



High-Field Thermal Conductivity of OP Bi-2212 wires

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Outline



- Motivations
- Samples
- Experimental investigation of the *RRR* of the matrix in reacted conductors
- Study of the thermal conductivity of Bi-2212 wires in magnetic fields up to 19 T
- Conclusions



High-Field Thermal Conductivity of OP Bi-2212 wires

Motivations

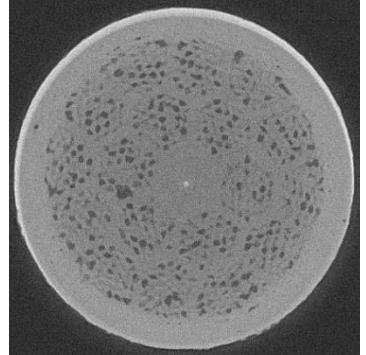
Motivations



Bi-2212 round wire is a promising candidate for next-generation magnet technology

J_{Eng} and B_{Irr} at 4.2 K competitive with REBCO CCs' values

- New record $J_{Eng} \sim 1200 \text{ A/mm}^2$ @ 4.2 K, 15 T
OST NHMFL 50bar OP J. Jiang *et al.* August 2017 unpublished



Whether Bi-2212 can be preferred to other HTS for high field applications depends also on:

- Mechanical strength (see also Alexander Otto's contributions)
 - Thermal and Electrical Stability
- Very few experimental investigations of κ
- No direct measurements of the RRR of the Ag matrix
- This Talk's Focus



The importance of the *RRR* of the stabilizer

Technical Superconductors: the low- T thermal and electrical stabilities are assured by the stabilizer (St)

Thermal Properties

$$\kappa_{St} \gg \kappa_{SC}$$

High *RRR* \rightarrow High κ

Normal metals: electron-defect scattering processes determine the thermal conduction at low temperatures.

Electrical Properties

$$\rho_{St} \ll \rho_{SC}^{normal\ state}$$

Current sharing Joule heating

$$g_j(T) = \rho_{St}(T)J_{St}(T)J$$

ρ_{St} : stabilizer electrical resistivity

J_{St} : current density in the stabilizer

J : current density in the composite

High *RRR* desired both for the thermal and electrical stability



High-Field Thermal Conductivity of OP Bi-2212 wires

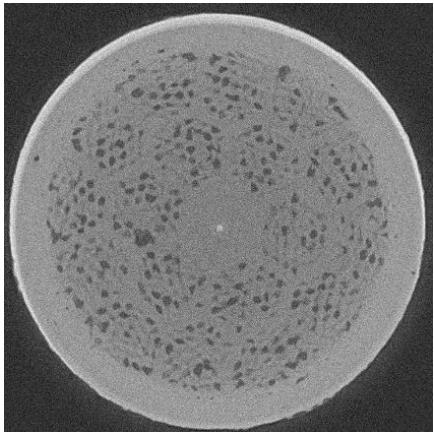
Samples

Samples

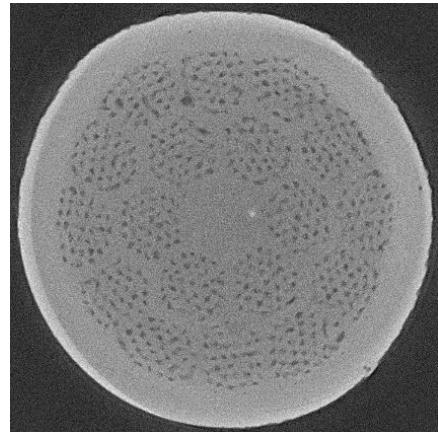
Samples reacted at the NHMFL under different total pressures of **1, 10 and 100 bar**, at a fixed O₂ partial pressure of 1 bar, with $T_{max} = 890^{\circ}\text{C}$.

Manufacturer	OST
Billet number	ppm130723
Diameter	0.8 mm
Number of filaments	37 x 18
Matrix	Ag
Reinforcement	Ag-0.2wt.%Mg

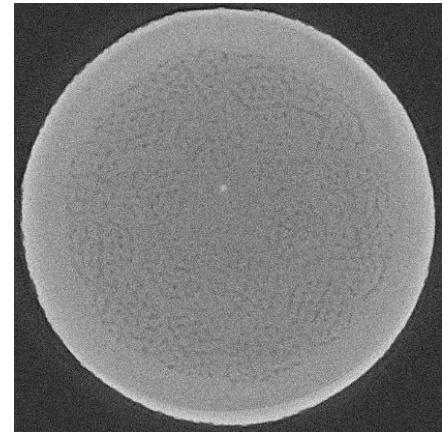
Void reduction observed by high-energy X-ray micro tomography
 (C. Barth *et al.* unpublished)



1 bar



10 bar



100 bar



High-Field Thermal Conductivity of OP Bi-2212 wires

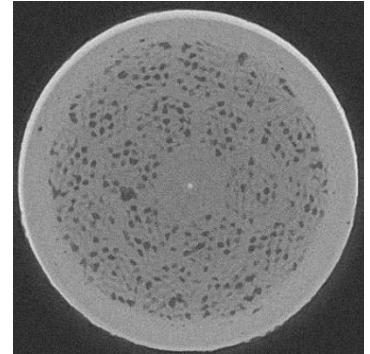
Experimental investigation
of the RRR of the matrix in
reacted conductors

«The Bi-2212 problem»

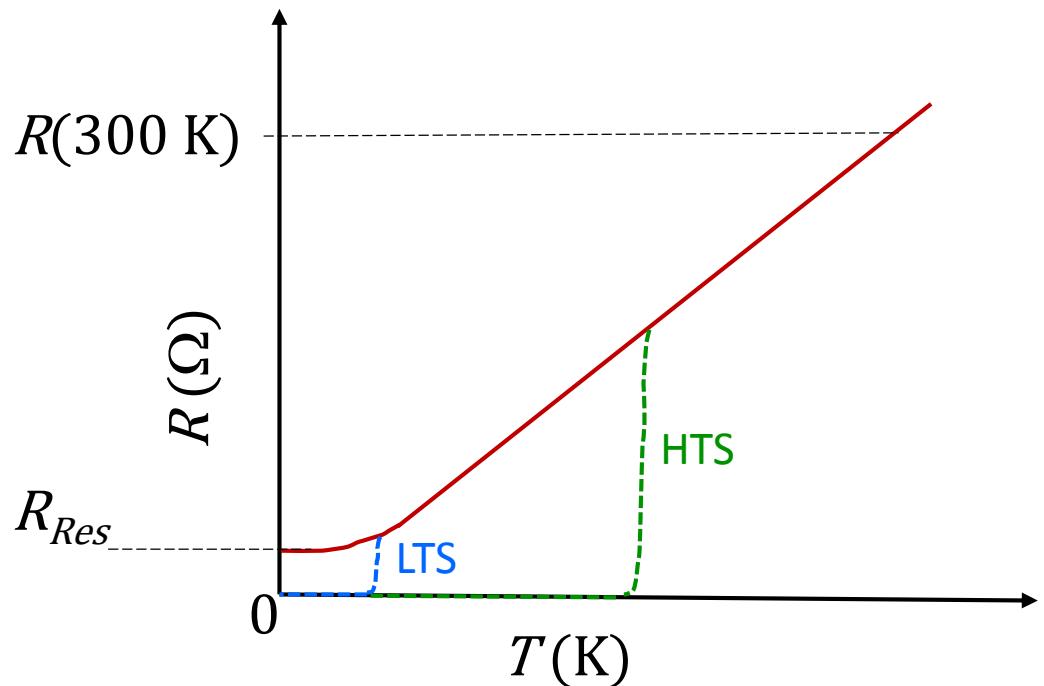


The reaction passes through the melting of Bi-2212 powders in a Ag matrix (no diffusion barrier)

Cu diffusion is expected to contaminate the Ag matrix
(Cu in Ag diffusion coefficient $\sim 2\text{-}3 \cdot 10^{-11} \text{ cm}^2/\text{s}$ @ 890°C)



Contrary to the case of LTS, the *RRR* of the matrix in HTS technical conductors cannot be evaluated from an electrical-resistivity measurement performed on the whole conductor.



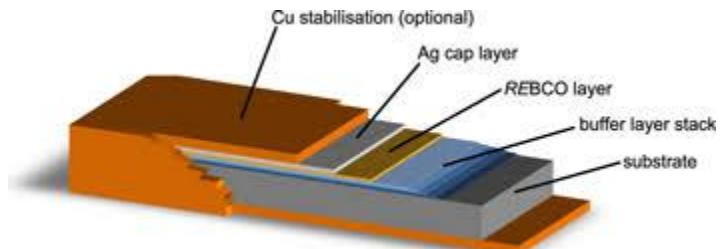
Solutions to measure the RRR in HTS

REBCO CC: Cu is soldered or electroplated.

The Cu layer can be separated from the SC

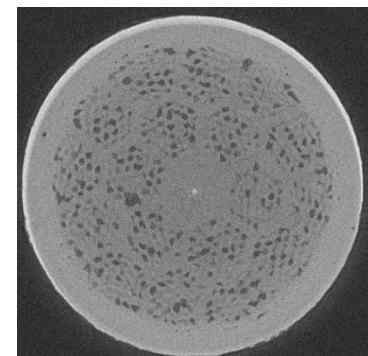
→ RRR_{Cu} measurement performed

[M. Bonura and C. Senatore, SuST 28, 025001 (2015)]



Bi-2212 wire: Superconducting filaments embedded in Ag matrix.

The separation of the stabilizer from the superconducting phase is much less practical.
New solutions have to be found.





Procedure to remove the Bi-2212 filaments

Chemical attack in glacial acetic acid

- magnetic stirrer (low frequency \approx 2 turns/sec, no heater)
- duration \approx 8 days

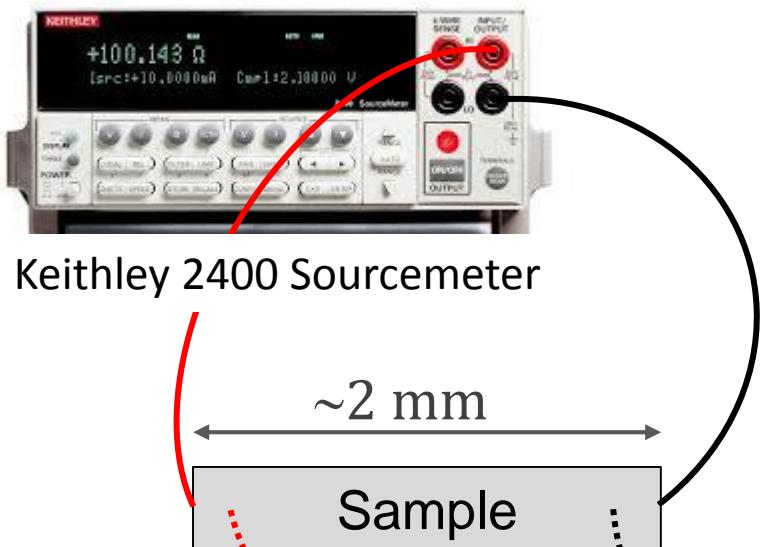
We succeed in removing completely the Bi-2212 (without attacking the normal metal matrix) in short (2 mm) wires

We did not manage to fully remove the superconducting filaments from pieces longer than \approx 2 mm, even extending the duration of the chemical attack

RRR Measurement Experimental Setup



A 4-wire electrical resistance measurement on a high- RRR few-mm-long metallic sample demands high requirements for the measurement setup sensitivity ($R \sim 100 \text{ n}\Omega$).



Keithley 2400 Sourcemeter



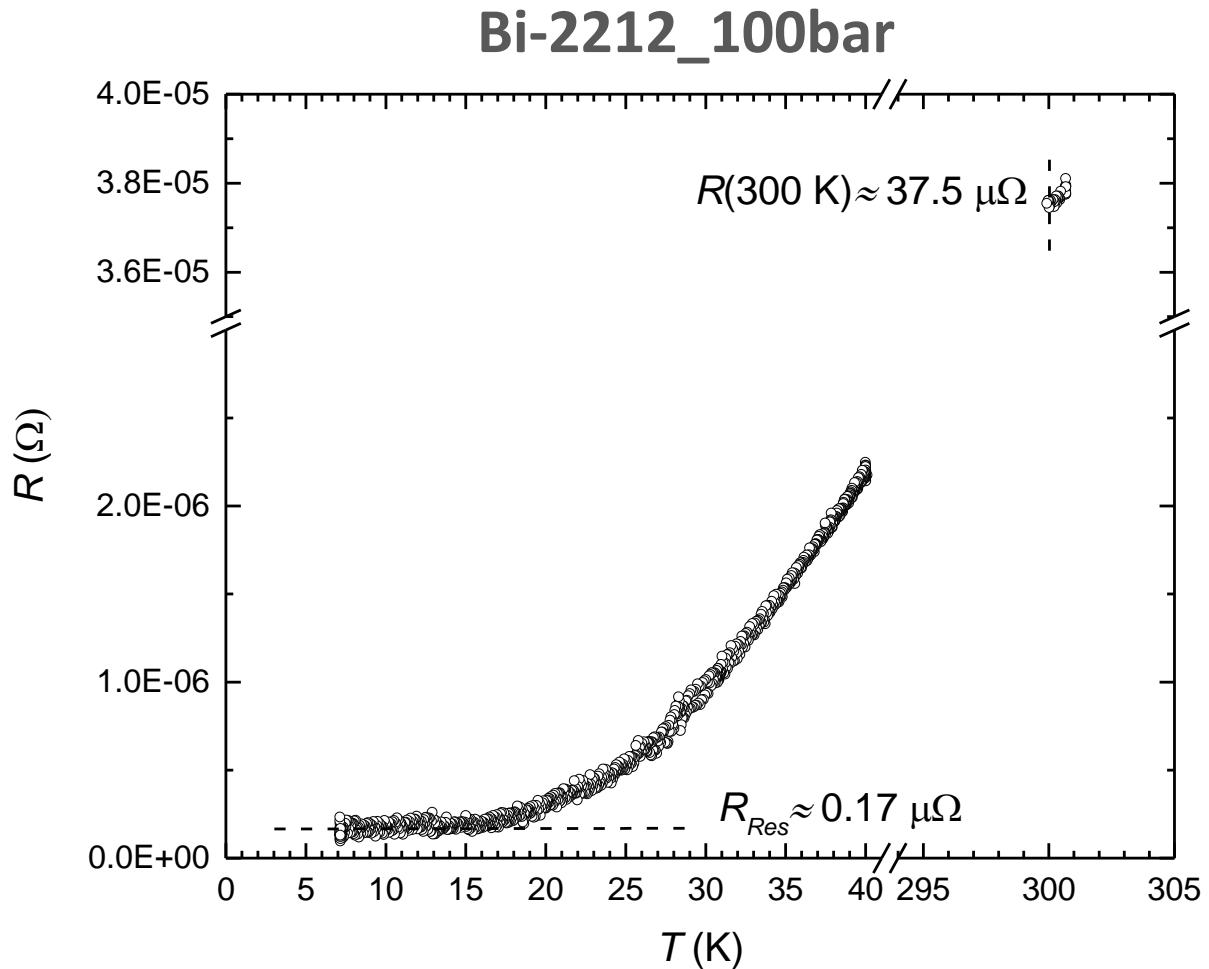
Keithley 2182A nanovoltmeter



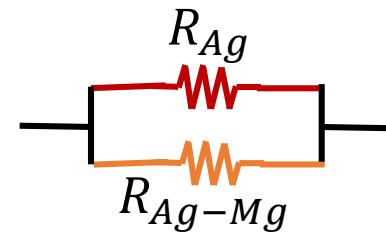
EM-Electronics nanovolt amplifier

Measurement probe

RRR Measurement Results



$$RRR = \frac{R(300 \text{ K})}{R_{Res}} \approx 220$$



@ low $T \rho_{Ag} \ll \rho_{AgMg}$

@ 300 K $\rho_{Ag} \approx 16.1 \text{ n}\Omega \text{ m}$
 $\rho_{AgMg} \approx 19.7 \text{ n}\Omega \text{ m}$

$Ag/AgMg$ fraction = 2.25

$RRR_{Ag} \approx 208$

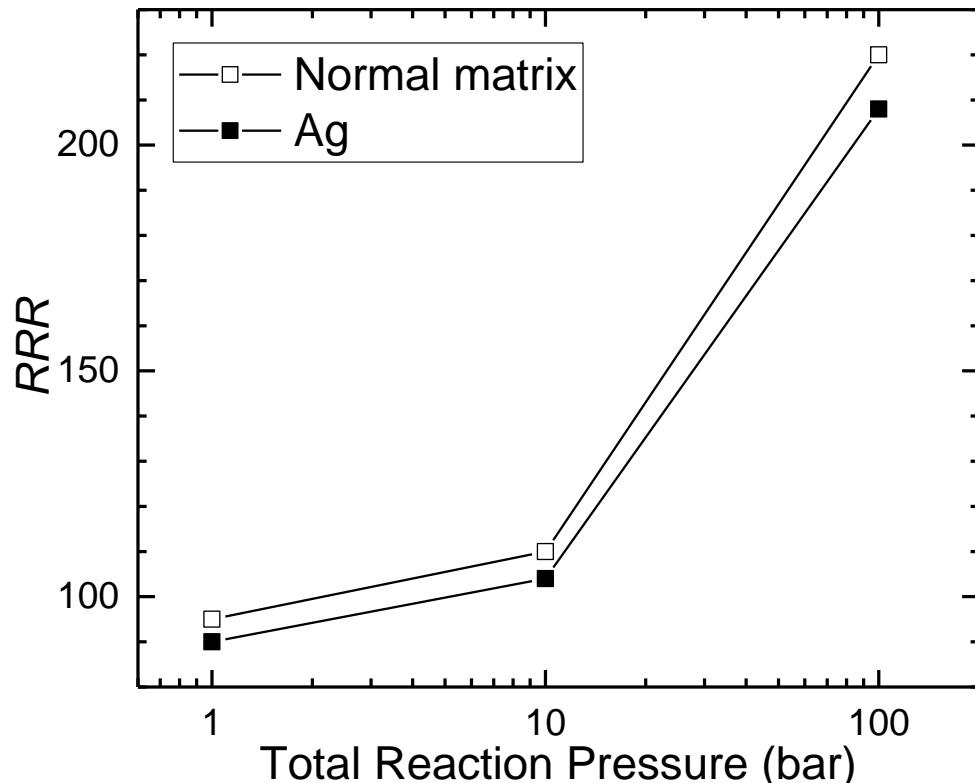
Heat-treated stand-alone Ag from OST: $RRR_{Ag} \approx 214$ [1]

[1] P. Li, L. Ye, J. Jiang, T. Shen, IOP Conf. Series: Materials Science and Engineering 102, 012027 (2015)

RRR Results' Summary



	Bi-2212_1bar	Bi-2212_10bar	Bi-2212_100bar
$RRR_{Normal-Matrix}$	95	110	220
RRR_{Ag}	90	104	208





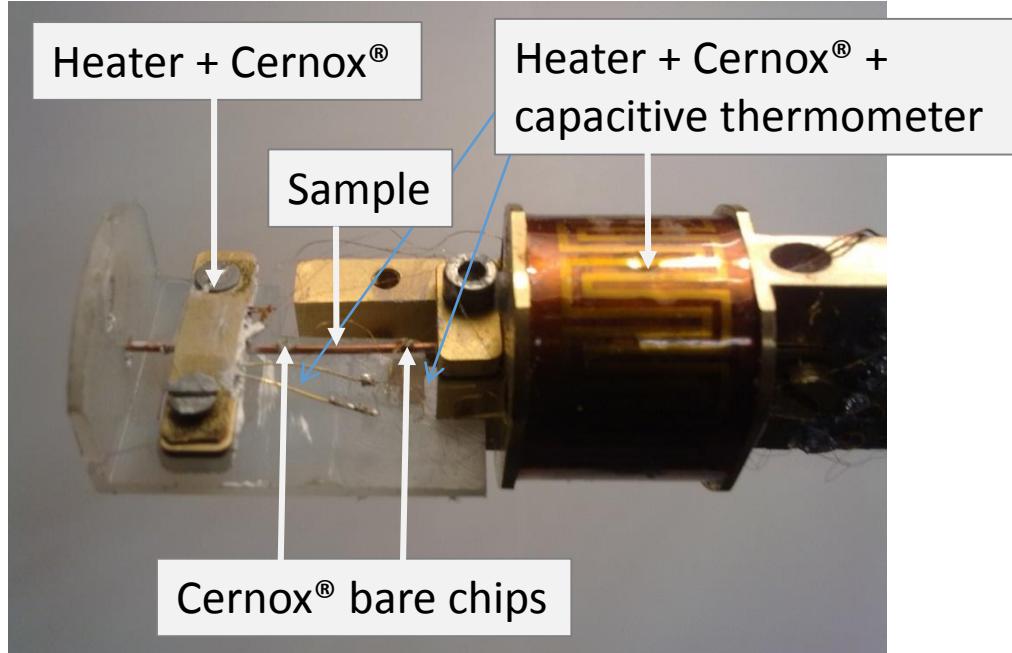
High-Field Thermal Conductivity of OP Bi-2212 wires

Experimental Investigation of the
in-field thermal conductivity

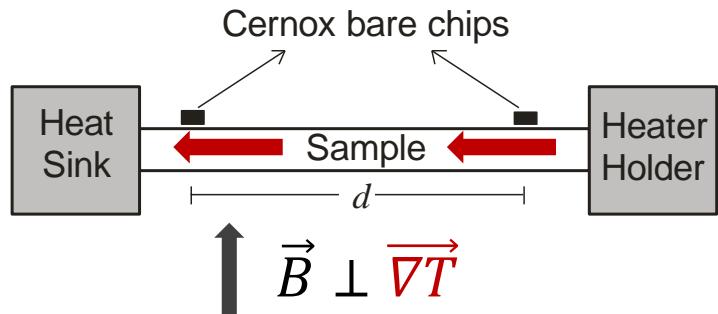
Thermal Conductivity Experimental Setup

Thermal Conductivity (κ) of Bi-2212 wires

Different magnetic fields: $B = 0, 1, 7, 19 \text{ T}$



2 different orientations between the field and thermal flow directions possible



$$\kappa = \frac{Q}{\Delta T} \frac{d}{w \cdot t}$$

Q : heat

ΔT : temperature gradient

d : thermometer distance

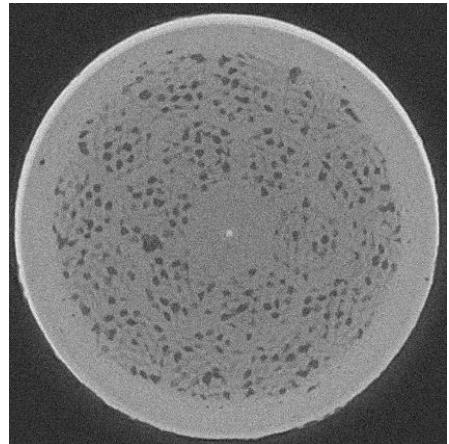
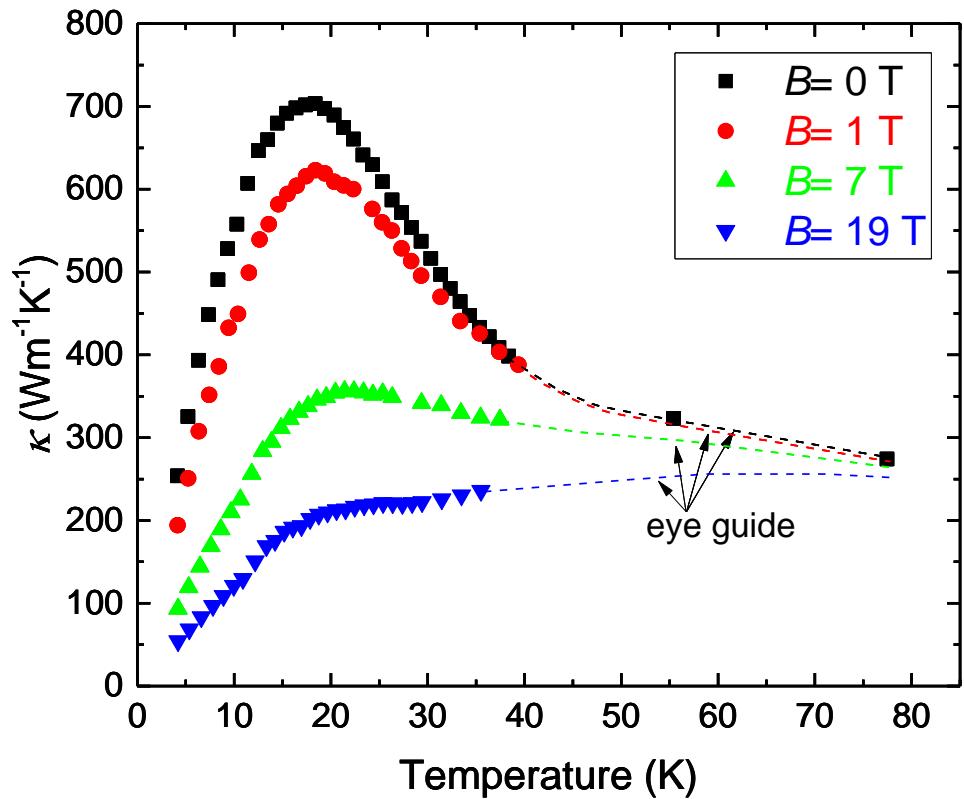
w : sample width

t : sample thickness

Thermal Conductivity Results

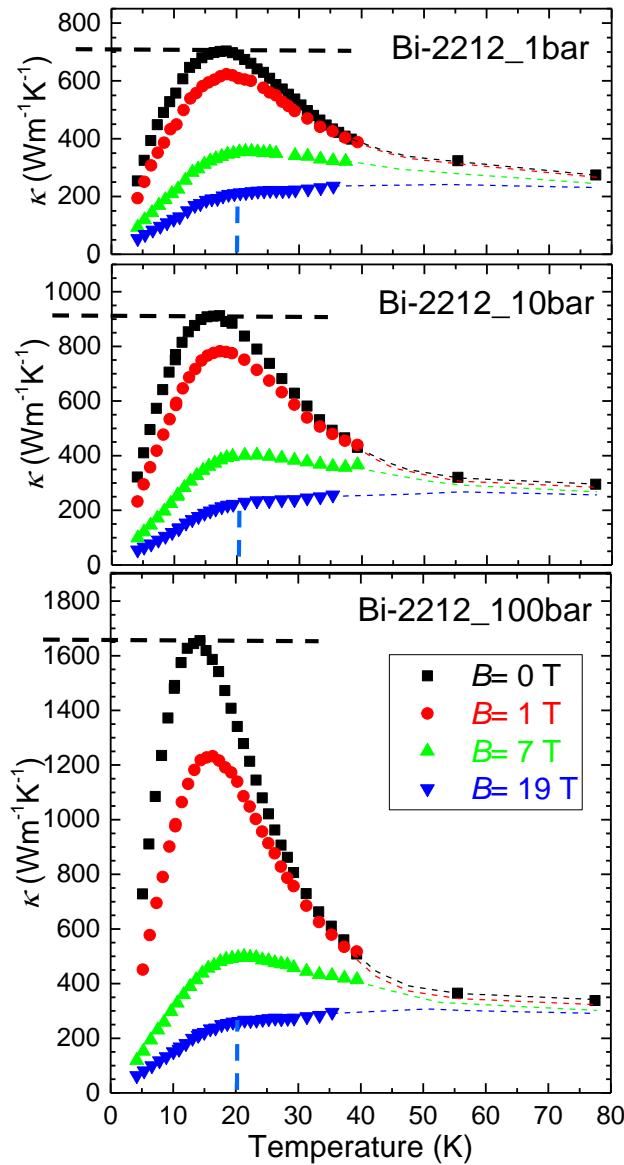


Experimental results on Bi-2212 wire reacted at 1 bar



1 bar

Thermal Conductivity Results



Experimental results on Bi-2212 reacted at 1, 10, 100 bar

	1bar	10bar	100bar
$\kappa_{peak}(0\text{T}) \text{ Wm}^{-1}\text{K}^{-1}$	700	910	1650
$\kappa(20\text{K}, 19\text{T}) \text{ Wm}^{-1}\text{K}^{-1}$	210	225	260
$\kappa(5\text{K}, 19\text{T}) \text{ Wm}^{-1}\text{K}^{-1}$	62	65	76

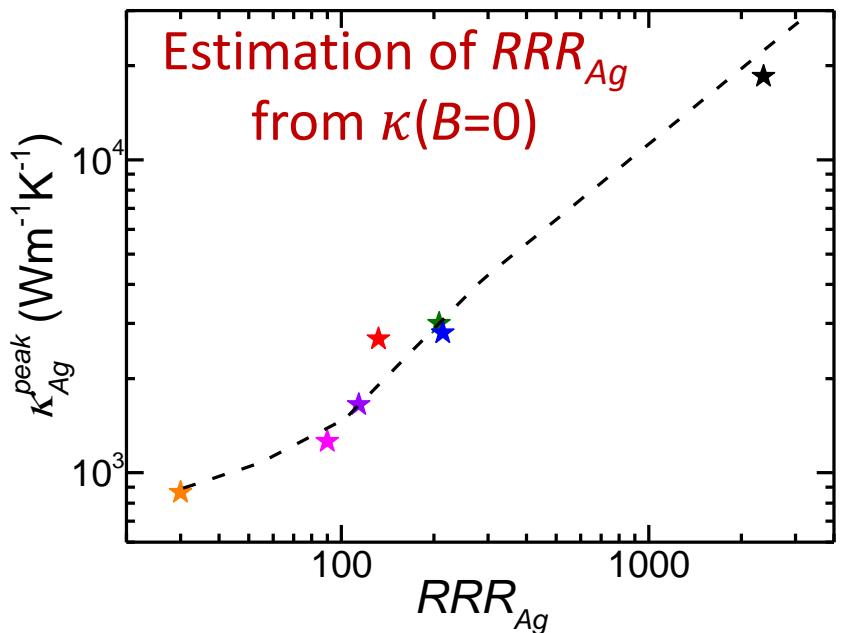
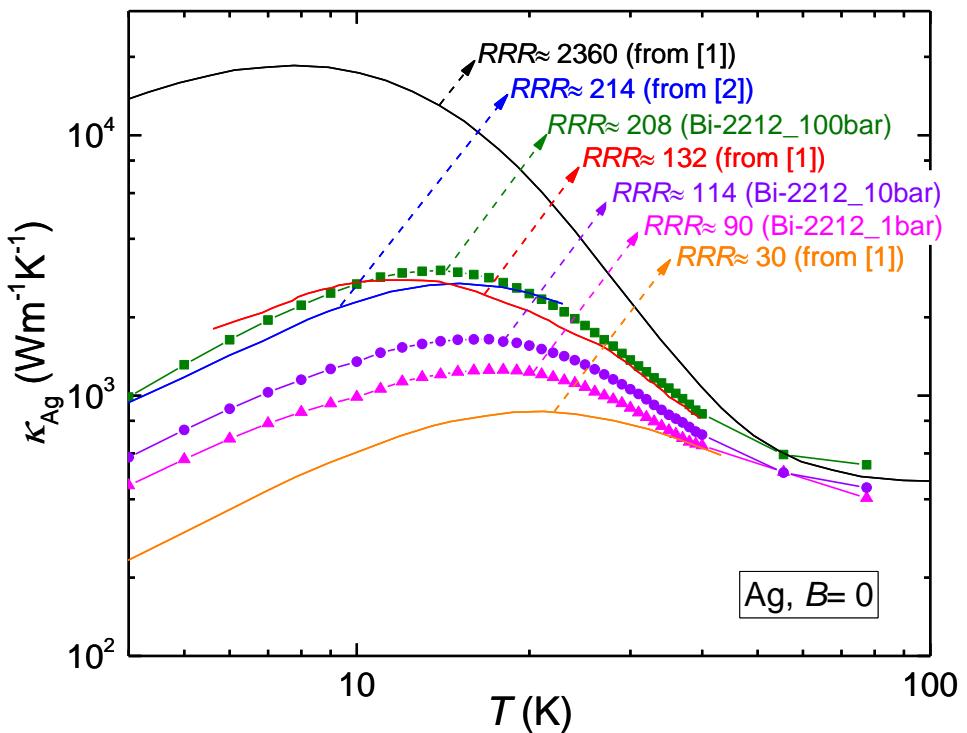
Reaction pressure from 1 to 100 bar:
 κ increased by $\approx 135\%$ at 0 T and
 $\approx 20\text{-}25\%$ at 19 T.

Thermal Conductivity of Ag

Longitudinal thermal conductivity in a composite conductor $\kappa = \sum \kappa_i s_i$

We can evaluate the κ of the Ag: $\kappa_{Ag} \approx (\kappa - \kappa_{AgMg} s_{AgMg}) / s_{Ag}$

κ_{AgMg} from [2]; $\kappa_{AgMg} s_{AgMg} \lesssim 0.1\kappa$ @ $T \lesssim 40$ K



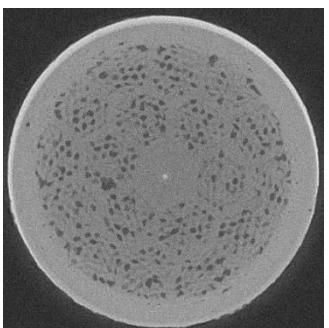
[1] D. R. Smith and F. R. Fickett, J. Res. Natl. Inst. Stand. Technol. 100, 119 (1995)

[2] P. Li, L. Ye, J. Jiang, T. Shen, IOP Conf. Series: Materials Science and Engineering 102, 012027 (2015)

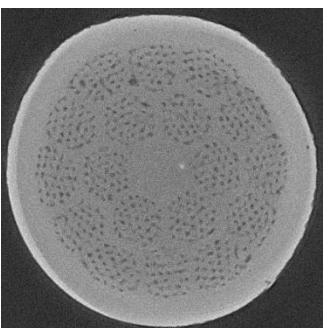
Results' summary



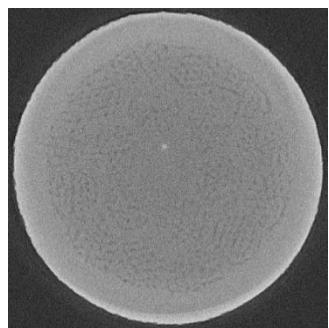
	Bi-2212_1bar	Bi-2212_10bar	Bi-2212_100bar
$RRR_{Normal-Matrix}$	95	110	220
RRR_{Ag}	90	104	208
$\kappa_{peak}(0T)$	700 Wm ⁻¹ K ⁻¹	910 Wm ⁻¹ K ⁻¹	1650 Wm ⁻¹ K ⁻¹
$\kappa(20\text{ K}, 19\text{ T})$	210 Wm ⁻¹ K ⁻¹	225 Wm ⁻¹ K ⁻¹	260 Wm ⁻¹ K ⁻¹
$\kappa(5\text{ K}, 19\text{ T})$	62 Wm ⁻¹ K ⁻¹	65 Wm ⁻¹ K ⁻¹	76 Wm ⁻¹ K ⁻¹



1 bar



10 bar



100 bar

Conclusions



- We measured the RRR of the metal matrix and the thermal conductivity (up to 19 T) of Bi-2212 conductors reacted at different pressures (1, 10, 100 bar)
- The Over-Pressure limits the matrix contamination during the wire reaction
- RRR_{Ag} and $\kappa_{peak}(0 \text{ T})$ more than doubled upon augmenting the reaction pressure from 1 to 100 bar
 κ increases by 20-25% at 19 T
- $RRR_{Ag} \approx 90$ for the standard reaction at 1 bar.
In Nb_3Sn , complex layout to keep the RRR above ~ 100 .

Thank You For Your Attention