IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2015.
Invited presentation 3A-WT-O1.1 given at EUCAS 2015; Lyon, France, September 6 – 10, 2015
Not submitted to *IEEE Trans. Appl. Supercond.*

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

EuCARD²

EUCAS 2015

FNSNF
FONDS NATIONAL SUISSE DE LA RECHERCHE SCIENTIFIQUE

Field and temperature scaling of the critical current density in commercial REBCO coated conductors

Carmine SENATORE, Marco BONURA, Miloslav KULICH, Giorgio MONDONICO, Christian BARTH

Département de Physique de la Matière Condensée & Département de Physique Appliquée
Université de Genève, Switzerland

Outline

- *Research on coated conductors @ UNIGE*
- *Overview of the industrial REBCO CCs*
- *$J_c(B,T,\theta)$ surface, scaling relations for the temperature and field dependences*
- *Critical current under mechanical loads*
- *Thermo-physical properties: thermal conductivity and normal zone propagation velocity*

Motivation

Towards 20 Tesla accelerator magnets for HEP

EuCARD² Funded by 7 CAPACITIES coordinated by CERN

Today : the record collision energy in LHC is 8 TeV

Scope : Future Circular Colliders, collision energy up to 100 TeV
Shed light on the physics beyond the Standard Model

Towards all-superconducting 30 T-class solenoidal magnets

Funded by FNSNF – Fonds national suisse, Schweizerischer Nationalfonds, Fondo nazionale svizzero, Swiss National Science Foundation *in collaboration with* BRUKER BIOSPIN

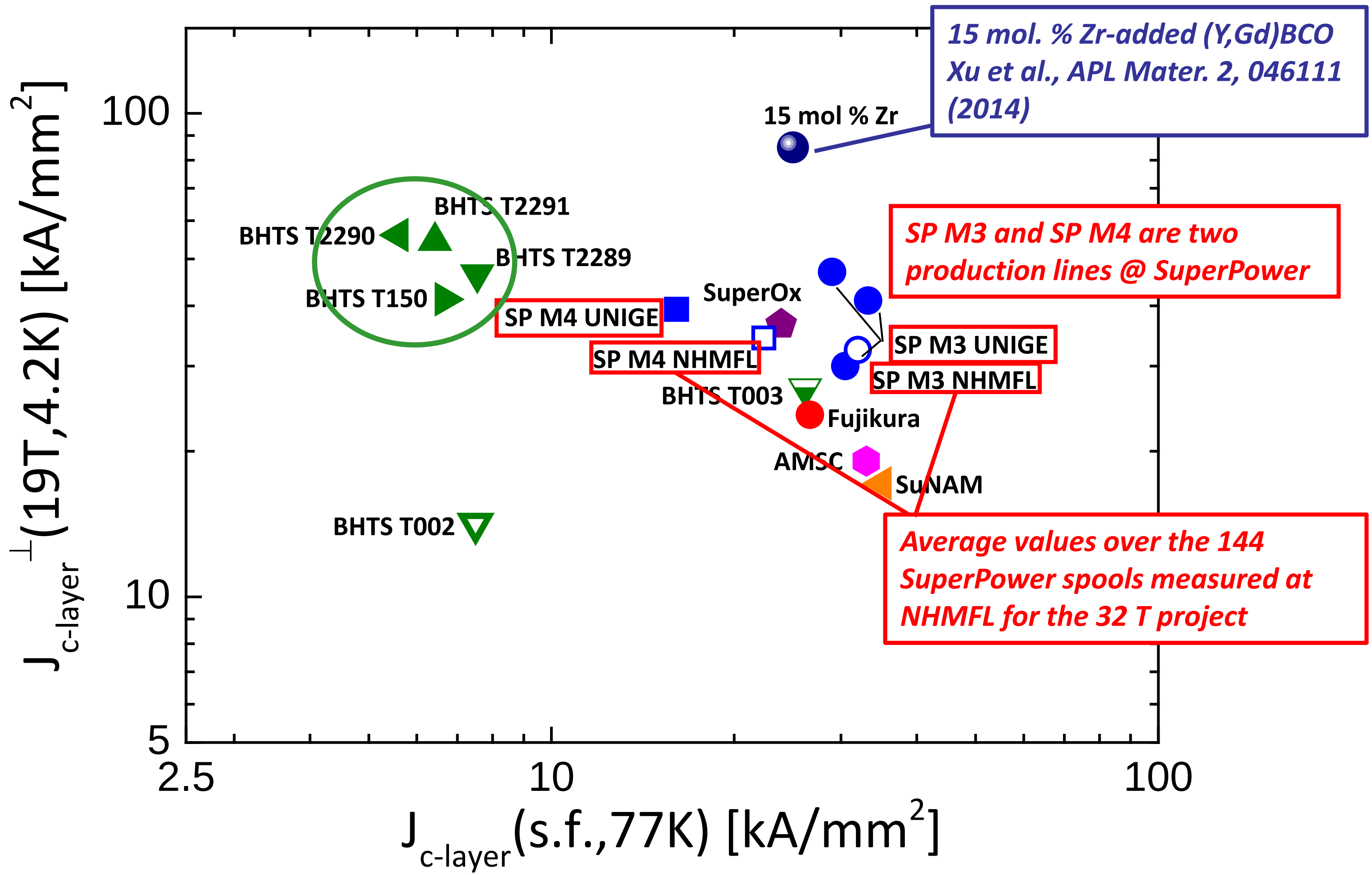
Today : commercial systems with B_{max} = 23.5 T @ T = 2.2K

Scope : high resolution NMR spectrometers, high field laboratory magnets

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	✓					
IBAD		✓	✓	✓	✓	✓
physical deposition		✓	✓	✓	✓	
chemical deposition	✓					✓
in situ *process*		✓	✓		✓	✓
ex situ *process*	✓			✓		
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

Performance overview: J_c(s.f.,77K) vs. $J_c^{\perp}$(19T,4.2K)



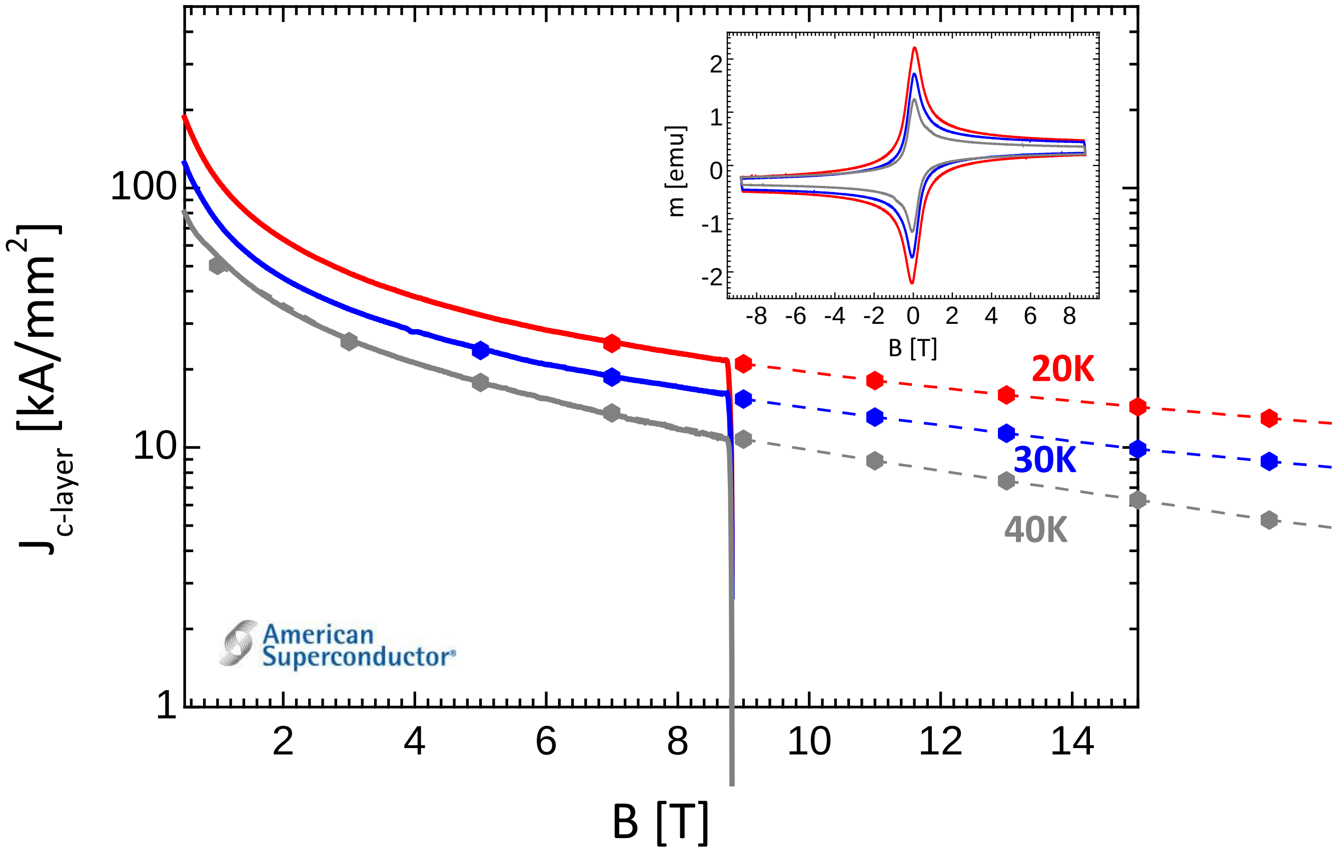
Practical characterization of REBCO CCs
Applications @ low temperature / high fields

- *J_c depends strongly on the orientation of the tape wrt the magnetic field*
- *B_{c2} at low temperature is ~100 T*
- *The operating temperature margin is 30 – 40 K*

  → Thermo-physical properties, c(T,B) & κ(T,B), are essential

- *The response of the tape to mechanical loads depends on its architecture (electromechanical properties)*

Transport and magnetic measurements of $J_c(B,T,\theta)$

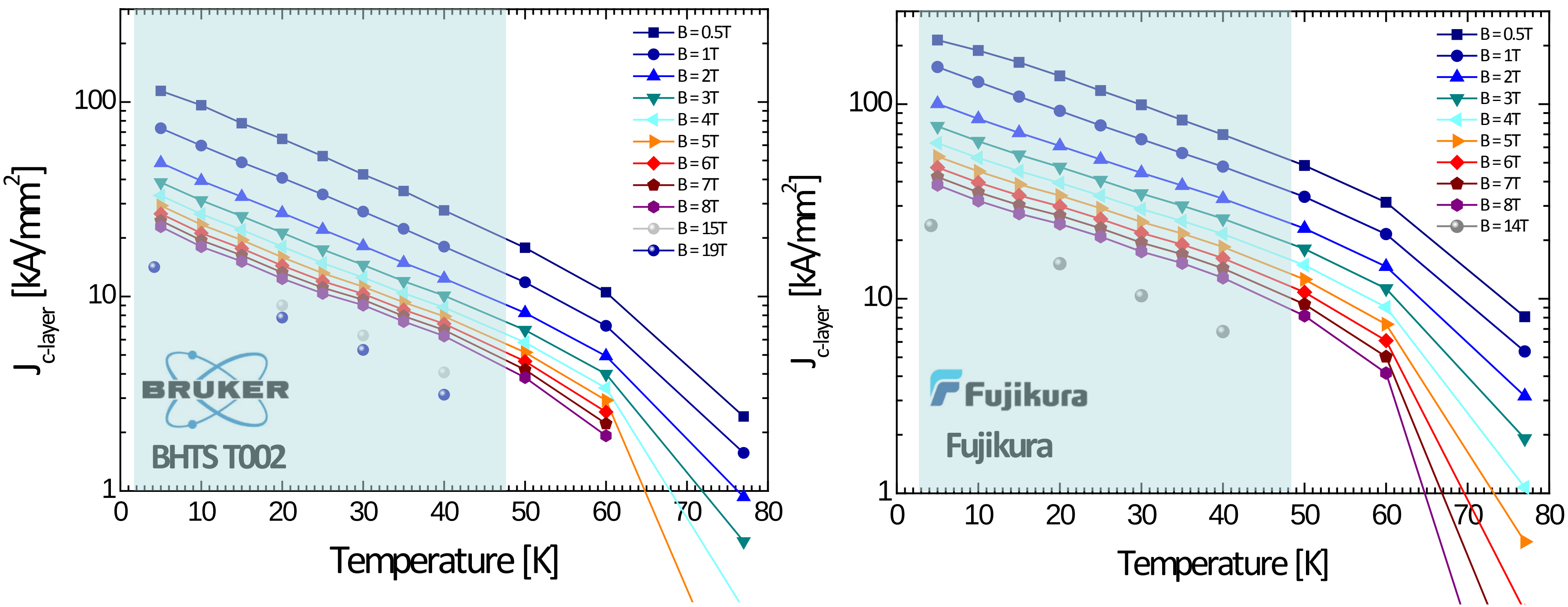


Only a limited portion of the critical surface is practically accessible from transport measurements

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

Temperature dependence of J_c

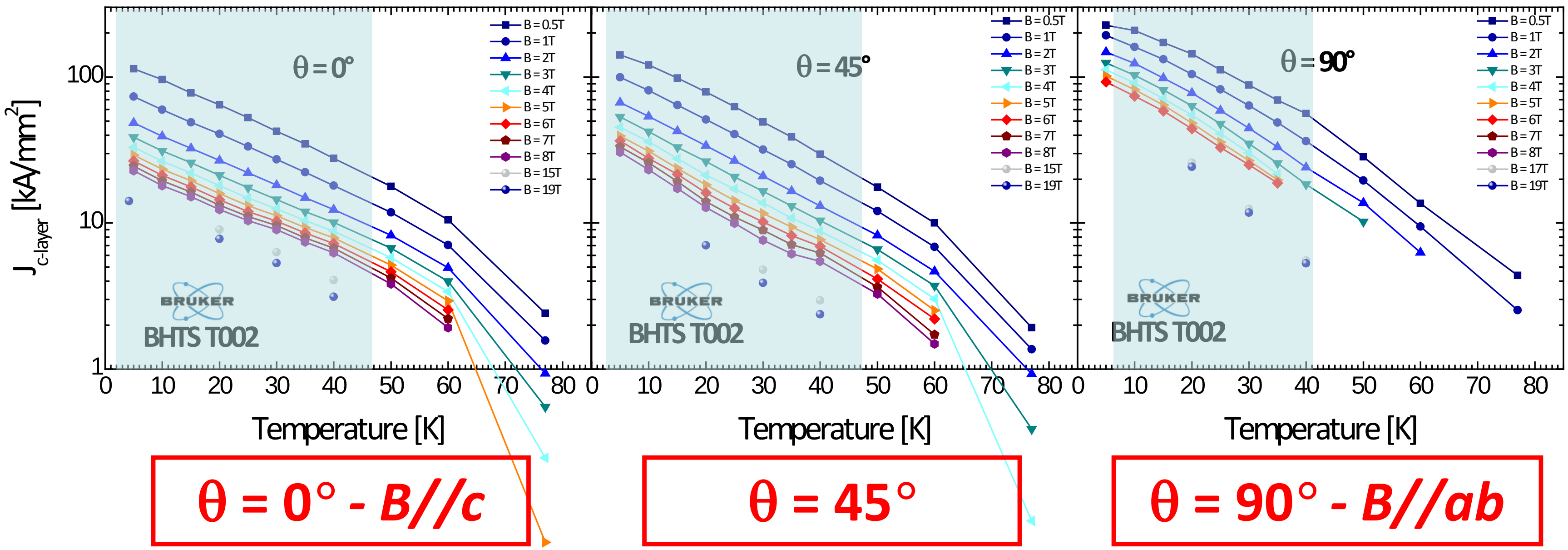
$\theta = 0° - B//c$



Temperature scaling relation

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

Temperature dependence of J_c : 3 orientations



θ = 0° - *B//c*

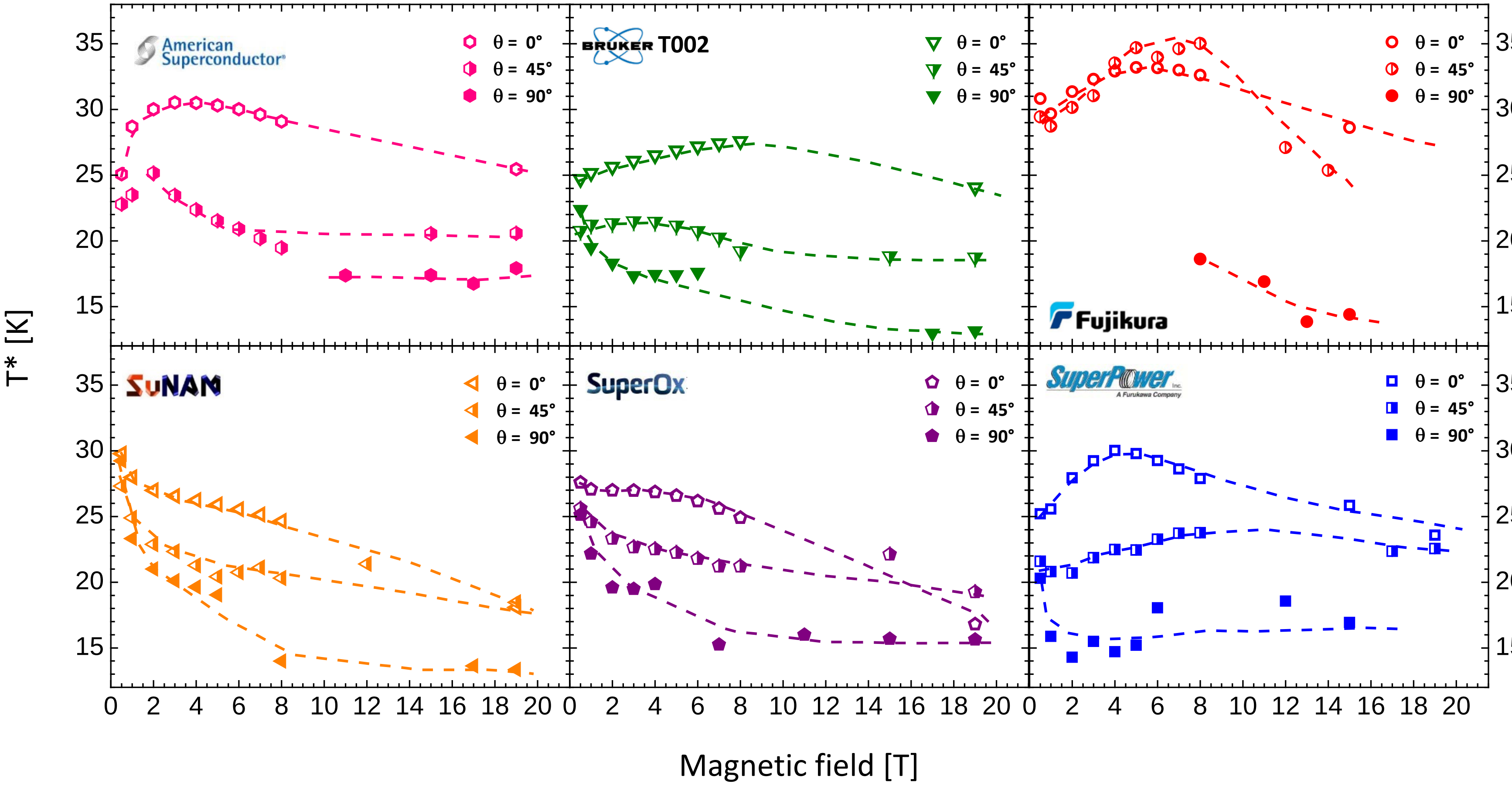
θ = 45°

θ = 90° - *B//ab*

The temperature scaling relation $J_c(B,T) = J_c(B,T=0)e^{-\frac{T}{T^*}}$ *holds also at 45° and 90° for T up to 40 K*

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

Temperature scaling parameter T*

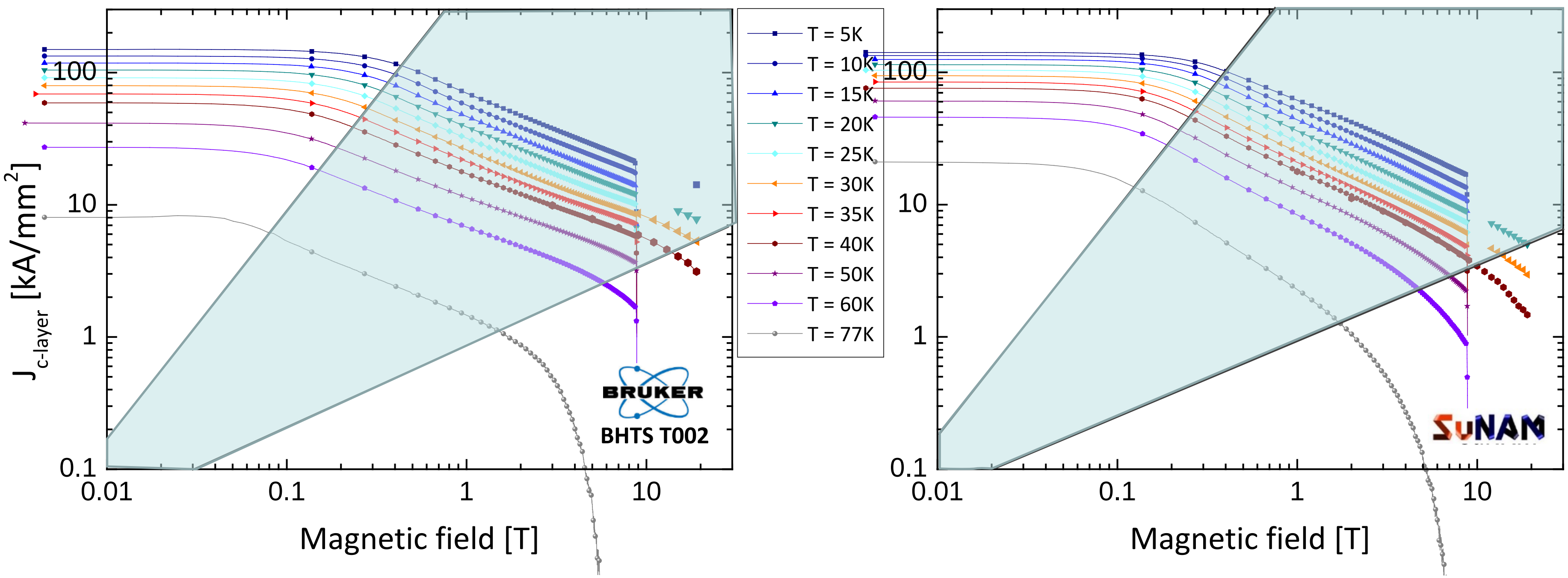


T* ranges between 15K and 35K – it depends on field and orientation

Lower T* values ⇒ faster decrease of I_c with increasing T

Field dependence of J_c

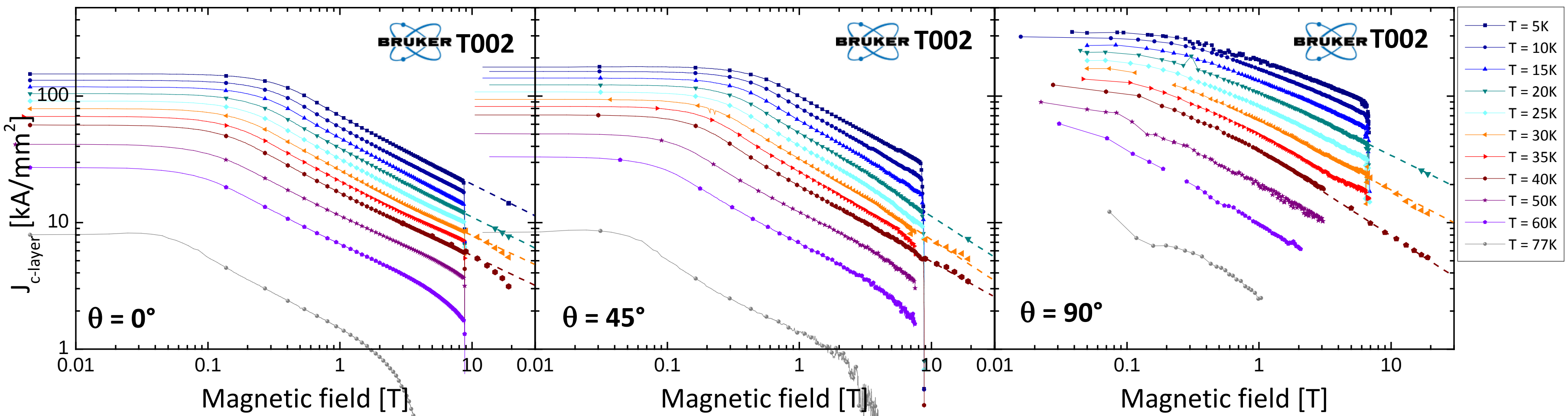
$\theta = 0° - B//c$



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

α is almost constant below 40 K, the value varies between 0.5 and 0.8

Field dependence of J_c : 3 orientations



θ = 0° - *B//c*

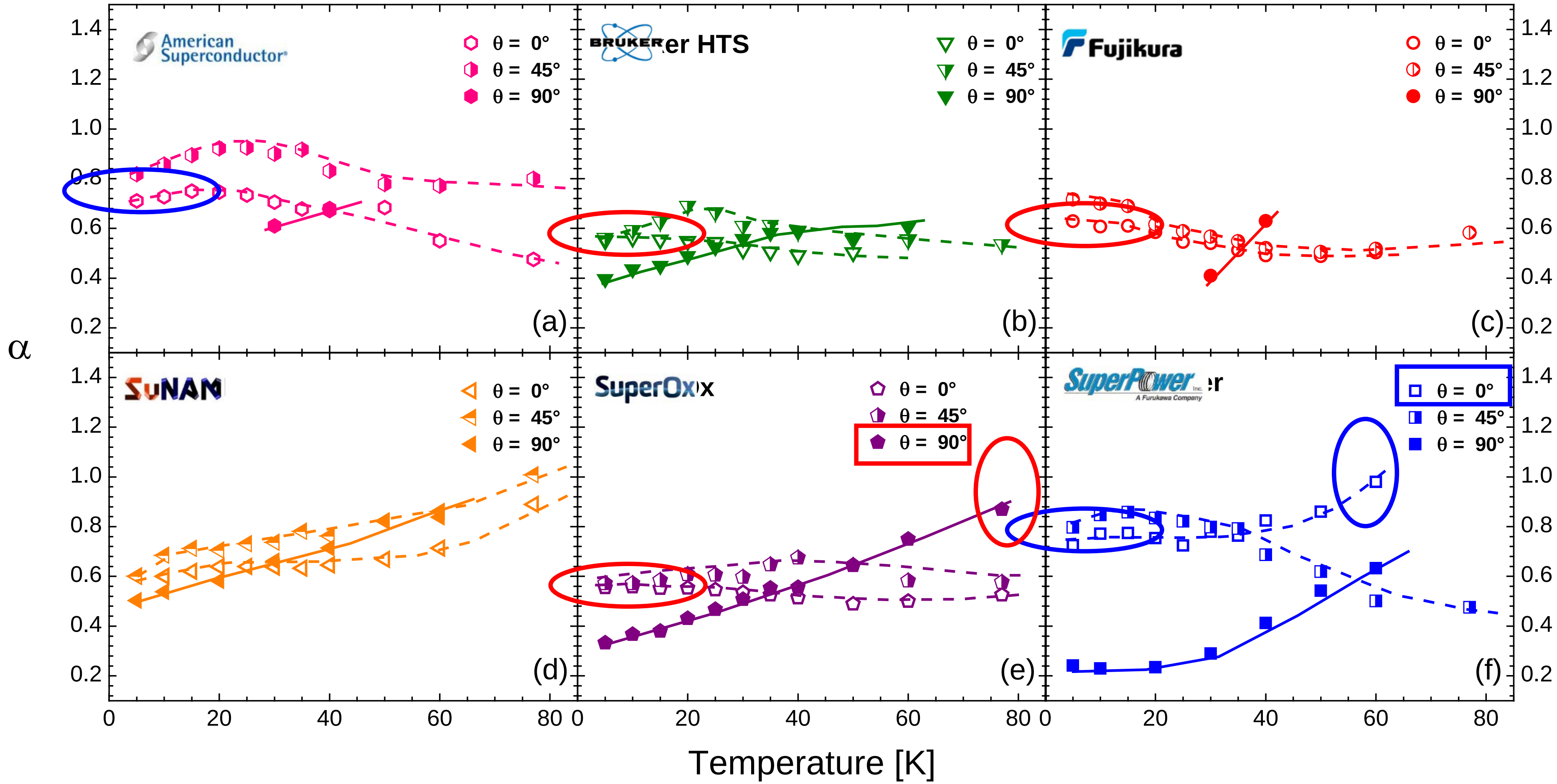
θ = 45°

θ = 90° - *B//ab*

Field scaling relation

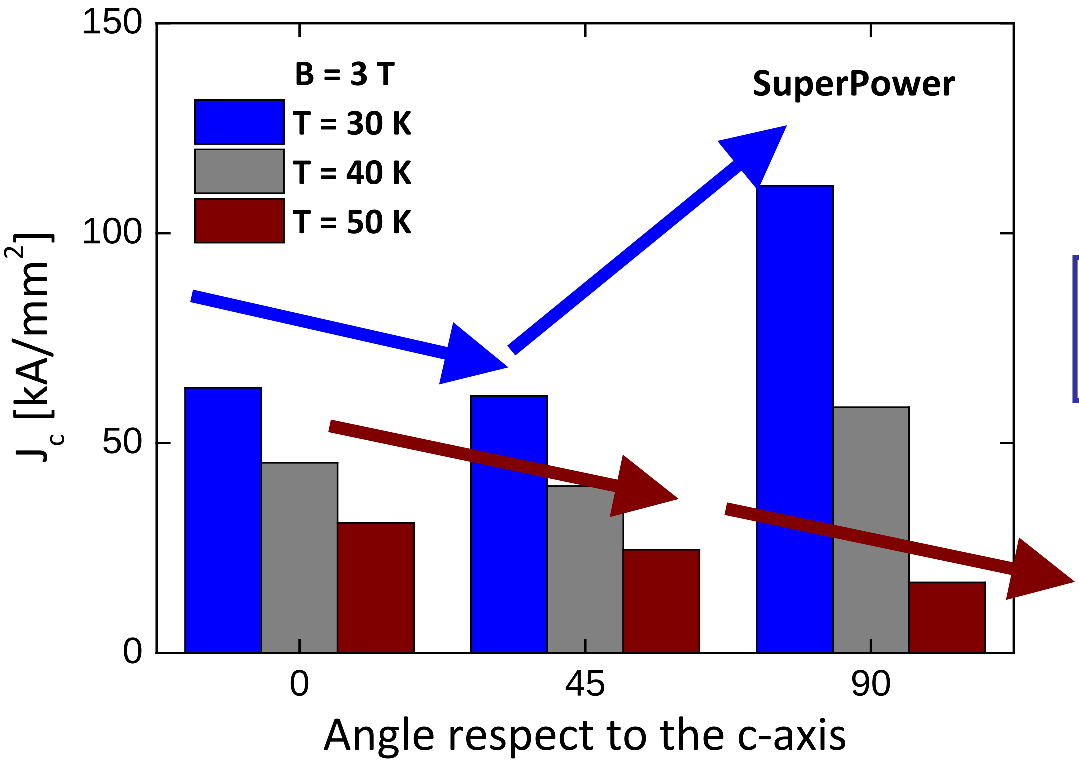
$$J_c(B,T) = J_c(B=0,T)\,B^{-\alpha}$$

Field scaling parameter α



Higher α values ⇒ faster decrease of I_c with increasing B

$I_c(T)$ angular dependence: SuperPower with AP



Effects of artificial pinning on the I_c anisotropy

$T < 30\ K \Rightarrow J_c(0°) < J_c(45°) < J_c(90°)$

$30\ K < T < 40\ K \Rightarrow J_c(0°) > J_c(45°)$ and $J_c(0°) < J_c(90°)$

$T > 40\ K \Rightarrow J_c(0°) > J_c(45°) > J_c(90°)$

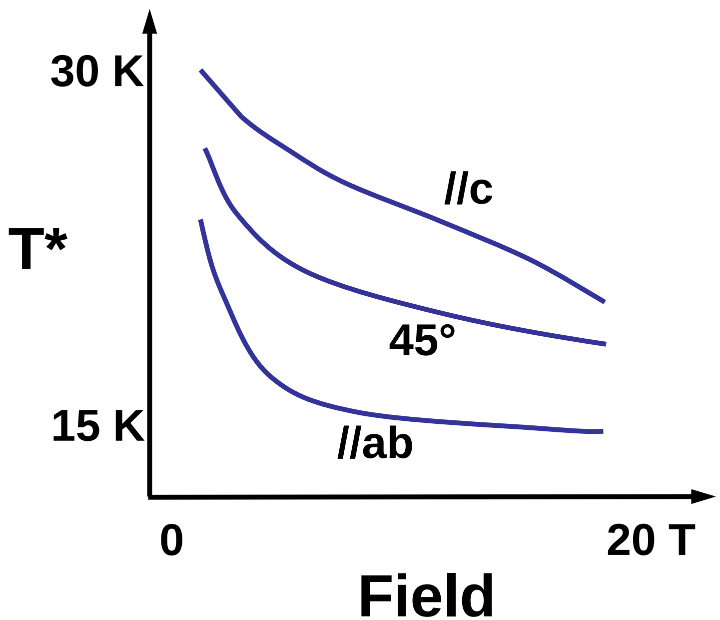
IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2015.
Invited presentation 3A-WT-O1.1 given at EUCAS 2015; Lyon, France, September 6 – 10, 2015
Not submitted to *IEEE Trans. Appl. Supercond.*

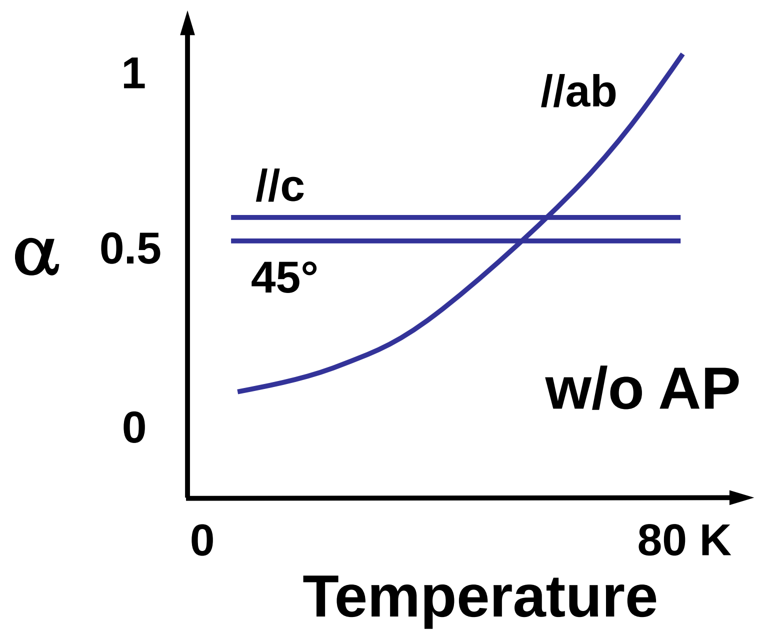
Temperature and field scaling of J_c

For temperatures below ~50 K, critical surface $J_c(B,T)$ in the form

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

Scaling relation verified for $\theta = 0°$, 45° and 90°, but T^* and α depend on θ





Lower T^* values ⇒ faster decrease of I_c with increasing T

Higher α values ⇒ faster decrease of I_c with increasing B

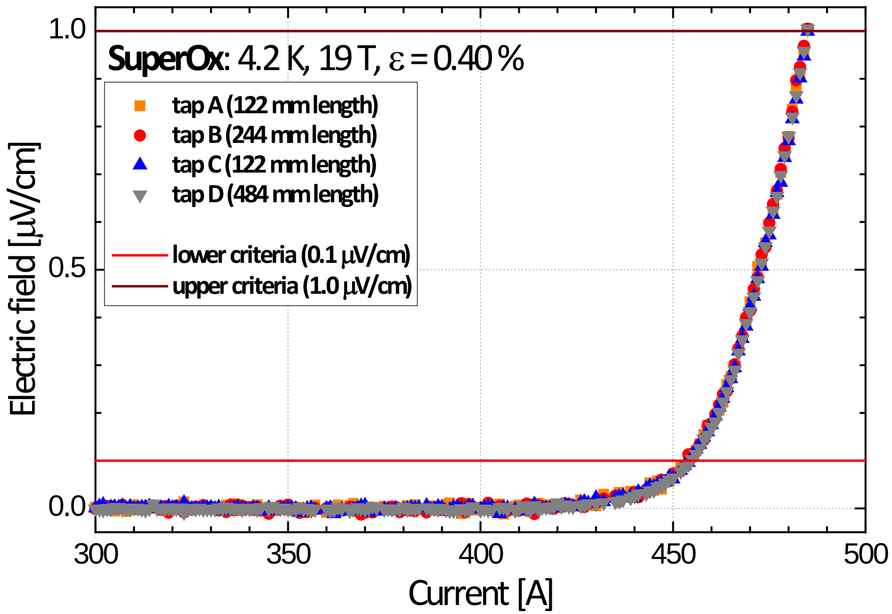
Critical current depends on

- ***temperature***
- ***field intensity***
- ***field orientation***
- ***mechanical loads***

I_c vs. axial strain: measurement method

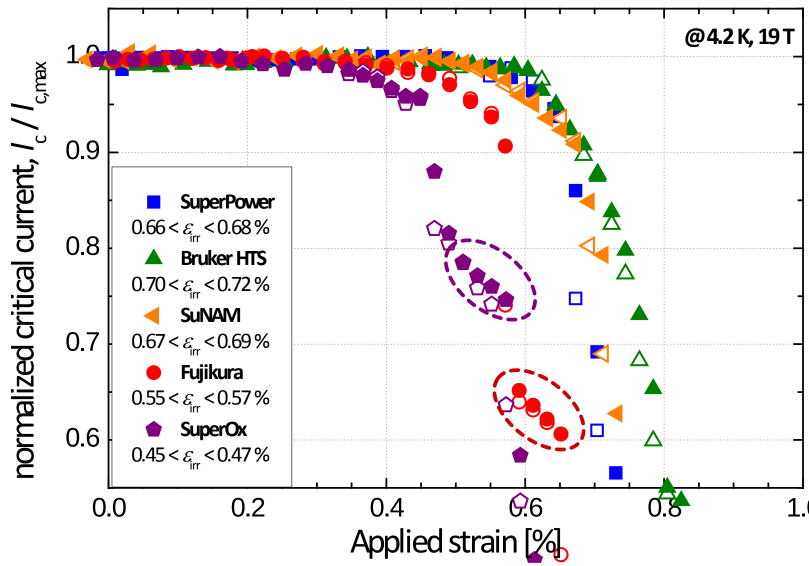
Walters spring (WASP)

- *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*

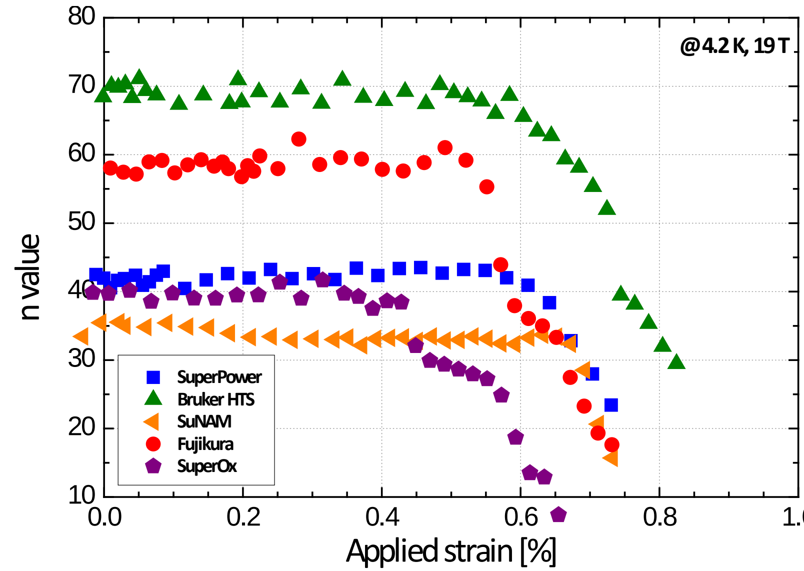


Dependence of I_c on axial strain @ 4.2 K, 19 T

I_c vs. applied strain



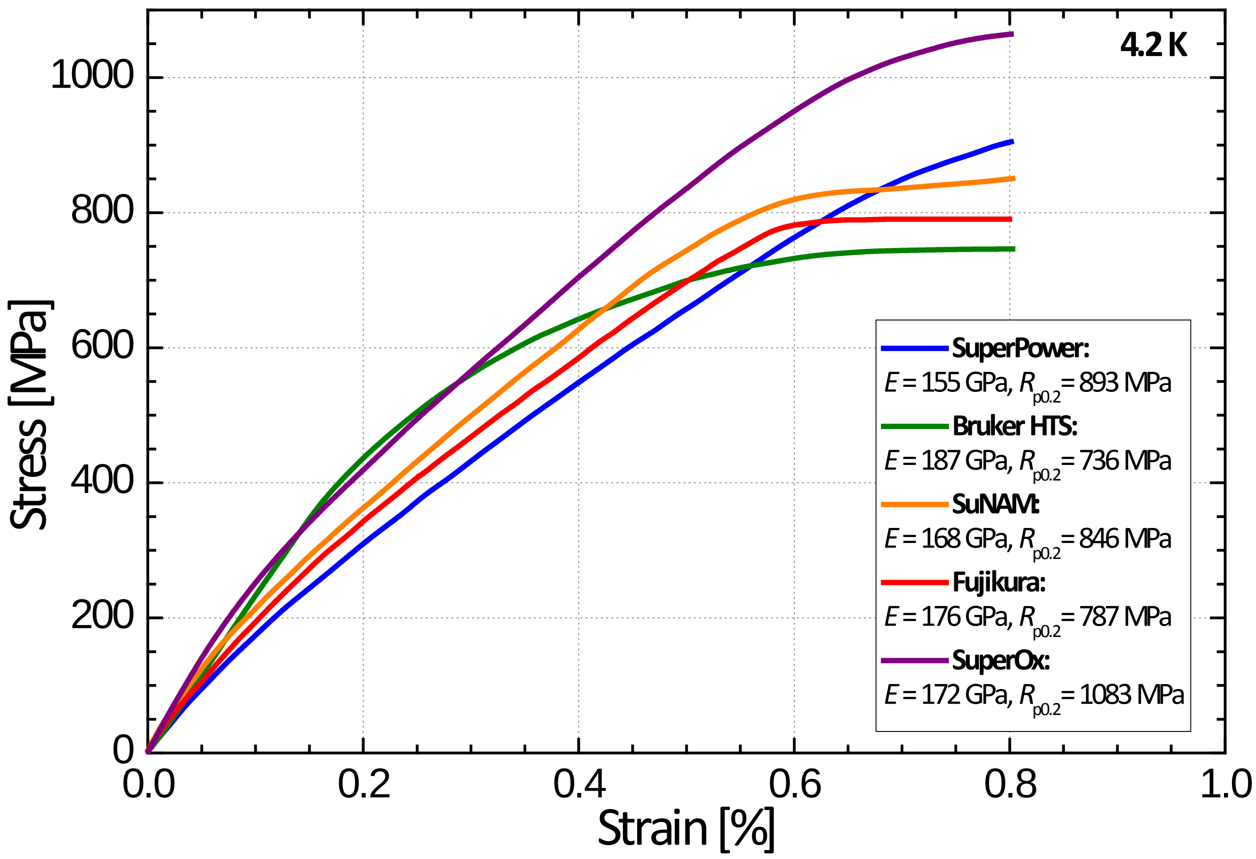
n value vs. applied strain



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

C. Barth, G. Mondonico and CS, SuST 28 (2015) 045011

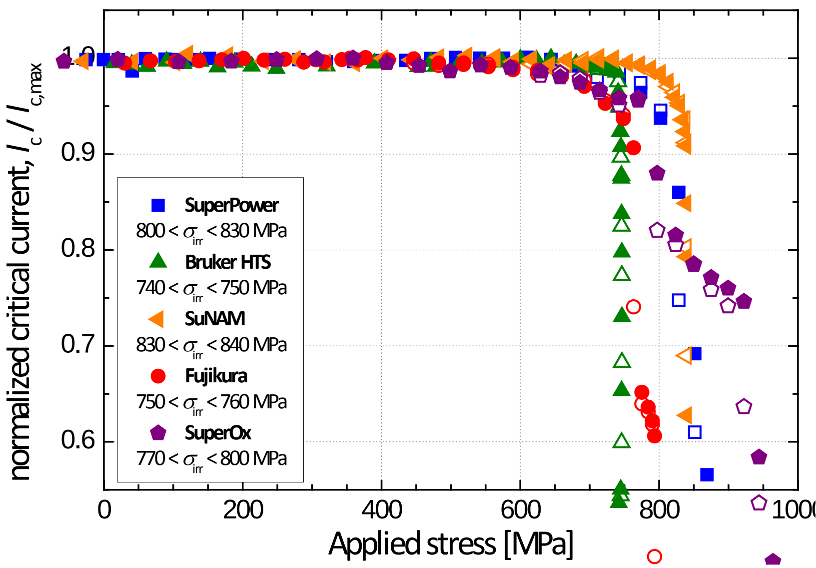
Stress vs. strain measurements @ 4.2 K



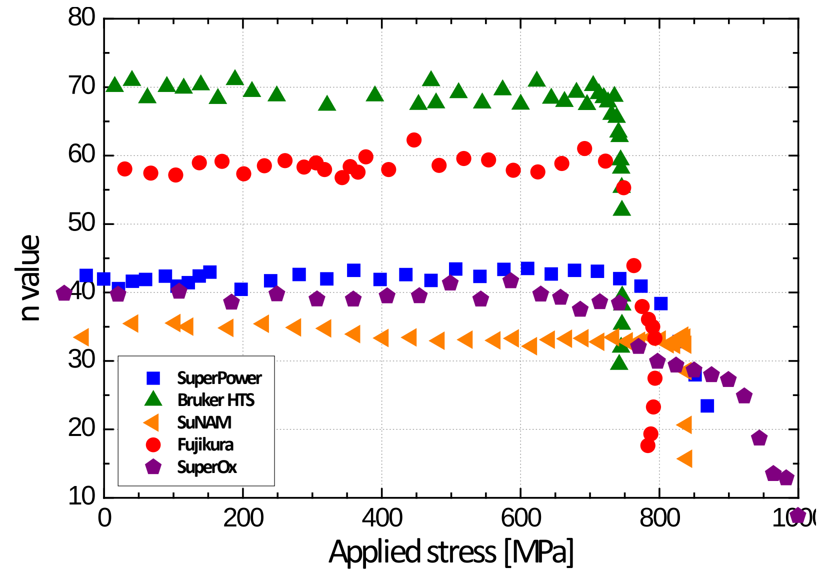
C. Barth, G. Mondonico and CS, SuST 28 (2015) 045011

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

I_c vs. applied stress



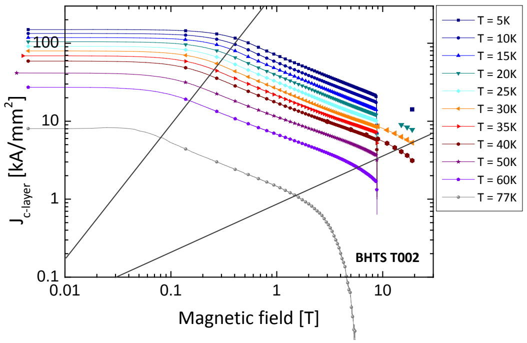
n value vs. applied stress



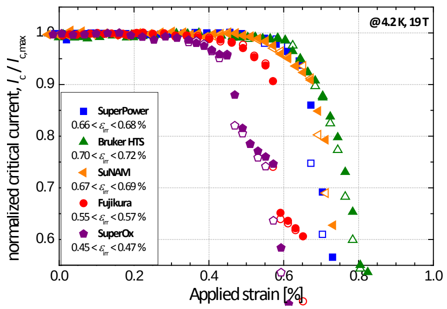
- ***All samples have a very similar behaviour***
- ***Very low stress effect → curves are flat in rev. region***
- ***Irreversible limits σ_{irr} in 740 – 840 MPa range***

C. Barth, G. Mondonico and CS, SuST 28 (2015) 045011

Electromagnetic properties ✓



Electromechanical properties ✓



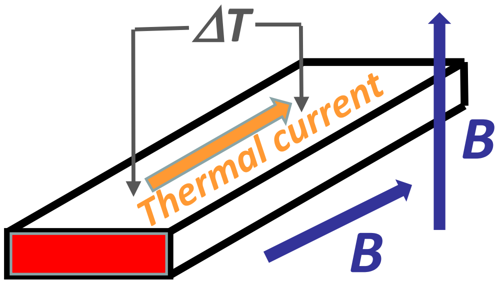
Thermo-physical properties → →

Thermal conductivity of REBCO CCs

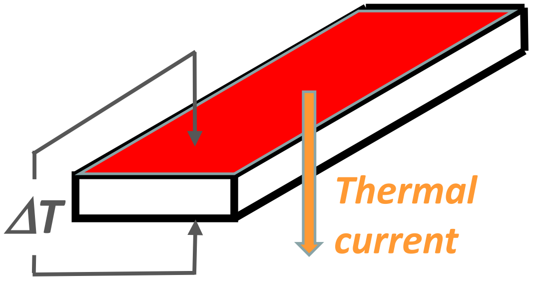
Thermal conductivity is an essential parameter for QUENCH studies

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

  B perpendicular & parallel to thermal current



- ***Transverse thermal conductivity***



M. Bonura and CS, SuST 28 (2015) 025001

M. Bonura and CS, TASC 25 (2015) 6601304

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2015.
Invited presentation 3A-WT-O1.1 given at EUCAS 2015; Lyon, France, September 6 – 10, 2015
Not submitted to *IEEE Trans. Appl. Supercond.*

Longitudinal thermal conductivity

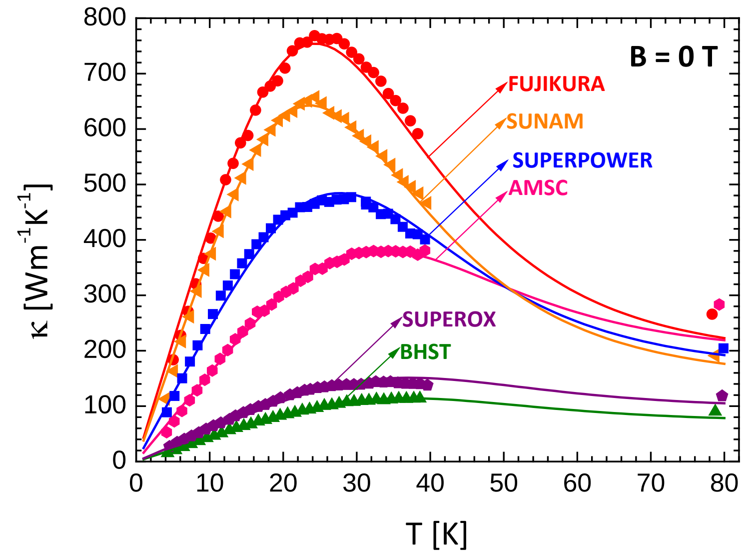
$$\kappa_{exp} = \sum_i \kappa_i \frac{S_i}{S_{tot}} \approx \kappa_{Cu} \frac{S_{Cu}}{S_{tot}} \quad \text{and } \kappa_{Cu} = f(RRR_{Cu})$$

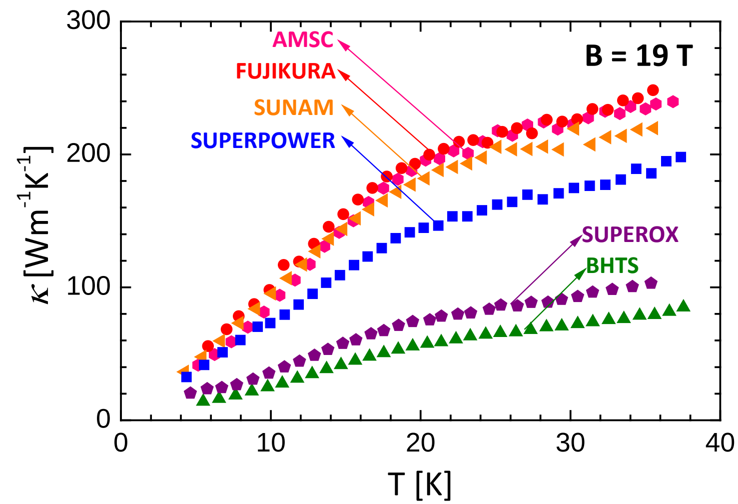
Manufacturer	RRR_{Cu} [*fit*]	RRR_{Cu} $[\rho(T)]$	S_{Cu}/S_{tot}
AMSC	20	19	0.51
BHST	14	17	0.20
FUJIKURA	62	59	0.44
SUNAM	69	61	0.34
SUPEROX	13	14	0.27
SUPERPOWER	39	42	0.40

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

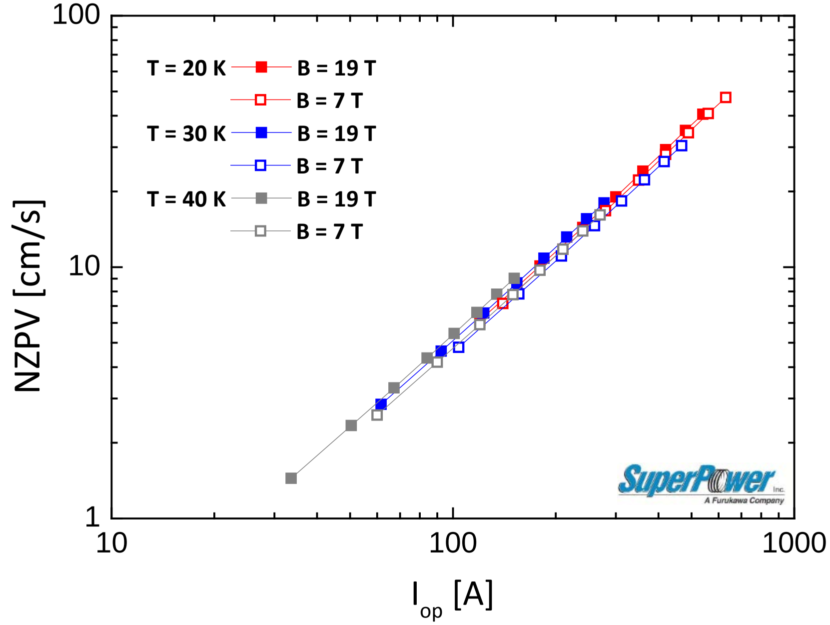
Cu/non-Cu ratio and RRR_{Cu} determine the in-field variation of κ

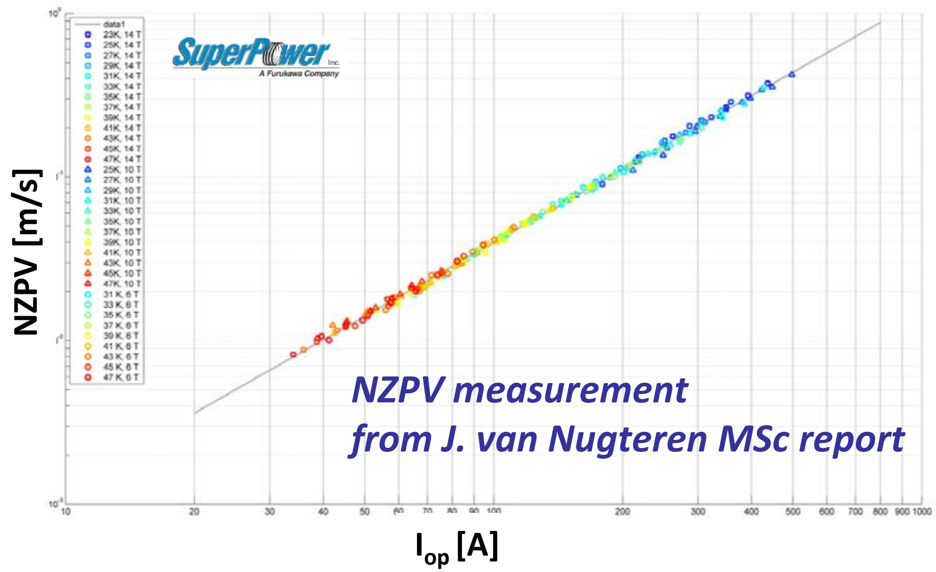
M. Bonura and CS, SuST 28 (2015) 025001





Normal zone propagation velocity





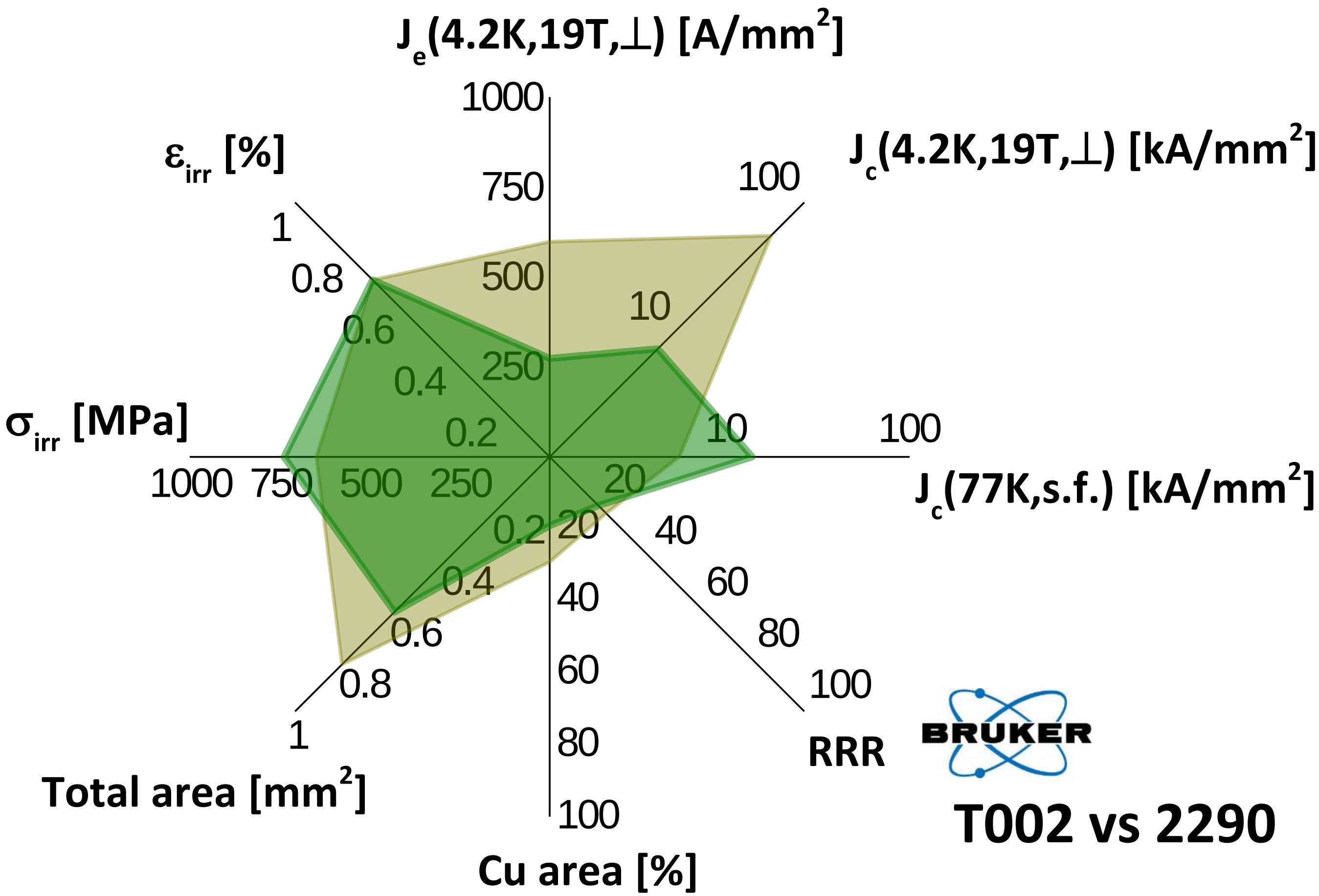
$$NZPV_L \approx \frac{I_{op}}{S_{tot}} \sqrt{\frac{\kappa(T_S)\rho(T_S)}{\int_{T_{op}}^{T_S} c_S(T_S)dT \left[c_n(T_S) - \frac{1}{\kappa(T_S)} \frac{d\kappa}{dT}\Big|_{T=T_S} \int_{T_{op}}^{T_S} c_S(T_S)dT \right]}}$$

where $T_S = T_{CS} + \frac{T_C - T_{CS}}{2}$

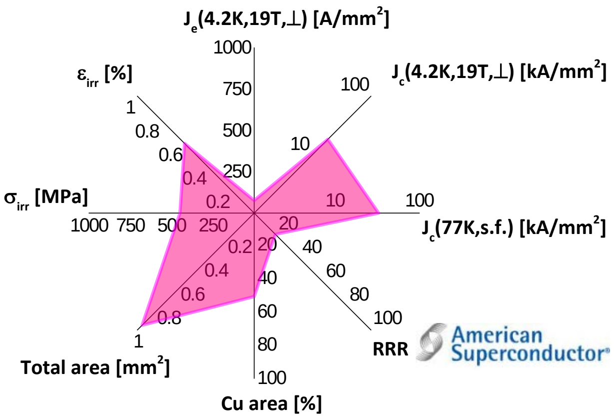
is determined by the $J_c(T)$ dependence

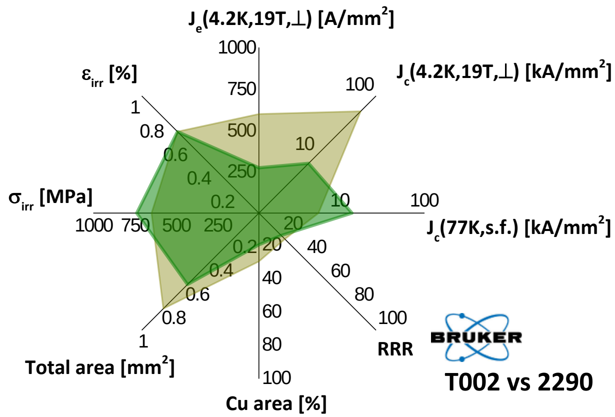
From the experimental κ, ρ, c, $J_c(T)$, NZPV is found to depend only on I_{op} following a power law

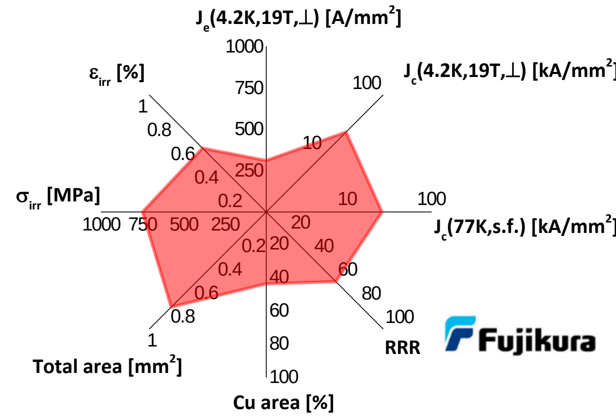
Summary - Main parameters at a glance

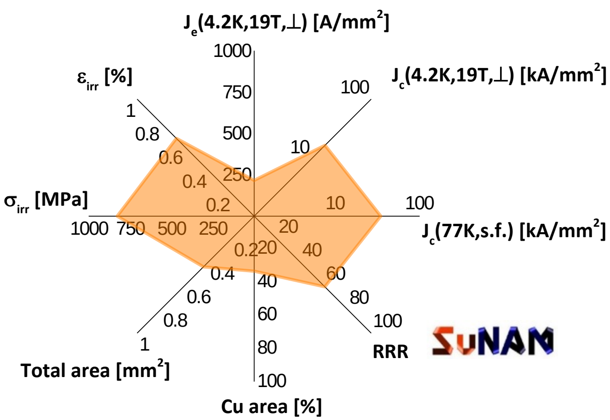


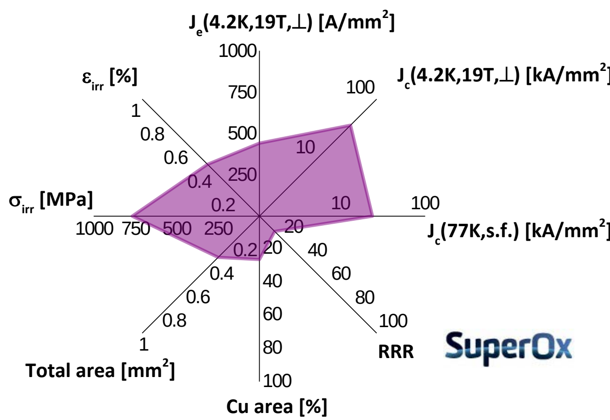
Summary - Main parameters at a glance

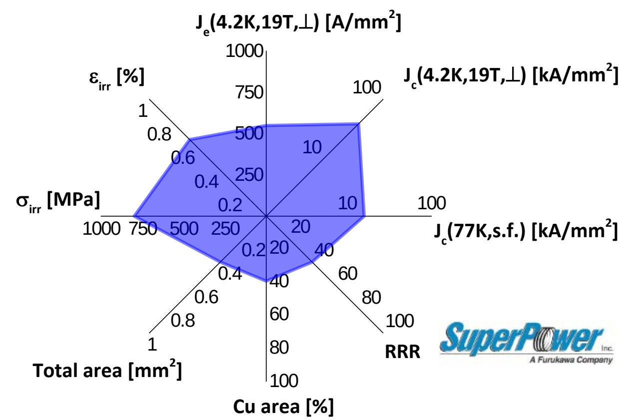












Conclusions

- *Explored the $J_c(B,T,\theta,\sigma)$ surface for CCs from 6 manufacturers*
- *Scaling of $J_c(B,T)$ with an exponential T dependence and a power-law B dependence*
- *Reconstruction of the critical surface possible with a minimum number of measurements*
- *Irreversible limit σ_{irr} under axial loads in 740 – 840 MPa range for all manufacturers*
- *Direct measurements of in-field thermal conductivity for quench propagation studies and calculation of the NZPV*