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Increasing the High-Field Performance of Nb_3Sn Wires by Pinning Landscape Modification

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April 12, 2016 — FCC Week

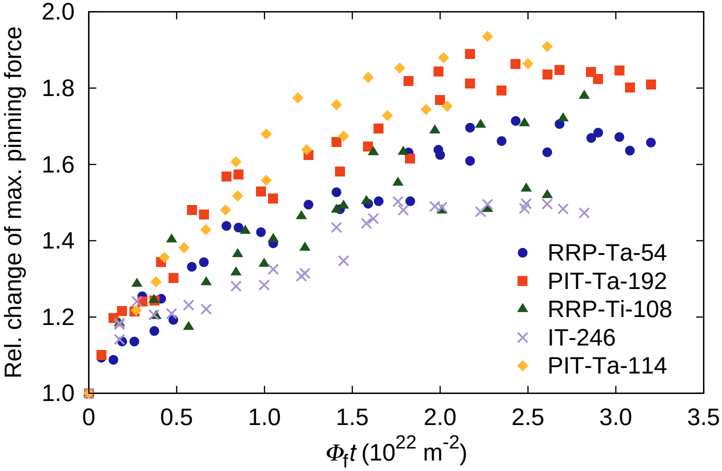
Outline

Outline

Background

- Previous collaboration between CERN and TU Wien (2010 – 2015): investigation of irradiation effects on Nb_3Sn wires intended for upgrading the LHC (inner triplet magnets)
- Most extensive fast neutron irradiation study on Nb_3Sn carried out so far
- Small fluence steps of approx. $2 \cdot 10^{21}\,\mathrm{m}^{-2}$, maximum cumulative fluence around $3 \cdot 10^{22}\,\mathrm{m}^{-2}$
- Most important result: large increase in the critical current density of all examined wire types

Background


Rel. change of max. pinning force
2.0
1.8
1.6
1.4
1.2
1.0
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
$\Phi_f t$ (10^{22} m^{-2})
● RRP-Ta-54
■ PIT-Ta-192
▲ RRP-Ti-108
× IT-246
◆ PIT-Ta-114

FCC Requirements

- 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
- New collaboration explores wire optimization strategies for achieving a 50% increase in the critical current density at 16 T relative to state-of-the-art wires

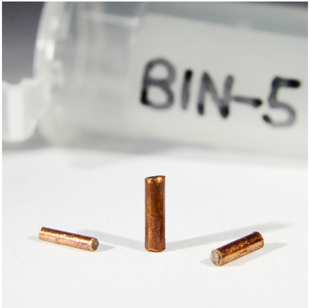
FCC Requirements

Property	**Unit**	**Requirement**
Wire diameter	mm	~ 1
Non-Cu $J_c(4.2\,\mathrm{K}, 16\,\mathrm{T})$	$\mathrm{A/mm^2}$	≥ 1500
$\mu_0 \Delta M(4.2\,\mathrm{K}, 1\,\mathrm{T})$	mT	≤ 150
$\sigma \mu_0 \Delta M(4.2\,\mathrm{K}, 1\,\mathrm{T})$	%	≤ 4.5
Effective filament diameter	µm	≤ 20
RRR		≥ 100
Unit length	km	≥ 5
Conductor cost	€/kA·m	~ 5

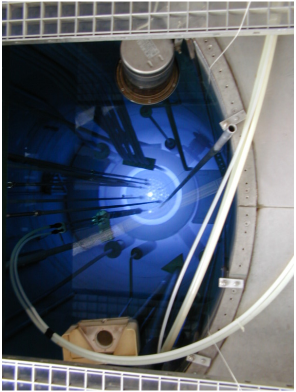
Outline

Samples

- Five types of multifilamentary Nb_3Sn wires (RRP / PIT, Ta- or Ti-alloyed, one binary wire)
- Short samples ($\sim$4 mm) for magnetometry were cut from straight pieces of reacted wire
- Transport samples were made by winding approx. 50 cm of wire onto mini-VAMAS barrels made from Ti-6Al-4V alloy



Fast Neutron Irradiation



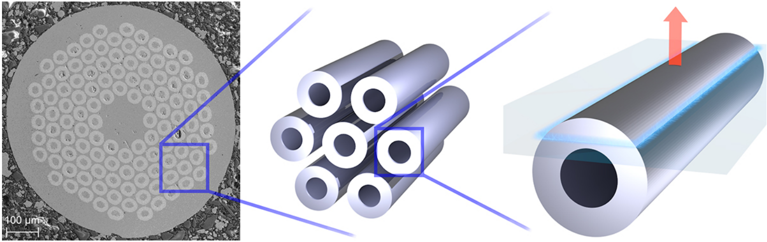
- Carried out in the TRIGA Mark-II reactor at Atominstitut (Vienna)
- Sequential irradiation of two magnetometry samples of each type in fluence steps of $\sim 2 \cdot 10^{21}\,\mathrm{m}^{-2}$
- Cumulative fast neutron fluences ($E > 0.1\,\mathrm{MeV}$) between $2.6 \cdot 10^{22}$ and $3.2 \cdot 10^{22}\,\mathrm{m}^{-2}$
- Nickel samples included for fluence monitoring (reaction threshold $\approx 1\,\mathrm{MeV} \Rightarrow$ fast neutrons only)

Measurement Techniques

- Short wire samples were used for SQUID magnetometry
- Magnetization measurements after each irradiation step to assess the fluence dependence of the critical current density
- Changes in the critical temperature were obtained from AC susceptibility measurements in the same system
- Transport measurements at 4.2 K were performed on 10 unirradiated and on 2 irradiated samples for comparison with magnetometry, and to obtain high-field data (up to 15 T)

Measurement Techniques

J_c from magnetometry



- Magnetization loops with field applied perpendicular to the wire
- Sub-elements regarded as parallel, uncoupled tubes
- Current is assumed to flow in planes perpendicular to the field
- J_c is connected to irreversible moment by proportionality factor[1]

$$J_c = \frac{3 m_{irr}}{4NL\left({\rho_o}^3 - {\rho_i}^3\right)}$$

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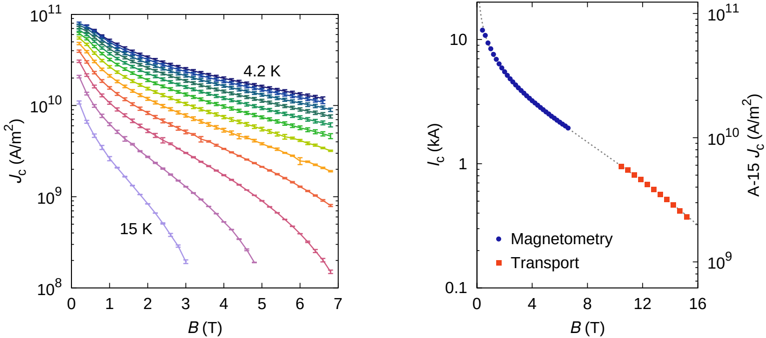
[1] T. Baumgartner et al.: *IEEE Trans. Appl. Supercond.* **22**, 6000604, 2012

Measurement Techniques

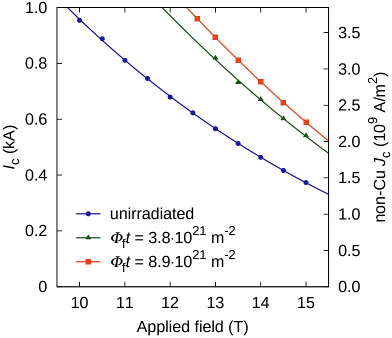
J_c from magnetometry – comparison with transport

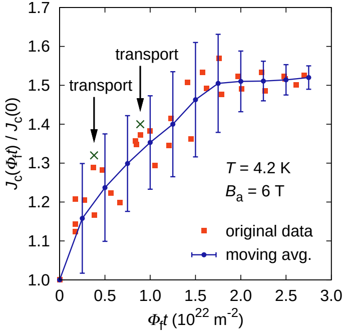


- J_c data available for $B < 7\,\mathrm{T}$ at 12 temperatures ranging from 4.2 to 15 K, spanning 3 orders of magnitude
- First-order self-field correction inherent to the method
- Good agreement with transport measurements (4.2 K, available up to 1000 A)

Outline

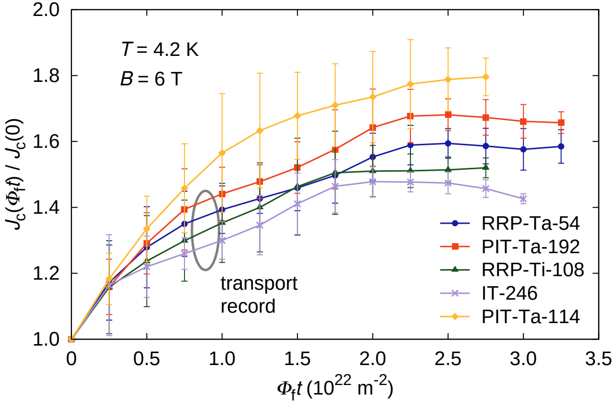
Critical Current Density





- RRP-Ti-108 wire: transport data of irradiated samples
- Transport measurements obtained from six unirradiated samples (only 1% standard deviation) and two samples irradiated to different fluences
- Extrapolated J_c enhancement at 6 T is in agreement with data obtained from magnetometry

Critical Current Density



- Record value[2] in transport measurement on RRP-Ti-108 at $\Phi_f t = 0.9 \cdot 10^{22}\,\mathrm{m}^{-2}$: $J_c(4.2\,\mathrm{K}, 12\,\mathrm{T}) = 4.1 \cdot 10^9\,\mathrm{A/m^2}$
- Large J_c increase in all wire types, saturation occurs around $2 - 3 \cdot 10^{22}\,\mathrm{m}^{-2}$

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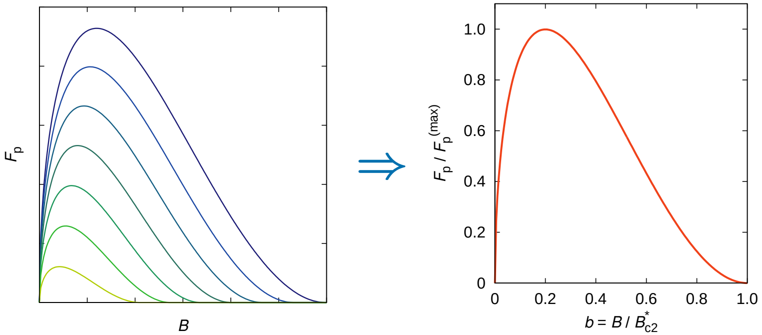
[2] T. Baumgartner et al.: *Sci. Rep.* **5**, 10236, 2015

Pinning Force

The concept of scaling



- $F_\mathrm{p} = |\vec{J}_\mathrm{c} \times \vec{B}|$ at different temperatures mapped onto single curve by normalizing F_p to max. value and B to scaling field
- $f(b) = C\, b^p\, (1-b)^q$ … Unified Scaling Law[3] pinning function
- Shape determined by two exponents which can be derived for different mechanisms[4]

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[3] J. W. Ekin: *Supercond. Sci. Technol.* **23**, 083001, 2010

[4] D. Dew-Hughes: *Phil. Mag.* **30**, 293–305, 1974

Pinning Force

Analysis of the magnetometry data

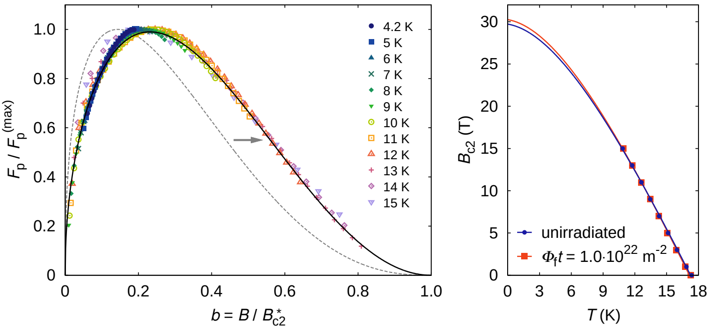
- $F_p = J_c\, B$ from magnetometry data normalized at each temperature
- $f(b) = C\, b^p\, (1 - b)^q$ used as a fit function
  $b = B/B^*_{c2}$
- Algorithm finds p and q which minimize the global error (entire temperature range included)
- Expected scaling exponents for Nb_3Sn (grain boundary pinning):

$$p = 0.5$$

$$q = 2$$

Pinning Force

Unexpected result



- Relatively good agreement with expected scaling exponents in the unirradiated state
- Pronounced peak shift in the pinning function after irradiation
- Change in the upper critical field B_{c2} is small ($< 5\%$ at $10^{22}\,\mathrm{m}^{-2}$), and cannot account for the large J_c increase

Pinning Force

A second pinning mechanism

- Possible contributions of other pinning mechanisms[4] were investigated to explain the shift

  $$f(b) = \alpha\, b^{p_1}\,(1-b)^{q_1} + \beta\, b^{p_2}\,(1-b)^{q_2}\ , \quad \alpha + \beta = 1$$

- Shift can be explained with a point-pinning contribution[5] ($p_2 = 1,\ q_2 = 2$) which increases with fluence

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[4] D. Dew-Hughes: *Phil. Mag.* **30**, 293–305, 1974

[5] T. Baumgartner et al.: *Supercond. Sci. Technol.* **27**, 015005, 2014

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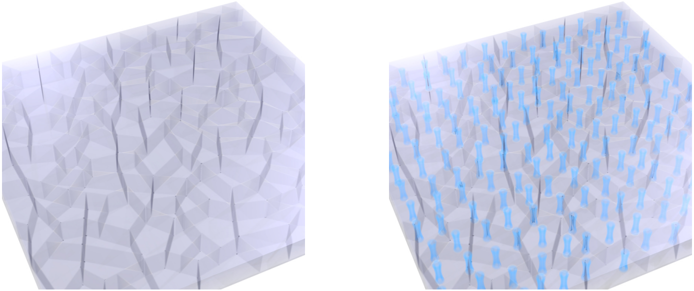

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[4] D. Dew-Hughes: *Phil. Mag.* **30**, 293–305, 1974

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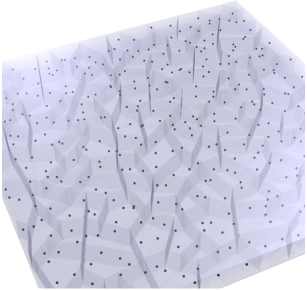

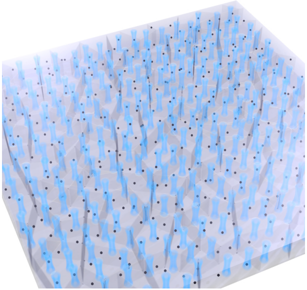

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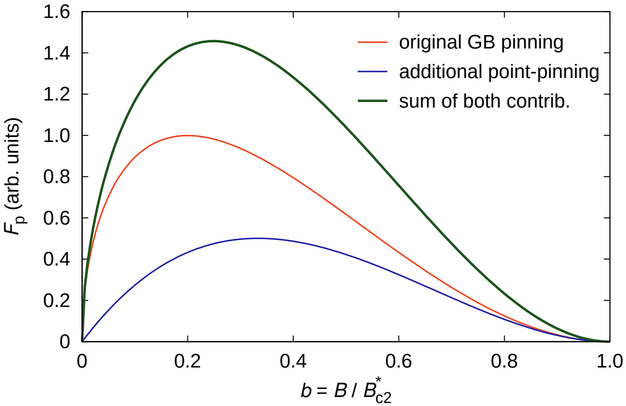
Pinning Force

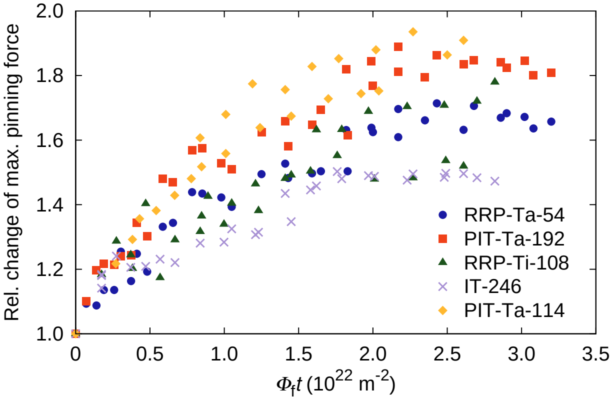
Point-pinning contribution



- Irradiation induced defects add a point-pinning contribution to the original grain boundary pinning
- Resulting volume pinning force is larger in magnitude and high-field behavior is improved

Pinning Force

Point-pinning contribution



- Large performance improvement in all examined wire types
- Maximum volume pinning force was increased by 50 – 90%

Outline

Conclusions

- We demonstrated by means of fast neutron irradiation experiments that the J_c of state-of-the-art Nb_3Sn wires has a large potential for improvement
- The introduction of point-pinning centers was identified as the responsible mechanism
- A similar pinning landscape modification in next-generation Nb_3Sn wires is likely to yield the J_c improvement necessary for meeting the FCC requirements
- Neutron irradiation is hardly a viable method for industrial production
- Alternative: embedding nano-particles in Nb_3Sn, which act as pinning centers

Conclusions

- Introduction of nano-particles (ZrO_2) was successfully demonstrated on a monofilamentary Nb_3Sn wire[6,7]
- Changes in magnitude and functional dependence of the pinning force are similar to our irradiation results
- Grain size was also refined by presence of ZrO_2 nano-particles
- Other fabrication challenges such as the small filament diameter still need to be addressed
- Feel free to have a look at my poster:

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

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[6] X. Xu et al.: *Appl. Phys. Lett.* **104**, 082602, 2014

[7] X. Xu et al.: *Adv. Mater.* **27**, 1346–1350, 2015

Thank you.

One sometimes finds what one is not looking for.

— Alexander Fleming