Superconducting Materials for Undulators

M.D. Sumption

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Symposium on Novel SC Materials and Technology

Monday, Feb. 25, 2013 starting at 10:00 am at Cog Hill Country Club

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Outline

- Undulators
- Superconductors
- Undulator Needs wrt SC
- Superconducting Materials
  - NbTi, APC, Nb_3Sn, Nb_3Al, MgB_2, YBCO, Bi-2212, Oxypnictide

- Focus on APC for Undulators
- Focus on Nb_3Sn Development for Undulators

- Issues: J_c, J_e, J_w, Stability, Insulation
- Summary

Undulators

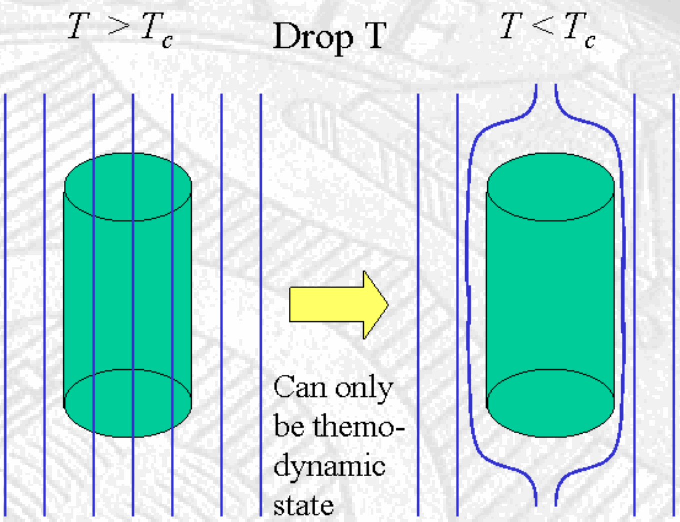
- Magnet structures which cause electrons to have undulatory paths, generating radiation, and can be of various type (helical, planar)
- Made with permanent magnets, or electrical conductors
- In the latter case, field, and performance, dictated by current density
- Normal conductors can be used, but superconductors achieve the highest current density in the windings, and thus can lead to undulators with high fields, and thus high performance
- To first order then – its about current and current density in the wire!

- What, then, are superconductors?
- What are their flavors?
- What do Undulators require of them, and how do they measure up?

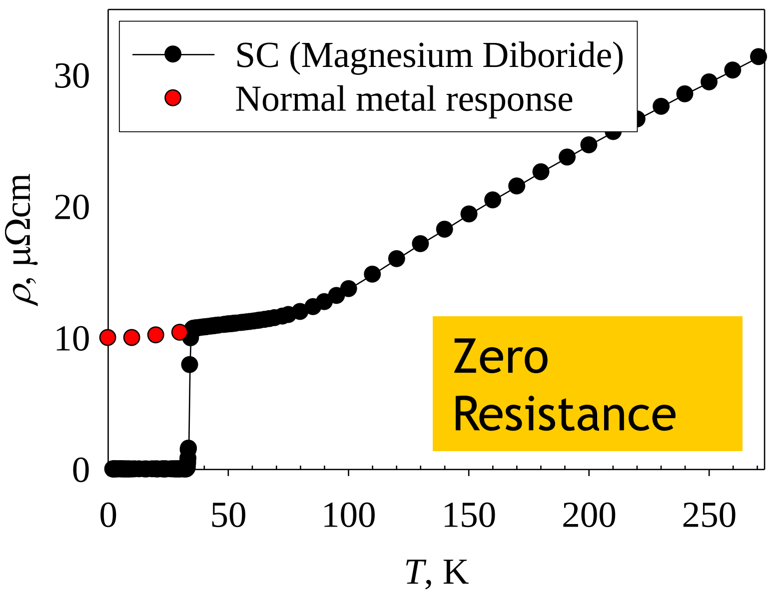
(1) Superconductor Properties

Superconductivity begins with a small attractive interaction term between electrons (sometimes E-P)

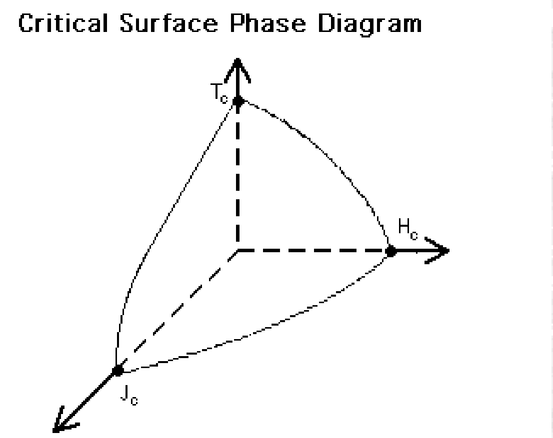
This leads to Cooper pairing of electrons, a collective state, and an "energy gap"



Magnetic Flux exclusion; full or partial (vortices)

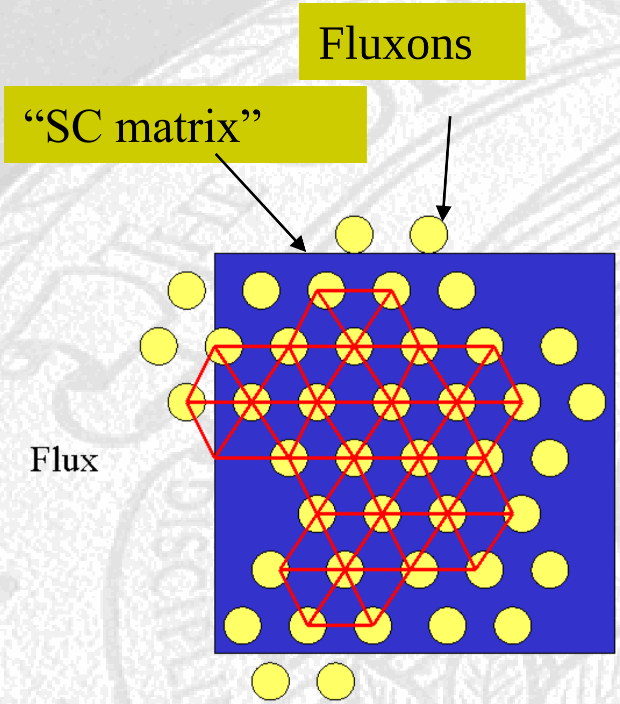


Zero Resistance

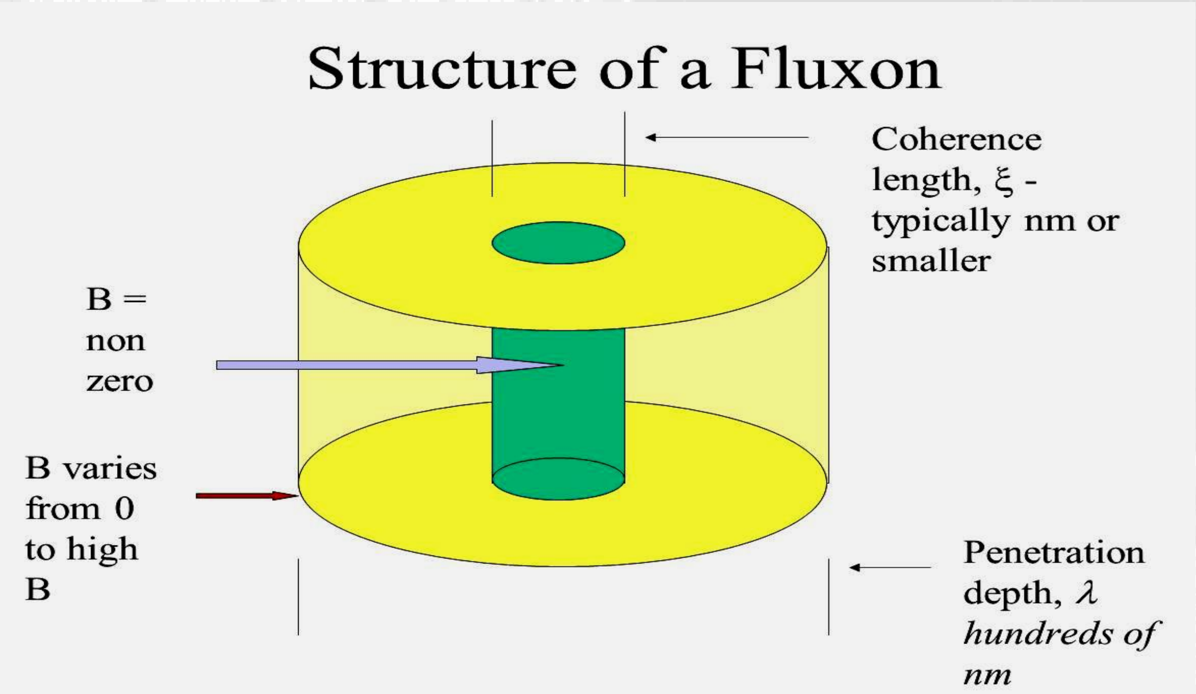


Superconducting properties below a critical
Temperature (T)
Field (B)
Current density (J)
surface

(2) Quantized Flux Vortices, and two length scales



If *B* is present, it is as quantized vortices in a triangular array



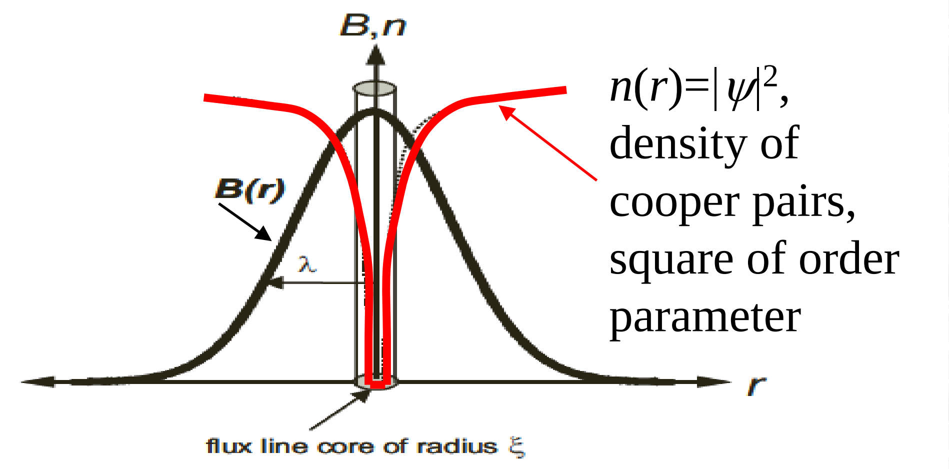
Structure of a Fluxon

Coherence length, ξ - typically nm or smaller

B = non zero

B varies from 0 to high B

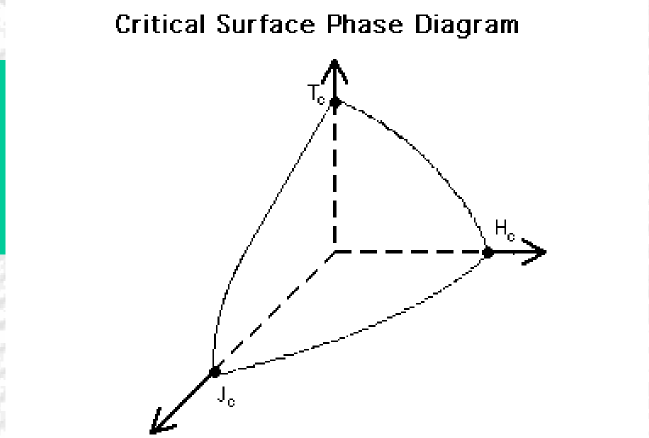
Penetration depth, λ *hundreds of nm*



$n(r)=|\psi|^2$, density of cooper pairs, square of order parameter

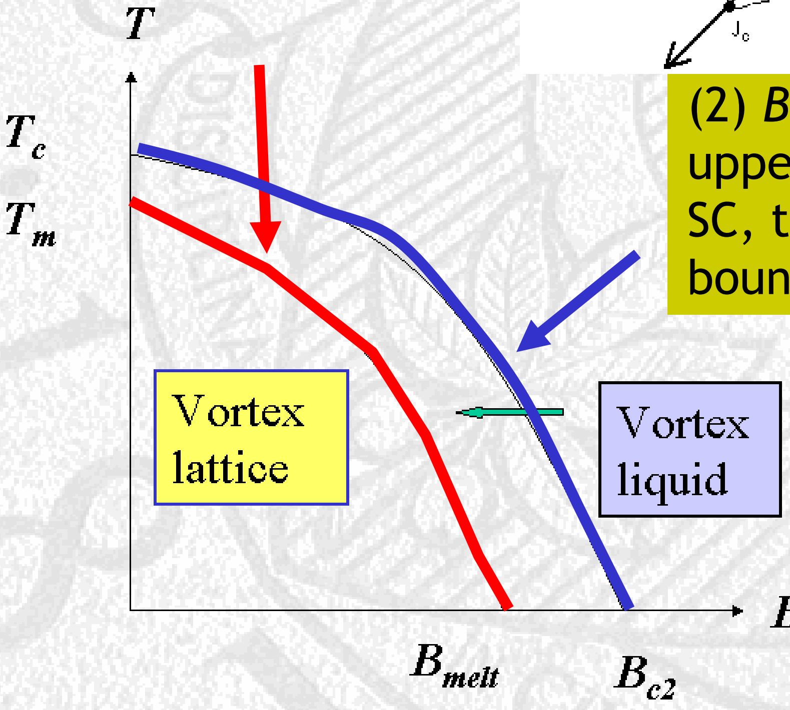
(3) Magnetic Phase Diagram of Superconductors and Concept of Pinning

(1) Tc is the limiting temperature of operation

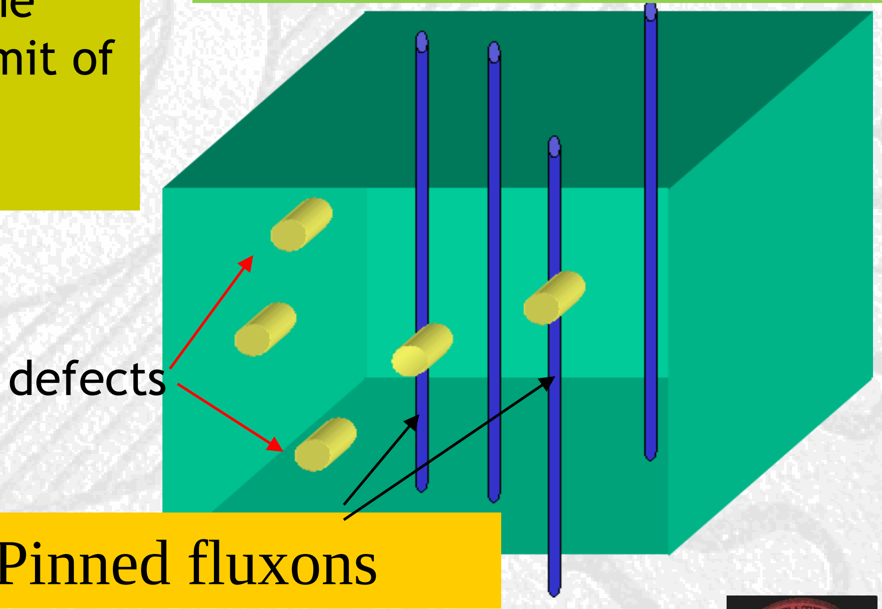

Critical Surface Phase Diagram

(3) Defects are needed to pin the fluxons that enter the SC to maintain SC

The third critical parameter is limiting current density - which is where we will focus



(2) B_{c2}(T) is the upper field limit of SC, the SC boundary line



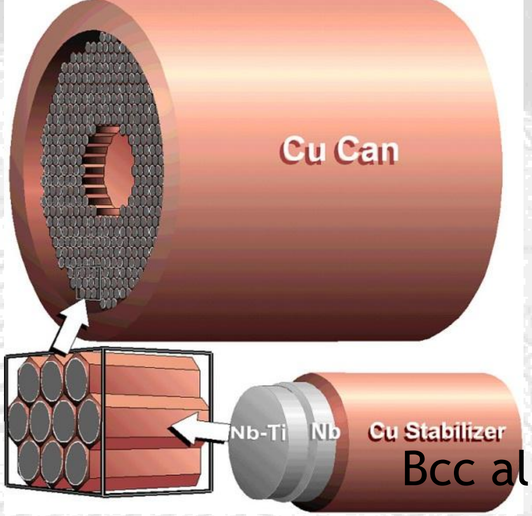
Pinned fluxons

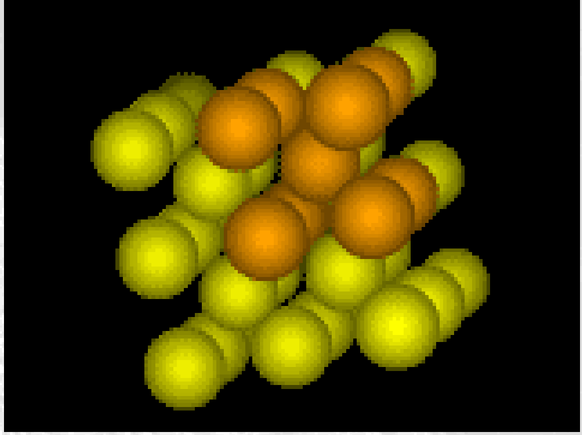
Practical SC Materials

- Solid Solution Alloy: **NbTi (9 K, Bc2 13.5 T)**
- Intermetallic compound: **Nb_3Sn (18 K, 25 T)**
- **BiSrCaCuO - 2212 and 2223** [High T_c (110 K), **layered**, high Bc2, moderate fab difficulty]
- **YBaCaCuO - 123** [High T_c (90K), **less layered**, difficult to process]
- **MgB_2** [inexpensive, easy, 39 K T_c]

Example SC --NbTi

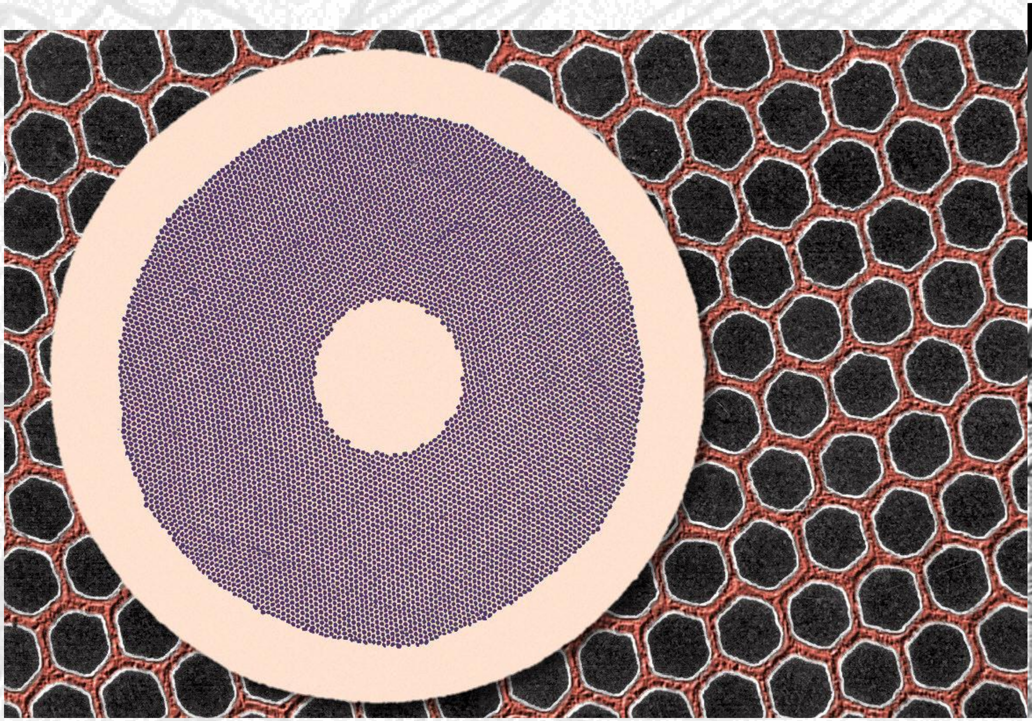
Filaments are about 5 microns, wire is about 0.8 mm OD

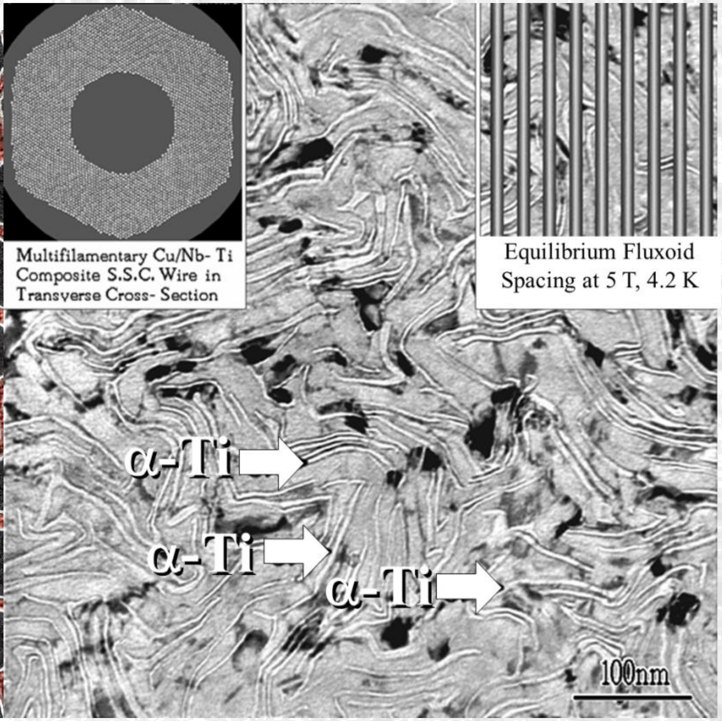




Bcc alloy

Inside a filament





What do Undulators require of Superconductors

- Of course, the undulators must be operated below the T_c of the SC
- Mostly, however, they require a high level of current density of the SC, in order to reach the high performance undulators required
- Let us look at an example helical and an example planar undulator

Helical Undulator – ILC-like

Majoros

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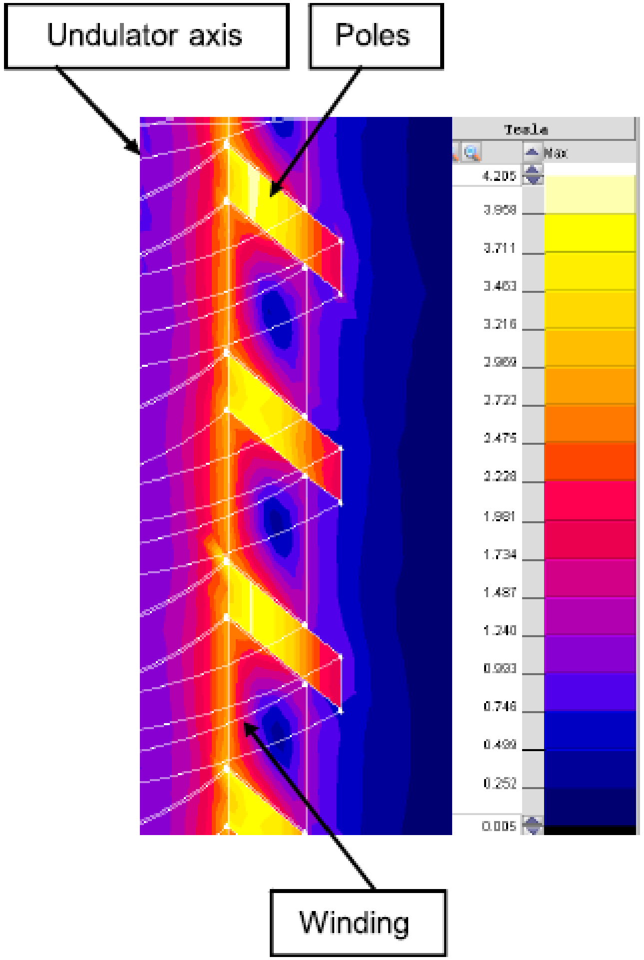
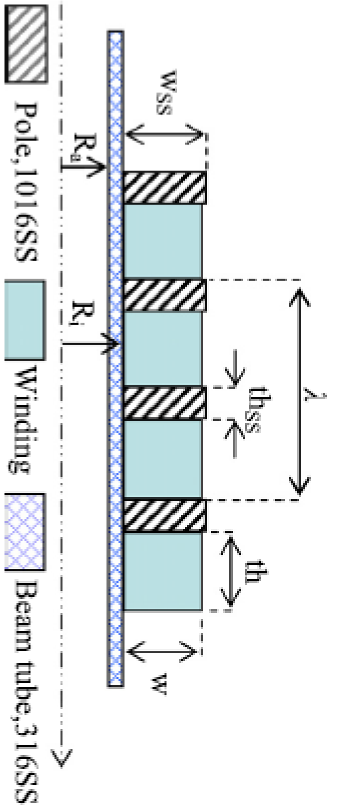
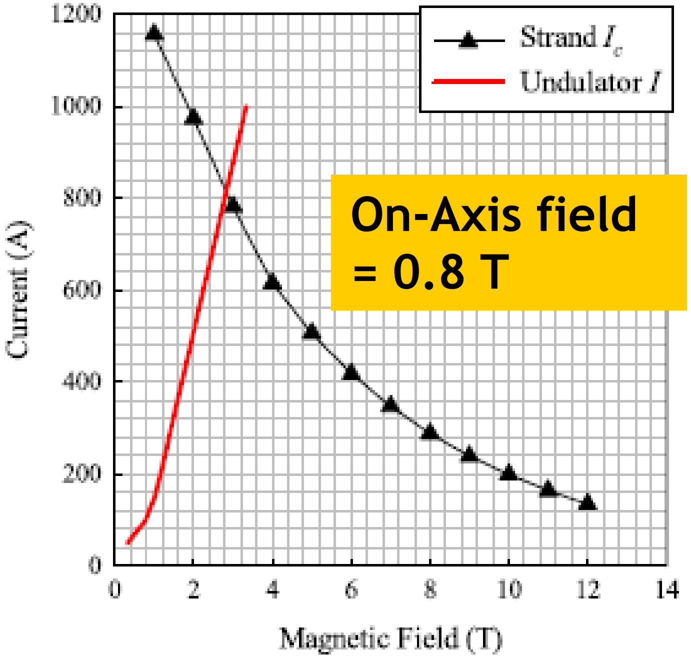


λ (mm)	14
R_a (mm)	3.5
R_i (mm)	4
th (mm)	5
th_{SS} (mm)	2
w (mm)	3.57
w_{SS} (mm)	5.53





On-Axis field = 0.8 T

Figure 4. Load line of the undulator and a short sample $I_c(B)$ curve of the strand (▲). Estimated critical current of the undulator = 815 A.

Table 1. Nb_3Sn strand specifications.

Outside diameter (mm)	0.5
Number of filaments	217
Filament diameter (μm)	24
Effective diameter (μm)	35
SC fraction (%)	45.6
12 T $J_{c,\text{non-Cu}}$ (A mm^{-2})	2200
4 T $J_{c,\text{non-Cu}}$ (A mm^{-2})	7650
4 T J_e (A mm^{-2})	3825
4 T I_c (A) for 0.5 mm outside diameter	622.22

Definitions

- $J_{c,layer}$ = I/Area of superconducting material
- $J_{non\text{-}Cu}$ = I/area which is not stabilizer
- J_e = I/area of strand
- J_w = I/area of winding

Pushing for higher freq. in ILC-like Helical Undulators

- Pushing to 11 -12 mm requires 1 T
- Pushing to 10 mm requires 1.07 T

(Assuming *K* = 1)

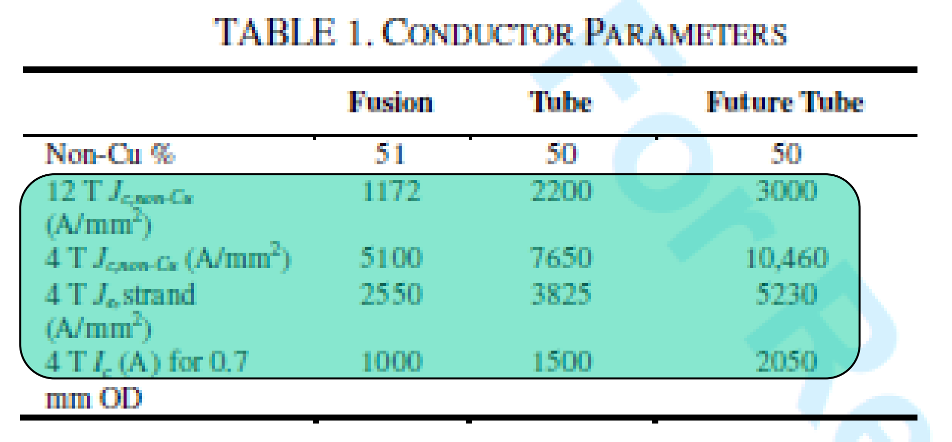


TABLE 1. CONDUCTOR PARAMETERS

	Fusion	Tube	Future Tube
Non-Cu %	51	50	50
12 T $J_{c,non\text{-}Cu}$ (A/mm^2)	1172	2200	3000
4 T $J_{c,non\text{-}Cu}$ (A/mm^2)	5100	7650	10,460
4 T J_e, strand (A/mm^2)	2550	3825	5230
4 T I_c (A) for 0.7 mm OD	1000	1500	2050

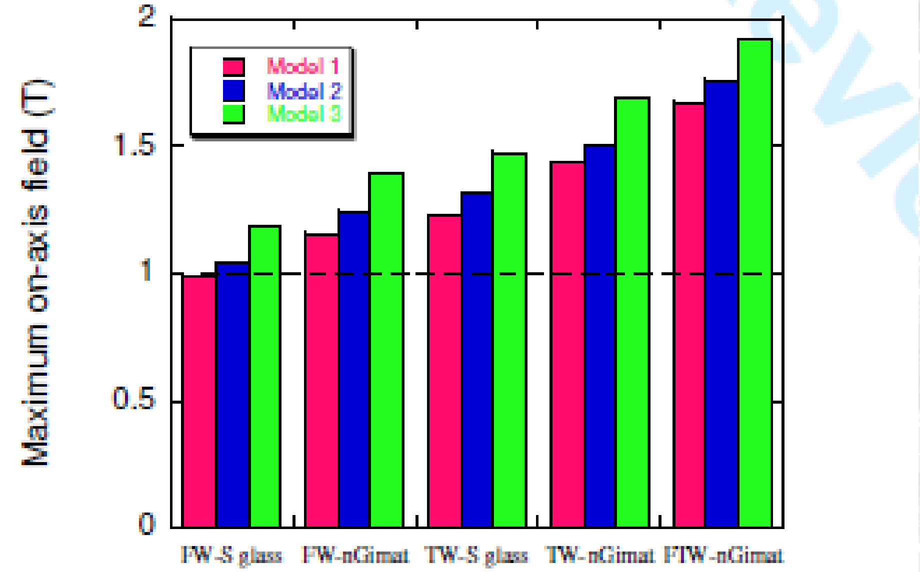


Fig. 9. Maximum on-axis magnetic field of the model undulators wound of different Nb_3Sn strands with different insulations. Straight horizontal dashed line indicates the 1 T requirement.

Majoros M *et al* 2010 *IEEE Trans. Appl. Supercond.* 20 270

Needs for Planar Undulators

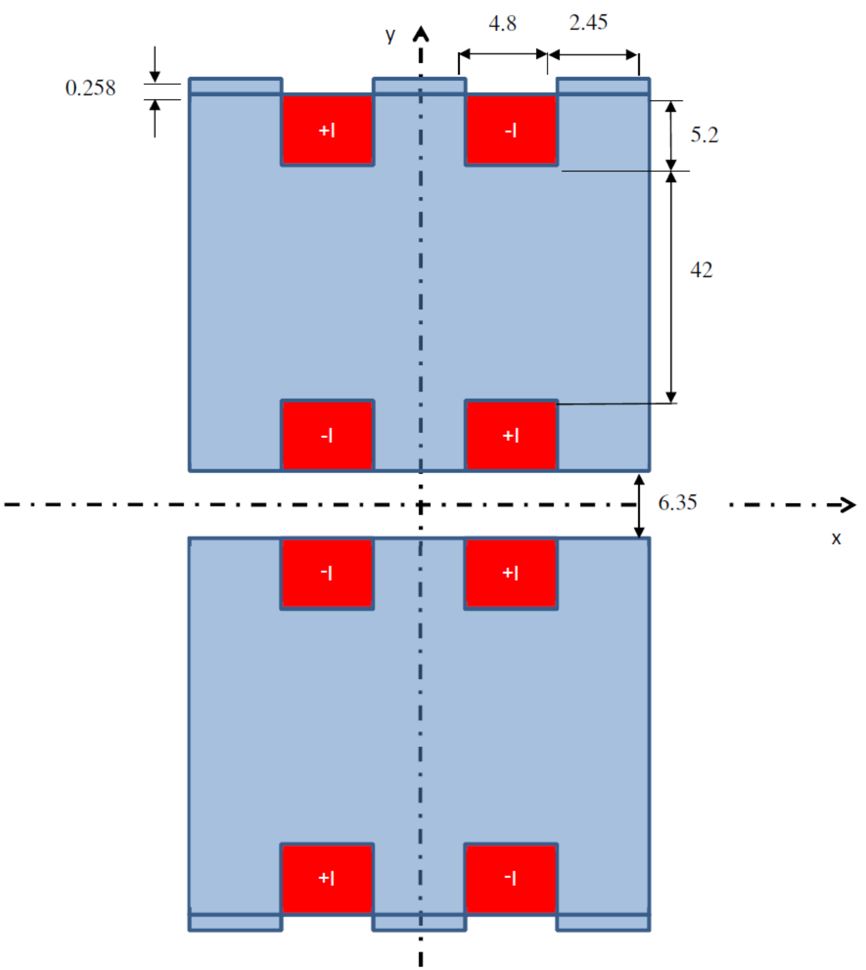
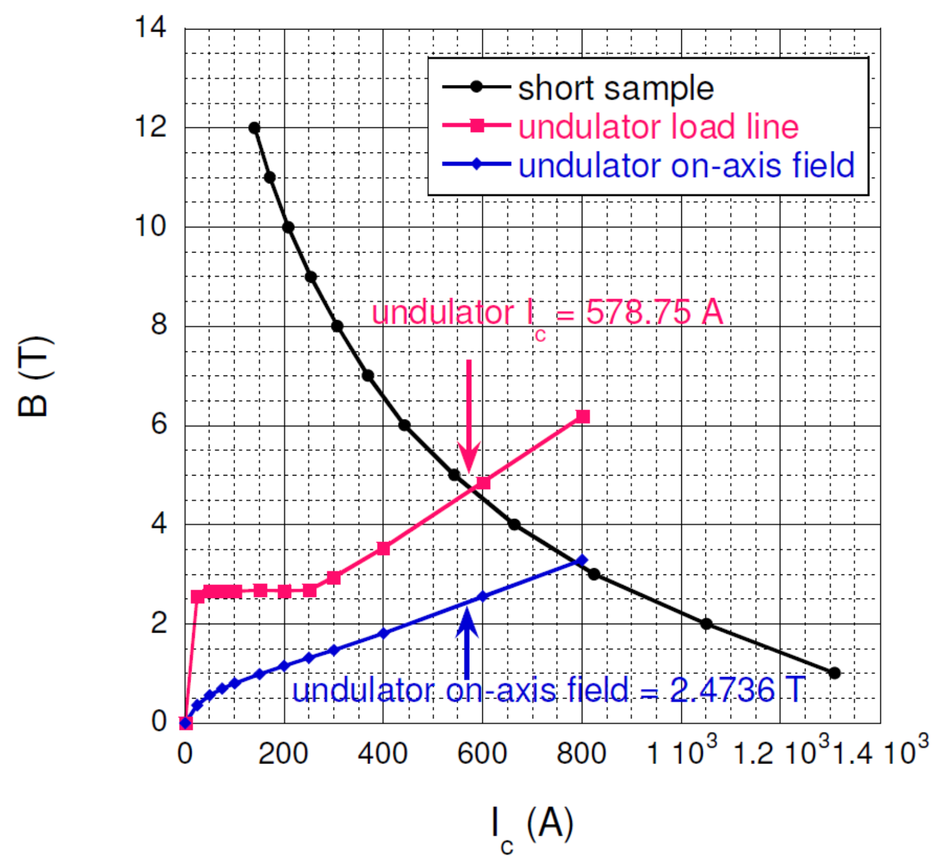


Fig. 3: Undulator cross-section (units: mm), period = 14.5 mm.



Conductor: Nb_3Sn tube-type 192 filament strand, 0.5 mm OD (not insulated), 0.65 mm OD (insulated)

Winding cross-section:, winding size 4.8 mm x 5.458 mm, 9 layers, number of turns = 60

J_e=2950 A/mm^2, 4.7 T

Translation to J_c

- For both Planar and helical, want something like
- J_e = 3800 A/mm^2 4 T
- J_e = 3000 A/mm^2 4.7 T

For Nb_3Sn, Ranging from 2550-5320 A/mm^2 4 T

But Assumed fill factor of SC in Nb_3Sn strand is 50% (can range 45-50%). Fill factor (λ) can vary for different SC)

So for targets, take J_e = 4000 A/mm^2 at 4 T →

For Nb_3Sn (λ=50%), J_c = 8000 A/mm^2

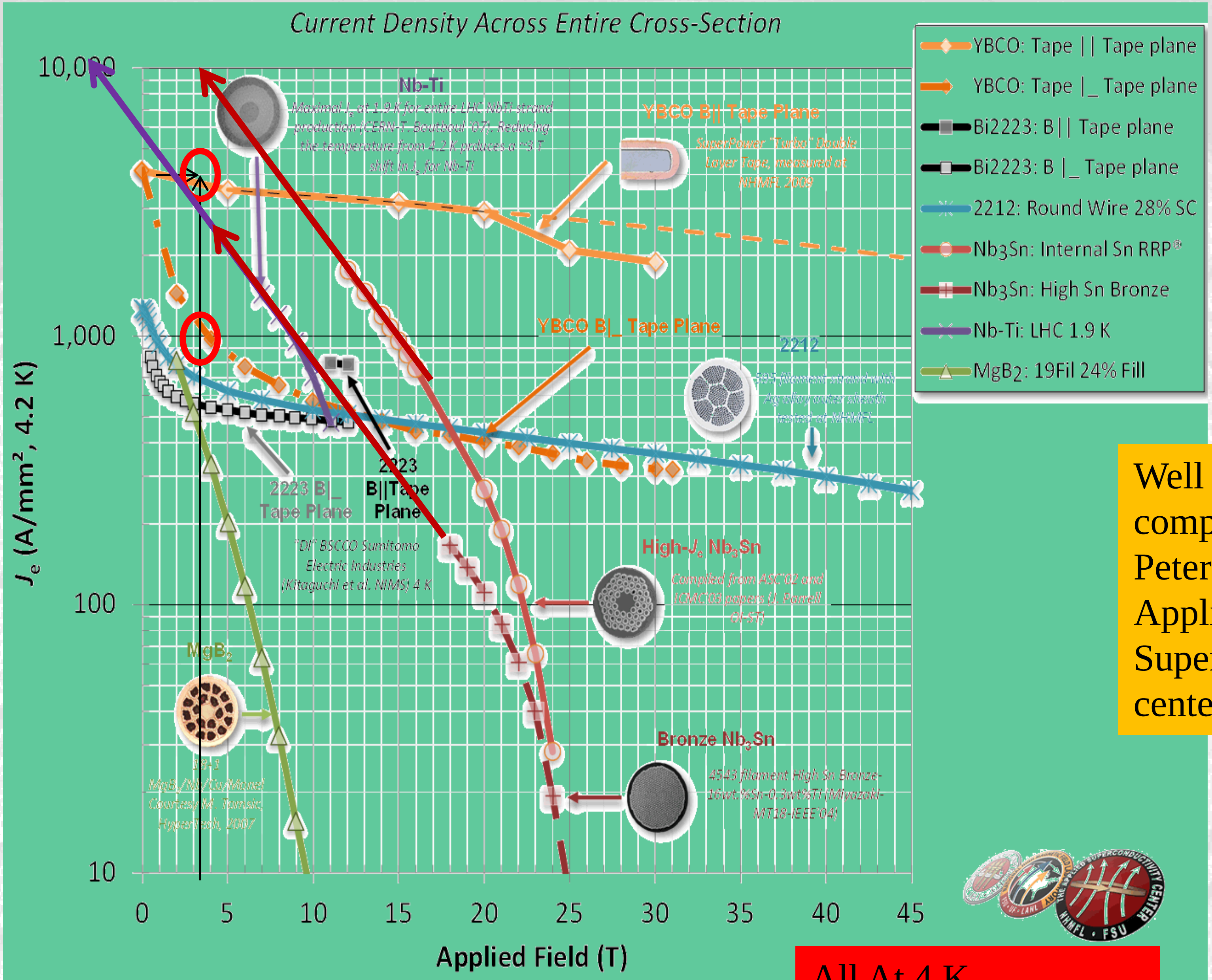
For NbTi (λ=65%), J_c = 6153 A/mm^2

For APC (assuming λ =30%), J_c = 13,333 A/mm^2

For Bi-based (λ= 25%), J_c= 16,000 A/mm^2

MgB_2-25% (λ=25%), J_c = 16,000 A/mm^2

YBCO (taking λ = 1-2%), J_c = 400,000-200,000 A/mm^2 = 20-40 MA/cm^2



→ YBCO EO

→ YBCO FO

→ NbTi

→ Nb_3Sn

~~Bi-2212~~

~~Bi-2223~~

Well known compilation from Peter Lee, FSU, Applied Superconductivity center

MgB2 seems too low here

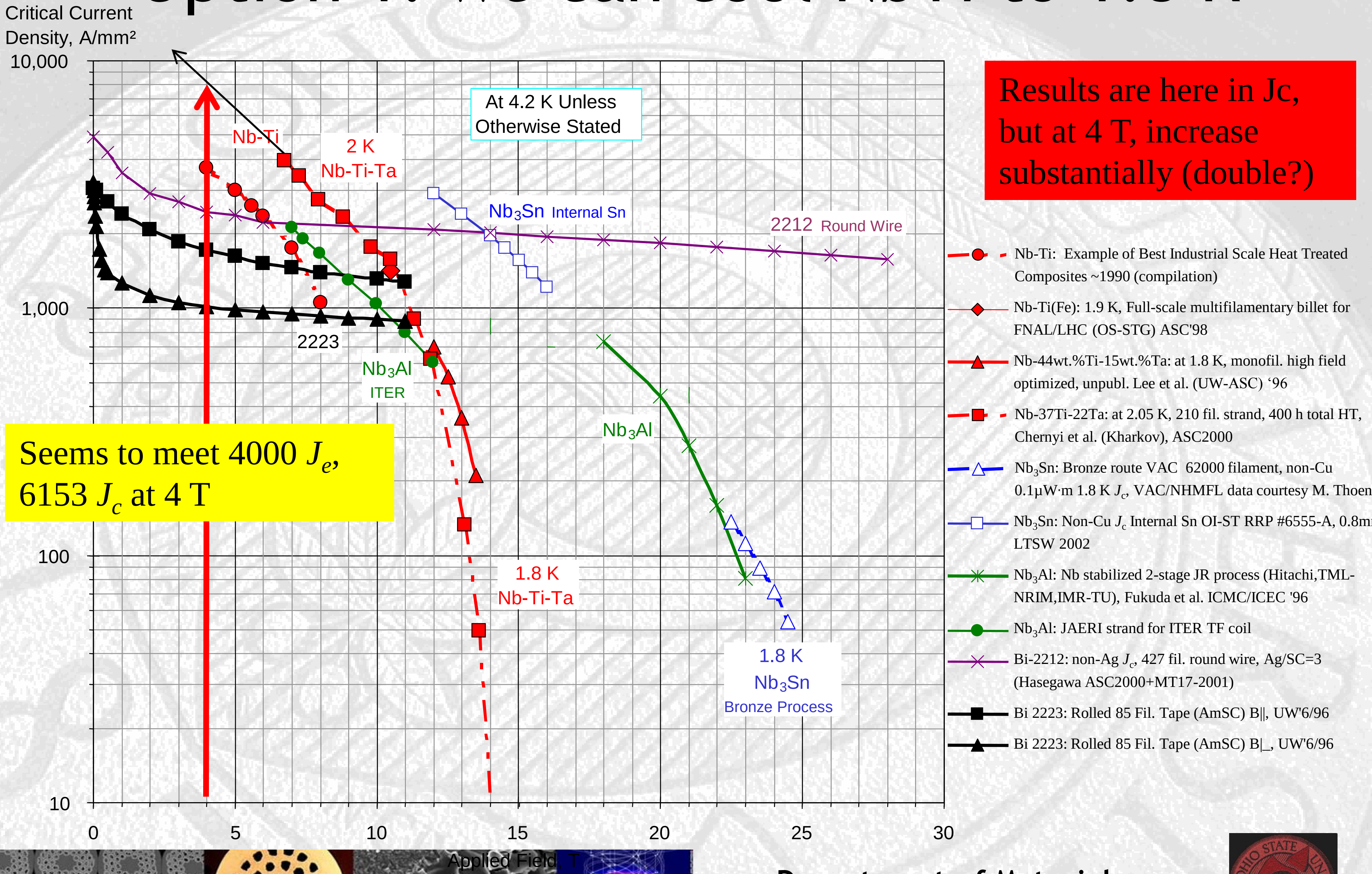
Oxipnictides are lower still

All At 4 K

So our options are ..

- NbTi at 4.2 K good performer, but has reached its limit
- YBCO (**expensive**, **inconvenient**, only meets Je **in parallel** and **at 4 K -so may not work**
- **Nb$_3$Sn**
- **Anything else??**

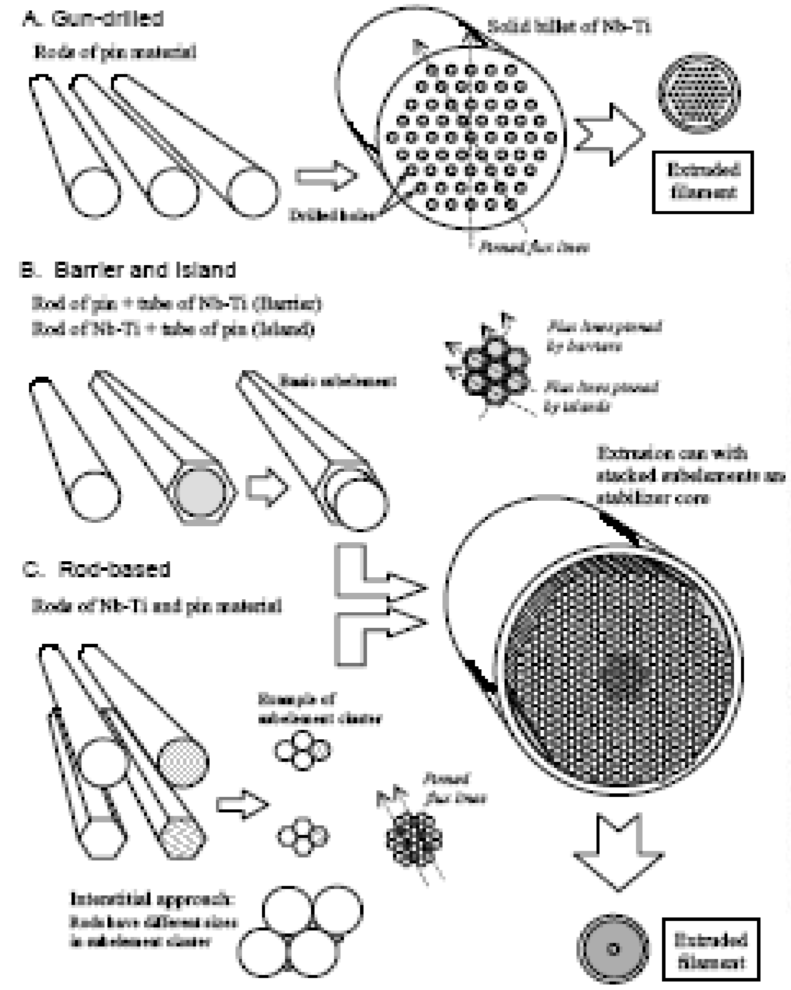
Option 1: we can cool NbTi to 1.8 K

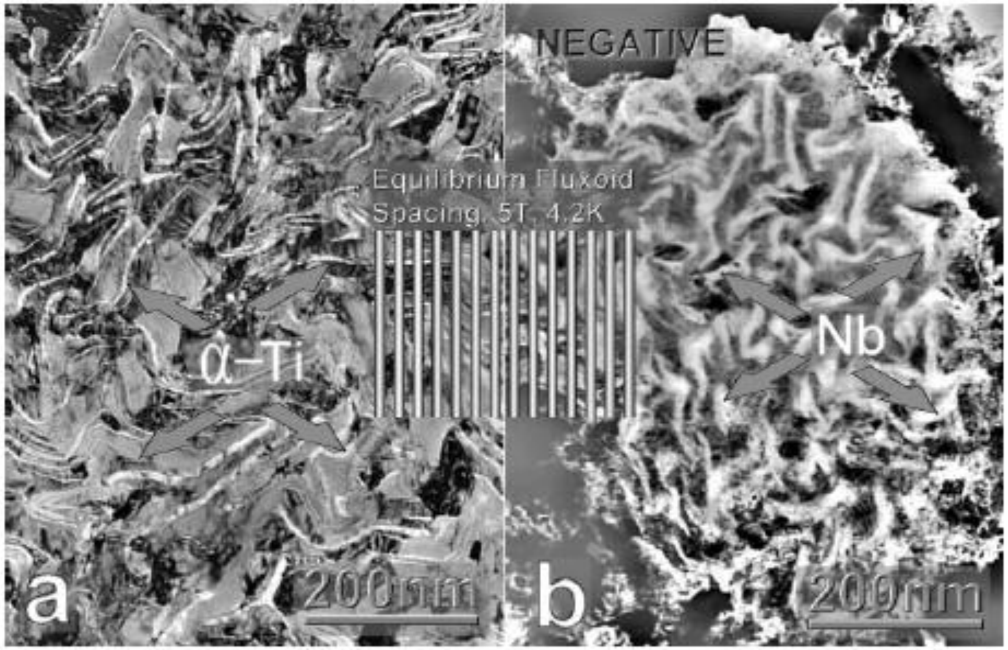


Results are here in Jc, but at 4 T, increase substantially (double?)

Seems to meet 4000 J_e, 6153 J_c at 4 T

Option 2: NbTi with APCs

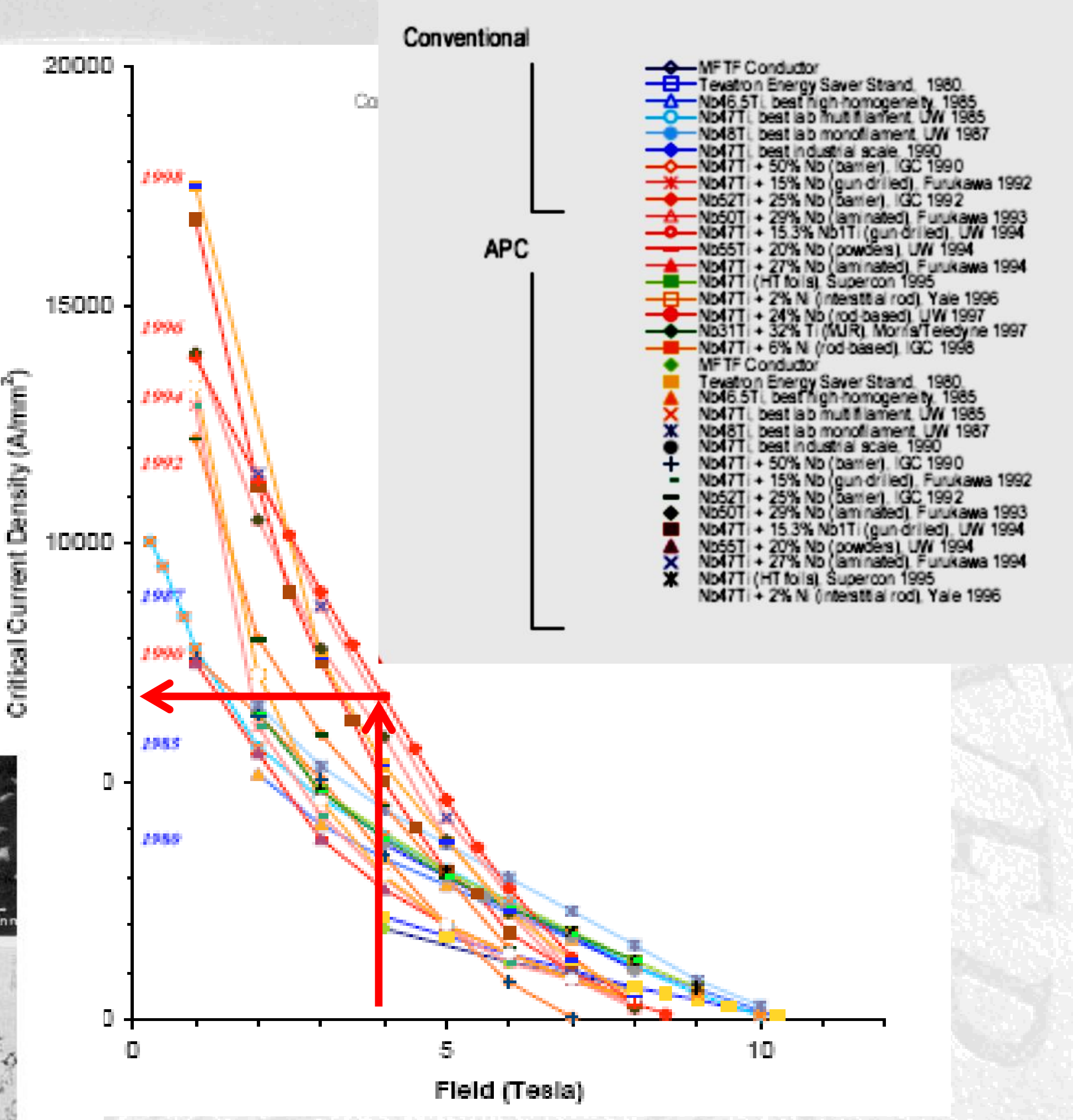




L D Cooley† and L R Motowidlo‡

Supercond. Sci. Technol. 12 (1999) R135–R151. Printed in the UK

Development of microstructure and Transport Results



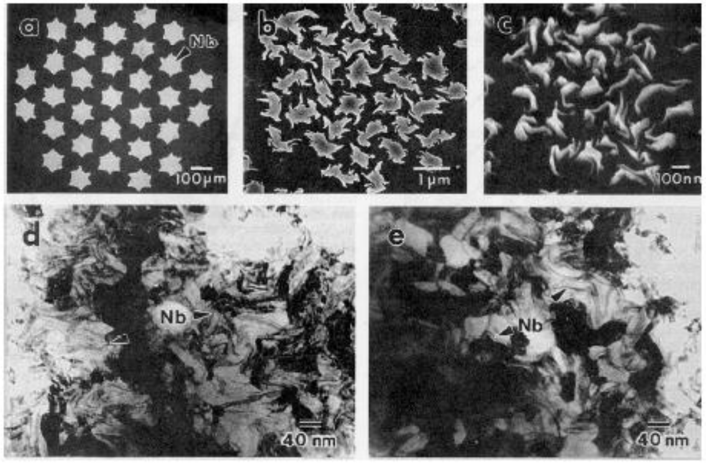
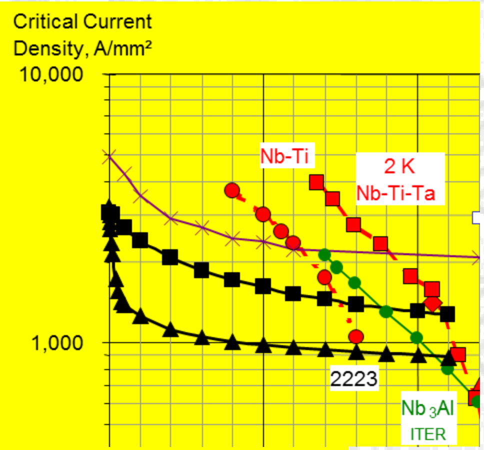
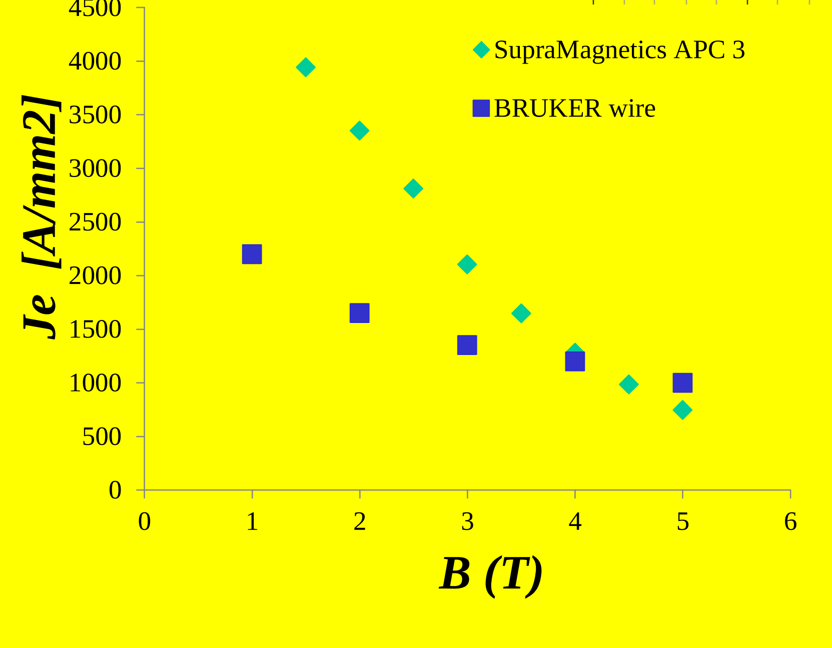


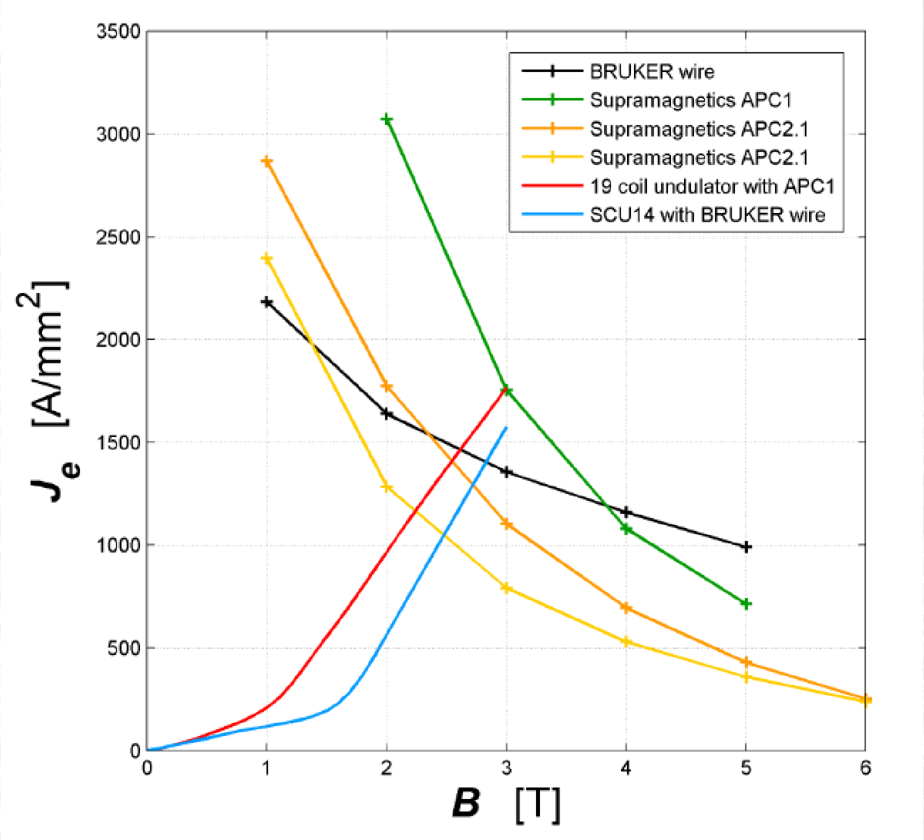
Figure 7. Scanning and transmission electron microscopy images of an Nb pinning centre array in an Nb47Ti matrix at (a) $d_p = 100\ \mu$m, (b) 600 nm, (c) 100 nm, (d), (e) 40 nm. This sequence shows the progressive changes in the shape of the pins from round to highly aspected ribbons. In (d) and (e) the actual pin thickness is 1–15 nm, much less than the calculated pin diameter from equation (1). (Imaged obtained from [56]).

APCs—Can beat NbTi, but only below 3 T

Because J_c increases rapidly with dropping B, but fill factor is lower

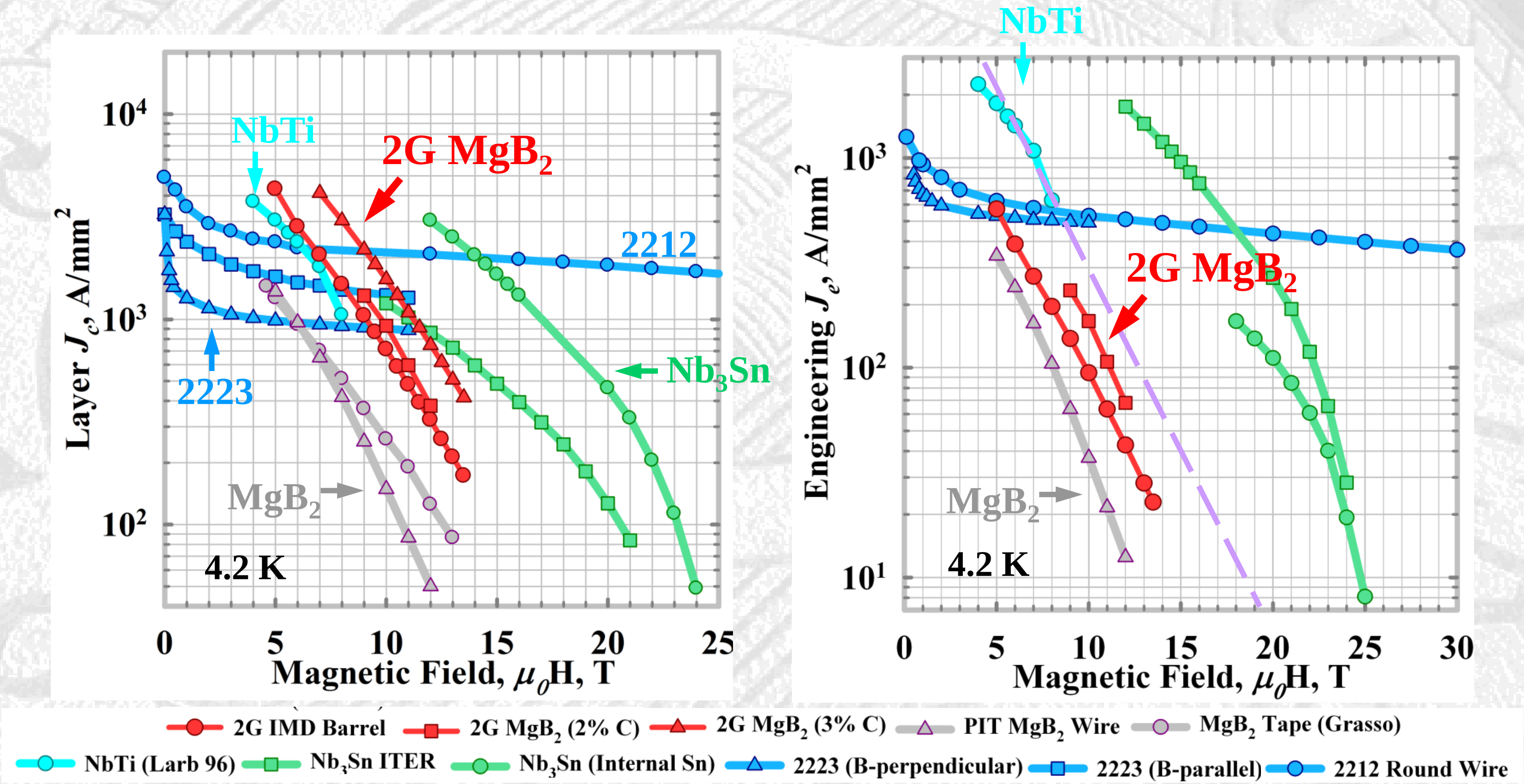






Recent Advances in MgB2 – Huge increases --

Second generation MgB_2 wires: both improved critical current density J_c and engineering J_e. Not able to beat NbTi wrt J_e yet, but is moderate cost, and could allow > 4 K operation



Layer $J_c = I_c / MgB_2$ area

So…

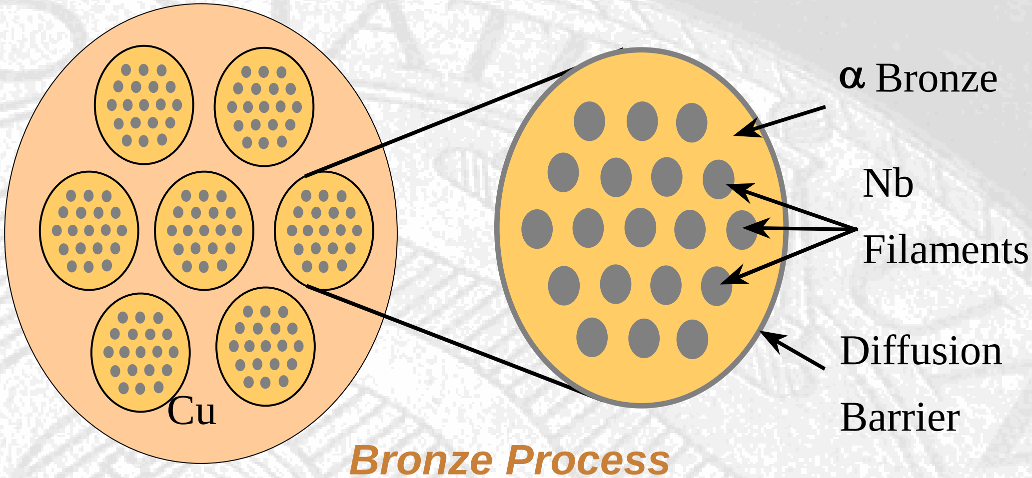
- Option 1: 1.8 K NbTi
- Option 2: APC NbTi, but only for designs with B 3 T and below
- Option 3: Nb_3Sn

But, Nb_3Sn comes in a variety of different flavors…

Flavors of Nb_3Sn

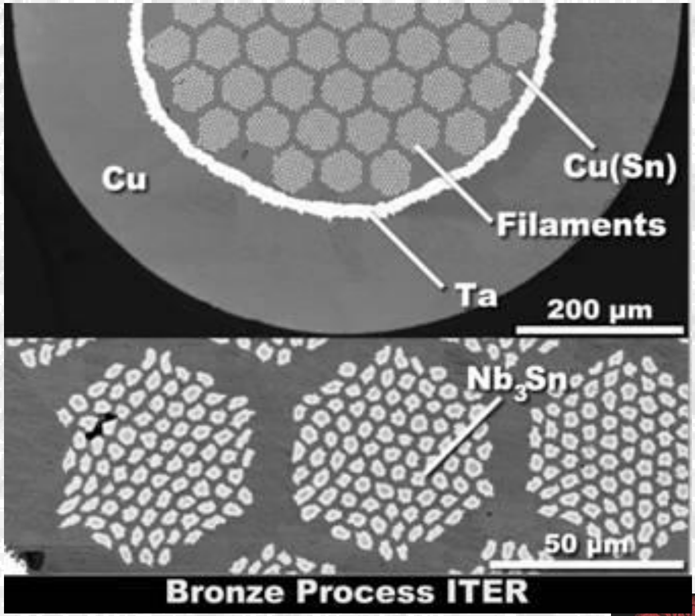
1. Bronze Route
2. Rod-In-Tube, Fusion-Type
3. Rod-in-Tube, HEP Type
4. Powder-In-Tube
5. Tube

The Bronze Process



Bronze Process

- Bronze route (Nb rods in Cu-Sn alloy)
  - Cu dissolves 9at.%Sn maximum while remaining single phase and ductile
  - Cu7.5at.%Sn used for years
  - NMR conductors see advantage, even for additional mechanical complexity in going to 8-8.5%Sn



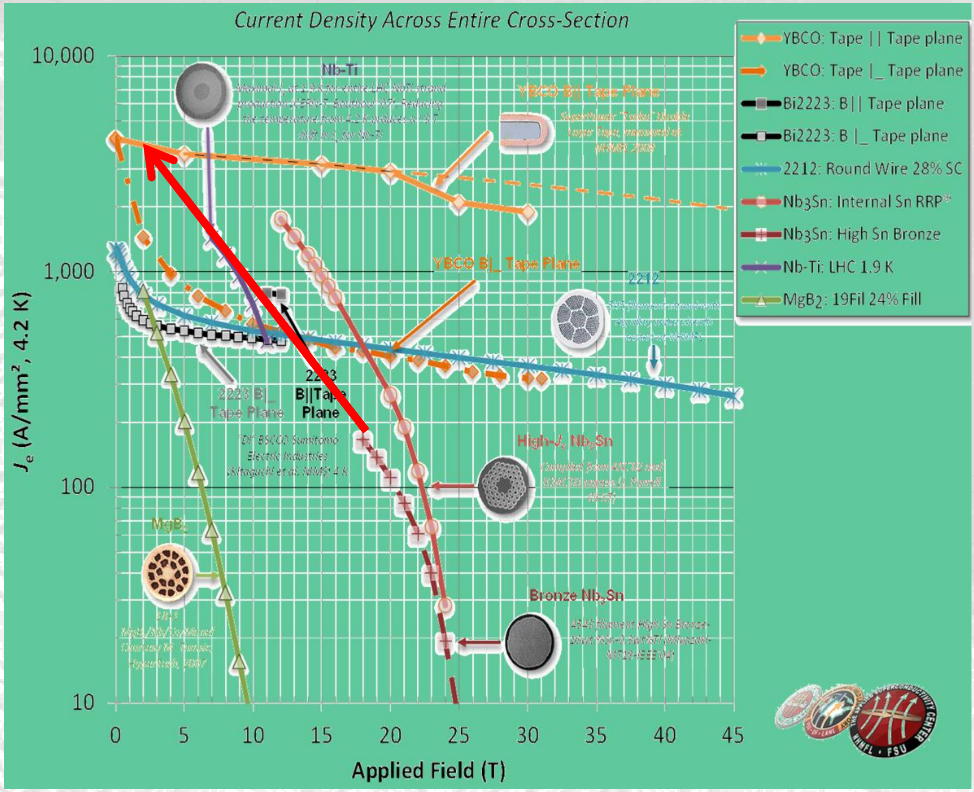
Bronze Process ITER

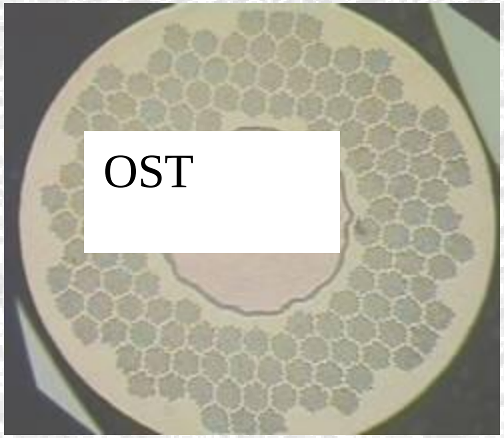
Bronze Process

Limited level of Sn limits amount of Nb that can be used and lessens final A15 stoichiometry

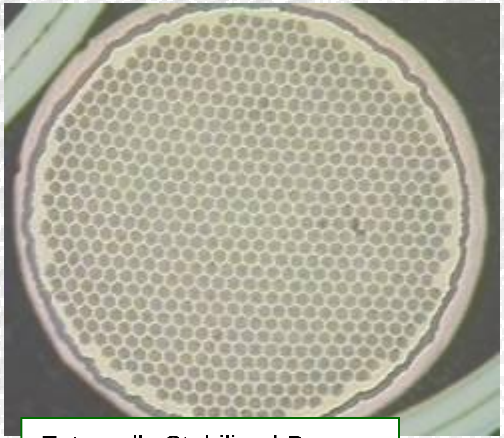
Annealing during wire drawing required because of work hardening

A bit lower than we want for Undulators

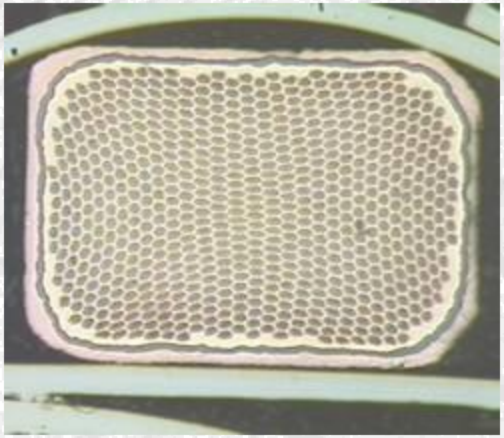




Internally Stabilized Bronze



Externally Stabilized Bronze



Externally Stabilized Bronze

Fusion Type RIT

- Bronze is OK – but we can’t cram enough Sn in (limited to 9 at%)
- This limits B_{c2} and J_c
- We can get around this by inserting ductile Cu/Sn composites and then in-situ reacting after wire drawing
- In this version of RIT, a Cu rod drilled full of holes, and Nb rods are inserted into the Cu with one large Sn rod in the center
- This leads to J_c values higher than bronze, but not usually much higher

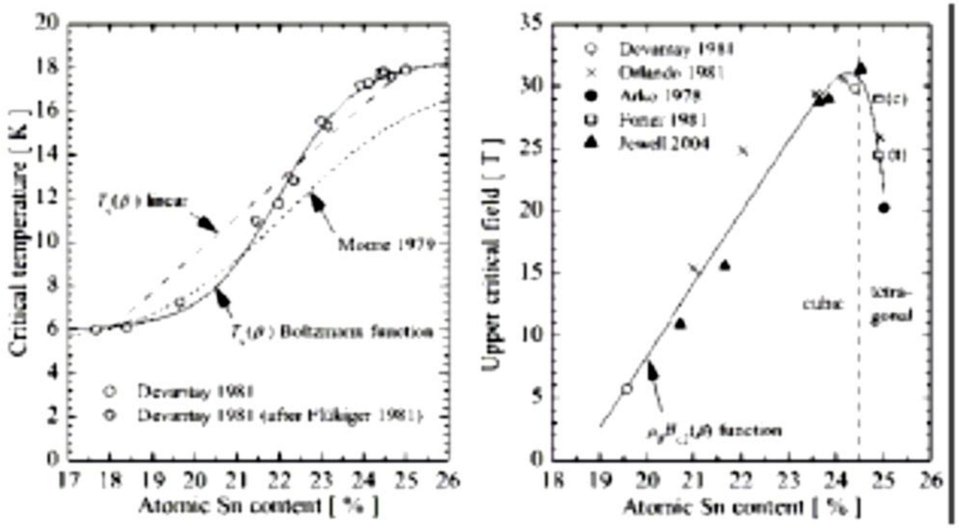
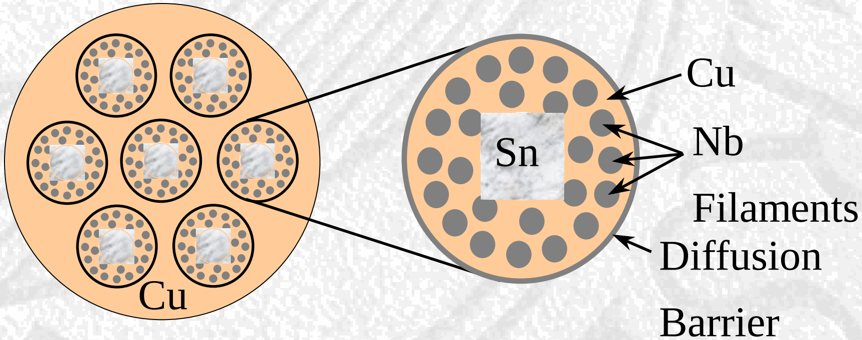
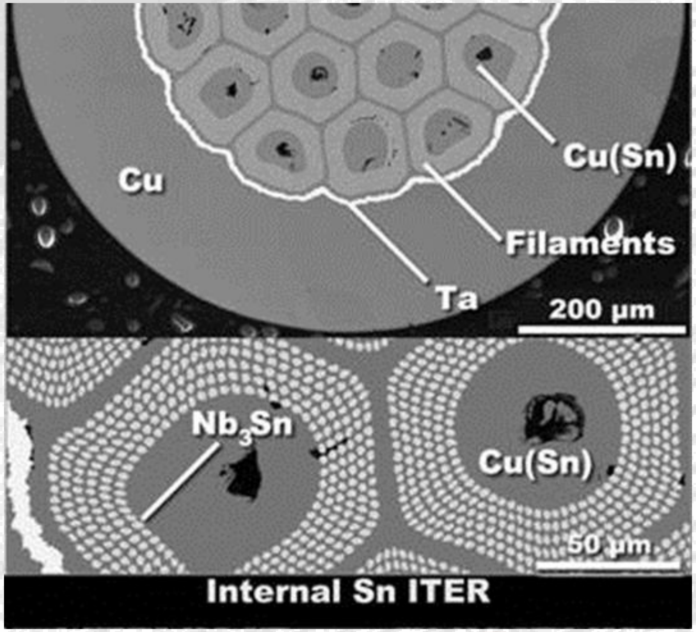


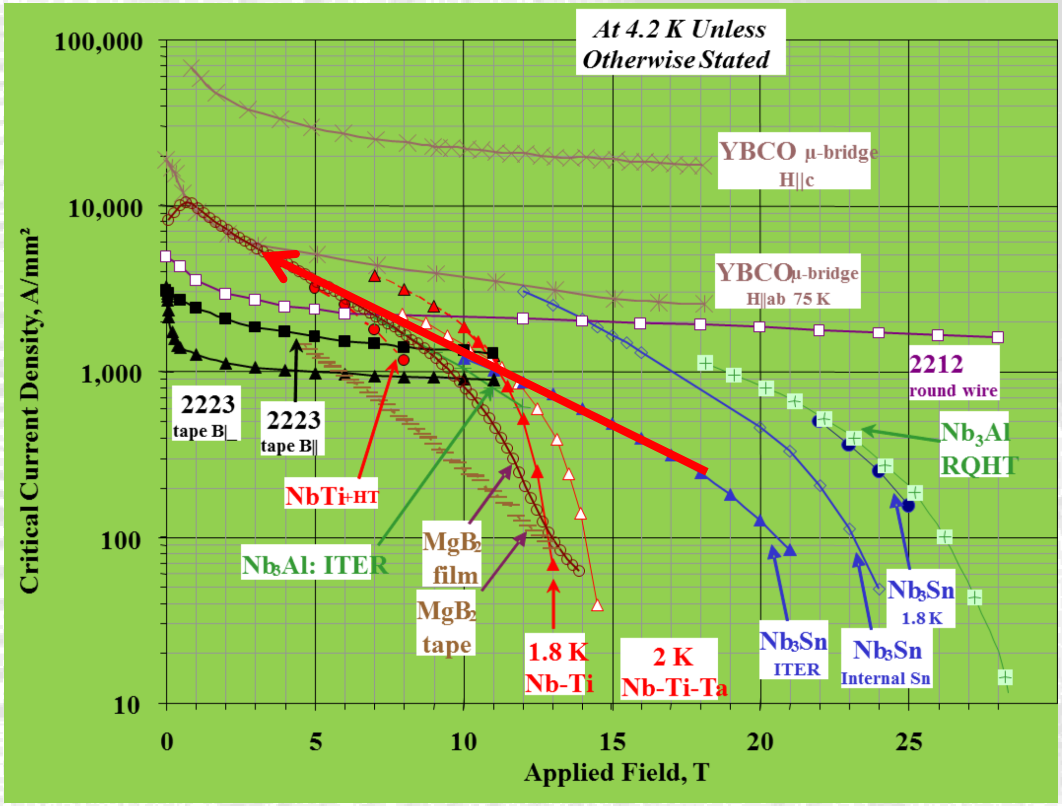
Figure 2.2 Variation of the critical temperature and upper critical field with atomic Sn content (reproduced from the work of A. Godeke [21]).

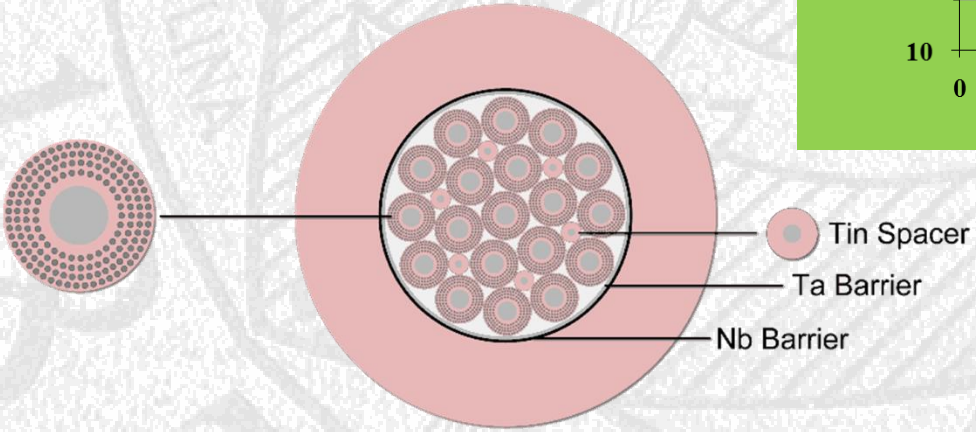


Internal Sn (Rod Process Shown)

Fusion type RIT



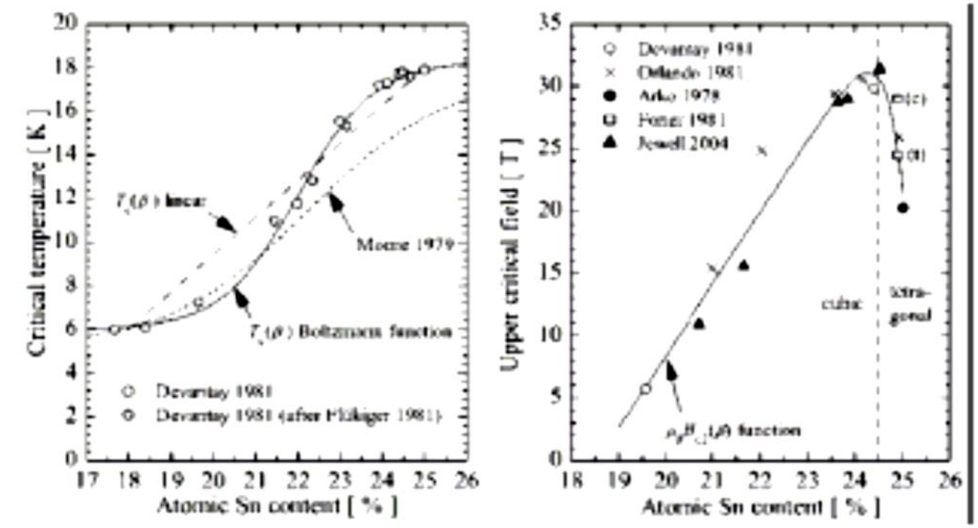




Getting closer, but need a bit more!

HEP Type RIT, i.e., Internal Sn, RRP, Distributed barrier

- One problem with Fusion-type RIT, where the rods are put in drilled holes, is that the hole density is limited, so the final amount of Nb_3Sn is limited
- In HEP type Nb_3Sn, Nb rods with thin Cu cans are stacked around a Cu center.
- This is extruded, and then a hole is drilled, and the Sn is packed in
- Has very high J_c, but can be unstable in the regime of interest for undulators



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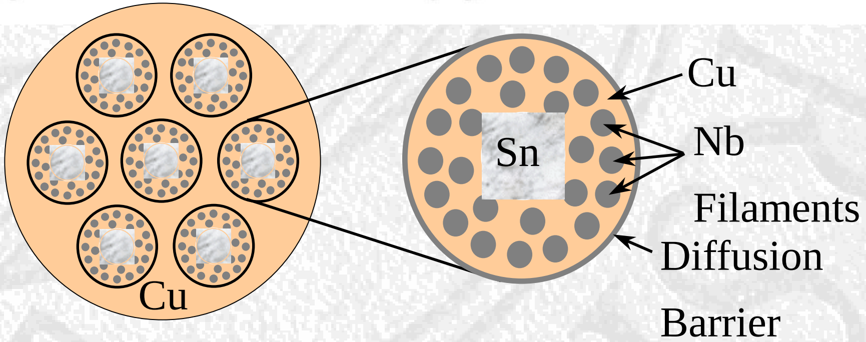
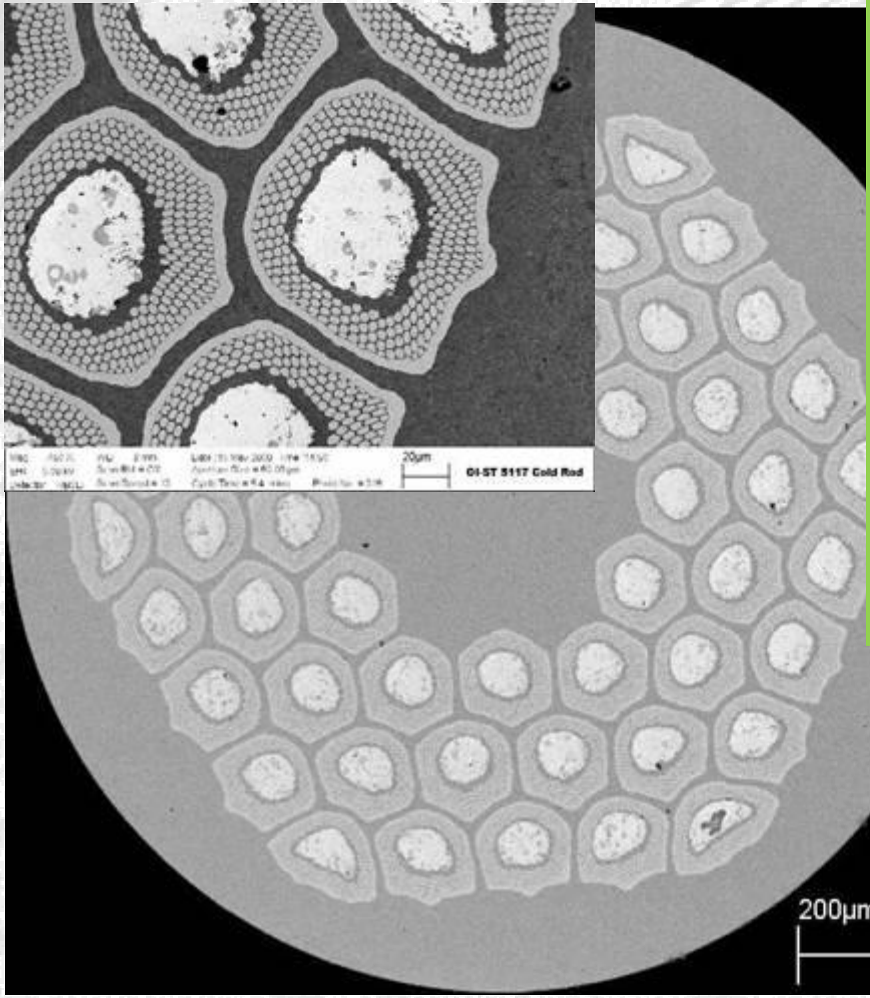
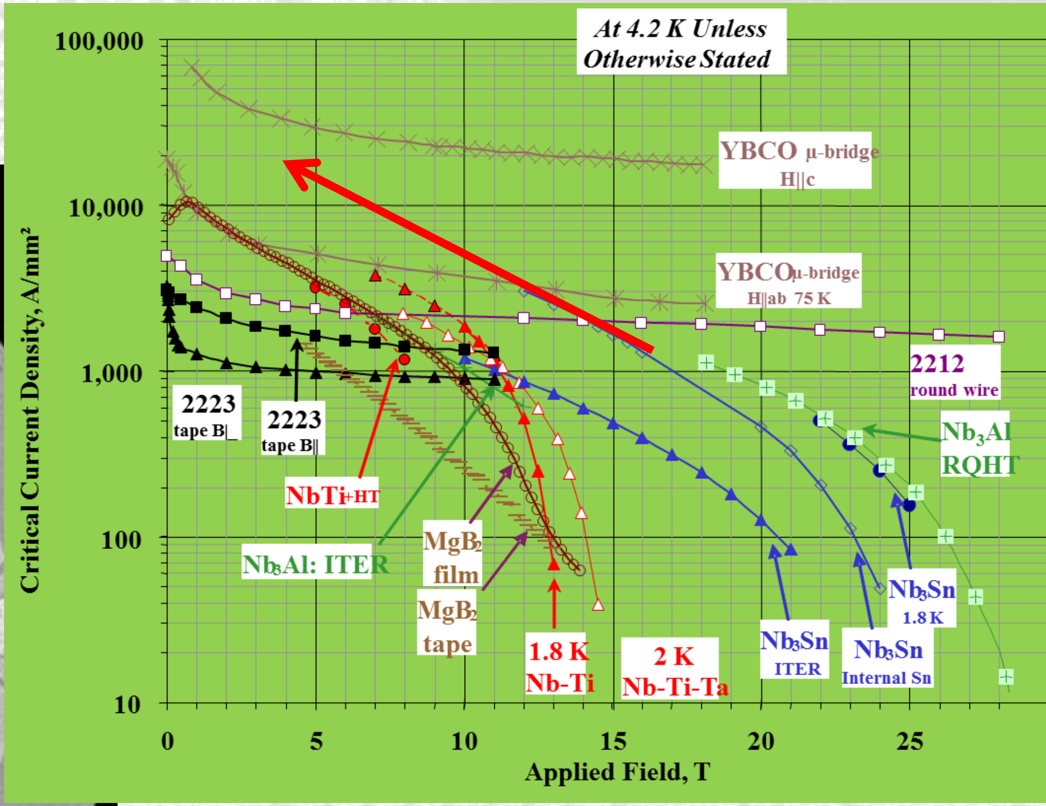


Internal Sn (Rod Process Shown)

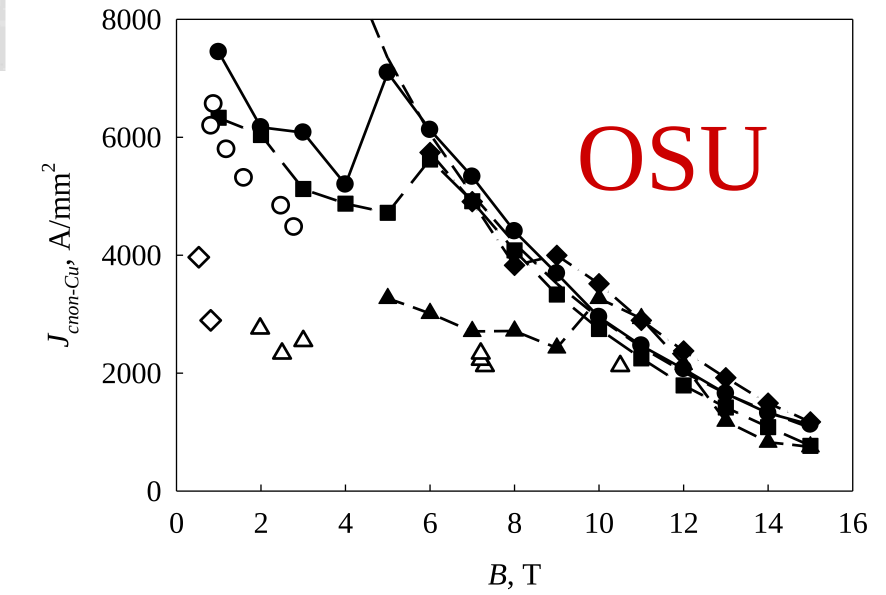
Oxford's version of the RIT

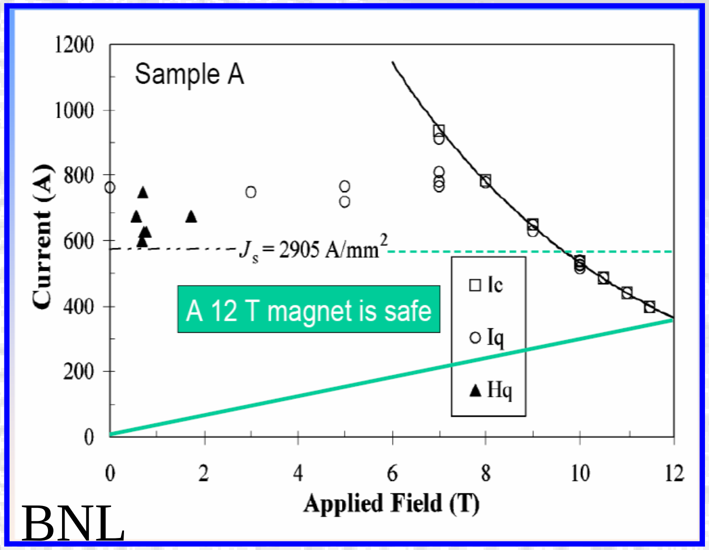




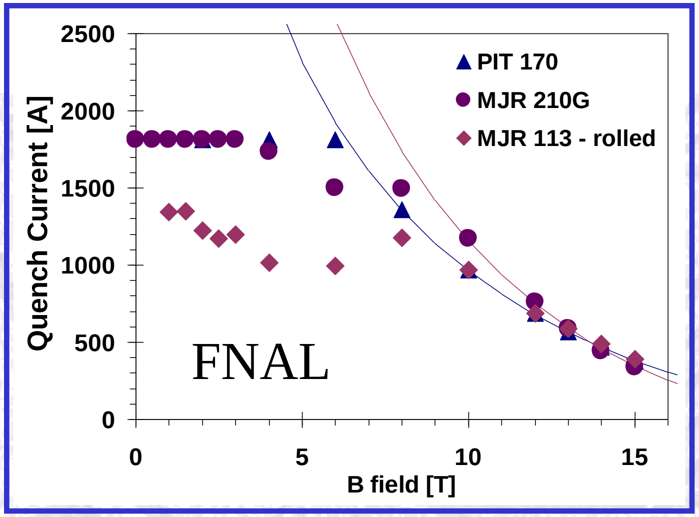
Performance is now well within the regime we need, but we will find it is not stable in the field range of interest

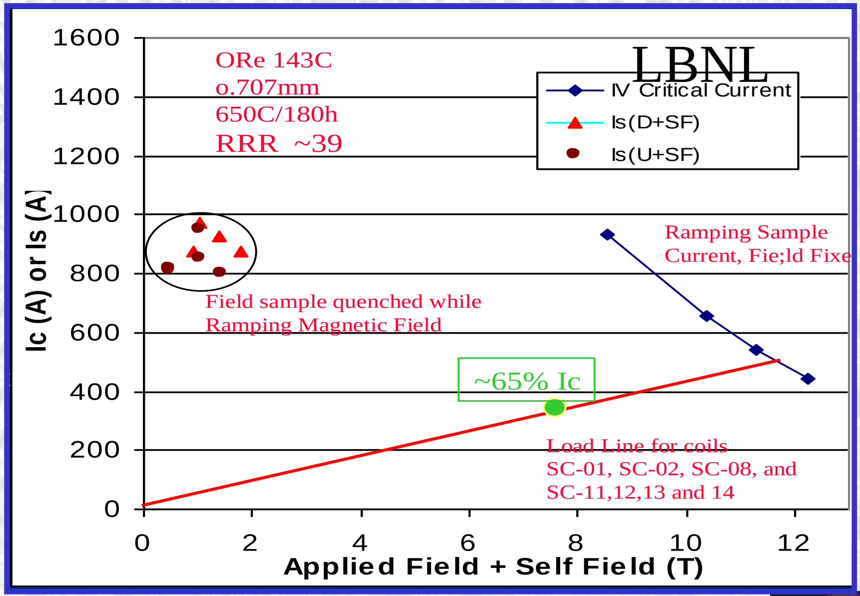
Instability of HEP type RIT at lower B





A 12 T magnet is safe





ORe 143C
o.707mm
650C/180h
RRR ~39

Ramping Sample
Current, Fie;ld Fixe

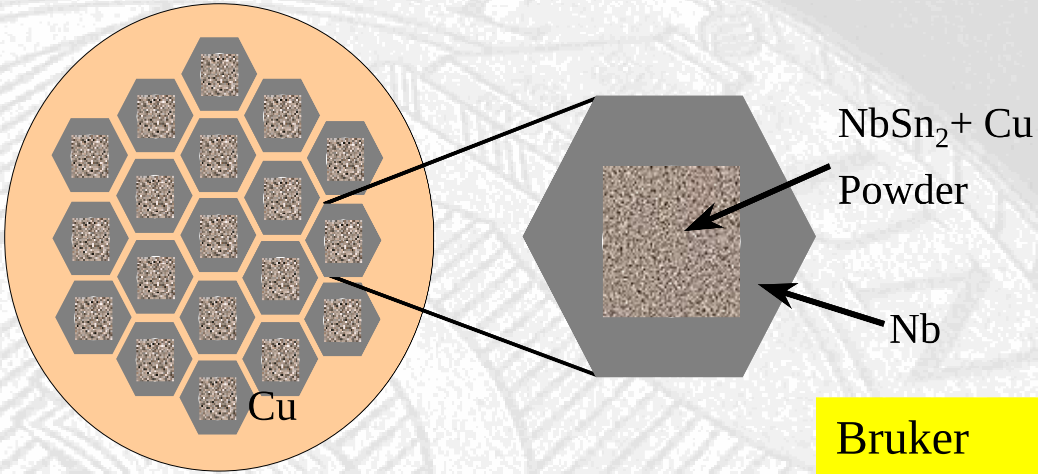
Field sample quenched while
Ramping Magnetic Field

~65% Ic

Load Line for coils
SC-01, SC-02, SC-08, and
SC-11,12,13 and 14

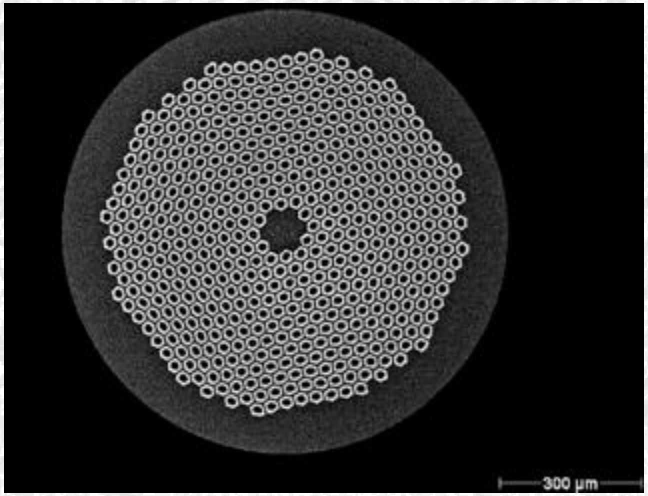
The PIT Route to Nb-Sn Wires

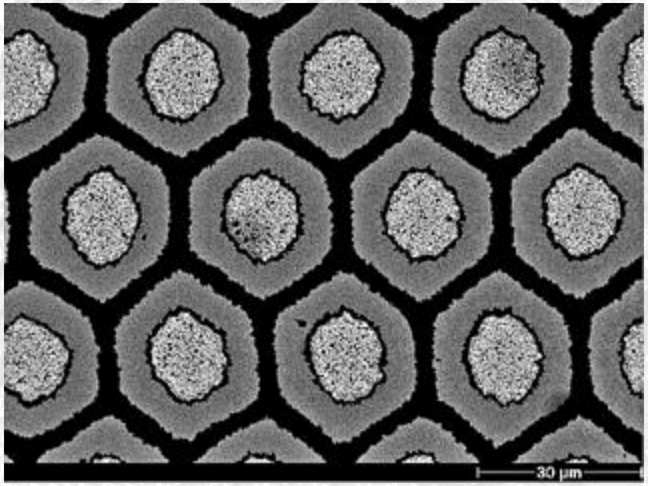
- Powder in Tube method places $NbSn_2$ inside Nb tubes



Bruker

PIT – Powder in Tube

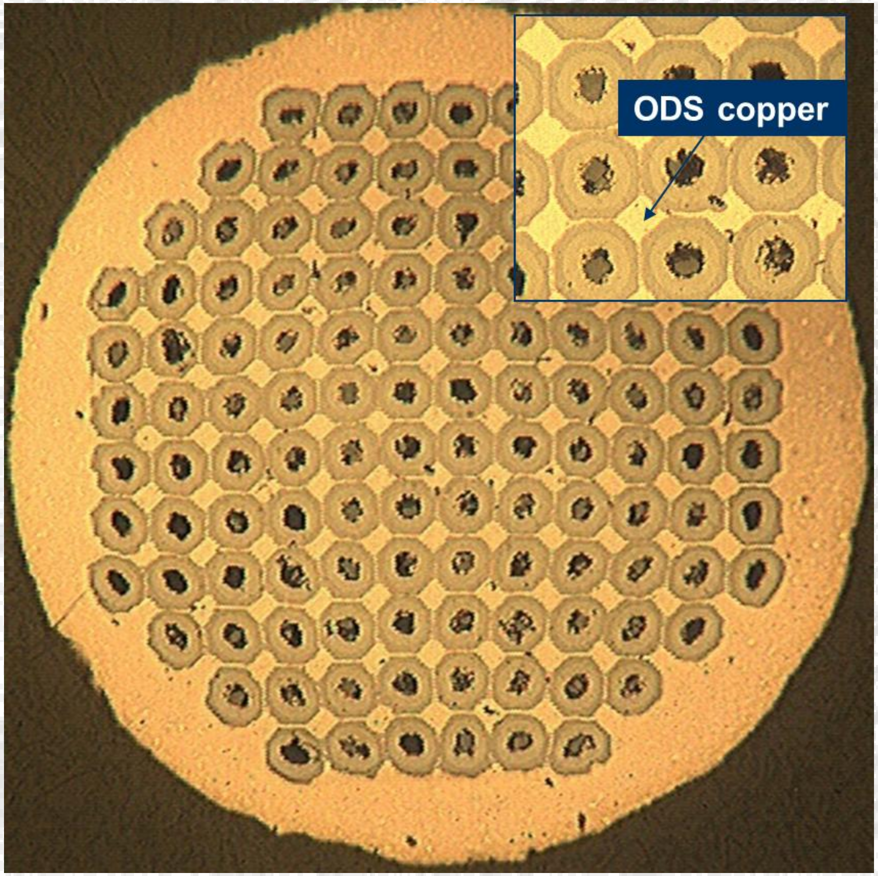


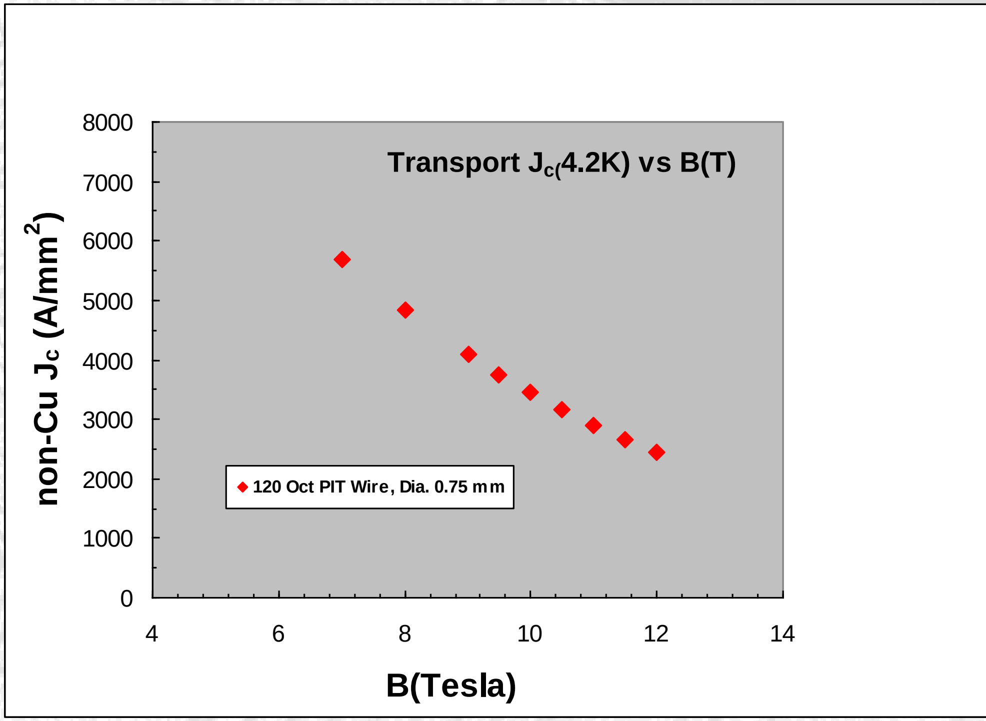


Schematic by Mike Naus

Octagonal Version of PIT

SupraMagnetics

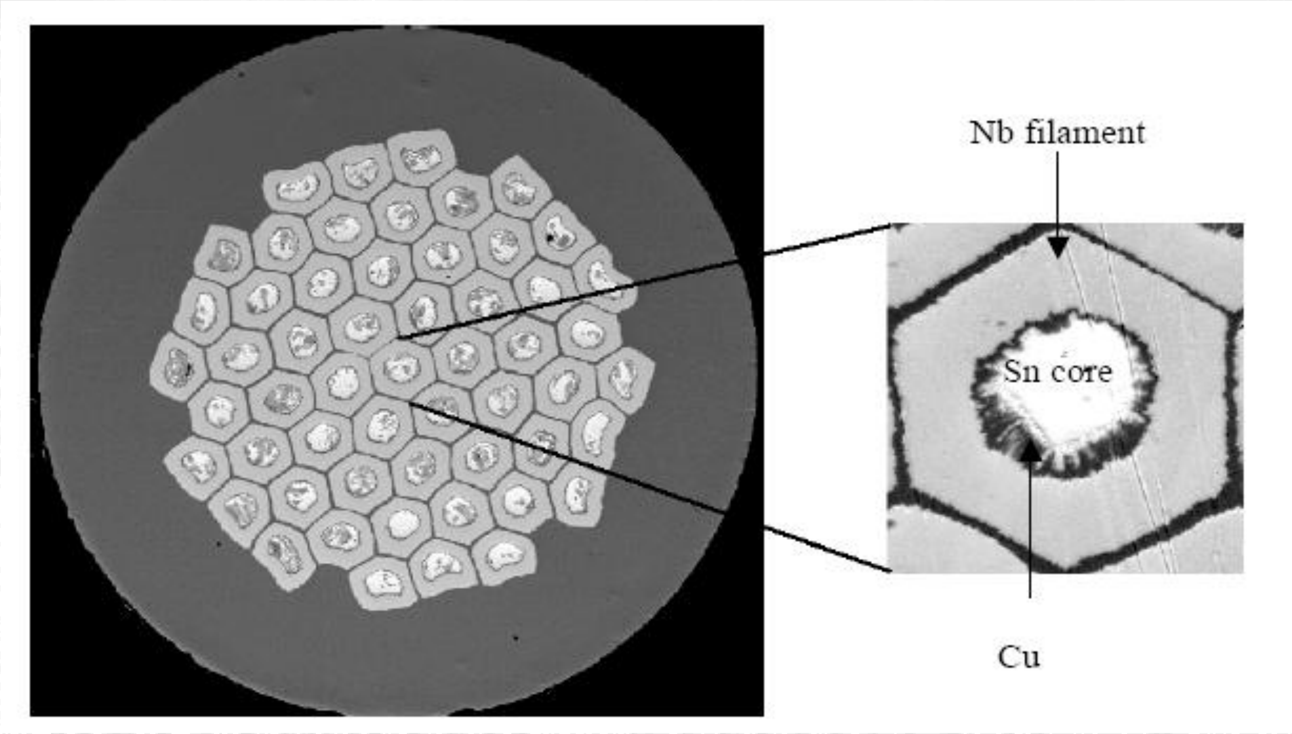




In the regime of interest

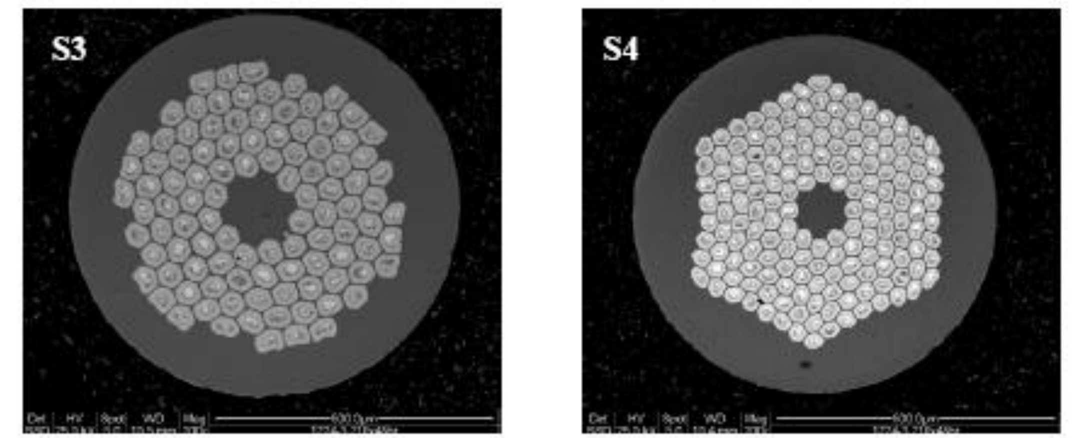
Issue to control powders

Tube Type Conductors

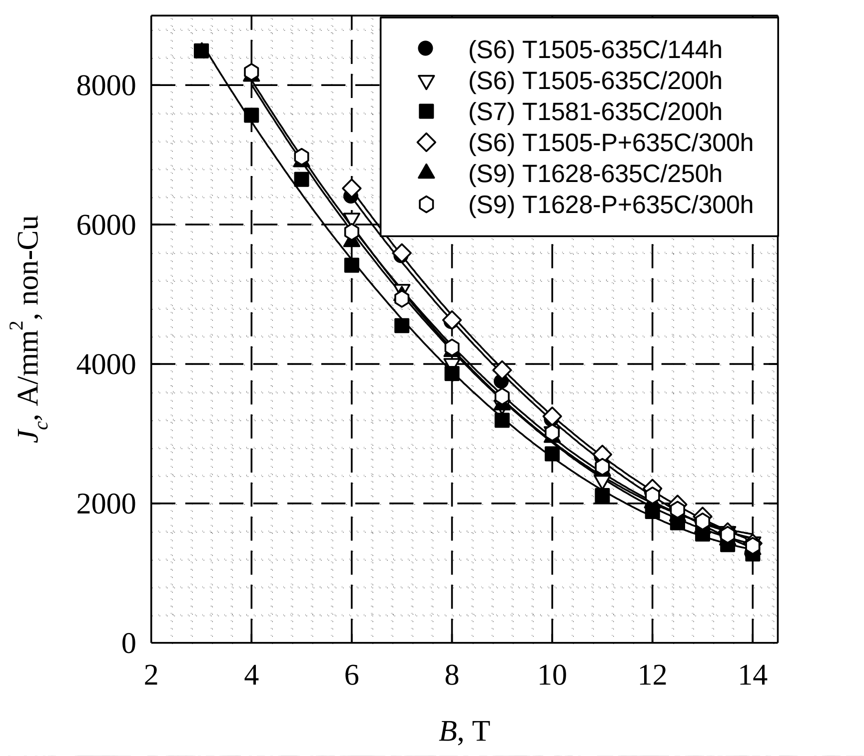


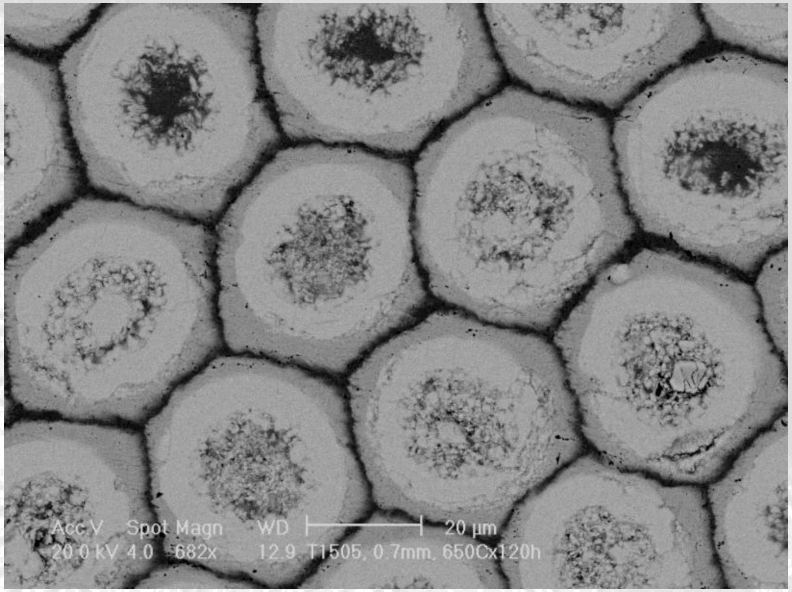
A Simple structure of Sn/Cu/Nb drawn and then

As developed by Supergenics, Hyper Tech, Global



Tube Conductor Transport





Also hitting the regime of interest

For undulator work

2250 A/mm^2 at 12 T in 217 stack conductor

Some final Comments and Considerations

- NbTi conductors have maxed out, unless we drop to 1.8 K
- Of the HTSC, YBCO seems most relevant, but seem to not quite hit targets even at 4 K
- MgB_2 making major strides, but not yet at J_e of NbTi
- APC has high J_c, especially at moderate to lower fields, but lower fill factor leads to it's beating standard NbTi only 3T and below
- Nb_3Sn is promising, but is a wind and react conductor, so must account for insulation when computing the final winding J_w
- Of the Nb_3Sn's, Bronze and Fusion type RIT are not high performance enough
- HEP type Nb_3Sn has more than enough performance, but has stability problems
- PIT and Tube Nb_3Sn are of interest for Undulator application