Design Optimisation, Cabling and Stability of Large-Diameter High J_c Nb_3Sn Wires

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Background

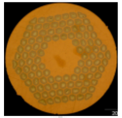
HFM
High Field Magnets

- In the context of the High Field Magnets (HFM) programme, Nb$_3$Sn conductor activities at CERN include:
  - Wire procurement and Rutherford cabling for magnet development:
    - Demonstrating a robust technology for 12 T accelerator magnets
    - Developing ultimate performance Nb$_3$Sn dipole magnets, both at CERN and in collaborations
  - Driving development of Nb$_3$Sn wire and cable towards the challenging performance targets of ultimate dipole magnets:
    - Non-Cu J_c of 1500 A/mm^2 (4.2 K 16 T), expected to require novel approaches (e.g. internal oxidation, novel alloying)
    - This also requires characterisation and optimisation of a broader range of parameters, e.g.:
      - Mechanical and electromechanical characteristics
      - Magnetothermal stability
- Supported by collaborations with academia and industry, including:
  - Industrial wire development collaborations with KAT, and in partnership with KEK, JASTEC and Furukawa

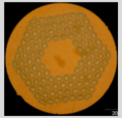
Introduction

- This presentation reports wire characterisation and cable development studies using:
  - RRP® wire procured from Bruker OST
  - Distributed tin wires developed by KAT
- including analysis of:
  - I_c and RRR degradation on Rutherford cabling
  - Stability (round and deformed wires)
  - Wire design aspects
- taking the HL-LHC RRP® conductors as a baseline for comparison
- Relative to that baseline, wires are:
  - Larger in diameter: 1.0 – 1.1 mm
  - Lower in copper: 0.9 – 1.0 Cu/non-Cu
  - Targeting higher J_c: For RRP®, ‘standard’ Sn stoichiometry

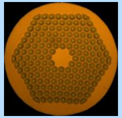
Nb_3Sn Wire Diameter



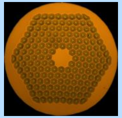
RRP® 108/127
HL-LHC 11 T dipole



RRP® 108/127
HL-LHC MQXF

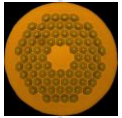


RRP® 162/169
FalconD

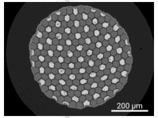


RRP® 162/169
R2D2 HT, TFD

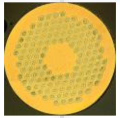
Maximum EuroCirCol



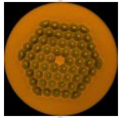
RRP® 78/91
ERMC



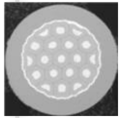
JASTEC R&D



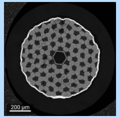
RRP® 132/169
FRESCA 2



RRP® 60/91
R2D2 LF



Internal tin
ITER TF



KAT R&D

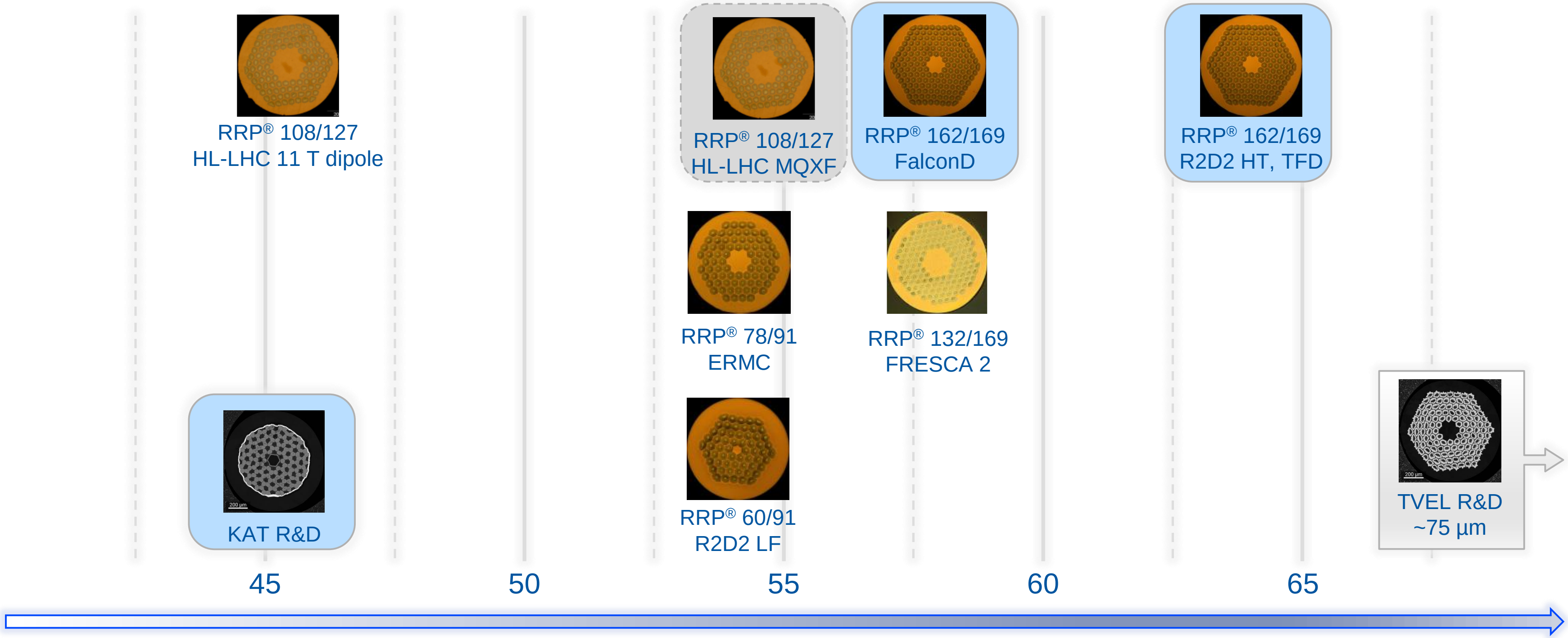
+ other FCC

Alstom 1.25 mm,
NED

0.6 0.7 0.8 0.9 1.0 1.1 1.2

Diameter (mm)

Nb_3Sn Sub-Element Diameter



RRP® 108/127
HL-LHC 11 T dipole

KAT R&D

RRP® 108/127
HL-LHC MQXF

RRP® 78/91
ERMC

RRP® 60/91
R2D2 LF

RRP® 162/169
FalconD

RRP® 132/169
FRESCA 2

RRP® 162/169
R2D2 HT, TFD

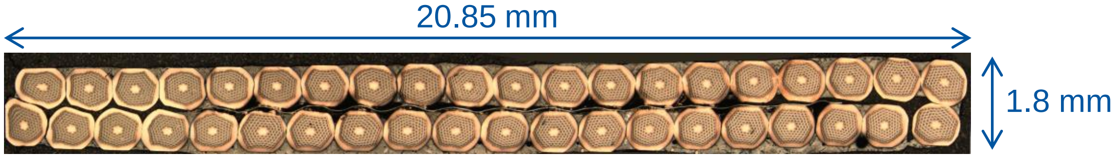
TVEL R&D
~75 µm

Geometrical sub-element size (µm)

Magnet Applications and Cable Layouts

- ERMC-1 and DEM-1.1 are assigned for use in two HFM magnet collaborations
  - ERMC-1 → **FalconD** (INFN): cos-theta dipole model targeting 12 T bore field
  - DEM-1.1 → **R2D2** (CEA): graded single-layer racetrack (DEM-1.1 for high field, DEM-0.7 for low field)
- ERMC-1 is also planned for use in CERN R&D coils
  - ERMC-1 → **eRMC** = enhanced Racetrack Model Coil, an established platform in which other 1.0 mm wires have previously been tested
- The corresponding cable geometries are summarised below (exact parameters subject to change)
- The FalconD and ERMC cable layouts have also been used for cabling trials to qualify R&D wire

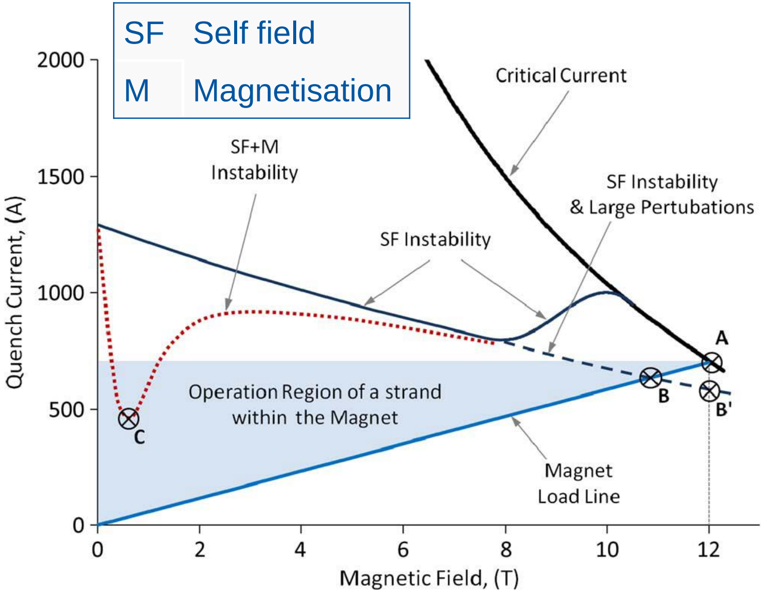
Type	Strands × diameter (mm)	Mid-thickness (mm)	Pitch (mm)	Keystone	Core
ERMC	40 × 1.0	1.82	120	None	Stainless steel (1.4404, 14×0.025 mm)
FalconD	40 × 1.0	1.800	110-120	0.5 °	
R2D2 HF	21 × 1.1	1.965	84	None	None



Example of cable cross-section in FalconD layout (optical micrograph)

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

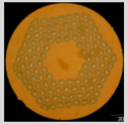
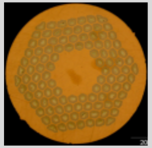
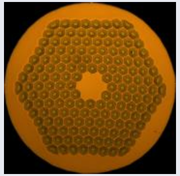
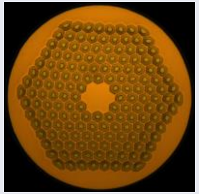
Bordini *et al.*, *IEEE Trans. Appl Supercond.* **22** (3) 4705804

Evaluation of Stability

- Self-field stability assessed here by *V*-*I* transport measurements:
  - Starting with an applied field of 15 T, and decreasing in small steps
  - Multiple *V*-*I* measurements performed at each field step
    - **Average** quench current or I_c presented in following plots
    - Values are plotted without self-field or temperature corrections
  - Maximum current ~2000 A
- Samples measured:
  - Round and rolled wires, and extracted strands
  - At 4.3 K and 1.9 K
  - Only one sample of each type measured to date
  - In most cases, samples had previously been measured (i.e. one previous thermal cycle):
    - Samples tested as pairs: increase in I_c expected, but does not affect relative conclusions

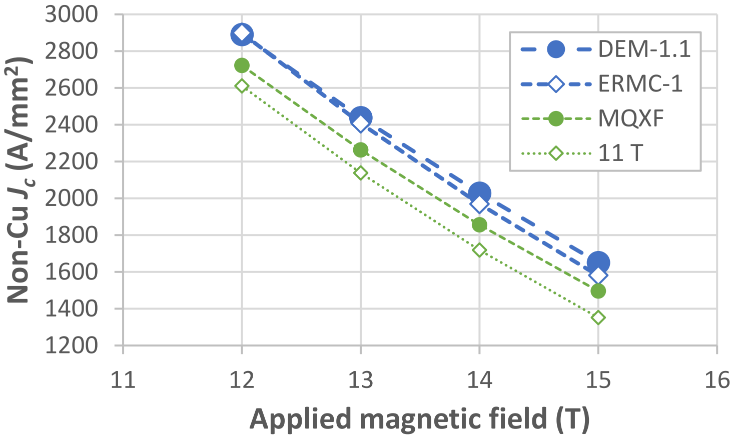
RRP® Wire

RRP® Wire Characteristics

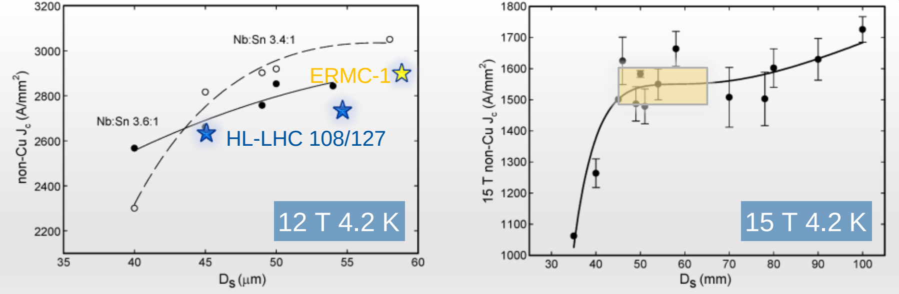
	HL-LHC		HFM	
	11 T dipole	**MQXF**	**ERMC-1**	**DEM-1.1**
				
Diameter (mm)	0.7	0.85	1.0	1.1
Layout	108/127		162/169	
d_s (µm)	45	54	58	64
Cu/non-Cu	1.15 ± 0.1	1.2 ± 0.1	0.9 ± 0.2	
Nb:Sn	3.6 (reduced Sn)		3.4 (standard Sn)	
Heat treatment	650 °C 50 h	665 °C 50 h	650 °C 50 h	665 °C 50 h

RRP® Wire Performance

- For the chosen heat treatments, the 162/169 wires have:
    - J_c higher than target, and significantly higher than HL-LHC reference (up to 10 % cf. MQXF, 20 % cf. 11 T)
    - RRR high, >200 rolled on average (comparable to MQXF)
    - Trends consistent with historical expectations from Sn stoichiometry and sub-element size



Mean non-Cu $J_c(B)$ at 4.3 K (CERN data, no corrections)



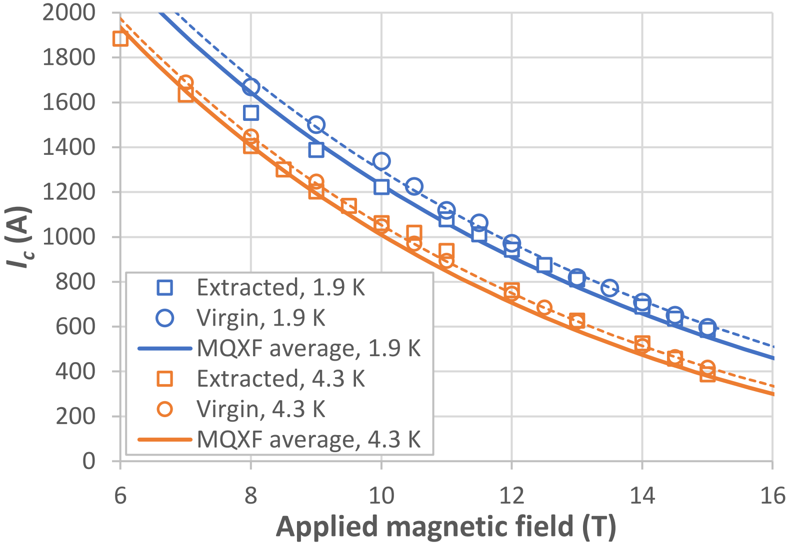
M. Field et al., *IEEE Trans. Appl. Supercond.* **24** (3) 6001105 (2014)

RRR (mean ± standard deviation)

RRR	11 T	MQXF	ERMC-1	DEM-1.1
Round	309 ± 35	345 ± 40	290 ± 33	266 ± 39
15 % rolled	174 ± 29	215 ± 29	206 ± 27	203 ± 36

Stability of MQXF Wire

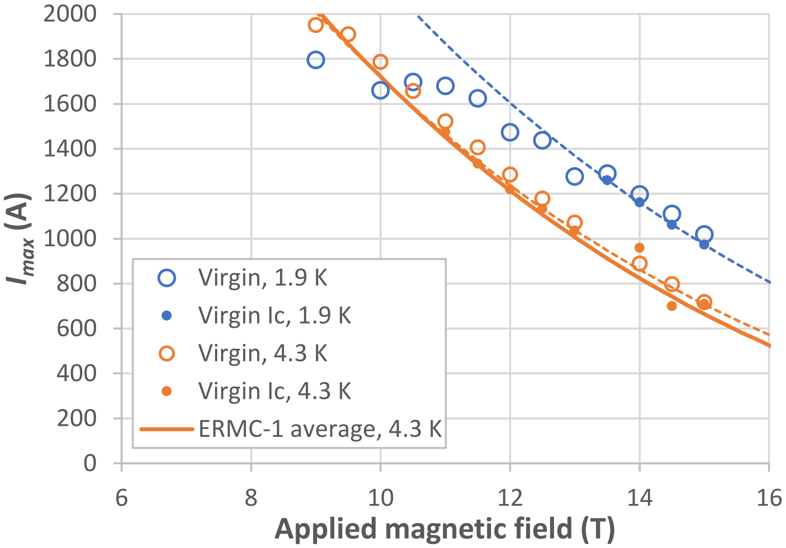
- As a baseline reference, measurements were performed for extracted and virgin HL-LHC MQXF strands
- Over the tested range (6–15 T), no quenches occurred, and the I_c followed the expected field dependence both at 4.3 K and 1.9 K



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: Virgin Wire

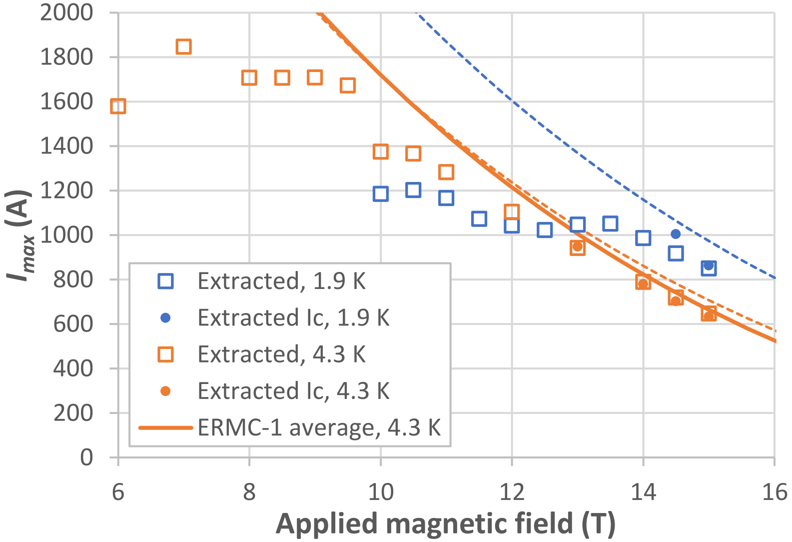
- For ERMC-1 wire with the standard heat treatment cycle (final step 650 °C 50 h)
  - At **4.3 K**, measured currents follow the $I_c(B)$ extrapolated from 12–15 T right up to the current limit below 9 T
    - …but a full transition is measured only at 11 T and above
  - At **1.9 K**, quenches occur 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
  - Quenches not experienced during routine acceptance tests (≥ 12 T, 4.3 K)



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

Stability of ERMC-1: Extracted Strand

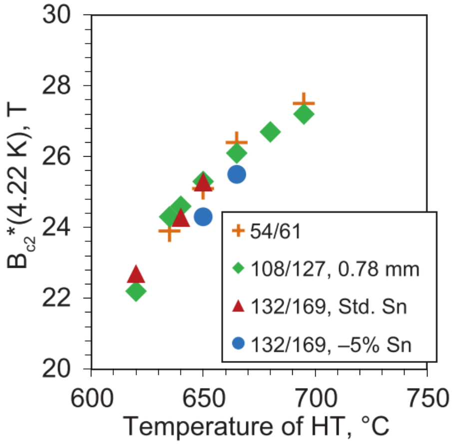
- For an ERMC-1 strand extracted from a trial cable for FalconD, after the standard heat treatment cycle (final step 650 °C 50 h)
  - At both temperatures, the I_c shows some degradation relative to virgin strand (dashed lines)
  - At **4.3 K**, the degraded $I_c(B)$ follows the same trend as virgin I_c only down to 13 T
    - Below 13 T, quenches occur at currents significantly below the extrapolated I_c
  - At **1.9 K**, 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
- Extracted strand shows markedly poorer stability than virgin ERMC-1, with stability limiting the achievable current over the full field range expected for applications



Measured $I_{max}(B)$ for extracted strand from FalconD trial cable after the standard heat treatment (650 °C 50 h). The lines show the virgin ERMC-1 wire I_c for comparison.

Heat Treatment Optimisation (1)

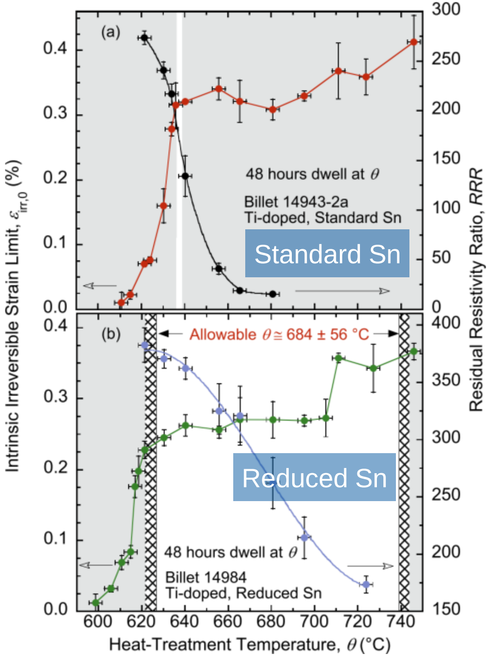
- Optimisation of the final heat treatment step generally seeks a balance between $I_c(B)$ and RRR
  - For ERMC-1, during production this was already revised from 665 °C 50 h (cf. DEM-1.1) → 650 °C 50 h to ensure the RRR spec could be met
  - Considering the very high I_c, potential to further adjust 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)
  - Little data available for very short heat treatments



Dependence of B_{c2} on heat treatment temperature comparing 132/169 with standard and reduced Sn
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
  - Provisionally associated with δ Cu-Sn
- First tests for standard Sn 162/169 RRP® suggest similar behaviour
  - See Cheggour *et al.*, Strain investigation of RRP® Nb_3Sn wires for the Test Facility Dipole Project TFD, presented at ASC 2022, 27 October 2022



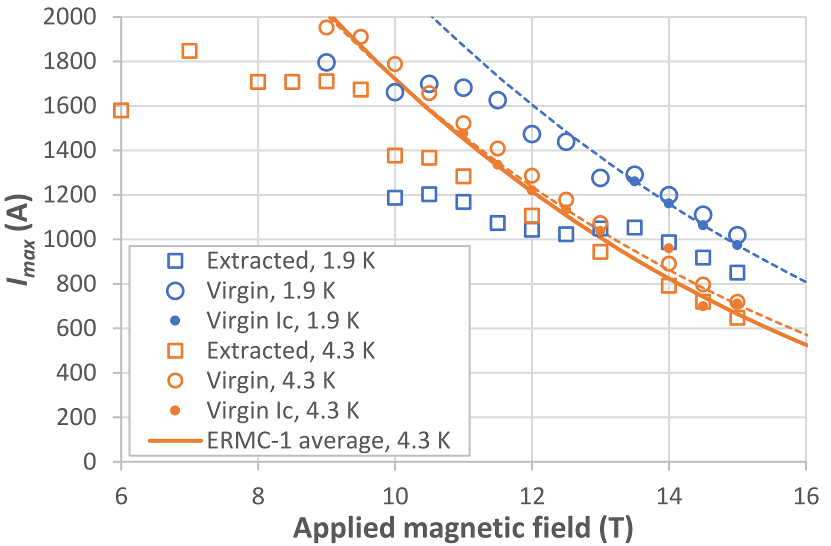
Dependence of irreversible strain limit and RRR on heat treatment temperature for Ti-doped 108/127
Cheggour et al. 2019, *Scientific Reports* **9** 5466

Heat Treatment Optimisation (2)

- Initial trials have therefore been with reduced **duration**
- Two heat treatments were performed to assess the effect of shorter reaction steps at 650 °C:
  - One heat treatment of I_c and RRR samples with a reduced duration of **30 h**
  - One heat treatment of short samples only (RRR and microscopy) for ejection at intermediate durations, **0–50 h**
- Samples included virgin, rolled and extracted strands
  - Note: for logistical reasons, extracted strand data are currently available only for the ERMC cable geometry, not FalconD

Stability of ERMC-1: Standard HT

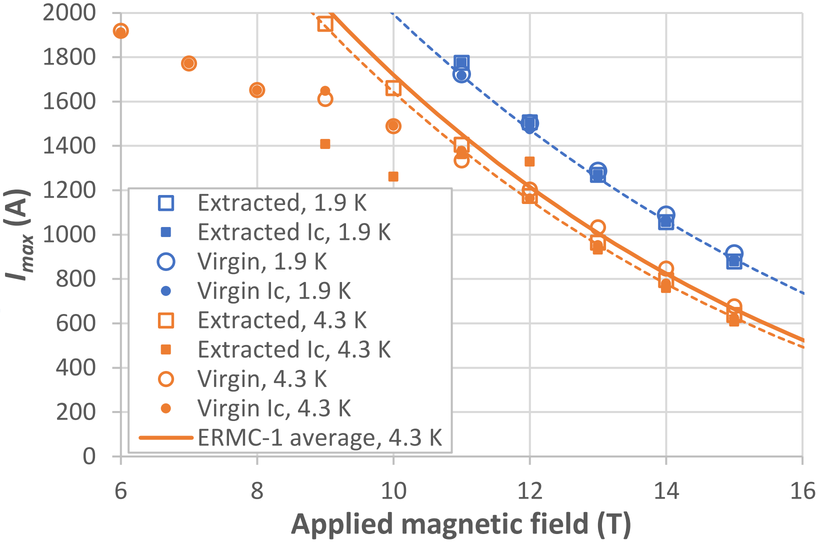
- For reference:
  - Virgin ERMC-1 wire (1.0 mm 162/169) and extracted strand (FalconD trial)
  - Standard HT heat treatment (650 °C 50 h)



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

Stability of ERMC-1: Shorter HT

- With the 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
  - At **4.3 K**, the behaviour is also improved, but quenches are still observed at 10 T and below
    - Some anomalous/inconsistent results
  - Additional testing is needed
    - Verify the effect of cable layout and obtain statistics

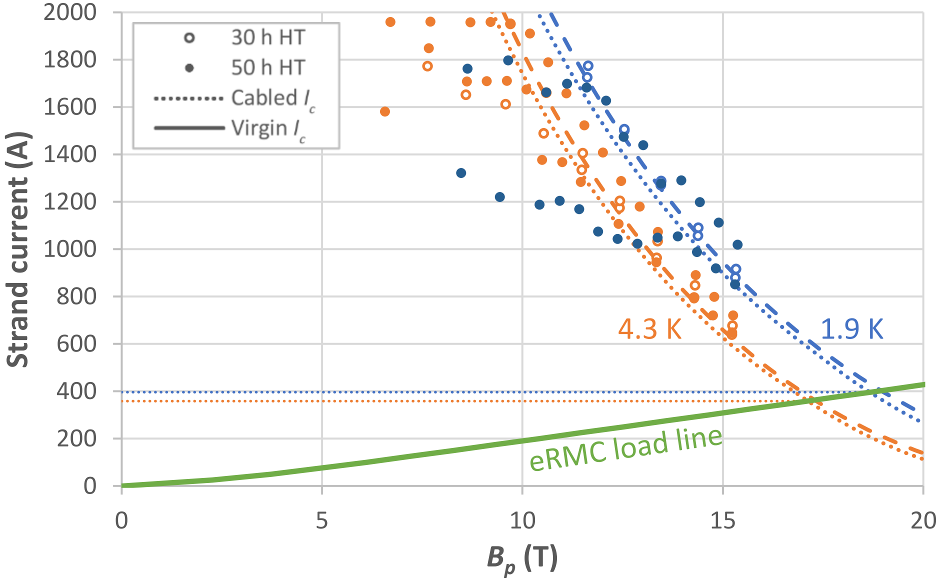


Measured $I_{max}(B)$ for a virgin ERMC-1 wire and a strand extracted from an **ERMC** cable after the **shorter** heat treatment (650 °C 30 h)

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

Stability of ERMC-1 for eRMC

- Previous data replotted against B_p (including self field) and eRMC load line overlaid
  - Extracted and virgin samples, for both heat treatments
  - Self-field stability seems acceptable
  - Note *average* quench currents shown, for single samples
    - More statistics needed

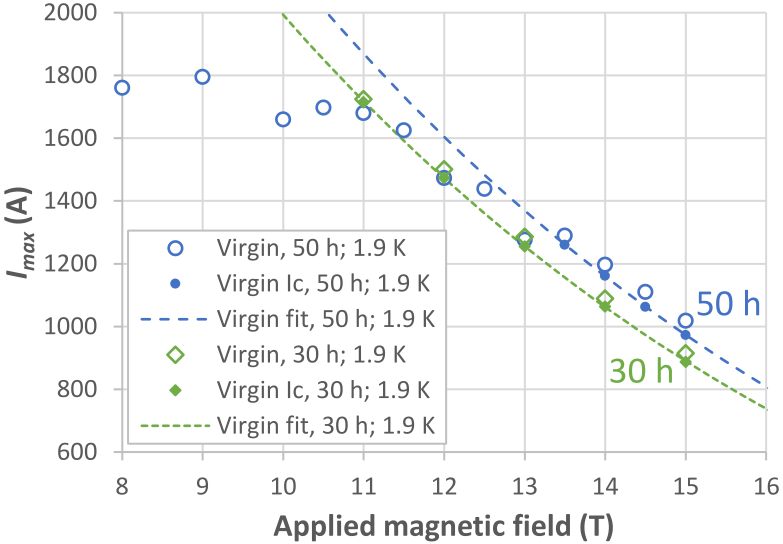


eRMC load line scaled to mean per-strand current, intercepts with fits to virgin and cabled I_c, overlayed with quench currents for both heat treatments

Cabled I_c is the lower of extracted strand I_c and 95 % virgin I_c for 30 h heat treatment

Shorter HT: Effect on I_c

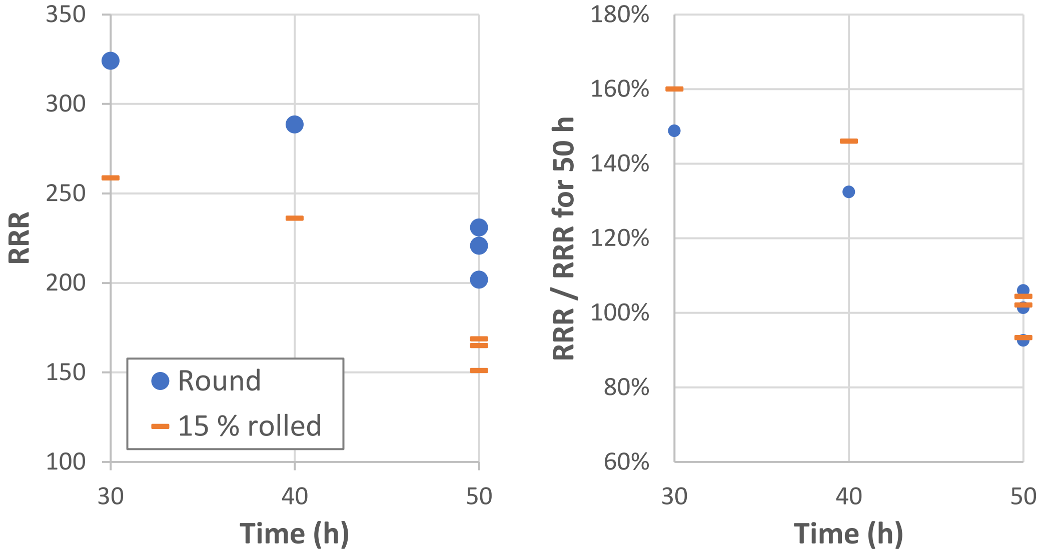
- Comparing the virgin wire data only, at 1.9 K:
  - The shorter 30 h step reduces I_c by **9 %**
  - The stable I_c for a 30 h heat treatment exceeds the quench current for a 50 h heat treatment below ~12 T
  - The identical scaling behaviour at high fields suggests no change in B_{c2}



Measured $I_{max}(B)$ for virgin ERMC-1 wire at 1.9 K for final heat treatment step durations of 50 h and 30 h

Shorter HT: Effect on RRR

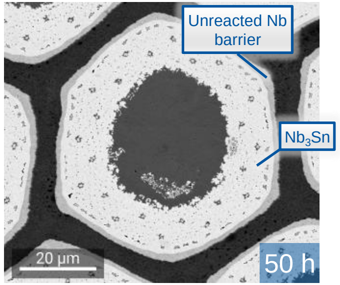
- Reducing the heat treatment duration increases RRR substantially both for rolled and round samples
  - ~50 % for 30 h
  - ~40 % for 40 h

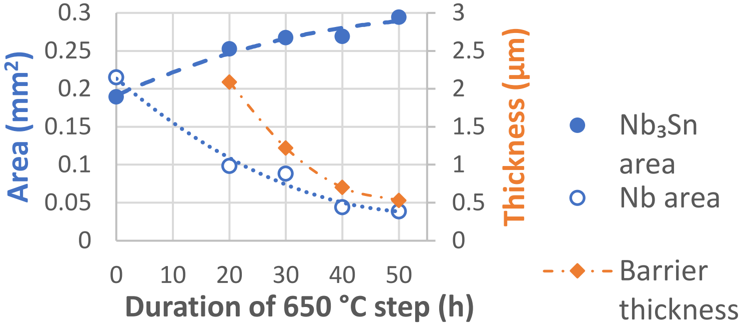


RRR of round and rolled wire after heat treatments with a final plateau of 30 h, 40 h and 50 h at 650 °C

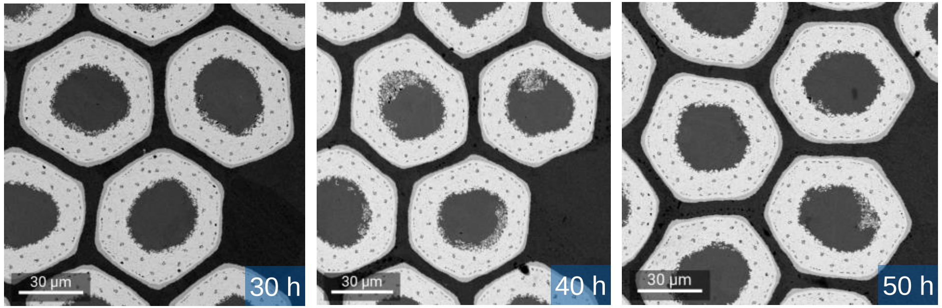
Shorter HT: Micrographs

- 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

ERMC-1: Cabling Degradation

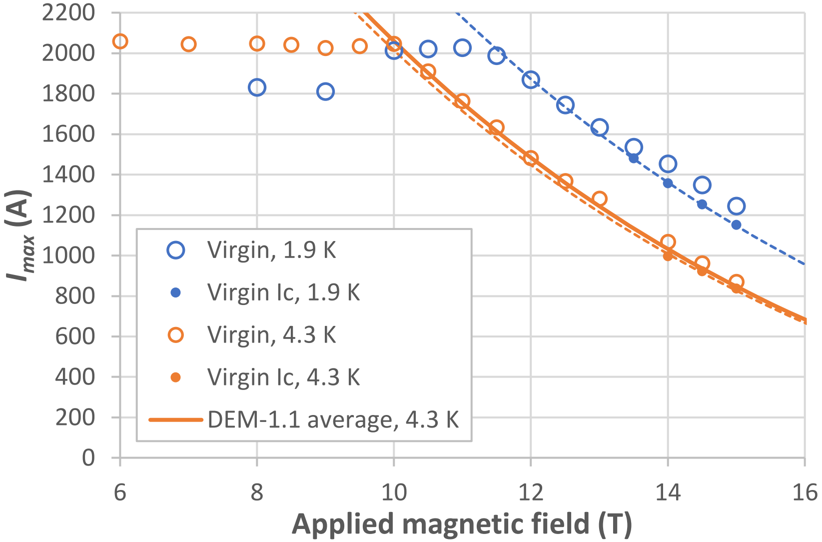
- For the cable samples tested to date, degradation on cabling of ERMC-1 strands is:
  - Much higher than typical for HL-LHC MQXF cable
  - Higher for the more compacted, keystoned FalconD trial cable than ERMC
    - Exceeds HL-LHC acceptance criterion of 5 % average I_c degradation
    - Substantial 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
- Stability data for the **30 h** heat treatment are currently only available for the less compacted ERMC layout – still to be determined how much of the difference is attributable to each factor

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 %

Increasing cabling degradation

Stability of DEM-1.1: Virgin Wire

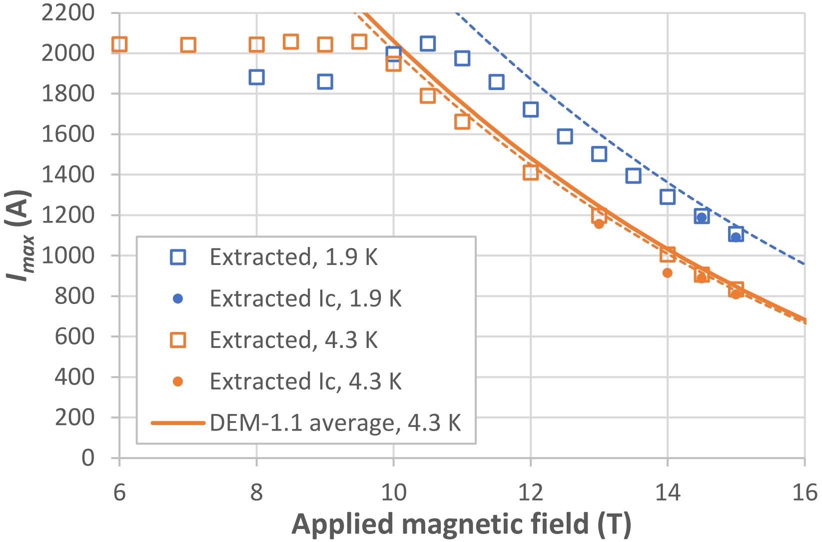
- For DEM-1.1 wire with the standard heat treatment cycle (final step 665 °C 50 h)
  - At 4.3 K, measured currents follow the $I_c(B)$ extrapolated from 12–15 T down to 10 T
    - A full transition is measured at 14 T and above
  - At 1.9 K, measured currents follow the extrapolated $I_c(B)$ down to 11.5 T
    - A full transition is measured at 13.5 T and above
    - At ~10 T and below, the quench current at 1.9 K is less than that at 4.3 K
- Complicated by current limit of ~2000 A:
  - Limited by current injection to the VAMAS
  - *Apparent* low-field quench currents are ~2000 A, so the true value may be higher
  - **If** the values at **1.9 K** are valid, note the 4.3 K/1.9 K cross-over is at the same field (10 T) for ERMC-1 and DEM-1.1 for the (different) standard HTs



Measured $I_{max}(B)$ for virgin DEM-1.1 wire (1.1 mm 162/169) after the standard heat treatment (665 °C 50 h), with average $I_c(B)$ for comparison

Stability of DEM-1.1: Extracted Strand

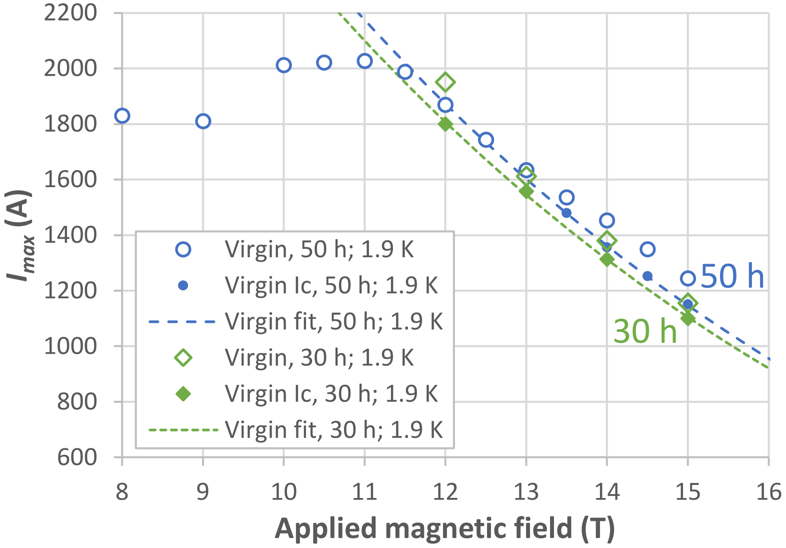
- For a DEM-1.1 strand extracted from a trial cable for R2D2, after the standard heat treatment cycle (final step 665 °C 50 h)
  - I_c shows some cabling degradation relative to virgin wire
  - But unlike the extracted strands of ERMC-1, stability behaviour is **almost identical** to the virgin wire



Measured $I_{max}(B)$ for extracted strand from R2D2 trial cable after the standard heat treatment (665 °C 50 h). The lines show the virgin DEM-1.1 wire I_c for comparison.

Effect of 650 °C 30 h HT: DEM-1.1

- The same alternative heat treatment as for ERMC-1 was assessed: 650 °C 30 h
- As before for ERMC-1, I_c was then measurable at 1.9 K down to a lower field: in this case, the lowest measured (12 T)
  - Note measurements were performed only until a current of 2000 A was reached for this tests
- The reduction in I_c due to the change in heat treatment was only **4 %**
  - Much lower than for ERMC-1, despite also reducing the temperature
  - B_{c2} reduced by ~0.5 T
- As expected from the previous slides, for the measured range this does not increase quench currents: further testing needed over the full field range, to currents > 2000 A



Measured $I_{max}(B)$ for virgin DEM-1.1 wire at 1.9 K for final heat treatment step durations of 50 h and 30 h

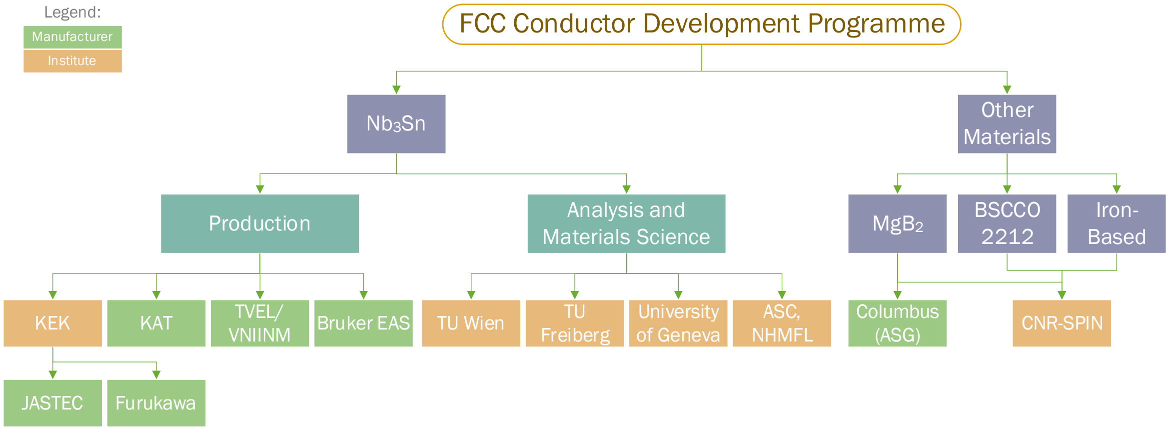
R&D Wires

Background for conductor development

KAT distributed tin wires

Conductor Development (1)

- 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

BSCCO 2212

Iron-Based

Columbus (ASG)

CNR-SPIN

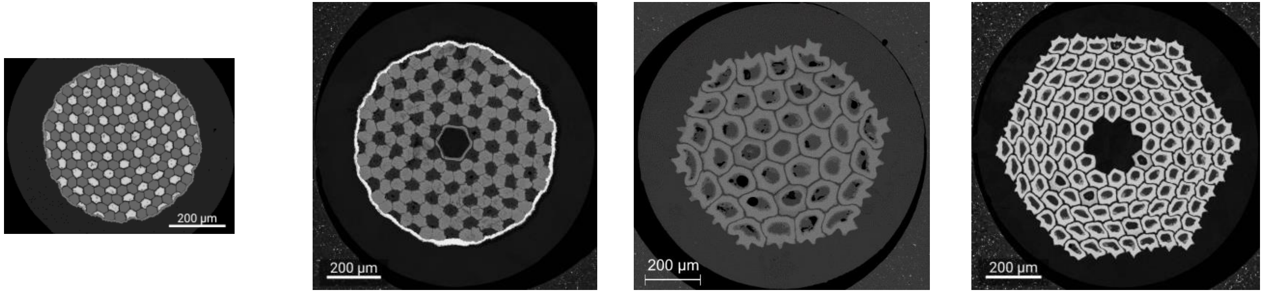
Conductor Development (2)

- Collaborations with manufacturers on new designs for high-J_c Nb_3Sn wires can be grouped in three types:
  - Distributed barrier: TVEL
  - Distributed tin: JASTEC, KAT
  - Tube-type: Furukawa
- JASTEC, KAT and TVEL wires have achieved $J_c(B)$ comparable to the HL-LHC specification, and been validated in rolling studies and/or cabling trials reported previously
- Methods to increase J_c beyond this state of the art (Hf alloying, internal oxidation) have also been studied

Conductor Development (3)

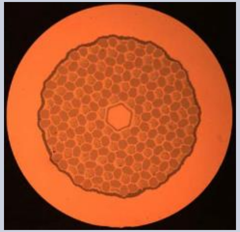
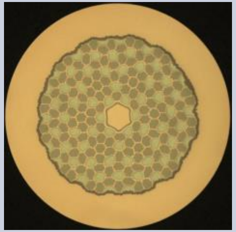
- Several iterations of JASTEC, KAT and TVEL wire have been validated in rolling studies and/or cabling trials reported previously

	EUCAS 2019, ASC 2020		**EUCAS 2021**	
	JASTEC	**TVEL**	**KAT**	**TVEL**
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



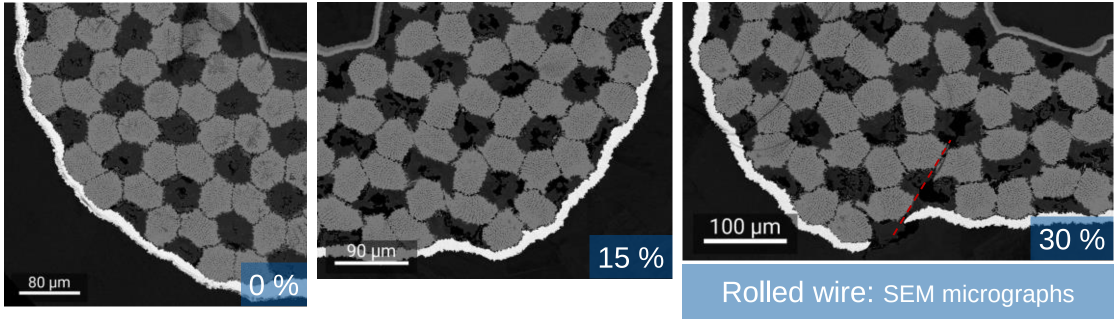
KAT Wire

- In the context of CERN collaboration agreement KE3449, KAT has been developing ‘distributed tin’ wires
- In 2020, the ‘task 4’ trial wire was produced
  - CERN rolling studies and trial cabling (FalconD layout)
- In 2021, pilot production was performed using a slightly optimised layout
  - 20 km delivered in long piece lengths (mean 1432 m)
  - Slightly reduced Sn content, with adapted heat treatment
  - Similar CERN trials to task 4

	2020: Task 4	2021: Task 5
		
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	

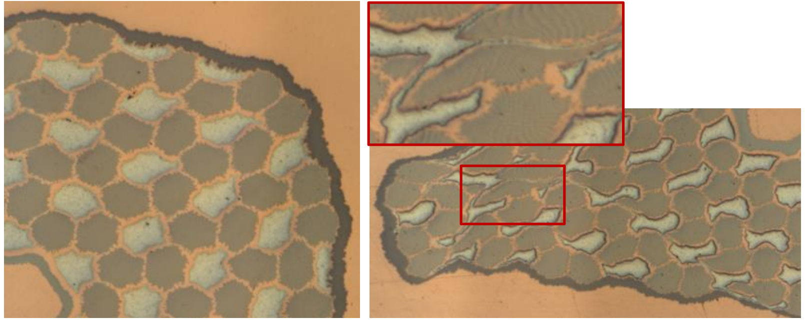
KAT: Geometry on Rolling/Cabling

- Recap of deformation behaviour presented for task 4 wire at EUCAS 2021:
  - On **rolling**, modules slide past each other without significant deformation
  - On **cabling**, in the most deformed edge sites, Nb modules are significantly distorted



Rolled wire: SEM micrographs

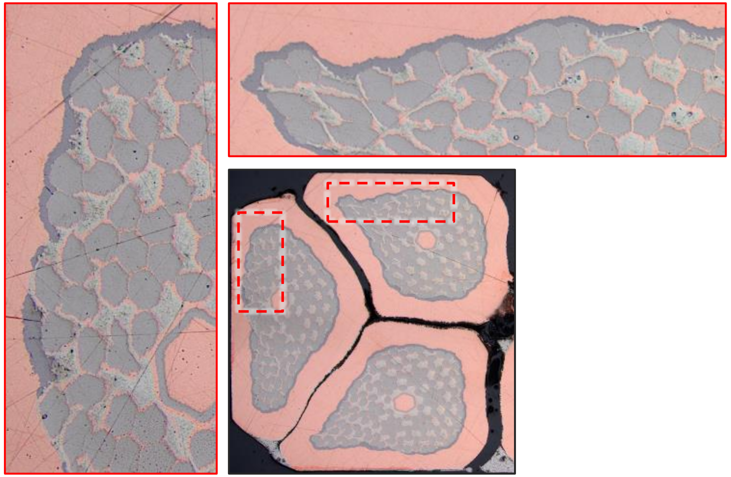
Cable: FalconD layout



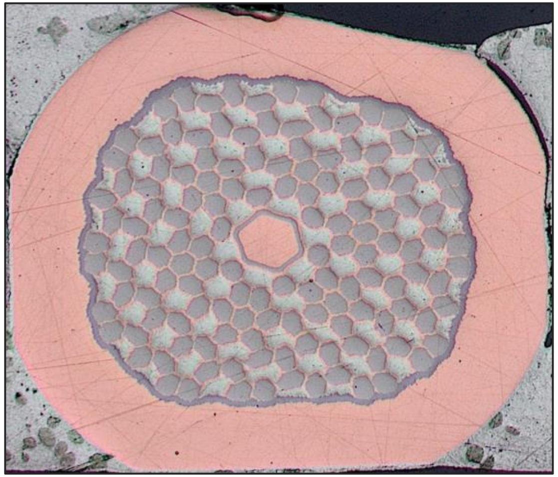
Cabled strands: Optical micrographs, near thin edge

KAT Cable Cross-Section

- Similar features are apparent in the cross-section of the current cable
- 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



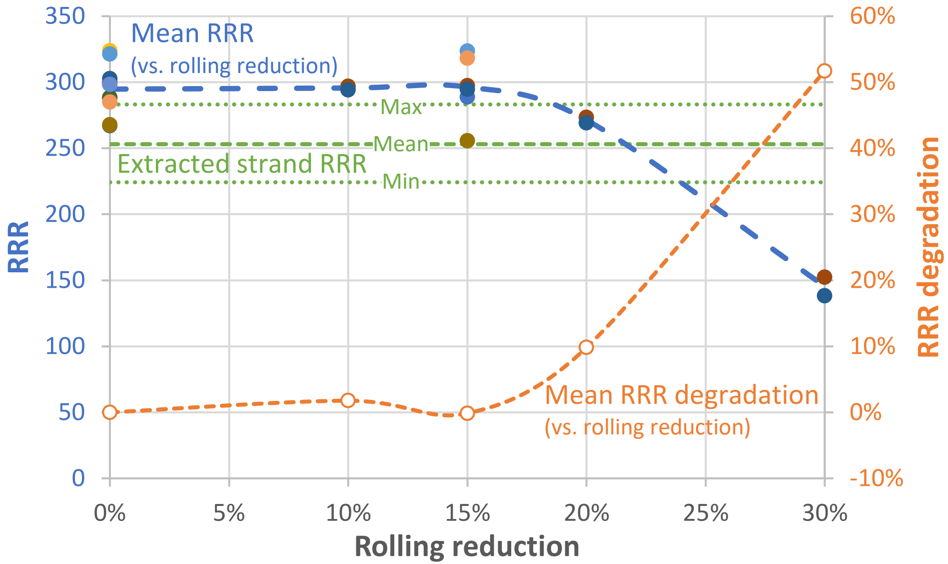
Near centre

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

KAT: RRR and I_c on Deformation

- Consistent with observations for previous wire generation:
  - Virgin wire RRR is very high (mean ~300)
  - Degradation on rolling is negligible up to 15 % rolling reduction, and increases rapidly for rolling of 20–30 % reduction
  - Extracted strand RRR remains high (degradation < 20 %)

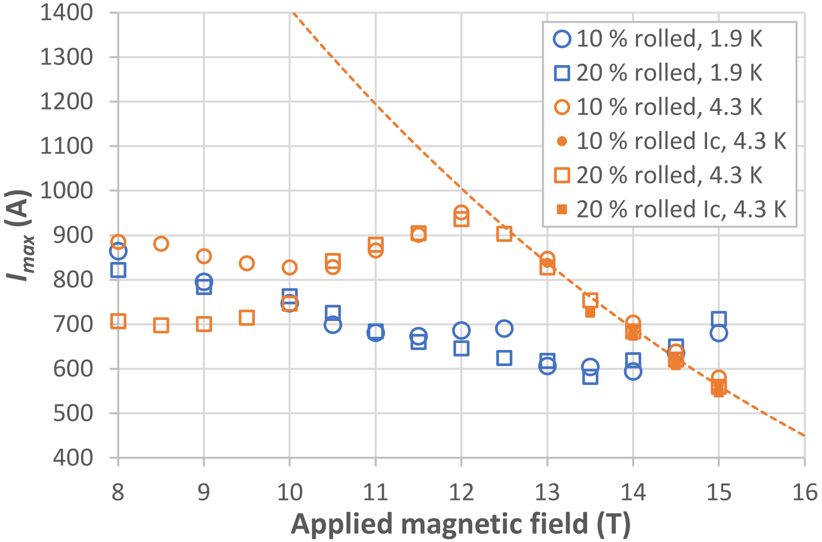
  as may be expected for a largely intact common diffusion barrier
- When measurable, I_c degradation on cabling is low (mean 1.3%, max 2.6%)
  - Limited sample size due to stability issues (see later)
  - Comparable to cabling trial of previous generation wire (range -5.9 % to +3.6 %)
  - Promising indication that < 5 % degradation can be expected



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.

KAT Wire Stability

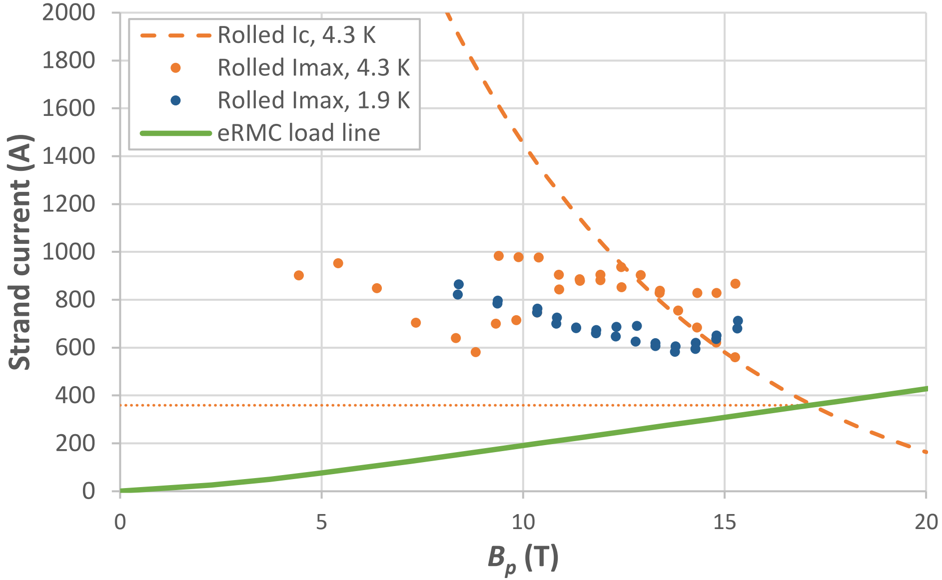
- The stability of two **rolled** samples of a KAT distributed tin wire (‘task 5’) was compared
    - Similar behaviour for both samples
    - At **4.3 K**, I_c could be measured to ~13 T
        - I_c degradation on rolling is low: ~3 % lower I_c after 20 % rolling cf. 10 % rolling
        - Quench currents are significantly below extrapolated $I_c(B)$ below ~12 T
        - At low fields, quench currents are (tentatively) lower for the more deformed sample
    - At **1.9 K**, all tests quenched, with consistent currents for both samples
        - Quench currents at 1.9 K are lower than I_c at 4.3 K in applied fields below 14.5 T



$I_{max}(B)$ for KAT ‘task 5’ wire rolled with reductions of 10 % and 20 %

KAT Wire Stability for eRMC

- Overlaying the eRMC load line, quench currents are marginal at 4.3 K
  - Note *average* quench currents from individual *rolled* (not extracted) samples
  - More statistics desirable, but improvements in wire stability are expected to be needed before magnet use



eRMC load line scaled to mean per-strand current overlayed with quench current data for rolled KAT samples

Shows data for 10 % and 20 % rolling; magnetic field includes self-field

Summary

Observations: RRP®

- In large-diameter RRP® wires optimised for high I_c, stability is a challenge, but not necessarily prohibitive
- Reduction of heat treatment duration to 30–40 h can be a viable strategy
  - Effective despite a very high RRR for the *standard* heat treatment, and a still high J_c
    - …but perhaps not much further headroom for even higher J_c wires, e.g. with APCs
  - For **round** wires, quench currents are only increased modestly and over a limited field range
    - The requirements and exact heat treatment should be assessed for each cable layout and application
- For ERMC-1:
  - For round wire, the resulting reduction in J_c consumes much of the difference in J_c relative to MQXF wire at 30 h
    - Further heat treatment optimisation may achieve a better compromise
  - Effects are most significant for extracted strand, and possibly marginal with more compacted keystoned cables (FalconD vs. ERMC) – i.e. *local* RRR degradation and sub-element distortion at thin edge
- DEM-1.1 behaves significantly better than ERMC-1, noting also the higher 'standard' heat treatment temperature
- The 'gain' in J_c of ERMC-1 cf. MQXF comes partly from increased sub-element size and higher ('standard') Sn stoichiometry
  - The latter constrains heat treatment optimisation and may be unfavourable on electromechanical grounds
  - Especially after deformation (cabling), the ERMC-1 sub-element size may already be marginal for standard Sn being suitable – at least in this layout and low Cu/non-Cu
  - Neither effect is likely to be available for smaller d_{eff} wires; and compensating measures in wire design (e.g. barrier thicknesses) may be in competition with low d_s, sub-element spacing, J_e etc.
- Further study needed to obtain statistics from multiple tests over the full field range

Observations: Distributed Tin

- By nominal characteristics, one may anticipate higher stability for this distributed tin wire than ERMC-1 or DEM-1.1
  - Very low *geometrical* sub-element size, higher Cu/non-Cu, comparable RRR and diameter, lower J_c (for standard heat treatment)
- Absence of distributed diffusion barriers has several effects:
  - Local contact between adjacent Nb_3Sn regions probable – especially after cabling deformation – increasing d_{eff}
    - Observed in magnetisation measurements
  - ‘Sub-elements’ separated by low conductivity Cu-Sn after reaction (Cu stabiliser is mostly at the periphery)
  - Heat treatment optimisation may have lower potential to address stability, as it must be optimised for longer range tin transport (relative to d_s)
- This may suggest:
  - A higher importance of optimising copper spacing, module geometrical uniformity and deformation behaviour than for distributed barrier designs – optimisation work in progress at KAT
  - More thorough analysis of the effect of stabiliser distribution and conductivity distributions would be valuable

Conclusions

- Stability and cabling degradation are more challenging, but not yet prohibitive, for the currently available high-J_c wire layouts at ≥ 1 mm diameter
  - Heat treatment optimisation provides some scope to achieve the desired compromise
  - …but should also be addressed at the wire selection and design level
  - Achieving higher J_c and smaller d_{eff} with sufficient stability poses different challenges and limits for distributed barrier and distributed tin wire types
- Routine testing, especially of new wire types, should be designed to assess stability and cabling degradation
  - Supplier tests (4.2 K only) and corresponding acceptance tests (I_c at 4.3 K and ≥ 12 T) do not necessarily identify cases of marginal stability
  - RRR tests of extracted strands underestimate local RRR degradation at cable edges
  - Greater sampling is needed to obtain sufficient statistics to reliably assess self-field stability
  - This testing becomes challenging for the high currents required for very high J_c wires
- More detailed study of instabilities, and correlations with wire designs/characteristics, is also needed
  - Measurements of the minimum trigger energy of magnetothermal instabilities initiated with a laser to be restarted
  - The effect of gradients of composition, microstructure and conductivity (longitudinally and in the cross-section) should be investigated

Acknowledgements

Thank you for your attention.

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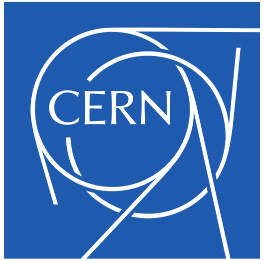
- Emma Gautheron for providing the eRMC load line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