An Introduction to Axial Strain Characterization of Nb_3Sn Wires

Workshop on Nb_3Sn Technology for Accelerator Magnets
Paris, October 12, 2018

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Agenda

1. High strain sensitivity of Nb_3Sn explained
2. Evolution of axial strain experiments

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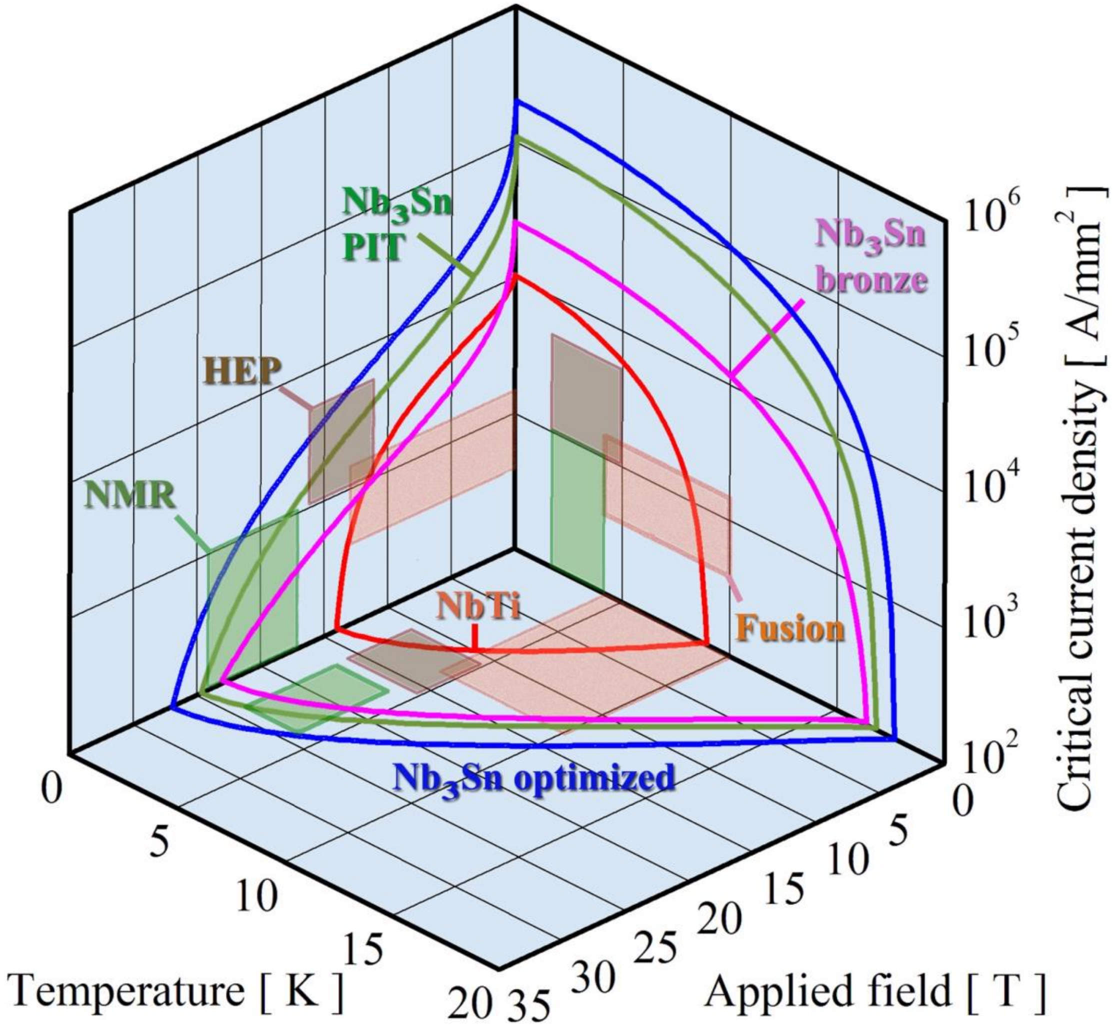
Nb_3Sn: Limits on *T*, *H*, and *J*

Limits on *T* and *H* are affected by strain, leading to a change in the maximum *J*

- Maximum *J*
  - Critical current density J_c
- Maximum *H*
  - Critical magnetic field H_{c2}
- Maximum *T*
  - Critical temperature T_c
- Critical surface
  - $J_c \rightarrow J_c(H,T,\varepsilon)$
  - Determines performance envelope for applications



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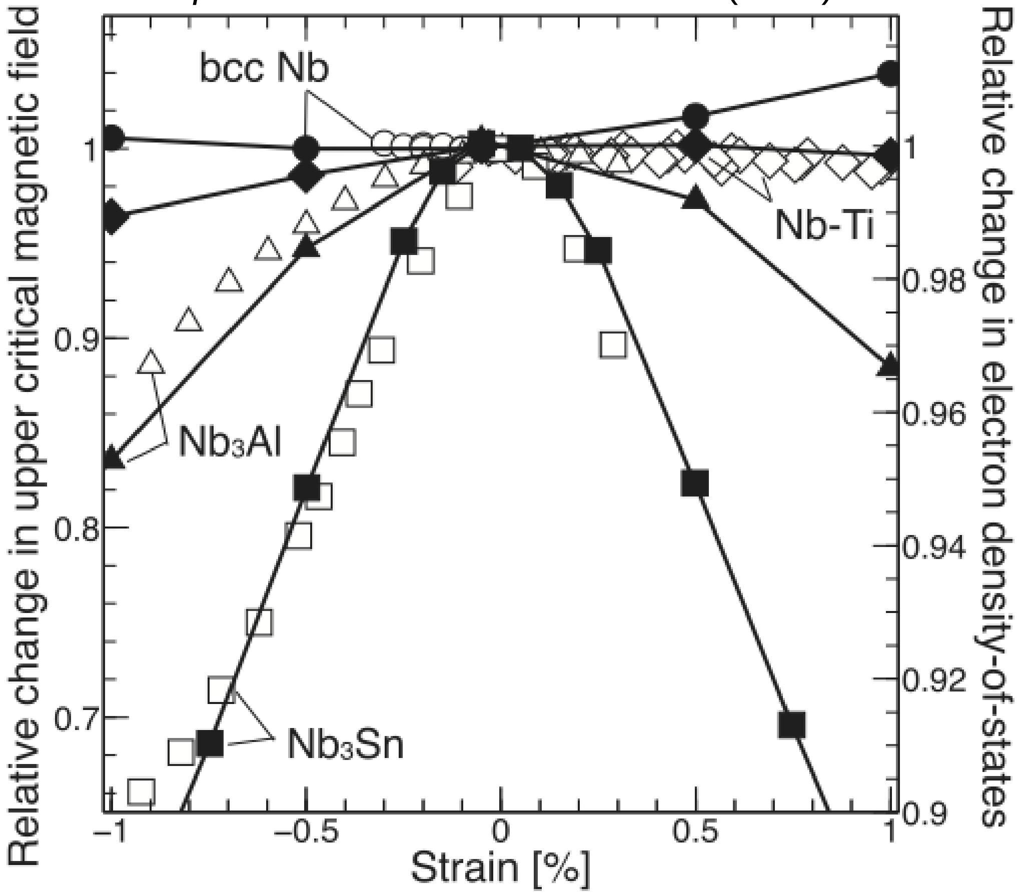
Probing $H_{c2}(\varepsilon)$ or $I_c(\varepsilon)$

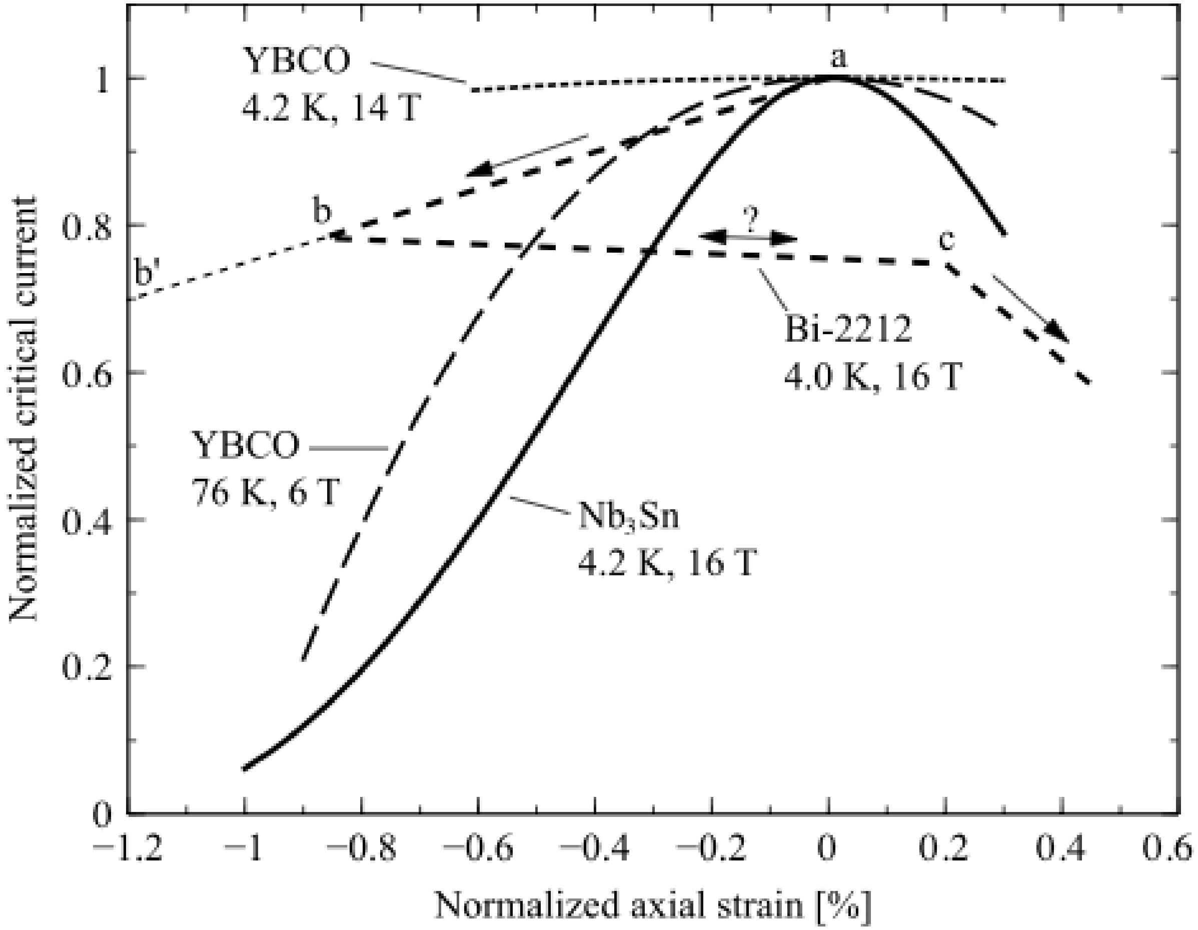
Nb_3Sn has ***due to sub-lattice instability*** a relatively high sensitivity to strain

Godeke, Hellman, ten Kate, Mentink
Supercond. Sci. Techn. **31** 105011 (2018)



Compared to other LTS

Bottura, Godeke
Rev. Acc. Sci. Techn. **5** 25 (2012)



Compared to HTS

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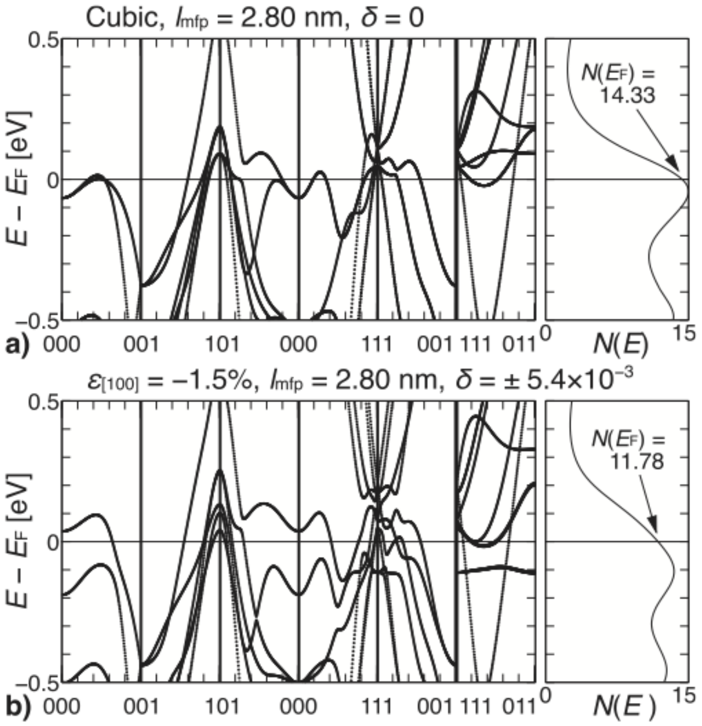
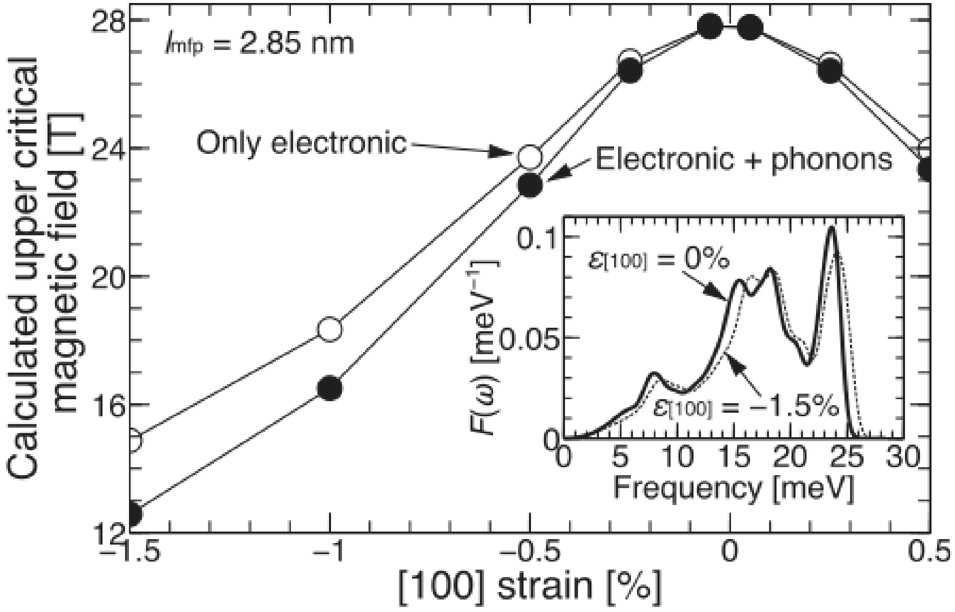
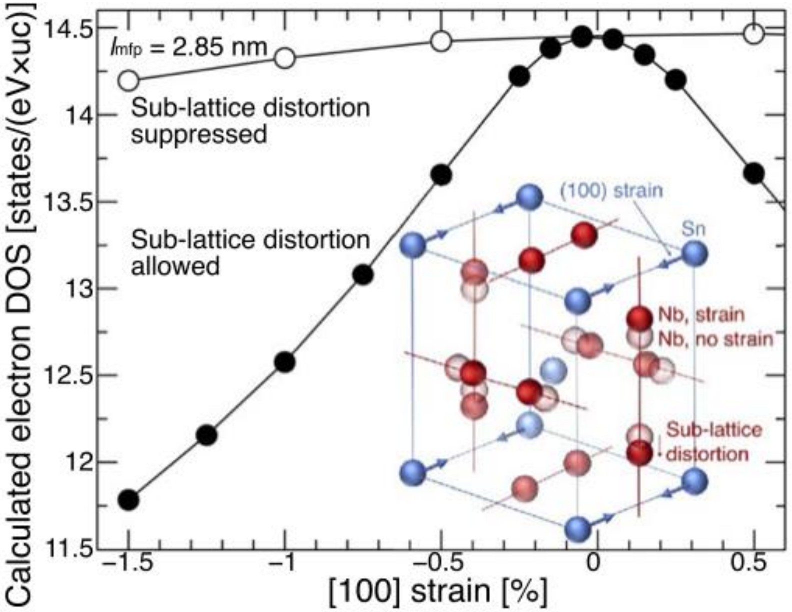
Fundamental origin of high strain sensitivity of Nb_3Sn

Ab-initio calculations + GLAG microscopic theory + experiments (Mentink PhD)

Godeke, Hellman, ten Kate, Mentink
Supercond. Sci. Techn. **31** 105011 (2018)







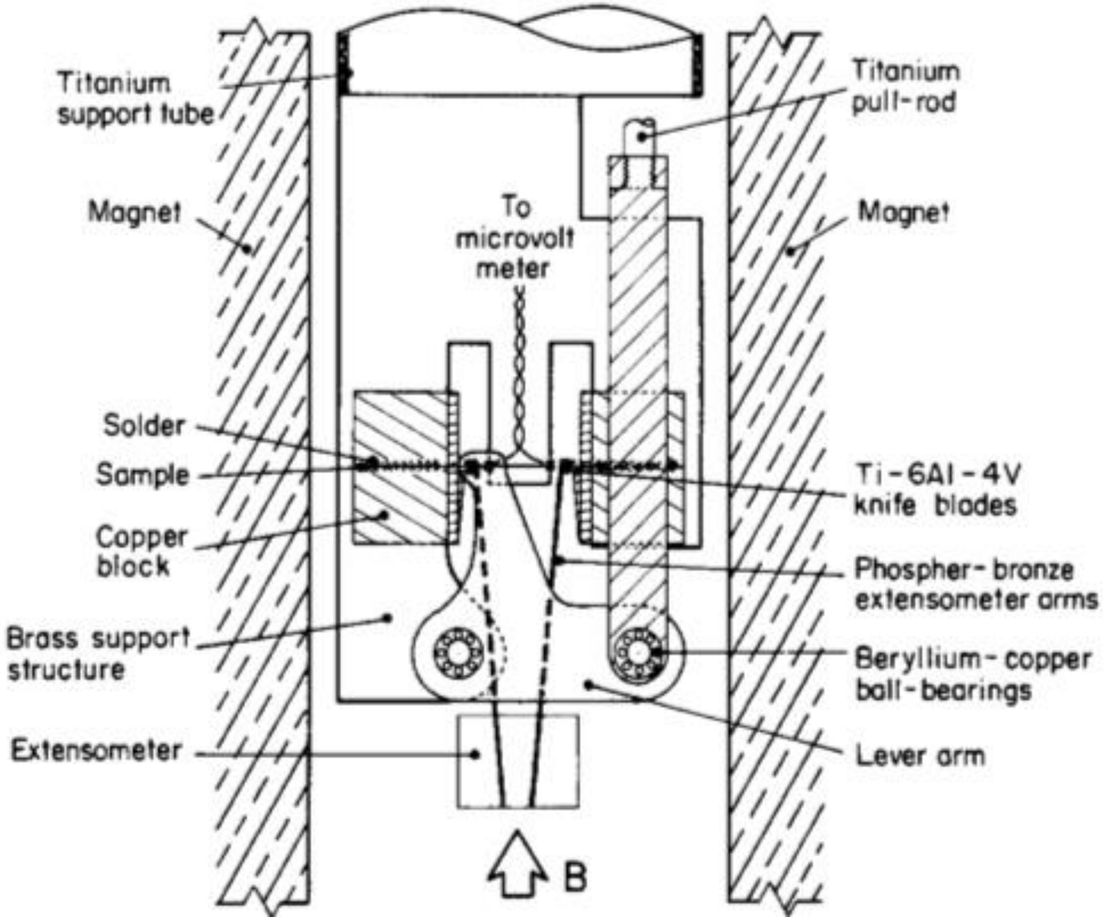
Electron DOS collapses
causing reduced SC properties

Strain sensitivity is for 80%
caused by electronic properties
20% is cause by phonons

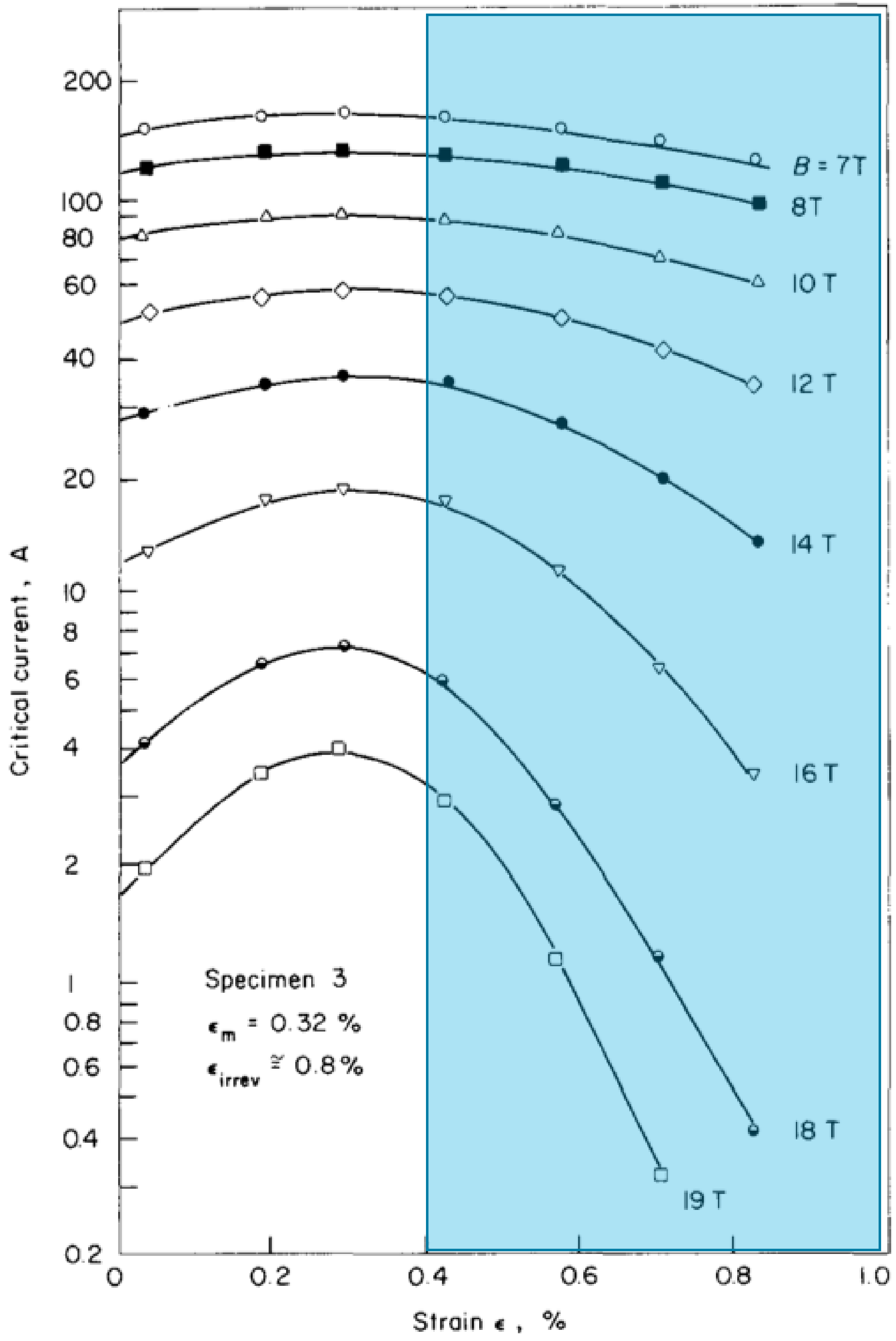
Electron DOS as proxy for sensitivity:
Sub-lattice distortion causes
large strain sensitivity

Early $I_c(\varepsilon)$ results

Tensile tests on short wire sections



Ekin
Cryogenics **20** 611 (1980)



OK for fine-filament bronze, but modern high-J_c wires break in this region

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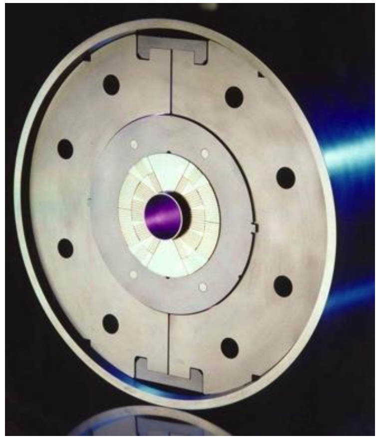
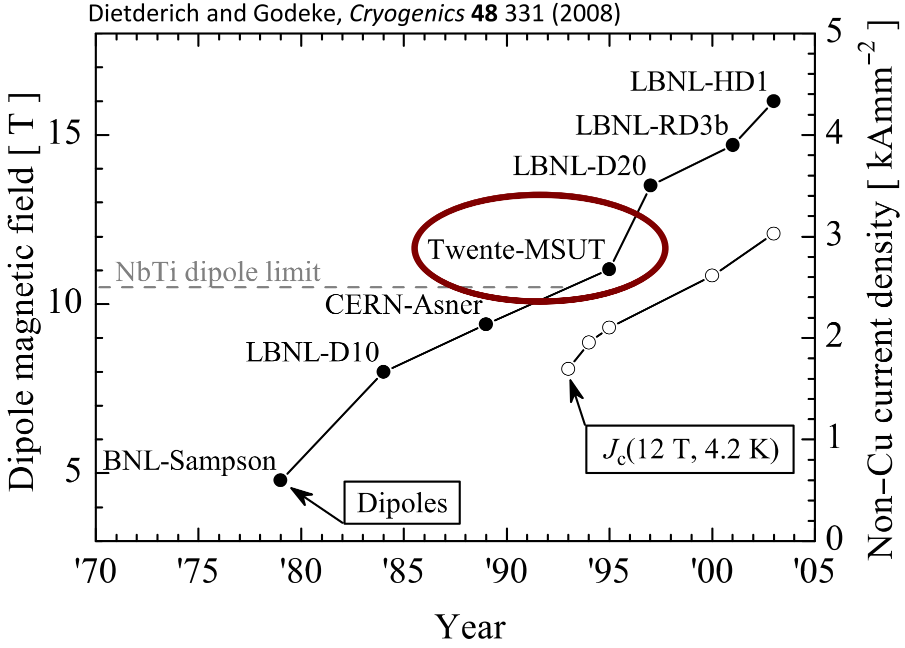
University of Twente, early 1990's

MSUT: An 11 T Nb_3Sn dipole magnet

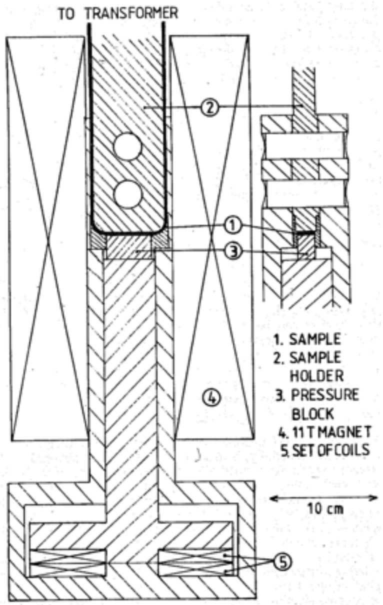
den Ouden, *et al.*,
IEEE Trans. Appl. Supercond. **7** 733 (1997)



Dietderich and Godeke, *Cryogenics* **48** 331 (2008)

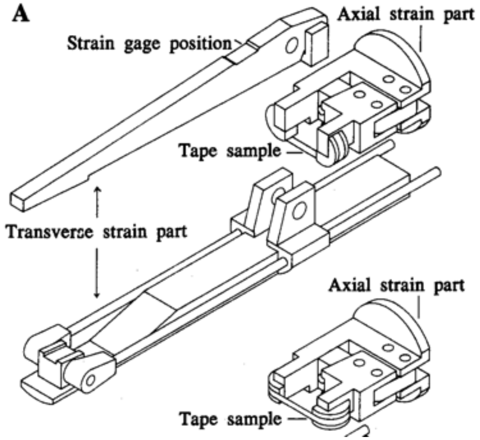


- Supporting R&D: I_c(strain, stress)
  - Nb_3Sn cables under load: $I_c(H,F_\perp)$



Boschman, *et al.*
IEEE Trans. Magn. **27** 1829 (1991)

- Nb_3Sn tapes under load: $I_c(H,F_\perp,\varepsilon_{axial})$



ten Haken, Godeke, ten Kate,
IEEE Trans Appl. Supercond. **3** 1273 (1993)

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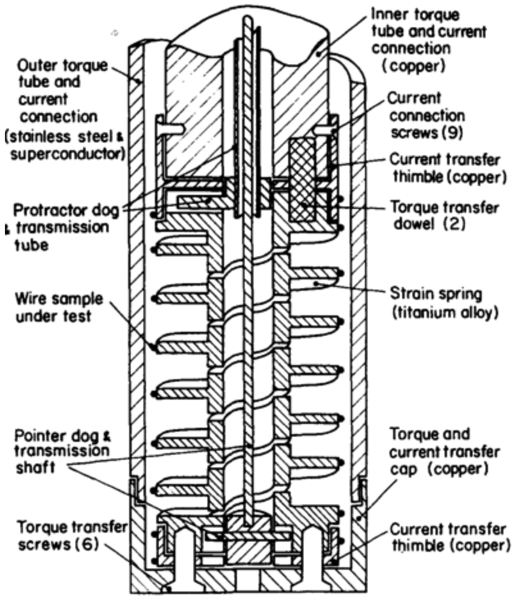
1992: U-shaped bending springs

CTE Nb_3Sn is low: Wires in compression

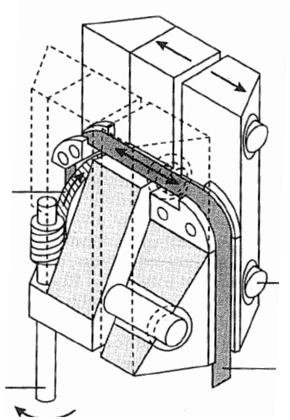
Look at compressive axial strain

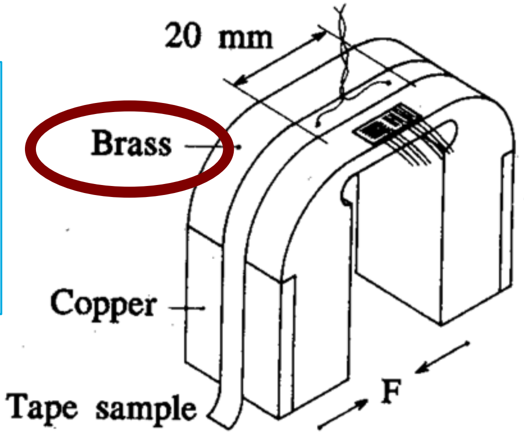
- Novel variable temperature
  - Flow cryostats have large time constants
  - Helium gas bubble under Kapton cup



Walters, Davidson, Tuck, *Cryogenics* **26** 406 (1986)

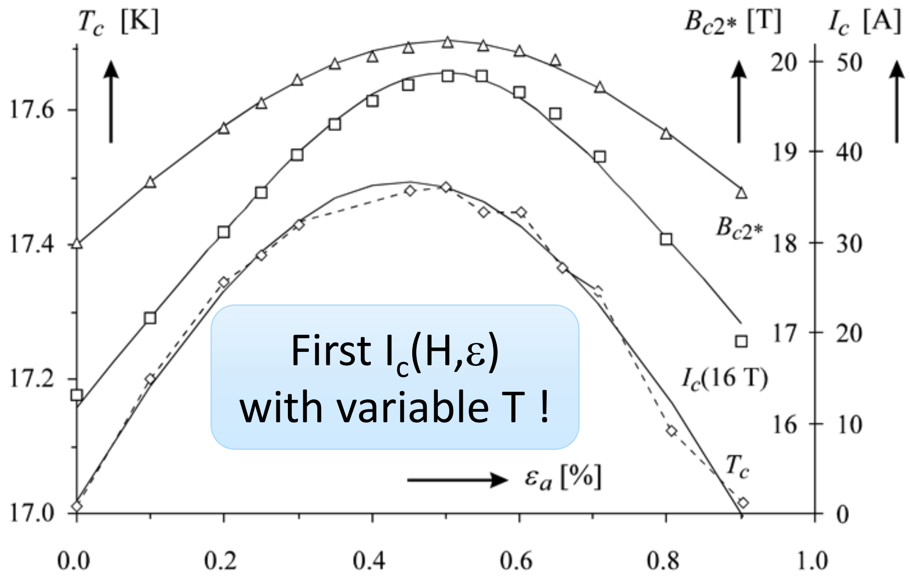
Godeke, *Graduation Report* (1992)





Soldering a sample on a substrate enables compression and homogenizes strain

ten Haken, Godeke, ten Kate, *IEEE Trans Appl. Supercond.* **3** 1273 (1993)



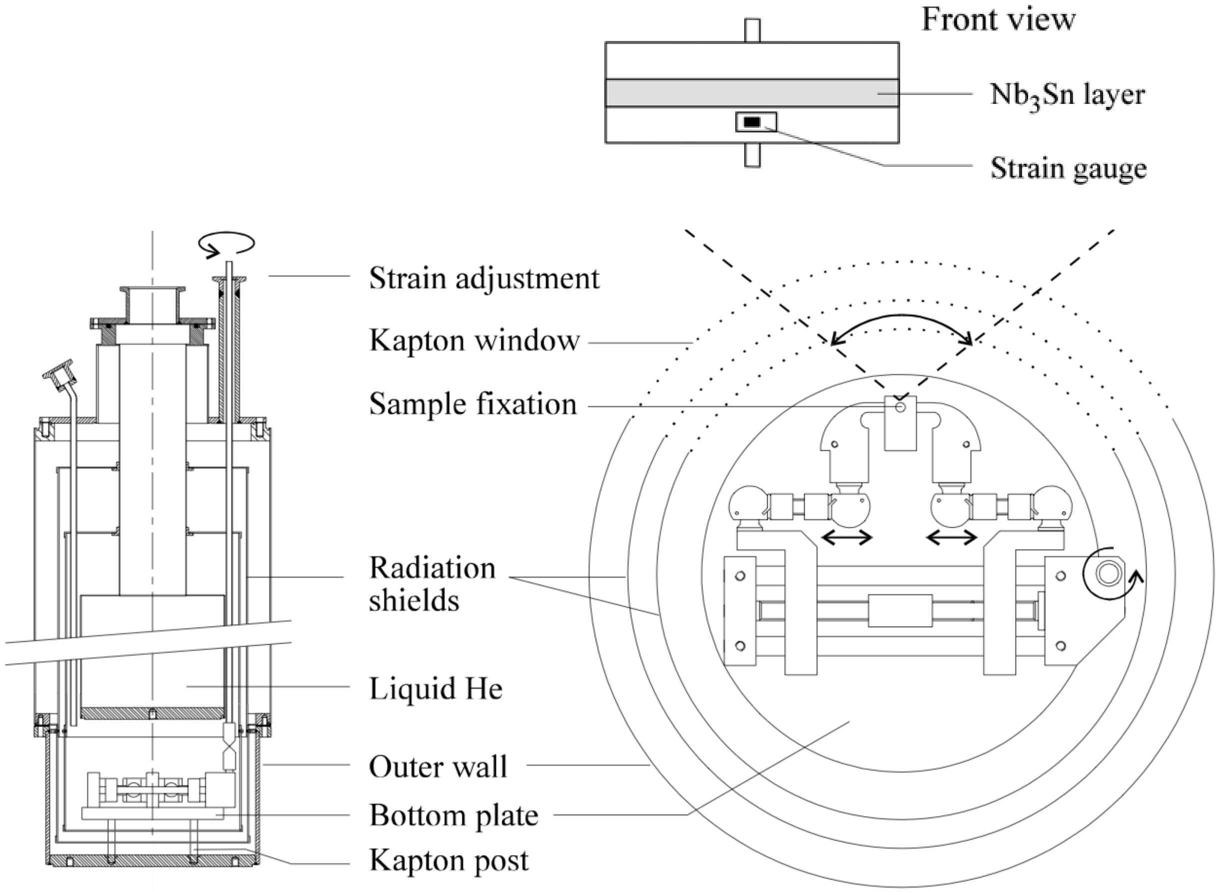
First $I_c(H,\varepsilon)$ with variable T !

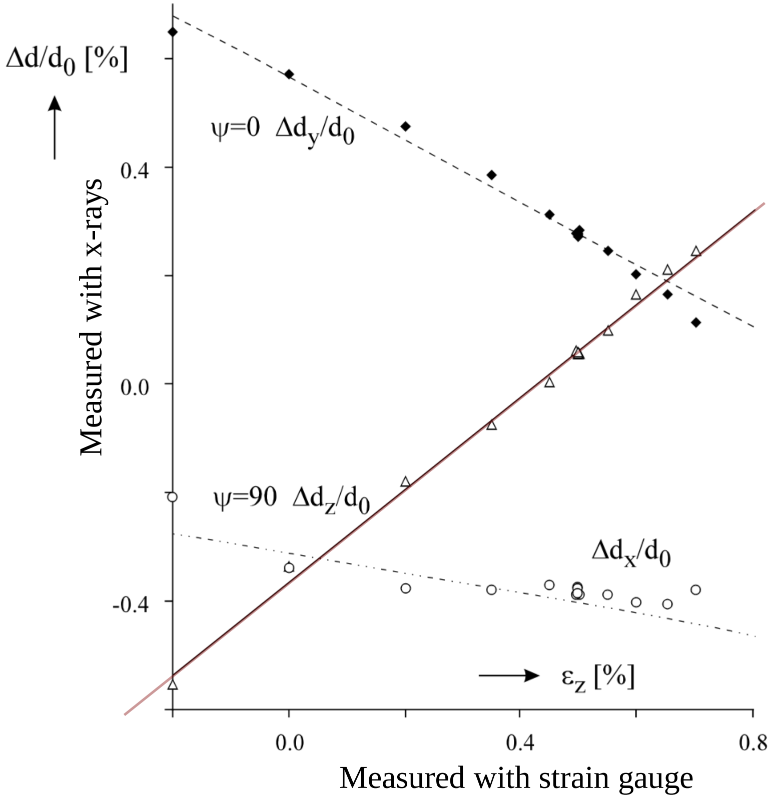
ten Haken, Godeke, ten Kate, *IEEE Trans Appl. Supercond.* **5** 1909 (1995)

1996: Does the lattice strain follow externally applied strain?

Is solder strong enough to transfer close to 1% longitudinal strain?

Low temperature X-ray diffraction experiment on tape with exposed Nb_3Sn





ten Haken, Godeke, ten Kate,
Adv. Cryo. Eng. **42B** 1463 (1997)

Lattice strain follows externally applied strain

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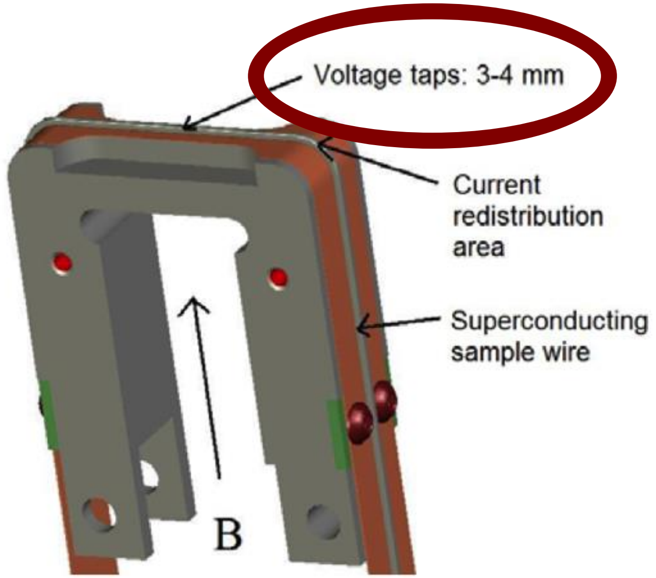
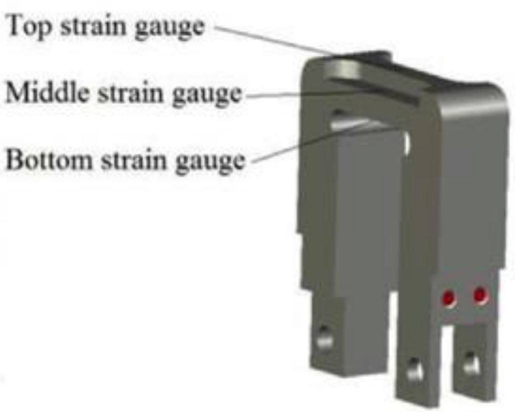
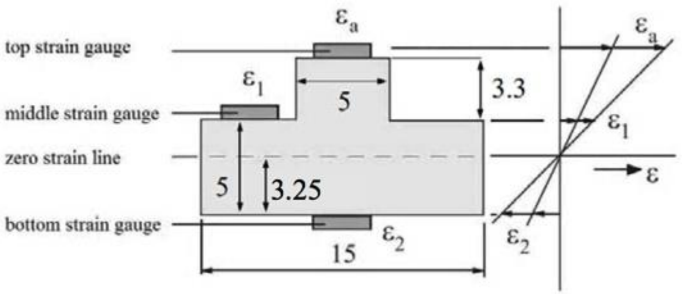
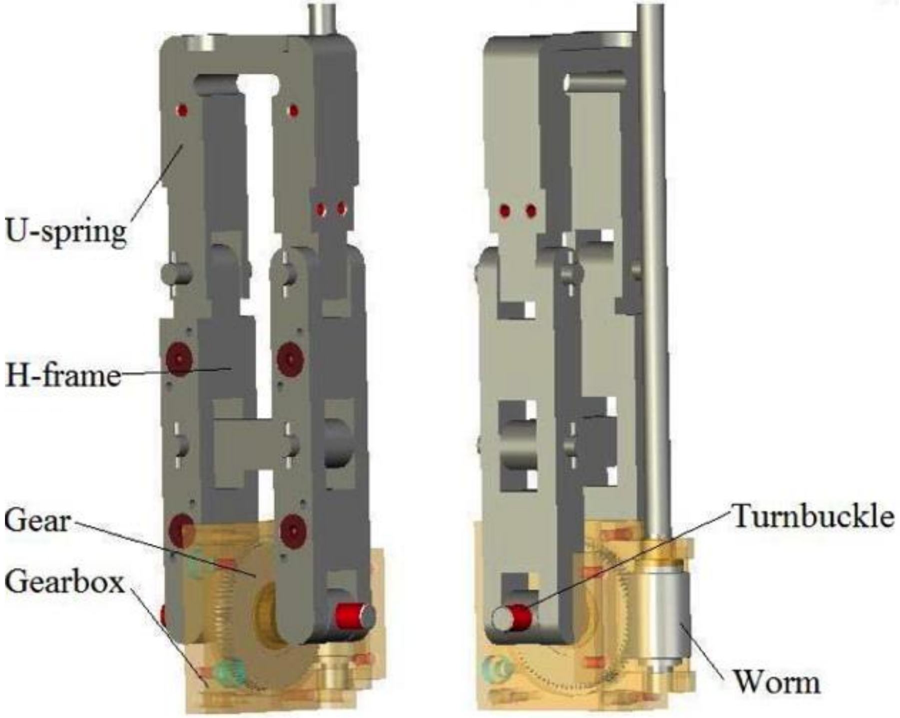
1997: Variable temperature, Ti-6Al-4V U-spring for wires

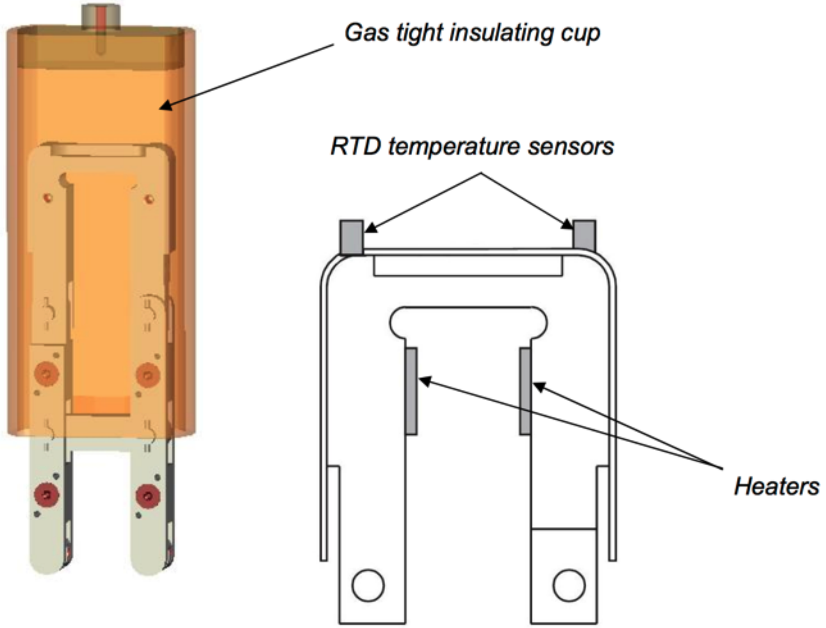
- Ti-6Al-4V elastic limit is 1.3% (Brass = 0.3%, Cu2w.%Be = 1%)
- Ti-6Al-4V CTE matches barrels
- Brazed Cu buffer layer to enable "regular" soldering
- Highest current in non-strained regions







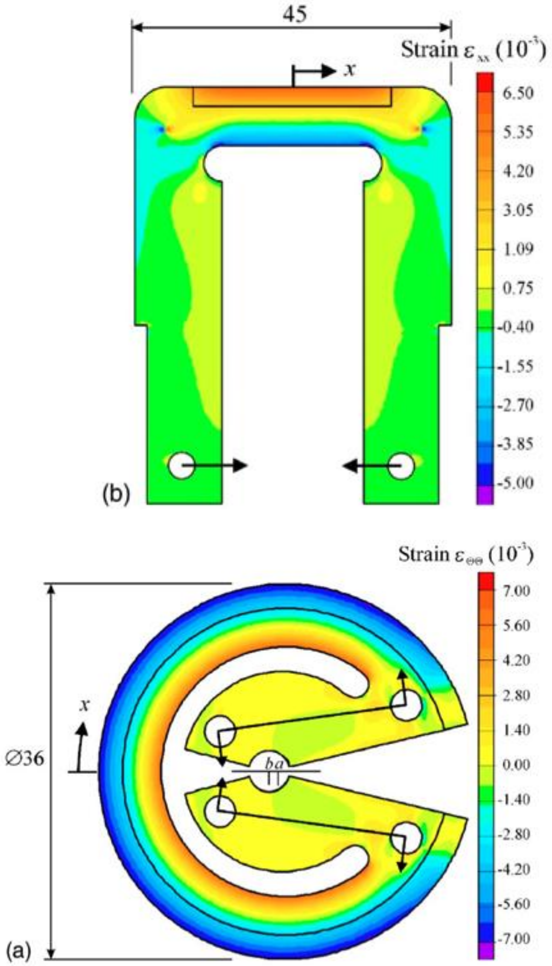


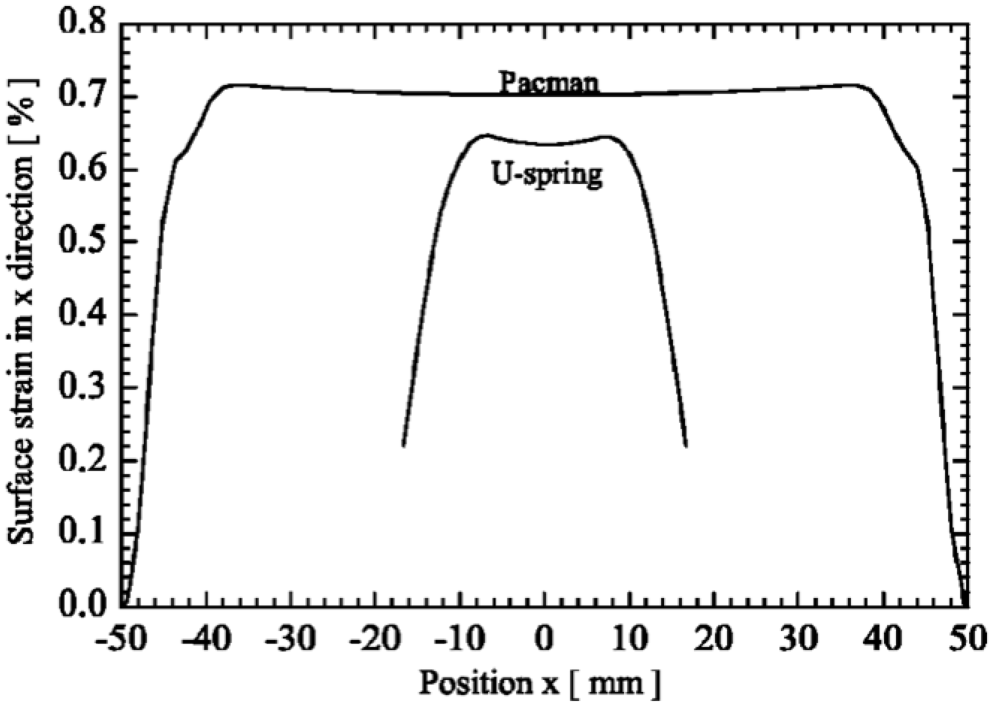


Godeke, *et al.*, EFDA Report (1998)
Godeke, ten Haken, ten Kate, *IEEE Trans. Appl. Supercond.* **9** 161 (1999)
ten Haken, Godeke, ten Kate, *J. Appl. Phys.* **85** 3247 (1999)

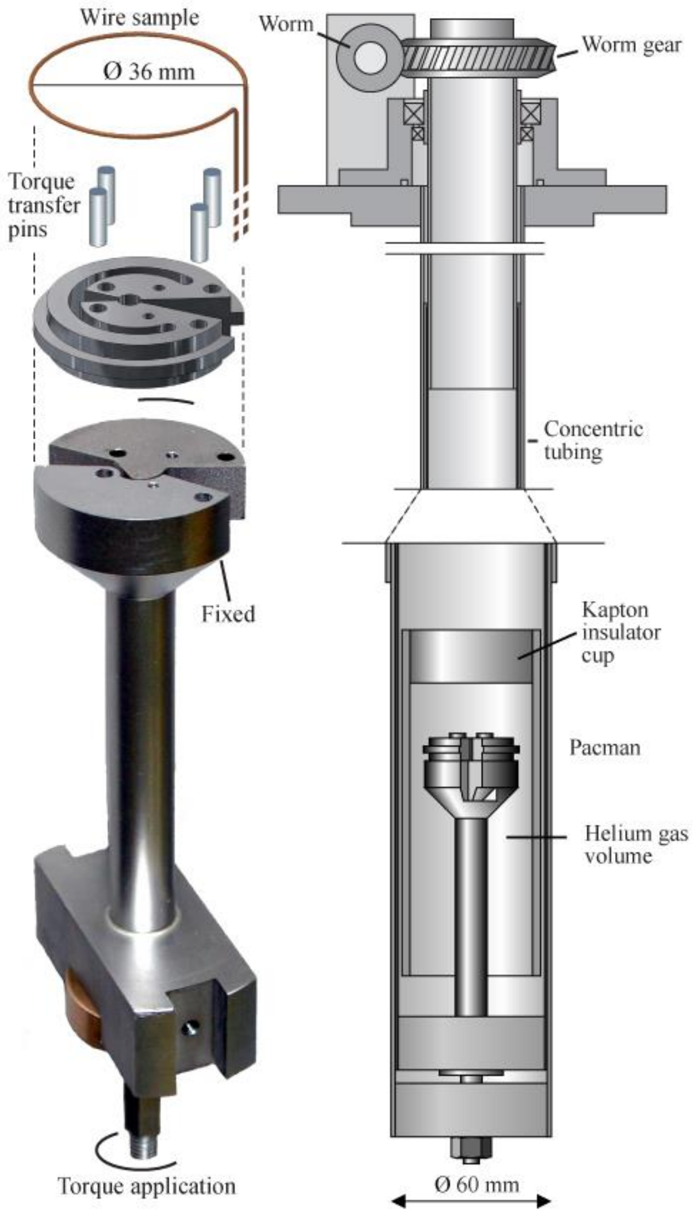
2002: Longer length strain experiments: "Pacman"

- From U-spring to Pacman
  - 10 x sample length (> 50 mm vs. < 5 mm)
  - 10 x voltage resolution (0.1 μV/cm vs. 1 μV/cm)
  - Thermodynamically optimized



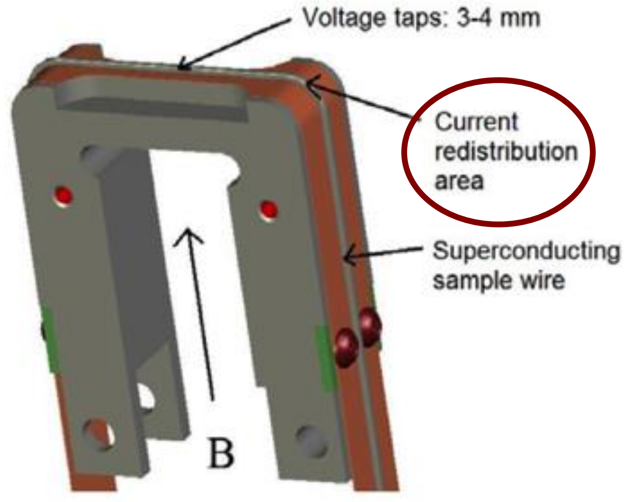


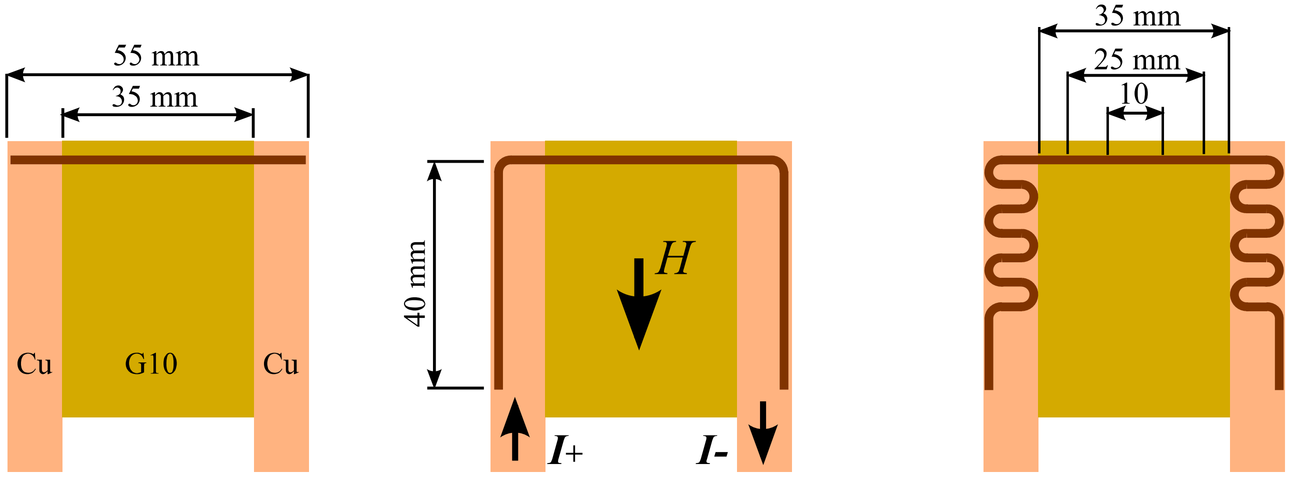
Godeke, *et al.*, *Rev. Sci. Instr.* **75** 5112 (2004)



2011: 0.1 μV/cm resolution possible on U-shaped springs

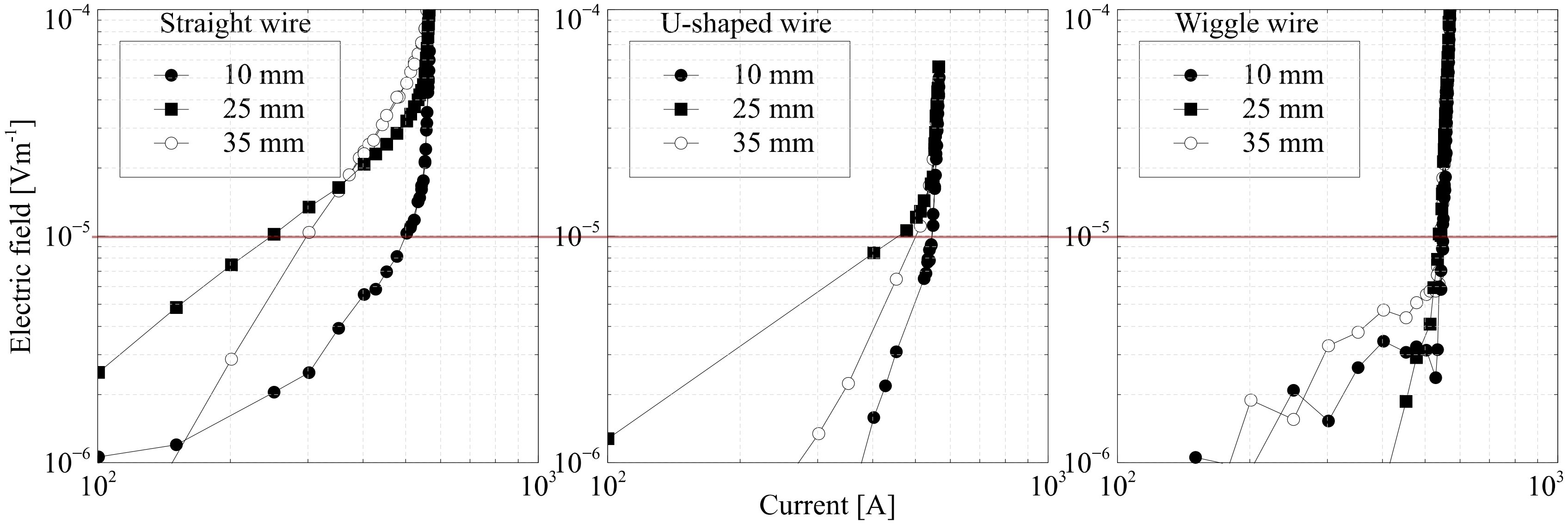
Going from I // B to I ⊥ B causes current redistributions that can be done earlier





a) Straight wire b) U-shaped wire c) Wiggle wire

Entrance voltages Redistribution voltages



Godeke, *et al.*,
Adv. Cryo. Eng. **58** 209 (2012)

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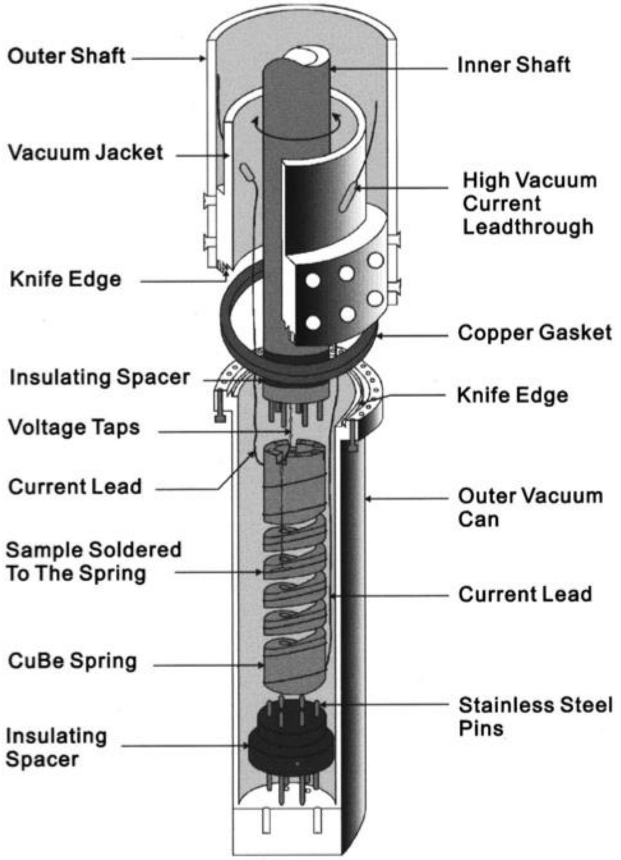
Selected Axial Strain Devices

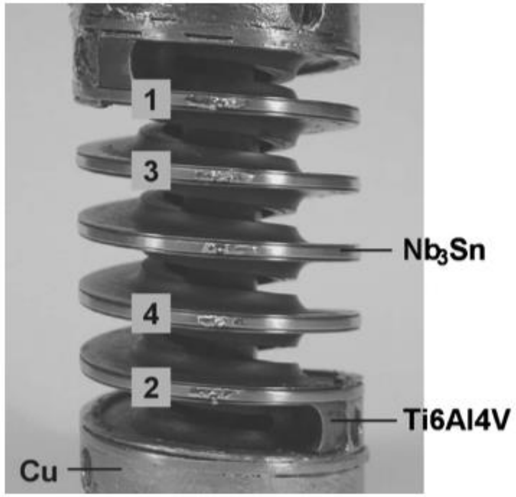
Twente setups already mostly shown

Cheggour, Hampshire
Rev. Sci. Instr. **71** 4521 (200)



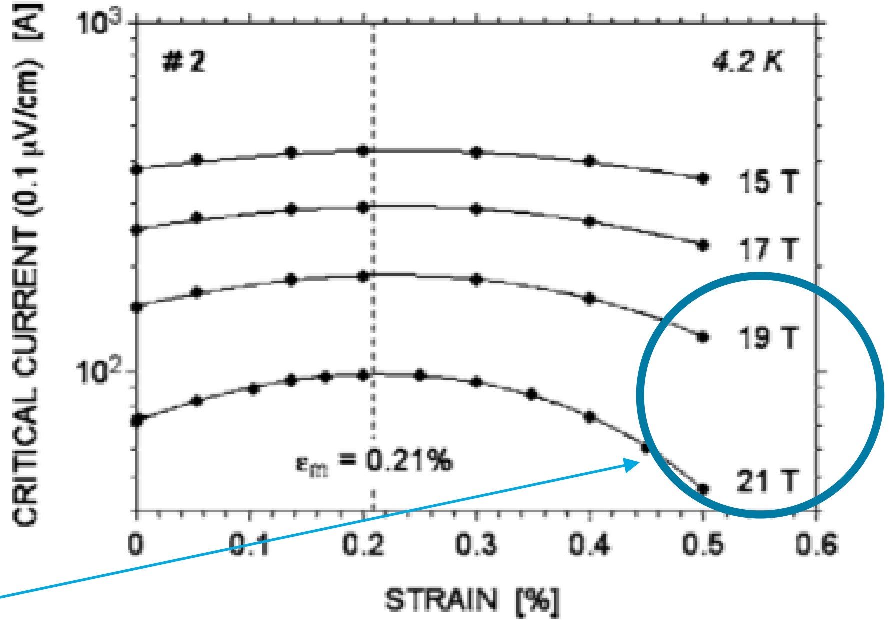
Durham Walters spring
Reproduced at NIST,
now at NHMFL

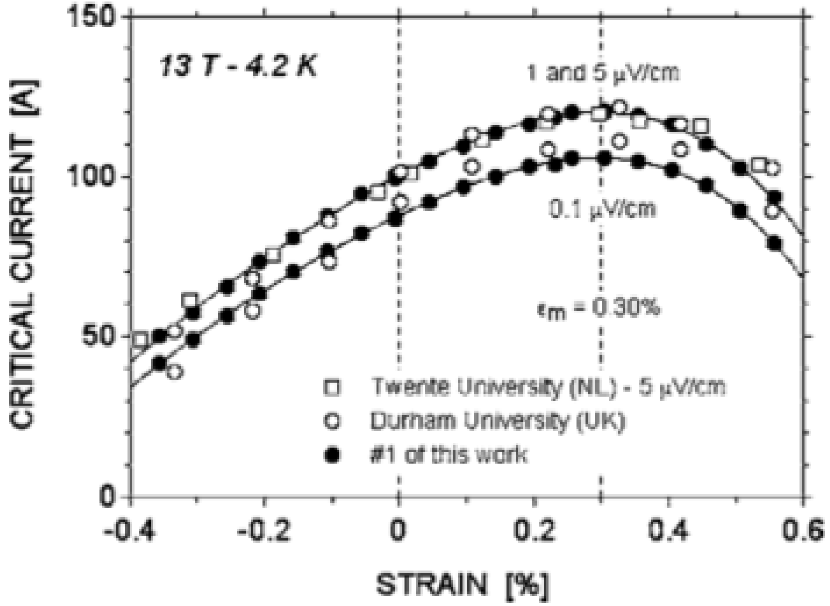
Seeber, et al.
Rev. Sci. Instr. **76** 093901 (2005)



Geneva Walters spring
Extended to transverse pressure

“Bending” springs at:
NIMS Tsukuba, Kyoto Univ., …





(Thank You)