1st Year Report - Matteo Bordonaro

Development of innovative superconductors for application in high field magnets for particle accelerators

This PhD project in Applied Superconductivity is part of a collaboration between the CNR-SPIN Institute and CERN. The work aims to develop multi-filamentary wires of Iron-Based Superconductors (IBSs), specifically $Ba_{0.6}K_{0.4}Fe_2As_2$, for next generation of particle accelerators like CERN's Future Circular Collider. The research will be conducted at the Physics Department and the SPIN Institute of the CNR. This project seeks to advance the technological steps toward a new generation of high-critical-temperature superconducting wires – processed through the Powder-In-Tube (P.I.T.) technique - using Iron-Based Superconductors from the (Ba, K)Fe_2As_2 (Ba-122) family. These materials exhibit high upper critical (H_{c2}) and irreversibility (H^*) fields [1]. With their low anisotropy and a higher critical temperature (T_c) of around 38 K, they can be used at liquid helium temperatures as well as at higher temperatures, up to around 20 K (liquid hydrogen). Although IBSs, like HTSs, face "weak link" issues, their larger critical misalignment angle of 7°-9° (versus 3°-5° for cuprates) makes them more easily processed via the P.I.T. technique, which yields high critical current density and cost-effective isotropic wires [2].

To successfully produce these wires, several critical aspects will need to be addressed:

- powder purity and microstructure: A key focus is an in-depth study of powders purity and microstructure, fundamental properties to achieving high performance in the final conductors.
- Grain connectivity: I will conduct a detailed investigation into grain connectivity within the samples.
- Compaction and texturing in mono-filamentary samples: I will tackle the challenges of powder densification and grain texturing in mono-filamentary conductors, exploring new metallic sheaths.
- Multi-filamentary wire development: Building on what I learned from the mono-filamentary samples, my work will expand to developing multi-filamentary wires. This will involve applying my knowledge to new architectures to produce high-performance isotropic wires.

[1] Alex Gurevich, Annu. Rev. Condens. Matter Phys., Vol. 5, 2014, doi: 10.48550/arXiv.1308.2016.
[2] Chao Yao and Yanwei Ma, iScience, Vol. 24, 2021, doi: 10.1016/j.isci.2021.102541.

Activities carried out in the first year:
Throughout the first year of my PhD, my research has focused on the development of Ba-122 superconducting mono-filamentary P.I.T. tapes. This technique involves filling a metallic tube, which provides the mechanical structure, with the powders of the superconductor. The filled tube is then mechanically deformed and heat treated. The sheath choice is crucial, as the metal must be both chemically compatible with the superconductor and easily cold-workable. The sheath also serves to compact and texture the powders within. The main goal during this period was to explore and optimize the metallic sheaths to enhance powder compaction and texture, thereby improving the superconducting properties.

Different experimental techniques were used to characterize the tapes:

- to evaluate compaction, I measured the Vickers Hardness using a micro-durometer. This device applies a known weight to the material, creating a square indentation in it whose diagonal is measured to calculate the hardness value, providing an indication of its densification.
- For texturing analysis, I conducted X-Ray Diffraction (XRD) on longitudinal section of each sample. Based on Bragg's law of diffraction, the heights of the peaks of the output diffractogram is used to determine the quantity of crystal planes arranged along specific crystallographic direction.
- The superconducting properties were measured using the four-terminal volt-amperometric method - where two outer contacts inject current while the inner ones measure the potential drop - allowing to measure very small quantities, approaching zero. T_c is determined by measuring electrical resistance as a function of temperature, while the critical current (I_c) is evaluated by measuring the potential drop as a function of the injected current, both studied as a function of the applied magnetic field.

The initial project phase involved fabricating tapes with pure silver (Ag) sheaths, a material that's easy to process but not sufficient to effectively compact and texture the powders inside. This limitation compromised both the powder's hardness and texture, thereby restricting the tape's overall performance.
To address this, I shifted the research to harder metals, introducing copper (Cu) and its alloys, such as CuNi (70% Cu, 30% Ni) and brass (65% Cu, 35% Zn). However, due to the risk of contamination from Cu and Ni during heat treatment, it was necessary to incorporate a silver barrier between the outer sheath and the superconducting core. A critical aspect of this phase was optimizing the sintering heat treatment; since Cu and Ag form a eutectic at 779°C, the treatment temperature had to be kept below this limit - typically around 740°C - for brief periods.
Three types of tapes were fabricated and fully characterized. The use of harder sheaths significantly increased powder hardness and texture, confirming the new approach's effectiveness. Nevertheless, the measured J_c (critical current divided by the superconducting area) values remained low, ranging from $0.6 \cdot 10^3$ to 10^3 A/cm^2 at 7 T. An in-depth SEM analysis of the tapes' longitudinal sections revealed the presence of micro-cracks at their centre tapes, which compromised the current flow.

To overcome the thermal limitations of the Cu-Ag eutectic, I explored a new chemical barrier, using niobium (Nb) between the CuNi sheath and the inner silver layer. This resulted in two new types of tapes: CuNi/Nb/Ag and CuNi/Nb (to determine if silver was still necessary). This new design allowed for a significant increase in both the sintering temperature and duration, reaching 840°C for 10 hours without any observed powder contamination. J_c measurements on the CuNi/Nb/Ag tape yielded high values, up to $7.2 \cdot 10^4$ A/cm^2 at 12 T. However, SEM analysis of longer samples revealed the presence of cracks.

The project's current phase is dedicated to understanding and eliminating these cracks. Different heat treatments are being tested to reduce their size, and the data suggest the issue is tied to both mechanical deformation and thermal treatment conditions. Future work will concentrate on optimizing these processes to produce crack-free tapes and will expand to developing multi-filamentary wires with new architectures.

Supervisors:
- Dr. Andrea Malagoli (CNR-SPIN).
- Prof. Marina Putti (Università degli Studi di Genova).

Course attended:
- Technology of wires, tapes and superconducting cables - A. Malagoli.
- Design of Superconducting Magnets - S. Farinon.
- Applied Cryogenics - R. Musenich.
- Advanced Crystallography: theory and experiments - A. Martinelli.

Conferences attended:
- Iron-based Superconductors: Advances towards applications 2025 (IBS2app 2025), Miyazaki, Japan.
- Poster session at the 17th European Conference on Applied Superconductivity 2025 (EUCAS 2025), Porto, Portugal.

Publications:
- A. Malagoli , A. Traverso , C. Bernini , F. Loria, A. Leveratto, E. Bellingeri, **M. Bordonaro**, M. Cialone, H. M. Hassan, V. Braccini, and A. Ballarino, *"Development of a Scalable Method for the Synthesis of High Quality (Ba,K)-122 Superconducting Powders"*, IEEE TAS (Aug. 2025), vol. 35, no. 5, pp. 1-5, Art no. 7300305.
- A. Traverso, **M. Bordonaro**, H. M. Ul Hassan, A. Leveratto, F. Loria, E. Bellingeri, C. Bernini, V. Braccini, A. Ballarino, and A. Malagoli, *"Impact of Powder Granulometry on the Transport Properties of $Ba_{0.6}K_{0.4}Fe_2As_2$ Superconducting Tapes"*, IEEE TAS (Aug. 2025), vol. 35, no. 5, pp. 1-5, Art no. 7300405.