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Development of novel aluminum-based stabilizer solutions for superconducting cables

Applicable to future detector magnets

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20 November 2013

WAMAS Workshop on Advanced Materials & Surfaces;
Wednesday, 20th of November 2013, 11h00

Large bore, High-field Magnets

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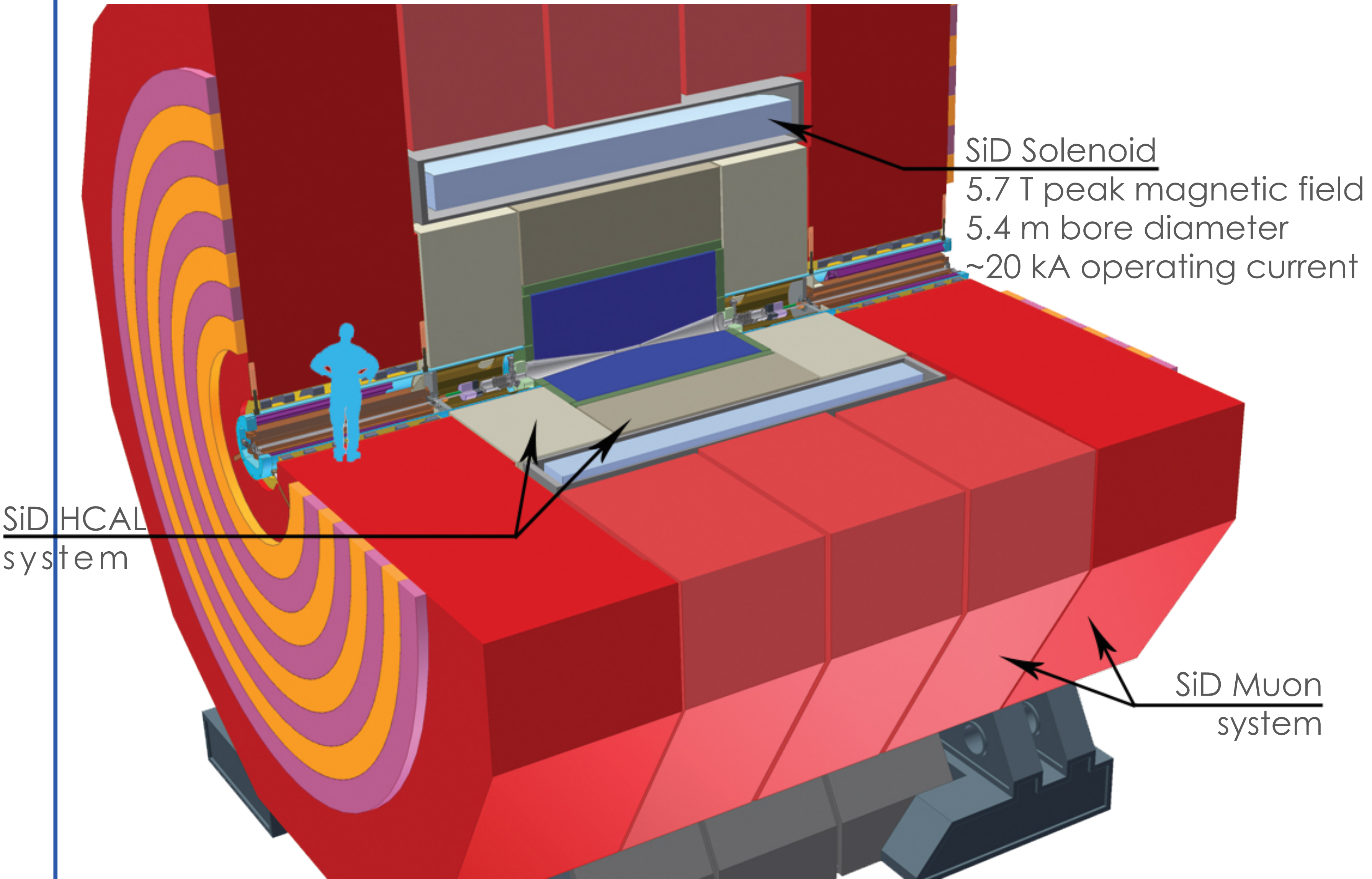

Stabilized Superconducting cable

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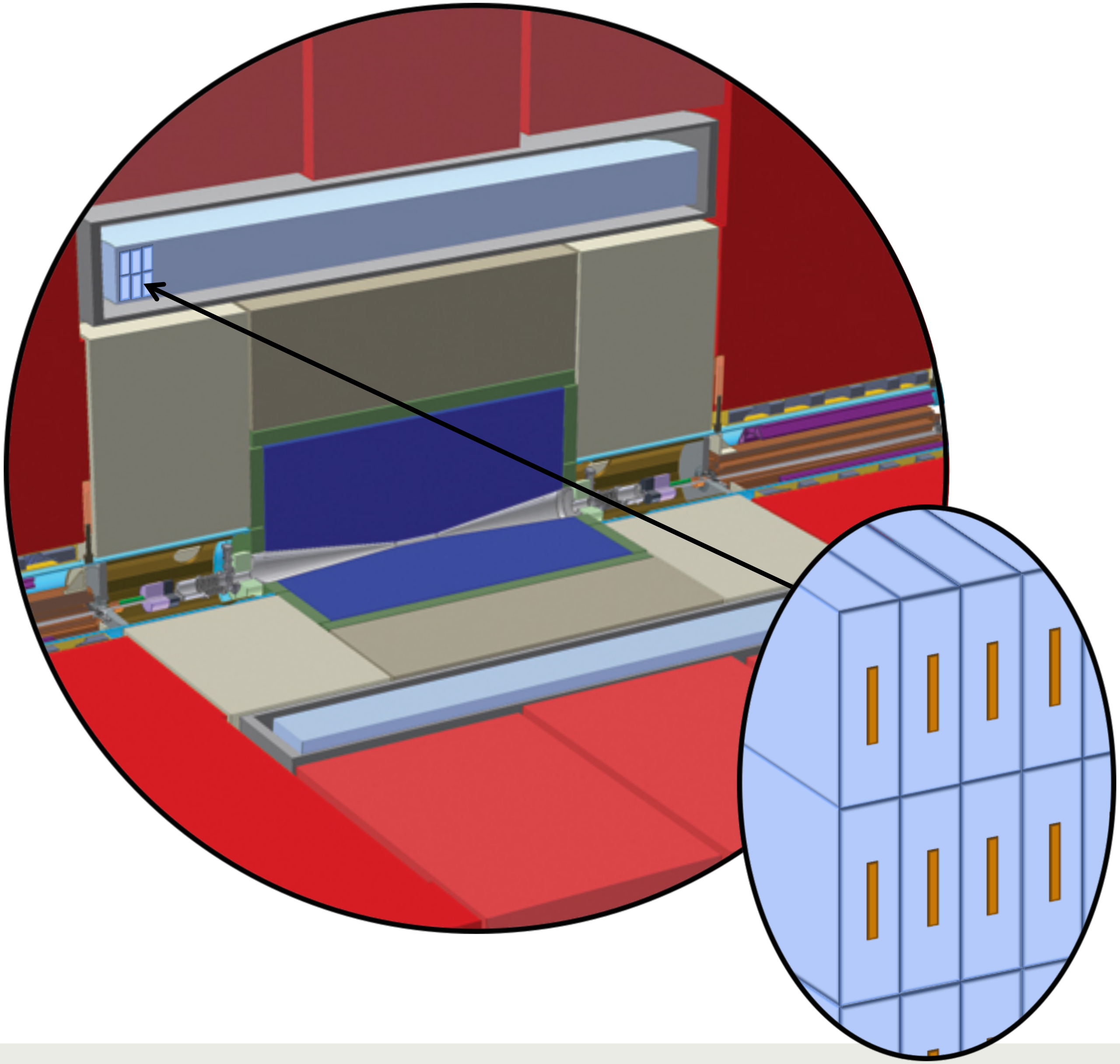

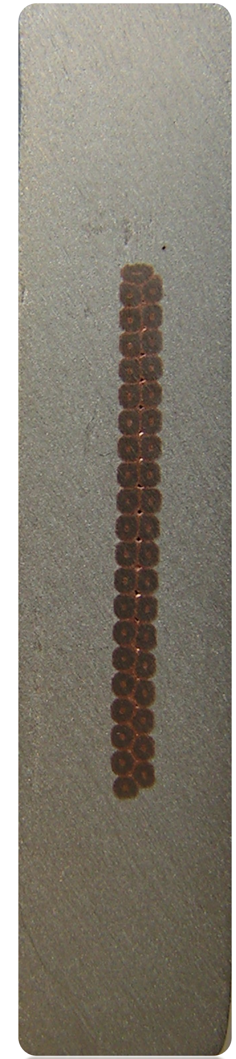

Stabilized Superconducting cable

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The self-supporting magnet structure needs to sustain a large hoop force as a result of the high peak magnetic field.

This requires for the conductor to exhibit challenging mechanical properties.

Goal is to develop a prototype for a 60 kA critical current, at 5 T class stabilized superconductor, operating at 4.2 K.

➜ Leading us to the development of a conductor with a ~2000 mm^2 cross-sectional area.

The stabilizer should feature a yield strength of >120 MPa at 4.2 K and an RRR of >500.

Reinforced Stabilizer

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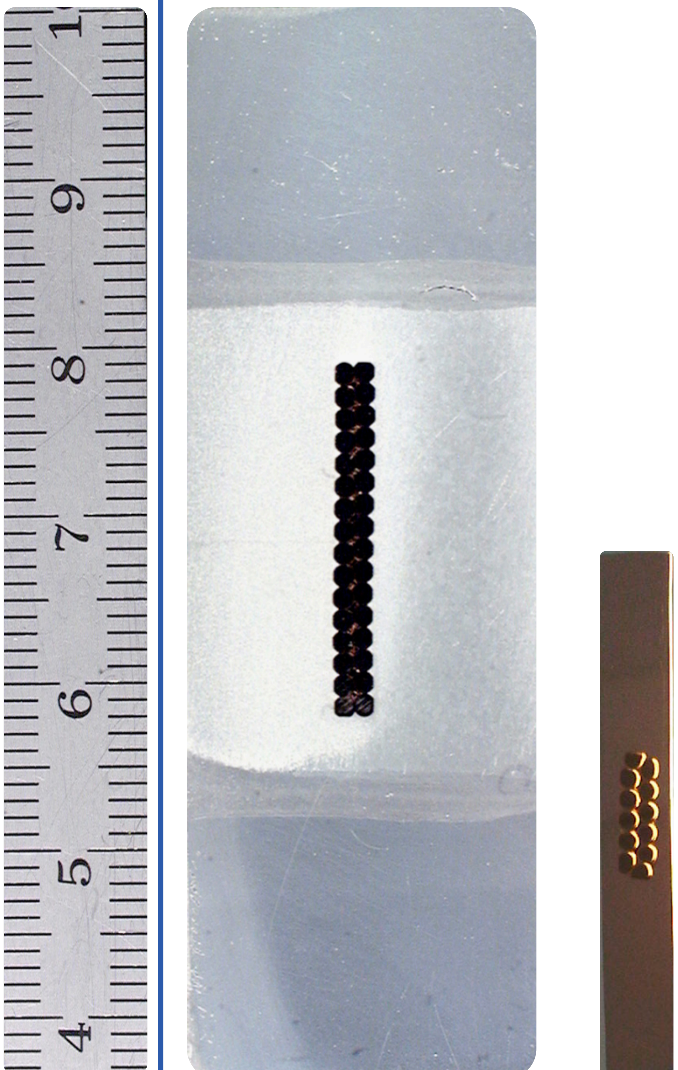


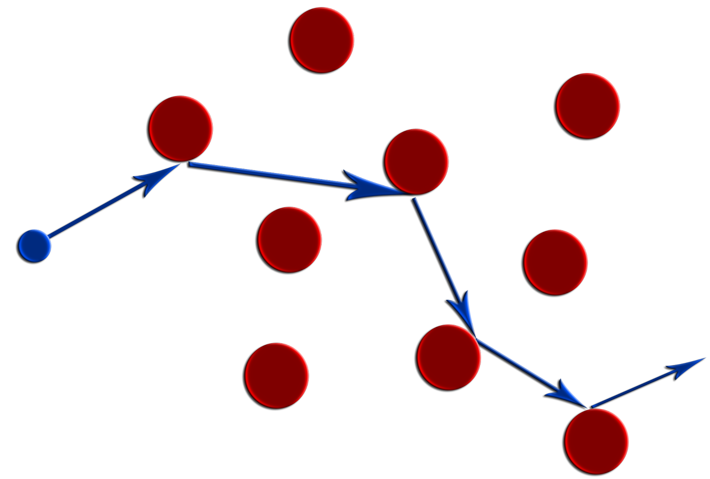
CMS (left) & ATLAS central solenoid (right) conductor

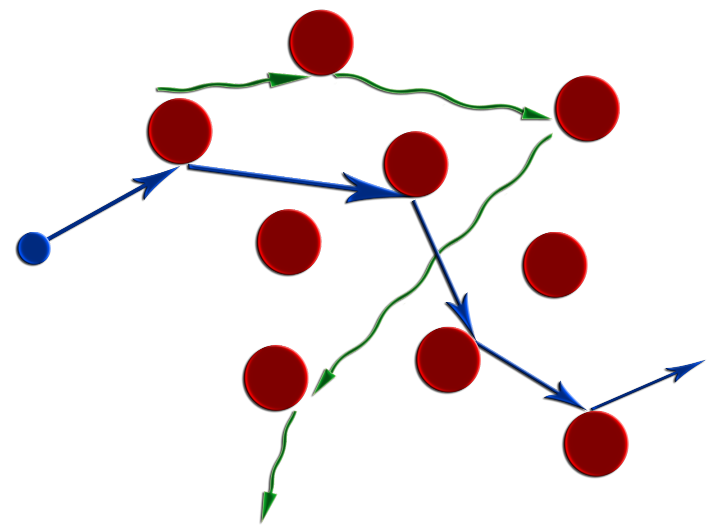
- Hybrid solution
  - preservation of conductivity properties ✓
  - mechanical reinforcement ✓
  - homogeneous deformation ~
  - conductor manufacturing ~

- Microalloying
  - preservation of conductivity properties ~
  - mechanical reinforcement ✓
  - homogeneous deformation ✓
  - conductor manufacturing ✓

Preservation of Conductivity

- Doped Aluminum
  - low solid solubility
- Mechanical Alloying
  - particle or whisker reinforced





Mean free path – Electrical and Thermal resistivity

Co-extrusion of Al-Ni stabilized conductor

Scale-up towards a prototype for a 60 kA at 5 T, 4.2 K class conductor

Co-extrusion of a large 40-strand Nb-Ti/Cu superconducting cable with a precipitation type Al-0.1WT%Ni stabilizer.

Microalloying with Ni contributes to the strength of the stabilizer while avoiding significant degradation in RRR due to its low solid solubility in Al.

The Al-0.1WT%Ni material was made available by KEK, Tsukuba, Ibaraki (J).

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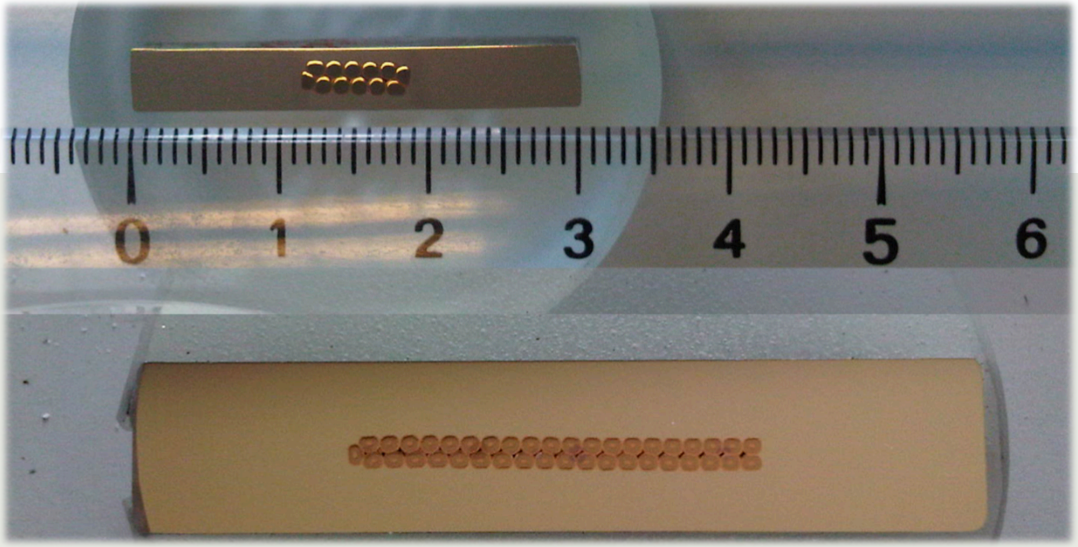
IEEE Transactions on Applied Superconductivity, vol. 23, no. 3, 4500504, 2013.



Al-0.1WT.%Ni stabilized ATLAS central solenoid conductor (top) & scaled-up Al-0.1WT.%Ni stabilized prototype conductor (bottom).

Co-extrusion of Al-Ni stabilized conductor

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Nexans Cortalliod (CH); Extrusion press

Continuous co-extrusion on a 3800 ton press at Nexans, Cortaillod (CH).

Using punch and die of the ATLAS BT conductor (57 x 12 mm^2).

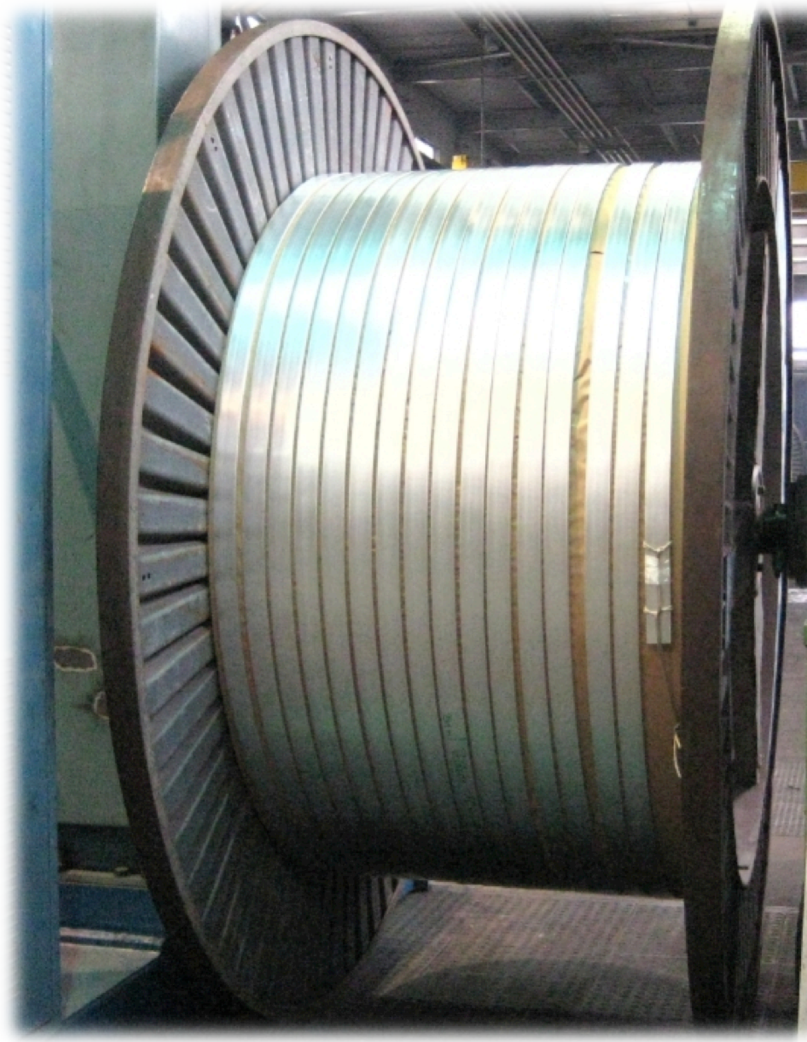
Cable preheated and brushed to ensure good bonding.

Temperature remained at a constant 400°C, while the pressure was increased with 20-25% with the introduction of Al-0.1wt%Ni, leading to a 1.5 m/min extrusion speed.

Co-extrusion of Al-Ni stabilized conductor

Leading to 200 m of 5N-Al co-extruded conductor and 100 m of Al-0.1wt%Ni co-extruded conductor.

Multi-pass uni-directional work hardening has been applied to increase the mechanical properties of the as-extruded temper.



Spool (3 m diameter) with co-extruded conductor

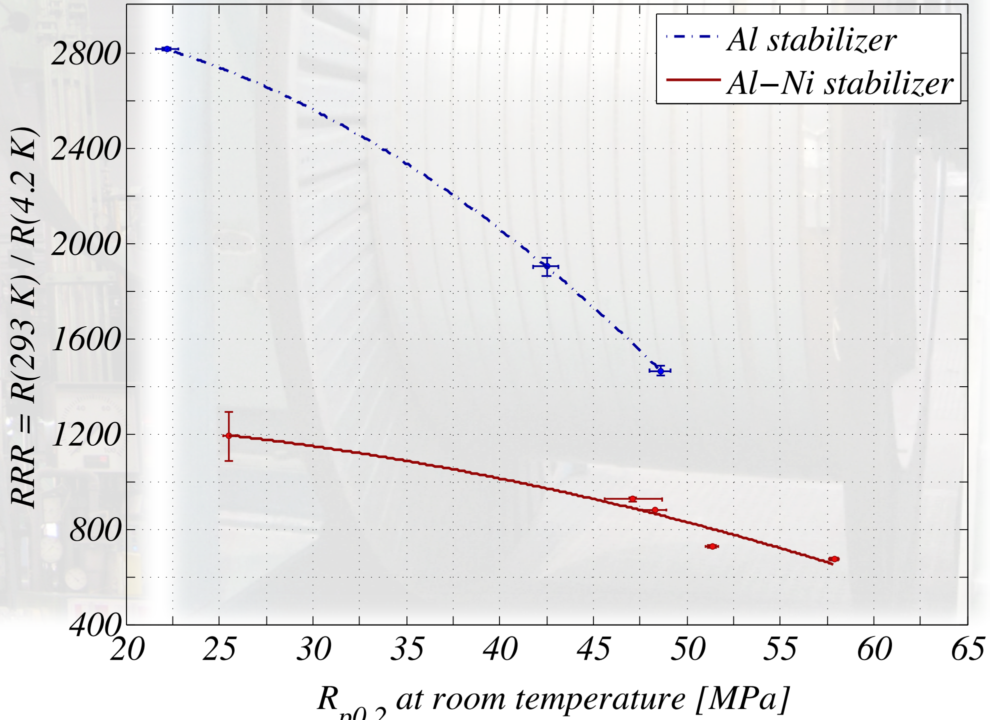
Mechanical Properties

TABLE 1. Properties of co-extruded 5N-Al and Al-0.1wt%Ni as a result of various cross-section reductions due to multi-pass rolling

	Mat.	RRR	$R_{p0.2}$ [MPa]	R_m [MPa]
As-extruded	5N-Al	2814	22	40
	Al-0.1wt%Ni	1191	26	53
20% single pass cold-rolled	5N-Al	1901	42	47
	Al-0.1wt%Ni	879	48	56
30% single pass cold-rolled	5N-Al	1464	49	53
	Al-0.1wt%Ni	673	58	63

RRR in relation to 0.2% yield strength for the two extruded stabilizer materials at the various cold-worked states:

Roughly linear interaction between RRR and $R_{p0.2}$



$R_{p0.2}$ and R_m are 0.2% yield strength and ultimate tensile strength respectively.

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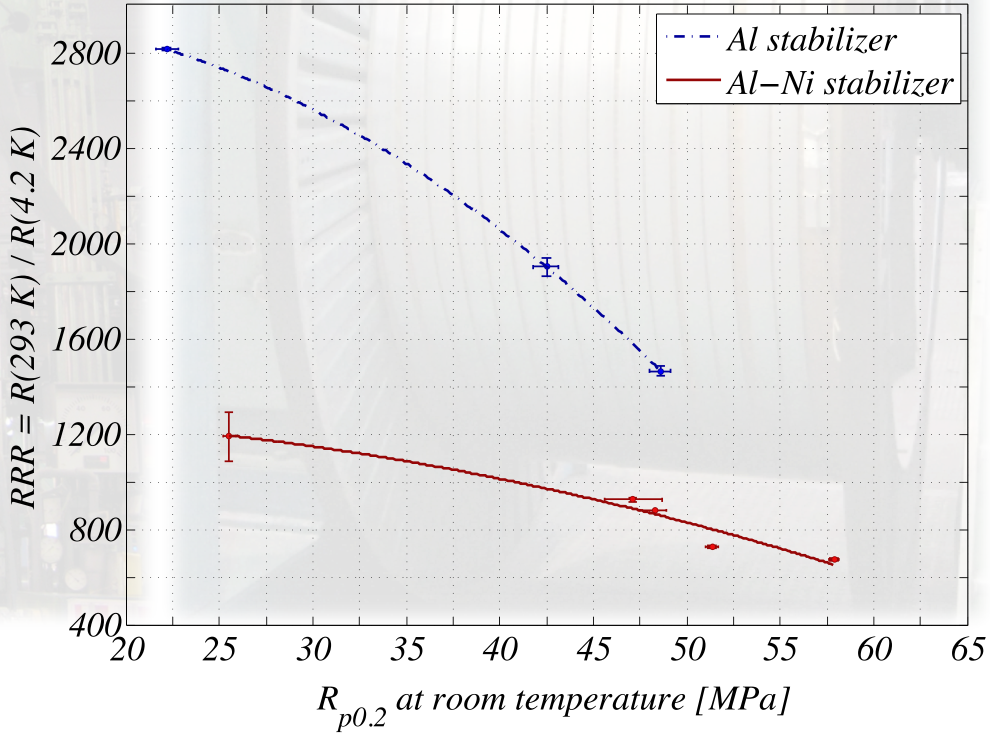
RRR in relation to 0.2% yield strength for the two extruded stabilizer materials at the various cold-worked states:

Roughly linear interaction between RRR and $R_{p0.2}$

Higher workability of the Al-0.1WT%Ni alloy

Increase in $R_{p0.2}$ with use of work hardening has a less detrimental effect on the RRR of the Al-Ni alloy.



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Work hardening; Bi-directional rolling

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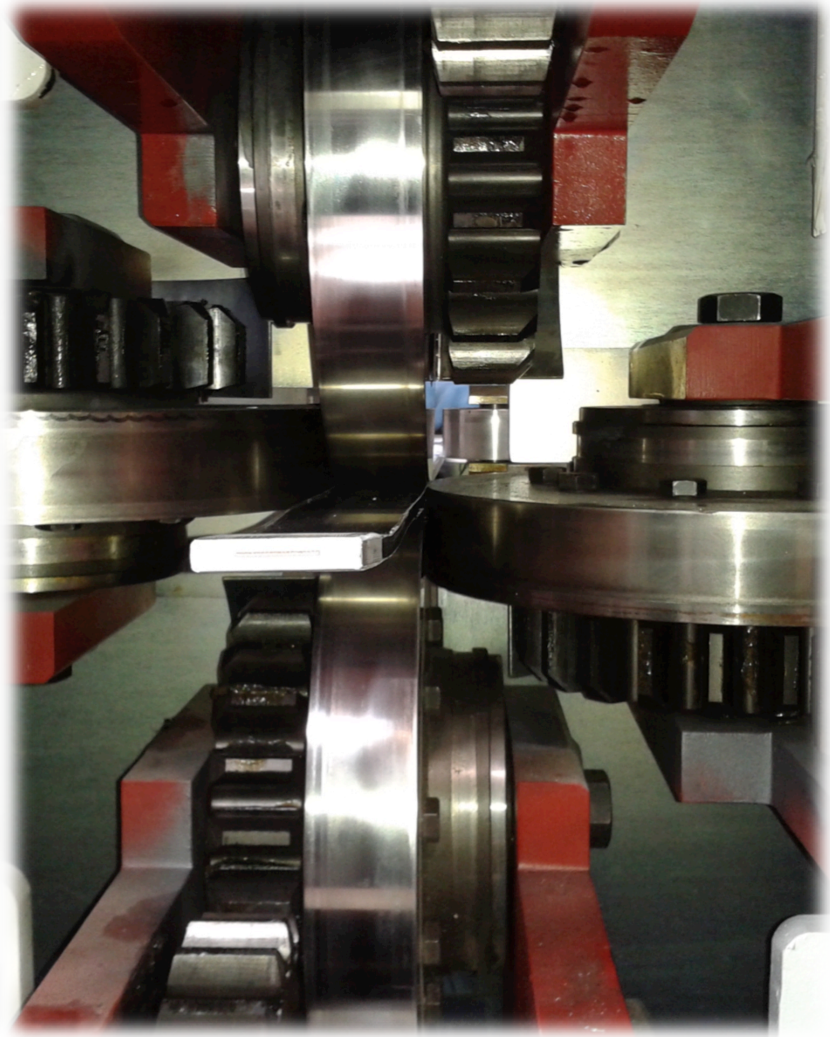
Bi-directional (Turks head) rolling was preformed on a 50 ton DEM rolling mill at Criotec, Chivasso (I).

A set-up used for ITER cable-in-conduit production.

Rolling was conducted on 1.5 m samples, width constrained to preserve cable integrity and a realistic aspect ratio.

The rolling process was made possible by ENEA, Rome (I).



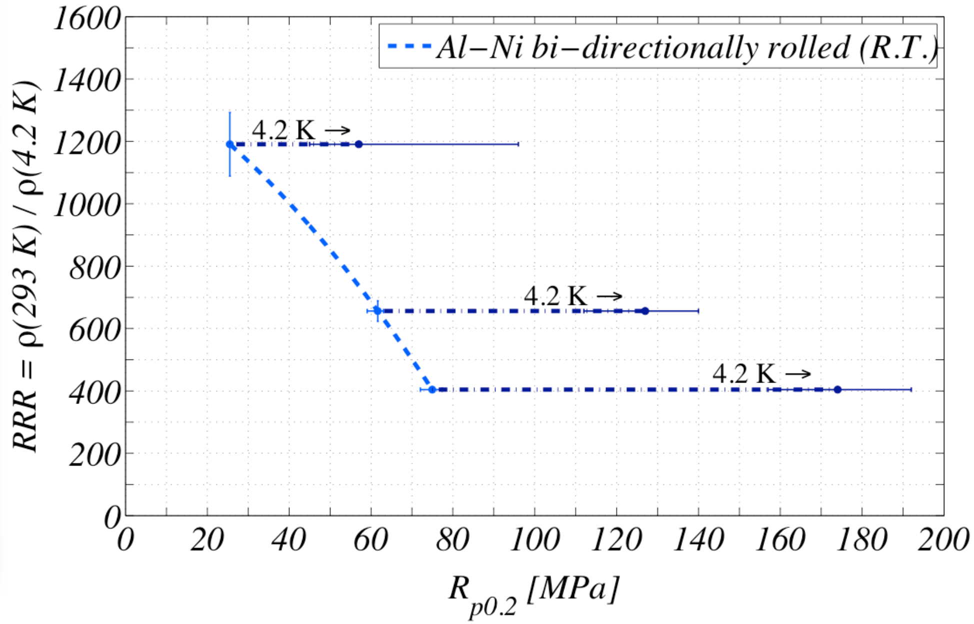
Mechanical Properties

TABLE 2. Properties of co-extruded Al-0.1wt%Ni as a result of various cross-section reductions due to bi-directional rolling

	Temp. [K]	RRR	$R_{p0.2}$ [MPa]	R_m [MPa]
As-extruded	293	1191	26	53
	4.2	-	57	303
20% single pass cold-rolled	293	656	62	67
	4.2	-	127	376
30% single pass cold-rolled	293	404	75	81
	4.2	-	157*	496

* deduced from two measurements

High workability of Al-0.1WT%Ni alloy in a production-scale work-hardening sequence.



Results for the co-extruded Al-0.1WT.%Ni conductor subjected to various work-hardening processes.

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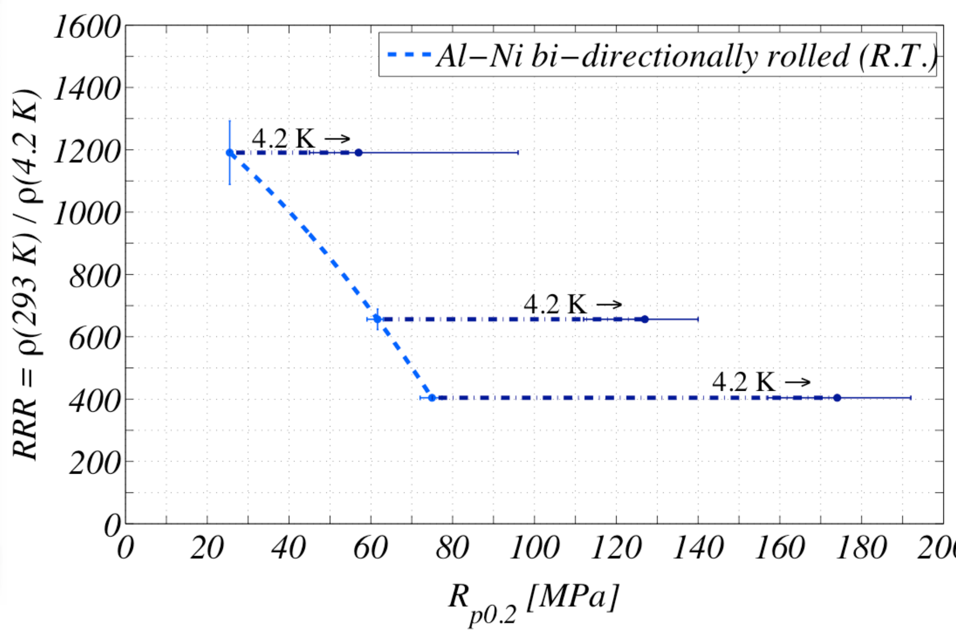
Significant increase in $R_{p0.2}$ at 4.2 K



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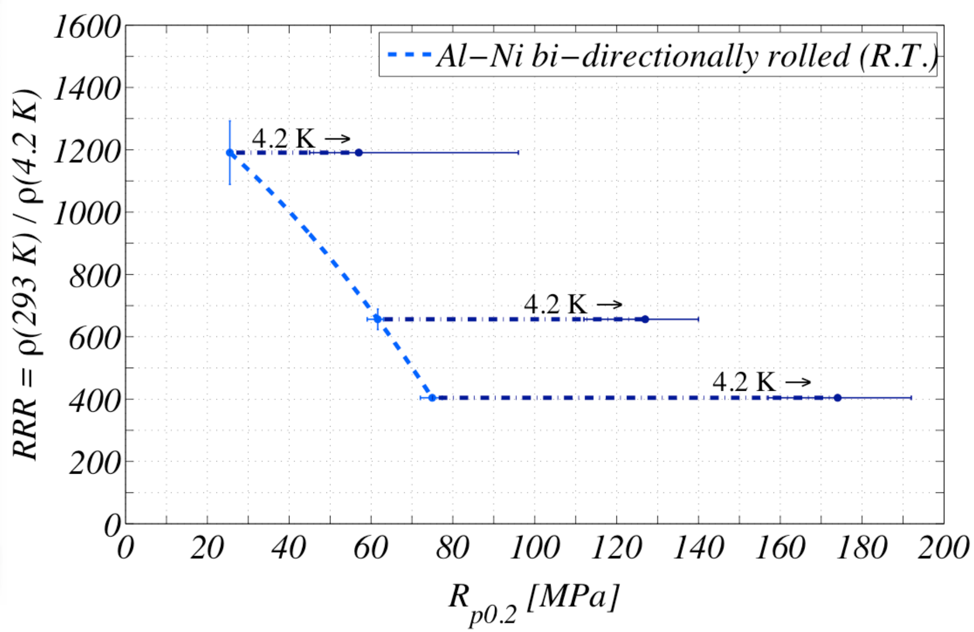
Significant increase in $R_{p0.2}$ at 4.2 K

Roughly linear interaction between RRR and $R_{p0.2}$

~120 MPa at 4.2 K when ~19% cold-reduced, maintaining an RRR of ~700.



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Single-pass vs. Multi-pass rolling

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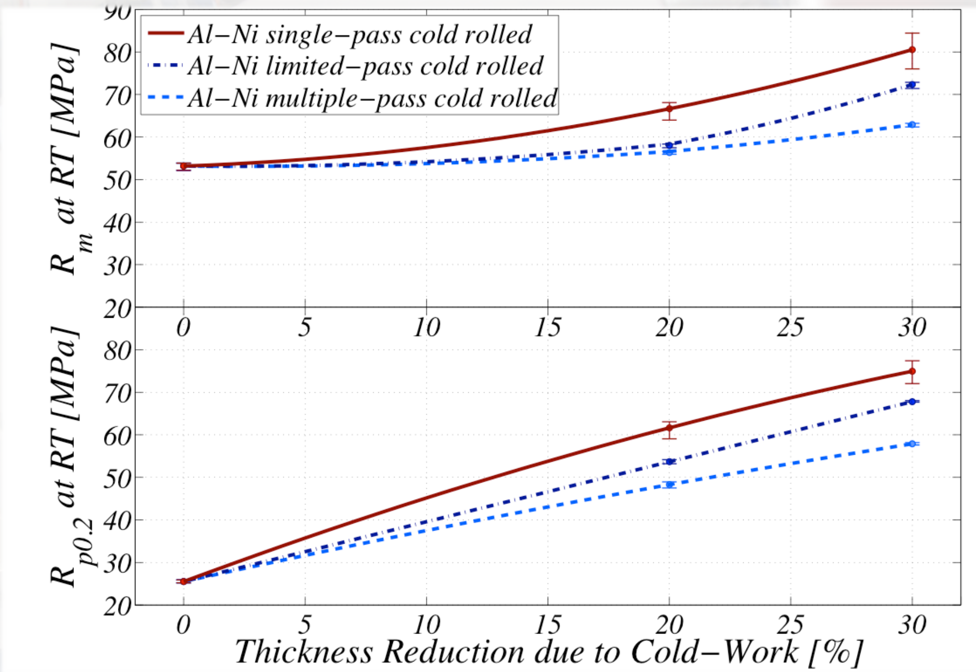
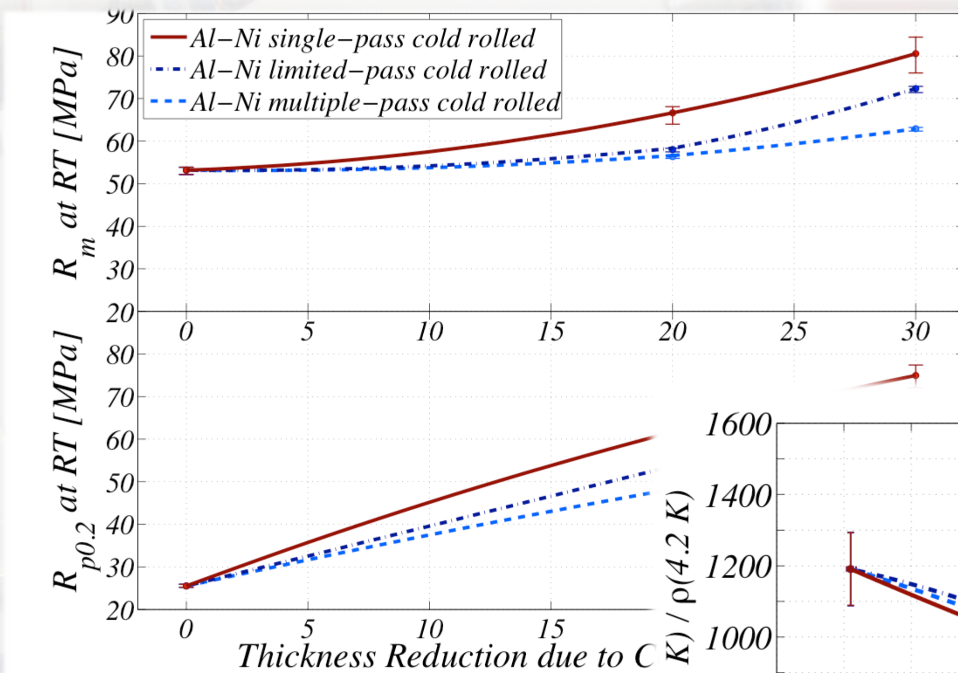


Tensile characteristics of the co-extruded conductor subjected to multiple-pass, single-pass and limited-pass cold rolling.

Distinct decrease in mechanical properties with number of cold-roll passes.

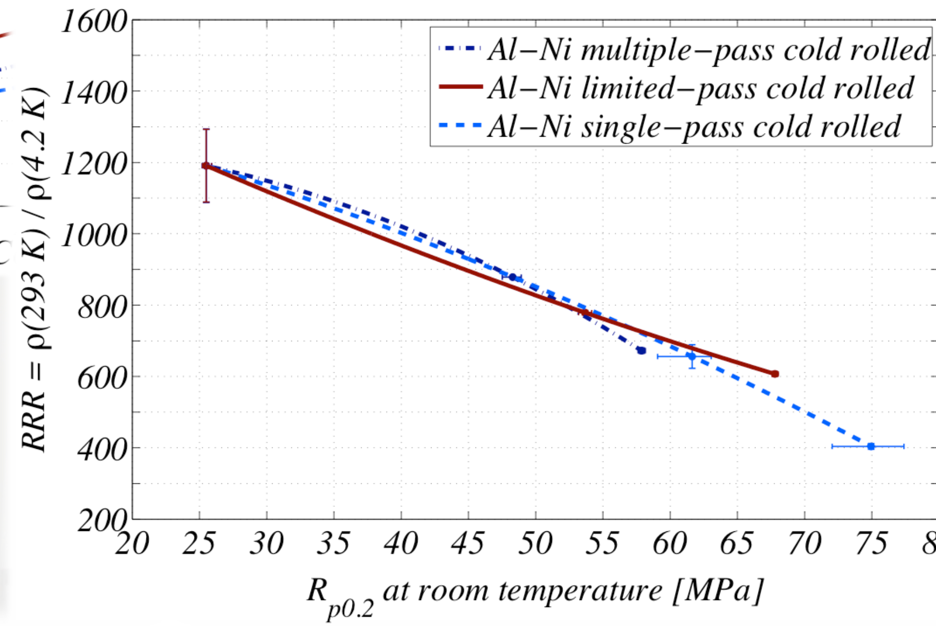
Process of recovery of dislocation pinning points in between passes in this dilute Al-Ni alloy.

Single-pass vs. Multi-pass rolling



Similar relationship is visible between RRR and $R_{p0.2}$ for the various work-hardening processes.

The mechanical and resistivity characteristics of Al-0.1WT%Ni are not only subject to the amount of work hardening, but also to the process.



RRR plotted as function of Rp0.2 for the various cold-worked states, for the different work-hardening processes.

Summary

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In collaboration with the industry a successful **co-extrusion of a record-size, ~700 mm², Al-0.1wt%Ni stabilized superconductor** has been achieved.

The expected **increase in $R_{p0.2}$ with dilute Ni alloying is confirmed.**

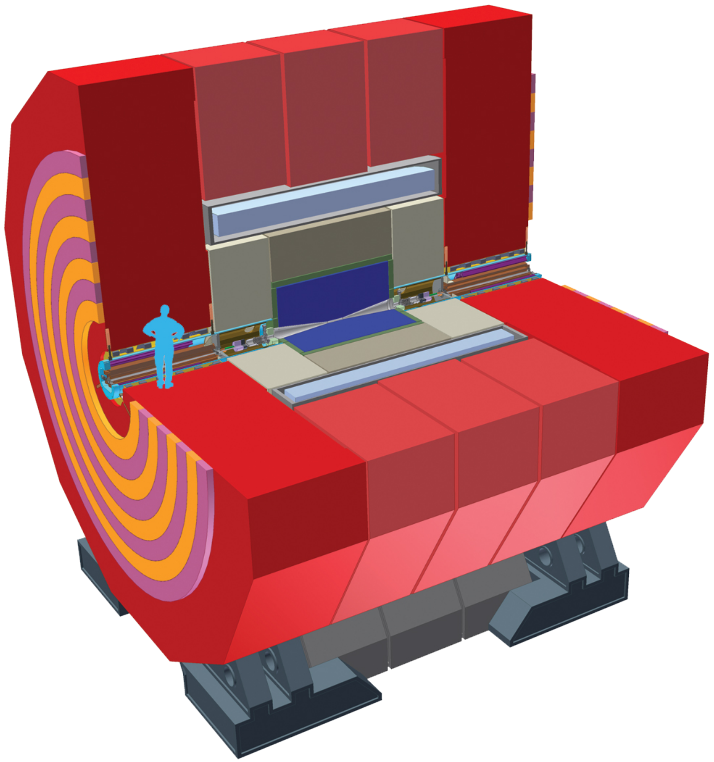
The **Al-0.1wt%Ni** material exhibits a **higher workability**, and shows a **less detrimental effect** of the work hardening **on the conductivity characteristics** with respect to 5N-Al.

the enhancement of the **mechanical properties at 4.2 K is promising** for future detector application.

The material characteristics of Al-0.1wt%Ni are subject to both work-hardening amount as well as certain parameters of the **work-hardening process**.

➜ An **optimal work-hardening sequence** needs to be developed.

Applications



Applications

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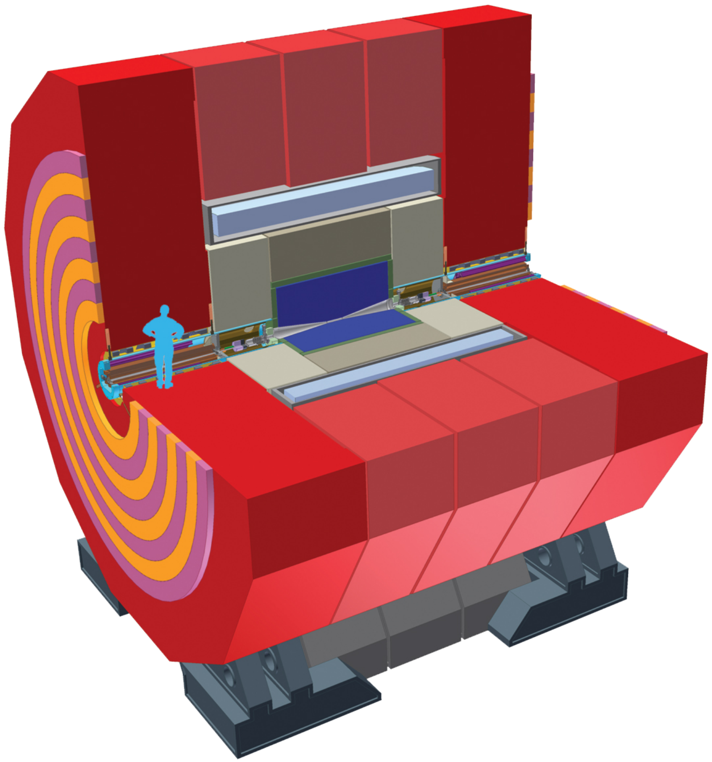

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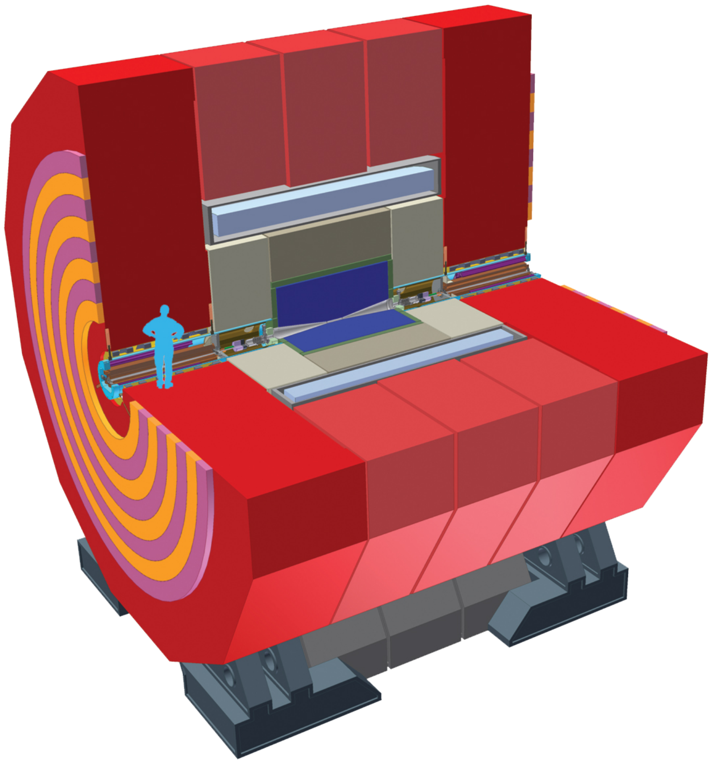
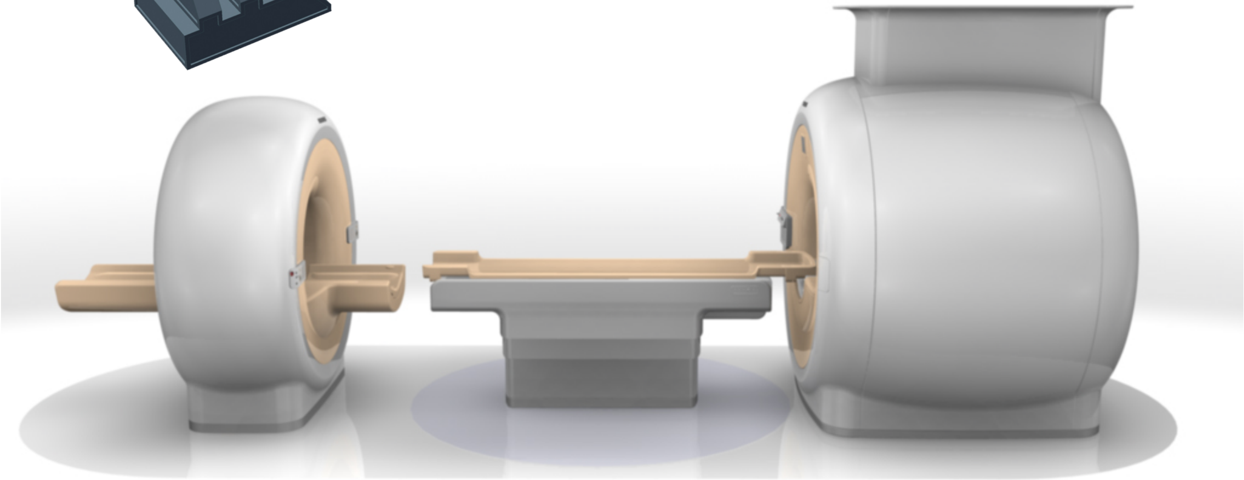




Thank you for your kind attention

Response to Partial Annealing

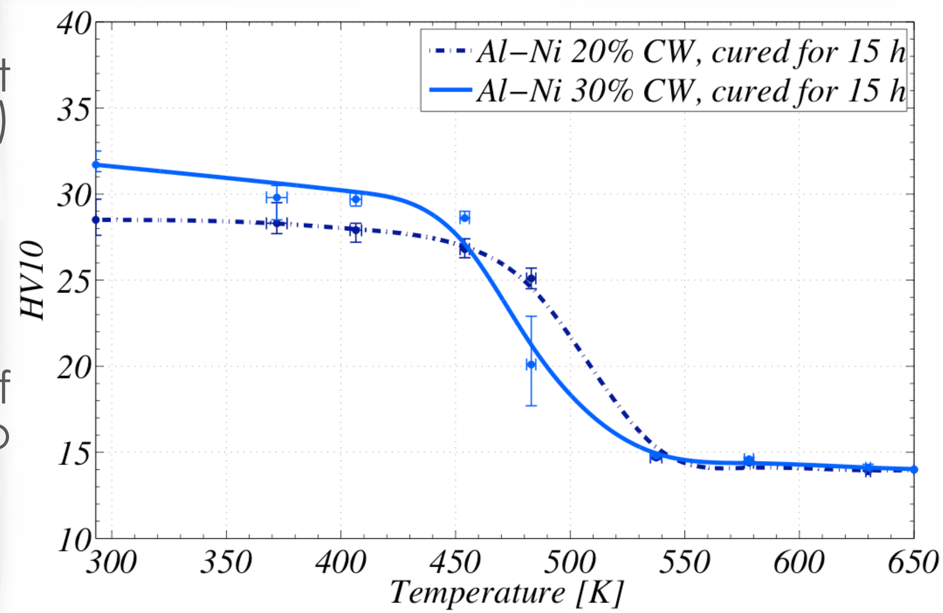
Clear temperature range where recovery of lattice defects takes place; reversing work-hardening.

- ➜ 470 K – 530 K for 20% reduced
- ➜ 450 K – 510 K for 30% reduced

Coil resin curing should not exceed temperatures (for 15 h) of:

- ➜ 470 K for 20% reduced
- ➜ 450 K for 30% reduced

No indication was found of precipitation hardening due to artificial aging.



Hardness, HV10, of 20% and 30% single pass cold-rolled short samples subjected to various thermal treatments with a duration of 15 h.