UNIVERSITY OF TWENTE.

THE ORIGIN OF STRAIN SENSITIVITY IN Nb_3Sn

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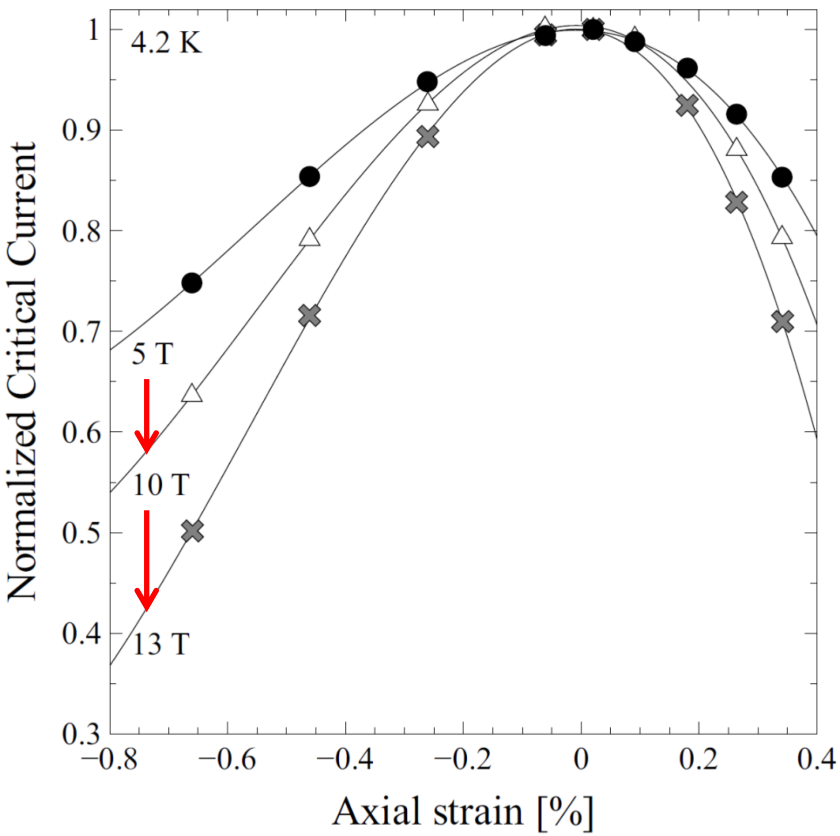
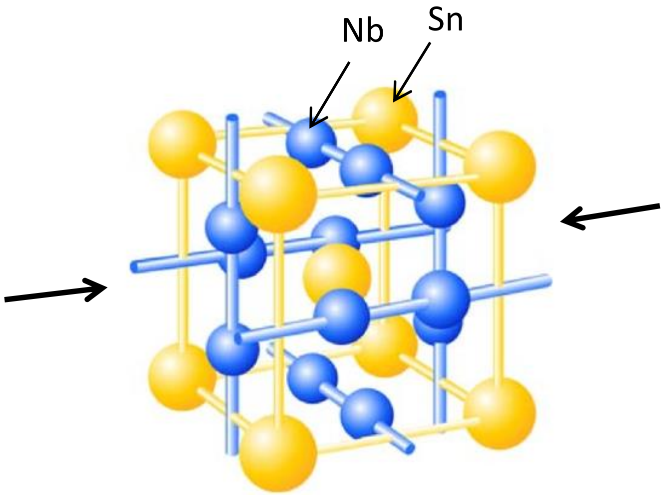
Motivation



Source: Godeke PhD thesis [1]



A15 Nb_3Sn

- Intrinsic strain sensitivity: Reduction in I_c with strain
- Affects the performance of high-field magnets utilizing Nb_3Sn
- Becomes an increasingly severe problem at higher magnetic fields
- Why?

Overview

- **How does the critical current depend of temperature, magnetic field and strain?**
- How can we model the disorder dependent critical temperature and upper critical field?
- Why is Nb_3Sn so strain sensitive?
- How does Nb_3Sn compare to other superconductors?

How does critical current depend on temperature, magnetic field and strain?

$$I_c\left(T,\mu_0 H,\varepsilon\right)=C\left(1-t^2\right)^{\mu}h^{p-1}\left(1-h\right)^q$$

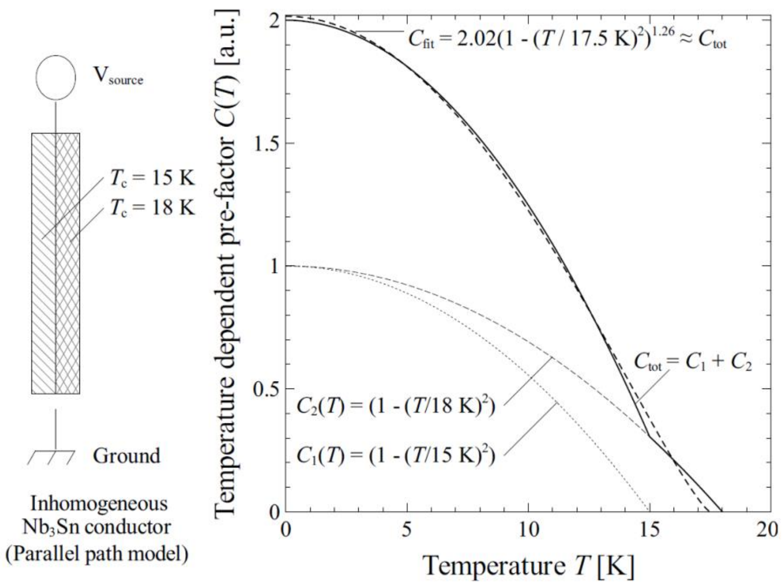
$$t=\frac{T}{T_c\left(0,\varepsilon\right)},\quad h=\frac{H}{H_{c2}\left(T,\varepsilon\right)},$$

$$H_{c2}\left(T,\varepsilon\right)\approx H_{c20}\left(\varepsilon\right)\left(1-t^{1.52}\right)$$

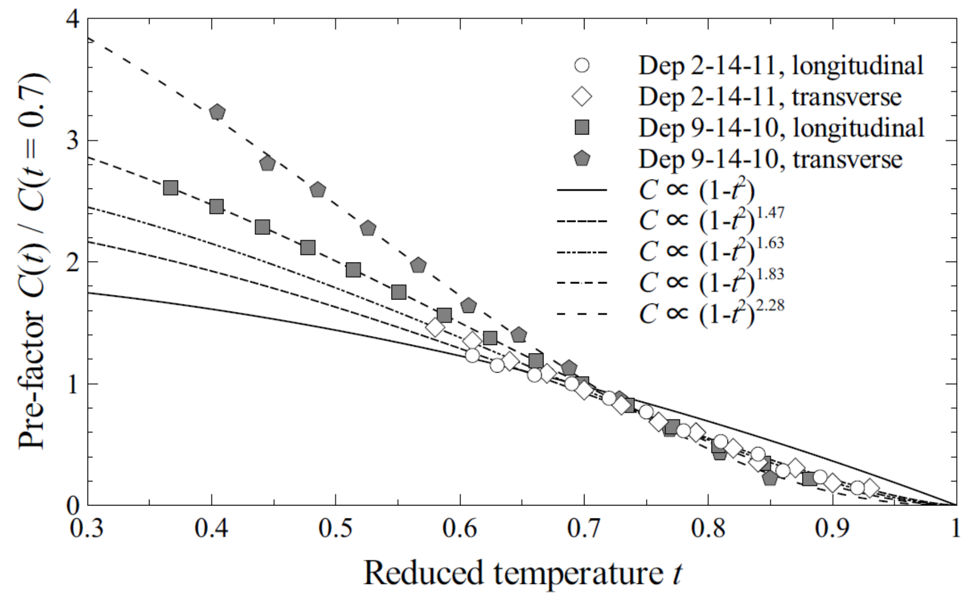
- MAG (Mentink-Arbelaez-Godeke) scaling relation for Nb_3Sn, with wire dependent parameters C, μ, p, q, $T_c(\varepsilon)$, and $H_{c20}(\varepsilon)$
- Used as standard model (with $\mu \approx 1$) for the HEP and ITER (mathematically equivalent form) communities [2,3]
- Strain sensitivity "hidden" in critical temperature $T_c(0,\varepsilon)$ and upper critical field $H_{c2}(T,\varepsilon)$
- Recent addition: free parameter μ for the temperature dependence

Why wire dependent free temperature parameter μ?

Mathematical argument: inhomogeneity



Experimental observation of binary thin films



$$I_{c1} = \left(1-\left(T/T_{c1}\right)^2\right) f\left(h\right),\ \ I_{c2} = \left(1-\left(T/T_{c2}\right)^2\right) f\left(h\right),$$

$$I_c\left(T,\mu_0 H,\varepsilon\right) = C\left(1-t^2\right)^{\mu} h^{p-1}\left(1-h\right)^q$$

$$I_{c,total} = I_{c1} + I_{c2} \approx 2\left(1-\left(T/T_{c2}\right)^2\right)^{\mu} f\left(h\right),\ \mu = 1.26$$

MAG scaling relation could benefit from free parameter μ

- Mathematical argument: If μ = 1 for perfectly homogeneous wire → $\mu \neq 1$ for inhomogeneous wire
- Experimental observations: (inhomogeneous) binary Nb-Sn thin films, Nb_3Sn wires [3,4,5]

How does MAG scaling compare with other Nb_3Sn scaling relations?

MAG scaling relation:

$$I_c\left(T,\mu_0 H,\varepsilon\right)=C\left(1-t^2\right)^{\mu} h^{p-1}\left(1-h\right)^q$$

Mathematically equivalent to the Ekin scaling relation [6]:

$$I_c\left(T,\mu_0 H,\varepsilon\right)=\frac{C_E}{\mu_0 H} s\left(\varepsilon\right)\left(1-t^2\right)^{\mu}\left(1-t^{1.52}\right)^{\eta-\mu} h^p\left(1-h\right)^q$$

Nearly equivalent* to the Durham scaling relation [7]:

$$I_c\left(T,\mu_0 H,\varepsilon\right)=A\left(\varepsilon\right)\left(T_c\left(\varepsilon\right)\left(1-t^2\right)\right)^2\left(\mu_0 H_{c2}\left(T,\varepsilon\right)\right)^{-0.5} h^{p-1}\left(1-h\right)^q$$

→ **Consensus has been reached**

* Except for a weakly strain-dependent pre-factor $s(\varepsilon)^{9/22}$, and with μ fixed to 1.38

How does MAG scaling compare with NbTi scaling?

Bottura scaling relation for NbTi [8]:

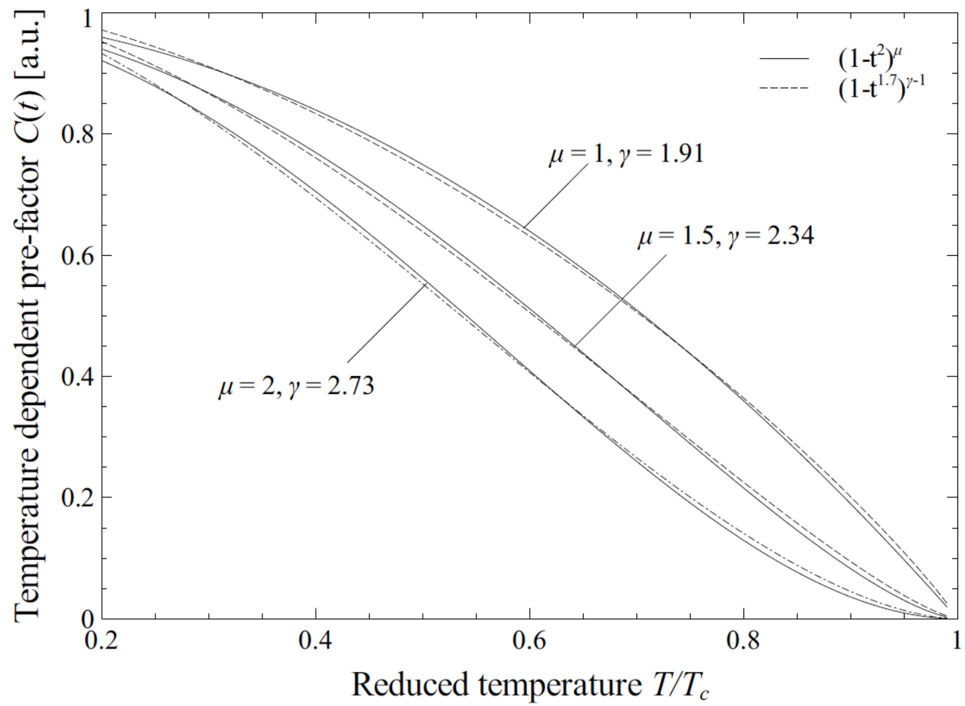
$$I_c\left(T,\mu_0 H\right)=\frac{C_B}{\mu_0 H}h^p\left(1-h\right)^q\left(1-t^{1.7}\right)^\gamma$$

Approximation:

$$\left(1-t^{1.7}\right)^{\gamma-1}\approx\left(1-t^2\right)^\mu$$

Rewritten to mathematically equivalent form

$$I_c\left(T,\mu_0 H\right)=C\left(1-t^2\right)^\mu h^{p-1}\left(1-h\right)^q$$



NbTi critical current

- MAG scaling relation for Nb_3Sn equivalent to Bottura scaling relation for NbTi (not considering strain)
- But different temperature dependence of H_{c2}: Nb_3Sn: $H_{c2}(t) \approx H_{c20}(1-t^{1.52})$, NbTi: $H_{c2}(t) \approx H_{c20}(1-t^{1.7})$

Critical current density of Nb_3Sn and NbTi

MAG scaling relation:

$$I_c\left(T,\mu_0 H,\varepsilon\right)=C\left(1-t^2\right)^{\mu} h^{p-1}\left(1-h\right)^{q}$$

$$t=\frac{T}{T_c\left(0,\varepsilon\right)},\quad h=\frac{H}{H_{c2}\left(T,\varepsilon\right)},$$

$$H_{c2}\left(T,\varepsilon\right)\approx H_{c20}\left(\varepsilon\right)\left(1-t^{1.52}\right)$$

Works for both Nb_3Sn and NbTi

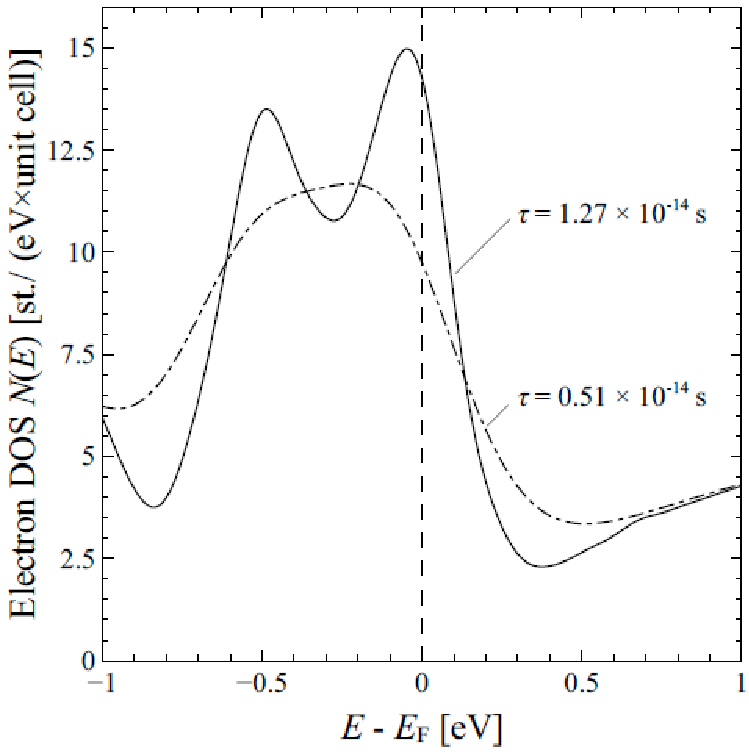
- Consistent with Ekin and Durham scaling relationships for Nb_3Sn
- Consistent with Bottura scaling relation for NbTi, but with different temperature dependence of upper critical field
- Nb_3Sn strain sensitivity “hidden away” in strain dependent critical temperature $T_c(\varepsilon)$ and upper critical field $H_{c2}(0,\varepsilon)$

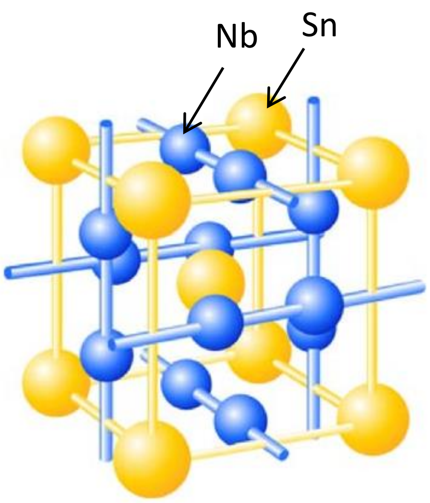
→ What determines strain dependent $T_c(\varepsilon)$ and $H_{c2}(0,\varepsilon)$?

Overview

- How does the critical current depend of temperature, magnetic field and strain?
- **How can we model the disorder dependent critical temperature and upper critical field?**
- Why is Nb_3Sn so strain sensitive?
- How does Nb_3Sn compare to other superconductors?

Influence of disorder on Nb_3Sn





A15 Nb_3Sn

- Superconducting properties of Nb_3Sn are strongly disorder dependent, so disorder must be included in calculations
- Ab-initio calculations of Nb_3Sn with Quantum Espresso [9]
- Electron-lifetime broadening approach [10]:

Disorder → Reduced scattering time τ → Electron-lifetime broadening $E_B = h/(2\pi\tau)$

Validation: Martensitic transformation

Experimental

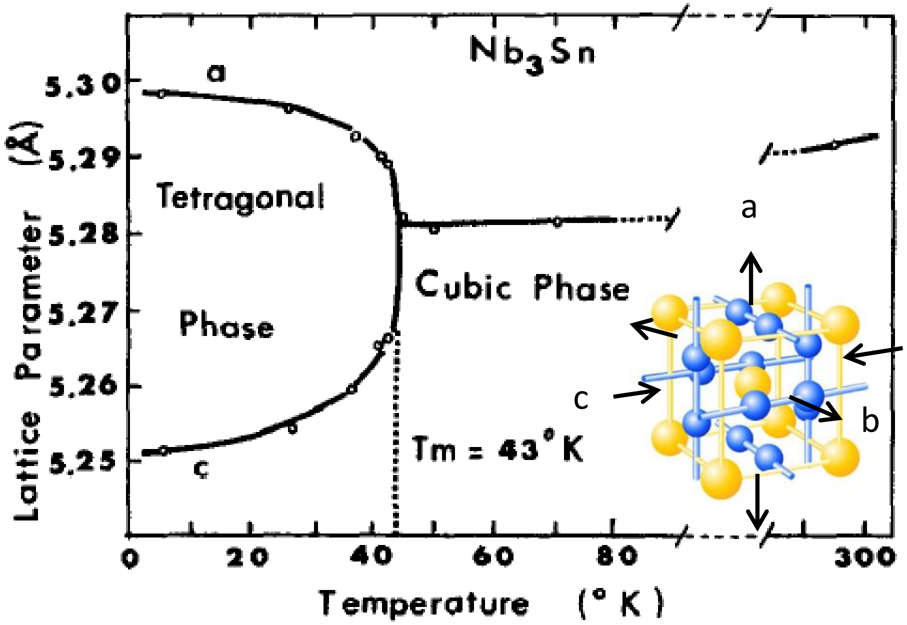
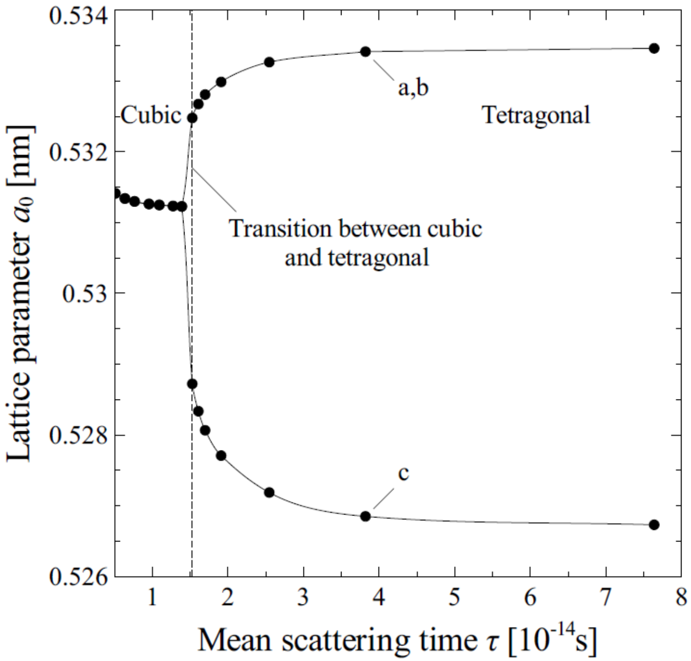


Fig. 1. Lattice parameter versus temperature for Nb_3Sn single crystal determined with film technique.

Ab-initio

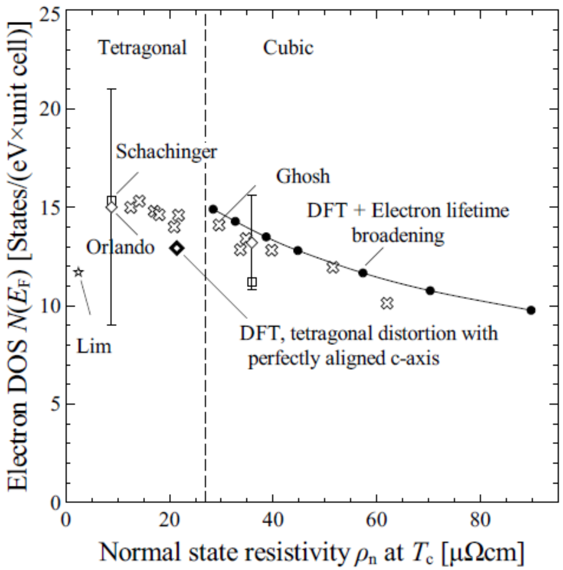


$$\rho_{\mathrm{n,x}} = \frac{V}{eN(E_{\mathrm{F}})\, v_{\mathrm{F,x}}^2 \tau}$$

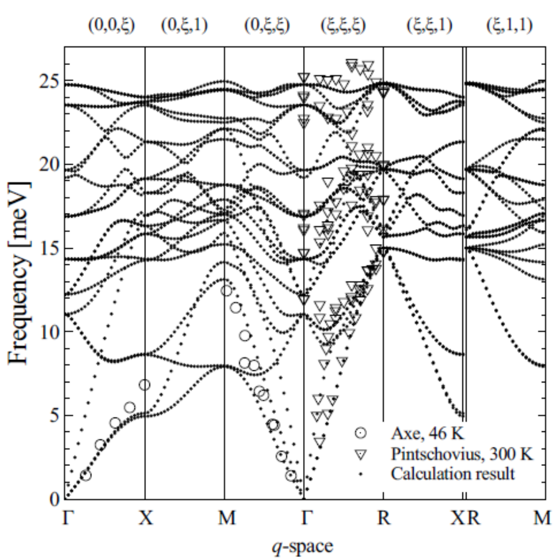
- Experimentally observed Martensitic transformation:
  - Spontaneous tetragonal distortion at low temperature (T < 43 K)
  - Not present in disordered samples, $\rho_n > 25 \pm 3$ µΩcm
- Ab-initio calculation:
  - Optimal shape tetragonal for $\tau > \tau_c = (1.53 \pm 0.08) \times 10^{-14}$ s, cubic for $\tau < \tau_c$
  - Corresponding calculated normal state resistivity: $\rho_n > 27.0 \pm 1.4$ µΩcm → **Consistent**

Connection to superconducting properties

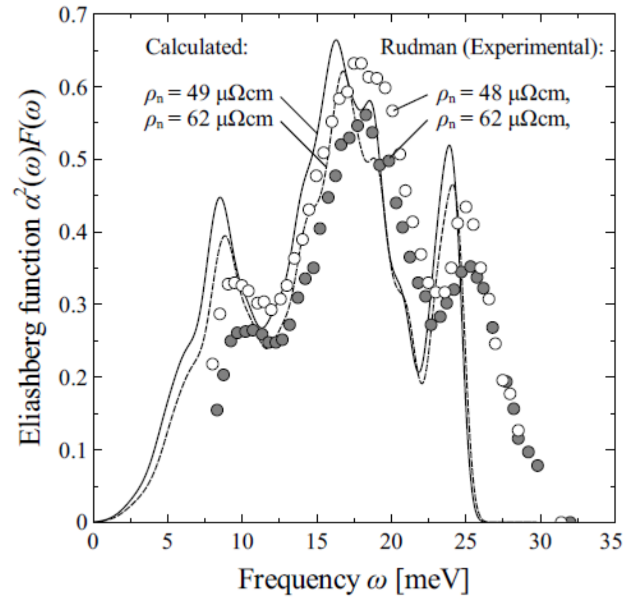
Ab-initio: Electron density of states



Ab-initio: phonon dispersion curves

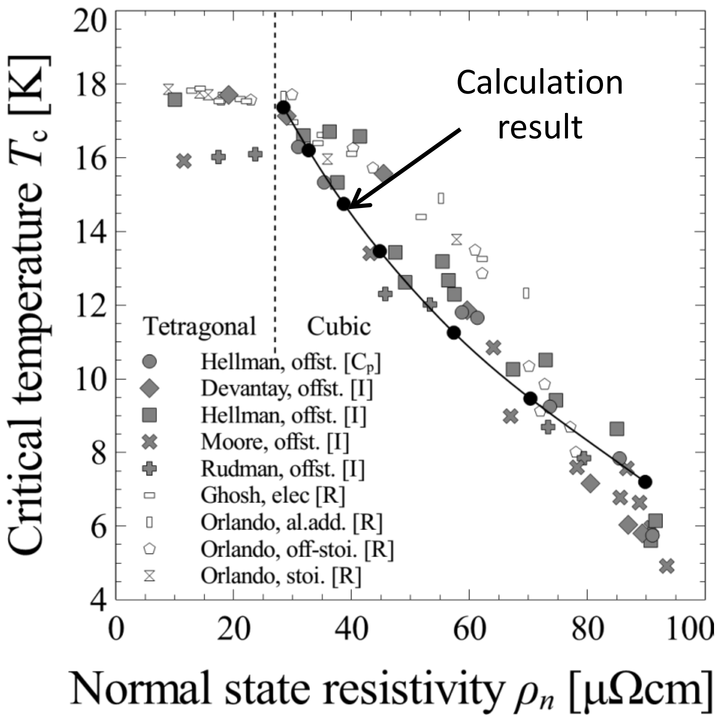


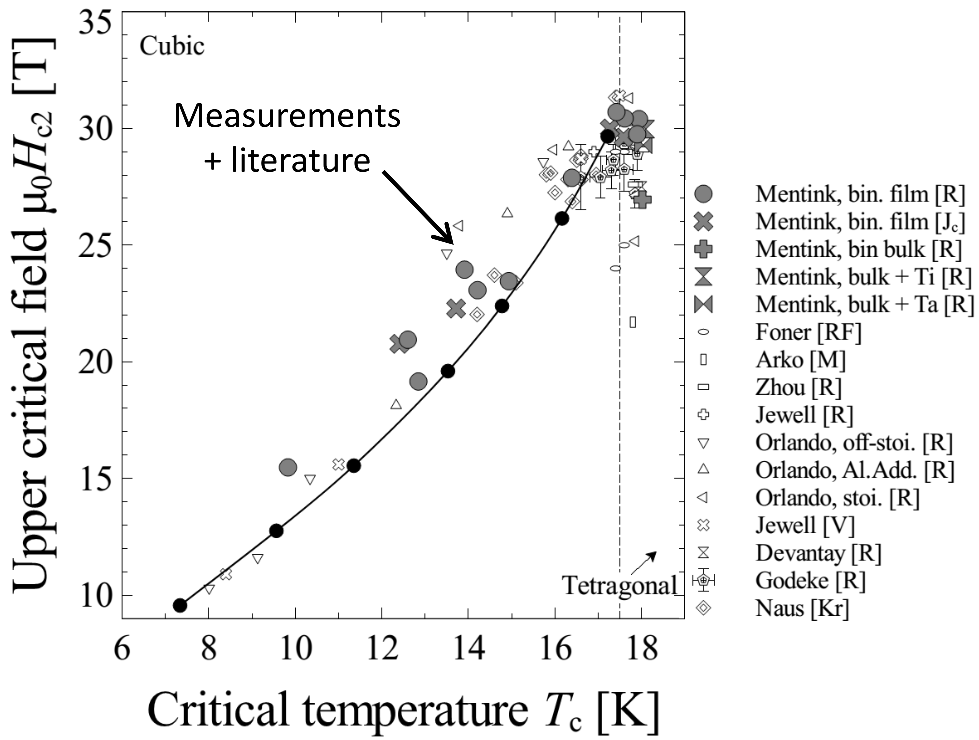
Eliashberg spectrum



- Global constants: α^2_{Eff}, ω_0, μ^*
- Electron-phonon coupling characteristic: $\alpha^2(\omega) = \alpha^2_{Eff} \times N(E_F) \times \exp(-\omega/\omega_0)$ [11]
- Ab-initio calculation of electronic and phonon density of states
- Result: Eliashberg spectrum

Calculation model for T_c and H_{c2}





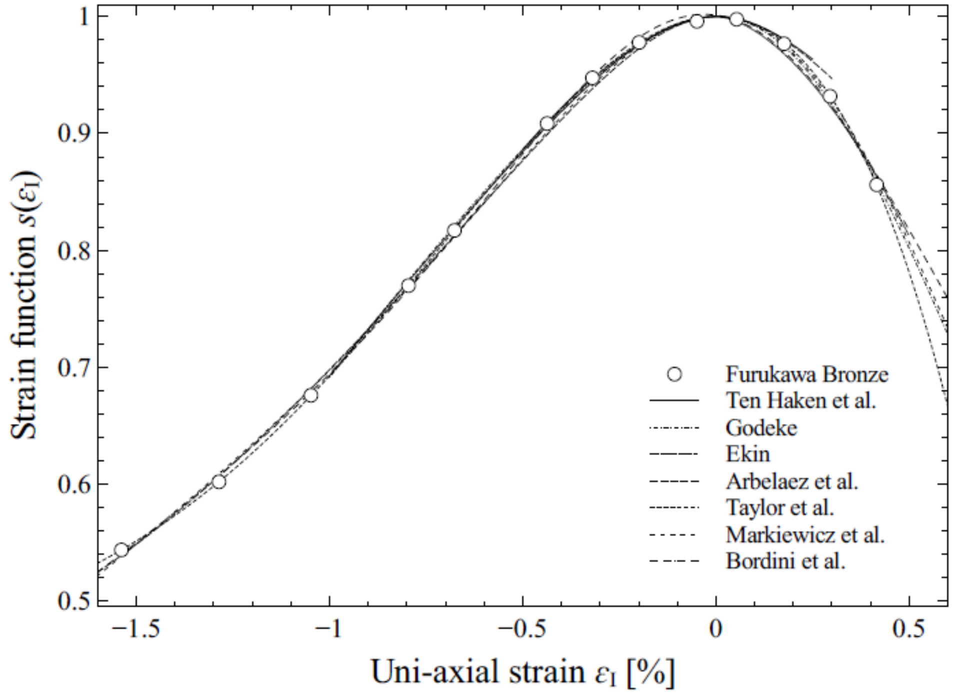
Calculation model for disorder dependent T_c, H_{c20}, and martensitic transition

- Calculation result:
  - Strong coupling corrected critical temperature
  - Strong coupling corrected variable limit upper critical field with Pauli limiting
- Validated with experimental observations

Overview

- How does the critical current depend of temperature, magnetic field and strain?
- How can we model the disorder dependent critical temperature and upper critical field?
- **Why is Nb_3Sn so strain sensitive?**
- How does Nb_3Sn compare to other superconductors?

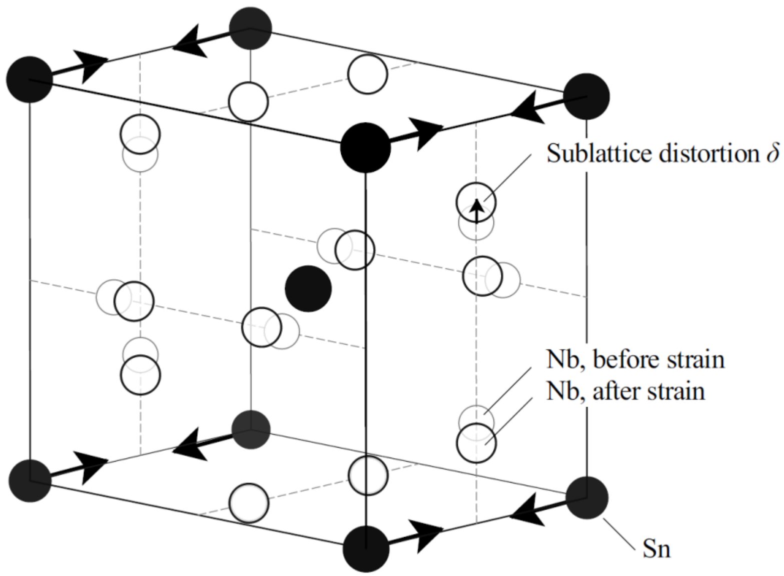
How are T_c and H_{c20} affected by strain?



$$H_{c20}(\varepsilon) = H_{c2m} s(\varepsilon), \qquad \frac{T_c(\varepsilon)}{T_{cm}} = \left(\frac{H_{c20}(\varepsilon)}{H_{c2m}}\right)^{1/w}$$

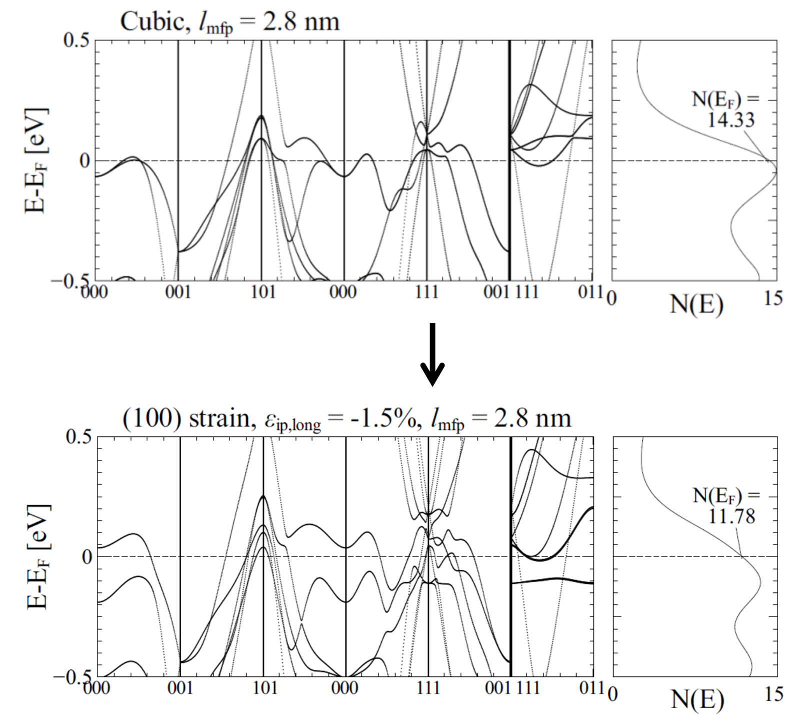
- Strain dependence of I_c through strain-dependent $H_{c20}(\varepsilon)$ and $T_c(\varepsilon)$
- Strain dependence of $H_{c20}(\varepsilon)$ expressed with strain function $s(\varepsilon)$ (well-known shape)
  - (Semi)-empirical expressions with free strain parameters
  - $T_c(\varepsilon) \sim H_{c20}(\varepsilon)^{1/w}$, $w = 2\ldots3$
- What determines (the strain dependence of) T_c and H_{c20}?

External application of strain: Sub-lattice distortion



Strained Nb_3Sn

Electronic band structure



Strain induced distortion of the niobium chains (Calculated ab-initio)

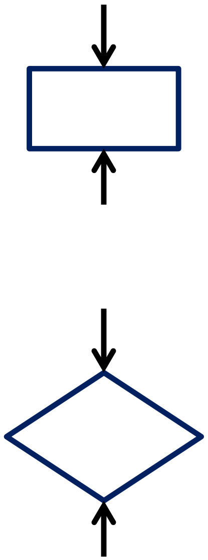
- Similar to occurrence during martensitic transition (= experimentally observed)
- Anisotropic in nature
- Affects the electronic and vibrational properties of the crystal

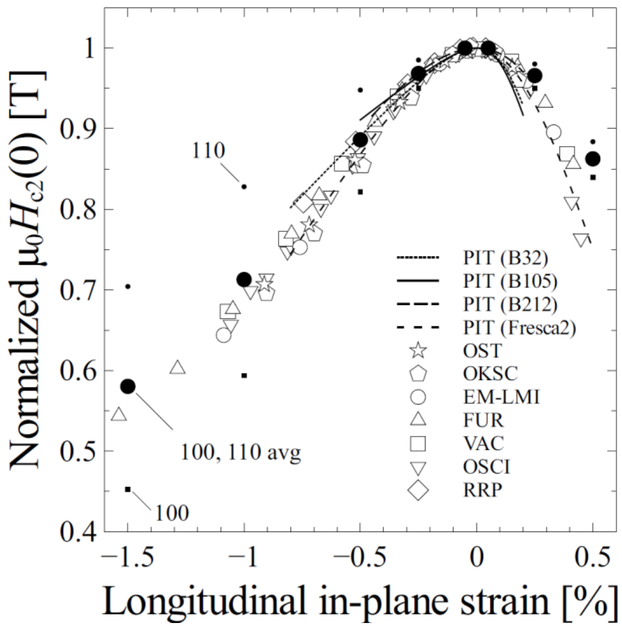
(Sublattice distortion suppressed → Properties of crystal barely affected)

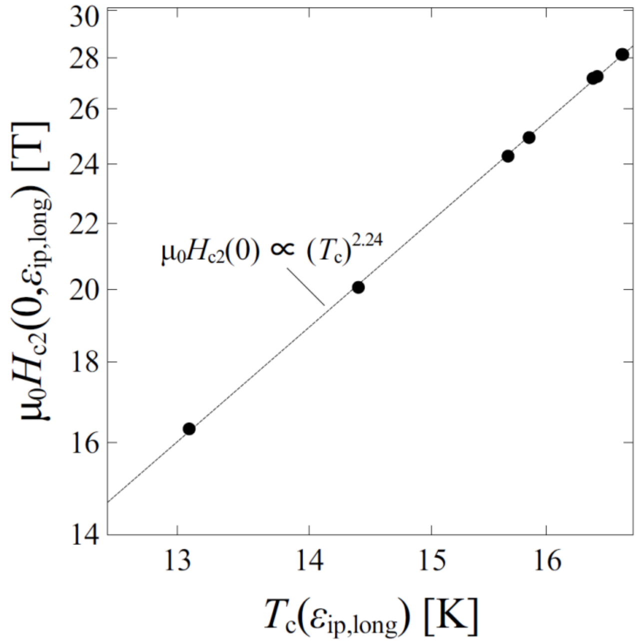
Strain dependent critical temperature and upper critical field

100 strain:

110 strain:



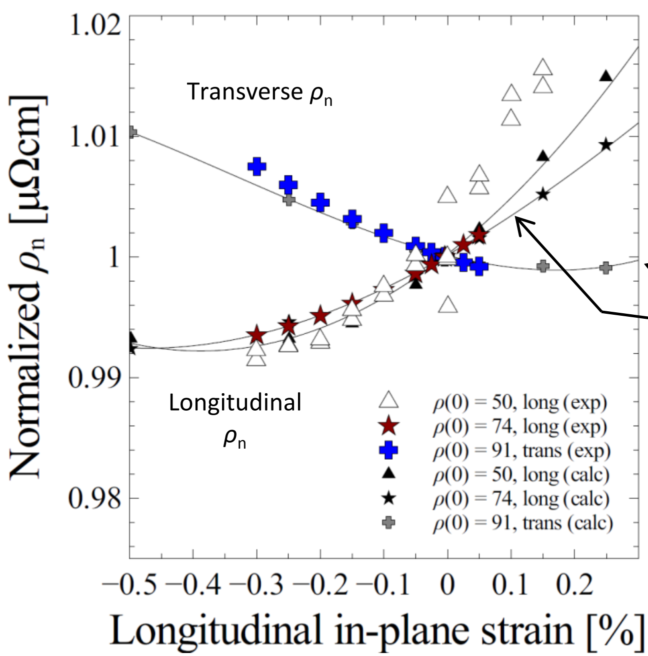


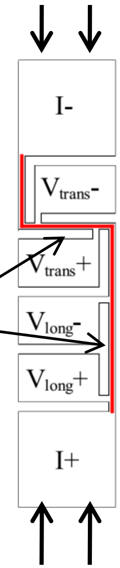


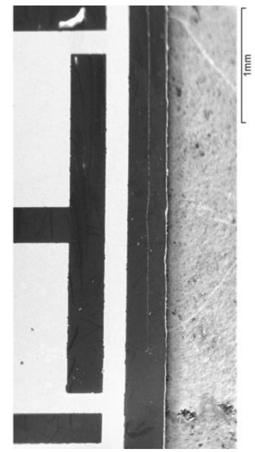
Calculation:

- Fixed mean free path so that T_{cm} = 16.7 K, $\mu_0 H_{c2m}$ = 28.1 T, no assumed strain behaviour or free strain parameters
- Calculated normalized $H_{c20}(\varepsilon)$ consistent with experimental observations in shape and magnitude
- Calculation: Power law dependence between T_c and H_{c2} with w = 2.24, consistent with experimental observations [7]

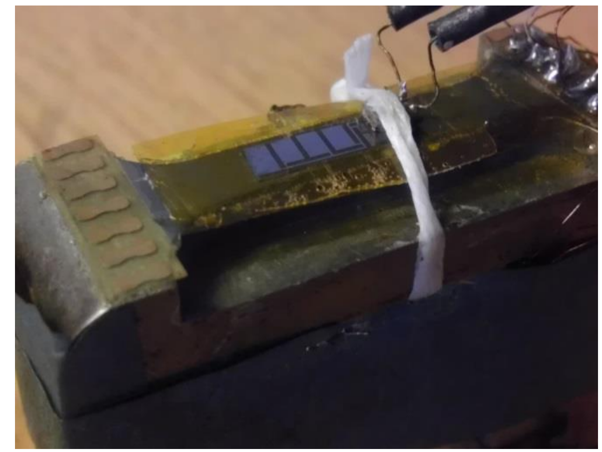
Strain dependent normal state resistivity





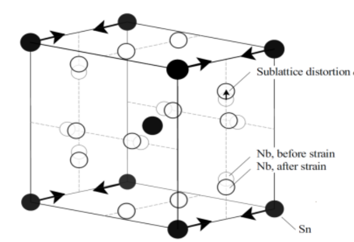


SEM image



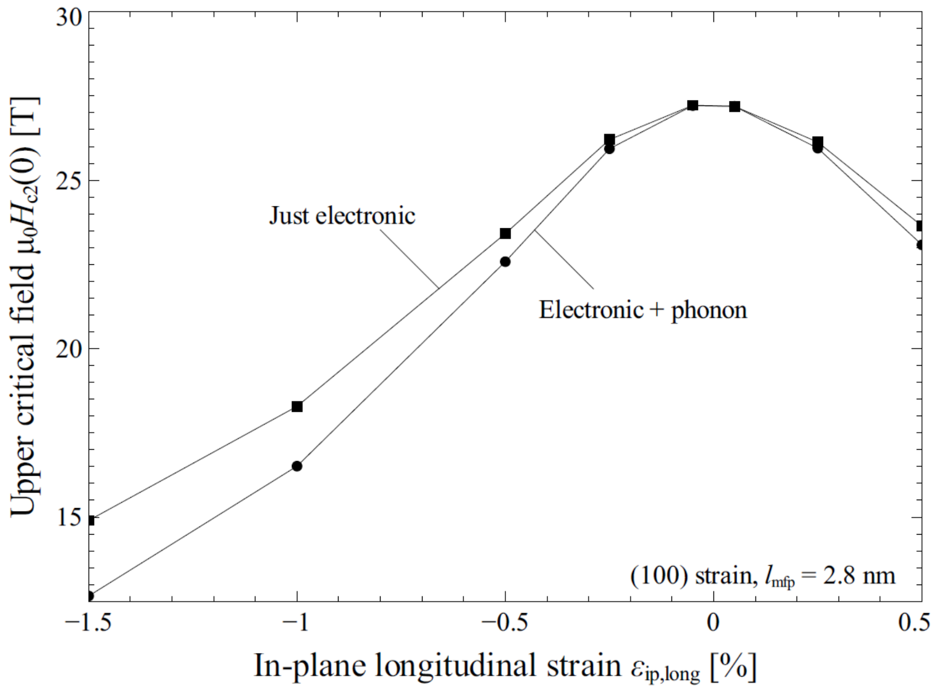
U-spring with etched thin film

Anisotropic normal state resistivity due to anisotropic nature of sublattice distortion



- Calculation result: Strain → Anisotropic resistivity
  - Compressive strain: Longitudinal ρ_n ↓, transverse ρ_n ↑
- Experiment:
  - Nb-Sn thin films etched into special patterns, allowing for longitudinal and transverse resistivity measurement
  - Result: Consistent with calculation result

Electronic and vibrational contribution to strain sensitivity



What is the relative contribution to strain sensitivity from the strain-dependent electronic and vibrational properties?

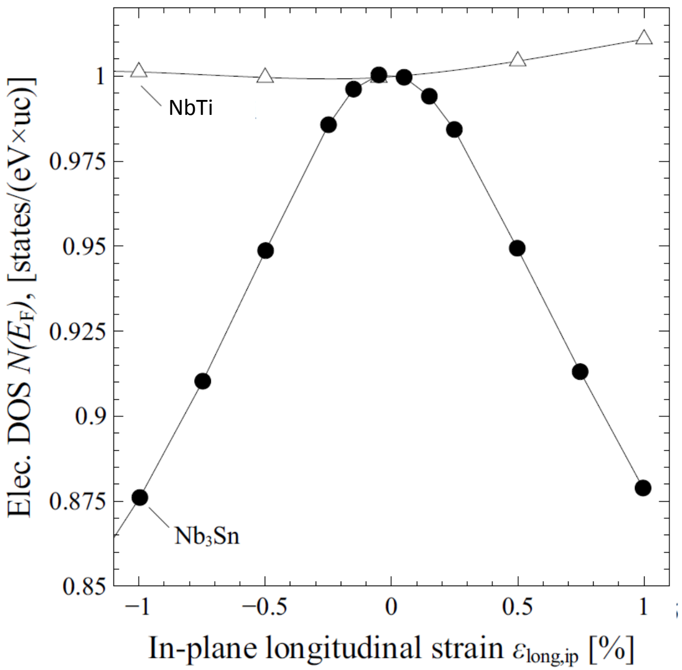
- Comparison: Strain sensitivity phonon DOS suppressed versus regular calculation
- Calculation result: Near stoichiometry, strain-sensitivity mainly (~85%) due to strain-dependent electronic properties
- Experimental evidence: Strain-dependent ρ_n → Strain sensitivity of electronic properties not negligible

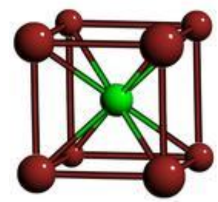
Overview

- How does the critical current depend of temperature, magnetic field and strain?
- How can we model the disorder dependent critical temperature and upper critical field?
- Why is Nb_3Sn so strain sensitive?
- **How does Nb_3Sn compare to other superconductors?**

Comparison between superconductors

Calculation

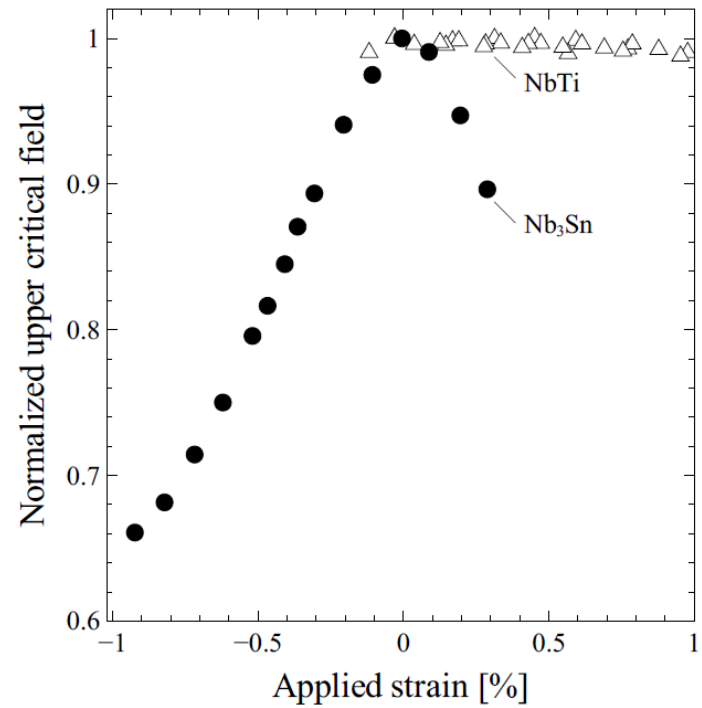




B2 NbTi

A15 Nb_3Sn

Experimental observation



Calculation result	**Experimental result**	**Why?**
Strain sensitivity Nb_3Sn > Nb_3Al	Consistent [12]	Lower degree of sublattice distortion in Nb_3Al
Strain sensitivity $Nb_3Sn \gg$ Nb	Consistent	No niobium chains in Nb
Strain sensitivity $Nb_3Sn \gg$ NbTi	Consistent [13]	No niobium chains in NbTi

Conclusions

- Critical current of Nb_3Sn as a function of temperature, magnetic field, strain
  - Consensus between most commonly used descriptions
  - Same as NbTi except for different temperature dependence of upper critical field
- Ab-initio calculations + microscopic theory:
  - Disorder dependent martensitic transformation, critical temperature, upper critical field
  - Validated with experimental observations
- Strain sensitivity in Nb_3Sn: due to strain-induced distortion of the niobium chains
  - Result: Strain sensitivity in superconducting and normal state properties
  - Validated with experimental observations
- Other superconductors:
  - Nb_3Al: Reduced sub-lattice distortion → Reduced strain sensitivity
  - Bcc Nb and NbTi: No niobium chains → Barely any strain sensitivity

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