Superconductors and Magnet Technology for 20 T Dipole Magnets

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Credits

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University of Twente
Enschede, The Netherlands

National High Magnetic Field Laboratory
Tallahassee, FL, USA

Applied Superconductivity Center
University of Wisconsin – Madison, USA (Now at FSU, Tallahassee, FL, USA)

U.S. DEPARTMENT OF ENERGY

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Outline

Superconductivity 1.01

- Terminology: T_c, H_{c2}, pinning, J_c, critical surface

Technological superconductors

- The materials science and performance of LTS wires

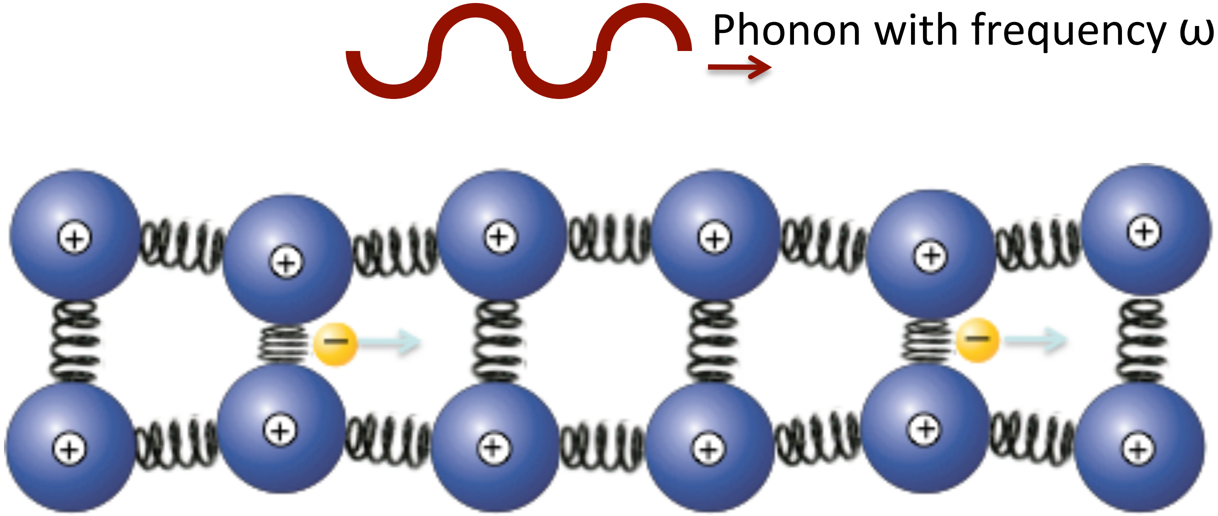
Superconducting dipole magnets

- Record fields, intrinsic limitations, the need for HTS

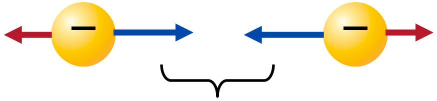
Superconductivity: Electron pairing

Electrons couple through lattice vibration quanta (phonons)

- Net attractive e-e interaction
  - Described by electron-phonon interaction constant $\lambda_{e\text{-}p}$



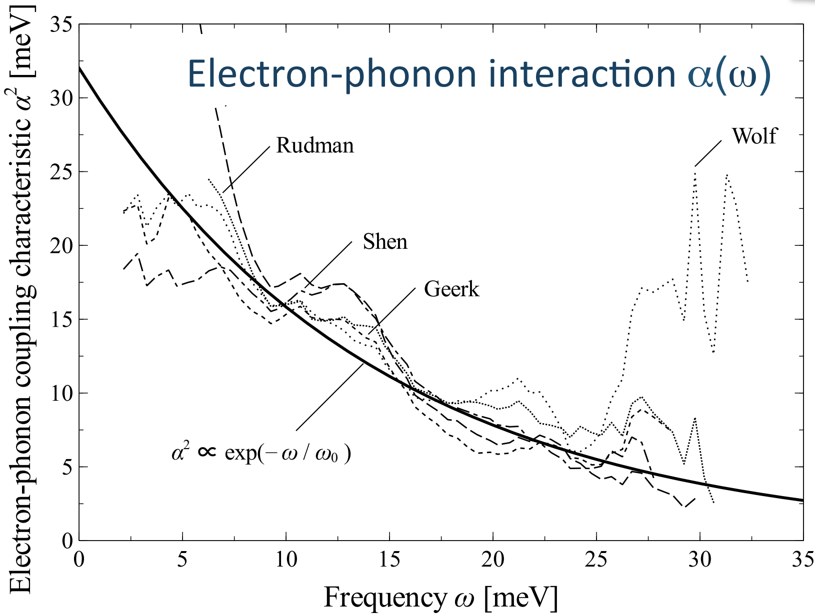
Phonon with frequency ω

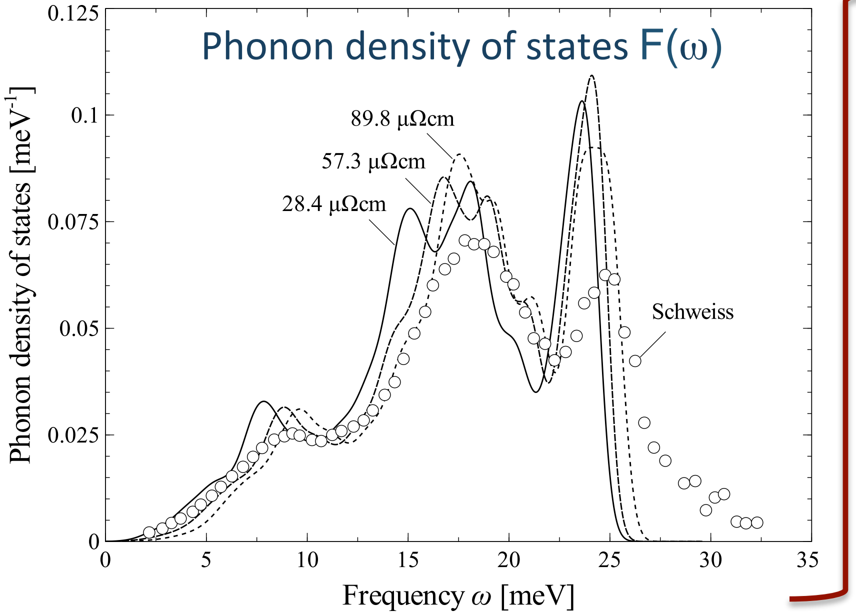


Coulomb repulsion

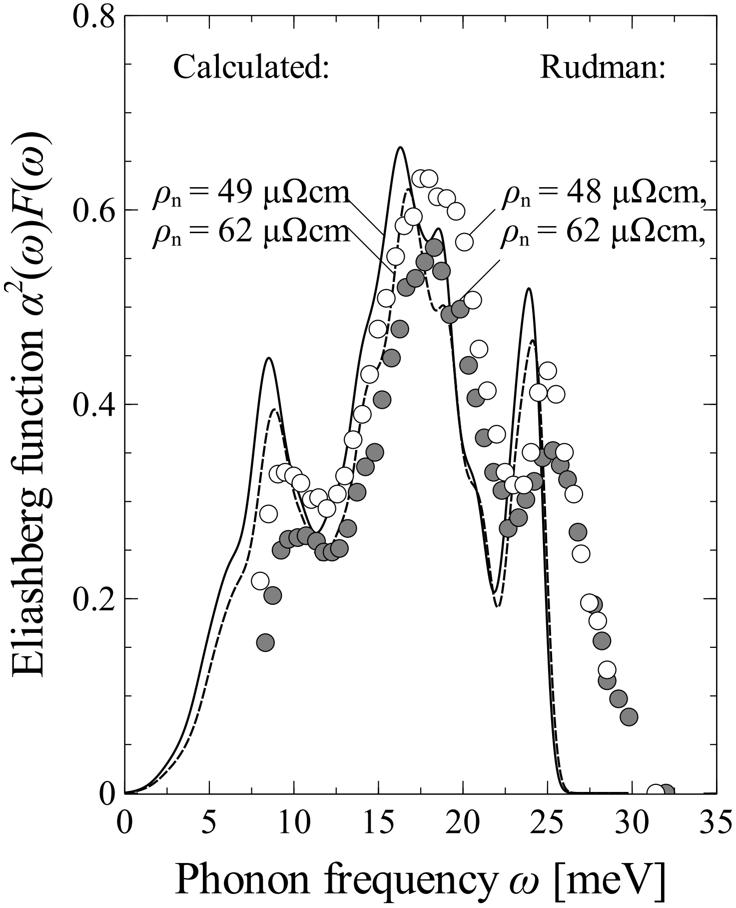
Attraction over communication distance ξ (coherence length)

Electron paring: Critical temperature T_c





x **=**



$$\lambda_{\text{ep}} = 2\int \frac{\alpha^2(\omega)F(\omega)}{\omega}\,d\omega$$

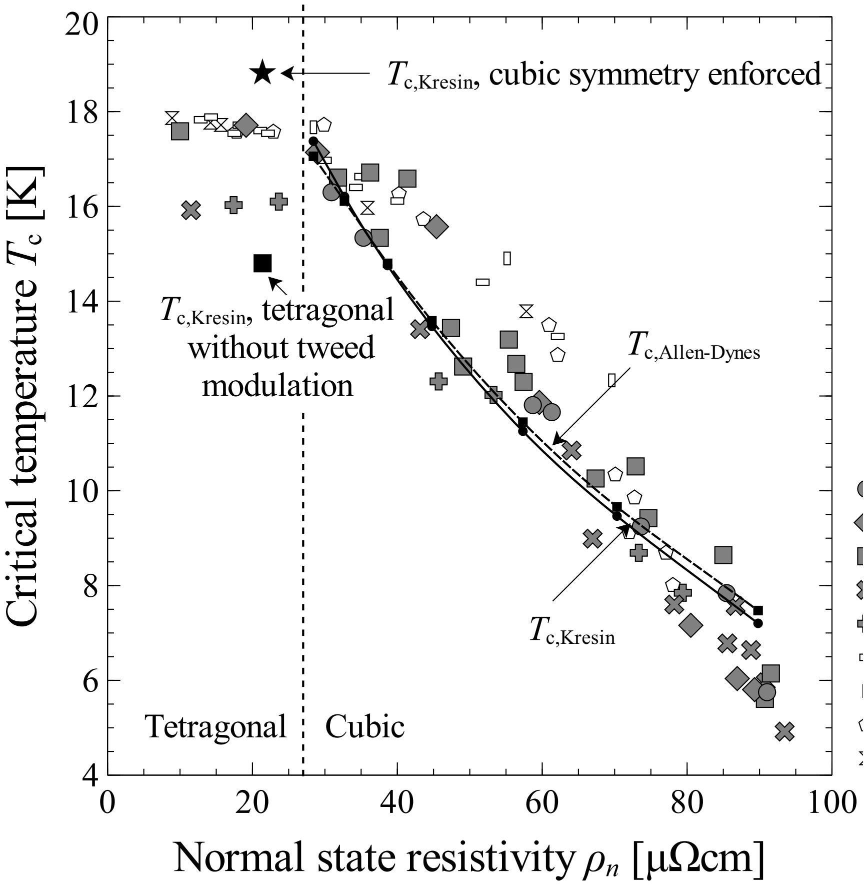
$$\lambda_{\text{eff}} = \frac{\left(\lambda_{\text{ep}} - \mu^*\right)}{\left(1 + 2\mu^* + 1.5\lambda_{\text{ep}}\mu^* e^{-0.28\lambda_{\text{ep}}}\right)}$$

$$T_{\text{c}} = \frac{0.25\left\langle \omega^2 \right\rangle^{\frac{1}{2}}}{\left(e^{2/\lambda_{\text{eff}}} - 1\right)^{\frac{1}{2}}}$$

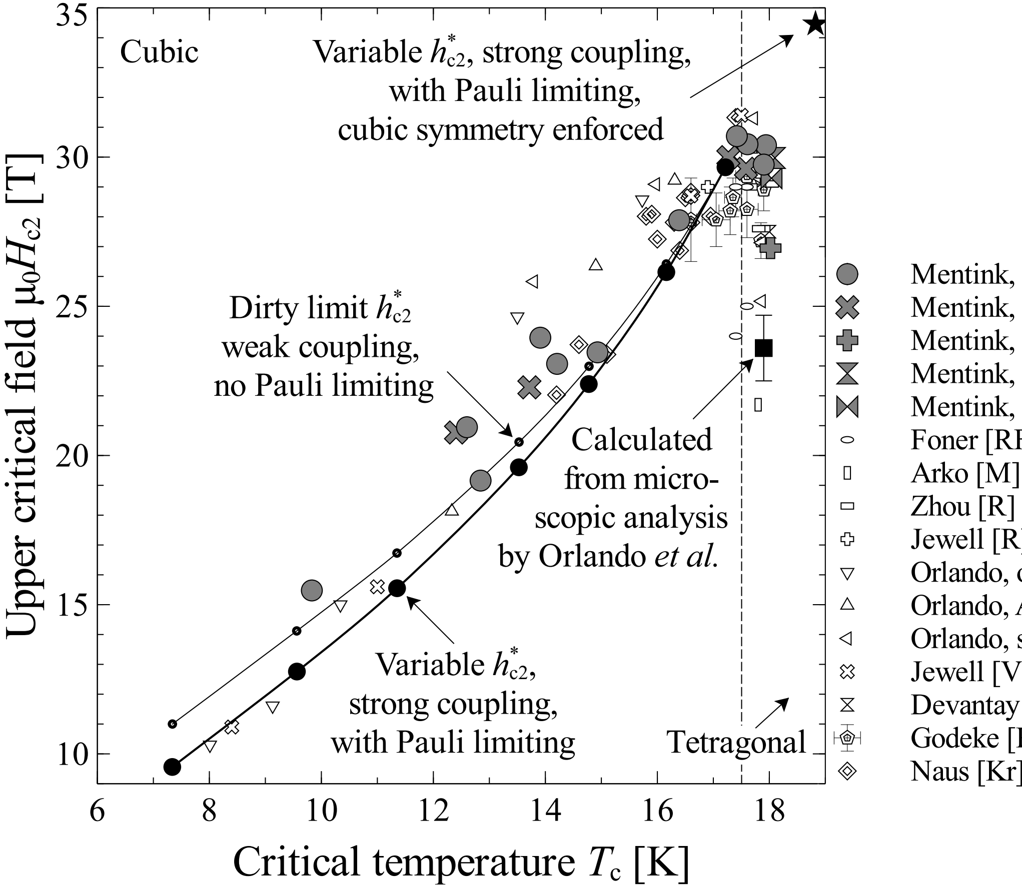
Subtract Coulomb repulsion

Mentink, *PhD thesis* (2014)

Ab-initio calculated and measured T_c and H_{c2}



(25 at.% Sn --------------- 18 at.% Sn)



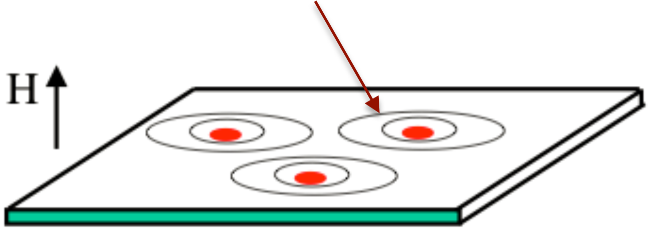
Nb$_3$Sn T_c and H_{c2} as a function of disorder (i.e. composition, strain,…) are now well understood

Mentink, *PhD thesis* (2014)

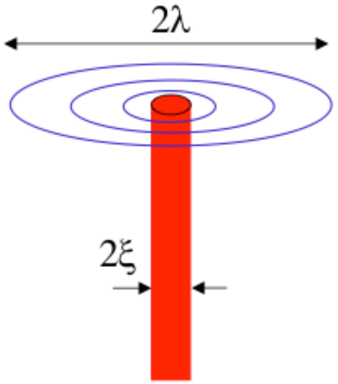
What does H_{c2} do for us?

Type II superconductor in field

- Field quanta $\phi_0 = h/2e$ (flux-lines) penetrate SC

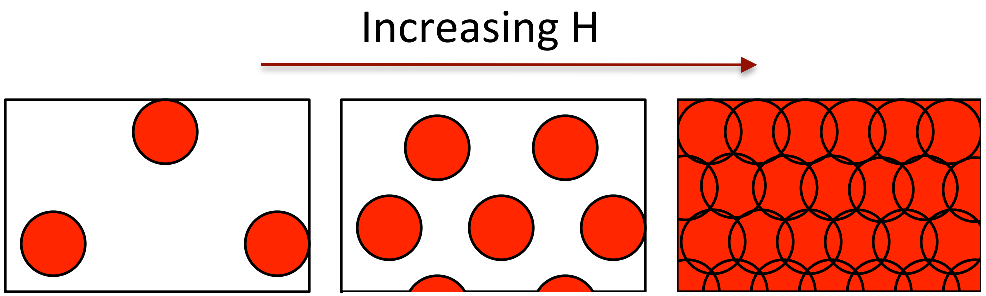


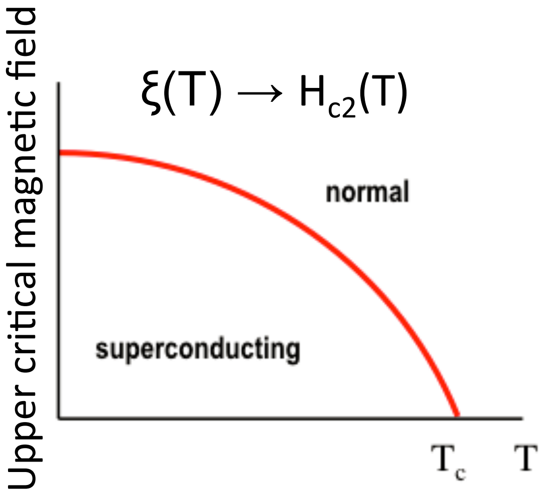
Super currents shield normal cores over penetration depth λ



Increasing magnetic field

- Normal cores start to overlap at $H = H_{c2} = \phi_0 / 2\pi\xi$





$\xi(T) \rightarrow H_{c2}(T)$

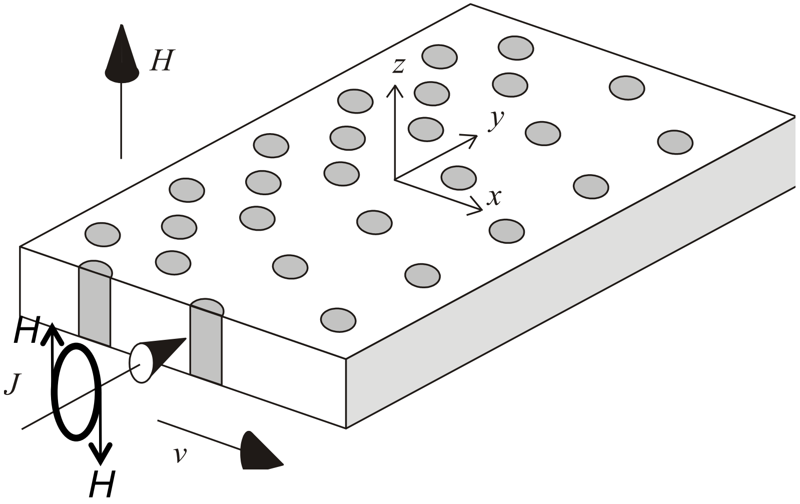
H_{c2}(T) provides maximum field a conductor can be used at

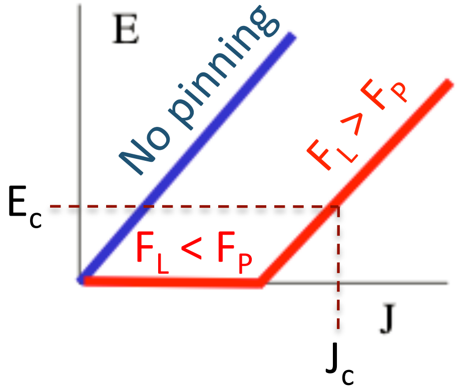
Gurevich, *Lectures UW-Madison* (2003)

What determines J_c? Type II SC carrying current in field

External field causes flux-lines to penetrate SC

- Current causes gradient in flux density B_x
- Flux-lines repel → move ($\nabla \times E = - dB/dt$) → E_y → Loss





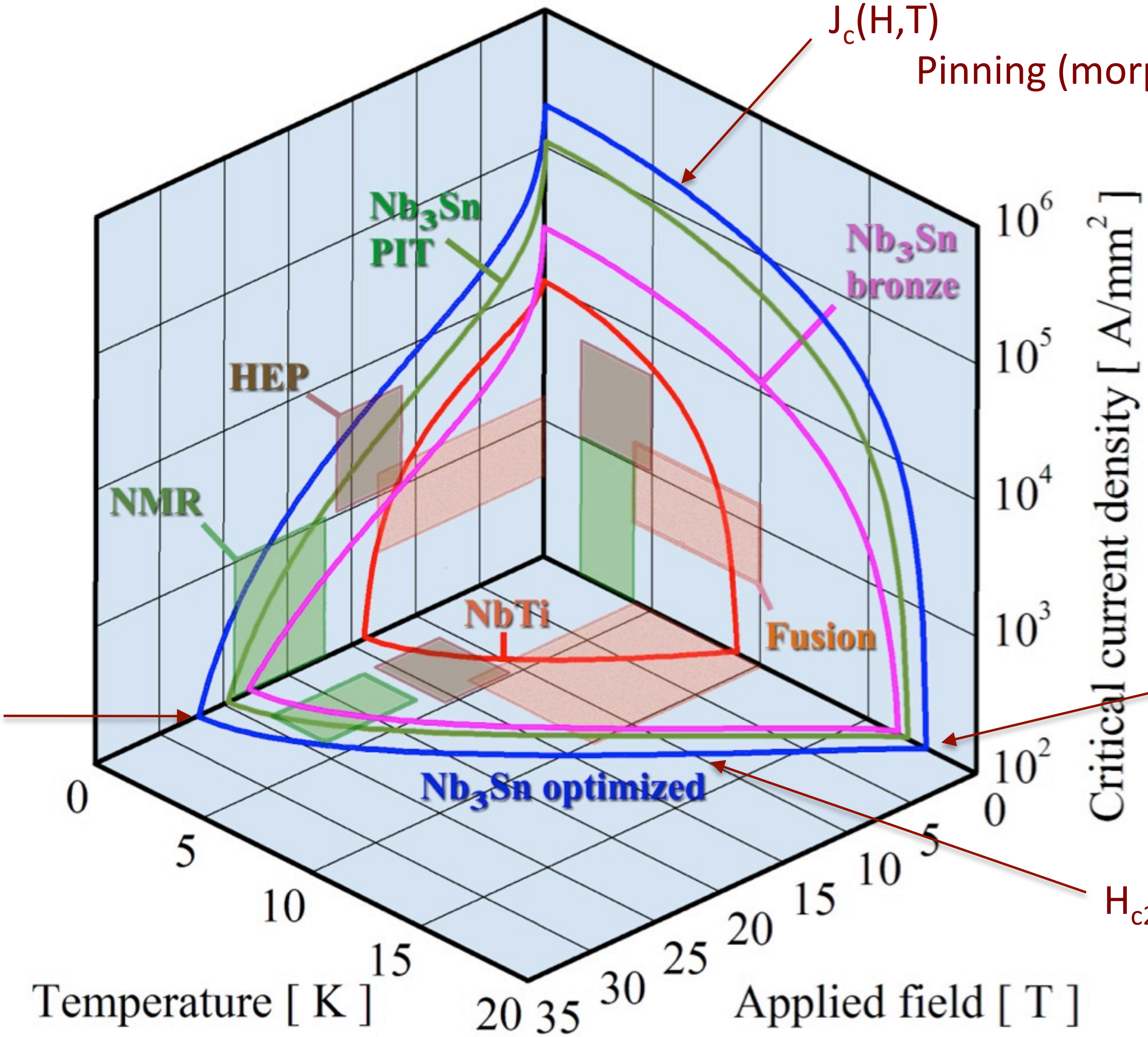
Flux-lines need to be '**pinned**' at '**pinning centers**' by '**pinning force**' F_P

- Pinning centers: Impurities, defects, grain boundaries, …

'De-pinning' for $F_L = J \times B > F_P$ → Critical current density $\mathbf{J_c}$

Godeke, *Ph.D. Thesis* (2005)

Superconducting Phase Boundary



$J_c(H,T)$

Pinning (morphology)

H_{c2}

T_c

$H_{c2}(T)$

Composition and strain state

Godeke, *Ph.D. Thesis* (2005)

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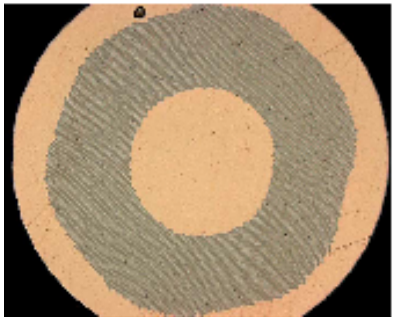
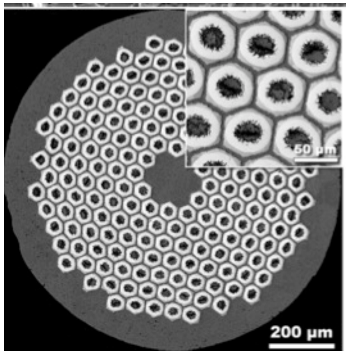
Technological superconductors

Examples of technologically relevant superconductors

NbTi 50% SC Nb_3Sn



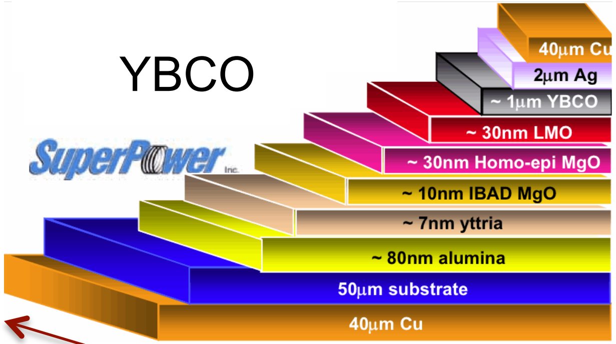
1 mm



1 mm

	$H_{c2}(0)$ [T]	$T_c(0)$ [K]
NbTi	14	9.5
Nb_3Sn	30	18
MgB_2	3.5-35	32-40
$YBa_2Cu_3O_7$	>100	93
Bi-2223	>100	108
Bi-2212	>100	95

YBCO

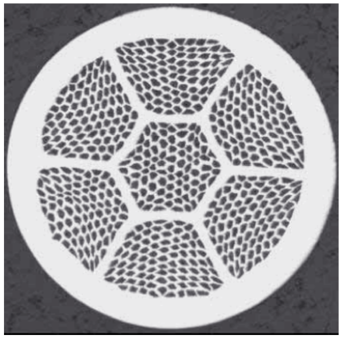


1% SC

0.15 mm

4-12 mm

1 mm



25% SC

Bi-2212

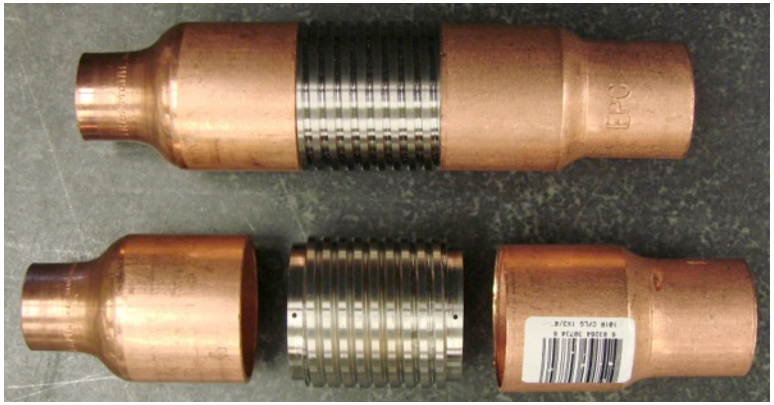
Bi-2223

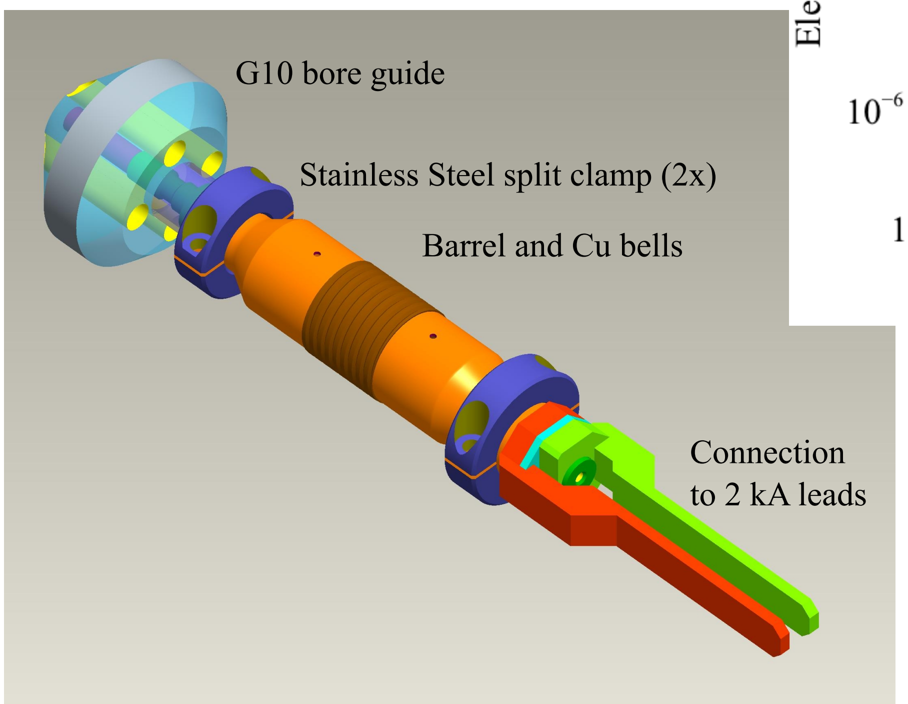
0.25 mm

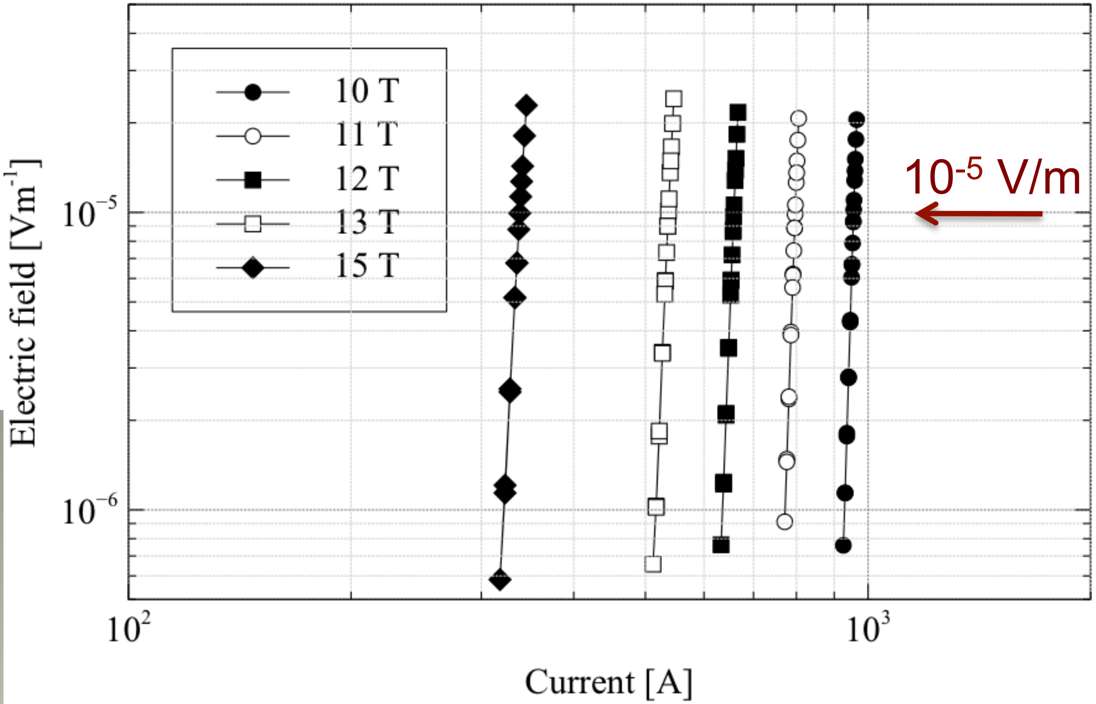
4 mm

Measurement of critical currents

Modern method for the measurement of high current wires







10^{-5} V/m

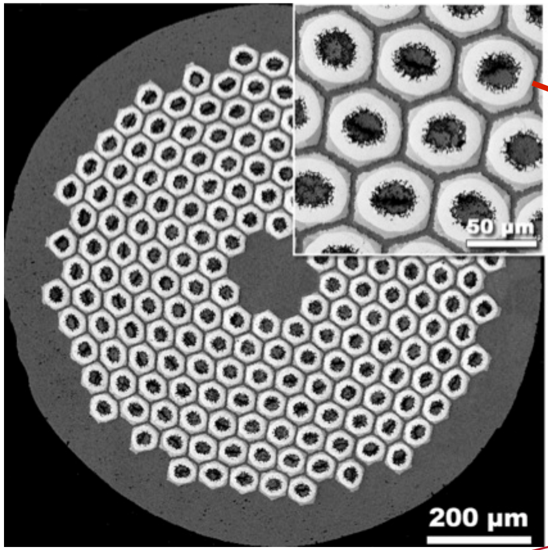
Intersect with E_c defines I_c

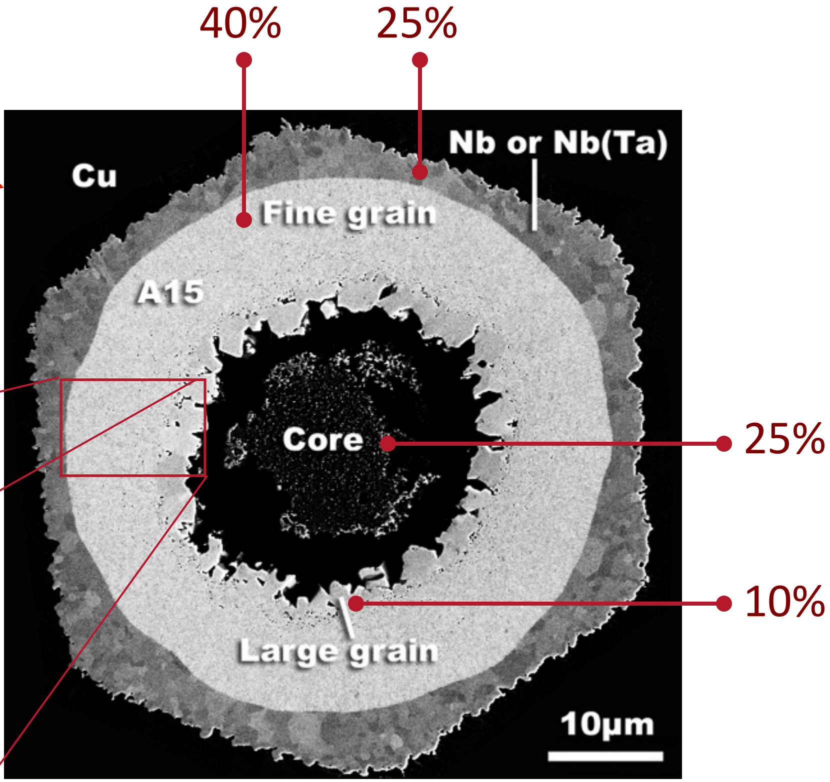
Godeke, *et al.*, *Adv. Cry. Eng.* **58** 209 (2011)

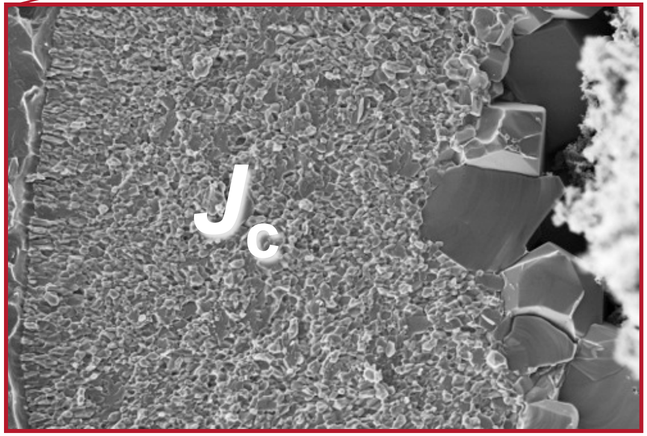
What determines J_c?

Powder-in-Tube wire

50% non-Cu fraction → **non-Cu J_c**





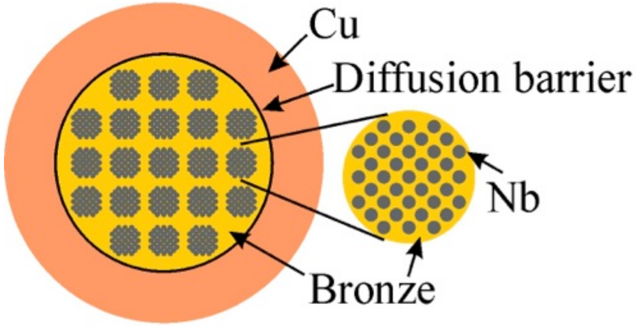


Only 20% of a wire carries current

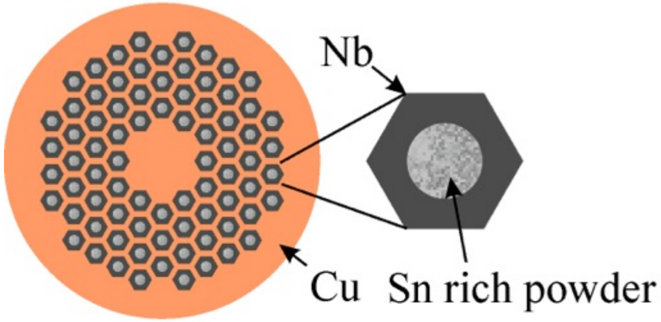
Godeke, *et al.*, *Cryogenics* **48** 308 (2008)

Performance comparison Nb_3Sn wires

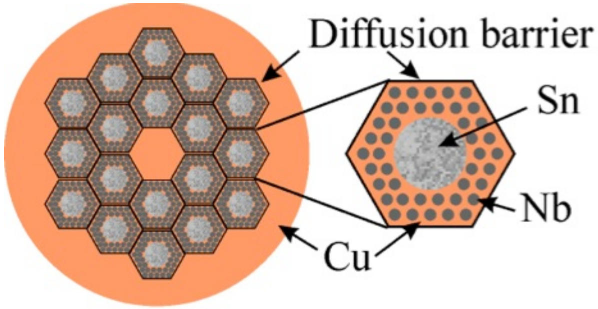
Different processes yield very different results



Bronze process



PIT process



Internal Sn process

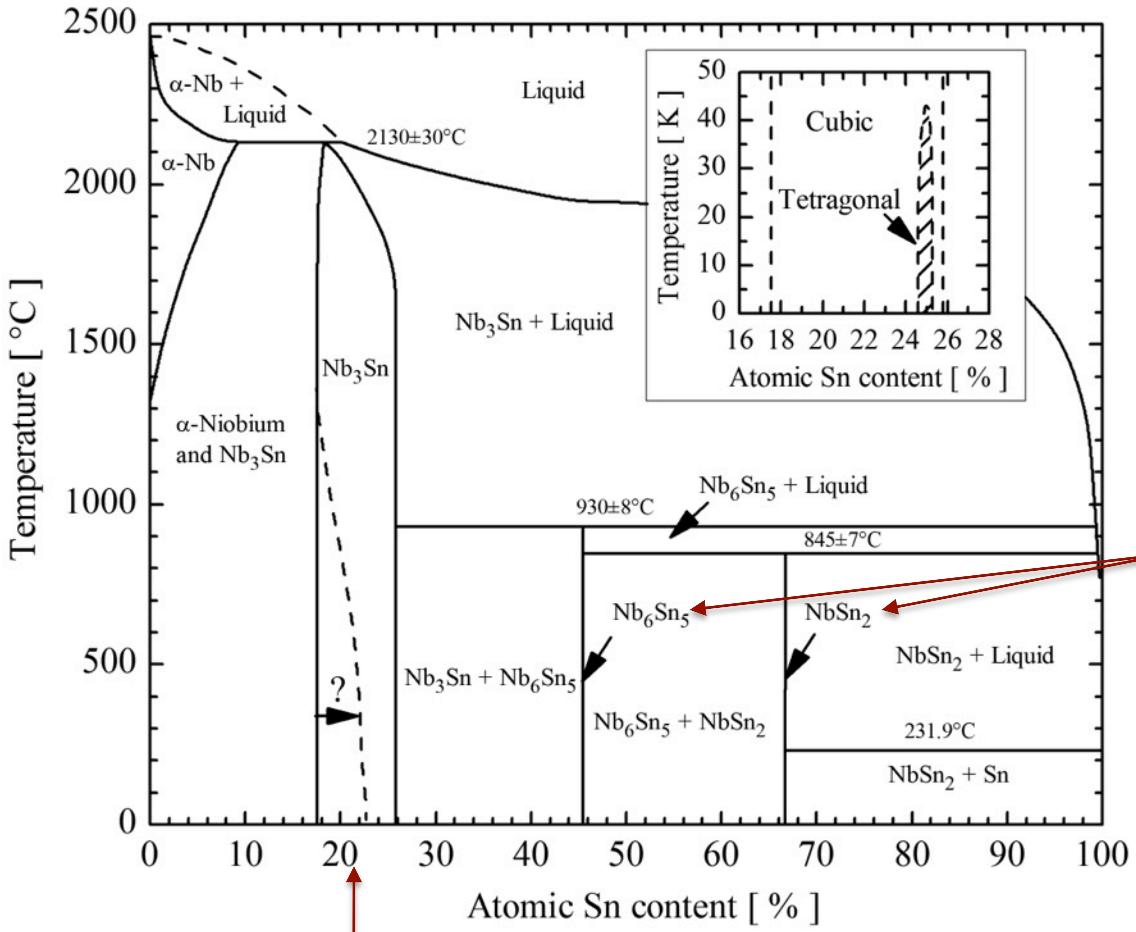
Technology	**Non-Cu J_c(12 T, 4.2 K)**
Bronze	720 A/mm^2
Powder-in-Tube	2250 A/mm^2
Internal Tin	3000 A/mm^2

Why such large differences in J_c?

Godeke, *Proc. WAMSDO* (2008)
Bottura and Godeke, *Rev. Accel. Sci. Techn.* **5** 25 (2012)

Differences occur mainly due to Sn content

Binary phase diagram for the Nb-Sn system



High Sn line compounds are destabilized by Cu

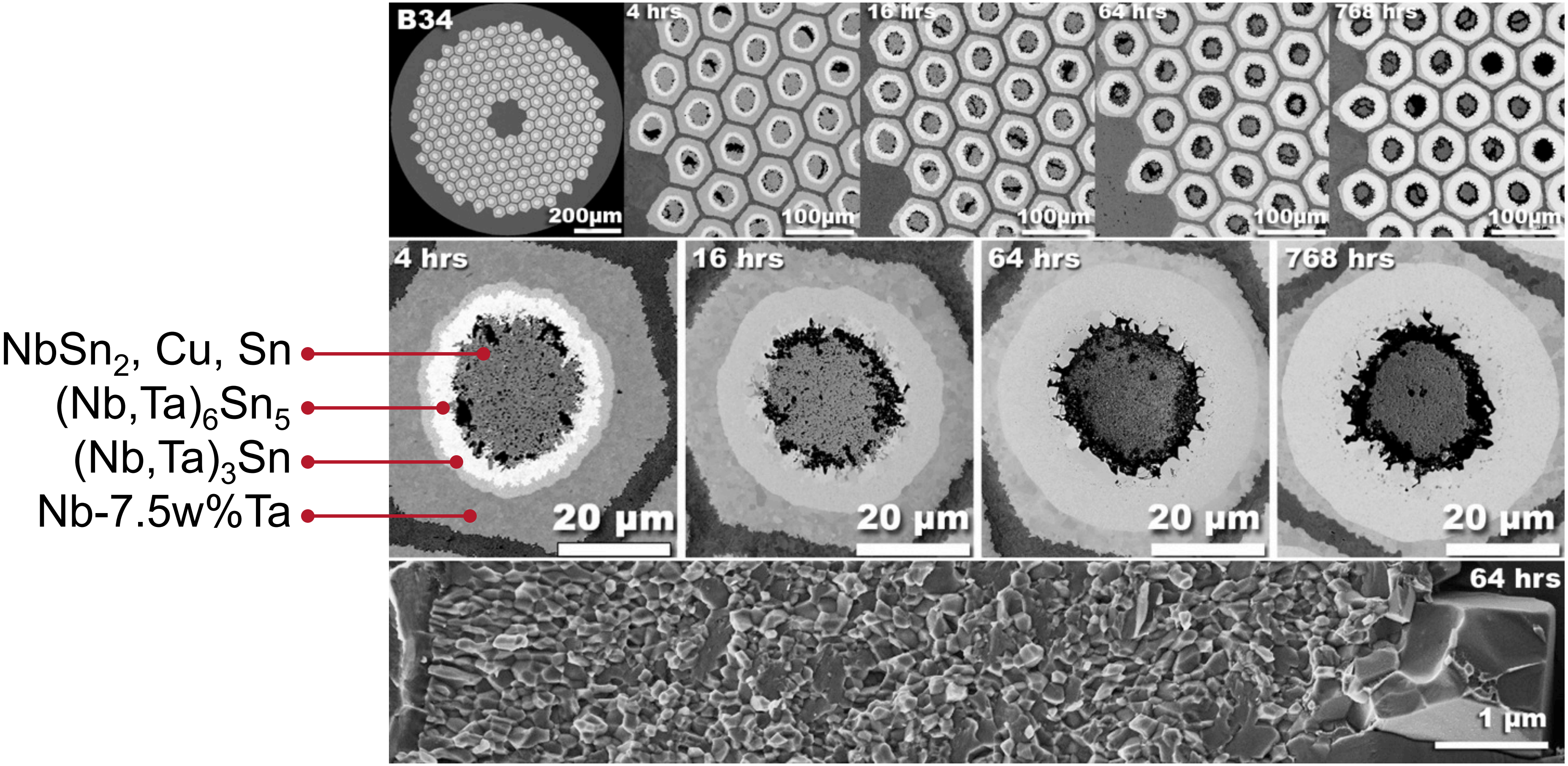
The relevant Nb-Sn phase is stable from 18 – 25 at.% Sn

Charlesworth, *et al.*, *J. Mat. Sci.* **5** 580 (1970)
Flükiger, *et al.*, *Adv. Cryo. Eng.* (1982)
Godeke, *Supercond. Sci. Techn.* **19** R68 (2006)

Nb_3Sn formation in wires

Nb_3Sn: Formed by a high temperature reaction in an inert atmosphere

- Example: Reaction progress at 675°C vs. time in a Powder-in-Tube wire



$NbSn_2$, Cu, Sn

$(Nb,Ta)_6Sn_5$

$(Nb,Ta)_3Sn$

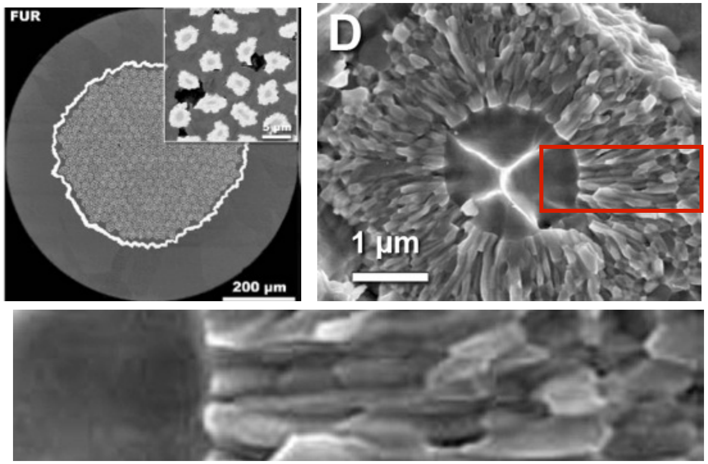
Nb-7.5w%Ta

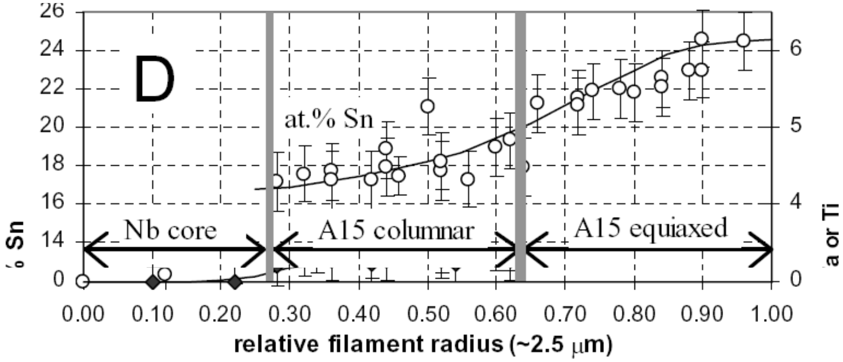
A solid state diffusion reaction results in compositional gradients

Godeke, *et al.*, *J. Appl. Phys.* **97** 093909 (2005)

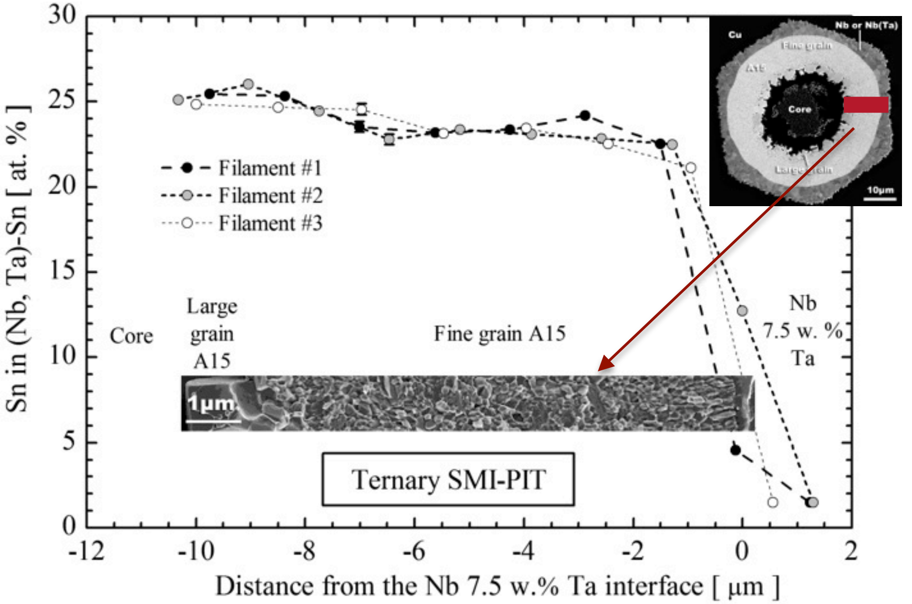
Sn gradients in wires after reaction

Bronze (**720** A/mm^2): **– 4** at.% Sn/μm

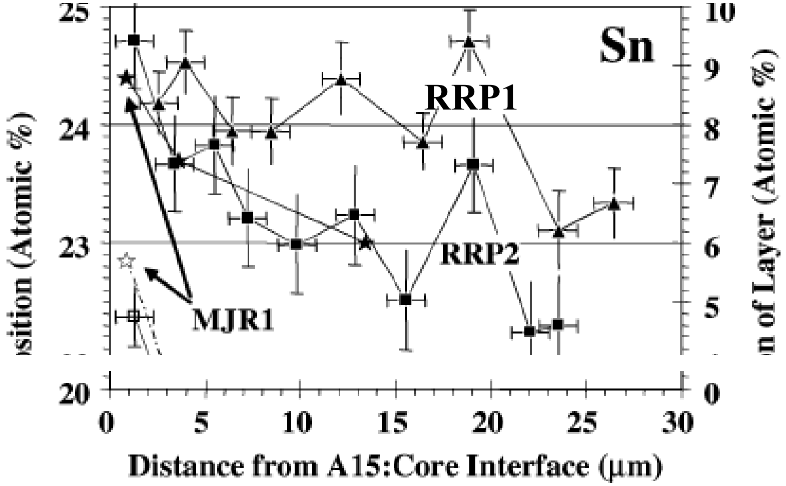




PIT (**2250** A/mm^2): **– 0.3** at.% Sn/μm



Int.-Tin (**3000** A/mm^2): **– 0.05** at% Sn/μm



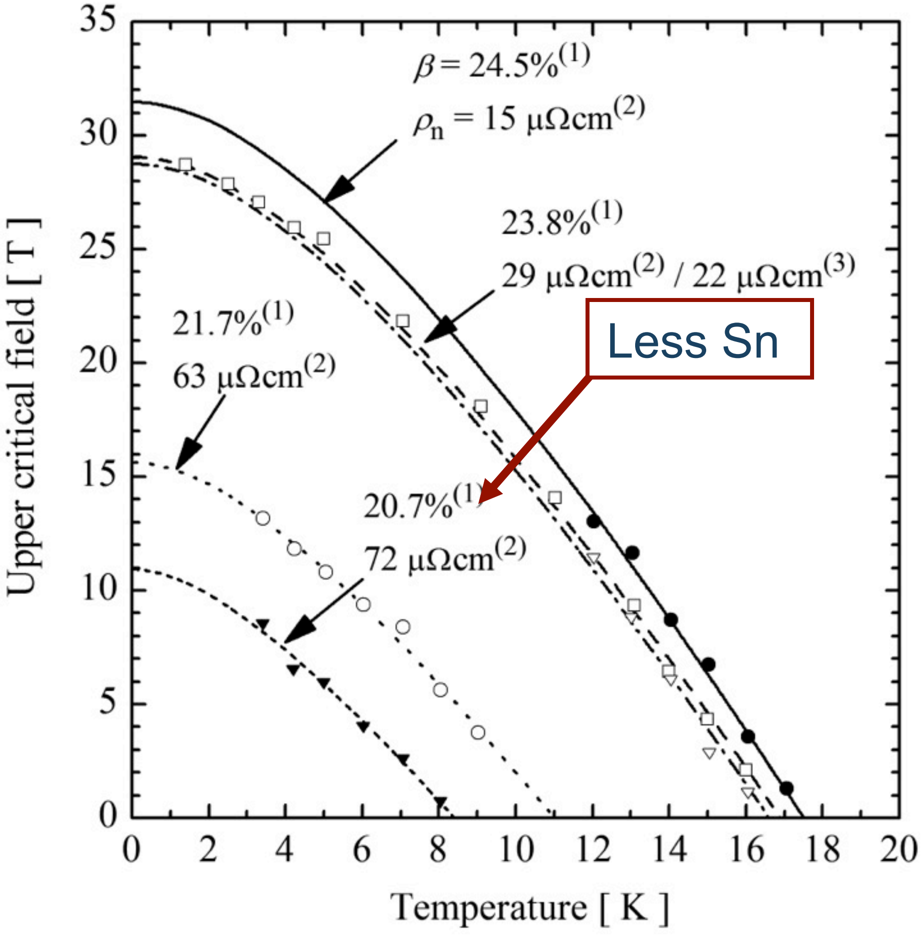
Large fraction with high Sn gives high J$_c$: WHY?

Abächerli, *et al.*, *IEEE Trans. Appl. Supercond.* **15** 3482 (2005)
Godeke, *et al.*, *Cryogenics* **48** 308 (2008)
Lee, *et al.*, *IEEE Trans. Appl. Supercond.* **15** 3474 (2005)

Sn deficiency suppresses $H_{c2}(T)$

Resistive data on bulk material…

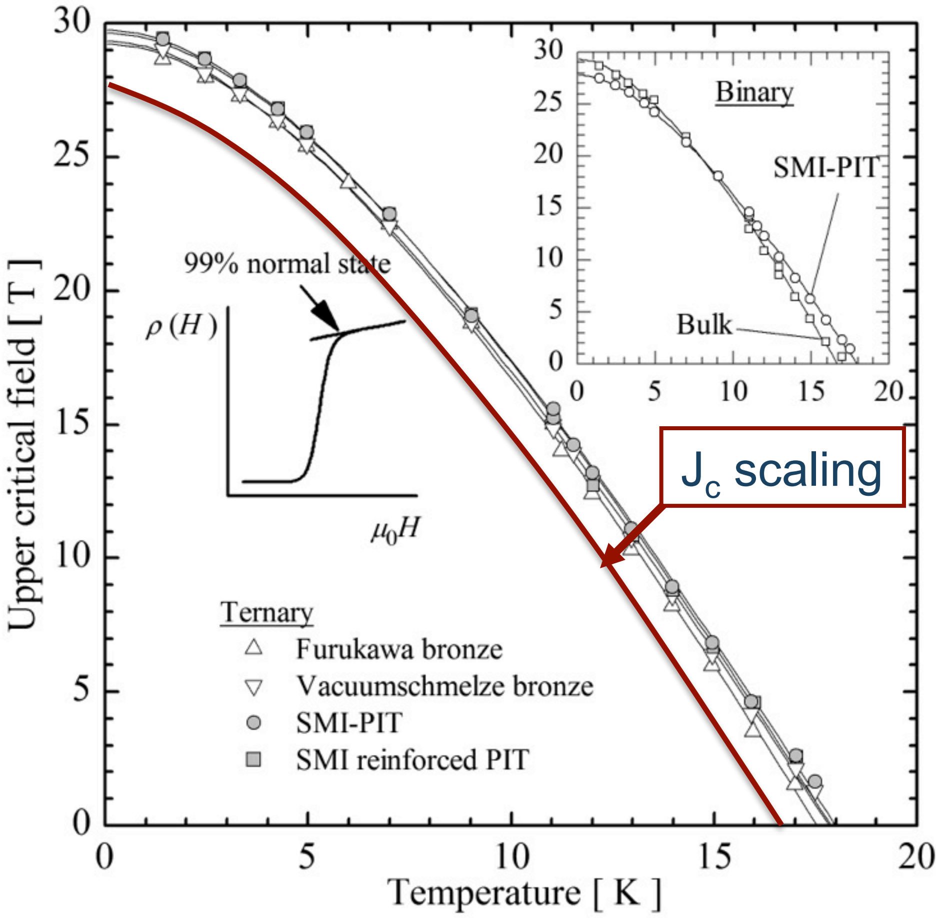
- Of different Sn content
- Low Sn sections not SC at high field



Less Sn

…and on wires

- Detecting only the best, stoichiometric bits that are present in all wires

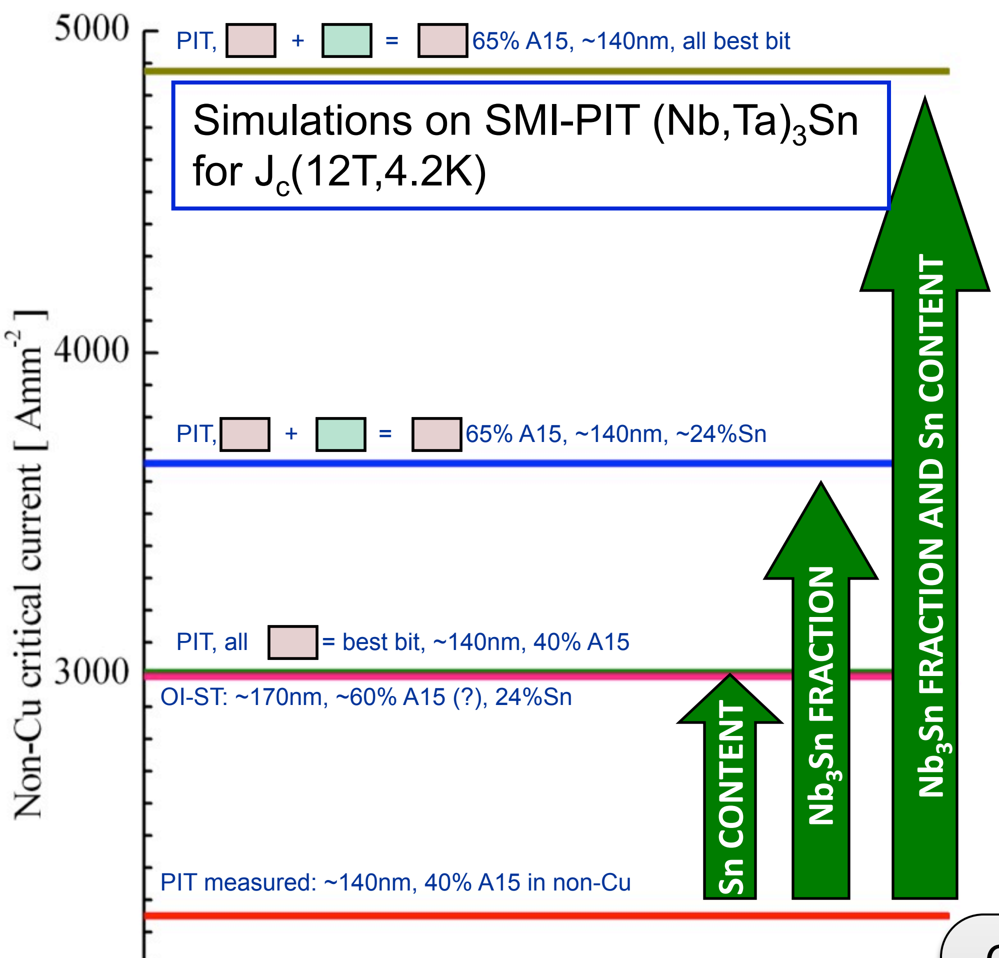


J_c scaling

Large fraction with high Sn, high $H_{c2}(T)$ yields high J_c wires

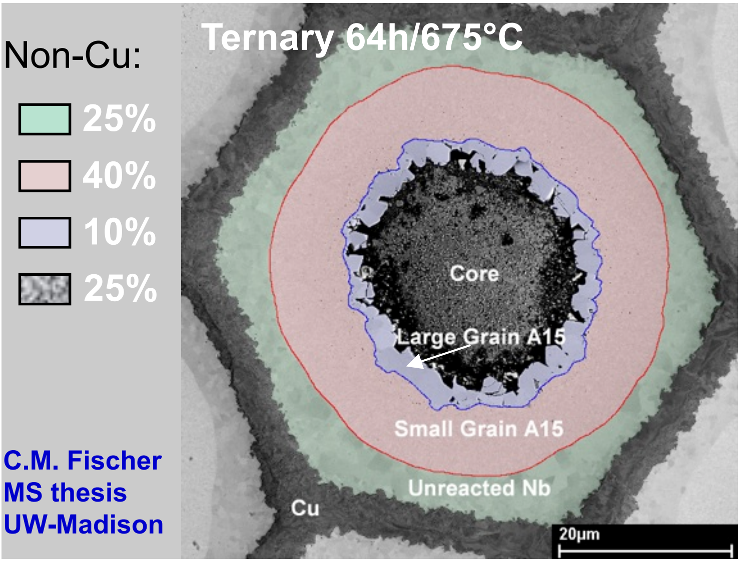
Jewell, Godeke, *et al.*, *Adv. Cry. Eng.* **50** 474 (2004)
Godeke, *Supercond. Sci. Techn.* **19** R68 (2006)
Godeke, *et al.*, *J. Appl. Phys.* **97** 093909 (2005)

Prospects for composition optimizations



5000 A/mm^2 is the academic limit
…for Sn content and Nb_3Sn fraction optimizations

12 T, 4.2 K non-Cu Jc



C.M. Fischer
MS thesis
UW-Madison

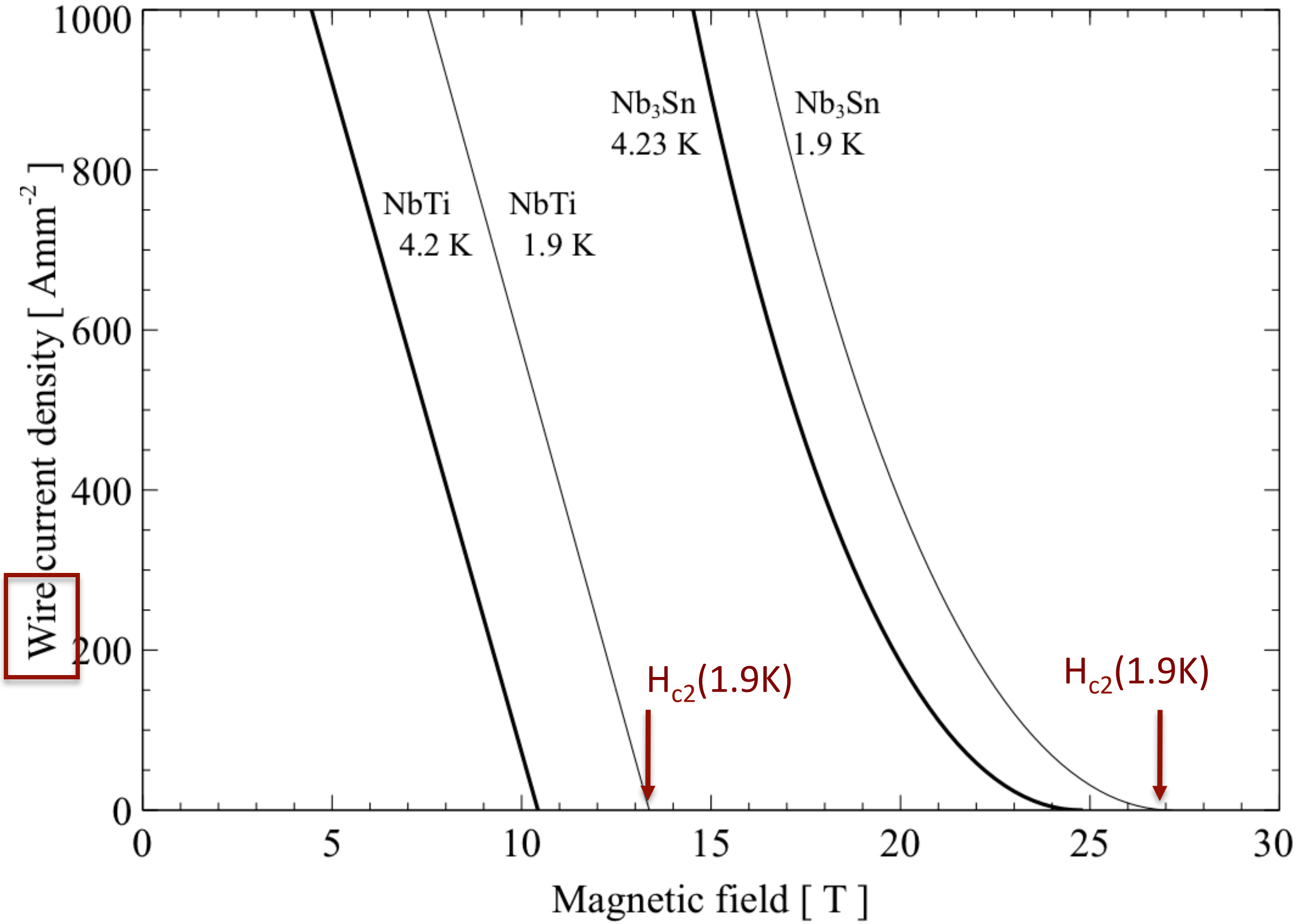
Achieved:
Bruker/EAS/SMI PIT: 2600 A/mm^2 (2008)
OST IT: >3000 A/mm^2 (since 2003)
Hypertech IT: 3400 A/mm^2 (2008)

Composition optimizations are exhausted
4000 A/mm^2 the practical limit? (2003)
3800 A/mm^2 measured in OST-RRP (2011)
Unless pinning can be improved!

Godeke, *LTSW* (2003)
Godeke, *et al.*, *J. Appl. Phys.* **97** 093909 (2005)

Pinning optimizations?

Comparison between NbTi and Nb_3Sn $J_E(H)$



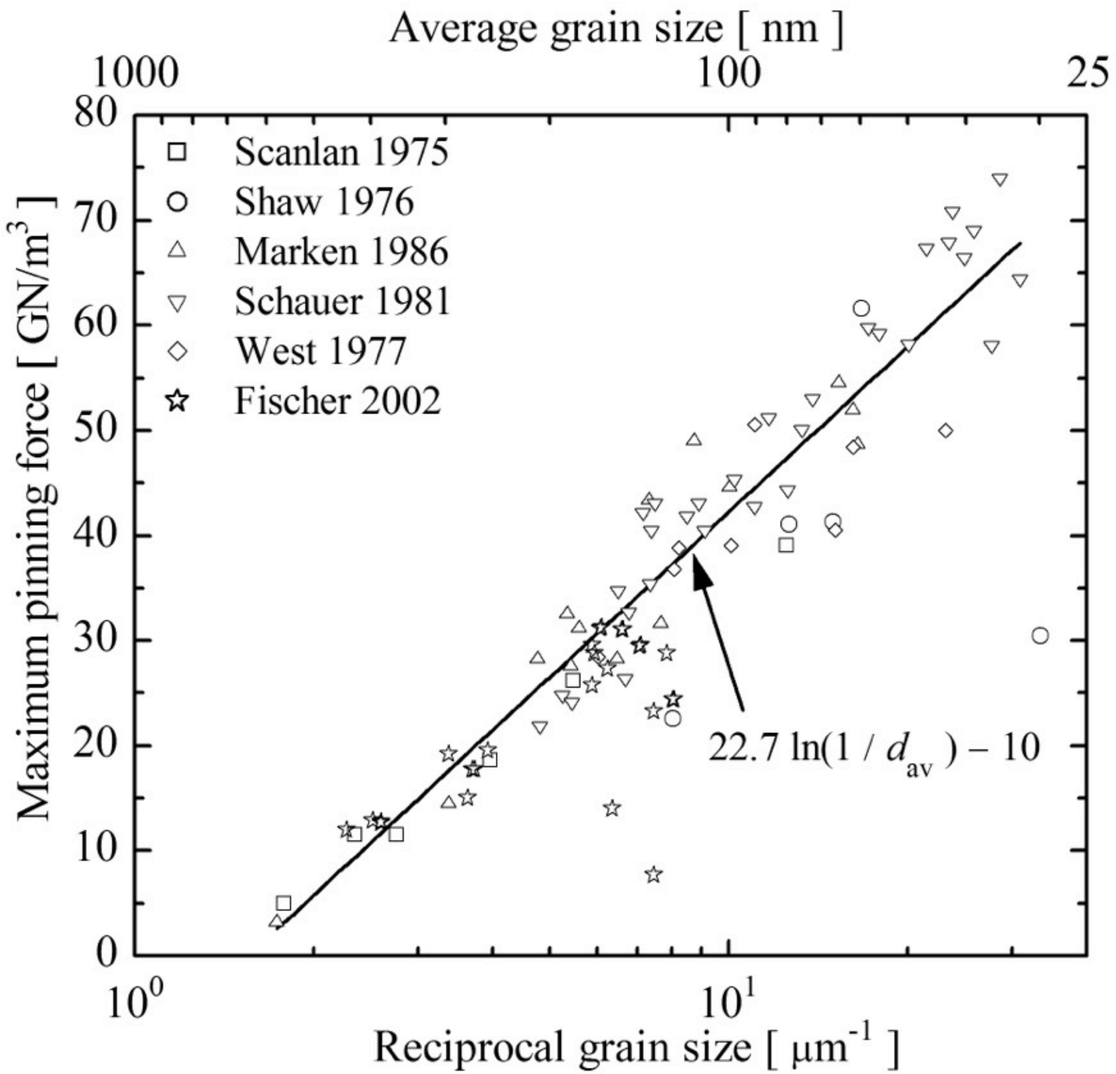
NbTi is more efficient approaching H_{c2} → WHY?

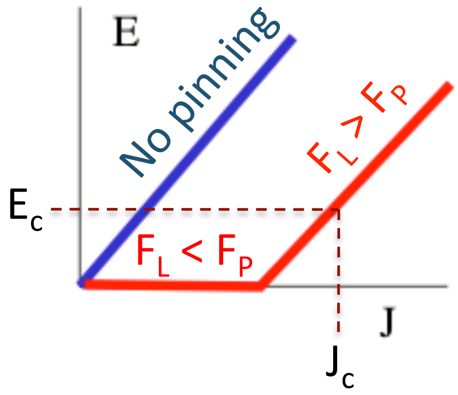
Godeke, *et al.*, *IEEE Trans. Appl. Supercond.* **17** 1149 (2007)

What determines J_c?

J_c is determined by the achievable pinning force F_P

- And thus by the average grain size…





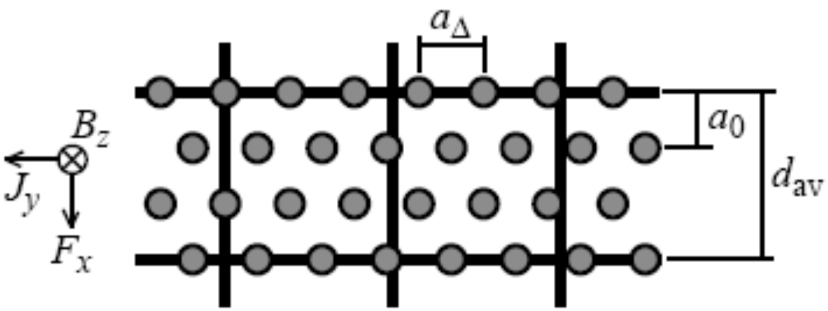
Grain boundaries are the main pinning centers in Nb_3Sn

Godeke, *Supercond. Sci. Techn.* **19**, R68 (2006)

What is an optimal grain size?

Ideal is 1 pinning center per flux-line

- Schematic: Cubic grains and flux-lines



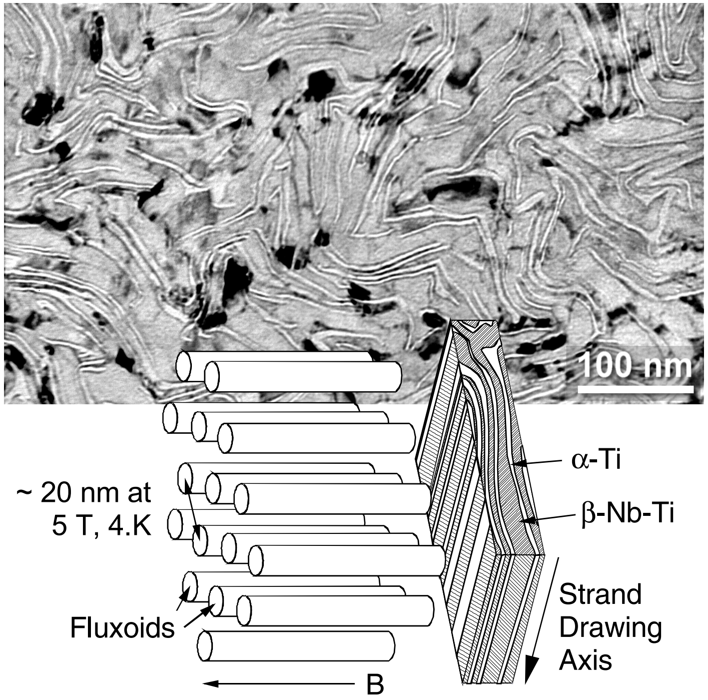
- Ideal: $d_{av} = a_0$

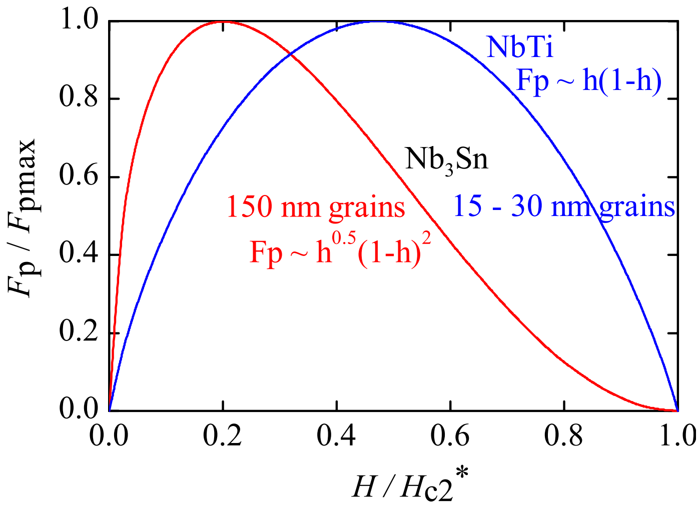
Flux-line spacing a_0 is field dependent

- E.g. at **12 T** $a_0 = (3/4)^{1/4}(\phi_0/\mu_0 H)^{1/2}$ = **12 nm**
- Grain size in Nb_3Sn wires → 100 – 200 nm

Grain size determines $F_{P,MAX}$
Grain size determines $F_P(H)$
Grain size Nb_3Sn factor 10 too large
Pinning NbTi is fully optimized

NbTi: Nanometer scale α-Ti precipitates





Dietderich and Godeke, *Cryogenics* **48** 331 (2008)
Lee, *et al.*, *Wire J. Int.* Feb. 2003

What happens when Nb_3Sn grains are refined?

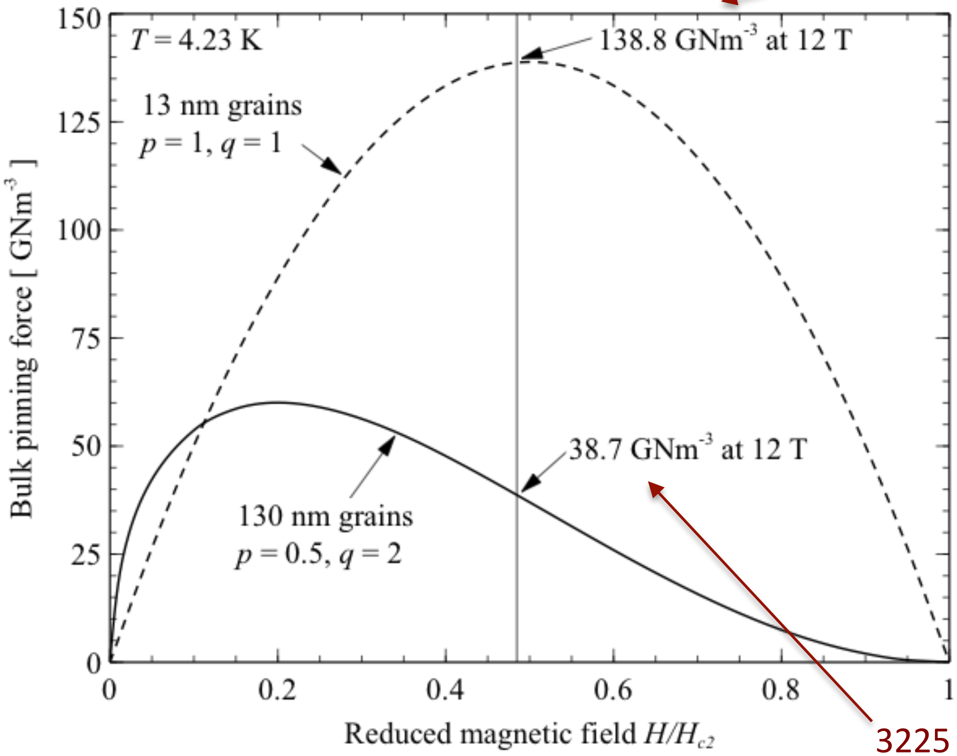
Pinning force ***predicted*** gains

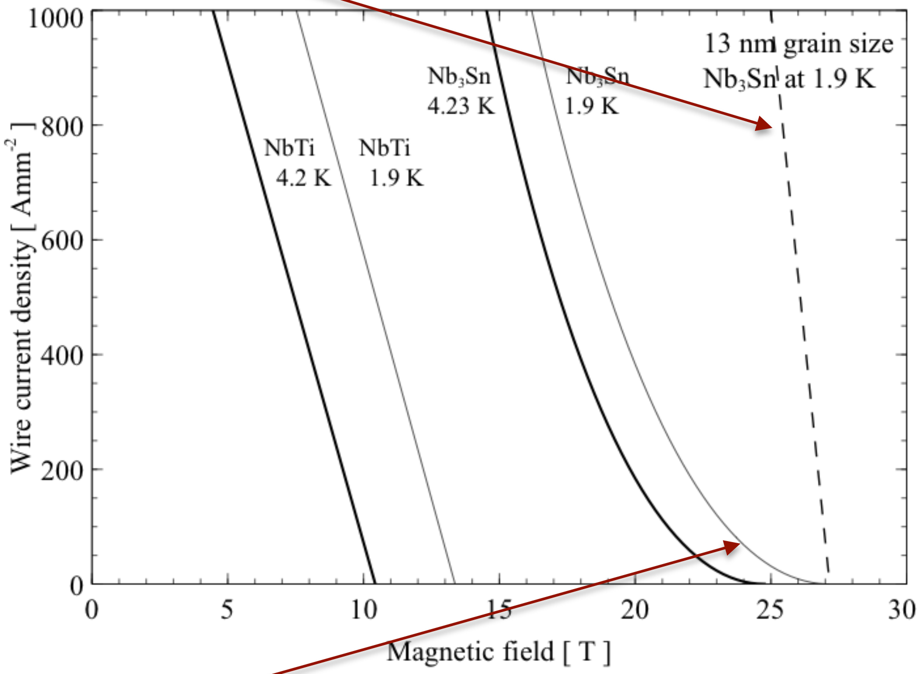
- 12 T, 4.2 K J_c increases by factor 3.6 (!)
  - A factor 3.4 is ***measured*** in thin films that were made and tested at LBNL

Critical current

- 20 – 25 T field regime is opened up
  - Much more efficient approaching H_{c2}
    - Finer grains are emerging for wires…

E.g. Xu, *et al.*, *Appl. Phys. Lett.* (2014)





11,567 A/mm^2

3225 A/mm^2

Gains confirmed on thin films.
How to do in wires is emerging…

Dietderich and Godeke, *Cryogenics* **48** 331 (2008)
Godeke, *et al.*, *Cryogenics* **48** 308 (2008)
Godeke, *et al.*, *To be published* (2014)

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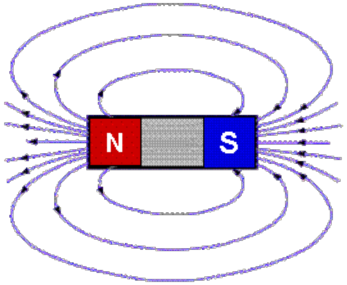
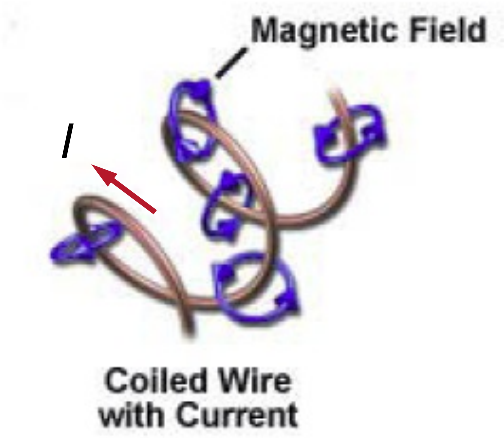
High J_c provides high magnetic fields

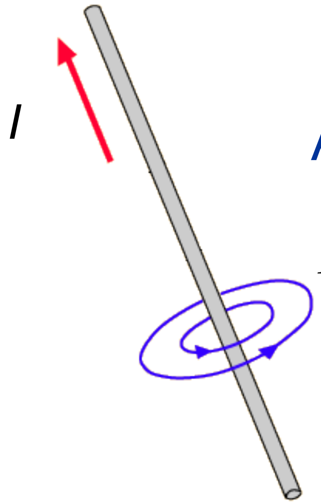
Permanent magnet: 1 T



Electro-magnet (SC solenoid): 20+ T

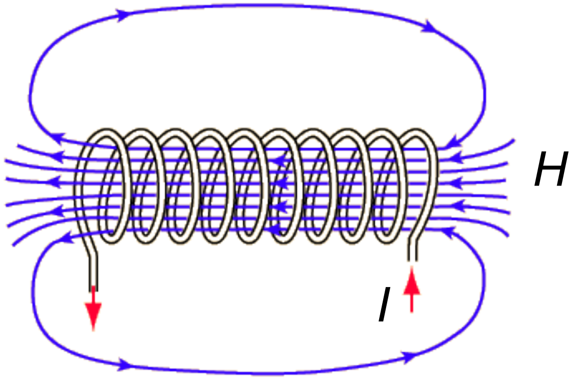


Hans Christian Oersted 1819:
Current generates a magnetic field



Ampere's law:

$$H = \frac{I}{2\pi r}$$



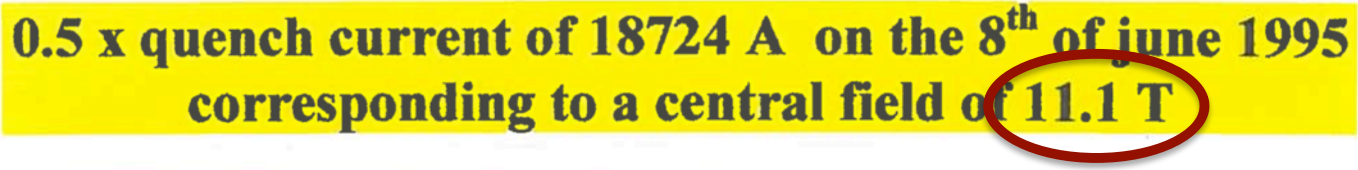
Increase H → Increase I, reduce r

***Caveat**: $F_L = J \times B$ increases also*

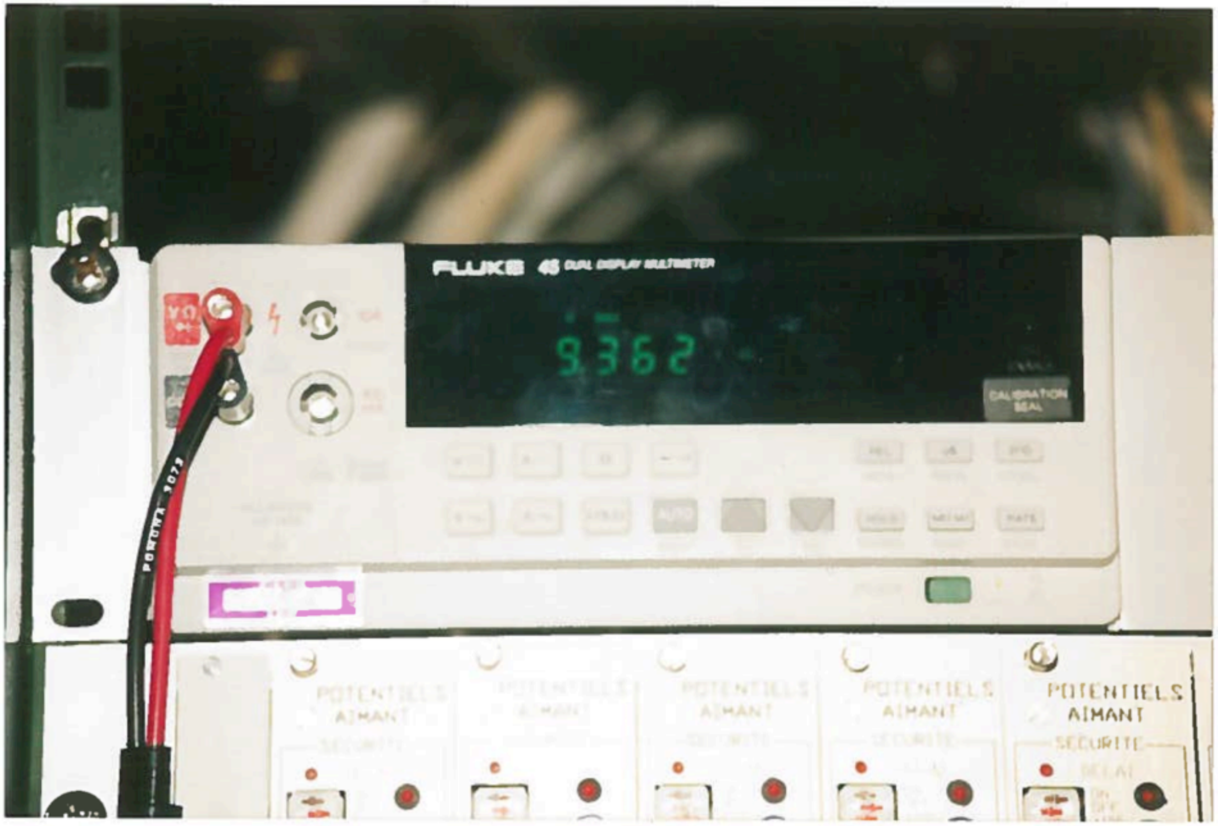
June 8, 1995: The dawn of dipoles beyond 10 T…

A new world-record dipole field…

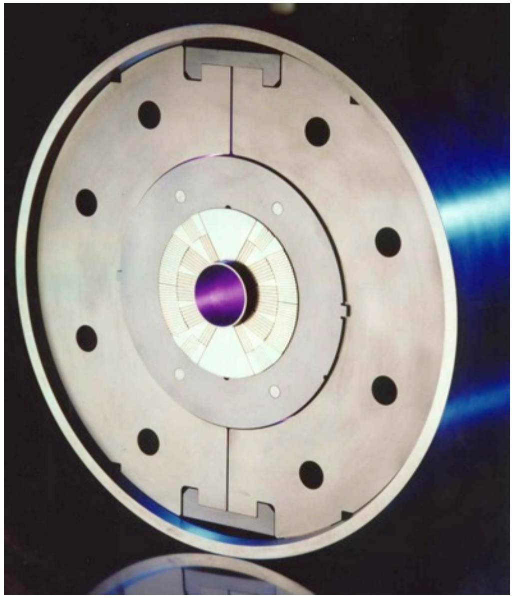
…and the first time a Nb_3Sn magnet surpassed the 10.5 T Nb-Ti limit



0.5 x quench current of 18724 A on the 8th of june 1995 corresponding to a central field of 11.1 T



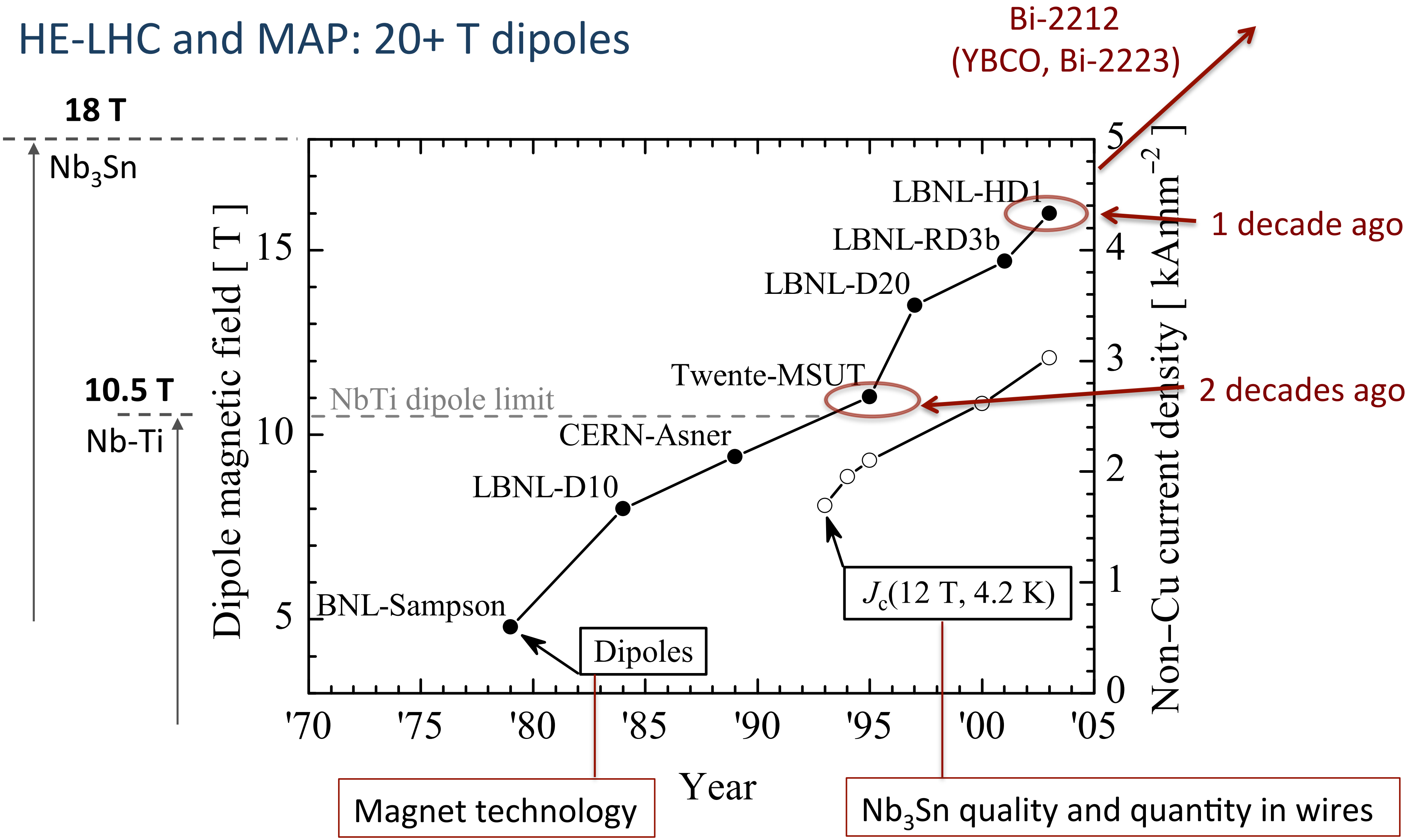
University of Twente



Pictures courtesy of A. den Ouden (U. Nijmegen) and W.A.J. Wessel (U. Twente)

Nb_3Sn dipole magnetic field records versus time

HE-LHC and MAP: 20+ T dipoles



Magnet technology

Nb_3Sn quality and quantity in wires

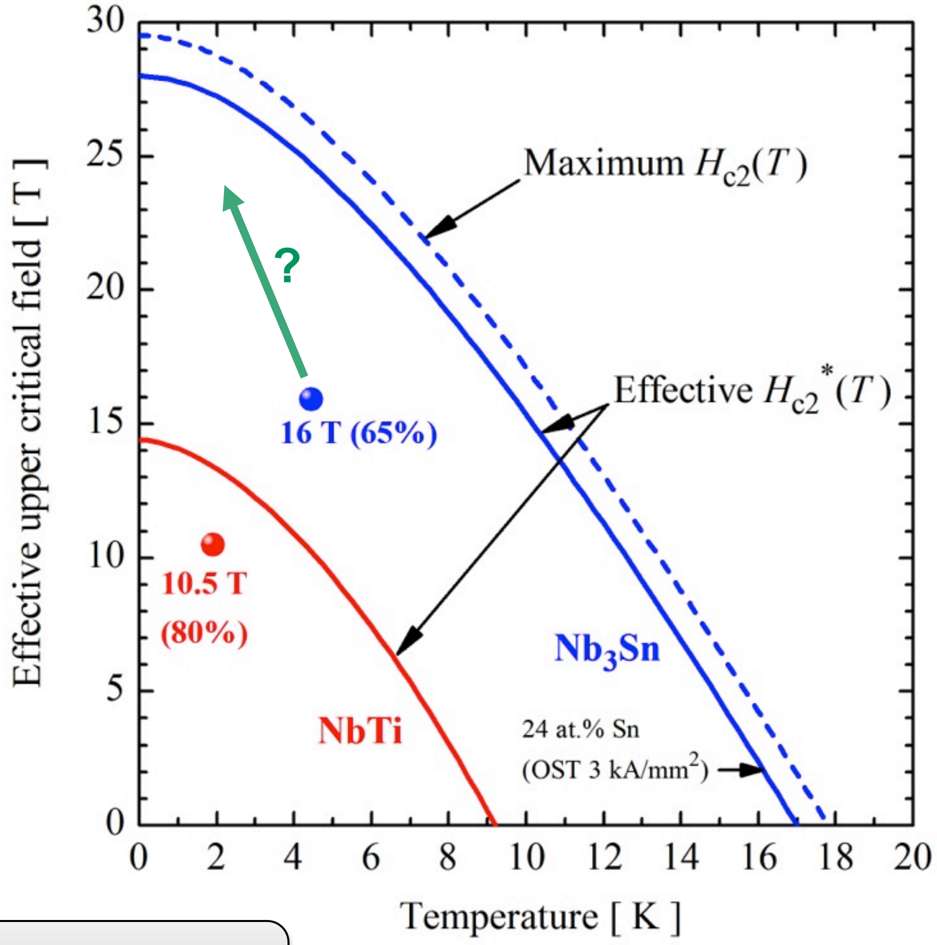
What limits Nb-Ti and Nb_3Sn?

Dietderich and Godeke, *Cryogenics* **48**, 331 (2008)

LTS intrinsic limits and dipole performance

Field – temperature limitations and achieved dipole fields

- NbTi
  - 10.5 T (CERN, 1998)
  - 80% of H_{c2}(1.8 K)
- Nb_3Sn
  - 16 T (LBNL, 2003)
  - 65% of H_{c2}(4.5 K)
  - 80% of H_{c2}(4.2 K) = 20 T?
  - 80% of H_{c2}(1.8 K) = 22 T?



NbTi is fully optimized
Nb_3Sn is limited by high field pinning inefficiency

Godeke, *et al.*, *IEEE Trans. Appl. Supercond.* **17** 1149 (2007)
Godeke, *et al.*, *J. Appl. Phys.* **97** 093909 (2005)

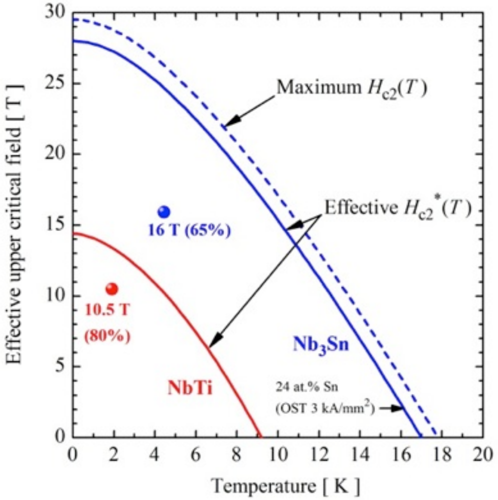
What are the dipole limits using LTS?

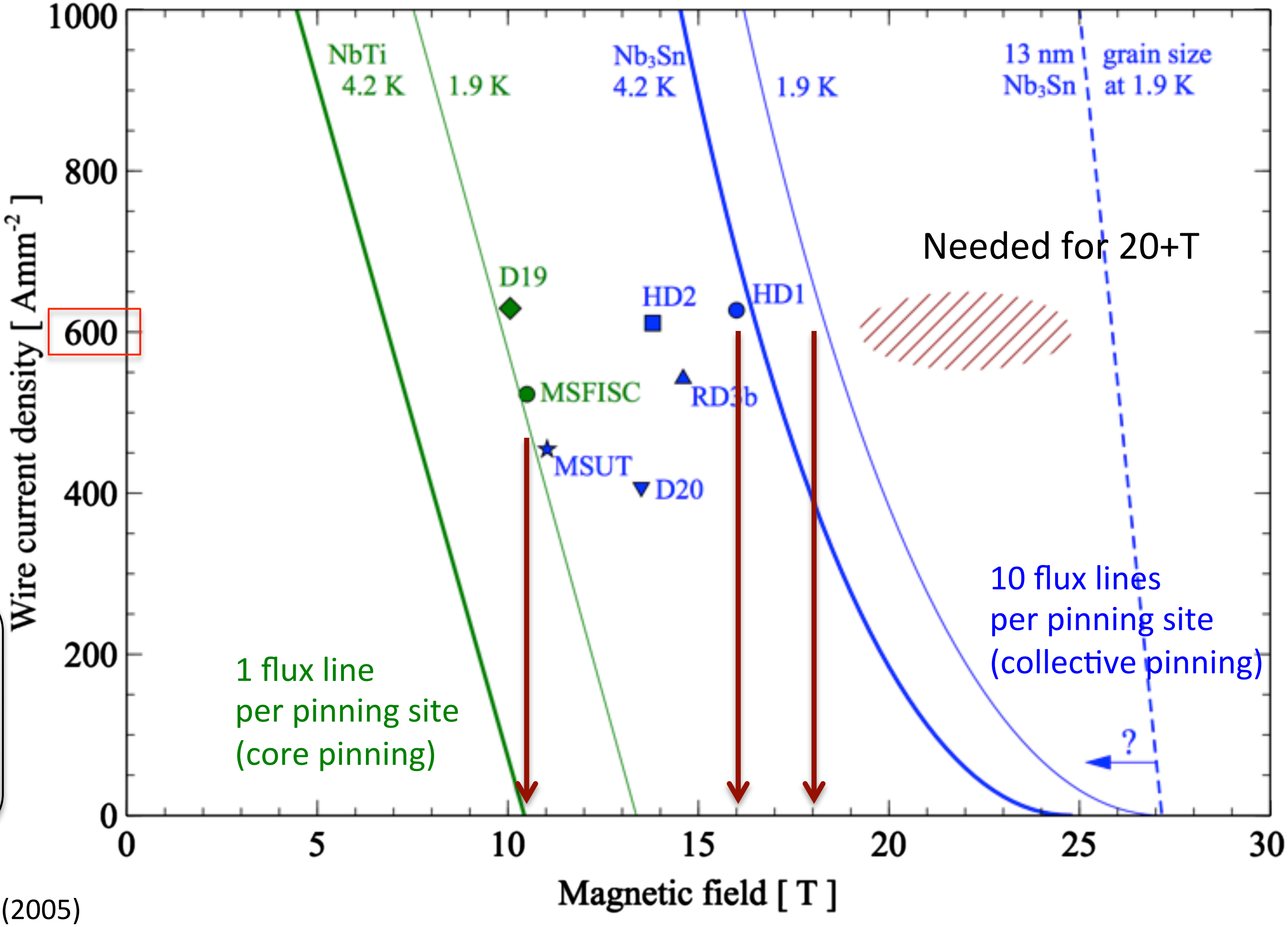
Nb-Ti reaches 80% of $H_{c2}(T)$

- α-Ti precipitates form pinning centers

Nb_3Sn reaches 65% of $H_{c2}(T)$

- Inefficient high field pinning





Needed for 20+T

10 flux lines per pinning site (collective pinning)

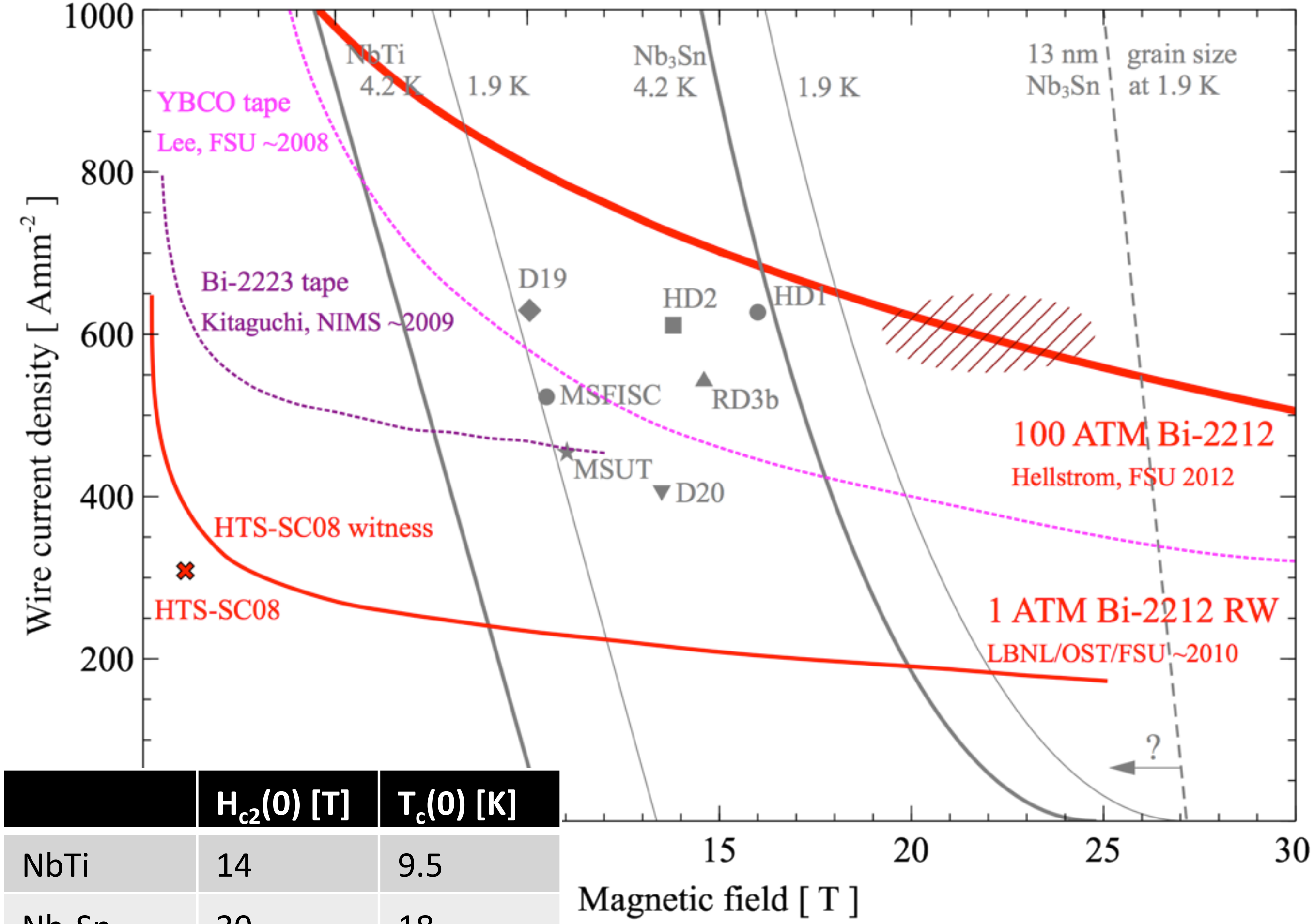
1 flux line per pinning site (core pinning)

Geometric and stress limitations

Limits:
10.5 T at 1.9 K for Nb-Ti
16 T at 4.5 K for Nb_3Sn
(or ~18 T at 1.9 K)

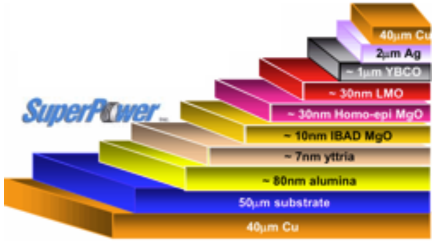
Godeke, *et al.*, *J. Appl. Phys.* **97**, 093909 (2005)
Godeke, *et al.*, *IEEE Trans. Appl. Supercond.* **17**, 1149 (2007)

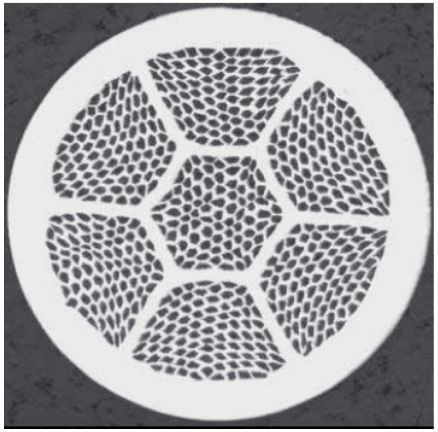
What dipole fields are possible using HTS?



	$H_{c2}(0)$ [T]	$T_c(0)$ [K]
NbTi	14	9.5
Nb_3Sn	30	18
MgB_2	3.5-35	32-40
$YBa_2Cu_3O_7$	>100	93
Bi-2223	>100	108
Bi-2212	>100	95

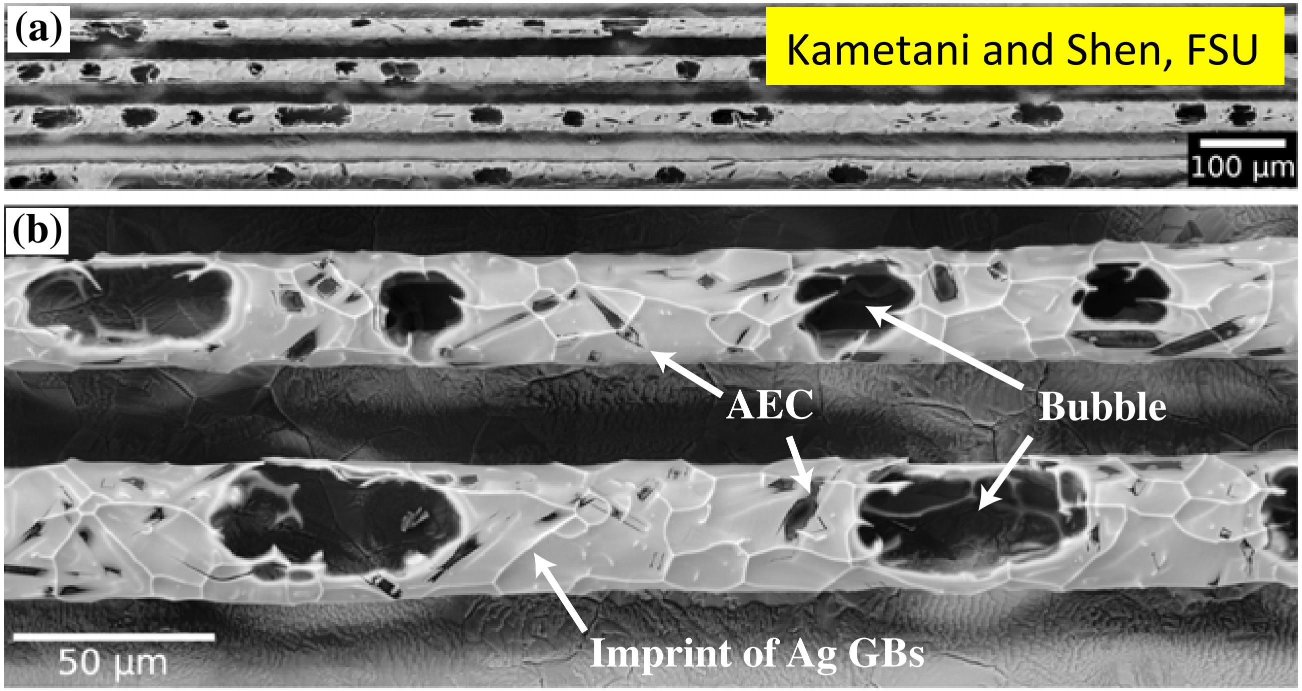
No field limitations





Bi-2212 is available as a round wire
...with significant potential!

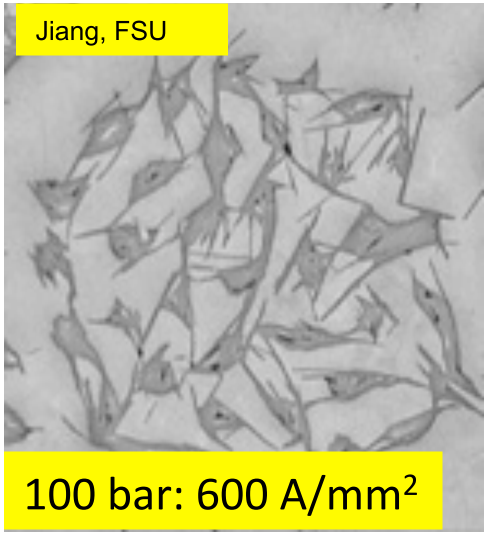
Bi-2212 requires densification during reaction


Kametani and Shen, FSU

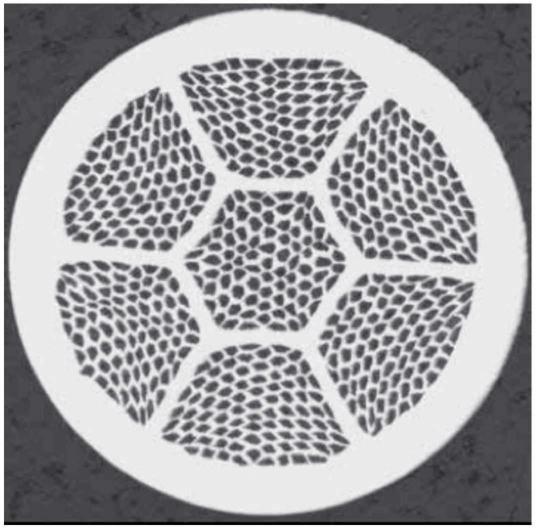
FSU and BSCCo collaboration:

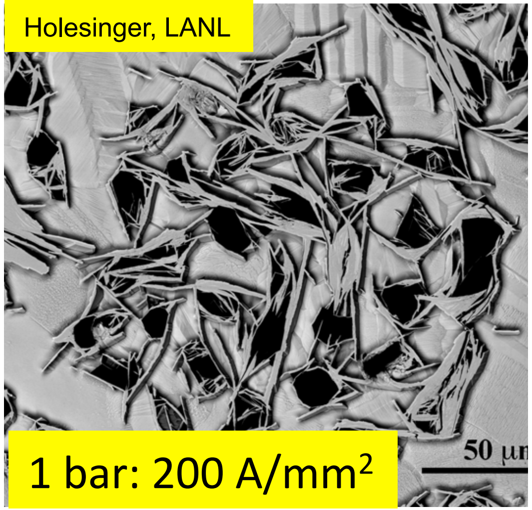
- Voids agglomerate into bubbles
- C and H react with O_2
- Internal pressure dedensifies 2212

Compensate with OP reaction at 25 to 100 bar


Jiang, FSU

100 bar: 600 A/mm^2




Holesinger, LANL

1 bar: 200 A/mm^2

20 T, 4.2 K J_E:
200 A/mm^2 for 1 bar
600 A/mm^2 for 100 bar

Larbalestier, *et al.*, *Nature Mat.* (2014)
Kametani, *et al.*; Jiang, *et al.*; Malagoli, *et al.*; *Supercond. Sci. Techn.* (2011-2013)

LBNL Bi-2212 efforts and collaborations


1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014

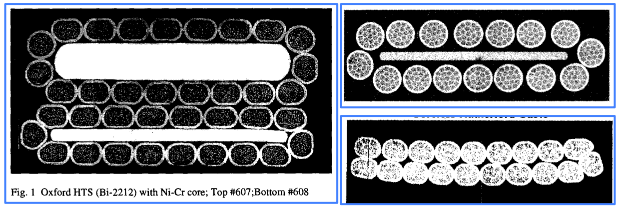
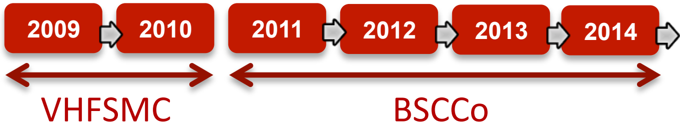


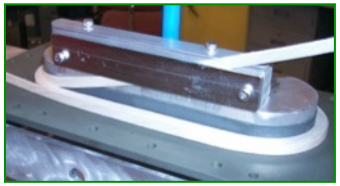
Fig. 1 Oxford HTS (Bi-2212) with Ni-Cr core; Top #607;Bottom #608

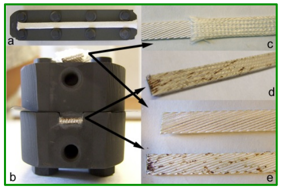
Rutherford cable developments
(with IGC, OST, Showa > 4.5 km SMES cable)

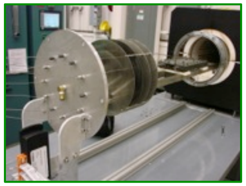

2009 2010 2011 2012 2013 2014

VHFSMC

BSCCo







Sub-scale W&R Bi-2212 racetracks with Showa and OST

Beyond 16 T dipole fields

- Optimize and refine Nb_3Sn
- Develop W&R Bi-2212
  - Collaborations
    - **SWCC** Showa Cable Systems Co. Ltd.
    - **OST** Oxford Instruments
    - **VHFSMC** U.S. National Program on Bi-2212
      - » BNL, FNAL, FSU, LBNL, NCSU, NIST, TAMU
    - **BSCCo** U.S. collaboration on Bi-2212
      - » BNL, FNAL, FSU, LBNL (+OST, CERN, Nexans)
- Side path: YBCO, Bi-2223, …

2006 – 2012: Bi-2212 subscale coils

- Purchase wire, make and insulate cable
- Coil on Inconel 600 former, react, pot, test
- 2 Ag dummies & 11 Bi-2212 coils

2013 onwards: Realistic Bi-2212 inserts

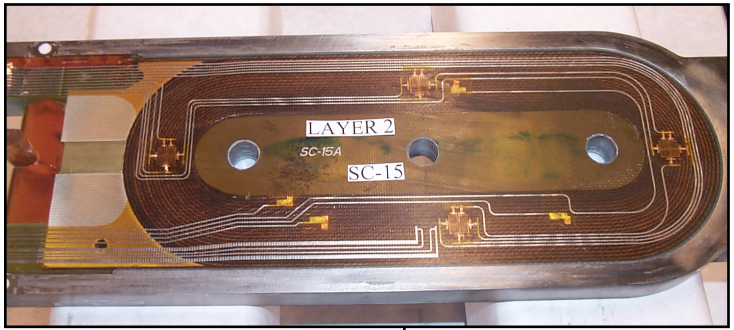
- Low strain, high J_E insert coil sets

Subscale magnets for basic coil technology

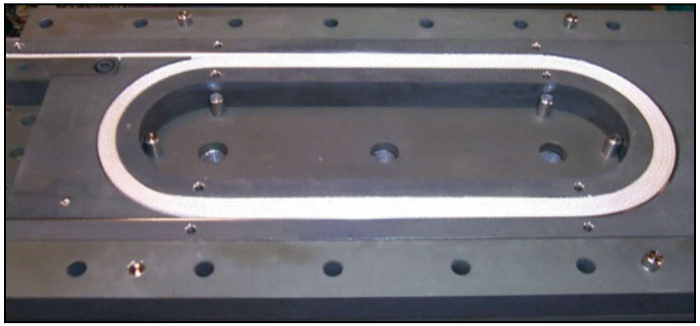
Sub-scale Coils and Structures

Sub-scale coils: Utilizing available Nb_3Sn infrastructure

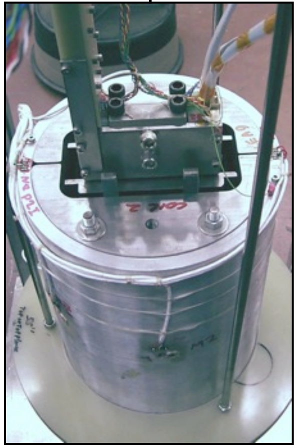
- LBNL Nb_3Sn technology base: Developed using sub-scale coils



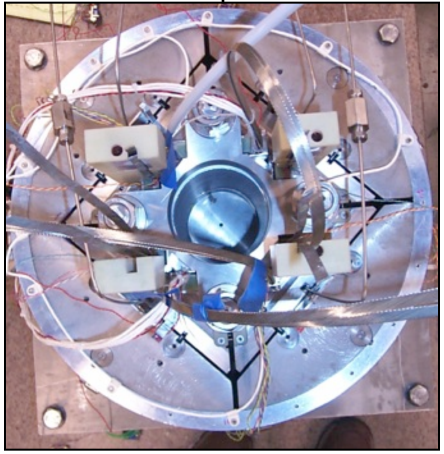
Nb_3Sn



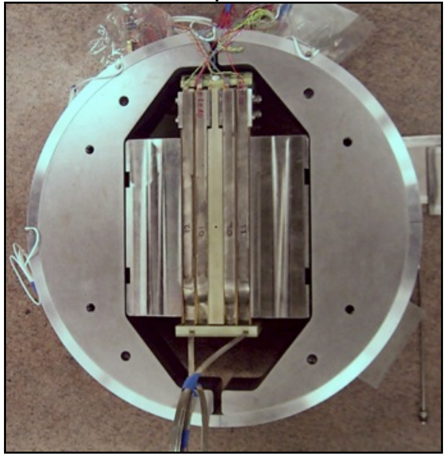
Bi-2212



SM
Low field
Low stress



SQ
High stored energy
High Axial forces



NMR
4-coil layout
High field

SD
High field
High stress

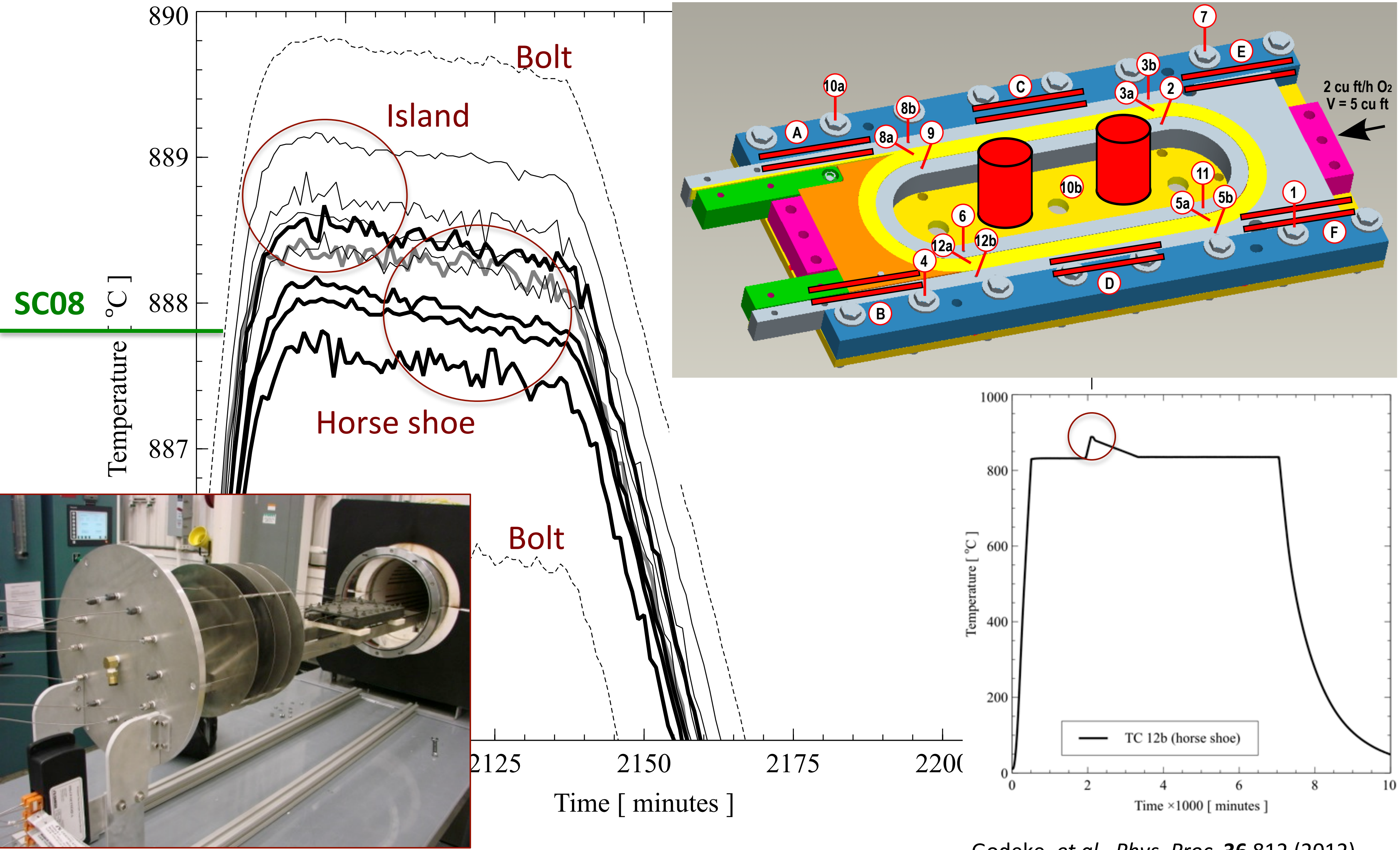
Addressing technology challenges for Bi-2212

Material	NbTi	Nb$_3$Sn	Bi-2212
Dipole Limit	10-11 T	16-18 T	Stress limited
Reaction	Ductile	~675^{0}C ± 5^{o}C in Ar/Vacuum	~890^{o}C ± 1^{o}C in O$_2$
Wire axial compression	N/A	Reversible	Irreversible?
Cable transverse stress	N/A	< 200 MPa	60 MPa?
Insulation	Polymide	S/E Glass	Ceramic
Construction	G-10, stainless...	Bronze, Ti, Stainless	~~Super alloy~~ Berkalloy!
Quench propagation	>20m/s	~20 m/s	0.1 m/s?

Godeke, *et al.*, *IEEE Trans. Appl. Supercond.* **17**, 1149 (2007)

Example: Precision reaction HTS-SC10 in 1 Bar O_2

Maximum temperature is 888.4 ± 0.8 °C (HTS-SC08 was 887.8 °C)



Godeke, *et al., Phys. Proc.* **36** 812 (2012)

Bi-2212 subscale coil overview

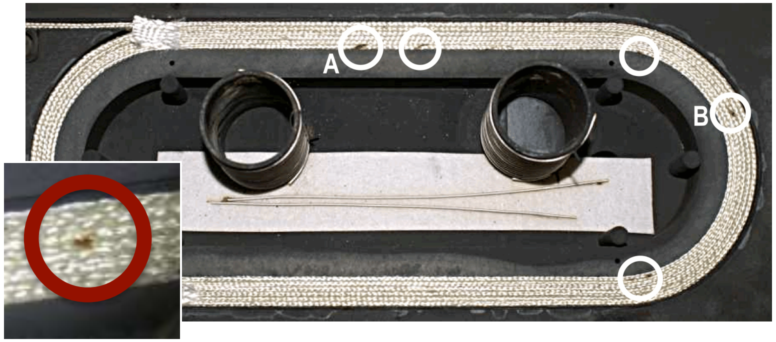
Coil ID	Conductor	Insulation	Sizing	Oxidation	Confined
🟩 HTS-SC01	Ag-dummy	SiO_2	During HT	Pre-oxidized	Full
HTS-SC02	Ag-dummy	SiO_2	During HT	Pre-oxidized	Full
HTS-SC03	SWCC Untwisted	Al_2O_3/SiO_2	During HT	Pre-oxidized	Full
HTS-SC04	OST Untwisted	Al_2O_3/SiO_2	During HT	Pre-oxidized	Low Y
HTS-SC05	SWCC Twisted	Al_2O_3/SiO_2	600°C/1hr	Pre-oxidized	Full
HTS-SC06	OST Untwisted	Al_2O_3/SiO_2	825°C/4hr	During HT	Low Y
HTS-SC07	SWCC Twisted	Al_2O_3/SiO_2	825°C/4hr	During HT	Low X&Y
🟥 HTS-SC08	OST Untwisted	Al_2O_3/SiO_2	825°C/4hr	During HT	Low Y
HTS-SC09	SWCC Twisted	Al_2O_3/SiO_2	825°C/4hr	During HT	Low X
🟩 HTS-SC10	OST Untwisted	Al_2O_3/SiO_2	825°C/4hr	During HT	Low Y
HTS-SC11	SWCC Untwisted	Al_2O_3/SiO_2	825°C/4hr	During HT	Low Y
🟩 HTS-SC12	OST Untwisted	SiO_2	During HT	During HT	Low X&Y
🟩 HTS-SC13	SWCC Untwisted	SiO_2	During HT	During HT	Low X&Y

Legend: 🟥 Technology PoP 🟩 Reacted at LBNL

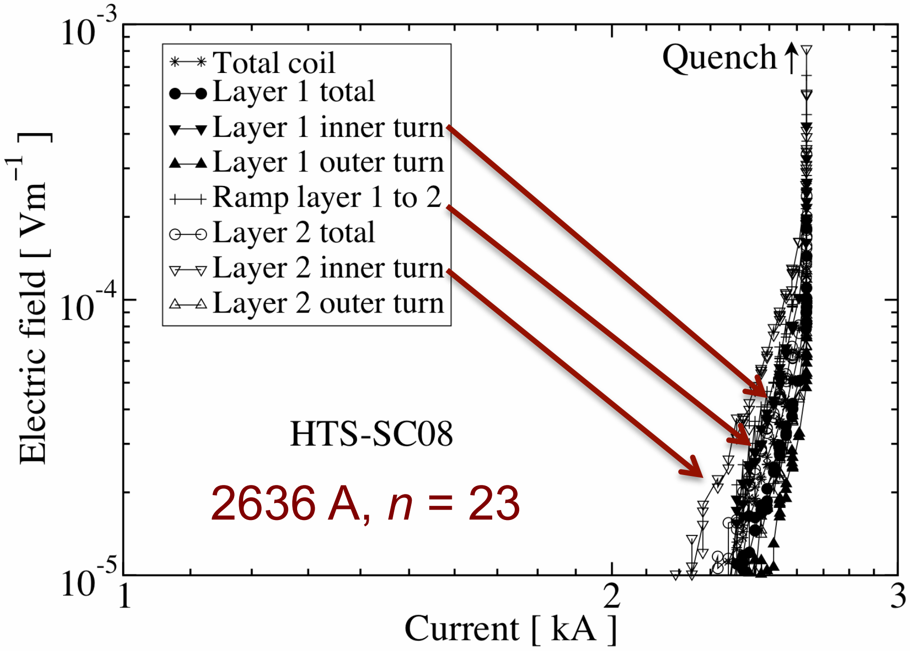
Key findings from subscale coil program

'Best of breed': HTS-SC08

- 1 bar reaction: Minor leakage (5 spots/side)



- Coil performance, 4.2 K, self-field (~1 T)



Since ~2012

Coil performance ✔ = By OP reaction

- Coil achieves 85% of *round wire* witness
  - Along the load-line
- ✔ Limited by inner turns and ramp
- HTS-SC10: 2417 A (within 10%)

W&R Bi-2212 is realistic

Godeke, *et al., Supercond. Sci. Technol.* **23** 034022 (2010)

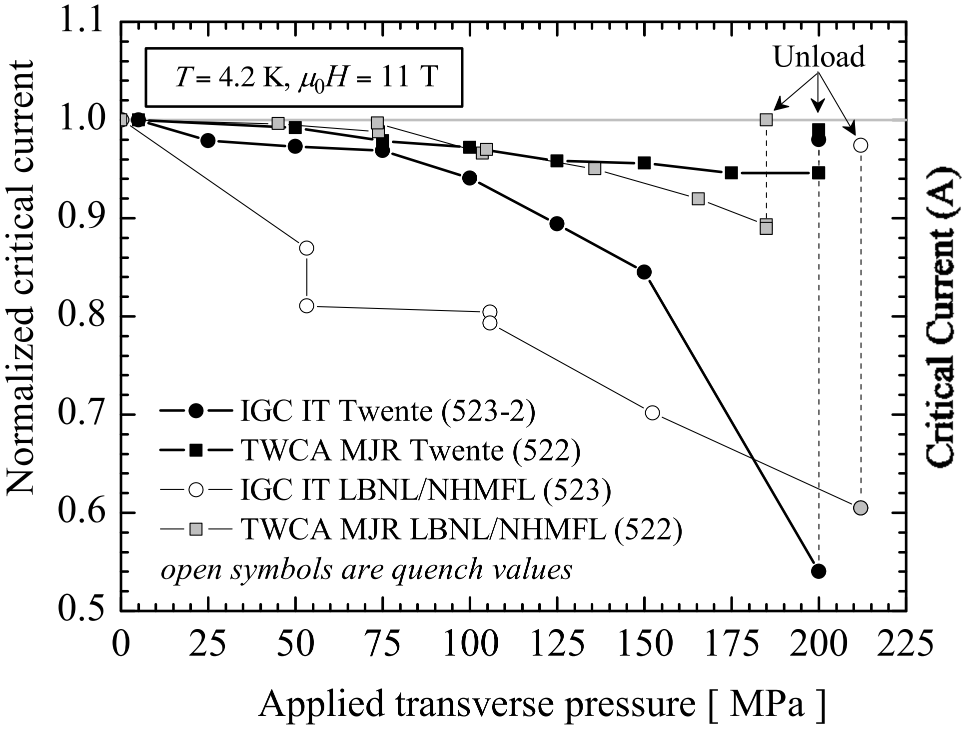
Pending issues ✔ = By OP reaction

- ✔ Increase wire J_e by factor 3 – 4
- ✔ Coil homogeneity (inner turns limit)
- ? Stress-strain sensitivity Bi-2212 **(CCT)**
- ✔ Leakage
- ✘ Further compatibility studies **(Berkalloy)**
- ✘ Quench protection(?)

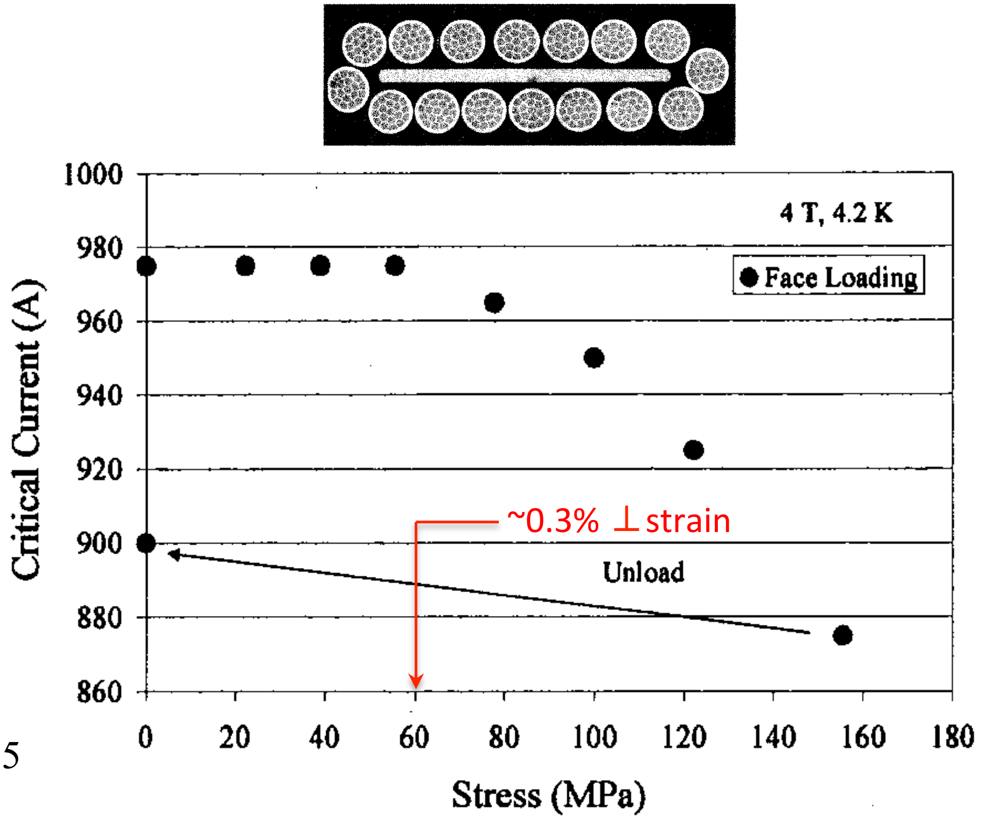
High I at small r: large H. *Caveat*: High loads

Transverse pressure on Nb_3Sn and Bi-2212 Rutherford cables

Typical behavior for Nb_3Sn Rutherford cables



Bi-2212 Rutherford cable with Ni-Cr core



Nb_3Sn can take ~200 MPa

Porous Bi-2212 cables can take ~60 MPa

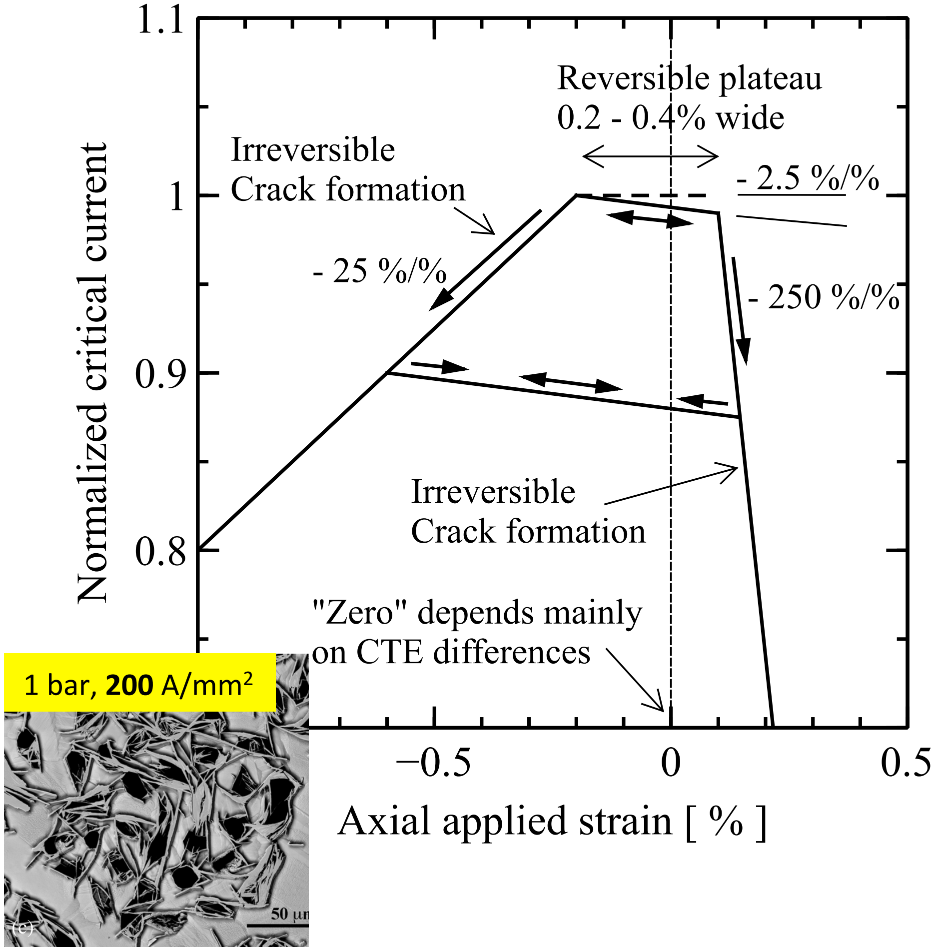
New experiment on dense cables in progress (LBNL/FSU/Twente)

Dietderich and Godeke, *Cryogenics* **48**, 331 (2008)

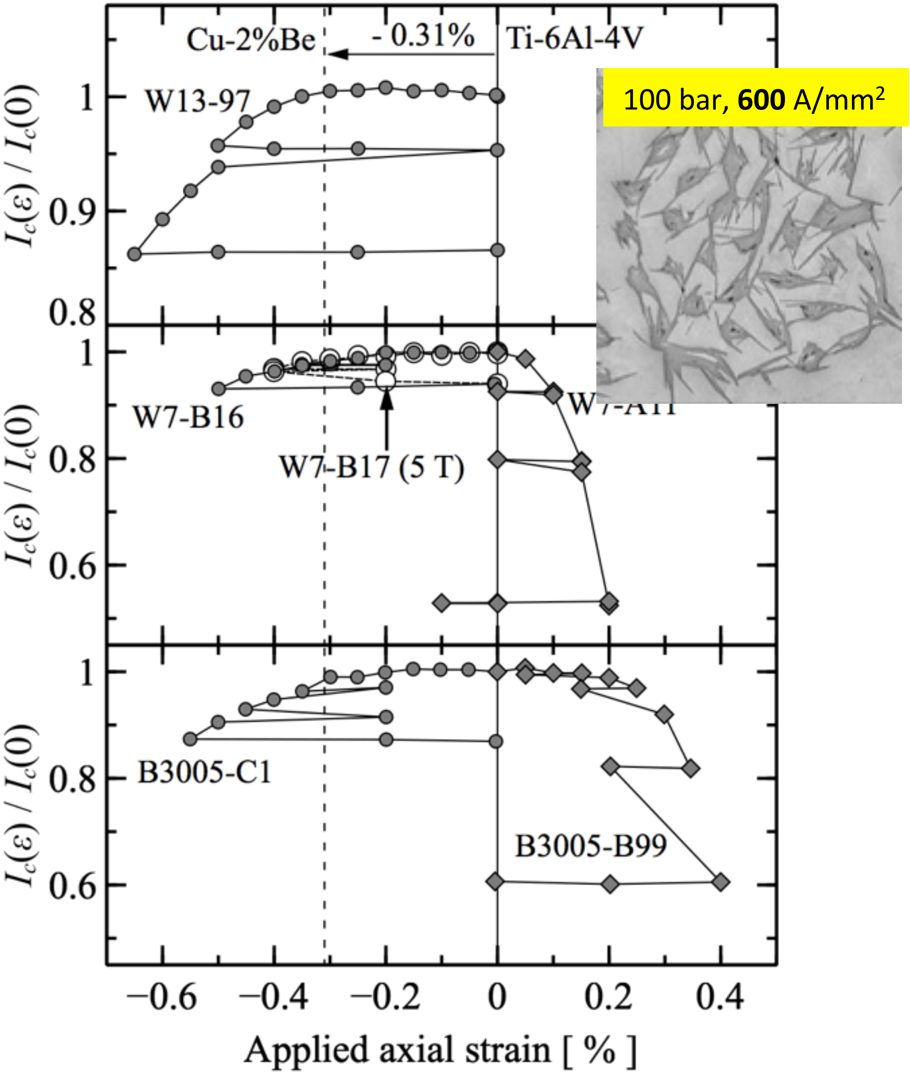
Dietderich, *et al.*, *IEEE Trans. Appl. Supercond.* **11** 3577 (2001)

Axial strain sensitivity of Bi-2212

Axial strain: 1 bar reacted porous wires



Axial strain: 100 bar reacted dense wires



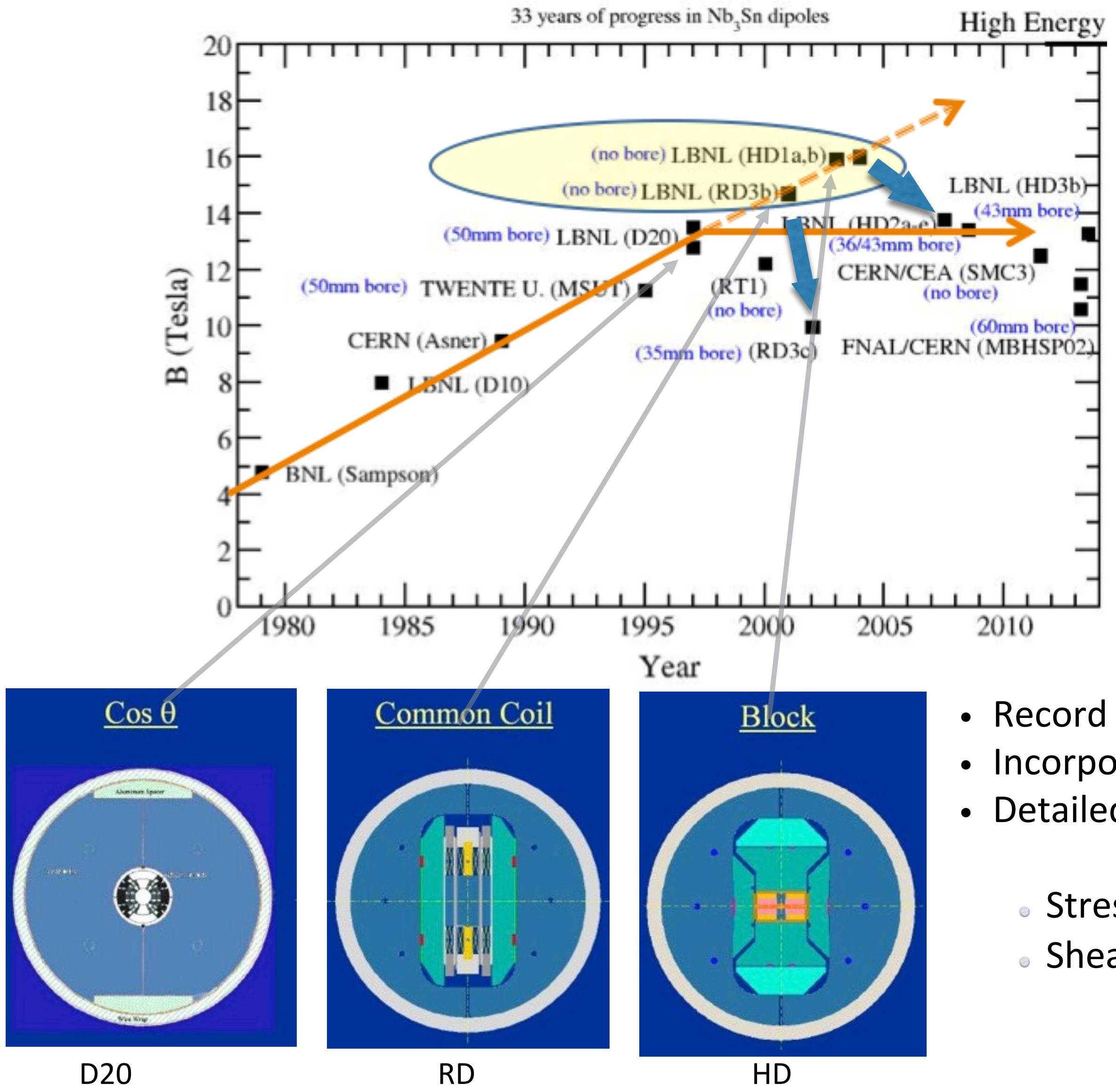
Porous and Dense wires have ~0.3% strain margin

Ten Haken, *et al., IEEE Trans. Magn.* **32** 2720 (1996)
Cheggour, *et al.*, *Supercond. Sci. Techn.* **25** 015001 (2011)

Godeke, *et al.*, to be submitted to *Appl. Phys. Lett.*

Stress/strain issues: Also apparent in Nb$_3$Sn

- Dipole magnet records in 3 configurations: Hit wall at ~14 T when a bore is present



Need a new paradigm

- For Nb$_3$Sn with bore
- To enable Bi-2212

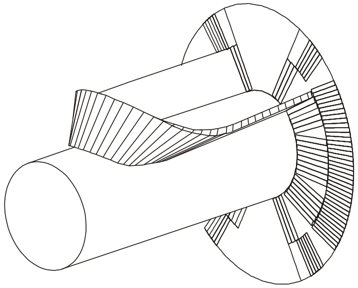
- Record dipoles >~14T in each configuration
- Incorporating bore reduces peak field attained
- Detailed investigations: Issue likely mechanical:
  - Stresses approach 200 MPa
  - Shear stresses / interface stress issues

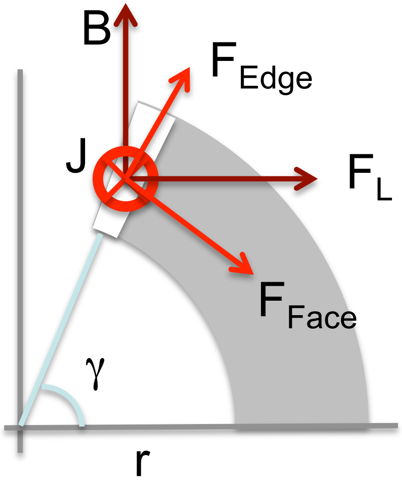
Gourlay, *et al.*, FCC meeting (2014)

Solution: Limit stresses in high field magnets

Conventional cosine theta insert

- Accumulating stresses





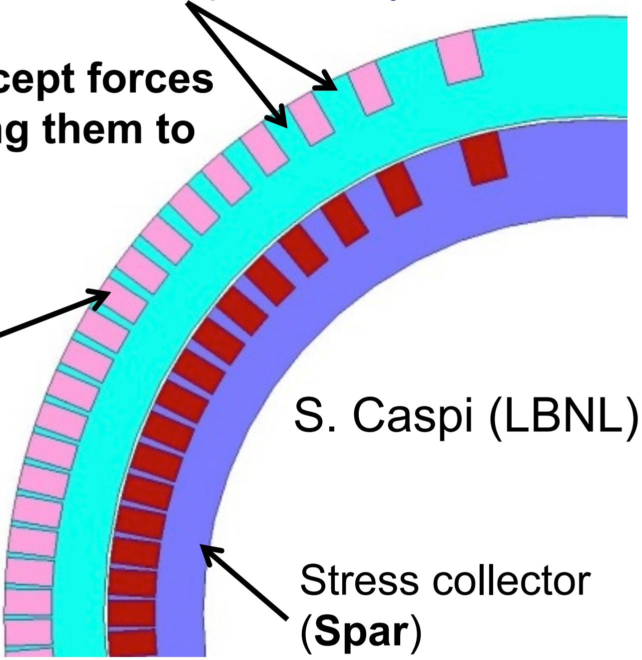
O of magnitude at 500 A/mm^2 and 20 T

- F_L = J x B = 10 GN/m^3
- γ = 75° => F_{Face} = sin γ F_L = 0.97 F_L = O F_L
- 1.5 mm wide cable
  - σ = O 10x10^9 x 1.5x10^{-3} = **15 MPa/cable**
- r = 20 mm => ~17 cables
- $\sigma_{midplane}$ = O 2/3 x 17 x 15 = **170 MPa**

Canted cosine theta (CCT) insert

- Support on cable level
- No stress accumulation => σ = O **15 MPa**

Individual turns are separated by **Ribs**

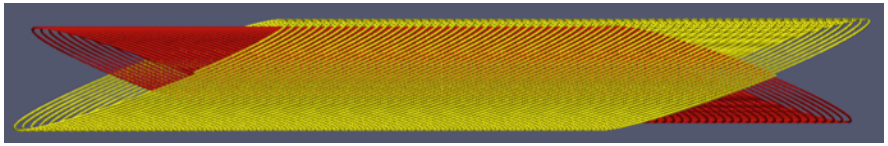


Ribs intercept forces transferring them to the spar

Individual turn

S. Caspi (LBNL)

Stress collector (**Spar**)



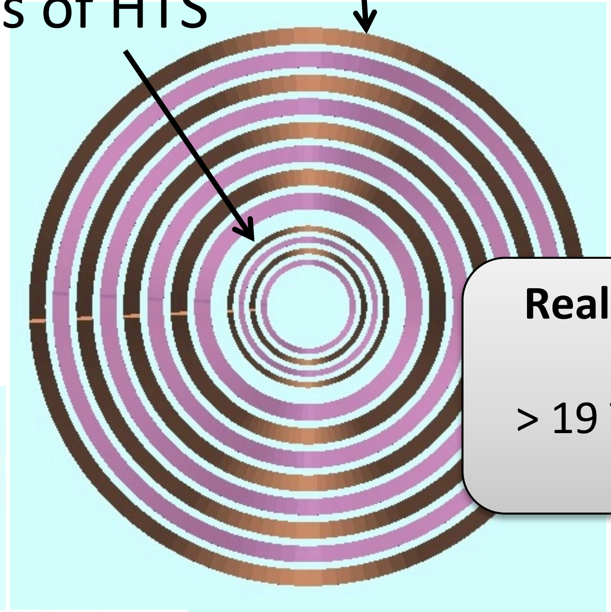
Stresses in CCT are one order smaller than in conventional designs
at the cost of 20 - 30% in $J_{winding}$ => Enabler for Bi-2212

High field CCT hybrid magnet (S. Caspi)

Un-graded coils (same size cable)

8 layers of Nb_3Sn

4 layers of HTS

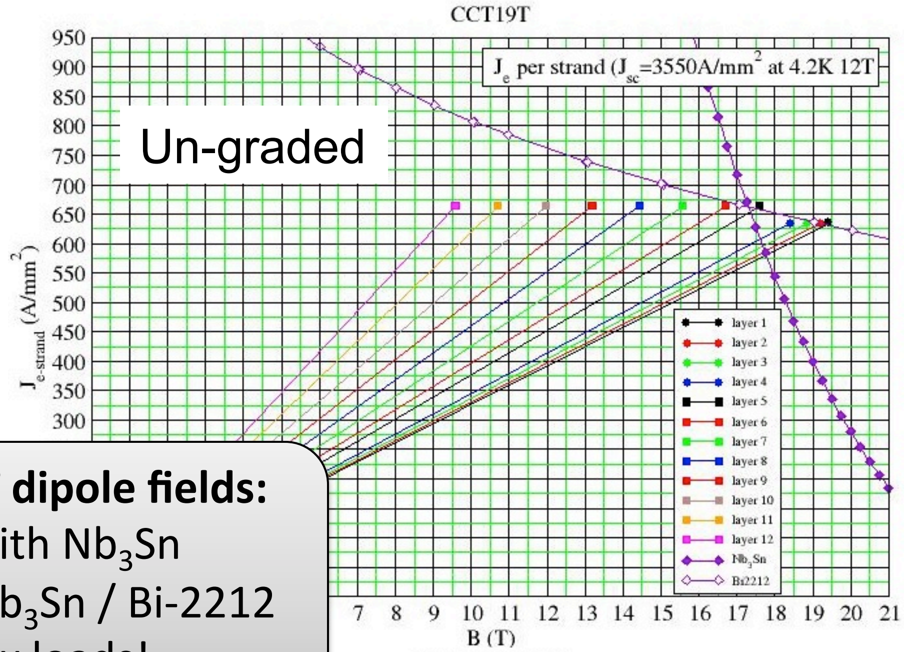


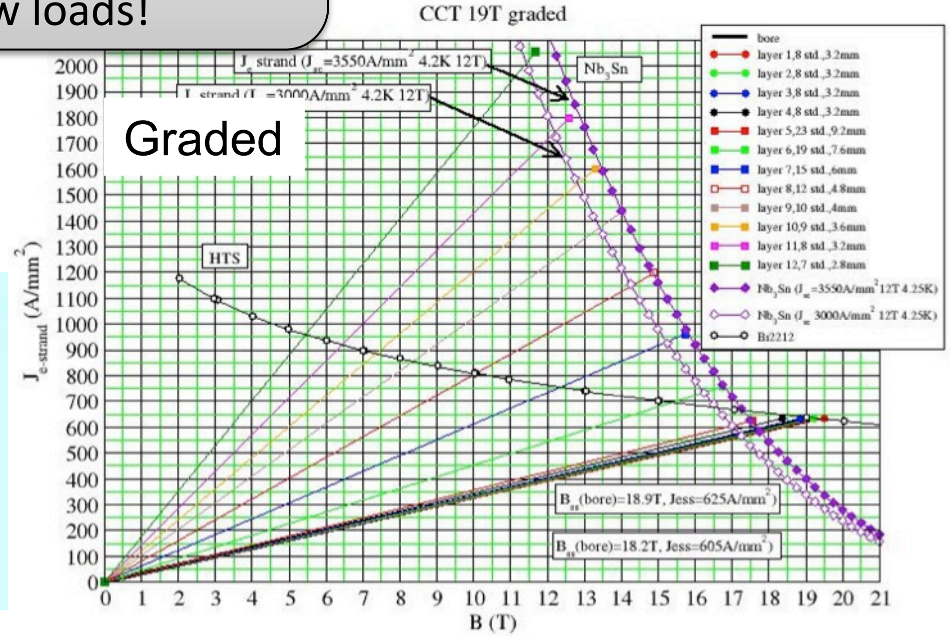
Realistic CCT dipole fields:

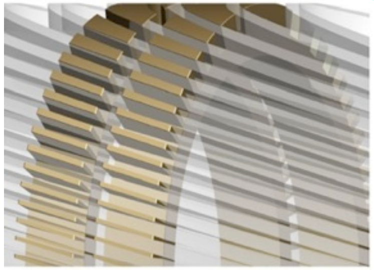
> 17 T with Nb_3Sn

> 19 T with Nb_3Sn / Bi-2212

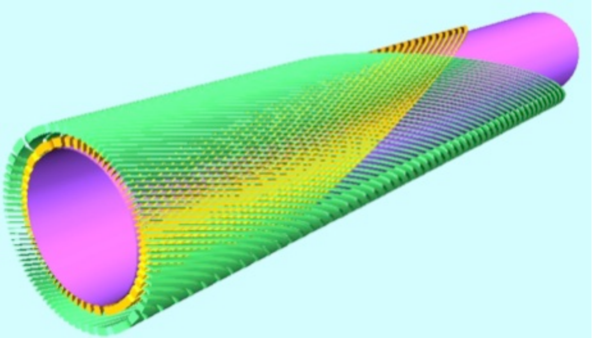
…at low loads!





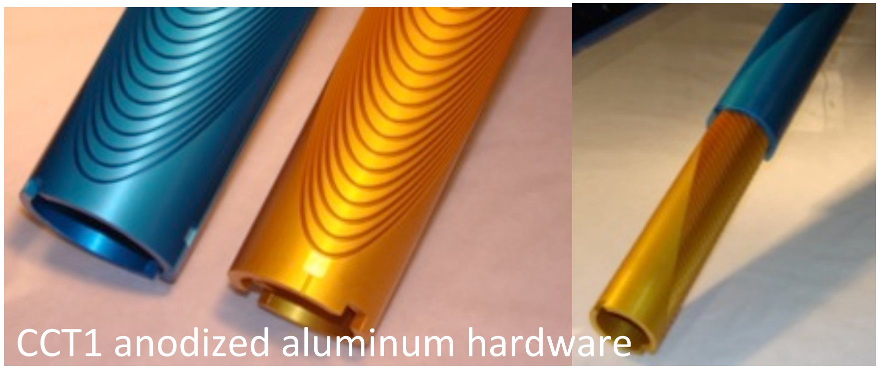


Laminations are an option



Proof-of-Principle NbTi coils and Bi-2212 inserts

CCT1: 2.6 T NbTi, 50 mm bore (Caspi)



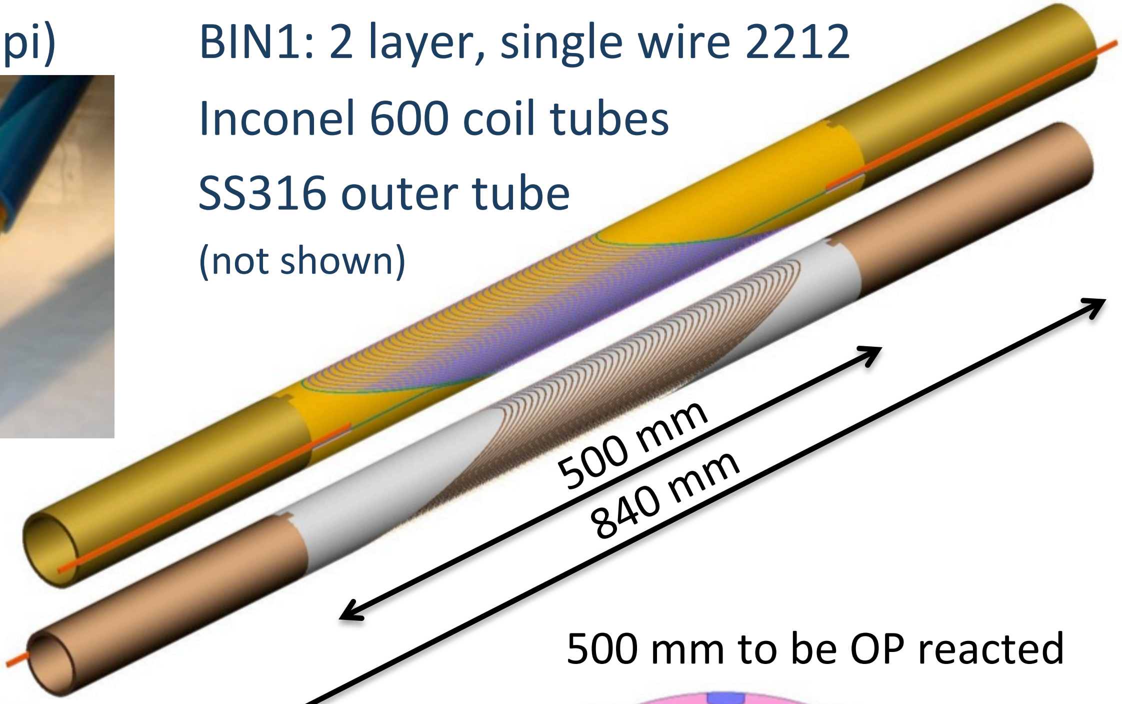
CCT1 anodized aluminum hardware

BIN1: 2 layer, single wire 2212

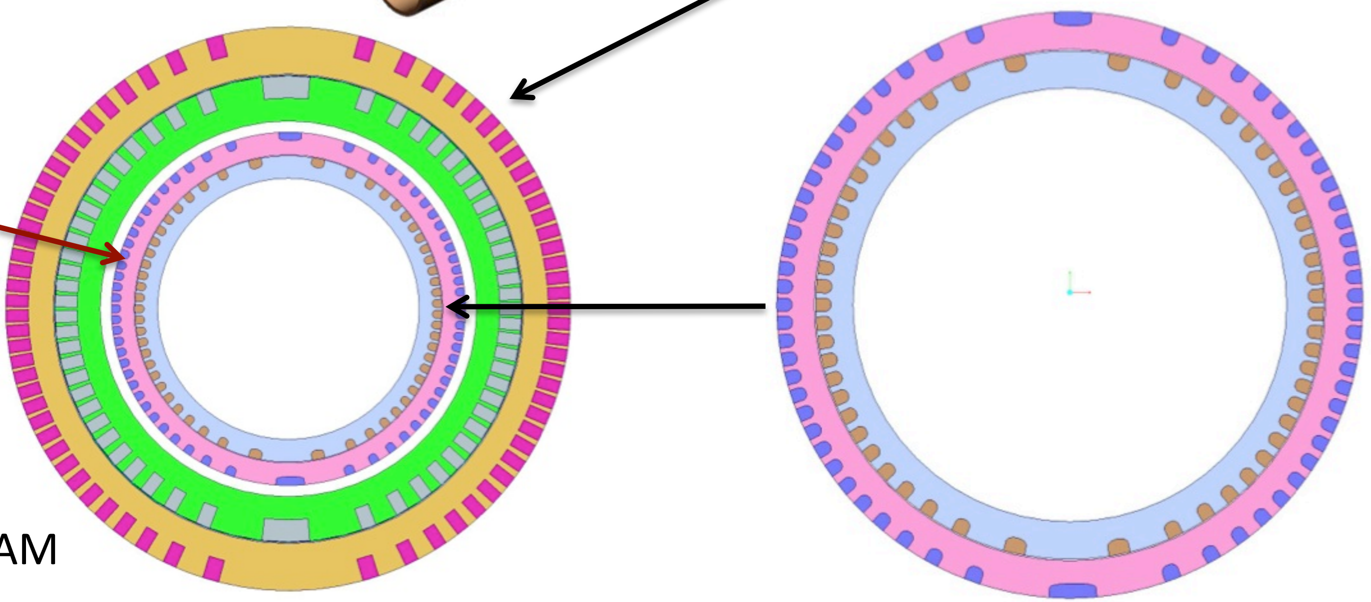
Inconel 600 coil tubes

SS316 outer tube

(not shown)



500 mm to be OP reacted



Self-supporting BIN1
inside CCT1

Quick turnaround
integrated CAD/CAM

Bi-2212 insert configurations

Towards 19 T hybrid

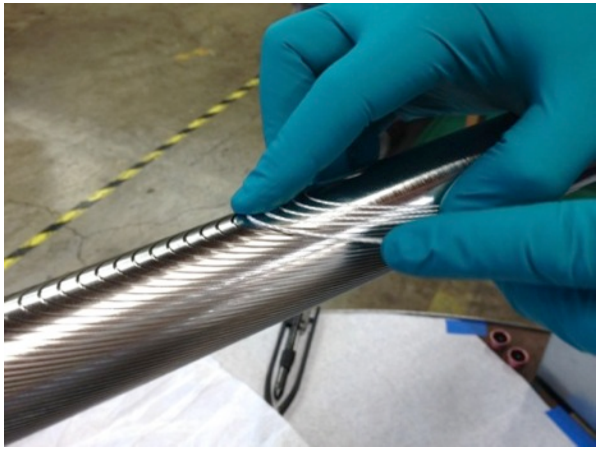
	BIN1	BIN2	BIN3
Conductor	0.8 mm wire	2.4 mm 6r1	Rutherford
Insulation*	alumina-silica braid	alumina-silica braid	TBD
Spar material*	Inconel 600	“Berkalloy”	“Berkalloy”
OD/ID [mm]	50.04 / 35.31	40 / TBD	100/ ~50
Test in	SF, CCT1	SF, CCT1, HD3/FRESCA1	Nb_3Sn CCT/FRESCA2
SS current [A] in SF	695	~4200	TBD
in 2.6 T CCT1	545	~3600	N/A
in 15 T	350	~2400	Around 10 kA
Field added [T] in SF	0.59	~1.7	TBD
in 2.6 T CCT1	0.47	~1.5	N/A
in 15 T	0.30	~1.0	> 4
σ_{cond} [MPa] in SF (from F_L)	0.5	~3	TBD
in 2.6 T CCT1	2	~6	N/A
in 15 T	7	~16	TBD

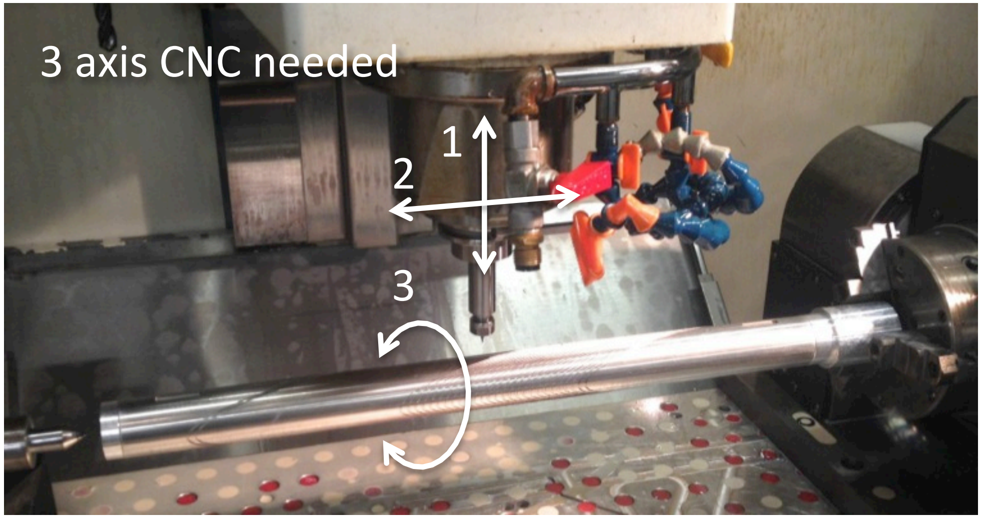
* Compatible spar materials, spar coatings, and insulations remain under investigation

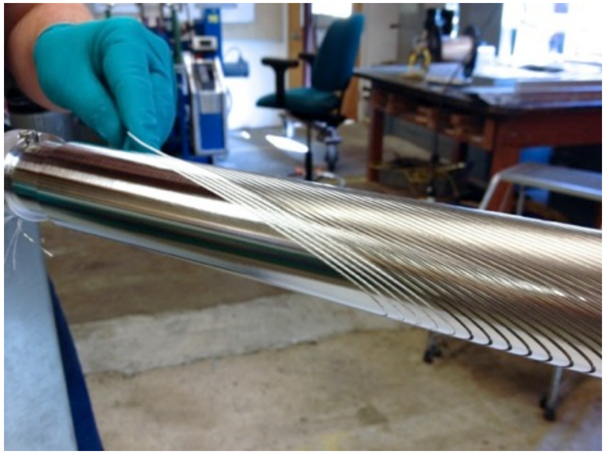
Status: BIN1 Wire wound coil set being fabricated

Inconel 600 works for square grooves (parametric CAD/CAM), but…

- Machining 22 m of 1 x 1 mm groove takes ~ 1 to 1.5 weeks
  - **~ 1 ft/hour per mm depth**
  - High aspect ratio grooves (e.g. 2 x 10 mm) not realistic
- Inconel 600 is expensive
- Inconel 600 is not "standard" material
  - Hard to get at desired dimensions
- Cr-Ag-oxides are a concern
- "Powdery" oxide surface after Bi-2212 reaction



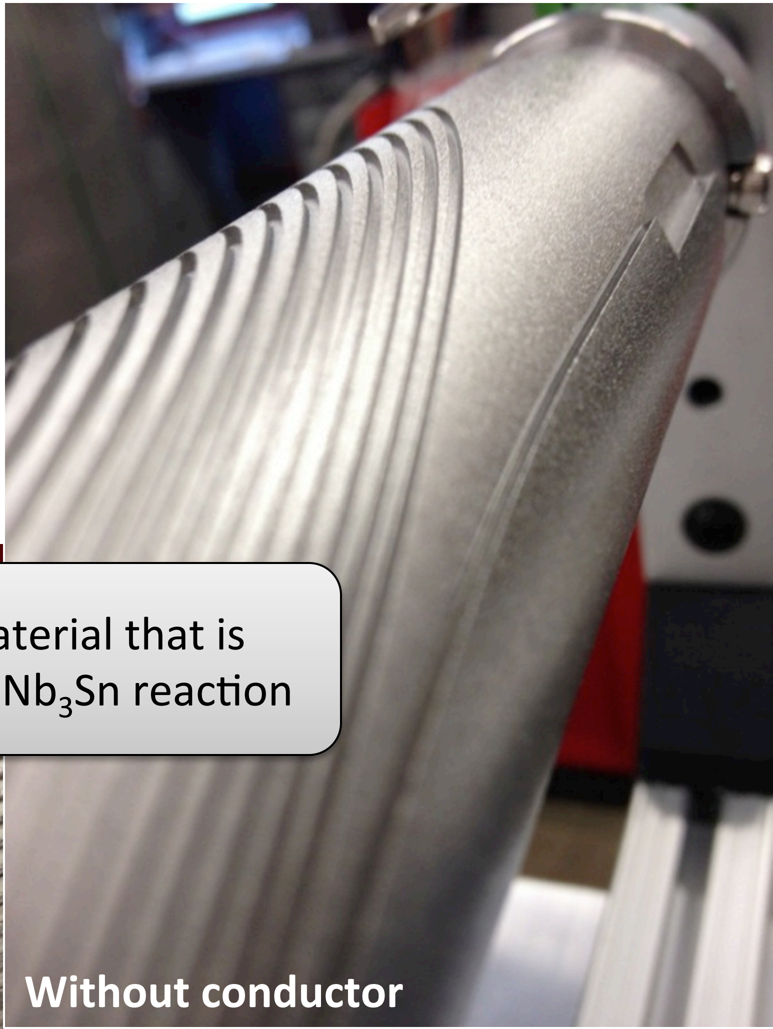

3 axis CNC needed



Bi-2212 in Inconel 600 can be done…

…but high aspect ratio grooves are desired

- To accommodate Rutherford cable
- To optimize J in windings
- Also for Nb_3Sn
  - SS316 and Ti-6Al-4V are considered…
  - …but 3D metal printing seems only option
    - Accuracy is concern



Without conductor

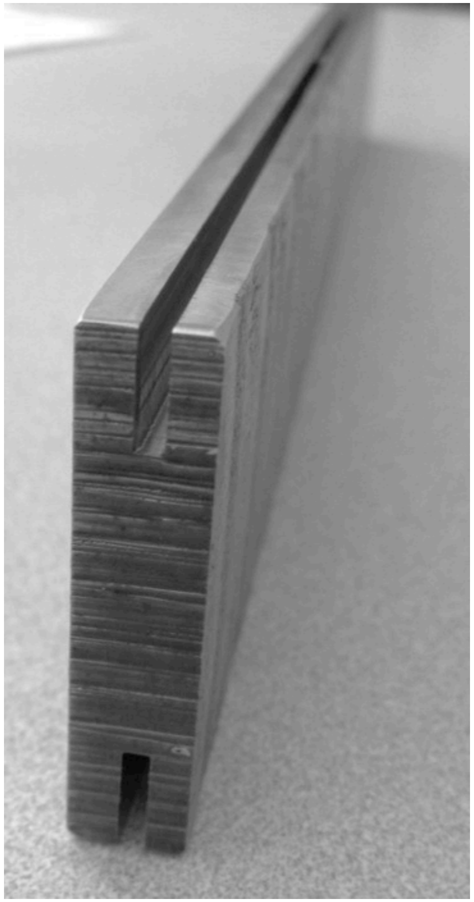
Need easier to machine material that is compatible with Bi-2212 and Nb_3Sn reaction

With conductor

Compatible material with great machinability

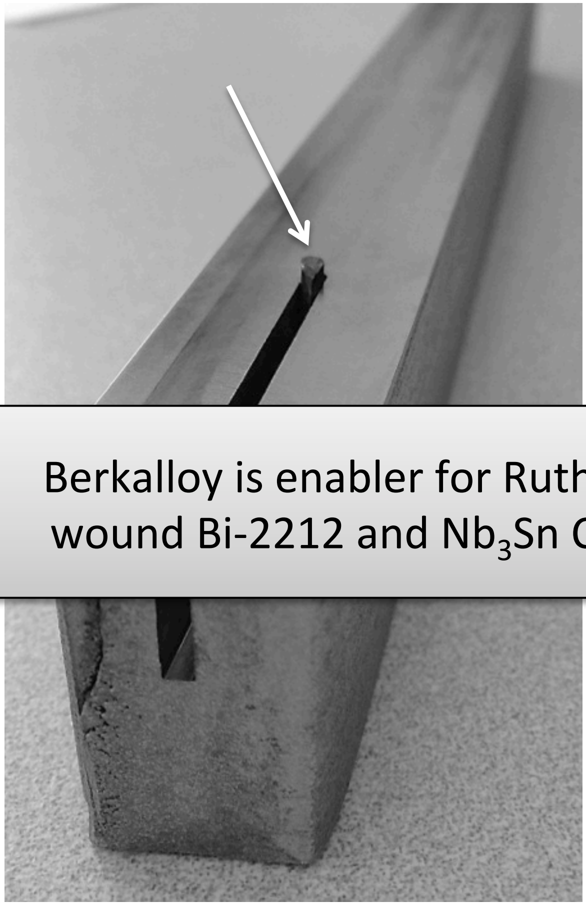
Berkalloy compatible with 900 °C in 100% O_2 (and also OK for Nb_3Sn)

Berkalloy



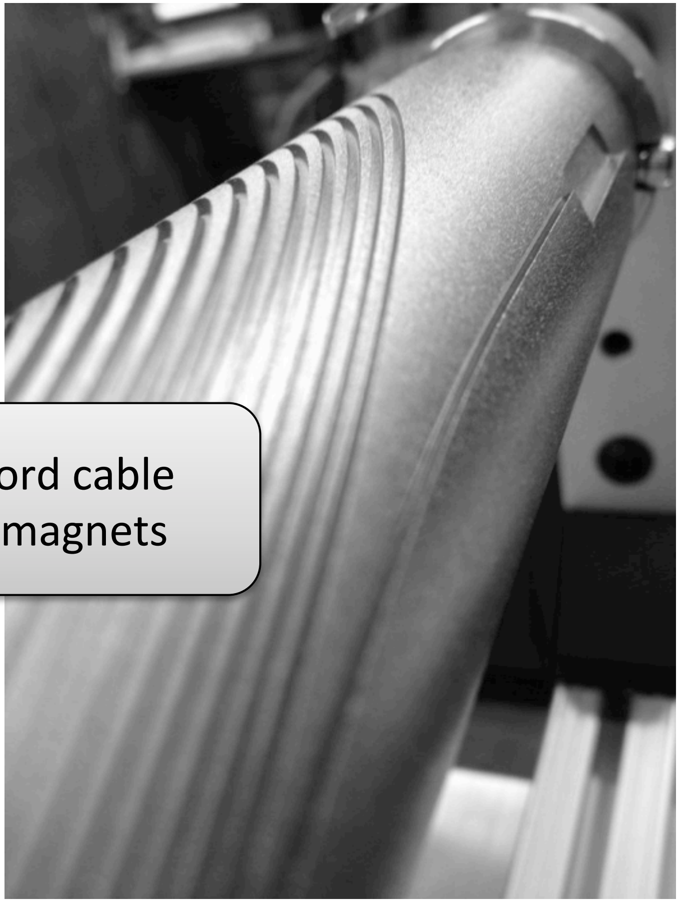
2 mm wide groove
Mill breakage at 15 in/min:
5 cuts, 1 ft/min, 10 mm depth
120 ft/h per mm depth

Stainless Steel 316



2 mm wide groove
Mill breakage at 1 in/min:
8 cuts, 0.75 in/min, 10 mm depth
4.7 ft/h per mm depth

Inconel 600



1.05 mm wide groove
1.25 mm depth

~1 ft/h per mm depth

Berkalloy is enabler for Rutherford cable wound Bi-2212 and Nb_3Sn CCT magnets

Summary

2 decades ago

- The dawn of dipole fields beyond 10 T (Twente MSUT)

1 decade ago

- Nb_3Sn dipole field halts at 16 T w/o bore (LBNL HD1), 14 T with bore (LBNL HD2/3)
  - Stress/strain wall
  - Lack of high field pinning efficiency in Nb_3Sn, Sn content exhausted

Now

- Promising developments in engineered pinning for Nb_3Sn in wires
- Densification of Bi-2212 yields required 600 A/mm^2 wire J_E
- Bi-2212 can be cabled, wound, reacted, potted: Carries 85% of round wire witness
  - 100 bar reaction of coils needs verification but appears realistic
- Canted cosine theta structure mitigates stresses
  - Enabler for > 14 T with bore and for Bi-2212 inserts
- New materials, e.g. Berkalloy, enable high aspect ratio grooves in CCT structures
  - Rapid turnaround, ease of magnet fabrication, combined magnets possible
    - No complex end-pieces, no support structure required, no pre-load required,…

We are at the dawn of a new era in very high field accelerator magnet technology!