



Future Circular Collider

PUBLICATION

The CERN FCC Conductor Development Program: A Worldwide Effort for the Future Generation of High Field Magnets

Ballarino, Amalia (CERN) *et al.*

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The CERN FCC Conductor Development Program: A Worldwide Effort for the Future Generation of High Field Magnets

A. Ballarino, S. C. Hopkins, B. Bordini, D. Richter, D. Tommasini, L. Bottura, M. Benedikt, M. Sugano, T. Ogitsu, S. Kawashima, K. Saito, Y. Fukumoto, H. Sakamoto, H. Shimizu, V. Pantsyrny, I. Abdyukhanov, M. Shlyakov, S. Zernov, F. Buta, C. Senatore, I. Shin, J. Kim, J. Lachmann, A. Leineweber, S. Pfeiffer, T. Baumgartner, M. Eisterer, J. Bernardi, A. Malagoli, V. Braccini, M. Vignolo, M. Putti, and C. Ferdeghini.

Abstract—The study of next generation high energy accelerators based on 16 T dipoles has emphasized the need for higher performance, cost-effective Nb₃Sn superconducting wires. A Conductor Development Program aiming to reach a non-copper critical current density (J_c) of 1500 A/mm² at 16 T and 4.2 K has been launched by CERN, with the involvement of industry and laboratories worldwide. In this article, the targets and strategy of the program are presented, with an overview of the wire layouts and development activities being pursued by each partner, and the latest characterization results are reported. Three of the four participating manufacturers have successfully reached the first stage J_c milestone, but a significant advance is still needed to achieve the final target. The next steps are briefly discussed, as the program focuses increasingly on novel alloys and methods to maximize J_c .

Index Terms—Accelerator magnets, niobium-tin, superconducting materials, superconducting filaments and wires.

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A. Ballarino, S. C. Hopkins, B. Bordini, D. Richter, D. Tommasini, M. Benedikt and L. Bottura are with the European Organization for Nuclear Research (CERN), CH-1211 Geneva 23, Switzerland (e-mail: amalia.ballarino@cern.ch; simon.hopkins@cern.ch; bernardo.bordini@cern.ch; david.richter@cern.ch; david.tommasini@cern.ch; michael.benedikt@cern.ch; luca.bottura@cern.ch).

M. Sugano and T. Ogitsu are with the High Energy Accelerator Research Organization, KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801 Japan.

S. Kawashima, K. Saito, and Y. Fukumoto are with Kobe Steel and Japan Superconductor Technology (JASTEC), Kobe, Japan

H. Sakamoto and H. Shimizu are with Furukawa Electric, Tokyo, Japan

V. Pantsyrny and I. Abdyukhanov are with the A. A. Bochvar High-Technology Research Institute of Non-Organic Materials, JSC VNIINM, Rogova Street 5a, Moscow 123060, Russia

M. Shlyakov and S. Zernov are with JSC TVEL, 49 Kashirskoe shosse, 115409 Moscow.

F. Buta and C. Senatore are with the University of Geneva, quai Ernest-Ansermet 24, 1211 Geneva 4, Switzerland.

I. Shin and J. Kim are with Kiswire Advanced Technology Company, Ltd., Deajeon, South Korea.

J. Lachmann and A. Leineweber are with the Institute of Materials Science, TU Bergakademie Freiberg, Gustav-Zeuner-Str. 5, 09599 Freiberg, Germany.

T. Baumgartner and M. Eisterer are with TU Wien, Atominstytut, Stadionallee 2, 1020 Wien, Austria.

S. Pfeiffer and J. Bernardi are with TU Wien, USTEM, Wiedner Hauptstr. 8-10, A-1040 Wien.

A. Malagoli, V. Braccini, M. Vignolo, and C. Ferdeghini are with CNR-SPIN, Corso Ferdinando Maria Perrone, 24, 16152 Genova, Italy.

M. Putti is with the University of Genova, via Dodecaneso 33, 16146 Genova, Italy.

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I. INTRODUCTION

HIGH Energy Physics has a long history of driving the development of superconducting magnets, and improvements in the design and performance of the superconducting wires used to produce them.

In the context of the High-Luminosity LHC (HL-LHC) Project, a major upgrade program to increase the luminosity of the LHC, Nb₃Sn accelerator magnets will be installed for the first time. The requirement for larger-aperture quadrupole magnets, and shorter dipole magnets to allow space for additional collimators, necessitates a significant increase in magnetic field — from a peak field of up to 8.6 T on the conductor in the LHC, to 11.6 T for HL-LHC — which cannot be achieved with Nb–Ti, as used for the LHC. Suitable Nb₃Sn conductors have been developed using both the Rod Restack Process (RRP[®]) and powder-in-tube technologies, and series production of these wires is advancing towards completion [1].

The proposed Future Circular Collider (FCC) would require another substantial step forward. The FCC Study is developing a number of conceptual designs for a successor particle collider to the LHC, but the baseline is a 100 TeV hadron collider in a 100 km tunnel with 16 T dipole magnets. The combination of the high operating magnetic field and the large scale of this facility, for which ~4800 dipole magnets would be required (including spares), imposes extremely demanding performance and cost targets on the superconducting wire.

The only candidate with proven large-scale industrial production is currently Nb₃Sn [2], but it is clear that these targets cannot be met by current state-of-the-art Nb₃Sn wires. In particular, a non-copper critical current density (J_c) of 1500 A mm⁻² is required at 16 T and 4.2 K, with a residual resistance ratio (RRR) exceeding 150 and a small effective filament diameter (d_{eff}) [2]. CERN has therefore launched a Conductor Development Program to drive the development of a suitable wire in partnership with industry and academia [3].

This article introduces the structure and strategy of the Conductor Development Program, presents a selection of the

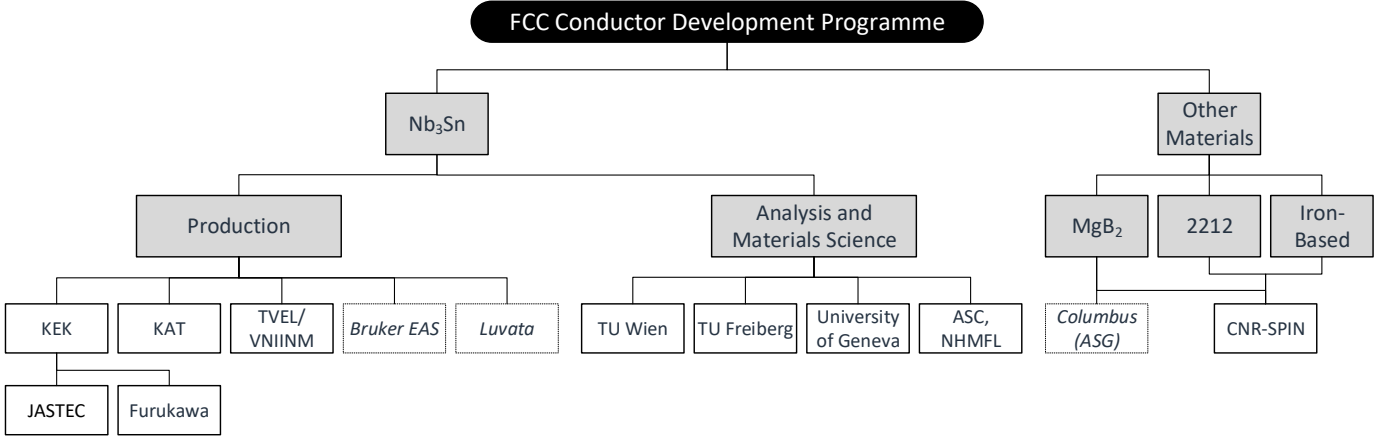


Fig. 1. Schematic of the FCC Conductor Development Programme, showing the activities (shaded boxes) and partners. A dotted outline and italic text indicate pending participants, whose participation is currently being finalised.

wire layouts currently under development, summarizes the progress achieved so far and comments on future prospects.

II. THE CONDUCTOR DEVELOPMENT PROGRAM

The Conductor Development Program aims to develop wires meeting the requirements of the superconducting magnets for the FCC, with proven scalability to long-length industrial production, and the potential for cost reduction.

As noted above, the program is centered on Nb_3Sn wires, for which the target parameters are listed in Table 1. The fundamental approach is to engage the broadest possible community in this effort. The program therefore includes prototyping and pilot production of a diverse range of wire designs with a worldwide network of industrial partners.

The strategy is to focus on two initial goals (also in Table 1): firstly, supporting industrial partners in achieving reliable production of internal tin Nb_3Sn wire with a performance comparable to the HL-LHC specification (stage 1), and then prioritizing increases in the high-field critical current performance (stage 2).

At present, industrial wire development projects are in progress with Kiswire Advanced Technology (KAT) in South Korea and TVEL in Russia, and activities with Bruker EAS and Luvata are planned. In addition, Japan Superconductor Technology (JASTEC) and Furukawa Electric are participating in the context of a joint collaborative program with the High Energy Accelerator Research Organization, KEK, Japan.

TABLE I
DEVELOPMENT TARGETS FOR Nb_3Sn WIRE

Parameter	Final	Stage 1	Stage 2
Wire diameter (mm)	0.7 – 1.1	~1	~1
Cu/non-Cu ratio	~1	~1	~1
Non-Cu J_c , 16 T and 4.2 K (A/mm^2)	≥ 1500	≥ 1000	≥ 1500
$\mu_0 \Delta M$ at 1 T and 4.2 K (mT)	≤ 150	-	-
d_{eff} (μm)	≤ 20	≤ 60	≤ 60
RRR	≥ 150	≥ 150	≥ 150
Unit length (km)	≥ 5	≥ 0.1	≥ 0.1
Price, 16 T and 4.2 K ($\text{€} / \text{kA m}$)	≤ 5	-	-

The Japanese program is supported by the universities of Tohoku and Tokai.

This activity is supported by characterization and analysis at CERN and by TU Wien, and more fundamental studies of thermodynamics and diffusion at TU Bergakademie Freiberg, to obtain a more complete understanding and identify opportunities for optimization. In addition, laboratory-scale studies of novel alloys and internal oxidation methods are in progress in the University of Geneva, and with effect from October 2018, the Applied Superconductivity Center of the National High Magnetic Field Laboratory (Florida State University), to identify routes suitable for industrial implementation that might provide a substantial step forward in J_c .

The program also supports smaller activities seeking a breakthrough in the high-field performance or cost effectiveness of alternative superconducting materials: currently including studies of MgB_2 , BSCCO 2212 and iron-based superconductors at CNR-SPIN (Genoa, Italy).

The Nb_3Sn program runs in synchronization with a Magnet Development Program, which aims to prototype, assess and refine the dipole magnet designs developed in the context of the EuroCirCol project. These magnets are designed to achieve the 16 T field target when suitable wire is available: for the first short model magnets, Nb_3Sn wire is being procured with comparable J_c to the HL-LHC wire, and the conductor program aims to supply higher-performance wire for the next stage of FCC model magnet development.

III. EXPERIMENTAL METHODS

For superconducting characterization at CERN, the following samples were prepared from unreacted wire: for critical current (I_c) measurement, a ~ 1.2 m length wound on a coated Ti-6Al-4V VAMAS-type barrel; for residual resistivity ratio (RRR), a straight length of ~ 150 mm; and for magnetization measurements, either a straight sample ~ 6 mm in length, or a mini-coil wound on a 5 mm thread to obtain a total length of ~ 125 mm. The manufacturer's recommended heat treatment was then performed under vacuum on this set of samples.

Transport critical current (I_c) measurements were performed in liquid helium (4.3 K) at 12–15 T, using an electric field criterion of 0.1 $\mu\text{V}/\text{cm}$. Magnetization was measured using a vibrating sample magnetometer (VSM; Cryogenic, UK) at 4.2 K with a field range of ± 10 T, from which the effective filament diameter (d_{eff}) was determined by comparison with the scaled transport J_e [4]. RRR was calculated from four-point resistance measurements at room temperature and ~ 20 K.

For scanning electron microscopy (SEM), wire samples were cut with a diamond wire saw, placed in a brass support and hot mounted in a conductive phenolic resin. For optical microscopy, cold mounting was used. The mounted specimens were prepared for examination with a sequence of grinding (SiC paper) and polishing (diamond suspension) steps down to 1 μm or smaller. SEM was performed using a Zeiss Sigma field emission SEM, typically using an accelerating voltage of 10 kV, and energy-dispersive x-ray spectroscopy (EDX) was used for compositional analysis.

In some cases, as indicated in the text, measurements are contributed by the manufacturer: these use identical heat treatments and comparable methods, but exact procedures may differ.

IV. PROTOTYPE Nb_3Sn WIRES

In this section, the designs and performance of a selection of wires produced by industrial partners in the program are summarized. Additional characterization based on image analysis is reported in [5].

A. TVEL/Bochvar Institute (VNIINM)

During a project running from 2016–2017, the Bochvar Institute (VNIINM) developed and prototyped several designs of internal tin Nb_3Sn wire, and performed pilot production at Chepetsky Mechanical Plant (ChMP) to demonstrate the feasibility of long-length manufacturing. The project included de-

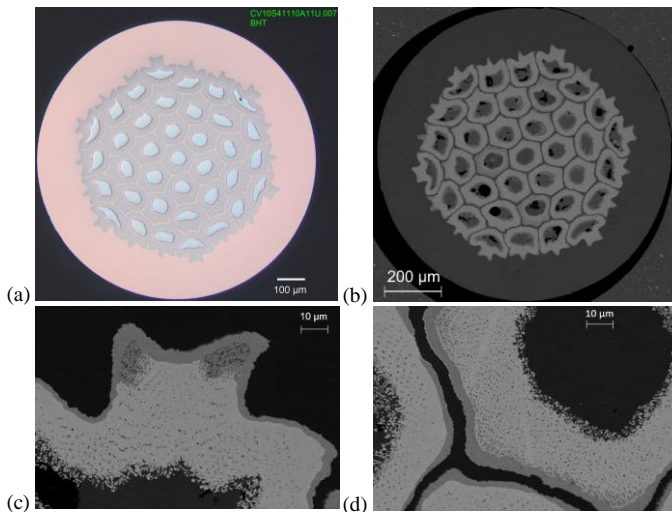


Fig. 2. Micrographs of the distributed barrier wire developed and produced by TVEL in late 2017. (a) Optical micrograph of an unreacted wire; (b) back-scattered electron micrograph of a reacted sample; and back-scattered electron micrographs of sub-elements showing incomplete reaction (c) at the periphery of a sub-element, and (d) particularly in distorted sub-elements.

TABLE II
CHARACTERISTICS OF TVEL DISTRIBUTED BARRIER WIRES

Parameter	Specification	Achieved ^a	Measured
Wire diameter (mm) ^b	1.000 ± 0.003	1.002–1.003	CERN
Cu/non-Cu ratio	1.2 ± 0.2	1.18–1.34	Both
Non-Cu J_c , 12 T and 4.3 K (A/mm^2)	$2450 \pm 5\%$ (4.2 K)	2329–2720	CERN
Best scaled J_c , 16 T and 4.2 K (A/mm^2)	N/A	1140	CERN
RRR	≥ 150	199–276 (mean: 249)	CERN
Geometrical sub-element diameter (μm) ^c	≤ 120	107–112 (mean: 110)	CERN
d_{eff} (μm) ^d	≤ 120	134–144	CERN
Unit length (m)	≥ 200	542–1435	TVEL

^aUnless otherwise specified, ranges represent the minimum and maximum values measured across the 11 piece lengths supplied.

^bMeasured by laser micrometer for two samples.

^cDiameter of circle of equal area to the sub-element, as determined by image analysis: the reported range is for all sub-elements in a single wire sample.

^dMeasured for one mini-coil sample each from two piece lengths.

signs with common (single) and with distributed diffusion barriers, of Ta, Nb and Ta/Nb. In addition, a sub-element layout with Cu separators was prototyped in order to reduce d_{eff} .

A 37 sub-element layout with distributed niobium barriers was selected for trial production (Fig. 2), and 12 km of 1 mm diameter wire was successfully produced and delivered to CERN in piece lengths averaging more than 1 km. The wire was designed for a higher Cu/non-Cu ratio, 1.2, than the present FCC target.

After heat treatment (100 h at 370 $^\circ\text{C}$, 40 h at 665 $^\circ\text{C}$), the resulting characteristics are tabulated in Table II. All results are consistent with the intended specification, except d_{eff} , which exceeds the geometrical sub-element size: this may be due to the non-uniform geometry of peripheral sub-elements (Fig. 2(c)), which is analyzed in more detail in [5]. The RRR is very high and consistent (the minimum value of 199 is an outlier). The measured critical current for all piece lengths is summarized in Fig. 3.

Scaling the non-copper J_c to the FCC reference conditions (an applied field at 16 T and 4.2 K) gives a value of 1140 A/mm^2 for the best sample. This is a promising result, and there is evidence that this can be further improved through

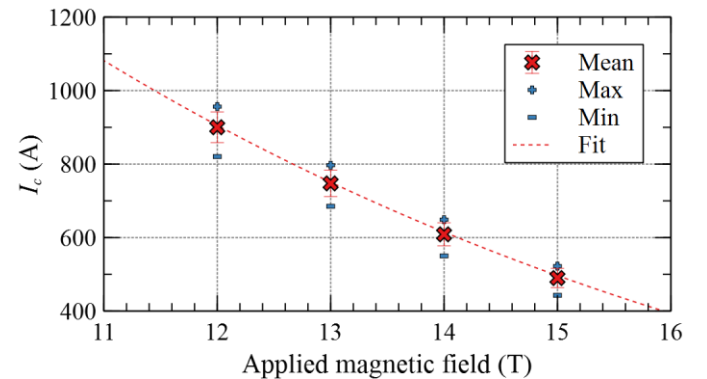


Fig. 3. Summary of I_c measurements at 4.3 K (performed at CERN) of TVEL trial wires. Error bars represent the standard deviation of measured values between piece length; the minimum and maximum values are also shown, along with an extrapolated fit of the mean values.

optimization of the heat treatment and deformation processing: residual niobium regions suggest incomplete reaction at the periphery of some sub-elements (Fig. 2(d)), and especially in distorted peripheral sub-elements (Fig. 2(c)) [5]. A detailed microstructural study of a selection of wires from TVEL is now in progress in TU Wien to identify the most promising directions for future development, and CERN and TVEL have recently signed a new agreement (September 2018) to continue this development for a further two years.

B. Kiswire Advanced Technology (KAT)

KAT began its four-year wire development project for the FCC Study in March 2017, and is pursuing three main types of common-barrier wire design, differing primarily in the distribution of tin and the niobium filament size. The detailed layout of each design is evolving through a series of trials, the most recent of which is summarized in Table III, supported in parallel by engineering tests of specific technologies and design approaches.

The most promising performance has so far been obtained with Type I designs (see table IV). For the best of the first trial wires, a J_c exceeding 1000 A mm^{-2} at 16 T and 4.2 K, and a high RRR ~ 200 was reported early in 2018 [6]. Electron microscopy analysis (Fig. 4) identified several opportunities for improvement. The residual tin content of the matrix was high (Fig. 4(c)), especially for the variant labelled design 3, and the radial profile was very uniform, perhaps suggesting that the long heat treatment (final plateaus of 200 h and 250 h at $650 \text{ }^\circ\text{C}$ for designs 2 and 3 respectively) could be reduced. Some bridging between sub-elements was also apparent, consistent with a larger d_{eff} than the nominal sub-element size determined from VSM data (Table III). The barrier thickness was also found to be as low as $3 \mu\text{m}$ in some locations, suggesting caution needed in reducing the nominal thickness.

TABLE III
CHARACTERISTICS OF KAT WIRE DESIGNS: CURRENT TRIALS

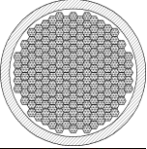
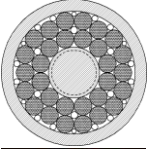
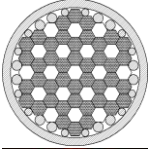
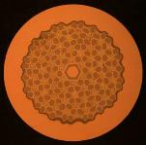
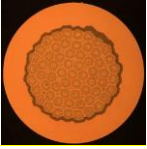
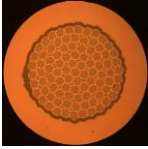
Parameter	Type I	Type II	Type III
Main Sn-Ti source	Between sub-elements	Center of sub-elements	Distributed in sub-elements
Diffusion barriers	1. Common, Ta 2. Core, Nb	Common, Ta	Common, Ta
Diameter (mm)	1.0	0.7	1.3
Cu/non-Cu	0.855	1.077	~ 1
Number of sub-elements	192 (132 Nb, 60 Sn-Ti)	61	91
Filament size (μm)	2.8	1.4	7.5
Sub-element design			
Cross-section (optical micrograph)			

TABLE IV
PERFORMANCE OF KAT TYPE I DESIGNS

Parameter	End 2017	Summer 2018
Number of modules	91 (60 Nb, 31 Sn-Ti)	192 (132 Nb, 60 Sn-Ti)
Diameter (mm)	0.700	1.004
Cu/non-Cu	0.928	0.855
Non-Cu J_c , 16 T and 4.2 K (A mm^{-2})	1019	995
RRR	196	186
Nominal sub-element size (μm)	44.2	43.1
d_{eff} at 1 T (μm)	103.4	69.2
d_{eff} (μm) ^a	74	Pending

Measurements performed by KAT unless otherwise stated

^aMeasurement performed by CERN; calculated for 8–10 T range

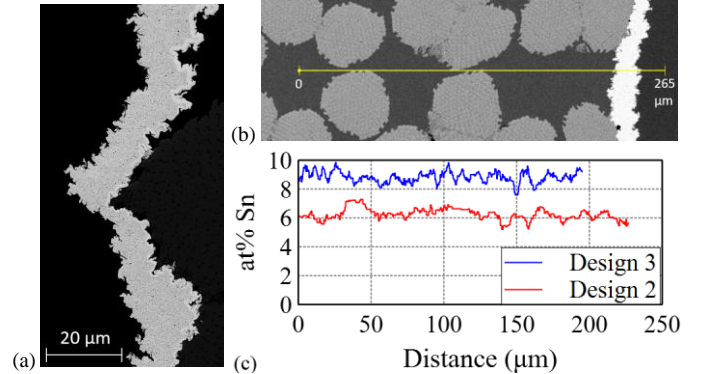


Fig. 4. Electron microscopy of the first trial type I wires produced by KAT. (a) Backscattered electron image of the diffusion barrier (both matrix and filaments are black) for a wire of design 2; (b) backscattered electron micrograph showing bridging between some sub-elements of a wire of design 2, with an overlay indicating the location of an EDX line scan; and (c) radial Sn composition profiles measured by EDX in the Cu-Sn matrix alone.

In the most recent trials, the barrier thickness has been successfully reduced from $20 \mu\text{m}$ to $10 \mu\text{m}$ in a 1 mm diameter wire whilst retaining the high RRR; and both the Nb filament diameter and the sub-element size have been decreased (when scaled according to the wire diameter). Importantly, the d_{eff} has also decreased, with a reduction in flux jumps at low field, whilst preserving comparable J_c . Heat treatment optimization, and an analysis of the distribution of Sn and Ti, is in progress to further improve the J_c .

Further trials are in progress to improve the deformation processing of type III wires with an increased number of sub-elements, further decrease d_{eff} in types I and III, and increase J_c by optimizing the component fractions and degree of reaction. After analysis of these trials, production of three R&D billets (each of 2 km) is planned for the start of 2019, when the resulting material will be characterized at CERN. The final stage of the project will include the supply of 20 km of a chosen design for cabling trials at CERN.

C. JASTEC

JASTEC, in the context of the Japanese program coordinated by KEK, is developing a series of distributed tin (DT) wires [7]. This common-barrier design contains tin islands distributed between the niobium sub-elements. This design has been

TABLE V
CHARACTERISTICS OF SELECTED JASTEC DISTRIBUTED TIN DESIGNS

Parameter	Trial 1	Trial 3: 1	Trial 3: 2
Wire diameter (mm)	0.6 – 1	0.8	0.8
Cu/non-Cu ratio (nominal)	0.34 ± 0.05	1.0 ± 0.2	1.0 ± 0.2
Number of sub-elements	84 Nb, 37 Sn-Ti	139 Nb, 72 Sn-Ti	139 Nb, 72 Sn-Ti
Non-Cu J_c , 16 T and 4.3 K (A/mm ²) ^a	952	1036	1090
RRR ^b	135		
d_{eff} (μm) ^b	267	54.5	55.0

^aMeasured at JASTEC (trial 1 at 0.75 mm diameter); trial 3 pending verification at CERN

^bMeasured at CERN; trial 1 at 0.7 mm diameter

developed through three trials, the third of which was recently completed, and a fourth is about to begin (see Table V).

The cross-section of the trial 1 wire design, before and after reaction, is presented in Fig. 5. This wire was produced with very low Cu fraction, in an effort to maximize J_c , which had an impact on stability; but a promising J_c of 950 A mm⁻² at 16 T and 4.3 K was measured by the manufacturer, and was consistent with scaled measurements at CERN.

At small wire diameters (0.6–0.7 mm), extensive bridging between sub-elements is apparent as shown in Fig. 5(b), and resulted in a very large d_{eff} (Table V). The radial profiles of residual tin content measured near the centers of the original tin cores (Fig. 6) are similar for wires 0.6 and 0.7 mm diameter. The majority of the niobium sub-elements are well reacted, and the average residual tin content is low, suggesting an appropriate niobium fraction; but the decrease in concentration

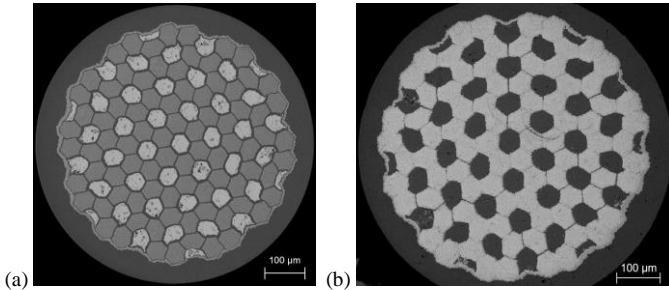


Fig. 5. Backscattered electron images of JASTEC's first trial DT wire at 0.7 mm diameter (a) before and (b) after reaction.

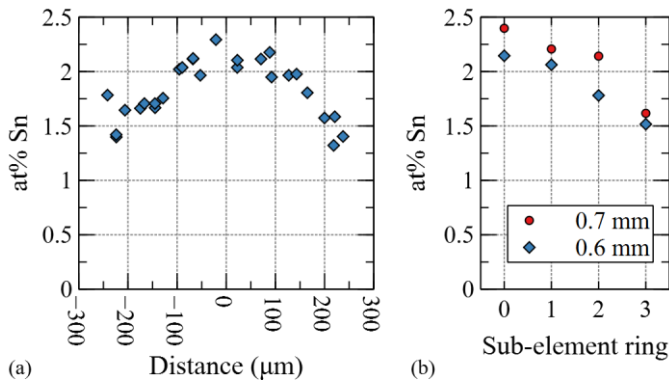


Fig. 6. Radial profiles of residual tin content in the matrix of reacted JASTEC first trial wires, from EDX spectroscopy: (a) all measured points as a function of radial position for a 0.6 mm diameter wire, and (b) a comparison of the profiles for 0.6 and 0.7 mm diameter wires, averaged by the sub-element ring number (increasing away from the centre).

towards the periphery is correlated with locally incomplete reaction, demonstrating some potential for optimization of the tin distribution. This topic is analyzed in detail in [5].

The design for the third trial addressed these issues with a reduction in sub-element and filament sizes. Magnetization measurements confirmed that d_{eff} (at 0.8 mm) was successfully reduced to ~ 55 μm. Two variants were produced with reduced Ti concentration: the J_c measured at 16 T at JASTEC was ~ 5 % higher for the lowest Ti content, but considering the modest difference, this conclusion will be verified following comparative measurements at KEK and CERN. The fourth trial has two aims: to increase the Nb (and hence Nb₃Sn) fraction, and to complete the optimization of Ti addition and deformation behavior. Results are expected early in 2019, after which a wire design will be selected for 5 km pilot production.

D. Furukawa

Furukawa is also participating in the joint CERN-KEK Japanese program. Furukawa is an established manufacturer of bronze route Nb₃Sn, e.g. for ITER, and is now developing internal tin wires of two types: a niobium tube design and a distributed tin layout conceptually similar to the one developed by JASTEC and KAT. In the current program, Furukawa is prioritizing the Nb tube design. Four trials have been performed to date, advancing from an initial 48-filament layout to an 85-filament geometry as shown in Fig. 7.

E. Summary of Progress

Industrial Nb₃Sn wire development is progressing well, with four active and engaged manufacturers producing several trial wires per year. In all cases, progress towards the FCC development targets (Table I) has been achieved between successive trials: either an increase in J_c or a decrease in d_{eff} .

The J_c results are summarised in Fig. 8, with values for the wires procured for HL-LHC for comparison. Three manufacturers have successfully achieved the stage 1 J_c target (Table 1) comparable to the HL-LHC specification (but it should be noted that Cu/non-Cu ratio, d_{eff} and diameter differ): this is approaching a suitable level for FCC cabling and magnet trials, and provides a good baseline for further development.

Stage 2 of the program, targeting 1500 A mm⁻² at 16 T and 4.2 K, will still require a major step forward beyond incremental improvements; and novel approaches are therefore a growing focus for the next two years of the program. Work in this direction is currently driven by laboratory studies (section V), and will be enhanced by new partners in the coming months.

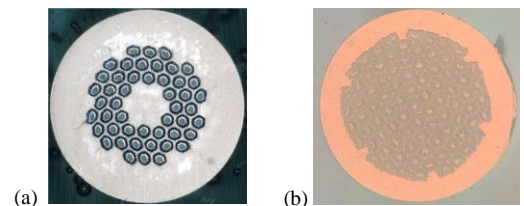


Fig. 7. Optical micrographs of Furukawa tube type wires with (a) 48 and (b) 85 filaments.

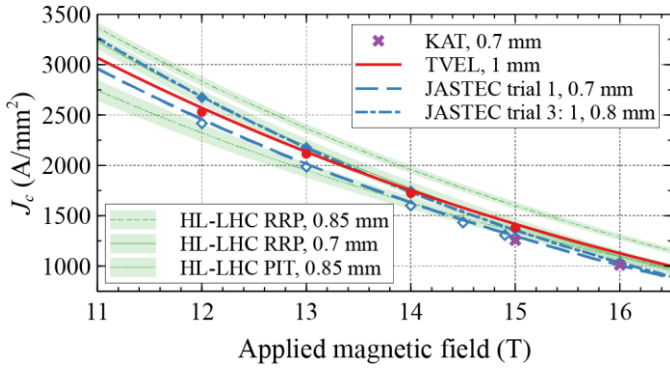


Fig. 8. The $J_c(B)$ performance achieved by manufacturers in the Conductor Development Program, compared to the average performance of HL-LHC wires (pale green bands represent the standard deviation). Plotted points are from measurements at CERN and by manufacturers at 4.2–4.3 K; an extrapolated fit is presented (scaled to 4.22 K) where sufficient data are available.

V. Nb_3Sn LABORATORY STUDIES

A. Analysis of Tin Gradients and Non-Uniformity in State of the Art Wires (TU Wien)

TU Wien’s participation in the conductor development program explores the correlation between microstructure, local superconducting properties and the macroscopic performance of Nb_3Sn superconducting wires, and is a collaboration between USTEM (electron microscopy) and the Atominstitut (superconducting properties and irradiation). The work is performed on state-of-the-art commercial Nb_3Sn wires and on prototype wires produced in this program and elsewhere.

As a result of the diffusion reaction in which Nb_3Sn is formed, the sub-elements in a wire always exhibit Sn concentration gradients, which influence the wire performance due to the strong dependence of the intrinsic properties on stoichiometry. The spatial variation of the Sn content within sub-elements of different wires has been examined by EDX. Fig. 9(a) shows typical results obtained from a Ti-alloyed RRP wire. The Sn content data were averaged over several sub-elements, and the fitted profile was used as input for the simu-

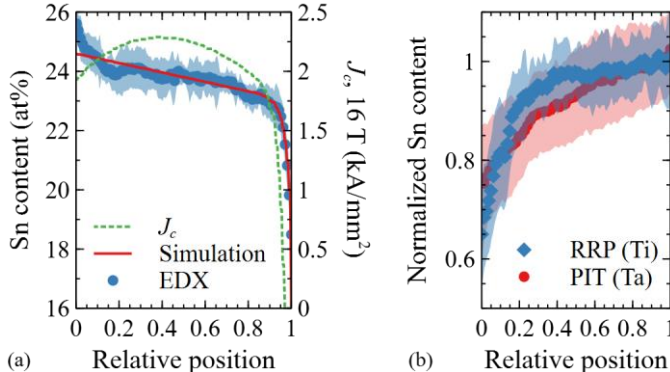


Fig. 9. (a) Tin concentration variation across sub-elements in a Ti-alloyed RRP wire measured by EDX (blue dots), the fit (red line) used for simulation of J_c , and the calculated J_c profile (dotted green line; 4.2 K, 16 T). (b) Normalized tin concentration gradients measured by TEM EDX within the grains of a Ta-alloyed PIT wire and a Ti-alloyed RRP wire. In both cases, the relative position is measured outwards from the centre (0) to the barrier/boundary (1); and pale bands around the EDX values represent the standard deviation.

lation code described in [8] to calculate the J_c distribution at 4.2 K and 16 T within the sub-elements (a grain size of 100 nm is assumed). As shown in Fig. 9(a), the gradient in stoichiometry leads to a significant variation in J_c .

Reports of a discrepancy between the T_c distributions of Nb_3Sn wires obtained from calorimetry and magnetometry [9] led to the conjecture that intra-granular Sn concentration gradients must also exist. This has been confirmed by transmission electron microscope (TEM) EDX analysis. Results obtained from two different wire types, averaged over several grains, are shown in Fig. 9(b), in which the Sn content is normalized to its maximum value (at the grain boundary). It is noteworthy that the grains of the Ta-alloyed PIT wire exhibit an almost linear variation of the Sn content, whereas a sharp drop near the center was found in grains of the Ti-alloyed RRP wire. The effects of such intra-granular gradients on the performance of Nb_3Sn wires are not currently known.

B. Thermodynamics and Phase Transformations in the Cu–Nb–Sn System (TU Bergakademie Freiberg)

Despite decades of research on growing Nb_3Sn in Cu–Nb–Sn composite wires (often with the addition of Ti or Ta), knowledge of the thermodynamics of this system is incomplete. This is exemplified by the observation of the ternary phase nausite ($\text{Nb}_{0.75}\text{Cu}_{0.25}\text{Sn}_2$) [10], which is not present in the evaluated phase diagram. TU Bergakademie Freiberg is contributing to the FCC Study with a detailed investigation of phase equilibria in the Cu–Nb–Sn system, with particular emphasis on the temperature range of relevance to superconducting wires. Analysis of thermodynamics and diffusion-controlled phase transformations will provide information for optimization and modelling efforts [5]. This work will be extended to consider Ti additions, and the influence of oxygen and selected oxides, to support the development of practical high-field conductors and novel internal oxidation methods.

Investigations have so far been performed on Cu_6Sn_5 –Nb diffusion couples prepared by pre-reaction of dual Cu–Sn layers electroplated on a Nb substrate. Heat treatment of these couples at different temperatures provides information of the phases of the Cu–Nb–Sn system in equilibrium as a function

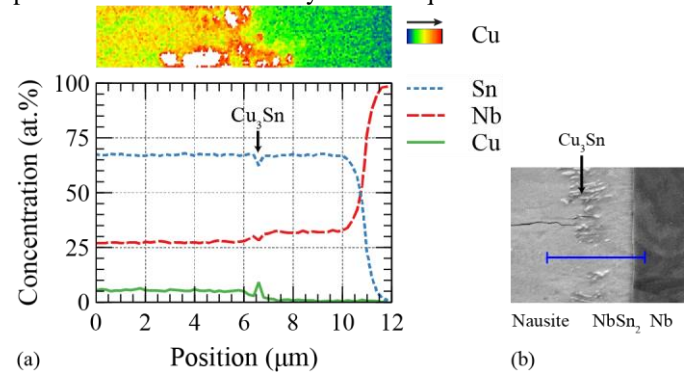


Fig. 10. Results of EDX measurements on a Cu_6Sn_5 –Nb diffusion couple after heat treatment at 500 °C, leading to development of a layered nausite/ NbSn_2 /Nb system [11]. (a) EDX line scan, and (top) a 2D EDX map showing the distribution of copper, measured in the direction shown in (b), a backscattered electron micrograph. Nausite is clearly distinguished from NbSn_2 by its higher copper concentration; local peaks in copper content (shown white in the EDX map) correspond to Cu_3Sn inclusions.

of temperature. Fig. 10 shows part of the microstructure which developed after annealing at 500 °C. Cu_6Sn_5 has been consumed during the heat treatment, resulting in a nausite/ NbSn_2 double layer on the thick Nb substrate. The EDX profile clearly shows the higher Cu content in nausite and the step in Cu/Nb content at the nausite/ NbSn_2 phase boundary, emphasizing the distinctness of these two phases at 500 °C [11].

C. Internal Oxidation Methods for Enhancement of Critical Current Density in Nb_3Sn Wires (University of Geneva)

Internal oxidation methods have recently received renewed attention as a promising approach for enhancing the J_c of Nb_3Sn wires. Typically, a Nb–Zr alloy replaces pure Nb, and SnO_2 is added, such that ZrO_2 precipitates are formed during heat treatment [12]. These precipitates can enhance J_c by grain refinement of Nb_3Sn [12][13] or by acting as artificial pinning centers (APCs). Combined Zr and O additions had been studied many years earlier [13][14]; recent work has demonstrated the potential for compatibility with PIT and internal tin wire designs [12], but implementation in high- J_c , high B_{c2} wires with ternary additions to Nb_3Sn remains work in progress.

Within the FCC program, a study in the University of Geneva (2017–2018) is investigating internal oxidation of Zr and other elements in $(\text{Nb},\text{X})_3\text{Sn}$ wires, and the effects on grain size and superconducting properties [15], using a monofila-

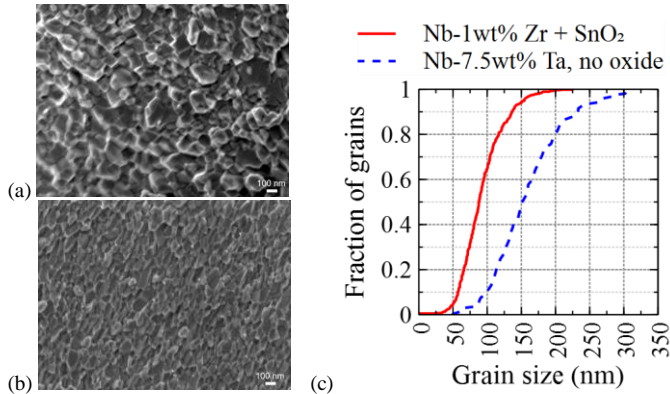


Fig. 11. Comparison of grain size distribution in a sample with internal oxidation (Nb–1wt% Zr with SnO_2) relative to a reference system (Nb–7.5 wt% Ta). SEM images of a fracture surface for (a) the reference sample and (b) with internal oxidation; and (c) the calculated grain size distribution (linear intercept method). Samples were heat treated for 300 h at 500 °C.

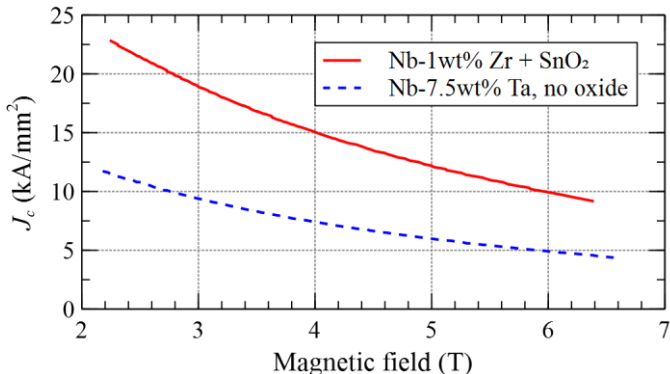


Fig. 12. Inductive $J_c(B)$ showing an enhancement in J_c for a sample with internal oxidation (Nb–1wt% Zr with SnO_2) relative to a reference system (Nb–7.5 wt% Ta). The heat treatment included plateaus at 210 °C (50 h), 400 °C (50 h), 500 °C (50 h) and 650 °C (200 h). J_c calculated from magnetization at 4.2 K based on the whole Nb_3Sn area (coarse and fine grained).

mentary model system with an oxide core and external Cu–Sn.

Early in the study, it was demonstrated that MoO_3 is not a suitable oxygen source. For the conventional combination of a Nb–1 wt% Zr alloy with a SnO_2 oxygen source [15], significant grain refinement has been obtained relative to a reference Nb–7.5 wt% Ta system: for the example shown in Fig. 11, the median grain size was reduced from 153 nm to 88 nm. It has also been demonstrated by inductive measurements that this results in an increase in J_c (Fig. 12). Work is in progress with alternative binary and ternary Nb alloys.

VI. OTHER MATERIALS

A. MgB_2

Research on MgB_2 at CNR-SPIN aims to develop methods to enable production of a cost-effective MgB_2 wire for high-field applications. The main goal is to increase B_{c2} and pinning strength [16]. The present study aims to achieve this in a scalable way by further developing a cost-effective freeze drying synthesis route for boron nano-powder with controlled defects [17][18]. In addition to pure boron nano-powders, samples with carbon doping and nano-aggregate additions are planned.

The freeze drying approach introduces defects homogeneously dispersed in the volume of the B precursor, producing an already doped nano-B by reduction. In comparison with conventional methods, the use of nano-B with dopants and additions would allow those additions to be introduced within MgB_2 grains during solid state MgB_2 synthesis.

A 60 g batch of pure nano-B powder has recently been produced and characterized by SEM, EDX analysis and X-ray diffraction (XRD). The morphology, as shown in Fig. 13, suggests a predominantly amorphous powder with a significant proportion of grains <50 nm in size, and a size distribution extending up to 140 nm. XRD analysis shows a few low-intensity peaks on a broad background, suggesting the presence of a small proportion of crystalline grains in predominantly amorphous material. The oxygen content determined by EDX is 1.6–1.8 wt%, comparable to commercial B powders. Production of a multifilamentary prototype wire with this material is planned at Columbus Superconductors.

B. BSCCO 2212

BSCCO 2212 has proven potential to achieve the target J_c for the FCC Study in an isotropic round-wire geometry [19].

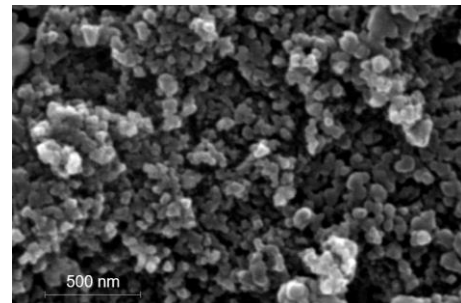


Fig. 13. SEM micrograph of pure nano-boron prepared at CNR-SPIN by a freeze drying process.

However, this has been achieved through over-pressure processing (50–100 bar), which would be challenging to implement for the manufacture of large magnets. At CNR-SPIN, an alternative groove rolling process is under development [20]. In the present project, the aim is to demonstrate a J_c of 500 A mm⁻² at 16 T and 4.2 K through optimization of the wire architecture, deformation processing and heat treatment.

A proper alternation of groove rolling and drawing steps results in greater powder densification than drawing alone, and the resulting reduction in filament porosity inhibits bubble formation during the subsequent heat treatment. In general, the larger the degree of densification (i.e. the larger the proportion of the reduction achieved by rolling), the better the J_c performance, even when cracks and disordered filaments are evident in the cross-section (Fig. 14). Further work is required to optimize the groove rolling steps to avoid distortion of the filament bundles, and hence maximize the effective cross-section.

To support heat treatment optimization, the partial melting process has been investigated by *in situ* x-ray and neutron diffraction [21]. This study clarified the role of oxygen activity in BSCCO 2212 texturing, and clarified the conditions under which undesired secondary phases form. New heat treatment profiles implementing these findings are currently under test.

Recent I_c tests on 1-m-long samples have shown almost identical J_c results to short samples, suggesting very good longitudinal homogeneity [22]. It is therefore expected that this processing route will be scalable to industrial production.

C. Iron-based superconductors

The recently discovered iron-based superconductors [23][24] are at a much less mature state of development, but they have considerable potential for high-field applications: indeed, they are the baseline solution for dipole magnets in the proposed CEPC and SPPC accelerators [25]. CNR-SPIN is seeking to develop two prototype conductors with a J_c of $\sim 10^3$ A mm⁻²: a BaFe₂As₂ (122) PIT wire and a FeSe_xTe_{1-x} (11) coated conductor (CC).

The 122 PIT activity is currently focused on powder synthesis. The aim of the work was to identify a reproducible and efficient route to synthesize large polycrystalline samples (~ 5 g) of Ba_{1-x}K_xFe₂As₂ with purity >96 wt% (Fig. 15(a)). The optimized route needs three steps: preparation of a FeAs precursor, reaction of Ba, K and FeAs, and sintering of the (Ba,K)Fe₂As₂ pellet. Recently, samples with a Ba/K ratio very close to one and a T_c of ~ 38 K were successfully produced.

The 11 CC activity aims to develop substrates with a simpler, more cost-effective template than the traditional Rolling Assisted Biaxially Textured Substrates (RABiTS) and Ion-Beam Assisted Deposition (IBAD) routes developed for

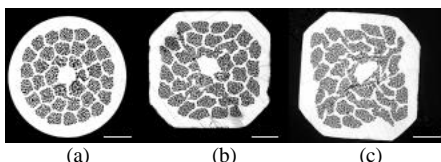


Fig. 14. SEM micrographs of BSCCO 2212 wires with different proportions of the reduction achieved by drawing and groove rolling: (a) drawn, (b) mostly drawn, (c) mostly groove rolled. The scale marker represents 250 μ m.

YBCO. This is feasible because the critical angle at which J_c starts to decrease exponentially is about 9°, much larger than for YBCO ($\sim 3^\circ$), and because 11 thin film deposition is performed at low temperature (300 °C) under high vacuum.

An Invar 36 substrate with strong cube texture and misorientation angles (in and out of plane) of less than 10° was developed (Fig. 15(b)). Even without a buffer layer, epitaxial 11 thin films were successfully deposited at 200 °C on a 11 seed layer with misorientation angles of less than 8°. These films were not superconducting because of Ni poisoning revealed by transmission EDX analysis [26]. In parallel, the deposition of 11 films was also performed on Ni-5 wt% W substrate with a 50 nm thick CeO₂ buffer layer, supplied by ENEA in Frascati. On this substrate, 11 thin films with a T_c of about 18 K and a J_c of 10⁵ A/cm² at 4.2 K in self-field were obtained [27].

Ni-5 wt% W with other oxide buffer layers, and Invar 36 substrates with nitride buffer layers, are now under study.

VII. CONCLUSIONS AND FUTURE DIRECTIONS

In the context of the FCC Study, a Conductor Development Program has been established at CERN to develop a superconducting wire meeting the performance targets: notably, a non-copper critical current density (J_c) of 1500 A mm⁻² at 16 T and 4.2 K. Four Nb₃Sn wire manufacturers are currently participating, three of which have successfully achieved the stage one target J_c comparable to the HL-LHC specification, in one case in kilometer piece lengths. Evidence has been presented of the potential for further increases in J_c , and these development activities will continue for at least two more years.

Achieving the ultimate target J_c is likely to require a major innovative step, and this is a growing focus of the program. Investigations of novel alloys and internal oxidation methods are in progress, and will be enhanced by the recent addition of a new research partner (NHMFL, FSU); and two new manufacturers are expected to join the program in the coming months to develop novel wire layouts. This work is supported by fundamental studies of thermodynamics and detailed analysis of Nb₃Sn microstructures and pinning.

Nb₃Sn remains the baseline solution, but novel approaches are also being investigated to develop MgB₂, BSCCO 2212 and iron-based superconductors for high field applications.

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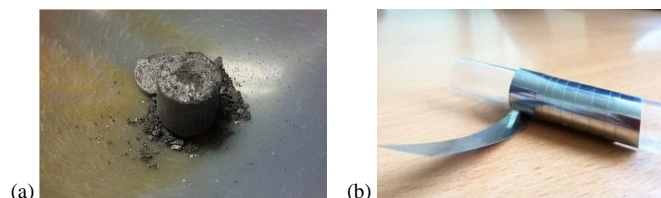


Fig. 15. (a) 122 pellet produced by a synthesis route developed at CNR-SPIN. The product is dark grey, dry, crystalline and rather compact, but brittle. (b) Invar 36 substrate, 70 μ m thick.

and the technical staff of the Superconductors and Superconducting Devices section (TE-MSC-SCD) for performing heat treatments and electrical measurements.

REFERENCES

- [1] E. Todesco et al., “Progress on HL-LHC Nb₃Sn Magnets”, *IEEE Trans. Appl. Supercond.*, vol. 28, no. 4, Jun. 2018, Art. no. 4008809.
- [2] A. Ballarino and L. Bottura, “Targets for R&D on Nb₃Sn Conductor for High Energy Physics”, *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, Jun. 2015, Art. no. 6000906.
- [3] A. Ballarino, “Superconductors for Future Circular Colliders”, presented at the 24th Int. Conf. Magn. Technol. (MT24), Seoul, Korea, Oct. 21, 2015. [Online]. Available: <https://fcc.web.cern.ch/Pages/news/Magnet-technology-conference-features-techniques-for-the-FCC.aspx>
- [4] B. Bordini, “Magnetization Measurements of High- J_c Nb₃Sn Strands”, *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, Jun. 2013, Art. no. 7100806.
- [5] S. C. Hopkins, A. Baskys, A. Canós Valero, and A. Ballarino, “Quantitative Analysis and Optimization of Nb₃Sn Wire Designs Towards Future Circular Collider Performance Targets”, *IEEE Trans. Appl. Supercond.*, submitted for publication.
- [6] J. Kim, “Development Status of Nb₃Sn Strand for FCC”, presented at FCC Week 2018, Amsterdam, Netherlands, 2018. [Online]. Available: <https://indico.cern.ch/event/656491/contributions/2920090/>
- [7] S. Kawashima et al., “Development of High Current Density Distributed Tin Processed Nb₃Sn Wire”, *IEEE Trans. Appl. Supercond.*, submitted for publication.
- [8] T. Baumgartner, S. Pfeiffer, J. Bernardi, A. Ballarino, and M. Eisterer, “Effects of inhomogeneities on pinning force scaling in Nb₃Sn wires,” *Supercond. Sci. Technol.*, vol. 31, no. 8, Aug. 2018, Art. no. 084002.
- [9] T. Baumgartner, J. Hecher, J. Bernardi, S. Pfeiffer, C. Senatore, and M. Eisterer, “Assessing composition gradients in multifilamentary superconductors by means of magnetometry methods,” *Supercond. Sci. Technol.*, vol. 30, no. 1, Jan. 2017, Art. no. 014011.
- [10] S. Martin, A. Walnsch, G. Nolze, A. Leineweber, F. Léaux, and C. Scheuerlein, “The crystal structure of (Nb_{0.75}Cu_{0.25})Sn₂ in the Cu–Nb–Sn system”, *Intermetallics*, vol. 80, 2017, pp. 16–21.
- [11] J. Lachmann, “Konstitution des Nb–Sn–Systems und Phasenumwandlung von Nb–Sn–Phasen unter Beteiligung von Kupfer”, Diploma Thesis, TU Bergakademie Freiberg, Freiberg, Germany, 2018.
- [12] X. Xu, M. Sumption, X. Peng, and E. W. Collings, “Refinement of Nb₃Sn grain size by the generation of ZrO₂ precipitates in Nb₃Sn wires”, *Appl. Phys. Lett.*, vol. 104, no. 8, Feb. 2014, Art. No. 082602.
- [13] L. E. Rumaner, M. G. Benz, and E. L. Hall, “The role of oxygen and zirconium in the formation and growth of Nb₃Sn grains”, *Met. Mater. Trans. A*, vol. 25, no. 1, 1994, pp. 213–219.
- [14] B. A. Zeitlin et al., “Results on Mono Element Internal Tin Nb₃Sn Conductors (MEIT) With Nb_{7.5}Ta and Nb(1Zr+O_x) Filaments”, *IEEE Trans. Appl. Supercond.*, vol. 15, no. 2, 2005, pp. 3393–3398.
- [15] F. Buta, L. Gamperle, C. Barth, J. Ferradas, and C. Senatore, “Towards a Nb₃Sn conductor for FCC”, presented at FCC Week 2018, Amsterdam, Netherlands, 2018. [Online]. Available: <https://indico.cern.ch/event/656491/contributions/2919973/>
- [16] M. Putti and G. Grasso, “MgB₂, a two-gap superconductor for practical applications”, *MRS Bull.*, vol. 36, no. 8, Aug. 2011, pp. 608–613.
- [17] M. Vignolo et al., “A Novel Process to Produce Amorphous Nanosized Boron Useful for MgB₂ Synthesis”, *IEEE Trans. Appl. Supercond.*, vol. 22, no. 4, 2012, Art. no. 6200606.
- [18] M. Vignolo et al., “Nano-sized boron synthesis process towards the large scale production”, *Chem. Eng. J.*, vol. 256, Nov. 2014, pp. 32–38.
- [19] D. C. Larbalestier et al., “Isotropic round-wire multifilament cuprate superconductor for generation of magnetic fields above 30 T”, *Nature Mater.*, vol. 13, no. 4, Mar. 2014, pp. 375–381.
- [20] A. Leveratto, V. Braccini, D. Contarino, C. Ferdeghini, and A. Malagoli, “New concept for the development of Bi-2212 wires for high-field applications”, *Supercond. Sci. Technol.*, vol. 29, no. 4, 2016, Art. No. 045005.
- [21] A. Martinelli et al., “In situ x-ray and neutron diffraction investigation of Bi-2212 in multifilamentary wires during thermal treatment”, *Phys. Rev. Mater.*, vol. 2, Aug. 2018, Art. no. 084801.
- [22] L. Leoncino et al., “Evidence for Longitudinal Homogeneity and No J_c Degradation in Bi-2212 Wires Realized by the GDG Process”, *IEEE Trans. Appl. Supercond.*, submitted for publication.
- [23] Y. Kamihara, “Iron-Based Layered Superconductor: LaOFeP”, *J. Am. Chem. Soc.*, vol. 128, no. 31, 2006, pp. 10012–10013.
- [24] Y. Kamihara, T. Watanabe, M. Hirano, and H. Hosono, “Iron-Based Layered Superconductor La[O_{1-x}F_x]FeAs ($x = 0.05$ – 0.12) with $T_c = 26$ K”, *J. Am. Chem. Soc.*, vol. 130, no. 11, 2008, pp. 3296–3297.
- [25] CEPC Study Group, *CEPC Conceptual Design Report: Volume I – Accelerator*, Aug. 2018, Institute of High Energy Physics (IHEP). [Online]. Available: http://cepc.ihep.ac.cn/CDR_v6_201808.pdf
- [26] G. Sylva et al., “Analysis of Fe(Se,Te) Films Deposited on Unbuffered Invar 36”, *IEEE Trans. Appl. Supercond.*, submitted for publication.
- [27] V. Braccini et al., *Supercond. Sci. Technol.*, submitted for publication.