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Title

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

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

Arno Godeke

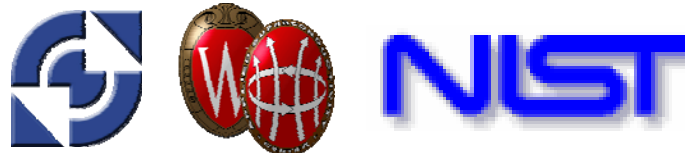
August 22, 2007

With kind contributions from

Najib Cheggour (NIST)

Danko van der Laan (NIST)

Shlomo Caspi (LBNL)

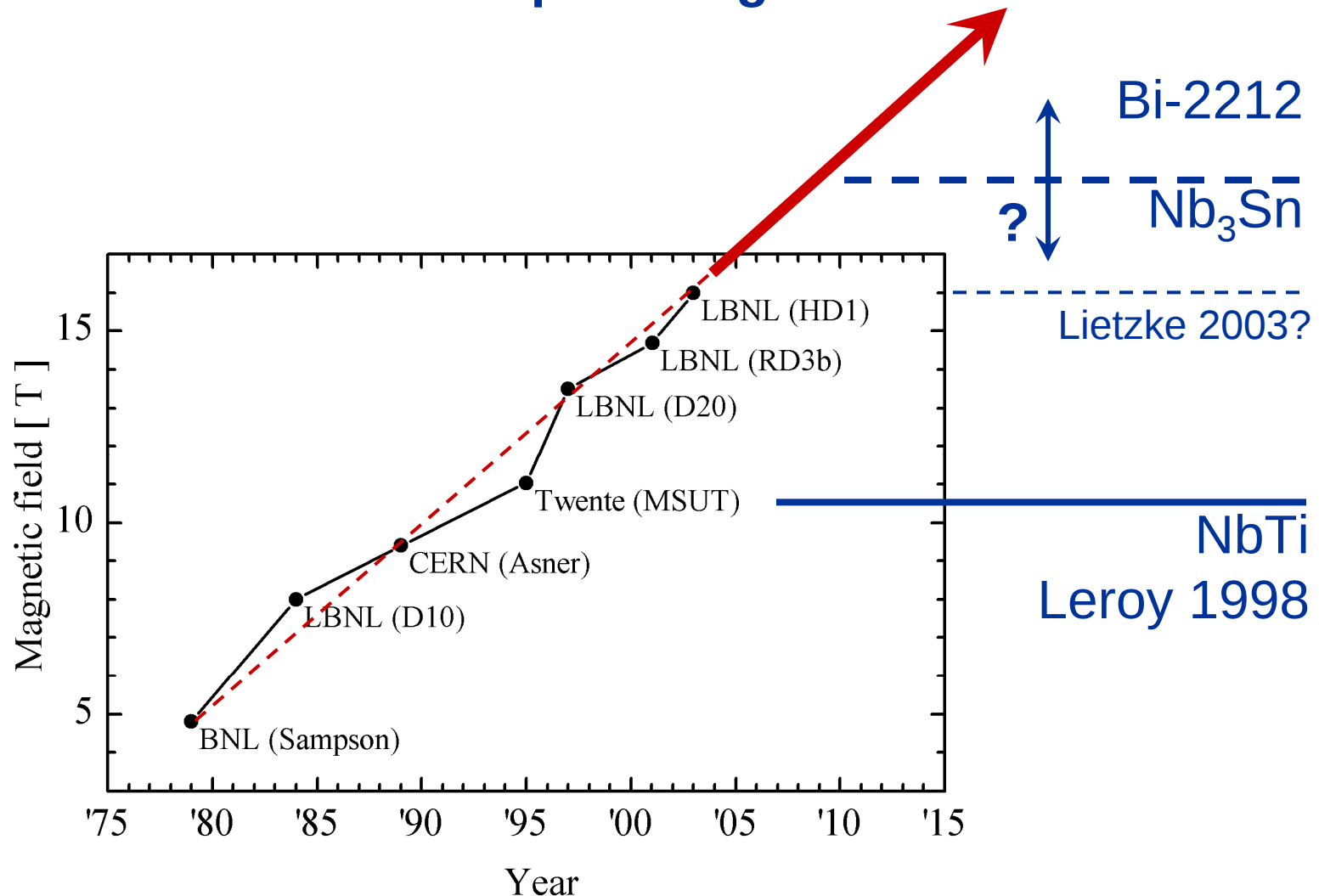


Funded by the US Department of Energy under contract No. DE-AC02-05CH11231

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Motivation

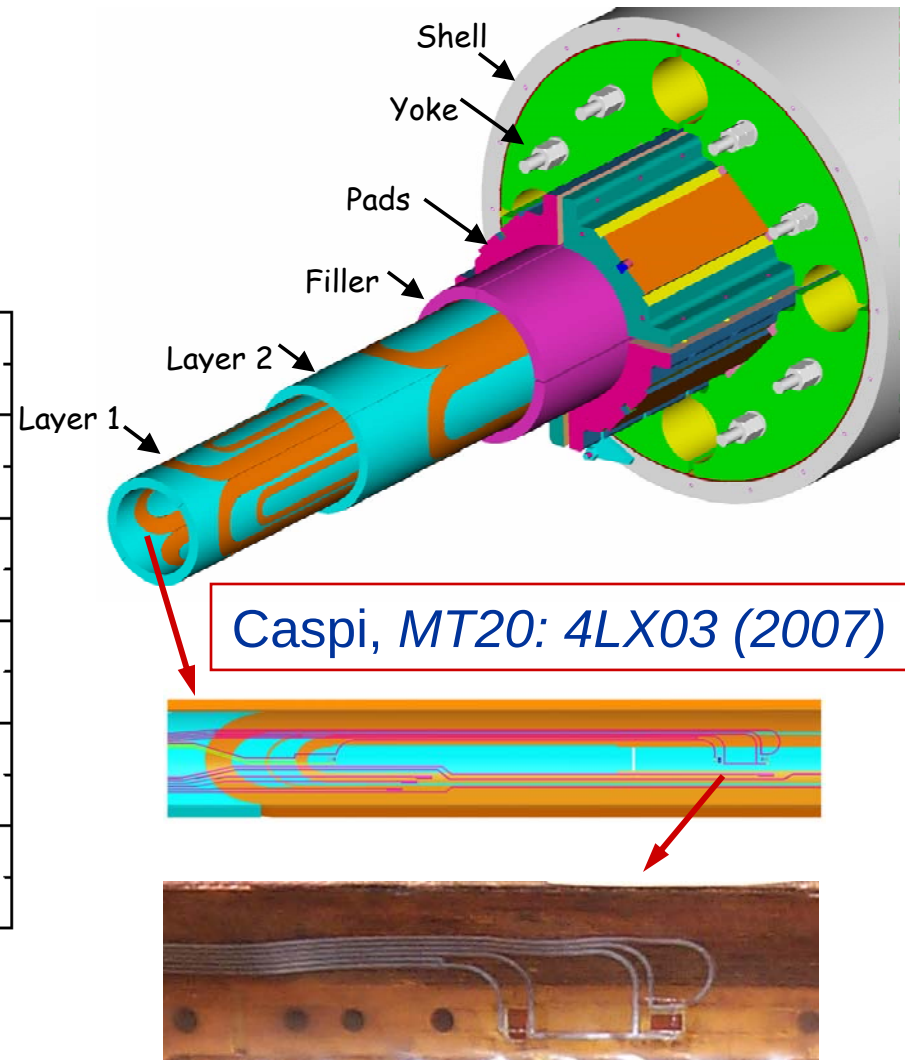
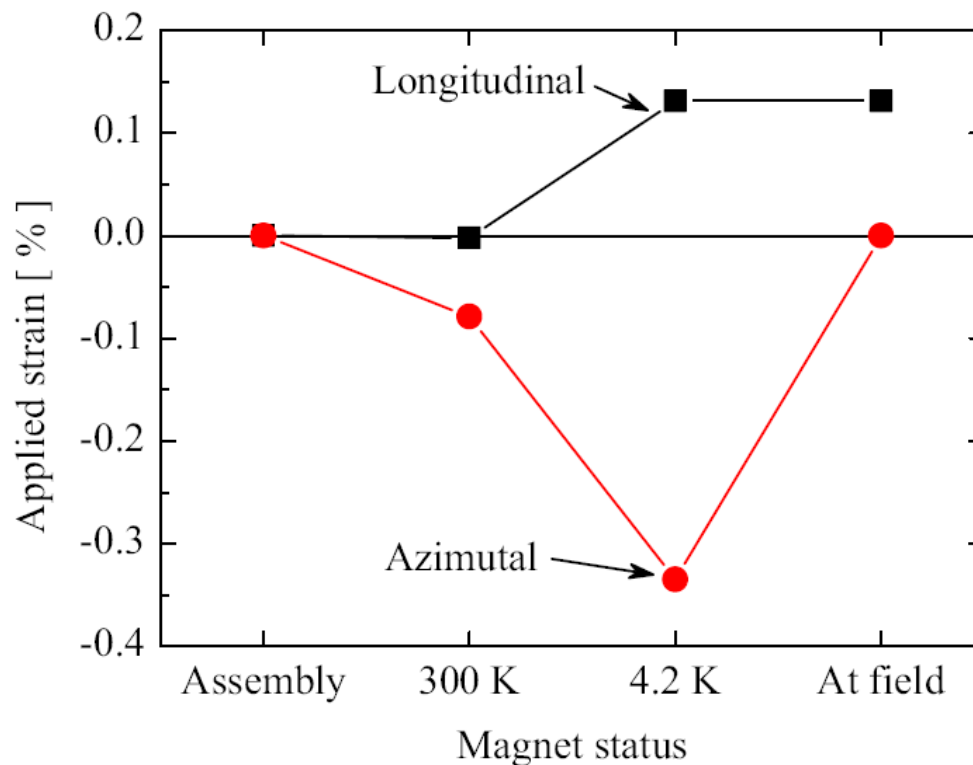
Magnetic field records in dipole magnets



How do Nb_3Sn magnets work?

Example: LARP Quad TQS01

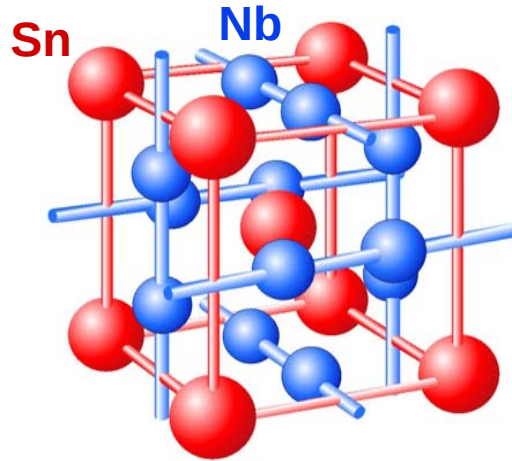
- Ti-6Al-4V poles
- 8 W&R cos Θ coils
- 90 mm bore, > 220 T/m



Reversible strain!

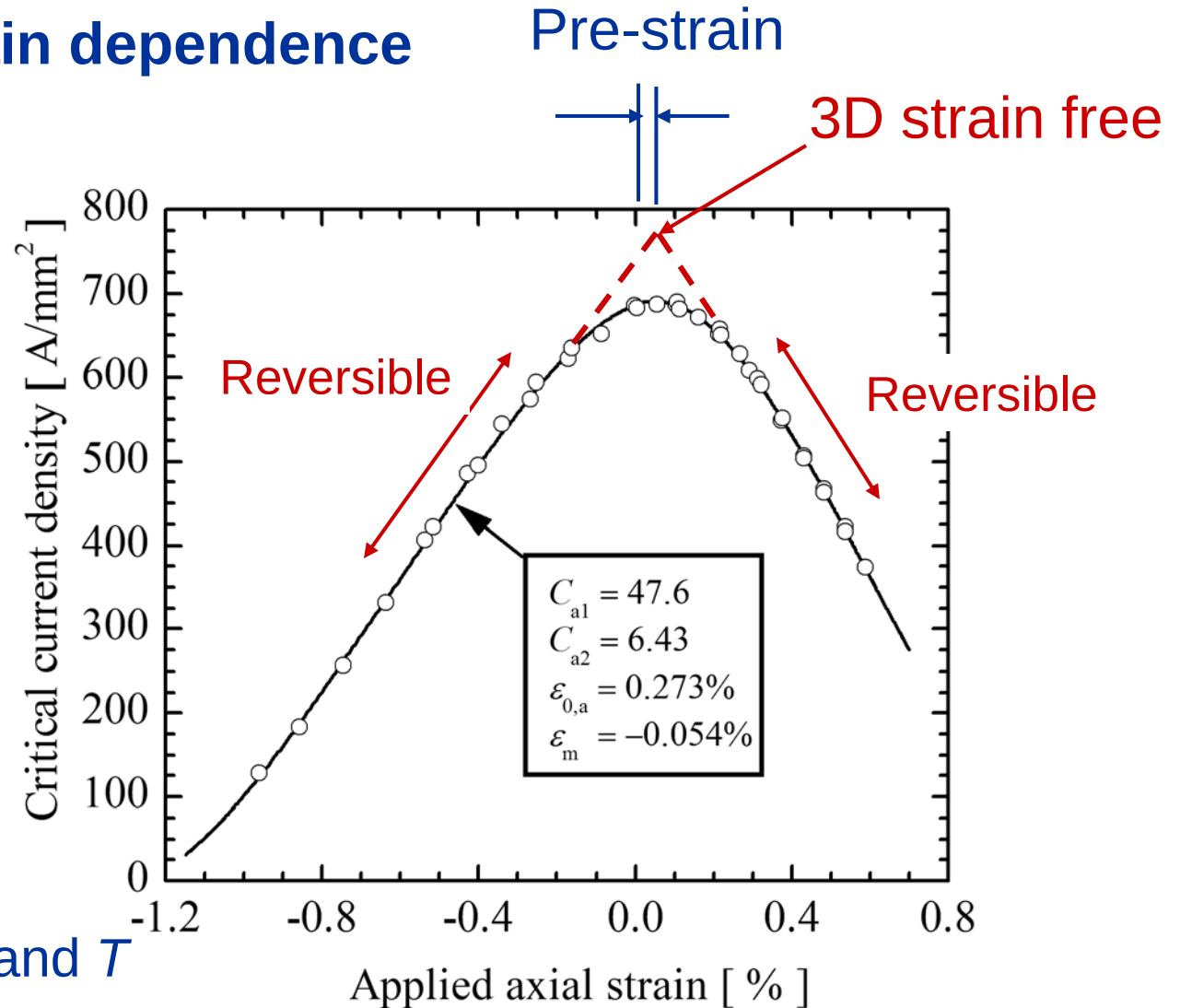
Why do Nb₃Sn magnets work?

Reversible axial strain dependence



Reversible means:

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



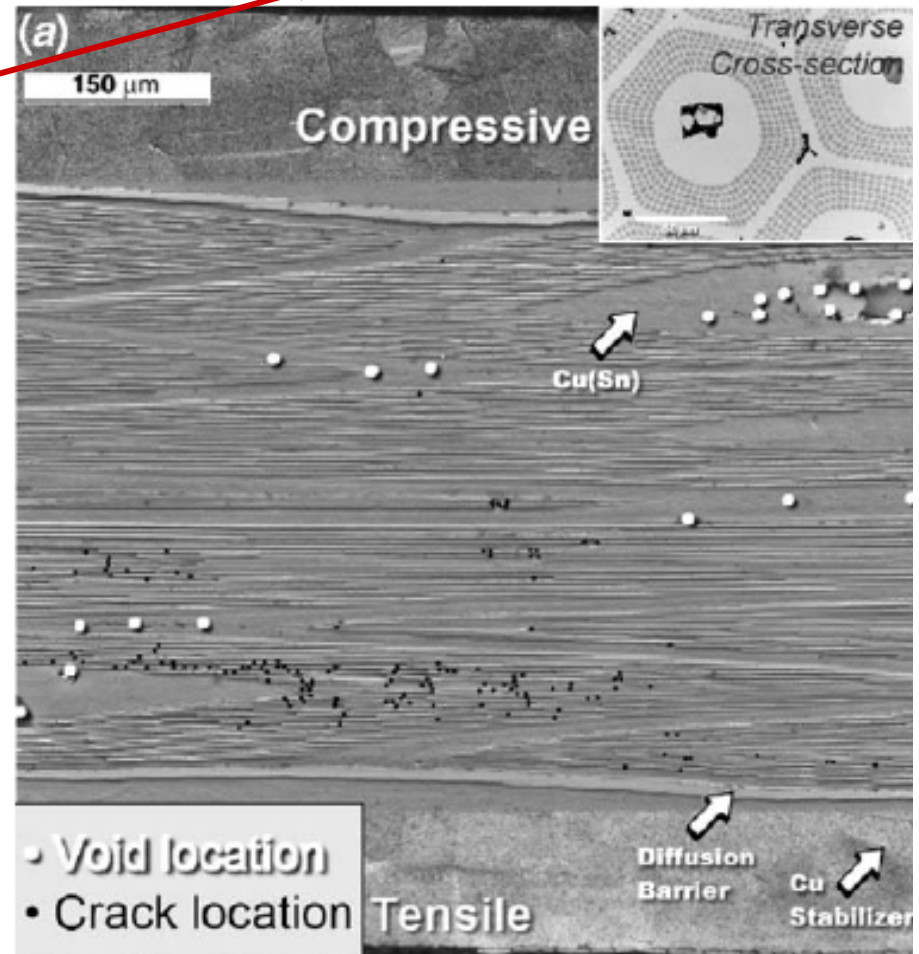
Godeke, SuST 19 2006

How can magnets fail?

'Preliminary' J_c collapse

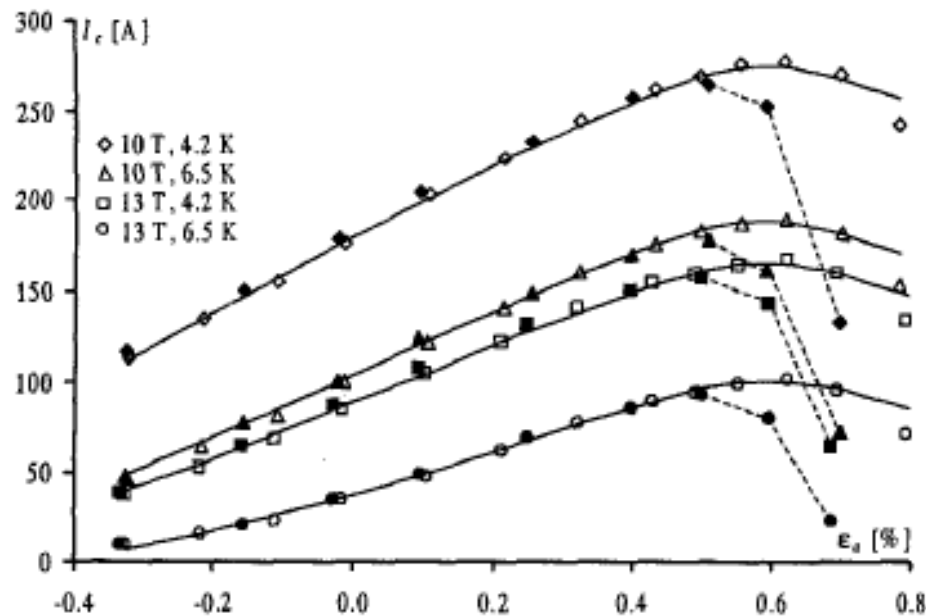
- Irreversible
- Crack formation

Bend tests IT wire:



Unrelated

Axial strain tests IT wire:



■ Godeke, *TAS 9* (1999)

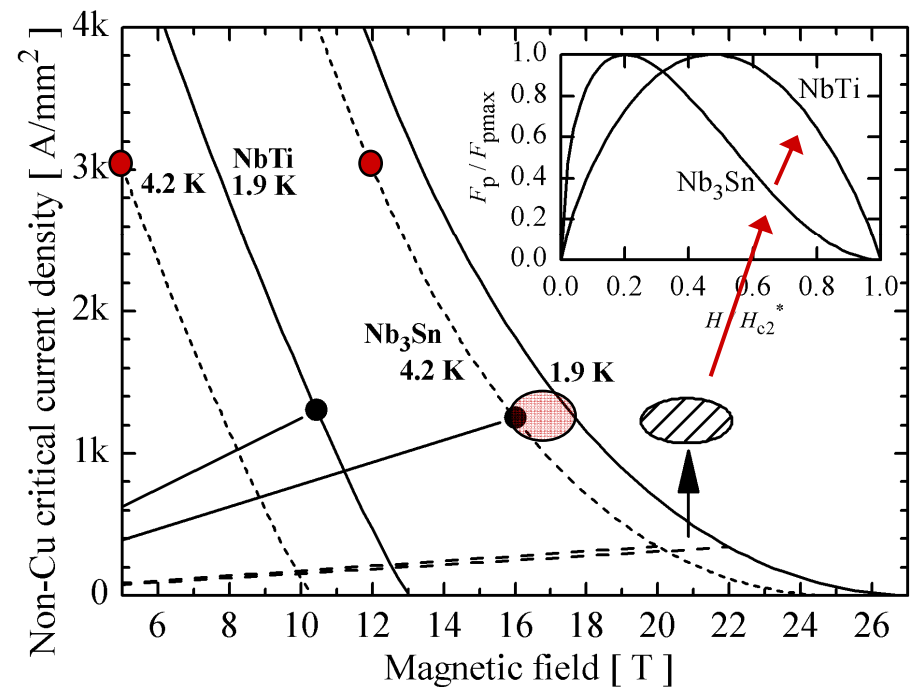
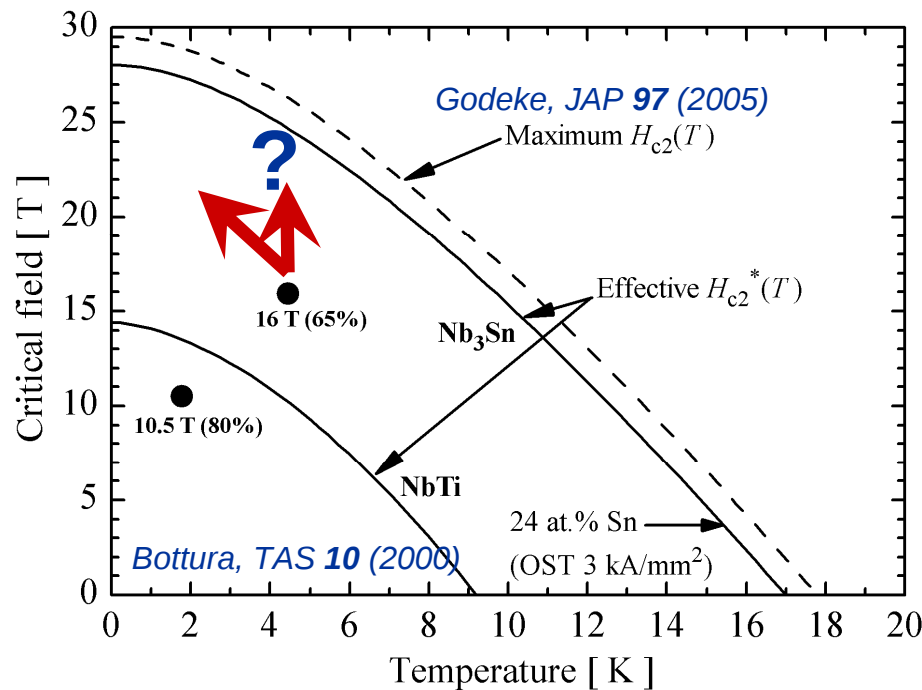
■ Jewell, *SuST 16* (2003)

This workshop!

Limitations of NbTi and Nb₃Sn

- Nb₃Sn dipoles are limited to 17 – 18 T
 - ➡ Provided that strain can be handled

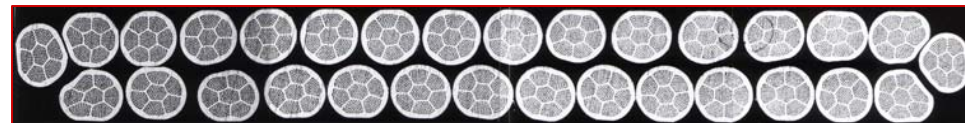
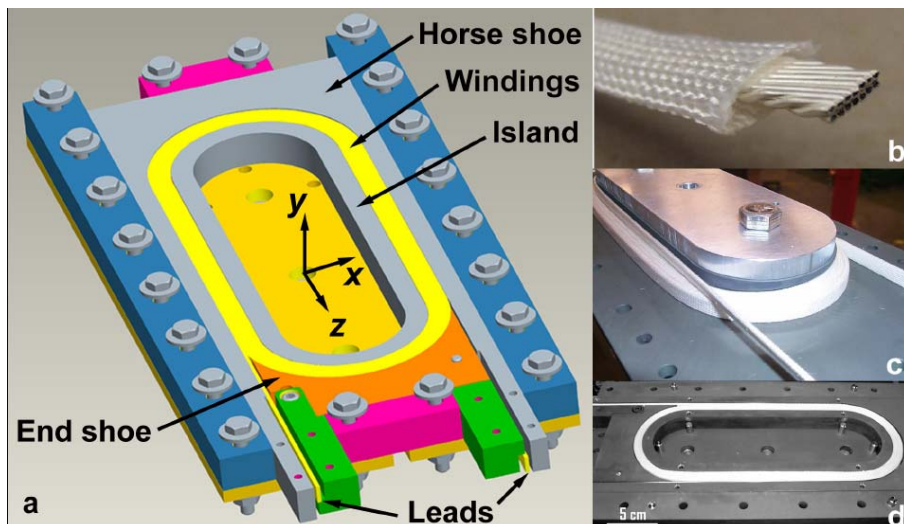
NbTi: Bottura, TAS **10** (2000)
 Nb₃Sn: Godeke, SuST **19** (2006)



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

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 ₃ Sn	675°C Ar/Vacuum	S/R glass	~ 20 ms ⁻¹
Bi-2212	890±2°C O ₂	Ceramic	< 0.05 ms ⁻¹

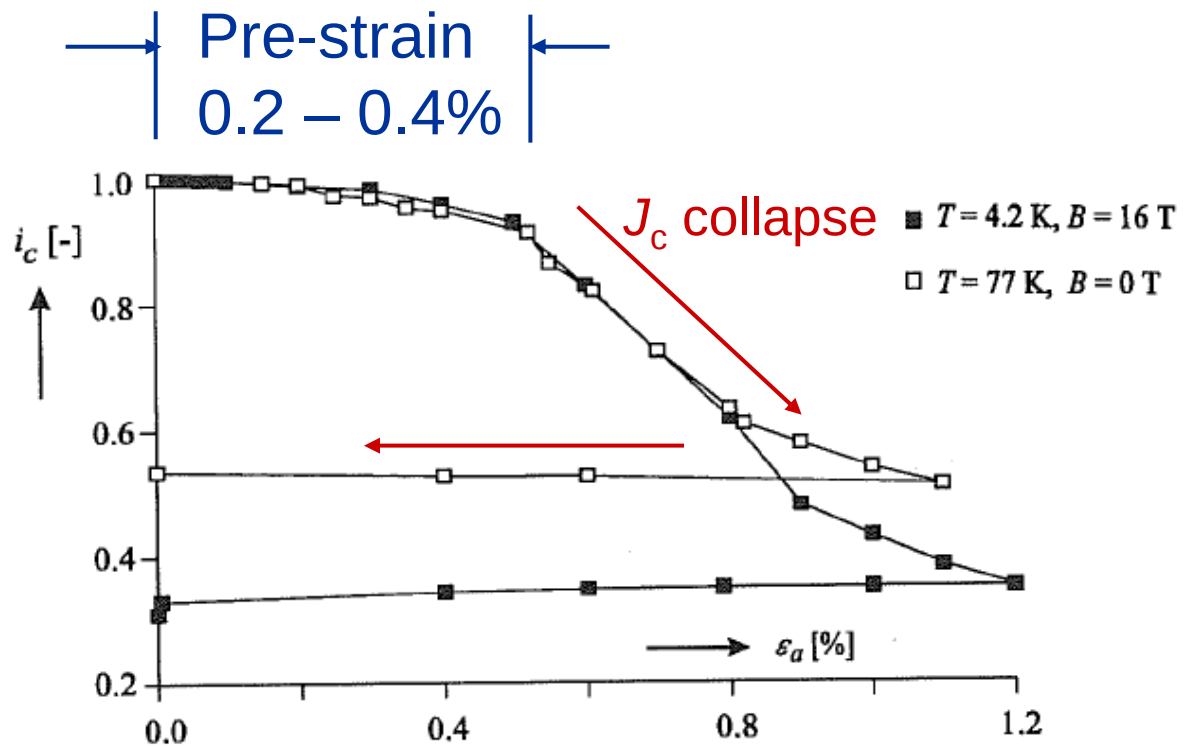
WIND-AND-REACT BI-2212 SUBSCALE COIL TEST CONFIGURATIONS

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 ₃ Sn hybrid dipole ^{ab}	2 × 19 (Bi-2212)	8.5	4595	2.4	34	0	20
	2 × 20 (×2 Nb ₃ Sn)						
1 × Bi-2212 / 2 × Nb ₃ Sn hybrid dipole ^{ac}	2 × 19 (Bi-2212)	9.9	4486 (Bi-2212)				
	2 × 20 (×2 Nb ₃ Sn)		6112 (Nb ₃ Sn)				

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

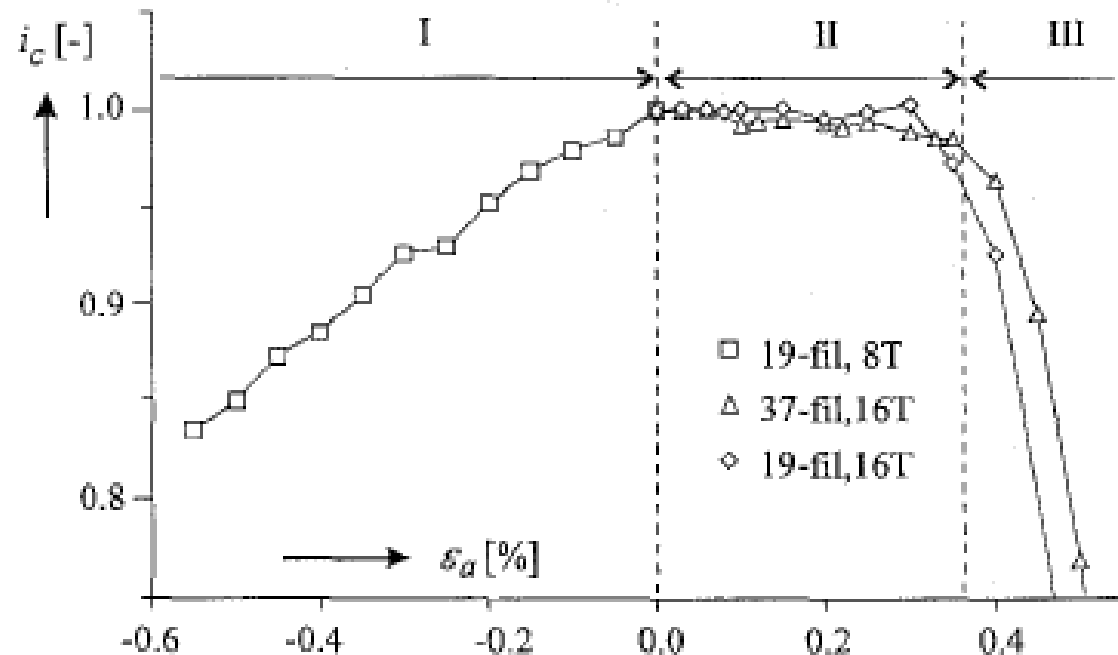


Fig. 1. The normalised critical current as a function of the axial strain. Measured on different samples for compressive and tensile strains (measured at 4.2 K and 8 or 16 T).

➡ Ten Haken, *ToM* **32** (1996)

A model for axial strain behavior in Bi-2212

Model...

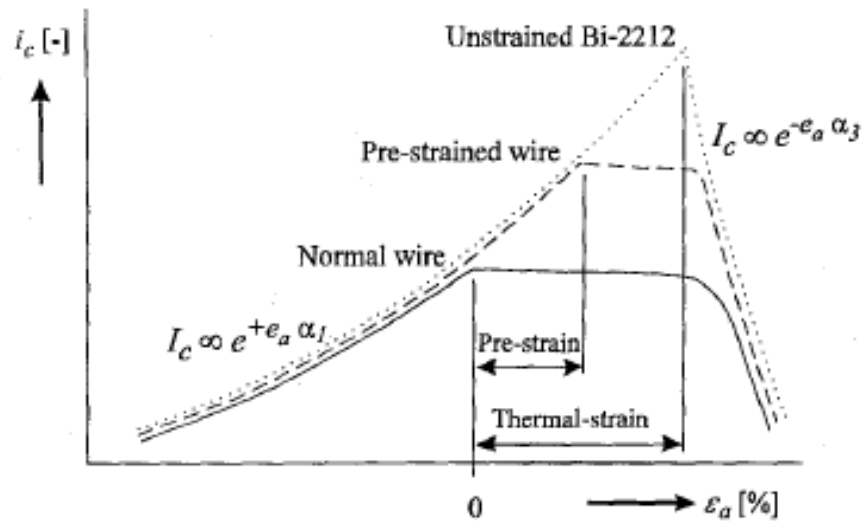
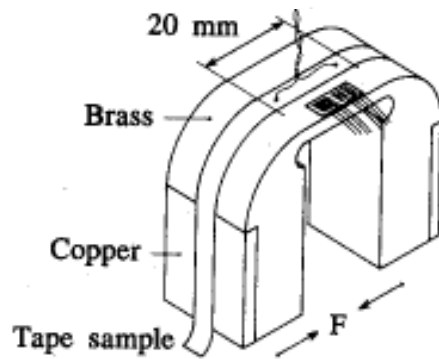


Fig. 2. The proposed description for the $I_c(\epsilon_a)$ dependence of Bi-2212.



...and measurement

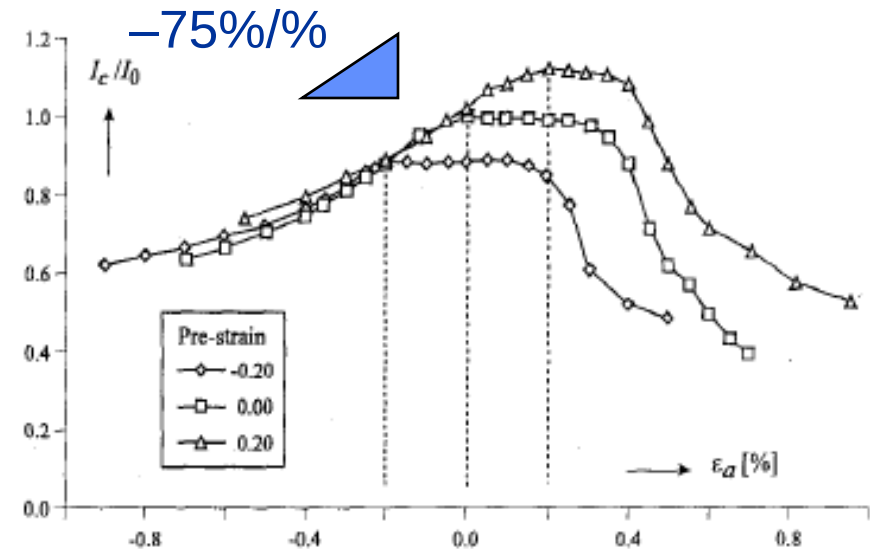


Fig. 3. The normalised critical current as a function of the axial strain measured on three pairs of pre-strained samples (measured at 4.2 K and 16 T).

► Ten Haken, *ToM* **32** (1996)

- All axial compressive strain irreversibly reduces J_c

Model and irreversibility

Repetitive 'low' strain variations

- All strain irreversible

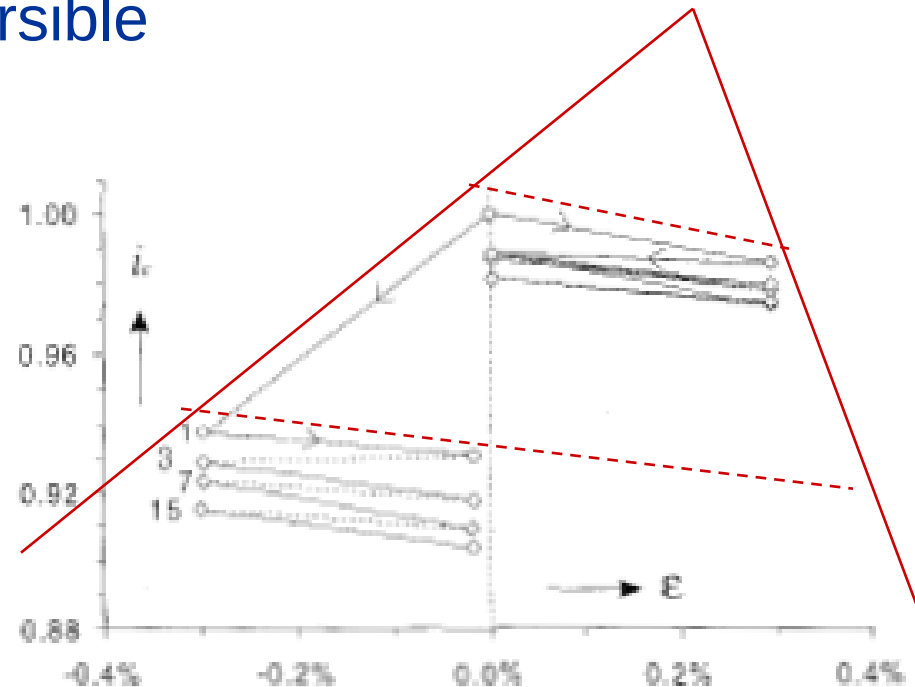


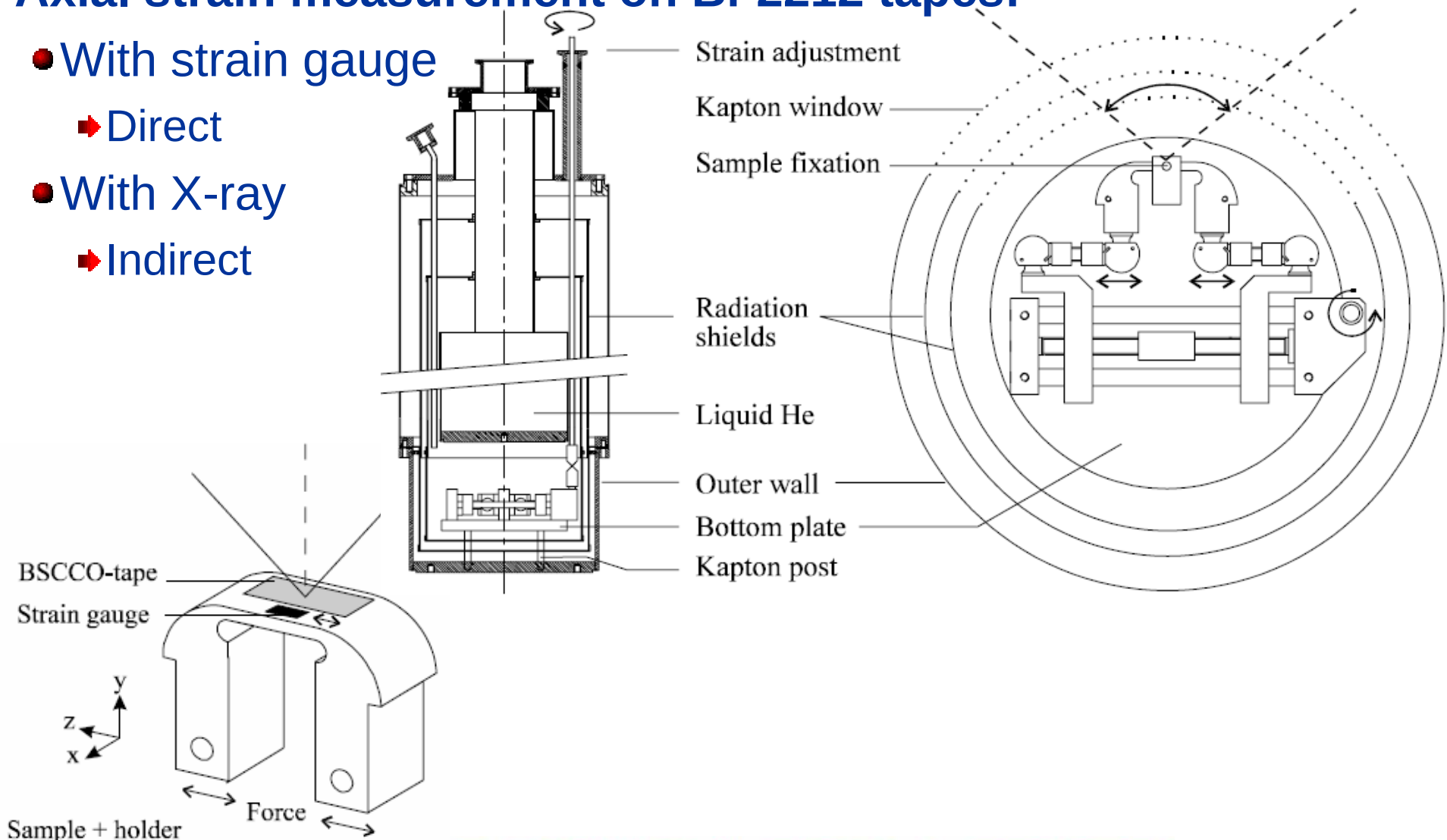
Fig. 5. The I_c versus strain in two samples of conductor A. First a cyclic deformation between 0 and 0.28% axial strain and then between 0 and -0.28% strain. The solid and dotted line follows the measuring sequence. The solid lines indicate two sequential I_c measurements and a dotted line is used when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

• Ten Haken, TAS, 1997

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

Axial strain measurement on Bi-2212 tapes:

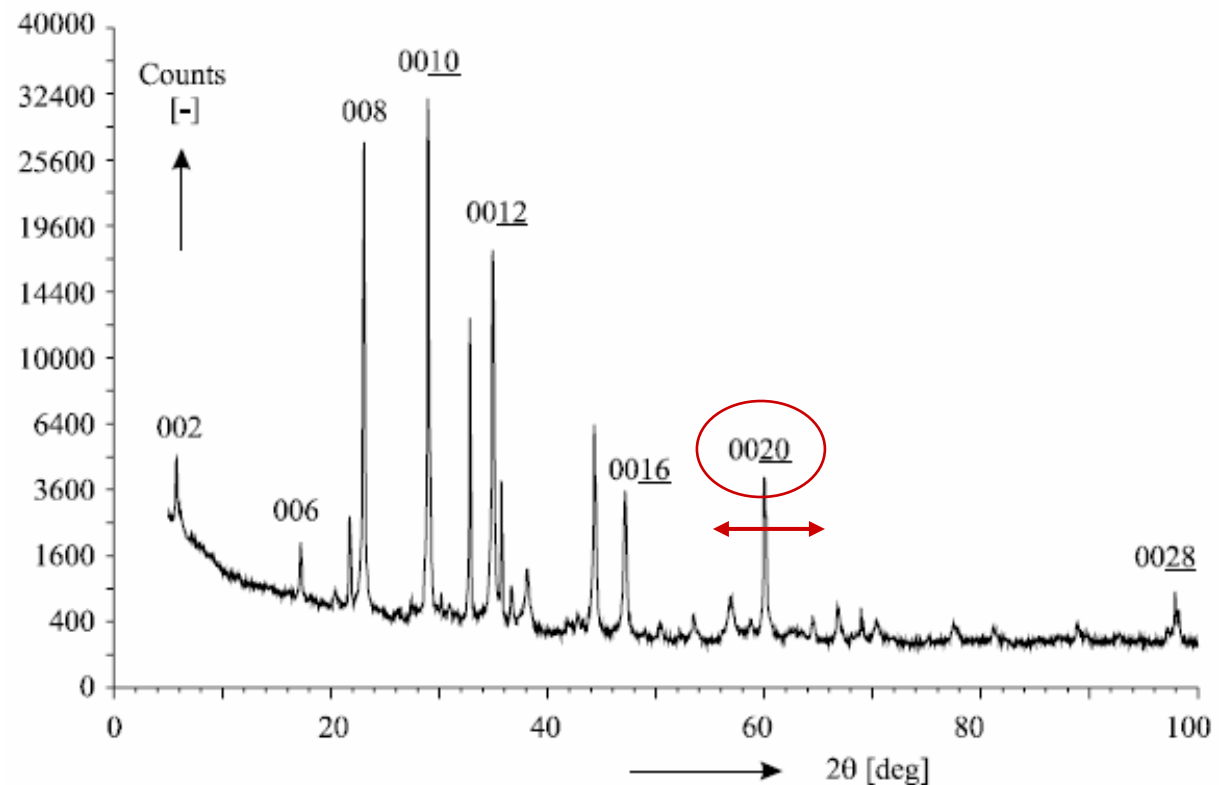
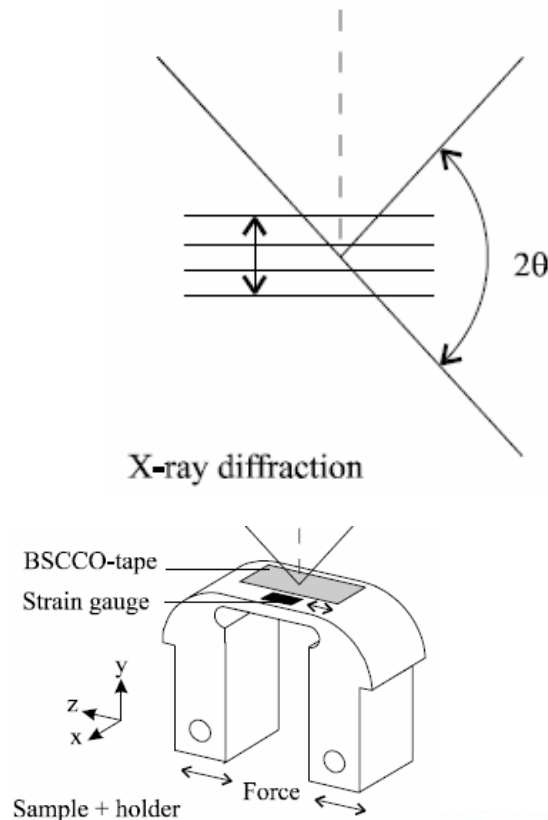
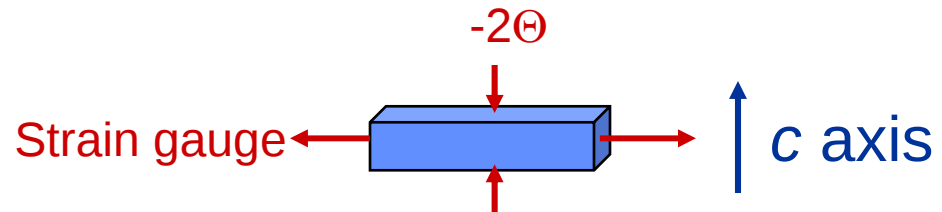
- With strain gauge
 - ➡ Direct
- With X-ray
 - ➡ Indirect



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)

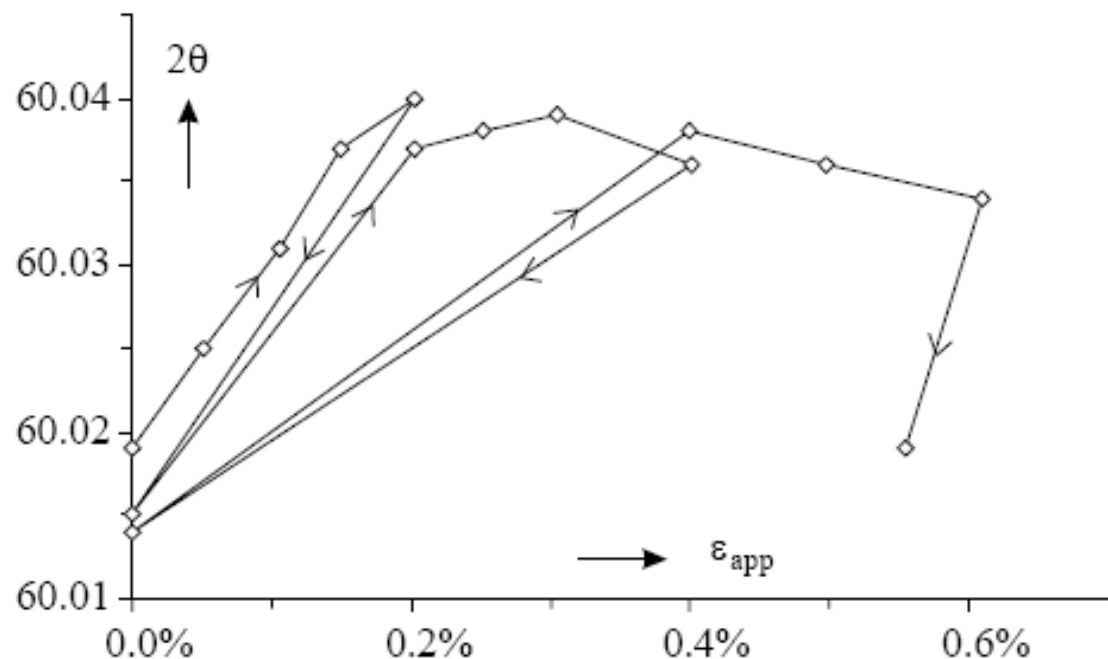
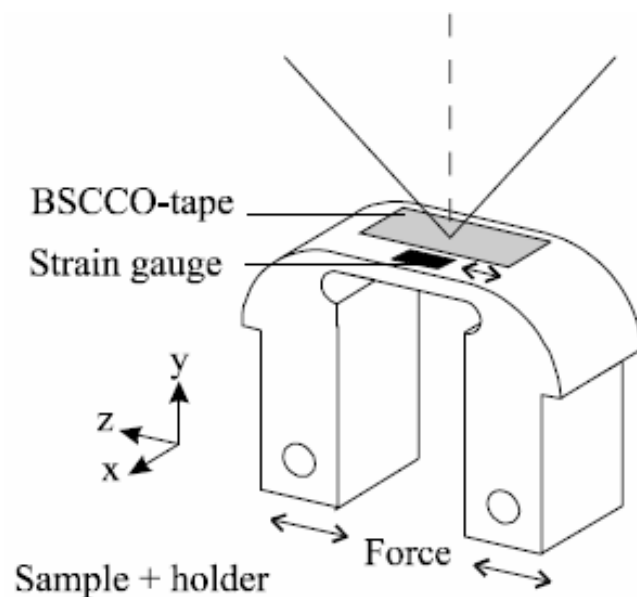
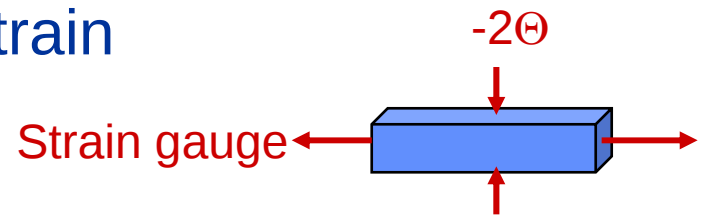
Strain behavior

• c-axis compression with axial tensile strain

➔ Elastic up to +0.2% axial

• $\epsilon_z \propto 2\Theta$

➔ Cracks above +0.2% a



➔ Ten Haken, *PhysC* 270 (1996)

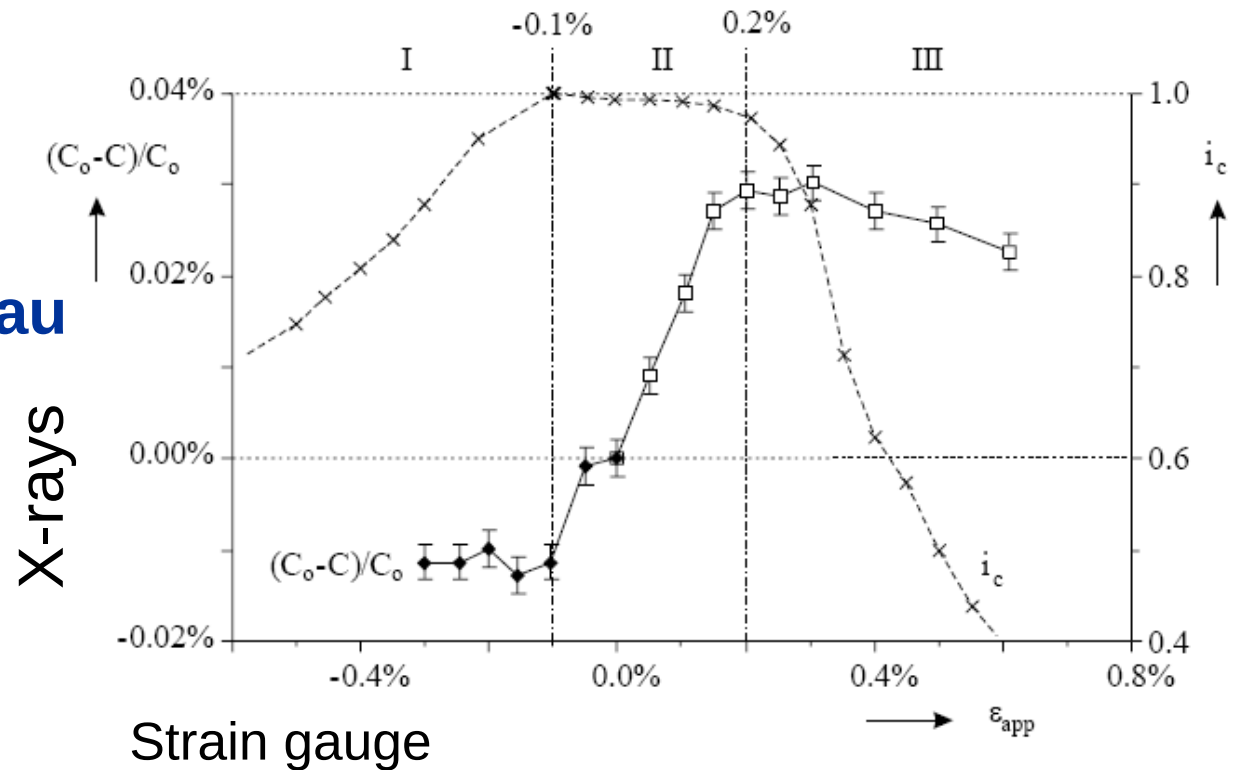
Microscopic strain and I_c Bi-2212

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

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

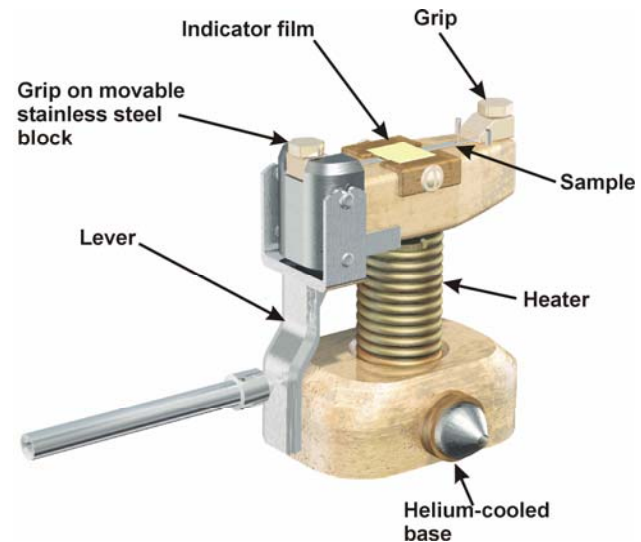
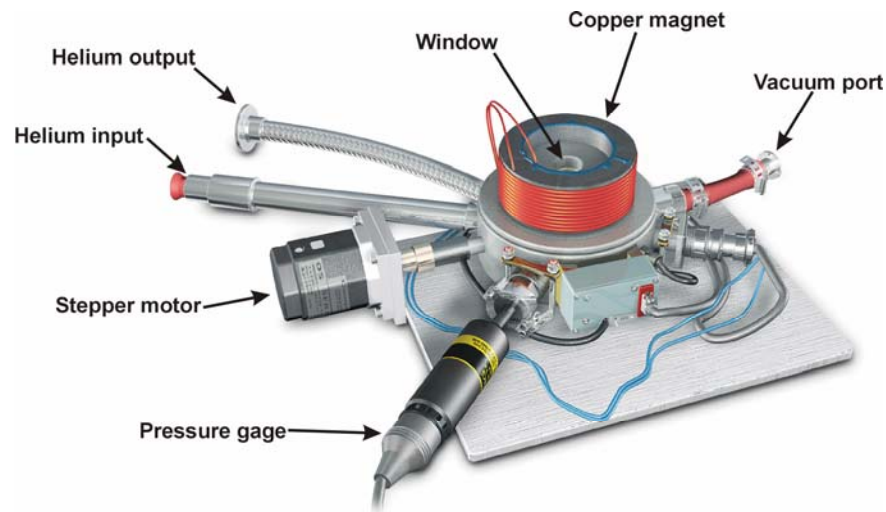
Outside $J_c(\epsilon_{axial})$ plateau

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

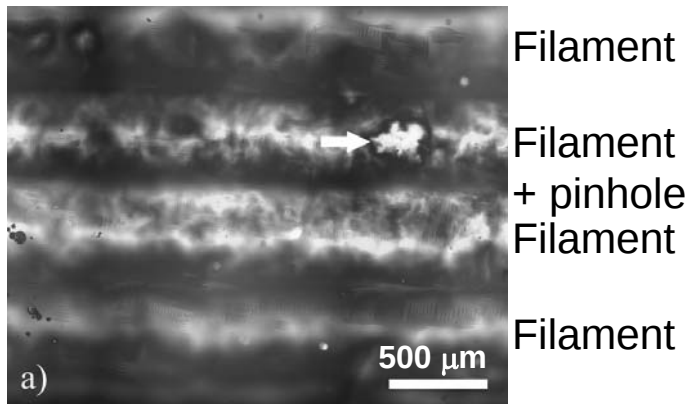


➡ Ten Haken, PhysC, 1996

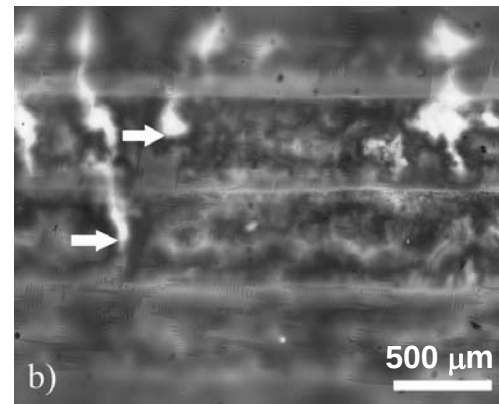
MOI on strained HTS: Cracks



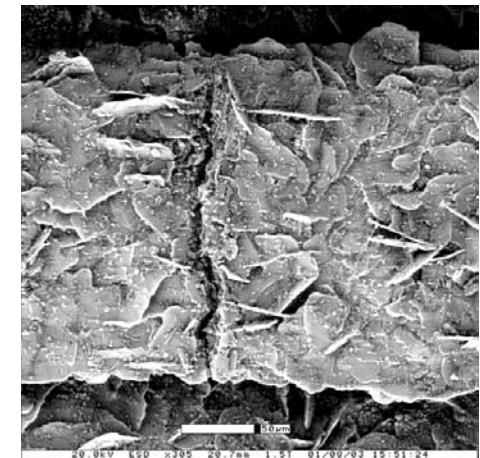
Unstrained Bi-2212



Strained Bi-2212



Strained Bi-2223

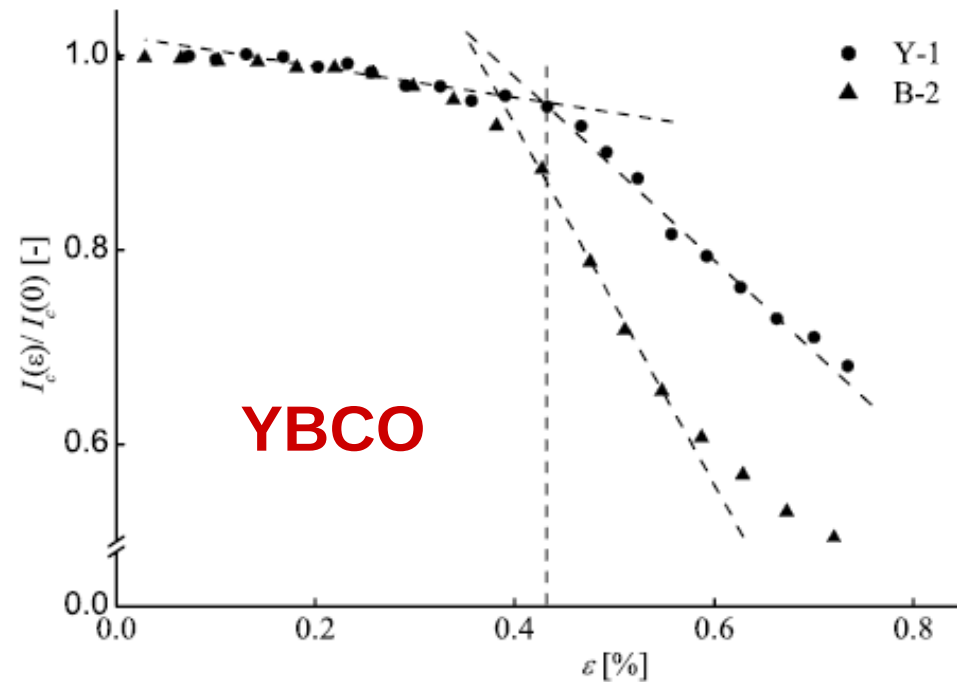
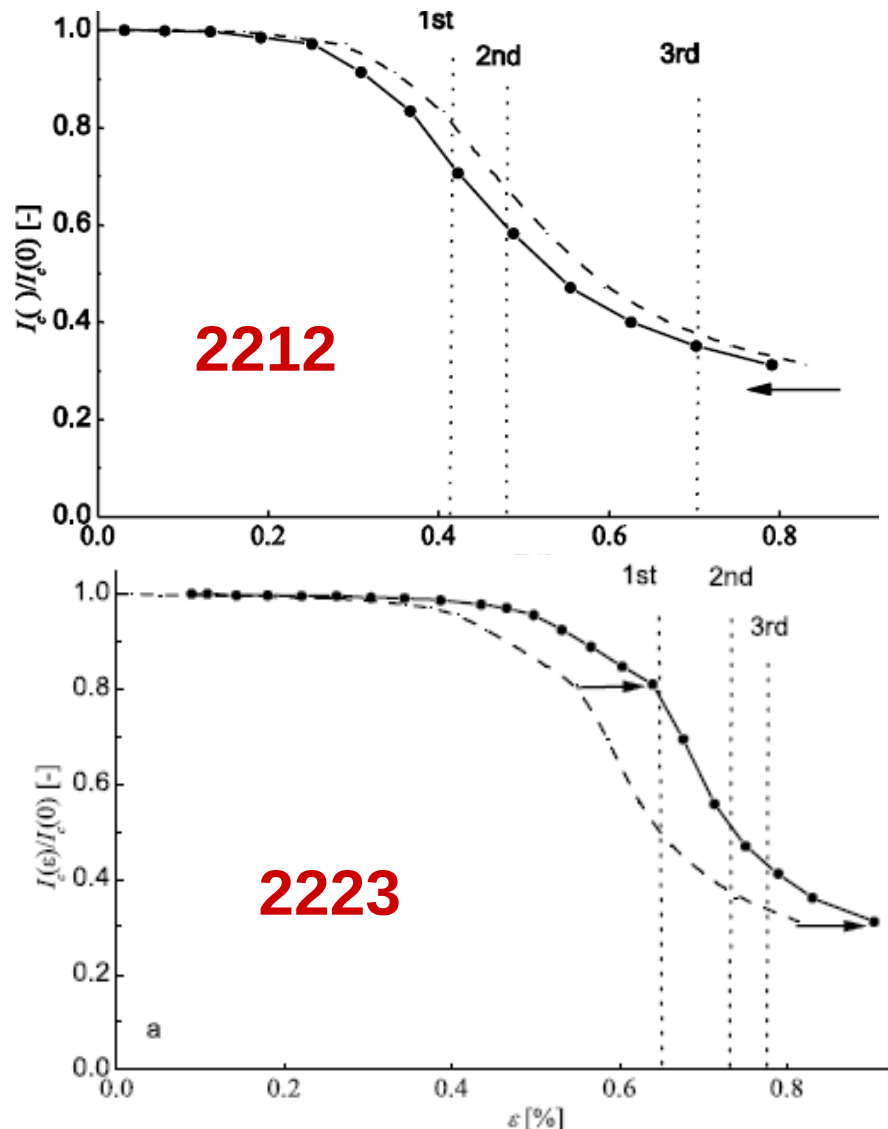


D.C. van der Laan – Ph.D. thesis, U. Twente 2004

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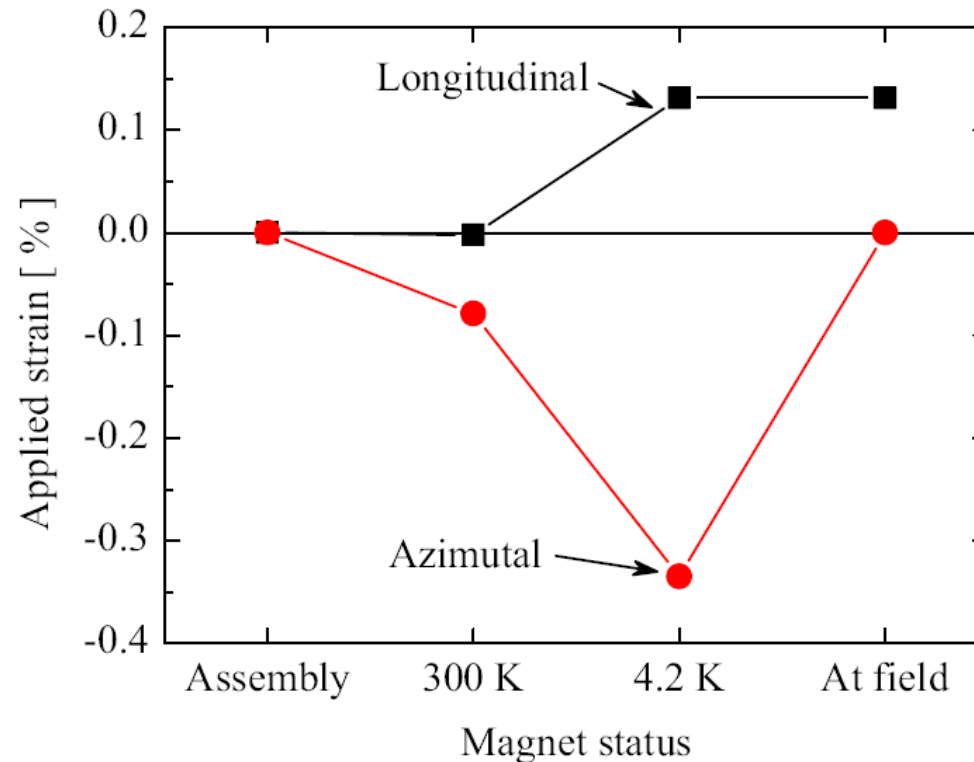
MOI and J_c on strained HTS: Cracks



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

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Magnets made from HTS?



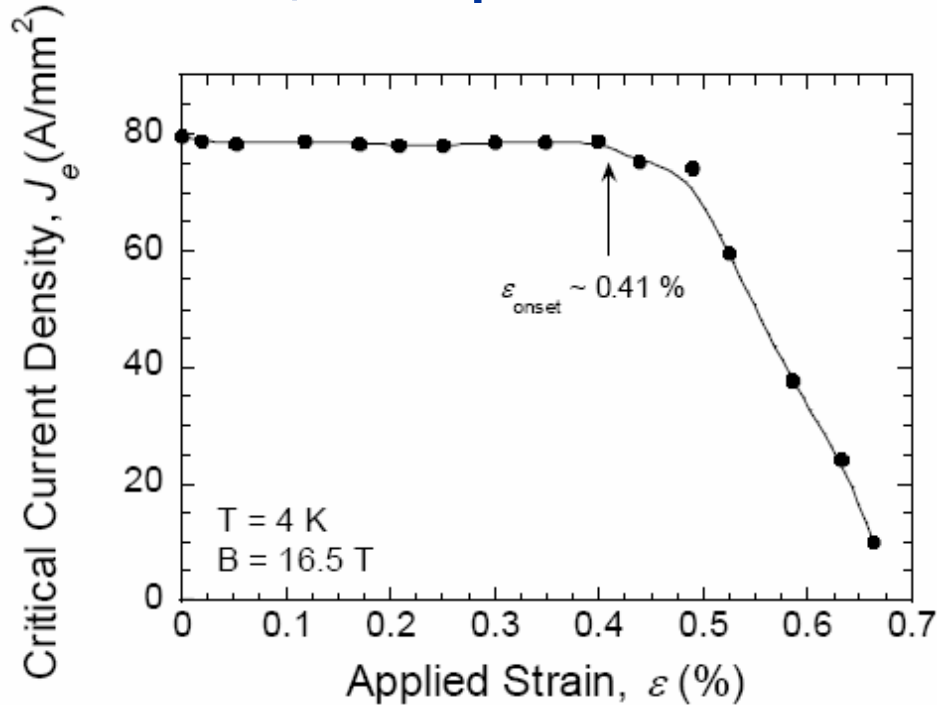
How are we supposed to set new magnetic field records with HTS materials that break into pieces under load?



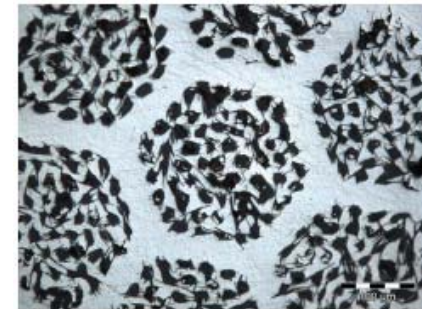
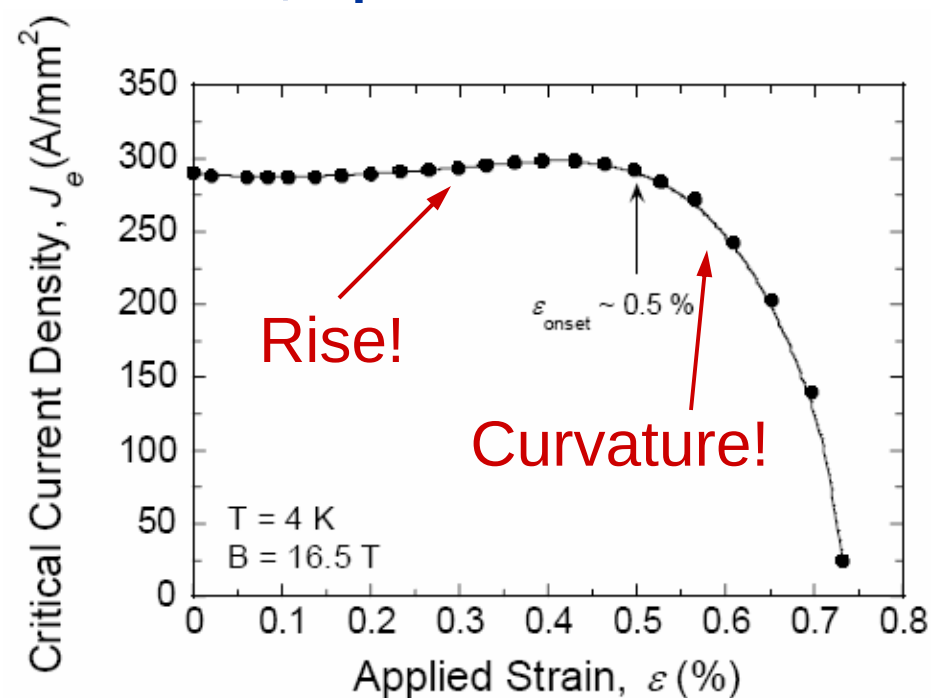
IGC Bi-2212 round wire, 7x61 filaments

Courtesy of Najib Cheggour – NIST

Ø 0.81 mm; Non optimized HT



Ø 0.81 mm; Optimized HT

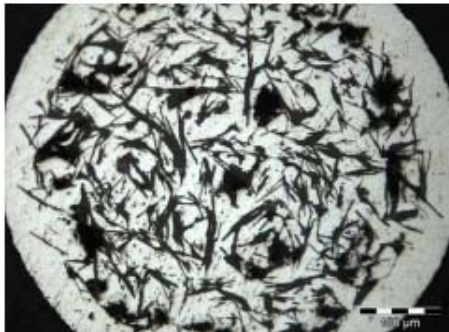
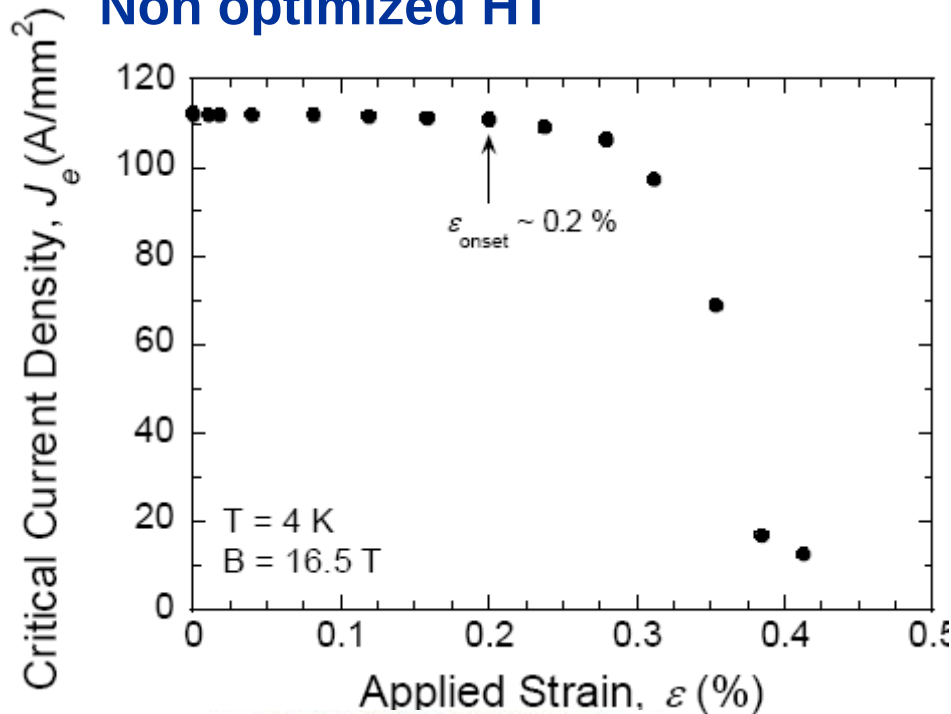




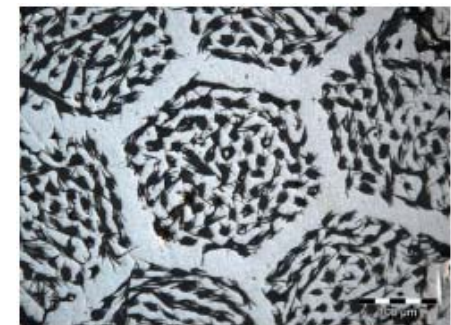
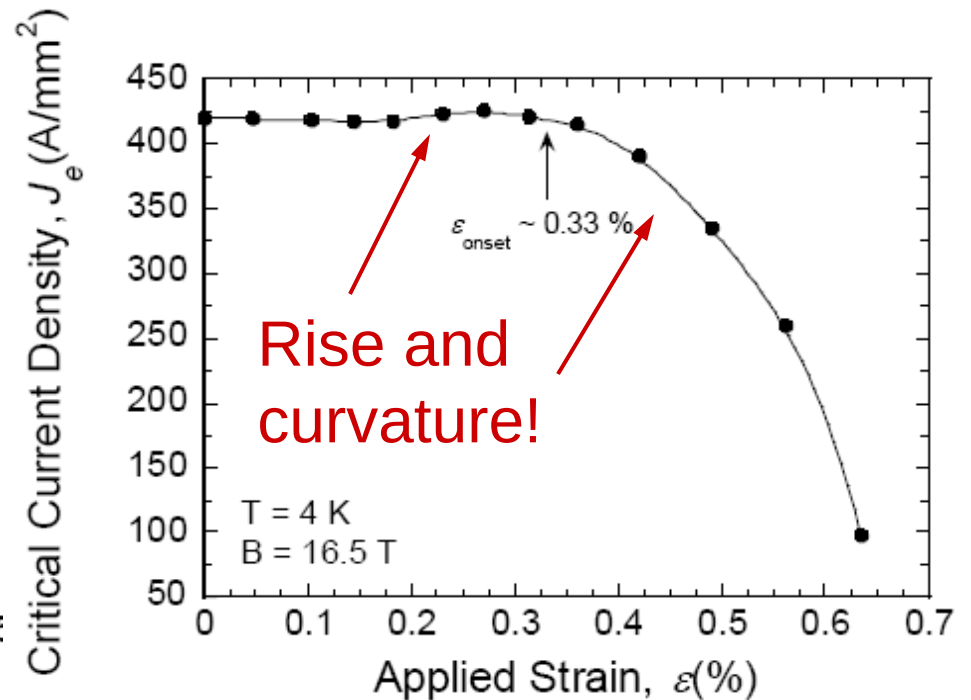
Showa Bi-2212 round wire

Courtesy of Najib Cheggour – NIST

Ø 0.57 mm; 19x37 filaments;
Non optimized HT



Ø 0.82 mm; 7x127 fil; Optimized HT



Modern wires appear much better than 1st generation tapes



MAGNETIC TECHNOLOGY DIVISION
BOULDER, COLORADO





SuperPower MOCVD-IBAD YBCO

Courtesy Danko van der Laan – NIST

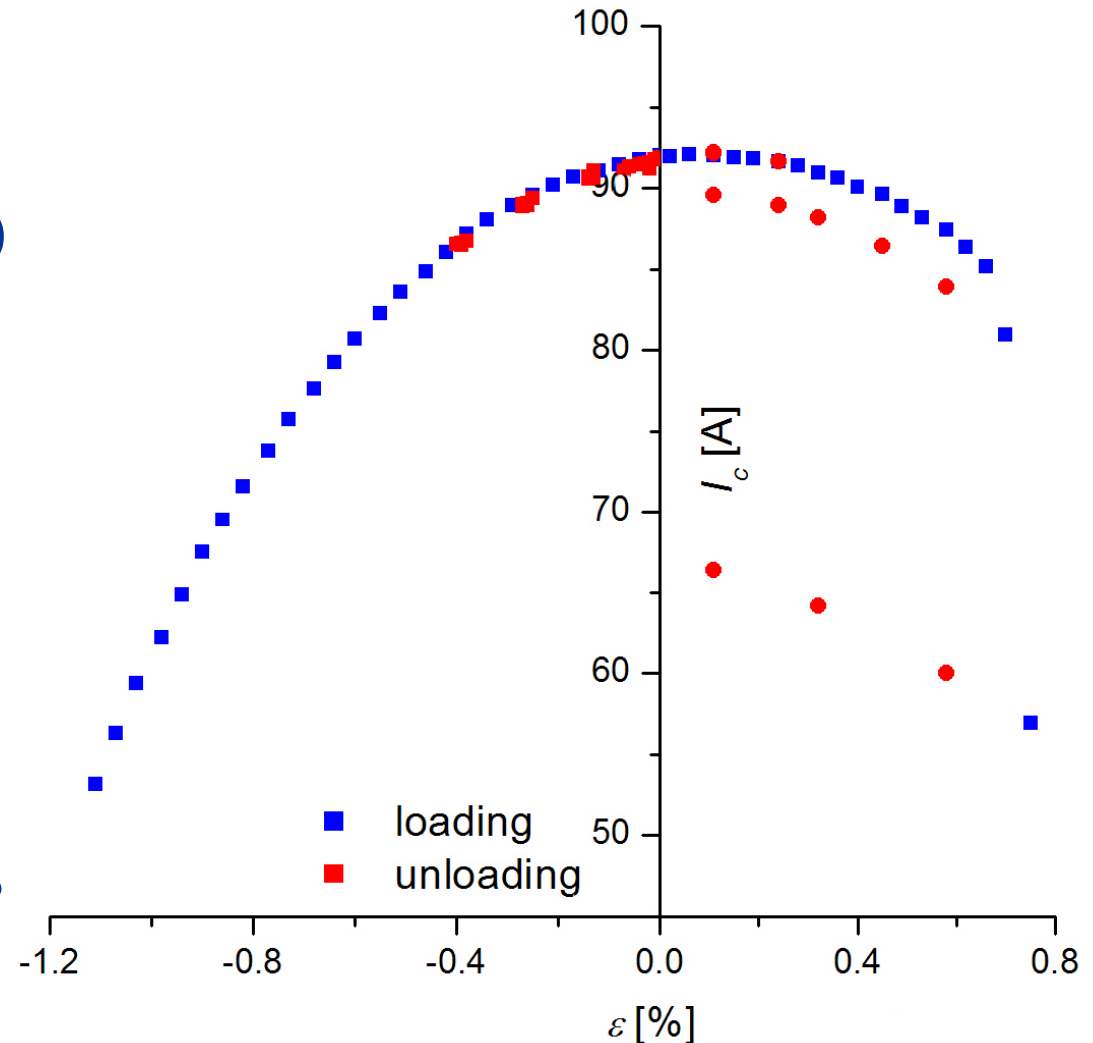
What we need!

- 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...?



MAGNETIC TECHNOLOGY DIVISION
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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 ?

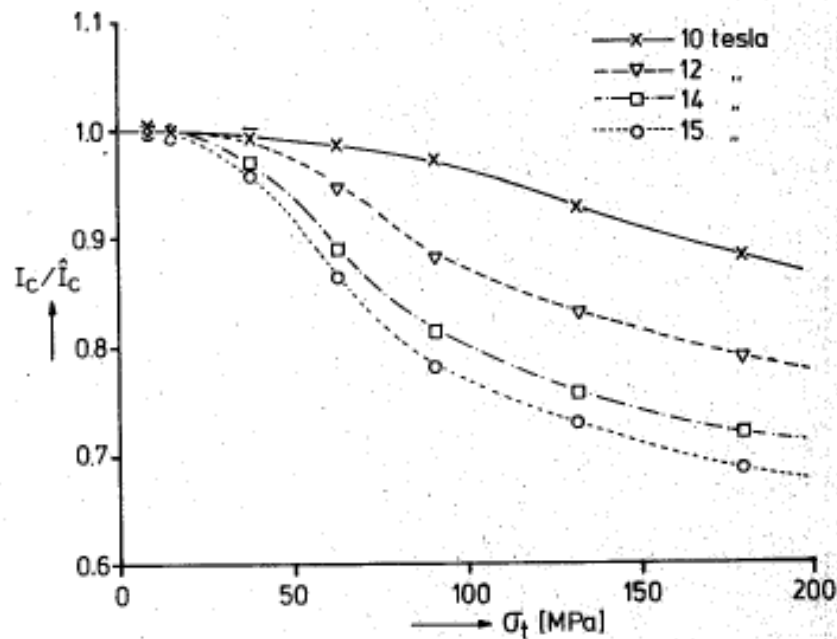


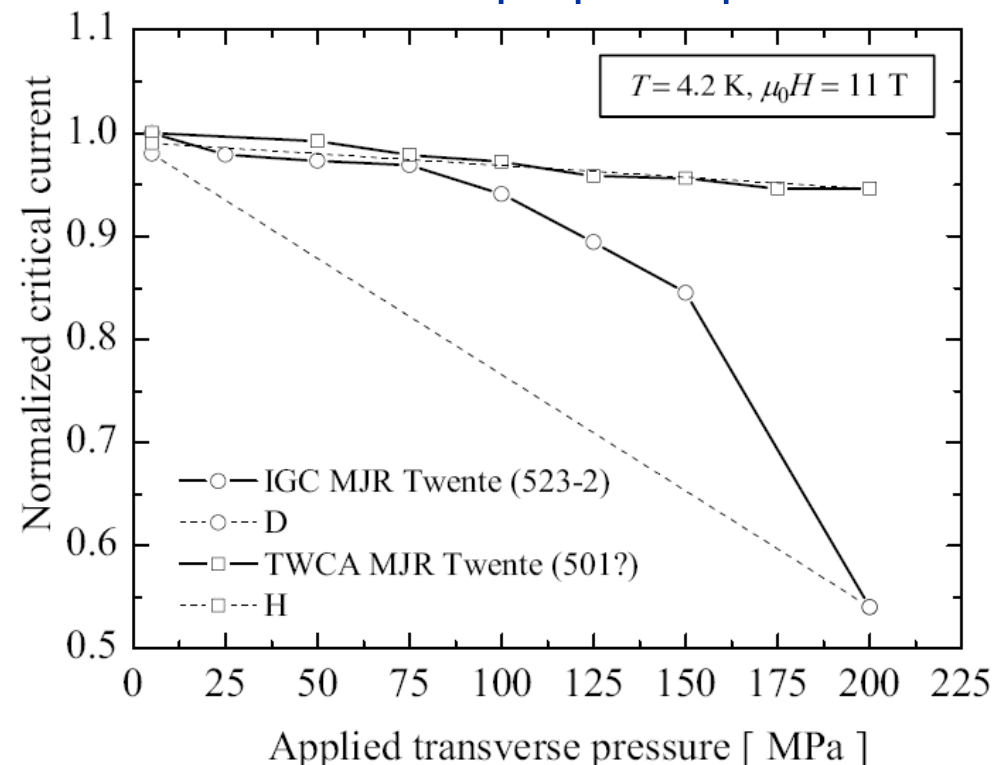
Fig. 4 The relative current density as a function of the transverse pressure at 4.2 K.

- 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!

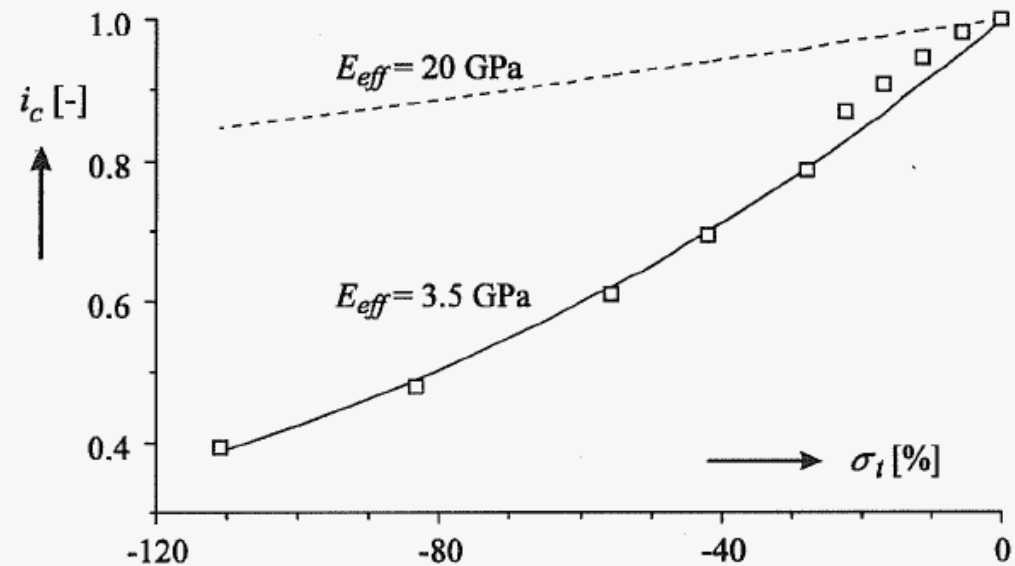
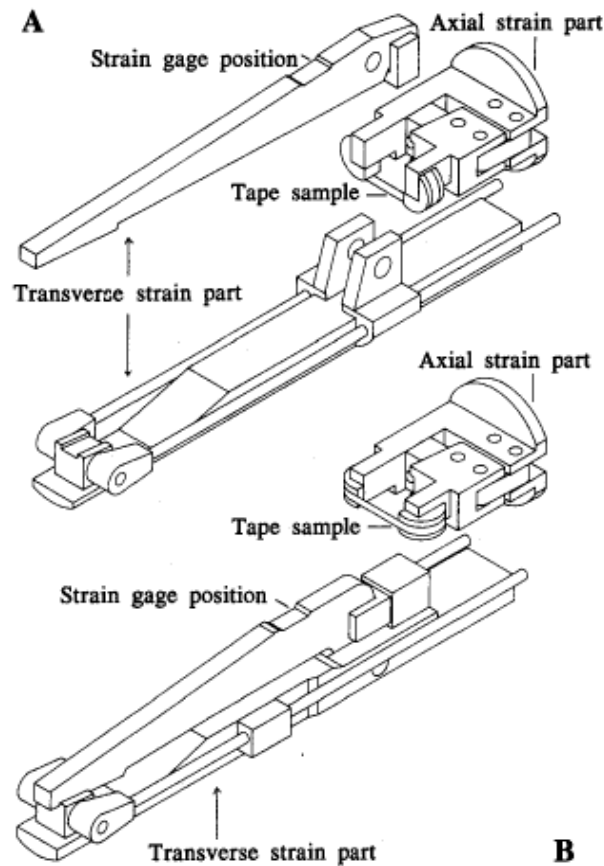


Figure 6.16: The normalised critical-current reduction of the Bi-2212 tape conductor (T-19) subjected to a transversal pressure, measured on the $F_t // B$ transverse press. The measured $I_c(\sigma_t)$ is compared with two lines representing the calculated I_c versus pressure dependence for two different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

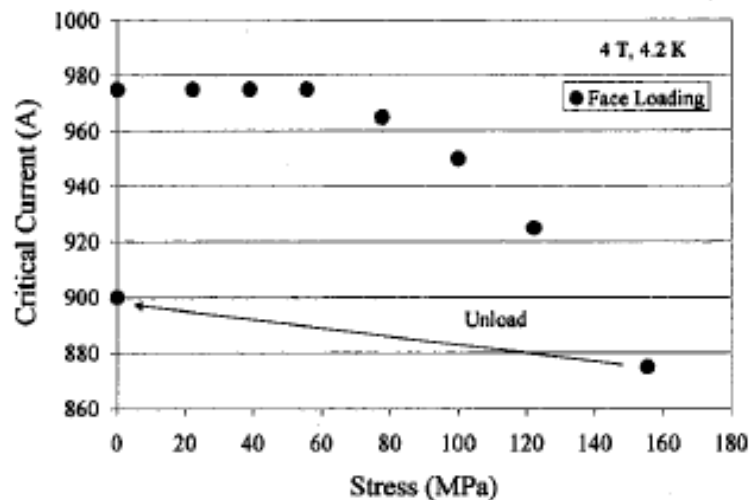


Fig. 3. Variation of the critical current (4 T, 4 K) with stress for a cable loaded on the broad face of the cable.

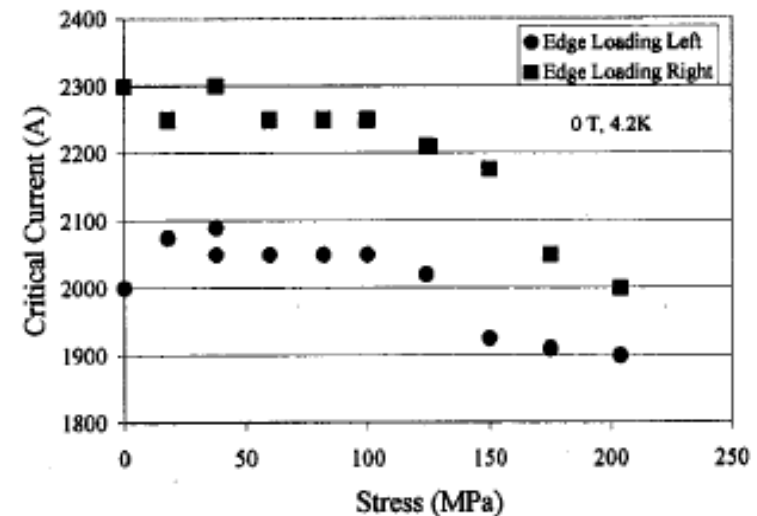


Fig. 4. Variation of the critical current (self-field, 4 K) with stress for a cable loaded on the edge of the cable.

➔ Dietderich, TAS, 2001