A-15 Inhomogeneity

The Underestimated Enemy of High-Performance Nb_3Sn Wires

T. Baumgartner [1], S. Pfeiffer [2], J. Bernardi [2], C. Scheuerlein [3], A. Ballarino [3], M. Eisterer [1]

[1] Atominstitut, TU Wien

[2] USTEM, TU Wien

[3] CERN

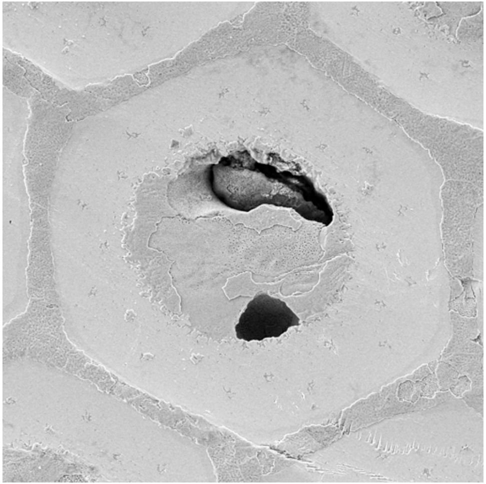
April 10, 2018 — FCC Week

Outline

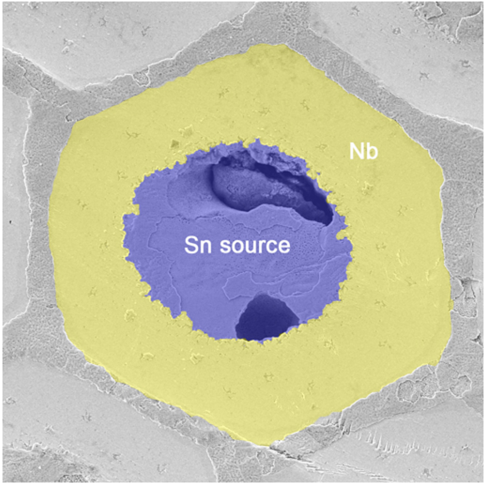
Outline

ATOMINSTITUT

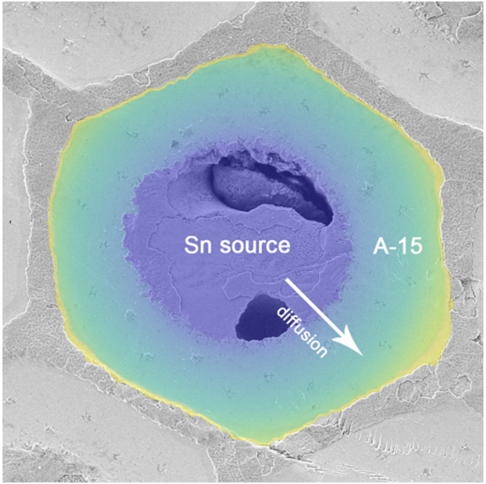
1. Introduction
   - The Problem
   - Examinations
2. Radial Inhomogeneity
   - EDX results
   - SHPM results
3. Local Variations
   - Different ‘magnetic look’ of sub-elements
   - Critical temperature
   - Intra-granular Sn concentration gradients
4. Simulations
   - Pinning force scaling
   - High-field performance
5. Conclusions



- Nb_3Sn is formed during heat treatment by diffusion reaction



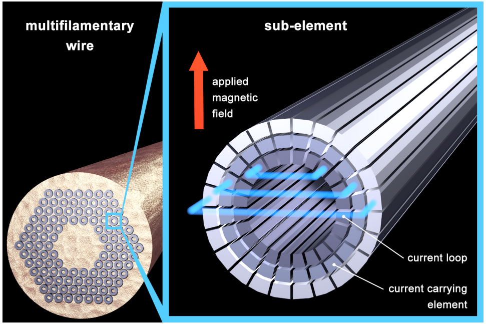
- Nb_3Sn is formed during heat treatment by diffusion reaction
- In modern wires a Sn source diffuses outwards into a region containing densely stacked Nb filaments (RRP) or a Nb tube (PIT)



- Nb_3Sn is formed during heat treatment by diffusion reaction
- In modern wires a Sn source diffuses outwards into a region containing densely stacked Nb filaments (RRP) or a Nb tube (PIT)
- Consequently, a radial gradient in stoichiometry is always present
- Other types of inhomogeneities, such as sub-element sausaging or barrier breakage, may also occur

- **Energy-dispersive X-Ray (EDX) analysis**
  Change of chemical element concentrations within sub-element cross sections
- **Scanning Hall Probe Microscopy (SHPM)**
  Magnetization maps of individual sub-elements, T_c distribution within sub-elements, and variation between sub-elements
- **SQUID magnetometry**
  T_c obtained from AC susceptibility measurements

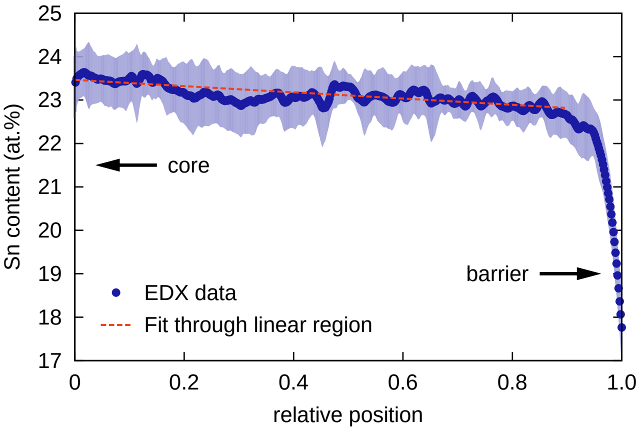
- **Simulations**
  Effects of radial Sn concentration gradients on pinning force scaling behavior and high-field performance



- Sub-element is sub-divided into many current carrying elements
- Sn concentration of these elements varies with radial position
- T_c and B_{c2} are computed based on Sn content[1]
- $J_c(T, B)$ is computed from intrinsic properties and grain size[2]

[1] Y. Li, Y. Gao: *Sci. Rep.* **7**, 1133, 2017
[2] T. Baumgartner et al.: submitted to *Supercond. Sci. Technol.*

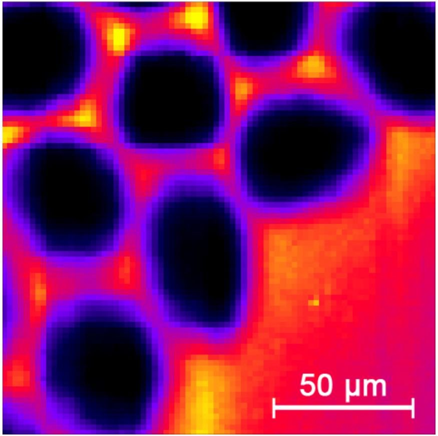
Outline



- Linear decrease of Sn concentration over wide radial range, and a steep fall-off near the barrier
- Similar behavior found in RRP and PIT wires
- Typical gradient in linear region: $\sim 0.1\,\text{at.\%}/\mu\text{m}$

ATOMINSTITUT

$T = 11\,\mathrm{K}$



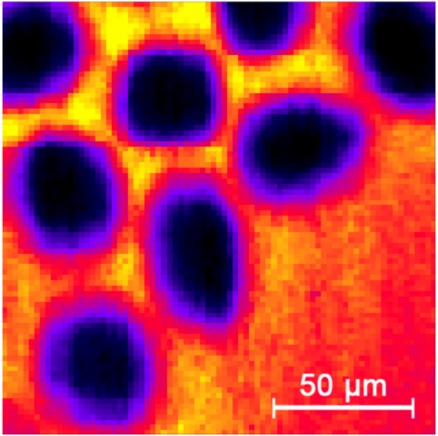
- SHPM was done on wire cross sections in the Meißner phase
- Wire sample is cooled, then a small field of (typically 5 mT) is applied
- Scanning at different temperatures allows visualizing the penetration of the magnetic field and hence the radial T_c gradient[3]

[3] T. Baumgartner et al.: *Supercond. Sci. Technol.* **30**, 014011, 2017

Radial Inhomogeneity

SHPM results

$T = 15\,\mathrm{K}$



- SHPM was done on wire cross sections in the Meißner phase
- Wire sample is cooled, then a small field of (typically 5 mT) is applied
- Scanning at different temperatures allows visualizing the penetration of the magnetic field and hence the radial T_c gradient[3]

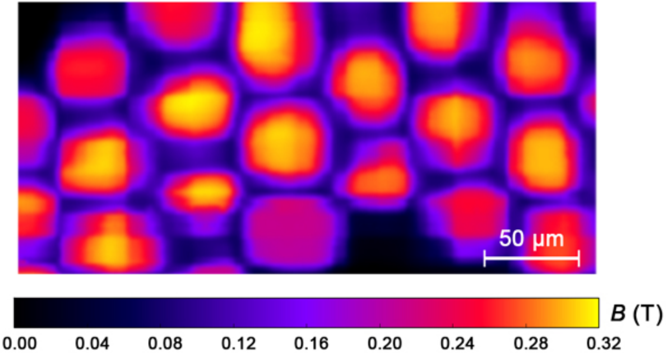
[3] T. Baumgartner et al.: *Supercond. Sci. Technol.* **30**, 014011, 2017

Outline

Local Variations

Different 'magnetic look' of sub-elements

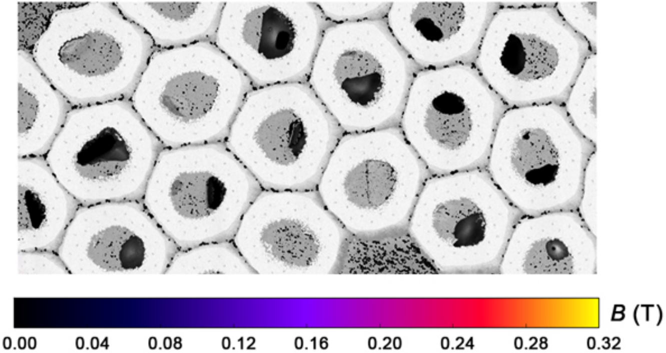
- SHPM on 1 mm long sample in remanent state shows large variations in size and shape of sub-elements as well as in remanent field (and consequently J_c)
- This was not expected based on SEM images of the cross section
- Indication of longitudinal variation of superconducting properties?

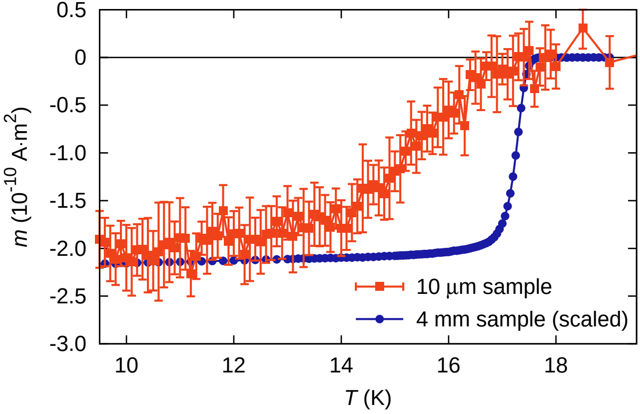


Local Variations

Different 'magnetic look' of sub-elements

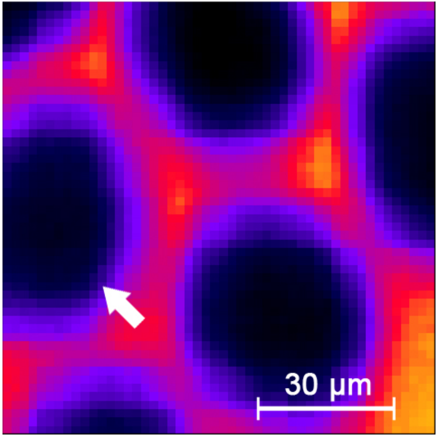
- SHPM on 1 mm long sample in remanent state shows large variations in size and shape of sub-elements as well as in remanent field (and consequently J_c)
- This was not expected based on SEM images of the cross section
- Indication of longitudinal variation of superconducting properties?





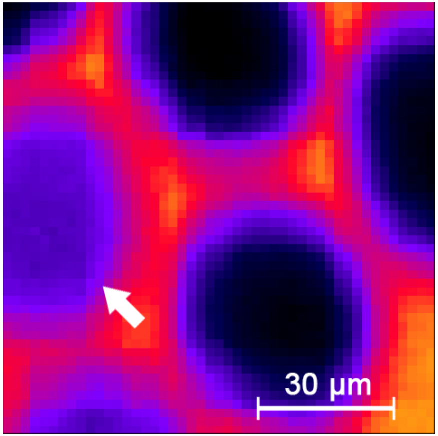
- AC susceptibility measurements revealed large differences between $\sim 10\,\mu$m thick disk cut from the wire and 4 mm long sample
- T_c onset appears to be identical, but transition is much broader in thin sample

$T = 13\,K$



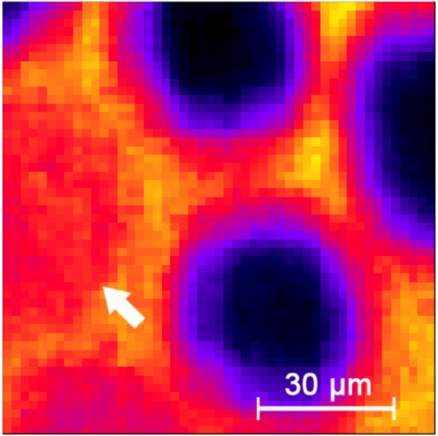
- SHPM in the Meißner phase showed large variations between individual sub-elements in the 10 µm thick sample
- At 15 K some sub-elements are not visible anymore, whereas others still exhibit complete shielding of their inside

$T = 14\,\mathrm{K}$

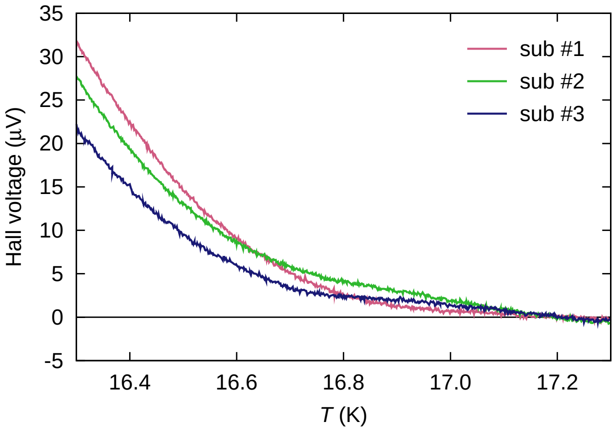


- SHPM in the Meißner phase showed large variations between individual sub-elements in the 10 µm thick sample
- At 15 K some sub-elements are not visible anymore, whereas others still exhibit complete shielding of their inside

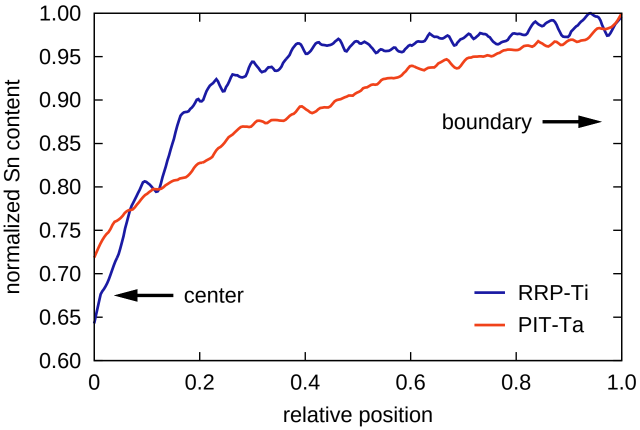
$T = 15\,\mathrm{K}$



- SHPM in the Meißner phase showed large variations between individual sub-elements in the 10 µm thick sample
- At 15 K some sub-elements are not visible anymore, whereas others still exhibit complete shielding of their inside



- Local T_c measurements on a 1 mm thick sample
- Sample magnetized, Hall probe positioned over one sub-element, temperature slowly ramped up
- Deviations indicate different T_c distributions



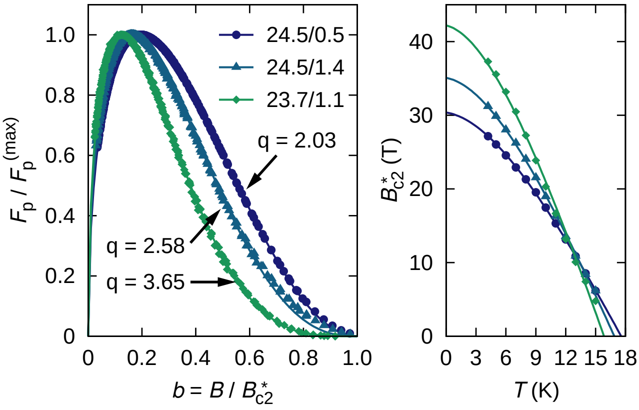
- Large Sn concentration gradients found inside individual grains by TEM-EDX
- Impact on J_c not yet clear, but adverse effect due to suppression of superfluid density is possible

Outline

- $F_\mathrm{p} = |\vec{J}_\mathrm{c} \times \vec{B}|$ at different temperatures is mapped onto single curve by normalizing F_p to maximum value and B to scaling field $B^*_{c2}(T)$
- $f(b) = C\, b^p\, (1 - b)^q$
  Unified Scaling Law pinning function[4]
- Shape determined by two exponents which depend on the pinning mechanism[5]
- $p = 0.5$, $q = 2$ for Nb_3Sn (grain boundary pinning)

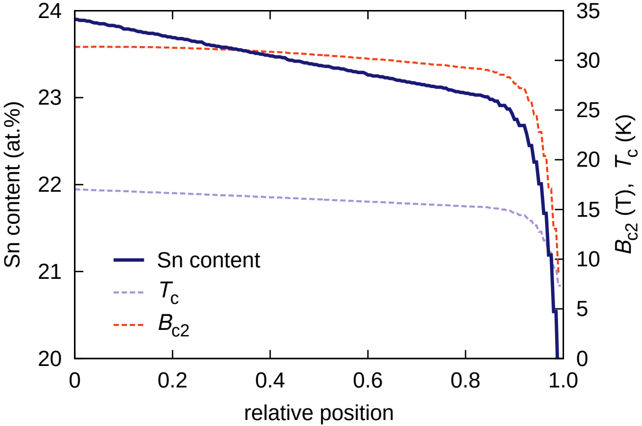
---

[4] J. W. Ekin: *Supercond. Sci. Technol.* **23**, 083001, 2010
[5] D. Dew-Hughes: *Phil. Mag.* **30**, 293–305, 1974

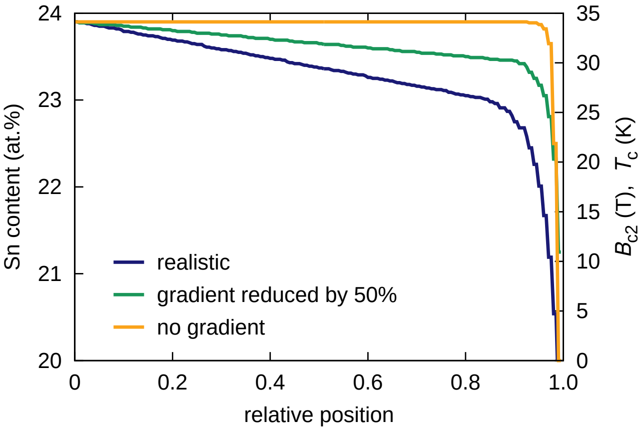


- Inhomogeneities lead to deviations from scaling behavior, since the material does not have a single T_c and B_{c2}
- Scaling analysis results depend on accessible temperature and field range (here 4.2 – 15 K, 0 – 7 T)
- Bad extrapolations of J_c to higher field values can be the result[2]

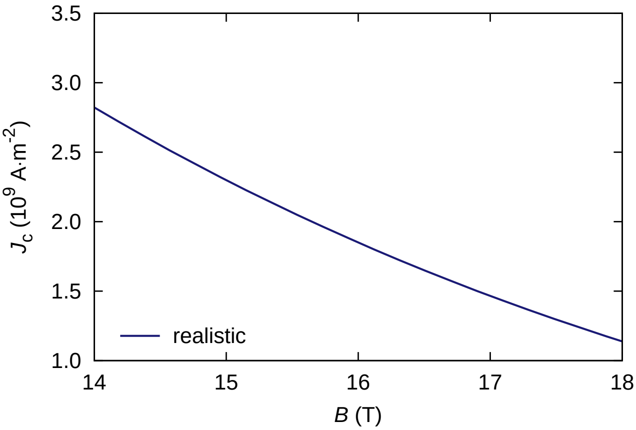
[2] T. Baumgartner et al.: submitted to *Supercond. Sci. Technol.*



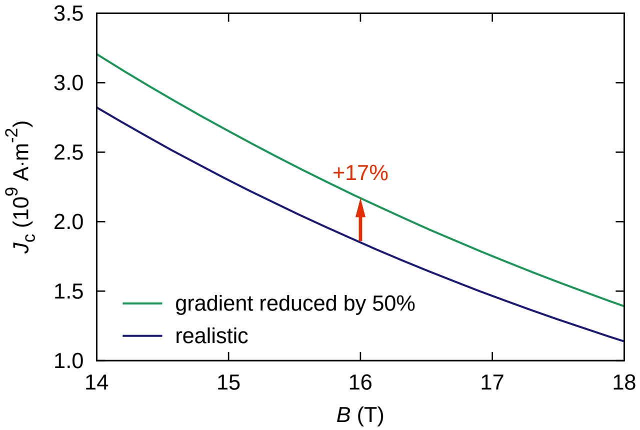
- Realistic Sn concentration profile used as input for simulation software



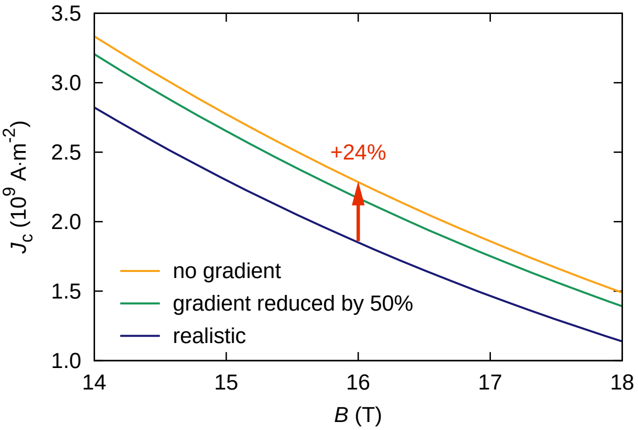
- Realistic Sn concentration profile used as input for simulation software
- Two hypothetical profiles with improved homogeneity simulated for comparison



- $J_c(B)$ at 4.2 K obtained from simulations



- $J_c(B)$ at 4.2 K obtained from simulations
- Significant increase possible by reducing the radial inhomogeneity



- $J_c(B)$ at 4.2 K obtained from simulations
- Significant increase possible by reducing the radial inhomogeneity

Conclusions

ATOMINSTITUT

- Radial Sn concentration gradients inside sub-elements cause a significant spatial variation of the superconducting parameters
- T_c gradients inside individual sub-elements can be examined using SHPM
- Evidence for longitudinal inhomogeneities was also found
- Variation of Sn content within individual grains was found, but importance is not yet clear
- Inhomogeneities cause deviations from scaling behavior, which can lead to incorrect J_c extrapolations to higher field values
- Performance can be improved significantly by reducing radial Sn gradients

Poster recommendation: 2AMSP45 (S. Pfeiffer on TEM examinations of Nb_3Sn wires)

Thank you.

I am just a child who has never grown up.
I still keep asking these 'how' and 'why' questions.
Occasionally, I find an answer.

— Stephen Hawking