Test of 60 kA coated conductor cable prototypes for fusion magnets

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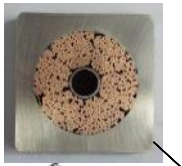
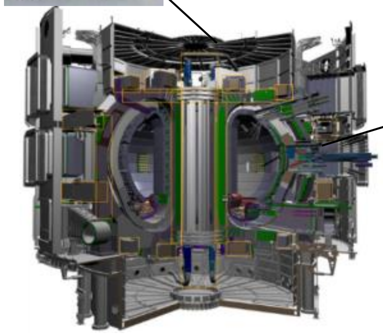
- Background and motivation
- Conductor design
- Conductor construction and EDIPO sample assembling
- Conductor test (assessment, DC, AC)
- Summary

Background

Requirements for Fusion Magnets

- *Peak field in the 10 T ~ 18 T range.*
- *Large bending radius (> 3 m) during winding.*
- *Very large current (>40 kA) and large Cu cross section (500 to 900 mm^2), thus low J_e.*
- *Moderate AC losses.*
- *Cheap and easy industrial production (at Km length).*
- *Steel structures takes up most of the longitudinal load (Hoop stress), but large transverse loads are still present.*

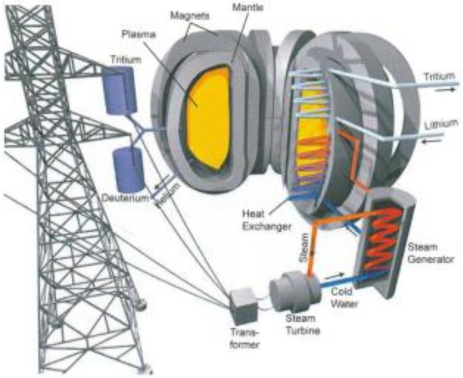




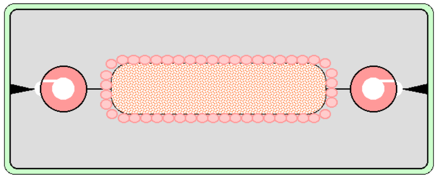
ITER
(2013-2030)

68 kA Cu: 530 mm^2
Void fraction 30%
J_e(5 K, 12 T) = 55 A/mm^2

DEMO
(2030-…)



Insulated conductor 112 x 45 mm



82 kA Cu: 800 mm^2
Void fraction 23%
J_e(5 K, 13 T) = 65 A/mm^2

Background – HTS vs LTS

HTS features

•High operating temperatures and fields are possible.

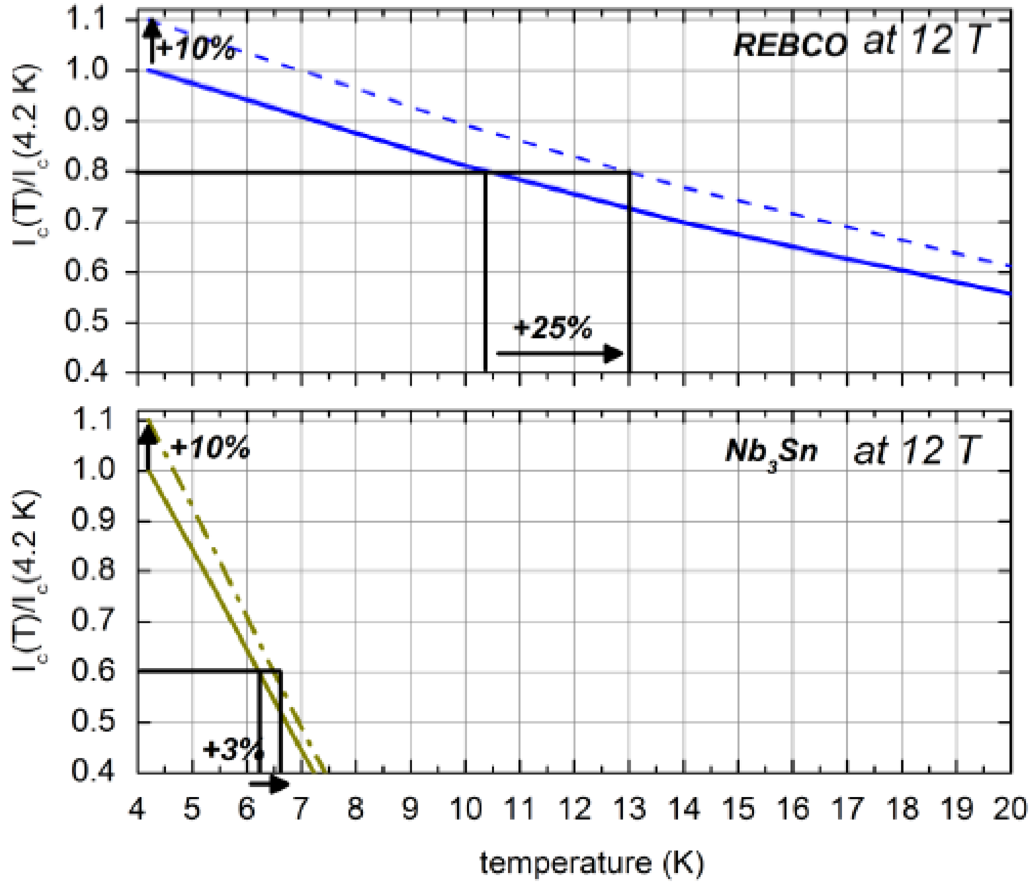
•Operating current can be higher than in LTS.

•Any improvement in I_c would be more effective in increasing T_{cs} than improvements in I_c in LTS.

•HTS (i.e. c.c) are much "younger" than Nb_3Sn ⇒ larger margin for improvements.

•Shallow transitions from superconducting to normal state when temperature crosses T_{cs} at constant current and field.

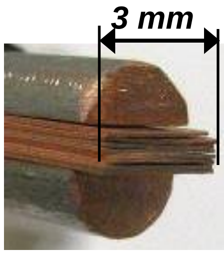
Main present drawback is the cost

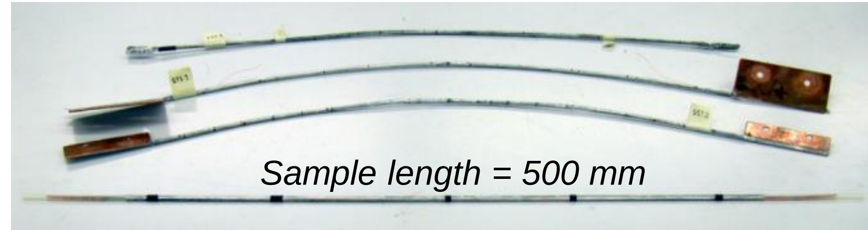


LHe | LHe can not be used for cooling large magnets | LH

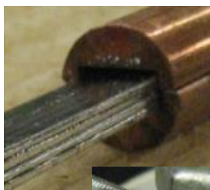
Development at CRPP-SG

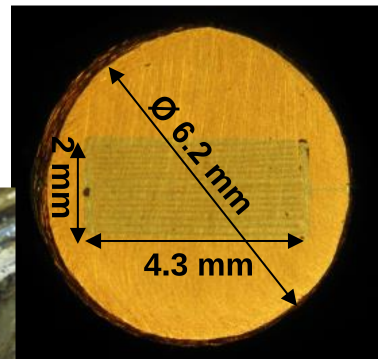
2012

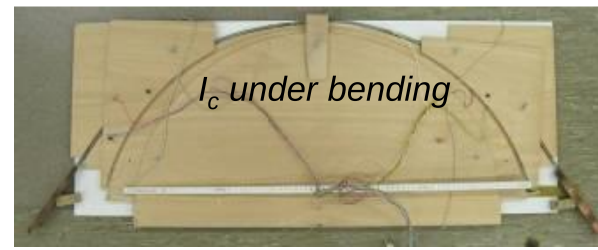




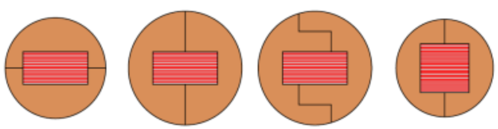
2013







2014



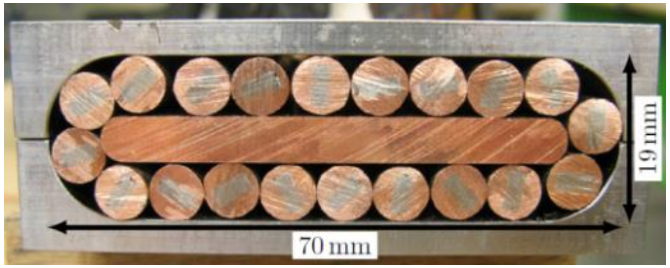
September 2014: cables prepared, I_c (77 K) measured.

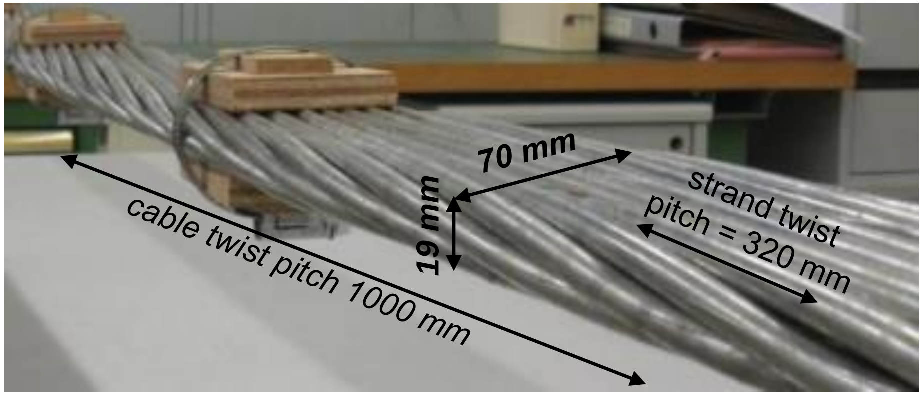
Missing: terminations, jacketing, assembling in EDIPO sample.

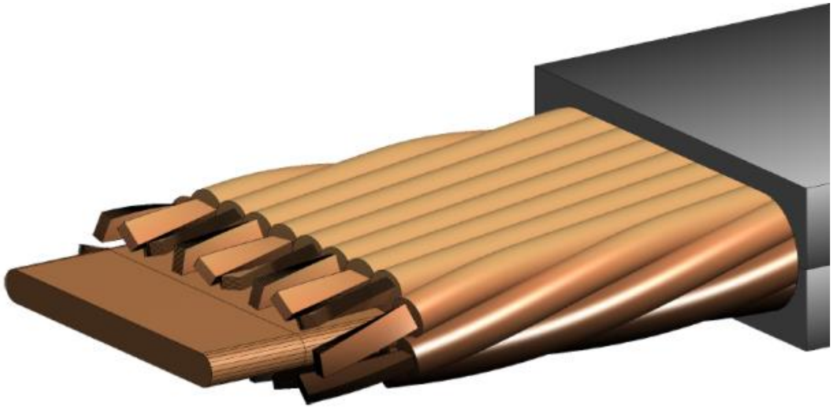
Conductor design

	Tot cross section (without jacket)	*Tot. copper cross section*	*Void fraction*	*Operating current and field*	*T_{cs} at operating conditions*	*Operating current density (non Cu)*
ITER TF (Nb_3Sn)	**1250 mm²**	515 mm²	400 mm² (32%)	68 kA, 11.1 T	5.8 K to 7.0 K	**280 A/mm²**
DEMO TF (Nb_3Sn)	**1220 mm²**	675 mm²	280 mm² (23%)	82 kA, 13.4 T	about 6.5 K	**300 A/mm²**
HTS prototype	**1250 mm²**	760 mm²	400 mm² (32%)	50 kA, 12 T 30 kA, 12 T	8 K 21 K	**500 A/mm²** **300 A/mm²**

Current capacity and copper cross section are in the range required for fusion magnets. Fine tuning depends on the reactor design.



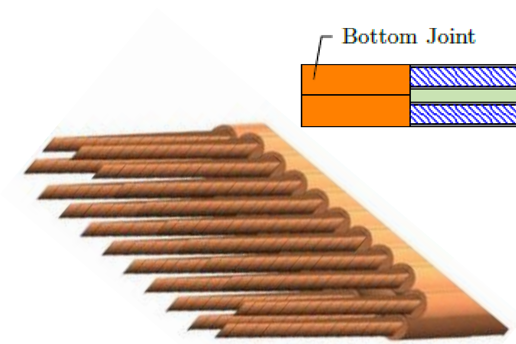


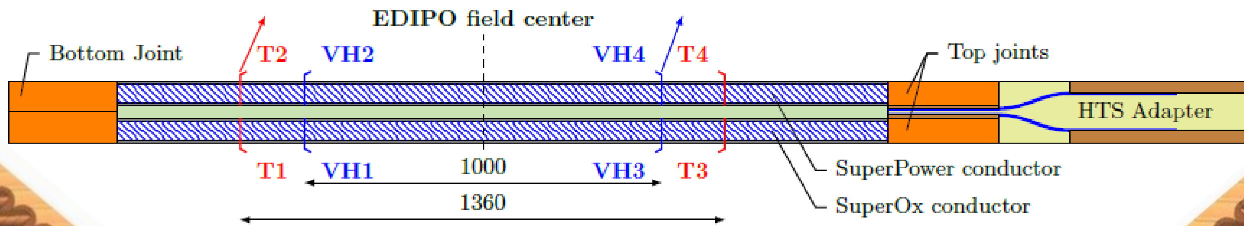


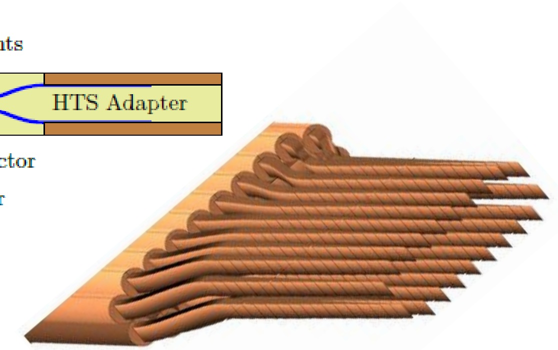
Cable length 2080 mm

Construction and assembly - Terminations

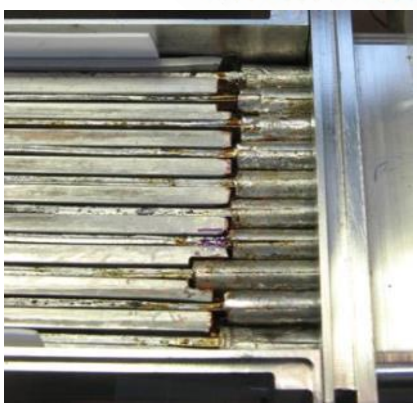
Terminations for SULTAN/EDIPO (sc transformer): **< 1 nΩ** each (< 10 nΩ for the whole circuit).
In ITER TF coils, joint resistance < 2.5 nΩ (about 10 W of dissipation)

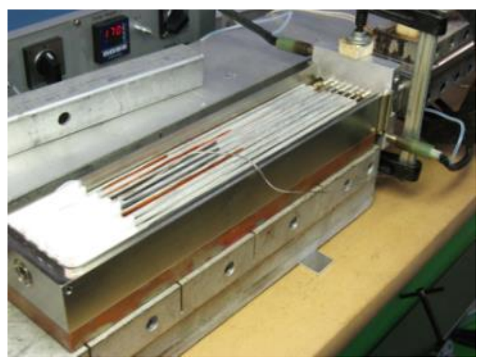


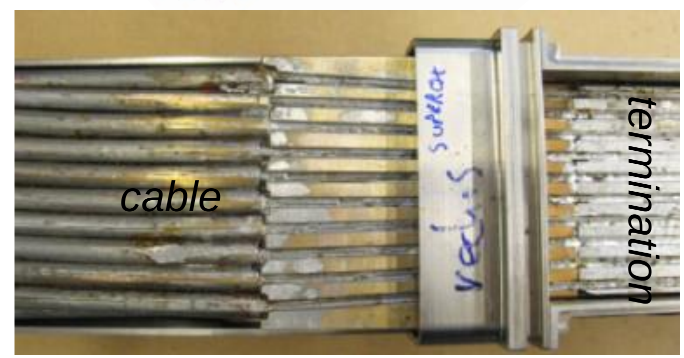




Staggered tapes at both ends

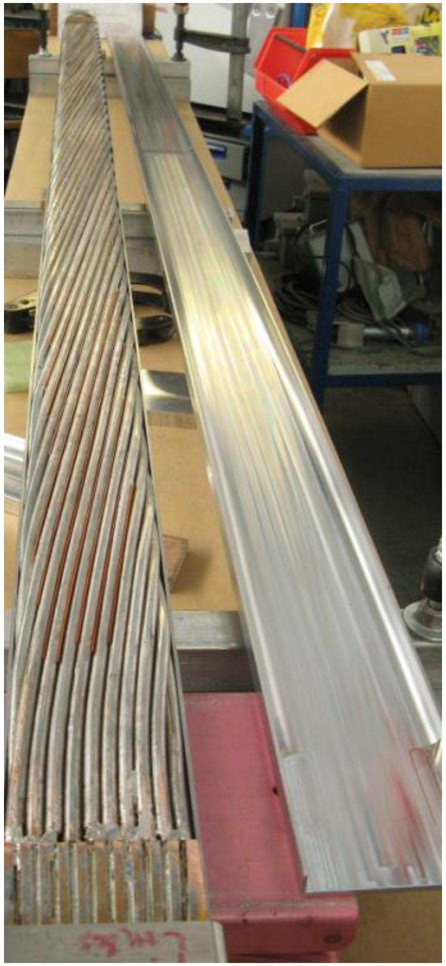






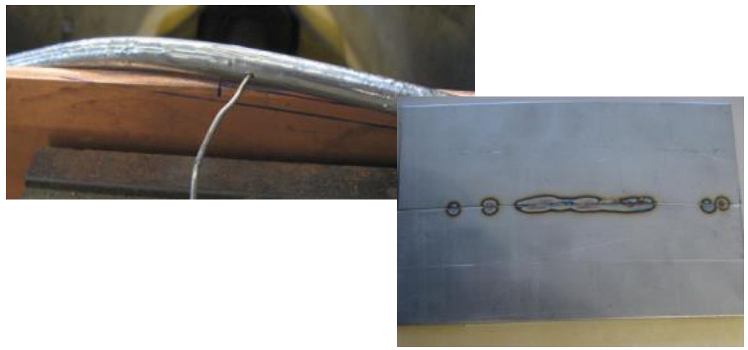
Staggered ends soldered in grooves machined in copper blocks

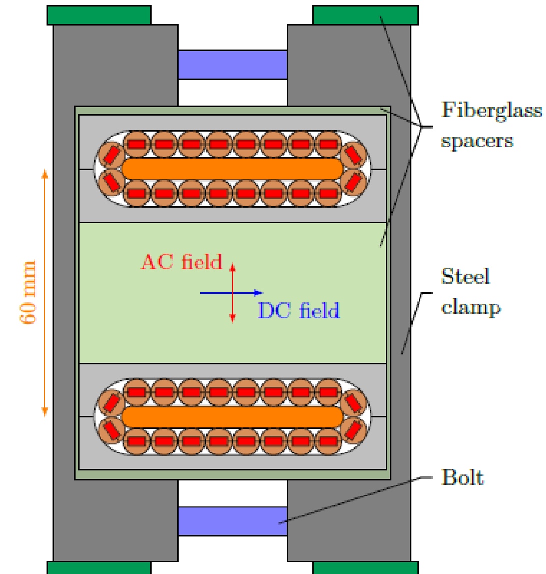
Construction and assembly



The jacket is composed of two machined profiles, welded around the cable

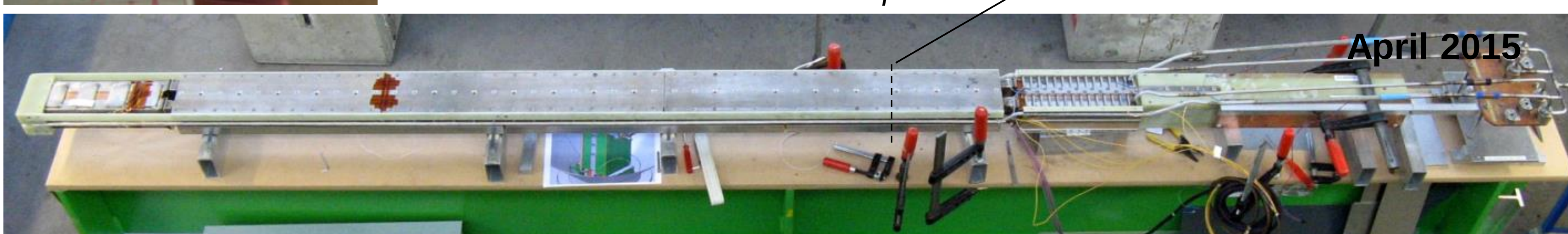
During welding the strand temperature did not exceed 90°C





Cross section

EDIPO sample



Test – resistance of joints and terminations

Assuming:

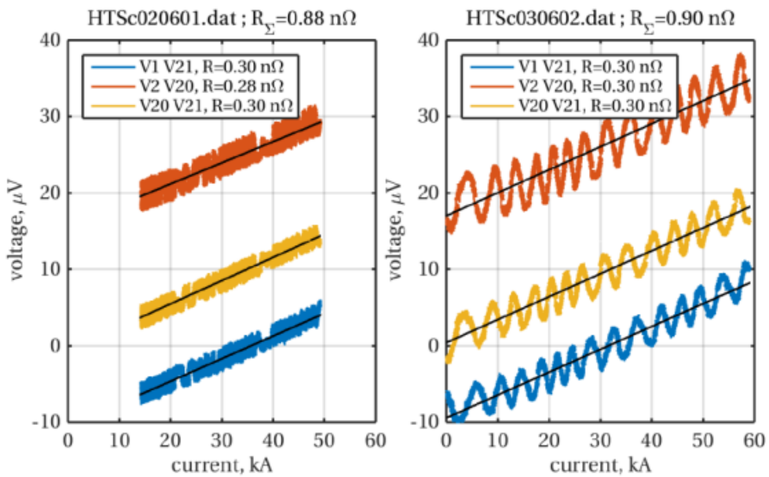
June 2015

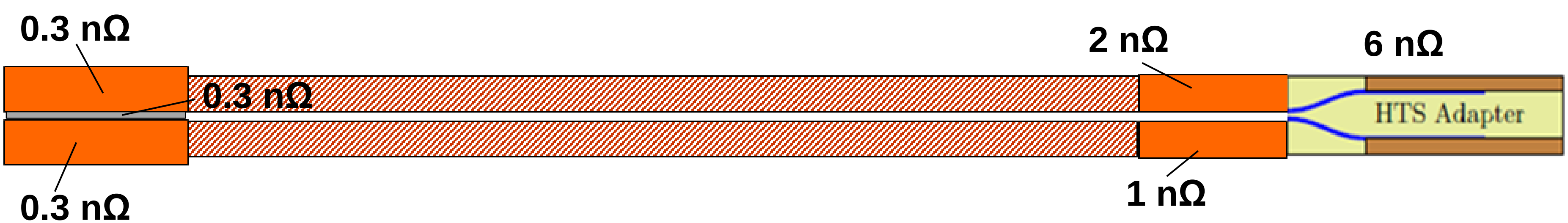
•Specific resistance of 10^{-11} Ω·m^2 (conservative value)

•Parallel resistance between 320 tape-to-copper connections (4 x 15 mm^2 contact area)

The total resistance of each termination should be about **0.5 nΩ**.

Measured at 4.5 K, 0 T, current up to 50 kA





Total circuit resistance is about 10 nΩ, most of it coming from the HTS adapter.

Test – assessment

850 m of tape per cable – measurement at 4.2 K, 12 T, 1 μV/cm

Superpower – about half of the spool (60% of the tape length).

Average $\mathbf{I_c(4.2\ K,\ 12\ T) = 191 \pm 7\ A}$

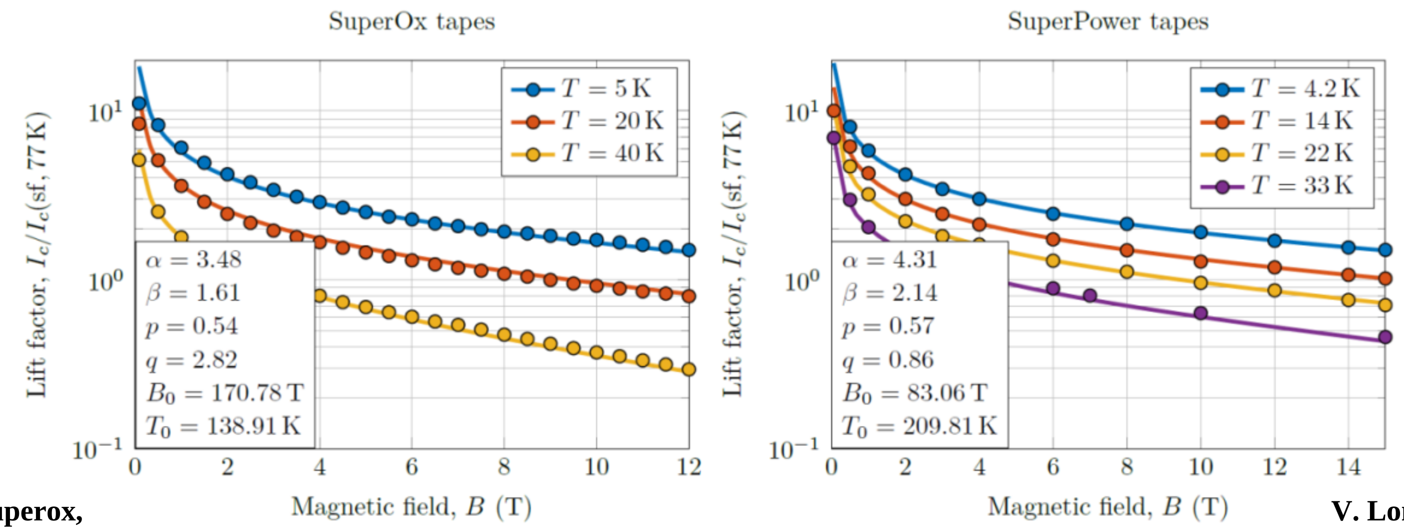
Superox – all four spools (100% of the tape length).

Average $\mathbf{I_c(4.2\ K,\ 12\ T) = 194 \pm 3\ A}$

Field and temperature dependence is obtained by scaling law:

$$I_c(B,T) = A\frac{B_0(T)^\beta}{B}\left(\frac{B}{B_0(T)}\right)^p\left(1-\frac{B}{B_0(T)}\right)^q$$

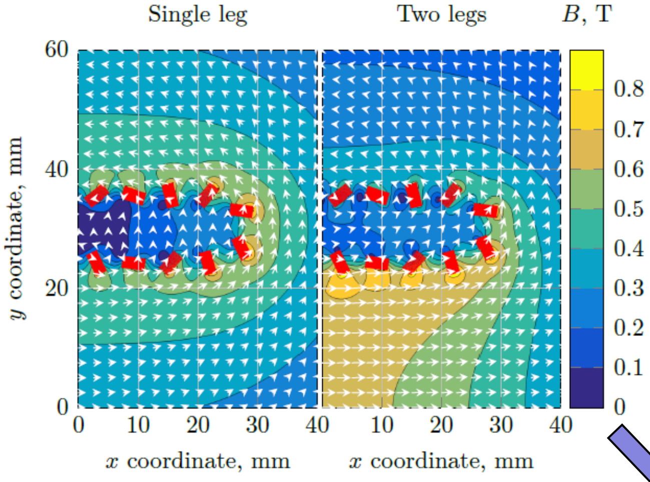
$$B_0(T) = B_0(0)\left(1-\frac{T}{T_0}\right)^\alpha$$



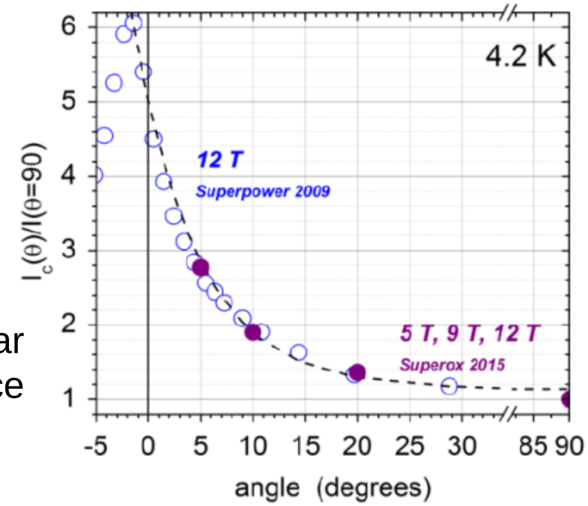
From Superox, measured at Frascati

V. Lombardo, IEEE TAS 21, 3247–3250 (2011)

Test – assessment



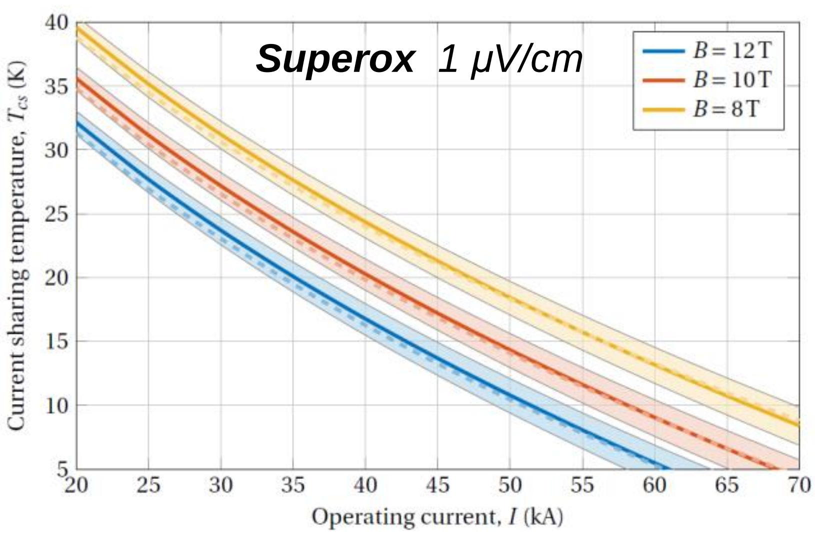
Contributions from the self field and from the return conductor.

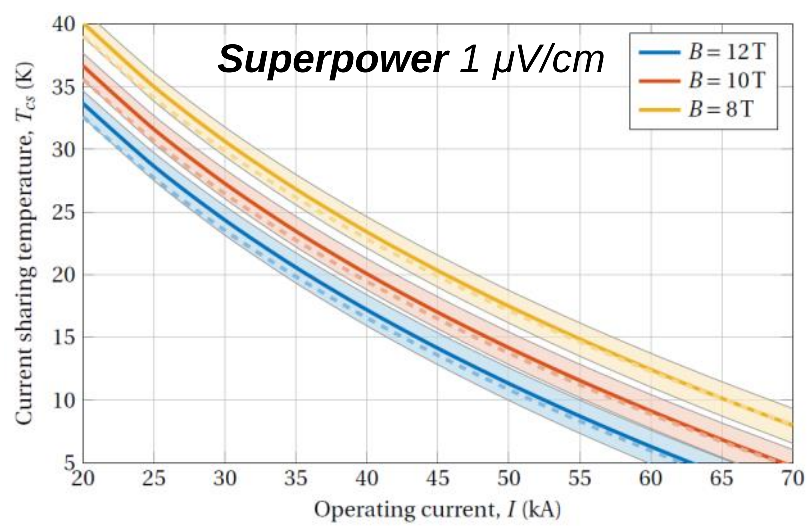


$I_c(B,T)$ scaling law

Angular dependence

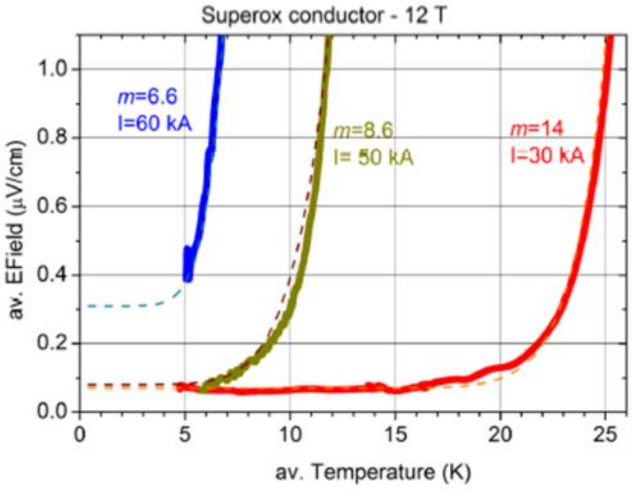
T_{cs} at various field and temperatures for both conductors





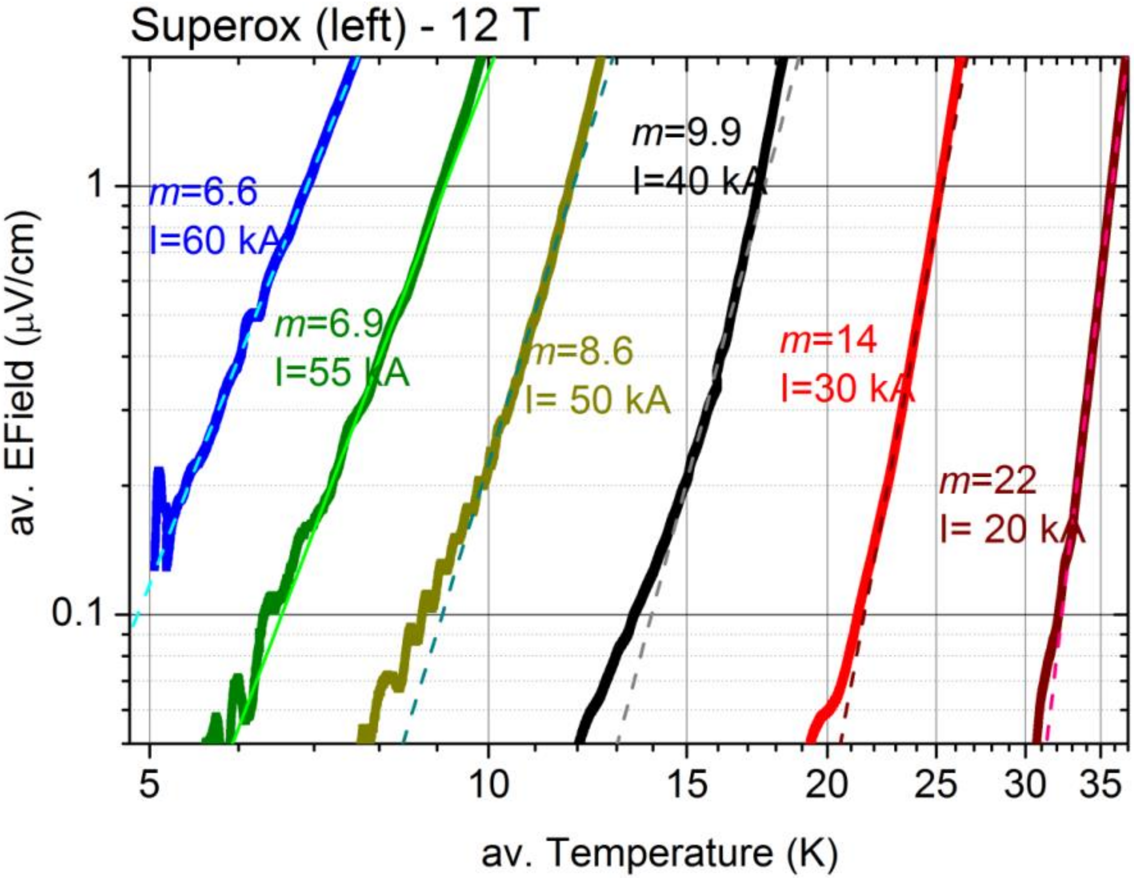
Self and return conductor fields have a small influence, which is compensated by the angular dependence

Test – DC



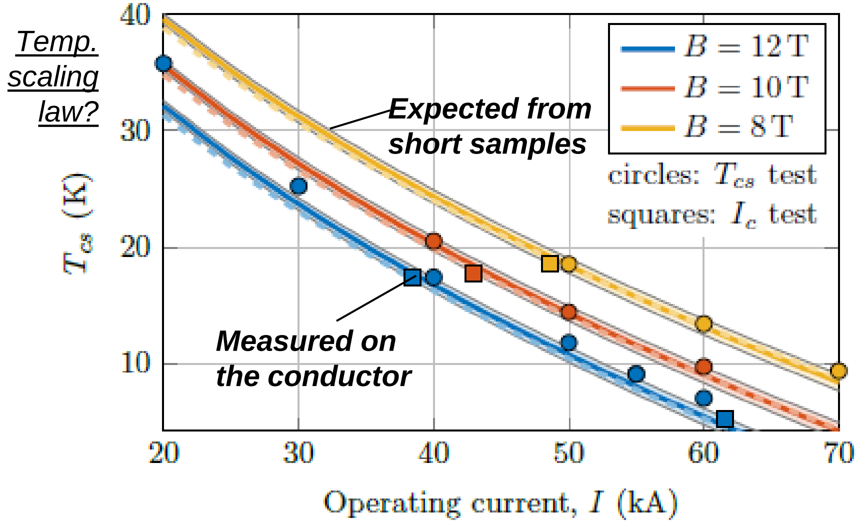
At high currents the transition starts at T< 4.5 K.

The data were fitted with $\mathbf{E(T)=E_{offset}+(T/T_{cs})^{m}}$

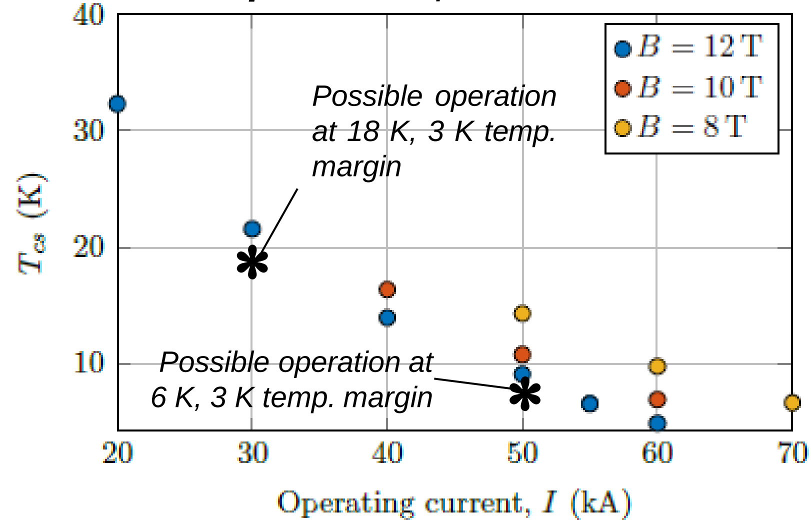


Test – DC

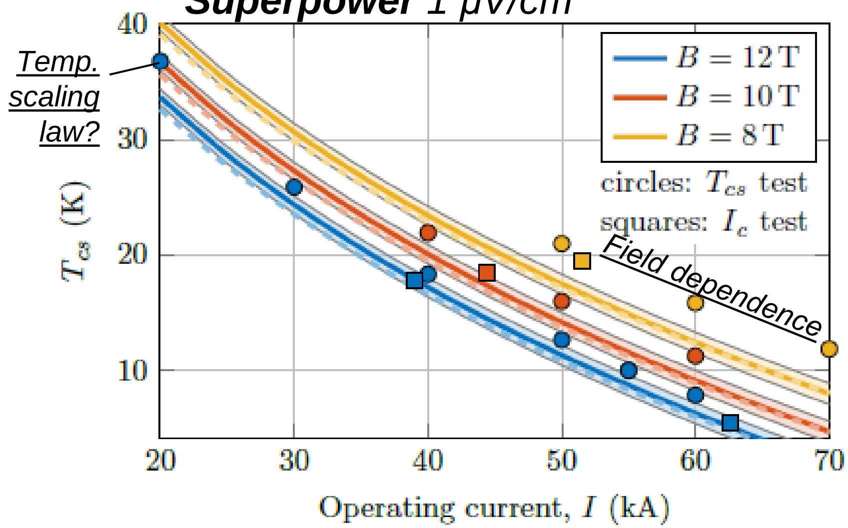
Superox 1 μV/cm



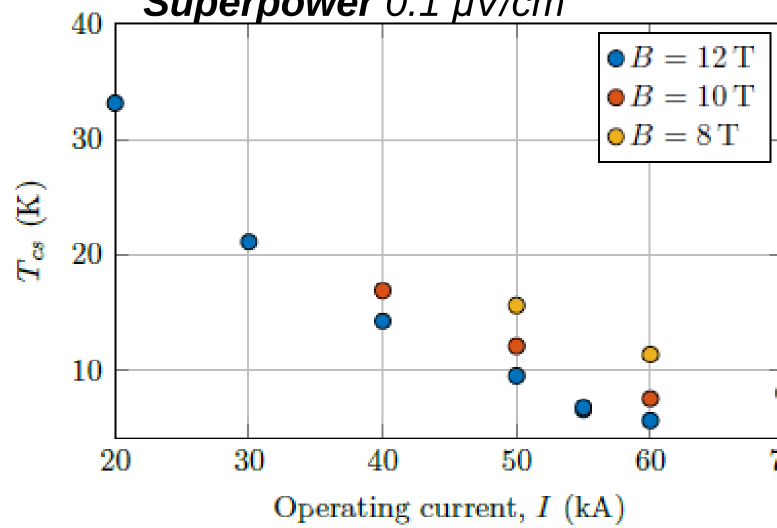
Superox 0.1 μV/cm



Superpower 1 μV/cm



Superpower 0.1 μV/cm



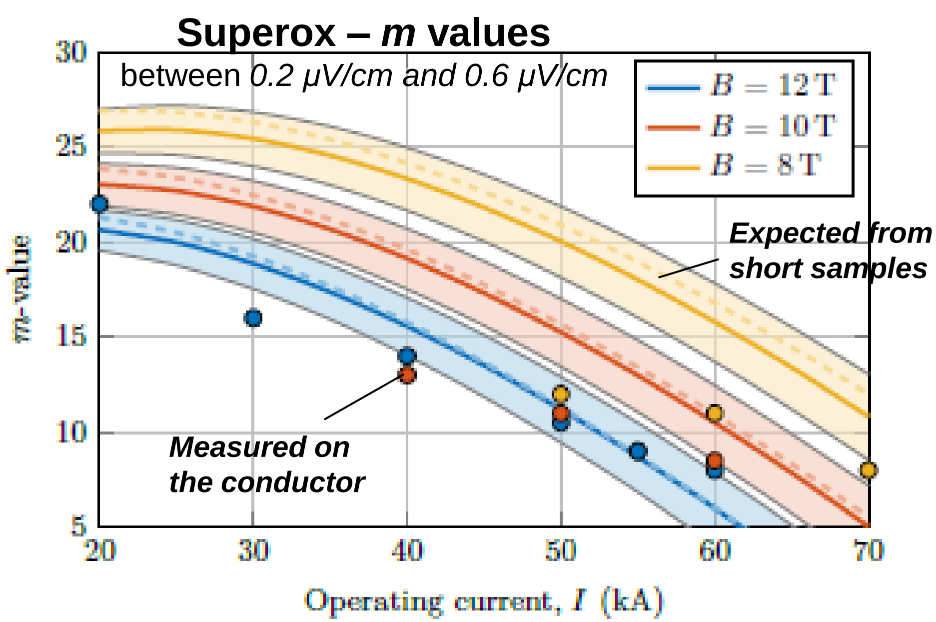
About 100% of the performances of short samples were retained in the conductors

Test – DC

77 K, s.f.	*n* **value - tapes**	*n* **value – strands on cable**
Superpower	21 ~ 30	21 ~ 26
Superox	30 ~ 35	27 ~ 29

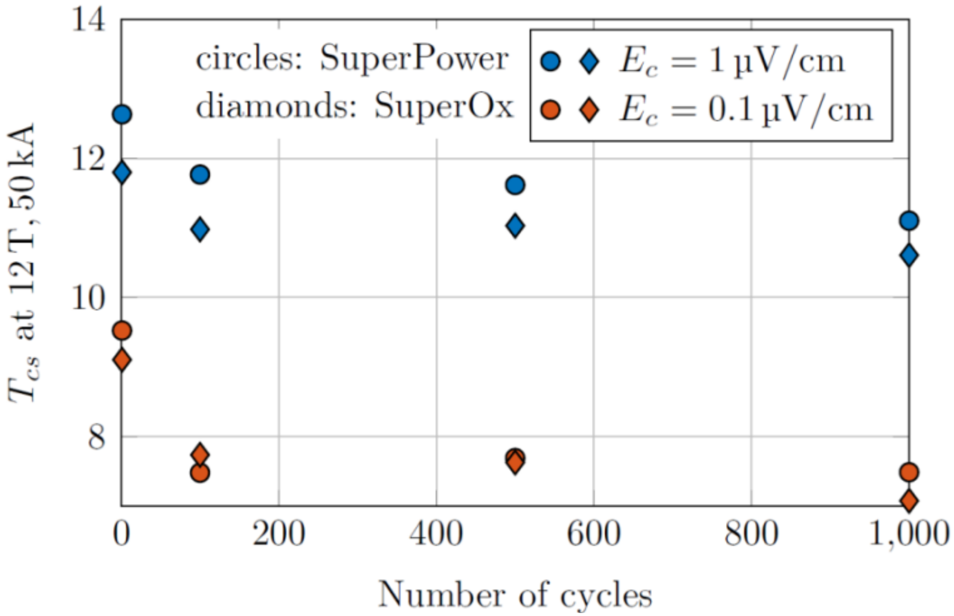
Little reduction of the *n* value from tapes to strand, because of higher self field.

5 K, 12 T	*n* **value – tapes**	*n* **value – cable**
HTS cables	30 ~ 50	12



In ITER conductors 20<*m*<30 at 6 K,10.8 T

Test – DC cycling



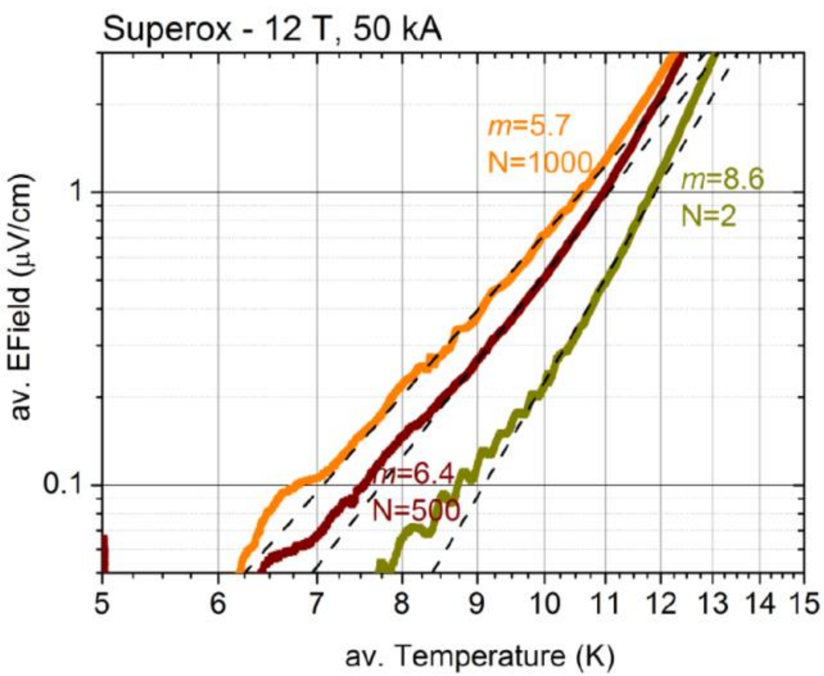
Slightly reduction is observed after electromagnetic cycling.

Could be to a change in strain or to fractures. To be investigated …

N = 1 N = 1000

100% of expected T_{cs} ⇒ 86%

100% of expected I_c ⇒ 97%



In ITER CS conductors

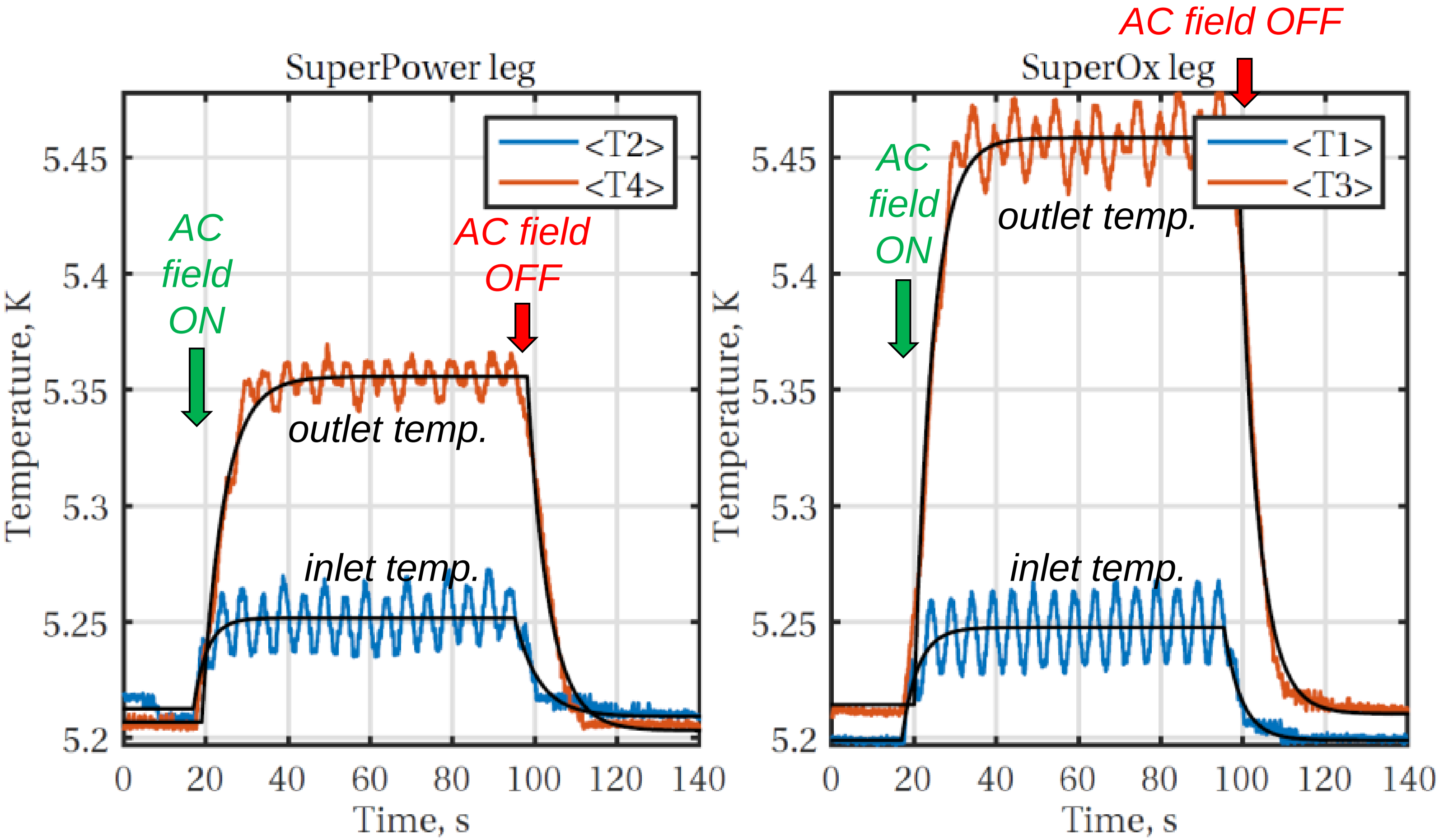
78%~89% of expected T_{cs} ⇒ 77%~90%

Much worse for I_c

Conductor must be reliable: degradation is not allowed.

Test – AC

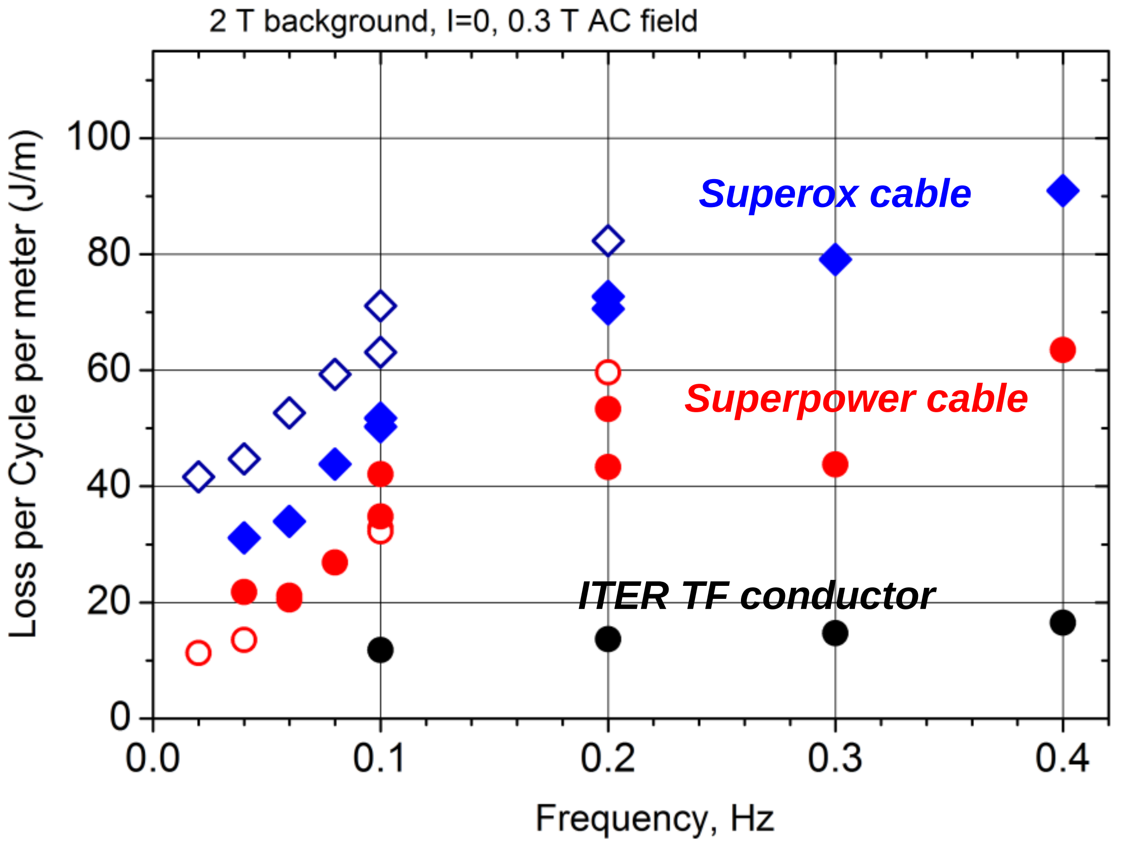
AC losses are measured by calorimetric method, as for ITER conductors in SULTAN.



$$P = \left(h(T_{out}, p) - h(T_{in}, p)\right) \dot{m} / l \qquad [\mathrm{W/m}]$$

$$Q = P / \nu \qquad [\mathrm{J/m/cycle}]$$

Test – AC



REBCO
sc cross section: 2~4 mm²

Nb_3Sn
sc cross section: 50~70 mm²

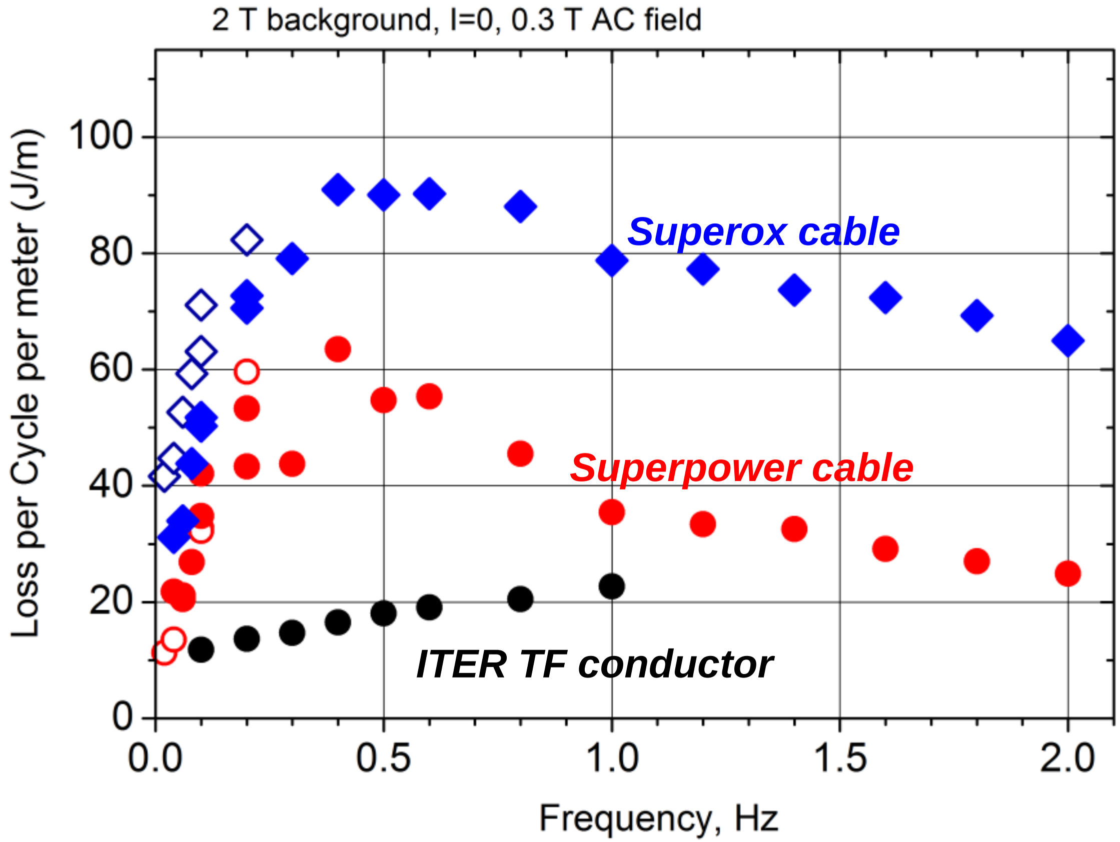
Hysteretic losses in the Superox cable are higher than in the Superpower. Maybe because of J_c(2 T, 5 K).

Hysteretic losses per unit volume of superconductor:

HTS cables: 1~8 J/mm³

ITER TF: 0.1~0.2 J/mm³

Test – AC



- Total losses are higher than in the TF conductors
- Most of the losses in the HTS cable are coupling losses among strands
- Coupling losses in the cable can be reduced by plating the copper core

SUMMARY

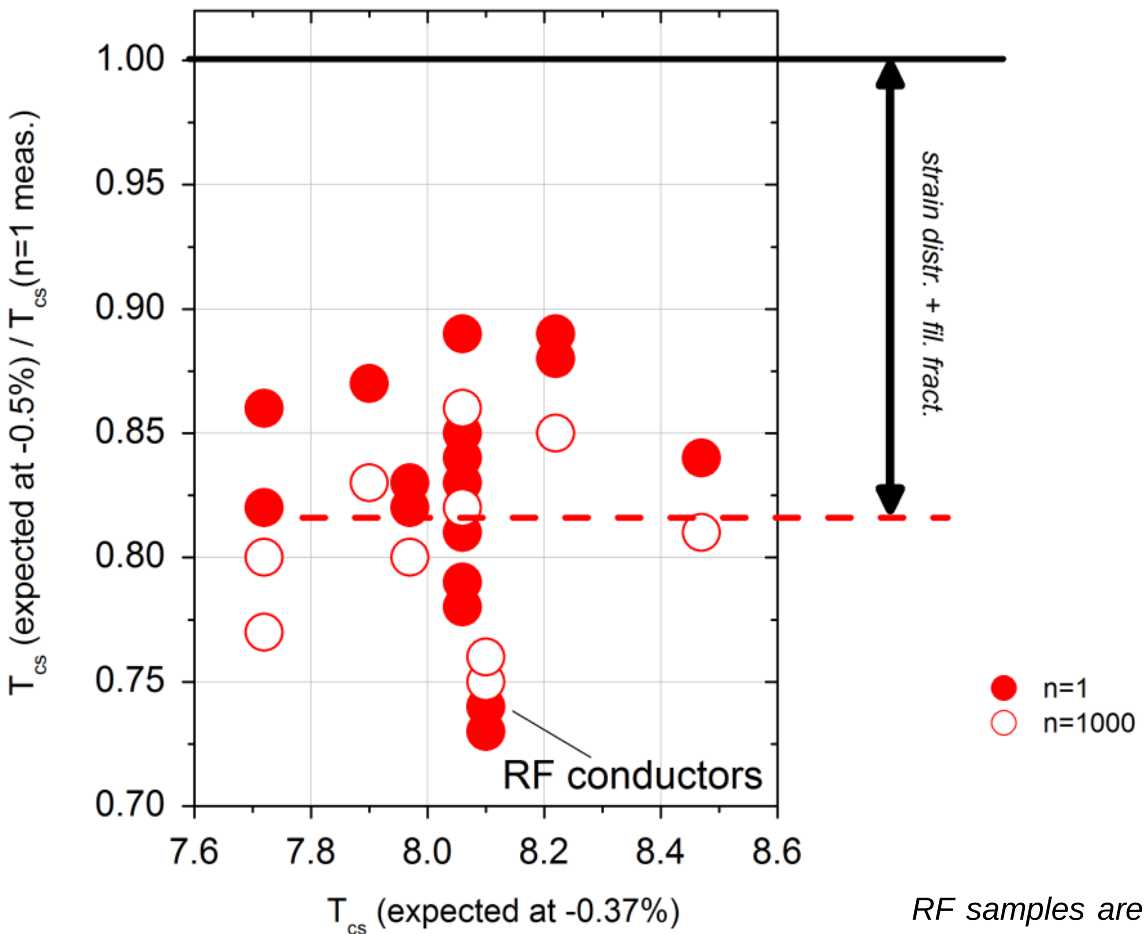
Two cable prototypes were manufactured at laboratory scale and tested in fields up to 12 T in the EDIPO facility. Both cables could carry currents of 60 kA at 5 K and 12 T background field.

Initial I_c and T_{cs} were within few % of the values measured on samples of the tapes used for the manufacturing: the superconducting transport properties of the tapes were fully retained in a large cable composed of partially transposed strands.

During e.m. cycling a reduction of T_{cs} was observed, reaching 10% after 1000 cycles. That corresponds to about 3% of reduction in I_c.
The reason is not yet identified; further tests and investigations are planned.

AC losses: values are from 2 to 10 times larger than in the ITER TF conductors, but reduction can be achieved in various way.

T_{cs} in TF samples



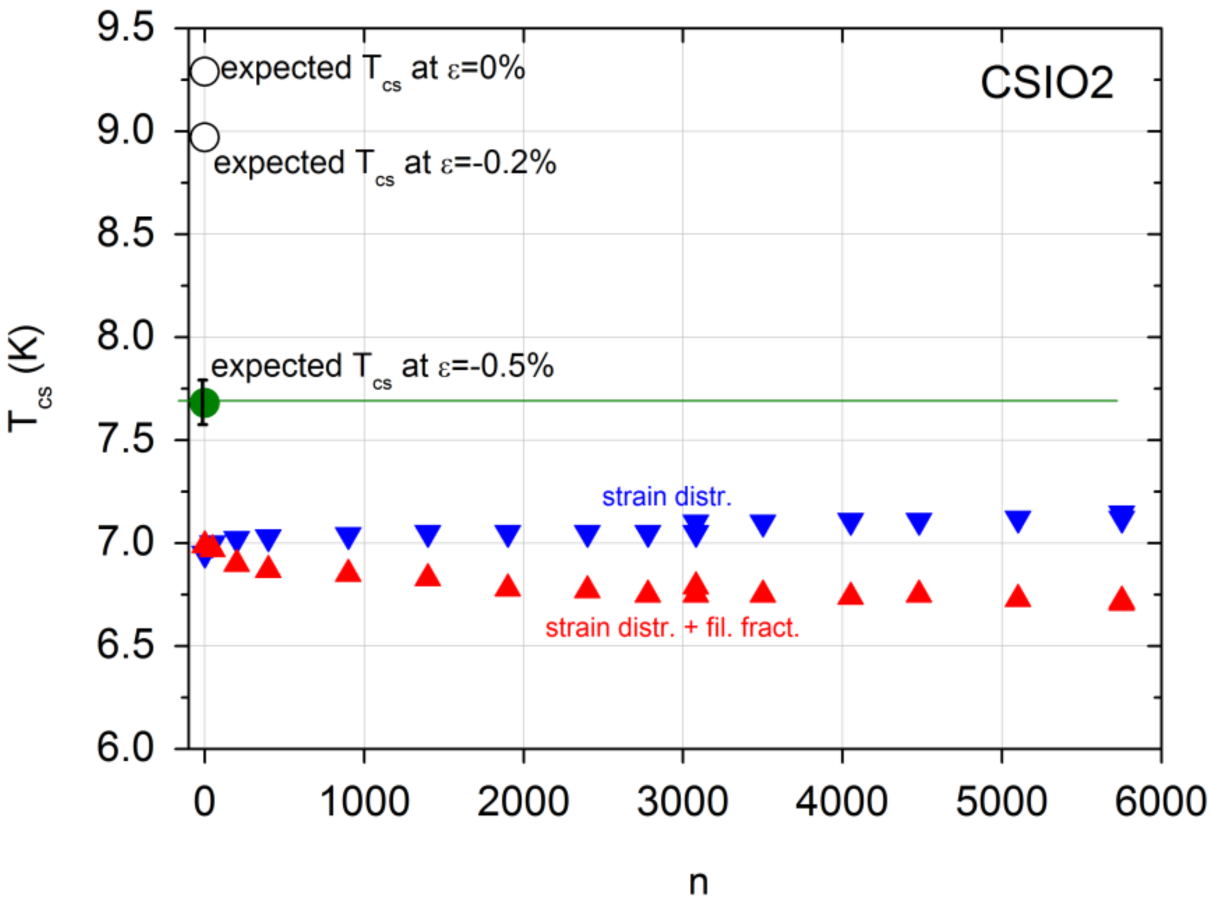
RF samples are the only TF conductors where T_{cs} does not decrease during cycling.
But the reduction with respect to the expected T_{cs} is the largest.

T_{cs} in CS samples

CSIO2 is a unique because both legs are made with the same strand, but:

Right leg has short twist pitch (strain distribution but no filament fractures)

Left leg has a long twist pitch (strain distribution and filament fractures)



Expected T_{cs} includes the strand scaling law and the self field effect.

It does not include the effect of filament fracture and strain distribution.