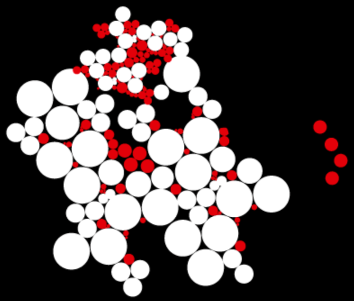
UNIVERSITEIT TWENTE.



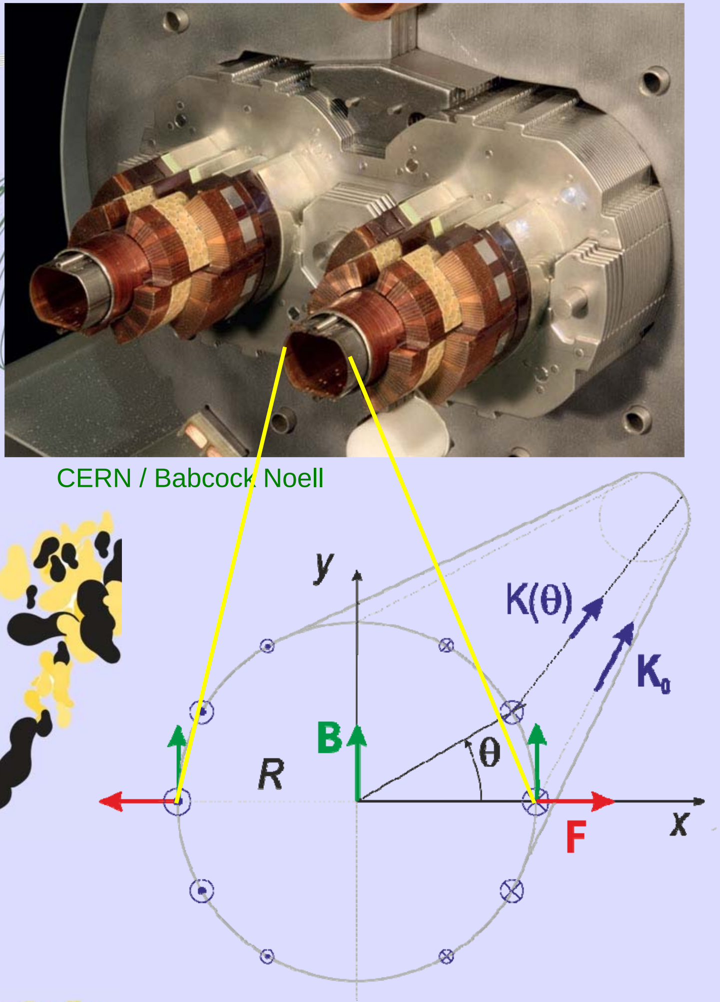
Transverse pressure sensitivity of state-of-the-art Nb_3Sn Rutherford cables

P. Gao, S. Wessel, M. Dhallé

CEA/CERN Workshop on Nb_3Sn technology for accelerator magnets
Paris, 11-12 October 2018

Content:

1. Introduction: *magnet designs & stress estimates*


CERN / Babcock Noell

High currents & - fields combine to high Lorentz forces !

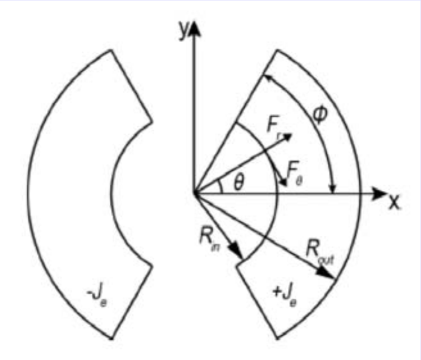
Let's make a (very rough) estimate for an 'idealized' cos-theta dipole:

$$\mathbf{K}(\theta) = -K_0 \cos(\theta)\,\hat{\mathbf{z}} \quad [\mathrm{A/m}] \qquad \mathbf{B} = \frac{\mu_0 K_0}{2}\,\hat{\mathbf{y}} \quad [\mathrm{T}]$$

$$\mathrm{d}\mathbf{F}(\theta) = \frac{\mu_0 K_0^2}{2} \cos(\theta)\, R\, \mathrm{d}\theta\, \hat{\mathbf{x}} \quad [\mathrm{N/m}] \qquad \sigma_{a,p} = \frac{2}{w} \int_0^{\pi/2} \mathrm{d}F_a = \frac{\mu_0 K_0^2}{2} \frac{R}{w} \quad [\mathrm{Pa}]$$

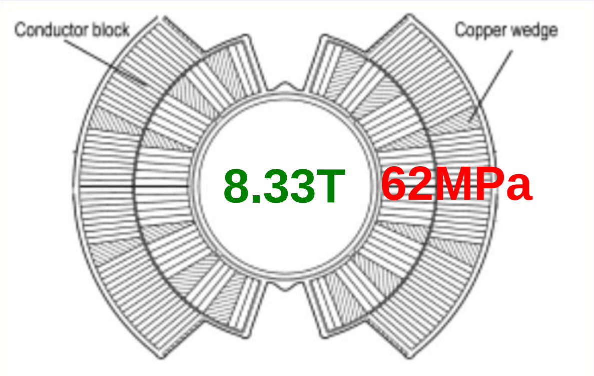
$$B \approx 10\,\mathrm{T} \quad \rightarrow \quad K_0 \approx 2\,10^7\ \mathrm{A/m} \quad \rightarrow \quad \sigma \approx 250\,\mathrm{MPa}$$

2D current model instead of 1D:



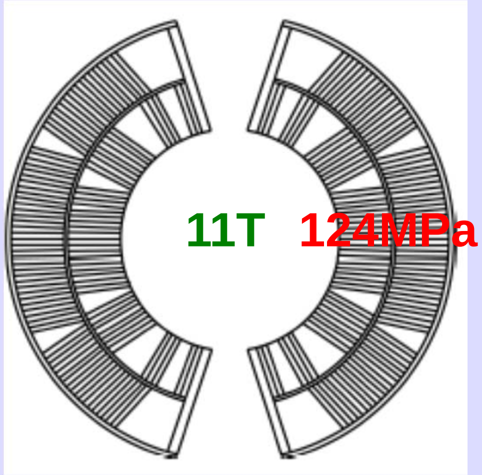
Rossi 2012

1. Introduction: magnet designs & stress estimates

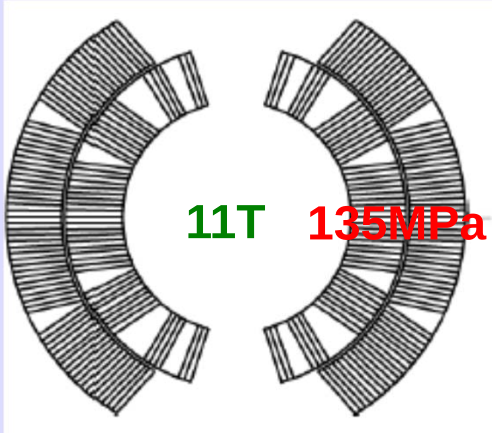


8.33T **62MPa**

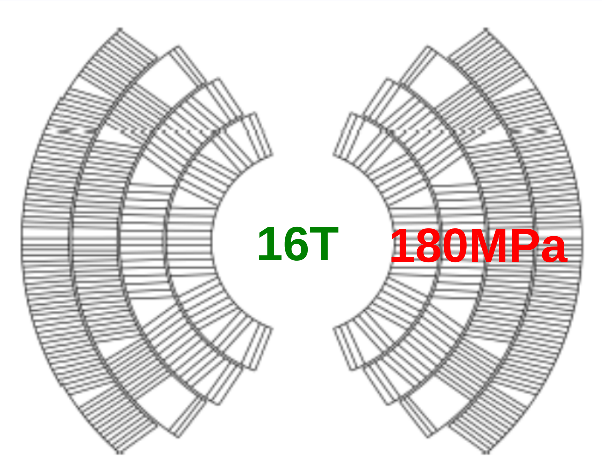
Ferracin 2002 (CERN)


11T **124MPa**

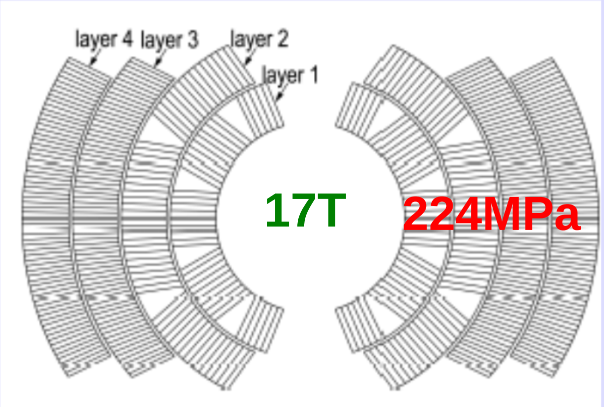
Bottura 2013 (CERN)


11T **135MPa**

Novitski 2016 (FNAL)


16T **180MPa**

Marinozzi 2018 (INFN)

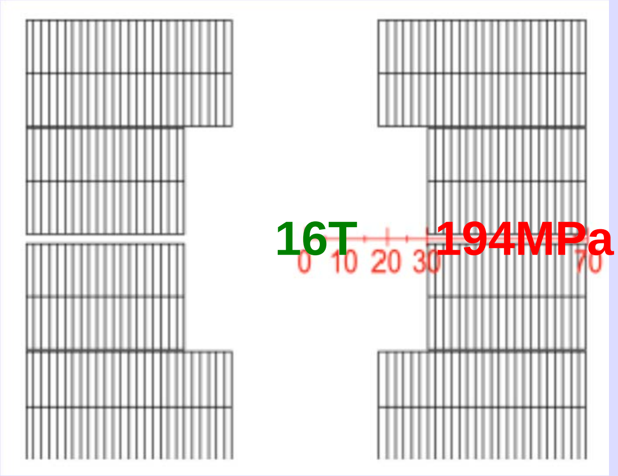


17T **224MPa**

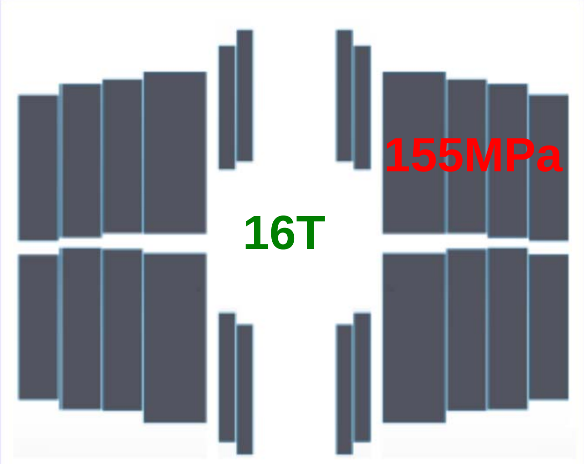
Kashikhin 2015 (FNAL)

Cos-theta designs

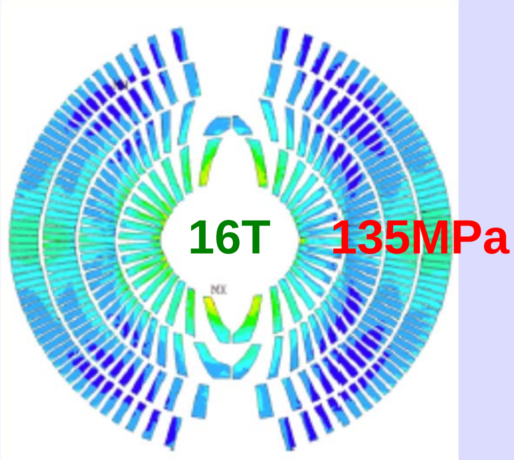
1. Introduction: *magnet designs & stress estimates*



Lorin 2018 (CEA)



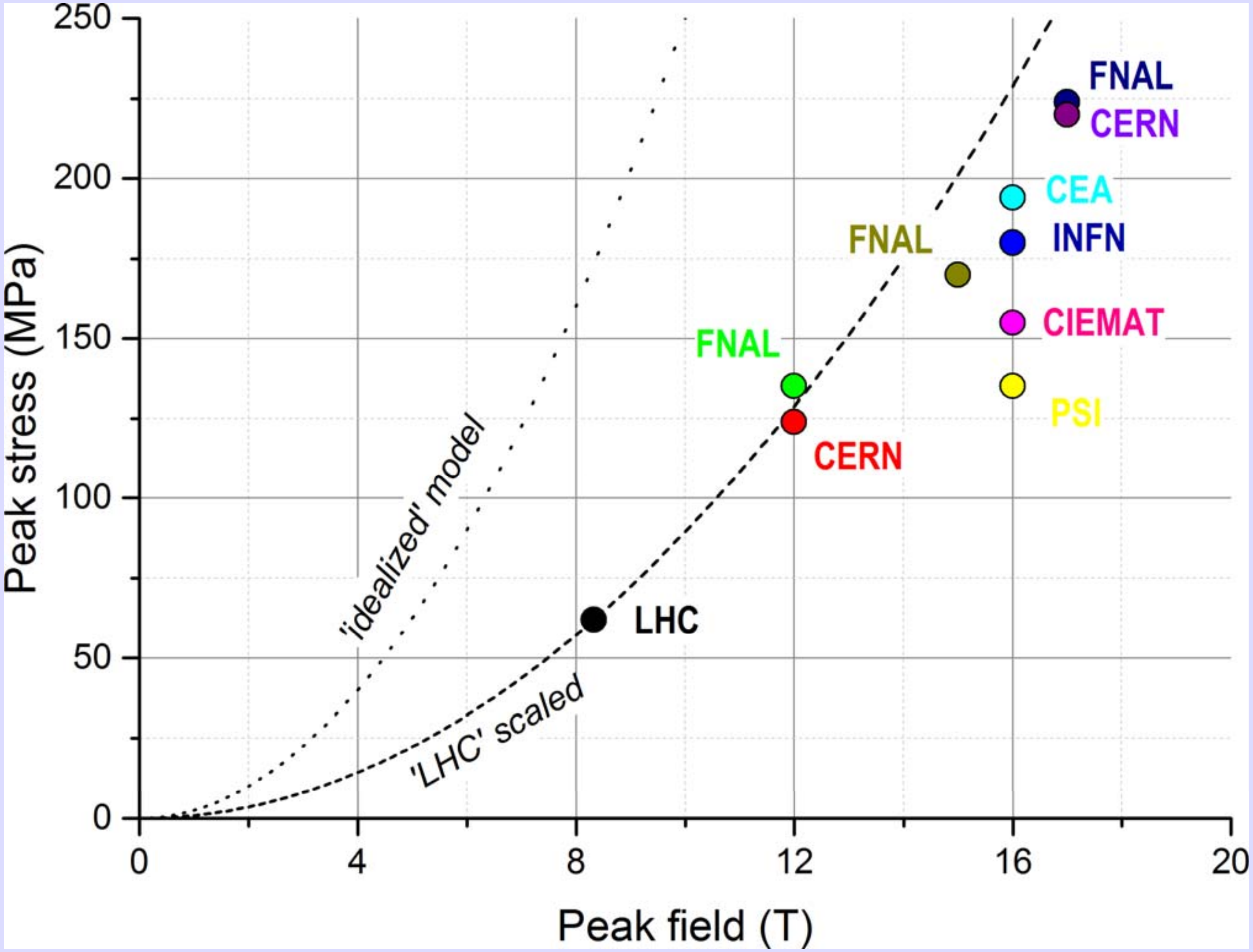
Toral 2018 (CIEMAT)



Auchmann 2018 (PSI)

Alternative designs

1. Introduction: magnet designs & stress estimates



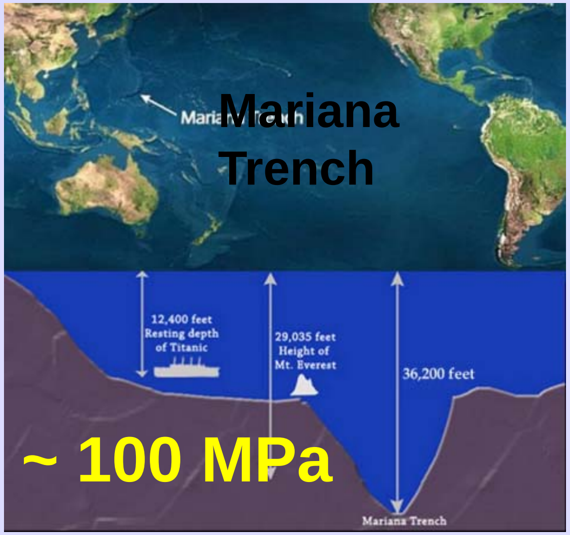
B = 16T ⇒ **σ ~ 150 – 200 MPa**

1. Introduction: *magnet designs & stress estimates*


~ 0.1 MPa


~ 1 MPa


~ 10 MPa


Mariana Trench

~ 100 MPa

1. Introduction: *strain response of Nb_3Sn strands*

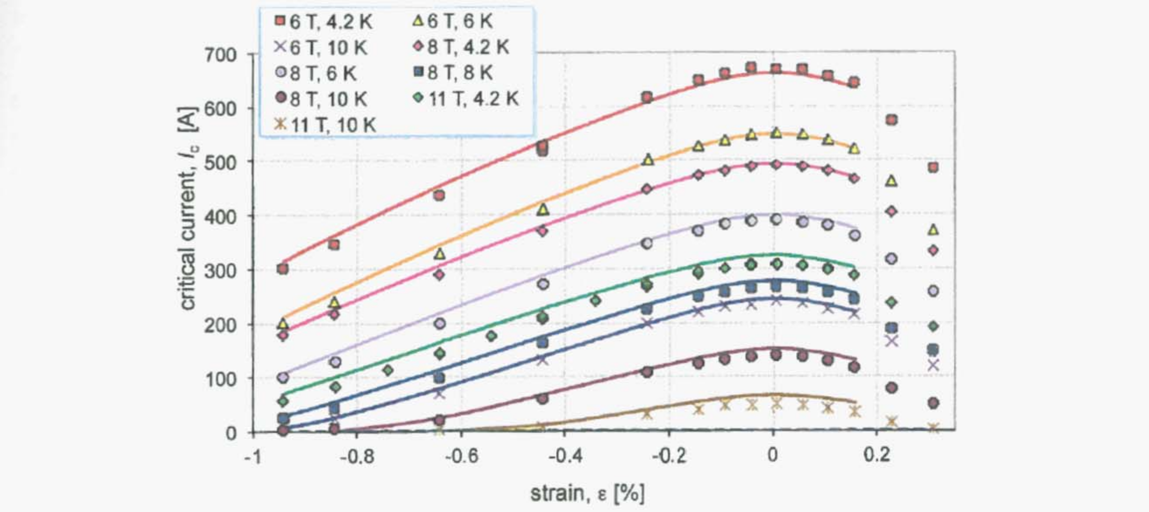


Figure 2.23. Critical current as a function of intrinsic strain, temperature and magnetic field. The points are measured on the PACMAN and the lines are calculated with Equation 1.5.

Nijhuis, 2016

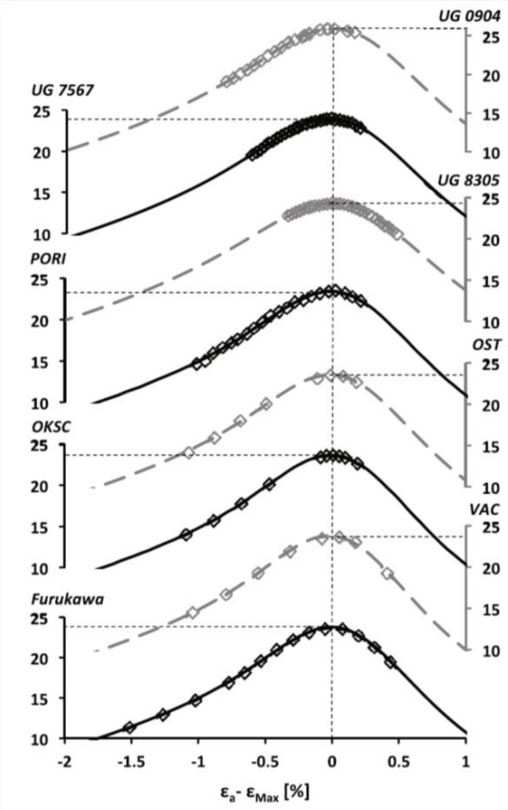


Figure 4. Comparison between the different datasets analyzed. Th ordinate axis, which represents the B_{c2} in T, have been shifted from one dataset and placed alternately on the left and on the right. The marks show the B_{c2} data at 4.2 K while the line shows the fits using the new two parameter exponential scaling law.

Bordini, 2013

It's well-established that all Nb_3Sn conductors exhibit a significant *intrinsic* strain-dependence in their critical current and in their 2nd critical field.

1. Introduction: *strain response of Nb_3Sn*

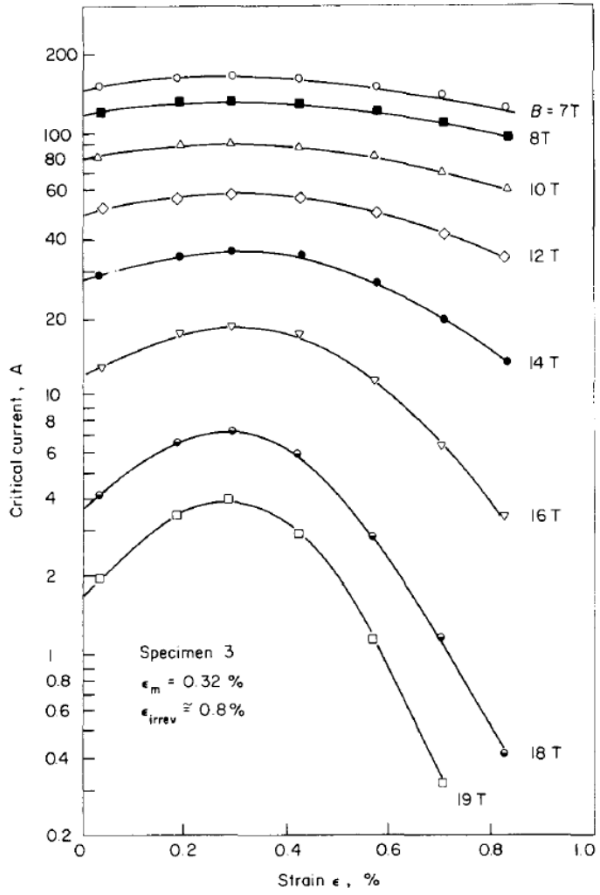


Fig. 2 Critical current I_c of specimen 3 as a function of uniaxial strain for magnetic fields ranging from 7 to 19 T. The strain ϵ_m where I_c is a maximum is 0.32% for this specimen. The strain ϵ_{irrev}, where the curve becomes irreversible upon unloading, is about 0.8% for this specimen

Ekin, 1980

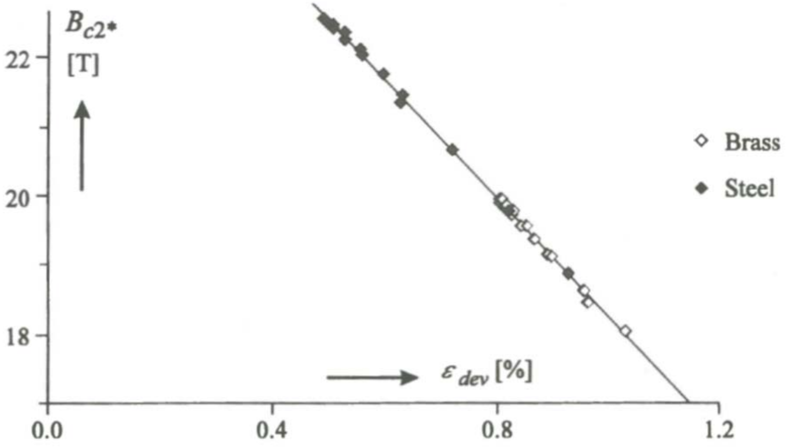
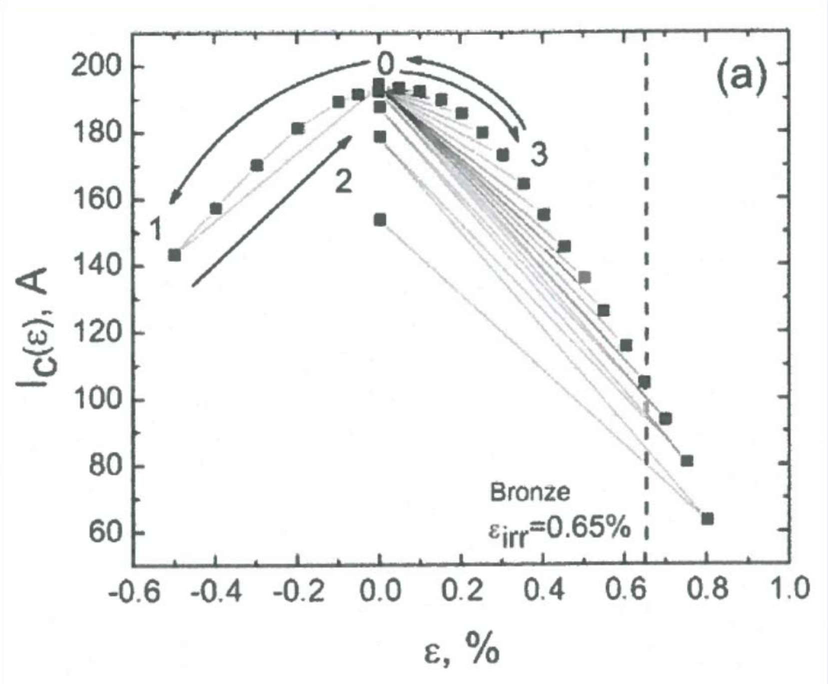


Figure 5.13: The extrapolated B_{c2*} as a function of the deviatoric strain calculated with the elastic model for the tape conductor. The indicated points are measured on two different bending springs U-steel and U-20 K (= brass) respectively.

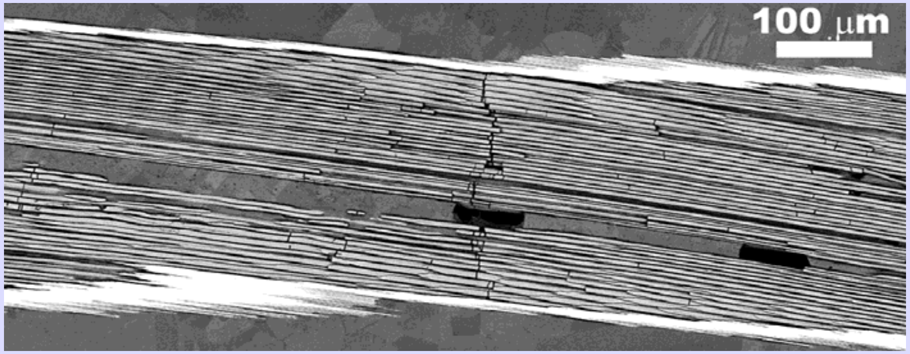
Ten Hake, 1994

The phenomenological understanding centers on strain scaling of the critical surface, and on the recognition of the *deviatoric strain* as the driving influence.

1. Introduction: *strain response of Nb_3Sn*



Nijhuis, 2016



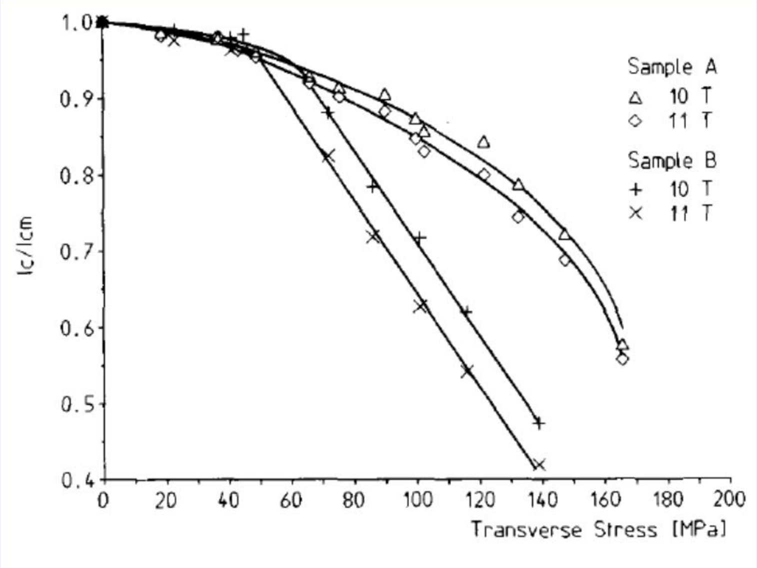
Jewell, 2008

The good news is that this *intrinsic strain sensitivity* is reversible and reproducible, meaning it can be ‘designed for’.

The bad news is that above a *reversible strain limit* the superconducting filaments start to crack and the critical current is not recovered upon strain release: the magnet degrades.

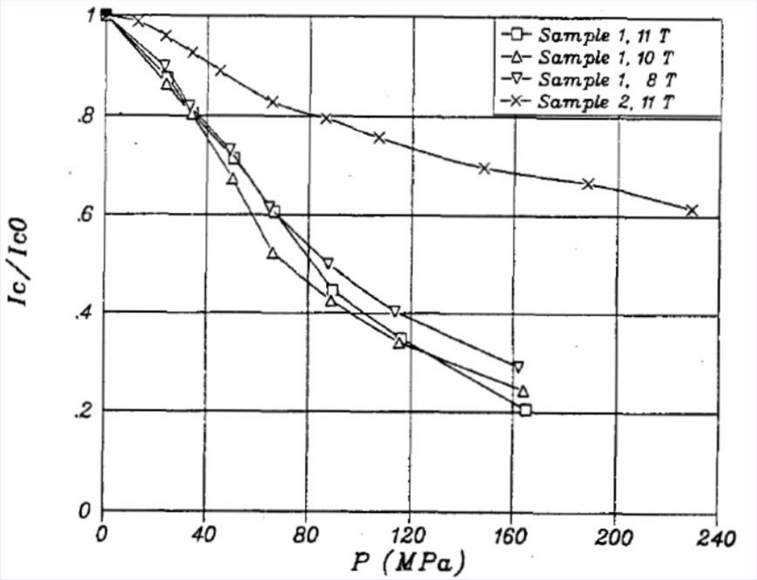
1. Introduction: *measuring the stress response of cables*

First cable measurements



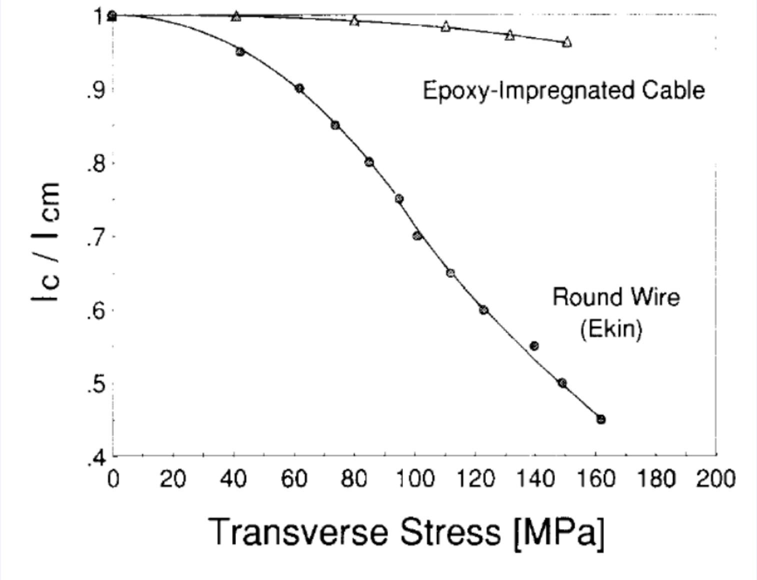
Jakob, 1989 (PSI, RT loading, short section)

- Short-sample
- Either RT- or in-situ loading
- Mitigating effect of *impregnation*



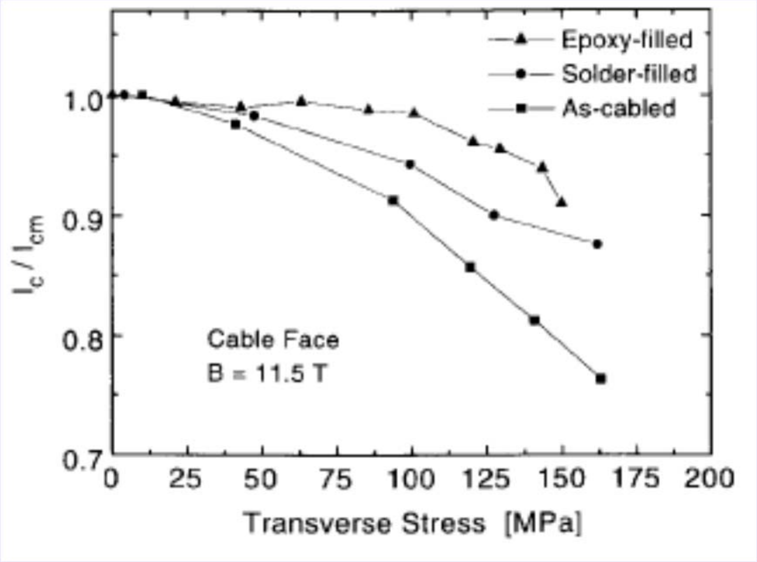
Boschman, 1991 (Twente, in-situ loading, short section, partial & full impregnation)

1. Introduction: *measuring the stress response of cables*



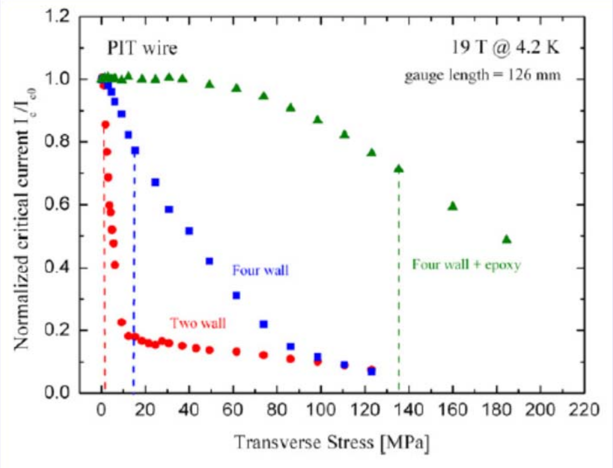
Jakob, 1991 (PSI, impregnated)

Further evidence of impregnation effect

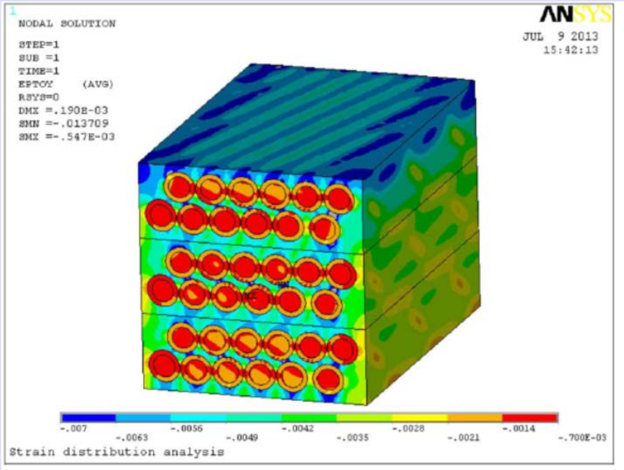


Pasztor, 1994 (PSI, different fillers)

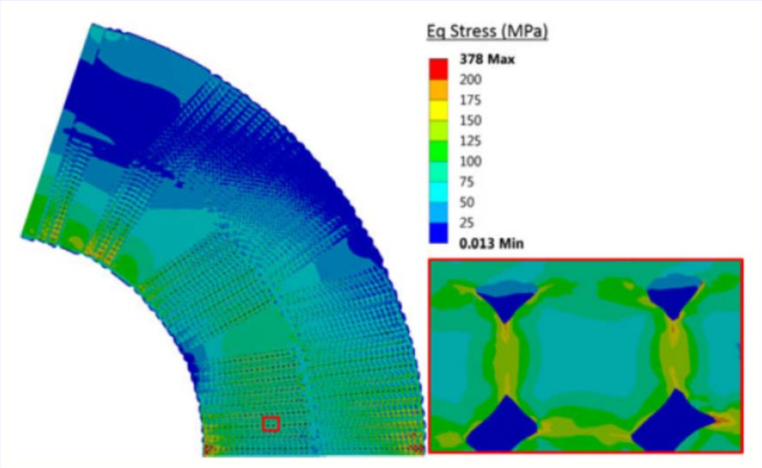
1. Introduction: measuring the stress response of cables



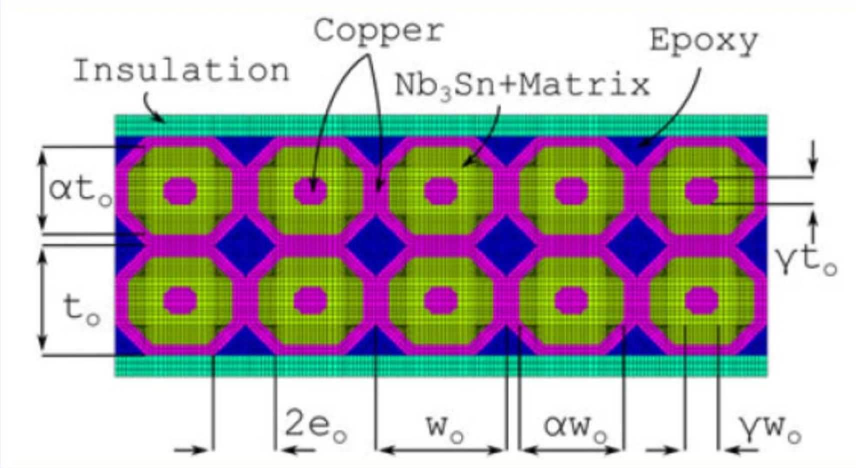
Mondonico 2012



Xu 2014

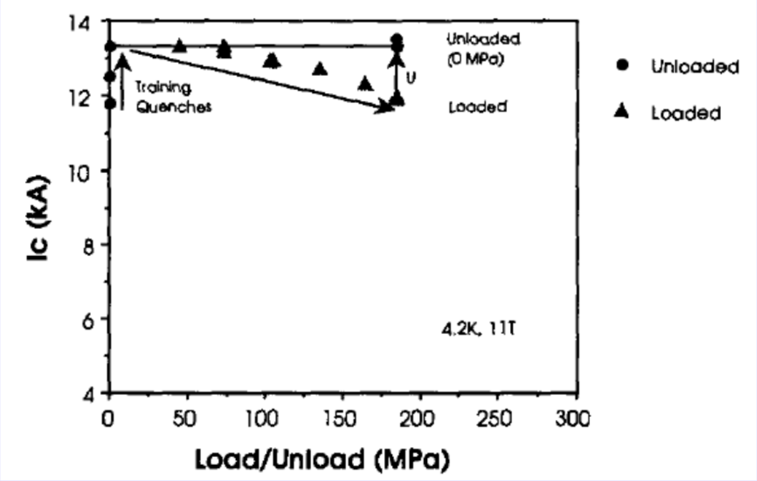


Daly 2018



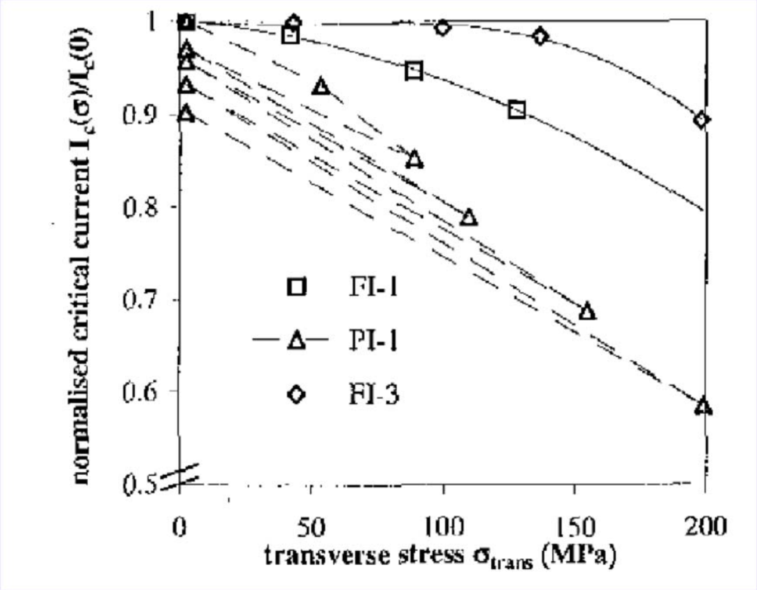
Valone 2018

1. Introduction: *measuring the stress response of cables*



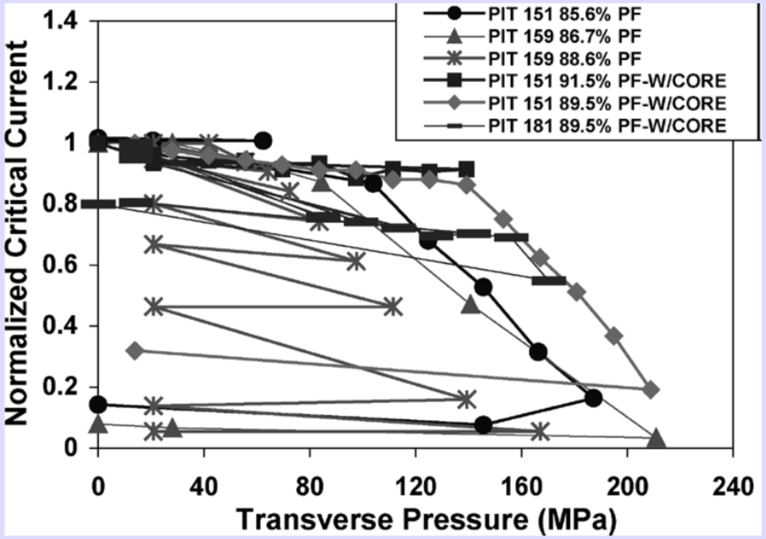
Dietderich, 1999 (LBNL, short sample, in-situ loading)

First explorations of
onset irreversible degradation …



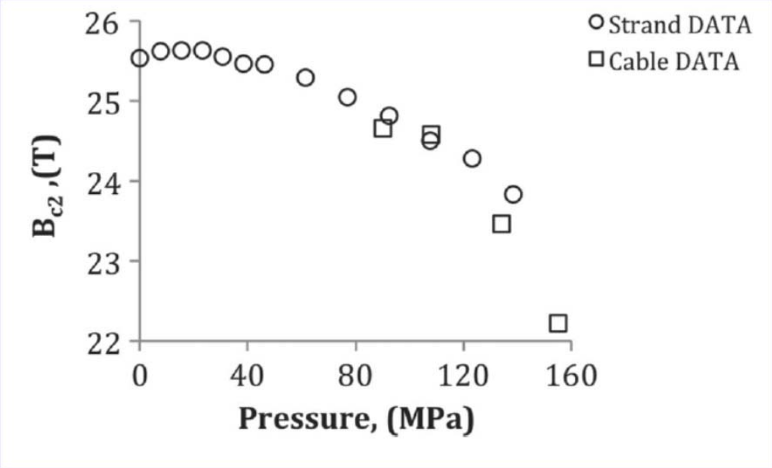
Den Ouden, 2000 (Twente)

1. Introduction: measuring the stress response of cables



Barzi, 2004 (FNAL, short sample, in-situ loading)

… and with reversible B_{c2} response



Bordini, 2014 (CERN, long sample, RT loading)

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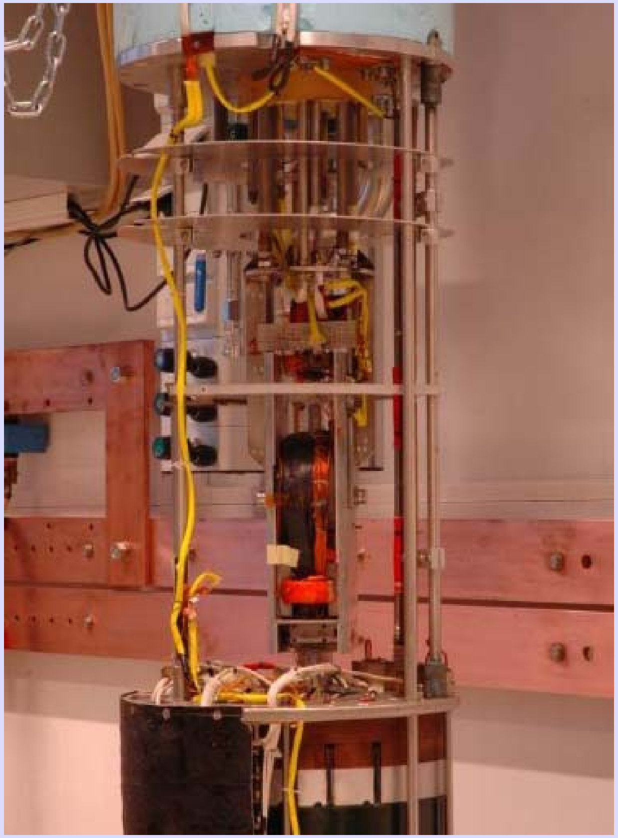
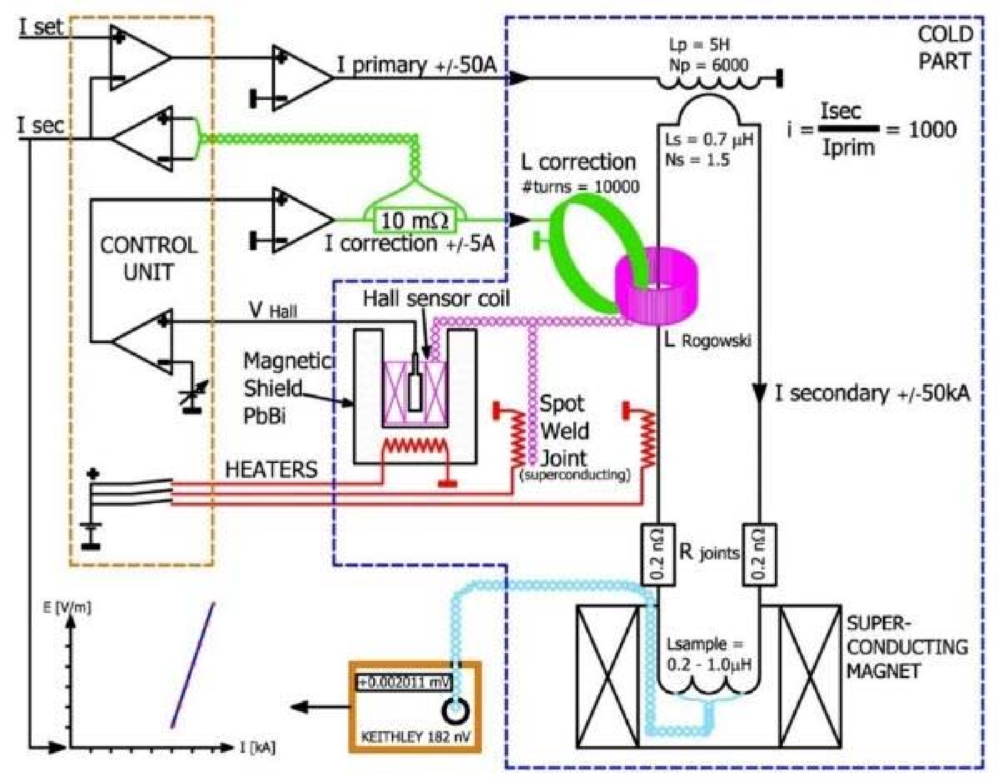
    - Measuring the transverse stress response of cables
2. Experimental
    - Set-up @ UTwente
    - Samples
3. Results
    - DS cables
    - SMC cables
4. Conclusions

2. Experimental: the set-up @ UTwente

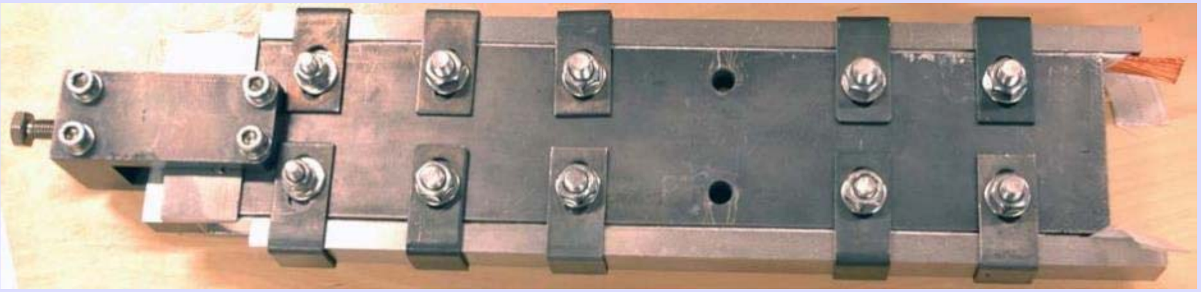




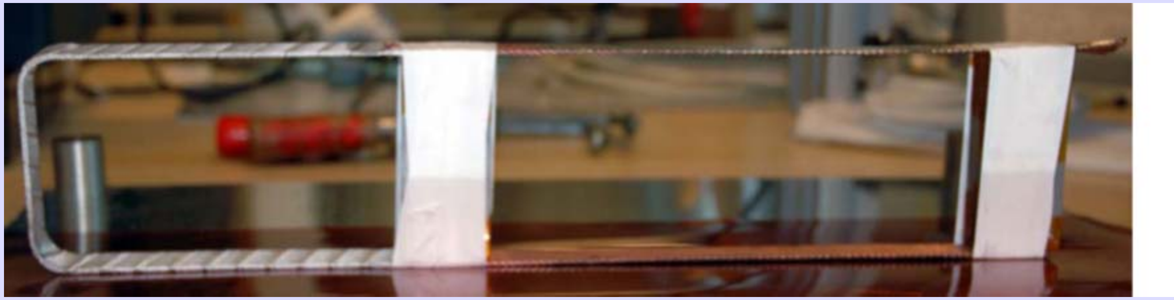
Van de Klundert, 1981

50 kA superconducting transformer in 11T solenoid

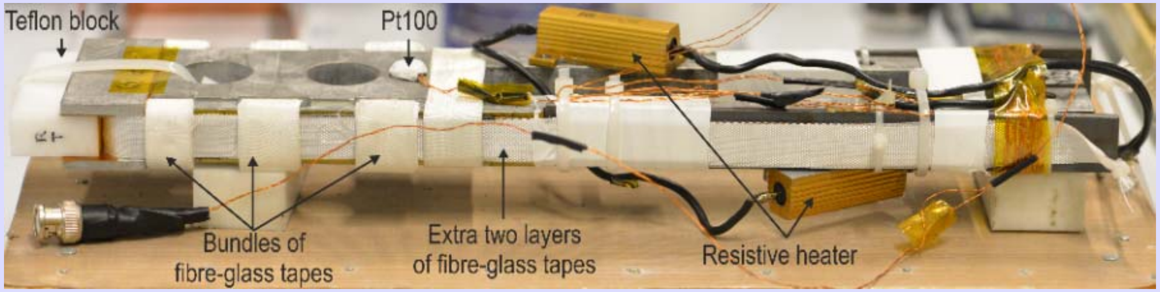
2. *Experimental:* *the set-up @ UTwente*



Heat treatment …



… transfer …

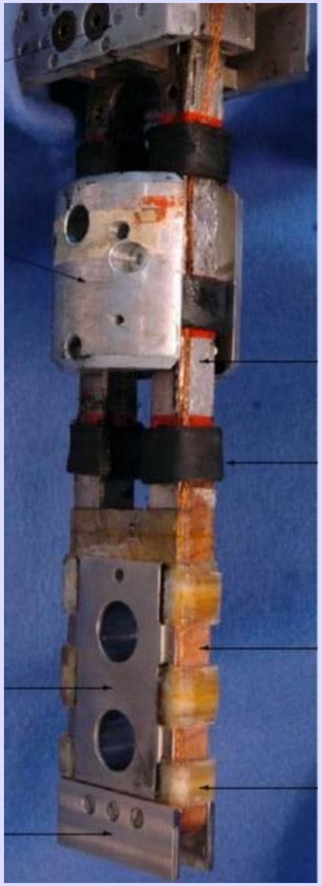


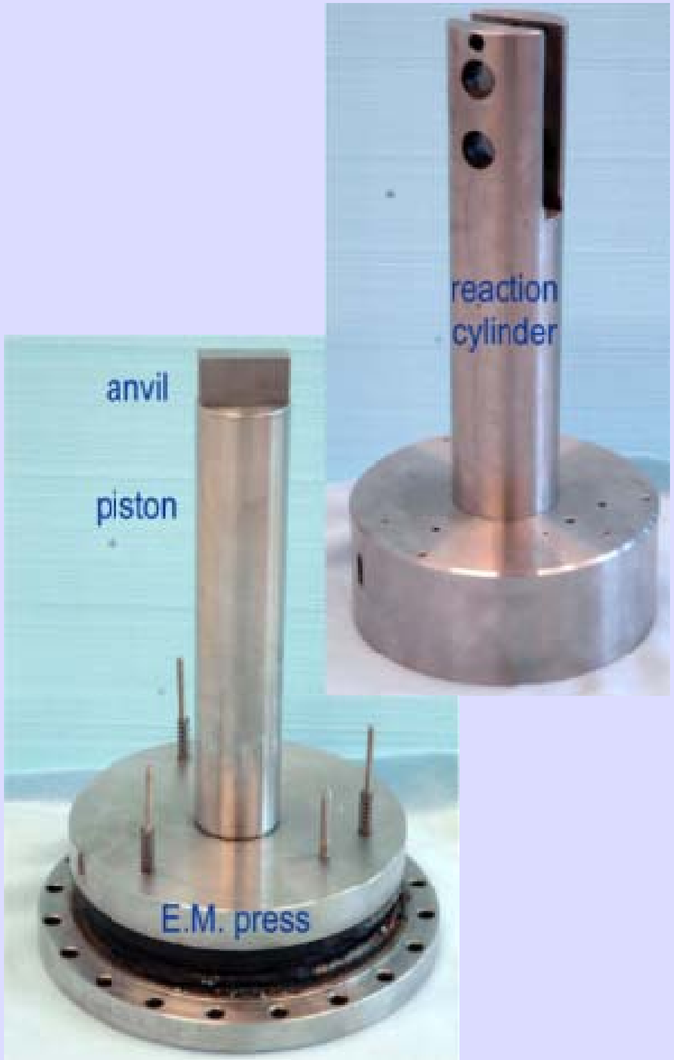
… impregnation

‘hairpin’- type samples

2. Experimental: *the set-up @ UTwente*

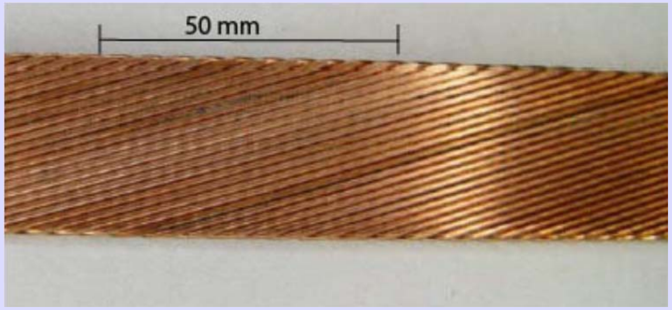
- 240 kN E.M.
  cryo-press
- custom-cut
  pushing anvil
  (w. strain gauges)
- Displacement
  read-out





2. Experimental: *State-of-the art cable samples*

Sample	cross section (mm^2)	strand type	# of strands	keystone (°)	transposition length (mm)
DS-RRP	14.7 × 1.25	RRP-108/127	40	0.75	100
DS-PIT-1	14.7 × 1.25	PIT-114	40	0.71	100
DS-PIT-2	14.7 × 1.25	PIT-114	40	0.71	100
SMC-RRP-1	10 × 1.8	RRP-132/169	18	0	63
SMC-RRP-2	10 × 1.8	RRP-132/169	18	0	63
SMC-PIT-1	10 × 1.8	PIT-192	18	0	63
SMC-PIT-2	10 × 1.8	PIT-192	18	0	63



Strand	diameter (mm)	Cu / non-Cu ratio
RRP-108/127	0.7	1.19
PIT-114	0.7	1.25
RRP-132/169	1	1.22
PIT-192	1	1.22

Impregnation

- DS : MY740/HY906/DY062 (100/90/02)
- SMC : CTD101-K (A/B/C = 100/90/1.5)

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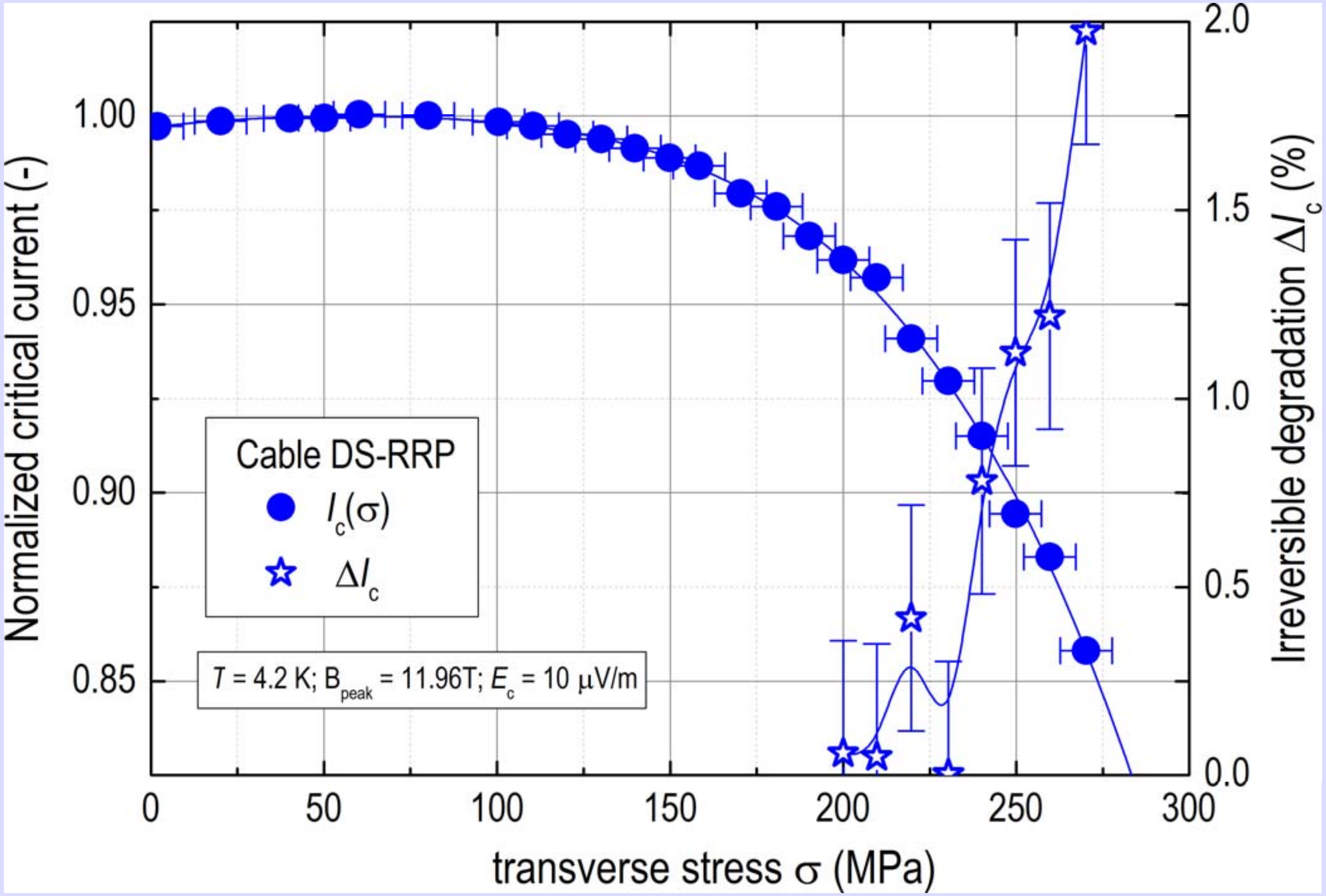
3. Results

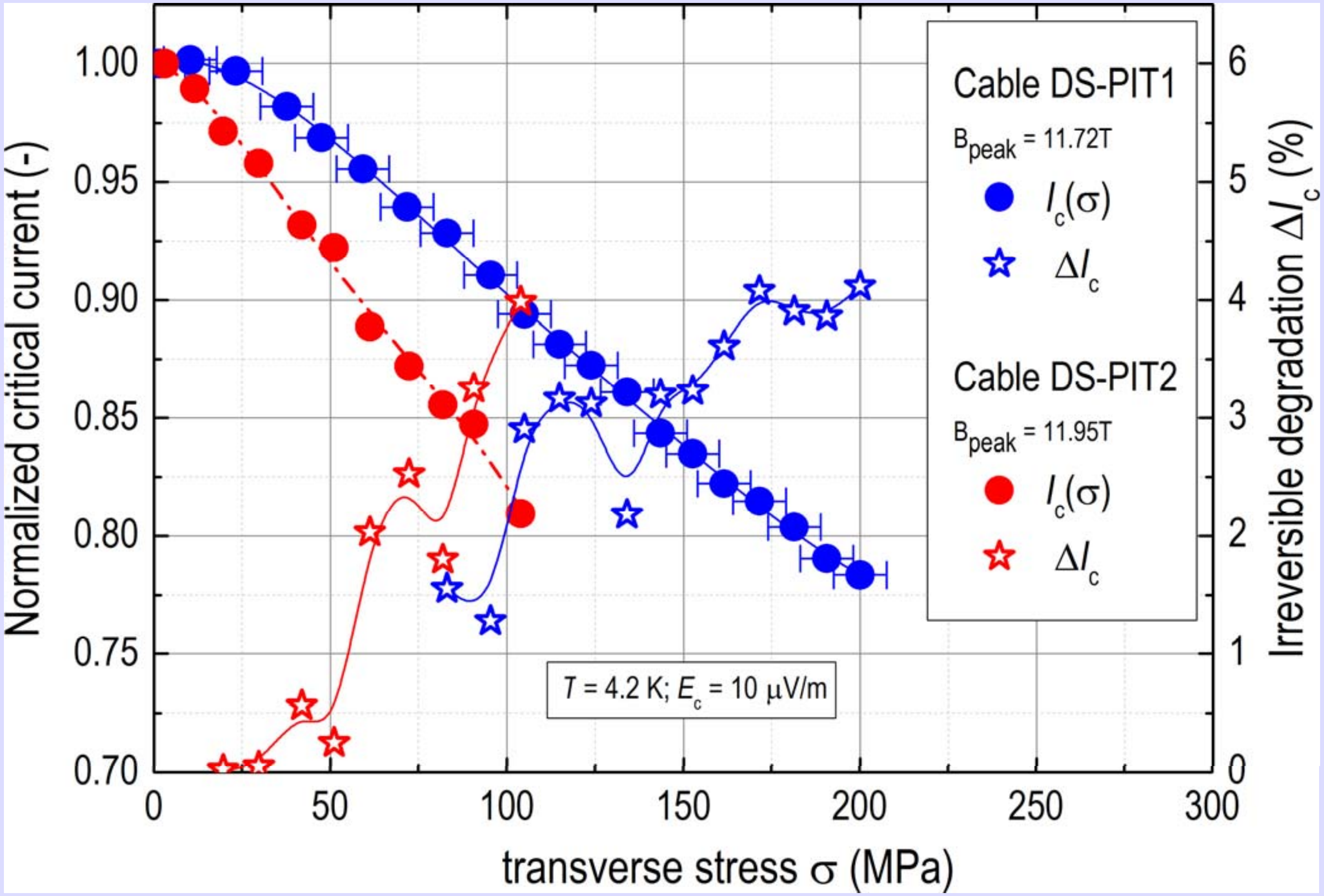
DS RRP cable



$\sigma_{-10\%} \approx$ 240 MPa ; $\sigma_{-1\%,\ irr.} \approx$ 250 MPa

3. Results

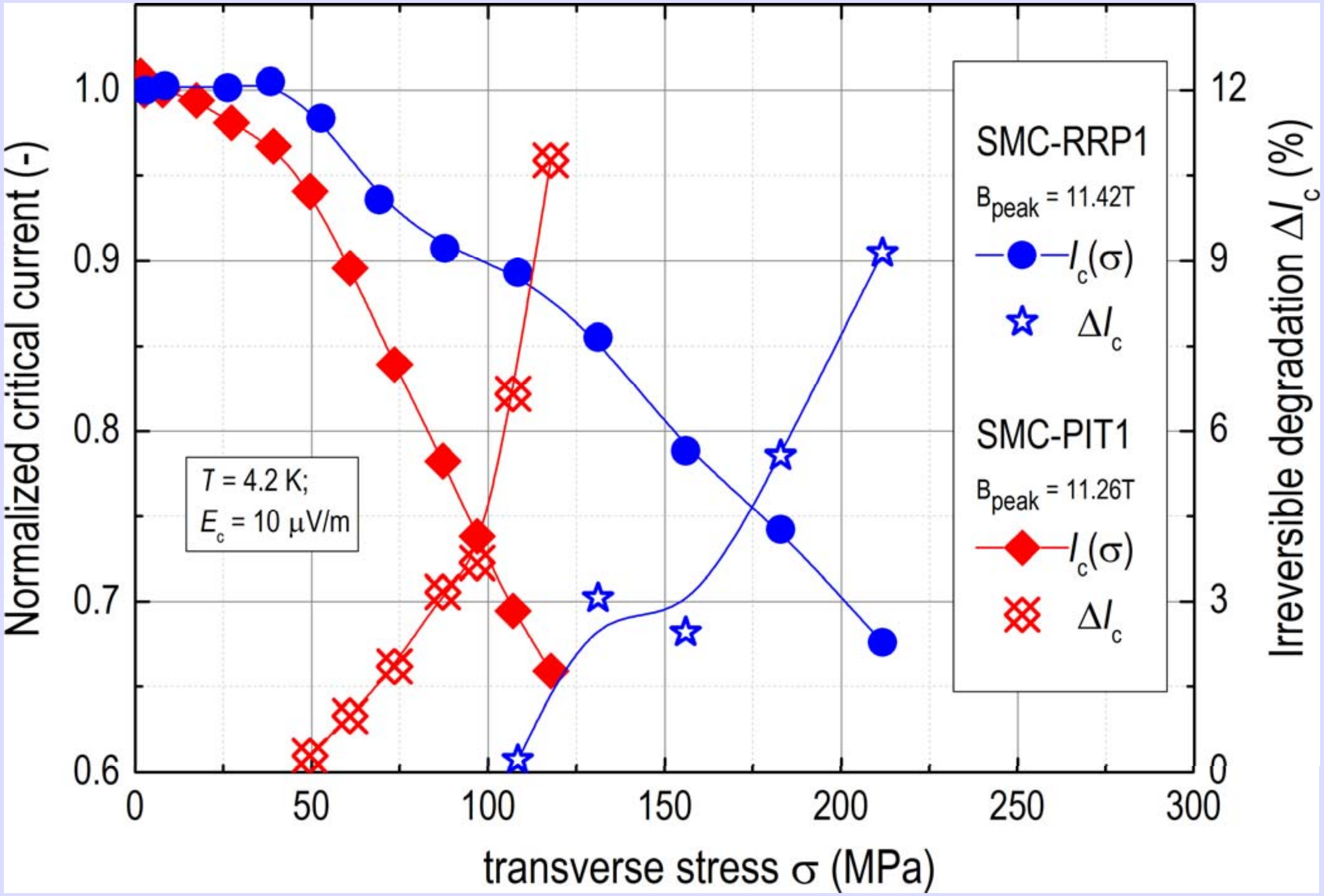
DS PIT cables



$\sigma_{-10\%} \approx$ 70-100 MPa ; $\sigma_{-1\%,\ irr.} \approx$ 50 MPa

3. Results

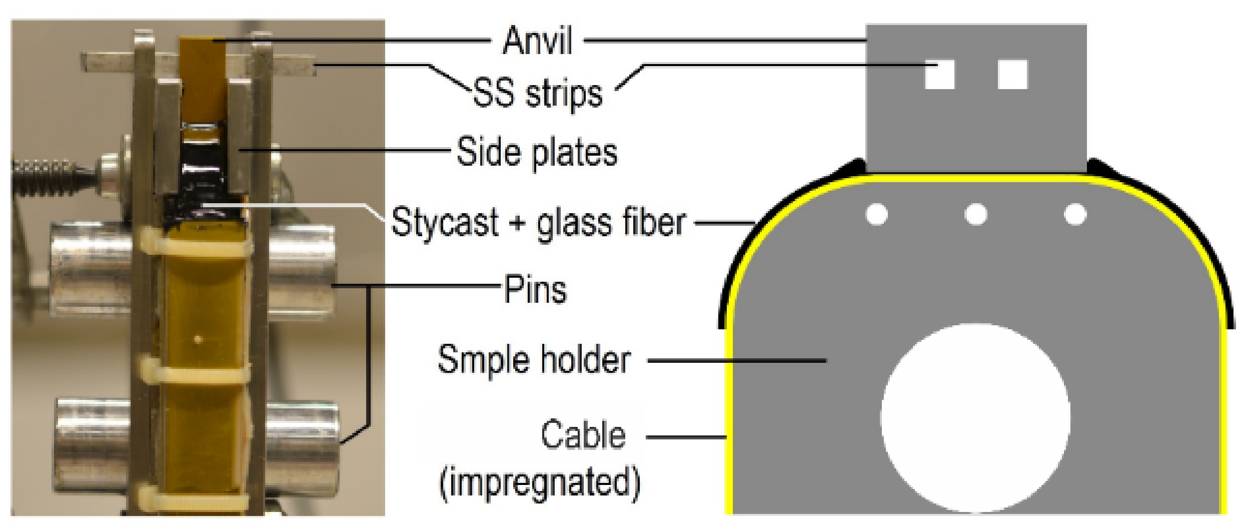
SMC cables



$\sigma_{-10\%} \approx$ 70-100 MPa ; $\sigma_{-1\%,\ irr.} \approx$ 70-120 MPa

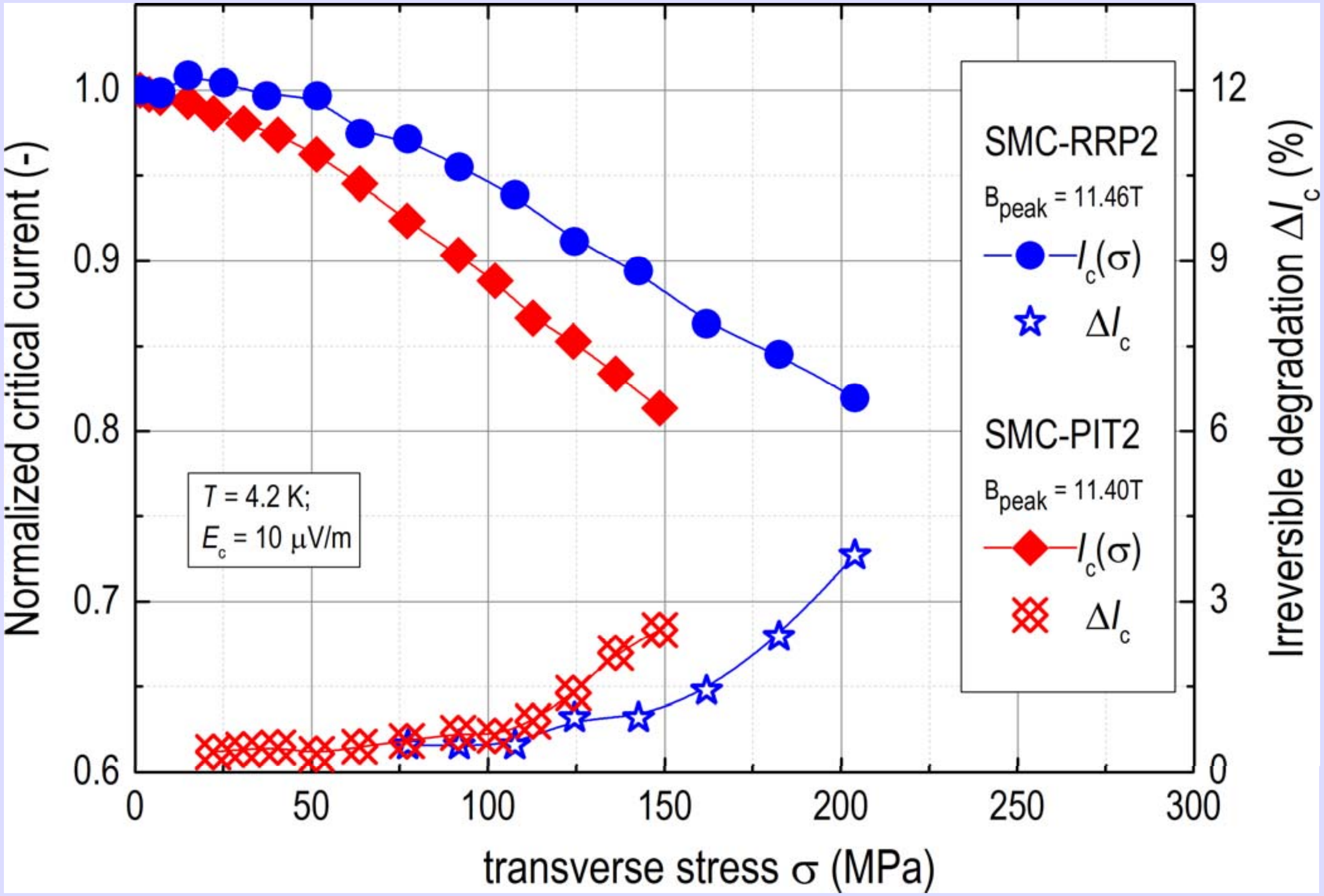
3. Results

- SMC comparison with CERN data inconsistent
- Problem was identified as parallelism issue (0.2° !)
- Remedied with extra tooling & second impregnation step



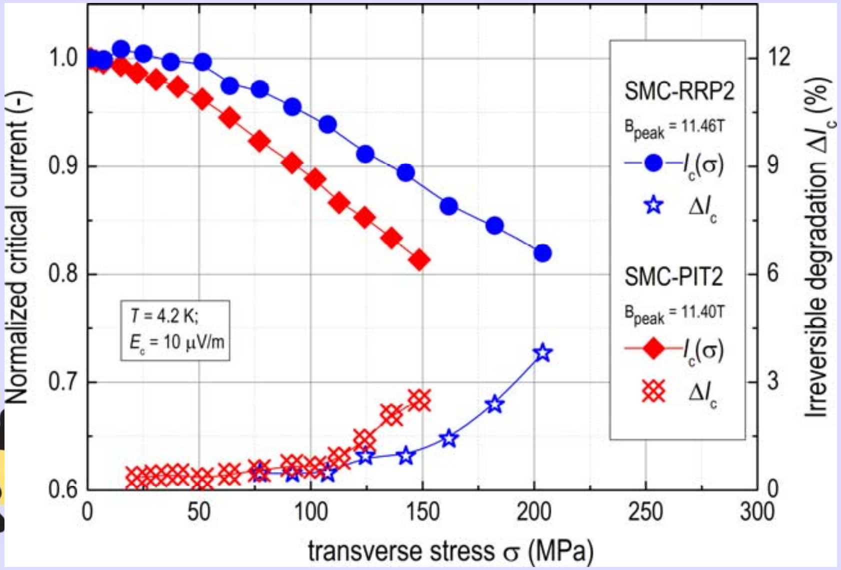
3. Results

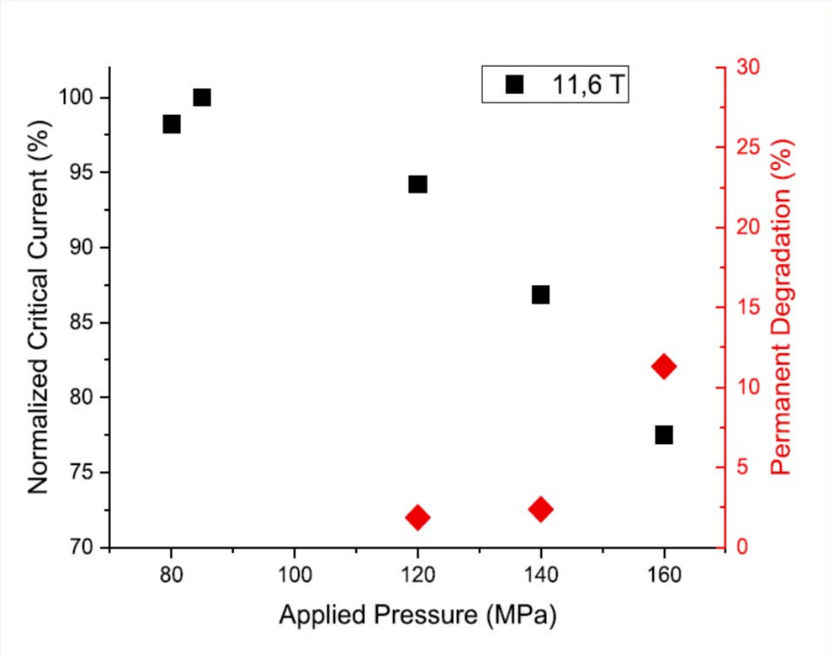
New SMC cables (of same strand material) after 2nd impregnation



$\sigma_{-10\%} \approx$ 100-140 MPa ; $\sigma_{-1\%,\ irr.} \approx$ 120-150 MPa

Benchmarking SMC RRP between UTwente & CERN





Duveauchelle, 2018 (CERN, RT loading)

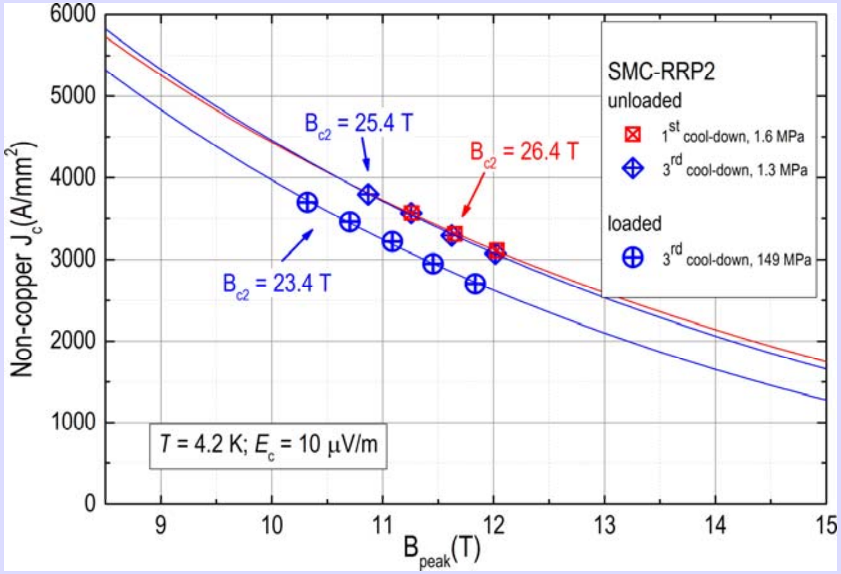
$\Delta I_c = -10\%$ @ $\sigma \approx 135$ MPa

$\Delta I_{c,\,irr} = -1\%$ @ $\sigma \approx 150$ MPa

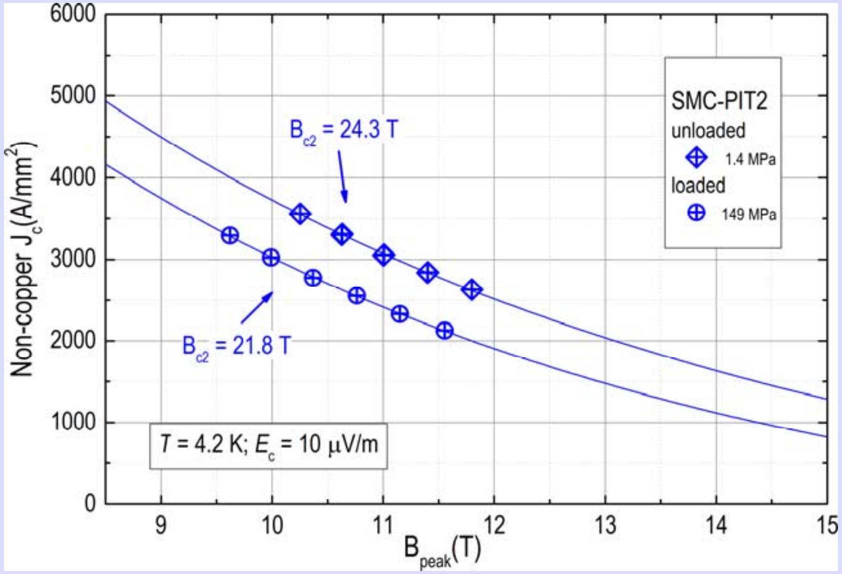
$\Delta I_c = -10\%$ @ $\sigma \approx 130$ MPa

$\Delta I_{c,\,irr} = -1\%$ @ $\sigma \approx 150$ MPa

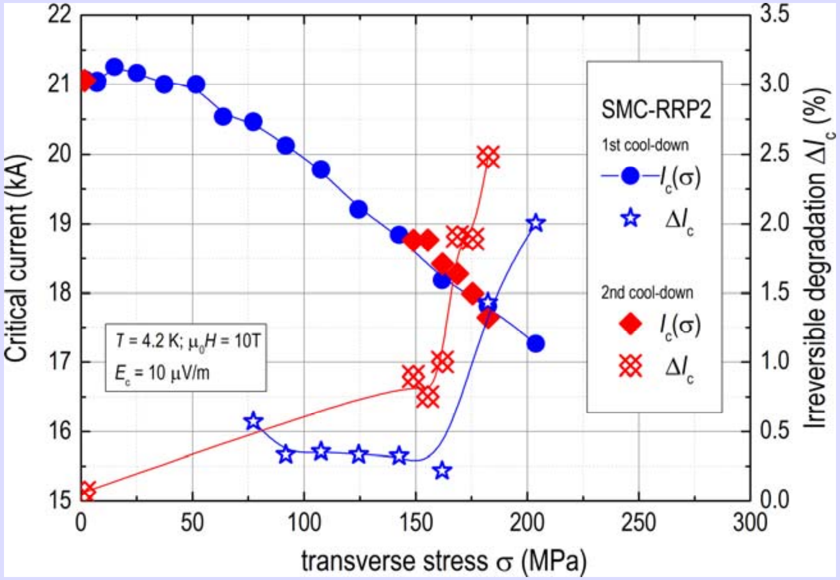
3. Results



Reversible effect on B_{c2} …



3. Results

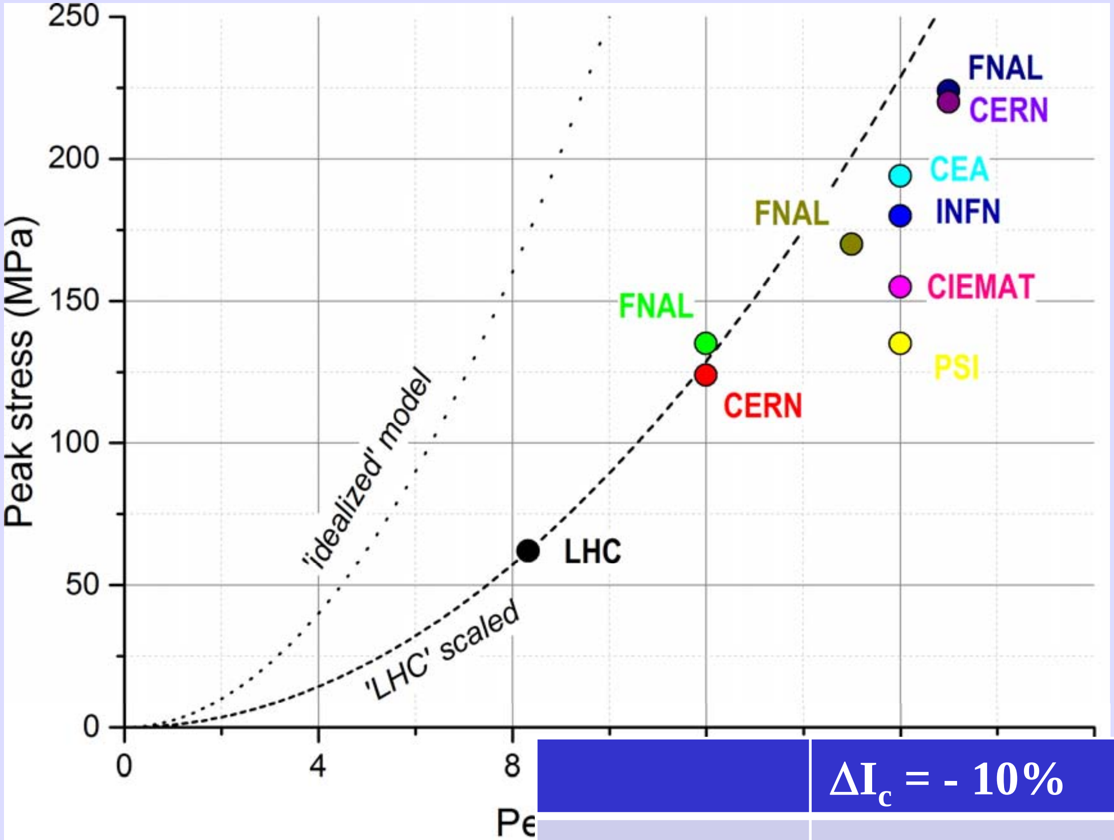


Effect of thermal cycling & mechanical cycling

Cycle	**SMC-PIT2** (1st cool-down)		
	I_c(149MPa) (kA)	I_c(1.6MPa) (kA)	ΔI_c irrev. (%)
1	14.78	17.57	-3.22
2	14.73	17.57	-3.22
3	14.74	17.53	-3.43
4	14.73	17.52	-3.50
5	14.75	17.51	-3.52

Cycle	**SMC-RRP2** (2nd cool-down)			**SMC-RRP2** (3rd cool-down)		
	I_c(149MPa) (kA)	I_c(1.6MPa) (kA)	ΔI_c irrev. (%)	I_c(175MPa) (kA)	I_c(1.4MPa) (kA)	ΔI_c irrev. (%)
1	18.67	20.86	-1.00	18.14	21.11	+0.16
2	18.91	20.87	-0.97	18.05	21.08	+0.02
3	18.72	20.90	-0.80	18.12	21.10	+0.11
4	18.76	20.88	-0.90	18.13	21.06	-0.07

3. Results



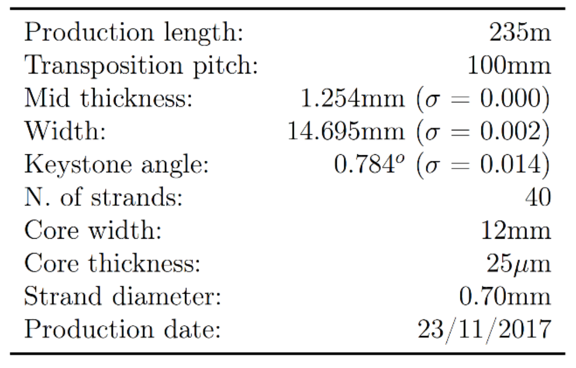
	ΔI_c = - 10%	$\Delta I_{c,irreversible}$ = - 1%
DS-RRP	250 MPa	~ 250 MPa
DS-PIT	70 – 100 MPa	~ 50 MPa
SMC-RRP	135 MPa	~ 150 MPa
SMC-PIT	90 MPa	~ 120 MPa

3. Results

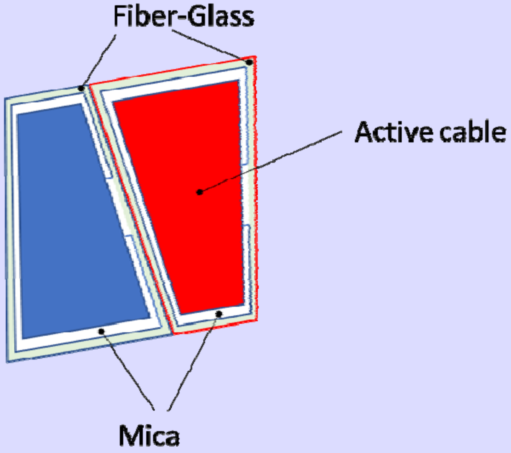
Coming up:

11T High-Lumni cable

H15OC0239C



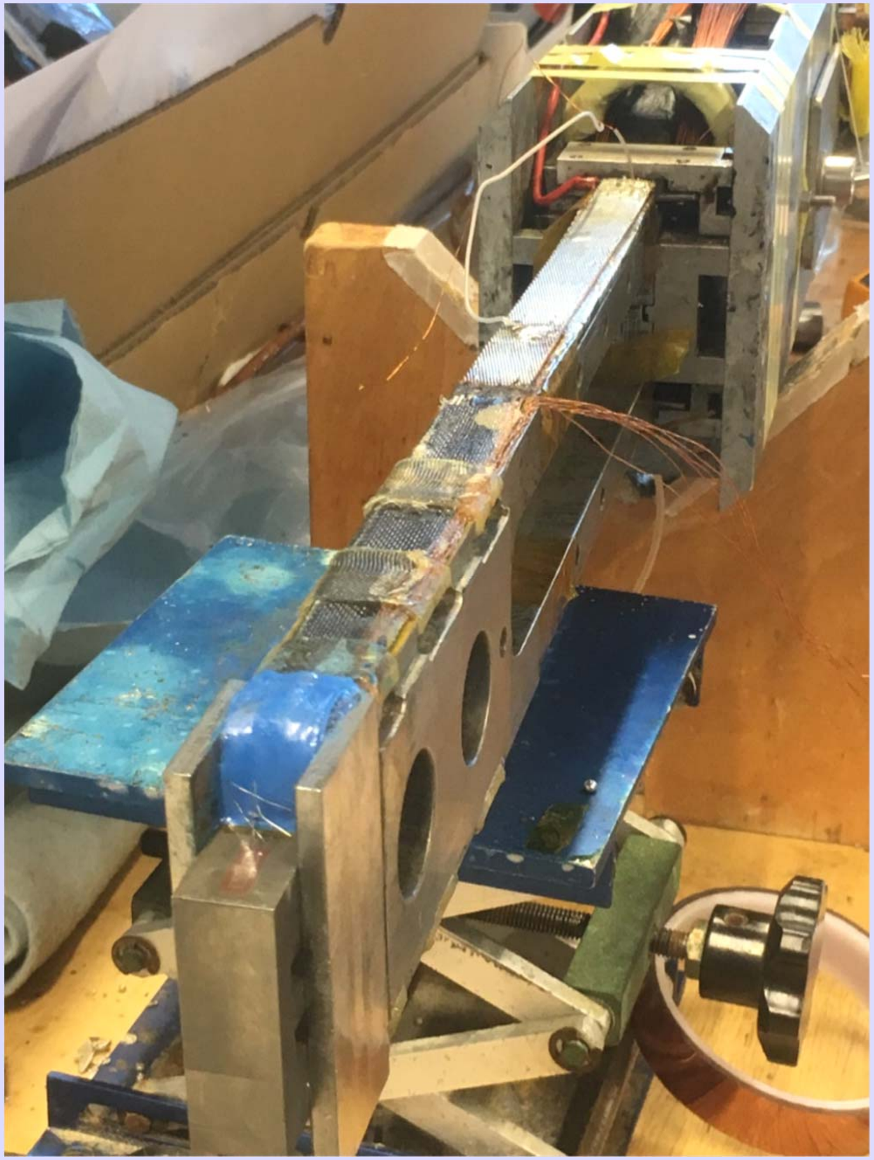
Production length:	235m
Transposition pitch:	100mm
Mid thickness:	1.254mm ($\sigma = 0.000$)
Width:	14.695mm ($\sigma = 0.002$)
Keystone angle:	0.784^o ($\sigma = 0.014$)
N. of strands:	40
Core width:	12mm
Core thickness:	25μm
Strand diameter:	0.70mm
Production date:	23/11/2017



Fiber-Glass

Active cable

Mica



4. Conclusions

- 16T-class magnets imply transverse pressures of ~ 150 – 200 MPa, cable data are scattered, but indicate this is ambitious;
- Better understanding of *local* stress distribution (and the parameters involved!) is needed (and evolving);
- Benchmarking exercises remain very useful;
- Magnet production quality control will be essential.