Analysis of FCC Nb_3Sn Conductors at CERN

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Acknowledgements:

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JASTEC, Kobe Steel

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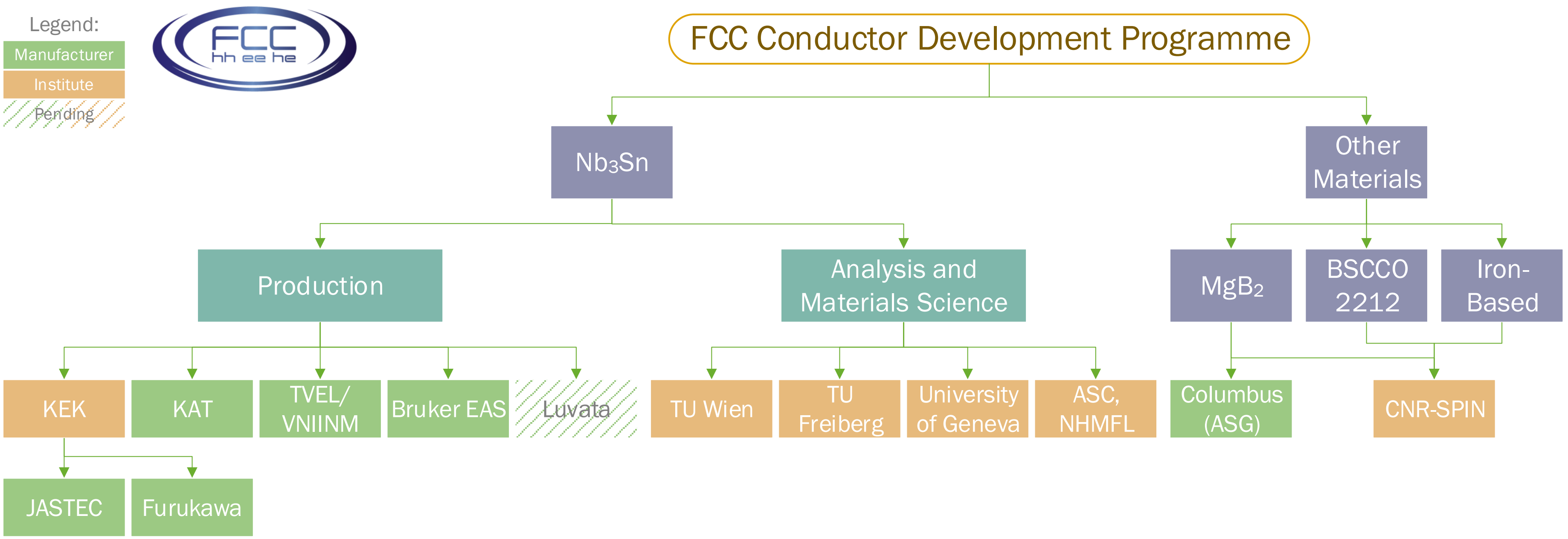
TVEL, VNIINM

Conductor Development Programme

- Established to develop wires meeting magnet requirements for the proposed FCC-hh
  - 100 TeV, 100 km, 16 T dipole magnets



Nb_3Sn Development Targets

- **Aim:** to achieve the following targets with proven scalability to long-length production

Parameter	Ultimate Target
Wire diameter / mm	~1
Cu:non-Cu ratio	~1
Non-Cu J_c (16 T, 4.2 K) / A mm^{-2}	≥ 1500
$\mu_0 \Delta M$ (1 T, 4.2 K) / mT	≤ 150
d_{eff} / µm	≤ 20
RRR	≥ 150
Unit lengths / km	≥ 5
Cost	5 EUR / kA m

1500 A/mm^2 at 16 T requires a significant increase over HL-LHC

Nb_3Sn Targets: Stage 1

- Initially, support additional manufacturers in achieving the HL-LHC wire specification

Parameter	Ultimate Target	Stage 1: HL-LHC
Wire diameter / mm	~1	~1
Cu:non-Cu ratio	~1	~1
Non-Cu J_c (16 T, 4.2 K) / A mm^{-2}	≥ 1500	≥ 1000; aim 1200
$\mu_0 \Delta M$ (1 T, 4.2 K) / mT	≤ 150	
d_{eff} / µm	≤ 20	≤ 60
RRR	≥ 150	≥ 150
Unit lengths / km	≥ 5	
Cost	5 EUR / kA m	

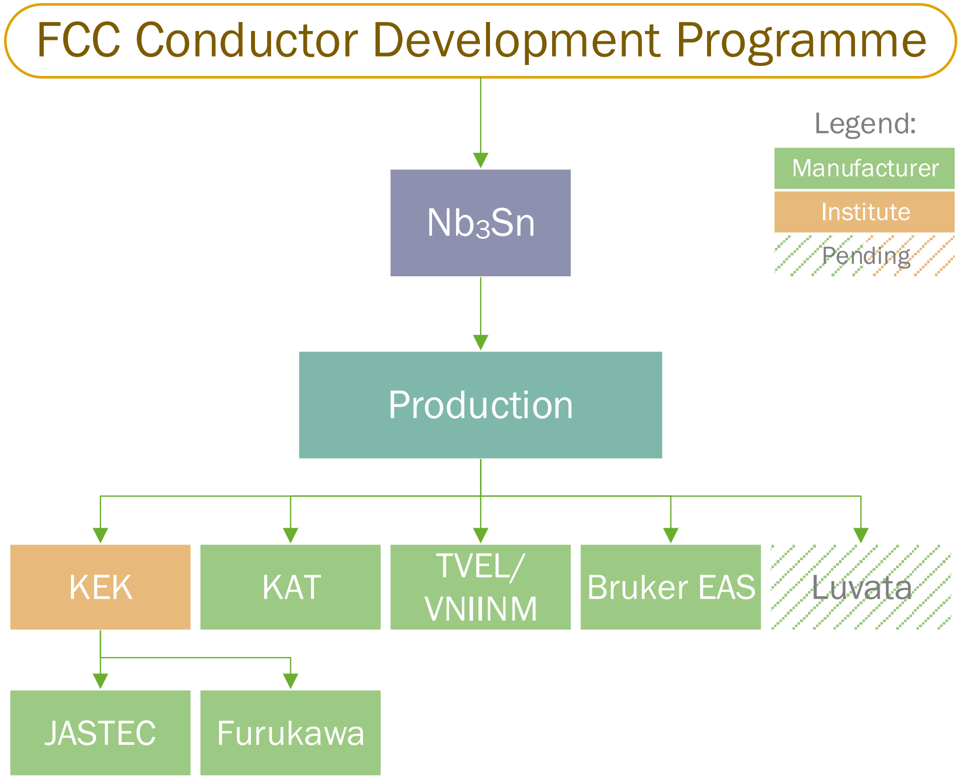
Nb_3Sn Targets: Stage 2

- Then focus on increasing J_c

Parameter	Ultimate Target	Stage 2
Wire diameter / mm	~1	~1
Cu:non-Cu ratio	~1	~1
Non-Cu J_c (16 T, 4.2 K) / A mm^{-2}	≥ 1500	≥ 1500
$\mu_0 \Delta M$ (1 T, 4.2 K) / mT	≤ 150	
d_{eff} / µm	≤ 20	≤ 60
RRR	≥ 150	≥ 150
Unit lengths / km	≥ 5	
Cost	5 EUR / kA m	

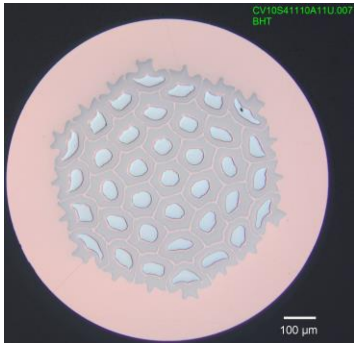
Nb_3Sn Wire Development

- This presentation:
  - Focus on CERN analysis of industrially produced wire
- 5 manufacturers:
  - TVEL: VNIINM (Bochvar Institute)
  - Kiswire Advanced Technology (KAT)
  - JASTEC
  - Furukawa
  - Bruker EAS

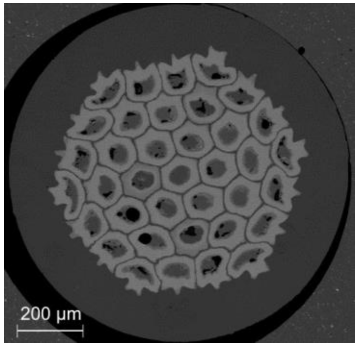


TVEL/Bochvar Institute (VNIINM)

- 2016-7 development concluded with 12 km trial production of distributed barrier wire



Optical, unreacted



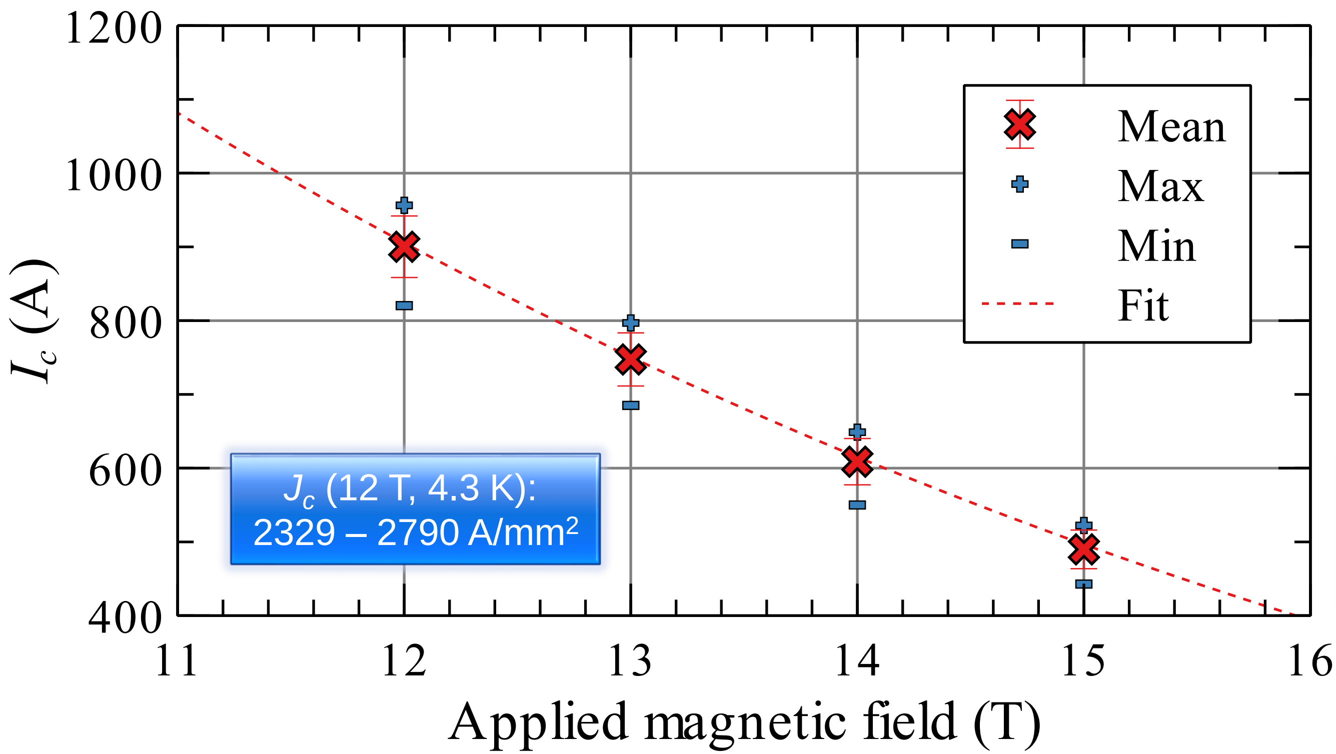
SEM, reacted

Diameter (mm)	1.0
Cu/non-Cu	1.2 (defined for HL-LHC)
Sub-elements	37 (ϕ 107–112 µm)
Diffusion barriers	Distributed, Nb
Delivered	12 km, end 2017

  - First results presented at FCC Week 2018
  - Characterised and cabled at CERN (next slides)
- New development started 2019 ➡ V. Pantsyrny

TVEL: I_c Performance

- 12 km of ϕ 1 mm wire, mean piece length > 1 km
  - Non-Cu J_c > 1100 A/mm^2, RRR ~ 250, d_{eff} ~ $d_{sub\text{-}element}$

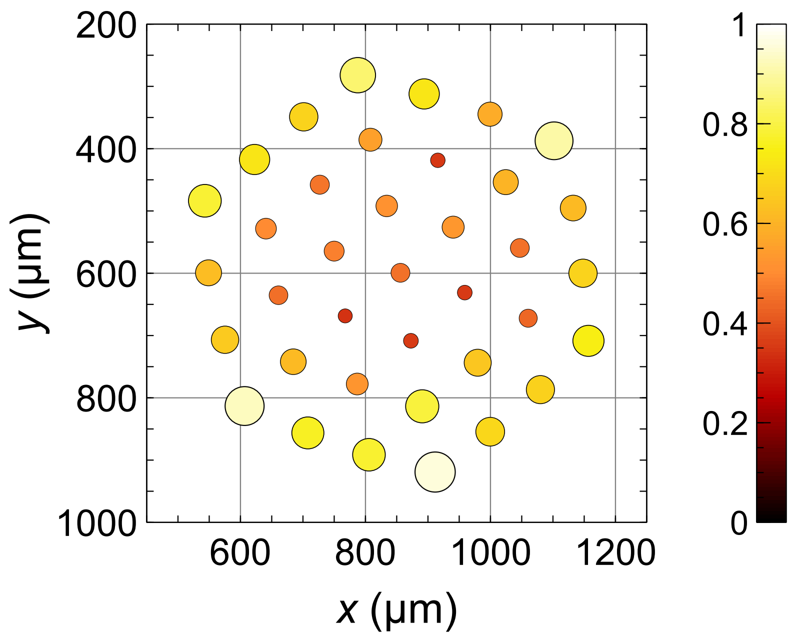


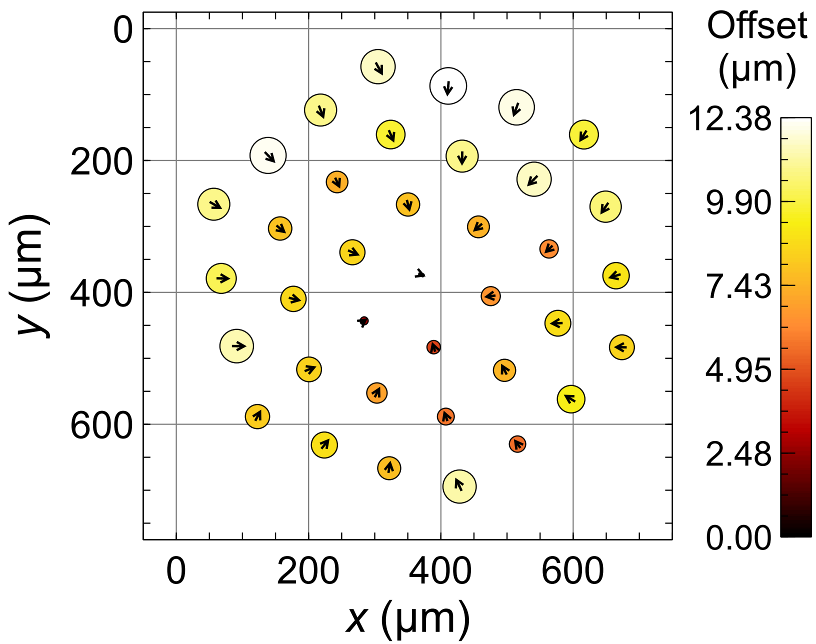
Variation in I_c between piece lengths measured at CERN (4.3 K)

Best scaled J_c (16 T, 4.2 K): 1140 A/mm^2

TVEL: Geometrical Analysis

- Analysis of sub-element distortion in round wire: core/sub-element shape and positions





Non-uniformity
Core and sub-element distortion (0 = perfect)

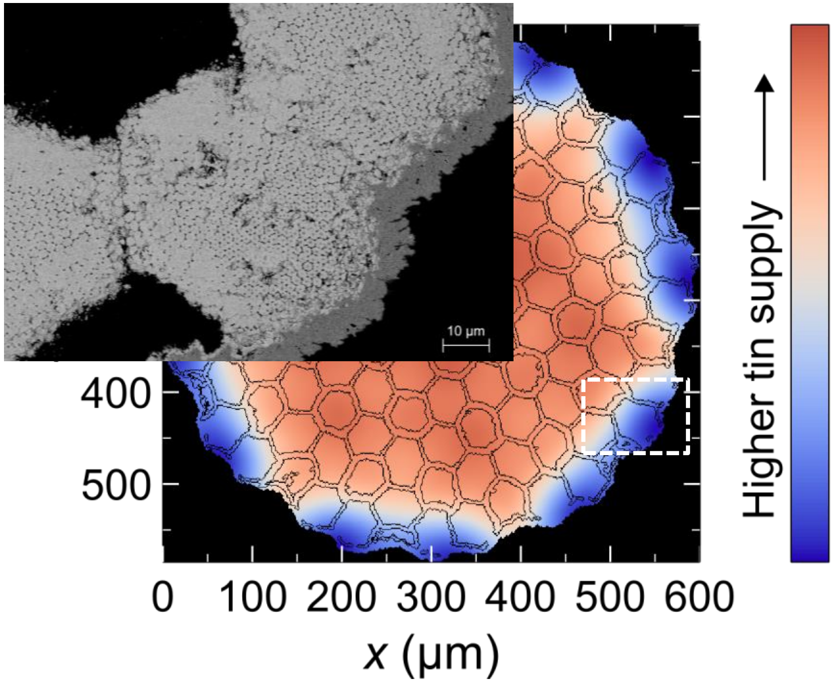
Centroid shift
Between sub-element and core

Tin Supply: Source-Sink Analysis

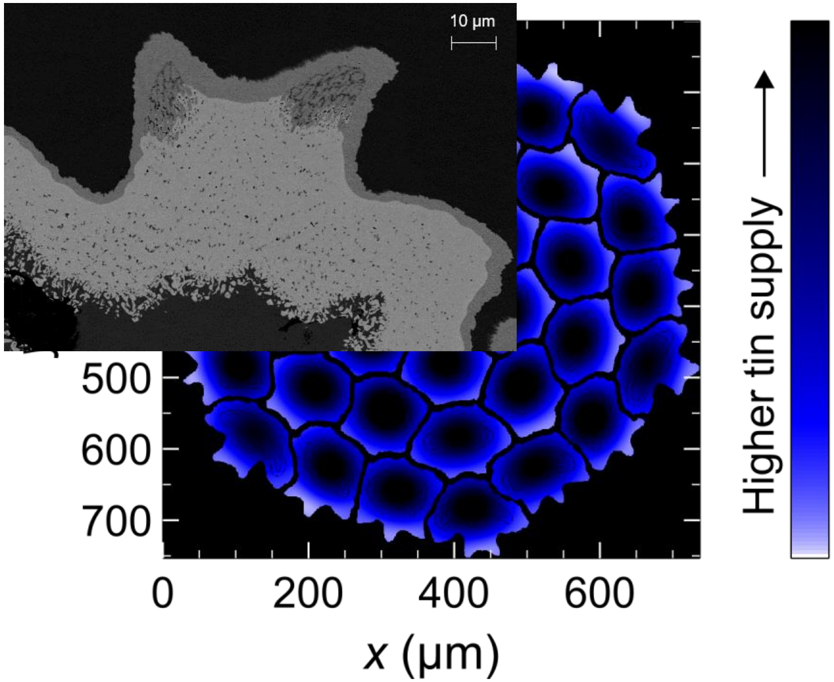
- Weighted sum over point sources (Sn) and sinks (Nb)

$$\Omega = w_1 \sum_i^{Sn} \exp(-kr_i^2) - w_2 \sum_i^{Nb} \exp(-kr_i^2)$$

JASTEC (across the wire)

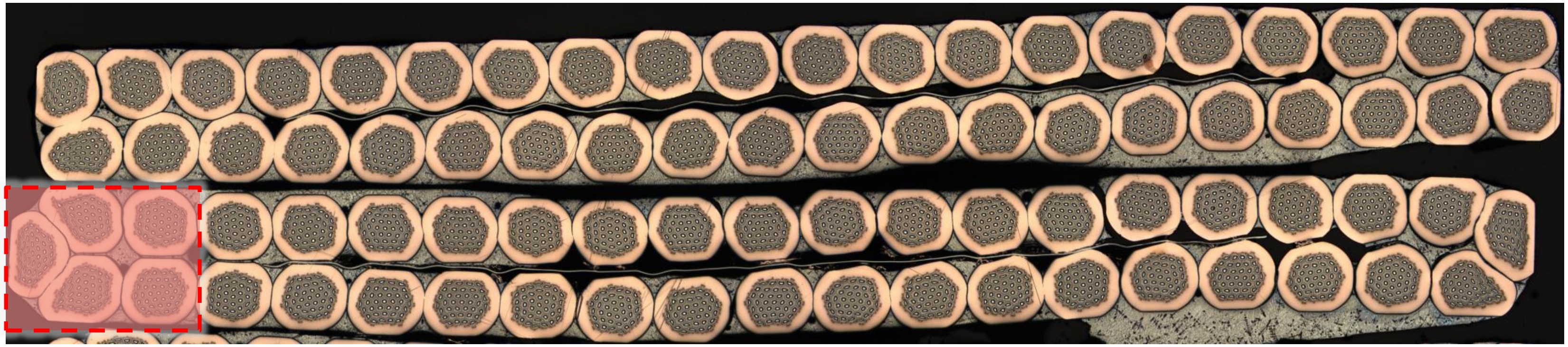


TVEL (within sub-elements)



TVEL: Cabling Trials at CERN (1)

- 50 m trial Rutherford cable produced:
  - 40 × 1 mm strands, SS core, ERMC geometry
  - Produced with 4 spools from 2 billets

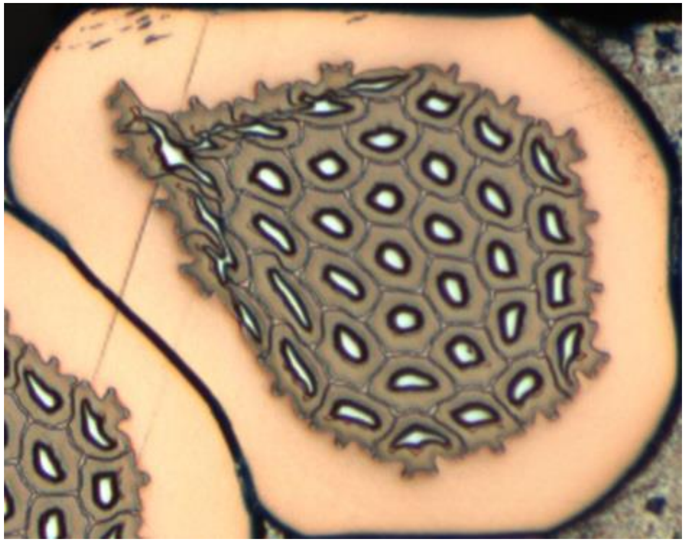


Two cross-sections of the trial cable, showing positions with more and less strand deformation

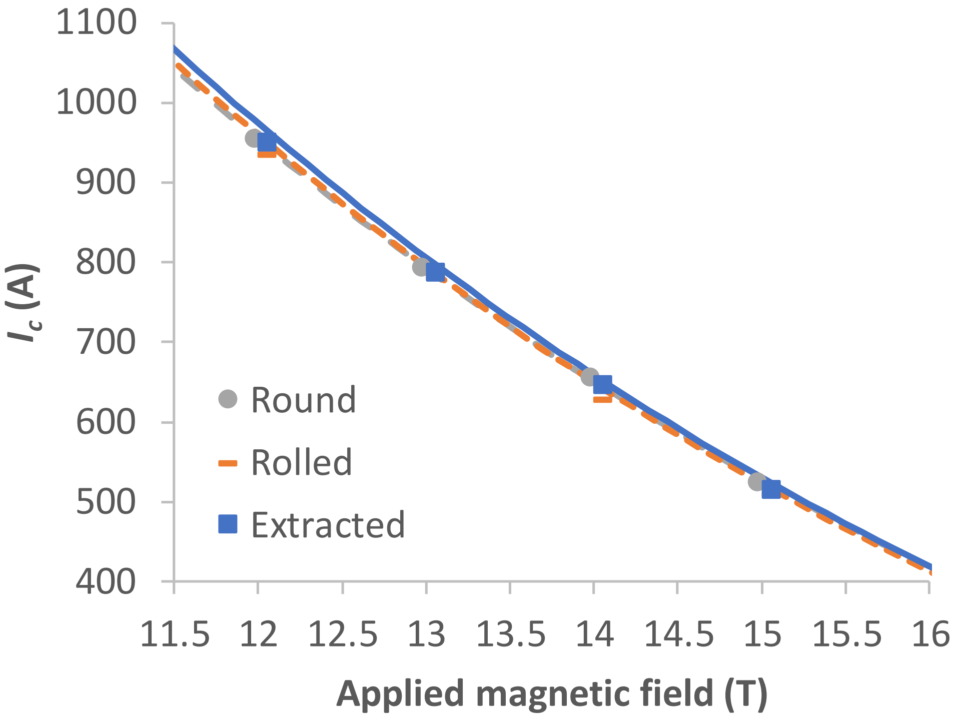
- Rolling test also performed (15% reduction)

TVEL: Cabling Trials at CERN (2)

- No degradation of I_c on cabling or rolling
  - …but damage to sub-elements at most deformed sites



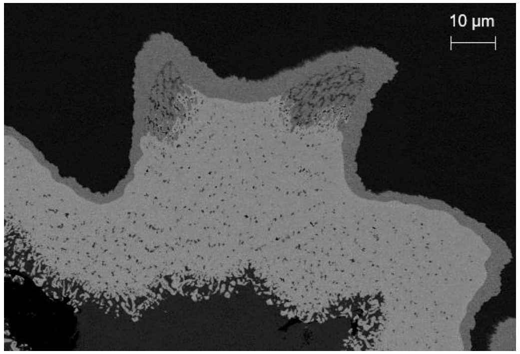
Cabled strand cross-section



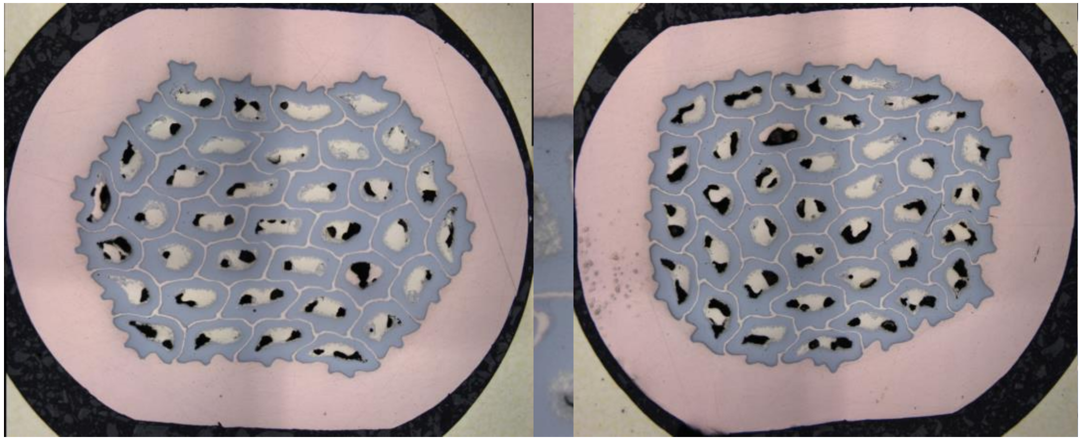
I_c at 4.3 K for round wire, a 15% rolled sample and an extracted cable strand

TVEL: Impact of Irregular Geometry

- Irregularly shaped peripheral sub-elements:
  - Incomplete reaction → opportunities for increasing J_c
    - Improved geometry under development in new addendum
  - Susceptible to barrier damage after cabling
    - RRR to be confirmed



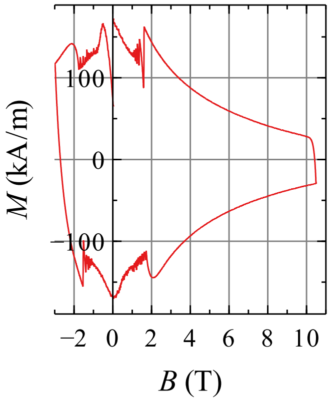
SEM (BEI) of a peripheral sub-element after reaction in round wire



Optical micrographs of rolled and cabled strands

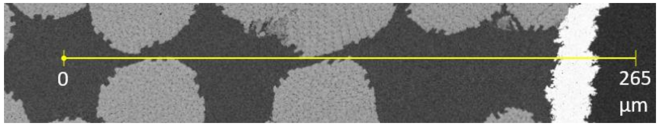
KAT

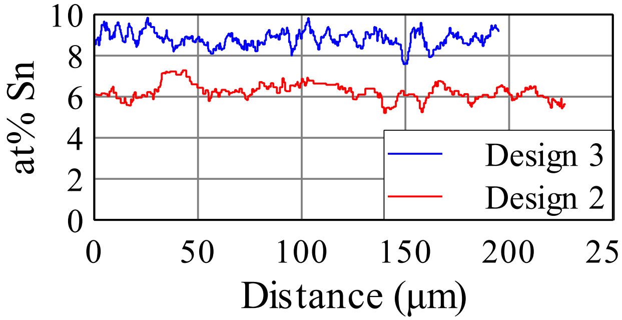
- Common Ta barrier wires with distributed Sn-Ti
- First trial: J_c (16 T, 4.2 K) > 1000 A/mm^2, but:
  - d_{eff} > 74 µm, cf. d_{Nb} of 44.2 µm



VSM data, 4.2 K (CERN)

  - High residual Sn content
    - Potential to increase Nb, shorten heat treatment





Radial Sn composition profiles in the Cu-Sn matrix after reaction (EDX)

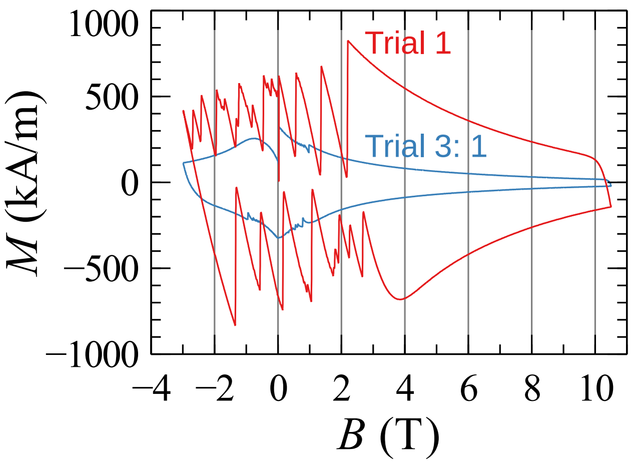
- Latest trials: J. Kim
  - Reduced d_{eff}, and scale-up to long lengths:
    - 6 km delivery imminent

JASTEC

- Developing distributed tin (DT) wires in a joint CERN-KEK Japanese programme
- Since the promising trial 1 wires presented at FCC Week 2018, trial 3 has achieved:
  - J_c (16 T, 4.2 K) of 1000–1100 A/mm^2
  - d_{eff} reduced from 267 → 55 µm

  in piece lengths > 100 m
- New trials in progress

T. Ogitsu

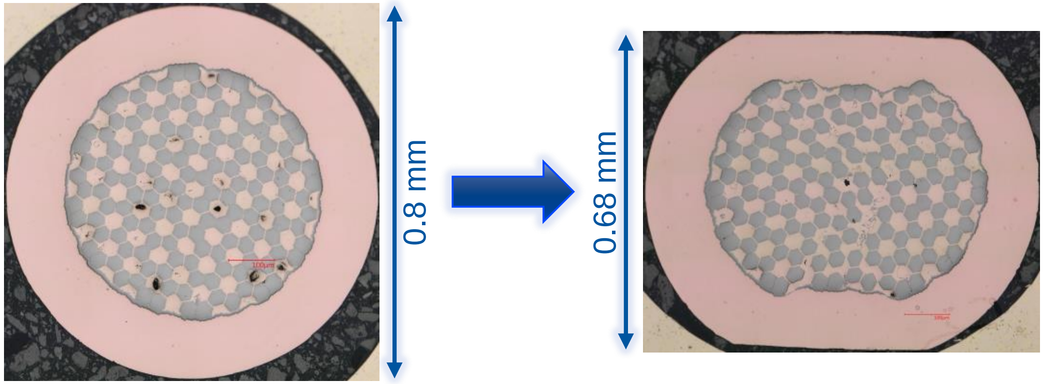


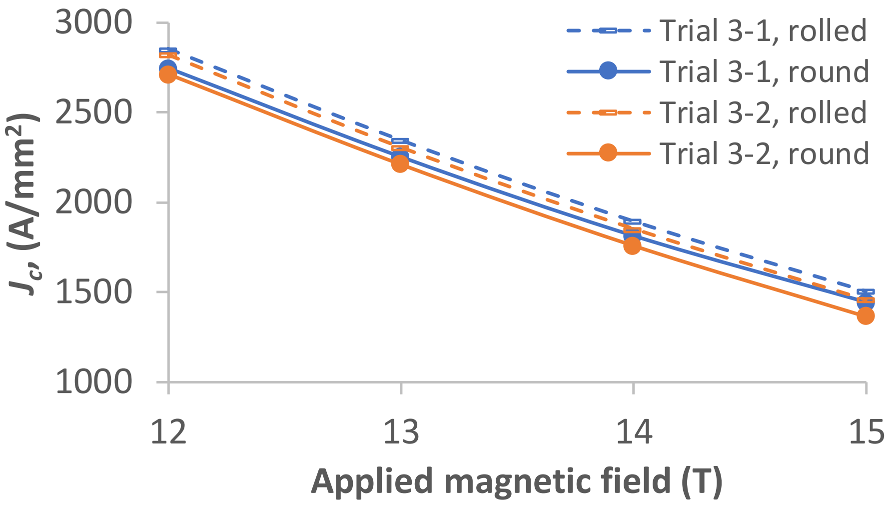
Magnetization measurements (VSM, 4.2 K) for trial 1 (ϕ 0.7 mm) and trial 3: 1 (ϕ 0.8 mm) samples

JASTEC: Rolling Trials at CERN

- 15% rolling test to assess suitability for cabling
  - No I_c degradation
    - ~5% increase
  - RRR > 150

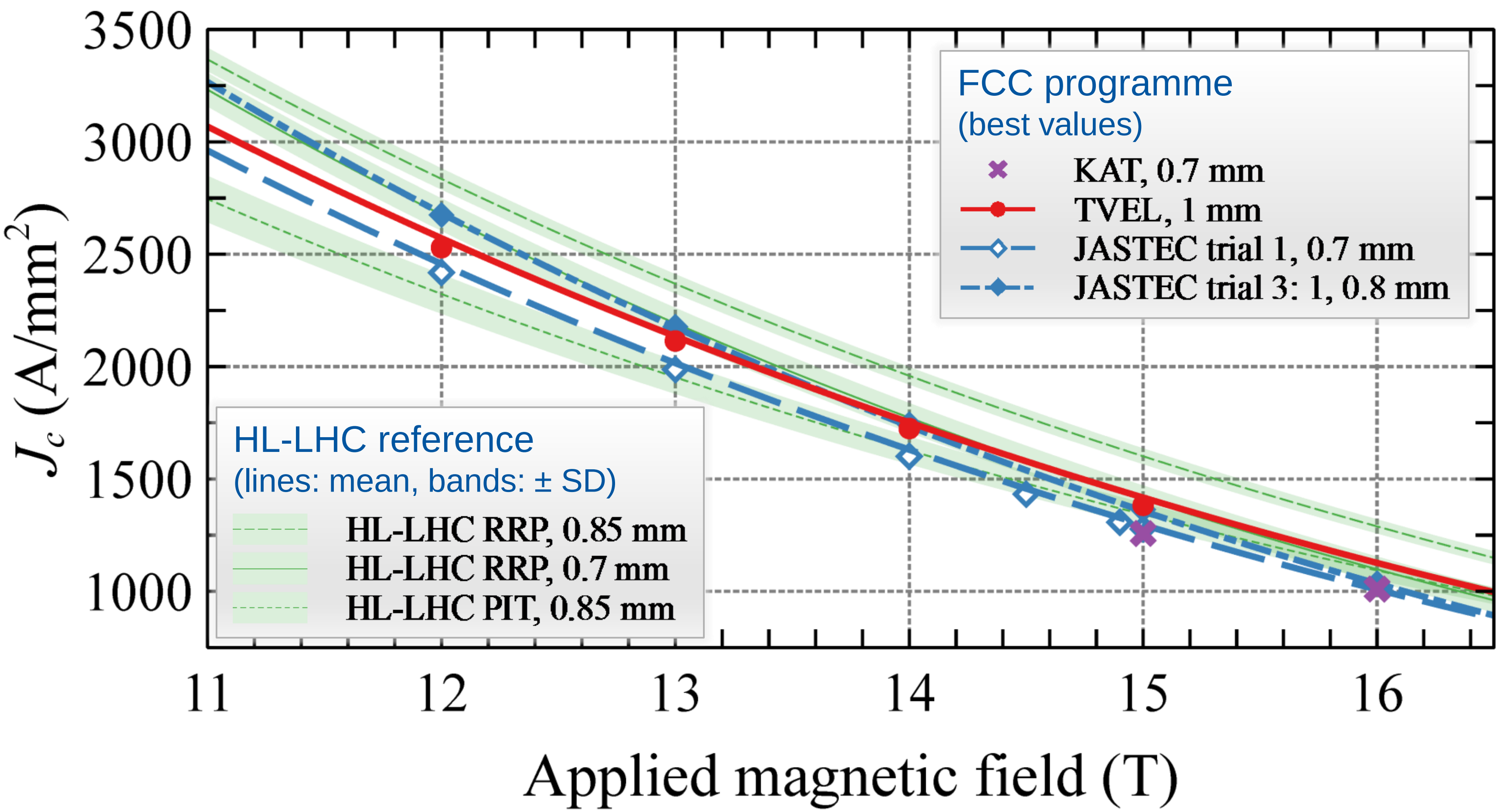
→ Meets HL-LHC specification for rolling behaviour





Non-Cu J_c values for trial 3 samples, round and after 15% rolling

J_c Summary



Summary of non-Cu $J_c(B)$ achieved so far, with HL-LHC wires for comparison
Points: measurements at 4.2–4.3 K   Lines: fits scaled to 4.22 K

Conclusions and Next Steps

- So far:
  - Interim J_c target achieved
  - Initial cabling trials successfully completed
  - Wire development supported by analysis at CERN and by academic partners
- Routes towards the J_c target identified:
  - Extremely promising reports for Nb-Ta-Hf alloys and internal oxidation
  - Multifilamentary wires implementing these methods are expected for analysis in the next year

Acknowledgements

- Wire development partners who provided the samples reported here

M. Sugano, T. Ogitsu KEK	S. Kawashima, K. Saito, Y. Fukumoto JASTEC, Kobe Steel
I. Shin, J. Kim KAT	V. Pantsyrny, I. Abdyukhanov, M. Shlyakov, S. Zernov TVEL, VNIINM

- Colleagues at CERN

Wire testing	Microscopy	Analysis
P. Jacquot, M. Malabaila and the personnel of labs 163 and 103	A. T. Perez Fontenla and colleagues	A. Canós Valero
TE-MSC-SCD	EN-MME-MM	TE-MSC-SCD