Conductor progress in EuCARD-2

Overview of electrical, mechanical and thermo-physical properties of REBCO CCs

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Laboratories in WP10.2 of EuCARD²

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KIT Karlsruher Institut für Technologie	*Anna KARIO, Wilfried GOLDACKER*
UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES	*Christian BARTH, Marco BONURA, Carmine SENATORE*
Grenoble INP cnrs dépasser les frontières	*Arnaud BADEL, Johnny HIMBELE, Pascal TIXADOR*
UNIVERSITY OF Southampton	*Yifeng YANG*
UNIVERSITEIT TWENTE.	*Marc DHALLÉ, Peng GAO, Simon OTTEN, Sander WESSEL*
BRUKER	*Alexander RUTT, Alexander USOSKIN*

Outline

- From the magnet to the cable design
- Overview of the industrial REBCO CCs
- $I_c(B,T,\theta)$ surface, scaling law for the temperature and field dependences
- Critical current under mechanical loads on tapes and cables
- Thermo-physical properties: thermal conductivity and normal zone propagation velocity

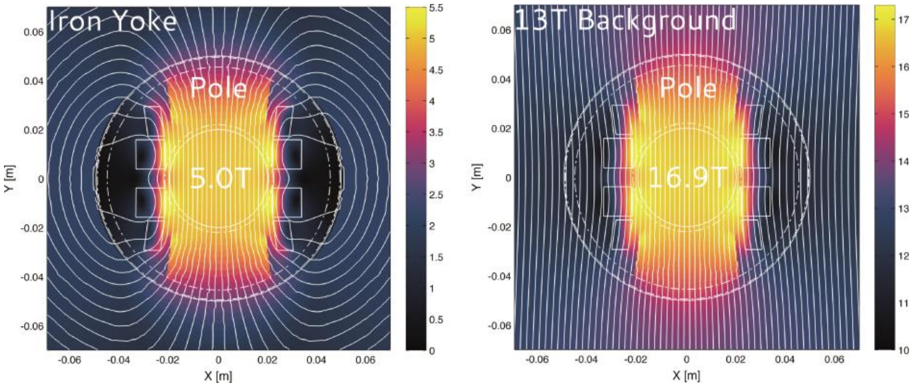
Scope of WP10.2 in EuCARD²

- ***WP10 goal** is the development of an accelerator-quality **dipole** demonstrator magnet based on **HTS** (**40 mm/5 T** in a 15 T background)*

- ***Objectives of the task WP10.2***
  - ***Improve the performance of the 2 candidate HTS materials (REBCO and Bi2212)***
  - ***Characterize electrical and mechanical properties of the basic materials (wires and tapes) and cables***
  - ***Select concepts & produce 10kA-20T HTS cable for coil winding***

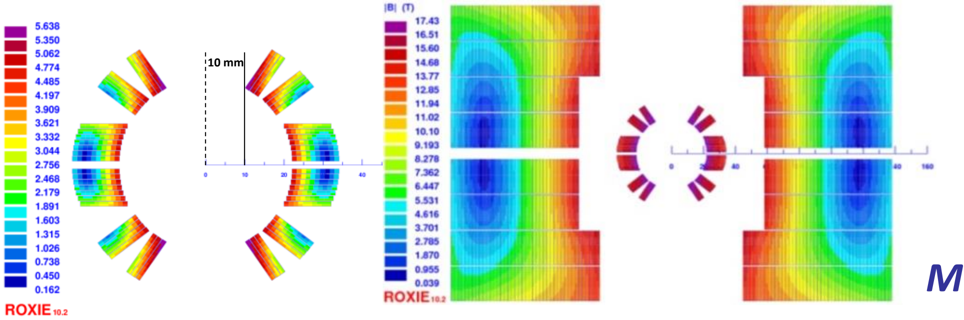
REBCO-based dipole magnet: 2 designs

- *Aligned block design*



G. Kirby & J. Van Nugteren

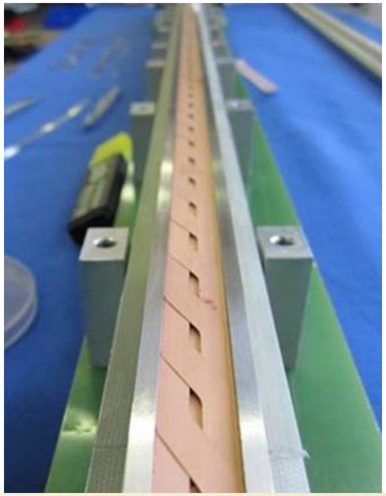
- *Cosine-theta design*

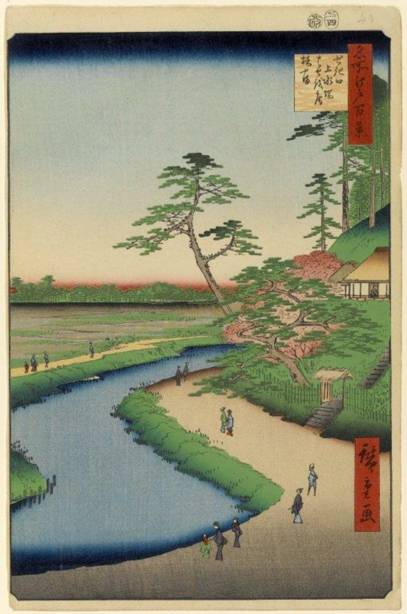


M. Durante & C. Lorin

Both designs rely on a 12-mm wide Roebel cable

REBCO Roebel cable baseline





design current : 5 to 10 kA @ 20 T, 4.2 K

cable width : 12 mm

# of tapes : 15

transposition length : 226 mm

Minimum requirements for the REBCO tape

I_c(4.2 K, 15 T, $\perp$) = 810 A for 12 mm-width

J_{eng}(4.2 K, 15 T, $\perp$) = 450 A/mm^2

Overview of the industrial CCs

	MOD *Dip-coating*	*PLD*	*PLD*	*RCE* *Co-evaporation*	*PLD*	*MOCVD* *Chemical vapor*
	American Superconductor	BRUKER	Fujikura	SuNAM	SuperOx	SuperPower Inc. A Furukawa Company
RABiTS	X					
IBAD		X	X	X	X	X
physical deposition		X	X	X	X	
chemical deposition	X					X
in situ *process*		X	X		X	X
ex situ *process*	X			X		
substrate	NiW 75 μm	SS 100 μm	Hastelloy 75 μm	Hastelloy 60 μm	Hastelloy 60 μm	Hastelloy 50 μm
thermal stabilization	Laminated (2 sides)	Electroplated	Laminated (1 side)	Electroplated	Electroplated	Electroplated

EuCARD^2 *partner*

Tapes from Bruker HTS

	T002	*T150*	*T191*	*T190*
Width	4.05 mm		4.2 mm	
Thickness	150 µm		200 µm	195 µm
Substrate material	Stainless steel			
Substrate thickness	97 µm			
Buffer layer	ABAD-YSZ + PLD CeO_2			
REBCO thickness	3.8 µm	0.9 µm	2.0 µm	
Ag *thickness*	1.0 µm		1.8 µm	
Cu *thickness*	50 µm		100 µm	90 µm
$I_c(77K,s.f.)$	109 A	25 A	54 A	47 A
$I_c(4.2K,19T,\perp)$	216 A	148 A	436 A	480 A

Thick REBCO w/o APC

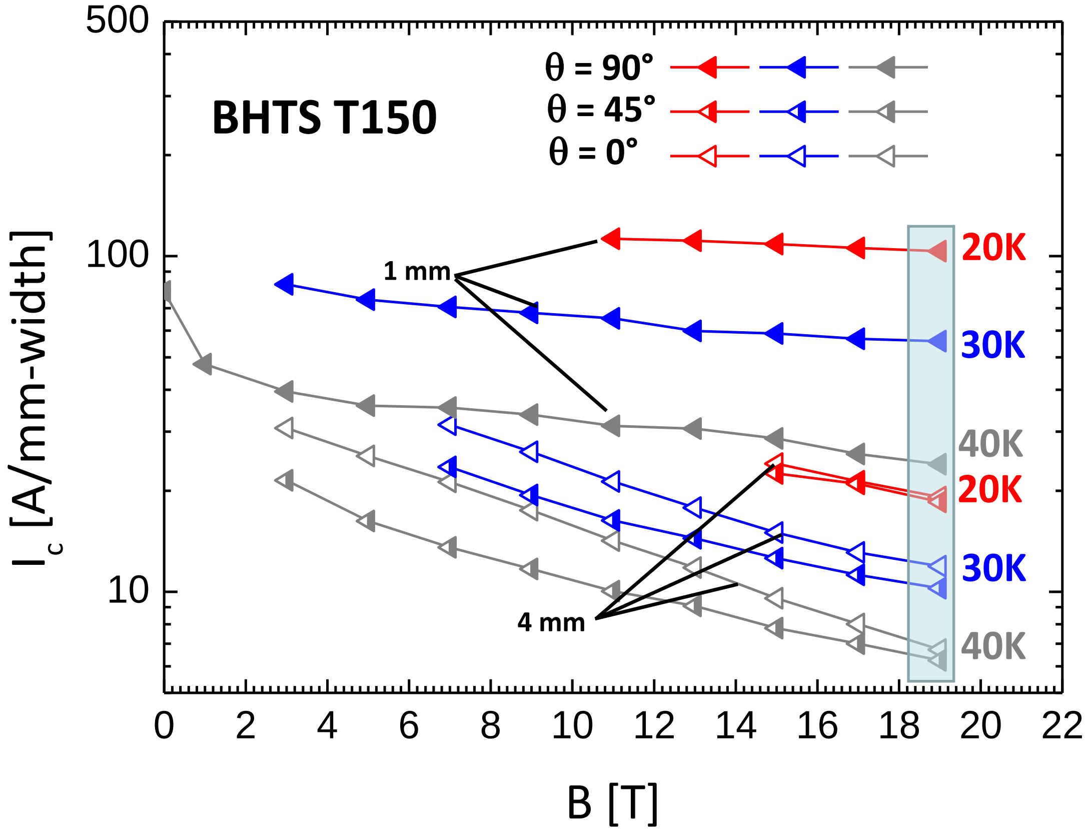
Thin REBCO with APC

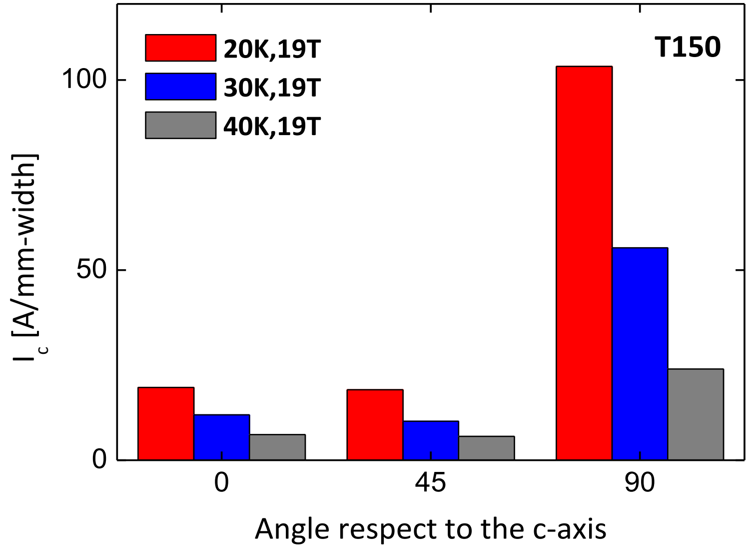
APC + crystal defects

B-HTS Tape T150 : an illustrative measurement

I_c(77K,s.f.) =25 A – width = 4 mm

RE123 thickness = 0.9 µm



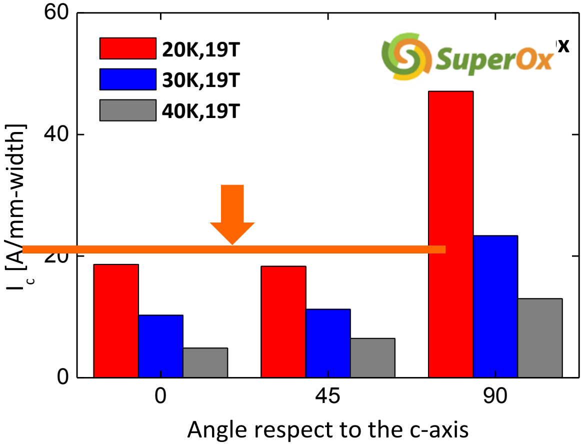


I_c(4.2K,19T) = 155 A/mm-width B//ab

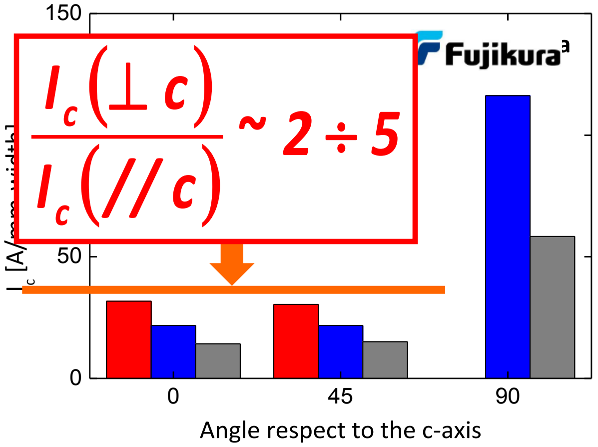
I_c(4.2K,19T) = 37 A/mm-width B//c

For θ = 90° (B//ab), samples with reduced width (1 mm) were prepared either by chemical etching or by spark erosion

Angular dependence of I_c at high fields

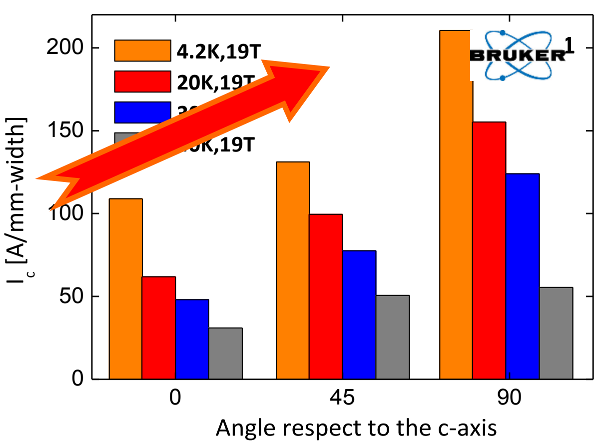


I_c(4.2K,19T) = 42 A/mm-width B//c

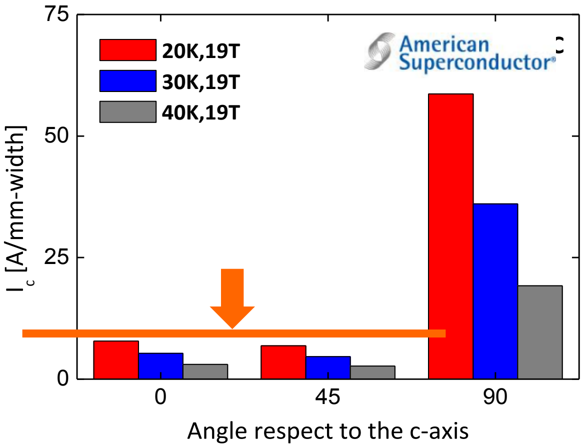


$$\frac{I_c(\perp c)}{I_c(//c)} \sim 2 \div 5$$

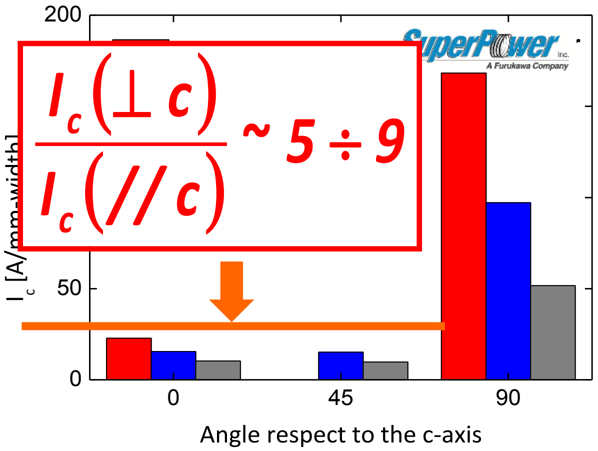
I_c(4.2K,19T) = 50 A/mm-width B//c



I_c(4.2K,19T) = 109 A/mm-width B//c

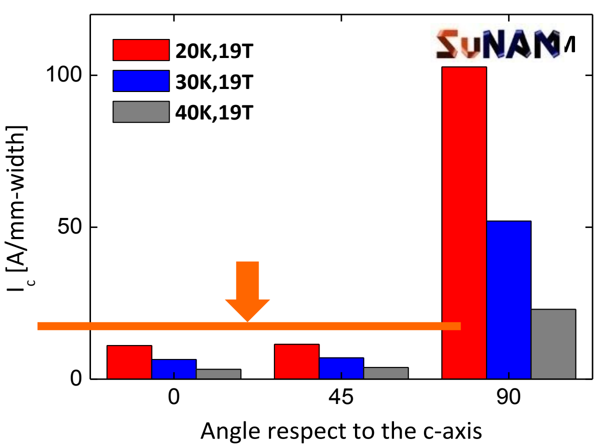


I_c(4.2K,19T) = 16 A/mm-width B//c



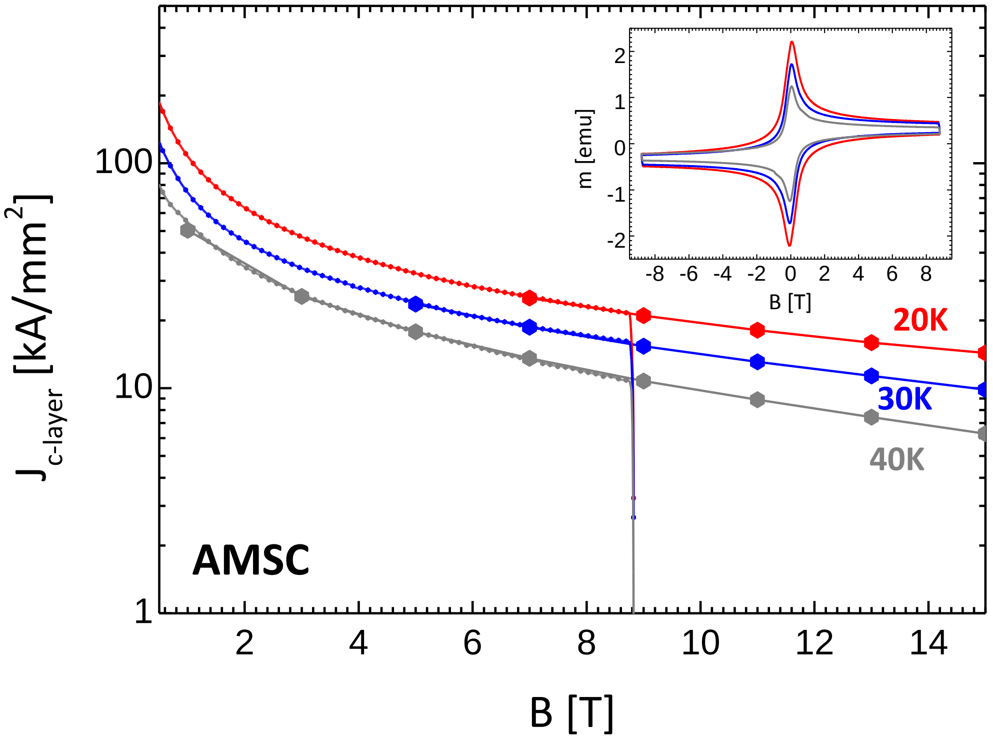
$$\frac{I_c(\perp c)}{I_c(//c)} \sim 5 \div 9$$

I_c(4.2K,19T) = 35 A/mm-width B//c



I_c(4.2K,19T) = 24 A/mm-width B//c

Working on a general scaling law for $J_c(B,T,\theta)$



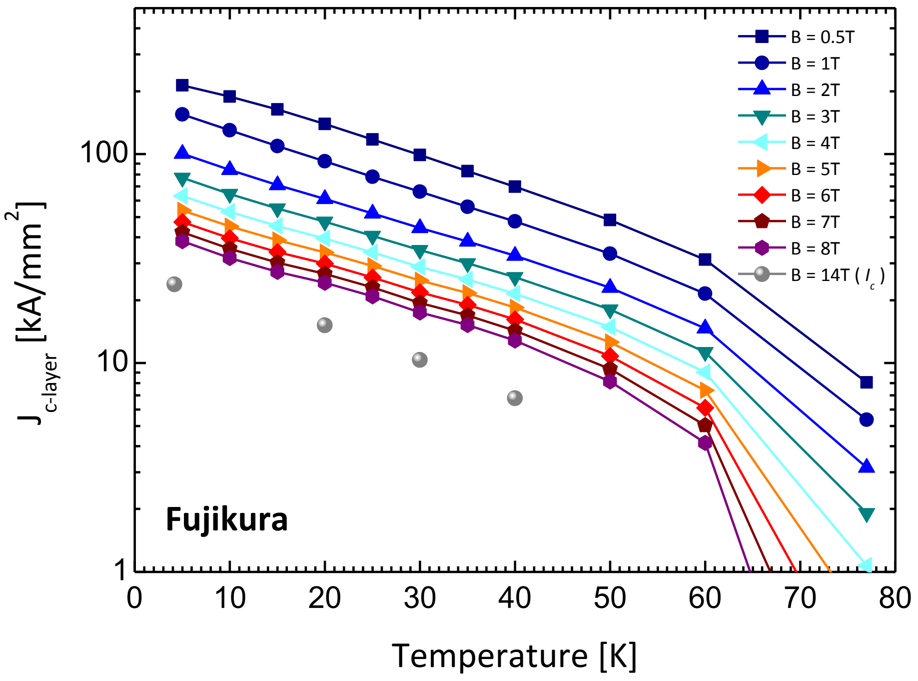
Only a limited portion of the critical surface is practically accessible from transport measurements

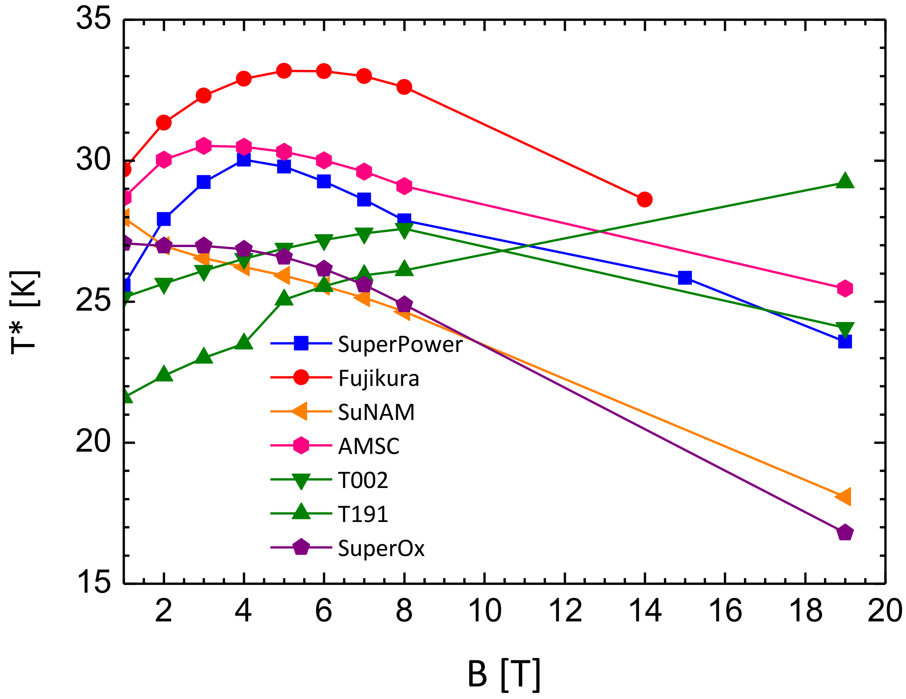
Magnetization measurements are the tool to explore a larger region of the critical surface

$5K < T < 77K$

$-9T < B_{\perp} < 9T$

Temperature dependence of J_c from magnetization



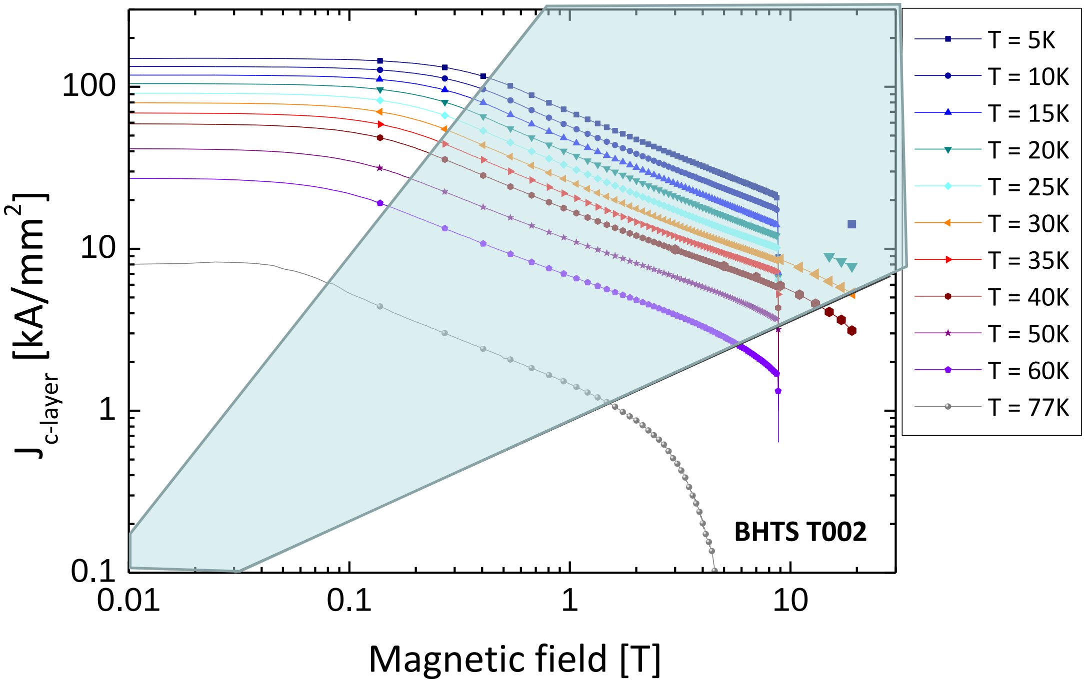


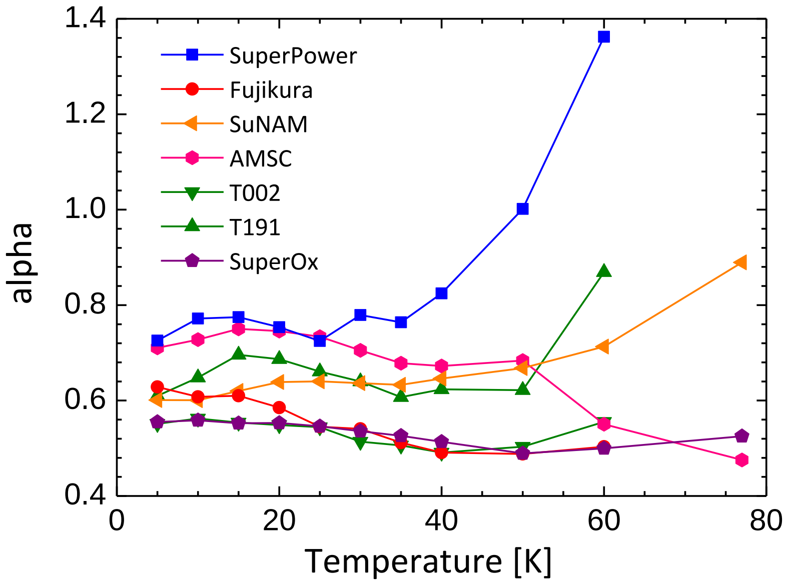
Temperature scaling law $J_c(B,T)=J_c(B,T=0)e^{-\frac{T}{T^*}} \Rightarrow \frac{J_c(B,T_1)}{J_c(B,T_2)}=e^{-\frac{T_1-T_2}{T^*}}$

T ranges between 15 K and 35 K – it depends on field*

$\theta = 0° - B//c$

Field dependence of J_c from magnetization



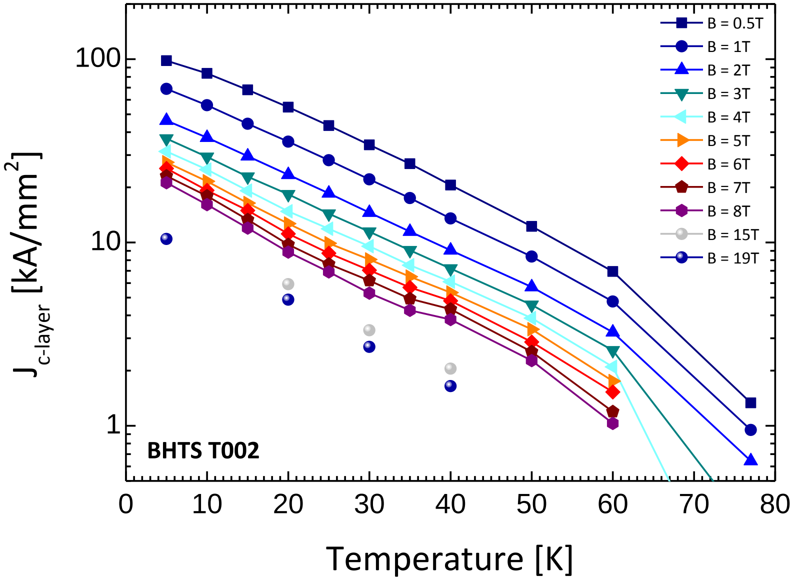


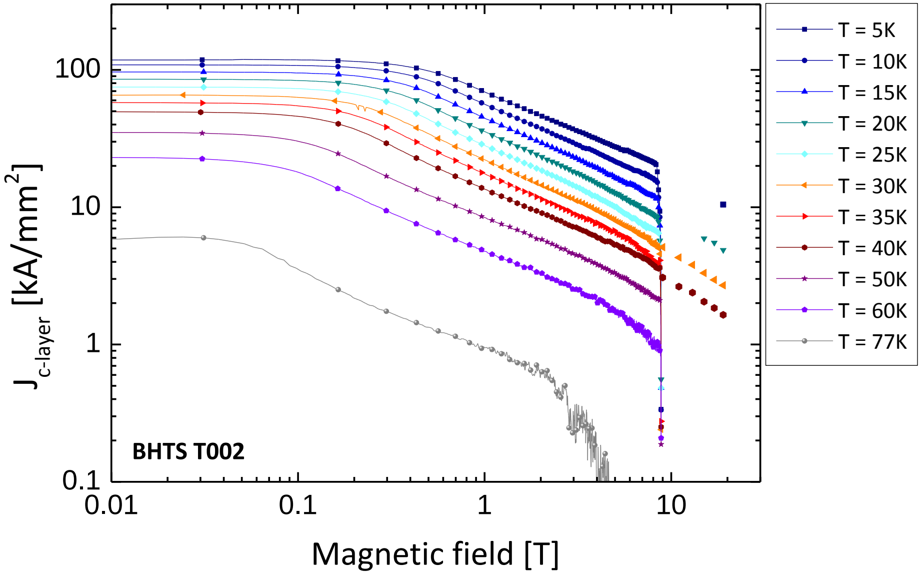
Field scaling law $J_c(B,T) = J_c(B=0,T)\,B^{-\alpha} \Rightarrow \dfrac{J_c(B_1,T)}{J_c(B_2,T)} = \left(\dfrac{B_1}{B_2}\right)^{-\alpha}$

α ranges between 0.5 and 0.8 – almost constant below 40 K

$\theta = 0° - B//c$

Temperature and field dependence of J_c , varying θ





Temperature scaling law

$$J_c(B,T) = J_c(B,T=0)e^{-\frac{T}{T^*}}$$

Field scaling law

$$J_c(B,T) = J_c(B=0,T)B^{-\alpha}$$

θ = 45°

Semi-empirical scaling law for $J_c(B,T)$

For temperatures below 40K, critical surface $J_c(B,T)$ in the form

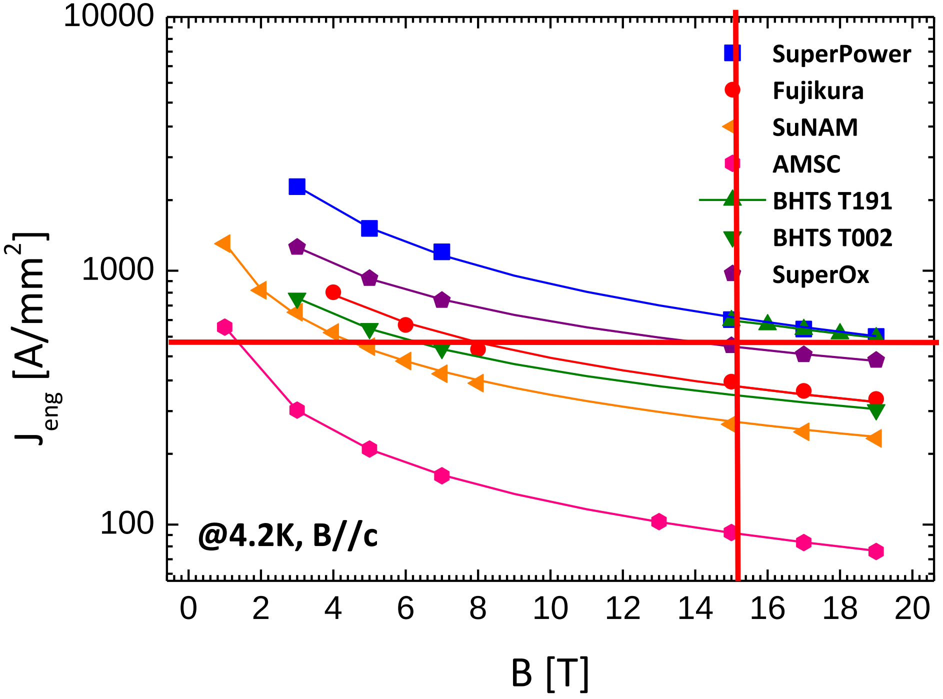
$$J_c(B,T) = J_c(B=0,T=0)B^{-\alpha}e^{-\frac{T}{T^*}}$$

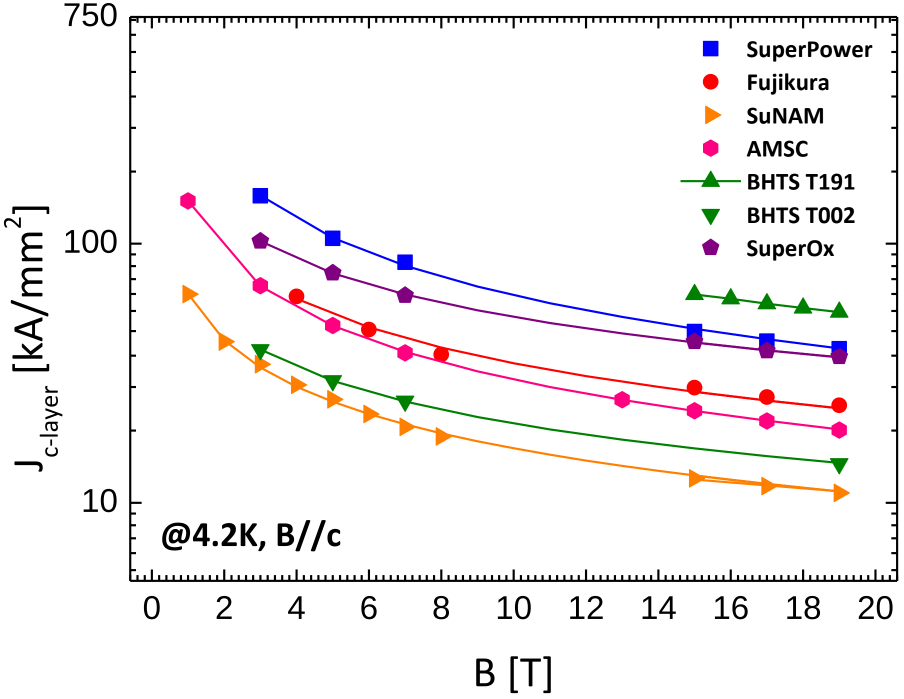
- α almost constant in temperature
- T^* depending on magnetic field

Minimum dataset to get the $J_c(B,T)$ surface:

- Magnetization data for $4K < T < 50K$
- Transport I_c at a single temperature – Field range has to overlap with magnetization data

Engineering J_c and layer J_c : Overall comparison @4K

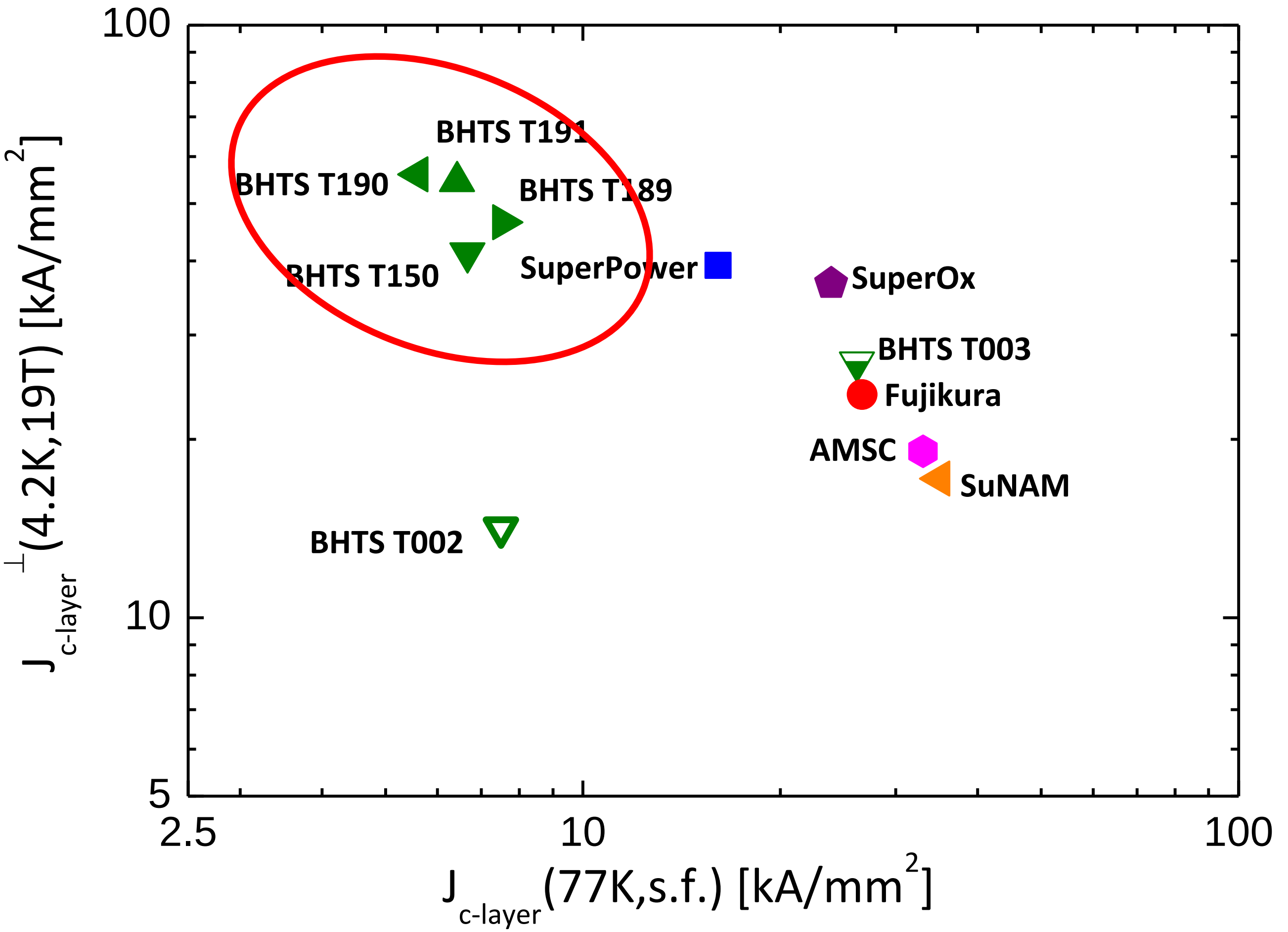




The line in the gap is a $B^{-\alpha}$ fit of the data

Spread among the manufacturer is reduced when $B \perp c$, as deduced from the angular dependence

Master Plot: J_c(77K,s.f.) vs. J_c(4.2K,19T)



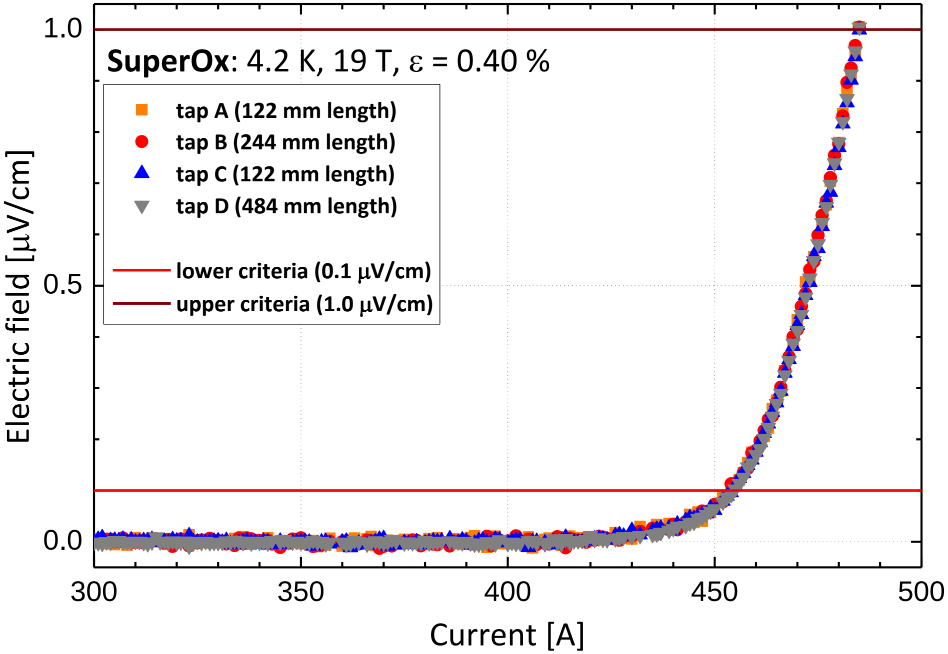
Critical current depends on

- *temperature*
- *field intensity*
- *field orientation*
- *stress*

I_c vs. axial strain: measurement method

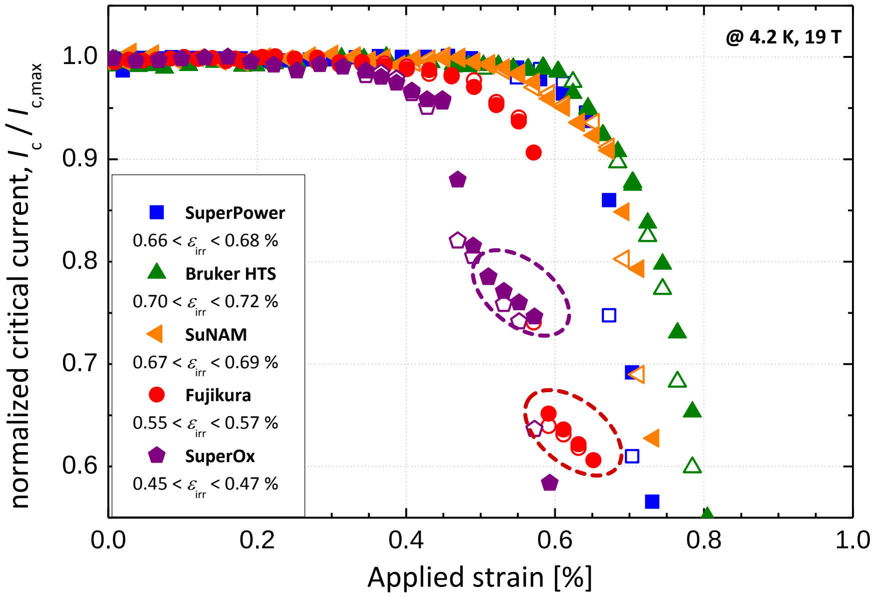
Walters spring (WASP)

- *Sample is soldered to Ti-alloy spring*
- *Turning the spring strains the sample*
  - *calibrated with strain gauges glued to the sample*
  - *sample is pre-strained upon cooldown due to thermal expansion mismatch*
  - *pre-strain is determined & subtracted*
- *1m-long sample*
  - *precise*
  - *low noise*
  - → *low I_c criteria*
  - → *get n values*

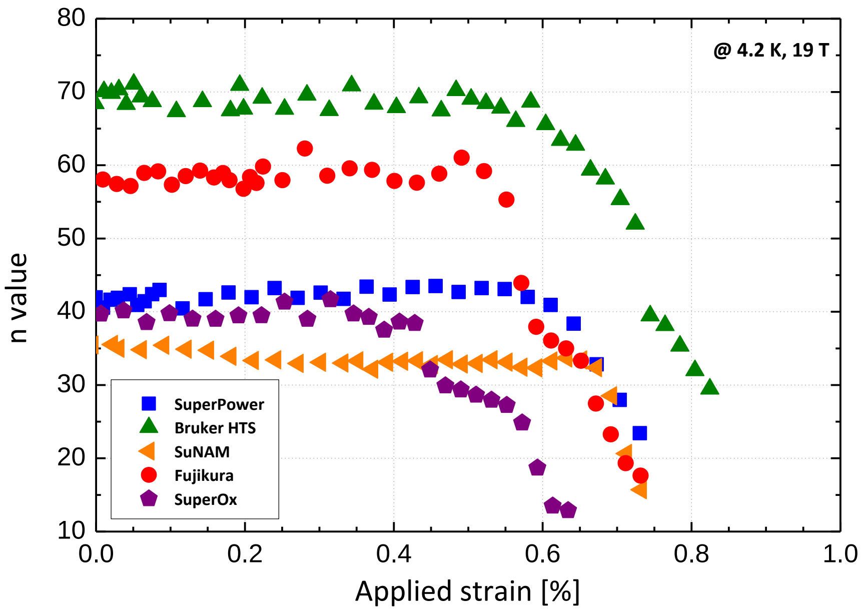


Dependence of I_c on axial strain @ 4.2 K, 19 T

I_c vs. applied strain



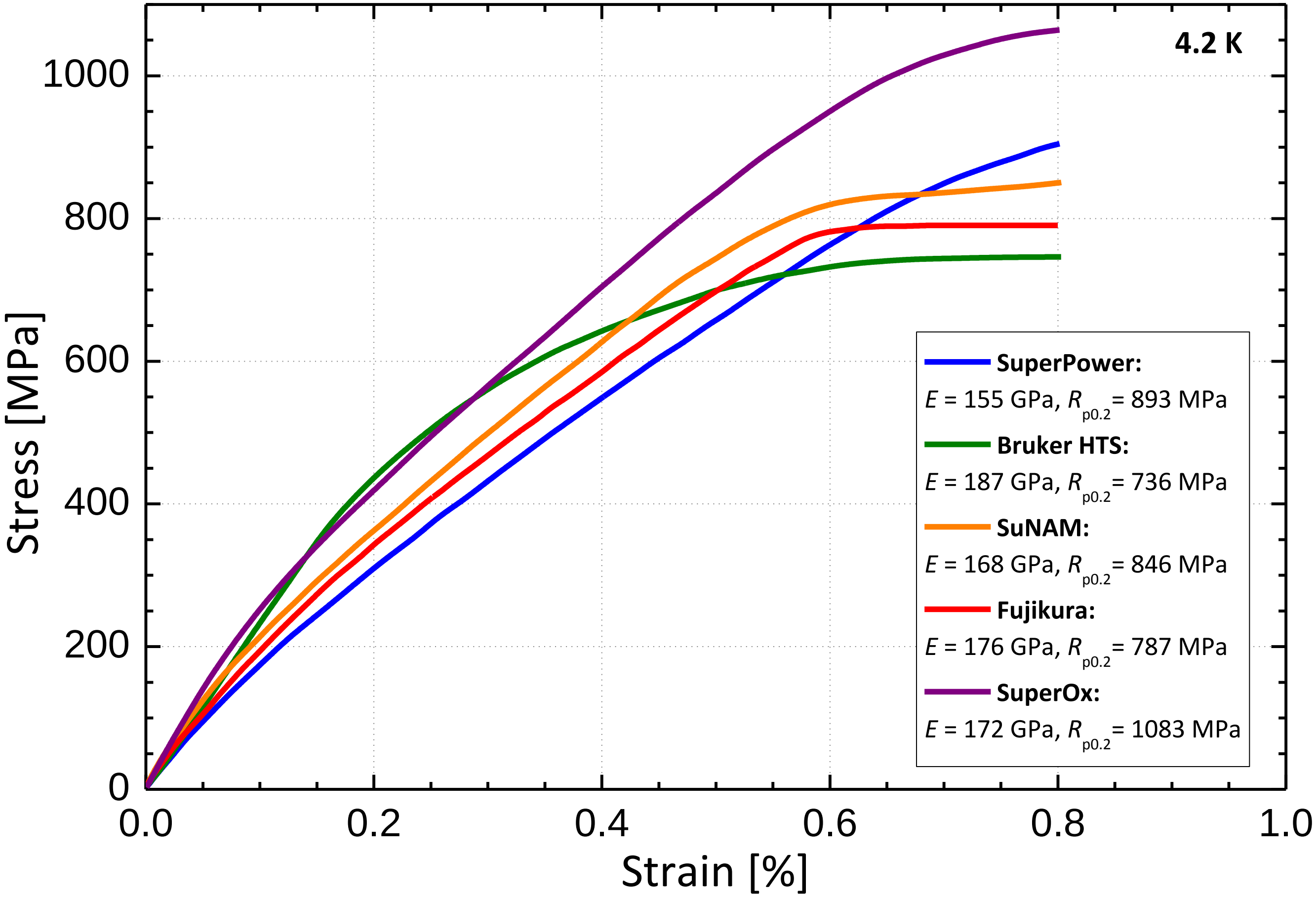
n value vs. applied strain



Fujikura & SuperOx: delamination → steps → lower ε_{irr}

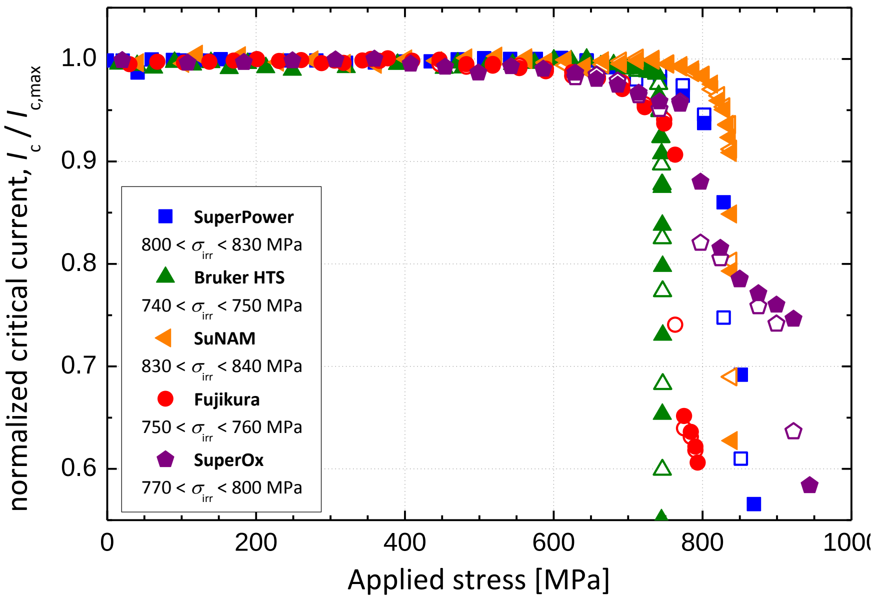
C. Barth, C. Senatore et al., submitted to SuST

Stress vs. strain measurements @ 4.2 K

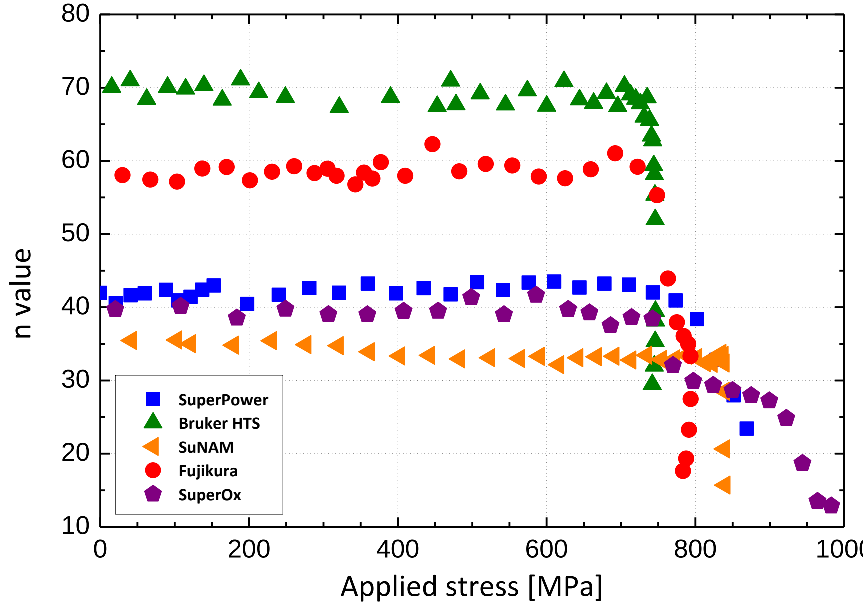


C. Barth, C. Senatore et al., submitted to SuST

Dependence of I_c on axial stress @ 4.2 K, 19 T



I_c vs. applied stress



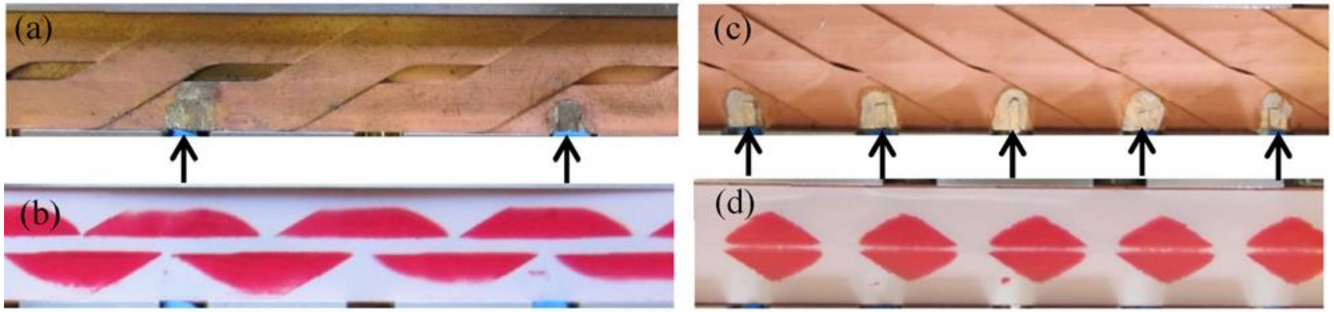
n value vs. applied stress

- *All samples have a very similar behaviour*
- *Very low stress effect → curves are flat in rev. region*
- *Irreversible limits σ_{irr} in 740 – 840 MPa range*

C. Barth, C. Senatore et al., submitted to SuST

Mechanical behavior of cables under transverse stress

Stress concentrates in REBCO Roebel cables submitted to transverse loads

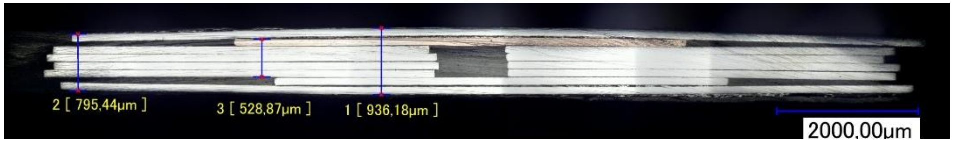


J. Fleiter et al., SuST 26 (2013) 065014

The problem can be avoided using an appropriate impregnation

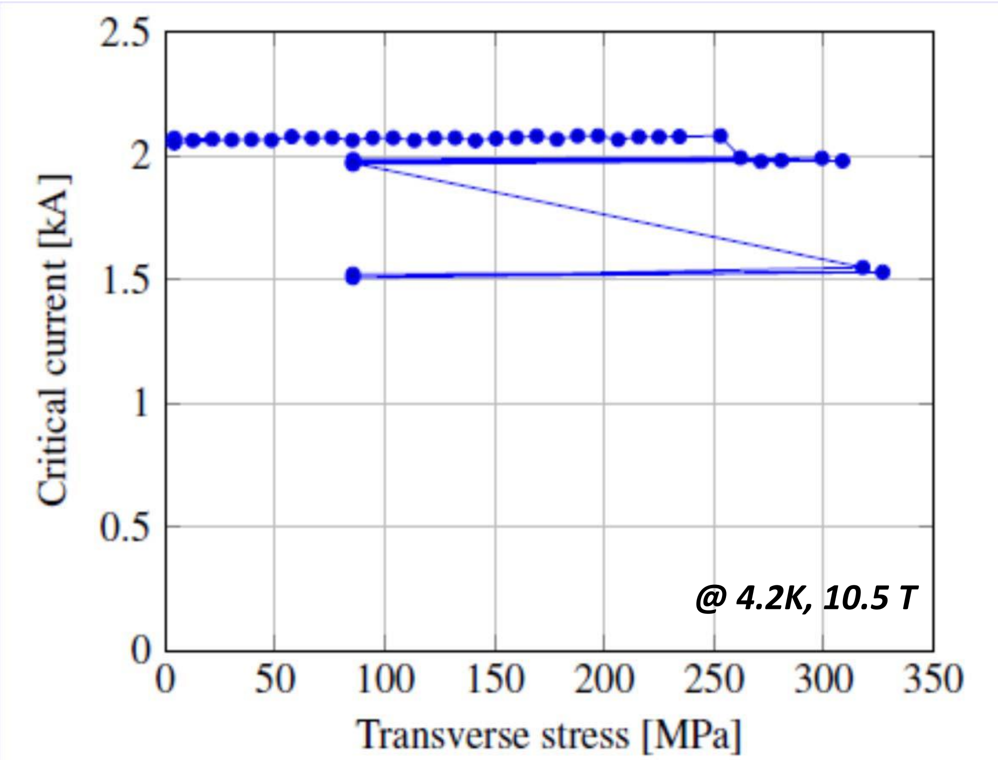
KIT Karlsruher Institut für Technologie - UNIVERSITEIT TWENTE. *collaboration in the frame of* EuCARD^2

Vacuum impregnation with Araldite and 50% fused silica of a dummy Roebel cable

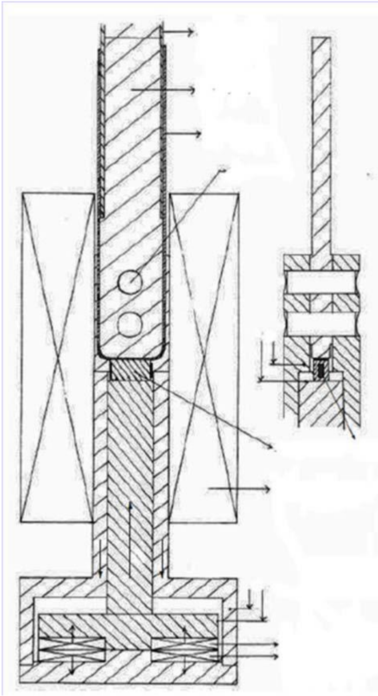


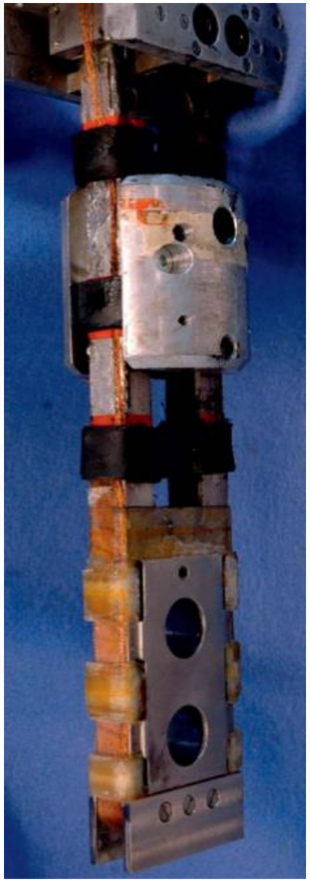
A. Kario et al., ICEC-ICMC 2014

Mechanical behavior of cables under transverse stress



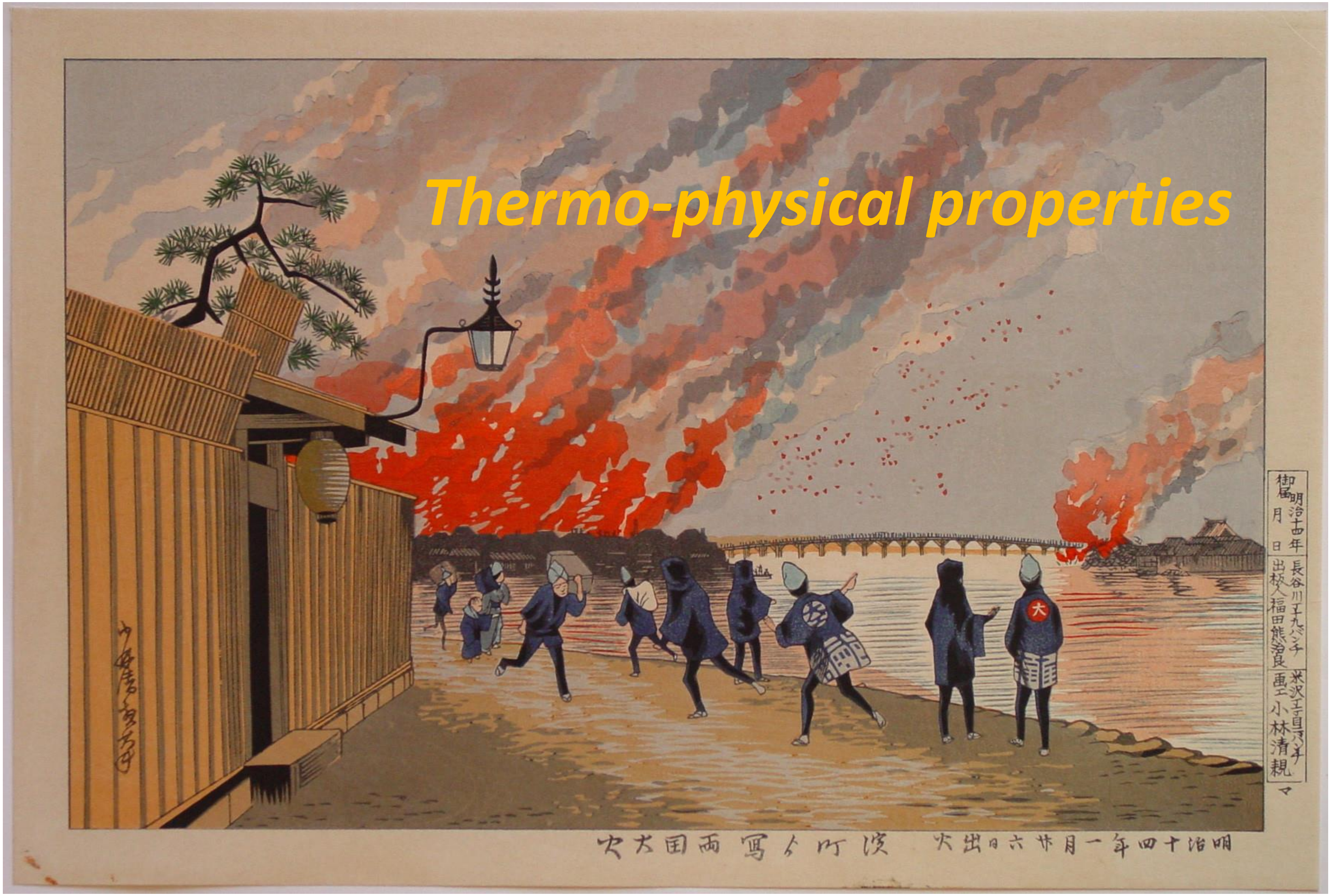
M. Dhallé, S. Otten et al., to be published





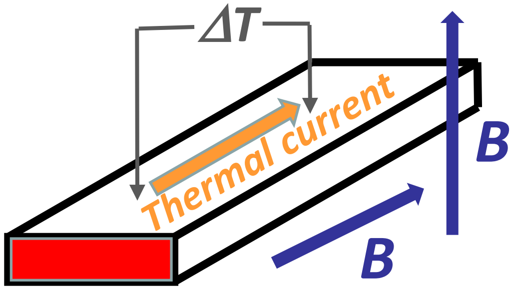
- Roebel cable made with 10 SuperPower tapes SCS12050-AP
- Vacuum impregnation with Araldite and 50% fused silica
- Preliminary results encouraging, σ_{irr} ~ 250 MPa

Thermo-physical properties



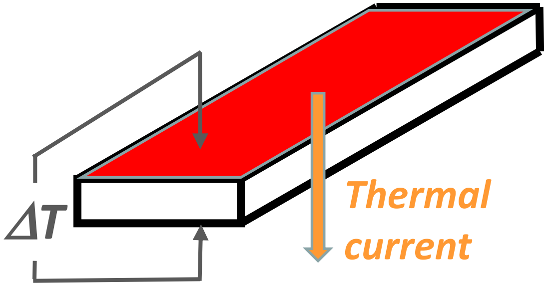
Thermal conductivity of REBCO CCs

Thermal conductivity is an essential parameter for QUENCH studies



- Longitudinal thermal conductivity in magnetic fields up to B=19 T

  B perpendicular & parallel to thermal current



- Transverse thermal conductivity

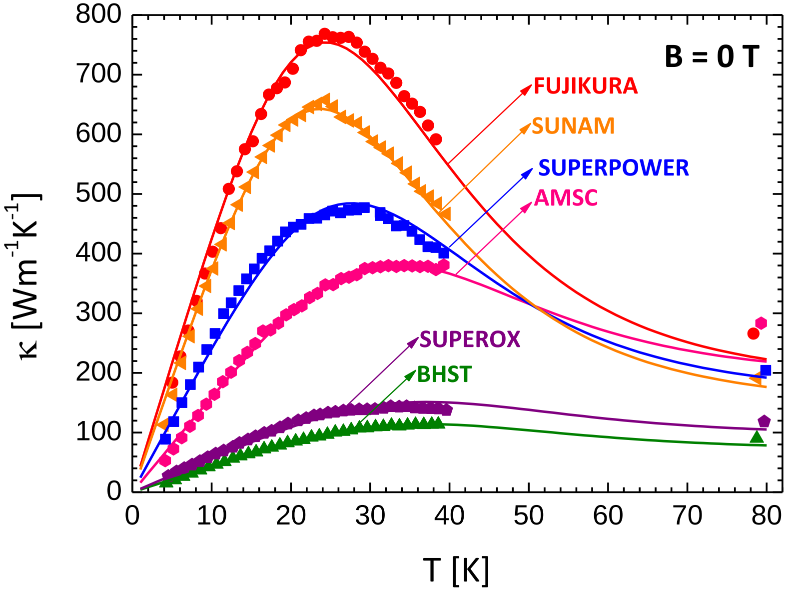
Longitudinal thermal conductivity

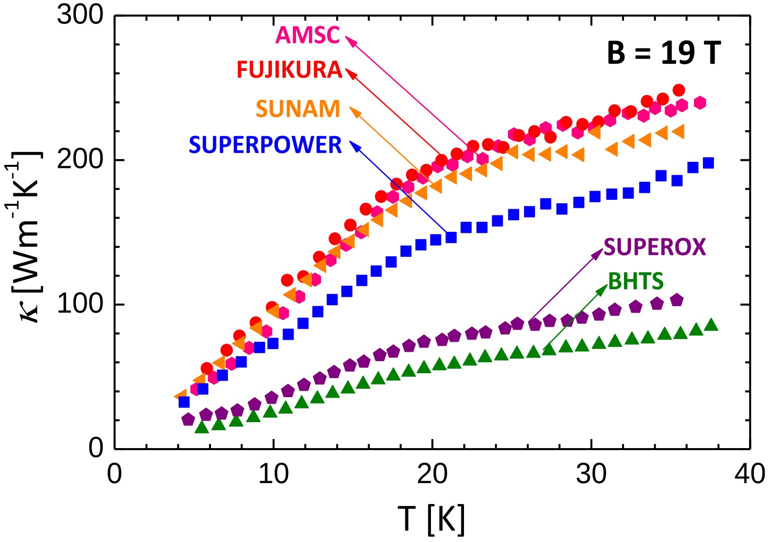
$$\kappa_{exp} = \sum_i \kappa_i \frac{S_i}{S_{tot}} \approx \kappa_{Cu} \frac{S_{Cu}}{S_{tot}}$$ **and $\kappa_{Cu} = f(RRR_{Cu})$**

Manufacturer	RRR_{Cu} [fit]	RRR_{Cu} [$\rho(T)$]	S_{Cu}/S_{tot}
AMSC	20	19	0.51
BHST	14	17	0.20
FUJIKURA	62	59	0.44
SUNAM	69	61	0.34
SUPEROX	13	14	0.27
SUPERPOWER	39	42	0.40

κ(T,B=0T) can be estimated (±15%) from RRR_{Cu} and S_{Cu}/S_{tot}

Cu/non-Cu ratio and RRR_{Cu} determine the in-field variation of κ



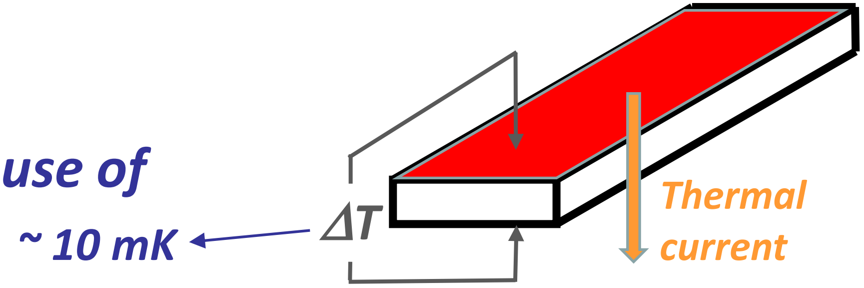


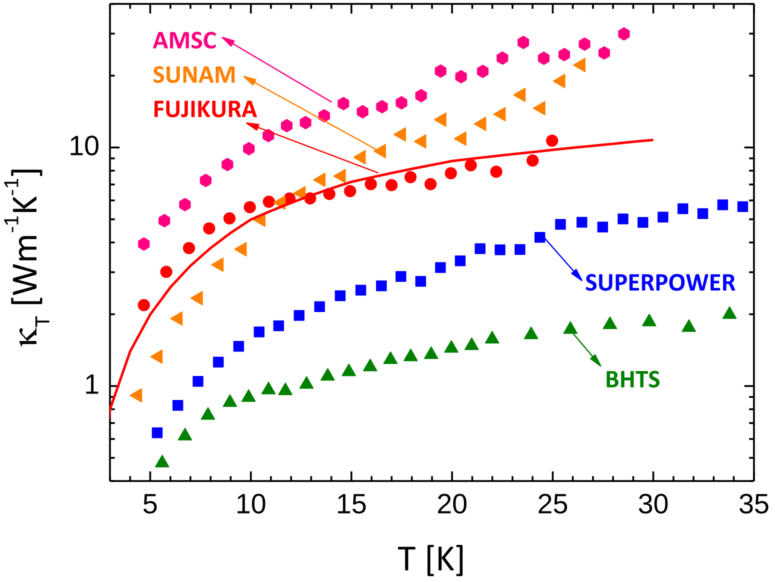
M. Bonura, C. Senatore, SuST, in press

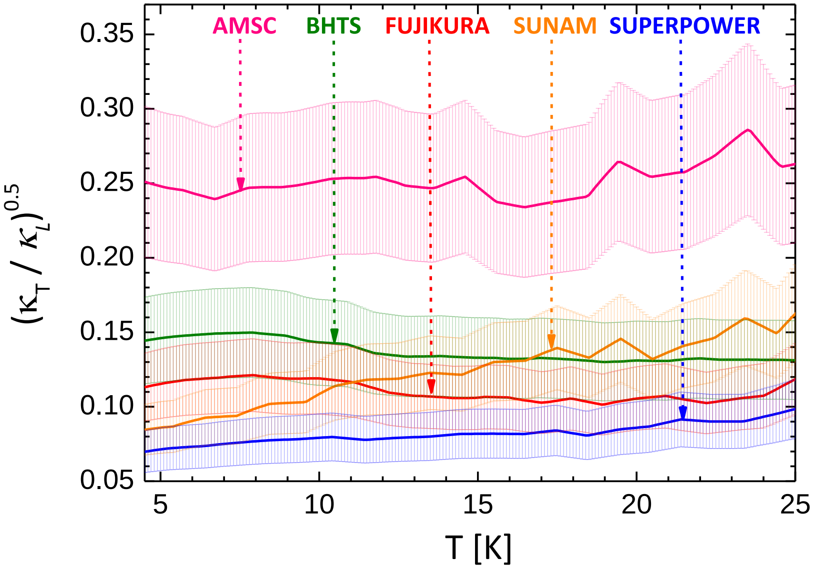
Transverse thermal conductivity

κ_T is dominated by the substrate

Measurements are challenging because of the reduced thickness of CCs







From the ratio between κ_T and κ_L we can calculate the ratio between longitudinal and transverse NZPV

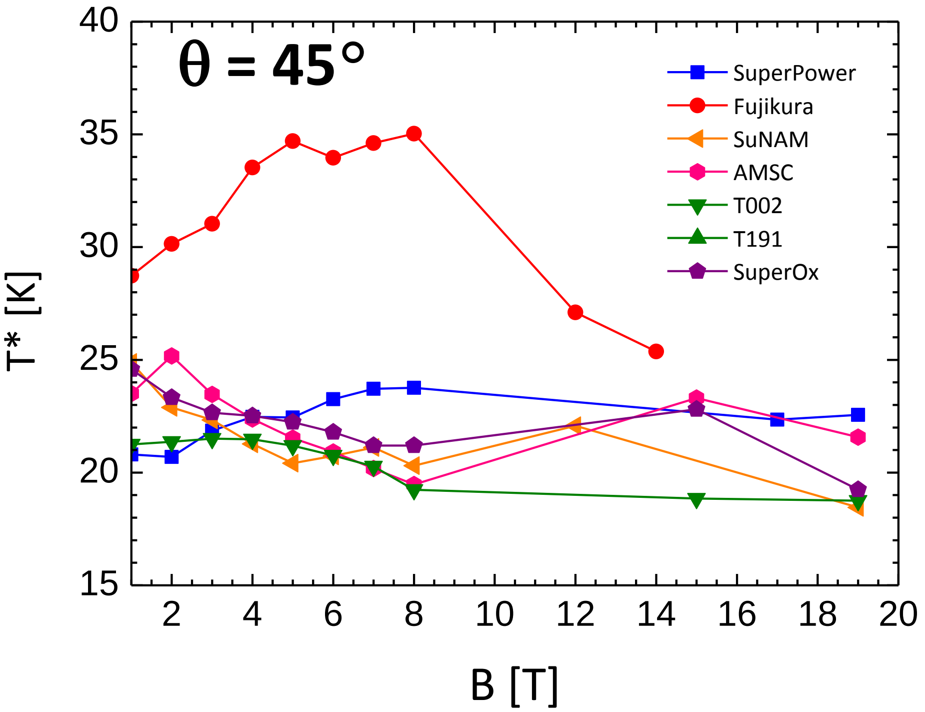
$$\boxed{\frac{NZPV_{Transv}}{NZPV_{Long}} = \sqrt{\frac{k_T}{k_L}}}$$

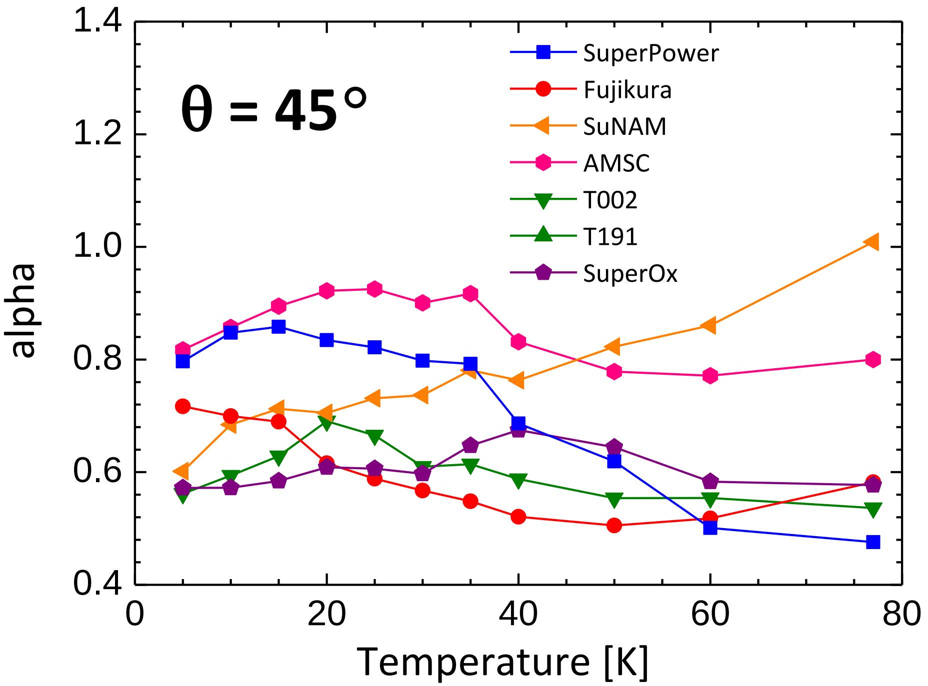
M. Bonura, C. Senatore, IEEE TAS, in press

Conclusions

- Explored the $J_c(B,T,\theta,\sigma)$ surface for CCs from 6 manufacturers
- Scaling law of $J_c(B,T)$ with an exponential T dependence and a power-law B dependence
- Irreversible limit σ_{irr} under axial loads in 740 – 840 MPa range for all manufacturers
- Impregnated Roebel cable withstands transverse loads up to 250 MPa
- Direct measurements of in-field thermal conductivity for quench propagation studies

Temperature and field dependence of J_c , θ = 45°





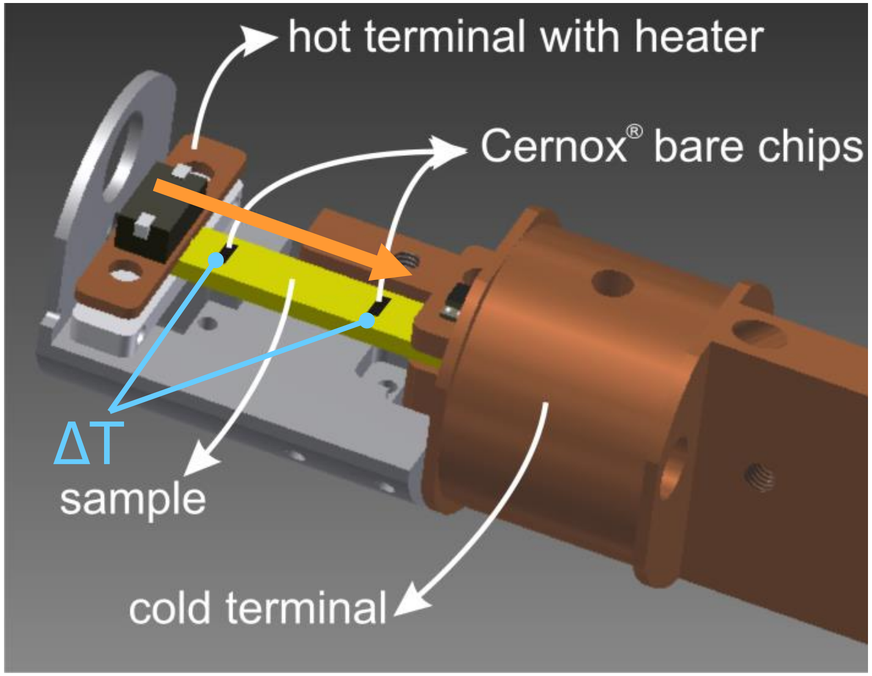
Temperature scaling law

$$J_c\left(B,T\right)=J_c\left(B,T=0\right)e^{-\frac{T}{T^*}}$$

Field scaling law

$$J_c\left(B,T\right)=J_c\left(B=0,T\right)B^{-\alpha}$$

New setup for thermal conductivity measurements up to 21 T



- Control of conduction, convective and radiative heat losses (error in Q<0.05%)
- Thermometers calibrated up to 21 T
- Wide temperature range 3-300K

Heat power

Cernox distance

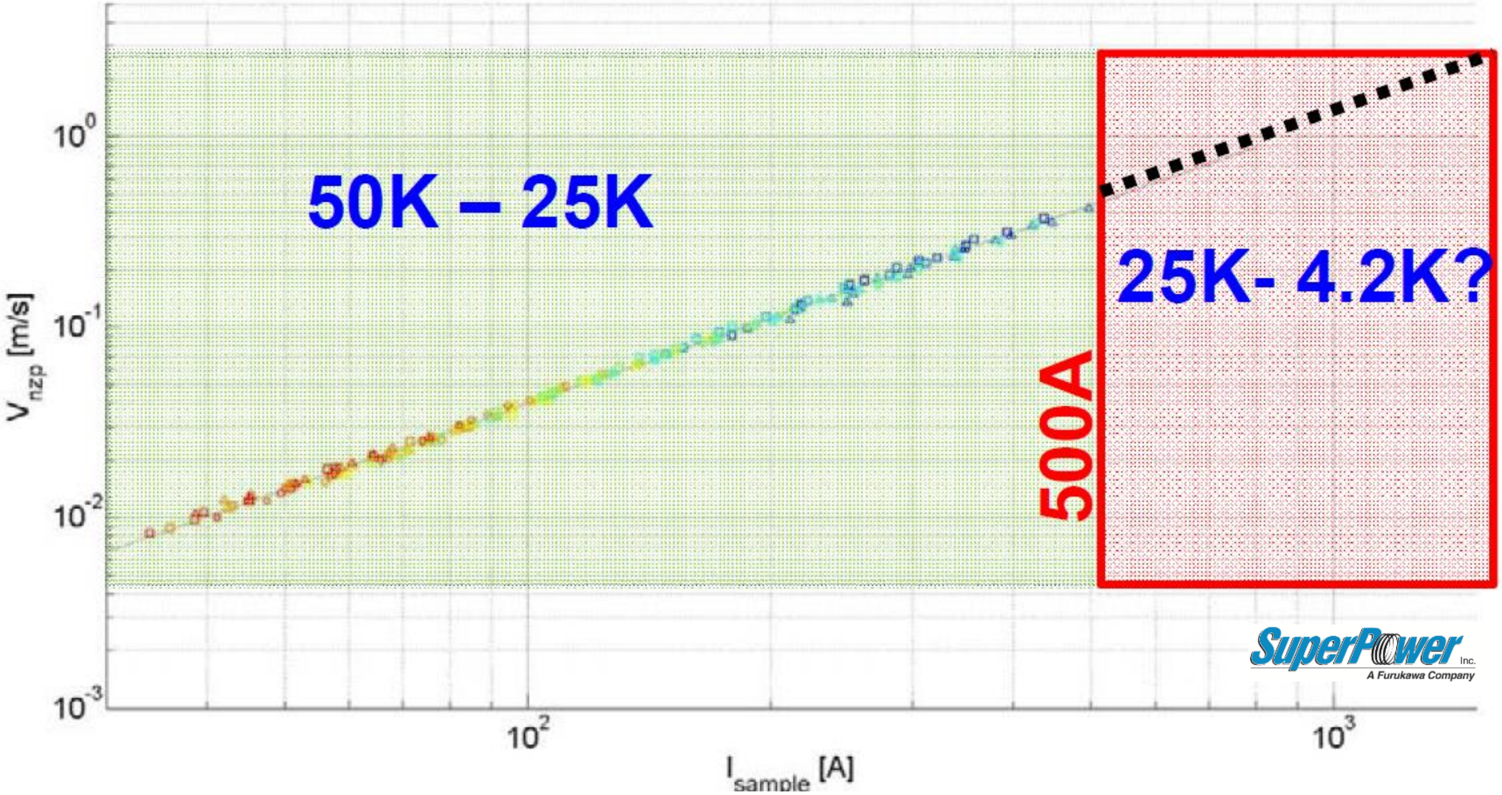
Thermal conductivity $$\kappa = \frac{Q}{\Delta T}\frac{l}{S}$$

Wire cross section

Temperature difference

M. Bonura & C. Senatore, IEEE TAS 23 (2013) 6000404

NZPV measurements at UTWENTE



J. Van Nugteren et al., ICEC-ICMC 2014

Puzzling result: normal zone propagation velocity depends on current but not on temperature