A-15 Inhomogeneity in Nb_3Sn Wires: A Potential Leverage Point for Conductor Improvement

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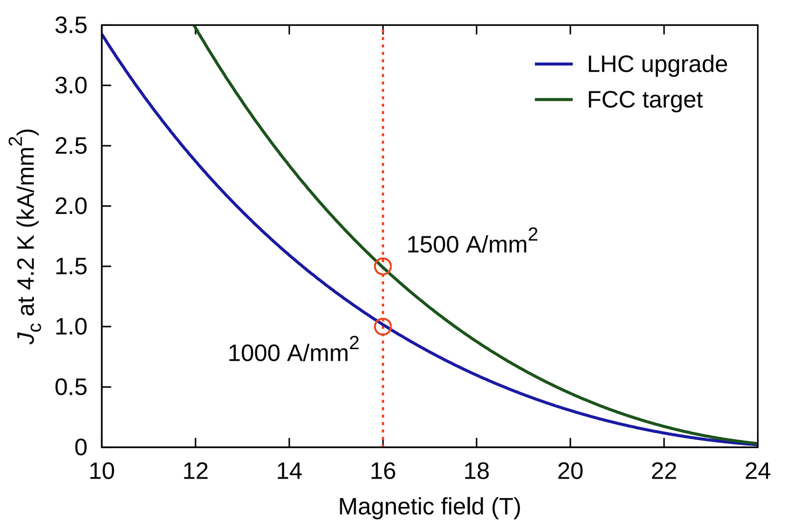
Introduction

- The FCC design aims at a dipole field of 16 T → Nb-Ti superconducting magnets (used in the LHC) are not an option
- Nb_3Sn is a promising candidate for the production of the dipole magnets, but the performance of currently available wires is insufficient
- A collaboration between CERN and Atominstitut explores wire optimization strategies for achieving a 50% increase in the critical current density at 16 T



Potential improvements include:

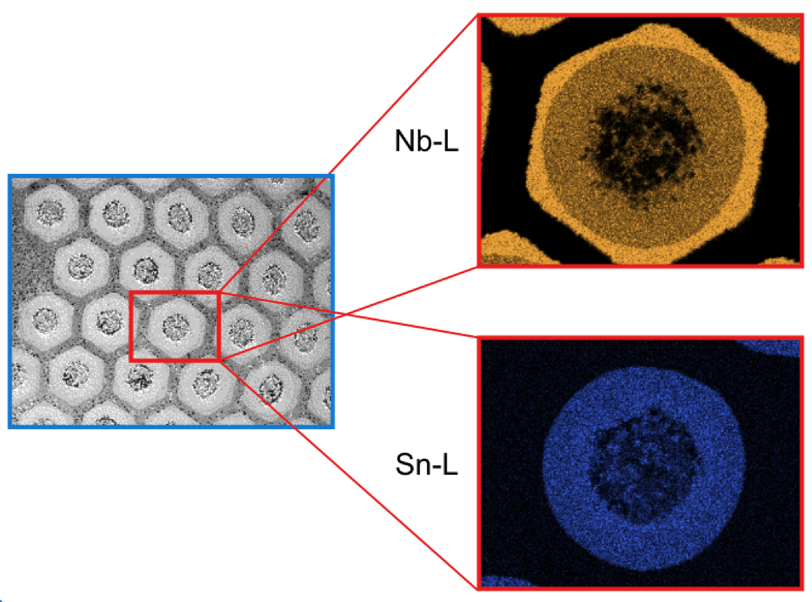
- Refinement of the grain size
- Introduction of additional pinning centers (we demonstrated this by means of fast neutron irradiation; cf. my talk in the session *Conductor Development*)
- Increase of A-15 phase homogeneity

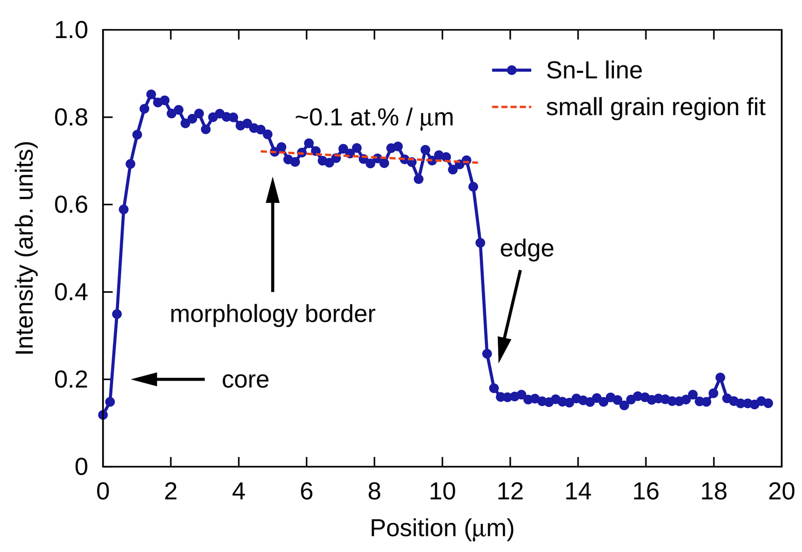
Here we focus on a quick magnetometry-based procedure we recently devised for assessing Sn concentration gradients inside sub-elements of (powder-in-tube) Nb_3Sn wires (cf. right panel), and compare the preliminary results to other techniques (cf. panels below).

Microstructural Analysis

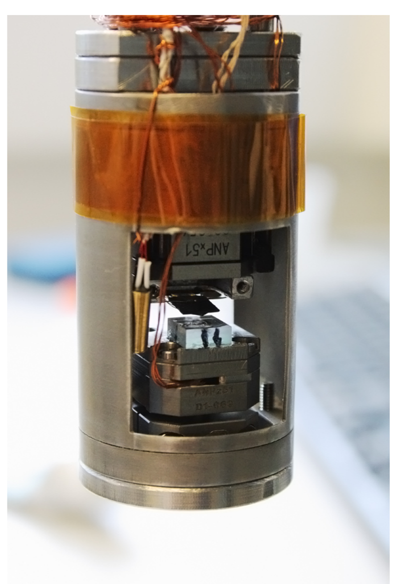
Scanning electron microscopy experiments using EDX are currently being carried out to check the data obtained from the AC magnetometry method. The initial results indicate the validity of the method, but more work has to be done:

- Increase data acquisition time to reduce the noise
- Scan many sub-elements to obtain representative average values
- Measure intra-granular Sn gradients (TEM sample preparation required)





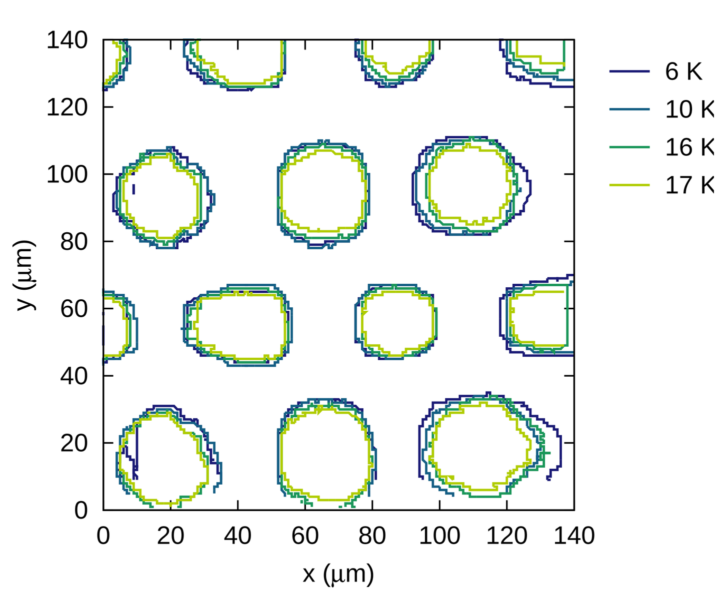
Scanning Hall Probe Microscopy

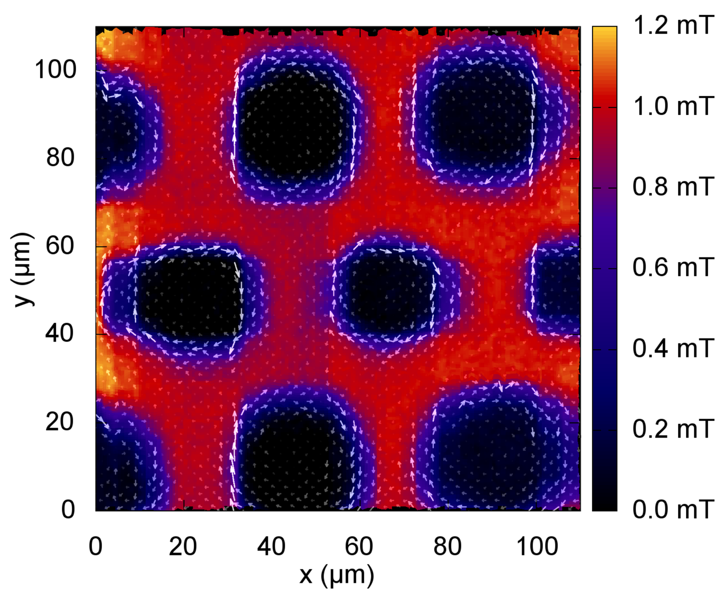


We performed Scanning Hall Probe Microscopy (SHPM) on a thin slice of the PIT wire under examination. This technique allows observing the paths of screening currents, thus providing information on A-15 phase homogeneity. The following procedure was used for comparison with the AC magnetometry results:

- Cool the sample to the desired temperature
- Apply a small DC field (order of 1 mT)
- Map the magnetic field above the sample surface (spatial resolution ~ 1 μm)

Comparing the perimeter at which the applied field at different temperatures decays by a certain percentage reveals the shrinking of the screened region with increasing temperature (left plot). The local current vectors can be obtained from the field map based on a numerical inversion of the Biot-Savart law (right plot).





AC Magnetometry Method

Sn concentration gradients within sub-elements of (PIT) Nb_3Sn wires lead to a radial T_c distribution. Under certain conditions (suitable geometry, monotonic Sn concentration, highest T_c on the inside) such gradients can be probed as follows:

Experiment:

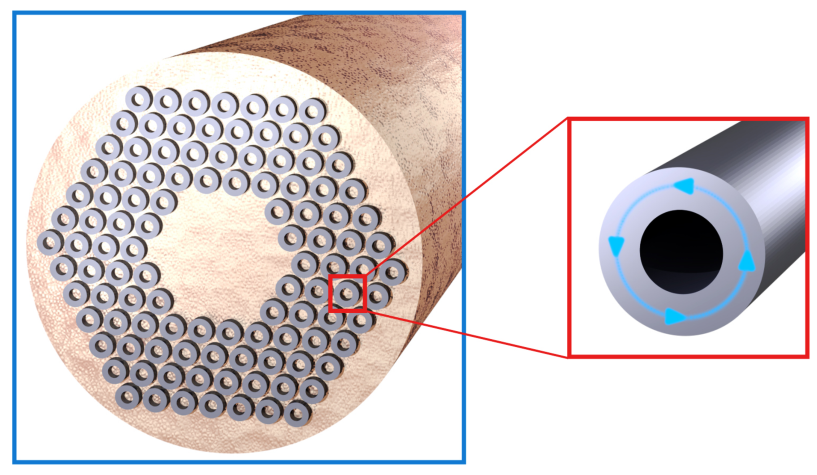
- Mount a short wire sample in a SQUID magnetometer such that the wire axis is parallel to the applied magnetic field
- Apply a small AC magnetic field, and measure the magnetic moment as a function of temperature

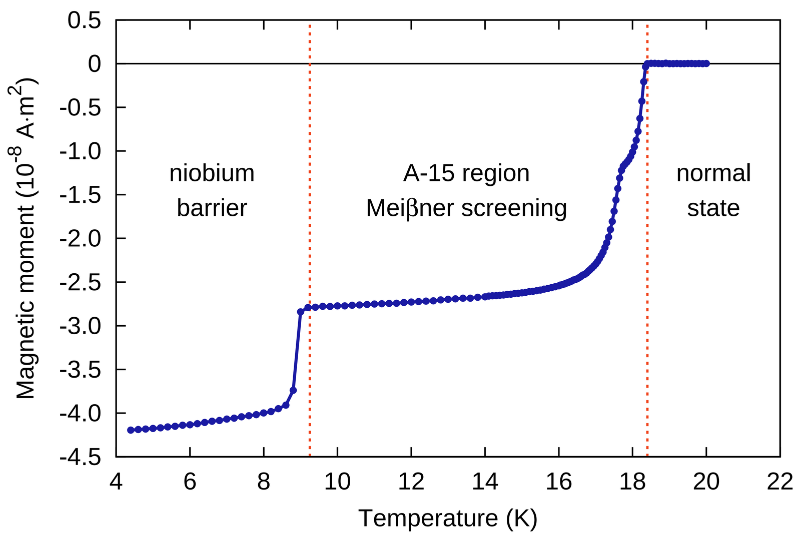
Evaluation:

- Sub-divide the sub-elements into shells, and assign initial T_c values to each shell
- Calculate an effective penetration depth of each shell (this allows considering an intra-granular Sn gradient as well) at each temperature value
- Compute the magnetic moment resulting from Meißner screening at each temperature value, and compare to the experimental data
- Iterate the shell T_c values by calculating intersections with the experimental curve until the changes are negligible

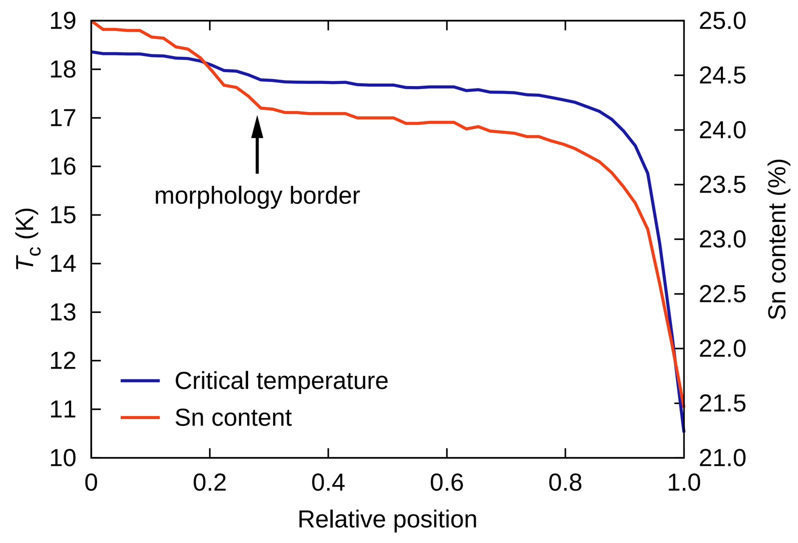
$L\dots$ sample length
$H\dots$ magnetic field

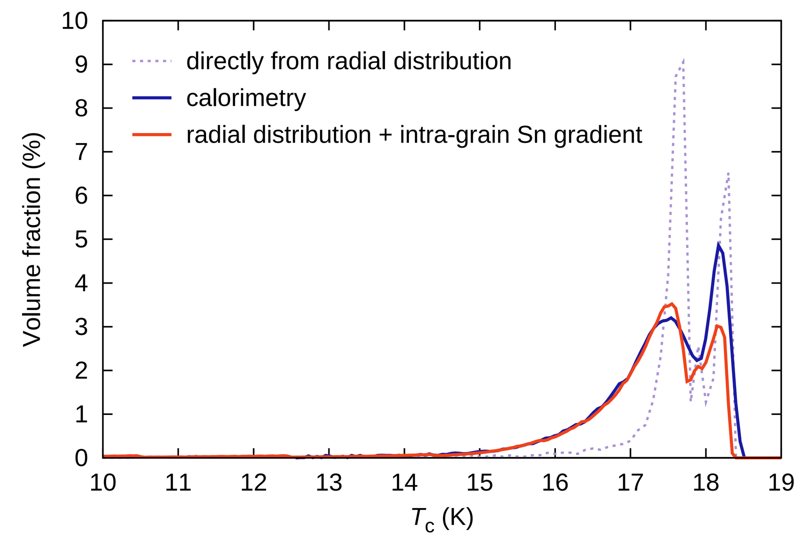
- Ginzburg-Landau temperature dependence of the penetration depth: $\lambda(t) = \lambda_0 \frac{1}{\sqrt{(1-t^4)}}, \quad t = \frac{T}{T_c}$
- Effective penetration depth at a given temperature, computed based on the superfluid density n: $n \propto \frac{1}{\lambda^2} \rightarrow \lambda_{\text{eff}} \propto \left[\int n(\vec{r})\mathrm{d}V\right]^{-1/2}$





- Screening current inside shell j with thickness d and radius r_j: $I_j = H_j L \left(1 - e^{-d/\lambda_{\text{eff}}}\right)$
- Contribution of shell j to the total magnetic moment of the sub-element: $m_j = \pi r_j^2 I_j$





- The T_c distribution of a PIT-type test sample exhibits a clearly visible gradient and a morphology border (large grains with high Sn content on the inside)
- The histogram computed based on the radial T_c distribution is very narrow
- Calorimetry measurements on the same sample produce a broader histogram, but they only yield global information without spatial resolution
- Assuming an intra-granular Sn gradient (in this case 1.5% from the grain surface to the center) reconciles the discrepancy, and yields a good agreement

Summary & Outlook

- AC magnetometry can be used to asses the radial T_c distribution, and hence the Sn concentration gradient, within sub-elements of Nb_3Sn wires
- Additional experiments (EDX, SHPM) are currently being carried out to check the accuracy of this method, and to provide additional insights

Next steps:

- Use the presented characterization technique to assess the potential benefits of A-15 homogeneity improvements in state-of-the-art wires
- Transfer our knowledge on pinning landscape modification by fast neutron irradiation to an industrial production technique (e.g. inclusion of nano-particles)
- Together with industry partners develop next-generation Nb_3Sn wires which meet the FCC requirements