Characterisation of accelerator magnet coils and coil constituents using neutron and synchrotron sources

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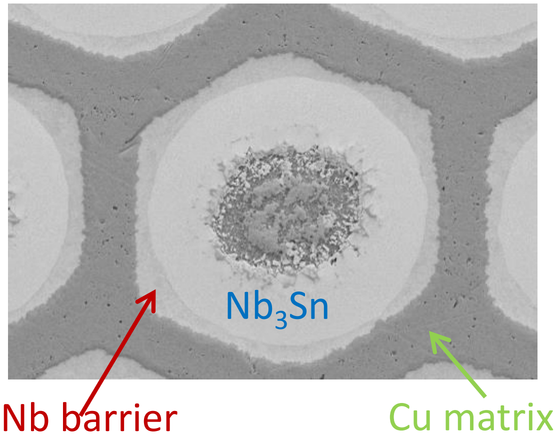
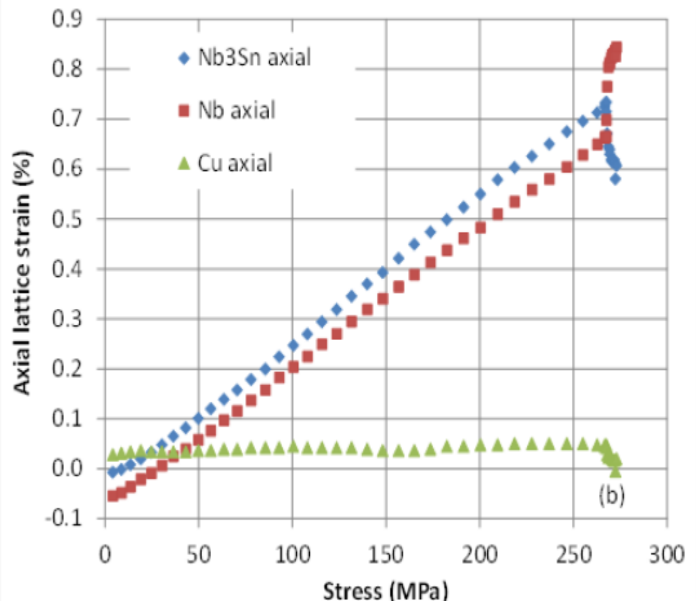
Outline

- Residual and applied strain in wires
- Residual strain mapping in coil cross sections
- Residual strain in massive coil segments
- Applied strain in the collared coil
- Neutron radiography of the collared coil
- Conclusion and outlook

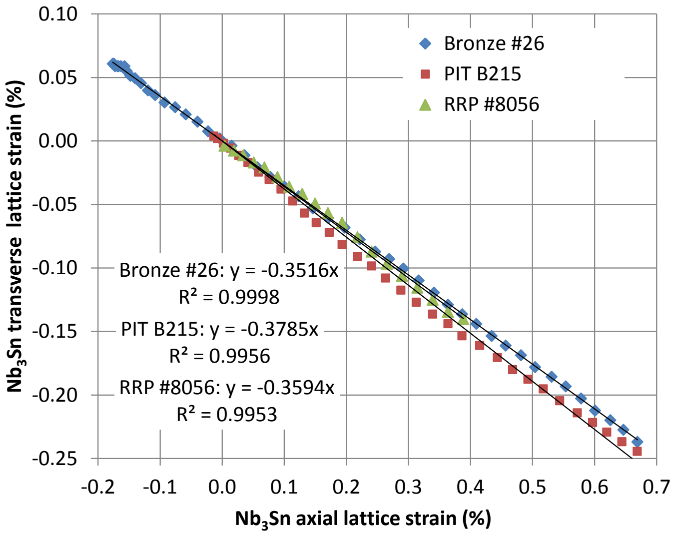
Residual and applied elastic strain in the Nb_3Sn wire constituents under uniaxial tensile loading at 4.2 K

- Elastic strain in wires is most conveniently measured by high energy synchrotron X-ray diffraction (XRD) in transmission geometry with an area detector.
- With an area detector two strain directions can be measured simultaneously.
- XRD-stress-strain results show
  - Nb and Nb_3Sn axial pre-compression
  - Linear elastic behaviour of Nb and Nb_3Sn
  - Load transfer from Nb_3Sn to Nb
  - Almost no load is carried by the annealed Cu matrix





Axial lattice strain vs uniaxial tensile stress.

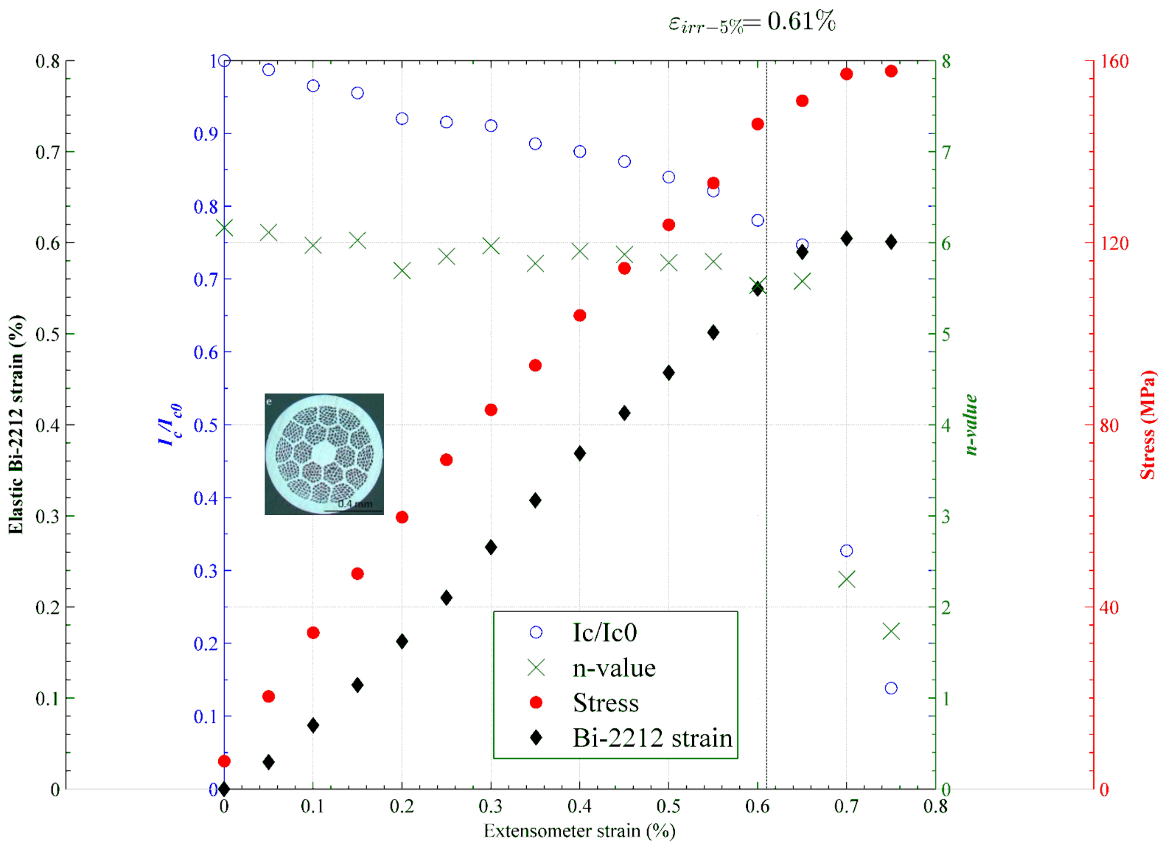


Comparison of the 4.2 K Nb_3Sn Poisson ratio in different wires.

Supercond. Sci. Technol. 27, (2014), 044021

Simultaneous measurement of Bi-2212 elastic strain, wire stress, strain, critical current and *n-value* at 77 K

Instrumented Bi-2212 wire with current leads, voltage taps and extensometer inside X-ray transparent cryostat.

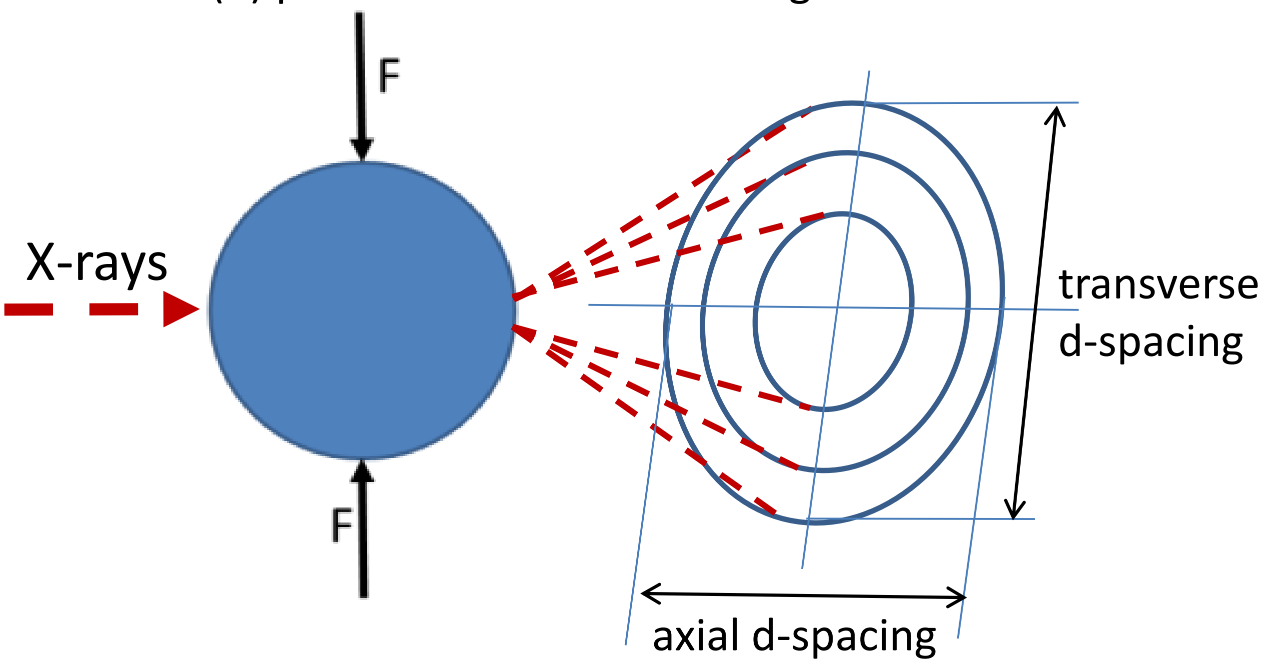


I_c, n-value, Bi-2212 elastic strain and stress as a function of the macroscopic wire strain of the OP processed Bi-2212 wire at 77 K

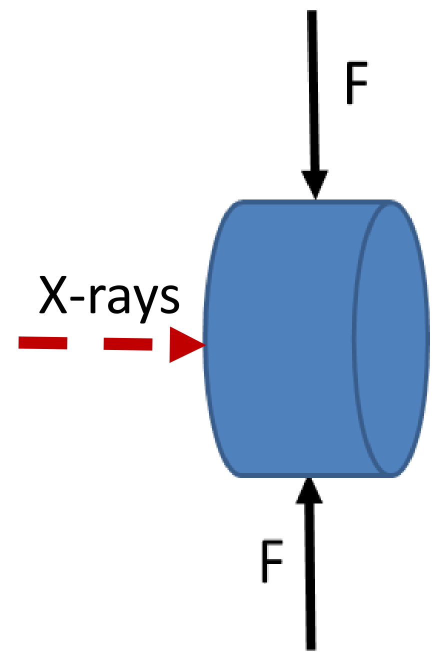
Supercond. Sci. Technol. 28, (2015), 062002

Measurement of elastic strain as a function of transverse compressive stress

- The main load case in accelerator magnet coils is transverse compression.
- Two possible test configurations for transverse compression tests with X-ray beam
  - (a) perpendicular to the wire drawing direction
  - (b) parallel to the wire drawing direction



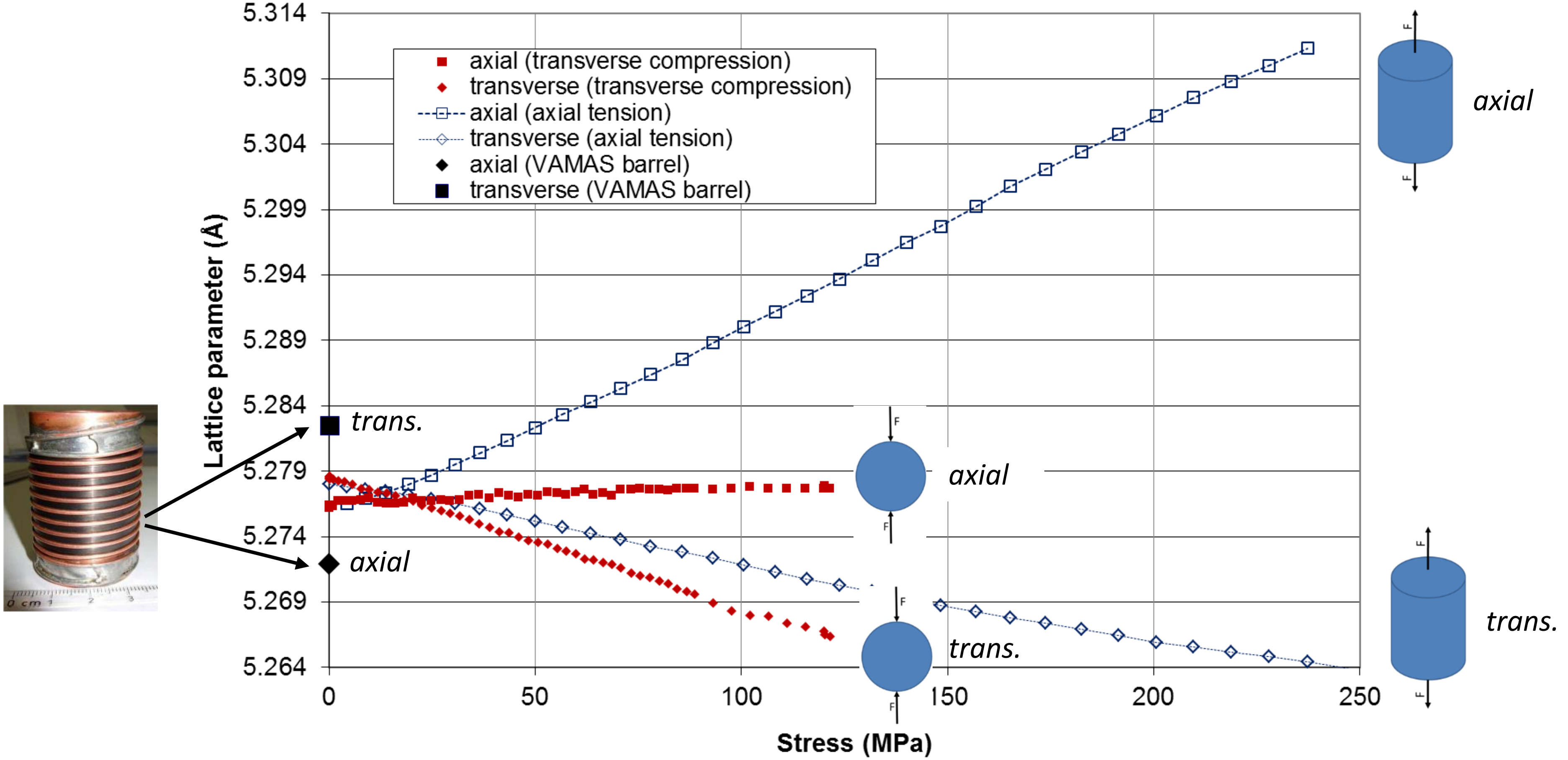
(a) Beam perpendicular to drawing direction.



(b) Beam parallel to drawing direction.

Axial and transverse Nb_3Sn lattice parameter changes as a function of axial tensile and transverse compressive stress

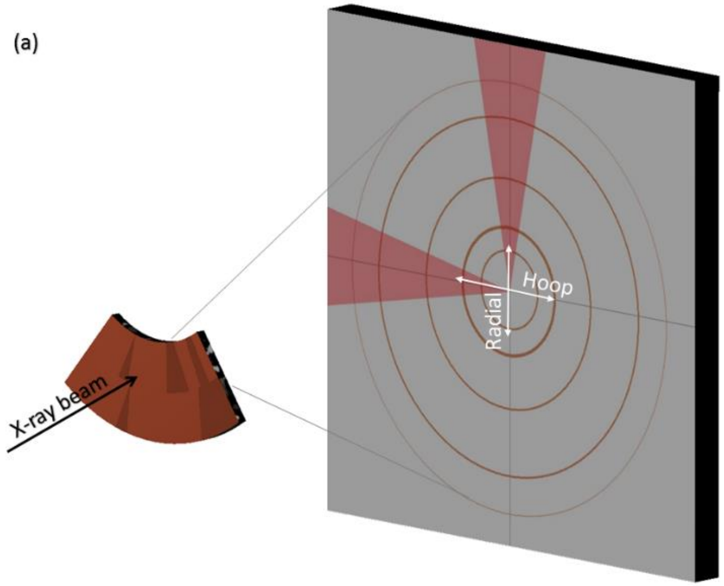
- Experiment performed in LHe cryostat in collaboration with Uni Geneva and ESRF (SuST 27, (2014), 044021).
- Nearly linear lattice spacing vs stress dependence.
- Slight d-spacing change in axial direction under transverse compression.
- Different axial Nb_3Sn pre-compression in straight wire and in wire on VAMAS barrel.

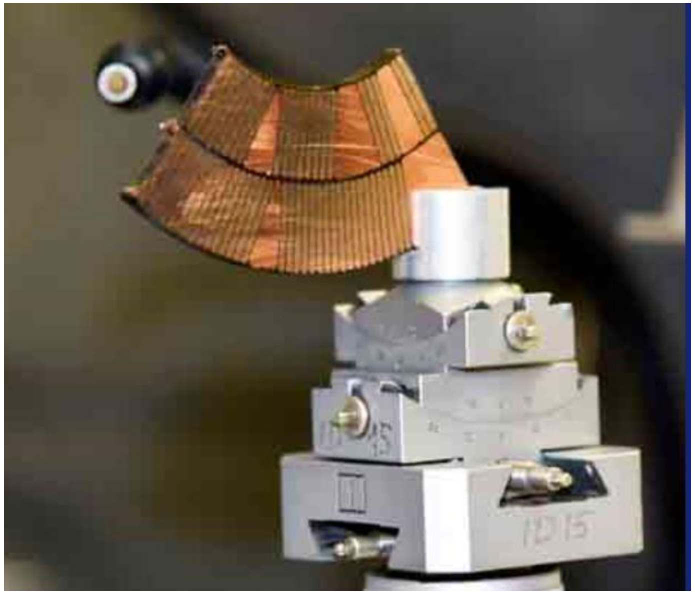


Nb_3Sn lattice parameter in axial and transverse direction as a function of axial tensile or transverse compressive stress. The results for the same PIT wire on a VAMAS barrel are shown for comparison.

Residual strain mapping across Nb_3Sn coil sections

- At ID15A beamline of ESRF with 150±0.3 keV X-ray beam.
- Very high photon flux and highly sensitive fast readout detector enable the acquisition of about 5’000 diffractograms per hour.
- Small sample to detector distance uncertainties are eliminated by acquiring a second strain map after 180° sample rotation, and averaging the results.
- Strain is measured in “radial” and “hoop” directions (not in “axial” direction).
- The “axial” lattice spacing was measured in extracted wires with beam perpendicular to the drawing direction. Nb_3Sn is under slight axial compression of about 0.01%, and Cu under slight axial tension of about 0.02%.

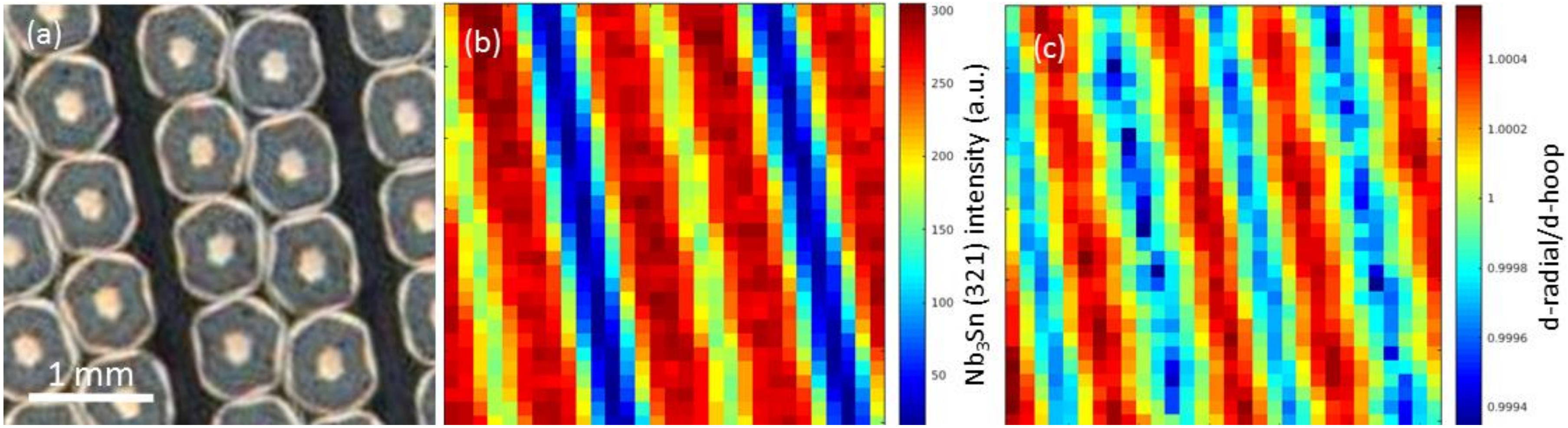




(a) Sketch of ID15A test configuration. (b) 11 T coil slice on the goniometer of the ID15A sample stage.

High spatial resolution strain maps

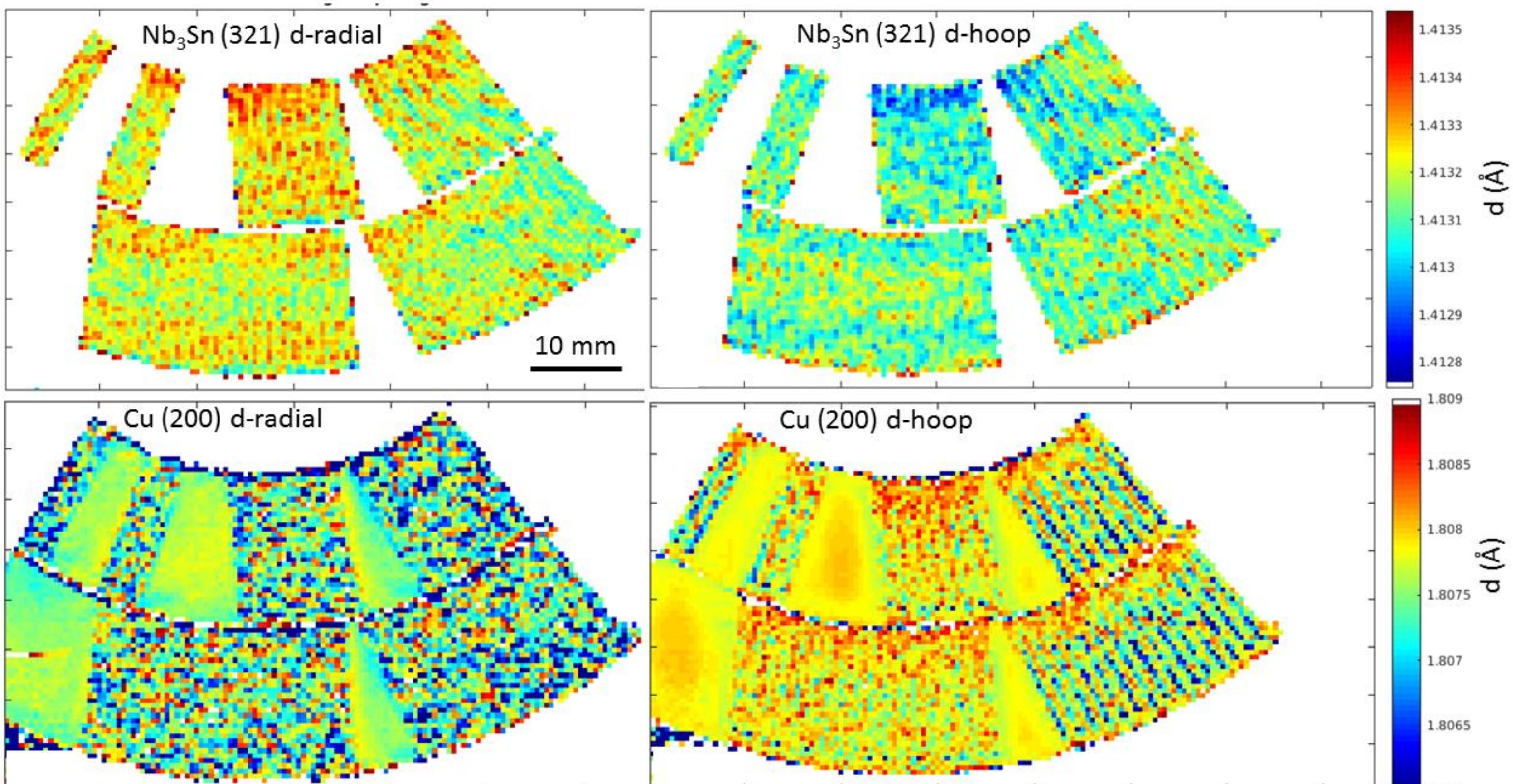
- 3×3 mm^2 area in the conductor block was scanned with a step size of 100 µm
- Photon beam cross section was 200 µm × 200 µm.
- The radial/hoop d-spacing ratio is shown instead of absolute d-spacing values because the ratio is not affected by sample to detector distance uncertainties.
- On the microscale the Nb_3Sn (321) d-spacing pattern is clearly correlated with the wire position within the coil, with lattice parameter variations of about ±0.03%.



(a) Micrograph of the conductor block center. (b) Nb_3Sn (321) peak area and (c) radial/hoop Nb_3Sn lattice parameter acquired by high resolution scans with 100 µm step size.

Nb_3Sn and Cu lattice spacing variations in radial and hoop direction

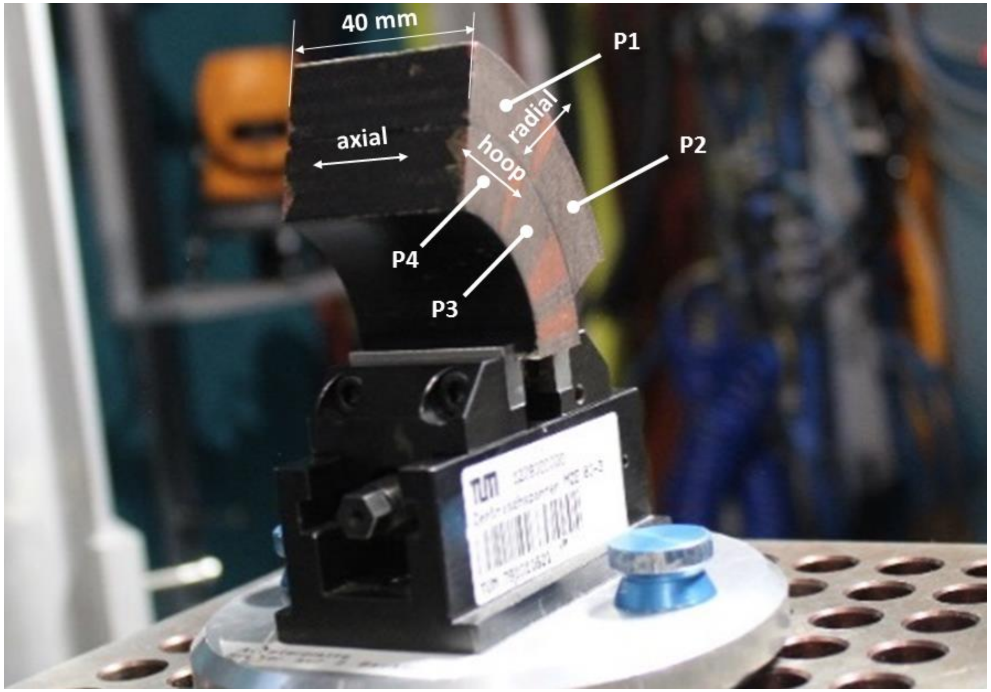
- Nb_3Sn (321) and Cu (200) strain maps in radial and hoop direction are calculated from 51'200 XRD pattern (the main Nb (100) peak is not present in this configuration).
- The Nb_3Sn (321) d-spacing is in average 0.01% smaller in the hoop direction than in the radial direction, while the Cu (200) d-spacing is slightly larger in hoop direction.
- The Nb_3Sn pattern might indicate a slight stress concentration at the cable edges. Such stress concentrations were also revealed by pressure sensitive tape measurements during coil assembly.



Nb_3Sn (321) and Cu (200) d-spacing distribution in the centre segment in radial and hoop directions.

Elastic strain measurement in massive coil segments

- Neutron diffraction experiments at the Stress-Spec diffractometer at the FRM II neutron source.
- Neutron beam wavelength λ=1.672 ±0.003 Å.
- Neutron penetration depth is mainly limited by absorption in the coil epoxy resin.
- Up to 4 cm thick coils can be measured in reflection geometry.
- Nominal gauge volume 5×5×5 mm^3.

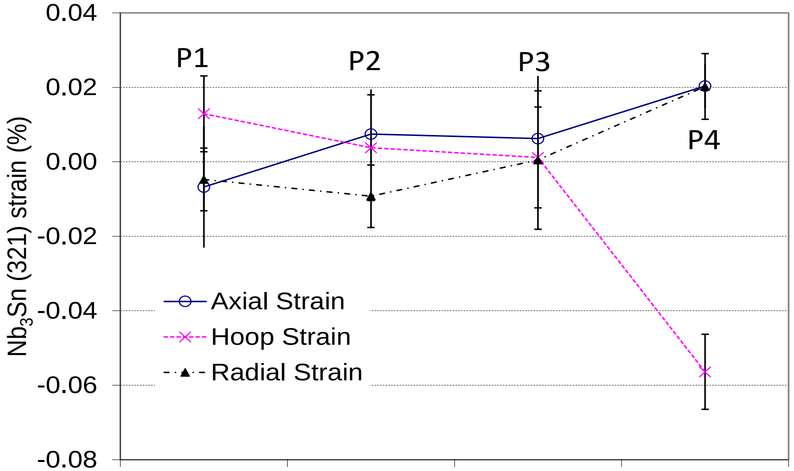


4 cm-long 11 T dipole coil segment on the Stress-Spec sample stage in axial test configuration. The gauge volume centre positions in radial and hoop position are labelled.

Residual strain calculation

- Residual Nb_3Sn (321) strain in axial, hoop and radial directions in the centre of the four largest conductor blocks of the 11 T coil segment.
- A significant Nb_3Sn residual strain value of -0.056±0.010% is found in P4 in hoop direction.
- The P4 conductor block at the coil midplane was presumably submitted to the highest stress during prior coil testing in a magnet.

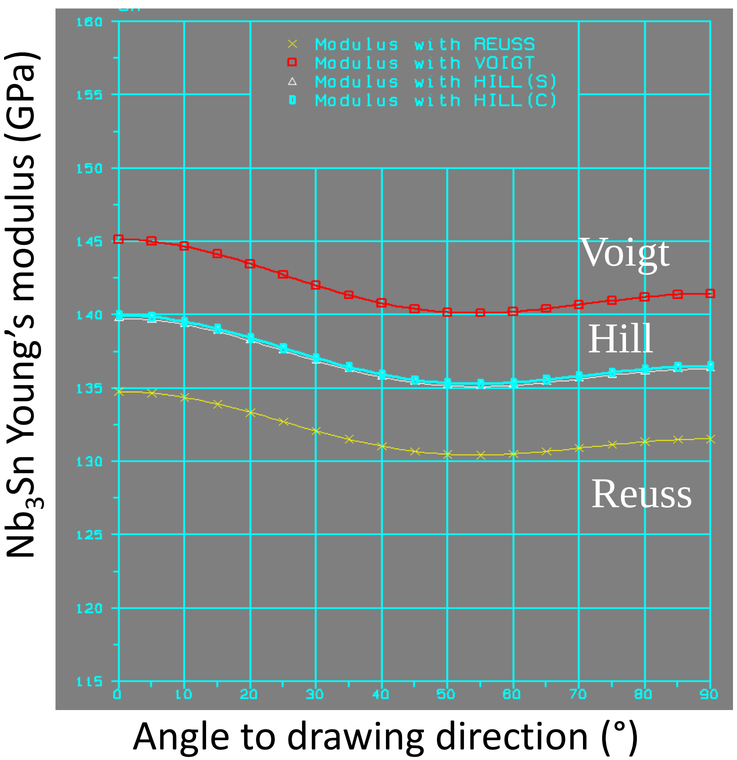
$$\varepsilon_{hkl} = \frac{d_{hkl} - d_{0,hkl}}{d_{0,hkl}} = \frac{\sin(\theta_{0,hkl})}{\sin(\theta_{hkl})} - 1$$



Residual Nb_3Sn (321) strain in axial, hoop and radial directions in the centre of the four largest conductor blocks of the 11 T coil segment.

Elastic anisotropy of the different coil constituents

- The mechanical properties of the coil materials are anisotropic and the angular dependence of the Young's modulus needs to be known for residual stress calculations.
- The angular dependence of Young's modulus can be calculated from the texture data and single crystal elastic constants.
- Texture measurements with StressSpec using 8×8×8 mm^3 cube samples.
- The DISCUP coil wedges are strongly textured which causes a strong elastic anisotropy of about 30%.

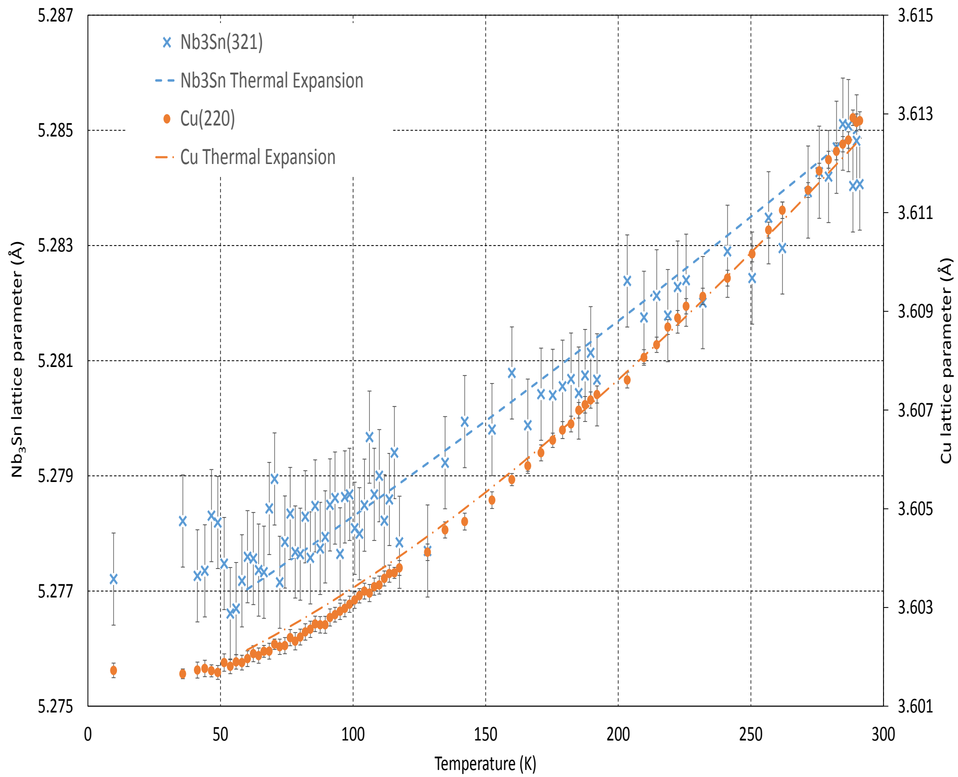


Angular Nb_3Sn Young's modulus dependence with respect to the wire drawing axis. Calculated assuming equal strains (Voigt) and equal stresses (Reuss) in all grains, respectively. Measurement and calculation courtesy of W. Gan.

Lattice parameter changes during cooling

- Nb_3Sn and Cu lattice parameter measurement possible in hoop and radial direction (for the calculation of residual strain the axial direction is missing).
- Relatively large statistical error in the Nb_3Sn lattice parameter measurements.

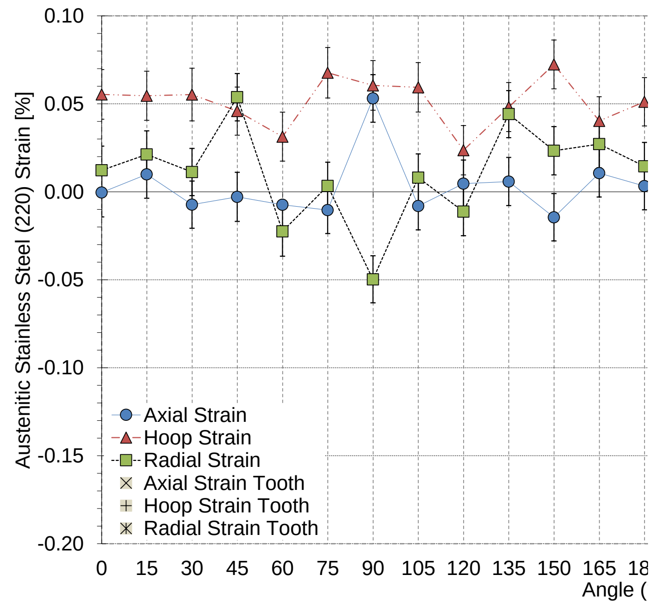
(a) 11 T dipole coil segment mount to the cryocooler cold head for measurements at cryogenic temperature. (b) Cryocooler on the StressSpec sample stage.



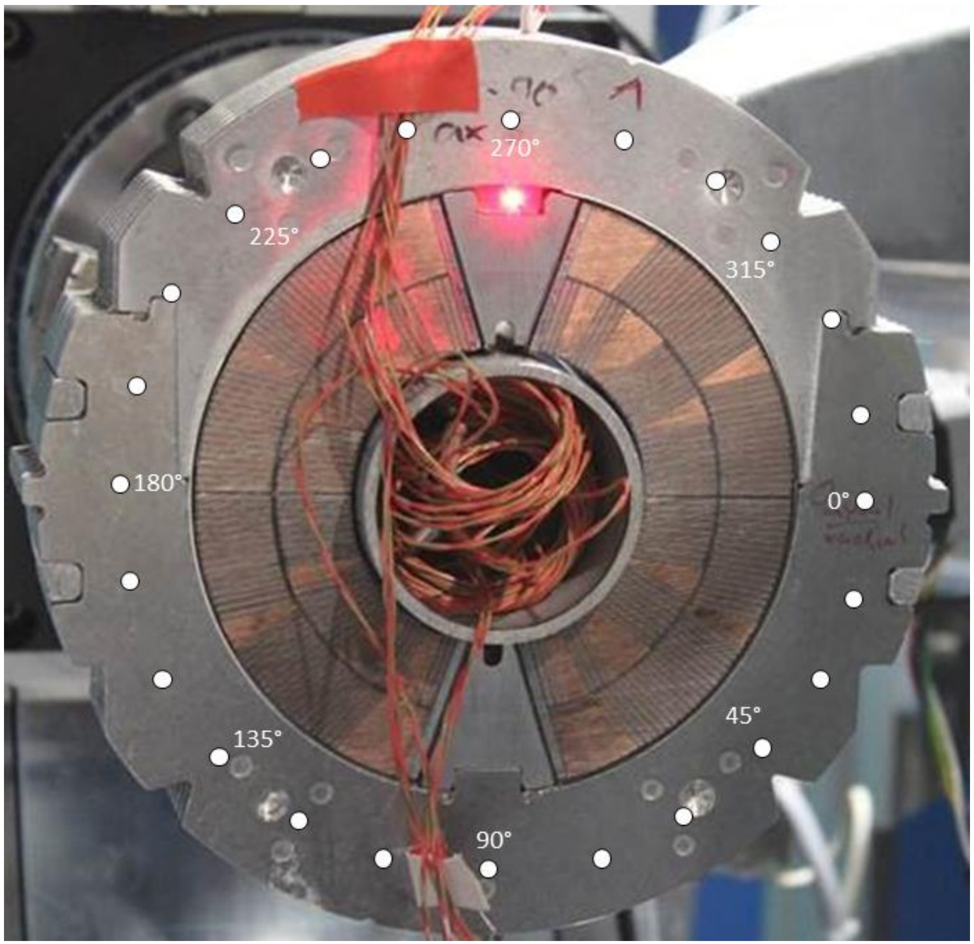
Nb_3Sn and Cu lattice parameter (P1 radial) vs temperature. The thermal expansion from literature is shown for comparison.

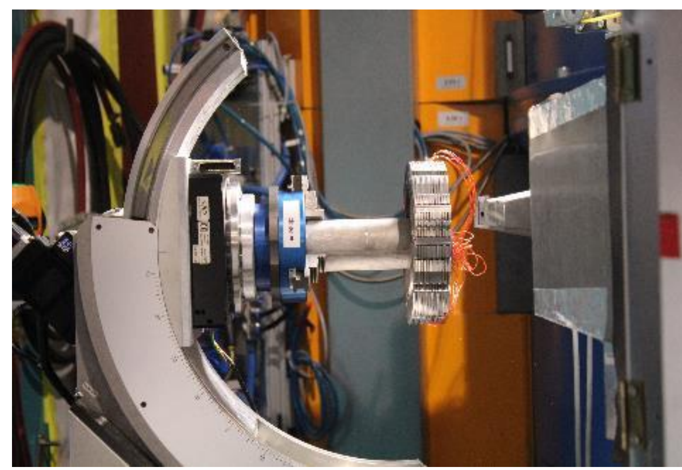
Applied strain measurement in collared coil segments

- Coil is mount on an Eulerian cradle and can be aligned for d-spacing measurements in hoop, radial and axial directions.



Strain distribution in the steel collar calculated assuming that the average axial strain is zero.

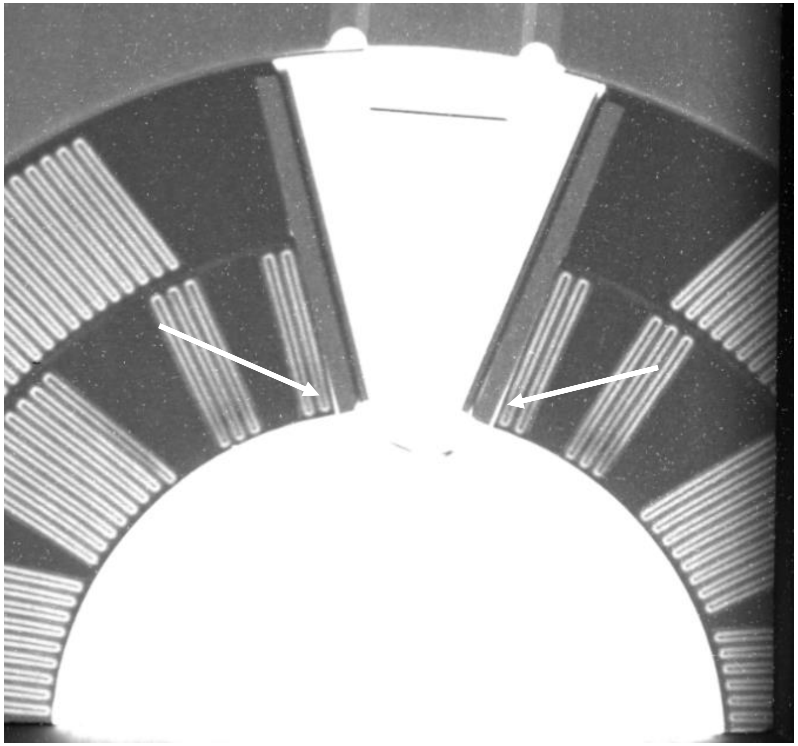


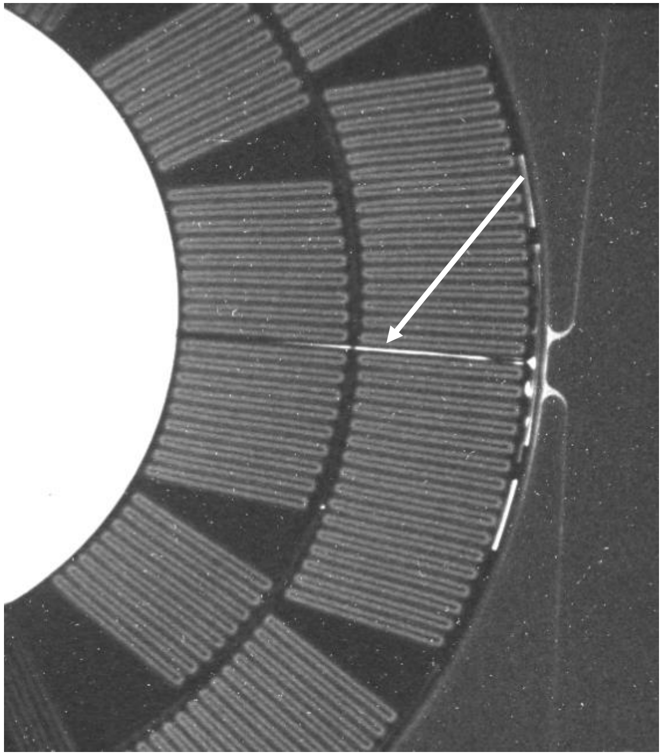


Collared 11 T dipole coil segment mounted on the Eulerian cradle on the StressSpec sample stage.

Neutron radiography of collared coil segments

- Neutron radiography was performed at the Antares imaging beam line with cold neutrons (λ=2 to 5 Å).
- Field of view 100 mm × 100 mm
- Spatial resolution is about 80 μm.
- Alignment imperfections are seen in the test coil between loading pole, shim, loading plate and at coil midplane.

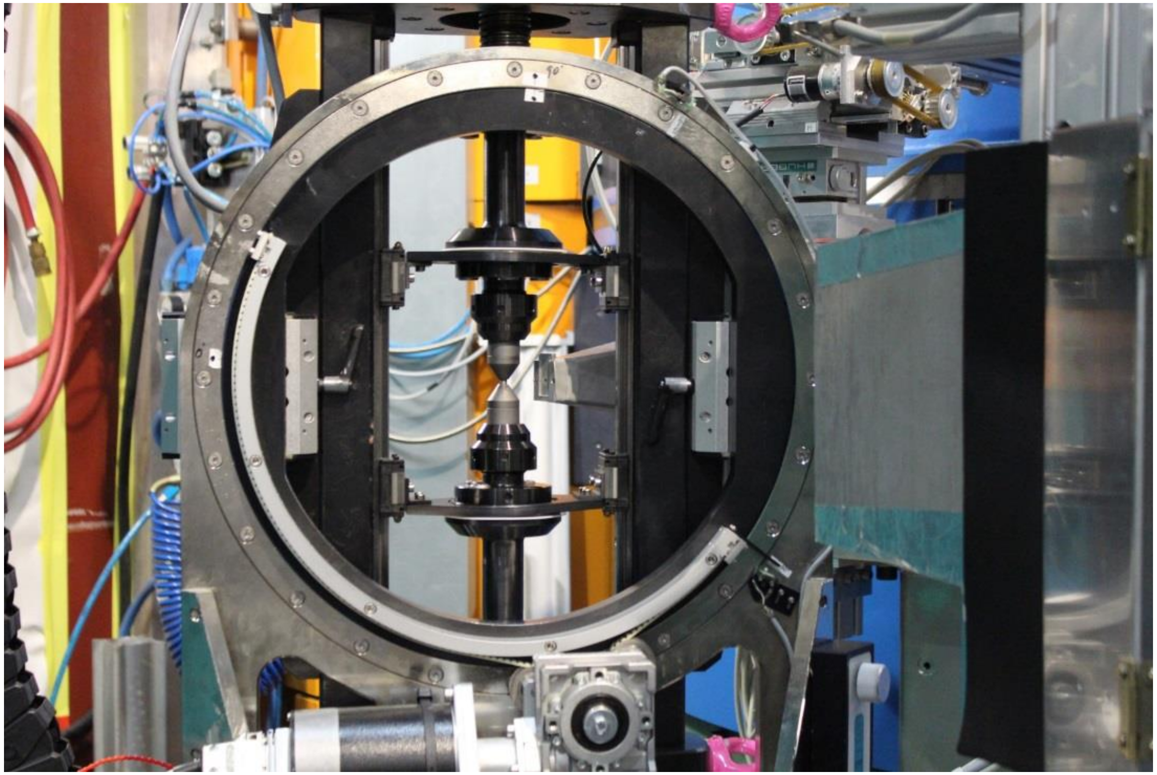




Neutron radiographs of 4 cm thick collared 11 T coil segment.

In situ diffraction measurements at StressSpec

- Finite Element simulations suggest that stress concentrations are present in the conductor blocks, and that the stress exerted on the brittle Nb_3Sn filaments depends on conductor geometry and the mechanical properties of the different composite materials.
- At StressSpec the magnitude of these stresses can be measured *in situ* as a function of an externally applied transverse compressive stress.



StressSpec set-up for applying transverse compressive stress in situ during strain measurements by neutron diffraction. The set-up consists of a load frame combined with an Eulerian cradle that enables rotation of the load axis with respect to the scattering geometry

Conclusion

- High energy synchrotron XRD enables residual and applied strain measurements in superconducting wires and very fast strain maps of coil segments of ≤ 3 mm thickness.
  - In the 11 T dipole coil conductor Nb_3Sn is at RT under slight axial compression of about 0.01%, and Cu under slight axial tension of about 0.02%.
  - In the 11 T dipole center coil segment the Nb_3Sn (321) d-spacing is in average 0.01% smaller in the hoop direction than in the radial direction, while the Cu (200) d-spacing is slightly larger in hoop direction.
  - On the microscale the Nb_3Sn d-spacing pattern is clearly correlated with the wire position within the coil, with hoop and radial lattice parameters oscillating by about ±0.03%.
- The relatively deep penetration of neutrons enables residual strain measurements in massive coil segments.
- The neutron diffraction results reveal a significant residual compressive Nb_3Sn hoop strain in the 11 T dipole conductor block P4 at the coil midplane (after prior coil testing in a magnet).
- Analysis of the first direct strain measurements in the steel collars, conductor blocks and wedges of a 11 T dipole coil is ongoing.
- Using a dedicated StressSpec set-up the stress distribution in the different coil constituents can be measured *in situ* as a function of an externally applied transverse compressive stress.