To Crack or Not to Crack: Strain in High Temperature Superconductors

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August 22, 2007

With kind contributions from

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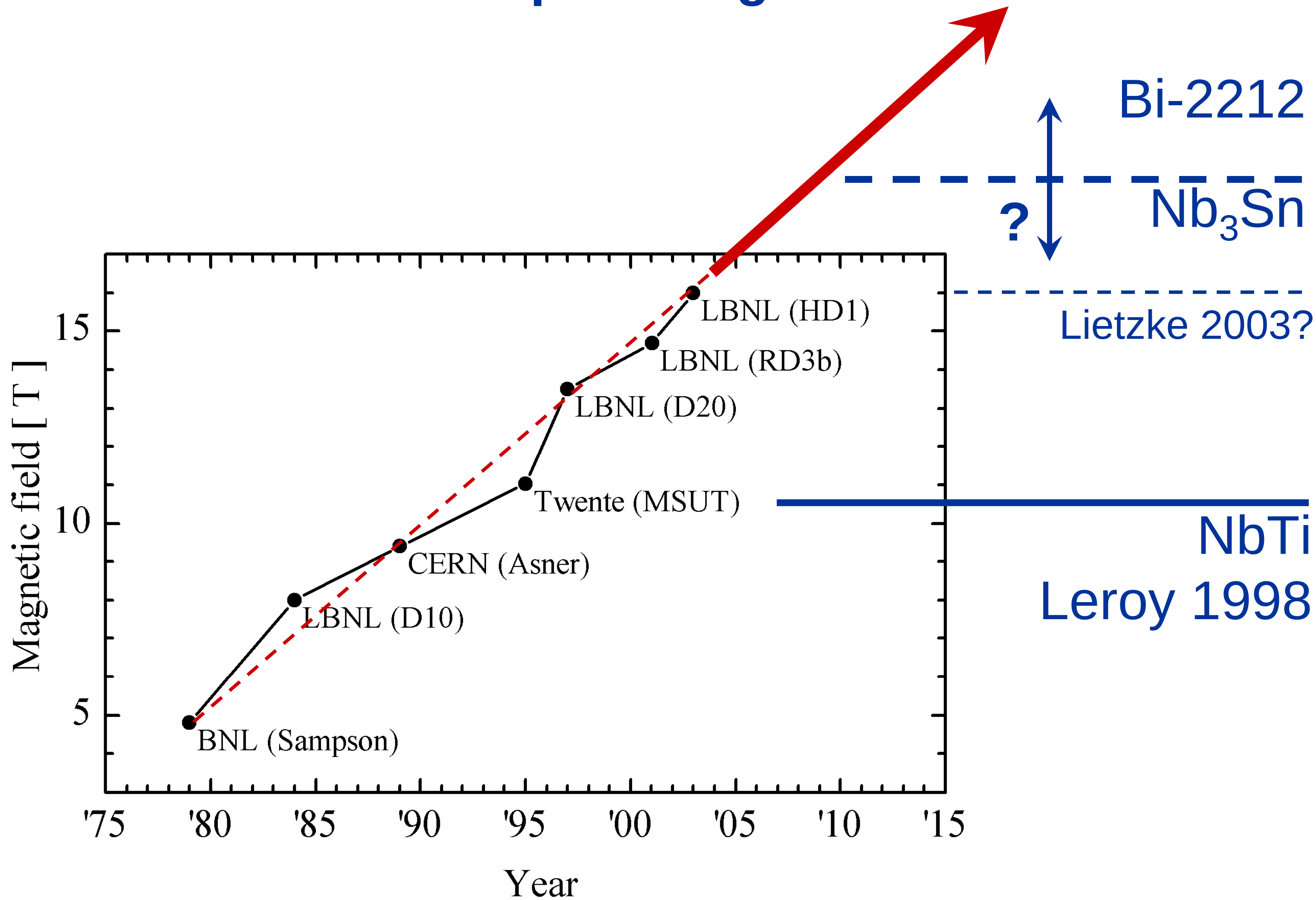
Danko van der Laan (NIST)
Shlomo Caspi (LBNL)

Funded by the US Department of Energy under contract No. DE-AC02-05CH11231

Motivation

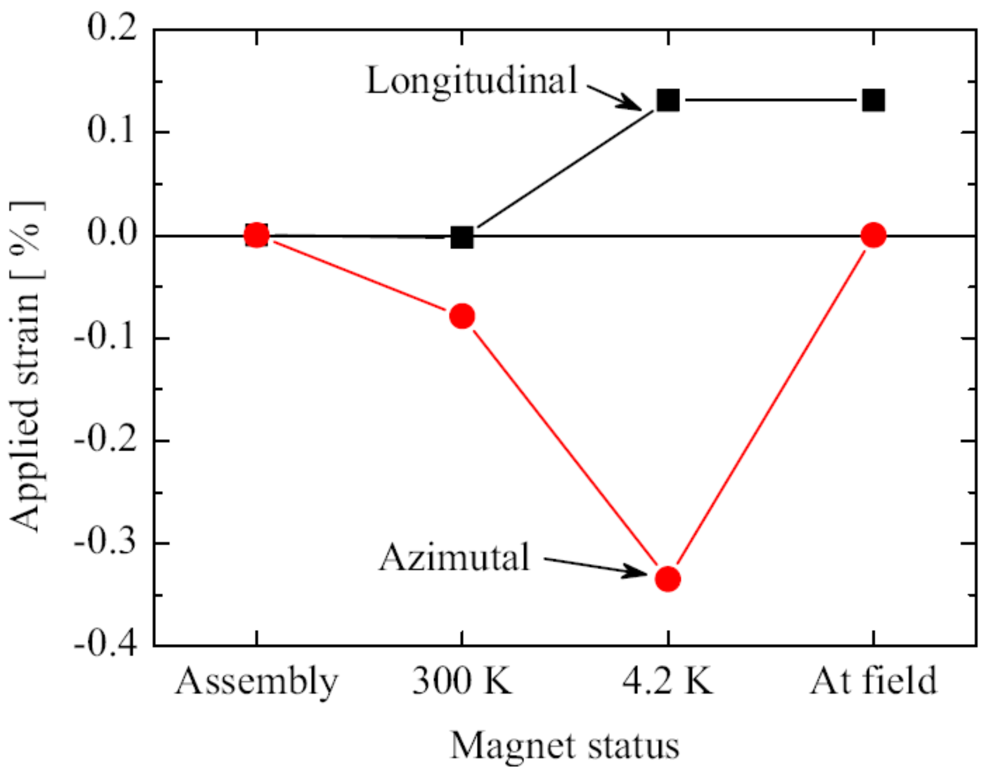
Magnetic field records in dipole magnets

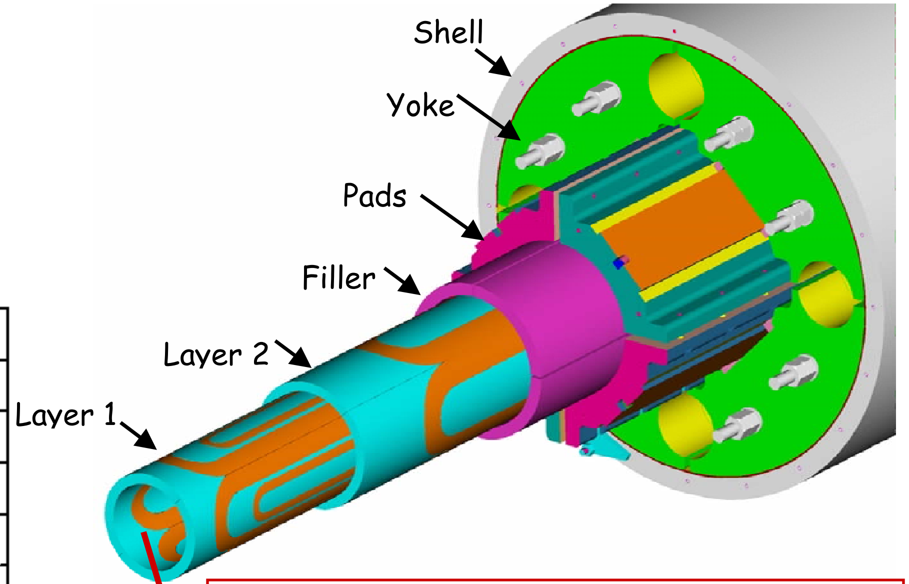


How do Nb_3Sn magnets work?

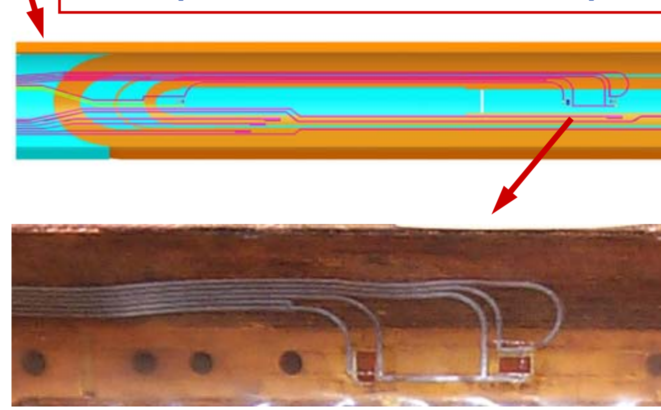
Example: LARP Quad TQS01

- Ti-6Al-4V poles
- 8 W&R cos Θ coils
- 90 mm bore, > 220 T/m





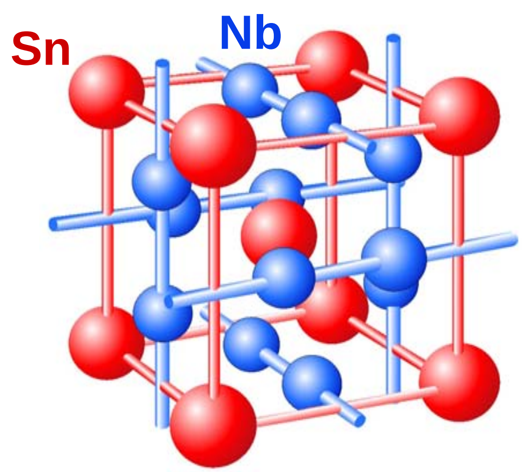
Caspi, *MT20: 4LX03 (2007)*



Reversible strain!

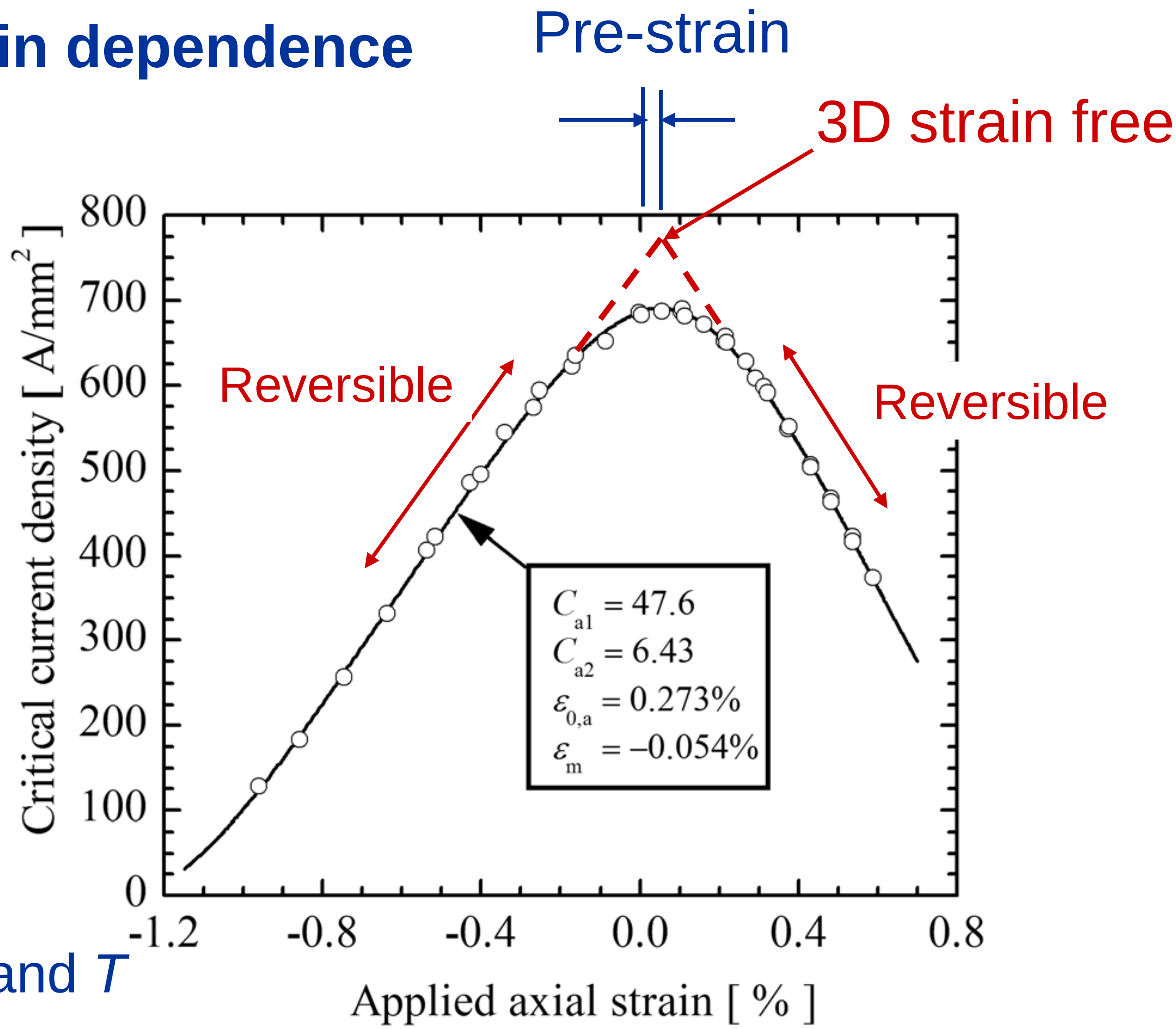
Why do Nb_3Sn magnets work?

Reversible axial strain dependence



Reversible means:

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



Godeke, *SuST* **19** 2006

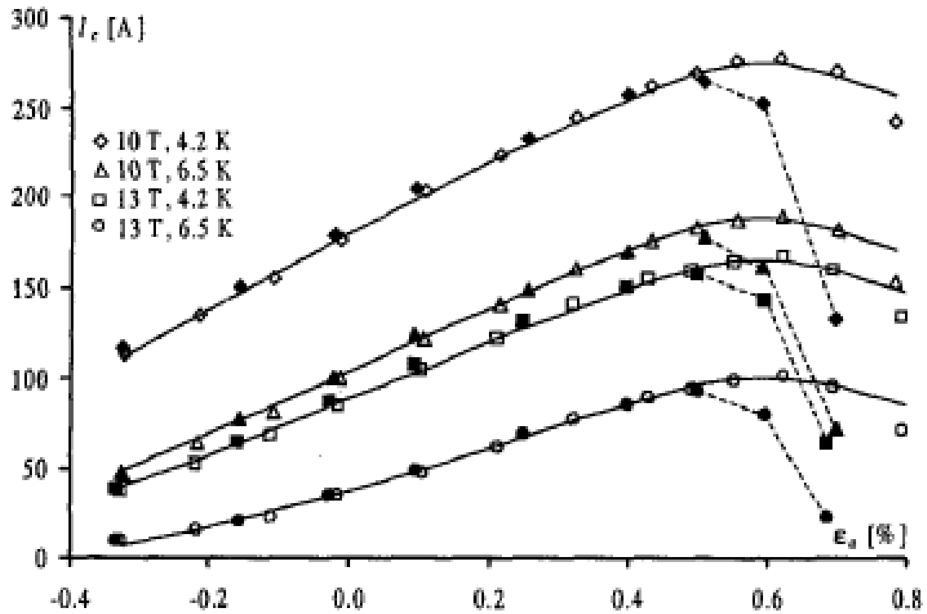
How can magnets fail?

‘Preliminary’ J_c collapse

- Irreversible
- Crack formation

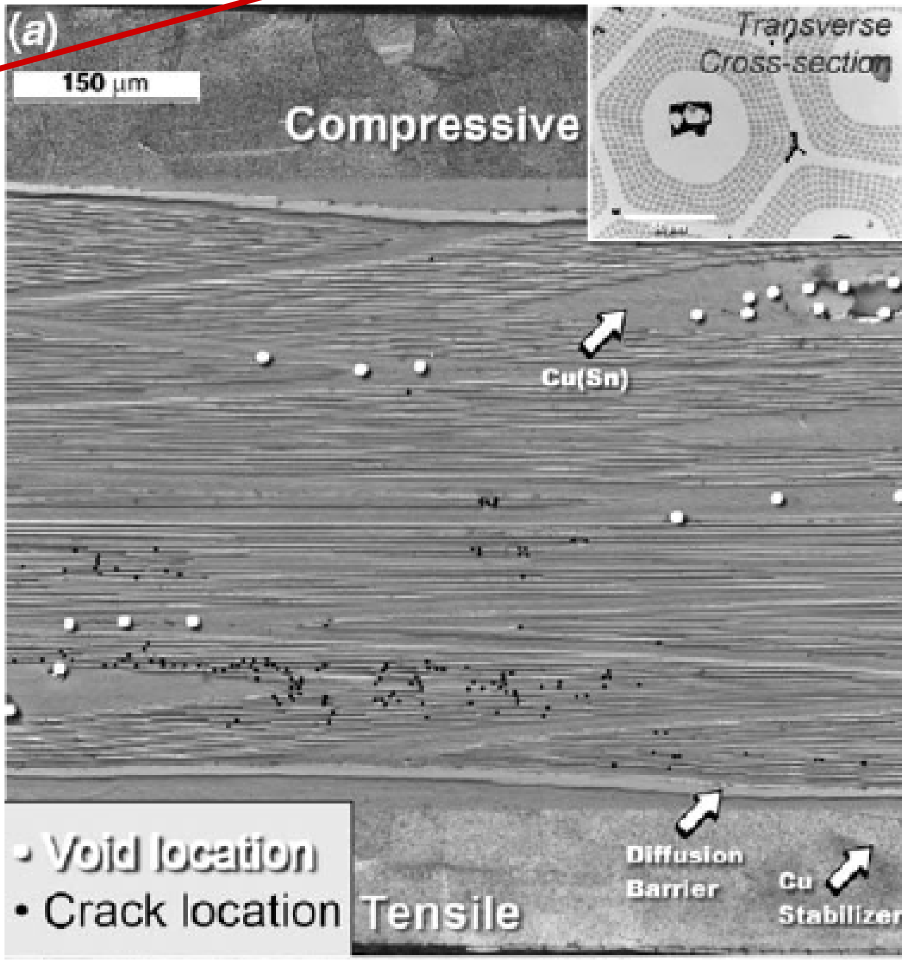
Unrelated

Axial strain tests IT wire:



➧ Godeke, *TAS* **9** (1999)

Bend tests IT wire:



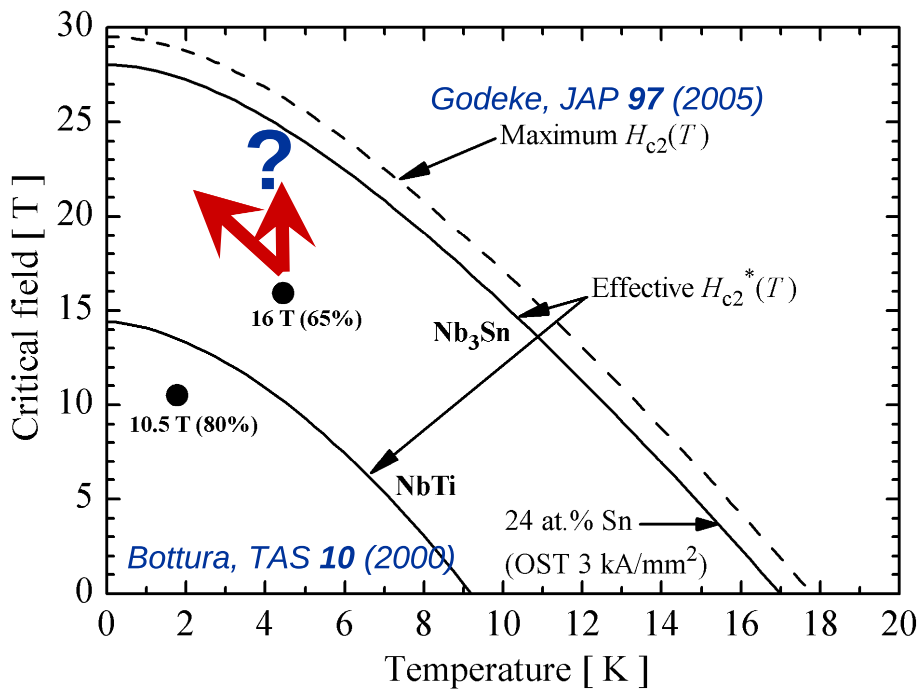
➧ Jewell, *SuST* **16** (2003)

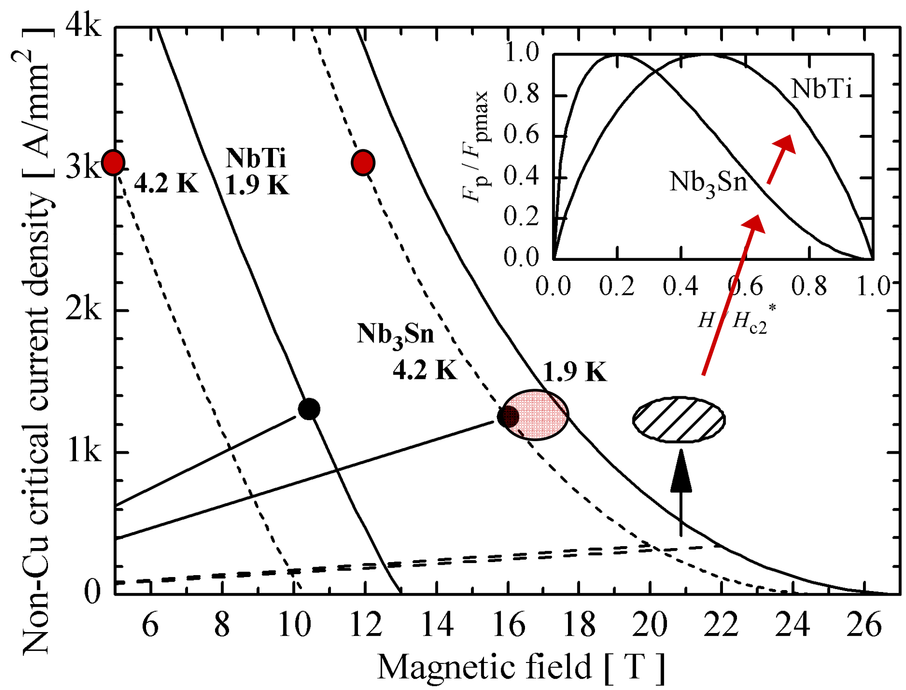
This workshop!

Limitations of NbTi and Nb_3Sn

- Nb_3Sn dipoles are limited to 17 – 18 T
  - Provided that strain can be handled

NbTi: *Bottura, TAS **10** (2000)*
Nb_3Sn: *Godeke, SuST **19** (2006)*

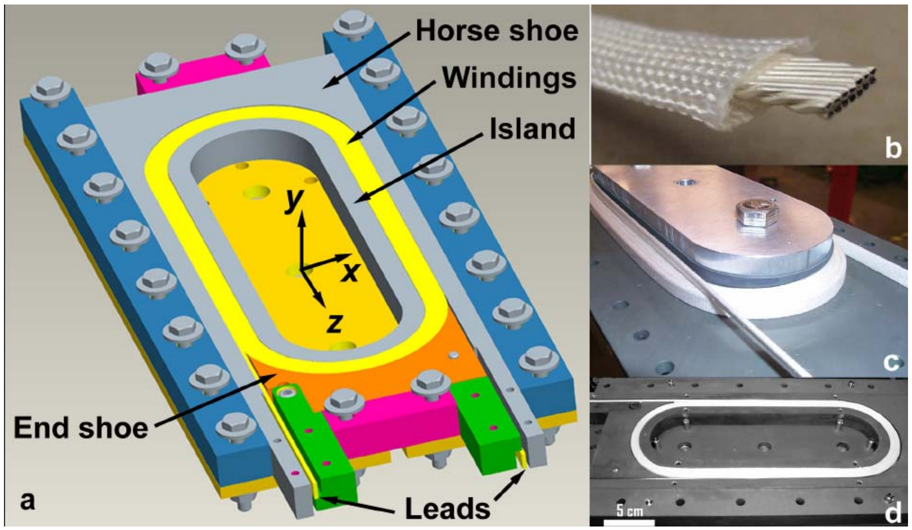


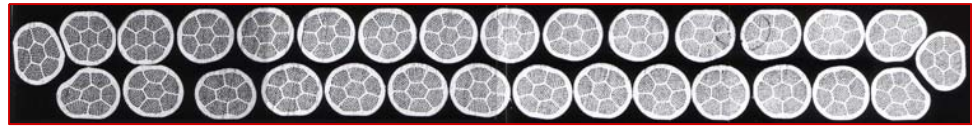


- A switch to Bi-2212 is inevitable: $\mu_0 H_{c2}^*(4.2\ K) \cong 85\ T$

Towards new magnetic field records

Bi-2212 W&R subscale magnet program





Material	Reaction	Insulation	Quench
NbTi	Ductile R&W	Polyimide	> 20 ms^{-1}
Nb_3Sn	675°C Ar/Vacuum	S/R glass	~ 20 ms^{-1}
Bi-2212	890±2°C O_2	Ceramic	< 0.05 ms^{-1}

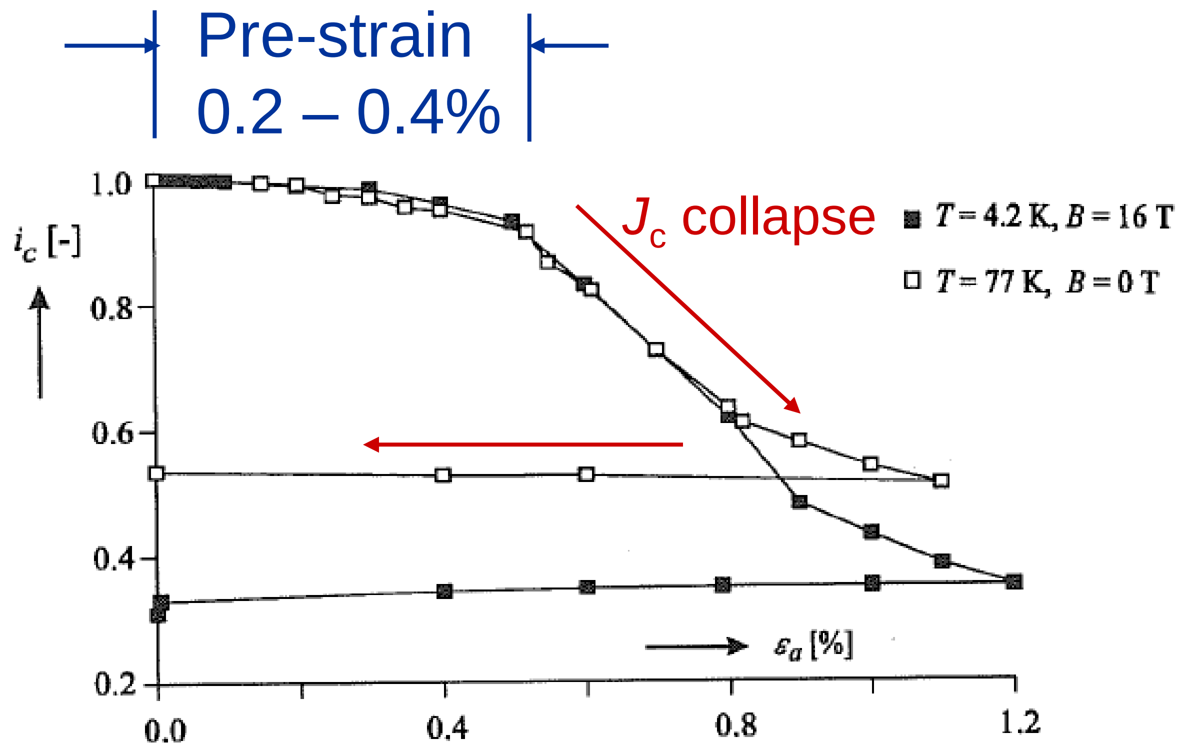
WIND-AND-REACT BI–2212 SUBSCALE COIL TEST CONFIGURATIONS

Layout	Turns	$\mu_0 H$ [T]	I_{ss} [A]	L [mH]	P_x [MPa]	P_y [MPa]	P_z [MPa]
Bi–2212 stand alone	2 × 6	2.6	6213	0.036	1.1	0	1.9
Bi–2212 stand alone	2 × 19	4.9	5179	0.25	9.7	0	9.4
Bi–2212 common coil[a]	2 × 19	5.8	4948	0.28	27	7.5	15
Bi–2212 dipole[a]	2 × 19	6.6	4777	1.2	1.6	14	3.2
1× Bi–2212 / 2× Nb_3Sn hybrid dipole[ab]	2 × 19 (Bi–2212) 2 × 20 (×2 Nb_3Sn)	8.5	4595	2.4	34	0	20
1× Bi–2212 / 2× Nb_3Sn hybrid dipole[ac]	2 × 19 (Bi–2212) 2 × 20 (×2 Nb_3Sn)	9.9	4486 (Bi–2212) 6112 (Nb_3Sn)				

Typical axial tensile behavior in Bi-2212

Axial strain dependence early (~1993) 2212 tapes

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



- Ten Haken, PhD Thesis, 1994

Generalized axial strain behavior in Bi-2212

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

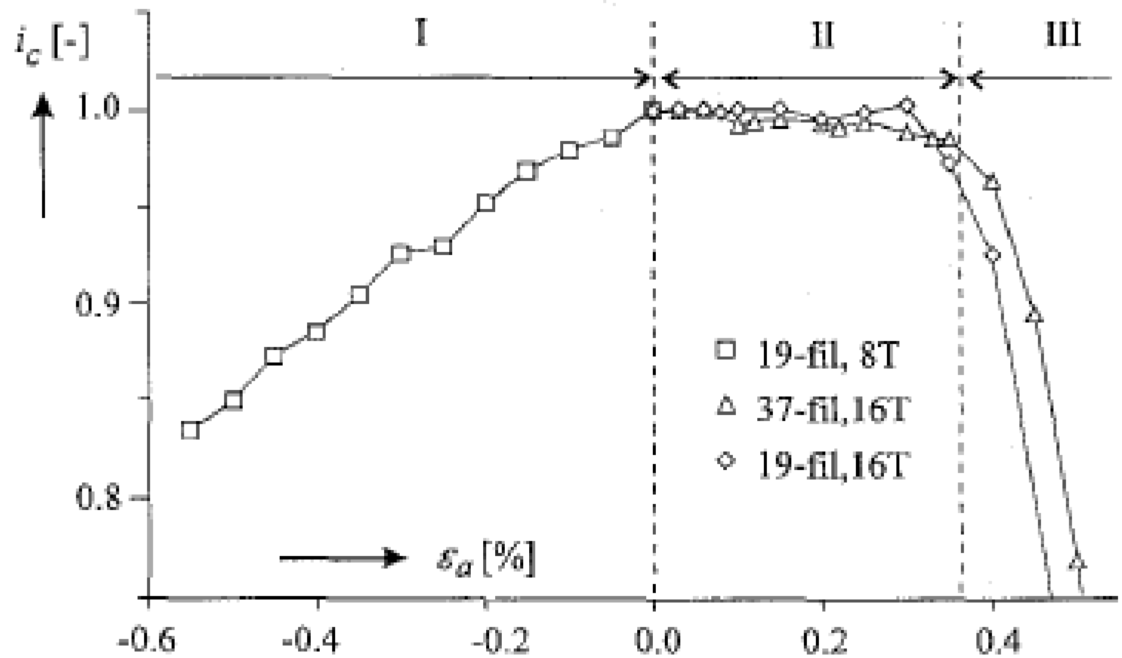


Fig. 1. The normalised critical current as a function of the axial strain. Measured on different samples for compressive and tensile strains (measured at 4.2 K and 8 or 16 T).

- Ten Haken, *ToM* **32** (1996)

A model for axial strain behavior in Bi-2212

Model…

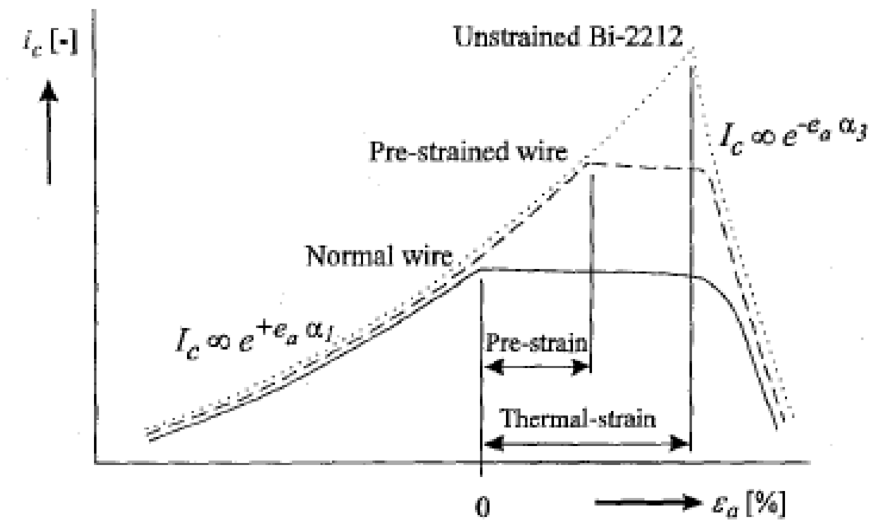
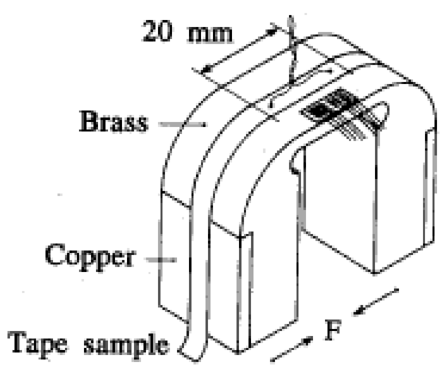


Fig. 2. The proposed description for the $I_c(\varepsilon_a)$ dependence of Bi-2212.



…and measurement

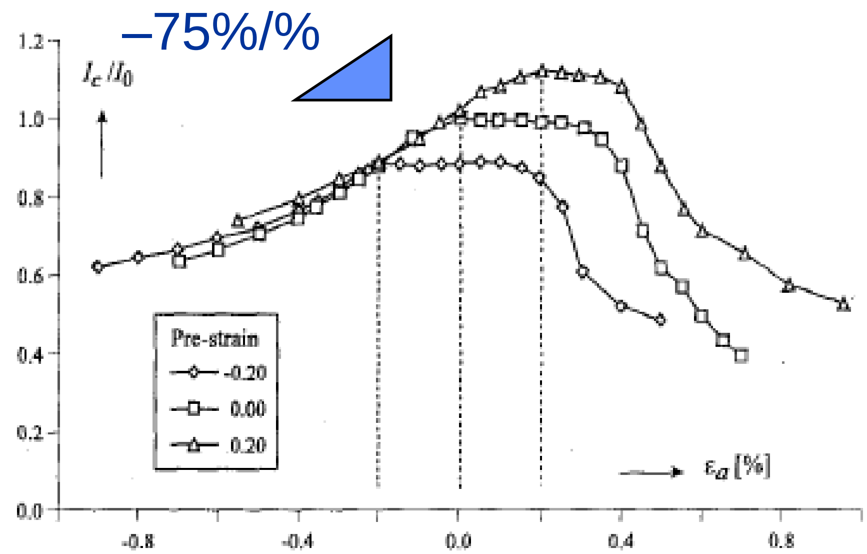


Fig. 3. The normalised critical current as a function of the axial strain measured on three pairs of pre-strained samples (measured at 4.2 K and 16 T).

- Ten Haken, *ToM* **32** (1996)

- All axial compressive strain irreversibly reduces J_c

Model and irreversibility

Repetitive 'low' strain variations

- All strain irreversible

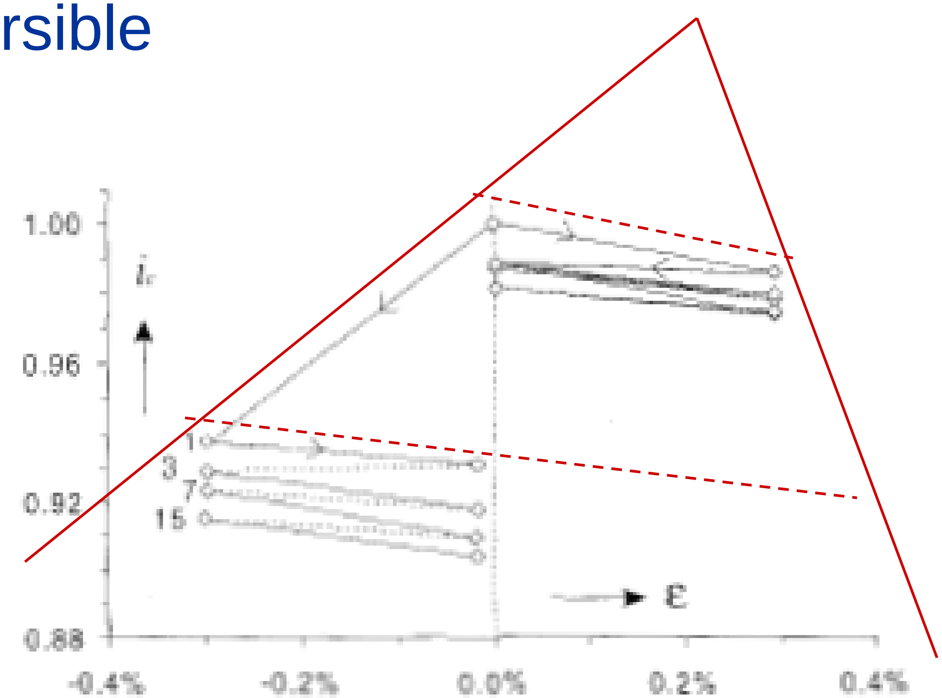


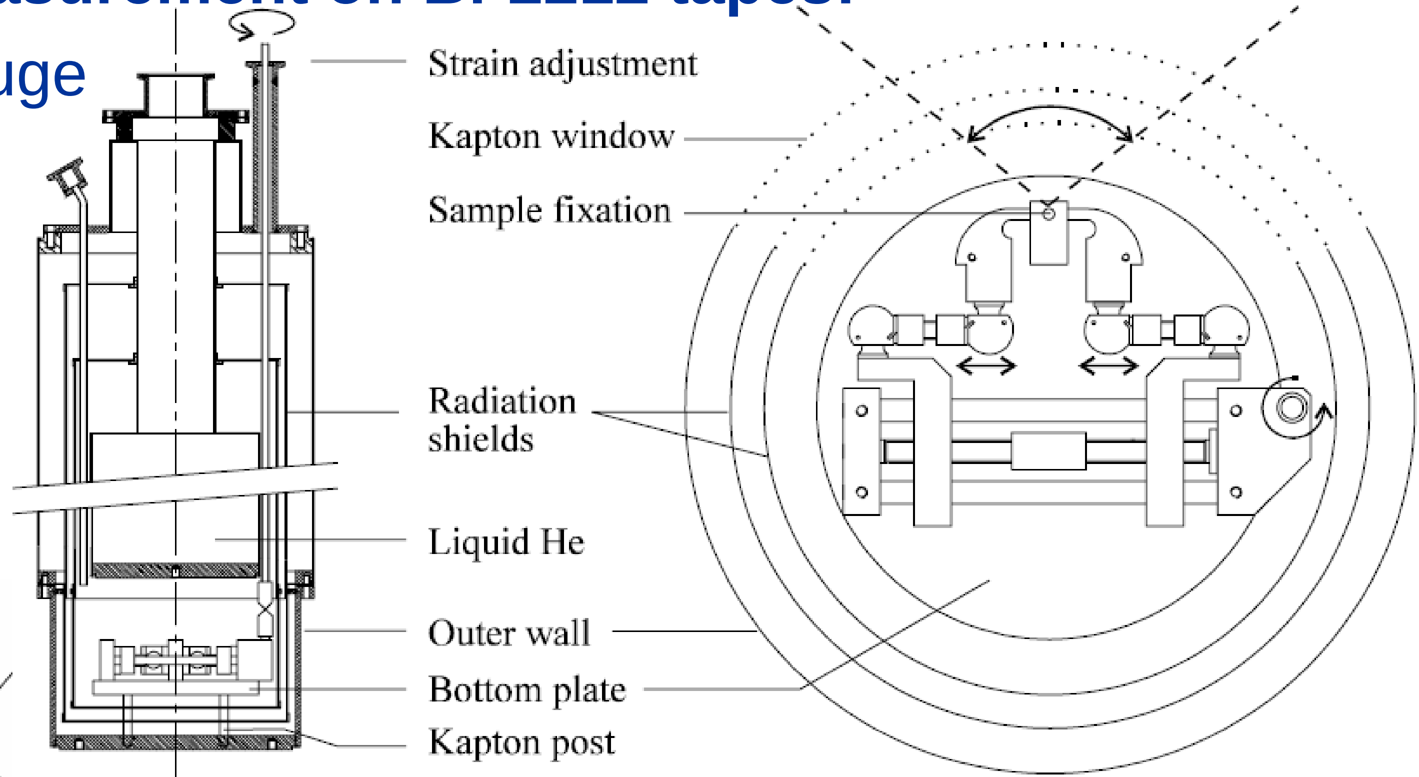
Fig. 5. The I_c versus strain in two samples of conductor A. First a cyclic deformation between 0 and 0.28% axial strain and then between 0 and -0.28% strain. The solid and dotted line follows the measuring sequence. The solid lines indicate two sequential I_c measurements and a dotted line is used when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

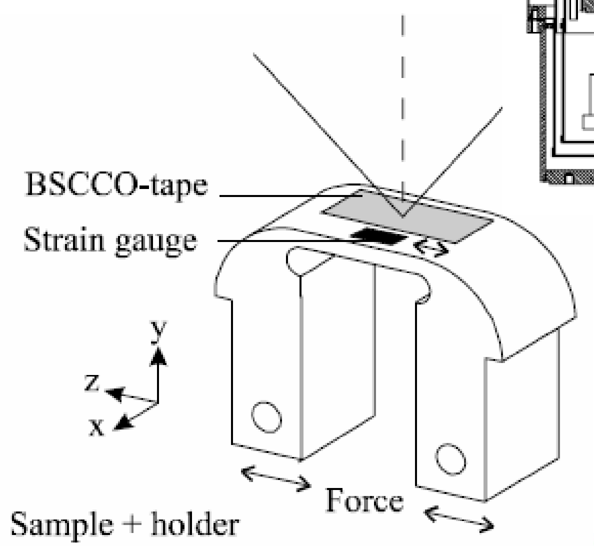
- Ten Haken, TAS, 1997

Are these ‘cracks’ real...? (~1996)

Axial strain measurement on Bi-2212 tapes:

- With strain gauge
  - Direct
- With X-ray
  - Indirect

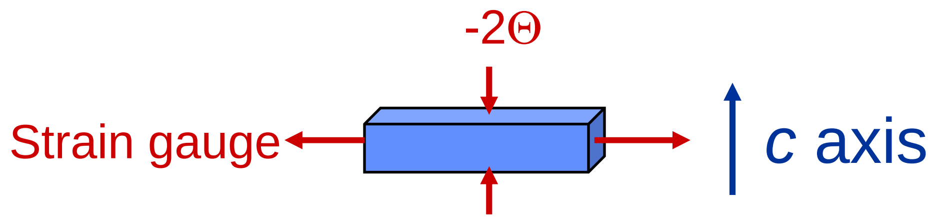


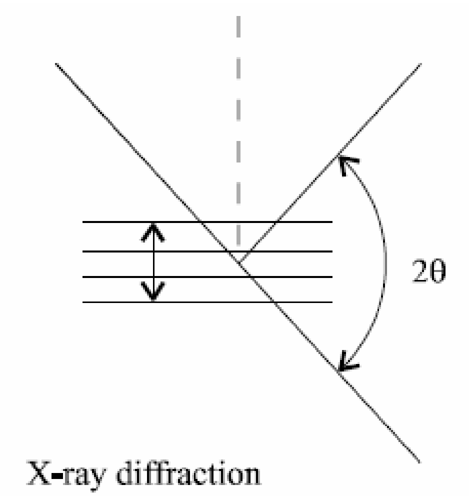


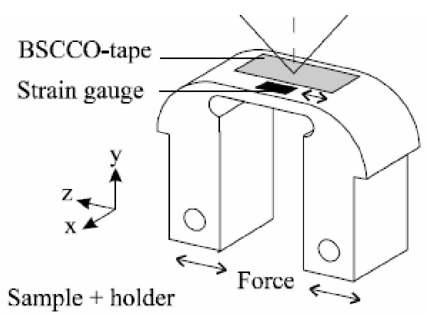
Are these 'cracks' real...? (~1996)

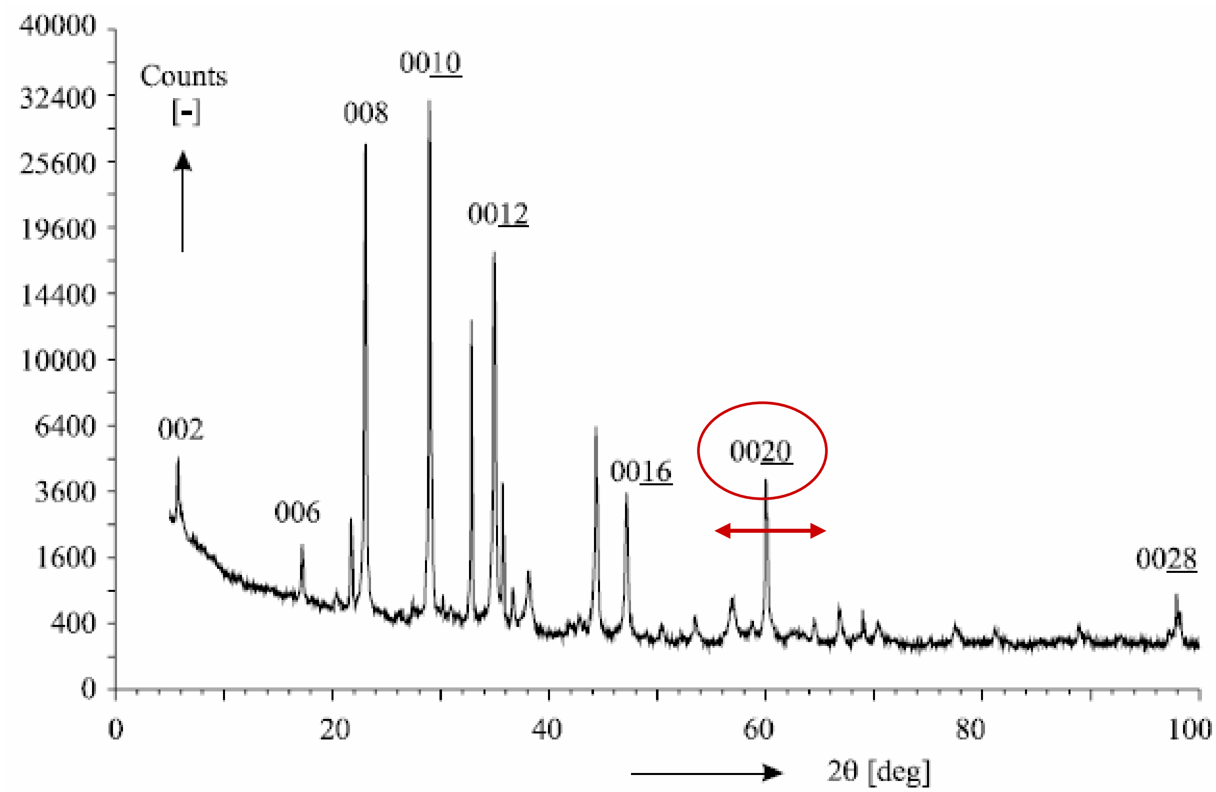
Apply external axial strain

- Shift in 2Θ for 0020 peak
  - Proportional to strain in *c* direction (if elastic)
  - $\varepsilon_y = -\nu_y\, \varepsilon_z \propto -2\Theta$







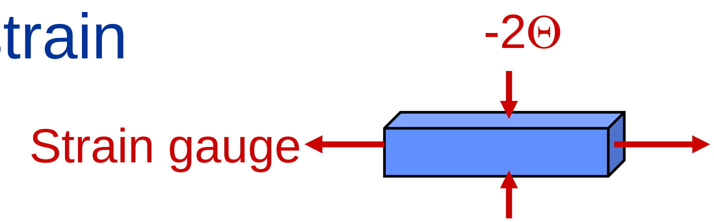


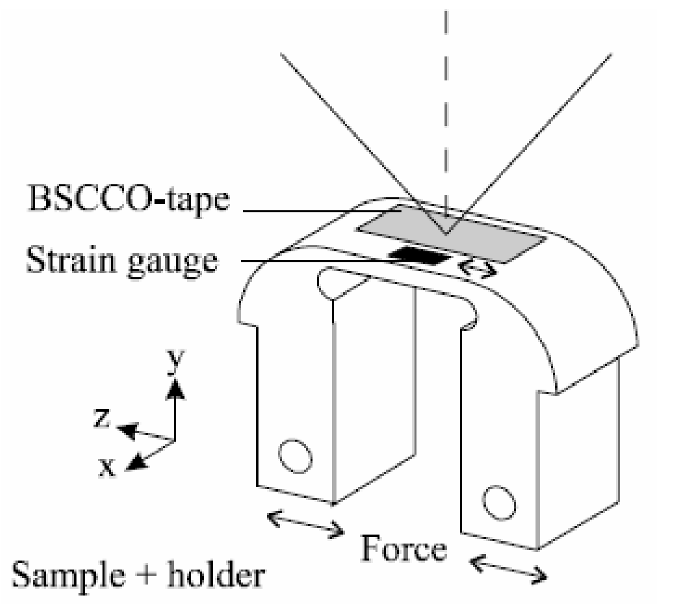
- Ten Haken, *PhysC* **270** (1996)

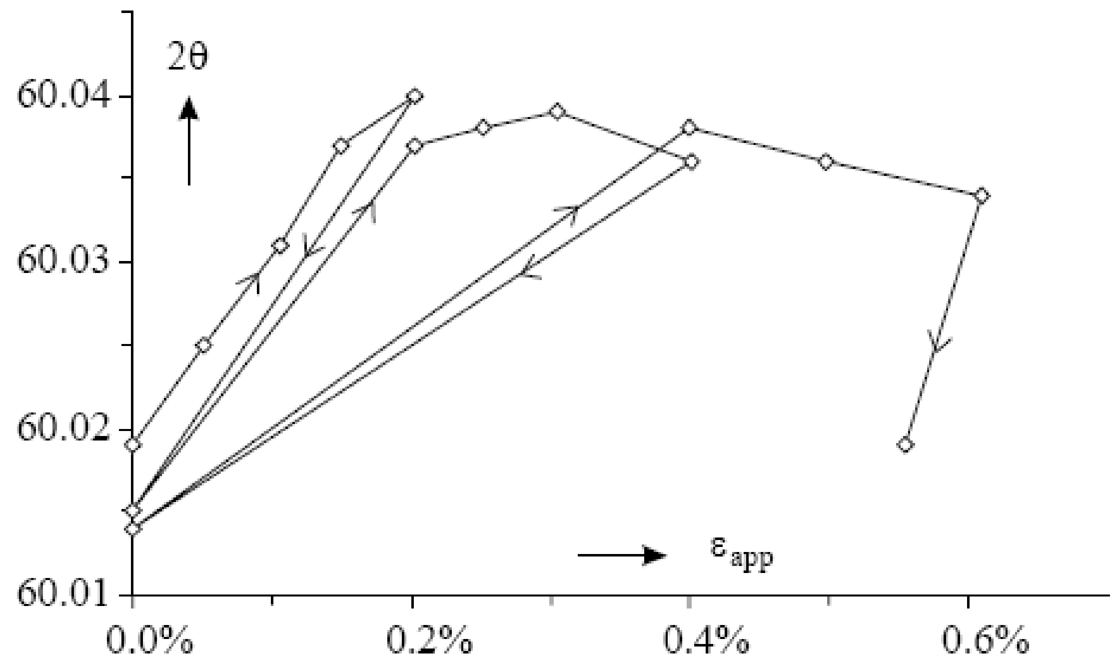
Yes, these cracks are real (~1996)

Strain behavior

- *c*-axis compression with axial tensile strain
  - Elastic up to +0.2% axial
    - $\varepsilon_z \propto 2\Theta$
  - Cracks above +0.2% a







  - Ten Haken, *PhysC* **270** (1996)

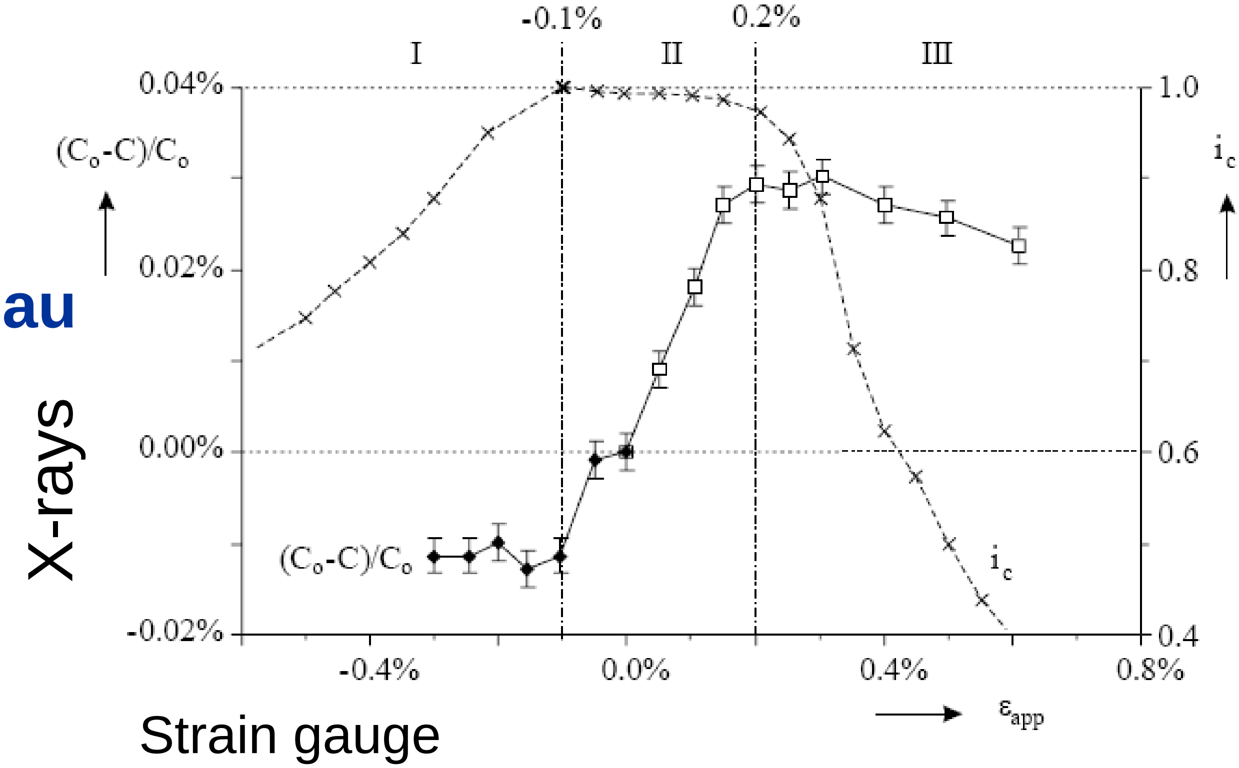
Microscopic strain and I_c Bi-2212

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

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

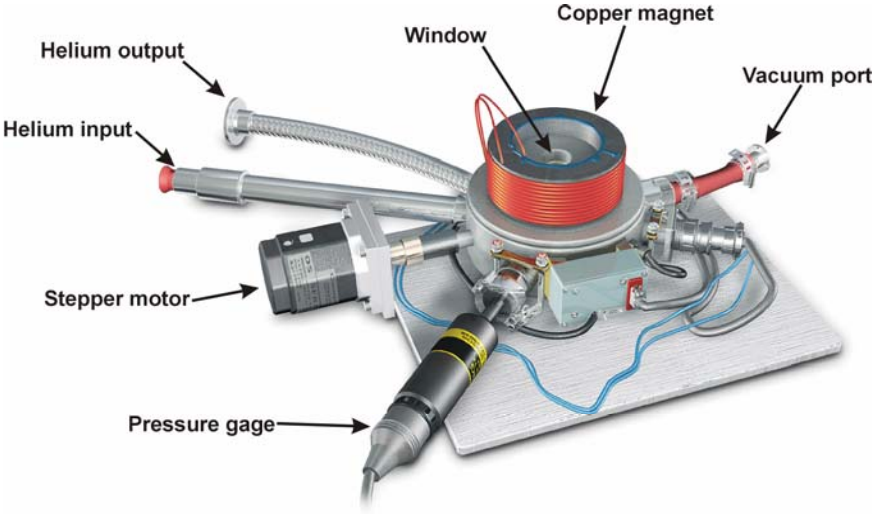
Outside $J_c(\varepsilon_{axial})$ plateau

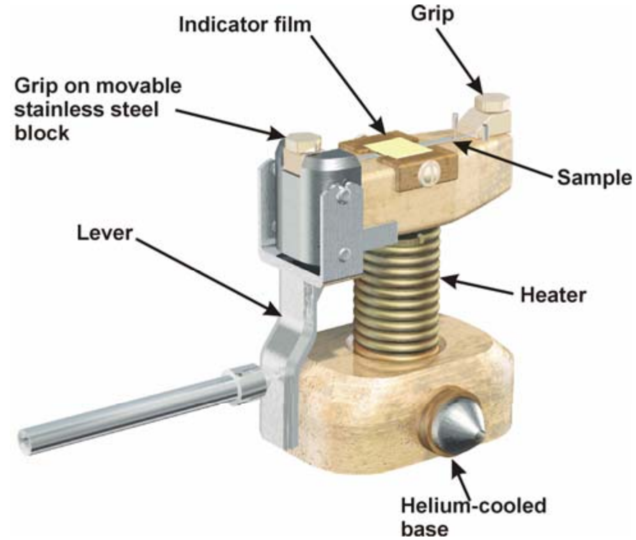
- *c*-axis is constant
- Elastic behavior disappears
- Crack formation



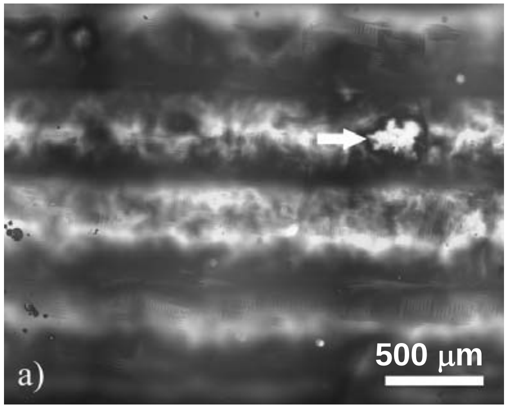
- Ten Haken, PhysC, 1996

MOI on strained HTS: Cracks





Unstrained Bi-2212



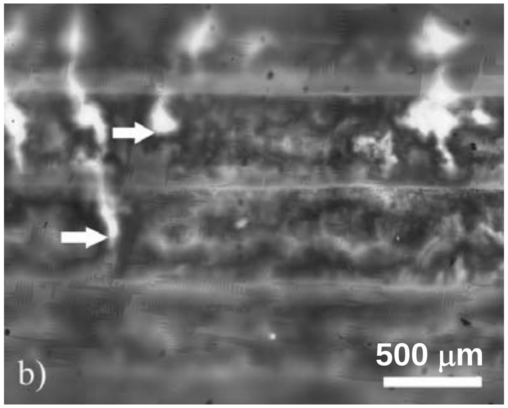
Filament

Filament + pinhole

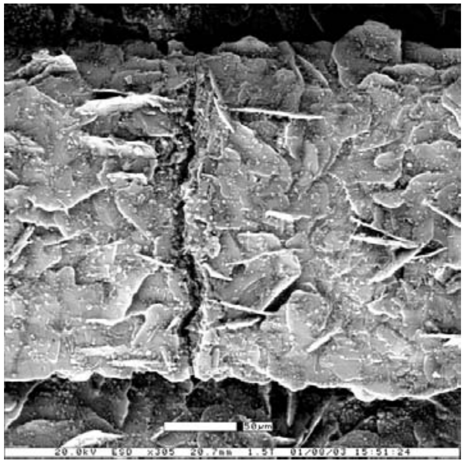
Filament

Filament

Strained Bi-2212

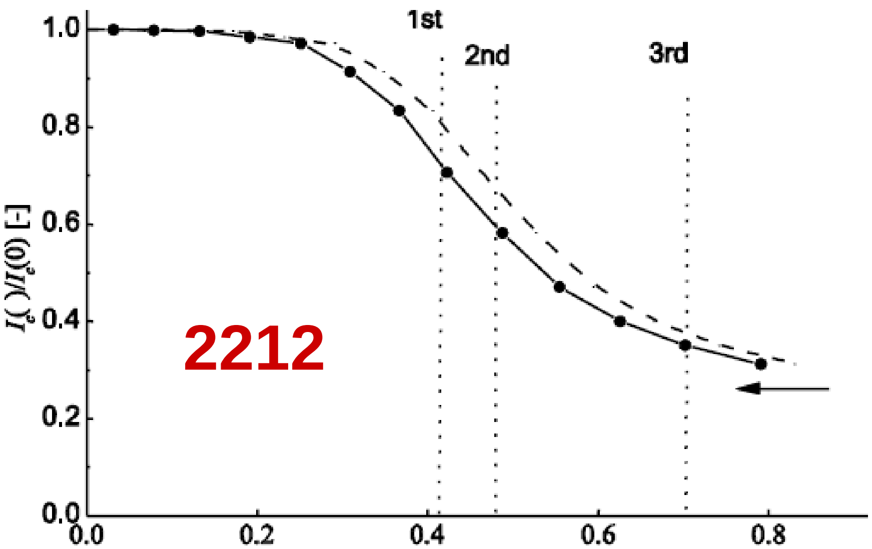


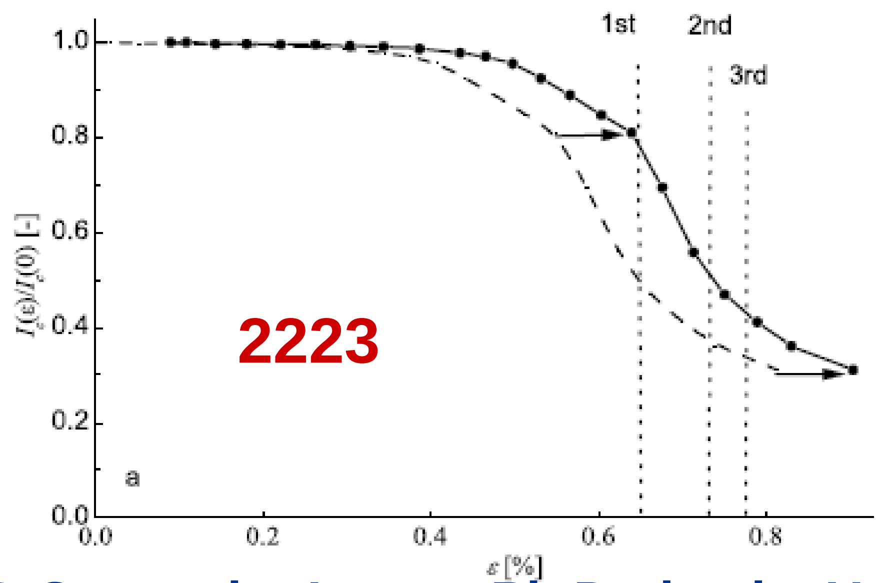
Strained Bi-2223

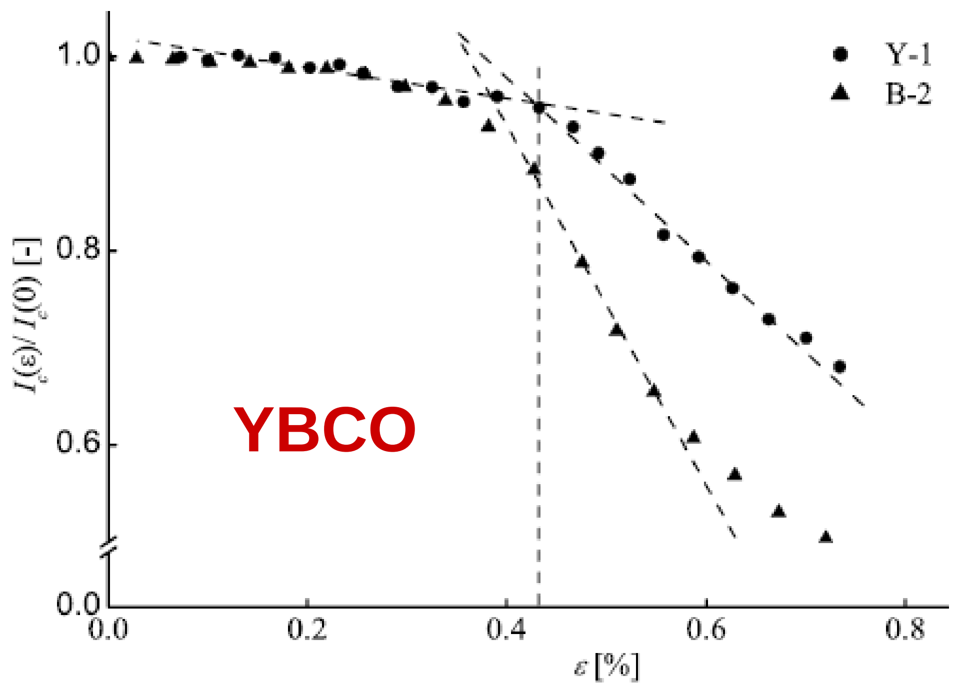


D.C. van der Laan – Ph.D. thesis, U. Twente 2004

MOI and J_c on strained HTS: Cracks

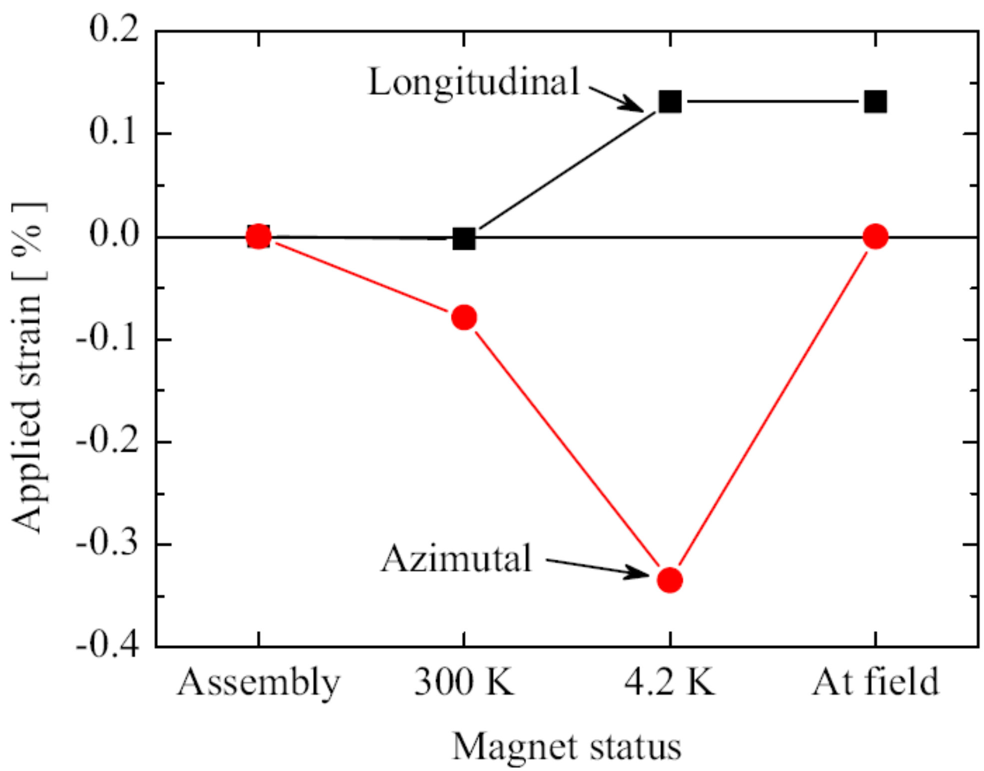






D.C. van der Laan – Ph.D. thesis, University of Twente 2004

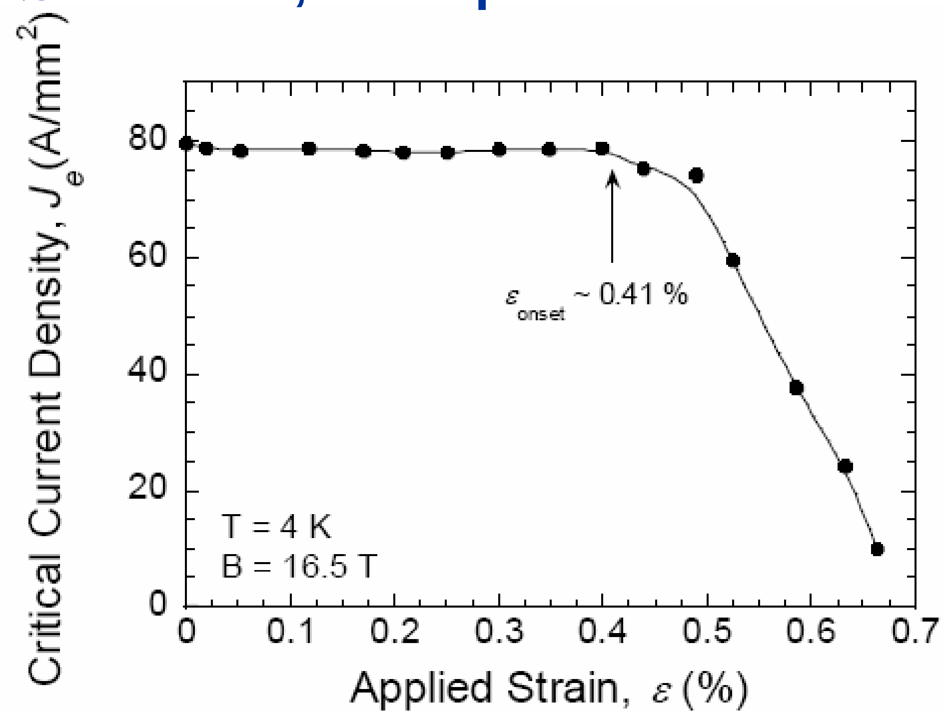
Magnets made from HTS?



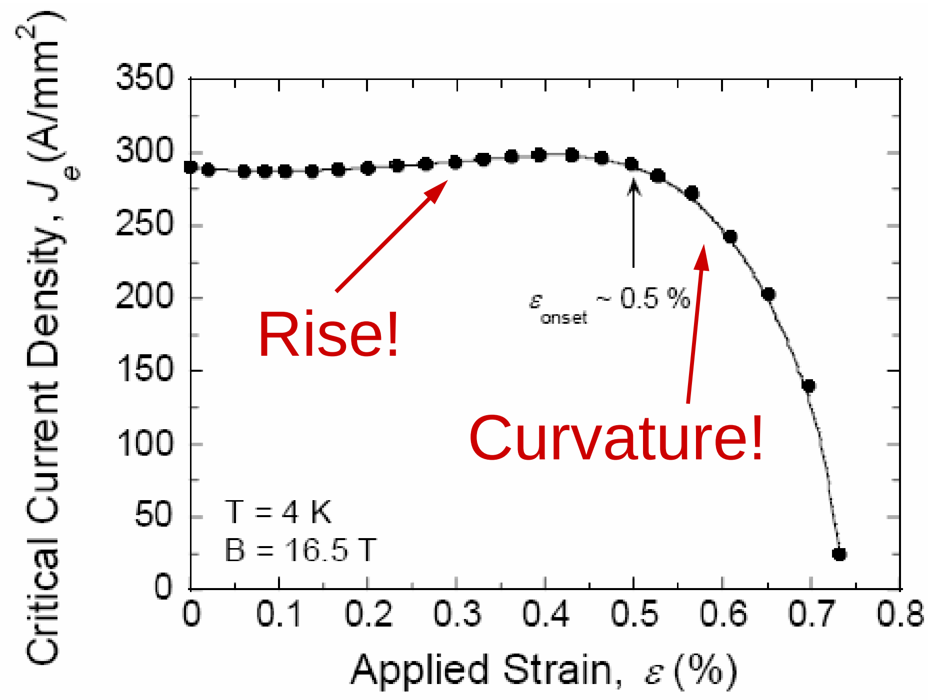
How are we supposed to set new magnetic field records with HTS materials that break into pieces under load?

IGC Bi-2212 round wire, 7x61 filaments Courtesy of Najib Cheggour – NIST

∅ 0.81 mm; Non optimized HT

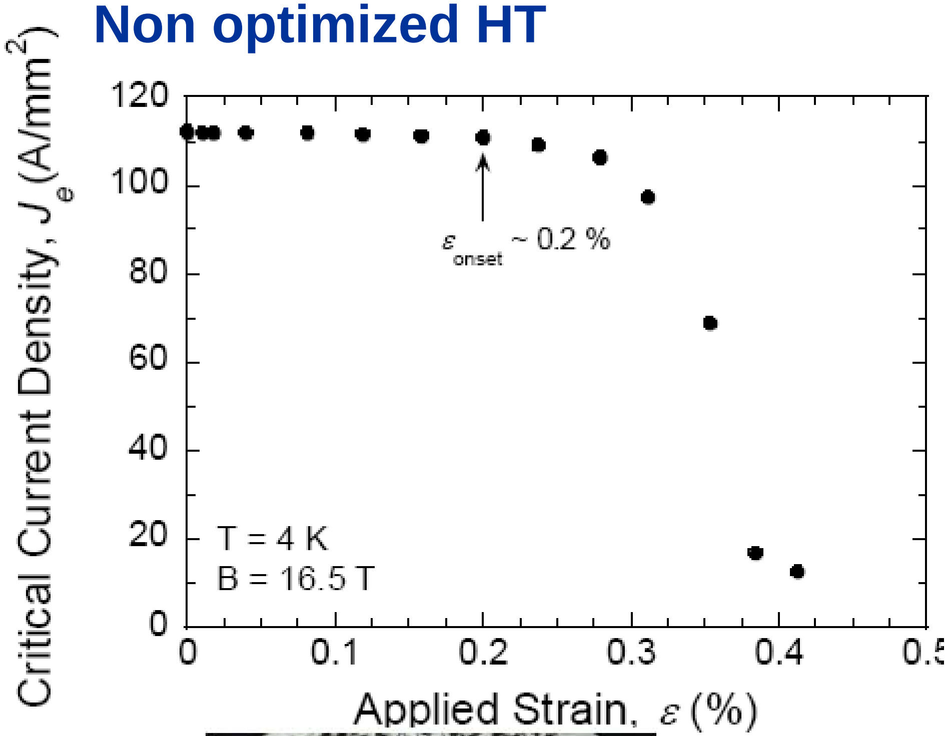


∅ 0.81 mm; Optimized HT

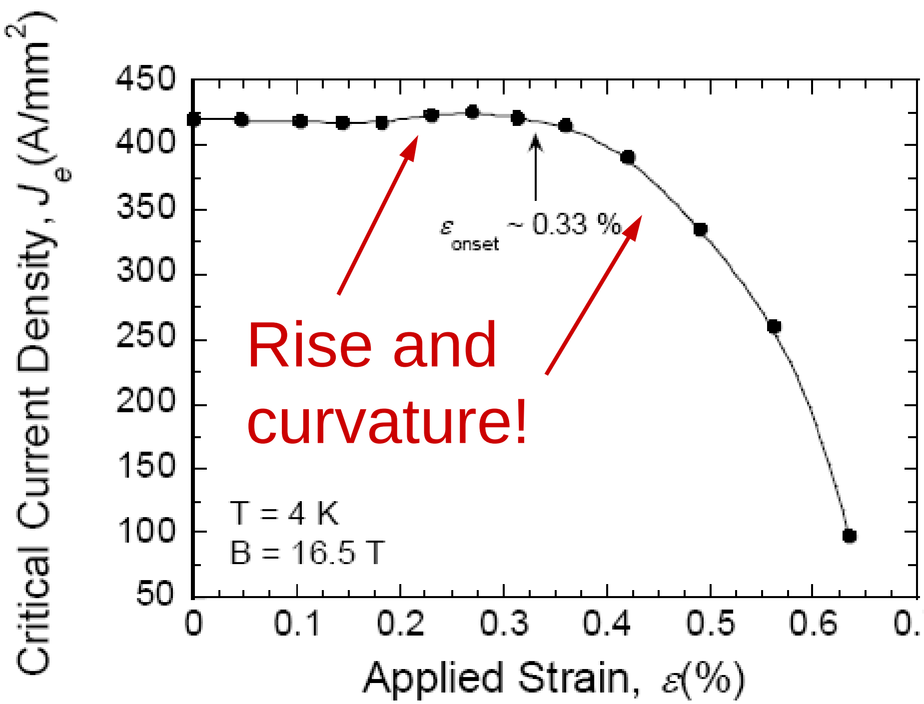


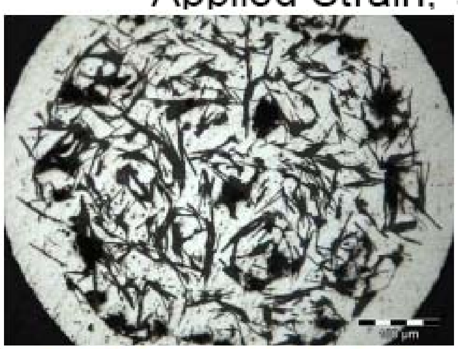
Showa Bi-2212 round wire
Courtesy of Najib Cheggour – NIST

∅ 0.57 mm; 19x37 filaments; Non optimized HT

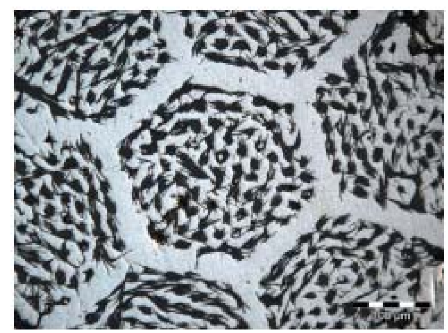


∅ 0.82 mm; 7x127 fil; Optimized HT





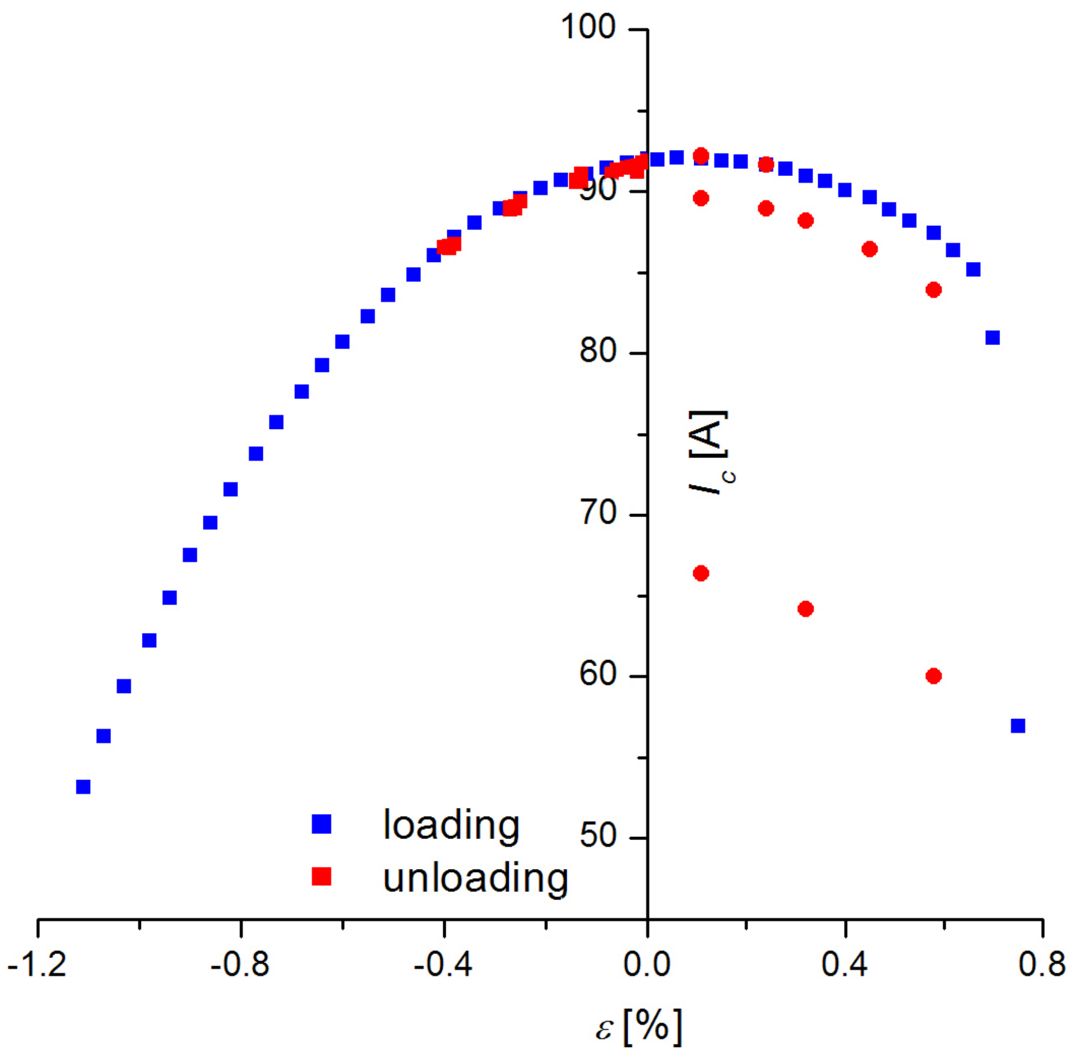
Modern wires appear much better than 1st generation tapes



SuperPower MOCVD-IBAD YBCO
Courtesy Danko van der Laan – NIST

What we need!

- Very much like Nb_3Sn
- No crack behavior
  - (but electronic in origin…?)



See:

- Van der Laan, *APL* **90** (2007)
- Talk this workshop

Could we get this in a wire…?

Summary

- (Accelerator) Magnet community prefers reversible strain behavior
  - Though we could work around some irreversible reduction
    - NMR type HTS insert magnets at NHMFL
- Crack formation dominates in (early generations) HTS tapes
- Latest generation wires appears much more promising
- YBCO rocks! (but for accelerator magnets we need wires…)

Spare slides on transverse pressure

A quick note on transverse pressure…

On short tape samples

- Worrying ?

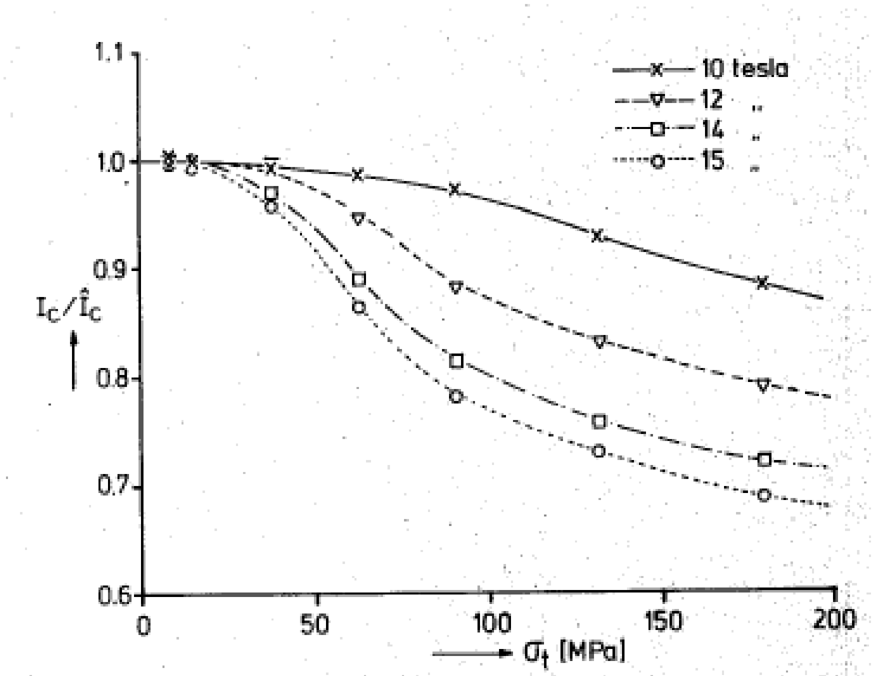
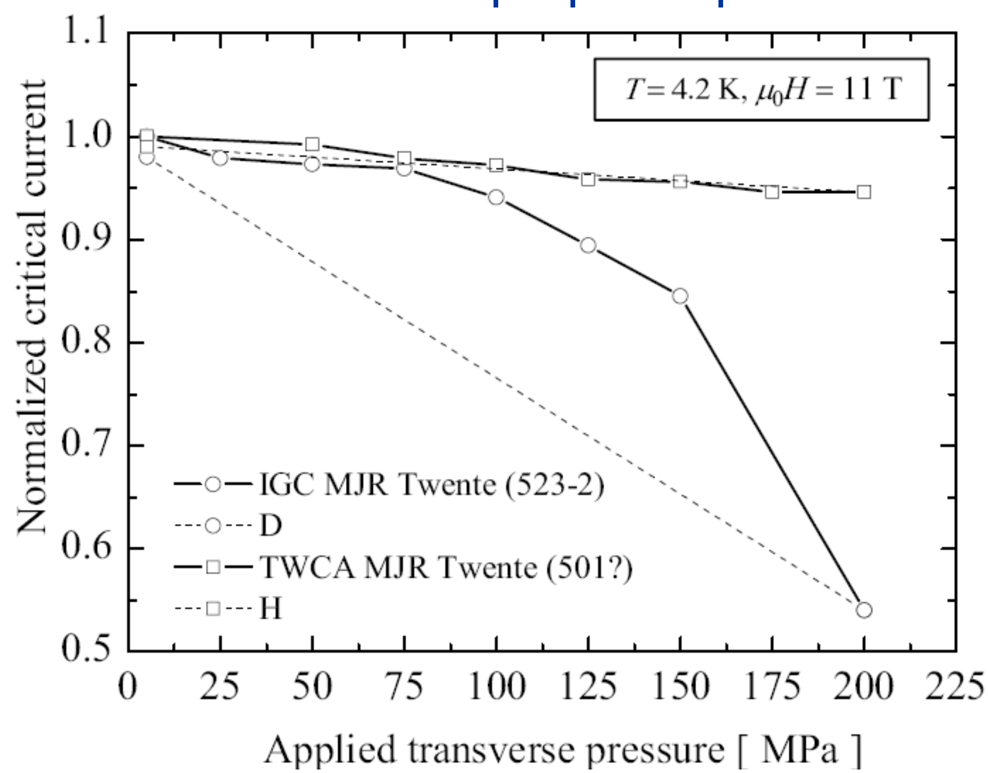


Fig. 4 The relative current density as a function of the transverse pressure at 4.2 K.

➧ Ten Haken, *TAS* **3** (1993)

On cables

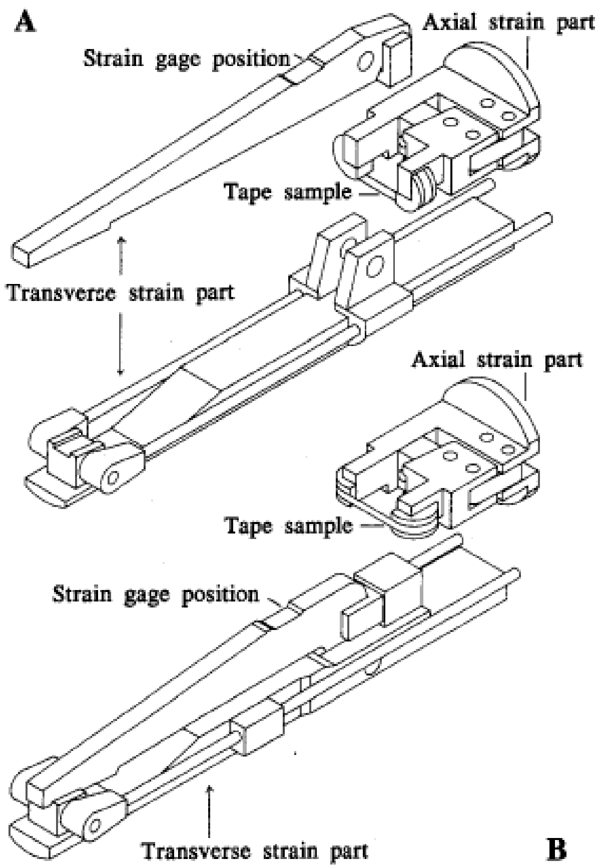
- OK !
  ➧ Sensitive to proper experiment



➧ Unpublished ~1993

Transverse pressure on Bi-2212 tapes

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



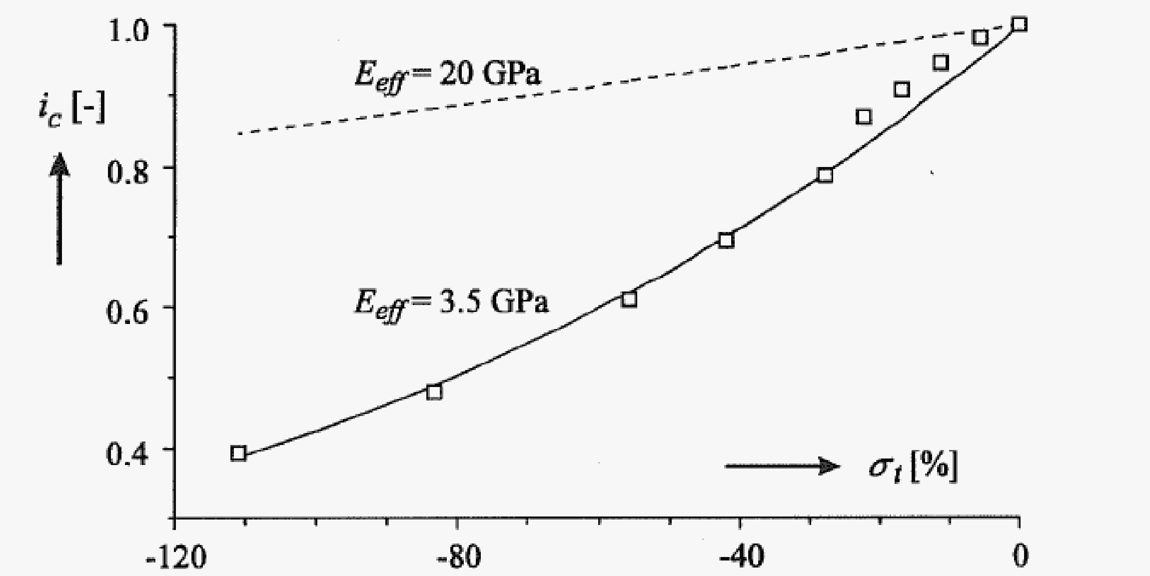


Figure 6.16: *The normalised critical-current reduction of the Bi-2212 tape conductor (T-19) subjected to a transversal pressure, measured on the $F_t // B$ transverse press. The measured $I_c(\sigma_t)$ is compared with two lines representing the calculated I_c versus pressure dependence for two different 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?

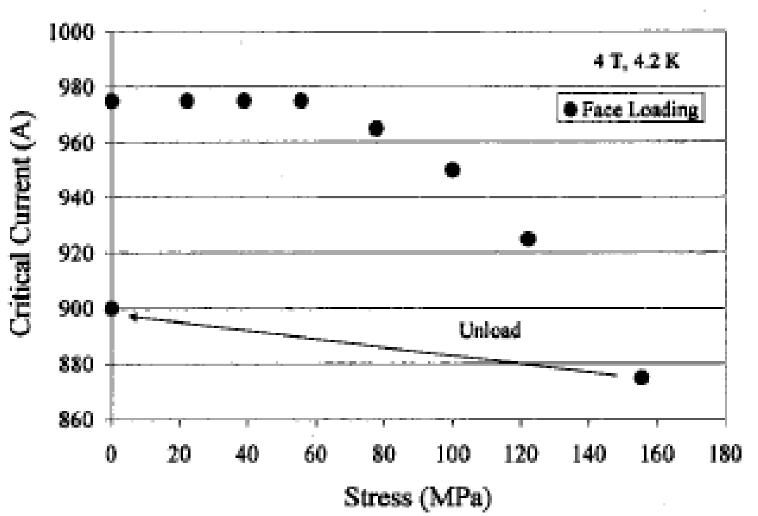


Fig. 3. Variation of the critical current (4 T, 4 K) with stress for a cable loaded on the broad face of the cable.

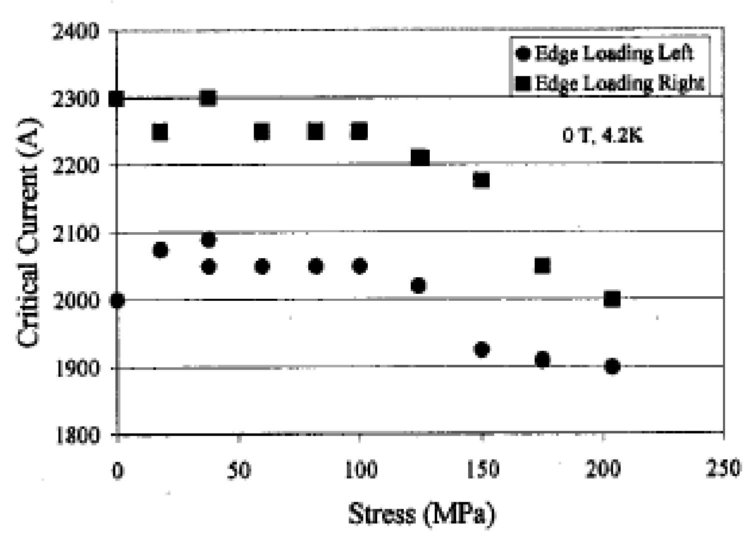


Fig. 4. Variation of the critical current (self-field, 4 K) with stress for a cable loaded on the edge of the cable.

- Dietderich, TAS, 2001