Influence of the Microstructure on the Pinning Force Scaling Behavior of Nb_3Sn Wires

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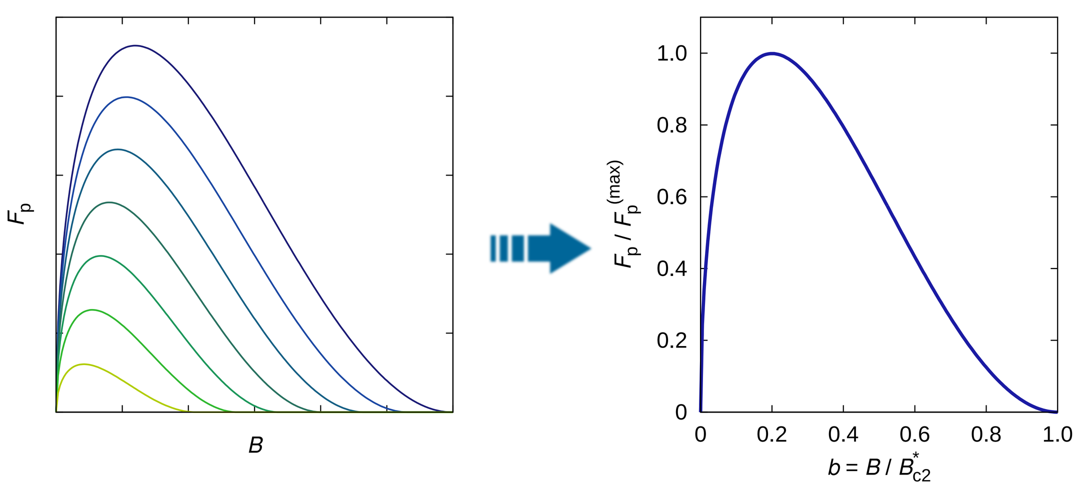
Introduction

Concept of pinning force scaling:

- $F_p = |\vec{J}_c \times \vec{B}|$ values are recorded at different temperatures.
- Normalize on both axes: to maximum $F_p(T)$ value and scaling field $B^*_{c2}(T)$.
- Values should fall onto a single curve (pinning function).



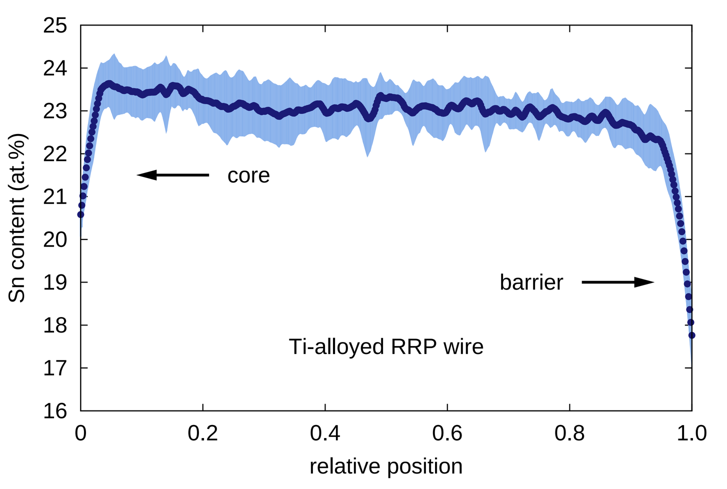
The pinning function can be written as: [1]

$$f(b) = Cb^p(1-b)^q$$
$$b = B/B^*_{c2}$$

For Nb_3Sn the exponents $p = 0.5$ and $q = 2$, corresponding to grain boundary pinning, are expected. [2]

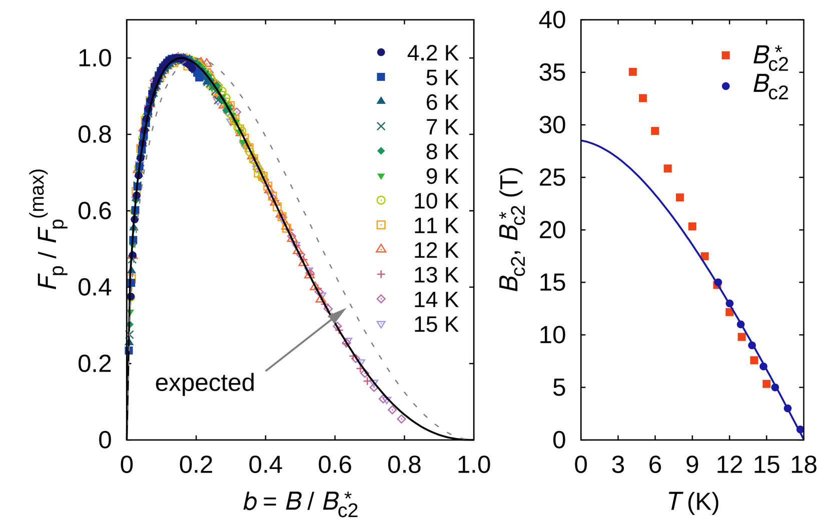
Motivation for this work:

- Our pinning force scaling analyses of data obtained from different state-of-the-art Nb_3Sn wires by means of SQUID magnetometry showed significant deviations from the expected behavior.
- We wanted to know to what degree A-15 inhomogeneities, in particular Sn concentration gradients, can cause such deviations.
- For practical reasons we were interested in the impact of the experimentally accessible field and temperature range (e.g. in our case $B \leq 7$ T and a wide temperature range for magnetometry, $I_c \leq 1000$ A at 4.2 K for transport) on the scaling analysis results.

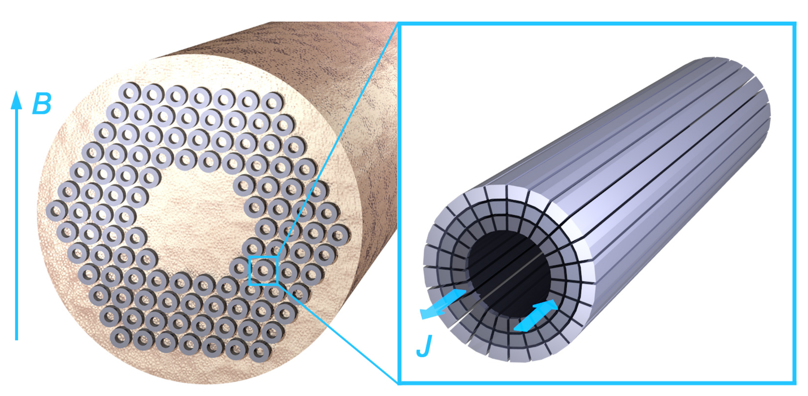


Scanning electron microscopy studies revealed a Sn concentration gradient of approx. 0.1 at.%/µm within the sub-elements of state-of-the-art Nb_3Sn wires. This A-15 inhomogeneity causes a gradient in T_c (and consequently B_{c2}), which can be probed for instance by AC magnetometry and scanning Hall probe microscopy. [3]

We found exponents which significantly differ from the expected values as well as unreasonably high scaling field values at low temperatures in both RRP and PIT wires. The plot on the right shows the pinning function and scaling field temperature dependence of a Ta-alloyed PIT wire with $p = 0.45$ and $q = 2.39$.



Simulation Model



We simulate $J_c(B)$ of Nb_3Sn wires for both magnetometry and transport in perpendicularly applied field. Assuming all sub-elements within a wire are identical, the behavior of one of them is simulated.

The algorithm performs the following tasks:

- Sub-divide the sub-element into concentric shells.
- Assign material properties (Sn content, grain size) to each shell based on a user-defined profile.
- Break down shells into current carrying elements (self-field breaks rotational symmetry of the problem).
- Compute T_c and B_{c2} of each element based on its Sn content using fits to data published in Ref. [4].
- Compute J_c of each element based on intrinsic properties and grain size, assuming ideal grain boundary pinning ($p = 0.5, q = 2$).
- Loop through applied field values at fixed temperature, and compute the J_c which would be measured under these conditions (transport: simple averaging, magnetometry: compute magnetic moment, and evaluate using Ref. [5]).

References

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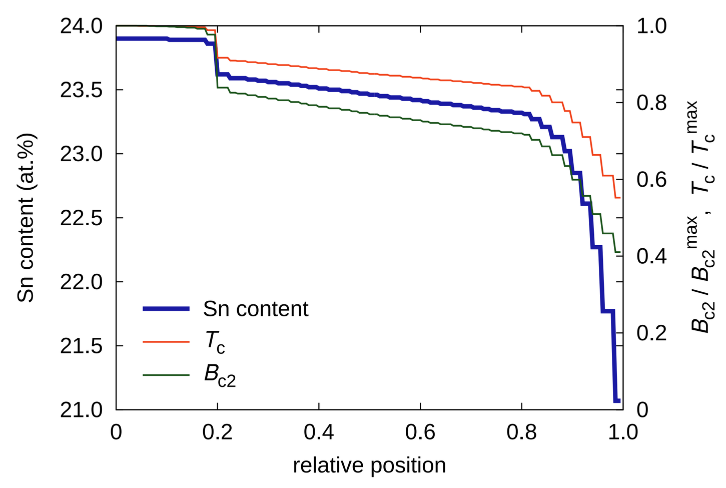
Simulation Results

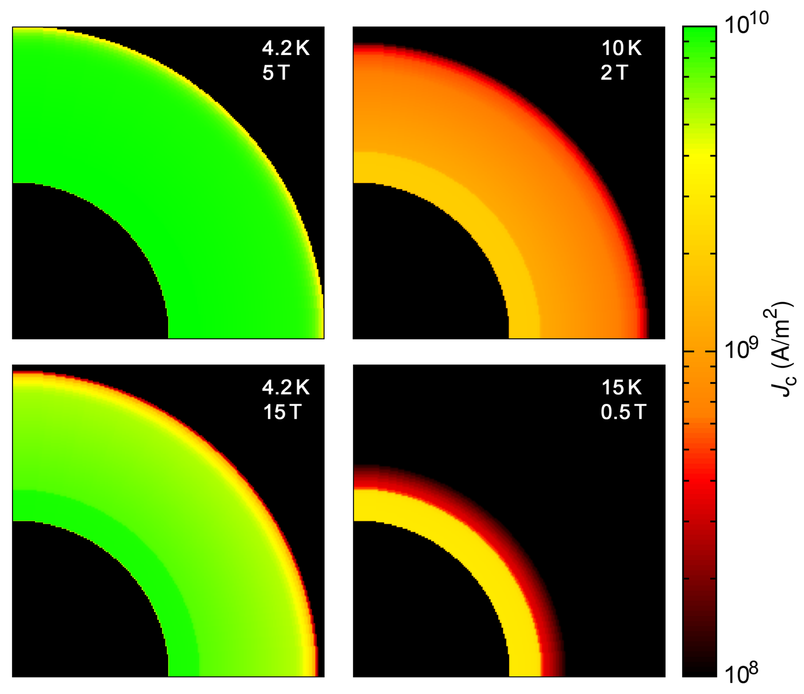
Sub-element Sn concentration profile:



The simulation results shown here were obtained using the Sn concentration profile on the left. Similar to the distribution measured by SEM-EDX, the Sn content exhibits a small plateau near the sub-element core, then decreases linearly towards the outside, and drops steeply near the barrier.

Current distribution:

At low temperatures and magnetic field values near the pinning force maximum or lower, the J_c distribution is very homogeneous (top left), whereas at high fields the A-15 inhomogeneity is non-negligible even at 4.2 K (bottom left). At elevated temperatures a significant J_c inhomogeneity can be found even at low field values (top right); at 15 K a large fraction of the cross section does not contribute to current transport anymore (bottom right).



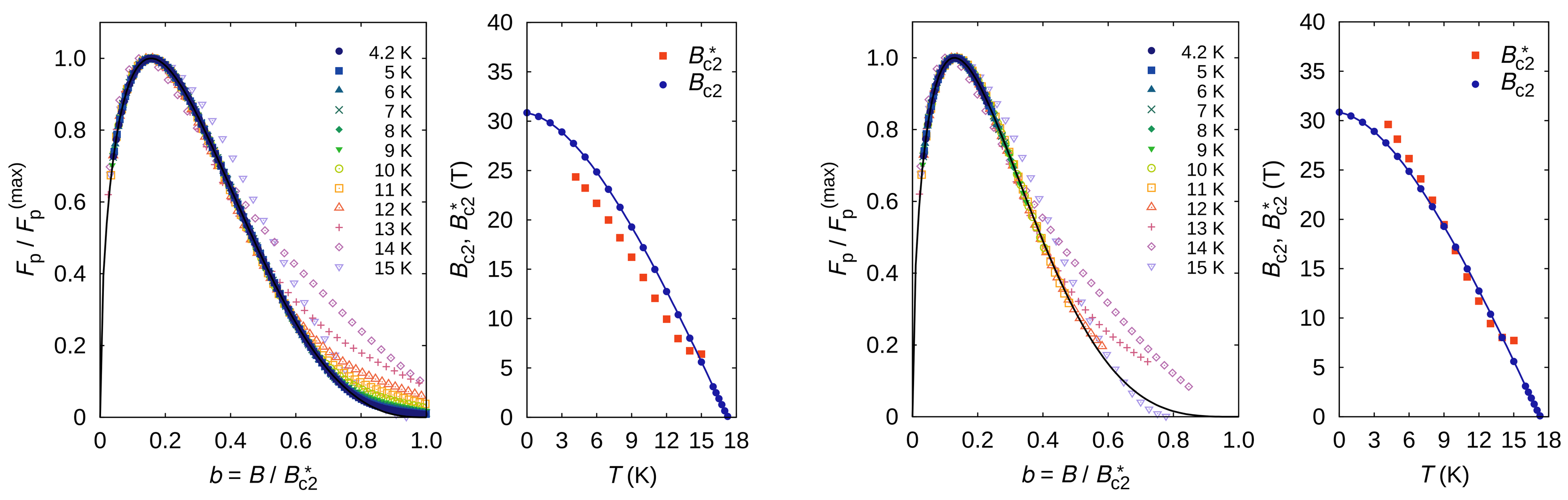
Scaling analysis:

The $J_c(B)$ output data of the simulation code were analyzed using the same algorithm we used on our real experimental data. It carries out the following steps:

- Normalize $F_p = J_c\,B$ data at each temperature.
- Use Unified Scaling Law pinning function for fitting. [1]
- Find p and q which minimize the global error (considering all temperatures).

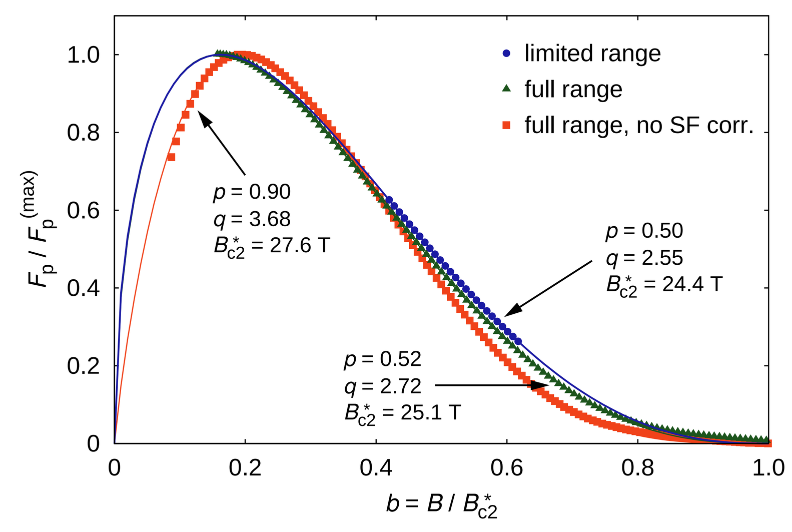
Magnetometry simulation:

- Full field range: $B \geq B_{c2}(T_i)\ \forall\, T_i$
- $p = 0.50,\ q = 2.68$
- Limited field range: $B \leq 7$ T
- $p = 0.51,\ q = 3.47$



Transport simulation:

- Variable temperature transport data are often not available → only data for $T = 4.2$ K used in analysis to simulate this shortcoming.
- Limited field range ($10\,\text{T} \leq B \leq 15\,\text{T}$) affects exponents, but the difference is not dramatic.
- Omitting the self-field correction can have a severe effect on the exponents (A-15 cross section $= 0.2\,\text{mm}^2$, max. $I_c = 2450$ A).



Conclusions & Outlook

- A-15 phase inhomogeneities, in particular Sn concentration gradients, can cause a large variation of J_c across the sub-element cross sections of modern Nb_3Sn wires at elevated temperatures or high magnetic fields.
- The results of pinning force scaling analyses are significantly affected by these inhomogeneities (high values of the exponent q, in agreement with our experimental data), and the covered temperature and field range can have a large impact. For transport data the self-field correction is important.
- We are currently doing scanning Hall probe microscopy on thin wire slices to directly visualize inhomogeneities in T_c and J_c.
- We are working on a vibrating coil magnetometer which can be operated inside our 17 T superconducting magnet to obtain high-field data, which can help improve our scaling analyses.

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