STATUS OF THE WOUND CONDUCTOR TASK

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Mechanical coil characterization by measurement and simulation

- **What can we measure directly in the Nb_3Sn coils or a magnet assembly**
- Winding tension during the winding process
- Coil geometry after impregnation (no ext. stress)
- Stress condition on shell assembly, axial stress reaction on end support plates, rods
- Strain conditions on supporting structures (collar nose in case of 11T)
- Pressure sensitive foils can provide information on pole and midplane stress and the related distribution

- **What we currently can not measure**
- Conductor stress-strain state during coil fabrication, magnet assembly, cooling & operation

- **What do we currently estimate from simulations**
- Stress-distribution in the coil cross-section (mainly in 2D) to develop knowledge on required pre-stress at ambient temperature, achieved precision is strongly depending on input parameters

- **Shimming of coils** to achieve and keep pre-stress during different operation conditions (cooling – operation) is presently based on the measured coil geometry and stress estimation from FEA simulations using the stiffness measurements from 10-stack sample (stacked cables comparable to coil cross-section)

CHARACTERIZATION OF Nb_3Sn WOUND CONDUCTOR

Irreversible degradation

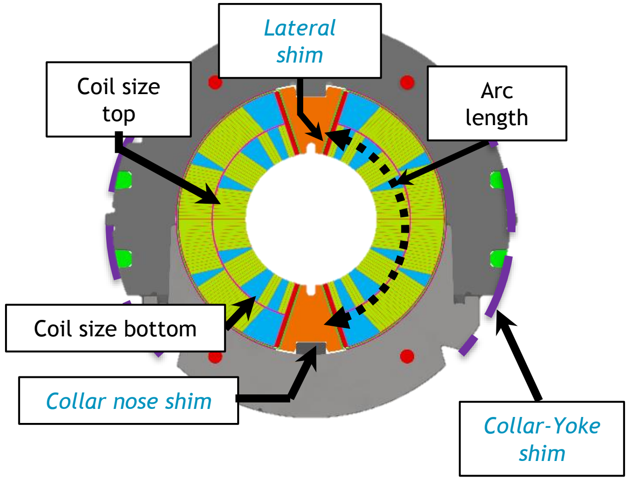
- Quantify irreversible degradation of the conductor during the magnet assembly at RT
- Develop knowledge about stress distribution on Rutherford cable stack under the transversal load

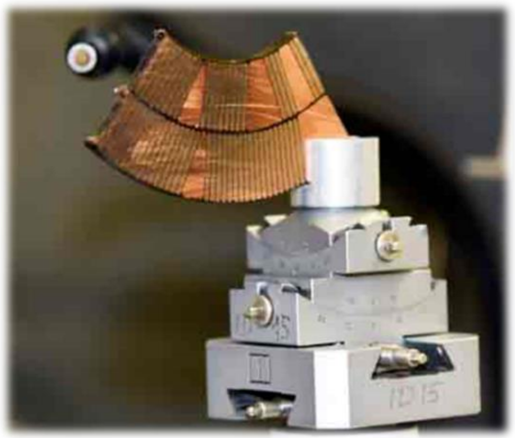
Windability

- Development of winding test setup to define a “windability factor” allowing comparison between different Rutherford cables
- Development of adequate scanning method to quantify strand displacements during the winding process

Material characterization

- Improving knowledge of magnet material parameters for refinement of FE modelling
- Improved FE meshing using tomographic coil characterization





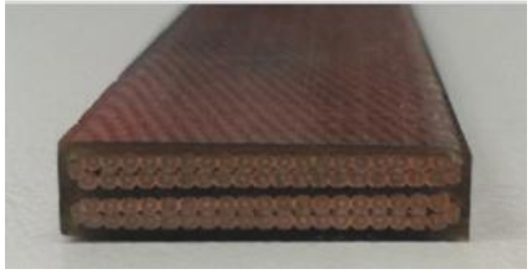
I_C DEGRADATION AFTER TRANSVERSAL PRESSURE AT RT

- The dominating load case in accelerator magnets is **transverse compressive**
- Coils are **loaded during the assembly, cooling, powering, quenching & thermal cycles**
- Experimental results about the room temperature (RT) stress limits of Nb_3Sn wires, cables and coils at which **irreversible conductor degradation** occurs are lacking
- The ongoing experiment aims to determine the **critical RT transverse compressive stress limits of cured, reacted and impregnated Nb_3Sn coil components**
- The degradation is quantified in terms of **critical current and n-value**

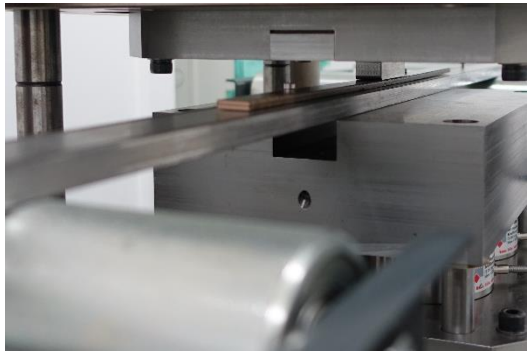
TESTING SEQUENCE

- The Ic of a reacted and impregnated two stack cable sample is measured in FRESCA
- Sample is taken out from FRESCA and compressed in a controlled manner at ambient temperature
- The sample is re-measured in FRESCA to check if, and by how much the compression has modified the I_C

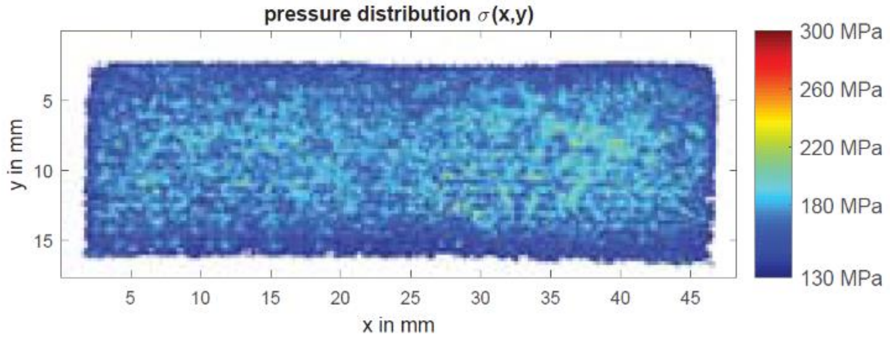
The test setup has been optimized in order ensure a known pressure distribution during the load step



FRESCA sample, RRP – Nb_3Sn 11T cable stack



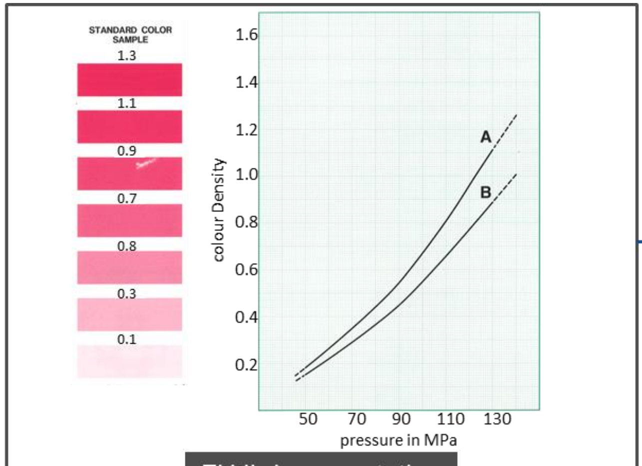
Cable compression on hydraulic press



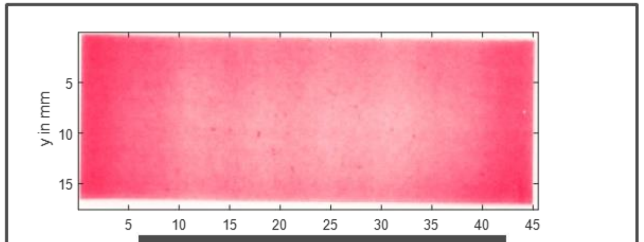
Improved knowledge on stress-distribution

OPTIMIZATION OF THE LOADING STEP

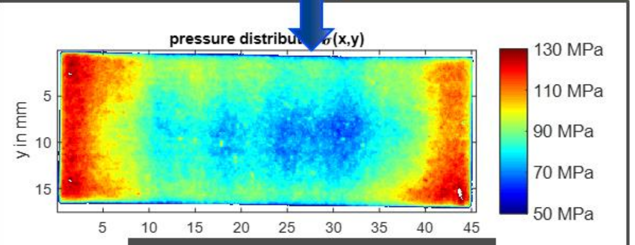
- Pressure measurement films from FujiFilm are used to measure the pressure distribution during the loading cycle
- We optimized the pressing tool to provide a reasonable uniform pressure on the sample



FUJI documentation

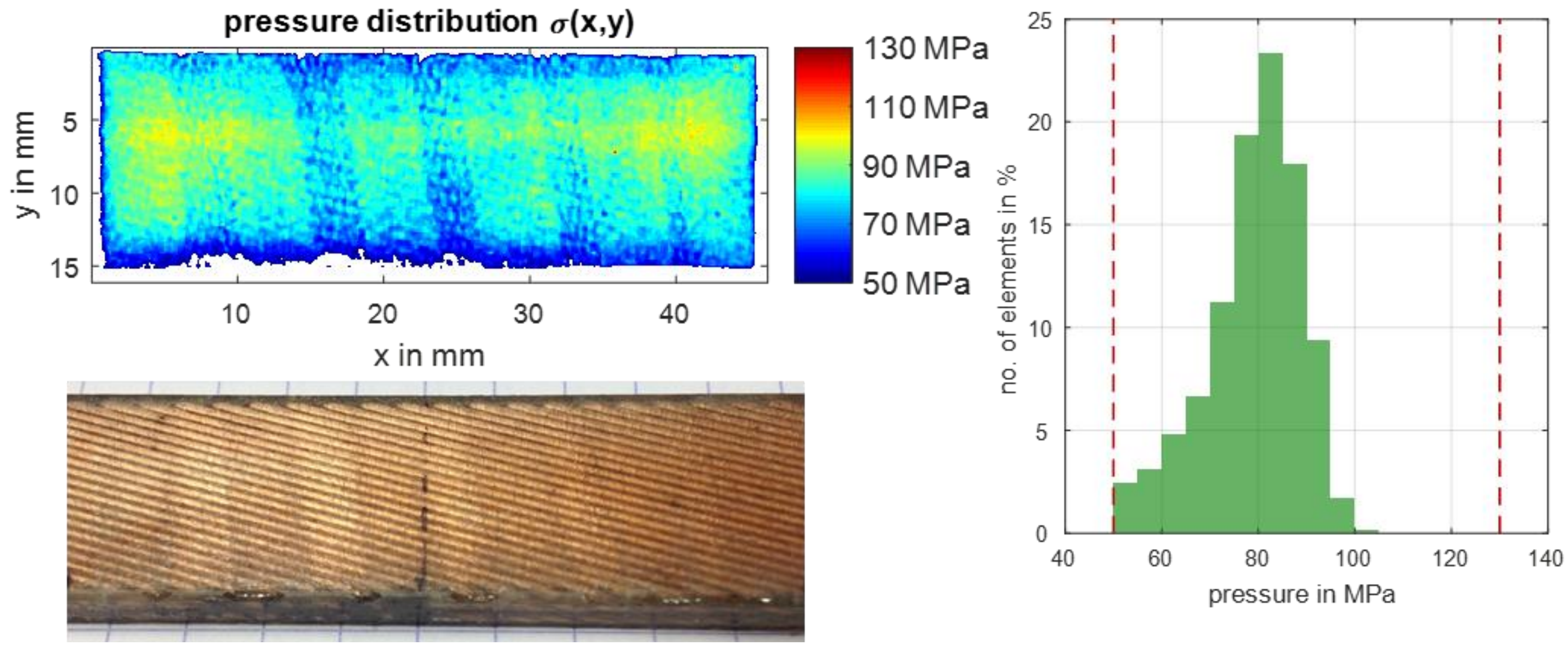


Colour scan



Pressure steel on steel

CASE 2 Steel – 8x polyimide foil – cable 85 MPa



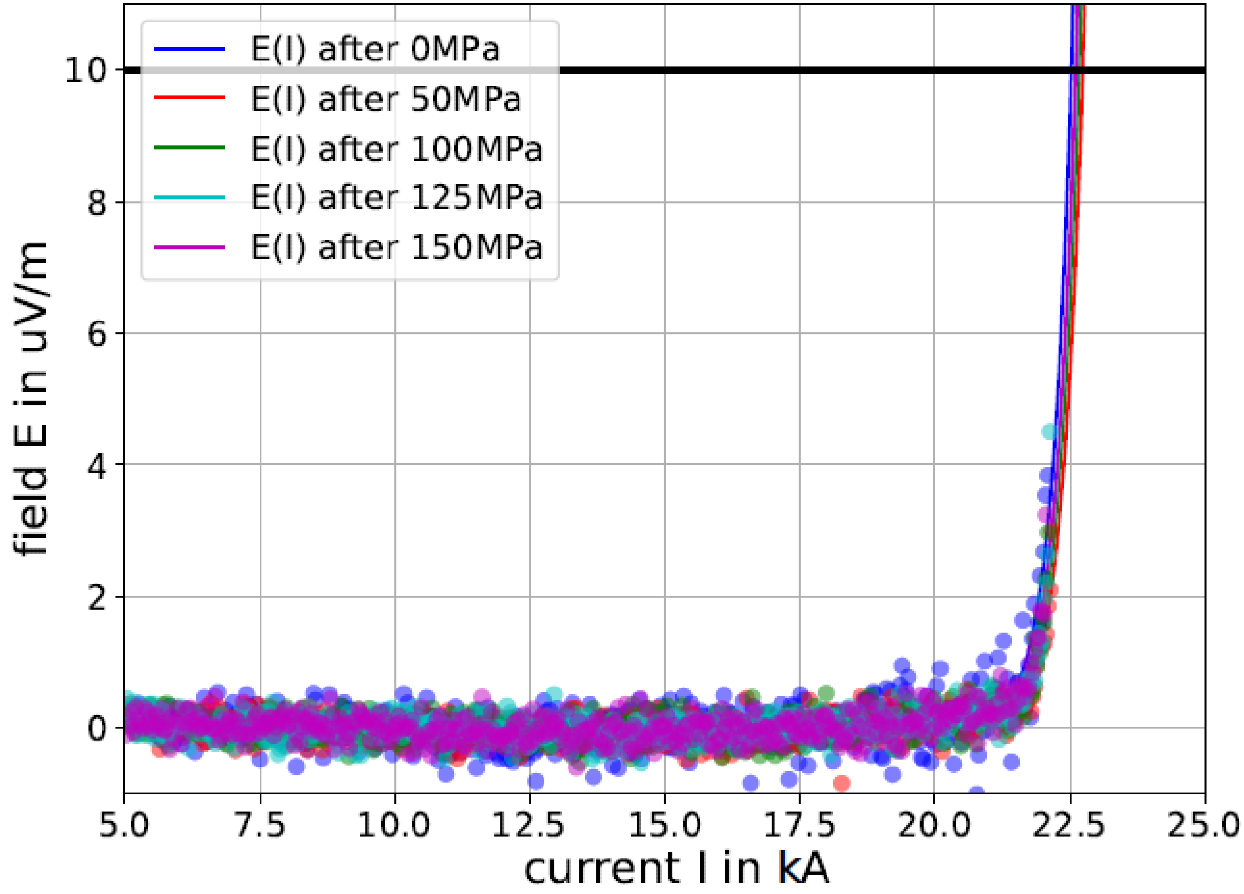
Courtesy of P. Ebermann & F. Wolf

RESULTS

- ❑ Comparison of fitted voltage-current-curves at *B*app = 9.6 T at *T* = 4.2 K
- ❑ No degradation observed up to 150 MPa

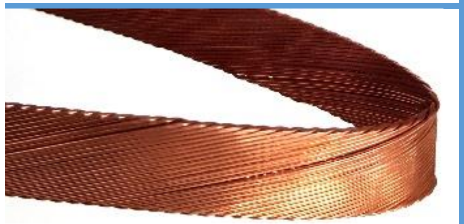
$\sigma_{desired}$	$I_c\|_{B_{app}=9.6\,\mathrm{T}}$	ε
MPa	kA	$\%$
0	22.5	0
50	22.7	0.9
100	22.7	0.9
125	22.6	0.4
150	22.6	0.4
175*	—	—

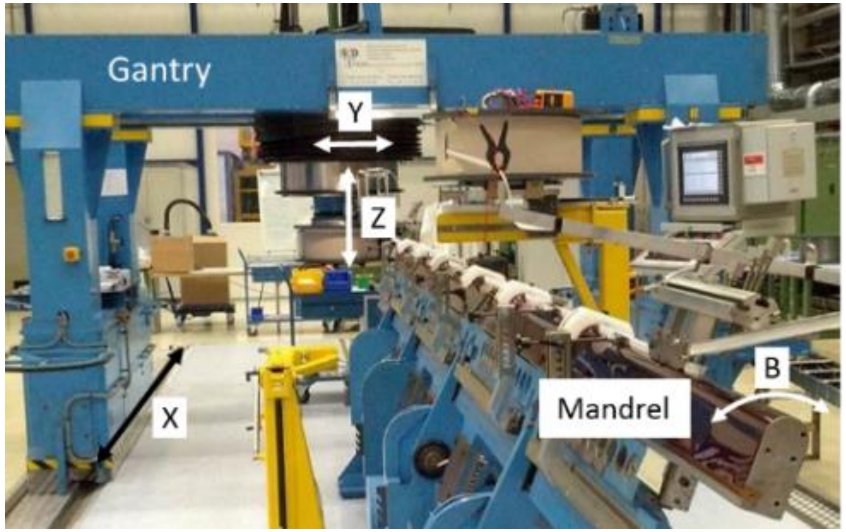
* Measurements are ongoing on 31st of May. First results at 4.2 K show relative degradation ε in the order of 2 – 3 %



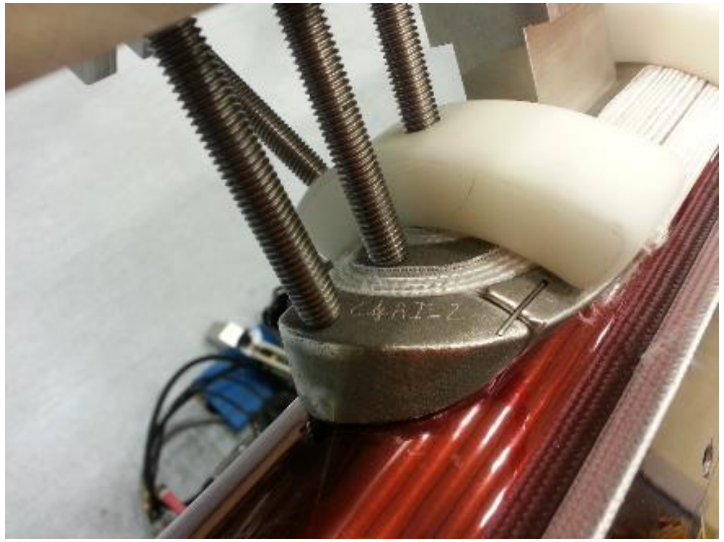
WINDABILITY

- Measure and model the geometrical evolution of cables during winding.
- Identification of the parameters dominating this process to possibly provide feedback for cabling & winding.
- Set-up a standard to quantify a “windability factor” or similar.

Rutherford cable behavior	Instability
	Opening
	Tightening
	Decabling
	Strand pop-out



CERN-LMF, 11T dipole winding machine

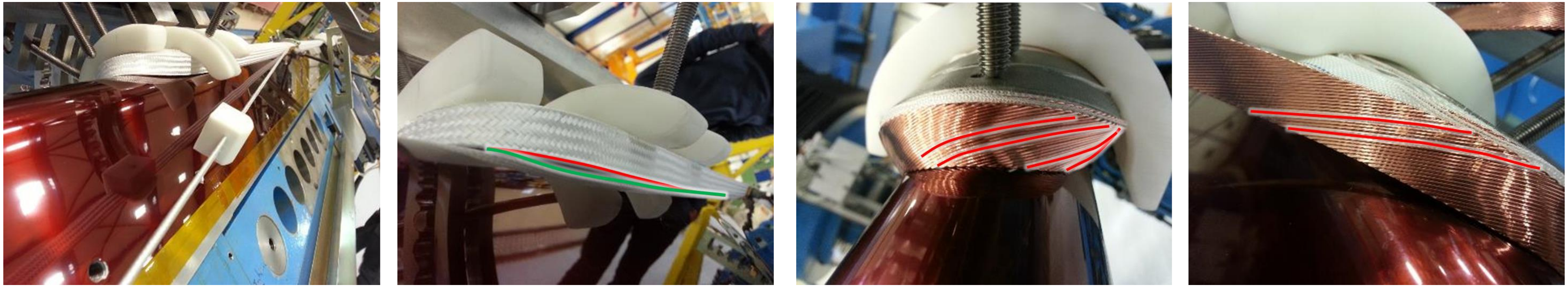


CERN-LMF, 11T dipole pole end

Courtesy of D. Pulikowski

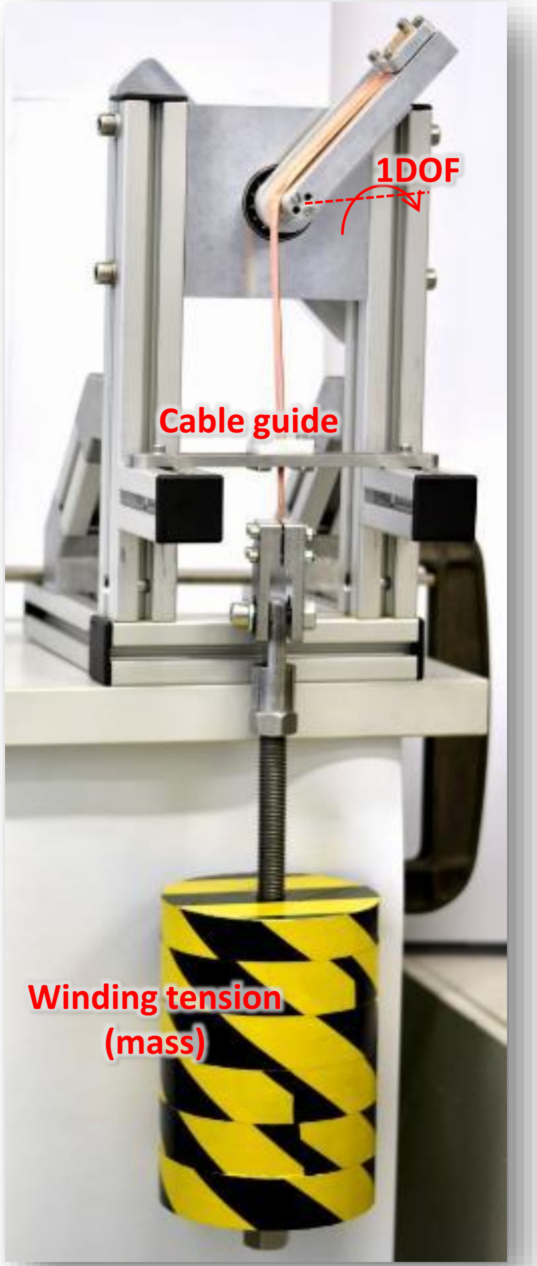
Typical findings during the winding of Nb_3Sn coils

- ❑ Protrusion from the mandrel surface
- ❑ Strand pop-out

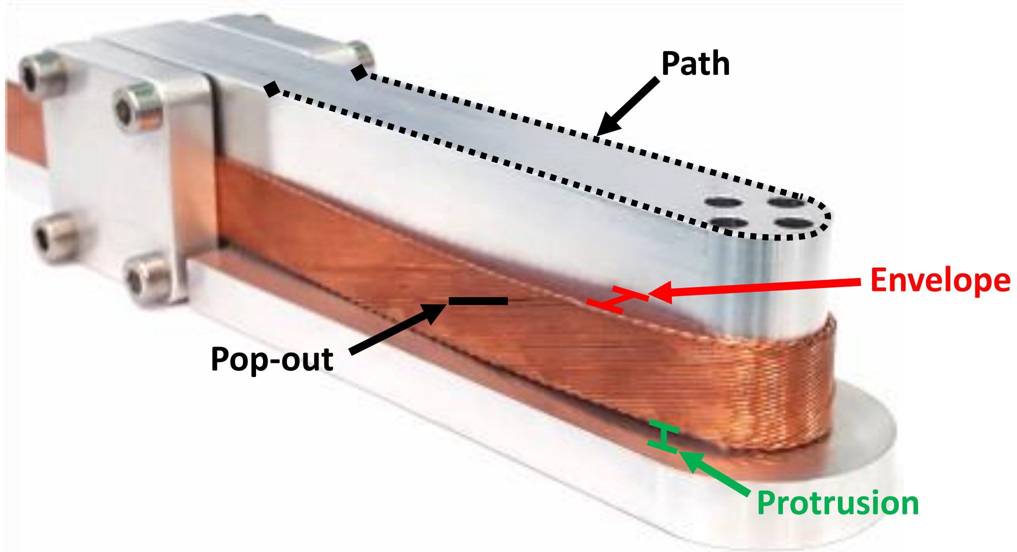


- ❑ Quantify geometrical displacements due to observed instabilities
- ❑ Proposal and definition of a "windability factor" allowing to compare results of different cable geometries

1 DOF WINDING MOCKUP

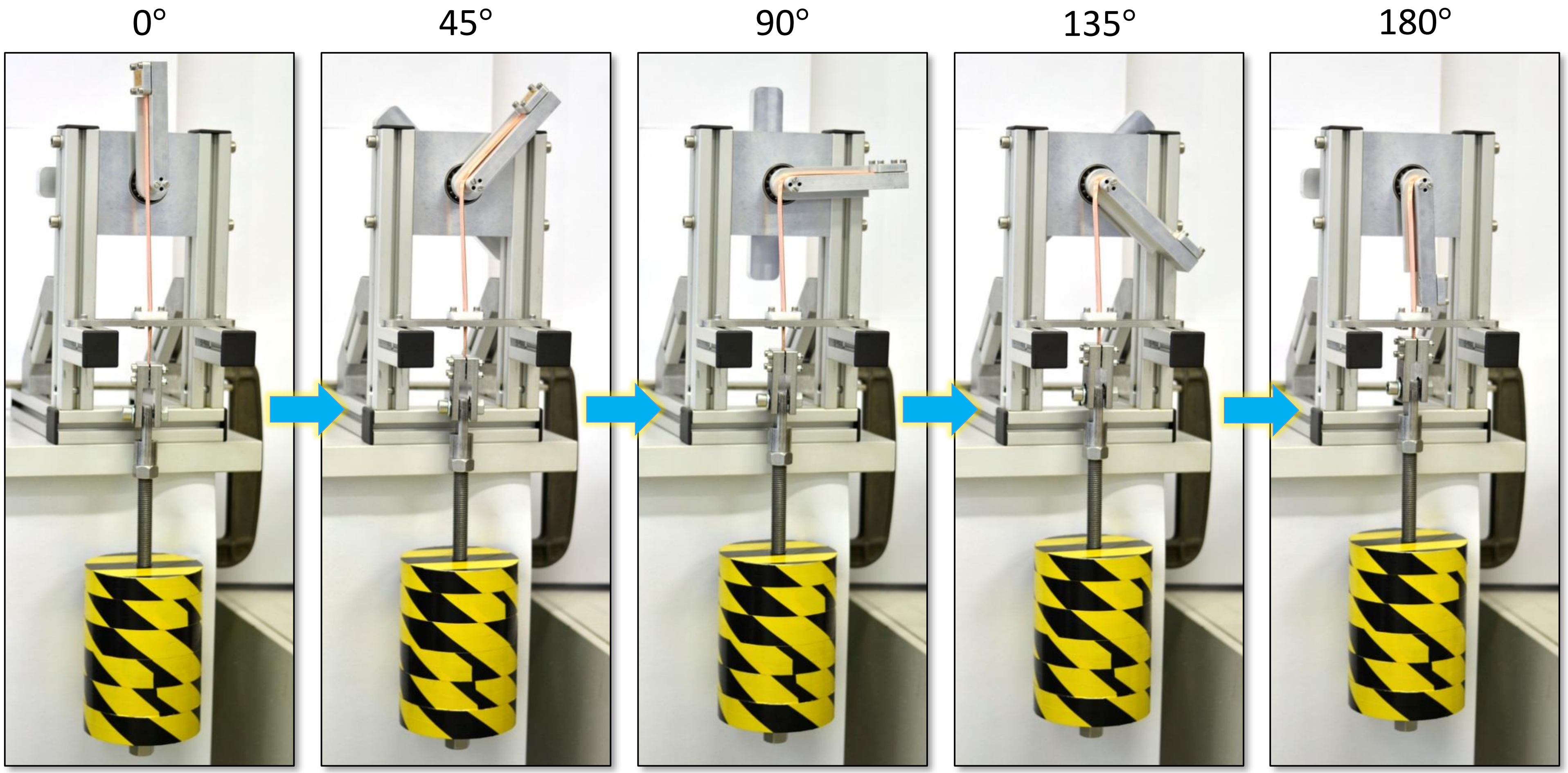


- ❑ Allows to wind specimens with the **Rutherford type cables in 1 DOF**
- ❑ Provides repeatable conditions;
- ❑ **Allows to adjust several winding parameters:**
  - ❑ Winding tension, Bending radius, Cable guide position and angle & winding direction.

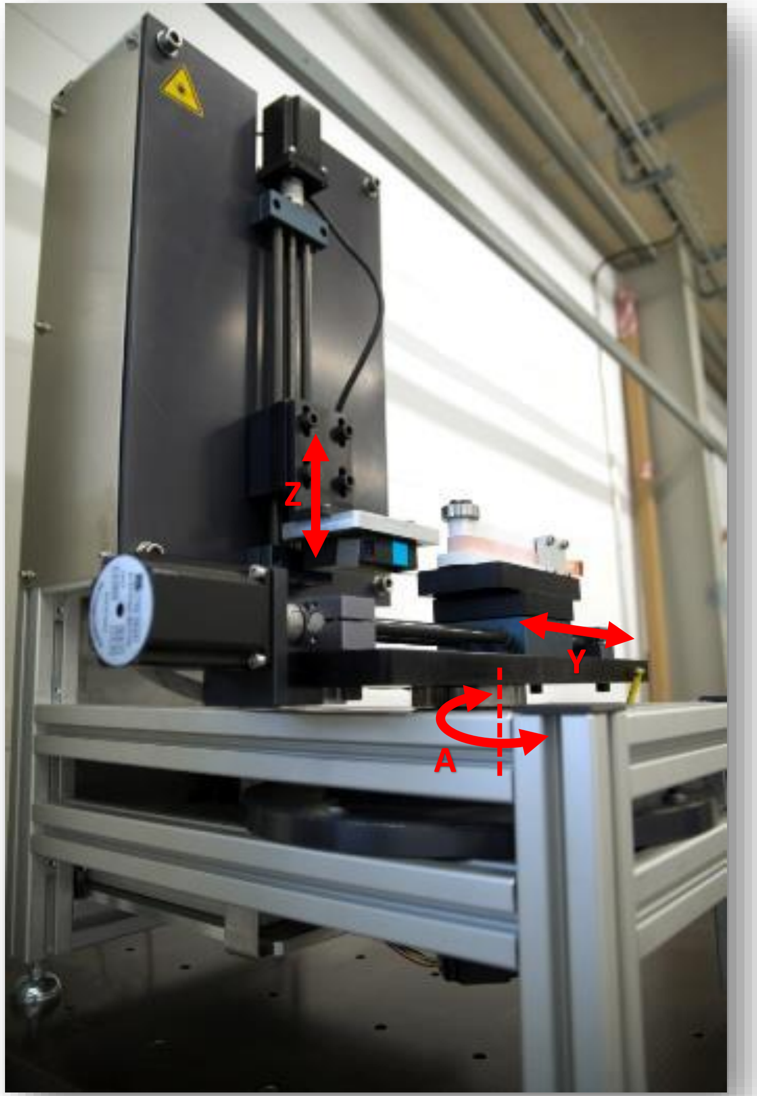


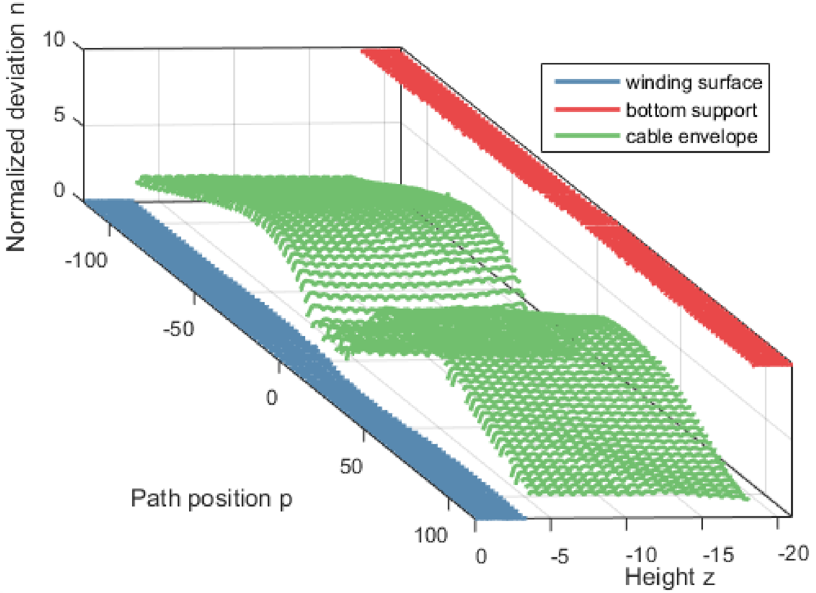
Sample holder for winding tests

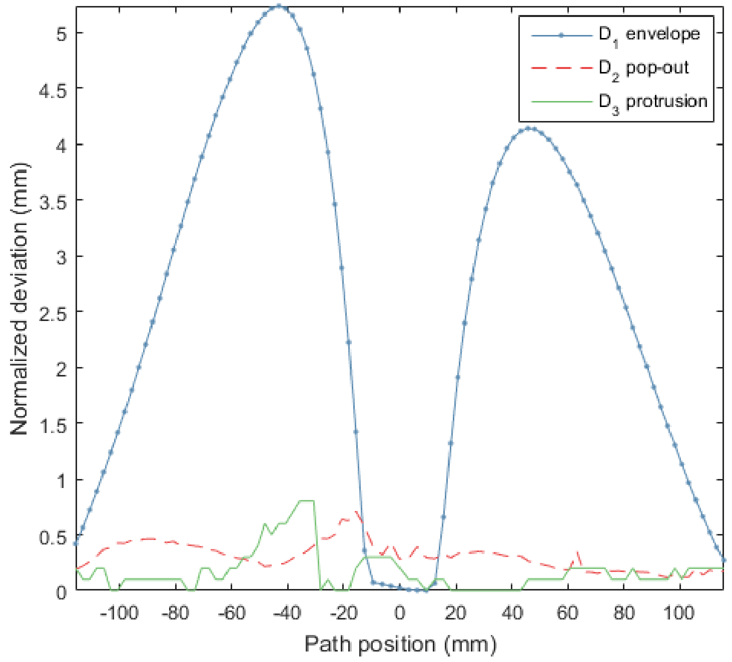
1 DOF WINDING MOCKUP

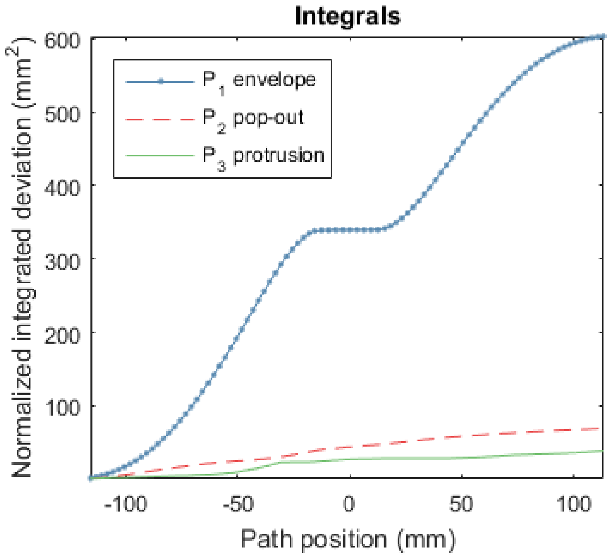


1 DOF WINDING SCANNER



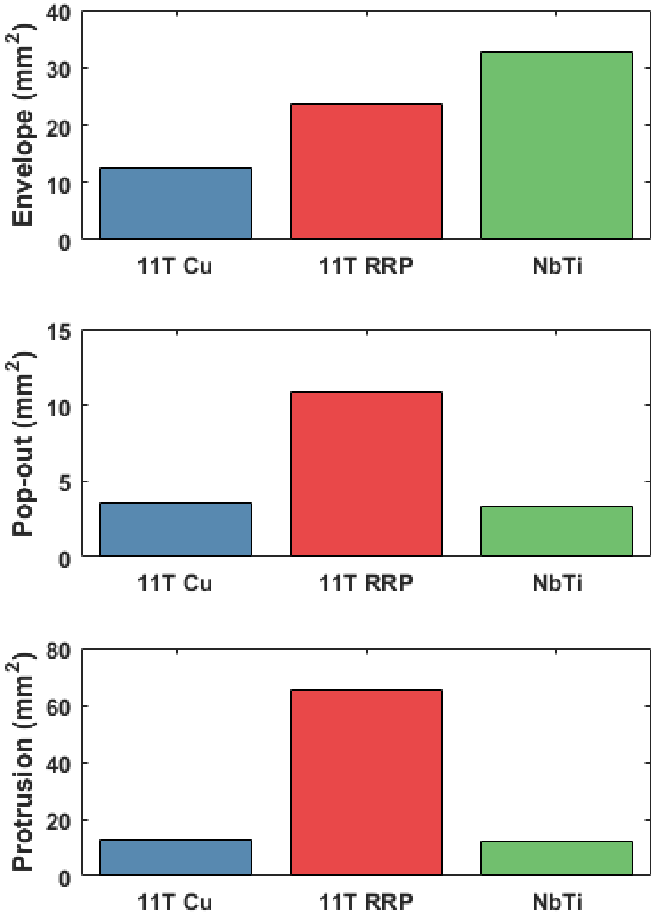




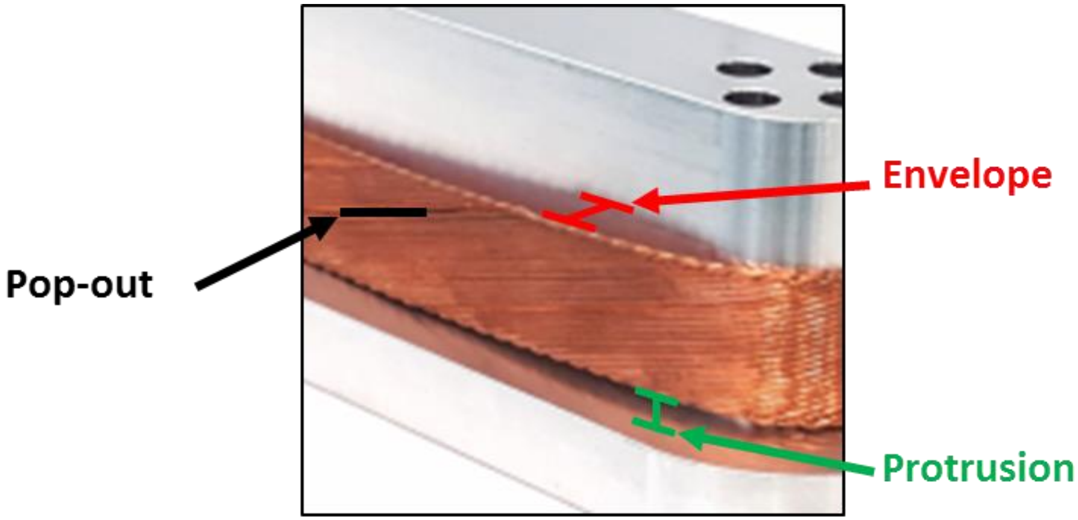


WINDING STABILITY OF Cu, Nb-Ti AND RRP Nb_3Sn CABLES

Stability of the winding is the average standard deviation (1σ) of three specimens for each winding tension and direction.

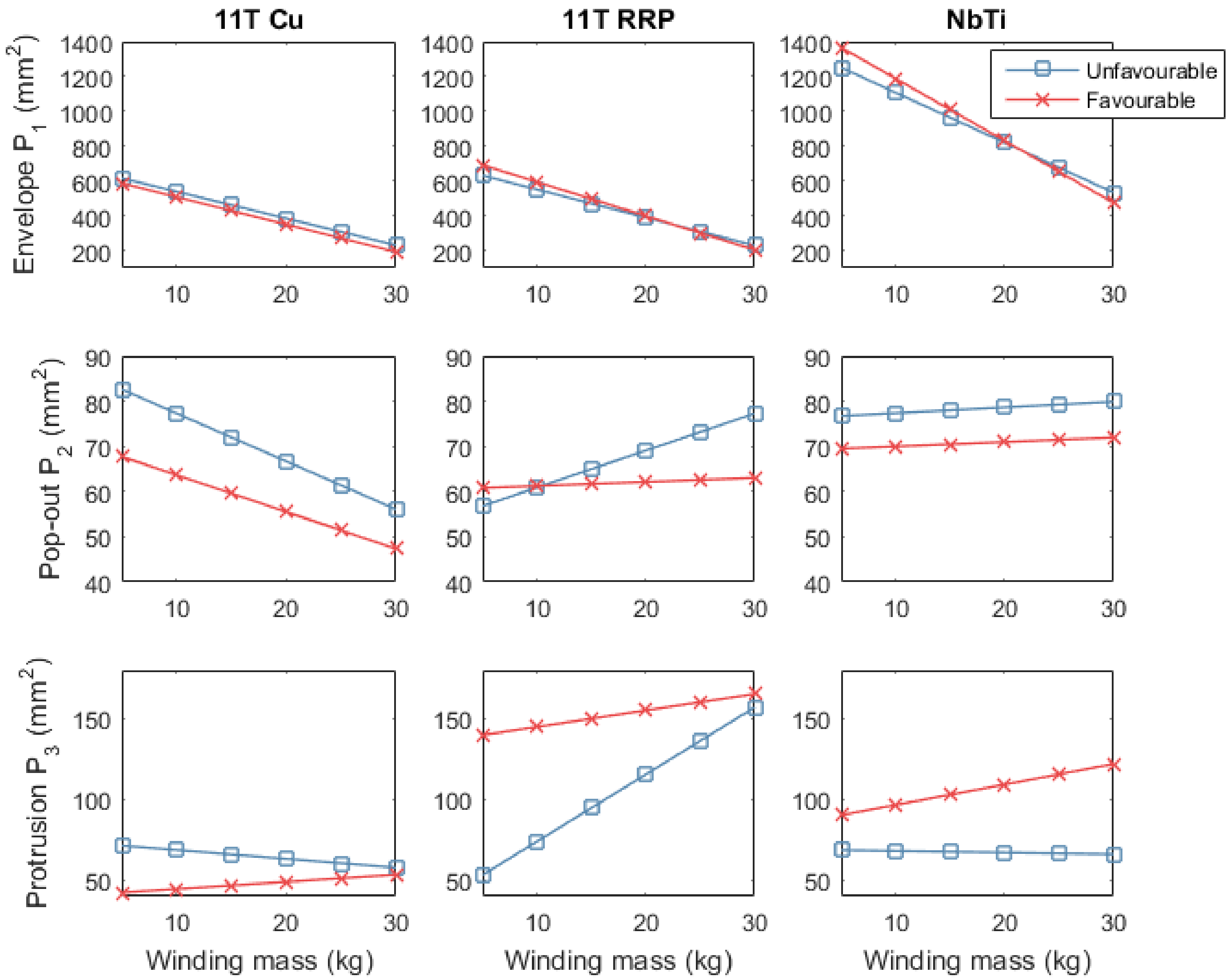


- It describes the performance spread for one parameter set.
- Nb-Ti shows the worse envelope instability.
- 11T RRP shows multiple times larger winding instability of pop-out and protrusion.

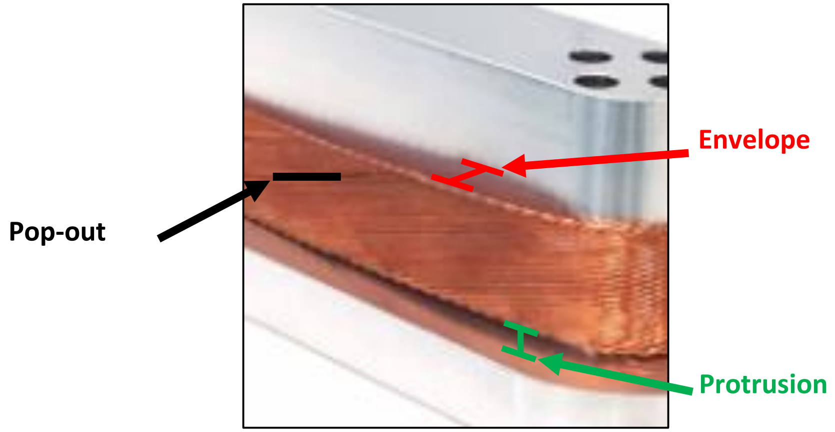


WINDING STABILITY OF Cu, Nb-Ti AND RRP Nb_3Sn CABLES

Preliminary results on first samples:



- Envelope trends are declining, the smallest deformation is achieved by 11T Cu cable.
- Pop-out: Nb-Ti shows least dependence on the winding tension.
- Larger protrusion deformation in favourable direction for 11T RRP and Nb-Ti.



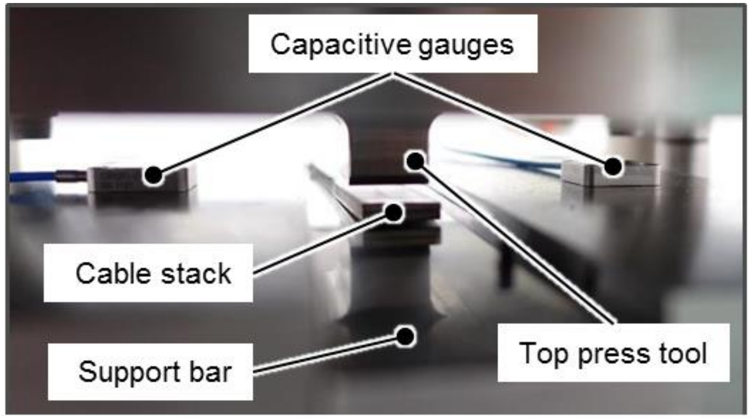
Impact of insulation and impregnation conditions on the coil stiffness

Variables:

- ❑The insulation (e.g. impact of Mica foil)
- ❑The impregnation (variation of compaction level of the cable stack)
- ❑The sample length (15 mm, 30 mm, 100 mm)

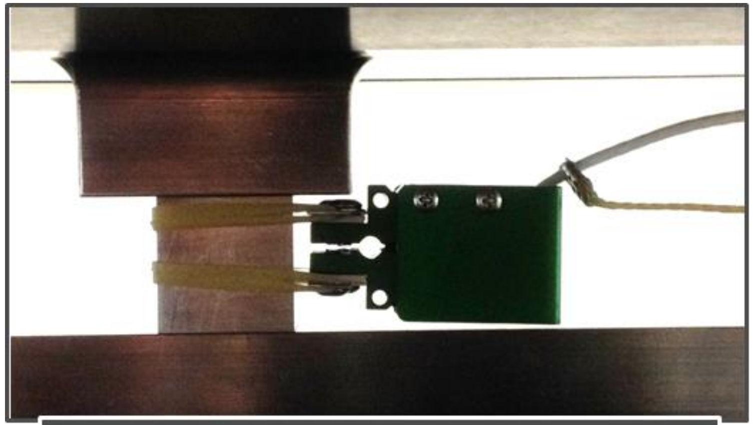
Measurements:

- ❑Force measurement by calibrated load cells in the force line of a hydraulic test setup
- ❑Displacement measurement direct at the sample with an extensometer
- ❑Displacement measurement of the press tools by capacitive gauges



Displacement measurement by capacitive gauges

Courtesy of F. Wolf



Calibration measurement with Ti-Al6-V4

FURTHER ACTIVITIES

Thermomechanical properties of a Nb_3Sn coil (11 T) and tooling constituents in collaboration with **Federal Laboratory for Materials Research and Testing (BAM), Berlin**.
Young's moduli, shear moduli, Poisson ratio and thermal expansion coefficients vs temp (-150°C to 700 °C).
To be completed by September 2017.

Friction coefficients between 11 T dipole materials pairs in collaboration with **Federal Laboratory for Materials Research and Testing (BAM), Berlin**. Friction measurements are performed at RT and in LHe. Materials pairs are TiAlV on 316L shim, TiAlV on Polyimide, steel on Polyimide, and the effect of MoS2 coatings on friction is studied (at RT and in LHe). To be completed by September 2017.

Nb_3Sn strain state distribution in a 11 T dipole coil, in collaboration with **ID15A beamline of European Synchrotron (ESRF)** and **StressSpec beamline at Heinz Maier-Leibnitz Zentrum (MLZ), Munich.**
Nb_3Sn strain state distribution at RT and at 10 K without externally applied stress
Nb_3Sn strain state distribution at RT with external stress applied through steel collars

Tomographic studies of the Nb3Sn conductor in 11 T dipole coils in collaboration with **Federal Laboratory for Materials Research and Testing (BAM)**, **Berlin, ANTARES beamline at Heinz Maier-Leibnitz Zentrum (MLZ), Munich, and Fraunhofer Institute for Industrial Mathematics (ITWM), Kaiserslautern**. Determination of the 3D shape of Rutherford cables in coils. To be completed by September 2017.

CONCLUSIONS

- The results coming from the characterization of the irreversible cable degradation at RT, though very preliminary seem encouraging and support the choices performed within the EuroCirCol study

- The winding setup may allow to define a windability factor useful for future cable development and winding process (robust and repeatable quality, production time)

- The study of the stiffness of cable stacks depending on their manufacturing procedure has been started

- A number of studies are under way to refine input parameters and meshes for FE analysis, and to characterize the internal stress distribution in Nb_3Sn coils