WP1.1 – Nb_3Sn Conductors for High Field Magnets

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HFM Annual Meeting: RD1 - Nb_3Sn Conductors

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Introduction

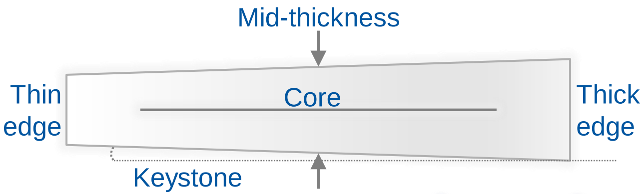
- Nb_3Sn conductor activities include development, procurement, production, qualification and characterisation of Nb_3Sn wire and Rutherford cables
  - to meet the needs of the magnet programme (RD3), and
  - towards the requirements of future accelerator magnets
- Goals for conductor development:
  - Addressing stress/strain sensitivity and degradation
  - Increasing J_c performance
  - Industrialisation
- …whilst maintaining
  - Low and consistent degradation on cabling
  - Magnetothermal stability

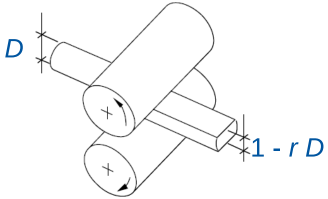
Selected Activities

- Wire procurement and acceptance tests
- Cable production and qualification
- Electron microscopy and quantitative image analysis
- Heat treatment optimisation
- Rolling studies and cabling trials
- Magnetothermal stability and magnetisation measurements
- Effects of transverse stress: crack analysis, I_c degradation

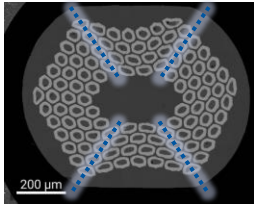
Rutherford Cabling and Rolling

- Strands at the centre of the cable width typically have a **nominal** thickness (diameter) reduction of ~11 %
- For wire qualification and acceptance testing, this is approximated by uniaxial rolling studies with 10 % or 15 % rolling reduction
- The real deformation, especially at the (thin) edge, is more severe and not uniaxial
  - All strands experience this periodically, at a transposition pitch typically shorter than samples used for I_c and RRR
- The stress configuration generates some common features, but the deformation of sub-elements depends on the wire type and even local orientation [1]
- Sub-element deformation affects performance via several mechanisms, e.g.:
  - Sub-element shearing and merging
  - Changes in local barrier thickness and diffusion distances

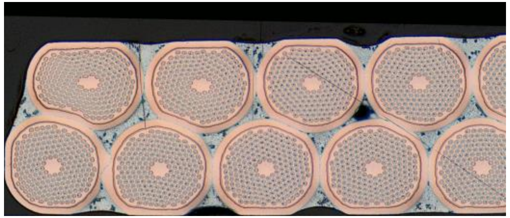




Rolling, reduction *r*



Typical shear directions

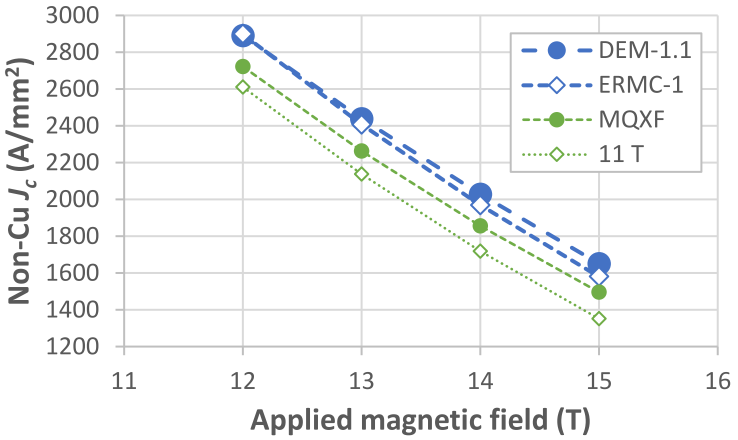


Strand deformation in cable (Al Baskys) [1]

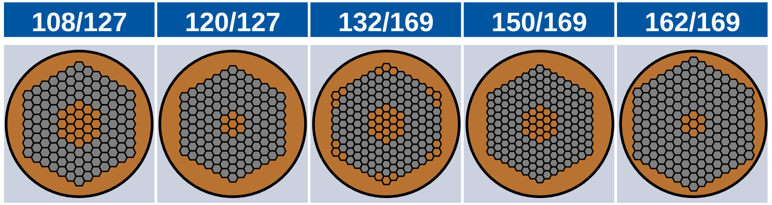
[1] *IEEE Trans Appl. Supercond.* **33** (5) 4801605

RRP® Wire

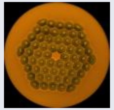
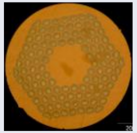
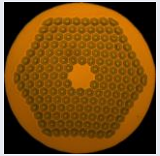
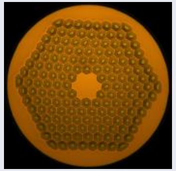
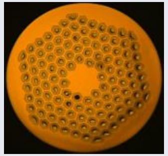
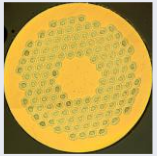
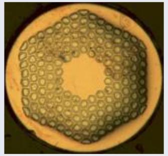
- Bruker OST RRP® wire, as used for HL-LHC MQXF, is effectively the state-of-the-art reference wire type
  - Proven versatility for different wire layouts, Cu/non-Cu, J_c vs. RRR optimisation etc.
  - For MQXF – very high RRR, good J_c, no stability issues
  - Production at scale with very few nonconformities
- Also procured for current HFM magnet activities (RD3)
- Optimisation and understanding has continued to progress in recent years (e.g. nausite and J_c vs. d_{eff}, strain cliff), but:
  - Differences in behaviour between layouts observed but not fully understood
  - When optimised for large diameter and high J_c, stability challenges can arise
  - Substantial J_c increases likely to require new processes, e.g. novel alloying and internal oxidation
- Continued study needed to select and validate the most promising designs for 14+ T:
  - Rolling and cabling degradation
  - Behaviour under transverse stress
  - Stability



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



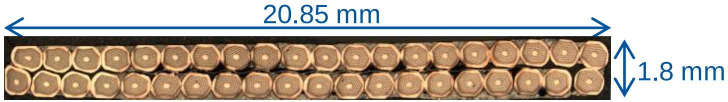
RRP® Wire Types

	HFM				Other Candidates		
	DEM-0.7	MQXF	ERMC-1	DEM-1.1	ERMC#101	FRESCA2	ERMC#102
							
d **(mm)**	0.7	0.85	1.0	1.1	1.0	1.0	1.0
Layout	60/91	108/127	162/169	162/169	120/127	132/169	150/169
d_s (µm)	54	54	58	64	64	58	57
Cu/non-Cu	1.8 (≥ 1.6)	1.2 ± 0.1	0.9 ± 0.2		1.06 ± 0.1	1.25 ± 0.1	1.08 ± 0.1
Nb:Sn	3.6 (reduced Sn)		3.4 (standard Sn)			3.4	
Dopant	Ti	Ti	Ti		Ti	Ti	Ti
Heat treat.	665 °C 50 h	665 °C 50 h	650 °C 50 h	665 °C 50 h	665 °C 50 h	650 °C 50 h	665 °C 50 h

Magnet Applications and Cable Layouts

- RRP® 162/169 wires at 1.0 and 1.1 mm diameter were allocated to ERMC, FalconD and R2D2 (high field) magnet programmes
  - The same cable layouts are also used for trials of R&D conductors
- For the 12 T robust/value-engineered programme, the baseline conductor is the MQXF wire (108/127) and cable developed for HL-LHC

Cable Type	Strands × diameter (mm)	RRP® wire	Mid-thickness (mm)	Pitch (mm)	Keystone	Core
MQXF	40 × 0.85	108/127 (MQXF)	1.525	109	0.4 °	Stainless steel (1.4404, 14×0.025 mm)
ERMC	40 × 1.0	162/169 (ERMC-1)	1.82	120	None	
FalconD			1.800	110-120	0.5 °	
R2D2 HF	21 × 1.1	162/169 (DEM-1.1)	1.965	84	None	None
R2D2 LF	34 × 0.7	60/91 (DEM-0.7)	1.253	79	None	None



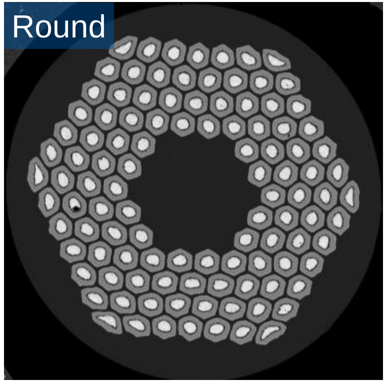
Example of cable cross-section in FalconD layout (optical micrograph)

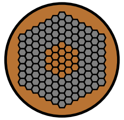
Cable Production

- Cable production for the needs of the Nb_3Sn magnet programme (RD3) and to qualify R&D wires
- In 2023 to date:
  - Production of Nb_3Sn cables (and related Nb-Ti busbars) for R2D2:
    - 452 m of R2D2 HF cable (C02OC0442A):
      - 21 strands of DEM-1.1 wire, 12.577×1.968 mm
    - 427 m of R2D2 LF cable (C03OC0448A):
      - 34 strands of DEM-0.7 wire, 12.570×1.255 mm
  - Trial to assess JASTEC distributed tin wire in the R2D2 HF cable layout:
    - 20 m of cable (C02KC0444A)
      - 21 strands of JASTEC DT wire, 12.566×1.948 mm

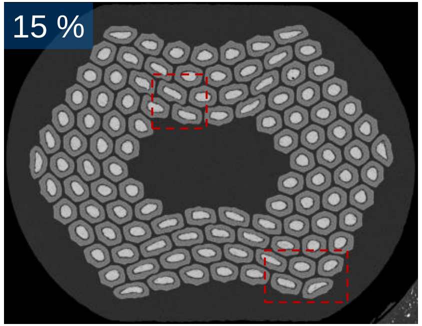
RRP® Rolling: Key Features

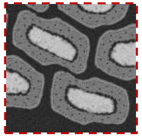
- For RRP®, increasing rolling reduction progressively:
  - Increases subelement aspect ratios
  - Locally reduces diffusion barrier (and Nb filament pack) thickness
  - Shears or merges adjacent subelements
- These observations can be quantified by image analysis



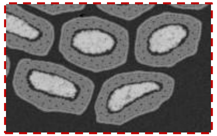


RRP® 108/127, 0.85 mm

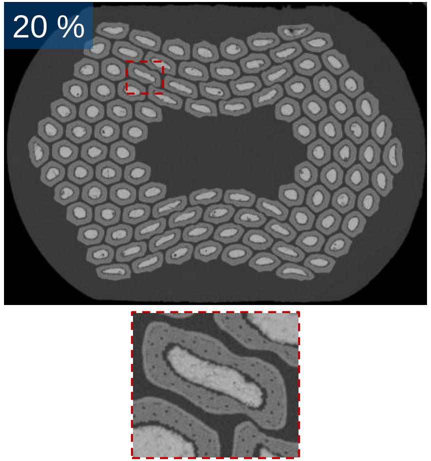


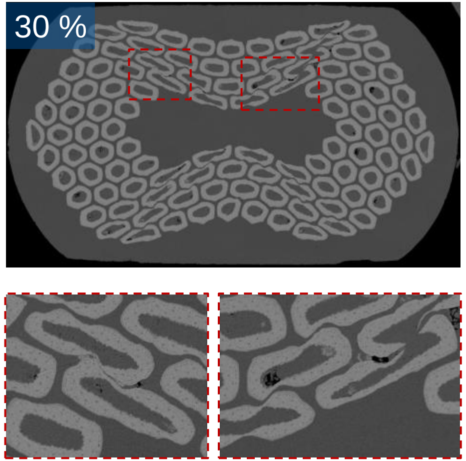


Local barrier thinning, reduction of separation



Increasing subelement aspect ratio

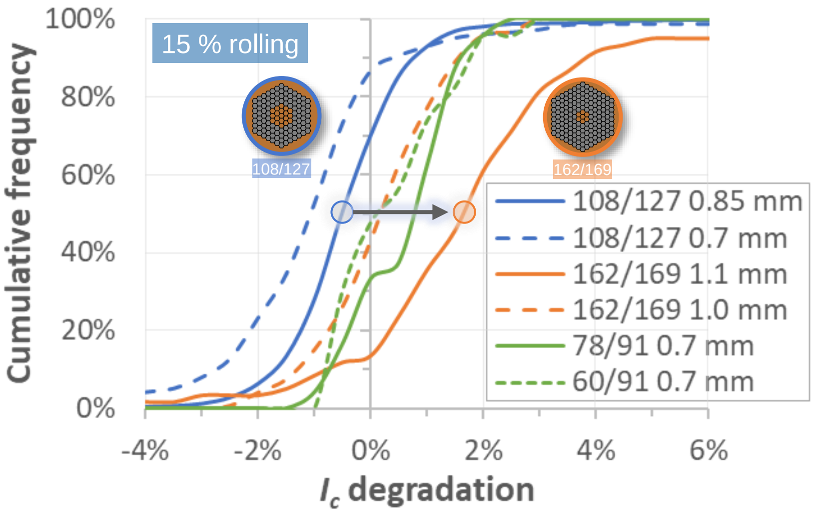


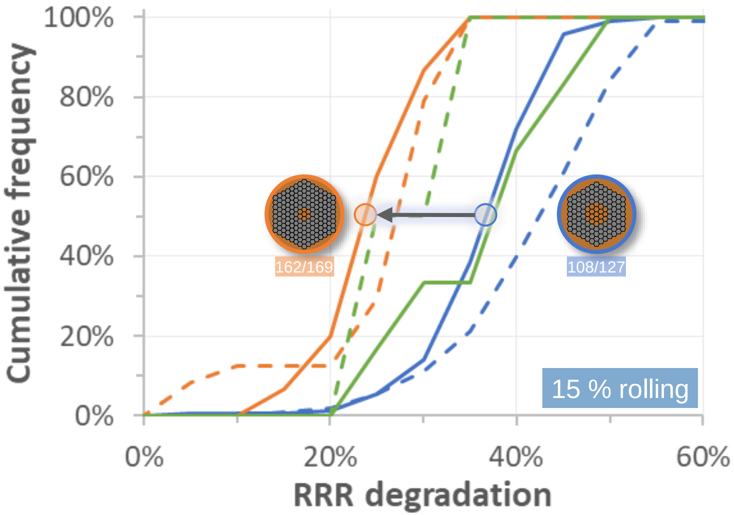


Subelement merging, shearing and barrier thinning

Rolling of Different RRP® Layouts

- For 15 % rolling, acceptance test statistics are available for a significant number of spools
- Relative to 108/127 at 0.85 mm, 162/169 at 1.1 mm shows (on average):
  - **Higher** I_c degradation –**1.5 %,** cf. -0.6 %
  - **Lower** RRR degradation – **23 %**, cf. 36 %

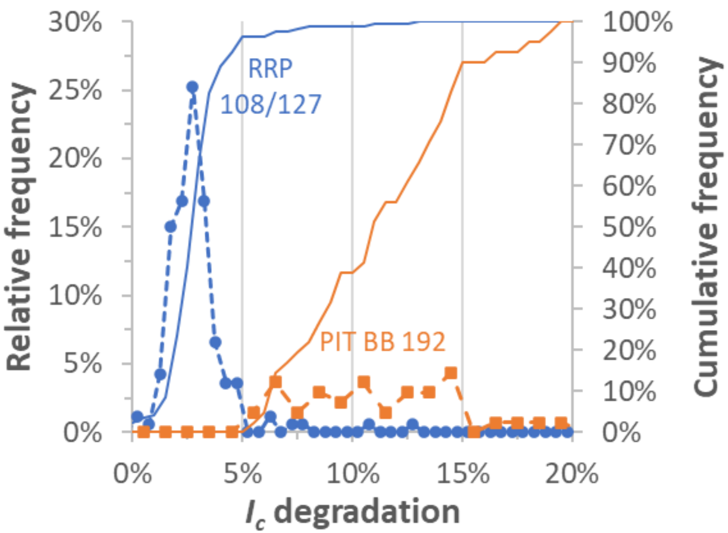


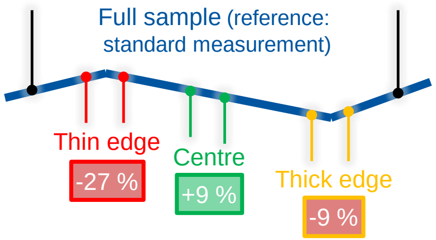


RRP® Cabling Degradation

- I_c degradation on cabling depends on the cable design
- Statistics available over HL-LHC MQXF production
- For RRP® 108/127, the **mean** I_c degradation is 2.8 % (cf. 5 % acceptance criterion)
  - For comparison, the corresponding value for PIT bundle-barrier wire is **11 %**
- I_c degradation **higher** than for 15 % rolling:
  - For RRP, comparable to a rolling reduction of ~**17.5 %**
- RRR degradation **16.9 %** on average, approximately **half** that of 15 % rolled samples
  - 15 % rolling reduction is larger than the compaction experienced across the majority of the cable width
  - Local degradation at cable edges is more severe, but averaged out for the usual test configuration

MQXF cable with 40 RRP® 108/127 strands)

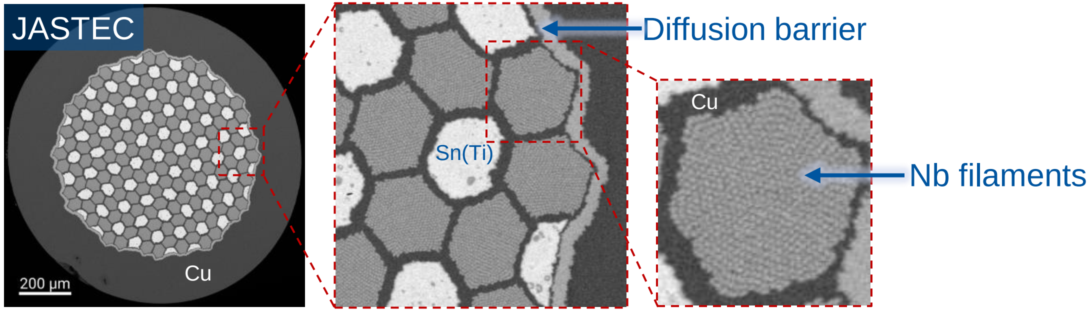


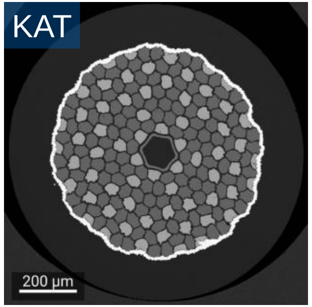


Schematic of voltage taps for local RRR measurement, and average relative values for two MQXF samples

R&D Wires: Distributed Tin (DT)

- Two manufacturers have developed ‘distributed tin’ wires in the scope of CERN collaborations:
  - JASTEC in collaboration with KEK and CERN (ICA-JP-0103 app. 19, 2016-2022)
  - KAT under collaboration KE3449 (2017-2022)



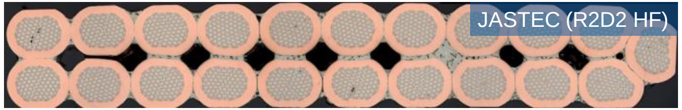


  - KAT’s designs have also included a copper core protected by an additional diffusion barrier

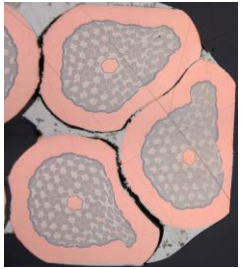
Supplier	*d* (mm)	Cu/non-Cu	Nb/Sn modules	Mean piece length (m)
KAT	1.0	0.93	138 + 54	1430
JASTEC	1.1	1.08	138 + 73	150

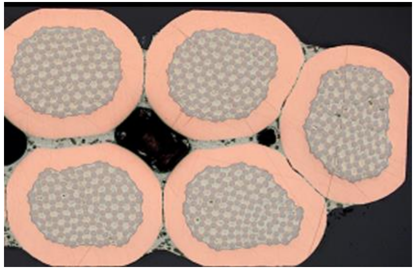
Distributed Tin Cabling Trials

Wire		Cable					
Supplier	*d* (mm)	Layout	Strands	Key-stone	Width (mm)	Mid-thickness (mm)	Core
KAT	1.0	FalconD	40	0.5°	20.95	1.8	14×0.025 mm 316L
JASTEC	1.1	R2D2 HF	21	None	12.579	1.969	None



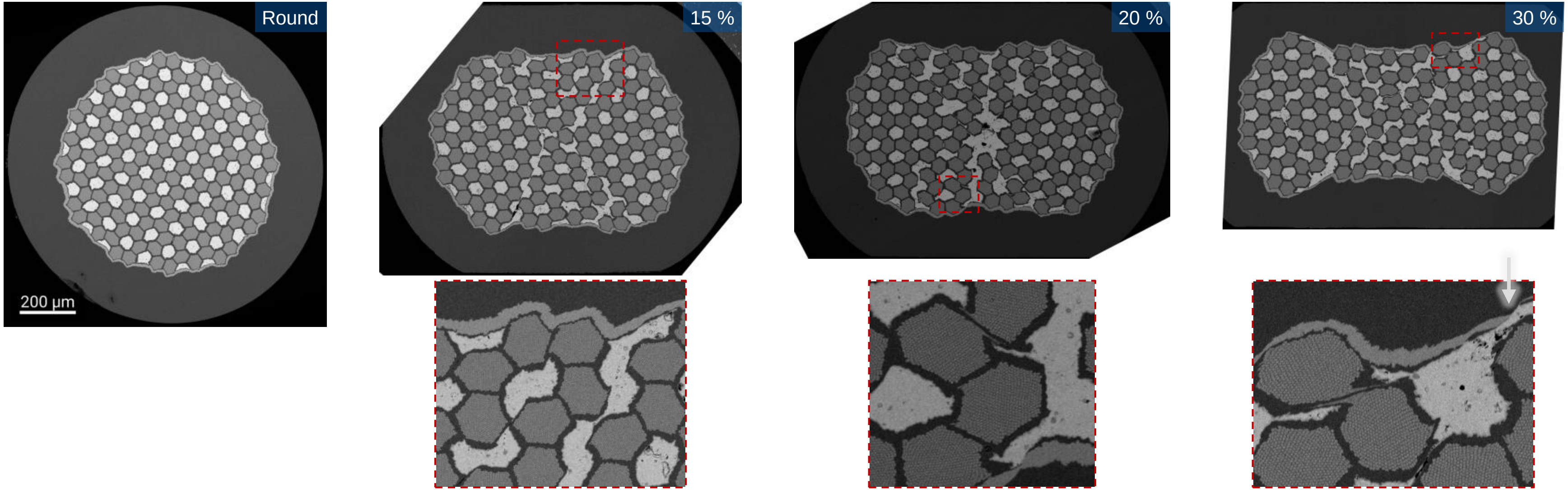
- Short trial cables successfully produced using cable designs established for magnet R&D activities
- Optical micrographs show, as expected:
  - Uniform strand cross-sections in the middle of the cable width
  - Significant distortion of module geometry and barrier thinning in the most deformed edge location





JASTEC DT Rolling: Key Features

- Sn regions deform and merge, whilst Nb modules are largely displaced intact



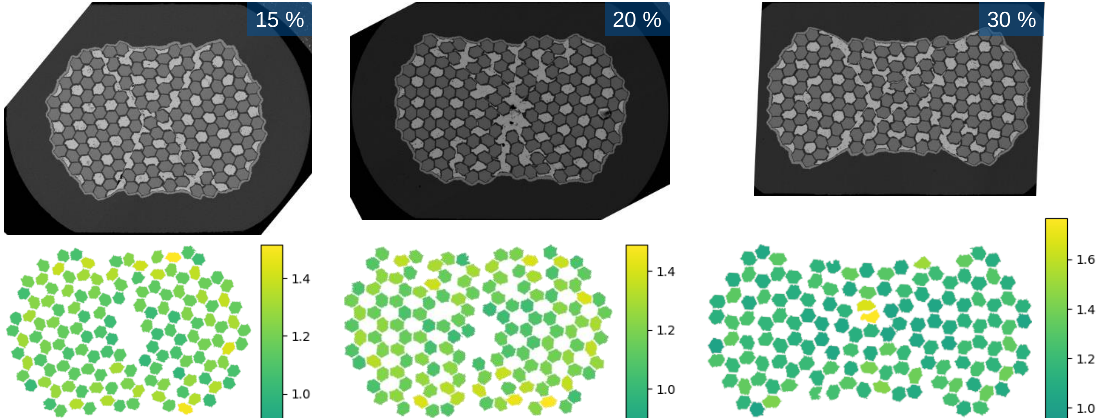
Relative displacement of Nb modules; Sn core merging

Shearing at periphery of Nb modules; barrier thinning

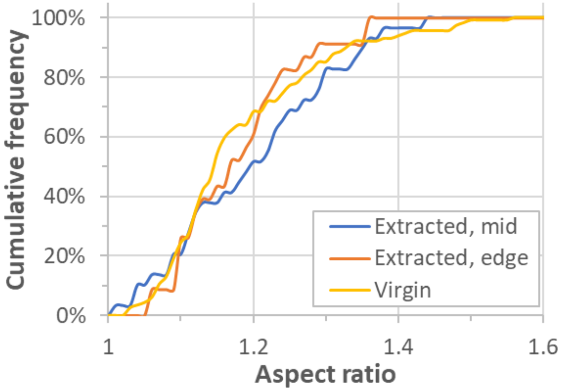
Barrier breakage, extended Nb module shearing

JASTEC DT: Aspect Ratios

- Aspect ratios do not show large increases, or form bands relative to the rolling direction:
  - Large variation in Nb modules between longitudinal positions, as broad Sn regions can open up locally

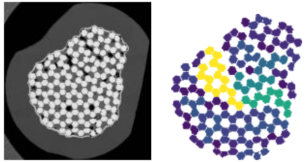


Distribution of aspect ratios of Nb modules before heat treatment



Aspect ratio distribution of well separated Nb_3Sn after heat treatment

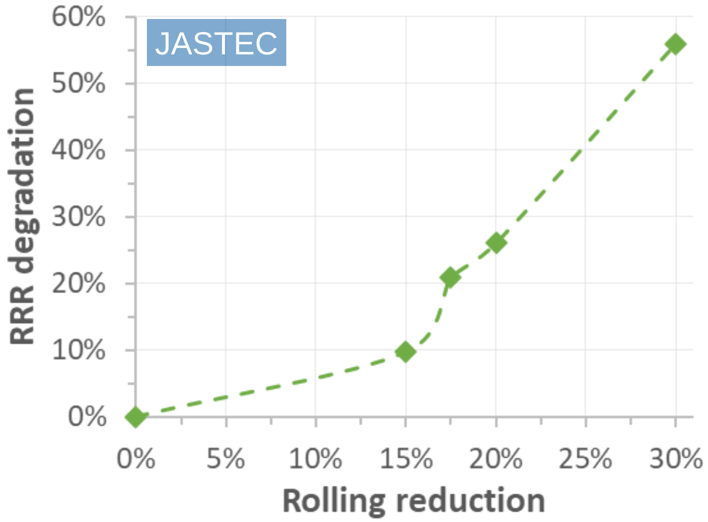
- After heat treatment, especially in cabled strands near the cable edge, the separation of some modules is small locally
  - Potential impacts for d_{eff} and stability
  - Nb_3Sn regions in contact excluded from aspect ratio statistics

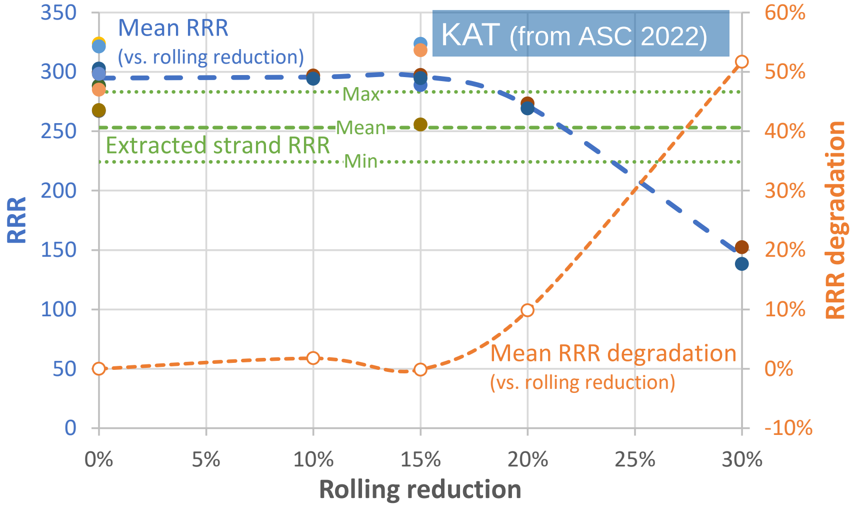


Reacted extracted strand cross-section at cable edge, and area distribution

DT RRR After Rolling/Cabling

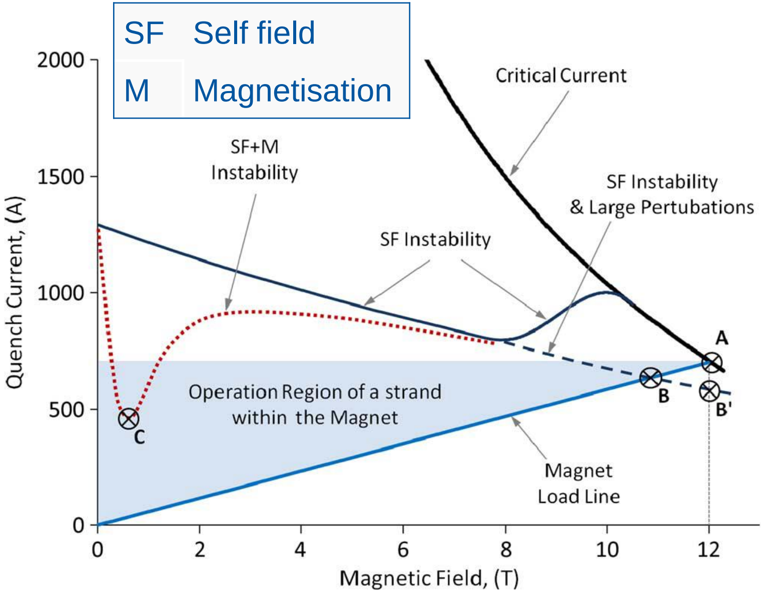
- The RRR of JASTEC and KAT rolled samples and extracted strands is extremely high due to the largely intact external diffusion barrier
  - RRR degradation reached ~50 % at 30 % rolling reduction for both JASTEC and KAT wire
  - RRR degradation appears a little higher at small rolling reductions for JASTEC, but few samples tested





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



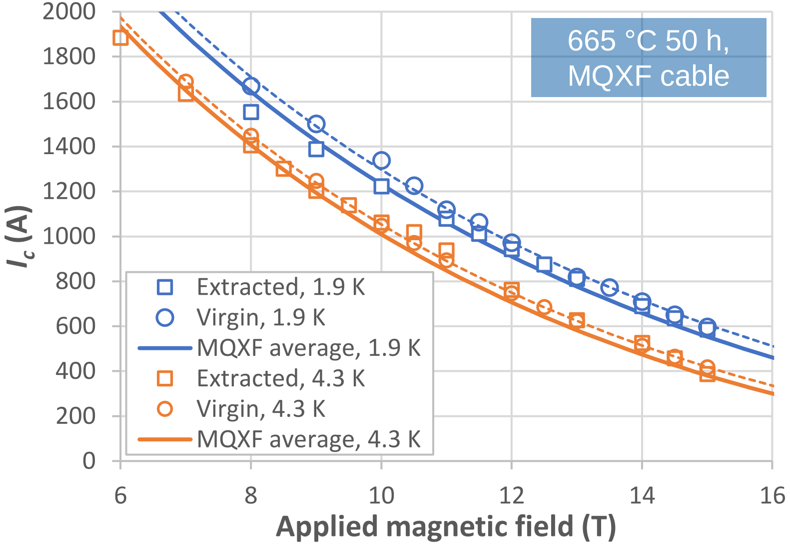
Bordini *et al.*, *IEEE Trans. Appl Supercond.* **22** (3) 4705804

Stability Testing

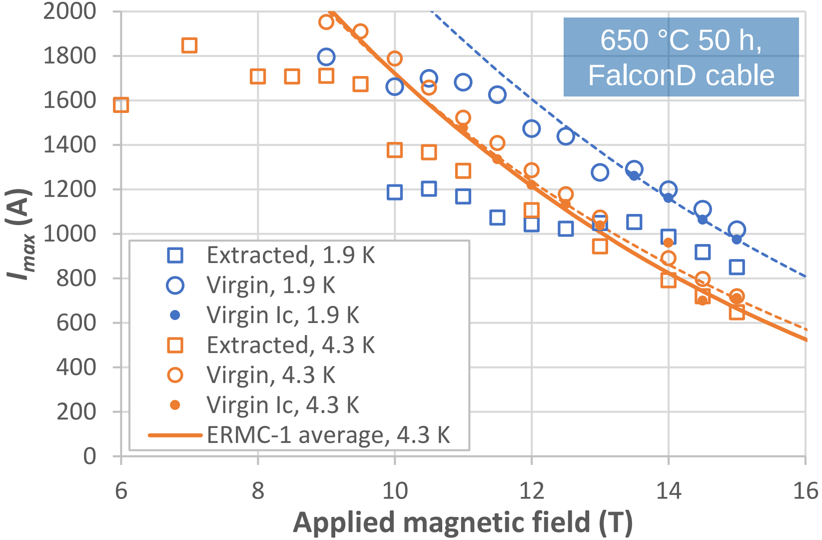
- Self-field stability being assessed by *V-I* transport measurements:
  - Starting with an applied field of 15 T, and decreasing in small steps, both at 4.3 K and 1.9 K
  - Multiple *V-I* measurements performed at each field step
    - **Average** quench current or I_c presented in following plots without self-field or temperature corrections
  - Maximum current ~2000 A
- To be complemented by:
  - *V-H* measurements – plans under consideration
  - Magnetisation data – VSM at CERN; benchmarking and measurement over expanded magnetic field range planned with collaborating institutions
  - Laser and thermally induced perturbations of controlled energy – PhD student (Joanna Kuczynska) project, equipment commissioning in progress

Stability of RRP® Wire

- MQXF (108/127 0.85 mm)



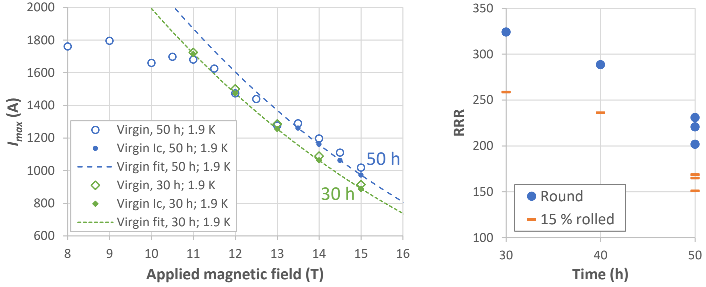
- ERMC-1 (162/169 1.0 mm)



- Comparison of two RRP® wires with differences in stability behaviour after their standard heat treatments
  - No premature quenches for MQXF wire and extracted strands
  - Stability limitations for ERMC-1: intersection of 1.9 K and 4.3 K curves at ~10 T and ~12.5 T for virgin and extracted strand

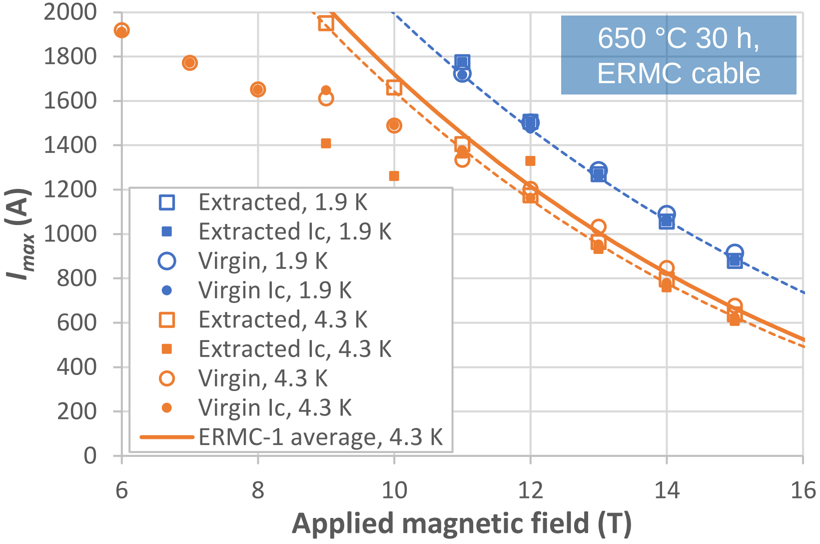
HT Optimisation for RRP® Stability

- Constraints on heat treatment optimisation:
  - Reducing temperature from an already low 650 °C risks decreasing B_{c2} and approaching the strain irreversibility cliff
  - Compromise for J_c and RRR
- 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
  - Reduction of ~9 % in I_c, with ~50 % increase in RRR: further fine-tuning possible and in progress



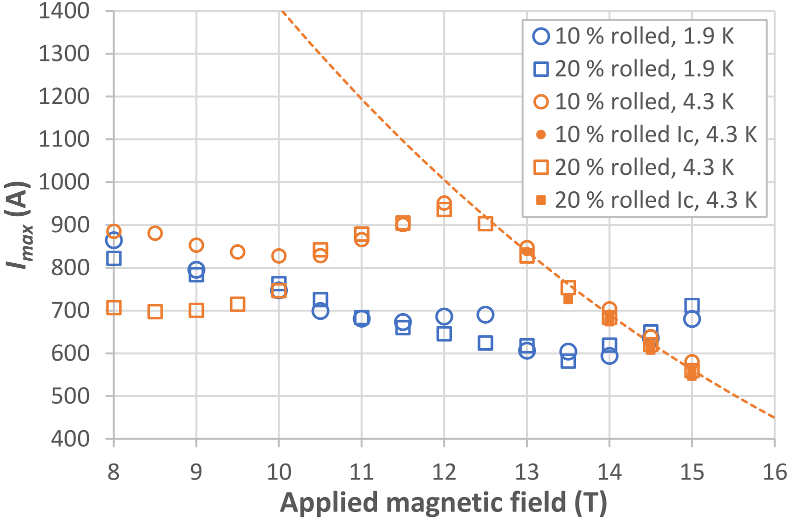
- Currently obtaining additional statistics for the wire and cable types of current interest

- ERMC-1 (162/169 1.0 mm)

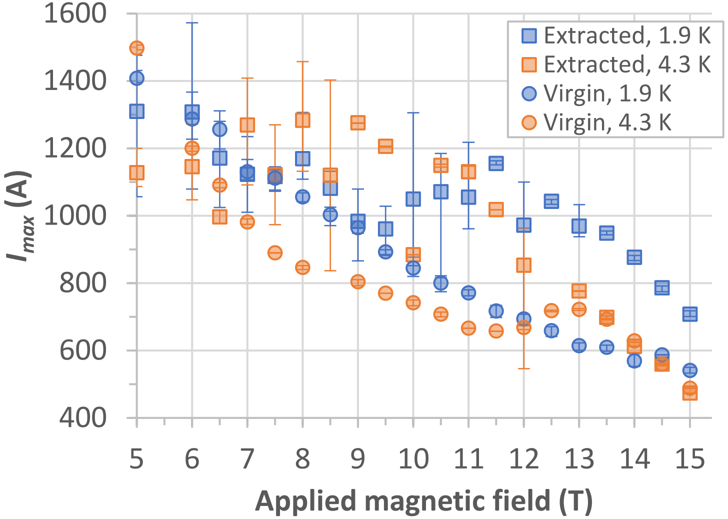


DT Wire Stability

- KAT (1.0 mm)



- JASTEC (1.1 mm)



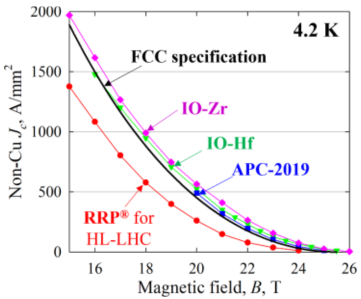
- Initial results for the stability of different DT wires show differences in behaviour, but a need for optimisation in both cases
  - Testing of additional samples and magnetisation measurements in progress

Prospects for DT

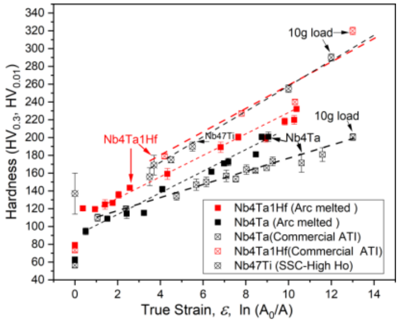
- Distributed tin wires are less fully characterised than established RRP® wires for the universal challenges (stress behaviour, cabling degradation, heat treatment optimisation), and have some specific challenges, notably:
  - Magnetothermal stability
  - Effect of separation of Nb modules during deformation to be assessed
  - Increasing piece length (JASTEC)
- …but initial results are promising:
  - J_c achieved interim target (comparable to HL-LHC specification)
  - Low geometrical distortion of Nb_3Sn sub-elements on rolling/cabling
  - Where measured, low cabling degradation of I_c and RRR
- Further development towards industrialisation under consideration

Higher J_c: Hf, Internal Oxidation

- A significant increase in J_c (relative to the RRP® baseline) expected to need new approaches:
  - Hf alloying was proposed to cause Nb_3Sn grain refinement by suppressing Nb alloy recrystallisation (NHFML, FSU, US)
    - S. Balachandran et al., *Supercond. Sci. Technol.* **32** 044006 (2019)
  - Internal oxidation of Zr or Hf in Nb alloys forms oxide precipitates, acting as pinning centres and refining Nb_3Sn grain sizes
    - X. Xu et al., Appl. Phys. Lett. **104** (8) 082602 (2014)
- Internal oxidation has been implemented in both PIT and internal tin wire types
  - The hardening behaviour of Hf-alloyed Nb-Ta poses some challenges in wire drawing, and potentially also in subsequent cabling
- PIT wires produced at Hyper Tech (in collaboration with Fermilab and OSU) have shown excellent J_c, but:
  - Limited validation of stability and cabling behaviour
  - Optimisation challenges similar to conventional Bruker PIT wires may apply
- Rod-in-tube wires are under development at UNIGE in collaboration with CERN
  - A similar J_c enhancement has been observed in model samples, and wire development is in progress – see G. Bovone, WP1.3
  - Collaborative FIB (EN-MME) and TEM analysis
- Possibilities for wire development towards higher J_c and for reinforcement under consideration



X. Xu et al., *Supercond. Sci. Technol.* **36** 035012 (2023)



S. Balachandran et al., https://dx.doi.org/10.2139/ssrn.4303410

Transverse Stress and RRP® Selection

- Effect of transverse stress applied at room temperature under study in CERN:
  - FRESCA measurements and analysis of cracking as a function of stress in progress for MQXF cable (Kirtana Puthran)
- Comparison of alternative RRP® wire layouts at 1.0 mm diameter (from previous procurement/stock) to support wire selection for 14+ T activities
  - Stability testing
  - Mould design/fabrication is in progress in preparation for crack analysis and FRESCA measurement
- Measurements with longitudinal strain and with transverse stress also in progress in UNIGE
  - R&D distributed tin wires
  - 1.0 mm RRP® wires

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  - All members of TE-MSC-LSC involved in cabling, sample preparation and testing of the wires in buildings 103 and 163 at CERN

- More details:
  - Design Optimization, Cabling and Stability of Large-Diameter High J_c Nb_3Sn Wires:

    - S. C. Hopkins, B. Medina-Clavijo, C. Barth, J. Fleiter and A. Ballarino, *IEEE Trans. Appl. Supercond.* **33** (5) 6000609, doi: 10.1109/TASC.2023.3254497
    - https://indico.cern.ch/event/1218461/#2-design-optimisation-cabling

  - Deformation Behaviour and Cabling Degradation of Nb_3Sn Wires:

    - https://indico.cern.ch/event/1329522/#1-deformation-behaviour-and-ca