SUPERCONDUCTING DETECTOR MAGNET WORKSHOP

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Development of Advanced Stabilized Superconductor (Part 2)

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Outline

- **Context: next generation HEP detector magnet**
- **Scope of the study**
- **The ATLAS-CS conductor**
- **Manufacturing process**
- **Results**
- **Conclusion and further works**

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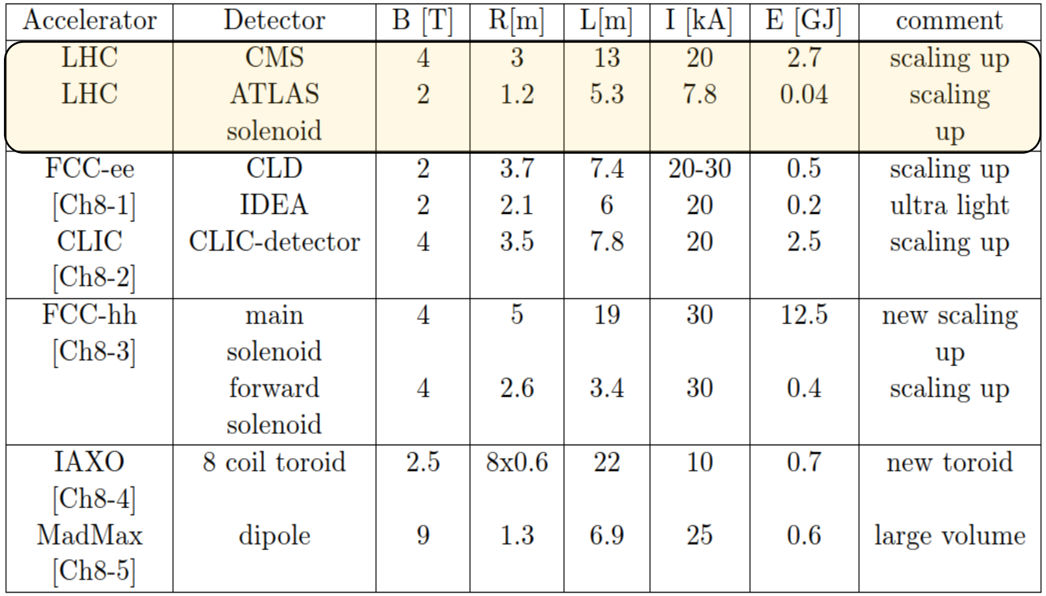
Context: next generation HEP detector magnet

Next detector magnets for collider and non-collider experiments (list non-exhaustive):

- **Thin coils** within the calorimeter volume, as transparent as possible for particles.
- **Large coils** with high stored energy and magnetic forces

All future coils need the use of **aluminum reinforced conductors.**

High purity aluminum stabilizer alone cannot be used (yield strength ~ 30MPa at 4K)



Accelerator	Detector	B [T]	R[m]	L[m]	I [kA]	E [GJ]	comment
LHC	CMS	4	3	13	20	2.7	scaling up
LHC	ATLAS solenoid	2	1.2	5.3	7.8	0.04	scaling up
FCC-ee [Ch8-1]	CLD	2	3.7	7.4	20-30	0.5	scaling up
	IDEA	2	2.1	6	20	0.2	ultra light
CLIC [Ch8-2]	CLIC-detector	4	3.5	7.8	20	2.5	scaling up
FCC-hh [Ch8-3]	main solenoid	4	5	19	30	12.5	new scaling up
	forward solenoid	4	2.6	3.4	30	0.4	scaling up
IAXO [Ch8-4]	8 coil toroid	2.5	8x0.6	22	10	0.7	new toroid
MadMax [Ch8-5]	dipole	9	1.3	6.9	25	0.6	large volume

Table 8.1: Examples of magnets for future experiments that represent the engineering and R&D challenges. The dimensions and fields refer to the free bore. The magnets for ATLAS and CMS are given for reference.

Source ECFA DRD Roadmap 2021

Scope of the study

→ **Reinforced aluminum stabilized NbTi/Cu superconductor.**

Baseline designs of future large magnet detectors benefit from the previous manufacturing breakthroughs of the CMS solenoid and the Atlas Central Solenoid (CS).

Example for CLICdet: a large conductor

→ **3 baseline options:**

a/ CMS-like:

High purity aluminium stabilizer

\+ Electron beam welded aluminum alloy profiles

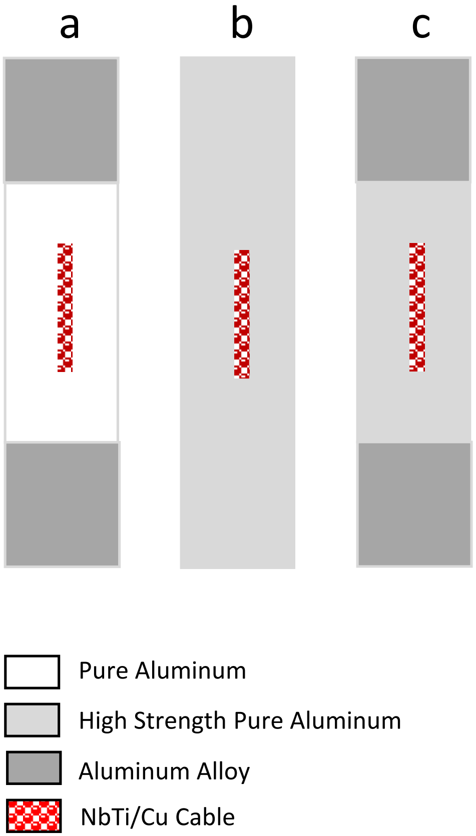
b/ ATLAS-CS like:

High strength stabilizer

\+ Cold working

c/ both a and b:

High strength stab. + cold work + EBW (Al alloy section may be smaller than in option a)



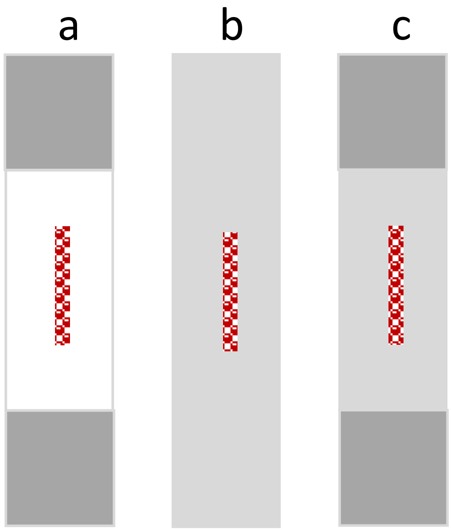
Scope of the study

Mechanical stress-strain for CLICdet

Option a compared to b and c

a: reinforcement in the elastic domain (CLICdet: σ_{eq}=150MPa), pure aluminium at 0.15% hoop strain in elasto-plastic domain (pure aluminum : yield strength ~ 30 MPa at 4K)

b & c: entire conductor cross section works in elastic domain (CLICdet: σ_{eq}=82 MPa, hoop strain : 0.08%).



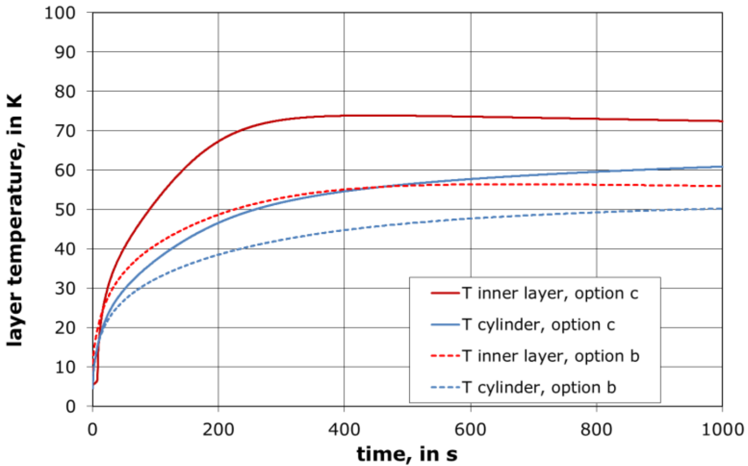
Quench protection for CLICdet

With a large cross-section (option b compared to c)

- Current density in stabilizer is smaller,
- The resistance increase in the coil is smaller

➢ less energy dissipation in the coil:

- **lower temperature post-quench** (CLICdet: 56K vs 74K),
- **smaller temperature gradients** (CLICdet: 11K vs 21K).



FD on 30 milli-ohm; RRR=590

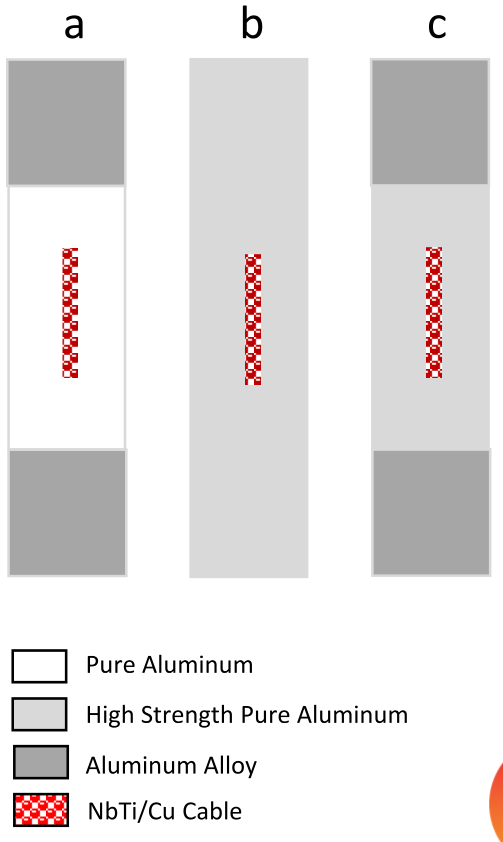
Scope of the study

Comparison of co-extruded conductor cross section for CLICdet options:

CMS (5N Al): 30 x 24 mm^2
Atlas BT (5N Al): 57 x 12 mm^2
Atlas CS (High Strength): 30 x 4.3 mm^2

Options a and c: 42.7 x 20.3 mm^2,
Option b: 82.8 x 20.3 mm^2

- New conductor have larger cross section, in particular for the high strength stabilizer option.



The study was led to investigate the feasibility of manufacturing a conductor with:

- **a high strength stabilizer,**
- **using the same material as the Atlas-CS conductor,**
- **with larger dimensions than the Atlas-CS conductor,**

A short prototype length was manufactured to characterize the properties that can be obtained.

The ATLAS-CS conductor

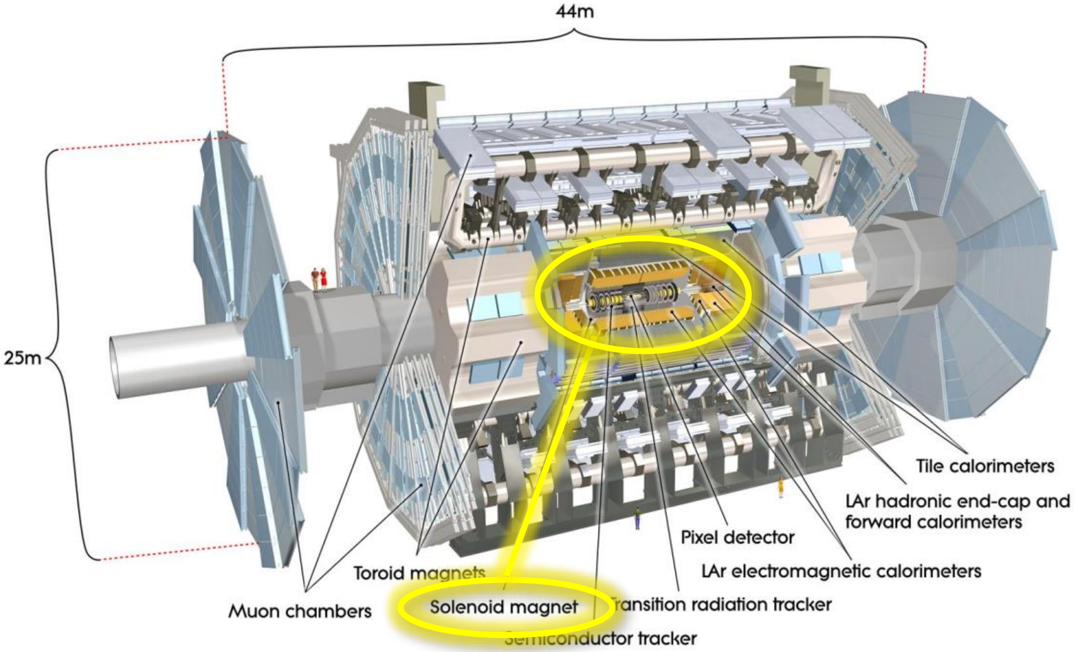
ATLAS Central Solenoid: designed by KEK, Japan

REF: A. Yamamoto et al., The Atlas Central Solenoid, Nucl. Instrum. Methods Phys. Res., A 584 (2008) 53-74

- 2.5-m inner diameter, 5.3-m long solenoid providing a 2-T field.
- Located inside the calorimeter: very thin magnet transparent to traversing particles.

The solenoid coil was manufactured by **Toshiba Corporation**, together with the radiation shields, chimney, vacuum vessel and control Dewar;

Final inner vacuum vessel was manufactured by **Kawasaki Heavy Industries Co. Ltd.** (KHI).

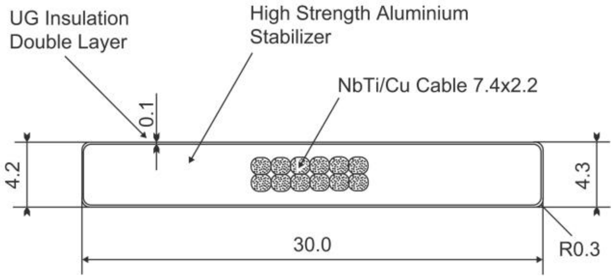


The ATLAS-CS conductor

The conductor was developed by KEK in cooperation with the **Furukawa Electric Co. Ltd.**, and procured from both **Furukawa** and **Hitachi Cable Co. Ltd.**

New materials were studied and developed to obtain high strength low alloy stabilizers with micro-alloying, in 2 steps:

1. **Adding additives** to high purity aluminium:
    - Ni-doped, in a crystallization/precipitation state,
    - Cu/Mg-doped, in a solid solution state.
2. **Cold work hardening** of the coextruded conductor



- A new material using **Aluminum–0.1 wt% Ni**, with cold reduction of 21%, was developed in collaboration with **Furukawa Electric Co. Ltd.**, which manufactured half of the conductor required.

REF: K. Wada, et al., Development of high-strength and high-RRR aluminum-stabilized superconductor for the ATLAS thin solenoid, IEEE Trans. Appl. Supercond., 10 (1) (2000), p. 373

- Material using **Cu (20 ppm)+Mg (40 ppm)**, with cold reduction of 15%, was developed in collaboration with **Hitachi Cable Co. Ltd.**, which manufactured the other half of the conductor.

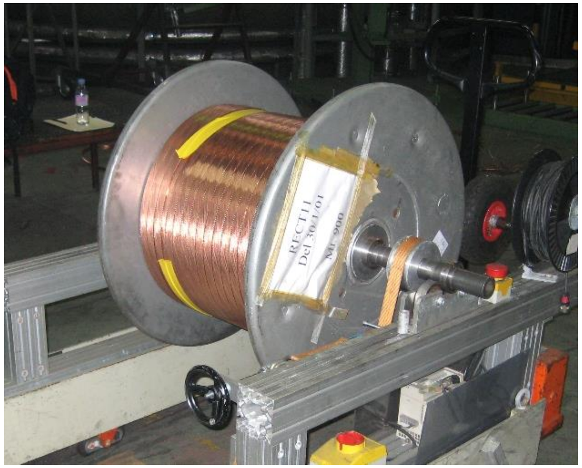
REF: A. Yamamoto et al., The Atlas Central Solenoid, Nucl. Instrum. Methods Phys. Res., A 584 (2008) 53-74

Mechanical properties are still well above the minimum required after the coil curing cycle (impregnation at 130°C - 15 hrs).

Manufacturing process

Co-extrusion

- done at **Nexans, Cortaillod, CH** (same press as CMS and ATLAS BT conductor coextrusion),
- Billet-on-billet co-extrusion process
- Double piston system, top and bottom, no stop,
- Atlas BT conductor die re-used,
- Rutherford cable from Atlas BT production used ~100-m of good leftover cable,
- 5N8 Al billets leftover from CMS production used.



Atlas BT conductor :

- 57 x 12 mm^2
- 40 strands
- Strand Cu/SC~1.2
- Strand ∅1.3mm

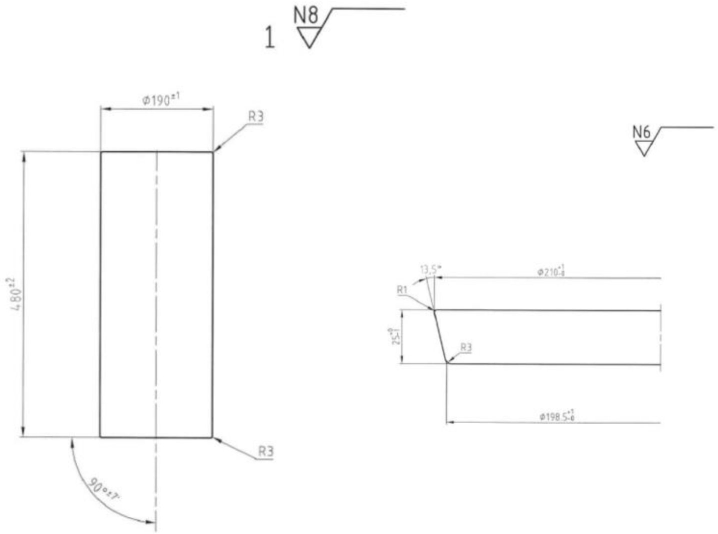
B. Blau, ETHZ

Manufacturing process

Acknowledgment:
Prof. A. Yamamoto; KEK, Tsukuba, Ibaraki (J)

High strength stabilizer

- **Al-0.1wt%Ni** billets used left over from the ATLAS Central Solenoid manufacturing kindly provided to CERN by Prof. A. Yamamoto, KEK.
- The billets had to be reshaped to fit the Nexans press:
  - Billet dimension Ø190mm x L480mm,
  - Process: forging (to increase the diameter), machining, EB butt-welding.
- 5 billets + 5 caps were available for the model length production at NEXANS (~100m)

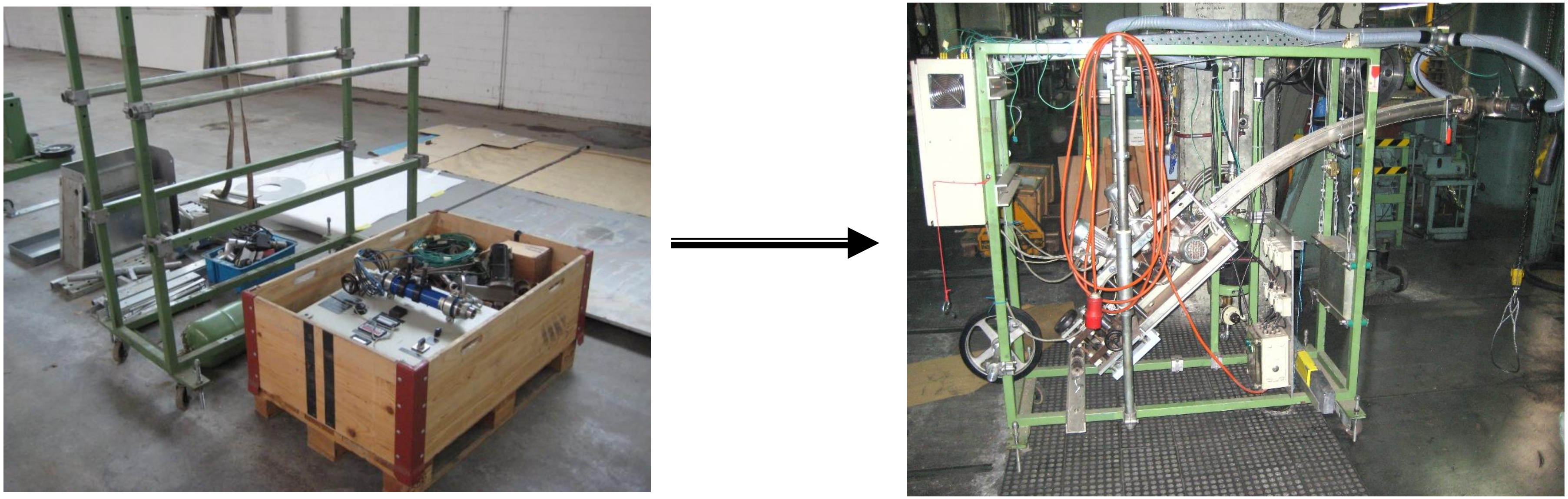


Dimensions of billets and caps

Manufacturing process

Specific tooling

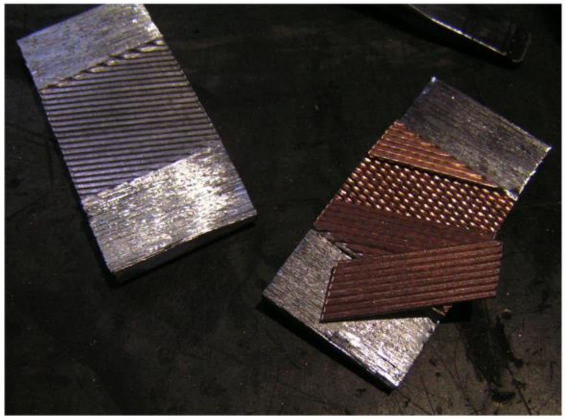
- Retrieved from ATLAS-BT and CMS manufacturing campaign
  - Cleaning (brushing) and pre-heating unit for the SC cable preparation before its introduction in the press.
  - It had to be completely revamped (with support from **Marti-Supratec AG**) as it was dismantled at the end of the LHC conductor production



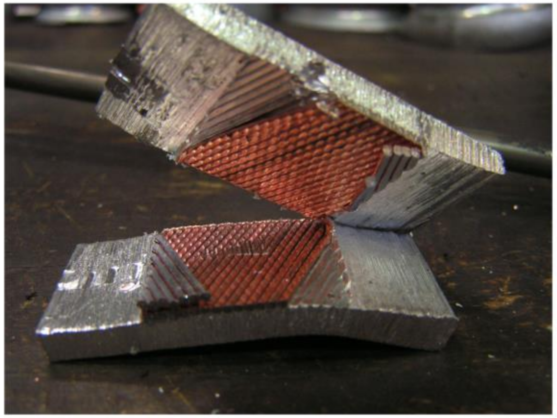
Manufacturing process

Production

- The production started with the co-extrusion of the SC cable with 5N8 Al, to adjust the press parameters + SC cable centering, bonding to aluminium (visual check with peel-off samples), external dimensions.
- Production speed: 1.5m/min (0.9m/min for billet change).
- During preheating, the peak temperature of the cable is held below 350°C.
- The extrusion temperature is set at 400°C. During the actual co-extrusion, a temperature of the cable in excess of 350°C is limited to a maximum duration of 30 s, followed by an in-line water quench.
- With the introduction of the Al-0.1wt.%Ni billets, the extrusion pressure is increased by ~20%, which was still well within the working margins of the 3800-t press.



(a) Peel-off witness sample showing inadequate bonding.



(b) Peel-off witness sample showing satisfactory bonding.

Manufacturing process

Acknowledgment:
Antonio della Corte; ENEA, Rome (I)

Cold working

- Done at **Cryotec, Chivasso, It,** with support from **ENEA, It,**
- On short length samples.

Equipment:

- 50-ton, actively driven, four-roll Turks head mill (DEM SpA),
- Used for production of the ITER cable-in-conduit [Della Corte et al., 2013].

Results

Studies led as part of the works for a PhD thesis, covering material studies for :

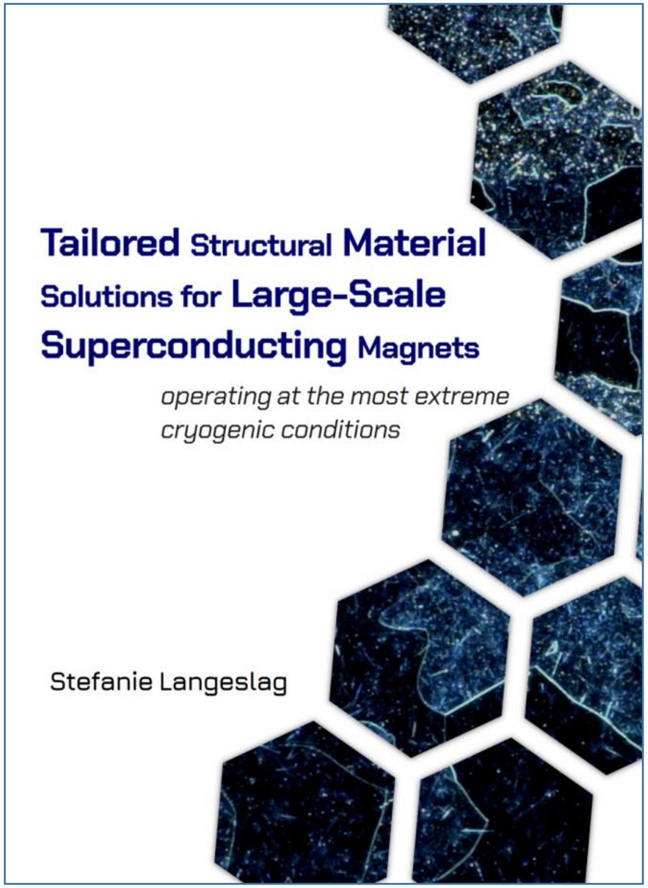
- Fusion magnet,
- HEP detector magnets.

Stefanie A. E. Langeslag

Tailored Structural Material Solutions for Large-Scale Superconducting Magnets operating at the most extreme cryogenic conditions

Ph. D. thesis, 28th May, 2020, University of Twente, The Netherlands

ISBN: 978-94-028-2052-2



Tailored Structural Material Solutions for Large-Scale Superconducting Magnets

operating at the most extreme cryogenic conditions

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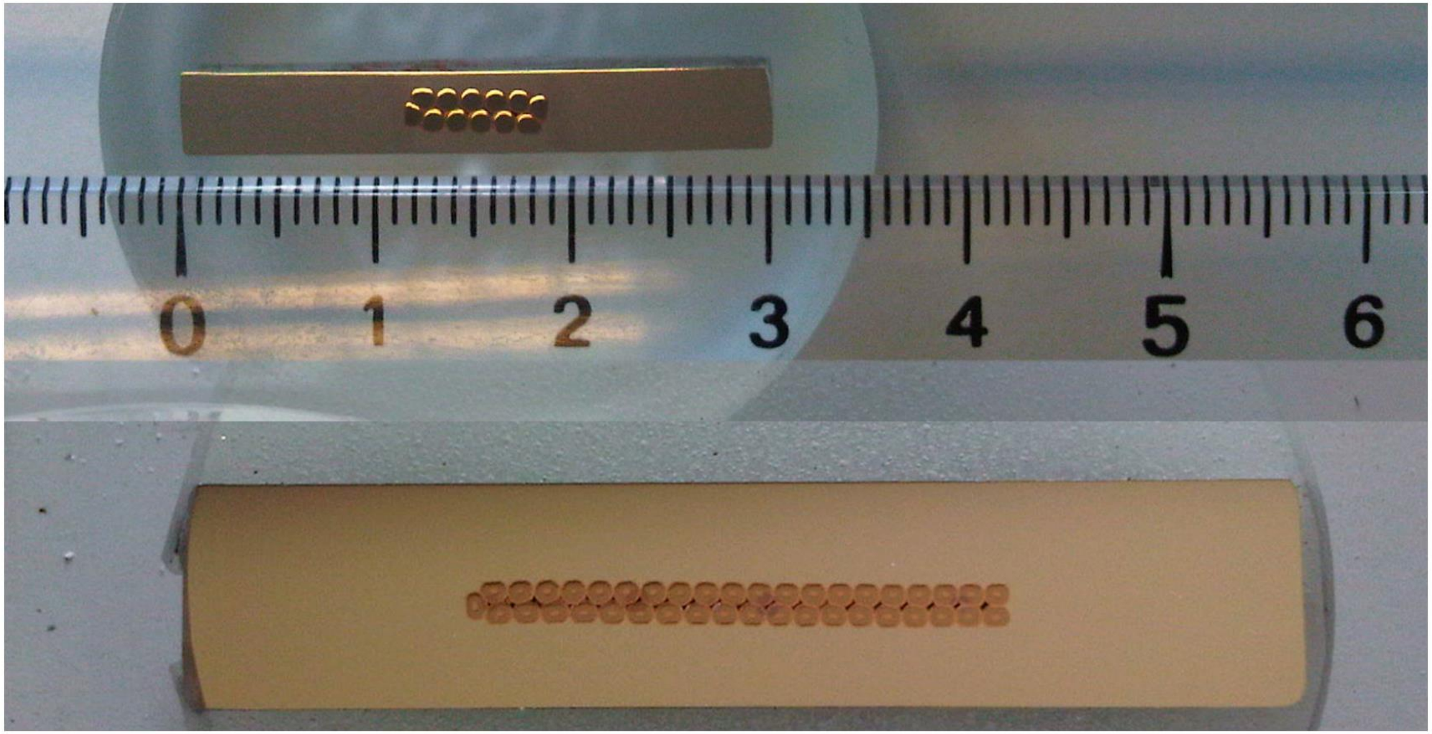
Results – co-extrusion



Cross-section of the ATLAS central solenoid conductor, 30 mm x 4.3 mm (top), and the 57 mm x 12 mm scaled-up conductor consisting of a 40-strand Nb-Ti/Cu SC cable co-extruded with an Al-0.1wt.%Ni alloy stabiliser (bottom).

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Results – co-extrusion

Characteristics:

- **continuous billet-on-billet extrusion** process,
- **changes from 5N-Al to Al-0.1wt.%Ni** (and vice versa at the end of the process),
- specific material flow in the press,

⇒ **long transitional areas** along the length of the conductor (inner volume of the press is **3.5 billets + caps**) ⇒ reduced length of conductor with homogeneous cross-section for testing**.**

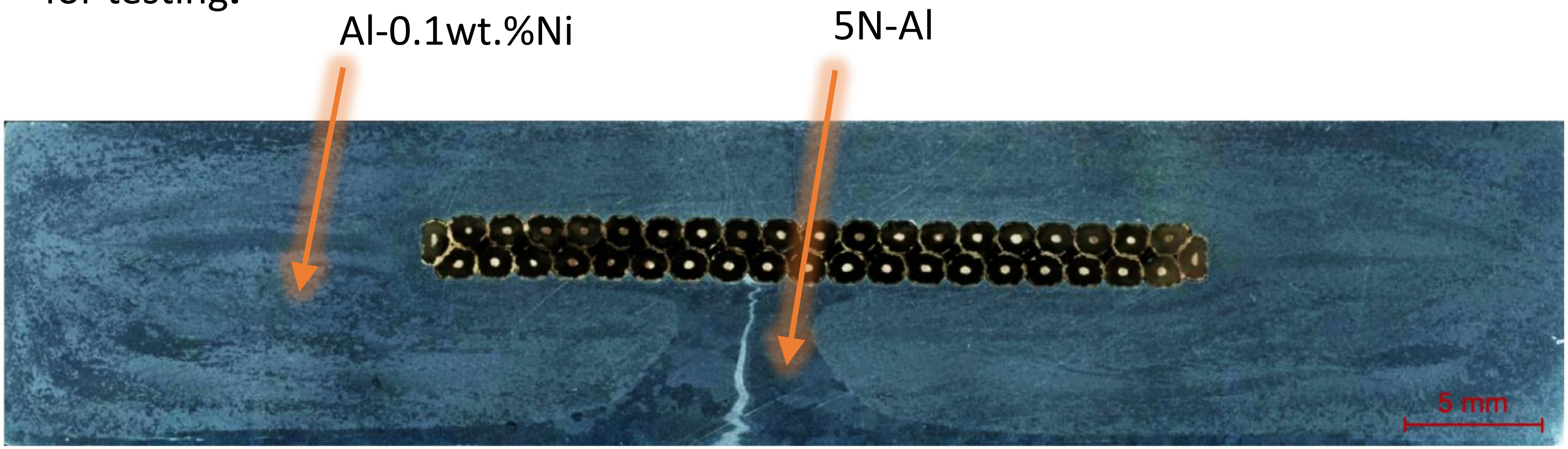

Image of the conductor cross-section, showing the transition from 5N-Al to Al-0.1wt.%Ni.

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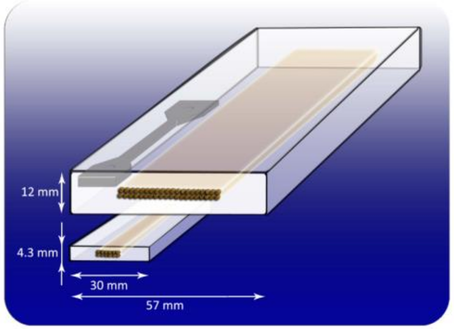
Results – co-extrusion

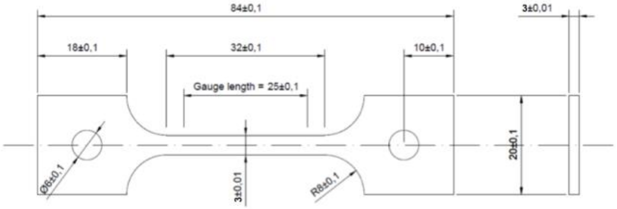
Measurements were conducted on the bulk section of the extruded Al-0.1wt.%Ni conductor as a conservative approach for mechanical properties (more work-hardening close to surface and Rutherford cable). Repeated 3 times at least.

Samples machining done by spark erosion to avoid strain induced hardening.

Mechanical tests done at RT & 4.2K at CERN
[set-up by S. Sgobba et al.]

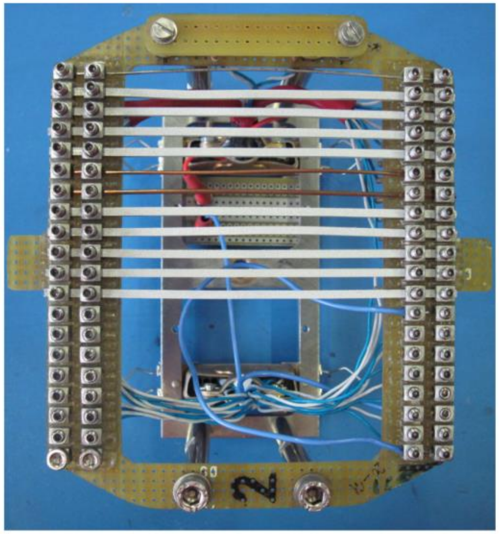


Schematic representation of the new co-extruded Al-Ni stabilised conductor, 57 mm x 12 mm (top). For comparison, the 30 mm x 4.3 mm ATLAS CS conductor is shown to scale (bottom). The shaded area indicates where measurement specimens are taken from the bulk section of the conductor.



Specimen design for both liquid helium and ambient temperature tensile tests.

RRR measurements done at CERN
[set-up by Charifoulline, CERN]



RRR specimen holder.

Sample 80mm x 2mm x 2mm
V-I curve from 4K to RT

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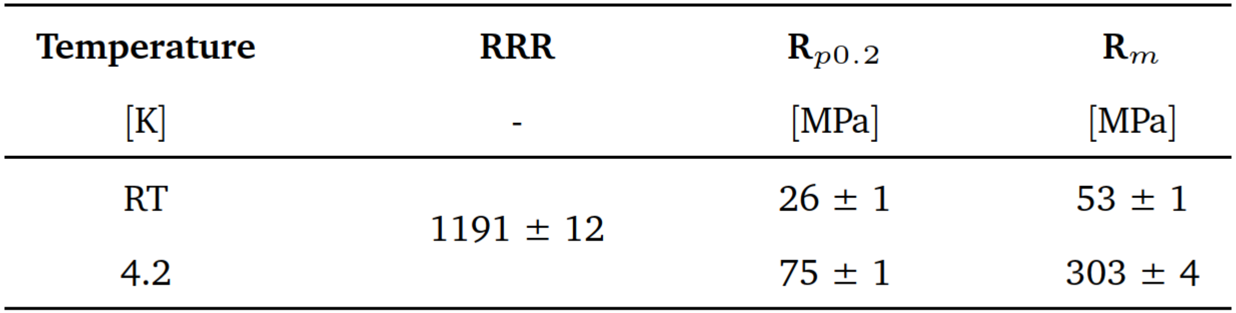
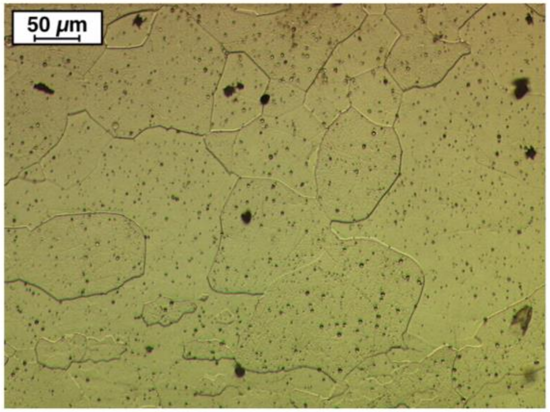
Results – co-extrusion



Temperature [K]	**RRR** -	**$R_{p0.2}$** [MPa]	**R_m** [MPa]
RT	1191 ± 12	26 ± 1	53 ± 1
4.2		75 ± 1	303 ± 4

Microstructural observation in the bulk material:



Micrograph of a co-extruded Al-Ni^c specimen, original magnification 200x.

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Results – cold work-hardening

Rolling done parallel to extrusion direction (Z direction),

Samples are rolled in contra-extrusion direction to account for spooling and de-spooling (cold work hardening not done on the same production line as the co-extrusion).

Reduction of the cross section :

a. **in single direction** (laboratory scale - CERN) - short transverse (ST) (X), sample lengths from 0.5 to 2m, with multiple passes, reduction of 15%, 20%, 25% and 30%. **Small side left free**.

b. **in two directions** (industrial scale – Criotec) - ST and WT (wide transverse) (X-Y), sample lengths of 1.5m, with single pass or passes in steps of 10% of initial cross-section:

   - **Small side constrained**,
   - one sample was subjected to a **homogeneous reduction in one single pass**, i.e. by applying an equal reduction in ST-direction and WT-direction.

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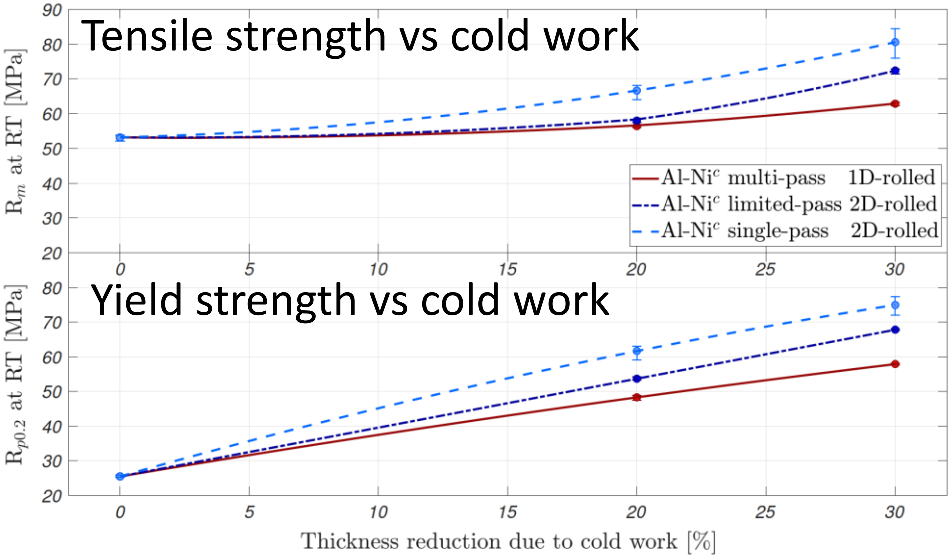
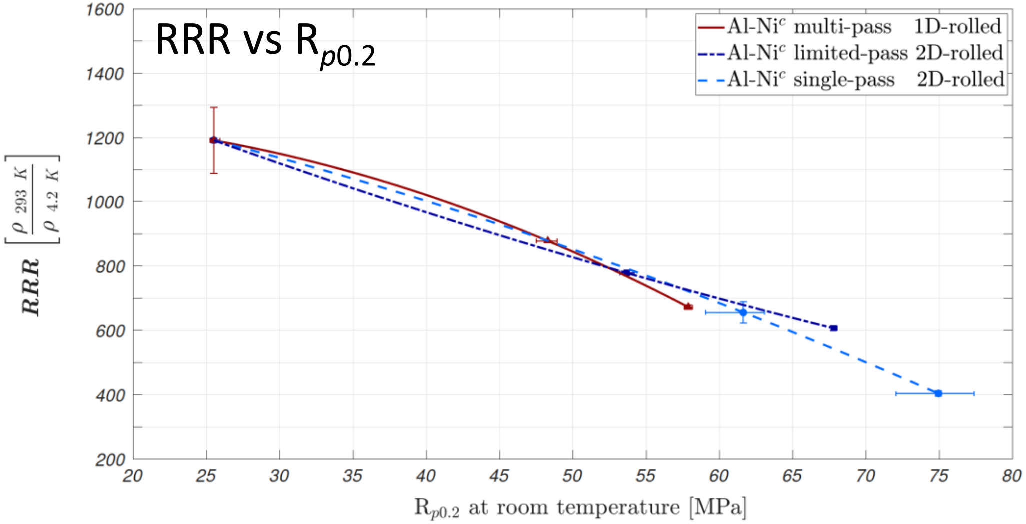
Results – cold work-hardening



Larger increase of the mechanical properties with a single pass (smaller increase with increasing amount of intermediate passes):
Possibly due to age softening at RT in-between passes.



The trend tends to an $R_{p0.2}$ value of ~70 MPa at RT and RRR value of 500 (multiple passes give higher RRR but lower $R_{p0.2}$).

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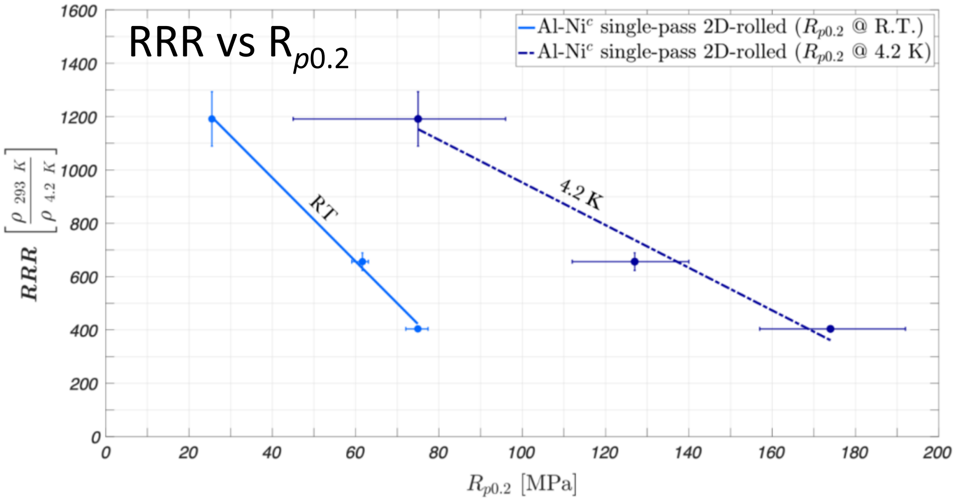
UNIVERSITY OF TWENTE.

Results – cold work-hardening

- *Without annealing simulating the coil curing (not defined, magnet-dependent).*

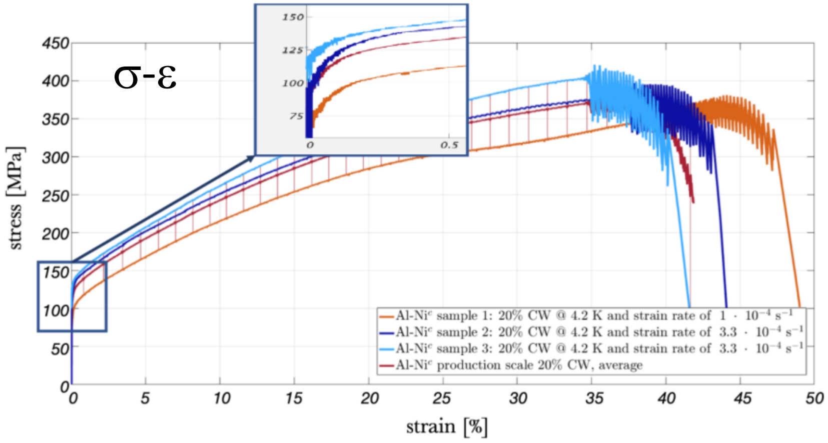
	Temp. [K]	**RRR** -	**$R_{p0.2}$** [MPa]	**R_m** [MPa]
As-extruded	RT	1191 ± 12	26 ± 1	53 ± 1
	4.2		75 ± 1	303 ± 4
20% single-pass cold-rolled	RT	656 ± 7	62 ± 1	67 ± 1
	4.2		127 ± 2	376 ± 5
30% single-pass cold-rolled	RT	404 ± 4	75 ± 1	81 ± 1
	4.2		174 ± 3[a]	496 ± 6

[a] deduced from only two measurements



RRR plotted against $R_{p0.2}$, for the various cold-worked states, at both room temperature and 4.2 K. Notice the large increase in $R_{p0.2}$ at 4.2 K compared to room temperature.

Strain-rate sensitivity observed on sample testing at 4.2 K:



Stress-strain curves at 4.2 K for co-extruded Al-0.1wt.%Ni subjected to 20% work hardening by single-pass cold-rolling.

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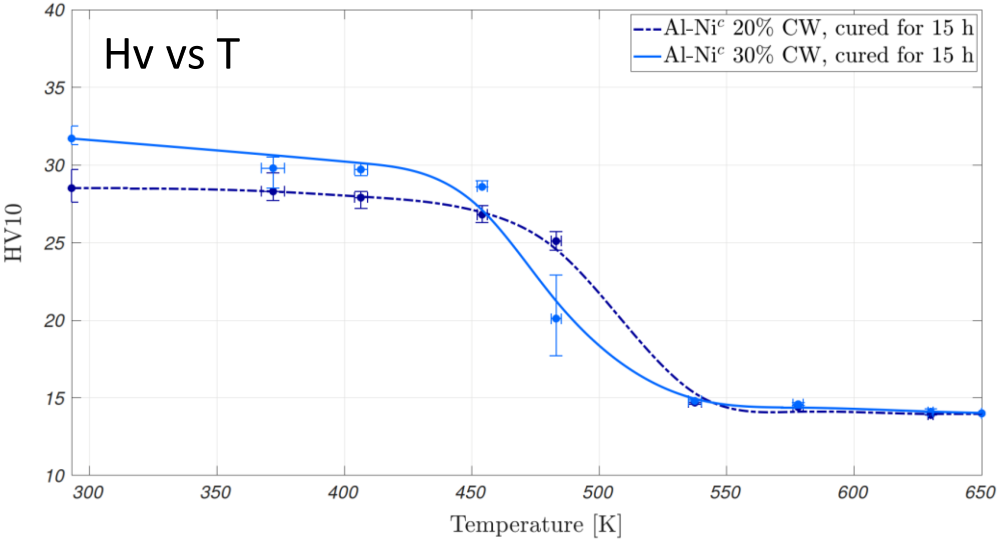
Results – cold work-hardening

- **Annealing tests** to assess the stability of the mechanical properties against different curing cycles, applying an ATLAS-CS curing cycle type : 15 h but at several temperatures.

Indentation hardness measurements performed on the thermally treated samples.



Vickers hardness, HV10, plotted as function of thermal treatment temperature. The data presents HV10 values of 20% and 30% single pass cold-rolled short samples subjected to various thermal treatments with a duration of 15 h.

- A recovery temperature (annealing) is found between 200°C and 260°C.
- No indication of precipitation-hardening due to artificial aging.

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Results – cold work-hardening

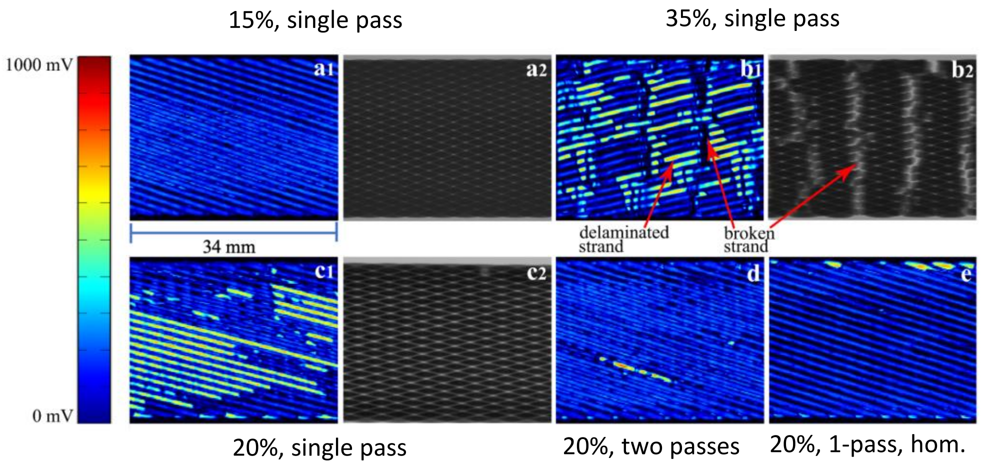
Bonding inspection

1. X-ray micro computed tomography (CT)
2. Ultrasonic pulse-echo immersion technique [Neuenschwander et al., 1998]

*Both done at the **Swiss Federal Laboratories for Materials Science and Technology** (EMPA), CH*

- ➢ Delamination at 20% with single pass, and cable break at 35%,
- ➢ Limited delamination at 20% with 2 passes,
- ➢ Delamination only at cable edge with homogeneous reduction 20% and single pass.

Initial bonding stabilizer-cable in as-extruded state (not measured) not fully optimized, as a change of the press configuration was not compatible with the prototype manufacturing plan agreed with Nexans.



Ultrasonic C-scans and radiography images of the co-extruded, cold-rolled Al-Ni stabilised conductor. Subfigures *a1*, *b1*, and *c1* show C-scans of selected sections of the 15%, 35% and 20% single-pass cold-rolled conductor, respectively. Subfigures *a2*, *b2* and *c2* show the corresponding X-ray images. Subfigures *d* and *e* show C-scans of selected sections of the 20% cold-rolled conductor in two passes (limited-pass), and the homogeneously reduced, respectively.

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Conclusion and further works

1. The study confirmed the potential use of Al-0.1wt.%Ni for large co-extruded stabilized conductors, with a great improvement of the mechanical properties while keeping a RRR well above 500.

2. The final parametrization of the process (co-extrusion + cold working) still has to be defined, as it depends on the production equipment, the conductor and magnet sizes.

3. The study gives a good background for further developments, that shall validate the final properties that can be reached after the last stage of manufacturing with the coil curing cycle

   e.g. for CLICdp design with criterion $\sigma_{eq} < \frac{2}{3} R_{p0.2}$
   then $R_{p0.2} > 123$ *MPa at 4.2K is needed.*