Bi-2212 Superconductors For High Field Magnet Use at the NHMFL

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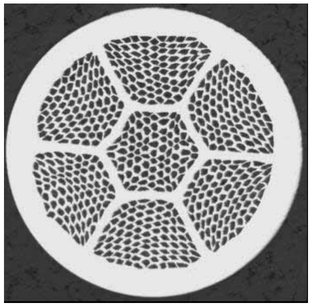
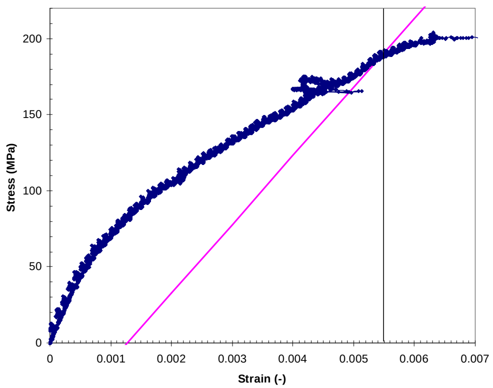
- **Our Goals**
  - NHMFL spends $6M per year on electricity with 20 MW magnets (~$1000/hr in electric costs)
    - Standard magnet is 33-35 T in 32 mm warm bore
      - 31 T in 50 mm bore
      - 20 T in 200 mm bore
      - 45 T (32mm warm bore) hybrid uses 11.5 T Nb_3Sn outsert
- **A 7T magnet to take us to 25-30T**
- **Present challenges**
  - Conductor technology
    - Understand and enhance Jc
  - Coil technology
    - Intense reactivity of conductor and leakage
    - Low strain tolerance of conductor
- **Next steps**

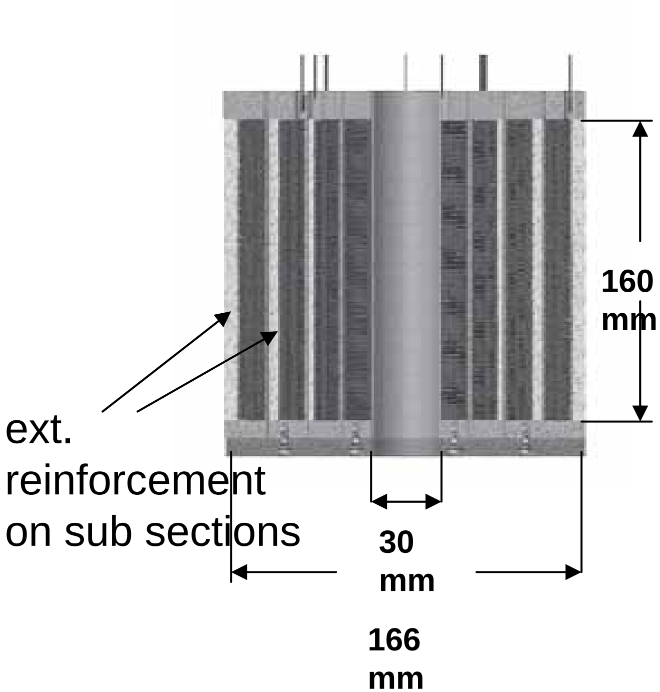
Our present plans

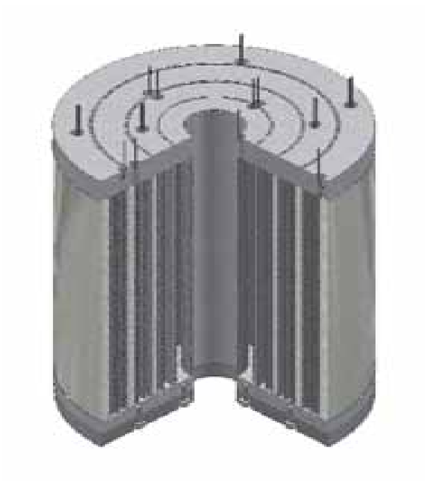


- **7T 2212 round wire magnet operating in background of 19T 20cm bore Florida Bitter (Ulf Trociewitz)**
- **YBCO tape magnet to make > 30T (Denis Markiewicz) – 26.8T achieved with SuperPower in 2007**



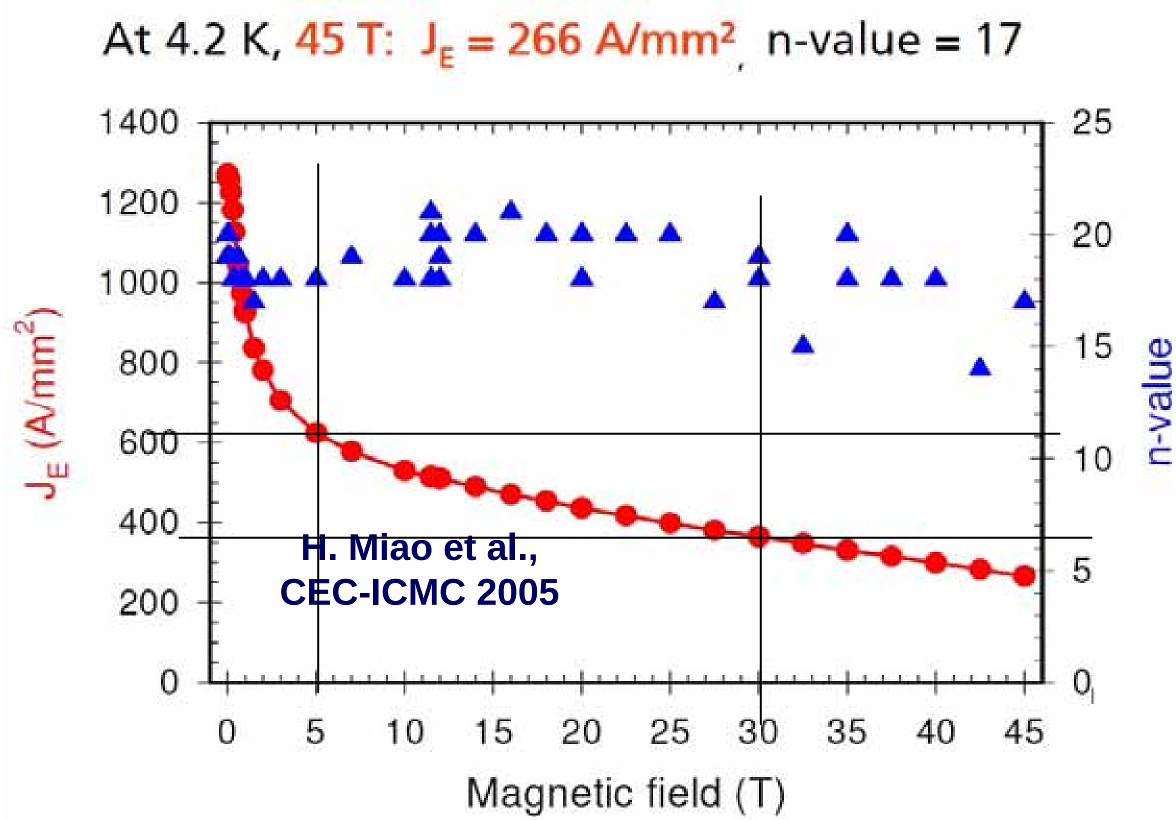
Weak conductor – plastic at ~ 100 MPa





Trociewitz

High current density in spite of poor texture

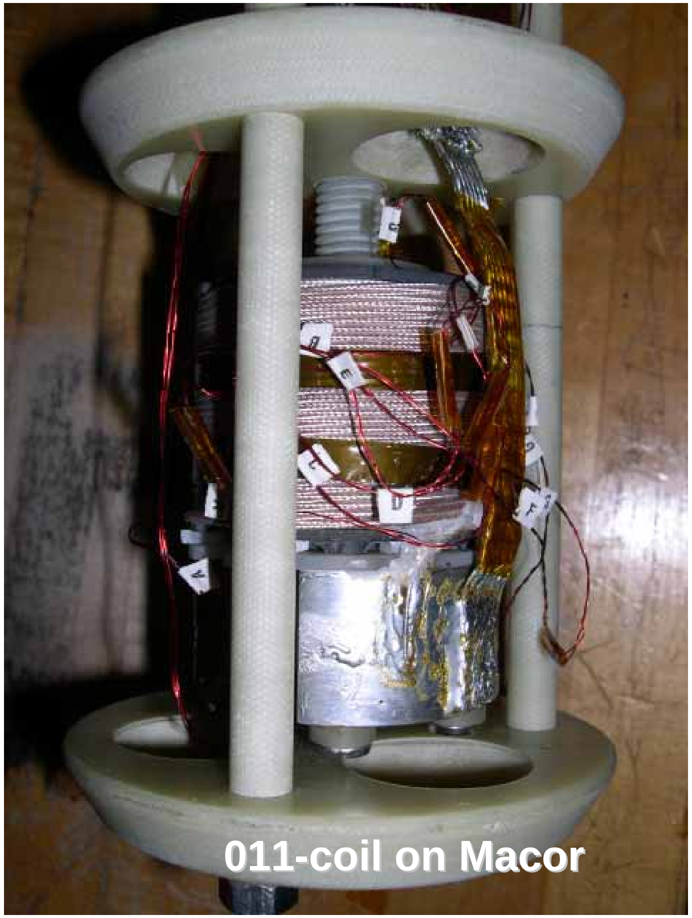


625 A/mm^2 at 5T

360 A/mm^2 at 30T

- **For Bi2212 round wires, poor texture doesn't always mean low J_c**
- **Recently, J_e = 266 A/mm^2 (J_c = 930 A/mm^2) at 4.2 K and 45 T**
- **Why is J_c of Bi2212 round wires so high?**

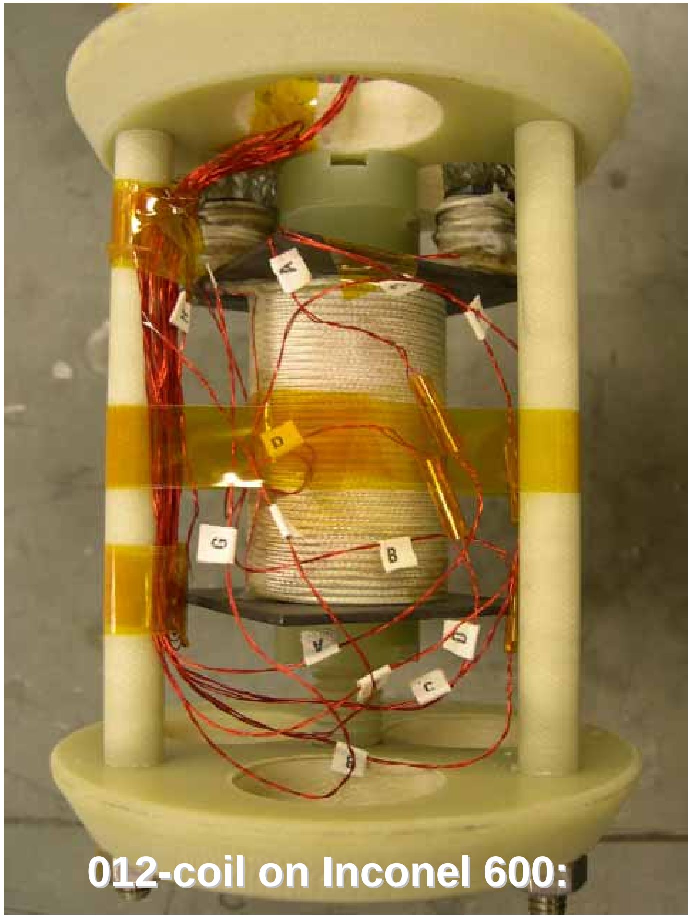
12 Test Coils processed at ASC in 2007 (11/12 leaked)



ID: 32.4 mm, OD: 56.4mm, total turns: 295, 10 layers

Wire length: ~ 44 m, PMM070214_1a

One leak after HT



ID: 25.4mm, OD: 35.0mm, total turns: 154, 4 layers

Wire length: 14.6m, PMM060811-1

no visible leakage

Trociewitz

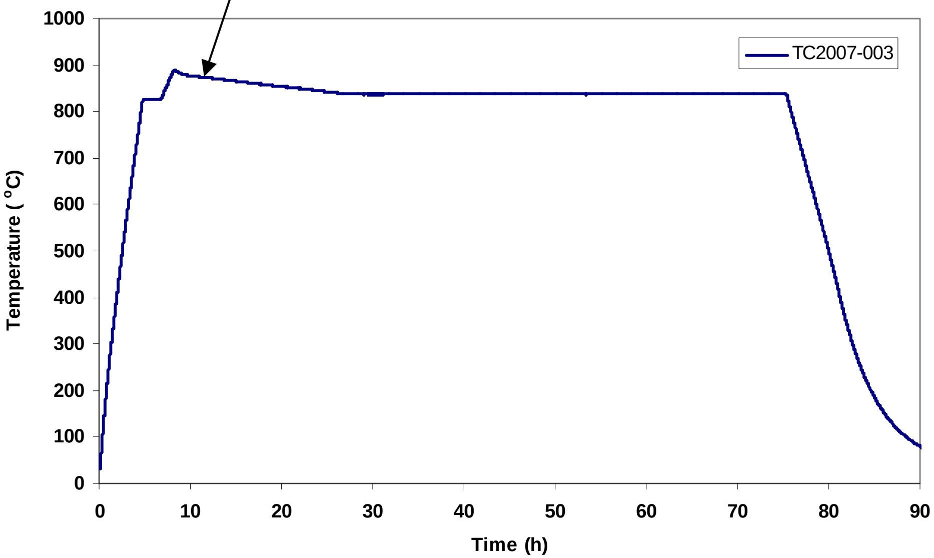
Critical Currents of Coils Varied Strongly
1 mm wire: Ic 60-281 A in 5T background

TC2007-	OST-batch	layers	turns/layer	HT	process gas	flow rate (l/min)	Tm (oC)	tm (h)	apparent leaks?	coil Ic(B=5T), 4.2 K	comment
1	PMM050629-2	10	12	3/9/2007	O2	0.5	890.6	0.2	y	n/a	not characterized as coil
2	PMM060811-1	10	12	4/5/2007	O2	0.5	891.6	0.2	y	n/a	not characterized as coil
3	PMM060811-1	10	12	4/17/2007	O2	0.5	888	0.2	y	213	
4	PMM060811-1	10	12	4/24/2007	O2	0.5	884.8	0.2	y	199	
5	PMM060811-1	10	12	5/1/2007	O2	0.5	882	0.2	y	60	
6	PMM060811-1	10	12	5/14/2007	O2	0.5	882.4	0.4	y	165	
7	PMM060811-1	10	12	5/18/2007	O2	0.5	890.7	0.2	y	175	
8	PMM060811-1	10	12	6/6/2007	O2	0.5	883	0.6	y	167	
9	PMM060811-1	10	12	6/26/2007	O2	0.5	883	1.2	y	151	
10	PMM060811-1	10	12	/7/2007	O2	1	890	0.2	y	210	HT at OST
11	PMM070214_1a	10	30	8/14/2007	O2	1	888.7	0.2	y	220	
12	PMM060811-1	4	38.5	/8/2008	O2	1	890	0.2	n	281	wound and HT at OST

Coil I_c: 60-281A in 5T background.

Expected Ic: 2x higher, based on OST benchmark for 0.8mm wire.

Highest J_E = 343 A/mm^2 at 5T, compared to expected 625 A/mm^2 for standard 0.8 mm dia. short samples



Trociewitz and Jiang

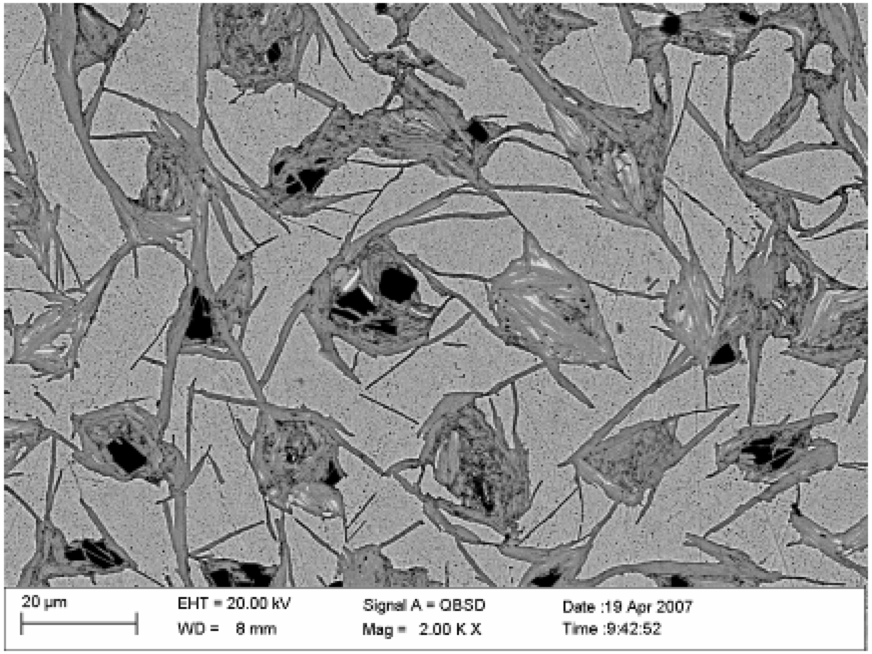
Threats to high field magnet goals

- **Too low a Jc**
  - **Why? Is Jc being lost due to:**
    - **Use of 1 mm dia wire to minimize packing fraction loss due to thick mullite insulation on wire optimized for 0.8 mm diameter**
    - **Loss of connectivity or unoptimized flux pinning?**
- **Reactions between wire and insulation**
- **Leakage of BSCCO through Ag**
- **Self damage during magnet energization**
  - **Conductors must be reinforced for stresses of ~100 MPa (or perhaps less)**

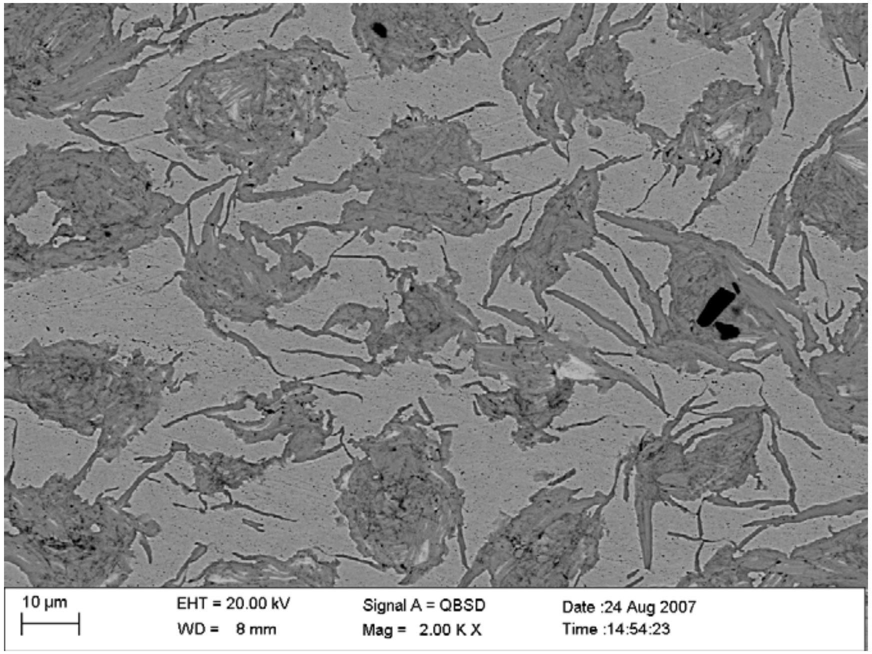
All work has been done on OST conductors using the BSCCO composition developed by Mark Rikel (Nexans) - $Bi_{2.17}Sr_{1.94}Ca_{0.89}Cu_{2.00}O_x$

Microstructure (wire short sample (2800 A/mm^2) vs. coil section 900 A/mm^2)

W521-3, 0.8mm, short and straight
J_c (4.2K, 5T) = 2880 A/mm^2
889°C/0.2 hrs



Test coil section from TC2007-003,
1.0mm dia wire J_c (4.2K, 5T) = 900
A/mm^2 888°C/0.2 hrs



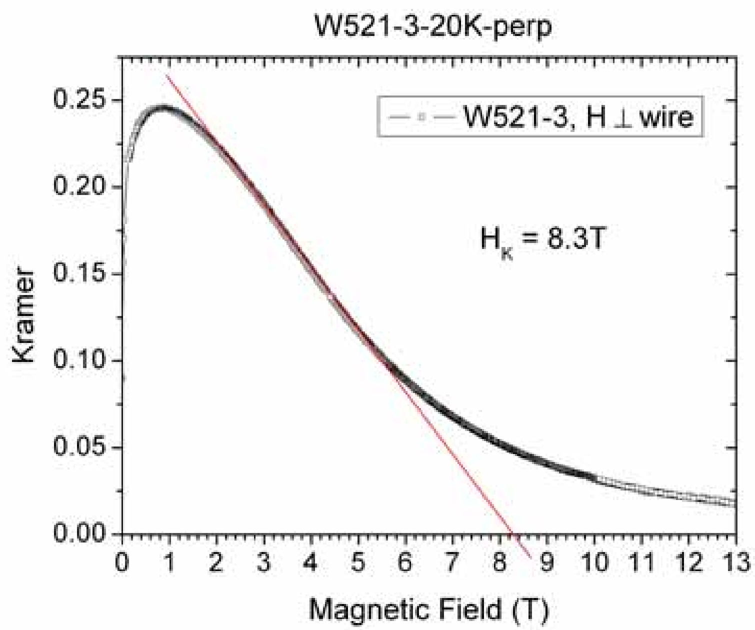
Almost a factor of 3 loss of Jc! Why?

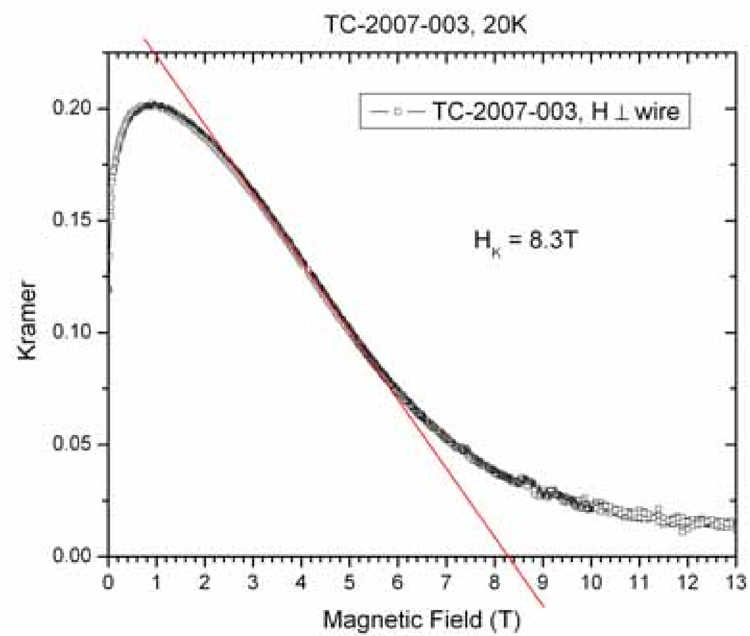
Jiang and Trociewitz

Is Jc difference due to loss of connectivity or of quality of 2212?

W521-3, 0.8mm, short and straight
J_c (4.2K, 5T) = 2880 A/mm^2
889°C/0.2 hrs

Test coil TC2007-003, 1.0mm
J_c (4.2K, 5T) = 900 A/mm^2
888°C/0.2 hrs

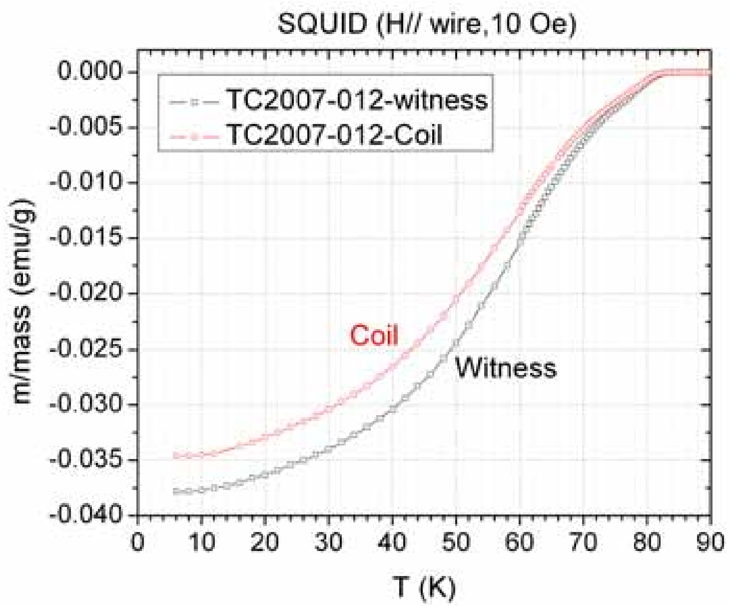


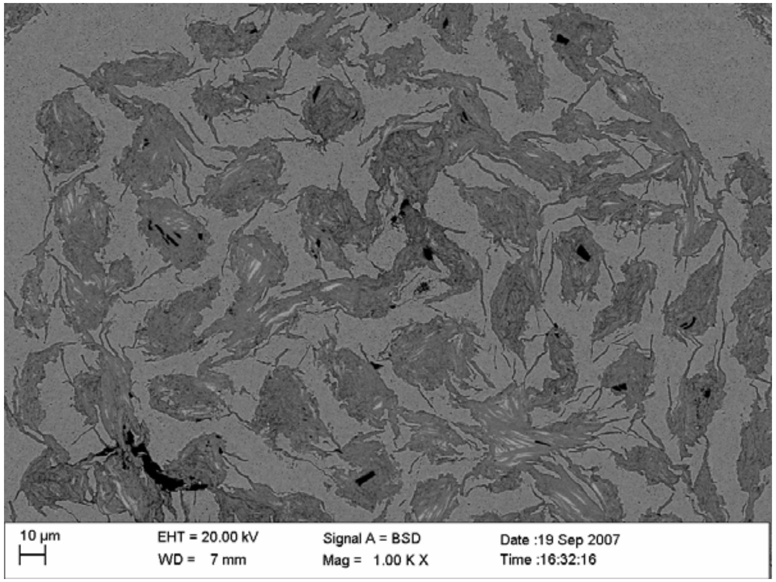


Because H_K is independent of Jc, we conclude that connectivity is the key variable, not vortex pinning

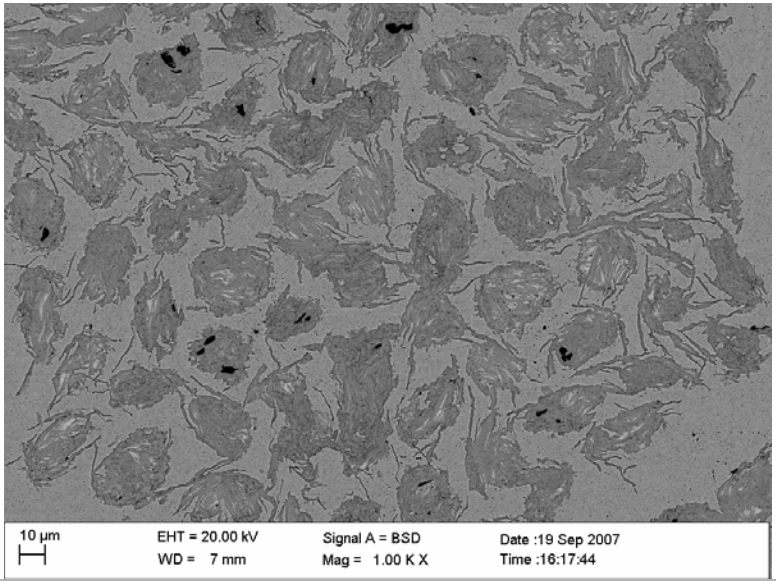
Jiang

T_c - Coil vs. Short Witness Sample





Coil



Witness

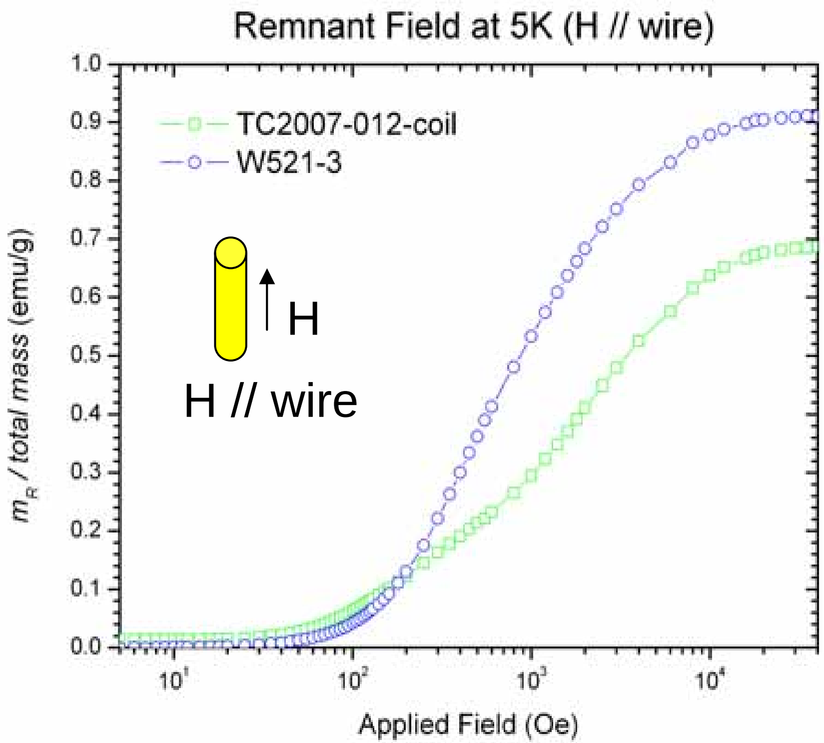
T_c transitions are not sharp!

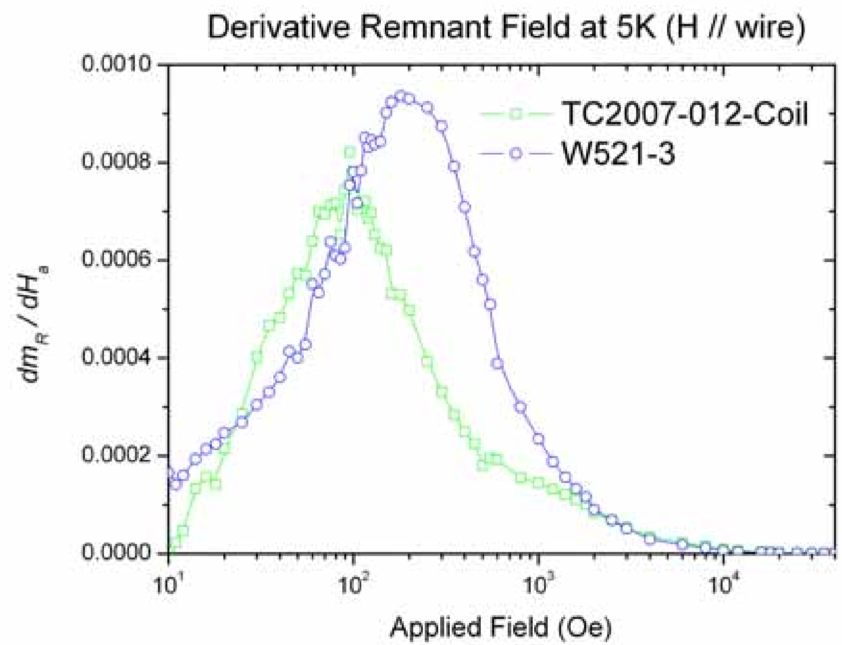
Witness short sample has higher moment at 4K than coil

Filament morphologies are not identical

Jiang

Remnant Magnetization Measurement



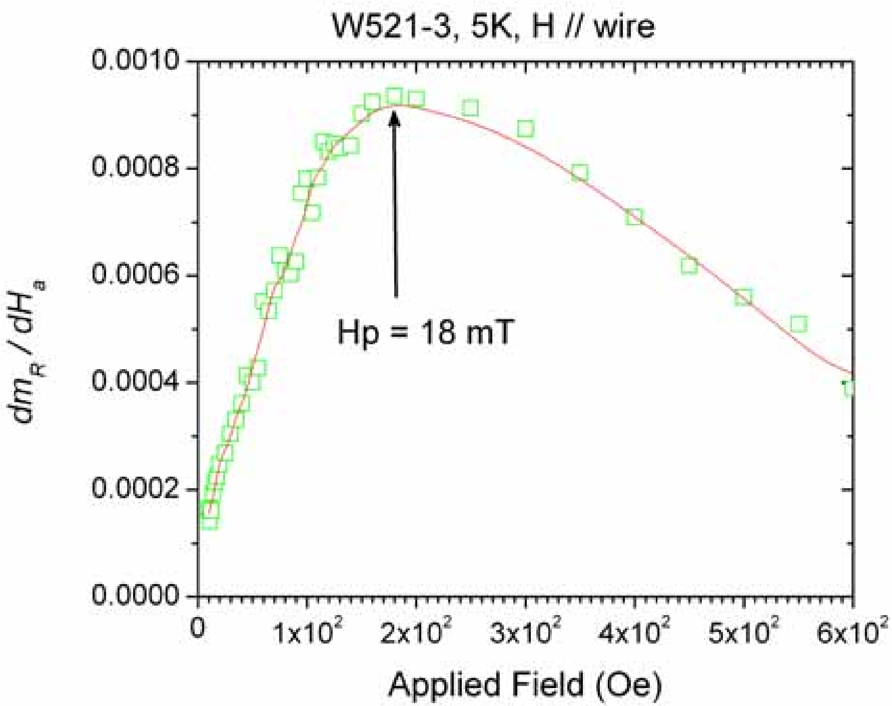


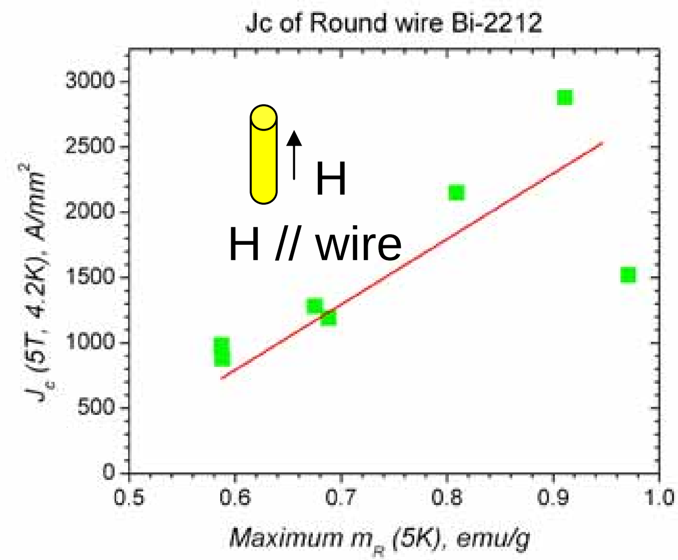
Flux enters the coil sample more easily than the good short sample - saturated m_R and the dm_R/dH peak position are higher for the higher Jc sample W521-3.

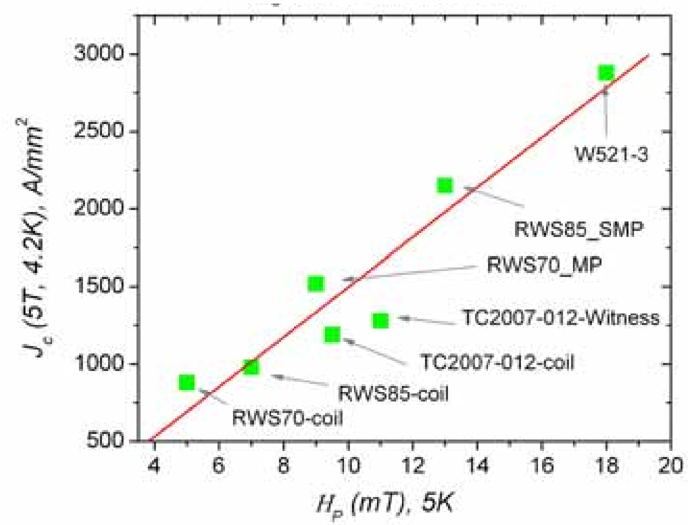
But there is no obvious low field intergrain peak separated from an intragrain peak – conclusion: connectivity is on a continuous spectrum

Jiang and Yamamoto

Connectivity of RW 2212 is better than for any other HTS – but not perfect! It determines Jc (4.2K, 5T) and is easily degraded!



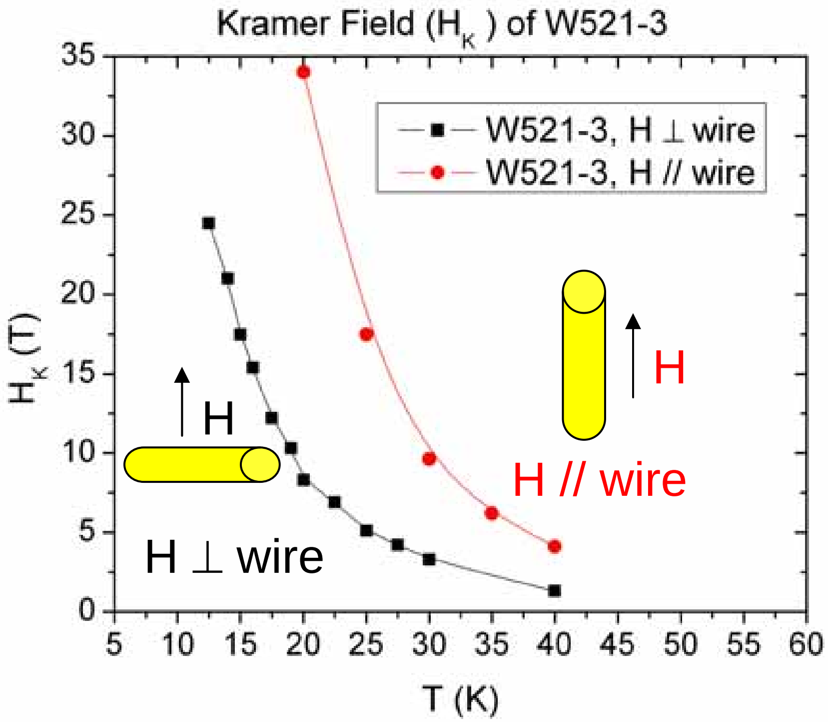


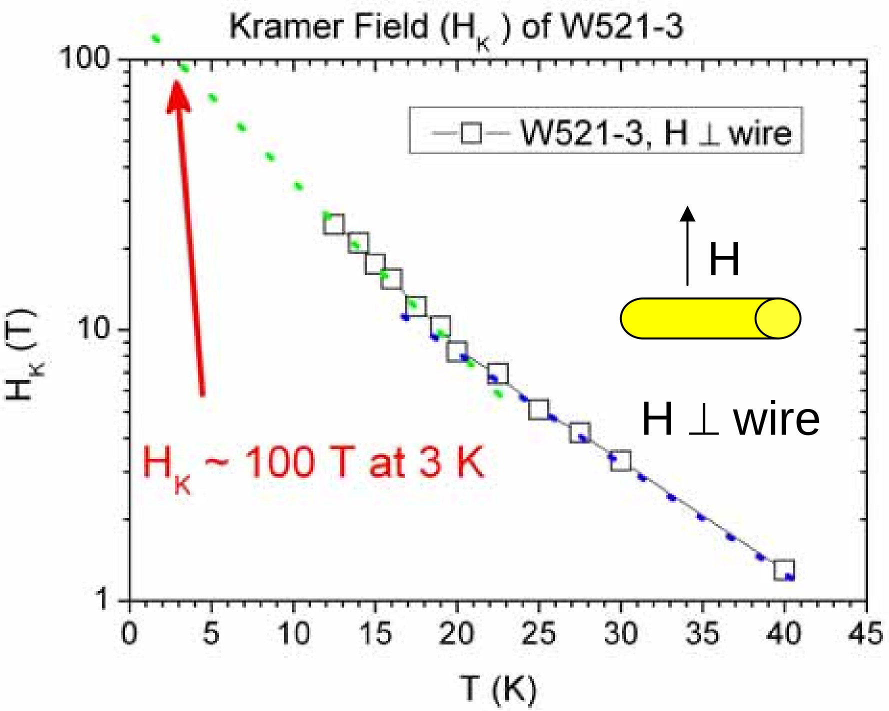


Jc correlates well to both m_R and to H_p, both of which are lower when conductors are less well connected.

Jiang and Yamamoto

How high is H_K at 4.2 K?



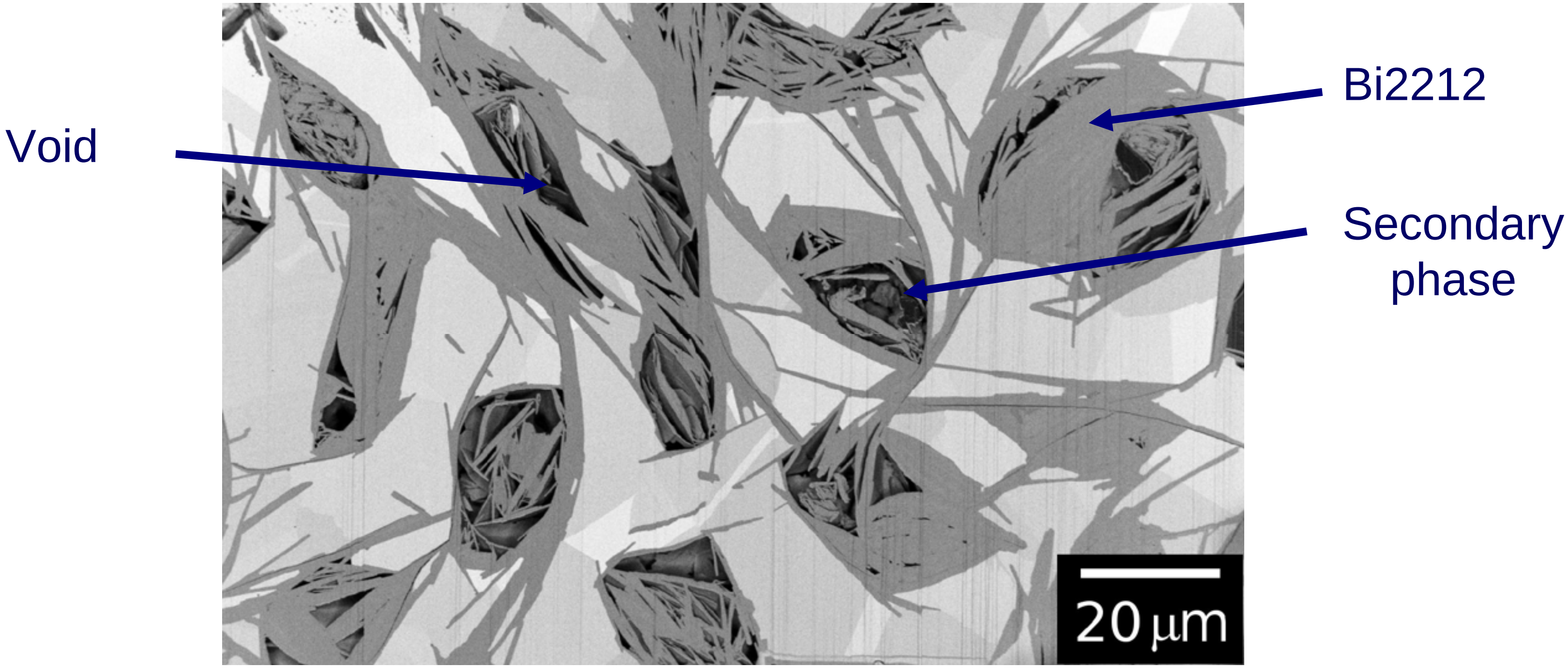


The Kramer field (Jc tends to zero) is lower for longitudinal currents than for azimuthal currents – connectivity problems do exist!

Compared to Nb_3Sn with H_K(2K) ~ 27T, Bi-2212 has enormous headroom

Jiang

Many filament bridges in RW Bi-2212



- Many voids and secondary phases in the center of filaments
  bad for connectivity
- But many bridges across the filaments too

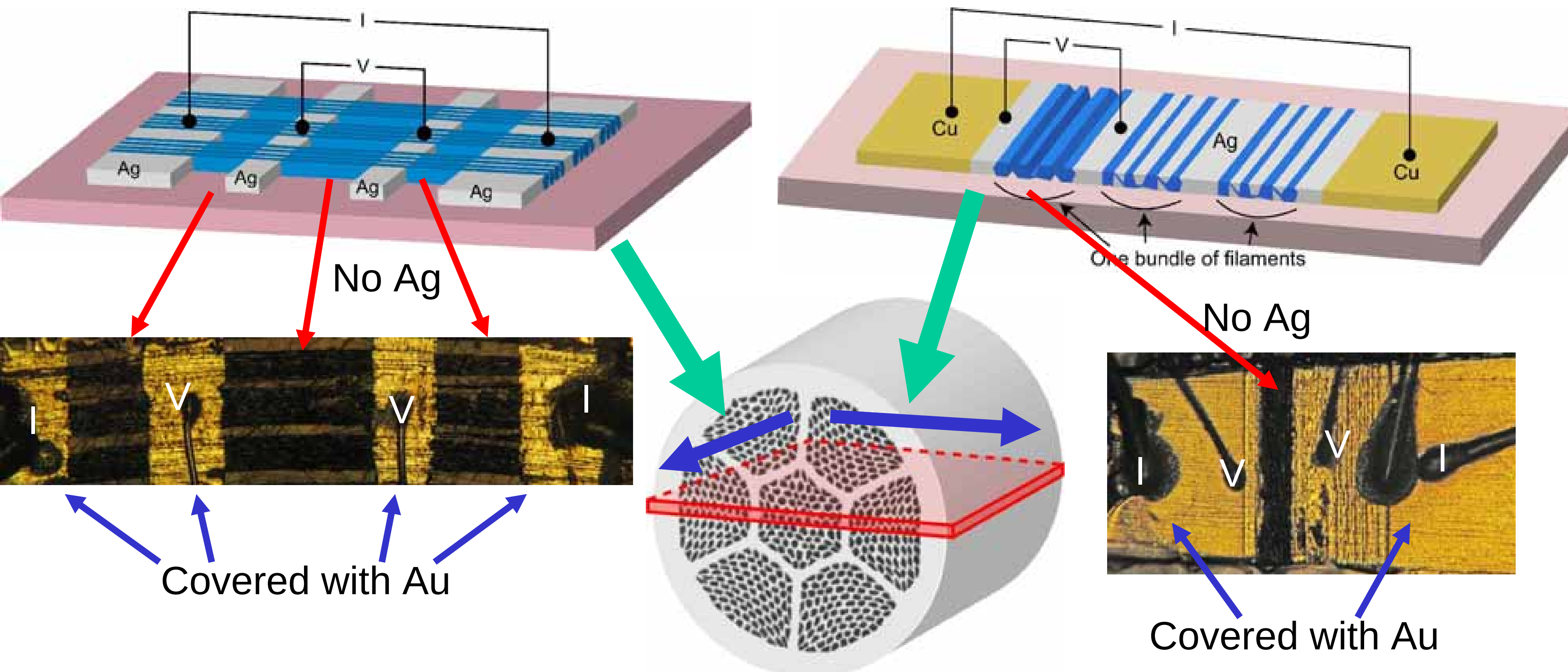
  Does this network explain the high Jc of RW Bi-2212?

Fumitake Kametani

Does current flow longitudinally or transverse or both?

Thin slice for
longitudinal current transport –
Measures current along filaments

Thin slice for
transverse current transport –
Measures current across bridges



Slice thickness : 20 ~ 35 um, glued to sapphire base

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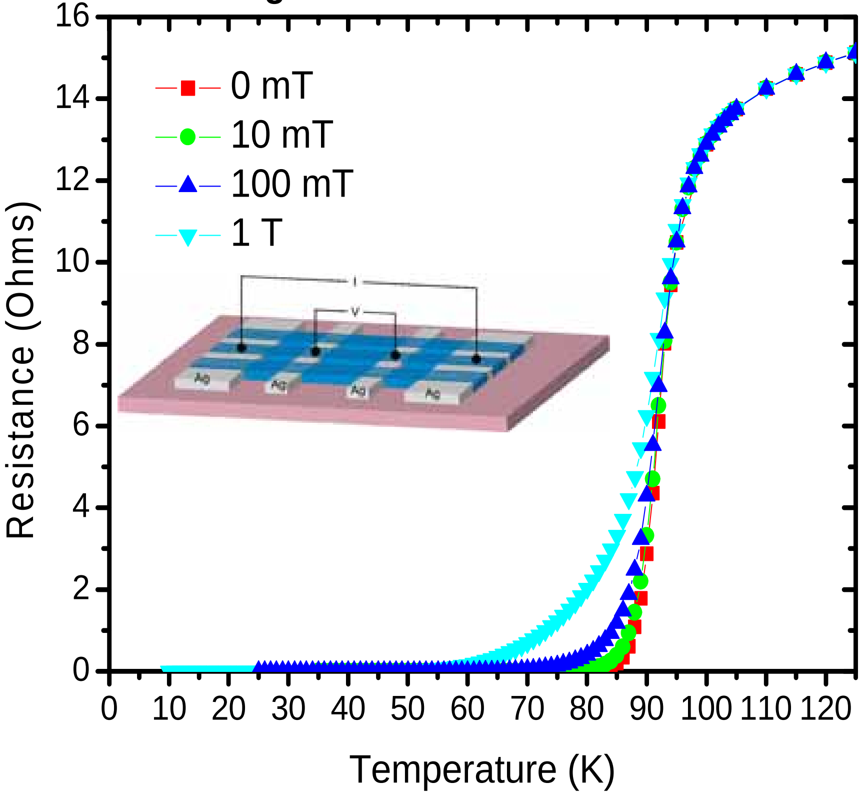
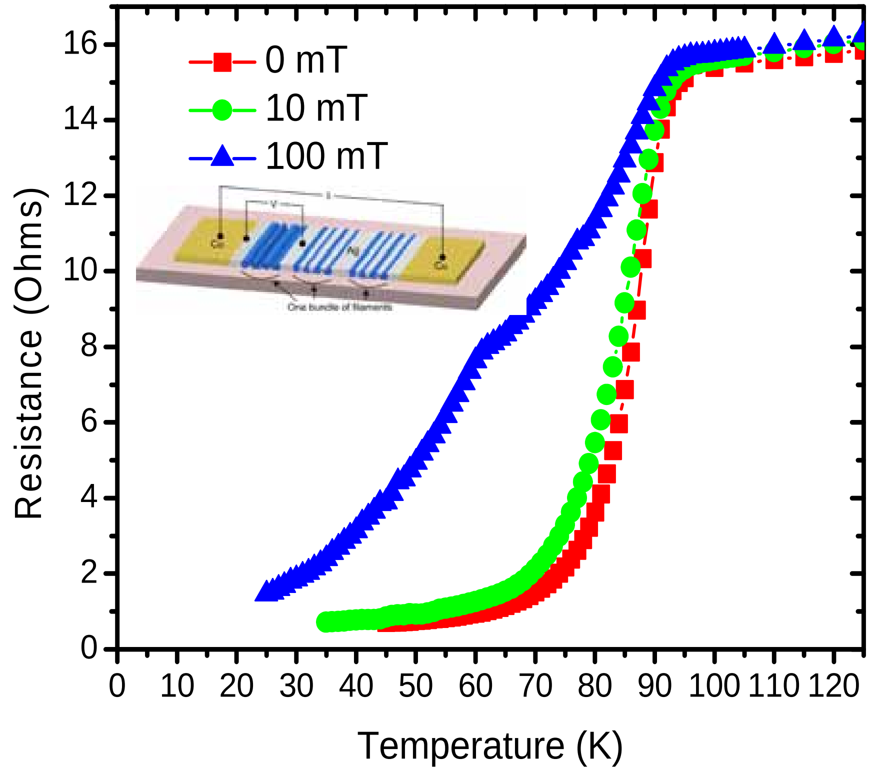
Passage along filaments is more strongly coupled than between them

Longitudinal direction of current



Transverse direction of current



Higher Jc is often correlated to many filament bridges – but first evaluations do not suggest that the bridges carry much current in field

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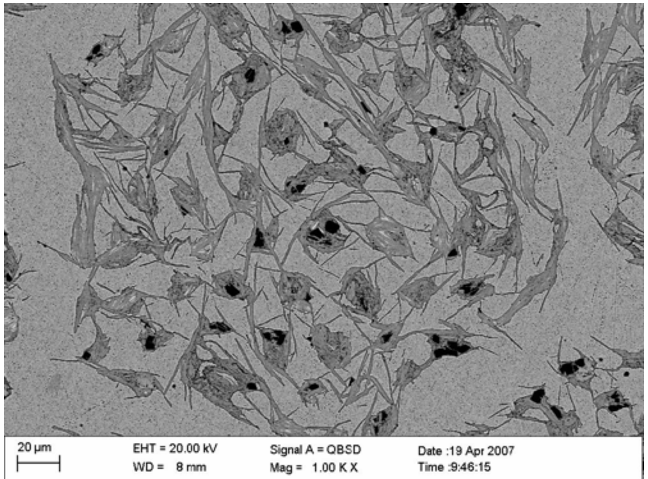
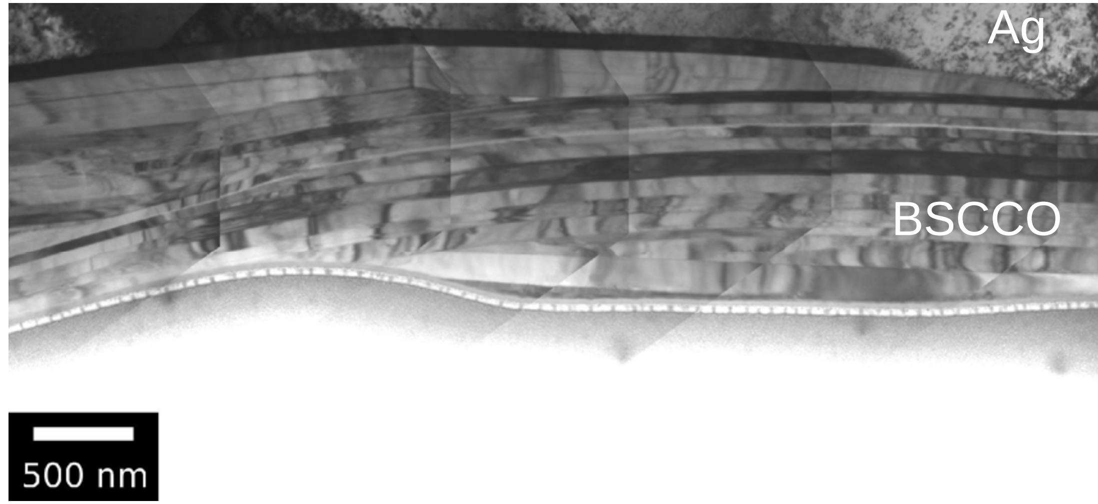
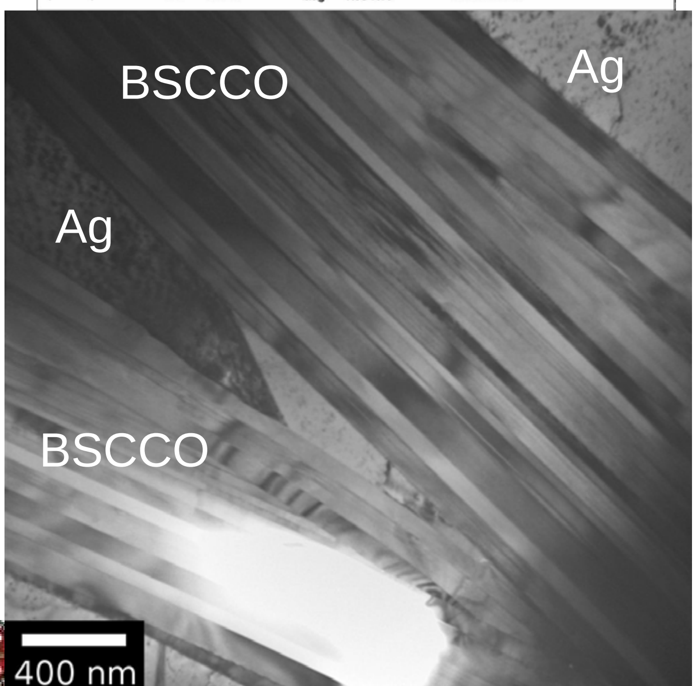
Bi-2212 grains can curve – significantly!







- Bi2212 grains always align along the Ag interface even when it curves
- Wetting phase at GBs is not common in standard Nexans composition, even at high angle GBs
- Grains are wide and long, with marked axial texture but no apparent azimuthal texture

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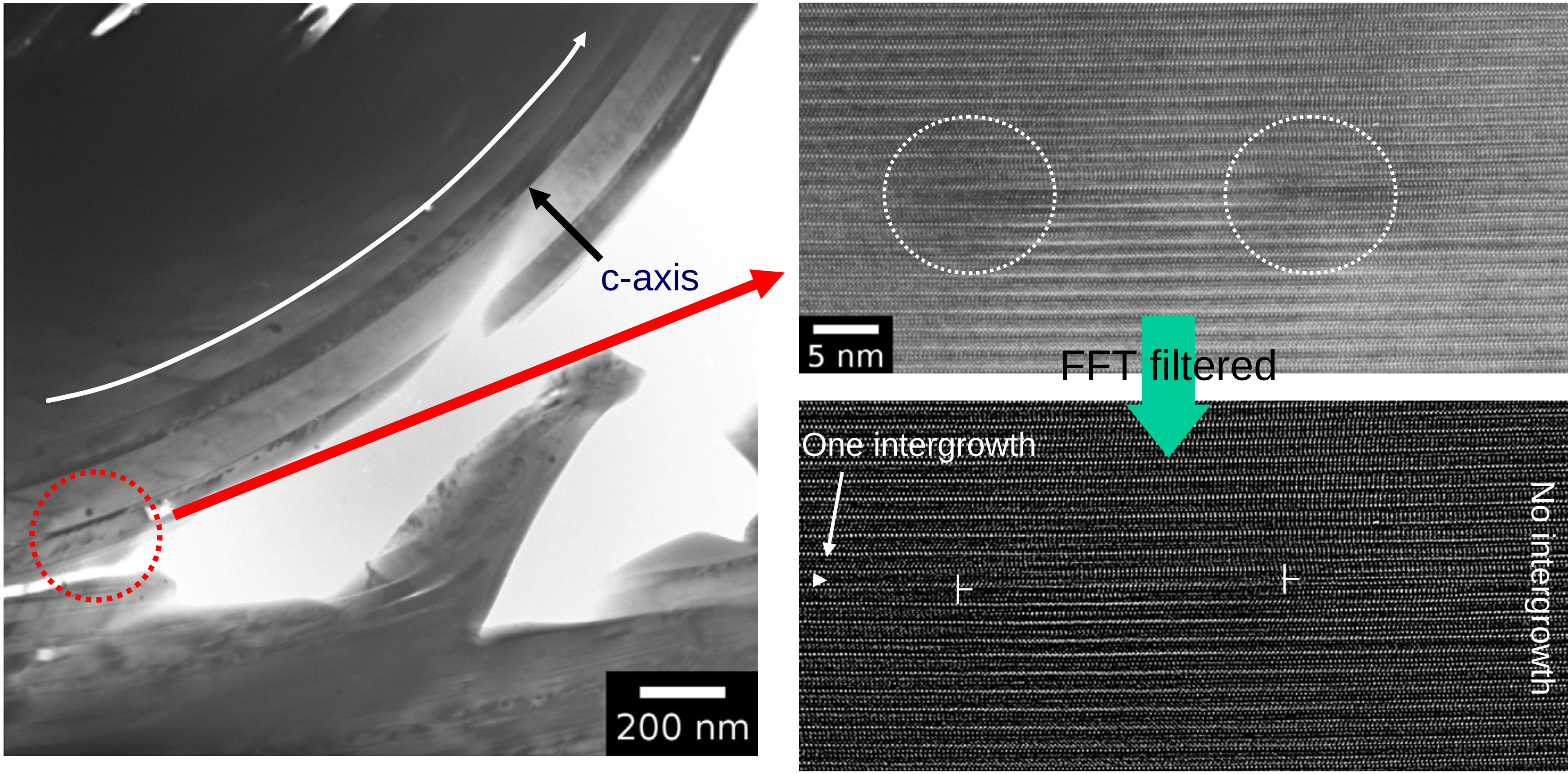
Bent grains may enhance grain connectivity



- **Bi2212 plate-like grains often bend, gradually changing the crystal orientation without any GBs along c-axis**
- **Arrays of edge dislocations enable the gradual change of the orientation**

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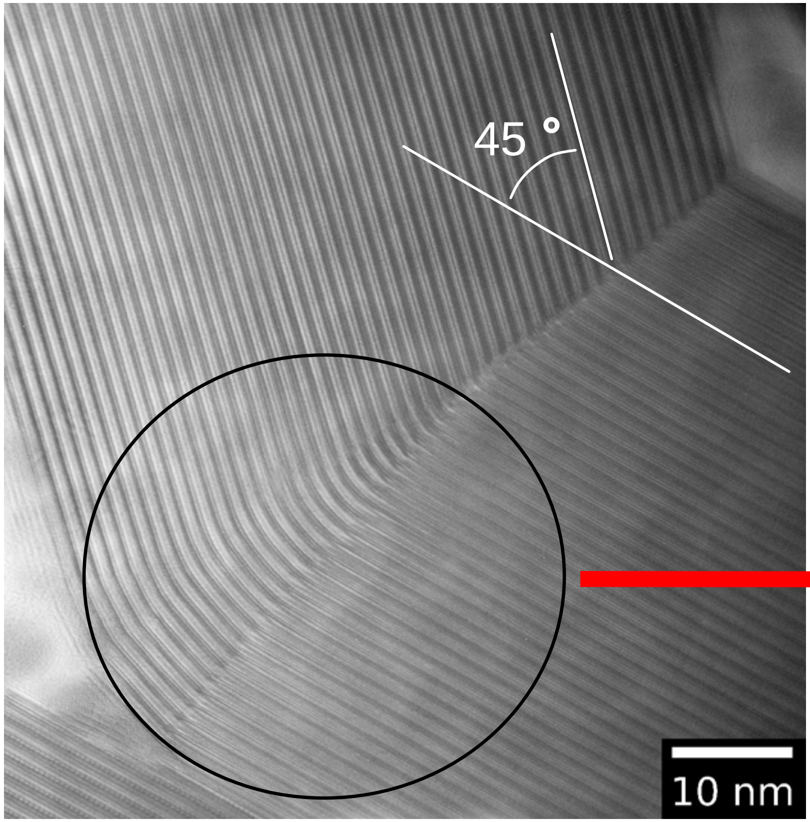
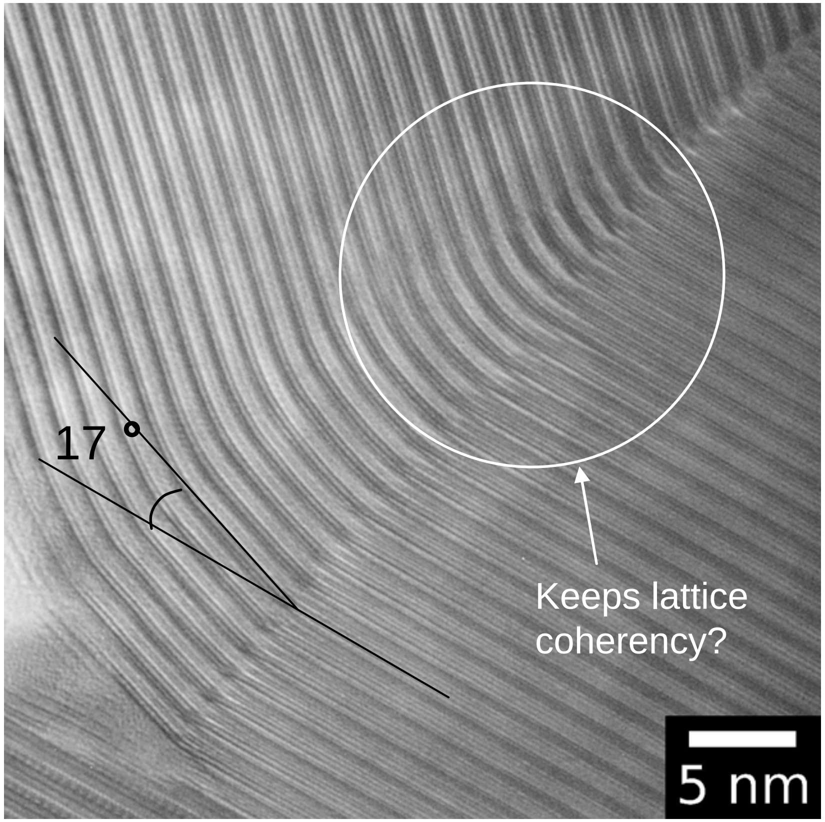
Bi2212 lattice planes easily change the direction





- **The tilt angle between these two grains is ~ 45°**
  - **Lattice plane bending reduces the tilt angle to 17°**
- **In the white circle, the boundary looks to be an anti-phase boundary, keeping lattice coherency**

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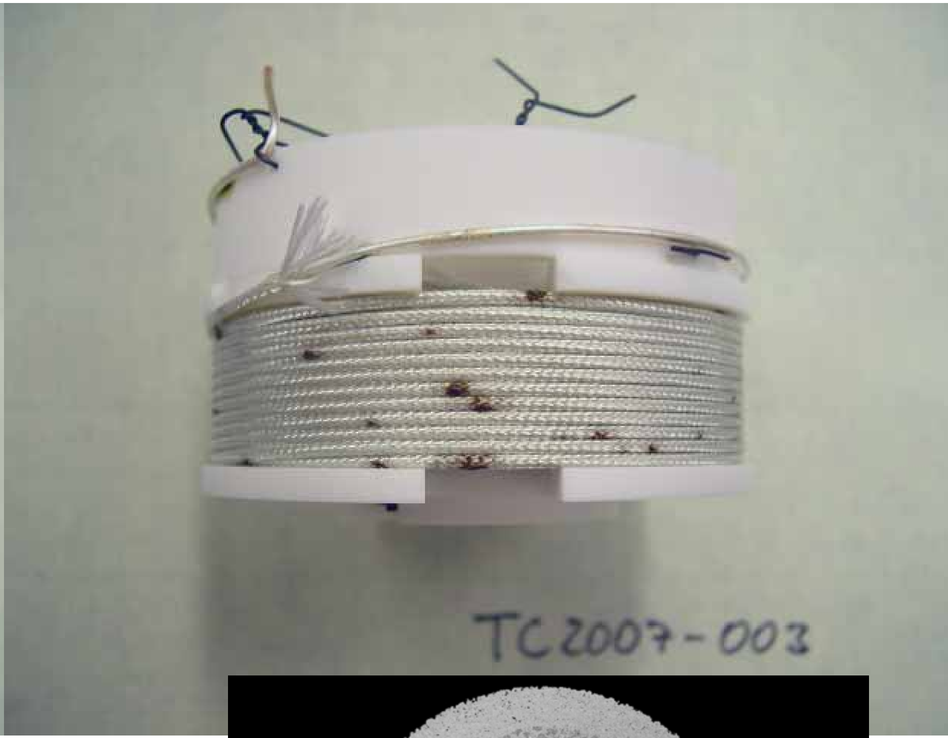
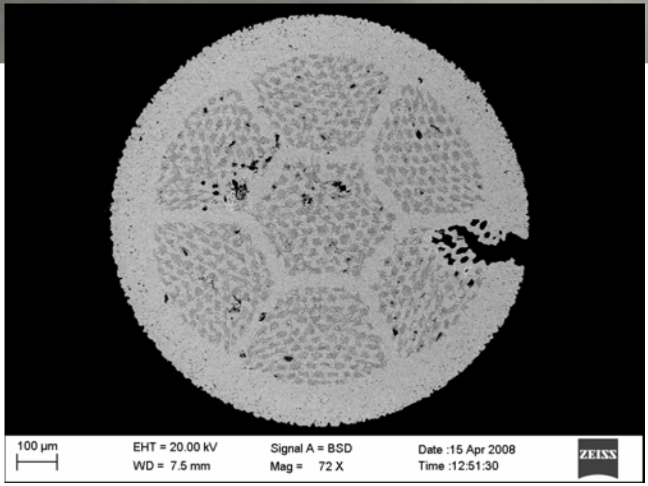
Coil leakage: TC2007-003

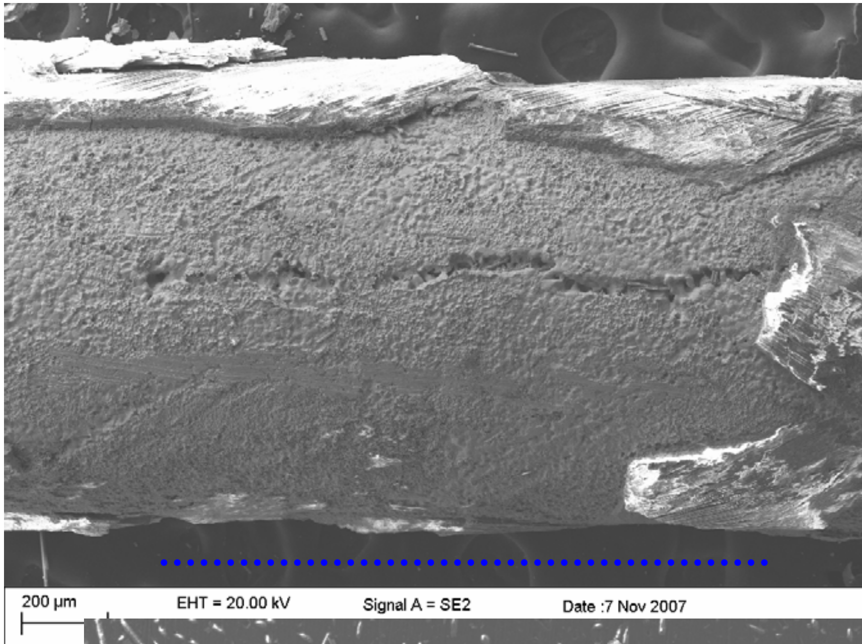


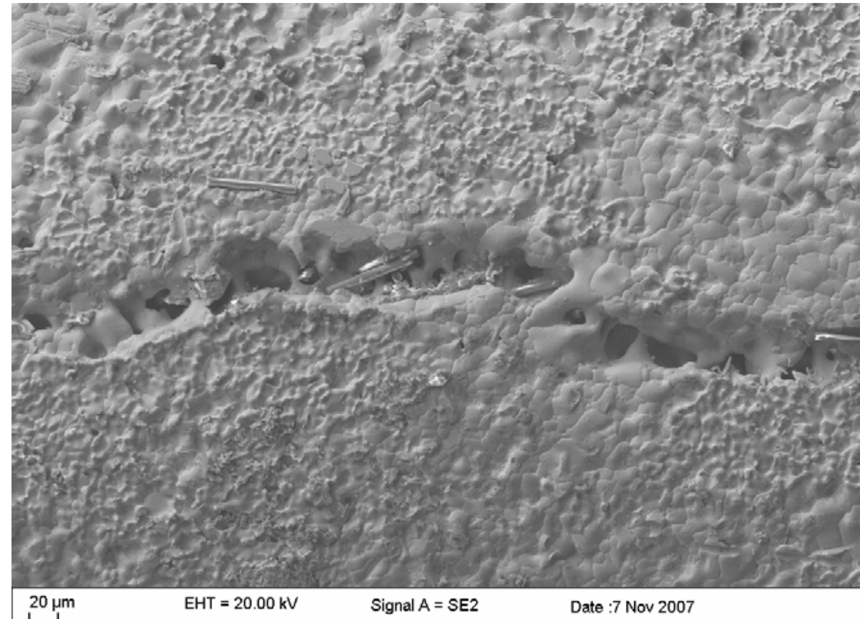
- **Wire: OST pmm060811-1**
- **Coil form: Macor**
- **Layers =10, Turns per layer = 12**
- **Coil wire length = 44 m**
- **T_{max} = 888C, and t at T_{max} = 0.2h**
- **Ic (4.2K, 5T) = 213 A**

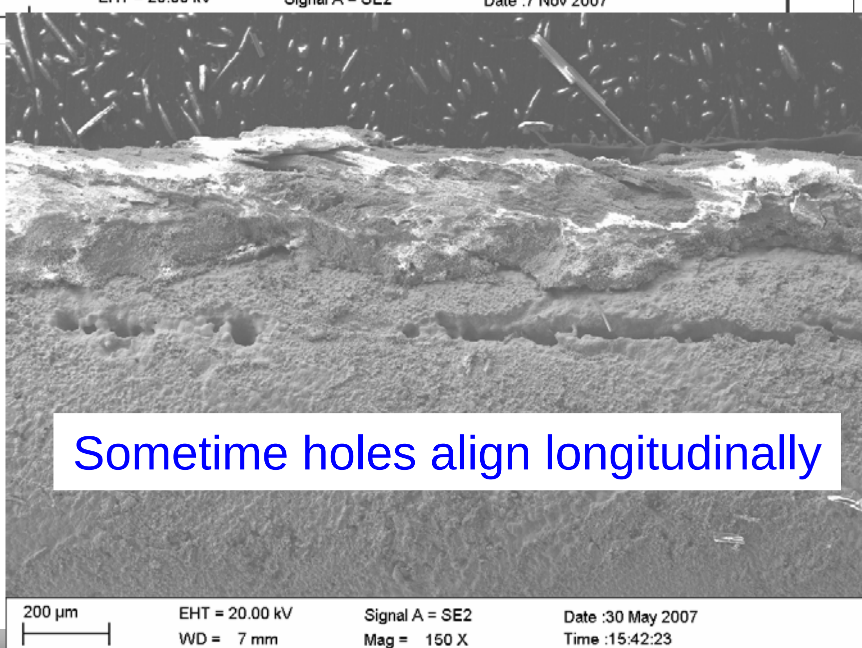


Jiang and Trociewitz

TC2007-003 leakage region

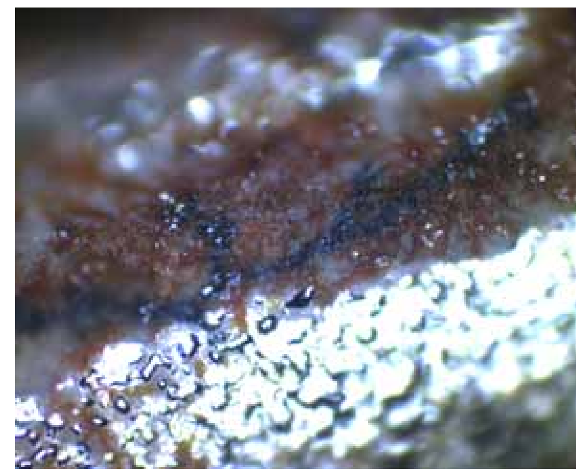






Reactions of mullite insulation in latest coil (MEL-08-002) wound on Inconel 600 form

- **T_{set} = 892 °C; O_2 flow: 3.5 l/min;**
- **Isolated leaks quite evident on outside**



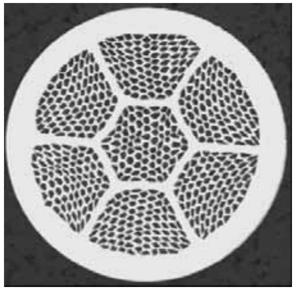
Conclusions: Reactivity of insulation and wire with each other and with coil construction materials are frequent!

Trociewitz and Myers

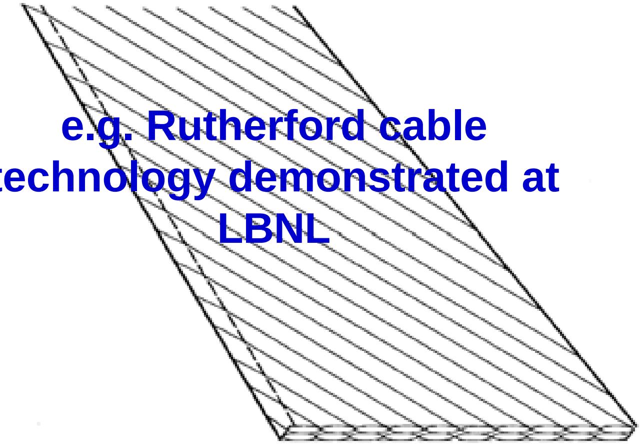
What does HEP really want from HTS?

- **An isotropic conductor form**
- **High connectivity AND high vortex pinning**
- **Ability to twist, to cable and to transpose**
- **Operation in domains of T and H inaccessible to LTS**
- **Strength, resistance to quench, compatible insulation and materials utilization technology**

20-30 strands of 500 A conductor



Can make a 10 kA cable



e.g. Rutherford cable technology demonstrated at LBNL

New reaction methodologies – e.g split melt process (Schwartz)

Next steps

- Collaboration amongst 2212 experts and users in US
  - BNL, FNAL, LANL, LBNL, NHMFL, NIST, TAMU
- Identify key problems and attack them
  - Jc – needs to be higher
  - Leakage and reactivity
  - Establish safe working stress envelope
- Generate some credible test coils to enable a RW 2212 magnet technology

Summary

- **Jc seems to be, practically, gated by an easily degraded connectivity**
  - How does damage occur?
  - What is the possible connectivity range?
  - What does the present complex HT process really do to develop high Jc?
- **Leakage is probably controlled by small surface defects**
  - If so, what causes them and can they be controlled?
    - Many post mortems are in progress
- **Reactivity of silver with glassy insulations is a problem**
  - BSCCO leakage and Cr-containing structures exacerbate the problems
- **The advantages of a round wire HTS should make the effort to master RW 2212 well worth it!**