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Development of high performance iron-based superconducting wires and tapes

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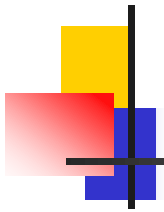


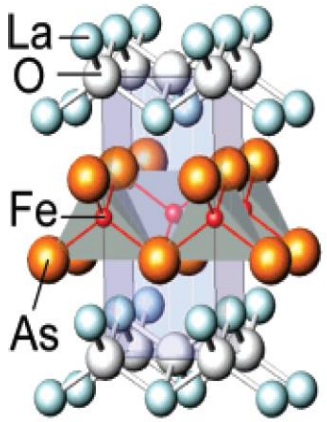
Outline

1. Background on Fe-based superconductor
2. High J_c 122 pnictide tapes by hot pressing
3. Other recent results about practical properties of 122 tapes
4. Conclusions

Main known Fe-based superconductors

Among them, the three phases most relevant for wire applications are 1111, 122, and 11 types with a T_c *of 55, 38 and 8 K, respectively.*

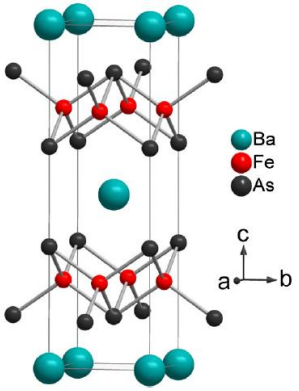
1111 Phase LnOFeAs



T_c ~55 K

Z. A. Ren et al., ***Chin. Phys. Lett.*** 25, 2215 (2008)

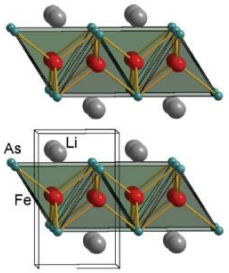
122 phase AFe_2As_2 (A=Ba, Sr, Ca)



T_c ~38 K

M. Rotter, et al., ***Phys. Rev. Lett.*** **101**, 107006 (2008)

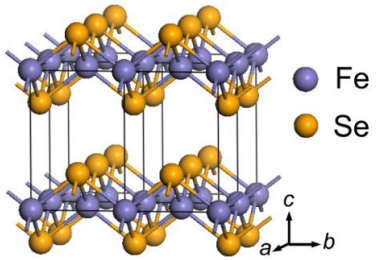
111 phase LiFeAs



T_c ~18 K

X. C. Wang, et al., ***Solid State Commun***. **148**, 538 (2008).

11 phase FeSe



T_c ~8 K

F. C. Hsu, et al., ***Proc. Natl. Acad. Sci. U.S.A.*** **105**, 14262 (2008).

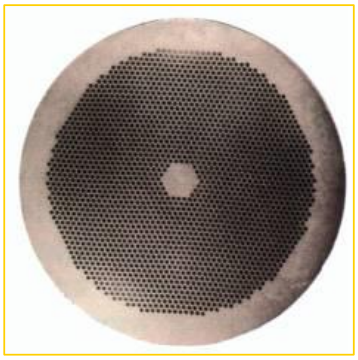
122 type wires potential for high-field applications

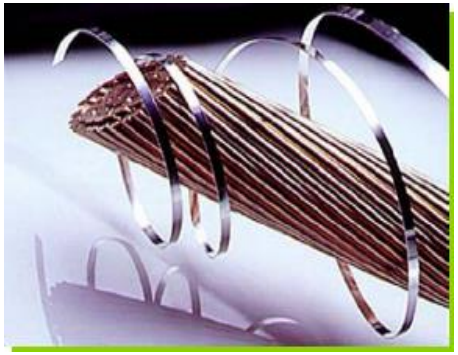
To apply superconducting materials to technologies related to magnets, they must be transformed into wires.

Merits:

High H_{c2} (>100T),

Low γ (<2)



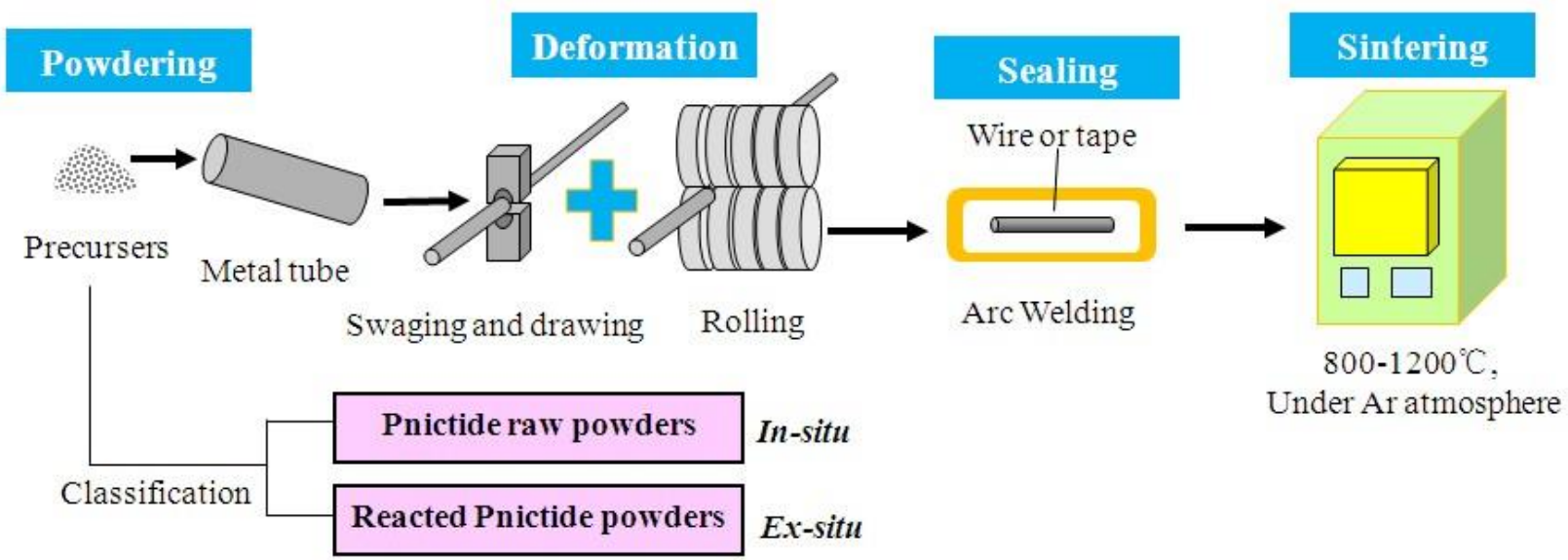


MRI

NMR

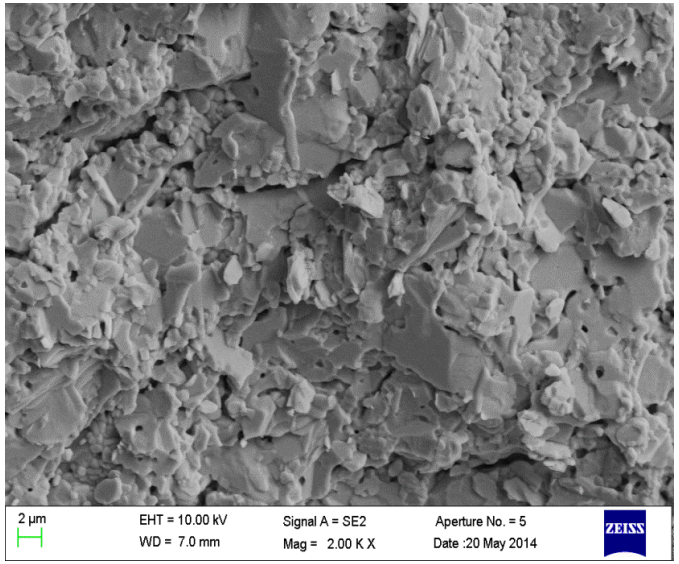
Development of high-performance wire conductors is essential

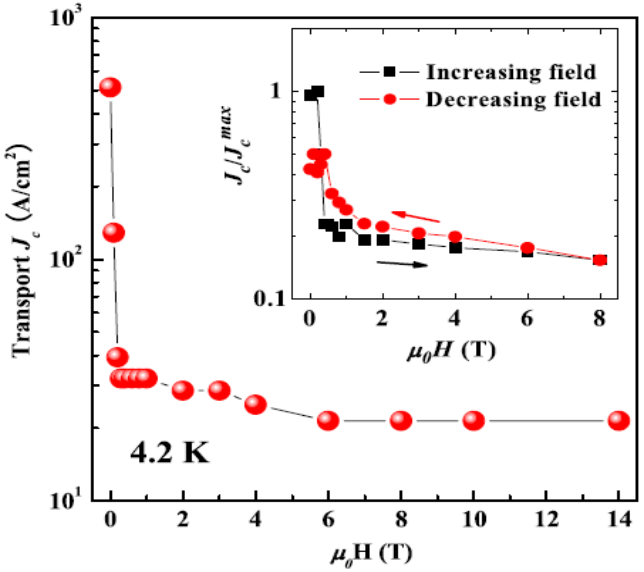
Fabrication process for $Sr_{1-x}K_xFe_2As_2$ wires (*Powder-in-tube method*)



– **Simple and scalable process, low cost**

Key problems for PIT wires: Low density and weak links





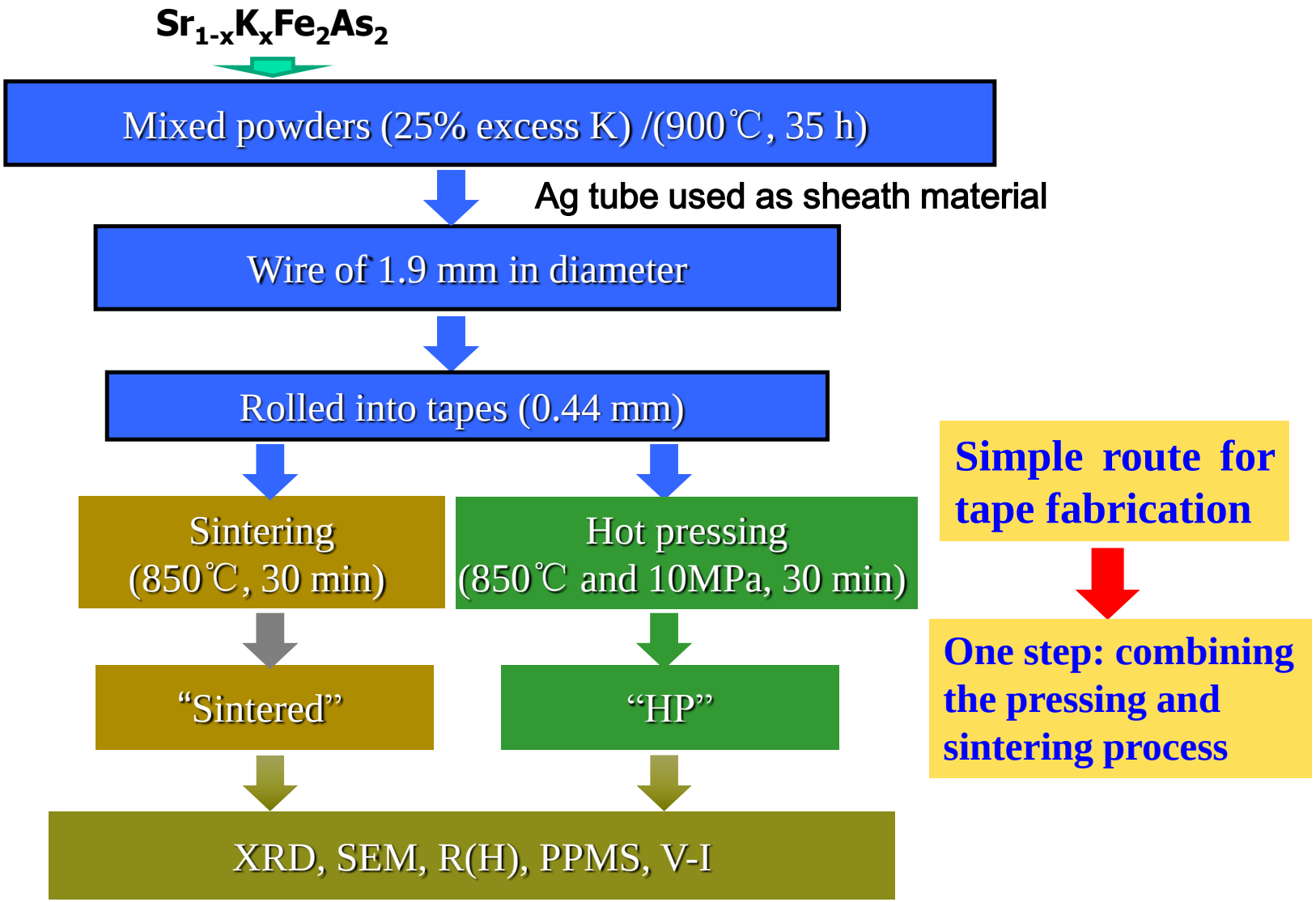
Low density: cracks and porosity

Hysteresis in transport J_c: signature of weak links

- Residual cracks and porosity always lead to poor grain connectivity in polycrystalline wires.
- A hysteretic phenomenon observed for transport J_c in an increasing and a decreasing field indicated a weak-linked behavior, similar to that of the cuprates.

Hot pressing may be an effective route to solve these problems

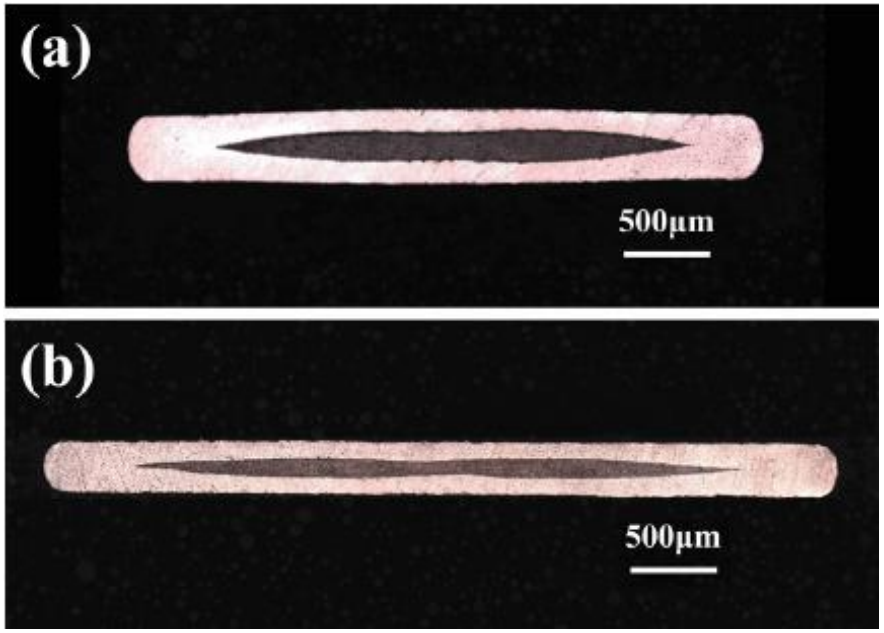
Hot pressing of Ag-sheathed Sr-122 tapes



Cross section of Sr-122/Ag tapes by Hot Pressing

Sintering

Hot pressing



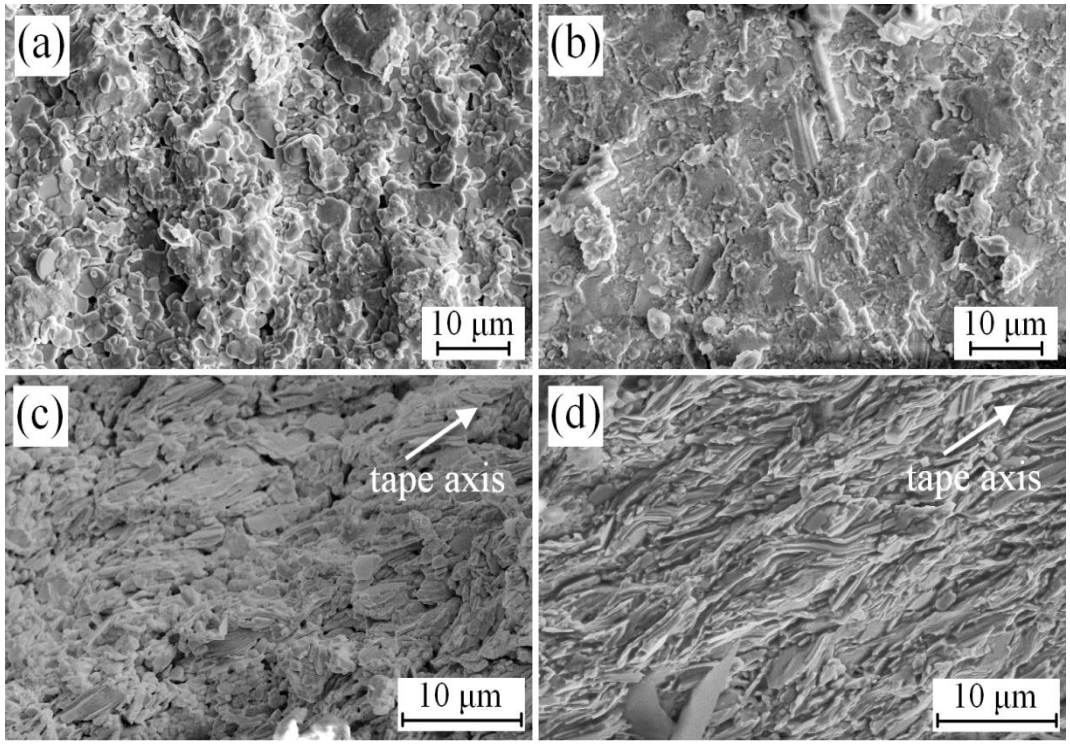
Hot pressing significantly decreased the tape thickness from 0.44 mm to 0.3 mm.

Evolution of microstructure

Sintering **Hot pressing**

Planar view

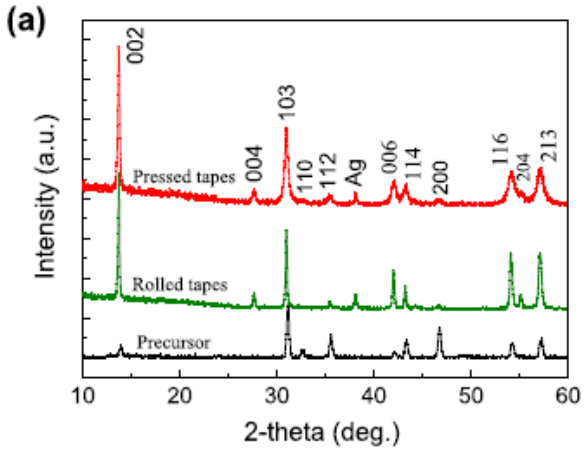
Longitudinal Cross-section

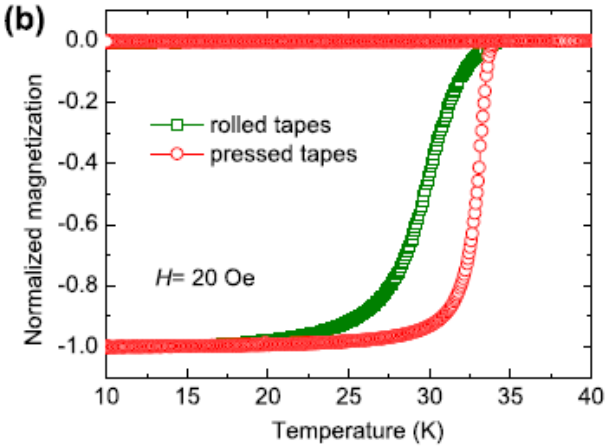


Sintered tapes: loose microstructure from more voids, and/or cracks

HP tapes: higher density with fewer voids

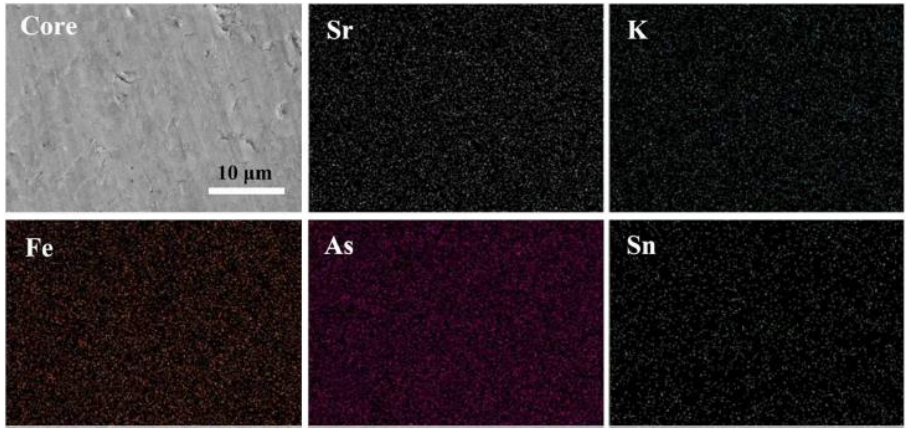
XRD and EDS analysis of HP tapes





Single phase!

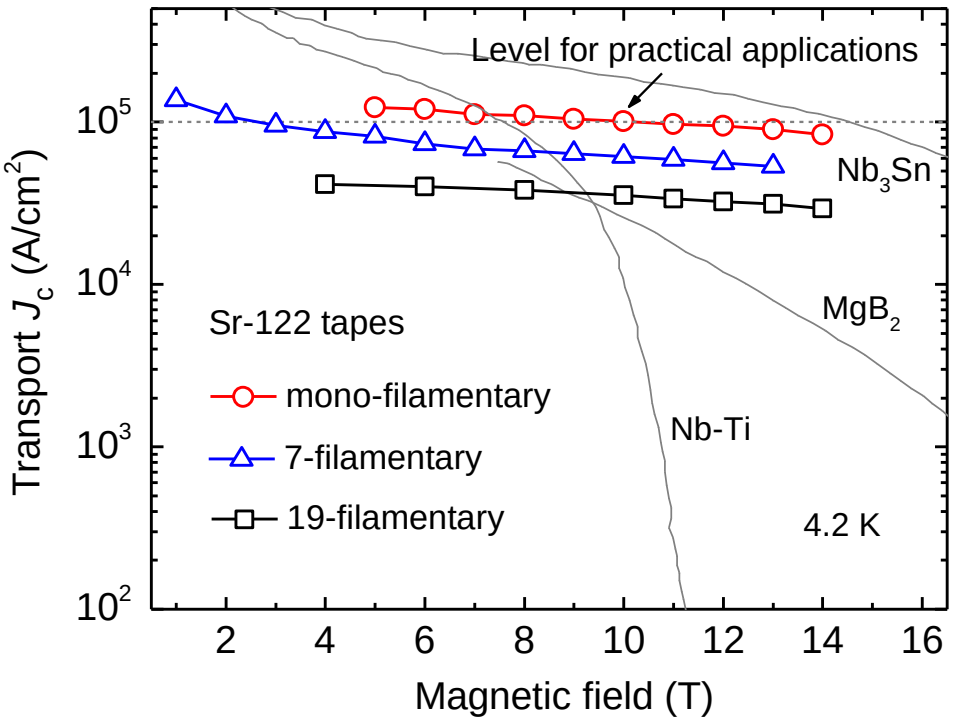
Uniform!



Demonstrating that the elements Sr, K, Fe and As of superconducting phase homogeneously distributed throughout the superconducting core in HP tapes.

Very High transport J_c were achieved in 122/Ag tapes: $J_c > 10^5$ A/cm^2 (4.2 K, 10 T) - by hot pressing

Highest and practical level J_c!



Even for hot pressed multifilamentary 122 wires

At 4.2 K, 10 T

7-core, $J_c = 6.1 \times 10^4$ A/cm^2,

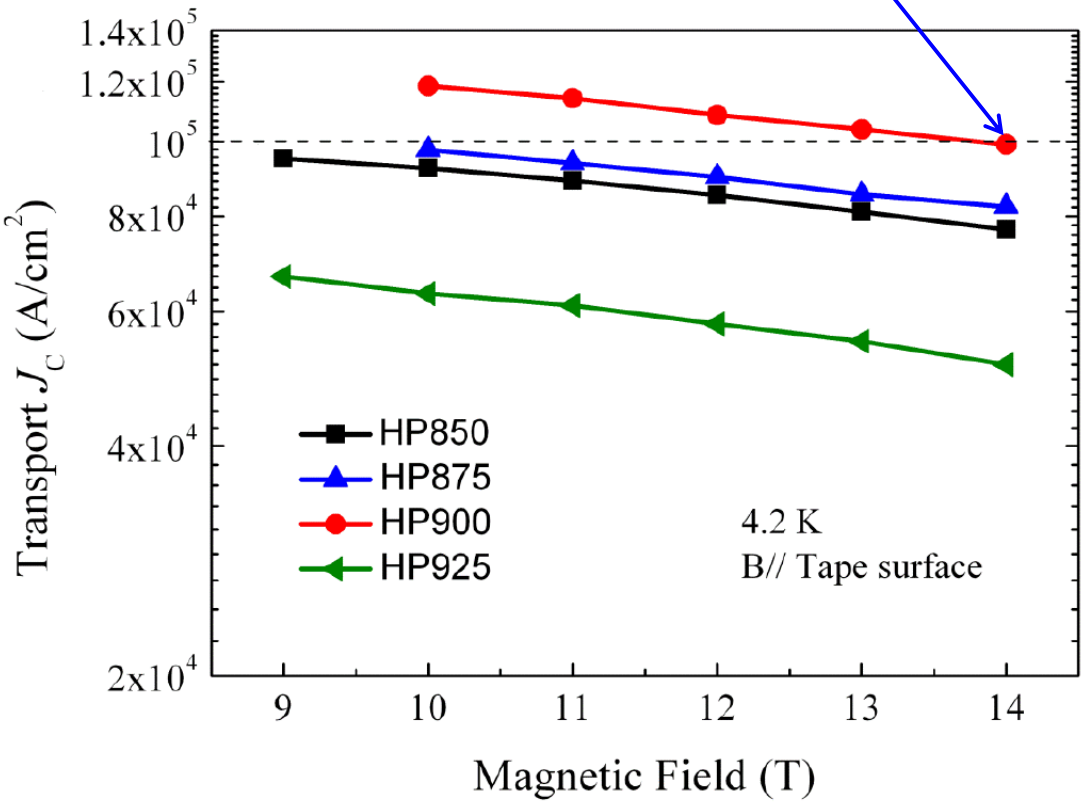
19-core, $J_c = 3.5 \times 10^4$ A/cm^2.

The superior J_c can be attributed to higher grain texture and improved densification.

Zhang et al., *APL* 104 (2014) 202601

By temperature optimization

The new record transport J_c values were achieved in 122/Ag tapes: $J_c \sim 1.0 \times 10^5$ A/cm^2 (4.2 K, 14 T)



Practical level J_c!

At 4.2 K and 10 T:

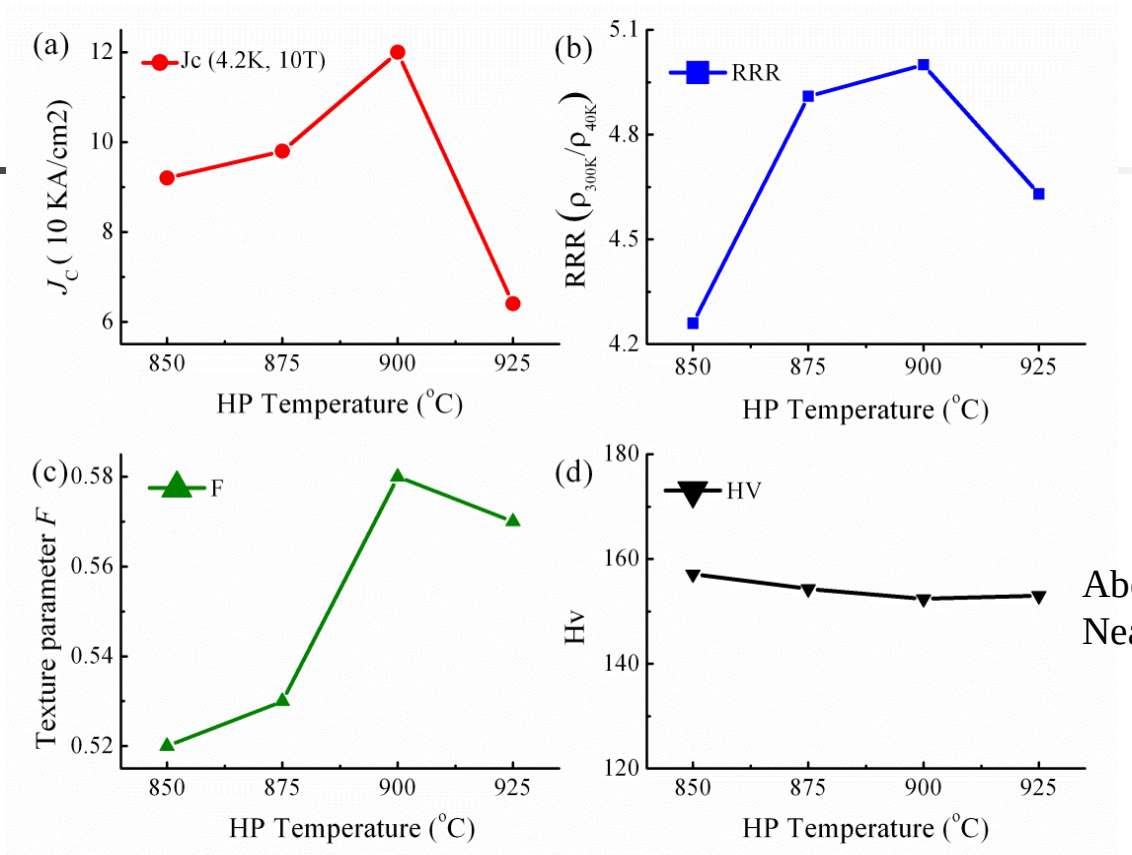
$J_c = 1.2 \times 10^5$ A/cm^2

Hot pressing is very effective to achieve high density core, thus significant increase in J_c.

Is there still a room for the J_c improvement by hot pressing?

Lin et al., *Sci. Rep.* 4 (2014) 6944

Reasons for high transport Jc in HP900 tapes



About 154.0
Nearly constant !

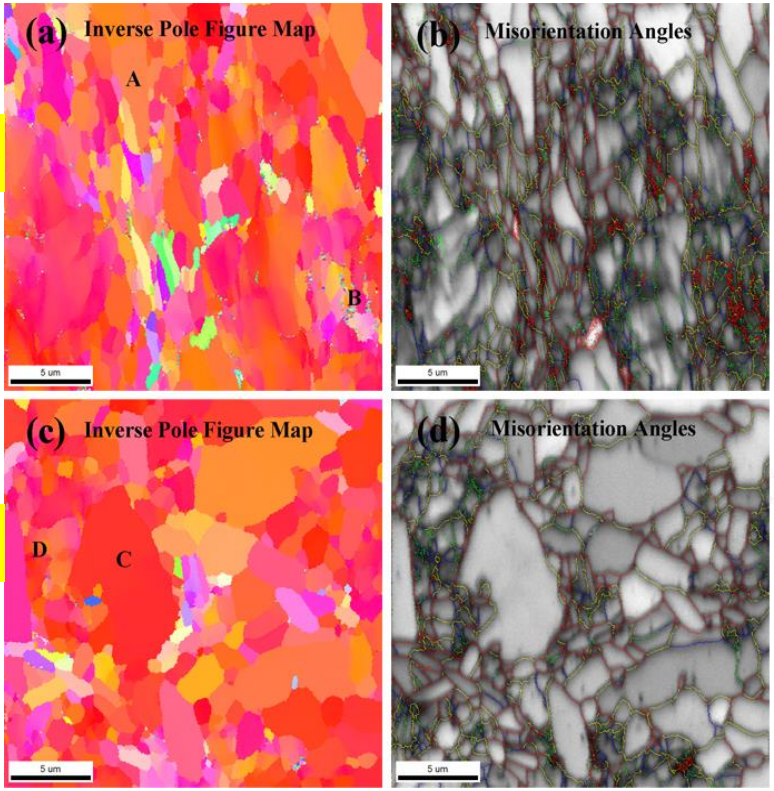
- **The variation tendency of J_c values was qualitatively similar to those of F and RRR values.**
- **The hardness was almost saturated as soon as the hot pressing was applied.**
- **The J_c increase for HP900 tapes was mainly attributed to higher degree of c-axis texture and enhanced grain connectivity.**

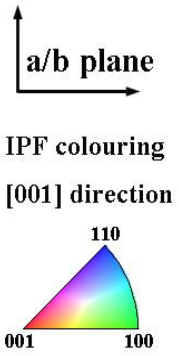
EBSD images: the orientation mapping of grains

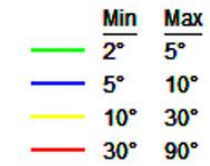
A useful tool to clarify the grain size, local orientation of the grains and misorientation angles between grains.

Upper: HP850

Lower: HP900







Inhomogeneous distribution of grain size

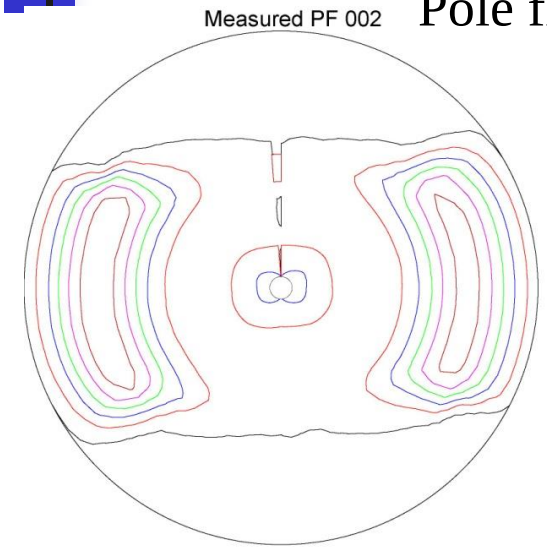
A room for the J_c improvement

- **The dominant orientation is (001) as the expected red color for both tapes, but there is a small (100) orientation for HP850 tapes as the green color.**
- **The large fraction of small misorientation angles between 2–10°C (HP850 tapes 23.3%, HP900 tapes 26.2%).**

Proof for the high texture in the Sr122 tapes

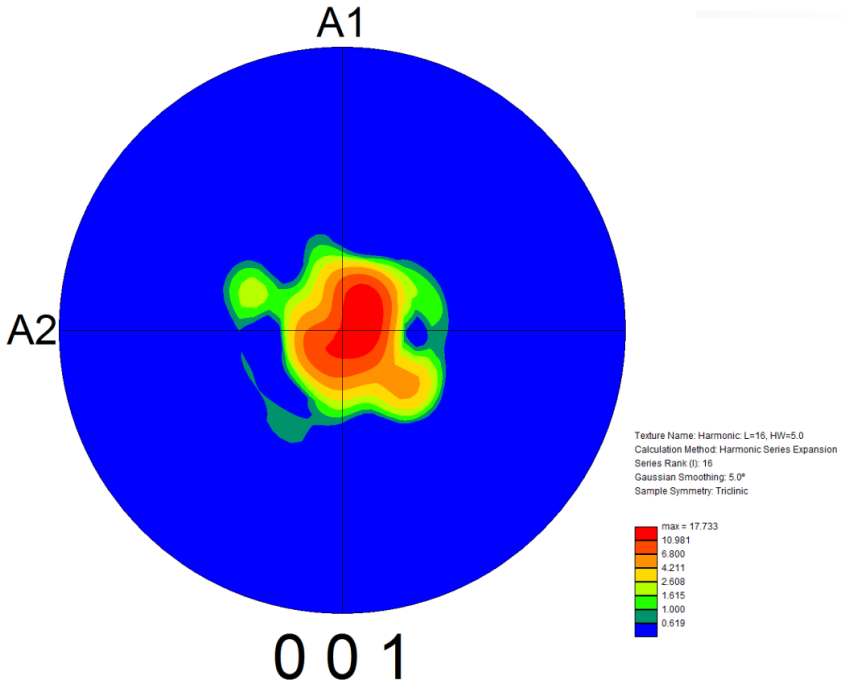
--Texture analysis

Pole figure



a marked texture

From XRD



From EBSD

A highly textured microstructure were obtained

Remarks for HP tapes

- **The significance of hot pressing**

  At 14 T, 4.2 K, the practical level J_c of 10^5 A/cm^2 has been achieved in Sr-122 pnictide tape, *indicating the strong potential for magnets*.

- **However, HP seems not suitable for the manufacture of long length wires.**

- **An scalable process is required to fabricate high performance long length superconducting tapes, e.g., *Hot Rolling or Hot isostatic press (HIP) process*…**

Other Latest Results in 122 Wires

Conductor requirements for practical applications

- Overall current density J_{cE} of conductor, not just of superconductor
- Performance in field
- Filamentary architecture essential for AC applications
- Anisotropy of J_{cE} with respect to field direction

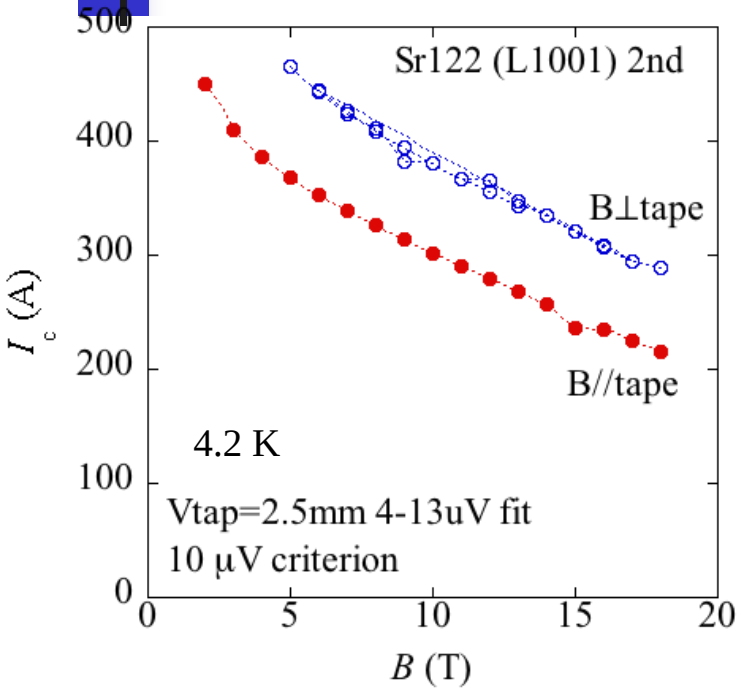
- Cost
  - Conductor itself
  - Cooling
- Scaleability of fabrication
- Mechanical
  - Strength, bend radius, …..
- Conductor shape
  - tape or wire

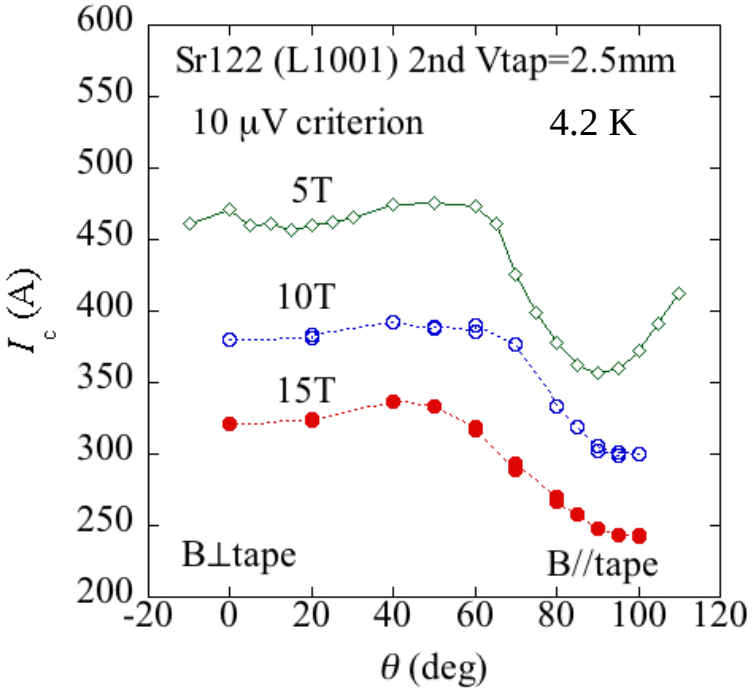
Larbalestier, ***Nature*** 414 (2001) 368

Small anisotropy

J_c properties at 4.2 K for HP Sr-122/Ag tapes

-- Measured by Dr. S. Awaji
HFLSM, Tohoku Univ.



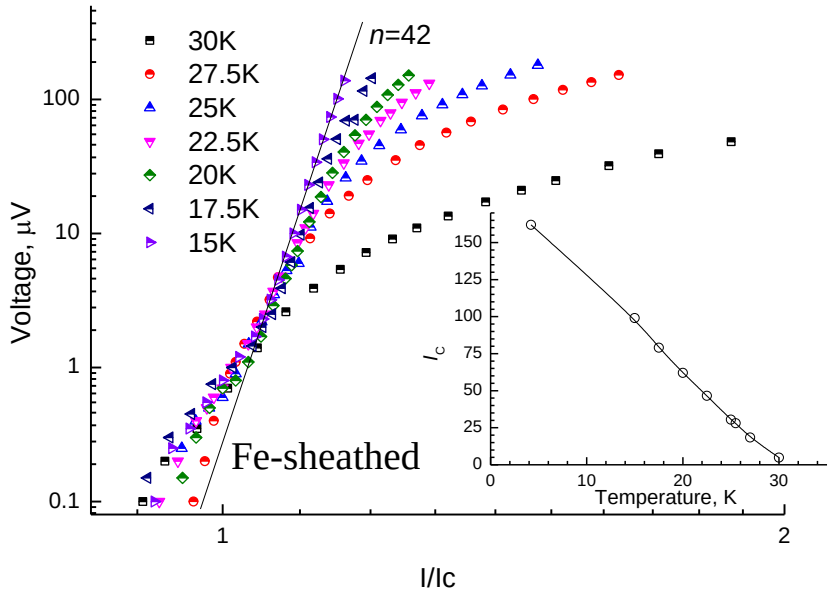


- The I_c in applied magnetic fields is slightly higher in the perpendicular field ($I_c^{\perp}$) than in the parallel field ($I_c^{//}$).
- The anisotropy ratio ($\Gamma = I_c^{\perp}/I_c^{//}$) is less than *1.5*, quite small, very promising for applications.

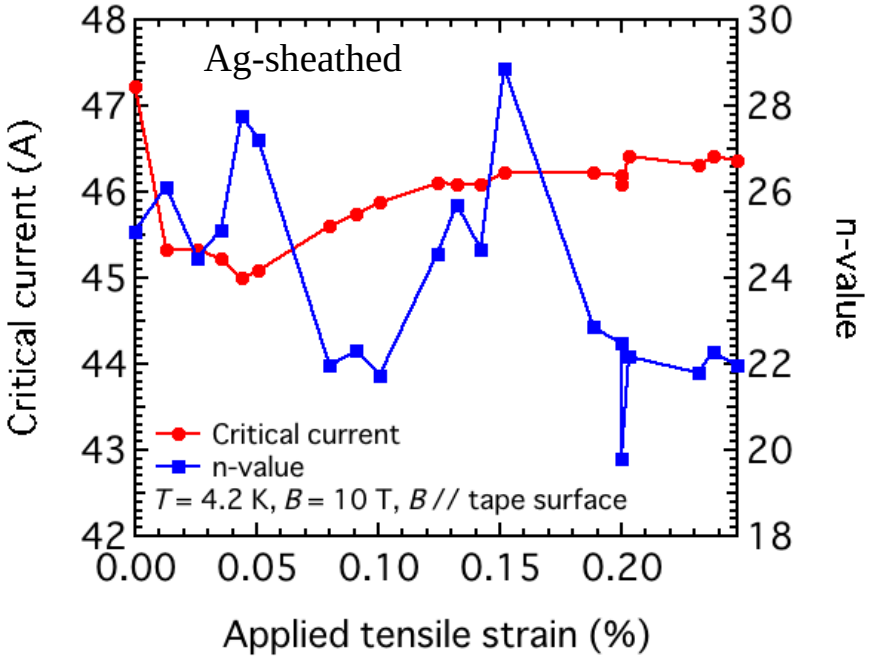
***n* value**

Temperature dependence of *n value* for Sr-122 tapes

-- Measured by Prof. Yang
Univ. of Southampton, UK



-- Measured by Dr. Oguro
HFLSM, Tohoku Univ., JP



At 20 K, the *n value* was over 30

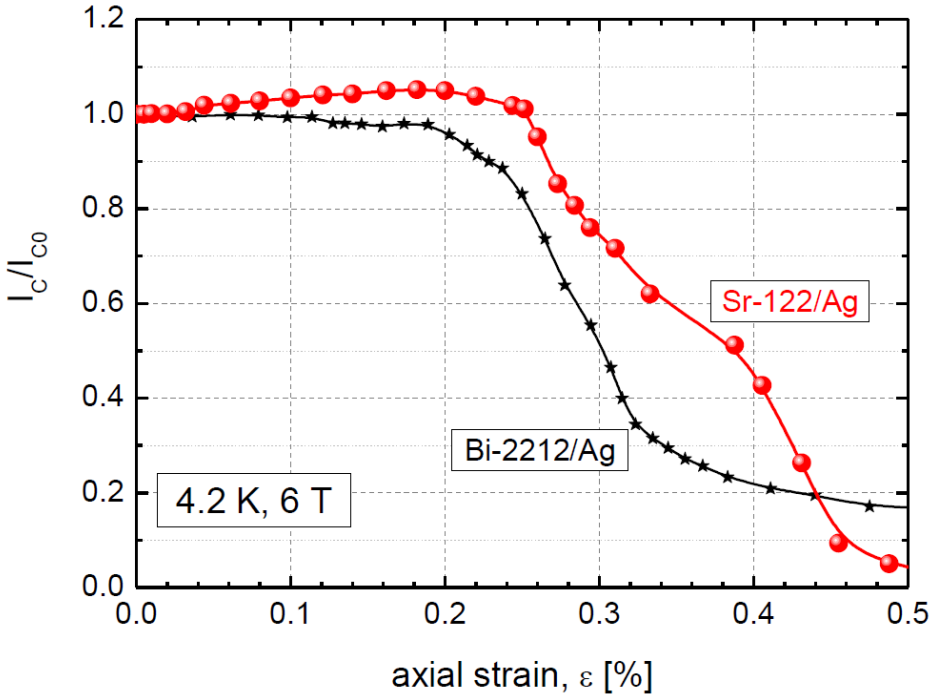
At 4.2 K, the *n value* was over 20

Strain property

Kovac et al., *SuST* 28 (2015) 035007

The first strain measurements of Sr-122/Ag tapes

-- Measured by Dr. Kovac
Slovak Academy of Sciences



At 4.2 K, 10 T: I_c >125A

Irreversible strains:

$\varepsilon = 0.25\%$

which seems better than that of Bi-2212/Ag

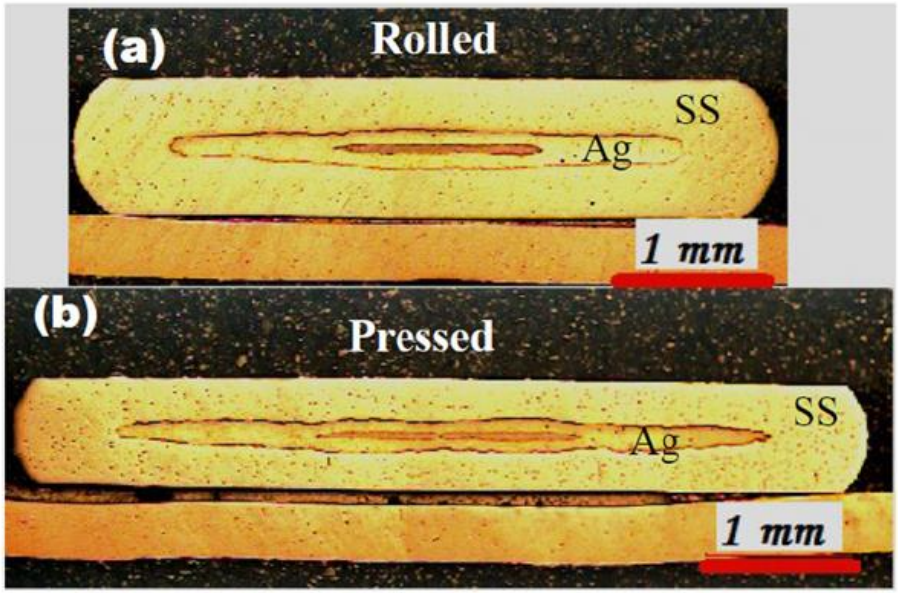
The first observation of strain effects on the critical current of 122 wires

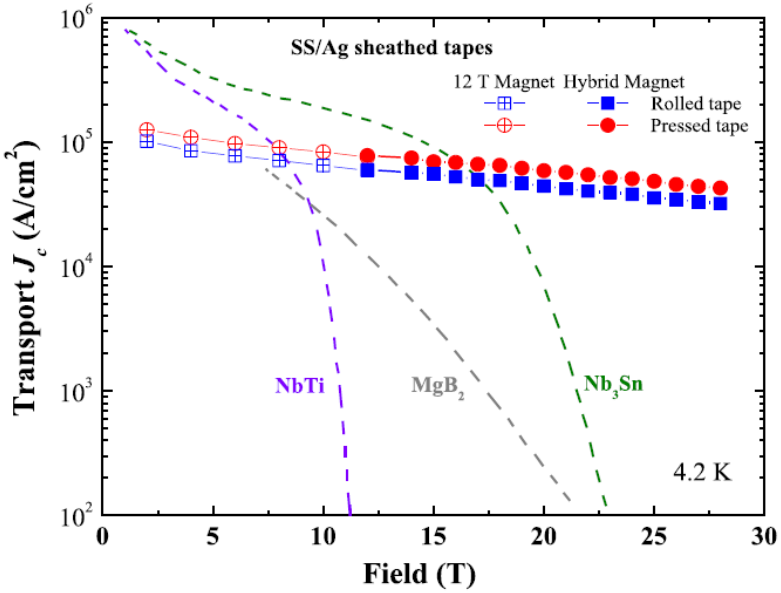
Next step:

Improvement of mechanical property of pnictide wires will be one of the major challenges for high field applications

Fabrication of stainless steel/Ag double sheathed Ba122 tapes

Highly mechanical property is expected!



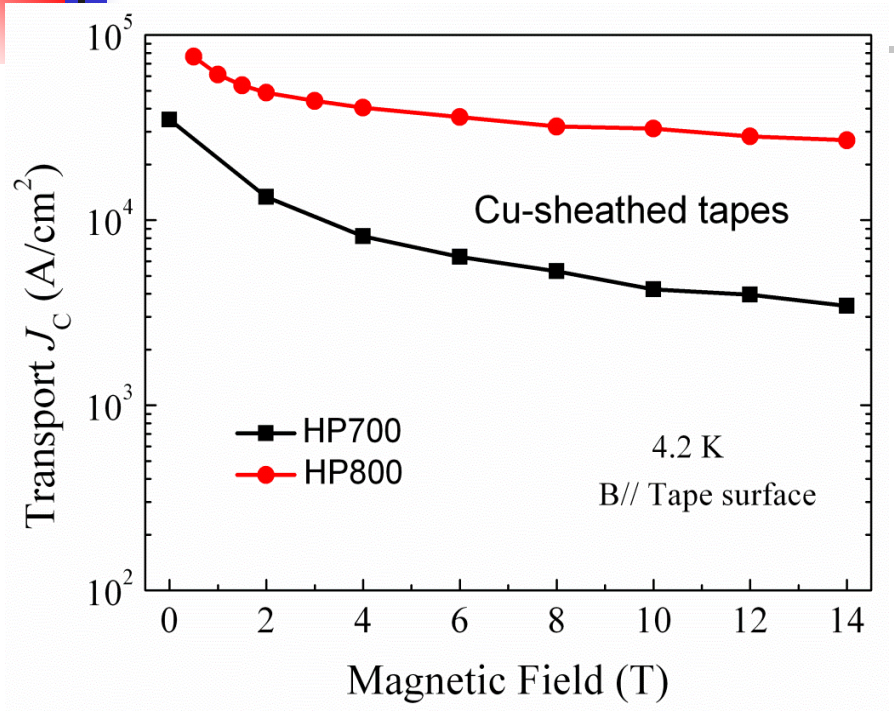


High J_c, but show lower J_e

NIMS group, ***Supercond. Sci. Technol.*** 28 (2015) 012001

Low material cost & good thermal stability

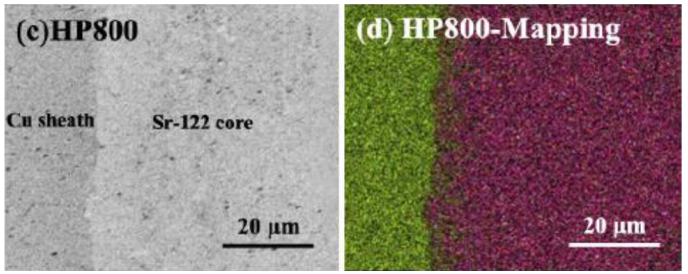
High J_c in Cu-sheathed Sr-122 tapes



At 4.2 K, 10 T

Transport J_c:
3.1×10^4 A/cm^2

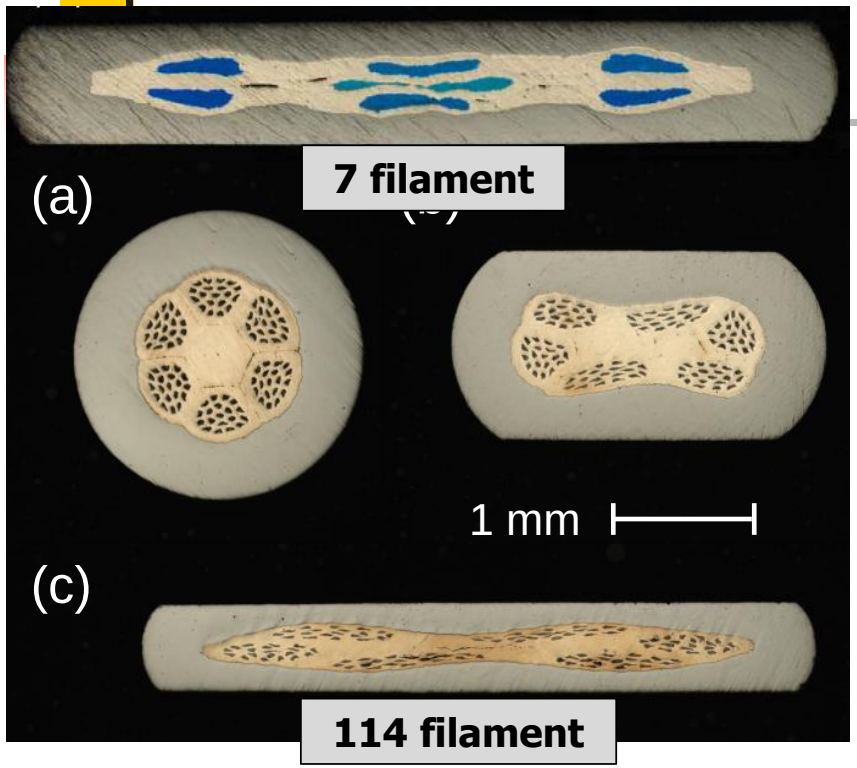
Engineering J_e:
$>10^4$ A/cm^2



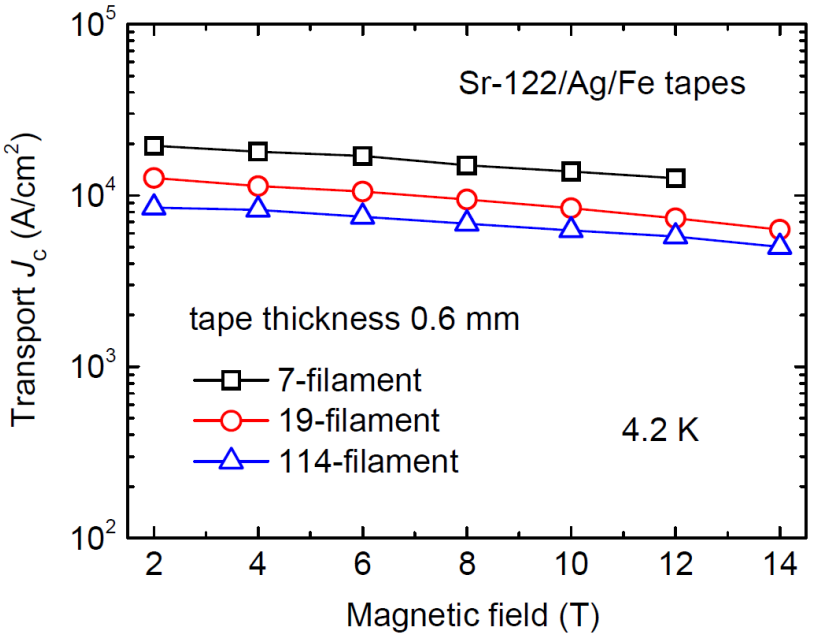
We obtained nearly phase-pure Sr-122 tapes with hot pressing at 800°C for 30 minutes. This rapid fabrication method can effectively thwart the diffusion of Cu into polycrystalline Sr-122 core.

Lin, et al., *Sci. Rep.* 5 (2015) 11506

Multi-filament wires have been made



--Very promising J_c



- **The transport J_c achieved 21.1 kA/cm^2 at 4.2 K in self field, and showed very weak magnetic field dependence at high fields.**
- **Latest result on 7-cores 122 wires: J_c (10T, 4.2 K) > 1.5×10^4 A/cm^2**

Yao et al., *JAP*, 2015

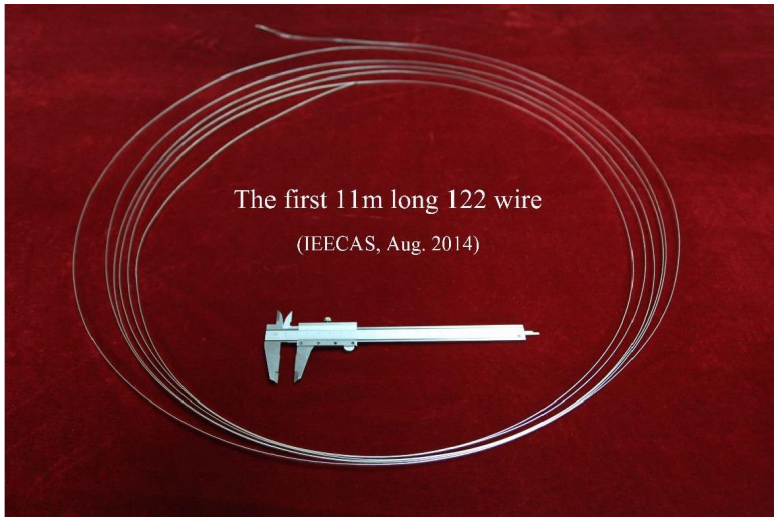
Significant breakthrough!

Ma , *Physica C* 516 (2015) 17

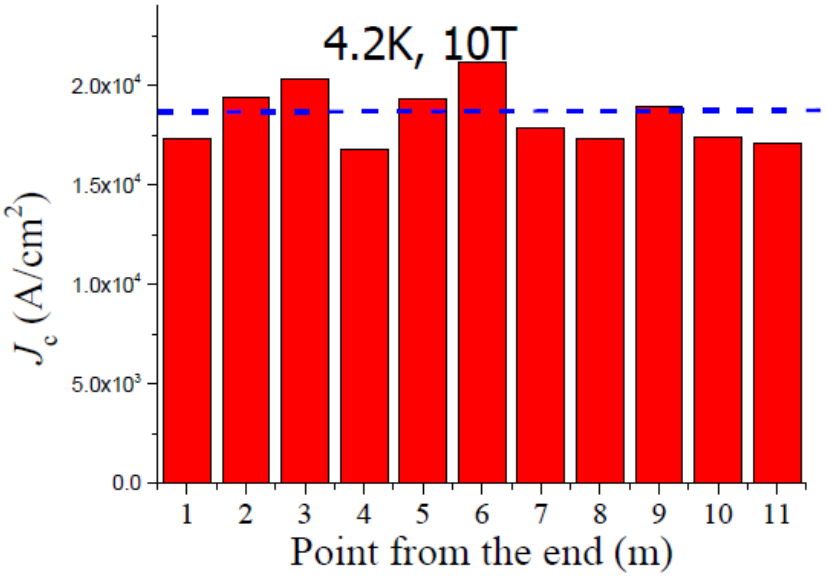
The first 11m long Sr-122 tape

-- by the scalable rolling process

The first long wire-- 11 m



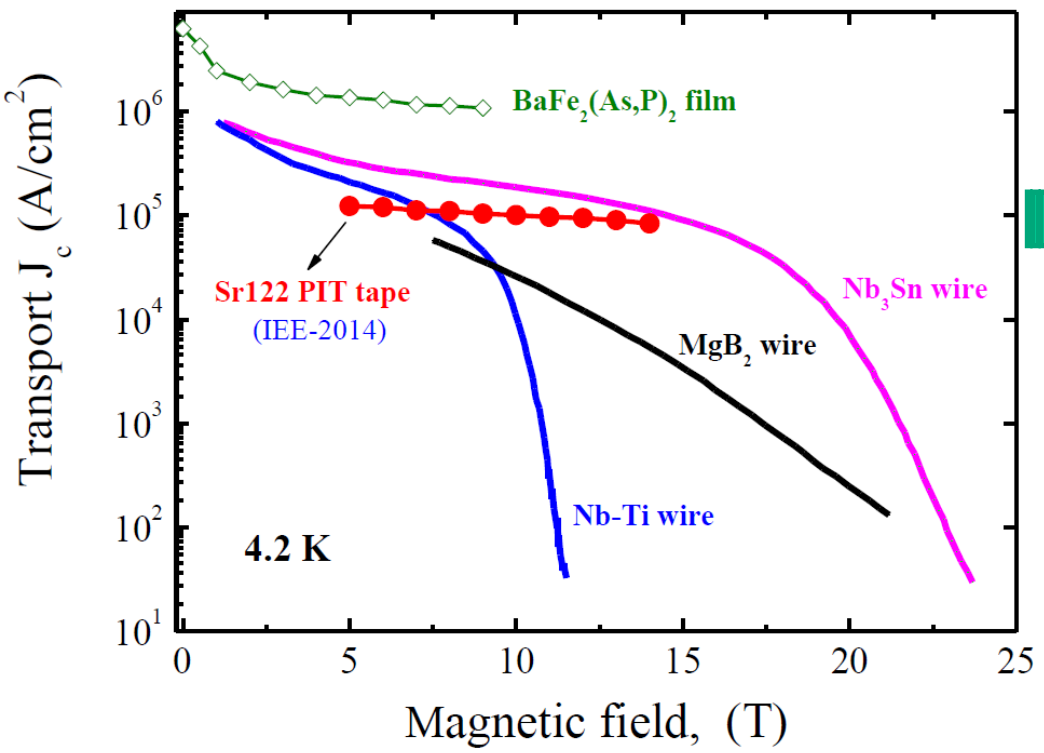
Uniform wires can be fabricated



The minimum $J_c \sim 1.7 \times 10^4 A/cm^2$

The average J_c of this long Sr122/Ag wire is ~ 18400A/cm²
The fluctuations of the J_c is ~5%

Prospects



Breakthrough work

Already reached practical level J_c at 10 T

+

Realization of the first 11 m long-length tape

Strong promising for high-field applications !

- **122 PIT tapes have achieved the practical level J_c, increasing it further is challenging. Still we are below the film J_c, so there is room for improvement.**
- **We believe that PIT process can be applied industrially to fabricate pnictide wires and tapes, as already demonstrated by the production of Bi-2223 and MgB_2 wires.**

Thank you for your attention!