New Superconductors for Fusion Magnets

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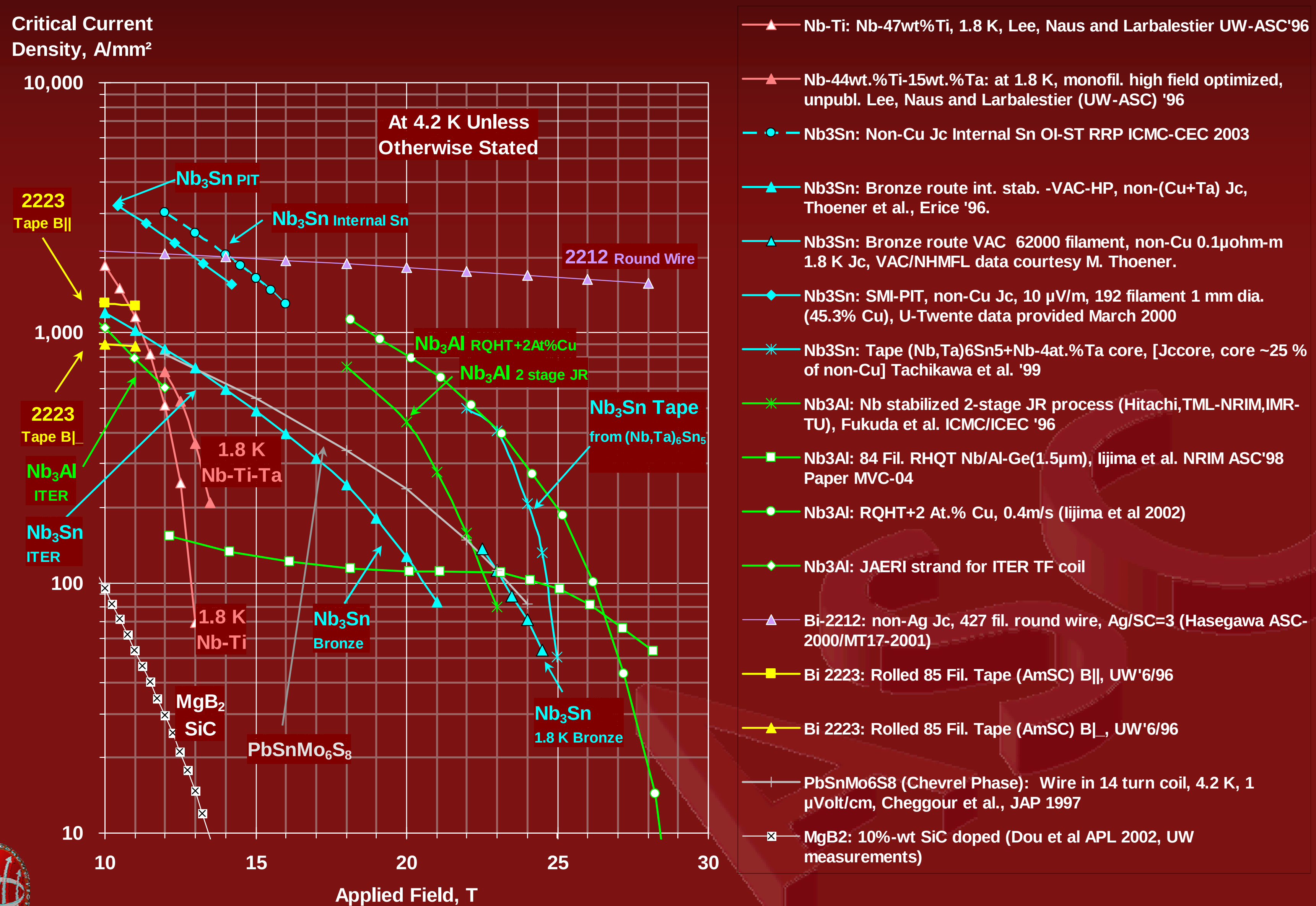
TOFE-16, Madison, WI, Sept. 2004

Outline

- High Field Fusion Superconductor Options
  - Nb_3Sn: New Designs, New Challenges
    - New Nb_3Sn have layer critical current densities more than twice that of ITER-CSMC strand – is there any hope that this can be translated into a low-loss Fusion strand
  - 2212
    - The only HTS strand available in round cross-section
  - MgB_2
    - New superconductor with very low raw material cost – does it have a role in future Fusion devices

High Field Superconductors



Nb_3Sn: Status

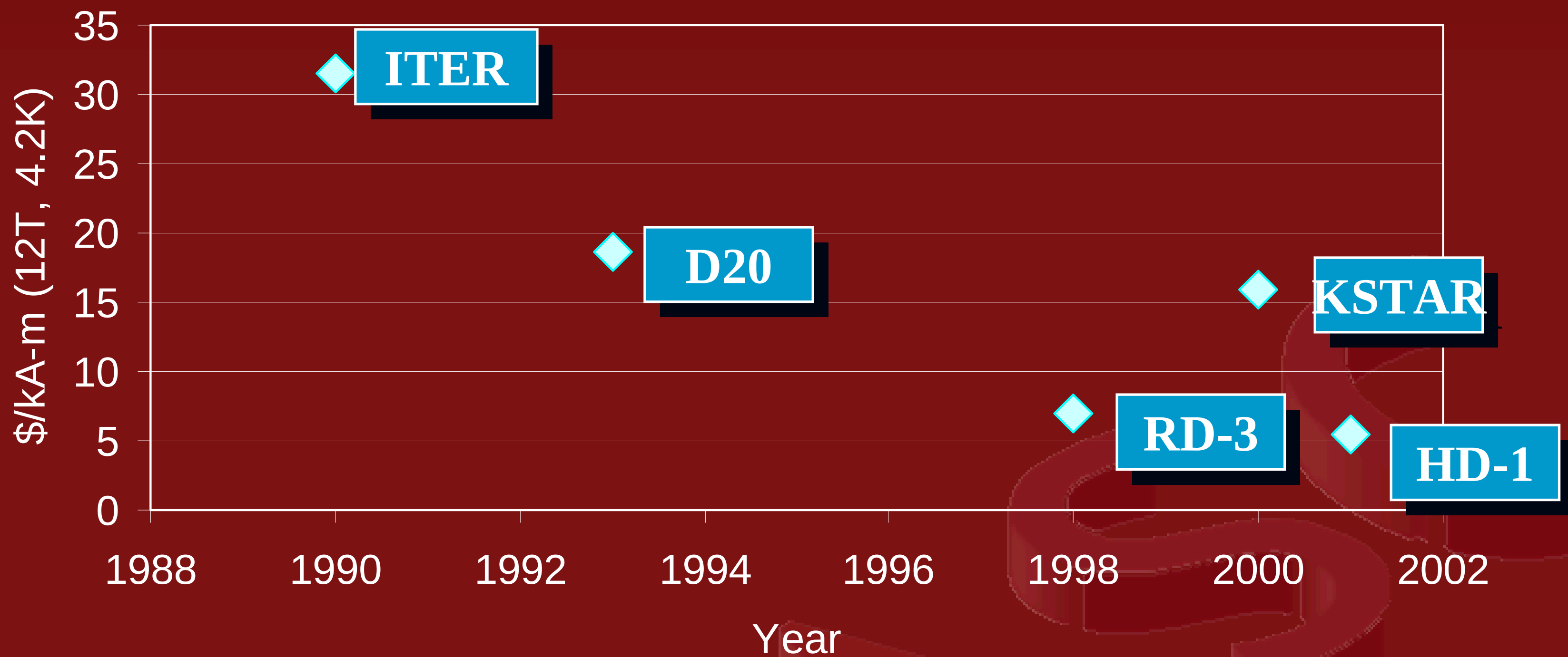
- J_c (non-Cu, 12 T, 4.2 K): 3000 A/mm^2 in VERY LARGE Filaments
  60-120 μm
  RRR May be compromised

  Small increases in Bronze process J_c from greater geometrical homogeneity and control of bronze homogeneity.
- Hysteresis Loss: D_{eff} ~ 26 μm for ITER-CSMC HP-I (J. Schultz). **But** $Q_h \propto J_c \cdot D_{eff}$
- Piece length: High J_c only in small billets so far (~1500 m).
- Heat treatment times: Use of PIT strand can reduce HT to 40 hrs
- Wire cost: \$6/kA·m (12 T, 4.2 K): Small Billet high J_c
  Nb_3Sn PIT ~\$30/kA·m, 2212 ~\$60/kA·m

Advantages of Nb_3Sn

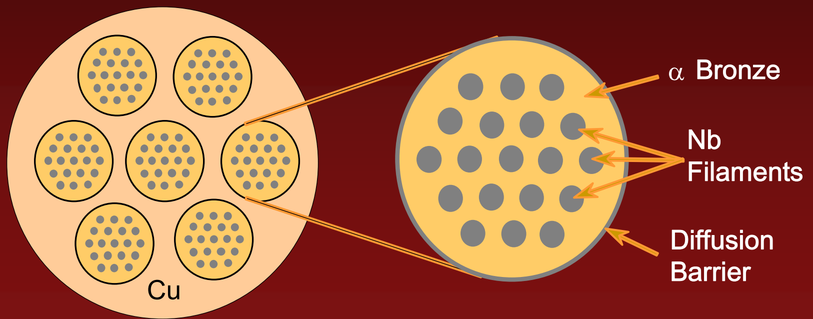
- Large Scale Production Experience
  - Strand production
  - Cable production
  - Successful sub-scale high field (16 T, 4.2 K) dipole magnets
  - ITER CS Model Coil
- Multiple Vendors internationally
- Cu Stabilizer
- Both React-and-Wind and Wind-and-React strategies available
  - Now have magnet production experience in both

Ron Scanlan (LBNL): ASC2002
\$/kA-m improvements mostly through J_c improvements:

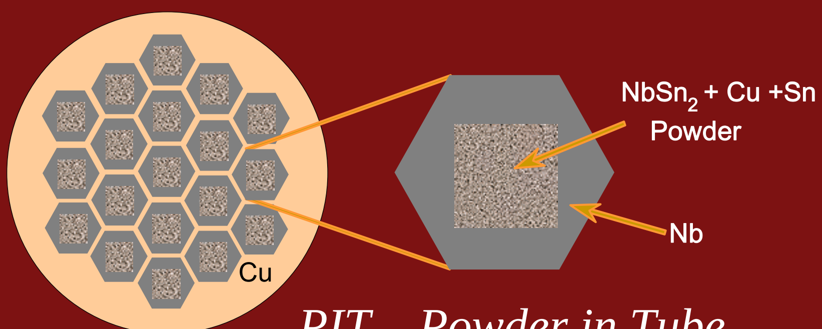


Further major cost improvements require improvements in processing

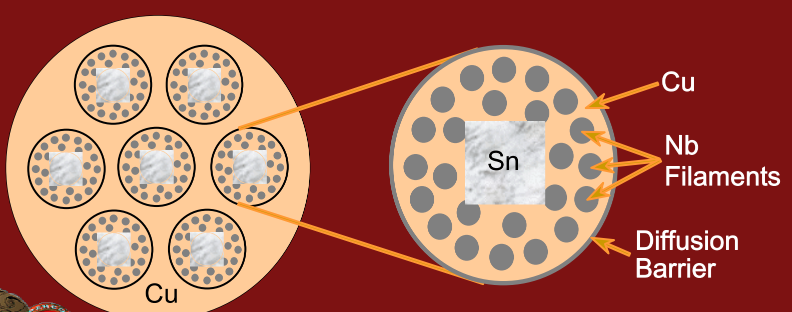
Industrial Nb_3Sn Fabrication Processes



Bronze Process



PIT – Powder in Tube



Internal Sn (Rod Process Shown)

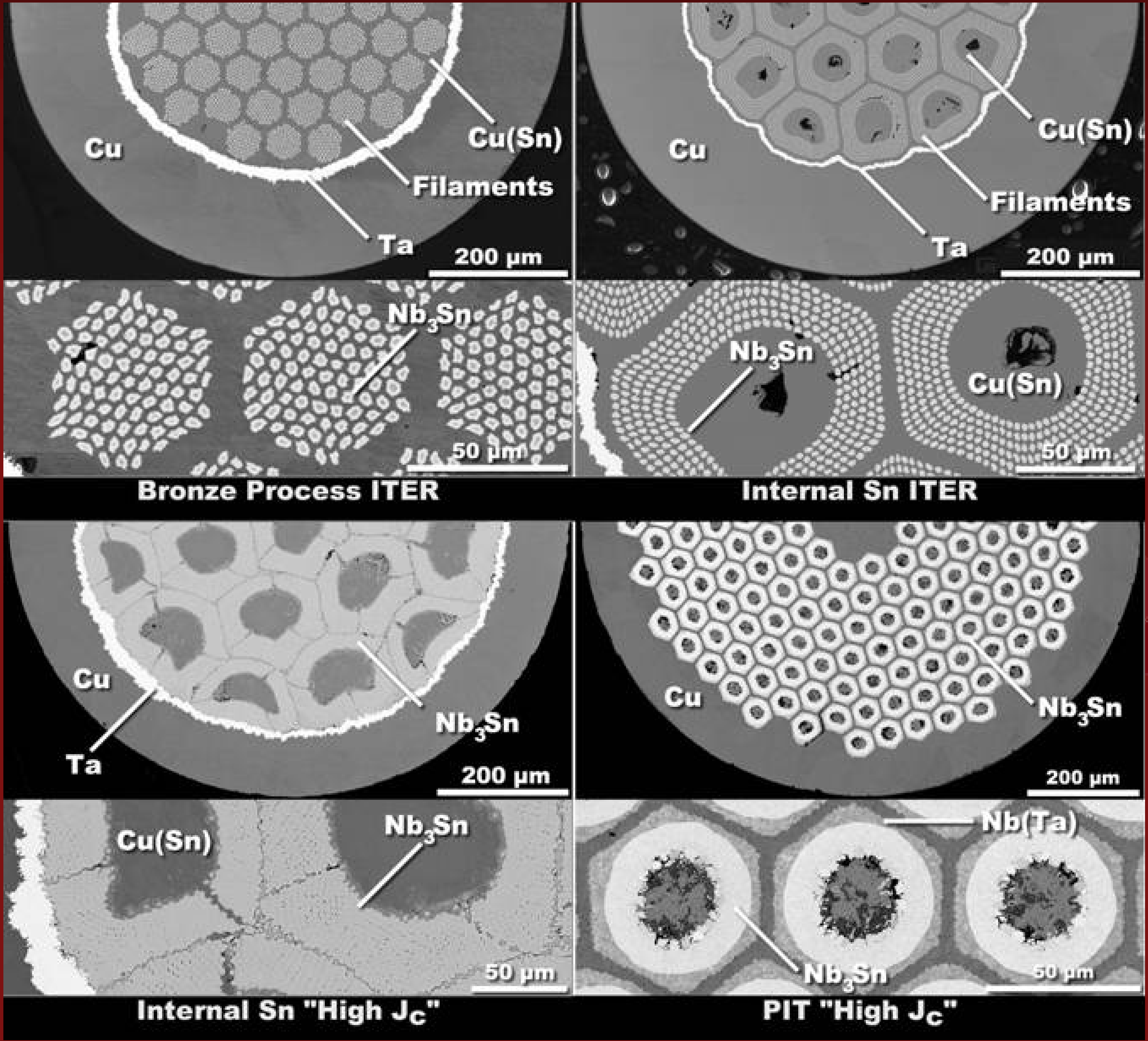
- The bronze process continues to dominate market for NMR where high *n*-value is critical. High Cu:Sn ratios means J_c limited.
- PIT produces $d_{eff}=d_{fil}$ and can produce high J_c but is expensive and is only commercially available from one manufacturer. SMI now has co-operative agreement with EAS.
- Internal Sn: Can produce 3000 A/mm² 12 T, 4.2 K. Large d_{eff} in high J_c strands.

Overview of Nb_3Sn Types

ITER: Distributed Filaments. Large Cu sink for Sn. Variable and low Sn composition in A15

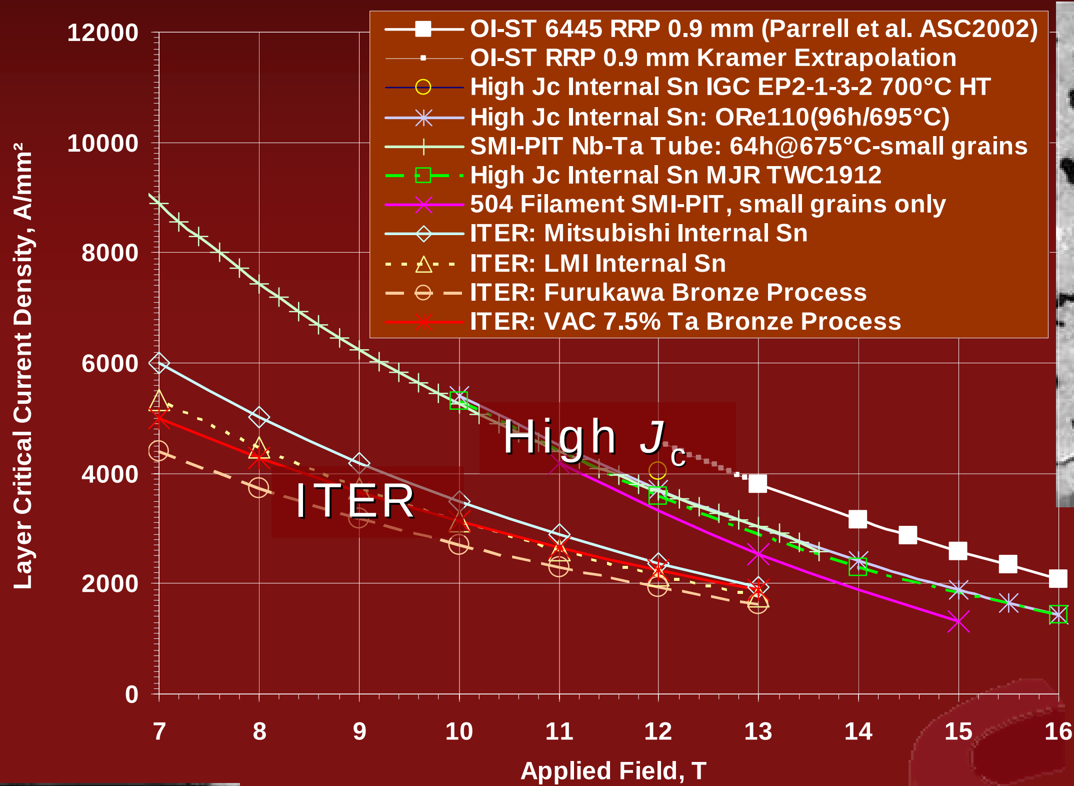
"High J_c"

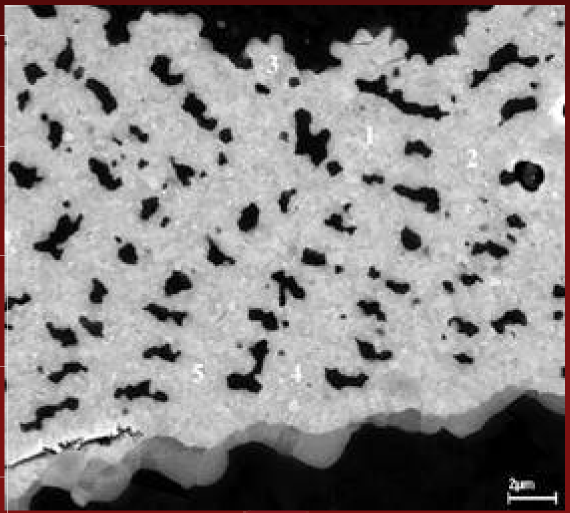
Low Cu, high Sn content in A15 and high homogeneity. Large or coalesced filaments.



So Where is the J_c coming from?

Layer J_c for low-loss ITER-style strand quite different to high J_c strand.





"High J_c" Internal Sn 23-24.5 At.% Sn in A15, equiaxed grains uniform across layer

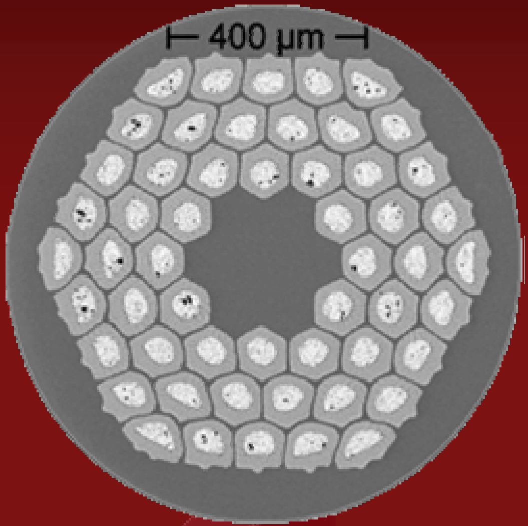
ITER internal Sn

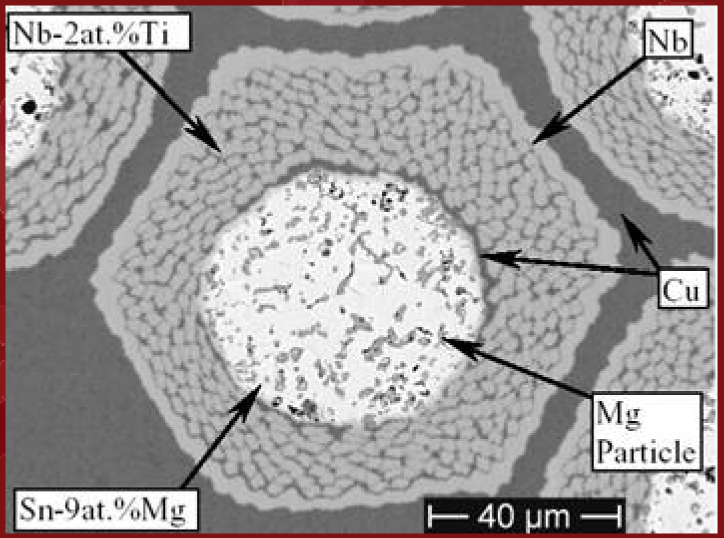
22-24 At.% Sn in A15, equiaxed to columnar transition

*"High J_c" strand has **much less Cu between filaments** (more hysteresis loss) and more Sn and Nb. High Sn levels maintained throughout reaction*

OI-ST MJR Very High J_c: 2900 A/mm², 12 T

- MJR (ORe137): <15 volume % Cu in sub-element: *Key departure from ITER CSMC designs*
- Significant excess Sn even including barrier
- The Sn core is larger than required to react all Nb and Nb(Ti) and form stoichiometric Nb_3Sn

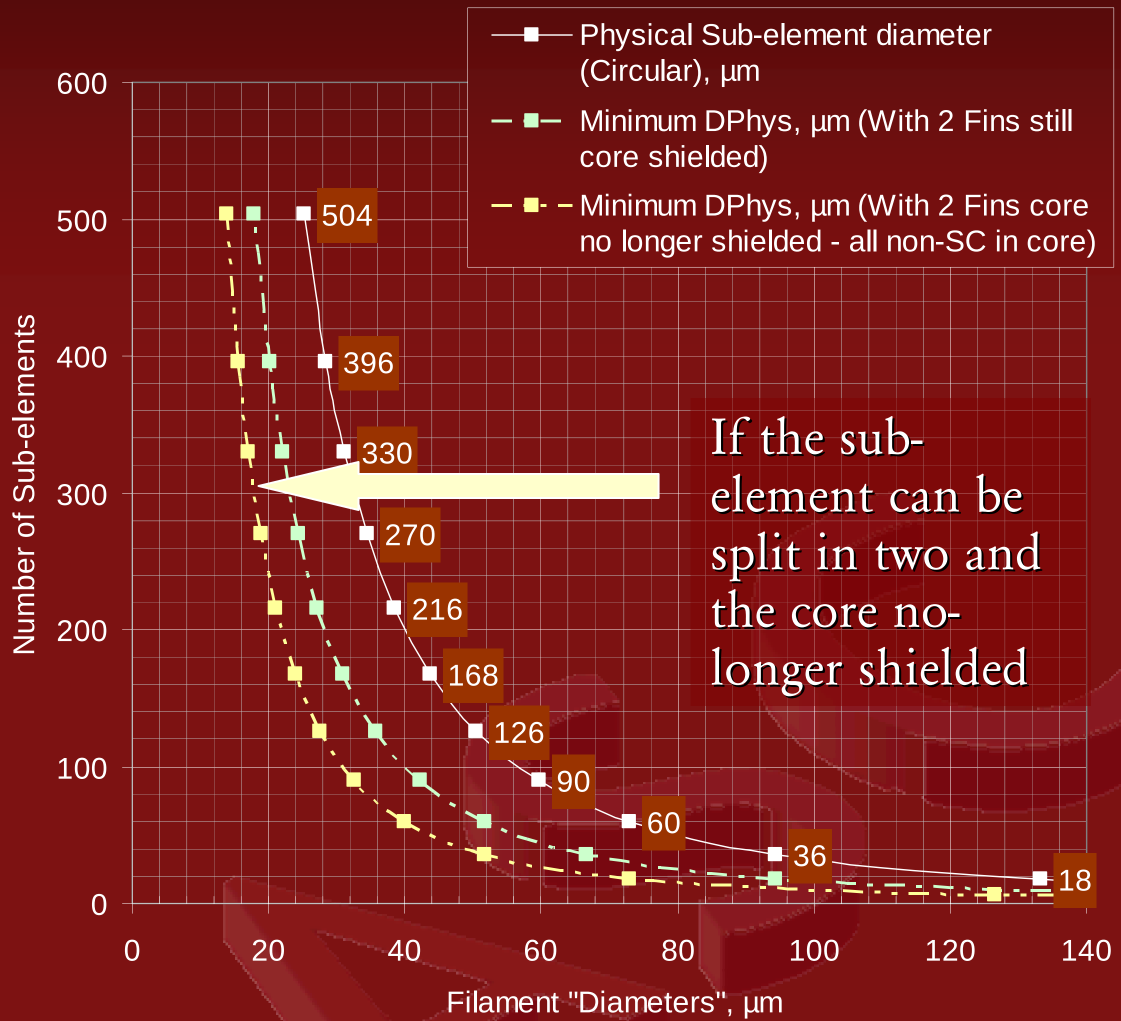




Mike Naus (LTSW '01) and PhD thesis 2002 shows important role of Sn:Nb in determining T_c and H_{c2}:
http://128.104.186.21/asc/pdf_papers/theses/mtn02phd.pdf

Many More Sub-Elements high J_c Sub-Elements Would be Required . . .

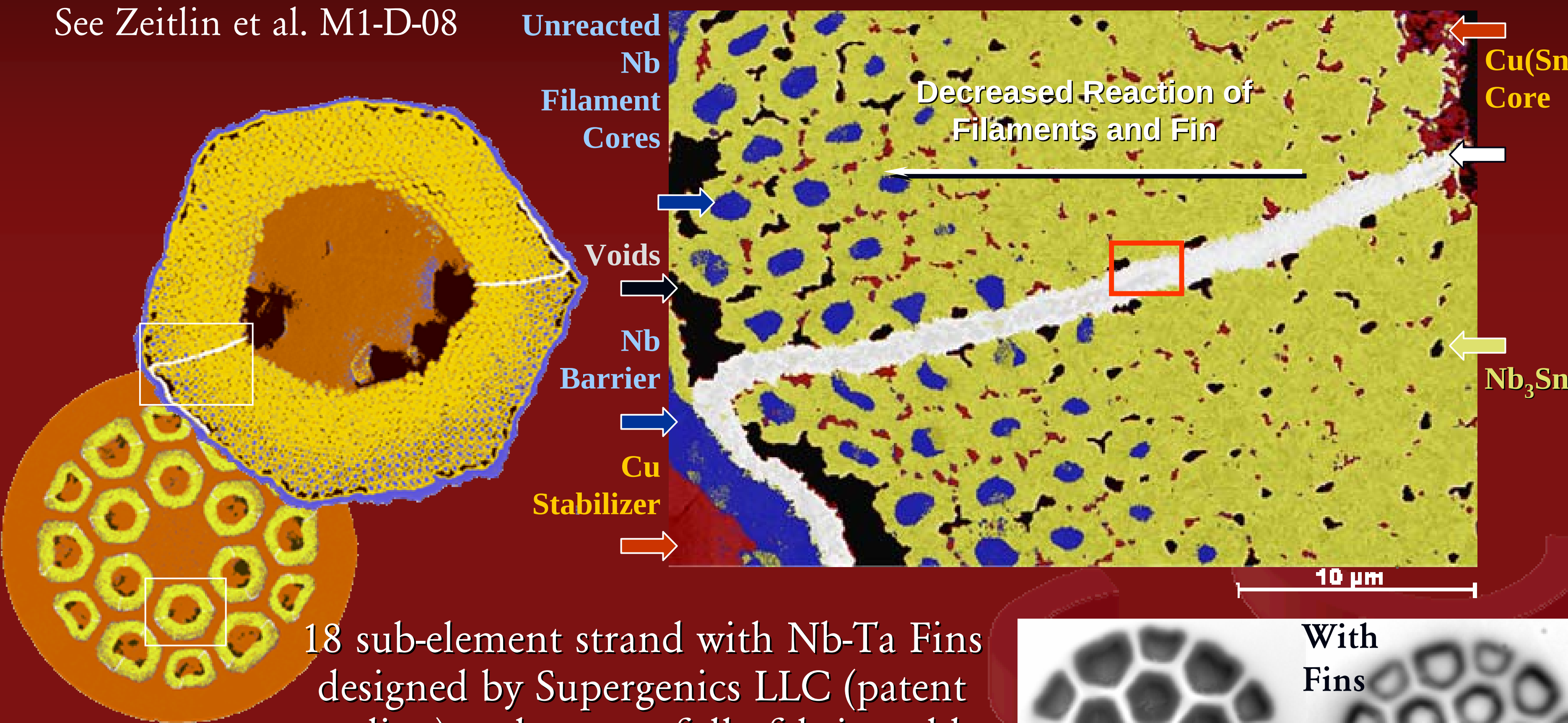
- Effective filament diameter limited by physical sub-element diameters.
- Large number of sub-elements needed – with associated stacking problems – unless the subelements are sub-divided
- Even so, >> 36 subelements required



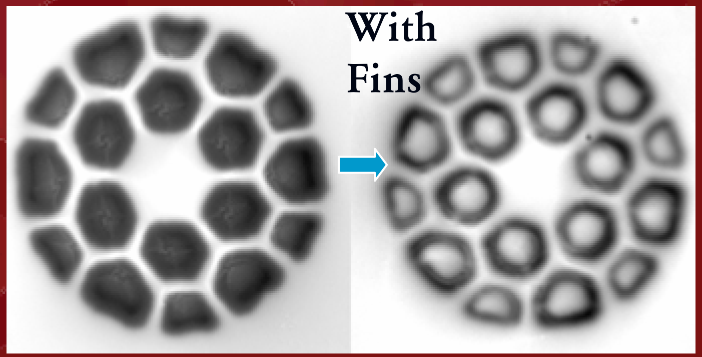
Adapted for D_{eff} Plot by Ron Scanlan at LTSW'02

Attempts are being made to sub-divide

See Zeitlin et al. M1-D-08



18 sub-element strand with Nb-Ta Fins designed by Supergenics LLC (patent pending) and successfully fabricated by OA-AS under a DOE SBIR program.



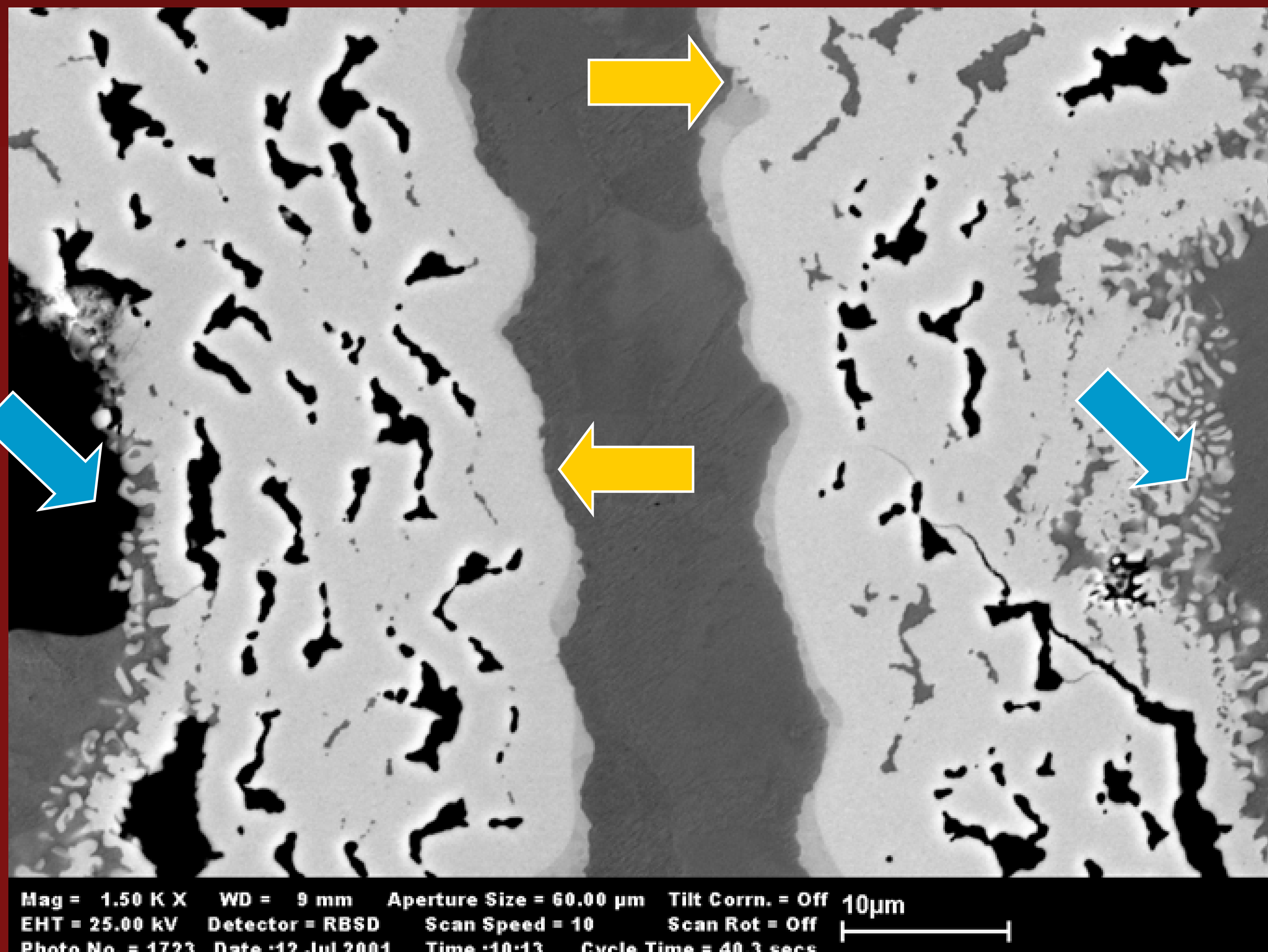
MO imaging reveals dramatic effect of Fin.

Each Fin only 0.8 % of sub-element CSA but absorbs Sn and affects Nb_3Sn grain boundary chemistry – under investigation

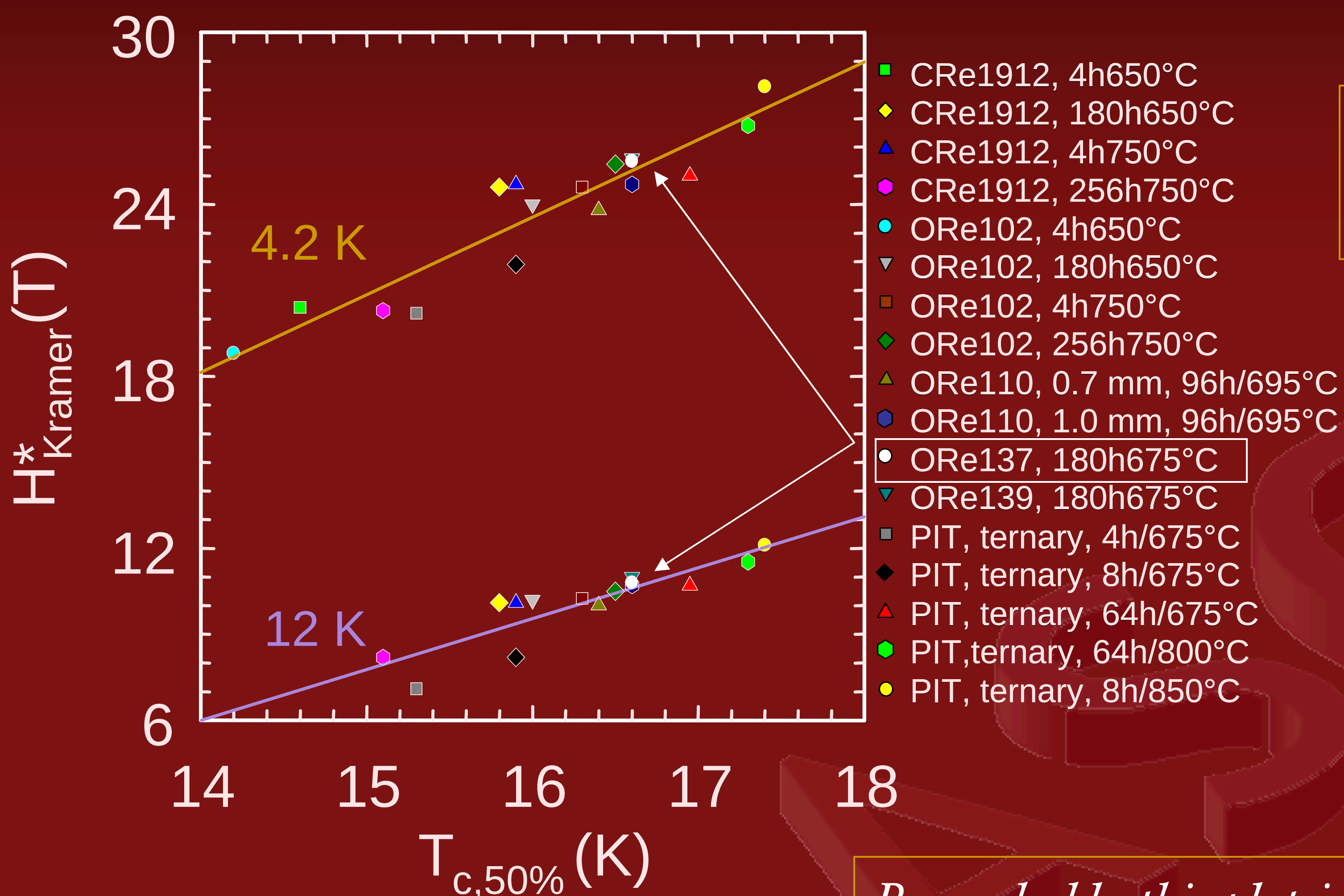
In low-Cu "high J_c" strand – Nb dissolution

Nb dissolution causes loss in contiguous A15 area.

When the Nb barrier is fully reacted, Sn diffuses in the stabilizer Cu - enabling LBNL SC group to control RRR by HT



Mike Naus: Universal Plot of Goodness



Mike Naus: LTSW 2001

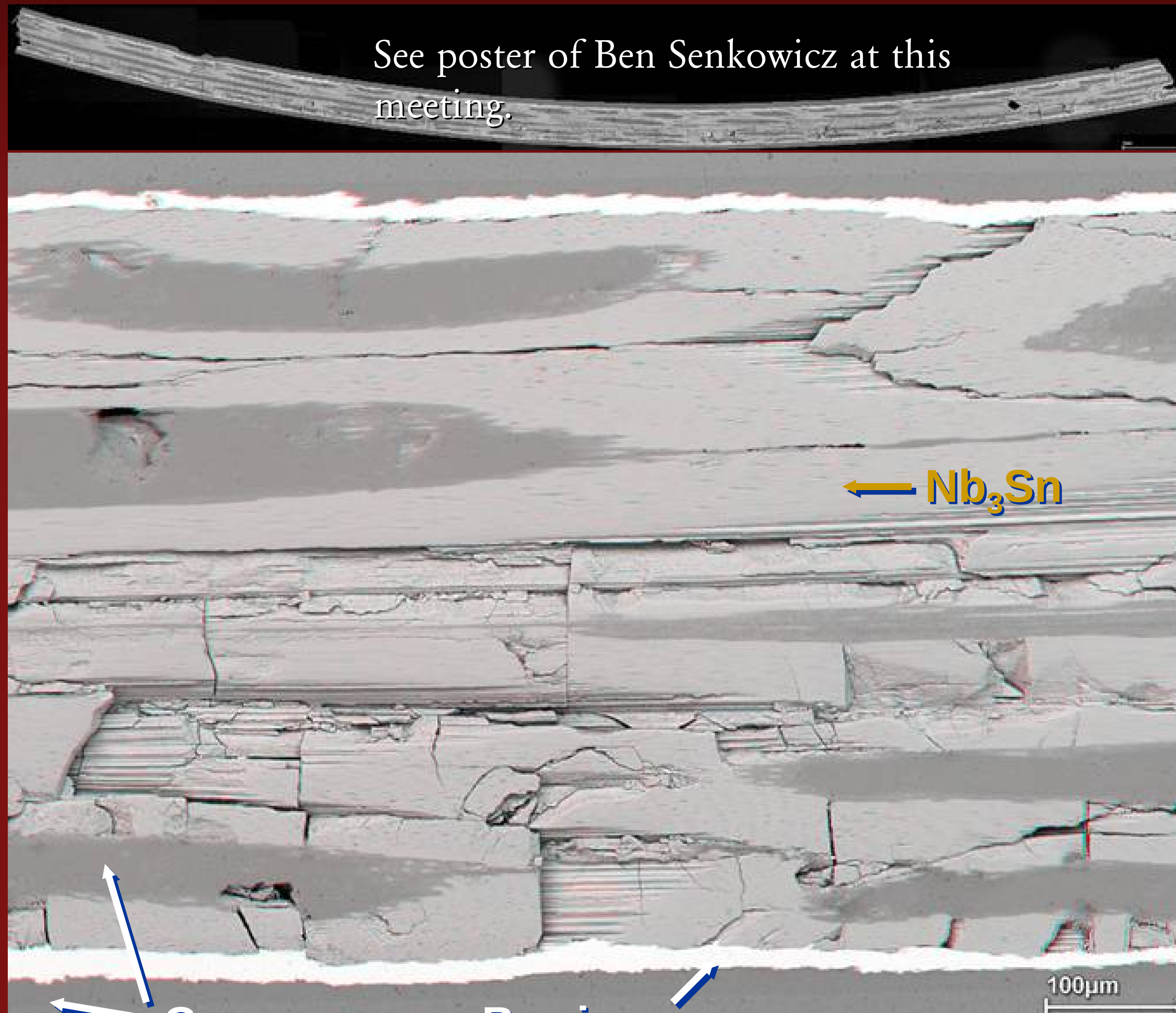
http://128.104.186.21/asc/pdf_papers/theses/mtn02phd.pdf

Remarkably this plot includes non-alloyed, Ta and Ti alloyed Nb_3Sn

High J_c Internal Sn Bend Strain Issues

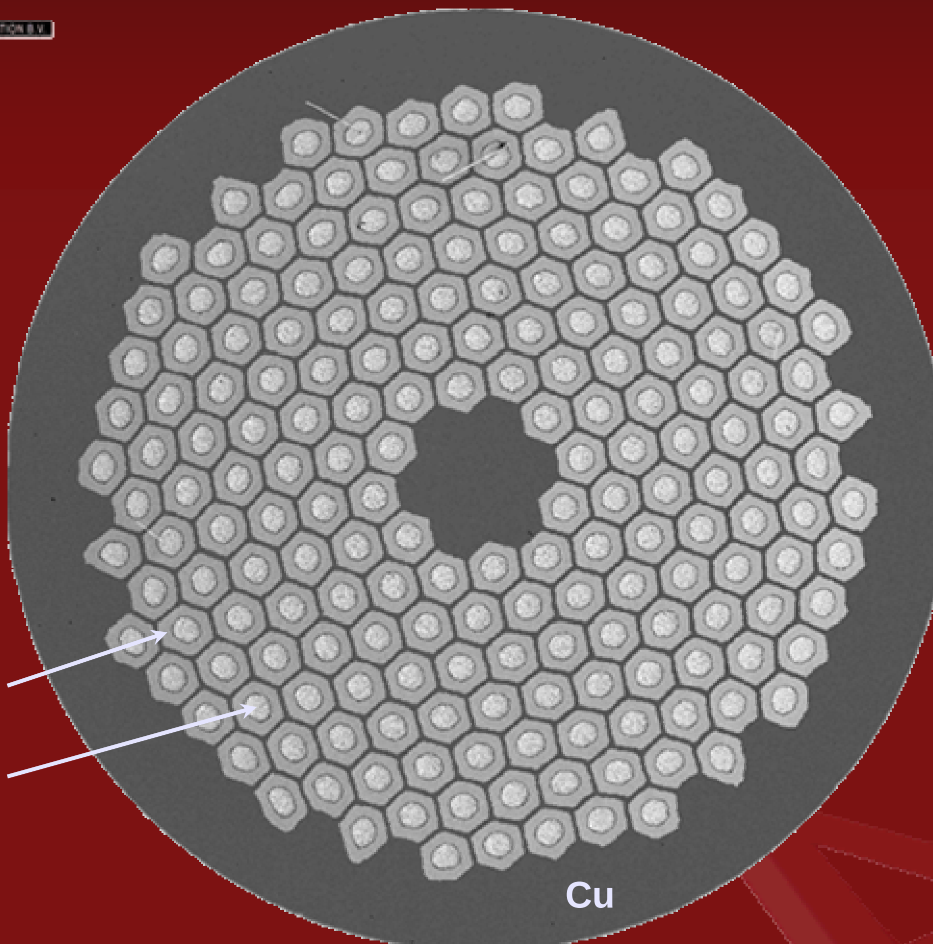
Nb_3Sn is susceptible to filament breakage under small bend strains ~0.5 %

If the Nb_3Sn layer us continuous (as in the prototype IGC-AS strand) breakage spans the entire tensile side.

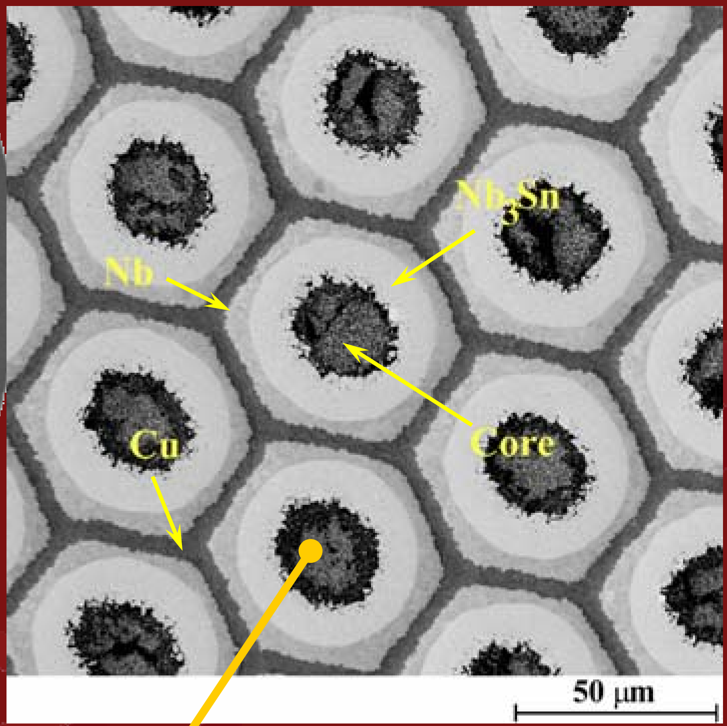


PIT geometry leaves thick unreacted Nb and corners of hexagonal filaments.

Commercial PIT strand is manufactured by Shapemetal Innovation BV, the Netherlands. This process was originally developed by ECN and is termed the ECN process.



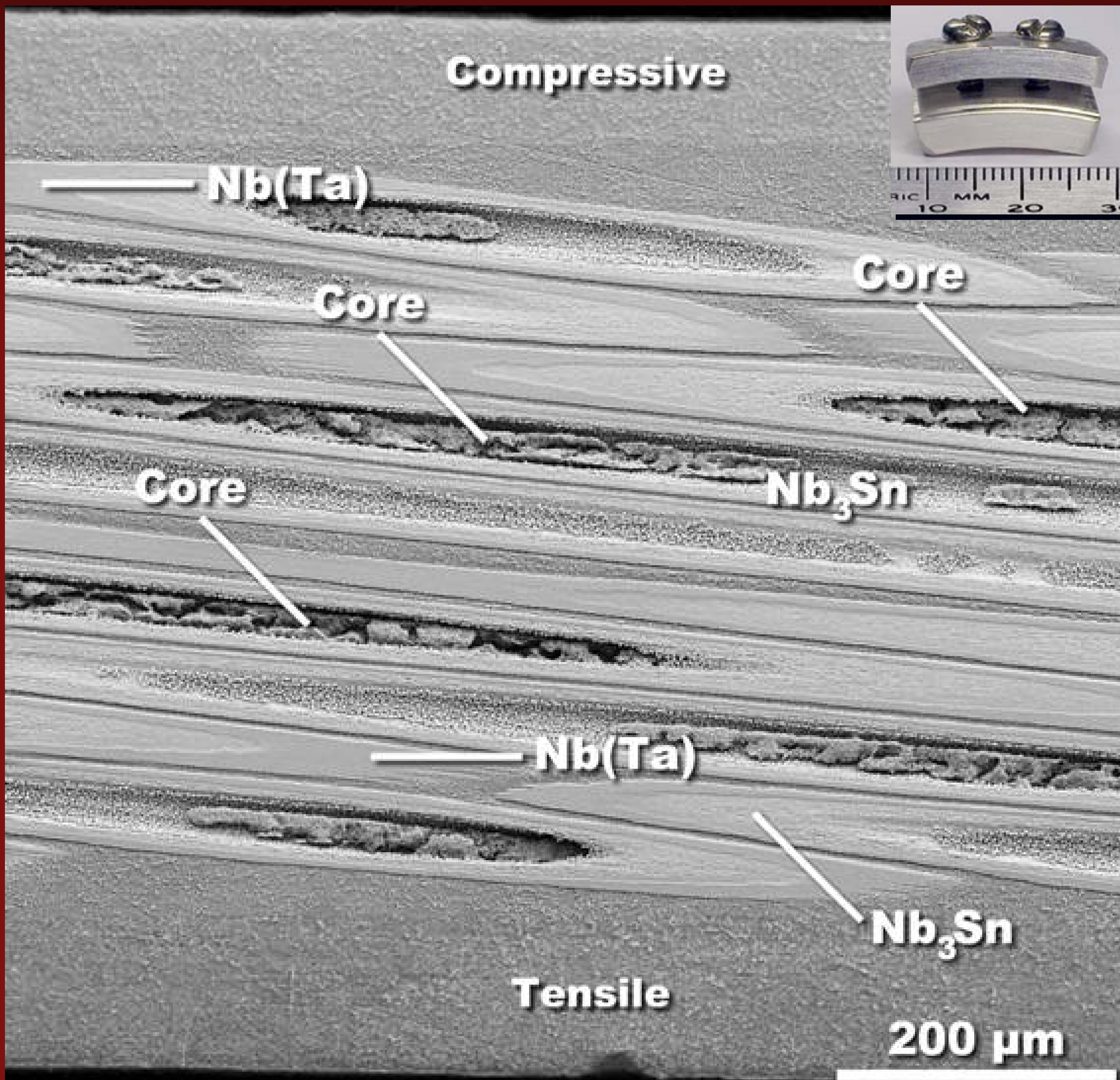
SMI-PIT filaments are otherwise remarkably homogeneous in area cross-section



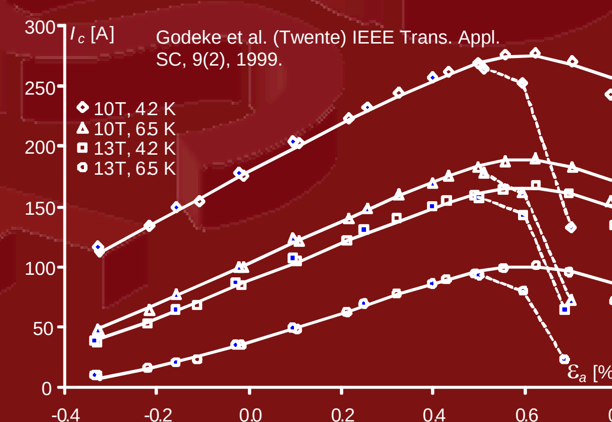
***Before HT*: Homogeneous stack of powder in Nb tubes**

***After HT*: Weakly bonded porous core left inside A15**

Powder-in-tube Nb(Ta): Twisted, 0.5% bend



- No cracking seen at 0.5% strain (eventually cracks at 0.6%)
- Although the Nb layer reduces the efficiency of the non-Cu package it applies more precompression to the A15



Matthew C. Jewell, Peter J. Lee and David C. Larbalestier, "The Influence of Nb_3Sn Strand Geometry on Filament Breakage under Bend Strain as Revealed by Metallography", Submitted at the 2nd Workshop on Mechano-Electromagnetic Property of Composite Super-conductors, for publication in Superconductor Science and Technology (SuST), March 3rd 2003. http://www.cae.wisc.edu/%7Eplee/pubs/pjl-mcj-mem03-sust.pdf

Summary: Nb_3Sn Advances

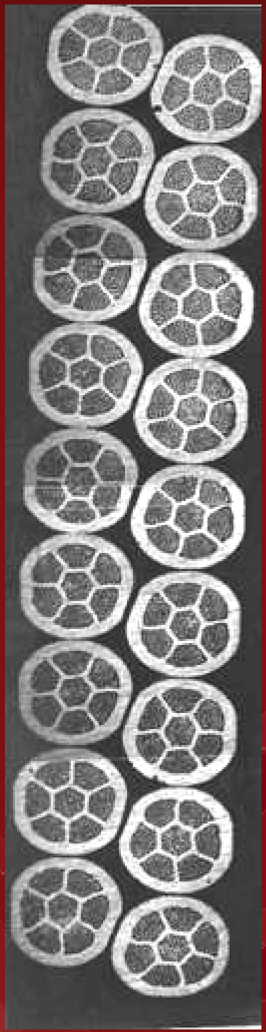
- Remarkable improvements in the critical current densities (layer and non-Cu) of Nb_3Sn have been observed in Nb_3Sn strand fabricated by the PIT and Internal Sn process since ITER-CSMC.
- These advances will be very difficult to apply to low loss strand.
  - Internal Sn: Successful sub-element sub-division technology would need to be developed
  - PIT: Advances in powder size refinement required (as well as cost reduction). Cost reduction is being examined by the EAS co-operative agreement with SMI.

Other High Field Superconductors

- Bi2212
  - Highest Critical Currents above 14 T
  - Flat J_c vs B
- Nb_3Al (Not covered here)
  - High Strength
  - High Critical Current Densities possible
  - Like Nb_3Sn, high J_c strand very different from low loss ITER strand.
- MgB_2
  - Only 2 years old, HTS is now a venerable 17 years!
  - Very low cost raw materials, Ag not required.
  - With improved H_{c2} provides both temperature and field margin.

Bi-2212 round wire has been cabled for accelerator magnets.

- J_c(12 T, 4.2 K, non-silver) > 2000 A/mm^2 in new material.
- Long lengths(> 1500 m) are being produced.
- J_c vs strain for Rutherford cables looks promising (LBNL results).
- React/wind (BNL) and Wind/react (LBNL) coils are being made.



Accelerator Cable made at LBNL From Showa strand

Ron Scanlan (LBNL) ASC2002

OI-ST Bi2212 high J_E strand

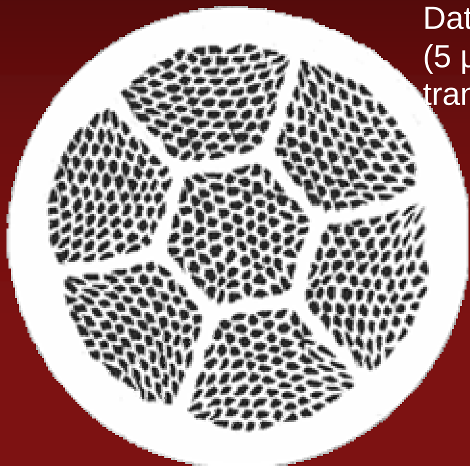


Image courtesy of K.Marken OI-ST

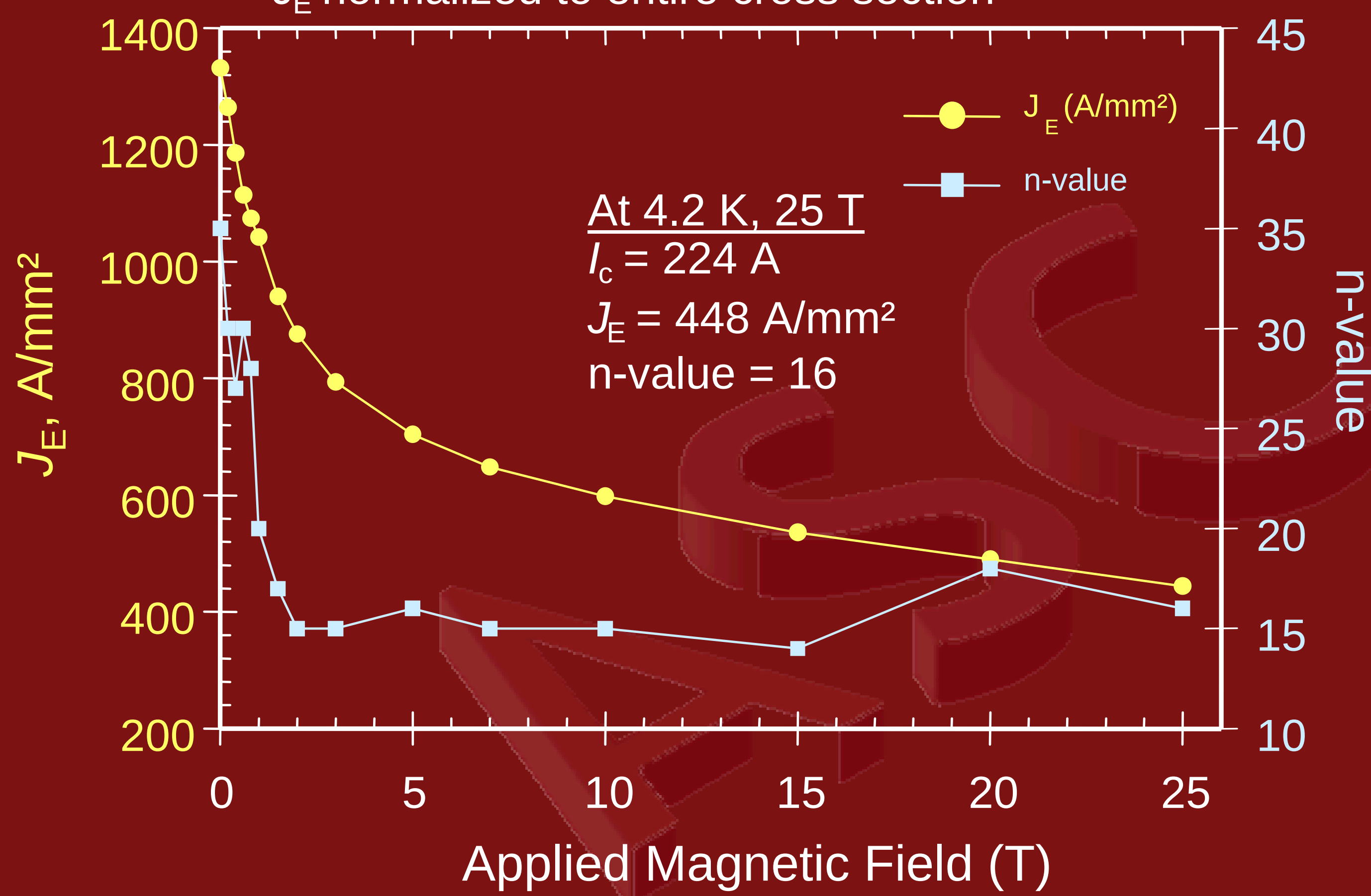
In the US OI-ST is still improving on their Bi-2212 round wire – they expect to report further improvements based on better powder

Data by Huub Weijers at NHMFL (5 µV/cm). ~20 mm long sample measured transverse in a 33T Bitter magnet

OST 2212 Wire Billet PMM030224

0.8 mm diameter, 28% superconductor

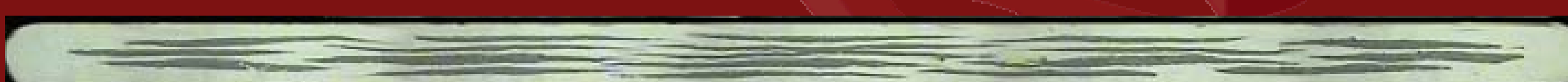
J_E normalized to entire cross section



25T Bi-2212 magnet

OST-NHMFL
25 T Demonstration
Using 5 T HTS Insert

- HTS magnet adds 5 T to 20 T background
- Tested in 20 T, 200 mm Large Bore Resistive Magnet at NHMFL
- **25.04 T** central field is the record field achieved in a superconducting magnet
- Clear bore is 38 mm, OD is 167 mm
- 3 coil sections: 2 inner stacks of double pancakes and an outer layer wound coil
- Contains approximately 2.4 km of OST 19 filament 2212 tape 5 x 0.2 mm



MgB_2: first 2-gap superconductor

Fermi surface from **out-of-plane** π-bonding states of B p_z orbitals:

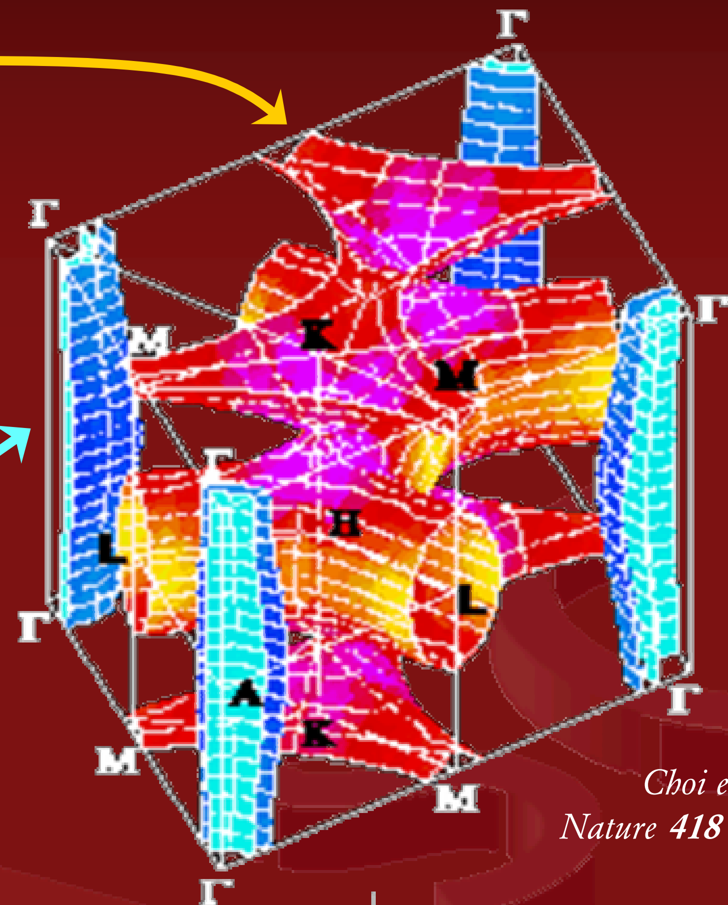
$\Delta_\pi(4.2K) \approx 2.3$ meV

small gap

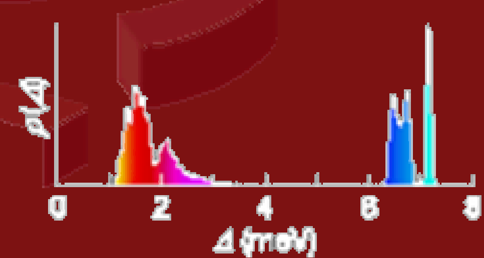
Fermi surface from **in-plane** σ-bonding states of B p_{xy} orbitals:

$\Delta_\sigma(4.2K) \approx 7.1$ meV

large gap

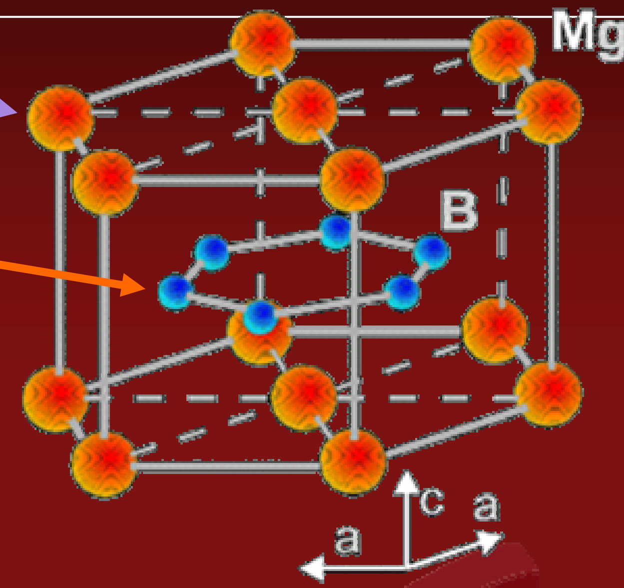


Choi et al., Nature ***418*** *(2002) 758*



Tunable impurity scattering

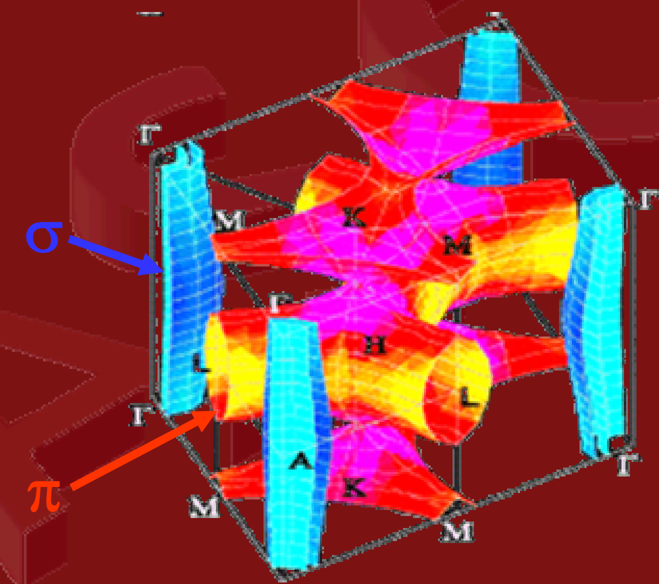
- Mg - substitution: 3D intraband π scattering
- B - substitution: 2D intraband σ scattering
- Weak interband scattering
- Selective atomic substitution produces quenched impurity or vacancy structures



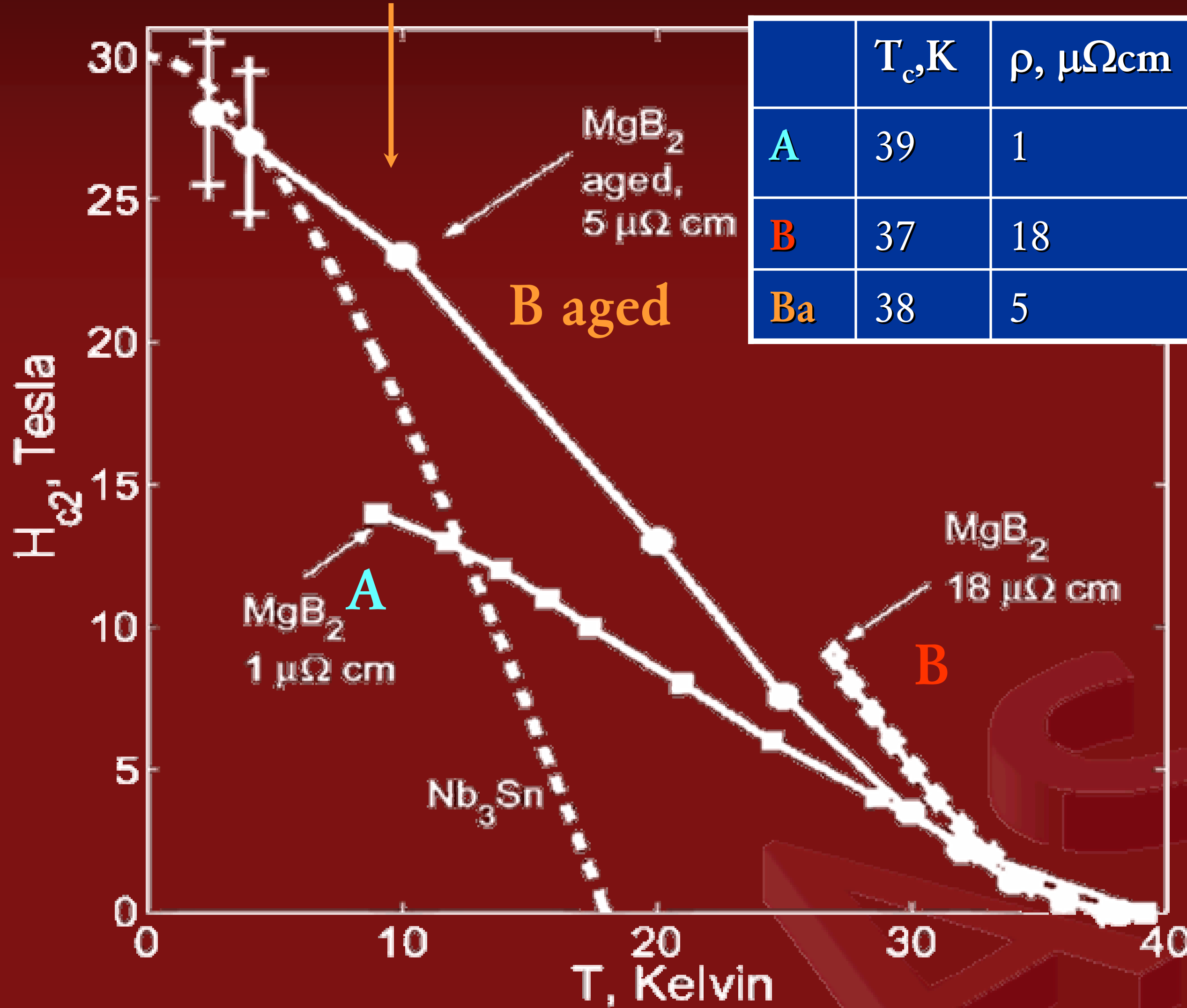
Anisotropic intraband electron diffusivities:

$$D_\sigma^{(c)} \ll D_\sigma^{(ab)}, \quad D_\pi^{(c)} \approx D_\pi^{(ab)}$$

$D_\sigma^{(ab)}/D_\pi^{(ab)}$ is a variable material parameter



Enhancement of Upper critical field possible . . .



	T_c,K	ρ, μΩcm	RR	dH_{c2}/dT
A	39	1	15	0.5
B	37	18	3	1.2
Ba	38	5	5	1

Untexured bulk samples suggest that MgB_2 is capable of >30 T at 4.2 K and >10 T at 20 K.

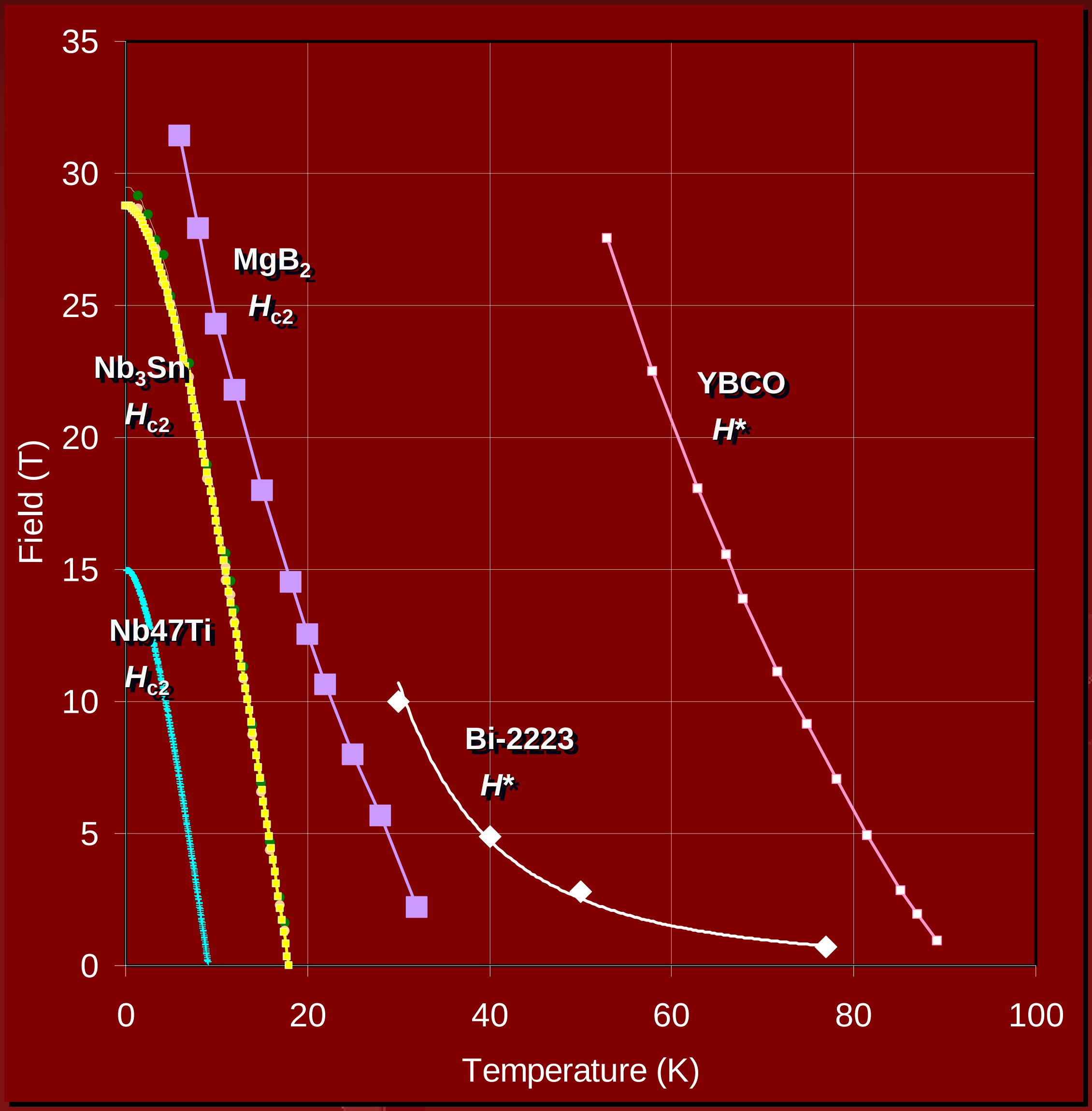
33 T resistive magnet at the NHMFL in Tallahassee, FL

V. Braccini et al. APS2003
A. Gurevich submitted

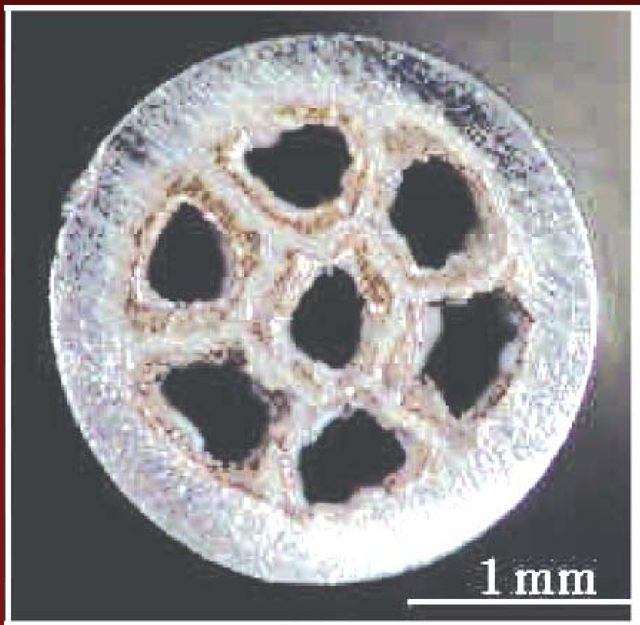
Upper critical fields (H_{c2}) and irreversibility fields (H^*)

- For MgB_2, Bi-2223 and YBCO the values plotted are the lower values appropriate to fields perpendicular to the strongest superconducting planes, the B planes for MgB_2 and the CuO_2 planes in the cuprates. Values plotted are the highest credible for each compound.

- H^* is 85-90% of H_{c2} for Nb47wt.%Ti, Nb_3Sn, and MgB_2 but much lower than H_{c2} cuprate superconductors.



Multifilament MgB_2 wires: Very Early Stages

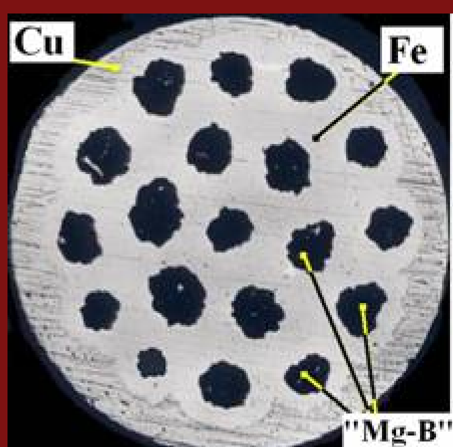


Multifilament wire produced by Giunchi et al. [46]

Multifilament wire produced by Hypertech [26]

~5mm

UW extrusion



Akimov 4D-p79 – 100m lengths

Many groups have made prototype MgB_2 wires by scalable, metal-working routes - see Flukiger Physica C 385, 286-305 (2003)

MgB2 and Neutron Irradiation

- ^{10}B (19.9%in natural boron) has a large capture cross-section.
- Neutron irradiation induces defects mainly by neutron capture of ^{10}B followed by the emission of an α particle.
- However the induced defects enhance mainly the normal state resistivity and therefore the upper critical field. ***Eisterer et al.*** *Supercond. Sci. Technol.* ***15*** *(2002) L9-L12*

Summary

- There has been a breakthrough in Nb_3Sn critical current density since ITER-CSMC but applying that breakthrough to ITER strand will require new processing techniques.
- Bi-2212 continues its steady progress in J_c but will remain of limited high field application because of its high cost.
- MgB_2 is a potential breakthrough conductor for ITER but is a long way from being a low hysteresis loss strand.