HFM

High Field Magnets

Introduction to the Activities of WP1.1 at CERN

RD Line 1 Kickoff Forum Meeting: Nb_3Sn Conductors

16 February 2023

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WP1.1: Aims and Challenges

- WP1.1, Nb_3Sn Conductors for High Field Magnets, aims to:
  - Develop, characterise and qualify Nb_3Sn wire and Rutherford cables meeting the requirements for future accelerator magnets
  - To produce and qualify the Rutherford cables needed for the magnet WPs
- The pursuit of ultimate performance 14+ T dipoles invokes some key conductor challenges – for example:
  - Increasing high-field J_c (target 1500 A/mm^2 at 4.2 K and 16 T) → APCs, internal oxidation, etc.
  - Transverse stress → reinforcement, understanding crack behaviour, design optimisation
  - Preference for wide cables of large high-J_c strands → magnetothermal stability

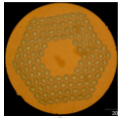
WP1.1 Activities (1)

- Conductor development, procurement, qualification and production for the magnets of RD3
  - Wire procurement
  - Industrialisation and qualification of R&D wires
  - Rutherford cable design, trials, qualification and production for CERN magnet programmes (12 T and 14+ T ultimate performance dipoles and technology development models) and collaborations (INFN FalconD, CEA R2D2)

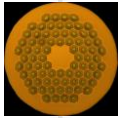
WP1.1 Activities (2)

- Characterisation, analysis, modelling and optimisation of performance, processing and electro/thermal/mechanical characteristics
  - Heat treatment optimisation
  - Quantitative image analysis and machine learning
  - Magnetothermal stability
  - Rolling and cabling deformation of strands
  - Axial and transverse stress behaviour
  - Mechanical properties and reinforcement
  - Thermomechanical characteristics
  - Modelling: mechanical, diffusion, magnetothermal
- Novel technologies for high-J_c wires
  - e.g. novel alloying, internal oxidation, APCs
  - Analysis of wire from collaborations and model samples

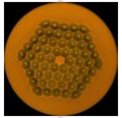
Nb_3Sn Wires



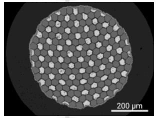
RRP® 108/127
HL-LHC 11 T dipole



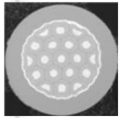
RRP® 78/91
ERMC



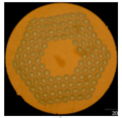
RRP® 60/91
R2D2 LF



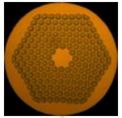
JASTEC R&D



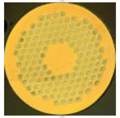
Internal tin
ITER TF



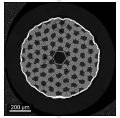
RRP® 108/127
HL-LHC MQXF



RRP® 162/169
FalconD

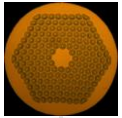


RRP® 132/169
FRESCA 2



KAT R&D

+ other FCC



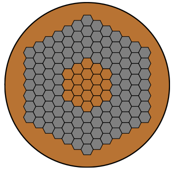
RRP® 162/169
R2D2 HT, TFD

Maximum EuroCirCol

0.6 0.7 0.8 0.9 1.0 1.1 1.2

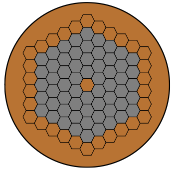
Diameter (mm)

Nb$_3$Sn Wire and Cabling

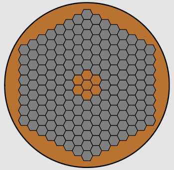
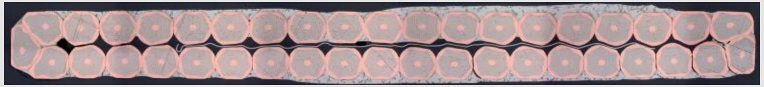
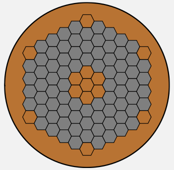


108/127
MQXF (0.85 mm)

HL-LHC MQXF



78/91
ERMC-0.7 (0.7 mm)

 162/169	ERMC-1 (1.0 mm)	FalconD 40 × 1.0 mm	 0.5° keystone, 1.8 × 20.95 mm, SS core
		ERMC 40 × 1.0 mm	No keystone, 1.8 × 20.95 mm, SS core
	DEM-1.1 (1.1 mm)	R2D2 (HF) 21 × 1.1 mm	 No keystone, 1.969 × 12.579 mm
 60/91	DEM-0.7 (0.7 mm)	R2D2 (LF) 34 × 0.7 mm	 No keystone, 1.253 × 12.579 mm

Analysis of Cabling Degradation

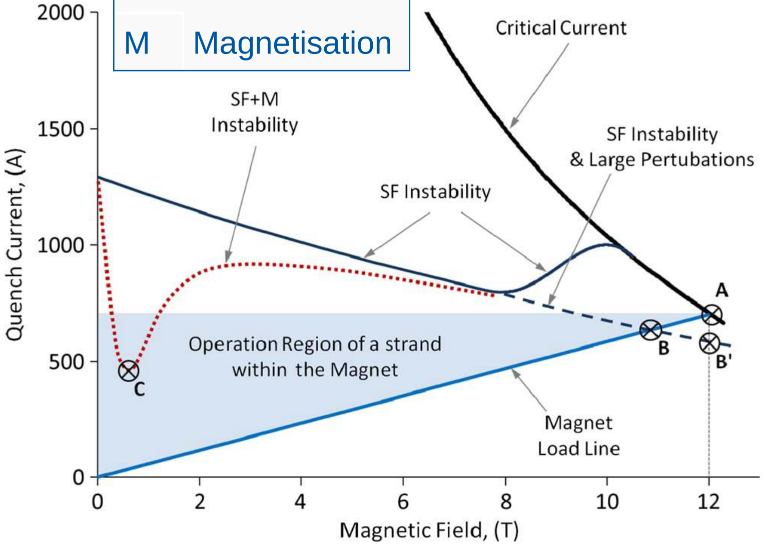
- For the cable samples tested to date, degradation on cabling of ERMC-1 strands is:
  - Much higher than typical for HL-LHC MQXF cable
  - Higher for the more compacted, keystoned FalconD trial cable than ERMC
    - Exceeds HL-LHC acceptance criterion of 5 % average I_c degradation
    - Substantial difference in RRR degradation (30 % cf. 20 %) – likely to underestimate effects locally at thin edge
- The same sub-element distortion and (local) RRR degradation is likely to contribute to the degraded stability of FalconD extracted strands with the standard heat treatment

Cable type	Keystone (°)	Pitch (mm)	I_c degradation		RRR		RRR degradation
			Mean	Range	Mean	Range	Mean
FalconD	0.426	110	5.5 %	2.2–8.6 %	202	175–232	30.9 %
	0.442	120	5.9 %	4.4–6.9 %	206	176–244	29.6 %
ERMC	0	120	4.1 %	2.0–8.0 %	228	189–265	20.5 %
MQXF	0.40	109	2.6 %				17 %

Stability

- Several causes of instability:
  - Self-field instability
    - Dominates at high field
    - Depends on J_c and strand diameter
    - Driven by uneven distribution of transport current in ramping
  - Magnetisation instability
    - Significant at low field for high magnetisation strand
    - Depends on J_c and d_{eff}
- Designing for stability includes:
  - Adiabatic stability: d_{eff} below threshold value
    - For RRP® wire: filaments merged and barrier partially reacted → d_{eff} almost fixed from geometry (wire diameter and geometrical sub-element size)
    - For distributed tin wires: depends on distribution of Nb filaments
    - Rolling or cabling deformation affects both (sub-element aspect ratio, displacement of Nb modules)
  - Dynamic stability: increasing RRR → increasing copper conductivity
    - Combination of design, materials and heat treatment optimisation

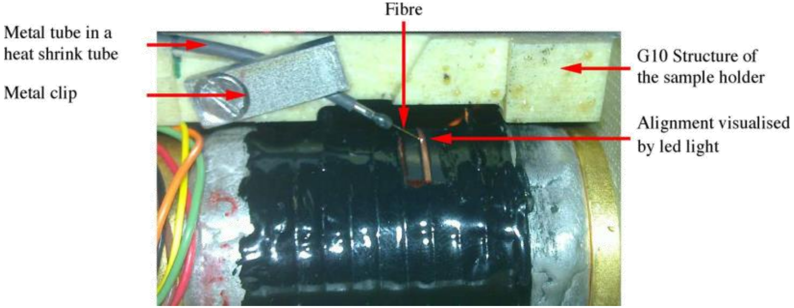
SF	Self field
M	Magnetisation

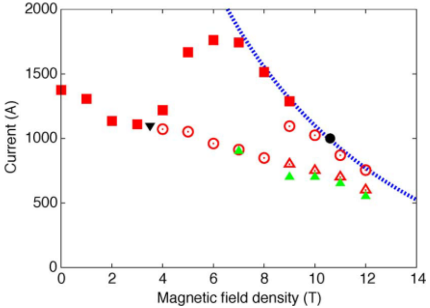


Bordini *et al.*, *IEEE Trans. Appl Supercond.* **22** (3) 4705804

Evaluation of Stability

- Self-field stability assessed by *V-I* transport measurements:
  - Of most interest for medium/high field range (8–15 T); maximum current ~2000 A; both 1.9 and 4.3 K
  - Recent and continuing work at CERN: examples on next slides
- Further activities beginning:
  - PhD student (J. Kuczynska) at CERN and UNIGE
  - *V-H* transport measurements and magnetisation measurements
  - Recommissioning system for laser triggering of magnetothermal stability

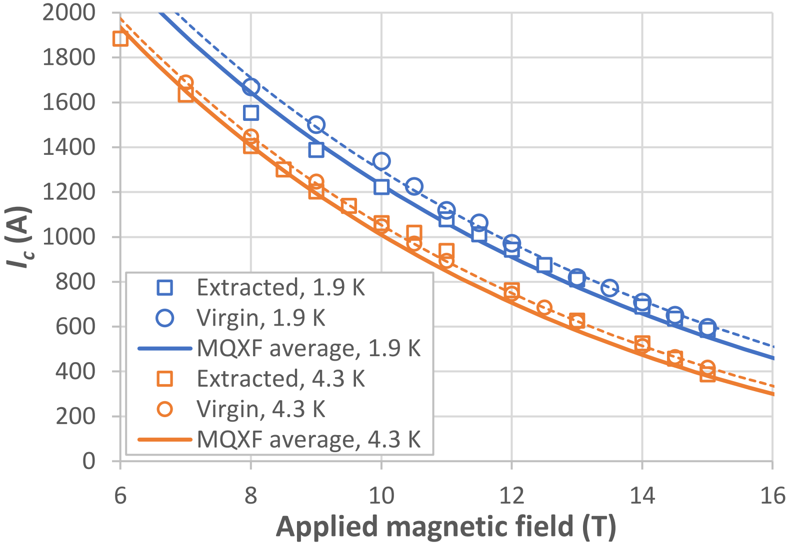




Examples from previous work at CERN: Takala et al., *IEEE Trans. Appl. Supercond.* **22** 6000704

Stability of MQXF Wire

- As a baseline reference, measurements were performed for extracted and virgin HL-LHC MQXF strands
- Over the tested range (6–15 T), no quenches occurred, and the I_c followed the expected field dependence both at 4.3 K and 1.9 K

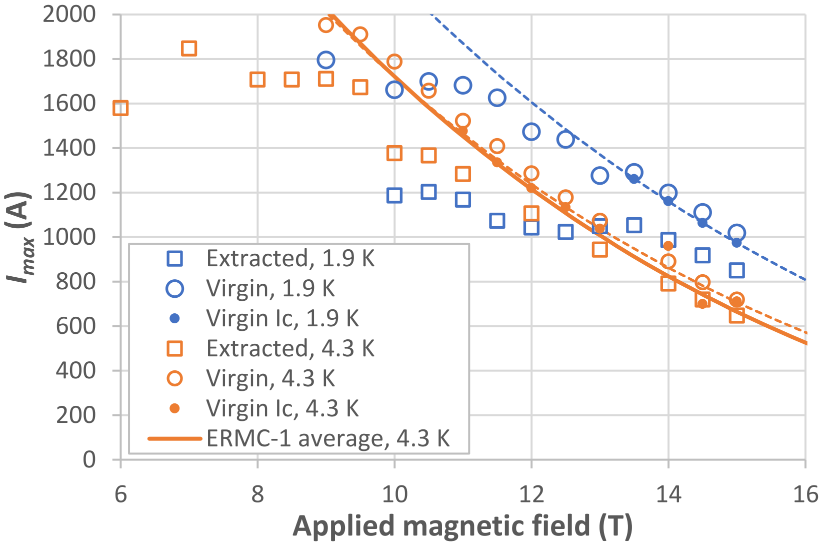


Measured $I_c(B)$ for a virgin and an extracted strand from MQXFA cable production, with average MQXF virgin wire $I_c(B)$ for comparison
(P43OL1123AE27, originating from spool PO08S00343A01U)

Stability of ERMC-1: Standard HT

Short HT

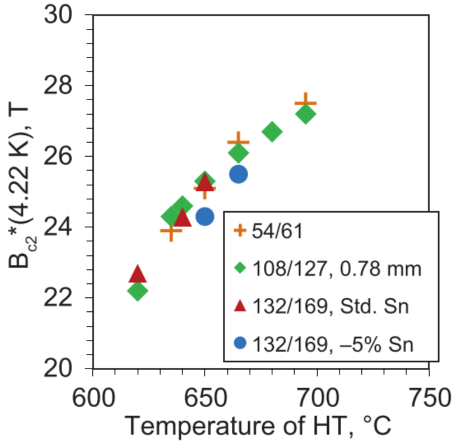
- For ERMC-1 wire with the standard heat treatment cycle (final step 650 °C 50 h)
    - For **virgin** wire, at **1.9 K**, quenches occur at currents less than the extrapolated I_c below 13 T
        - At ~10 T and below, the quench current at 1.9 K is less than that at 4.3 K
    - For an **extracted strand** from a FalconD trial cable, performance is limited by quenches below extrapolated I_c at 14 T and below
        - At ~12.5 T and below, the quench current at 1.9 K is less than that at 4.3 K



Measured $I_{max}(B)$ for a virgin ERMC-1 wire (1.0 mm 162/169) and a strand extracted from a FalconD trial cable after the standard heat treatment (650 °C 50 h), with average virgin wire $I_c(B)$ for comparison

Heat Treatment Optimisation

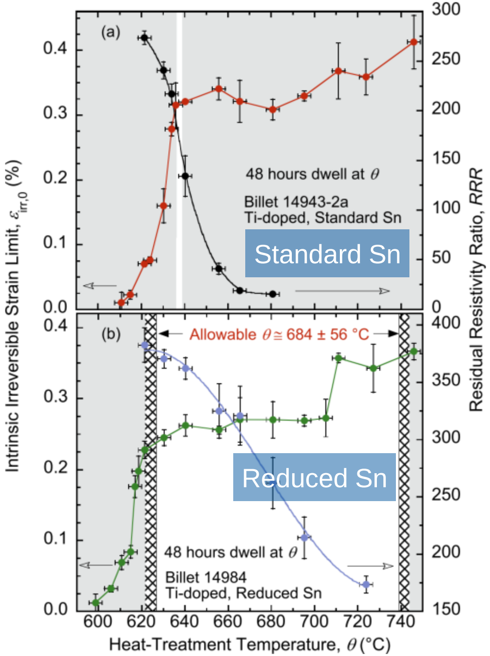
- Optimisation of the final heat treatment step generally seeks a balance between $I_c(B)$ and RRR
  - For ERMC-1, during production this was revised from 665 °C 50 h (cf. DEM-1.1) → **650 °C** 50 h to ensure the RRR spec could be met
  - Potential to further adjust that balance in exchange for improved stability and reduced cabling degradation
- Both time and temperature are already quite low – literature suggests:
  - Reducing temperature to 640 °C could reduce B_{c2} by ~1 T
  - For 'standard Sn' wire, approach the 'strain irreversibility cliff' (next slide)
  - Initial studies have been with reducing **duration** at 650 °C



Dependence of B_{c2} on heat treatment temperature
Cooley et al. 2017, *IEEE Trans. Appl. Supercond.* **27** 6000505

Strain Irreversibility Cliff

- ‘Strain irreversibility cliff’ (SIC, N. Cheggour): an abrupt reduction in the irreversible strain limit as a function of heat treatment temperature
  - Cliff temperature dependent on doping (Ti, Ta) and Sn stoichiometry
  - Heat treatment optimisation must *also* consider I_c and RRR
  - Much broader acceptable range for reduced Sn than standard Sn
  - First tests for standard Sn 162/169 RRP® suggest similar behaviour (N. Cheggour, ASC 2022)
- Provisionally associated with δ Cu-Sn:
  - Collaborative heat treatment and microscopy investigation in progress at CERN and TU Freiberg

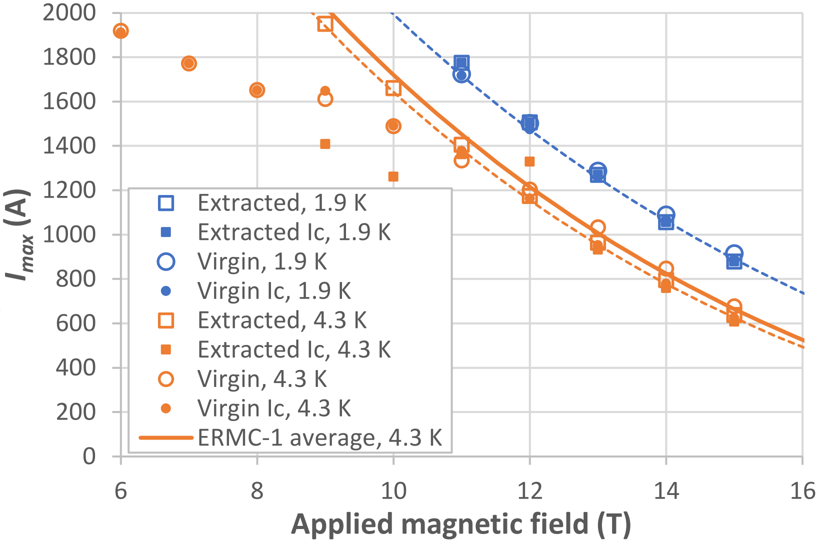


Dependence of irreversible strain limit and RRR on heat treatment temperature for Ti-doped 108/127
Cheggour et al. 2019, *Scientific Reports* **9** 5466

Stability of ERMC-1: Shorter HT

Standard HT

- With a shorter heat treatment cycle (final step 650 °C **30 h**)
  - At **1.9 K**, **dramatic improvement** in stability: virgin and extracted strand follow the same $I_c(B)$ dependence, with no quenches
    - Note extracted strand is from ERMC cable, not FalconD
- The shorter 30 h step reduces I_c by **9 %** (no change in B_{c2})
  - The stable I_c for a 30 h heat treatment exceeds the quench current for a 50 h heat treatment below ~12 T
- RRR increased ~50 %



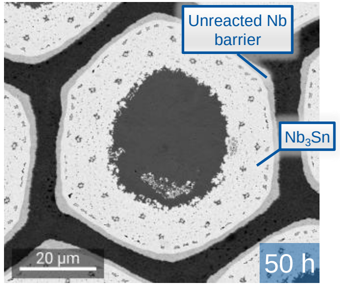
Measured $I_{max}(B)$ for a virgin ERMC-1 wire and a strand extracted from an **ERMC** cable after the **shorter** heat treatment (650 °C 30 h)

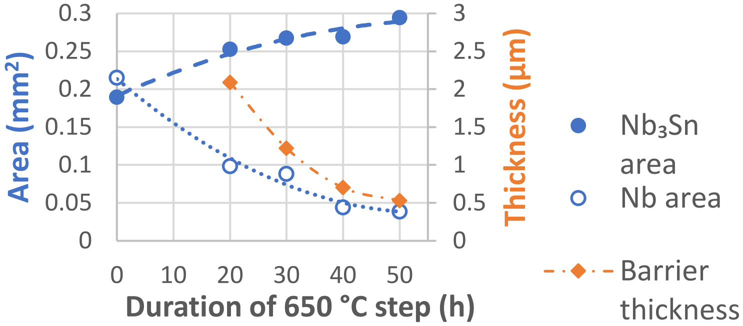
Dashed lines: virgin $I_c(B)$ with **30 h** HT, solid line: average virgin ERMC-1 $I_c(B)$ with 50 h HT

HFM
High Field Magnets

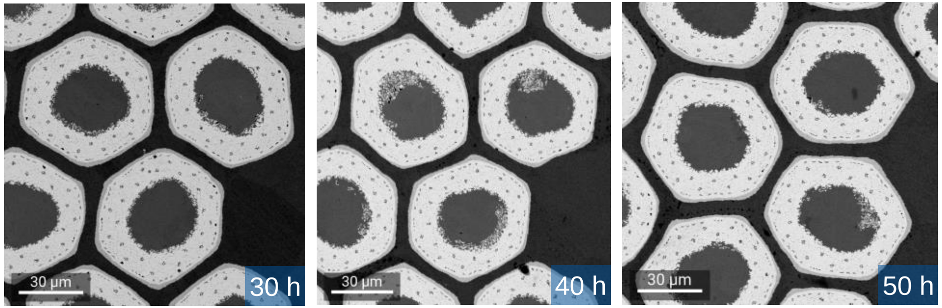
Shorter HT: Micrographs

- Image analysis of electron micrographs shows:
  - The thickness of unreacted barrier decreases sharply from 20–40 h
  - Overall Nb and Nb_3Sn areas change relatively slowly from 30 h onwards
  - The optimum compromise between I_c and RRR is likely to lie in the 30–40 h range





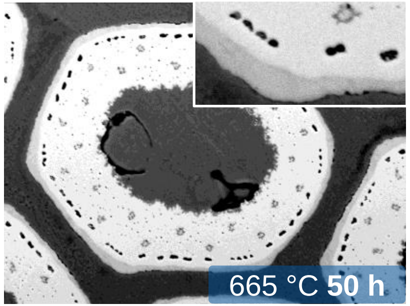
Dependence of Nb_3Sn and Nb area, and average barrier thickness, on duration of 650 °C plateau

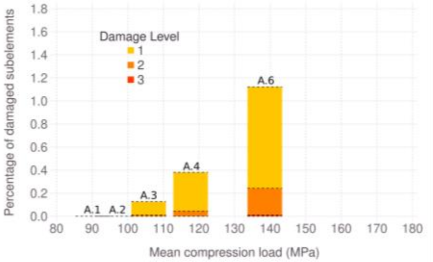


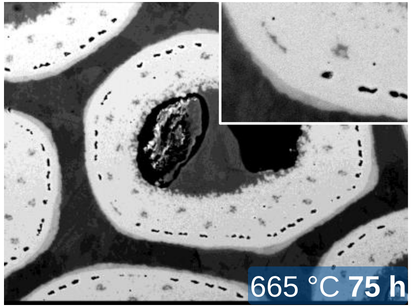
SEM micrographs of sub-elements after heat treatments with a final plateau of 30 h, 40 h and 50 h at 650 °C

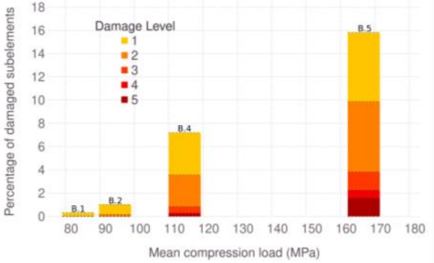
Effect of Transverse Stress

- Microscopy study of cracks induced by transverse compressive stress applied at room temperature to MQXF cables
  - Onset of cracking well below the stress at which I_c degradation is observed, ~110 MPa for standard heat treatment
  - Heat treatment dependent: onset stress significantly reduced, and damage level increased, on increasing the final plateau duration from 50 h to 75 h
    - Provisionally associated with reduced residual Nb barrier thickness



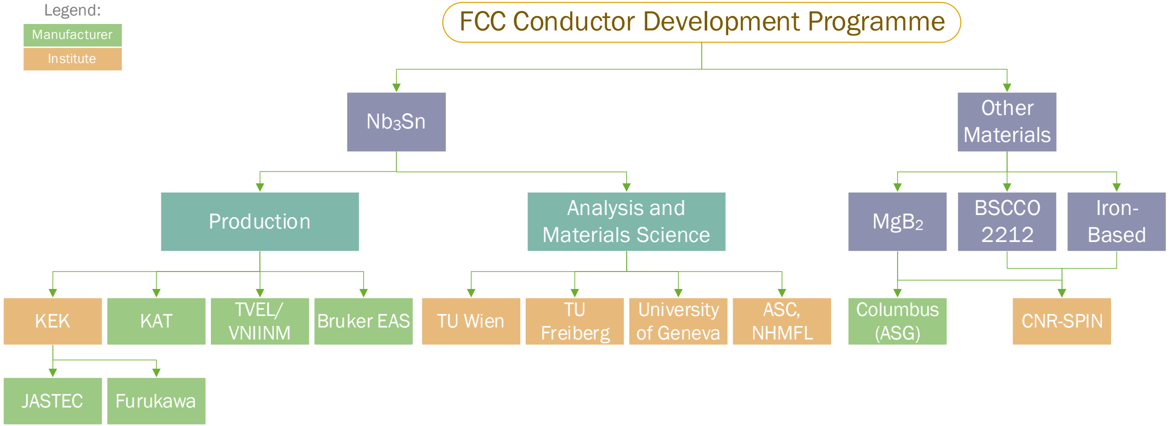






Conductor Development

- Conductor development activities for HFM have their origins in a development programme started in 2017 under the FCC study, which aimed to:
  - Advance the state of the art for Nb_3Sn wires to meet requirements for 16 T accelerator magnets
  - Foster industrial development of Nb_3Sn wires, supported by laboratory studies
  - Procure and cable Nb_3Sn wire for the magnet development programme
  - Investigate the potential of alternative superconducting materials



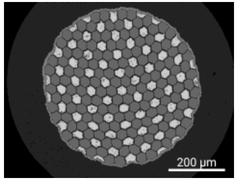
Legend:
- 🟩 Manufacturer
- 🟧 Institute

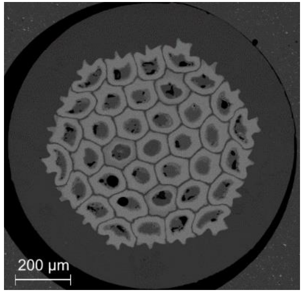
FCC Conductor Development Programme
- Nb_3Sn
  - Production
    - KEK
      - JASTEC
      - Furukawa
    - KAT
    - TVEL/ VNIINM
    - Bruker EAS
  - Analysis and Materials Science
    - TU Wien
    - TU Freiberg
    - University of Geneva
    - ASC, NHMFL
- Other Materials
  - MgB_2
    - Columbus (ASG)
    - CNR-SPIN
  - BSCCO 2212
    - CNR-SPIN
  - Iron-Based
    - CNR-SPIN

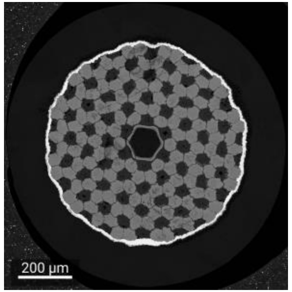
Conductor Development

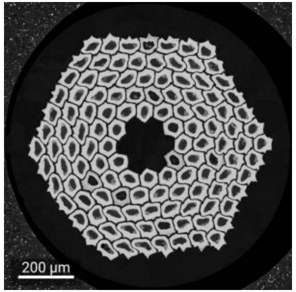
- Several iterations of JASTEC, KAT and TVEL wire validated in CERN rolling studies and/or cabling trials

	2019-2020		**2021**	
	JASTEC	**TVEL**	**KAT**	**TVEL**
	Distributed tin	**Distributed barrier**	**Distributed tin**	**Distributed barrier**
Diameter (mm)	0.8	1.0	1.0	1.0
Cu/non-Cu ratio	1.0 ± 0.2	1.2 ± 0.2	1.0 ± 0.1	1.0 ± 0.1
Nb modules (sub-els)	139	37	132	120
d_{eff} (µm)	55	132 – 144	-	71 – 79



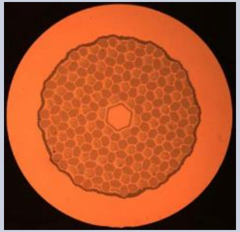
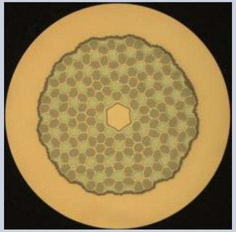






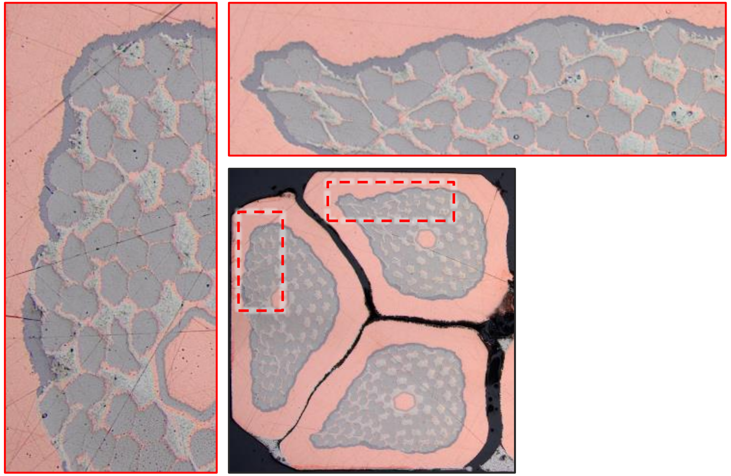
Distributed Tin Wire and Cabling Trials

- KAT:
  - CERN rolling studies and trial cabling of two iterations of distributed tin design developed at KAT
  - Pilot production: 20 km delivered in long piece lengths (mean 1432 m)
  - Electromechanical characterisation planned in UNIGE
- JASTEC:
  - Production currently being completed
  - CERN rolling and cabling trials expected in the coming months

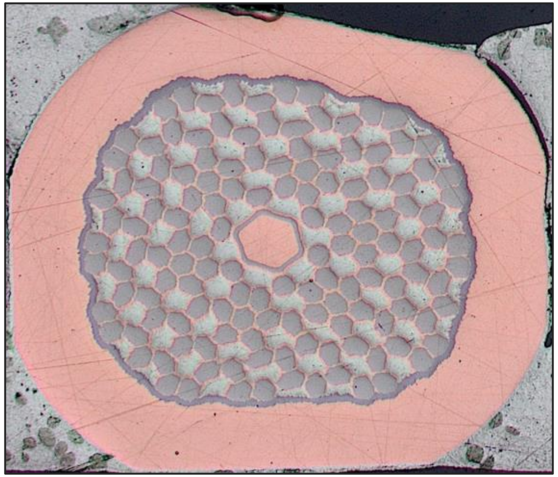
	2020: Task 4	**2021: Task 5**
Kiswire KAT		
Quantity delivered (km)	5	20
Mean piece length (m)	230	1432
Diameter (mm)	1.0	
Layout	E199R192	
Modules	132 Nb + 60 Sn-Ti	138 Nb + 54 Sn-Ti
d_s (µm)	45	44
Cu/non-Cu	1.0 ± 0.1	

KAT Geometry After Cabling

- Near the centre of the cable width:
  - Close to uniaxial deformation, < 15 % reduction
  - Barrier intact
  - Nb modules are relatively undeformed but their separations vary
- At the edge, in the least favourable configurations:
  - Local barrier breaches
  - Nb modules are significantly distorted



Thin edge

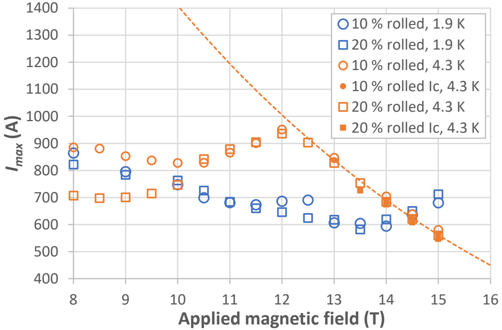


Near centre

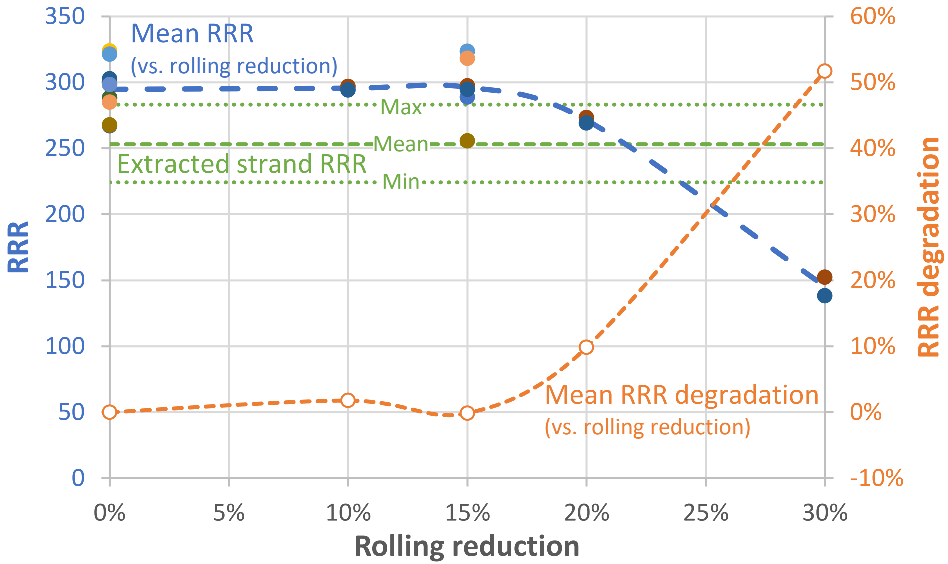
Optical micrographs of a cross-section of the trial cable produced with KAT task 5 wire

KAT: RRR and I_c on Deformation

- Virgin wire RRR is very high (mean ~300)
- Degradation on rolling is negligible up to 15 % rolling reduction
  - increases rapidly for 20–30 % rolling
  - Extracted strand RRR remains high
- When measurable, I_c degradation on cabling is **low** (mean 1.3%, max 2.6%)
- But stability requires improvement



$I_{max}(B)$ for rolled KAT 'task 5' wire



RRR for samples of KAT 'task 5' wire after rolling reductions of 0–30 %. The band of extracted strand RRR values is also marked for comparison.

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