A Review of Stress and Strain Effects on Bi-2212

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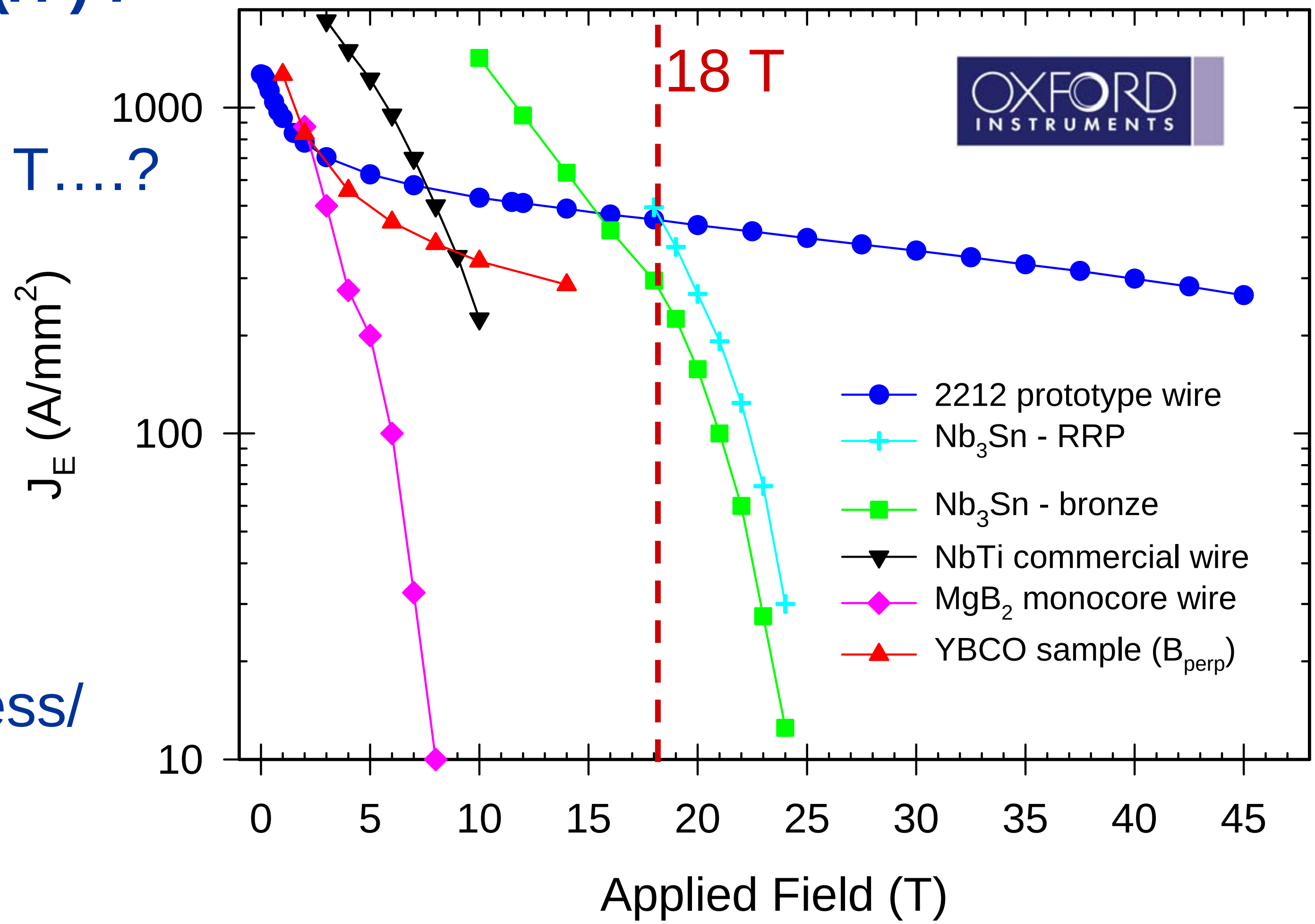
Bi-2212?

Engineering $J_E(H)$!

- 20 T, 30 T, 50 T….?



But…

- Bi-2212 is stress/ strain limited !

➧ K.R. Marken, MRS spring meeting 2006

Stress and strain in superconductors

Magnet systems

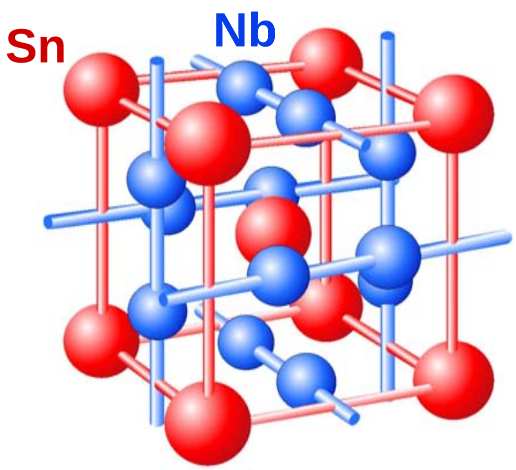
- Thermal contraction differences
- Lorentz loads

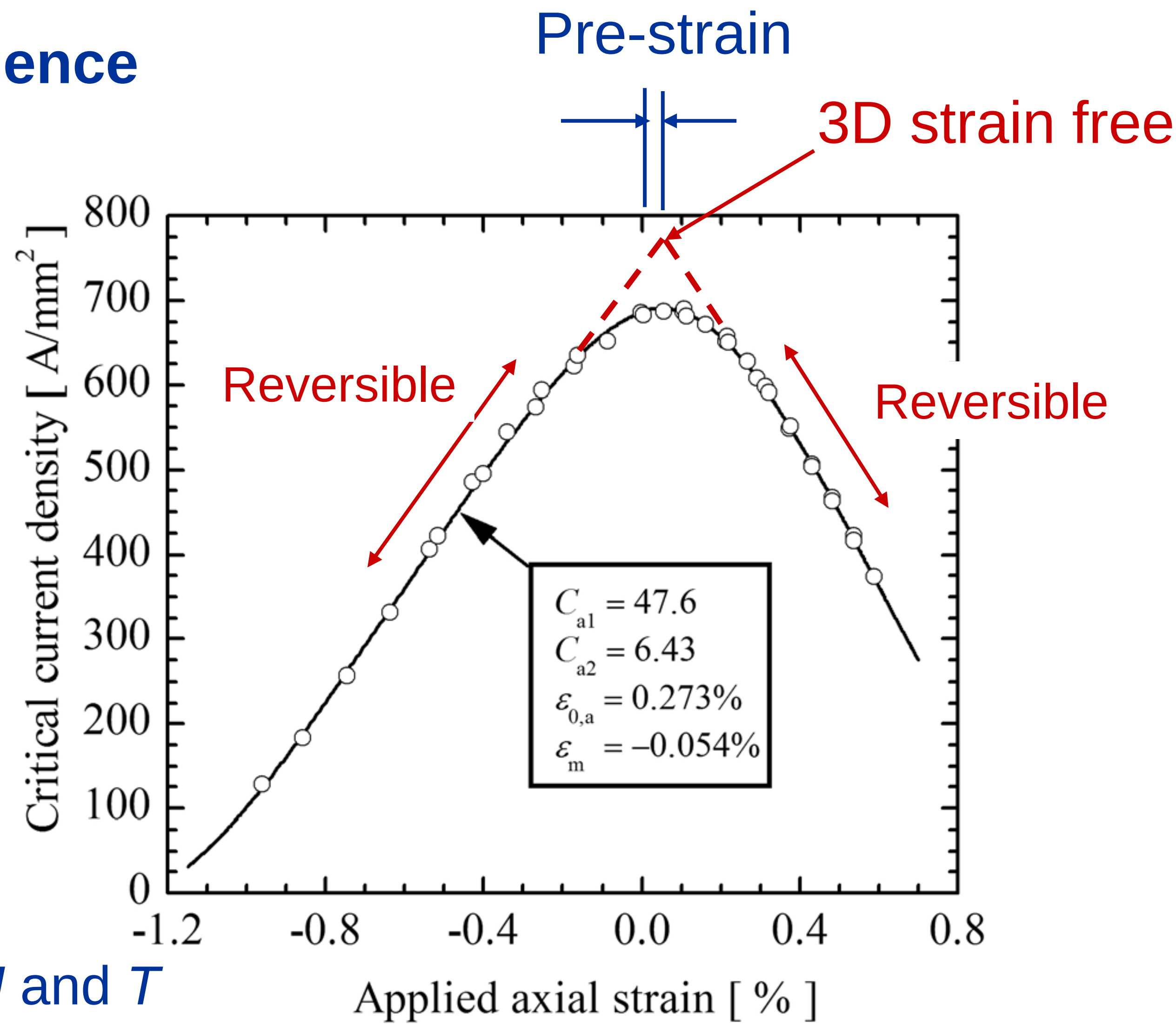
Short sample tests

- Axial load
- Transverse pressure
- Hydrostatic pressure

Nb_3Sn in a nutshell: Axial strain

Axial strain dependence





Reversible:

- $\Delta\varepsilon \rightarrow \Delta N(E_F)$, $\Delta\lambda_{ep}$
  - ΔT_c and ΔH_{c2}
  - ΔJ_c
- Slope depends on *H* and *T*

➡ Godeke, SuST, 2006

Nb_3Sn in a nutshell: Crack formation

'Preliminary' J_c collapse

- Irreversible
- Crack formation
  - Two (*unrelated*) ITER IT wires

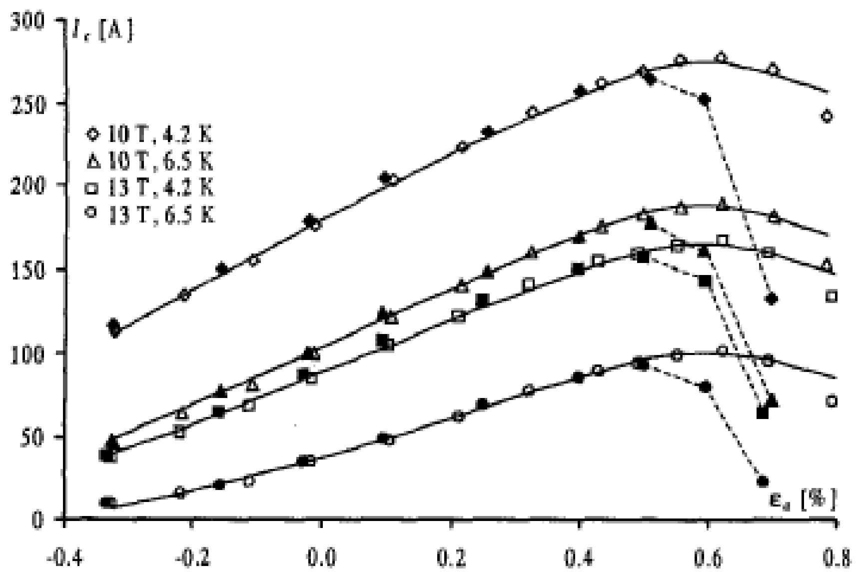
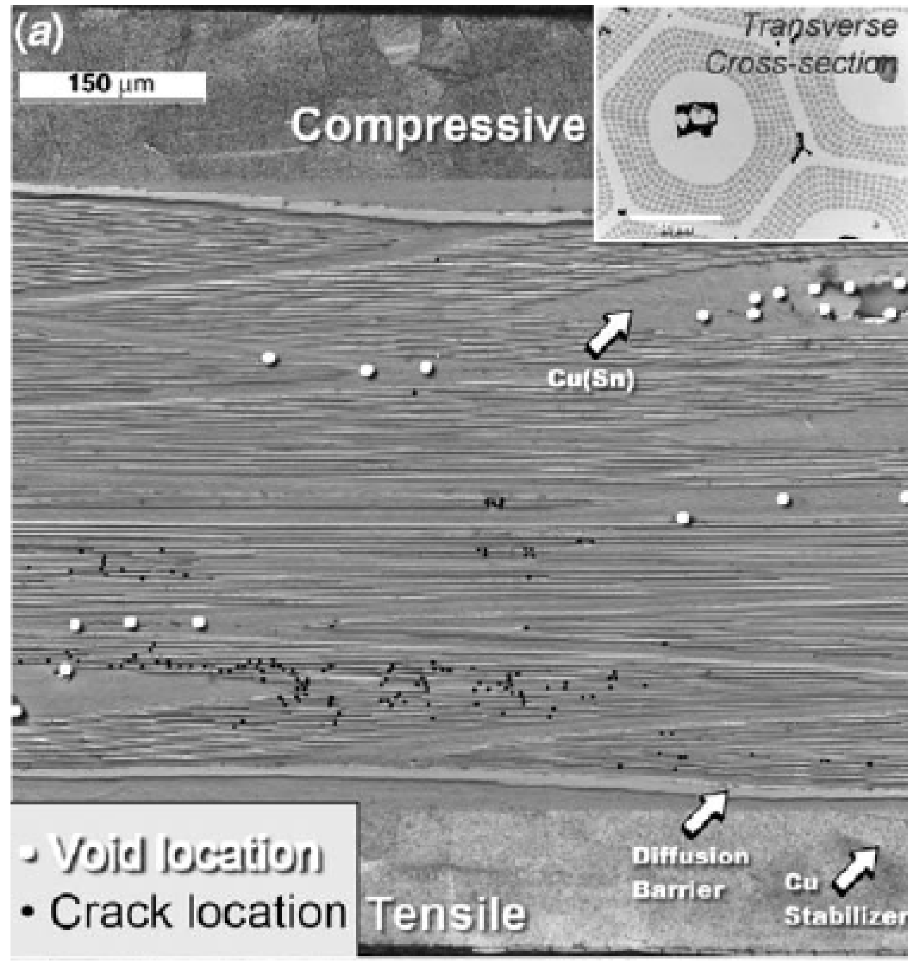


Figure 4: The deformation measurements for conductors B1 and B2 (open and filled markers). The points are measured and the solid lines are calculated with (8), with parameters as listed in Table 2 and Table 3. The dashed lines indicated the deviation from (8).

- Godeke, TAS, 1999



- Jewell, SuST, 2003

Nb_3Sn in a nutshell: Transverse pressure

On short tape samples

- Worrying ?

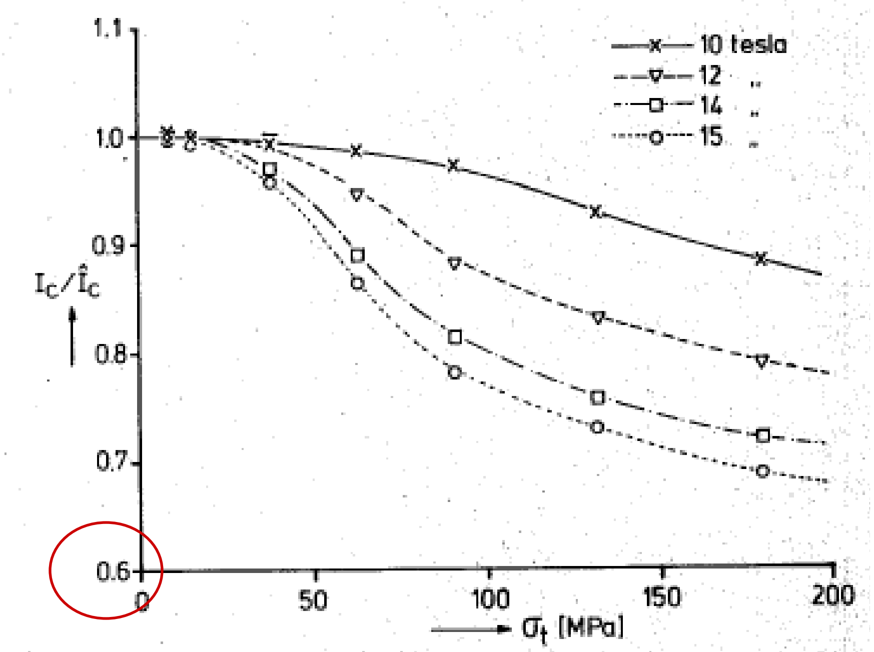
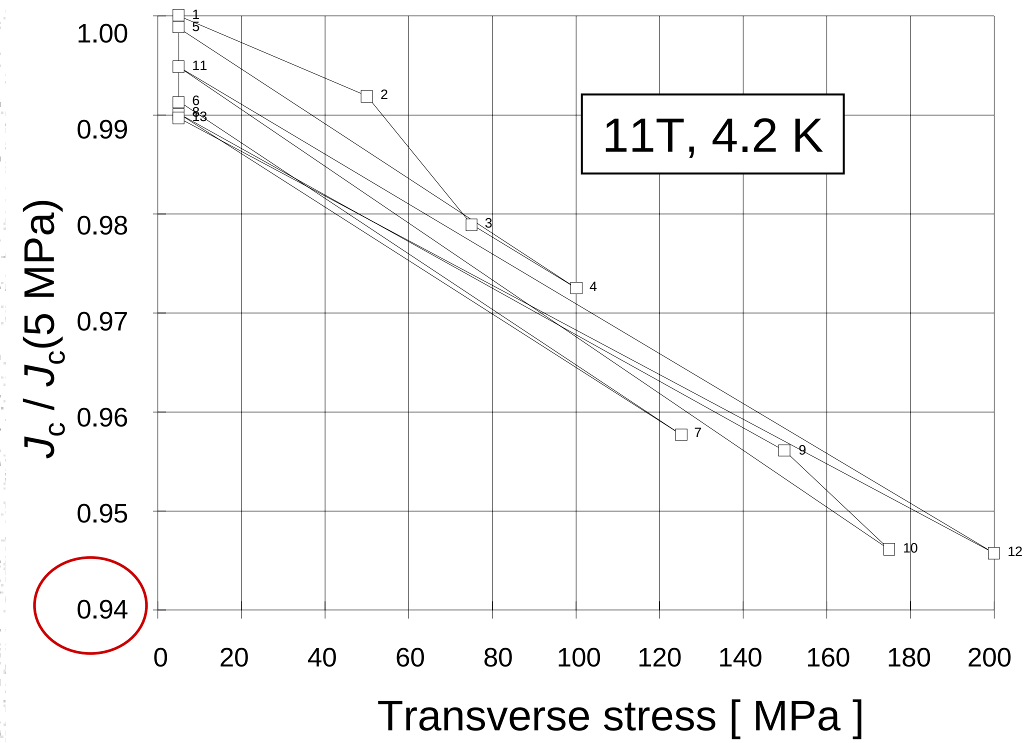


Fig. 4 The relative current density as a function of the transverse pressure at 4.2 K.

- Ten Haken, TAS, 1993

On cables

- OK !
  - Sensitive to proper experiment



- Godeke, Report, 1993

Bi-2212 – Typical axial tensile behavior

Strain dependence

- Independent of *H* and *T*
- *Always* irreversible
  - ➡ Crack formation
- J_c collapse point depends on pre-strain

Pre-strain
0.2 – 0.4%

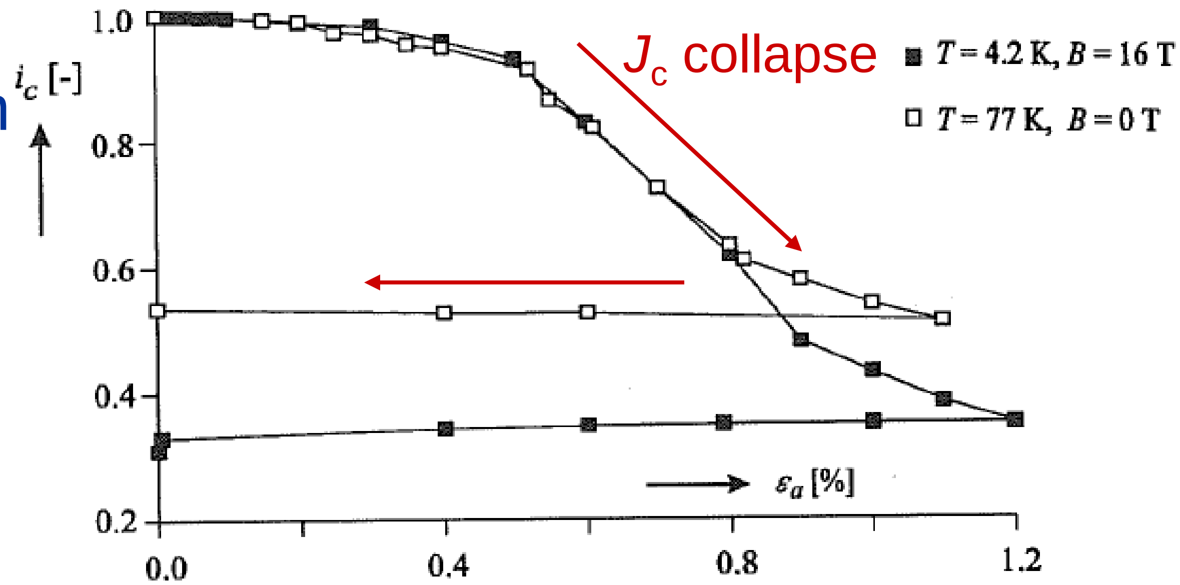
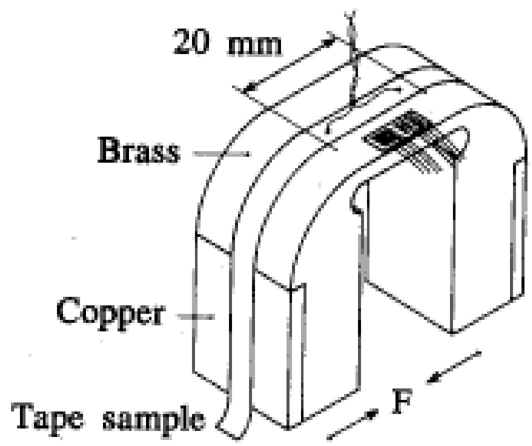


Figure 6.7: A comparison of the axial strain dependent critical current at two different conditions, n on the A-19 sample (Critical-current criterion: $E_c = 10^{-3}$ V/m).

➡ Ten Haken, PhD Thesis, 1994

Compressive: U-shaped bending springs



- Ten Haken, TAS, 1993

Generalized axial behavior

3 regions

- I and III
  - J_c collapses
  - Significant cracks
- II
  - Quasi constant
    - (Still irreversible)
    - Quasi-elastic behavior
    - Small cracks?
  - Length corresponds to pre-strain

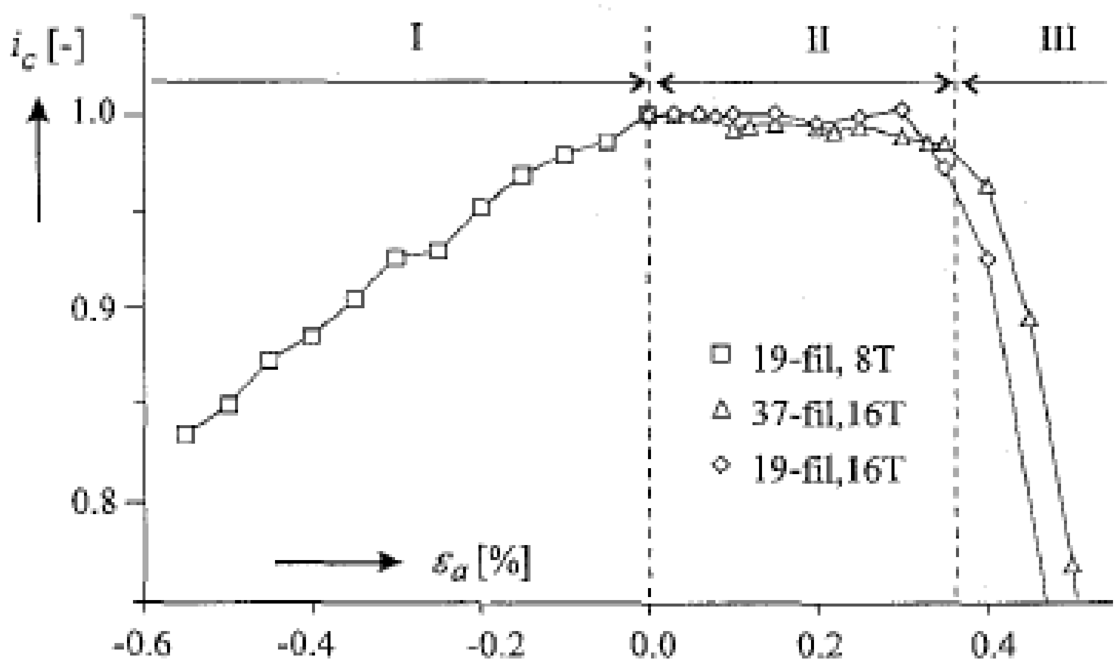


Fig. 1. The normalised critical current as a function of the axial strain. Measured on different samples for compressive and tensile strains (measured at 4.2 K and 8 or 16 T).

- Ten Haken, ToM, 1996

Generalized axial behavior: A model

Model…

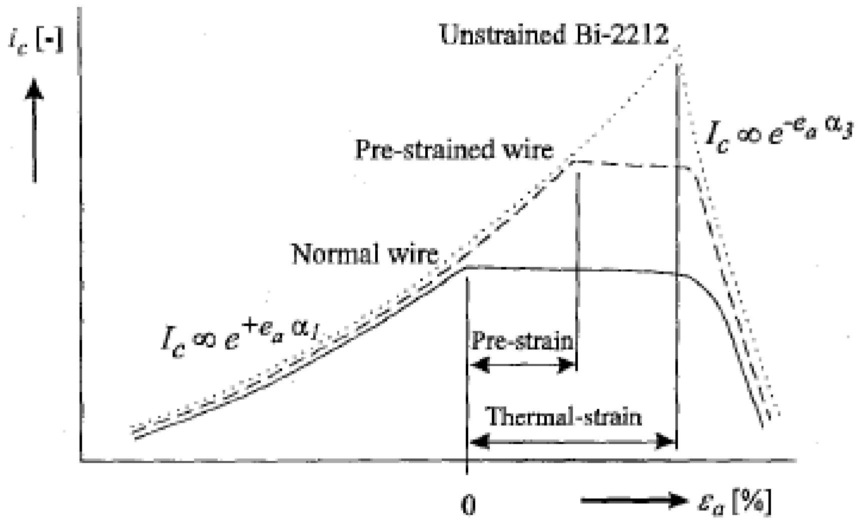
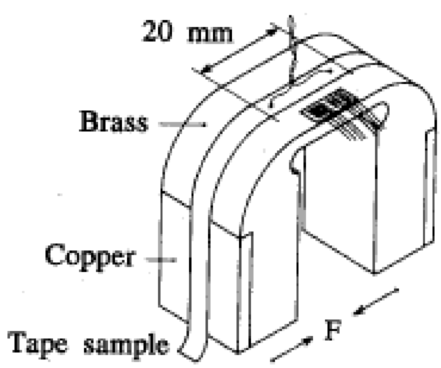


Fig. 2. The proposed description for the $I_c(\varepsilon_a)$ dependence of Bi-2212.



…and measurement

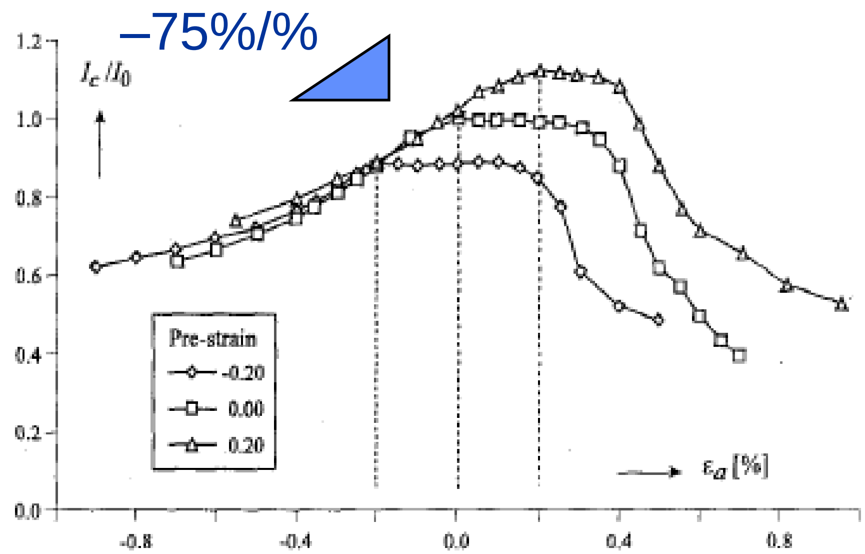


Fig. 3. The normalised critical current as a function of the axial strain measured on three pairs of pre-strained samples (measured at 4.2 K and 16 T).

- Ten Haken, ToM, 1996

- All axial compressive strain irreversibly reduces J_c

Model and irreversibility

Repetitive 'low' strain variations

- All strain irreversible

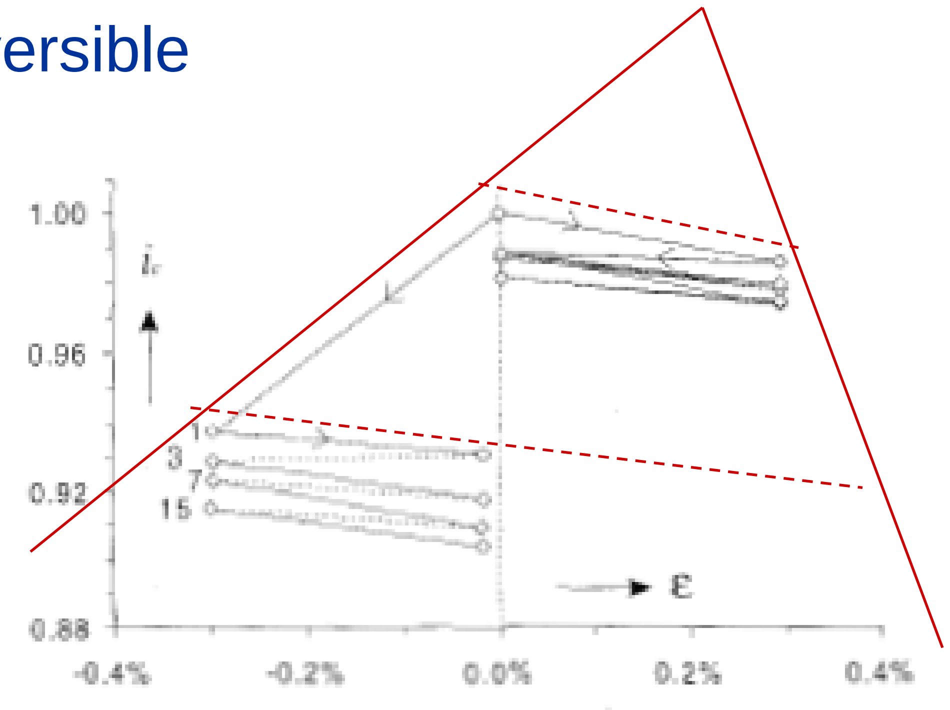
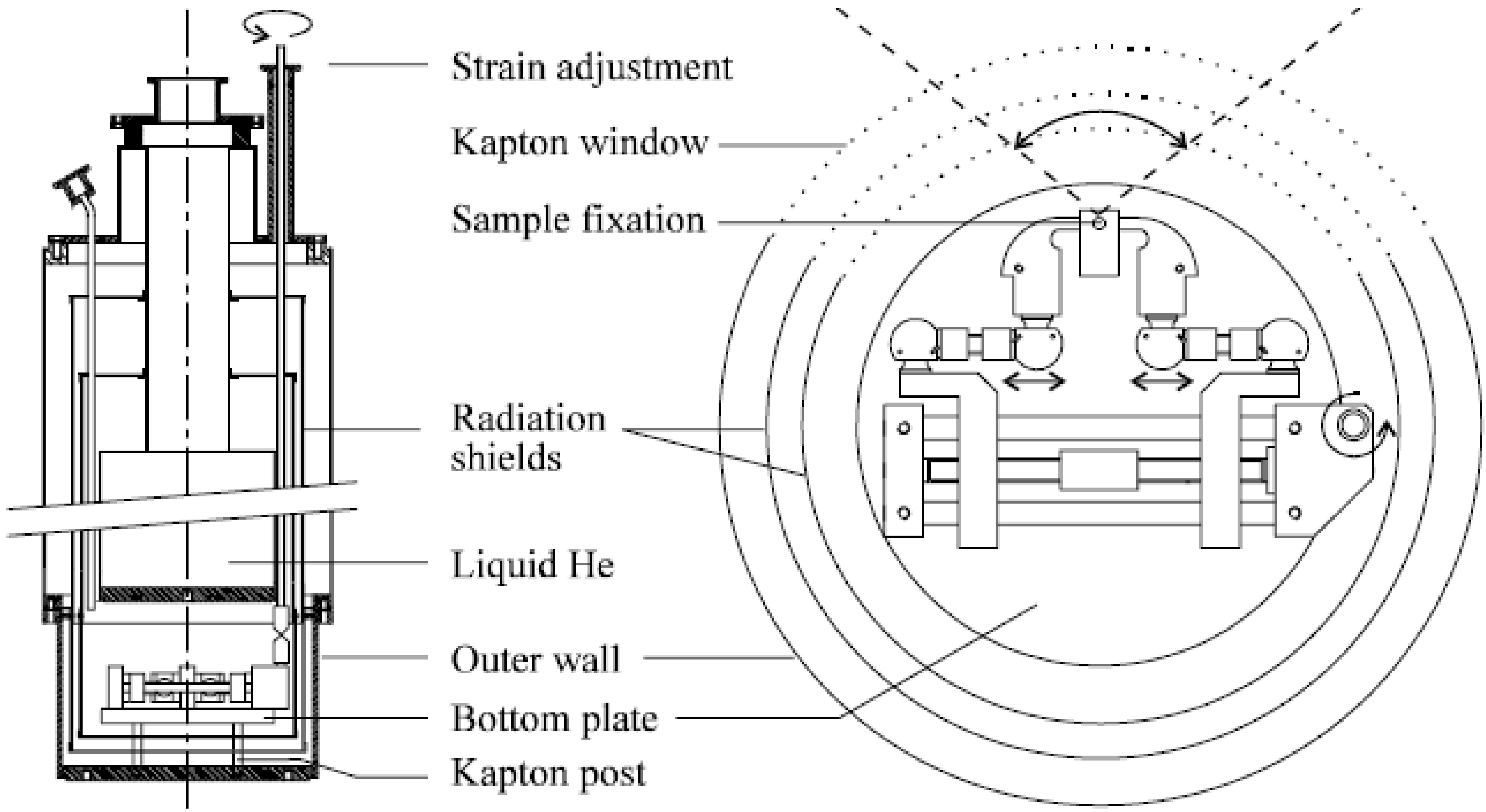


Fig. 5. The I_c versus strain in two samples of conductor A. First a cyclic deformation between 0 and 0.28% axial strain and then between 0 and -0.28% strain. The solid and dotted line follows the measuring sequence. The solid lines indicate two sequential I_c measurements and a dotted line is used when one or more strain cycles are skipped.

- Ten Haken, TAS, 1997

Crack formation?

Strain and X-ray diffraction

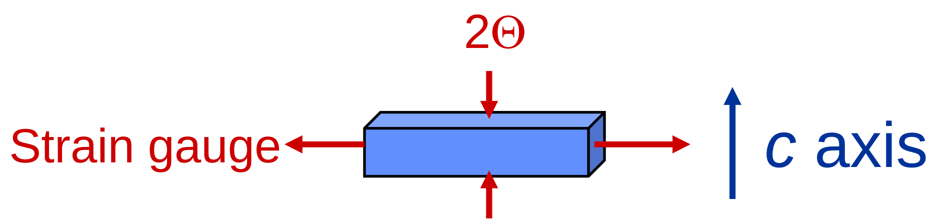


- Ten Haken, ACE, 1997

Microscopic strain analysis with X-rays

Apply external axial strain

- Shift in 2Θ for 0020 peak
  - Strain in *c* direction
  - $\varepsilon_y = \nu_y \, \varepsilon_z$



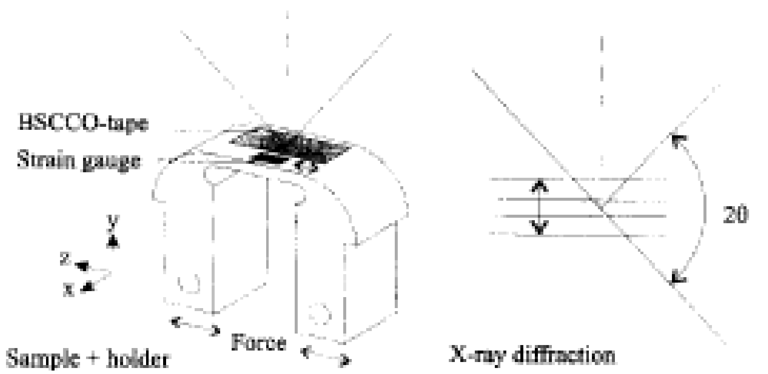


Fig. 1. Bi-2212 sample on the brass sample holder for the X-ray diffraction experiment.

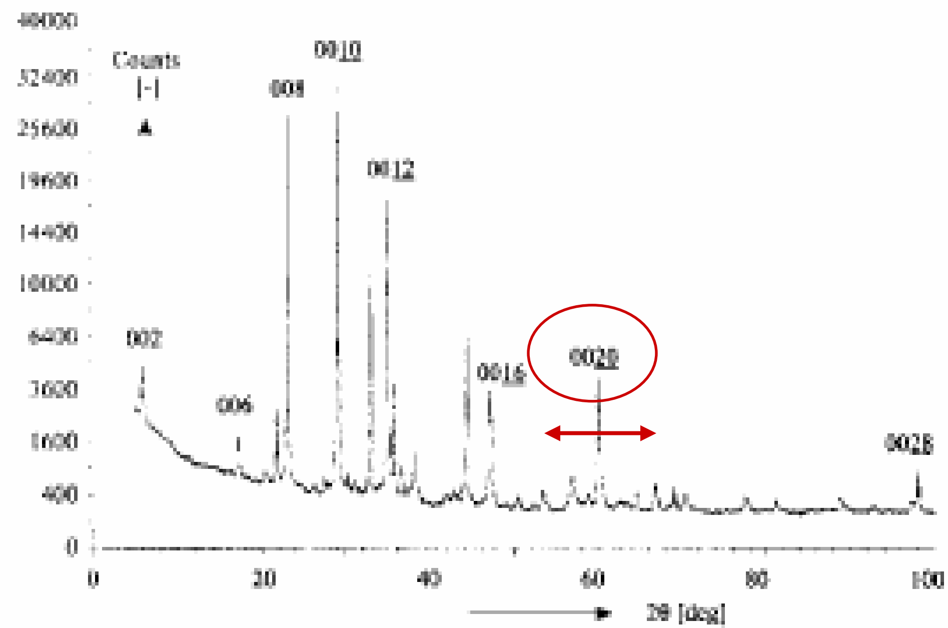


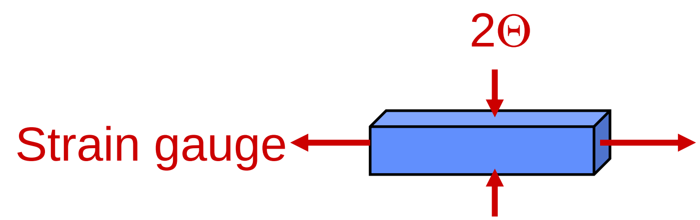
Fig. 2. The diffraction pattern with Cu-Kα radiation on polycrystalline Bi-2212 at 300 K, on a non-deformed sample holder.

- Ten Haken, PhysC, 1996

Shift 0020 position versus tensile strain

Strain behavior

- *c*-axis compression with axial tensile strain
  - Elastic up to +0.2% axial
  - Cracks above +0.2% axial



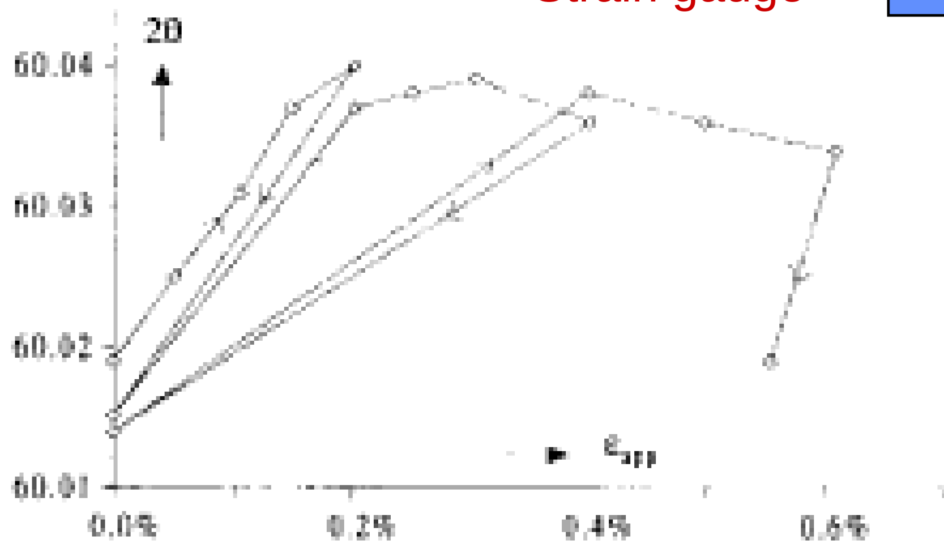


Fig. 3. The position of the diffraction peak of the 00<u>20</u> reflection as a function of the applied axial strain as measured with the strain gauge at 300 K.

  - Ten Haken, PhysC, 1996

c-axis deformation and $J_c(\varepsilon_{axial})$

At $J_c(\varepsilon_{axial})$ plateau

- *c*-axis deformation proportional to ε_{axial}
- Elastic behavior

Outside $J_c(\varepsilon_{axial})$ plateau

- *c*-axis is constant
- Elastic behavior disappears
- Cracks formation

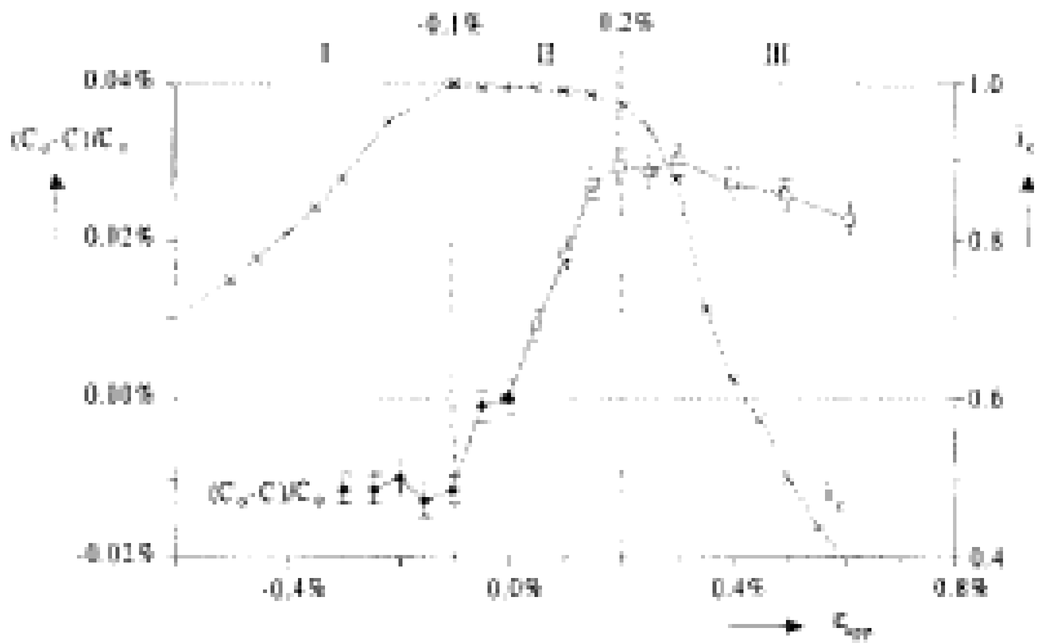
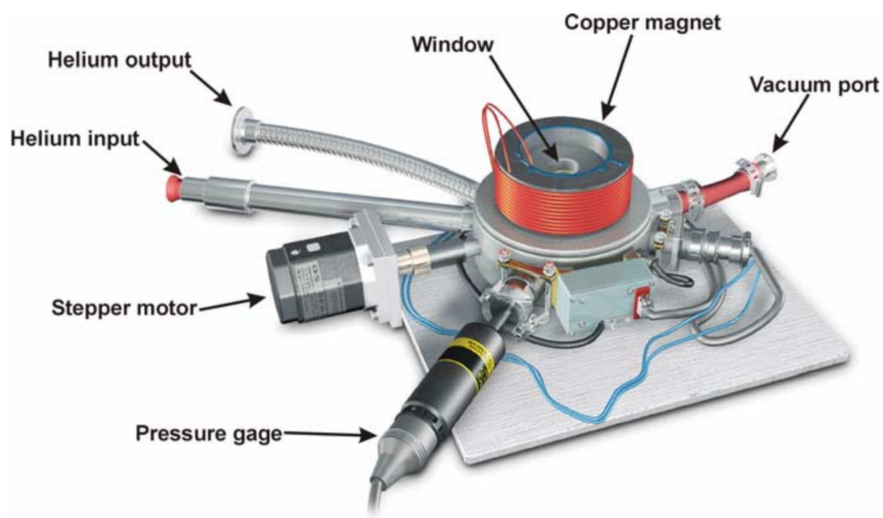
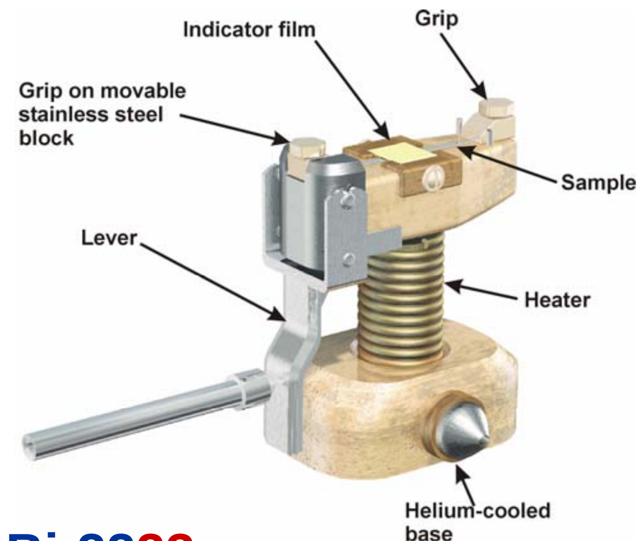


Fig. 4. The deformation of the *c*-axis as a function of the applied strain at 300 K, compared with the normalised I_c measured at 77 K on a deformed Bi-2212 mono-core wire [4].

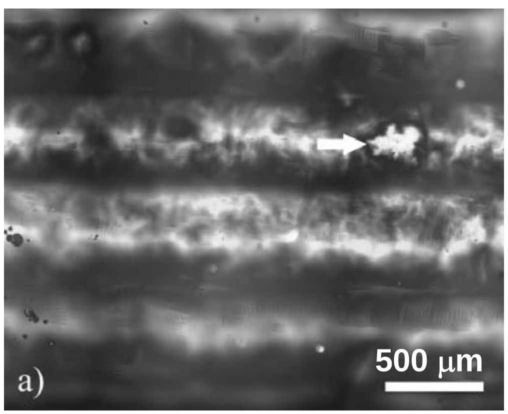
➡ Ten Haken, PhysC, 1996

Cracks: MOI on strained Bi-2212





Unstrained Bi-2212

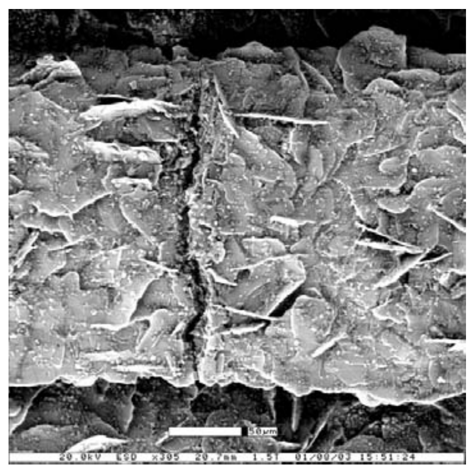


Filament

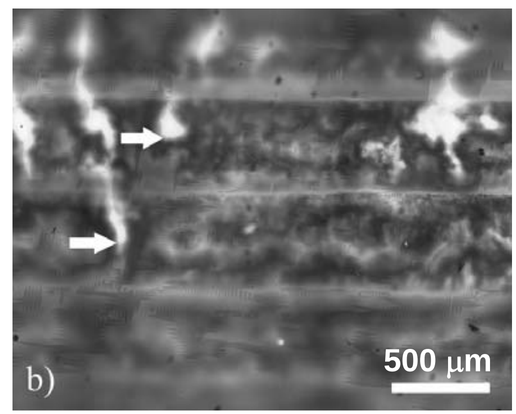
Filament
+ pinhole
Filament

Filament

Strained Bi-2223



Strained Bi-2212



D.C. van der Laan – Ph.D. thesis, U. Twente 2004 (see Schwartz talk)

Crack formation confirmed with MOI

Axial strain results: Crack formation from MOI and $J_c(\varepsilon)$

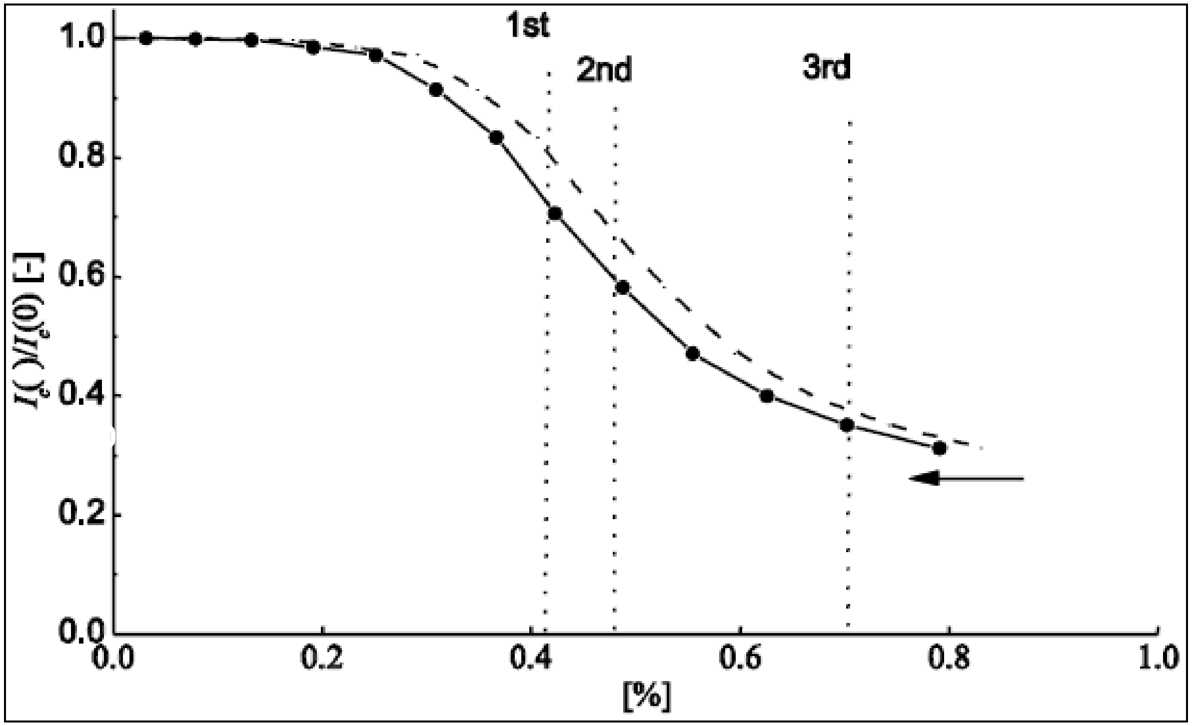
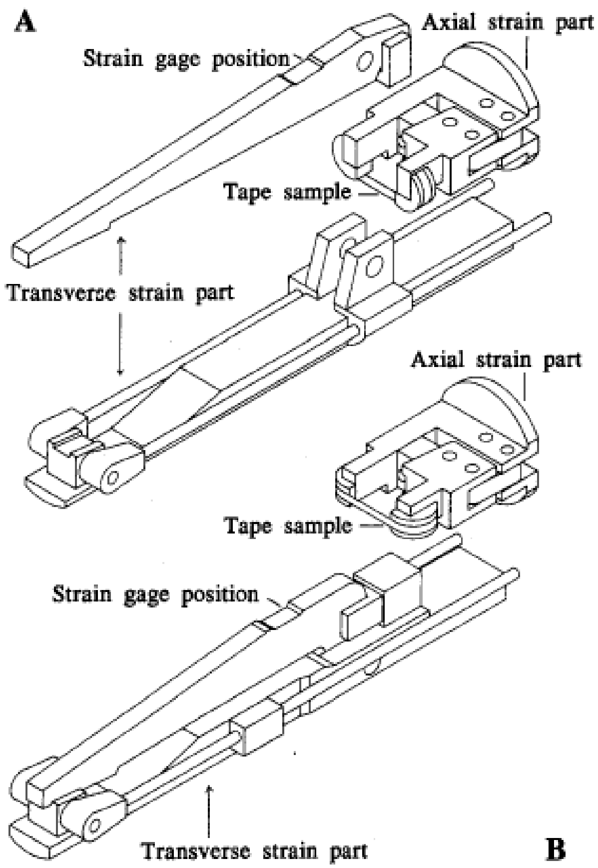


Figure 3.25. Normalized critical current vs. strain of Bi-2212 tape B-3 at 4.2 K. Cracks appear at applied strain of 0.41 % (1st), 0.48 % (2nd) and 0.70 % (3rd). The arrow shows the direction in which the curve shifts when correcting for the difference in pre-compression.

D.C. van der Laan – Ph.D. thesis, University of Twente 2004

Transverse pressure on Bi-2212 tapes

From the ‘*House of Horrors*’… ➔ Very discouraging!



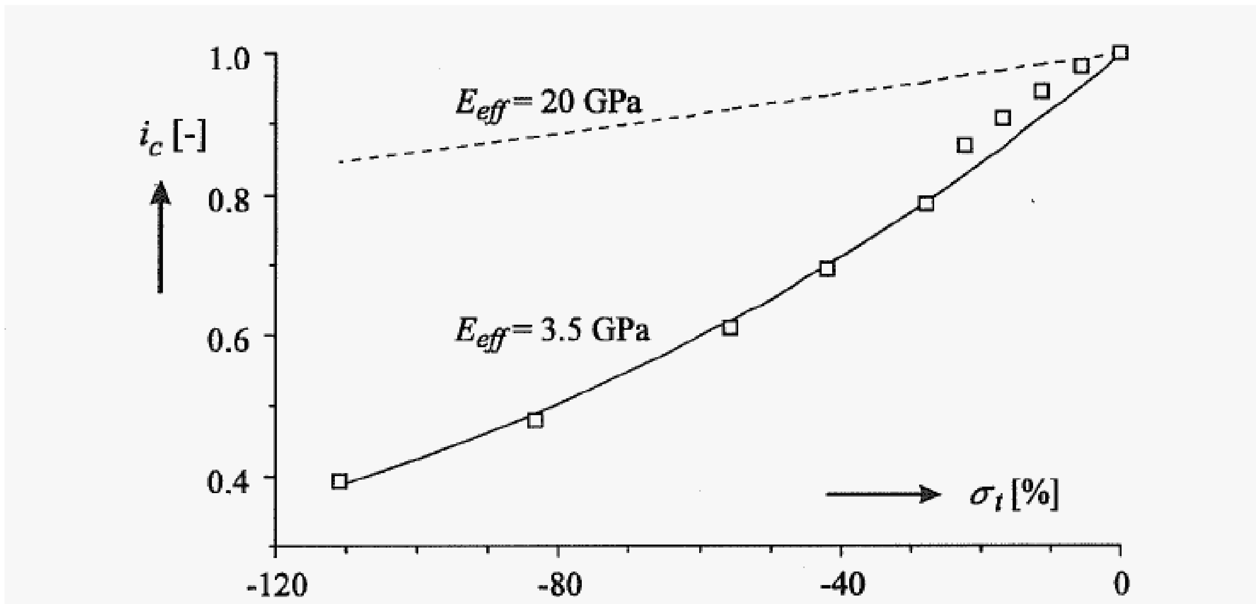


***Figure 6.16:** The normalised critical-current reduction of the Bi-2212 tape conductor (T-19) subjected to a transversal pressure, measured on the $F_t // B$ transverse press. The measured $I_c(\sigma_t)$ is compared with two lines representing the calculated I_c versus pressure dependence for two different Young's moduli (E_{eff} = 20 and 3.5 GPa).*

- Ten Haken, TAS, 1993; PhD thesis, 1994

Transverse pressure on Bi-2212 cables

Better than tapes…

- …but insufficient?
- Limited to 60 MPa broad face load?

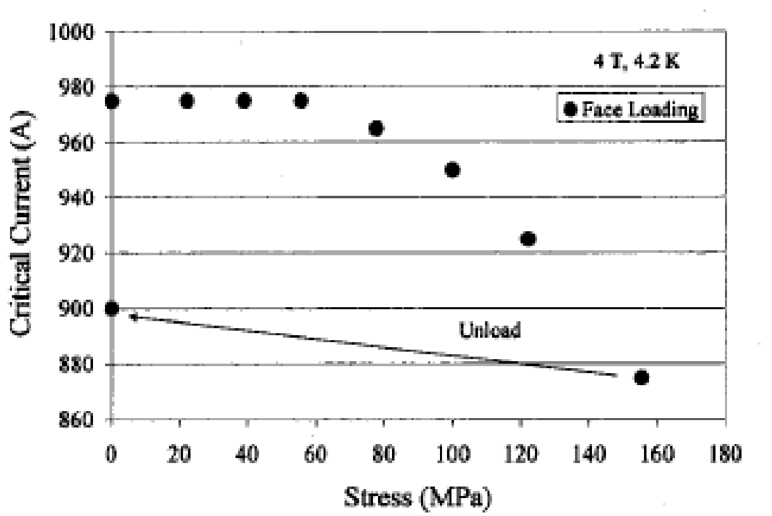


Fig. 3. Variation of the critical current (4 T, 4 K) with stress for a cable loaded on the broad face of the cable.

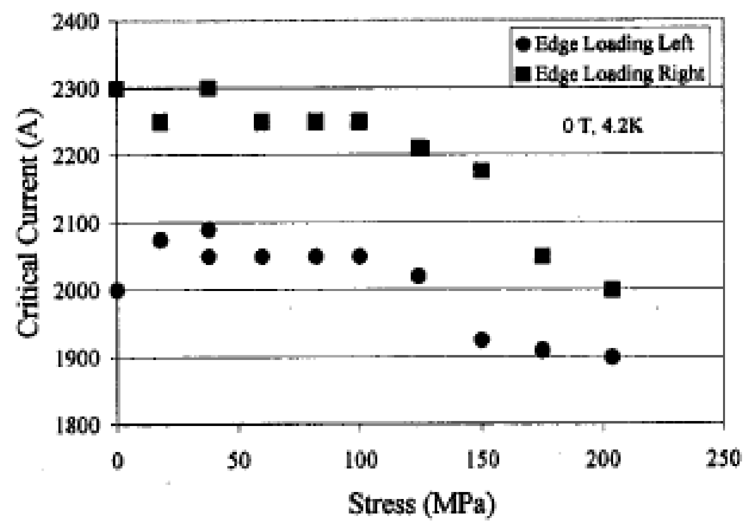


Fig. 4. Variation of the critical current (self-field, 4 K) with stress for a cable loaded on the edge of the cable.

- Dietderich, TAS, 2001

Summary

- All strain causes an irreversible reduction of J_c
  - Avoid it! (e.g. match thermal contractions)
- Irreversibility is a result of crack formation
  - Confirmed with X-ray diffraction
  - Confirmed with MOI
- No contradictive results found to 1996 model
  - Plateau length grows with pre-strain
  - Apparent larger ‘strain margin’
    - At the cost of irrecoverable J_c reduction
- Transverse pressure effects cables better than on tapes
  - Similar as for Nb_3Sn
    - But limits appear far from Nb_3Sn’s 200 MPa
  - Conductor reinforcement / stress relieve required