR magnet installed in Lyon 2009



HTS tape requirements:

- very high critical current @ B > 23.5T
- long length > 1000m
- high mechanical strength
- state of the art quality control

The next step – hadron colliders

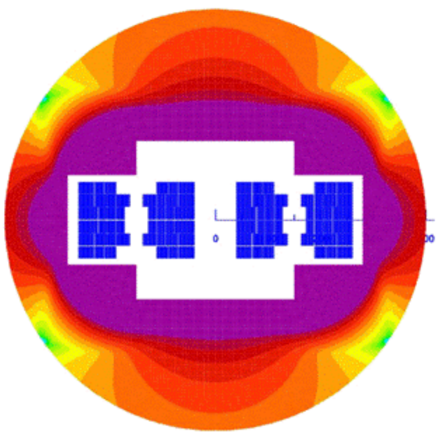


LHC	HE-LHC	VHE-LHC	VHE-LHC
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.o.m.)	33 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)

The essential role of the superconductors *in the search for higher energy*

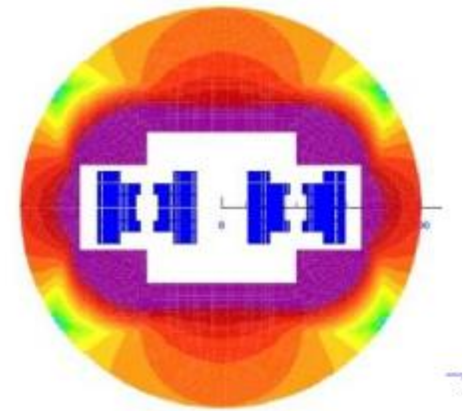
A 20 T HE-LHC dipole
E. Todesco, L. Rossi (CERN)

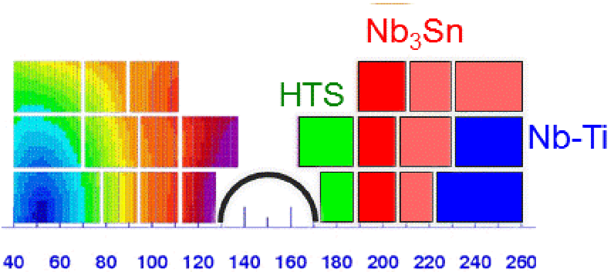
Proceedings of MT-23



J_{eng} ~ 400 A/mm²

Nb-Ti up to	8 T
Nb_3Sn up to	13 T
HTS up to	20 T



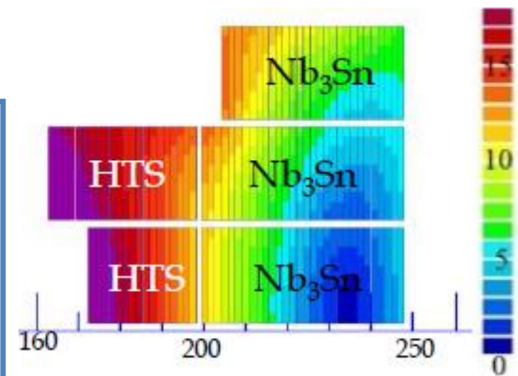


Cost optimized, graded winding

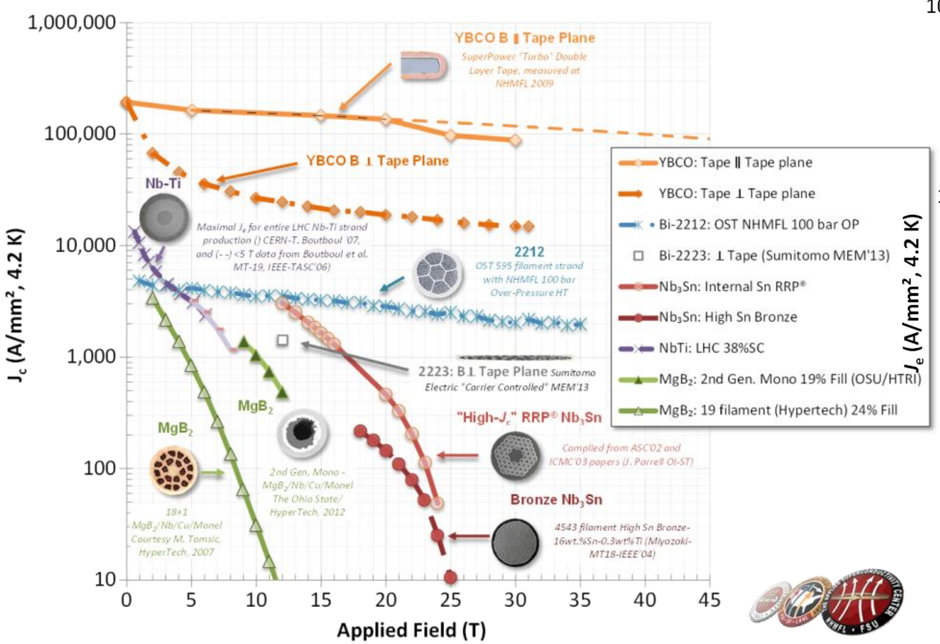
HTS: more than 1500 tons procurement by 2030

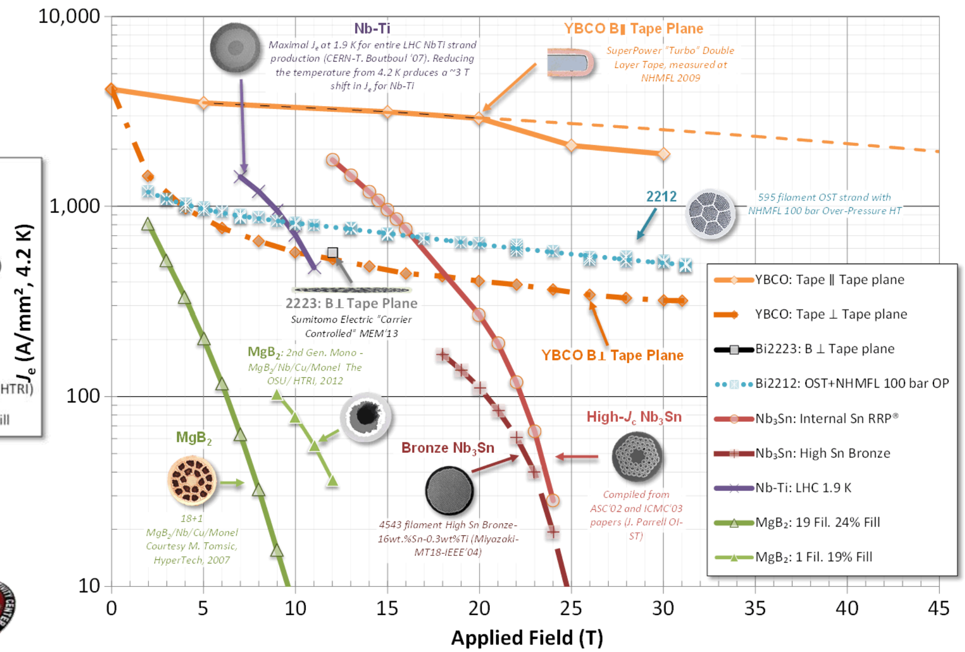
↓

Concept and models now



Why HTS for high field magnets? There is no other option!





Database maintained in public domain by P. Lee, NHMFL, FSU

First suggestion (1988) of high field HTS magnets, assumed 125 A/mm^2 at 22.4 T:
D.R. Cohn, J. Schwartz, L. Bromberg and J.E.C. Williams, “Tokamak Reactor Concepts Using High Temperature, High Field Superconductors,” *Journal of Fusion Energy* **7**(6), 91-94 (**1988**)

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HTS Magnet R&D Issues

- **Conductor**
  - **Scalability to “industrial production”**
- **Magnet Field Engineering**
- **Electrical Insulation**
- **Mechanical Engineering**
- **Safety and Protection**
- **Cryogenics**

Magnet R&D Issues

Conductor

Magnet Field Engineering

Electrical Insulation

Mechanical Engineering

Safety and Protection

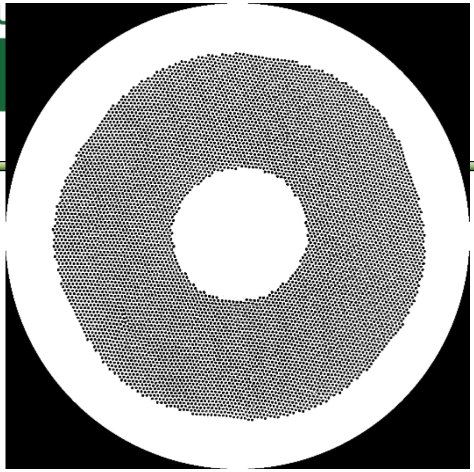
Cryogenics

HTS Conductors…

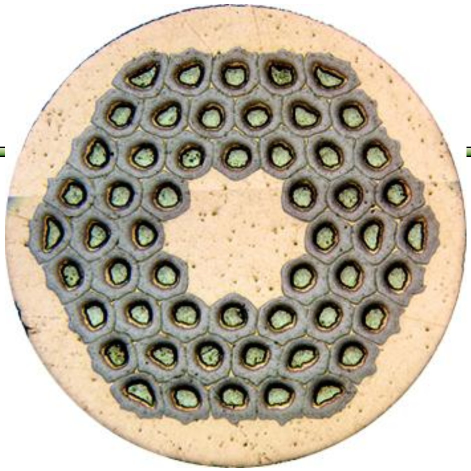
What do magnet builders want?

- ✓The highest H_{irr}/H_{c2}, $J_c(H,T)$ and $J_E(H,T)$, T_c
- ✓Fabricability into wires with flexible architectures
- ✓Low cost/performance ratio
- ✓Small environmental footprint
- ✓High strength
- ✓Ability to wind as is
- ✓Long lengths
- ✓High Current Cables
- ✓Low ramping losses and magnet protection

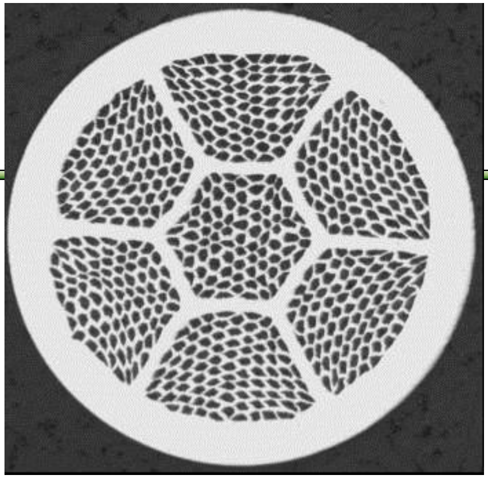
What do we have now…….?



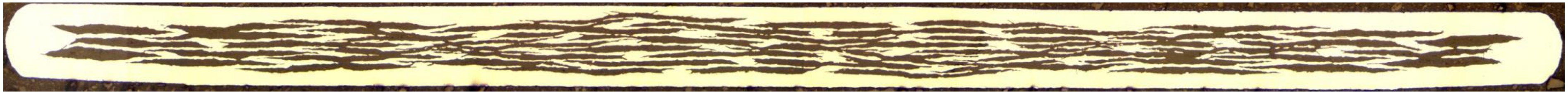
Nb47Ti (OST)



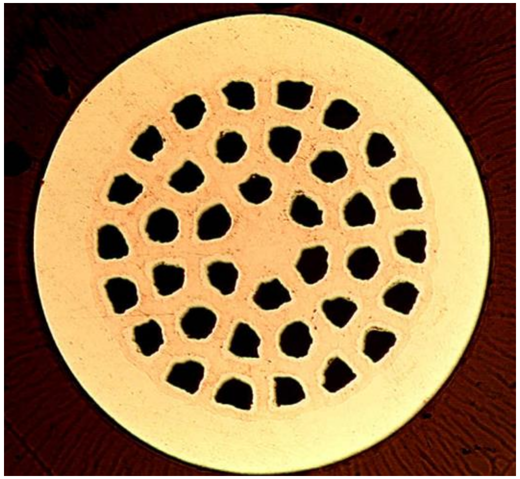
Internal Sn Nb_3Sn



Bi-2212 (OST)



Bi-2223 (AMSC)



MgB_2 (Hypertech)

YBCO coated conductors next…………….

Preferred conductor features:

Multifilament

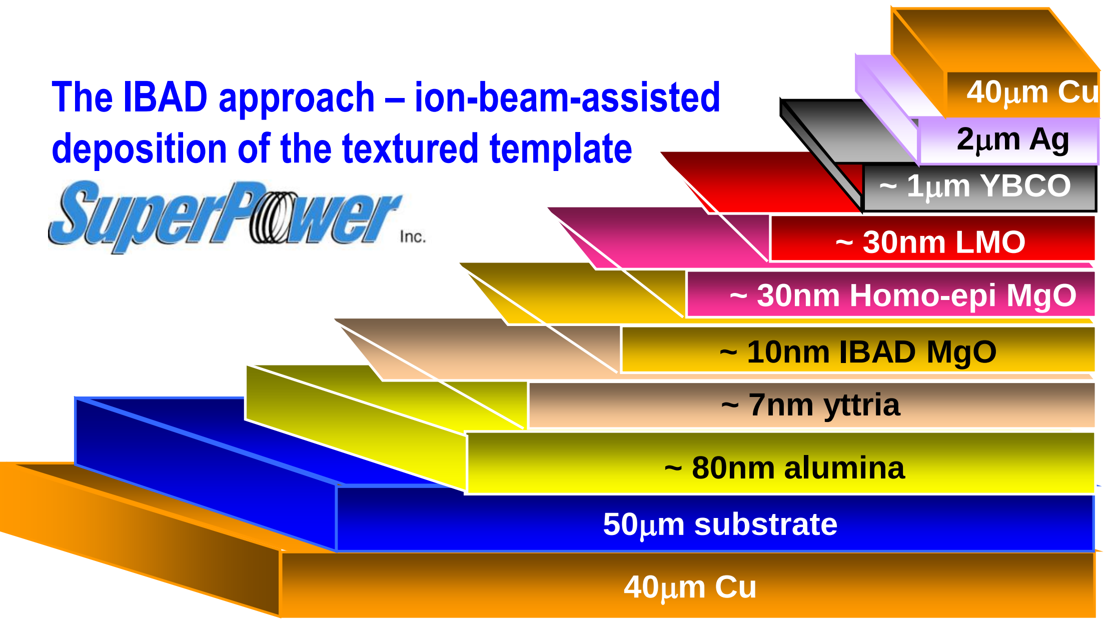
Round or lightly aspected shape with no J_c anisotropy

Capability to wind in unreacted form while conductor fragility is minimized

And coated conductors of YBCO which approximate single crystals by the mile…….

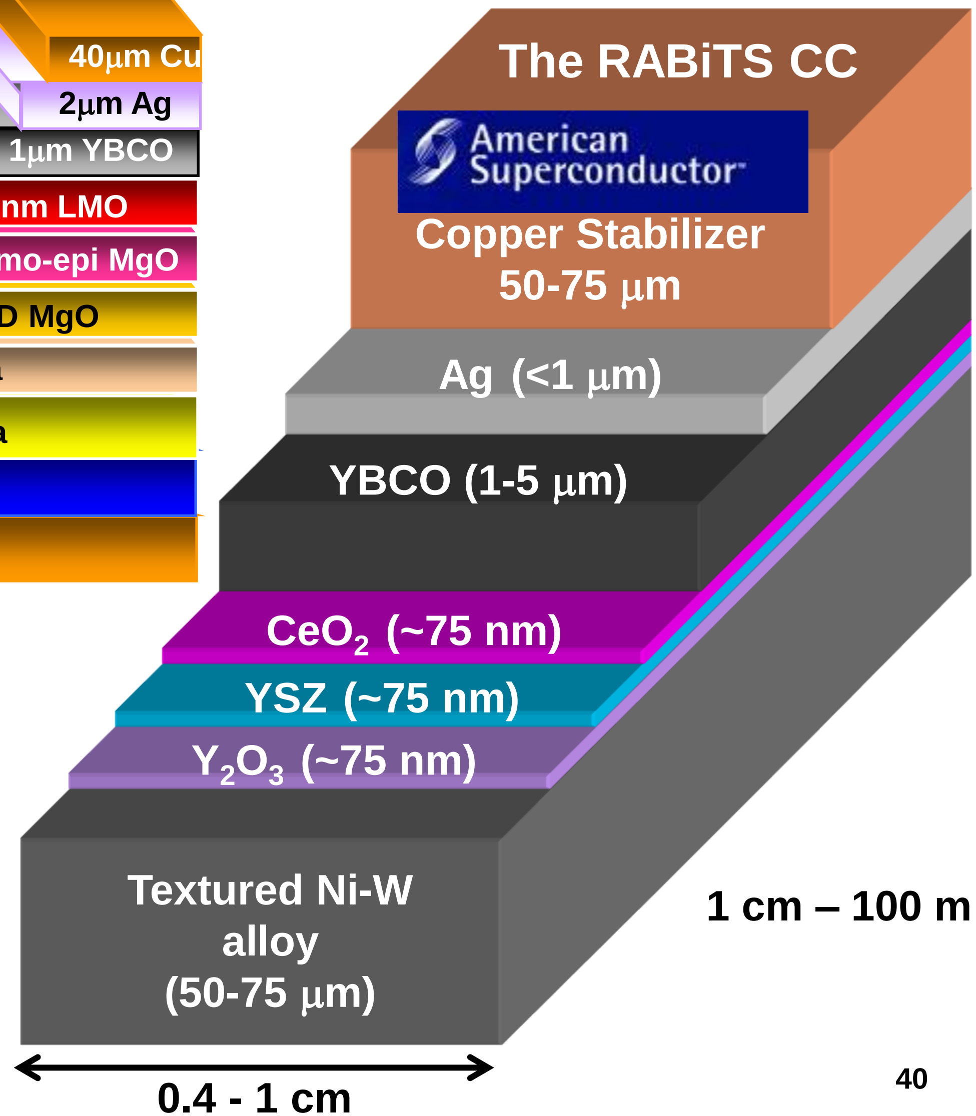
The IBAD approach – ion-beam-assisted deposition of the textured template

SuperPower Inc.



Pilot production of 100-500 m lengths. Now approaching 1km

Metallurgical Texture introduced here (RABiTS)



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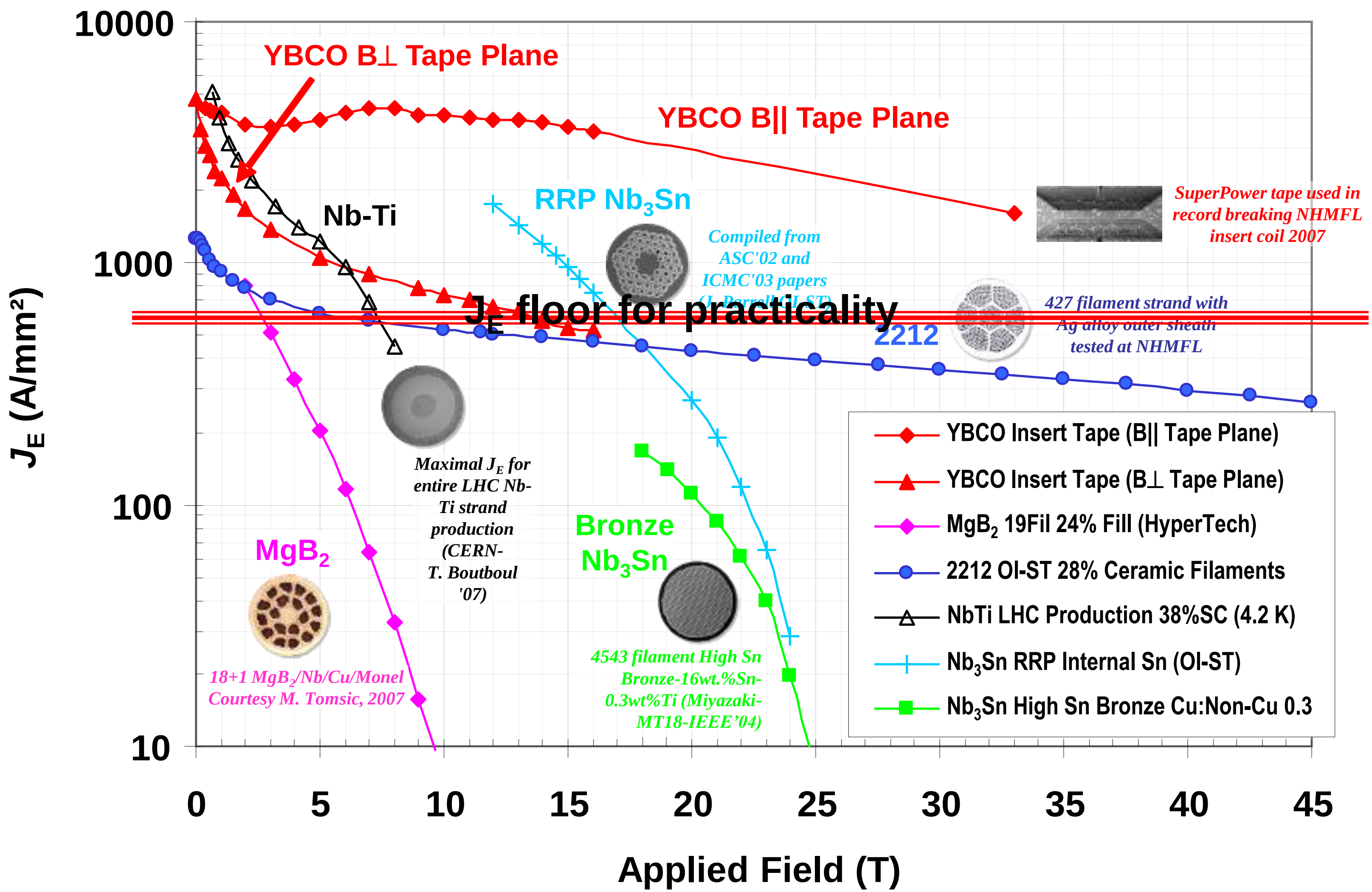
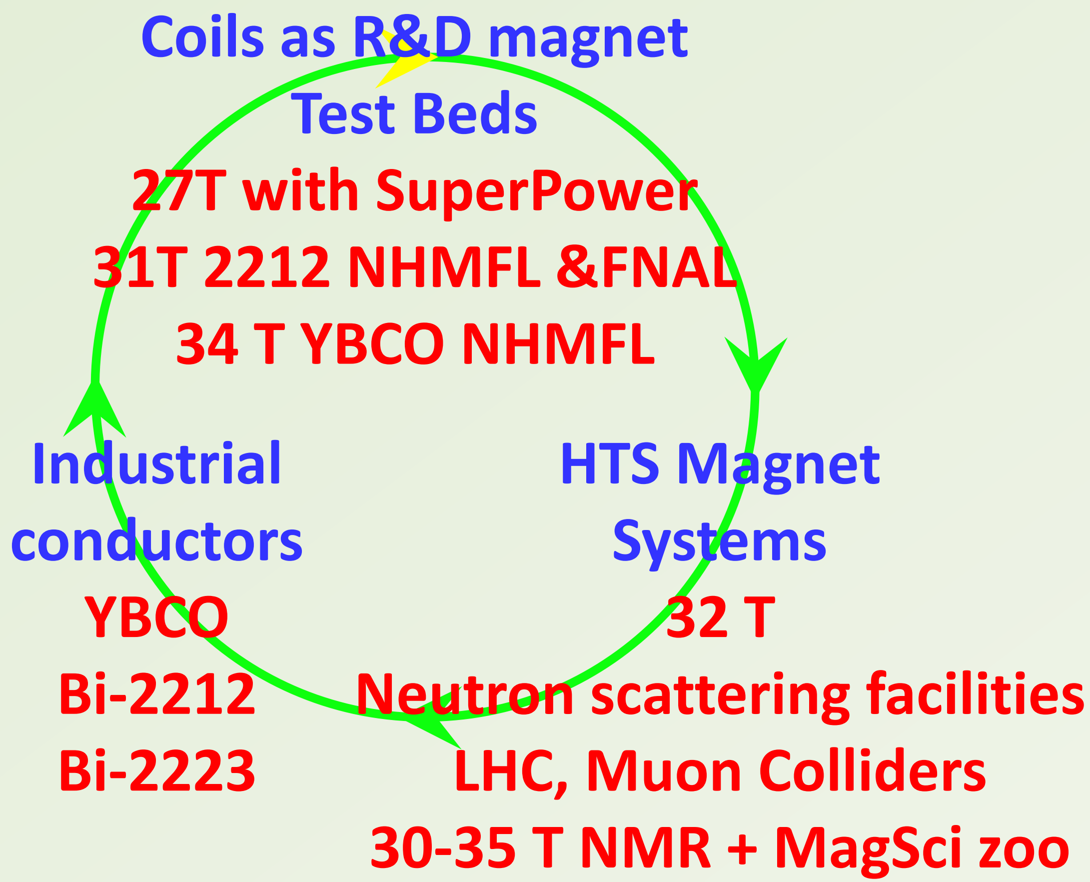
…even though HTS greatly extends properties at 4K…



Courtesy Peter Lee www.asc.magnet.fsu.edu

What conductor attributes are needed for a secure HTS magnet technology?

- A real applications pull that can generate continuous conductor orders
- Conductors worth continuous orders

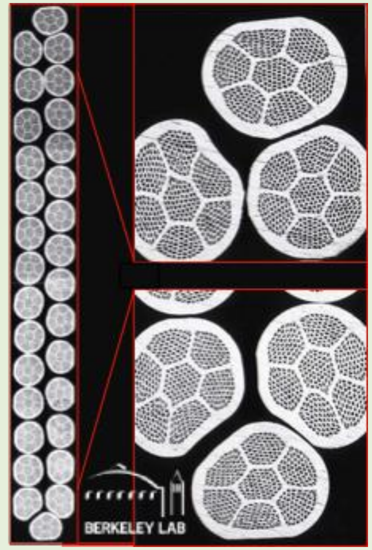


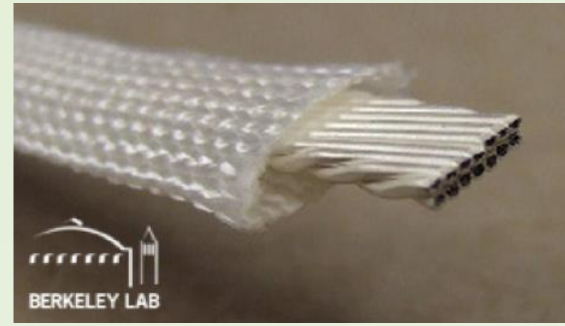
Large magnets are better protected when operated at high current– cables!

- Easy path to 2212 cables through the standard Rutherford cable

- REBCO cables are harder (Coated Conductor is a single filament) – (MIT)

- Cables vital for 60 T hybrid at the NHMFL, an LHC energy upgrade and a neutrino machine based on a Muon Collider at Fermilab

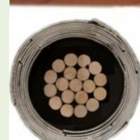




Bi-2212 Rutherford cables (Arno Godeke LBNL) with mullite insulation sleeve

REBCO coated conductor cable wound in many layers helically on a round form

Other variants too: e.g. Roebel cable



Advanced Conductor Technologies LLC
www.advancedconductor.com
Danko van der Laan

SWOT – getting HTS into the big (MagSci) time (not comprehensive)

Strengths

- High Jc at B impossible for Nb
- Proof of principle to 35T so far
- Insulation technologies for both REBCO and 2212 (Lu and Kandel)
- Strong US industry
- Interest by many

Weaknesses

- Conductors are $$$ - $75-100/m
- Defect rich!
- REBCO is very capital and team expensive
- Good 2212 requires 20-100 bar HT

Opportunities

- MagSci magnets
- HEP machines – MAP and LHC
- 35-40 T POP in 31 T in view
- Solution NMR demonstrations with 2212 or REBCO
- Collaborations with multiple sectors

Threats

- REBCO cannot be sustained by magnet projects and may be at risk if electric utility demand disappears
- Overenthusiasm without proper support

HTS Conductor Program is all Magnet Pulled

- REBCO conductor QA and evaluation underpins
  - 32 T (H. Weijers)
  - Platypus 1 (L. Frydman, U. Trociewitz)
- 2212 is targeted for
  - Platypus 2 (MT23 comments much more positive for 30 T NMR with 2212 than REBCO)
  - High Energy Physics magnets at CERN, LBL and Fermilab
  - 30 T magnet for Advanced Photon Source at ANL (ANL LDRD with major funds to NHMFL submitted)
- Both REBCO and 2212 (strand and cable) vital for large projects

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Magnet R&D Issues

Conductor

Magnet Field Engineering

Electrical Insulation

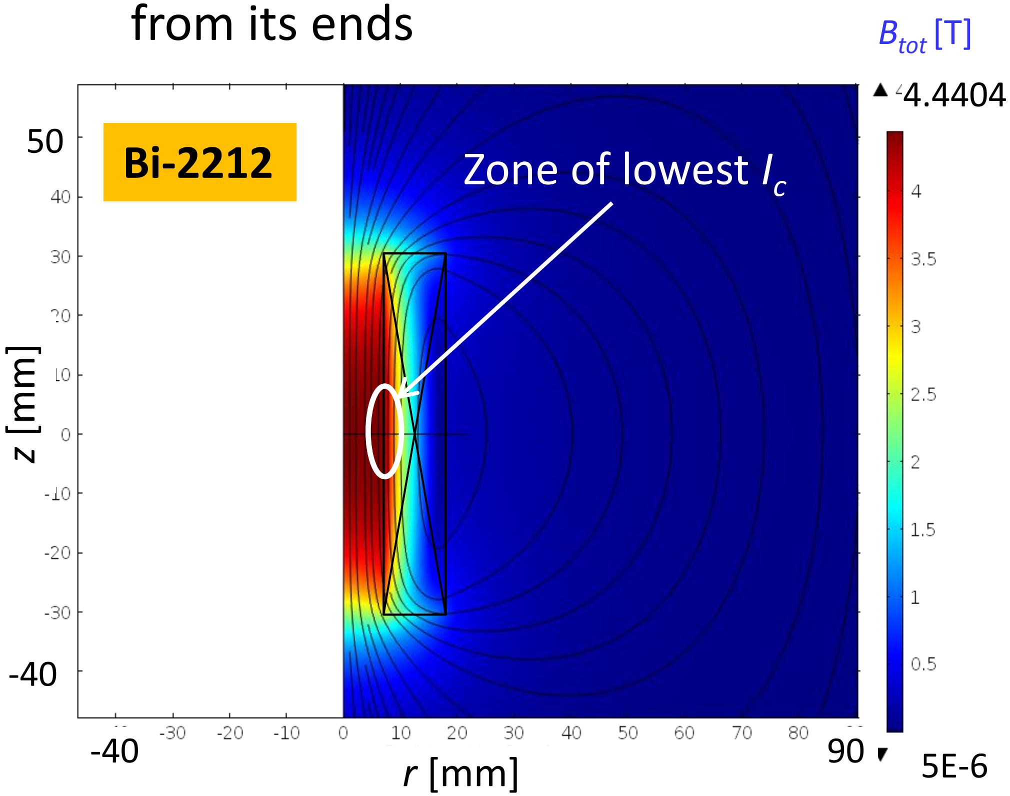
Mechanical Engineering

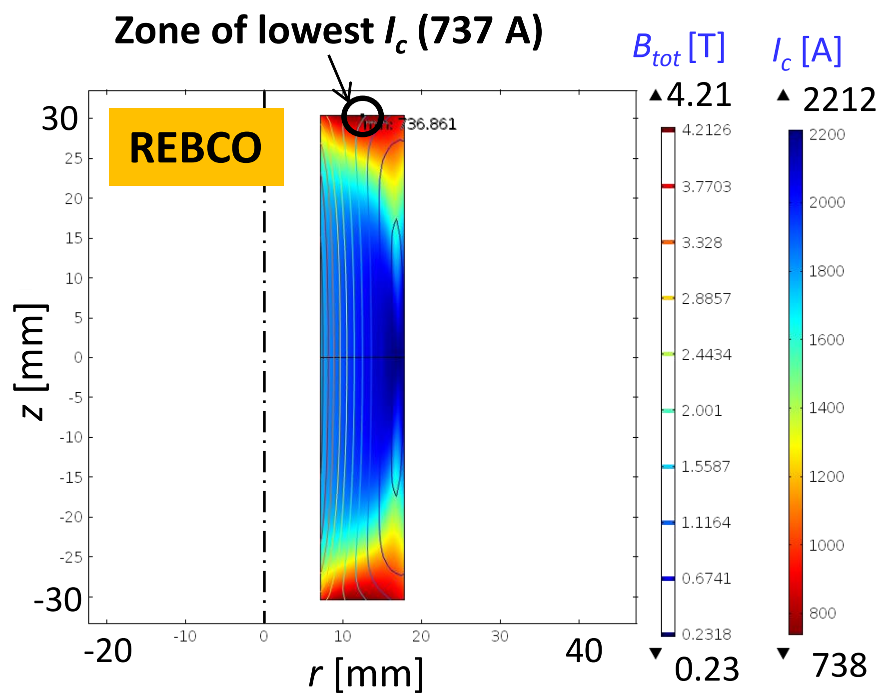
Safety and Protection

Cryogenics

Intricacies of REBCO tape *vs.* Bi-2212 RW:
Conductor (An)isotropy and Transport Current in Coils

- Bi-2212 isotropic: I_c scales with the field: high $|\underline{B}|$ => low I_c, with no field orientation dependence
- REBCO anisotropic: both $|\underline{B}|$ and its orientation matter
- In absence of other defects (hot spots *etc.*) a Bi-2212 RW coil will likely have tendency to quench from inside out while REBCO coil will quench from its ends





(uses $I_c(B,\varphi)$ fit by D.K. Hilton)

Splices…

Magnet R&D Issues

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Magnet R&D Issues

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Mechanical Engineering…

- **Forces ~B^2**
- **Energy ~B^2**
- **Strain management vs. stress management**
- **Virial Theorem**
  - **M~E/σ**

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Magnet R&D Issues

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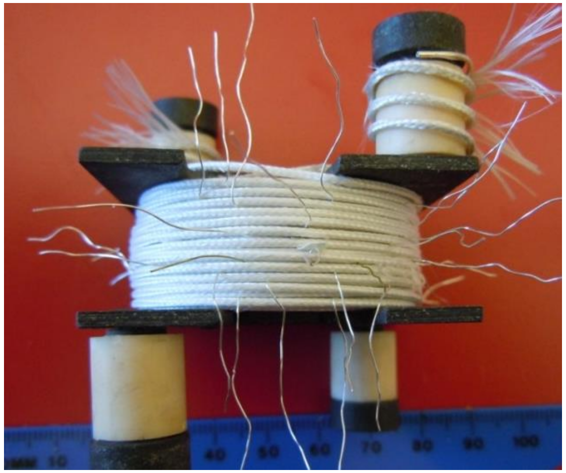
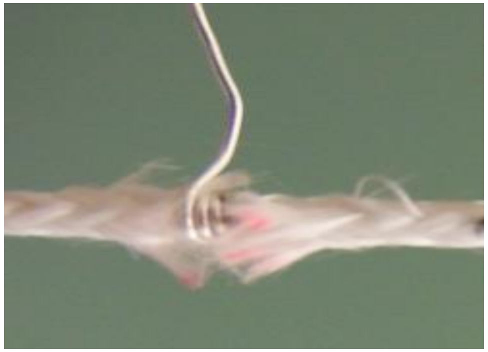
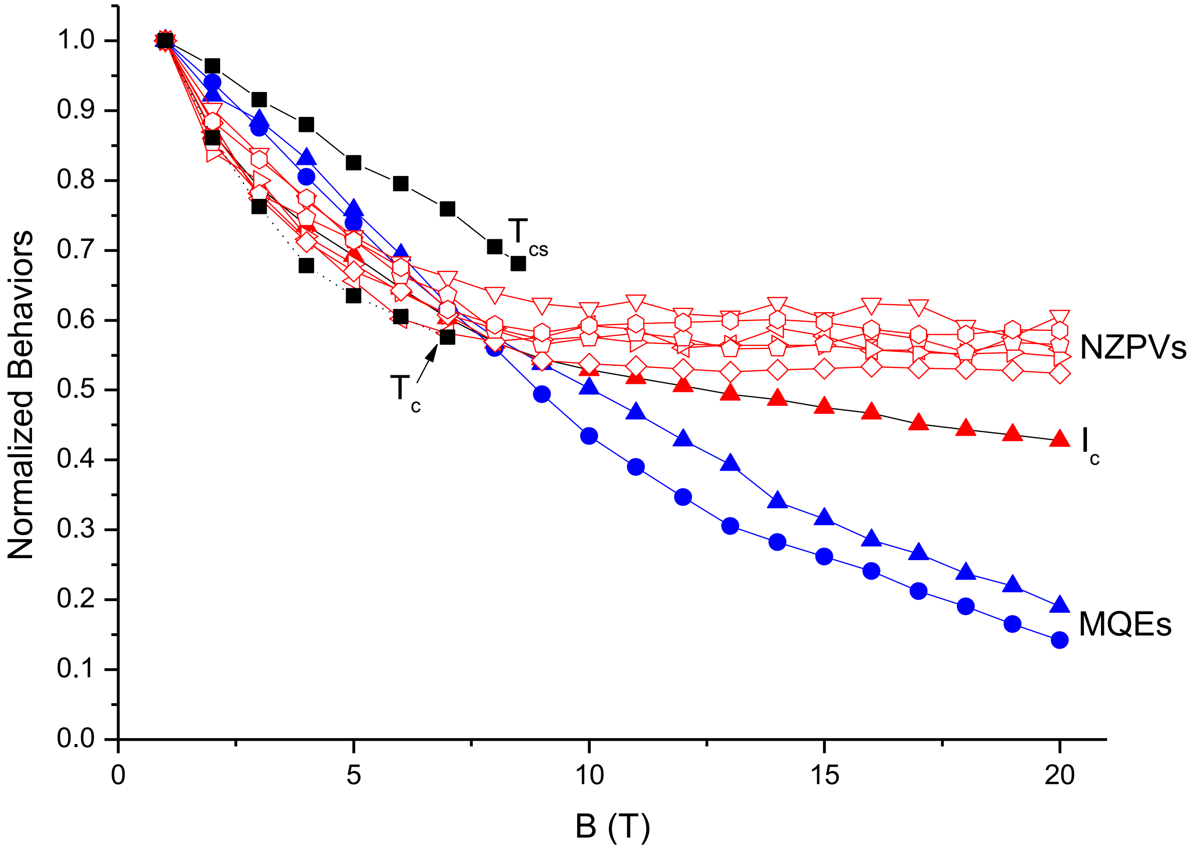
High field does ***not*** improve propagation but reduces stability margin







L. Ye, F. Hunte and J. Schwartz, *SuST* **26** 055006 (8 pp) (2013)

NC STATE UNIVERSITY
SCHWARTZ GROUP
Department of Materials Science and Engineering

Protection is a race:
Detect & protect before degradation

- Bi2212 and YBCO degradation is defect driven & limits can be increased

Improved electromechanical behavior → increased quench limits → more time to detect/protect

- Enhanced quench detection → buys more time to protect
- Reduced rate of temperature rise by distributing energy

Magnet R&D Issues

Conductor
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Cryogenics

Cryogenics for HTS…

- Its still there!
- All the other engineering requirements of good cryogenic practice remain the same.

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So—you want a project

There are many entries on the web concerning the management of Megaprojects.

R-3560-PSSP

Understanding the Outcomes of Megaprojects

A Quantitative Analysis of Very Large Civilian Projects

Edward W. Merrow
With Lorraine McDonnell, R. Yılmaz Argüden

March 1988

Supported by the
Private Sector Sponsors Program

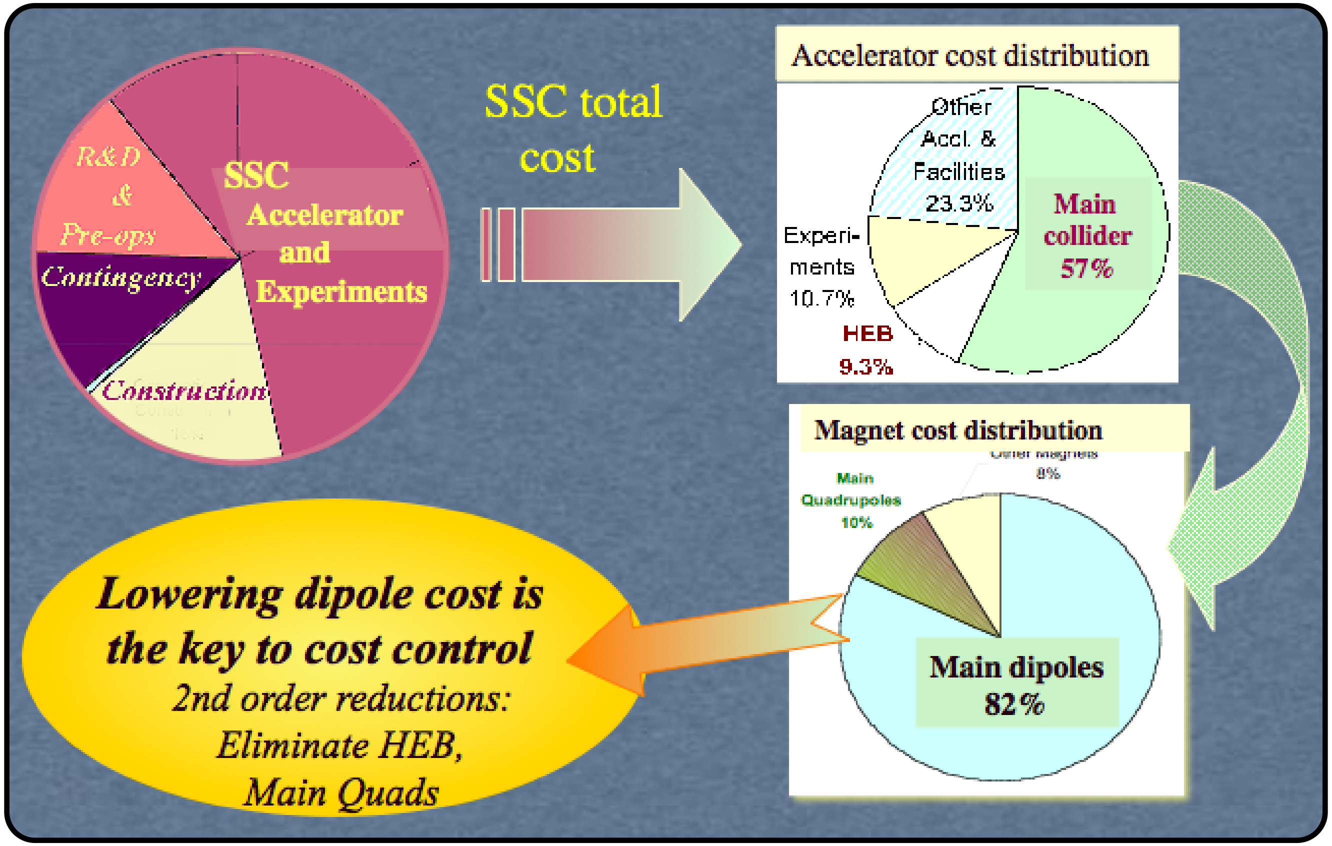
40 Years 1948-1988

RAND

So you want a project…

- State of technology
- State of technology transfer
- Optimization of parameter set
- Organization
- Funding
  - Budget and budget distribution

Magnets dictate collider cost



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

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

**L. Rossi, "TOE" talk*

Barletta

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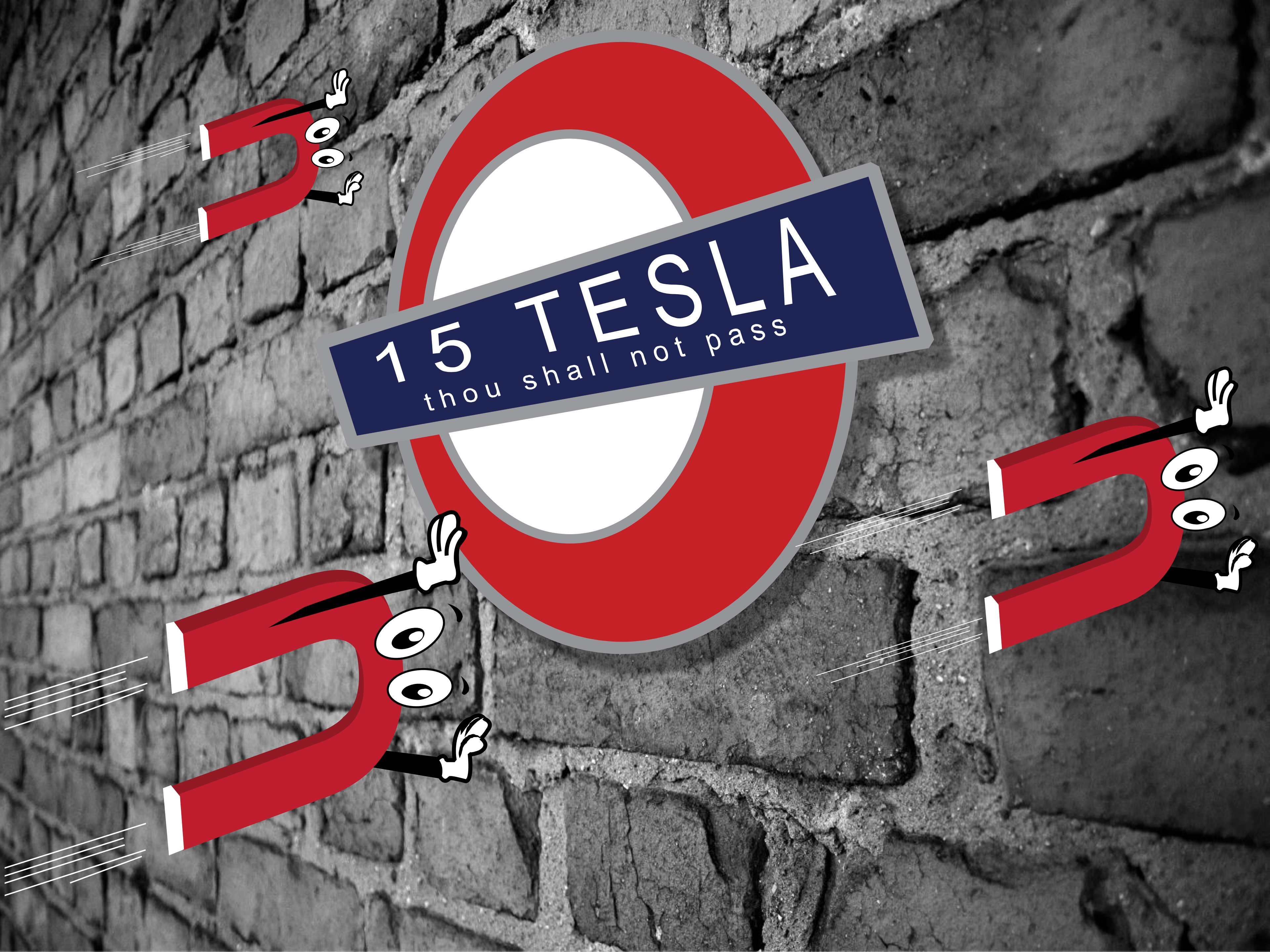
Thanks

Many thanks to the following for useful discussions and slides:

- **BNL: Peter Wanderer**
- **CERN: Luca Bottura, Gijs De Rijk, Lucio Rossi, Ezio Todesco**
- **DOE: Ken Marken**
- **FNAL: Giorgio Apollinari; Lance Cooley, Stuart Henderson,**
- **FSU: David Larbalestier, Peter Lee**
- **LBNL: Dan Dietderich, Steve Gourlay, Soren Prestemon, GianLuca Sabbi**


15 TESLA
thou shall not pass

THROW A GRENADE AT IT!