http://supra.unige.ch

High performance superconductors for next generation particle colliders

Material development and electromechanical studies at UNIGE

C. Senatore, F. Buta, C. Barth, L. Gamperle
Department of Quantum Matter Physics, University of Geneva, Switzerland

J. Ferradas, S. Hopkins, A. Ballarino, B. Bordini, D. Tommasini, L. Rossi
CERN, Switzerland

U. Betz, A. Usoskin
Bruker HTS, Germany

Outline

The FCC dipoles at 16 T: how to get there with Nb_3Sn (LTS)

Reach the ultimate performance:

Investigations on the enhancement of J_c in $(Nb,X)_3Sn$ superconductors by internally oxidized ZrO_2 particles

Withstand the electromagnetic forces:

Electromechanical tests – effects of the transverse stress

Dipole magnets at 20 T and beyond: the call for HTS

Conductor R&D based on YBCO coated conductors for dipole demonstrators

Outline

The FCC dipoles at 16 T: how to get there with Nb_3Sn (LTS)

Reach the ultimate performance:

Investigations on the enhancement of J_c in $(Nb,X)_3Sn$ superconductors by internally oxidized ZrO_2 particles

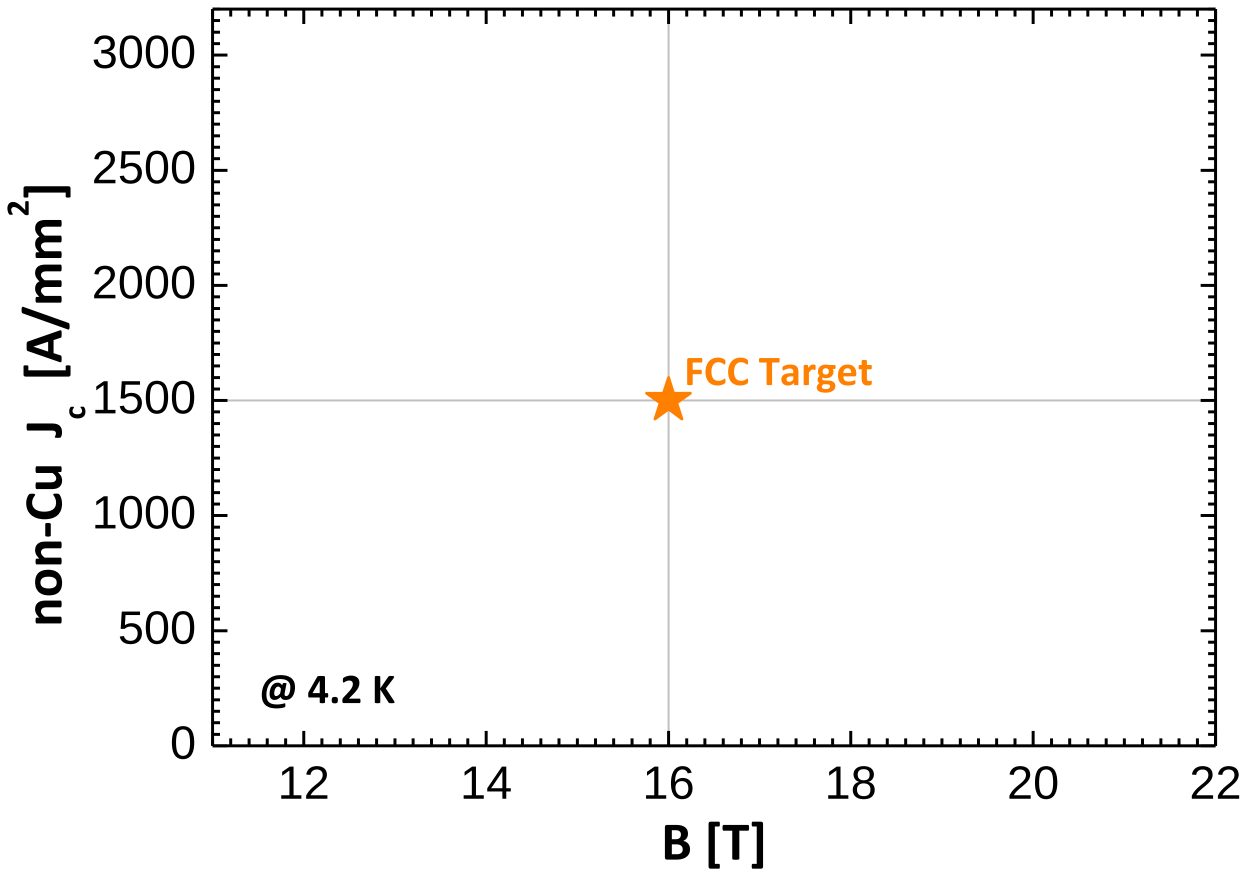
Withstand the electromagnetic forces:

Electromechanical tests – effects of the transverse stress

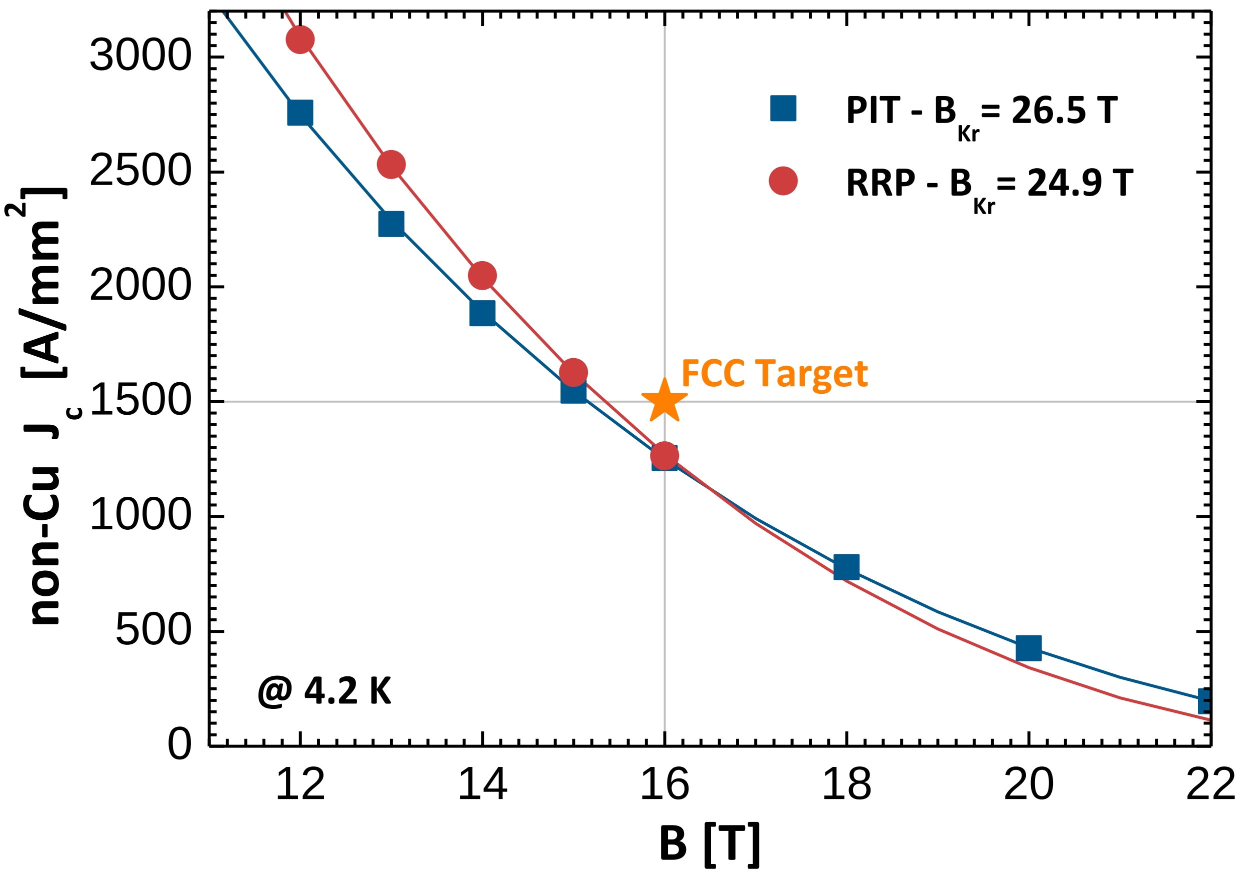
Dipole magnets at 20 T and beyond: the call for HTS

Conductor R&D based on YBCO coated conductors for dipole demonstrators

Performance target non-Cu J_c(4.2K,16 T) = 1500 A/mm²



Performance target non-Cu J_c(4.2K,16 T) = 1500 A/mm²



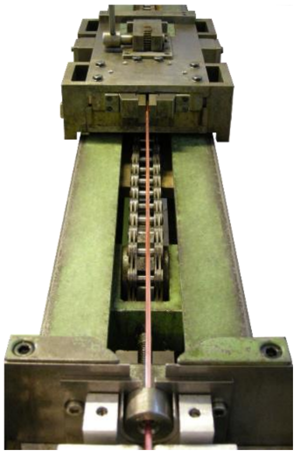
J. Parrell et al., AIP Conf. Proc. 711 (2004) 369

T. Boutboul et al., IEEE TASC 19 (2009) 2564

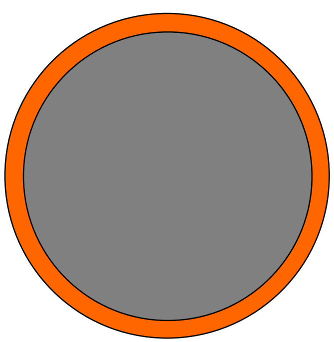
Equipment and experience in conductor R&D @ UNIVERSITÉ DE GENÈVE

FACULTÉ DES SCIENCES

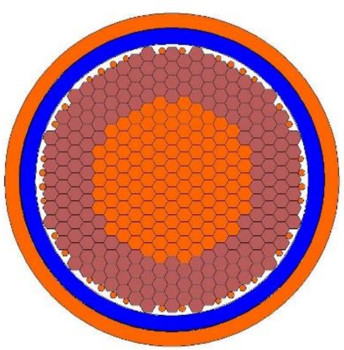
Deformation processes as for industrial production



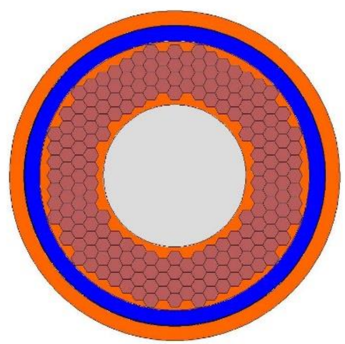
In-house manufacture of multifilamentary conductors



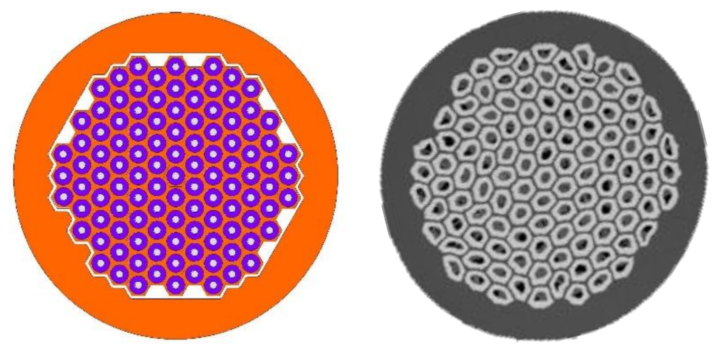
Cu/Nb-Ta rod



Sub-element bundle

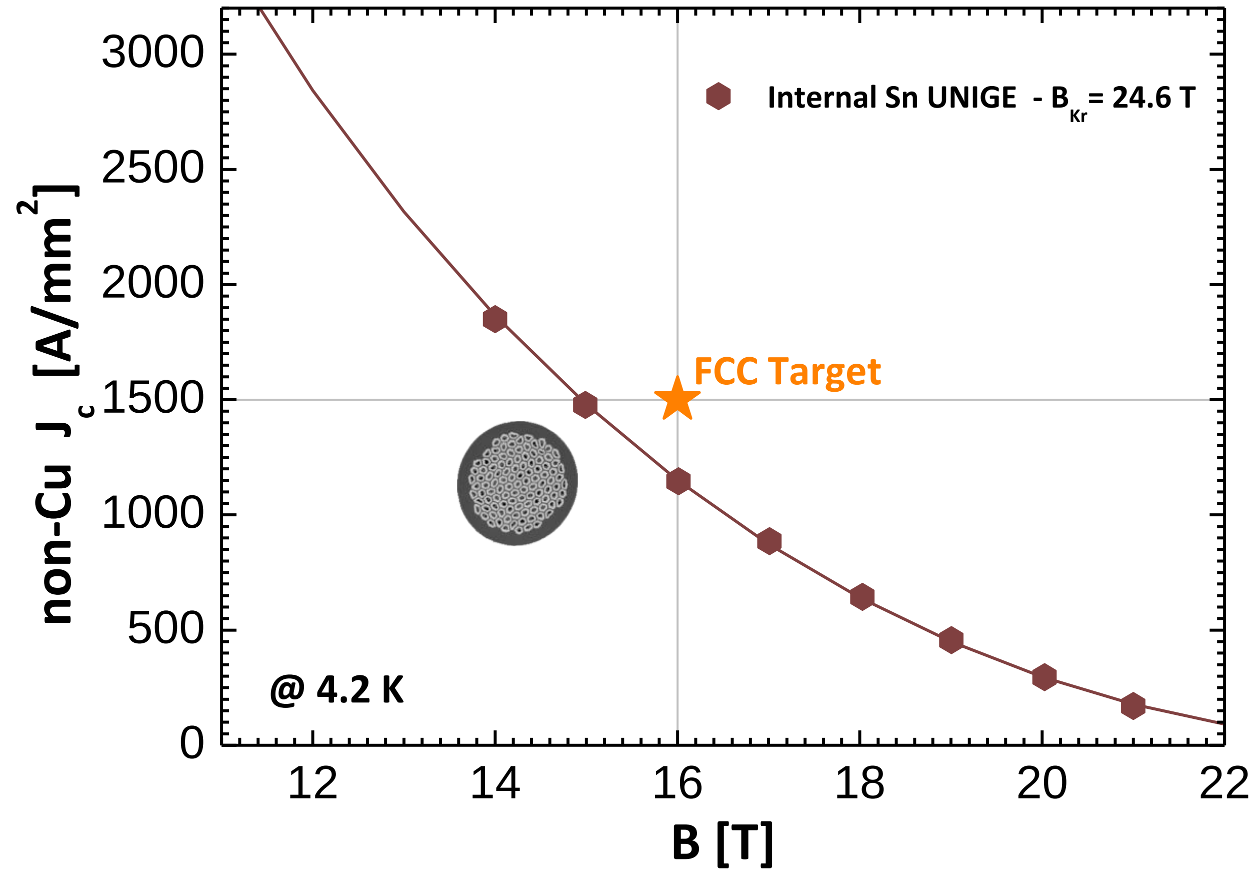


Sub-element with pure Sn core



Final wire
109 sub-elements

Performance target non-Cu J_c(4.2K,16 T) = 1500 A/mm²



F. Buta, R. Flükiger, CTI 9049.1 PFIW-IW final report, 2011

Grain refinement by Internal Oxidation in Nb_3Sn

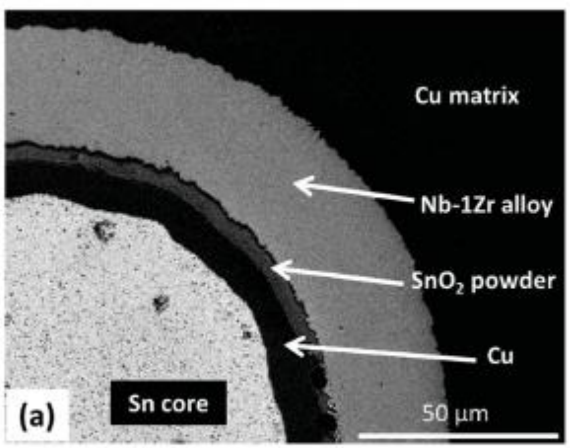
Idea from Benz (1968) to form fine precipitates in Nb to impede the Nb_3Sn grain growth

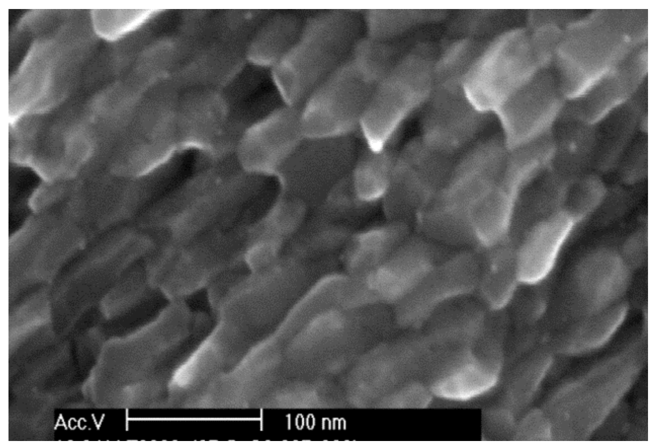
M.G. Benz, Trans. Metall. Soc. AIME, 242 (1968) 1067-1070

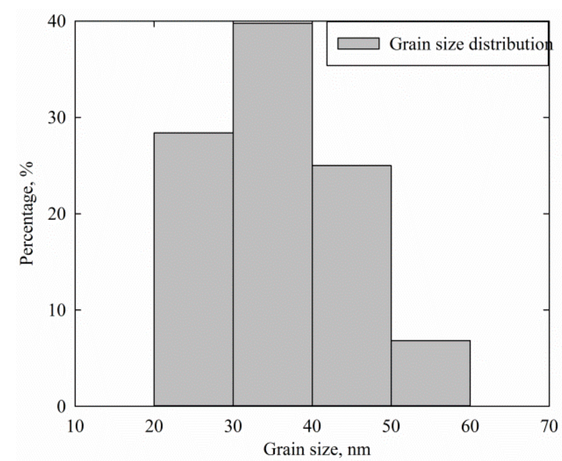
Use of a Nb-Zr alloy: Zr has stronger affinity to oxygen than Nb

THE OHIO STATE UNIVERSITY

Oxygen supply added to the composite: oxidation of Zr and formation of nano-ZrO_2







X. Xu et al., APL 104 (2014) 082602
X. Xu et al., Adv. Mat. 27 (2015) 1346

Average grain size is reduced down to ~ 50 nm in binary Nb_3Sn

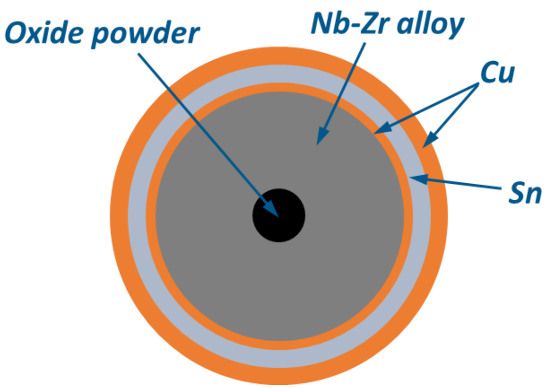
Recent advances on Ta-doped Nb_3Sn

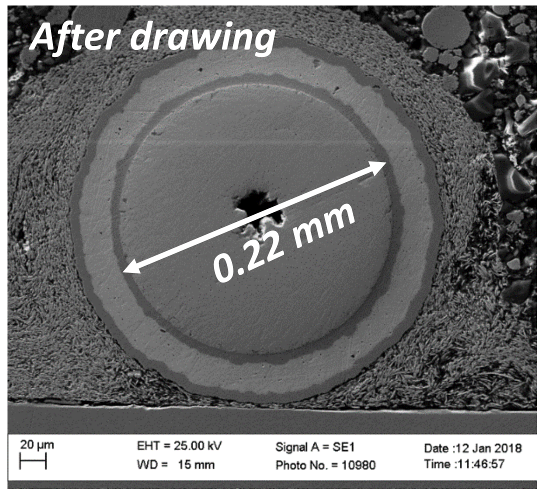
- **48 filaments, Zr addition, grain size 70-80 nm**
  X. Xu et al., SuST 32 (2019) 02LT01
- **monofilaments, Hf addition, grain size 50-70 nm**
  S. Balachandran et al., arXiv: 1811.08867 (2018)

Enhancement of J_c in $(Nb,X)_3Sn$ superconductors by internally oxidized ZrO_2 particles

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

Addendum FCC-GOV-CC-0112 (KE3545/ATS)





Nb alloy	Metal oxide
Nb-7.5wt%Ta	none
Nb-1wt%Zr	MoO_3
Nb-1wt%Zr	SnO_2
Nb-1wt%Zr	CuO
Nb-7.5wt%Ta-1wt%Zr	SnO_2
Nb-7.5wt%Ta-2wt%Zr	SnO_2

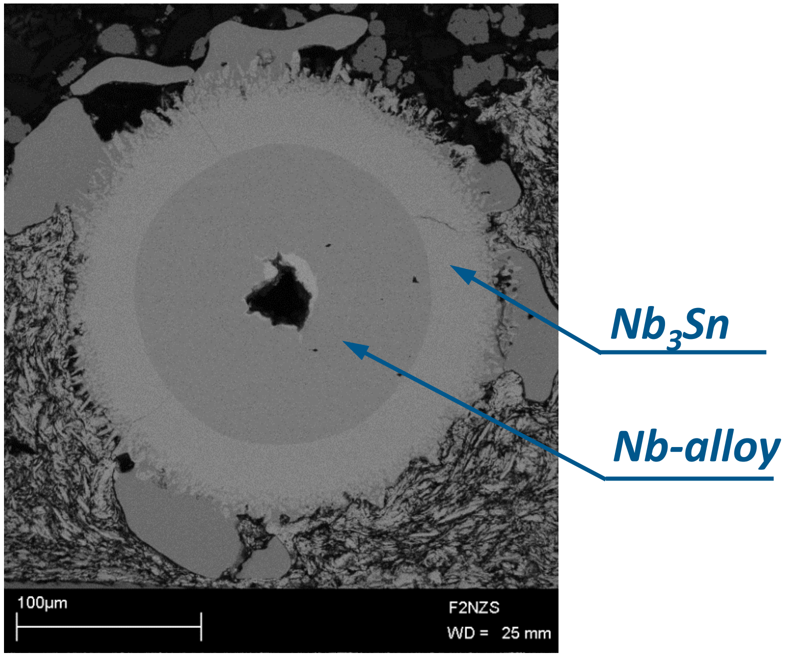
Ø 220 µm wires of Nb alloy were prepared by cold deformation of Ø 12 mm rod with nano-sized powders compacted in a central hole

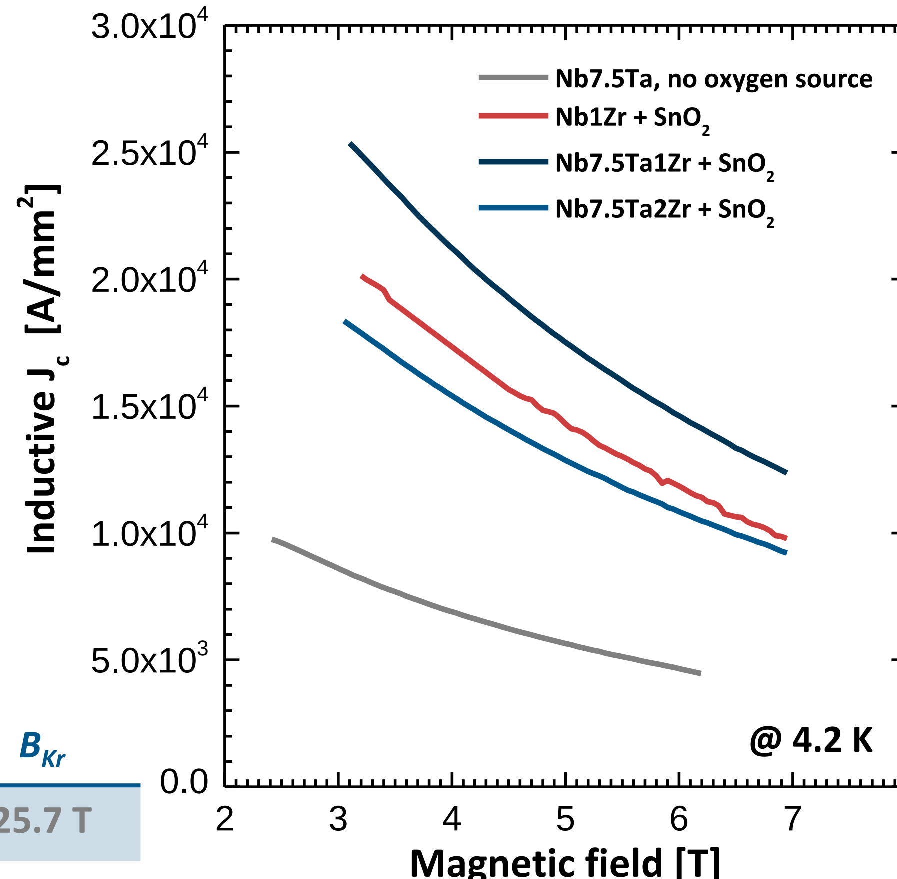
Nb alloy wire was then electroplated successively with: Cu, Sn, Cu

Evaluated different oxygen sources with

- *high Gibbs free energy of formation*
- *low hardness that would make it compatible with wire fabrication*
- *the metal resulting from the reduction not affecting superconductivity*

Results: critical current density





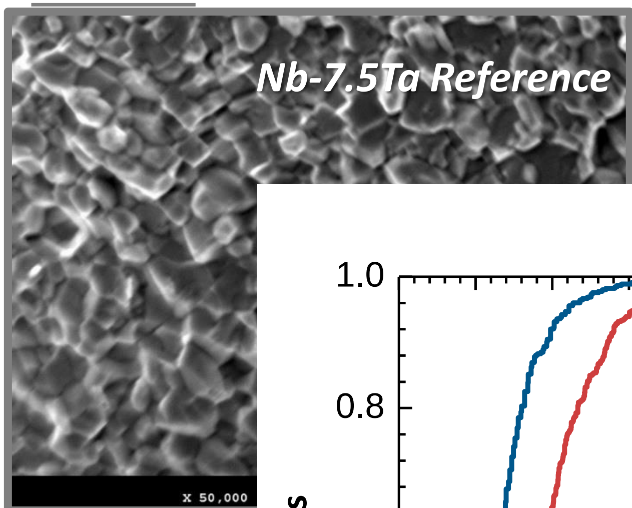
	F_p^{max}	B @ F_p^{max}	B_{Kr}
Nb-7.5Ta	28 GN/m³	5.29 T	25.7 T
Nb-1Zr	71 GN/m³	5.15 T	22.3 T
Nb-7.5Ta-1Zr	**88 GN/m³**	5.45 T	26.6 T
Nb-7.5Ta-2Zr	65 GN/m³	**5.8 T**	**28.3 T**

One-stage heat treatment @ 650°C/200h without oxidation step

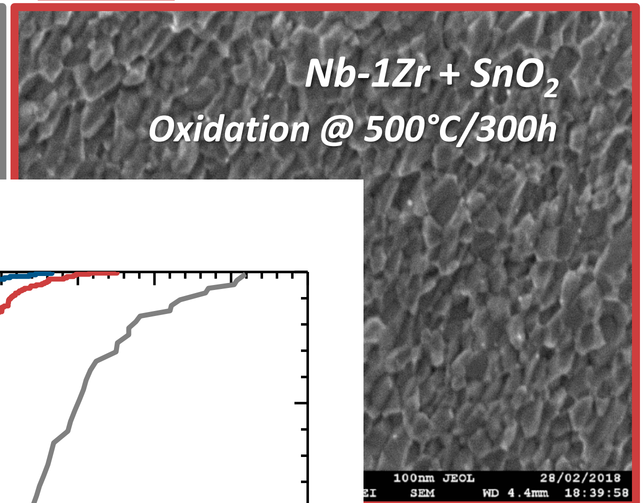
J_c calculated on the entire A15 layer including fine and large grains

Results: grain refinement

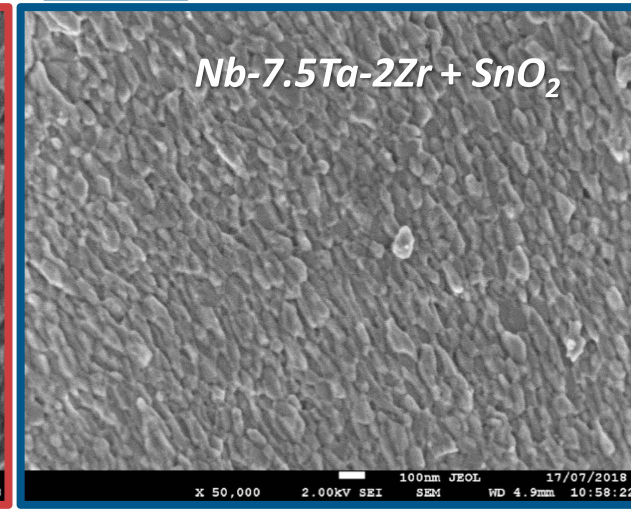
Median grain size
153 nm

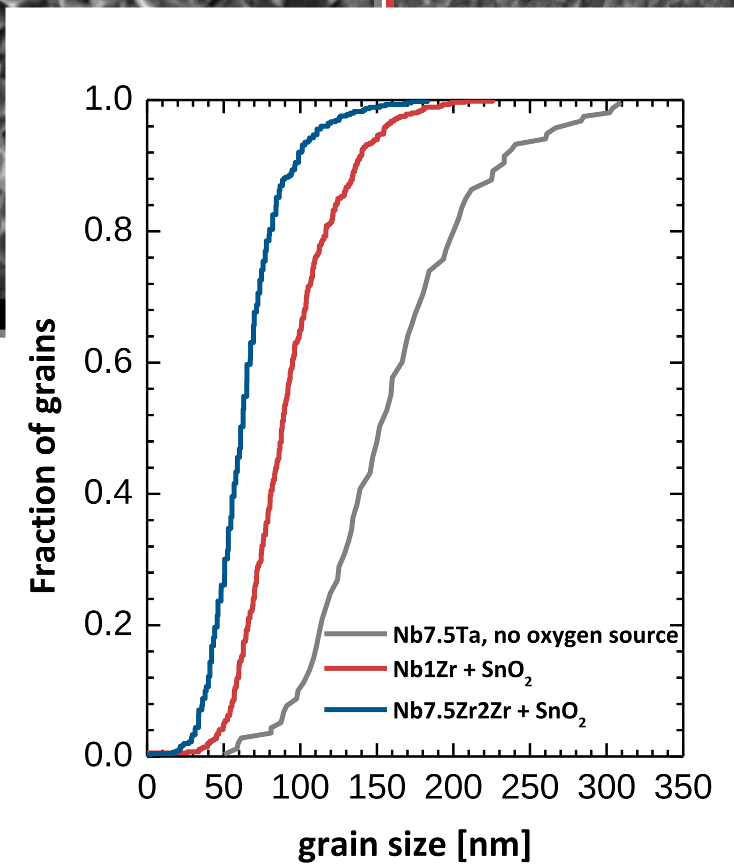


Median grain size
88 nm



Median grain size
61 nm





Outline

The FCC dipoles at 16 T: how to get there with Nb_3Sn (LTS)

Reach the ultimate performance:

Investigations on the enhancement of J_c in $(Nb,X)_3Sn$ superconductors by internally oxidized ZrO_2 particles

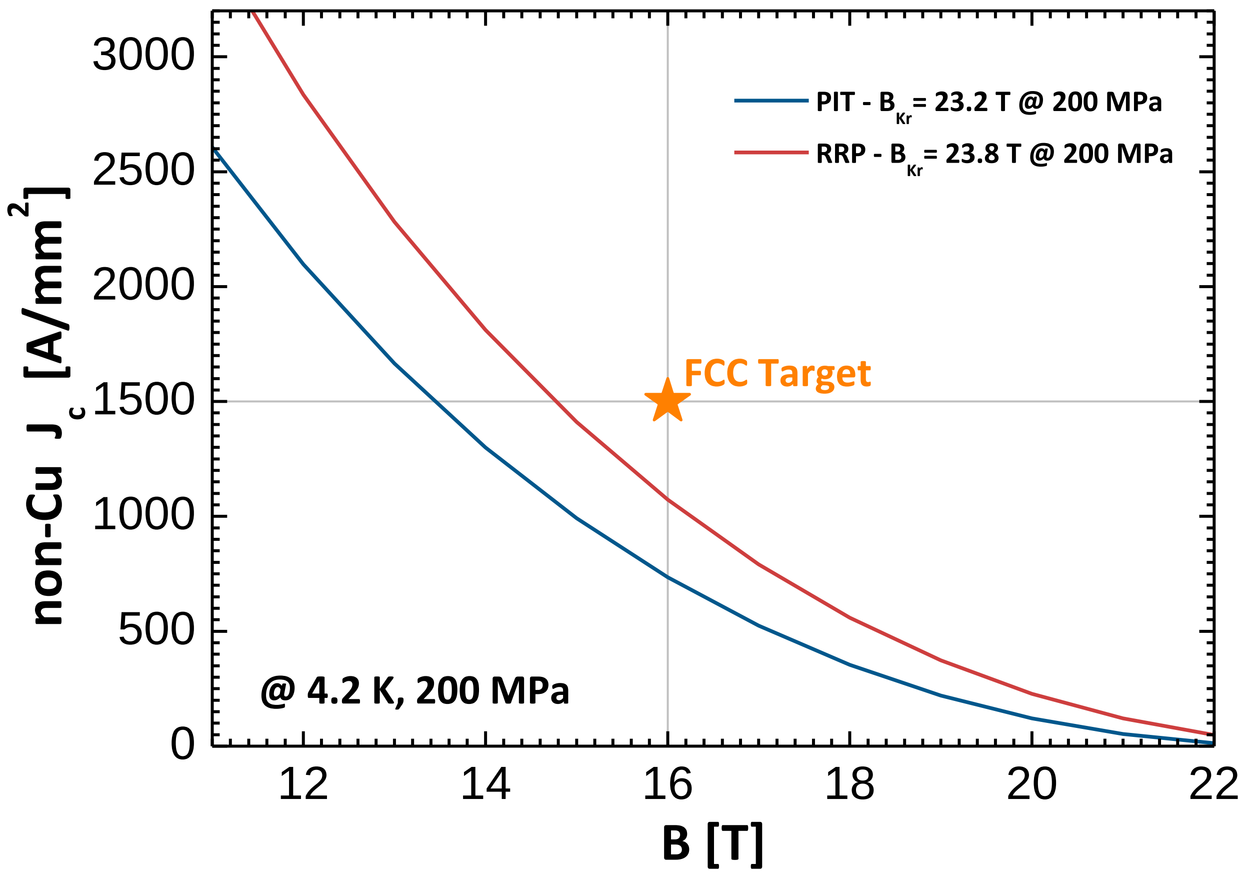
Withstand the electromagnetic forces:

Electromechanical tests – effects of the transverse stress

Dipole magnets at 20 T and beyond: the call for HTS

Conductor R&D based on YBCO coated conductors for dipole demonstrators

Performance target non-Cu J_c(4.2K,16 T) = 1500 A/mm²
and 200 MPa



J. Parrell et al., AIP Conf. Proc. 711 (2004) 369

T. Boutboul et al., IEEE TASC 19 (2009) 2564

Stress limits for the design of the 16 T dipoles for the Future Circular Collider

H2020 EuroCirCol WP5 Task 5: Conductor studies

The 16 T FCC dipoles are being designed with a peak stress of 150-200 MPa at operation

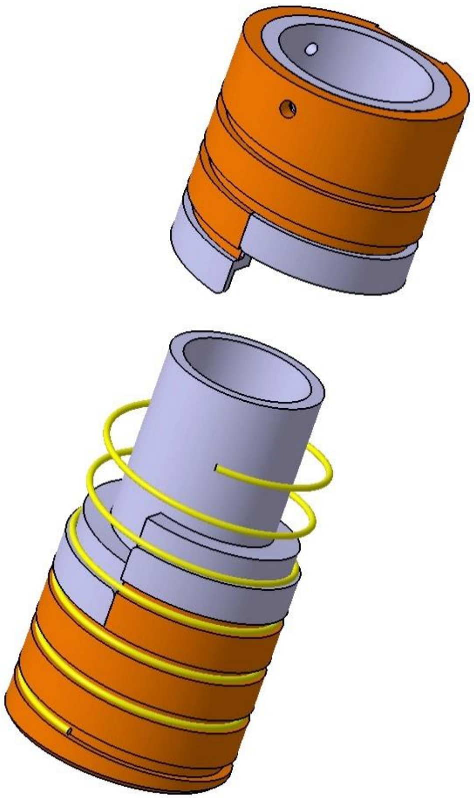
Are the Nb_3Sn wires in the cable able to withstand such a high stress level? Which degradation is tolerable?

Nb_3Sn Rutherford cable for HL-LHC, 40 strands

- Nb_3Sn wires are deformed during cabling
- Cables are braided with glass fiber
- The winding is impregnated with resin

Is it possible to extrapolate the behaviour of the cable from a single wire experiment?

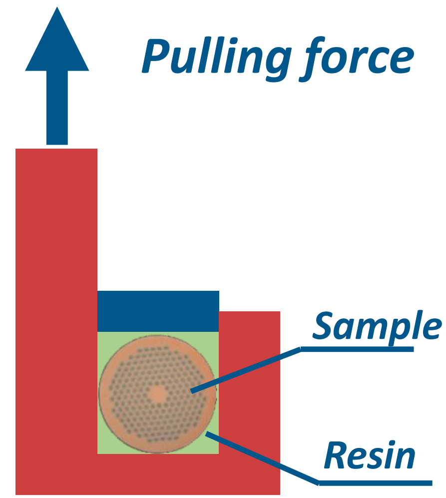
The WASP concept for I_c vs. transverse stress



B. Seeber et al., IEEE TASC 17 (2007) 2643

G. Mondonico et al., SUST 25 (2012) 115002

4-WALL + impregnation

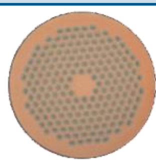
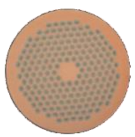
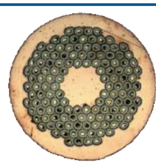


UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES

CERN

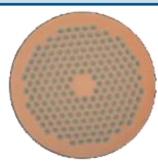
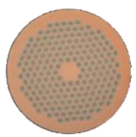
collaboration agreement K1629/TE (2009-2012)

Measurement campaign on high-J_c Nb_3Sn wires

	Technology	# of subelements	Diameter [mm]	Wire ID
	PIT	192	1.0	#0904 #31712 #14310
	PIT	192	0.85	#29992
	RRP	108/127	0.85	#14753 #14516 (Ta) #76A08U
	RRP	132/169	1.0	#15114 #114163
	RRP	132/169	0.85	#14393

Cu/non Cu ratio between 1.2 and 1.3 for all wires

Measurement campaign on high-J_c Nb_3Sn wires

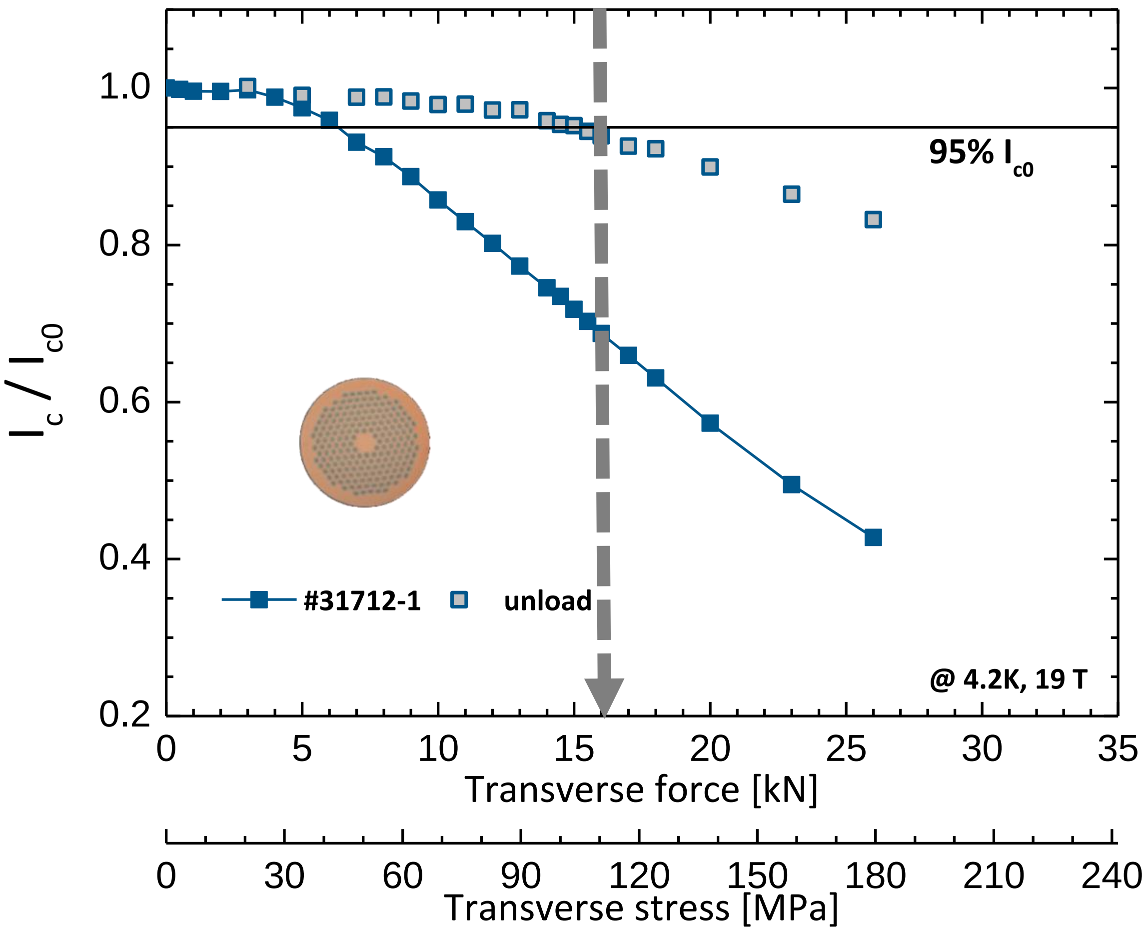
	Technology	# of subelements	Diameter [mm]	Wire ID
	PIT	192	1.0	#0904 #31712 #14310
	PIT	192	0.85	#29992

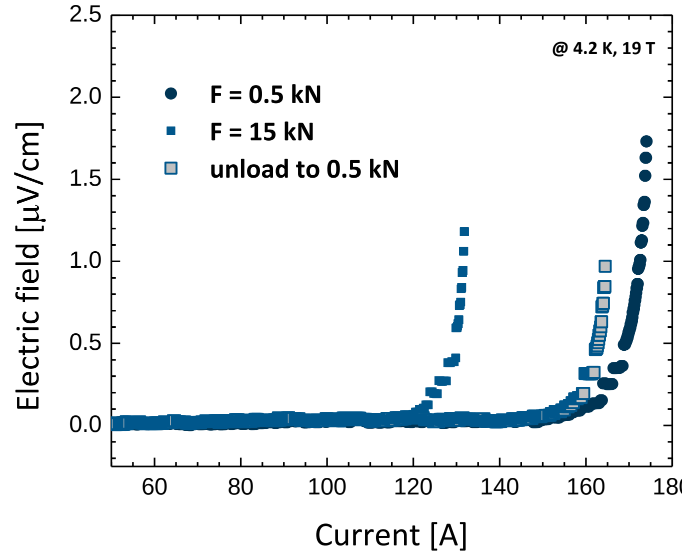
Impact of the impregnation type on the irreversible stress limits

Tests performed with

- *Epoxy L* — About the same elastic modulus as CDT 101K
- *Glass fiber sleeve + Epoxy L*
- *Stycast* — ~ 2x elastic modulus of CDT 101K

I_c vs. transverse stress
PIT 192 + epoxy L





The irreversible limit is defined at the force level leading to a 95% recovery of the initial I_c after unload

Here

$$F_{irr}(B=19T) = 16\ kN$$

The corresponding irreversible stress limit is

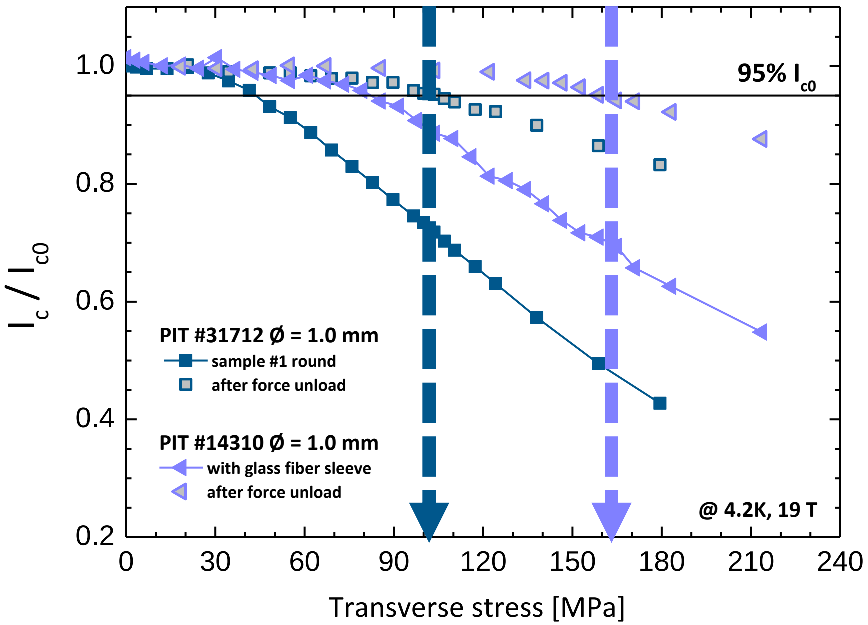
$$\sigma_{irr}(B=19T) = 110\ MPa$$

where

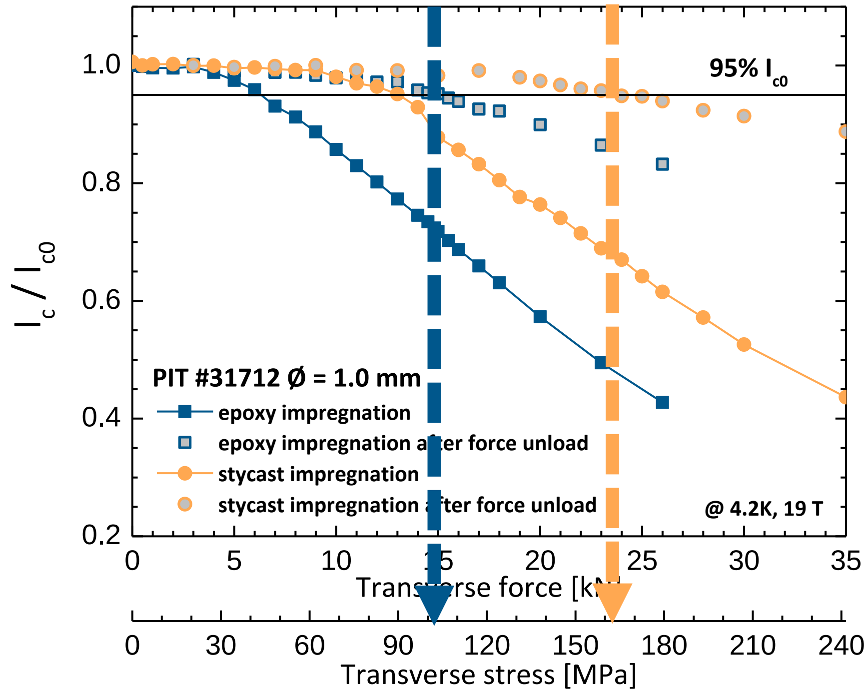
$$Stress = \frac{Force}{groove\ length \times groove\ width}$$

Reinforced impregnation

wire in a glass fiber sleeve + Epoxy L



wire + Stycast

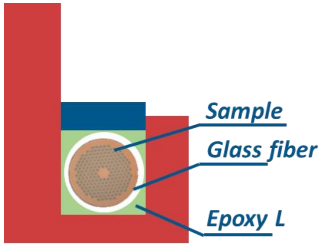


Epoxy L → σ_{irr}(B=19T)= 110 MPa

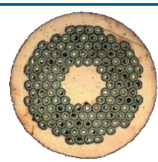
Glass fiber sleeve + Epoxy L → σ_{irr}(B=19T) = 165 MPa

Epoxy L → σ_{irr}(B=19T) = 110 MPa

Stycast → σ_{irr}(B=19T) = 162 MPa



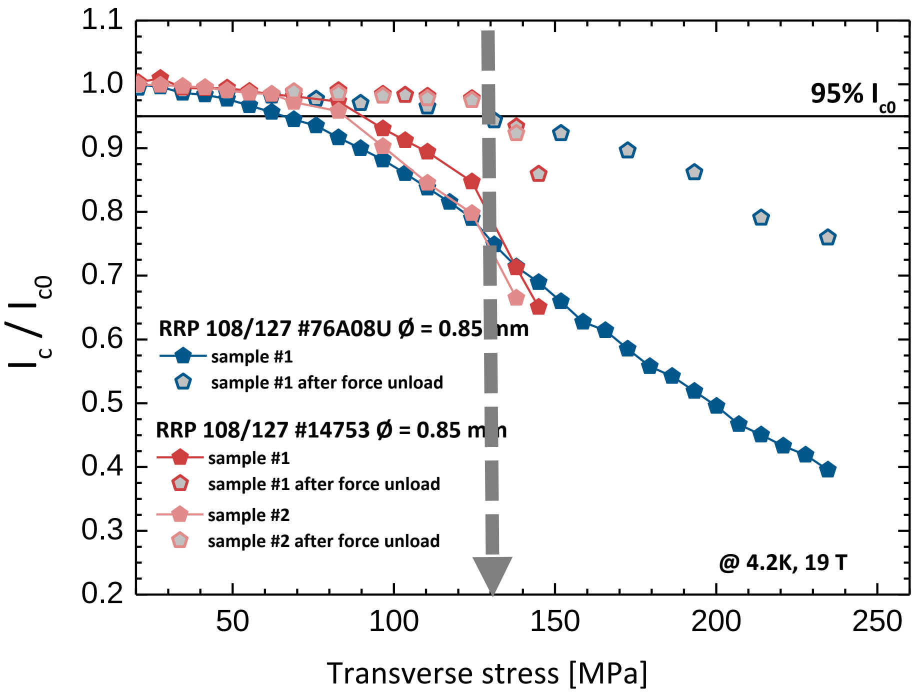
Measurement campaign on high-J_c Nb_3Sn wires

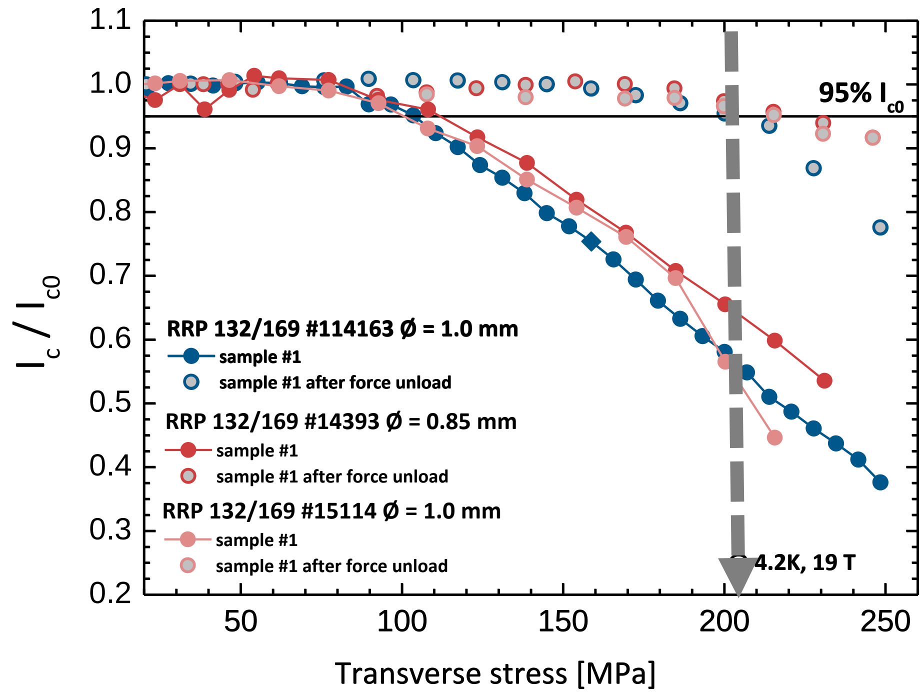
	Technology	# of subelements	Diameter [mm]	Wire ID
	RRP	108/127	0.85	#14753 #14516 (Ta) #76A08U
	RRP	132/169	1.0	#15114 #114163
	RRP	132/169	0.85	#14393

Impact of the wire layout on the irreversible stress limits

All tests performed with Epoxy L impregnation

RRP: 108/127 vs. 132/169





RRP 108/127

RRP 132/169

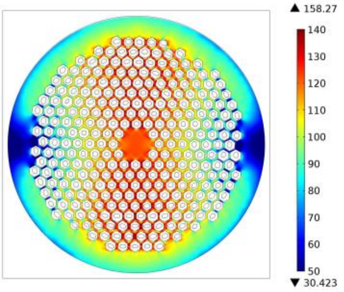
Irreversible stress limit ~130 MPa at 19 T

Irreversible stress limit ~200 MPa at 19 T

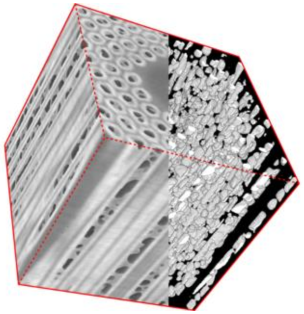
Better stress redistribution in RRP 132/169, likely due to the arrangement and to the smaller relative diameter of the subelements

Other effects under investigation

Mechanisms responsible of the irreversible degradation of the critical current



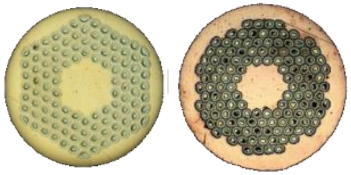
- *plastic deformation and residual stress vs. filament cracks*



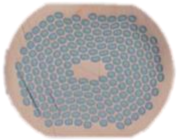
- *stress concentration at voids*

Redistribution of the applied stress

- *effects of the filament layout*



- *effects of the wire deformation during cabling*



Outline

The FCC dipoles at 16 T: how to get there with Nb_3Sn (LTS)

Reach the ultimate performance:

Investigations on the enhancement of J_c in $(Nb,X)_3Sn$ superconductors by internally oxidized ZrO_2 particles

Withstand the electromagnetic forces:

Electromechanical tests – effects of the transverse stress

Dipole magnets at 20 T and beyond: the call for HTS

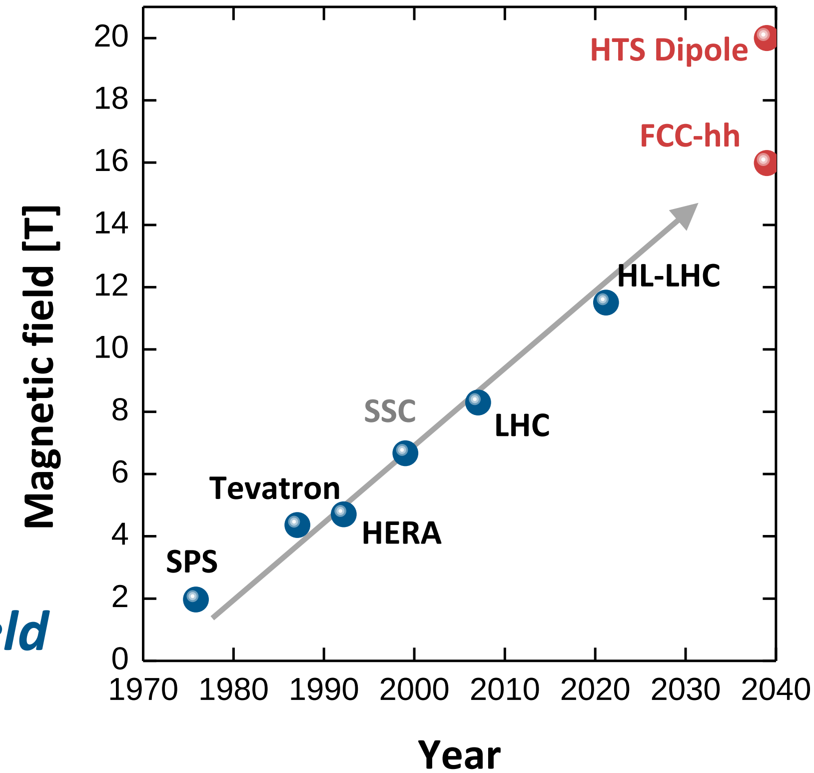
Conductor R&D based on YBCO coated conductors for dipole demonstrators

Setting the scene

The goal of 20 T in an accelerator quality dipole calls for HTS

EuCARD² has developed

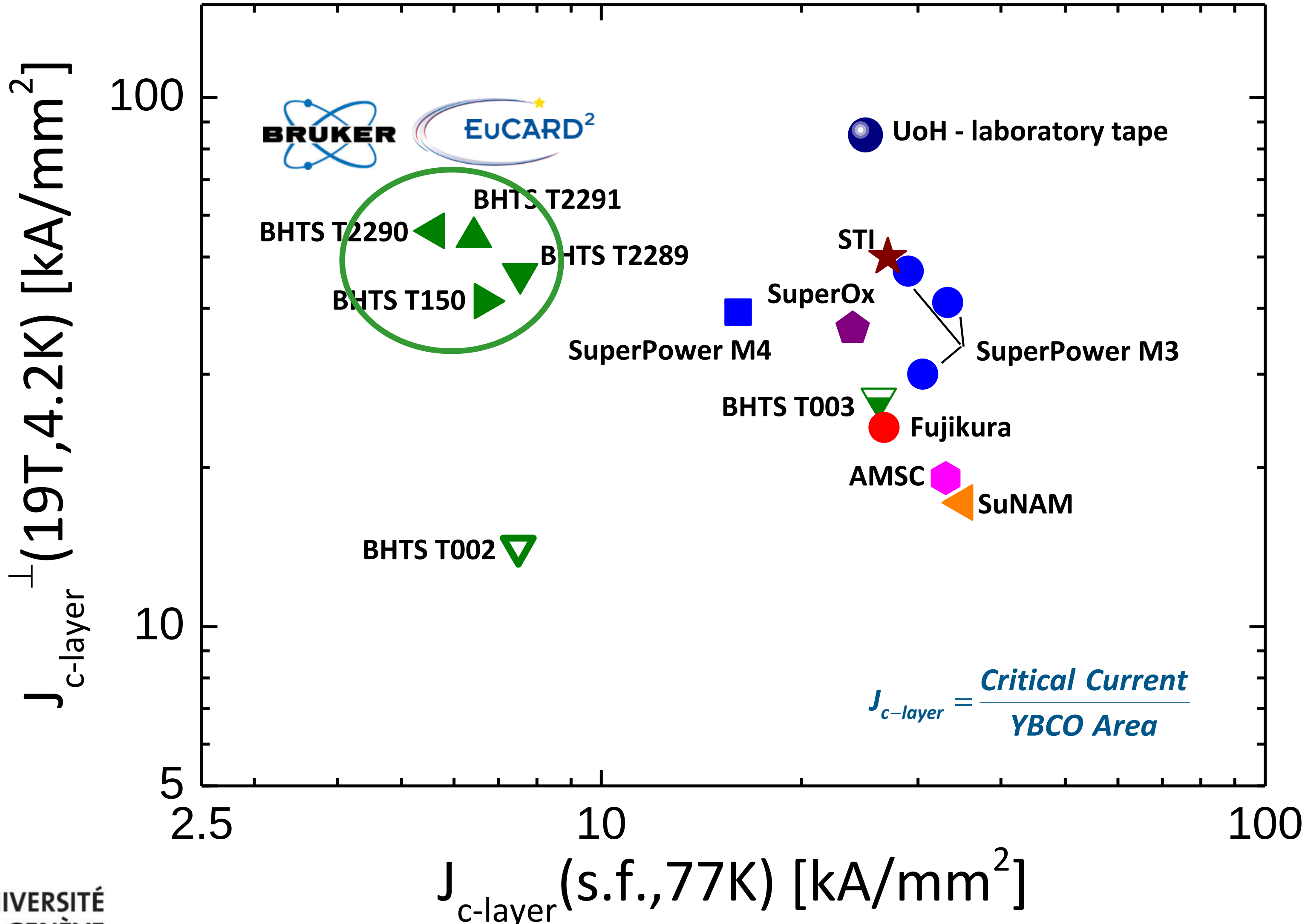
- *a HTS CONDUCTOR for accelerator dipoles (10 kA-class cable)*
- *a DIPOLE DEMONSTRATOR with accelerator quality (5 T, 40 mm bore)*



Tests of the coils as stand alone and in-field are ongoing

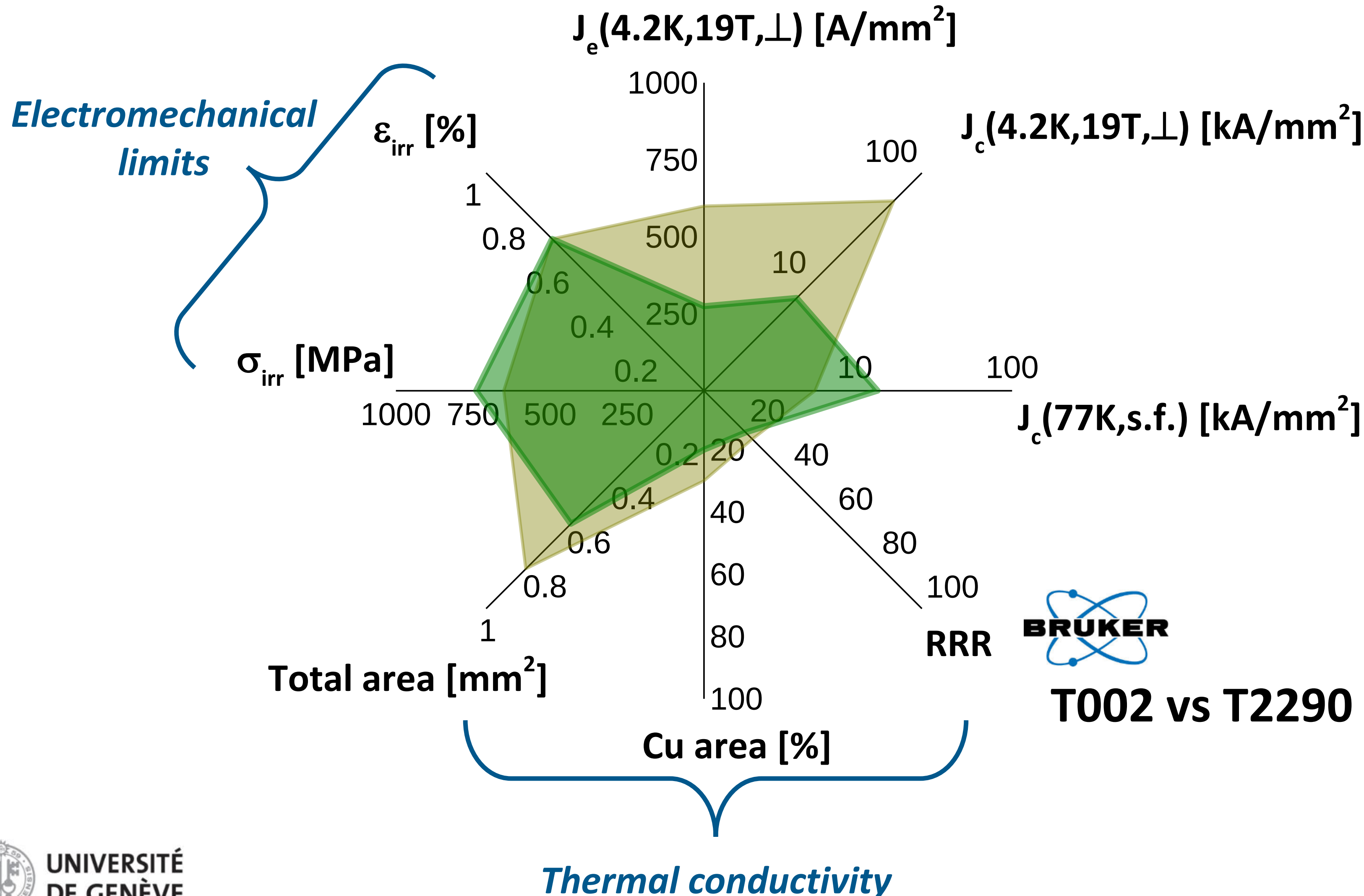
ARIES is building on the shoulders of EuCARD²

Performance overview: J_c(s.f.,77K) vs. $J_c^{\perp}$(19T,4.2K)
(Data from 2016)



UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

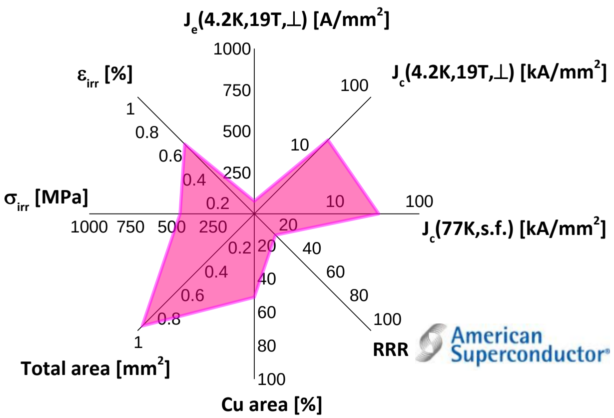
Is high J_c all you need ?

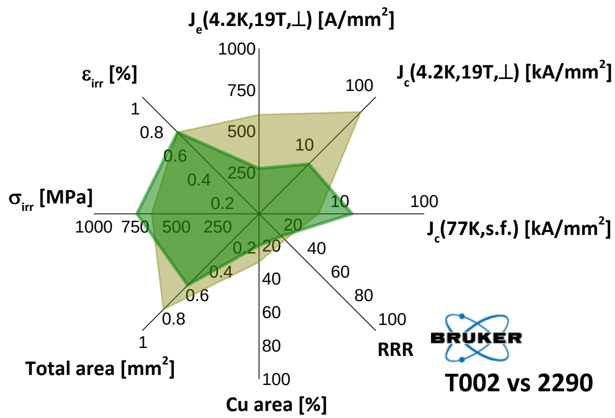


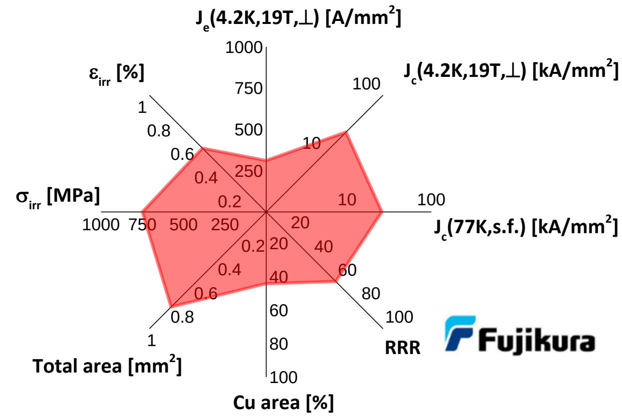
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

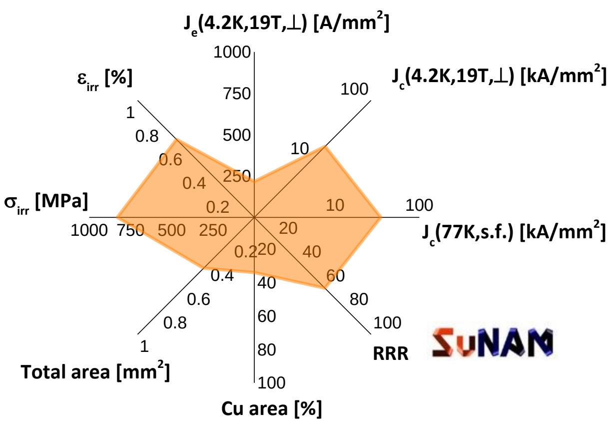
Main parameters at a glance

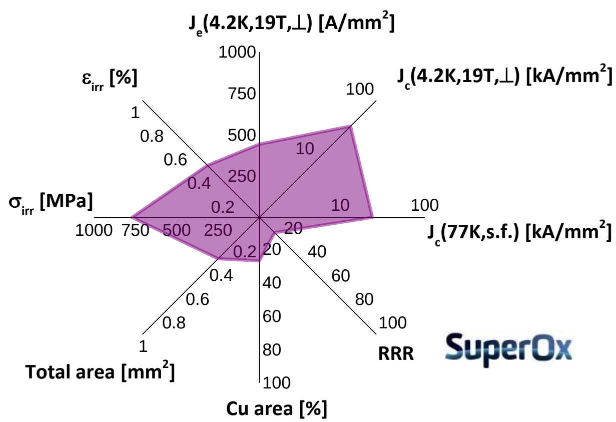
(Data from 2016)

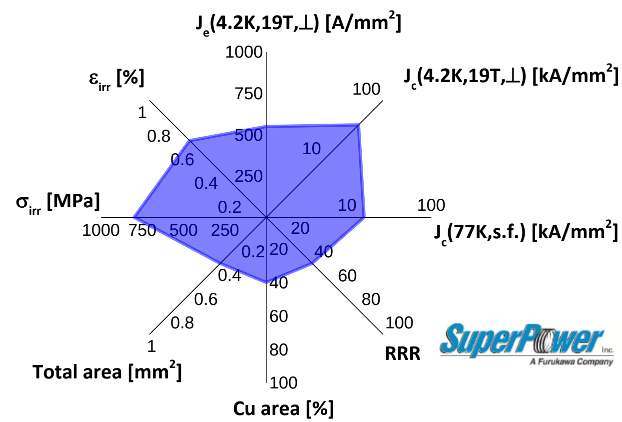




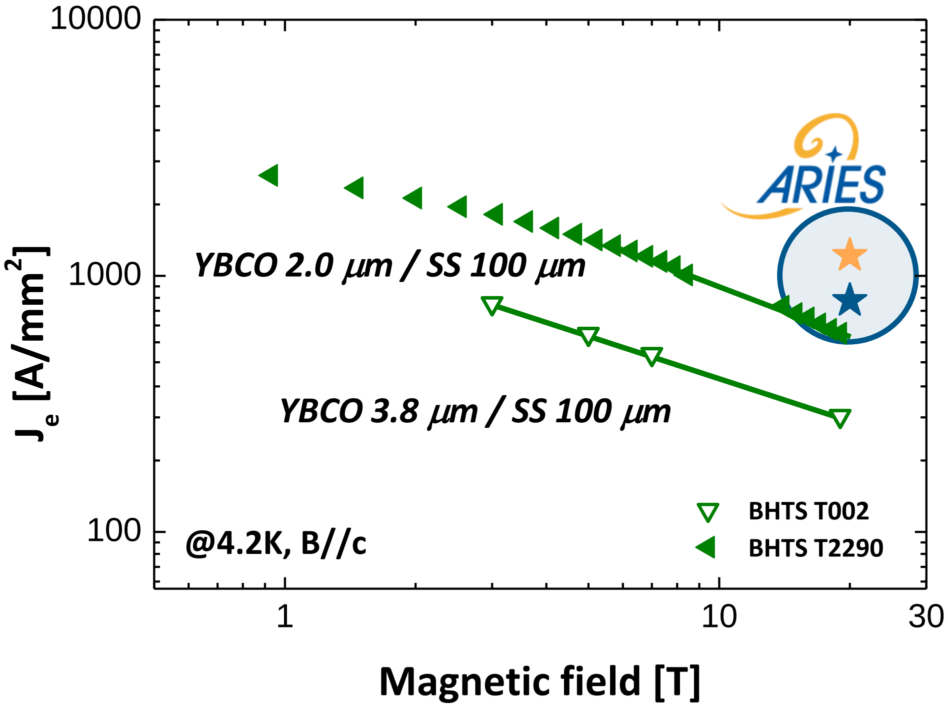


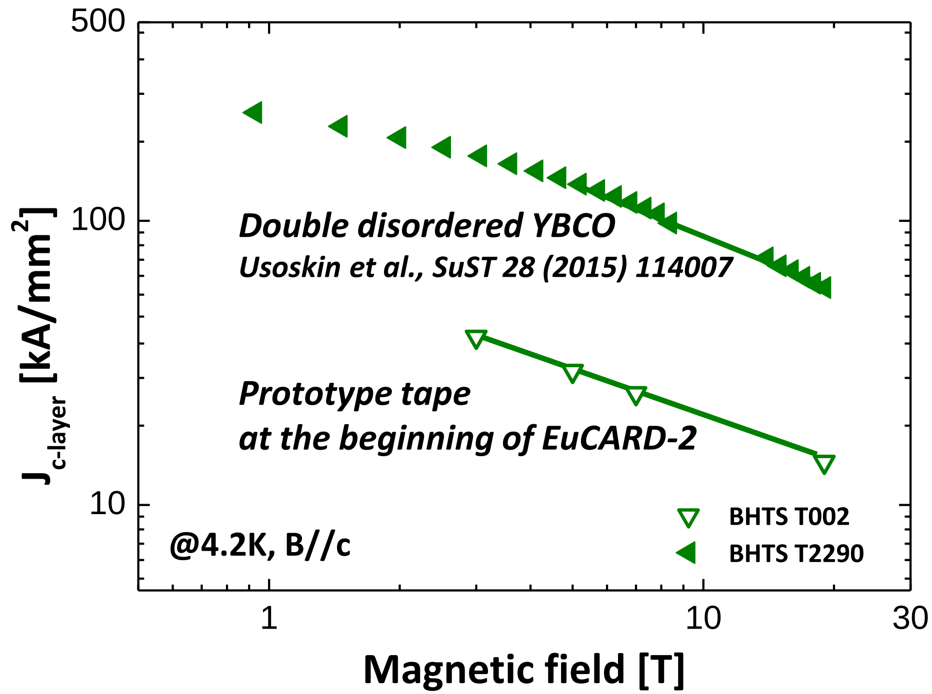






Performance target for ARIES: J_e (4K, 20T)= 800-1200 A/mm²



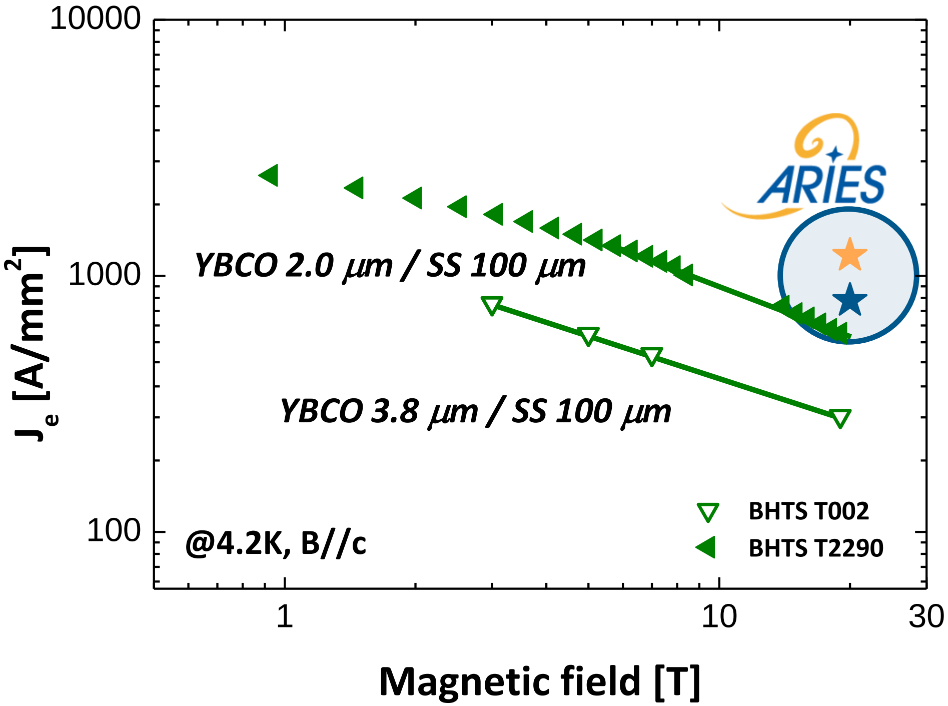


$$J_e = \frac{\text{Critical Current}}{\text{Total Area}}$$

$$J_{c-layer} = \frac{\text{Critical Current}}{\text{YBCO Area}}$$

ARIES Partners : CERN, CEA, Universiteit Twente, Université de Genève – Faculté des Sciences, Bruker

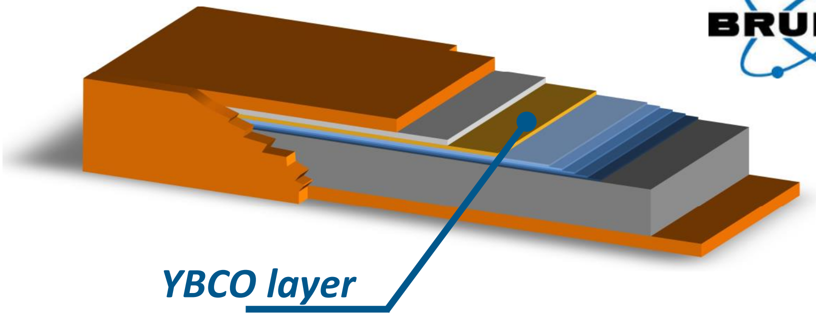
Performance target for ARIES: J_e (4K, 20T)= 800-1200 A/mm²



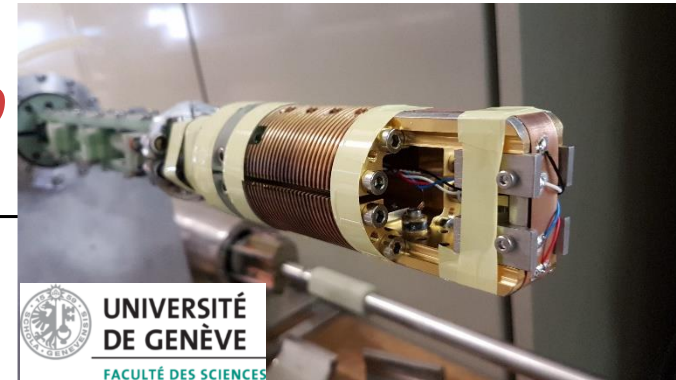
How to get there?

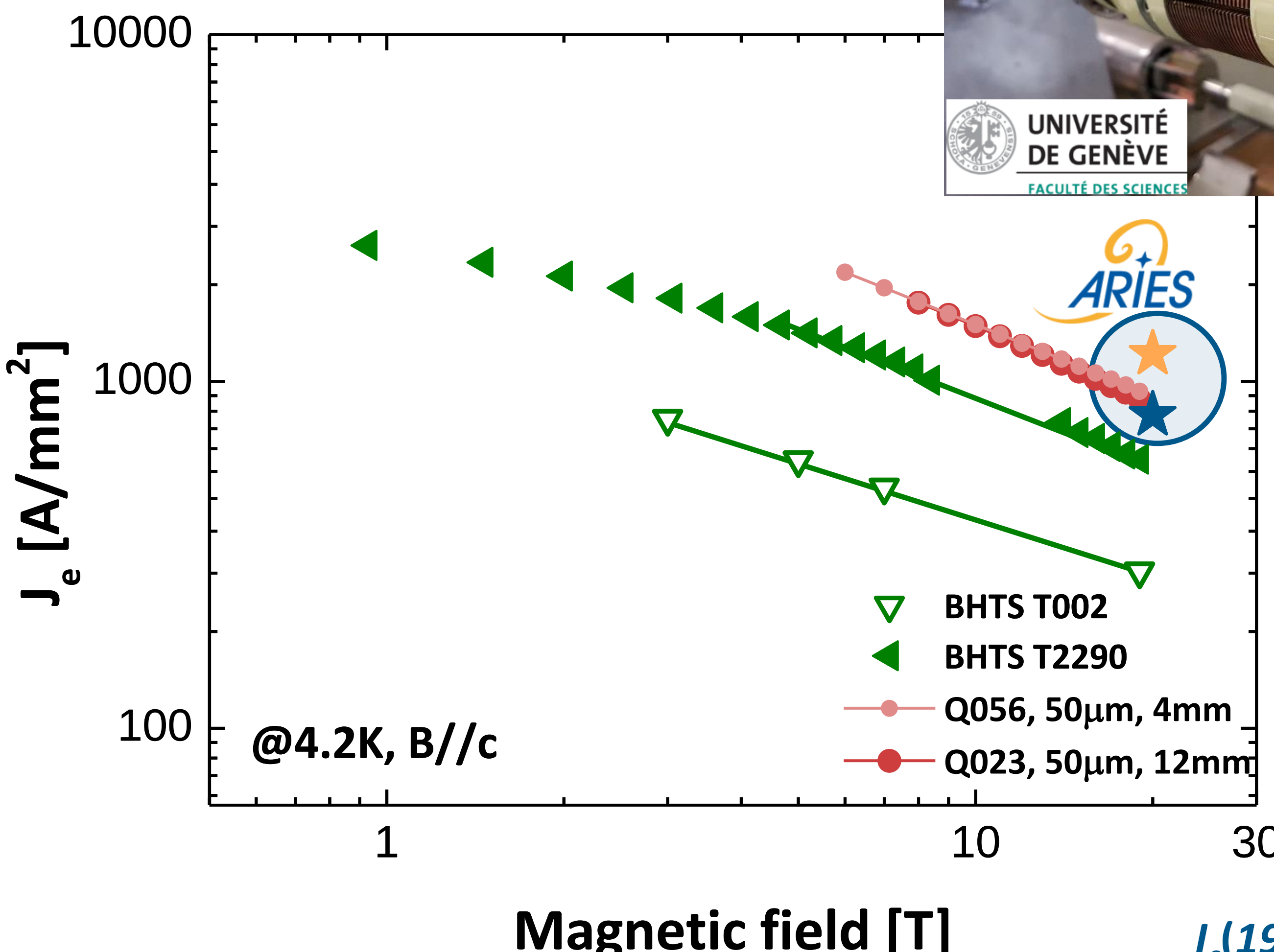
- *Increase the layer J_c of YBCO*
- *Increase the thickness of YBCO*
- *Reduce the thickness of the substrate 100 µm SS → 50 µm SS*

$$J_e = \frac{\text{Critical Current}}{\text{Total Area}}$$



First I_c measurements: where do





	$I_c(19T)$	$J_e(19T)$
12 mm	957 A	886 A/m²
4 mm	337 A	936 A/m²

Summary

Driving Nb_3Sn towards its ultimate performance

- *produced material with refined grains and high B_{Kr}*
- *further optimization of the process is ongoing*

Exploring the intrinsic and extrinsic effects behind the irreversible degradation of I_c under transverse stress

- *tested different impregnations and load configurations: resins with higher rigidity perform better*
- *RRP wires are less sensitive to transverse loads than PIT wires*

Improving the performance of YBCO coated conductors for applications to HEP magnets

- *obtained a record $J_e > 900$ A/mm^2 @ 4.2 K, 19 T*

Thank you for the attention !

Carmine SENATORE

carmine.senatore@unige.ch

http://supra.unige.ch