Results of Conductor Testing in SULTAN: A Review

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Introduction

In the last few years a large number of NbTi and Nb_3Sn sub- as well as full-size cable-in-conduit (CIC) conductors were tested in the SULTAN facility.

For many of these conductors, the strand critical current was measured separately as a function of field, temperature and strain.

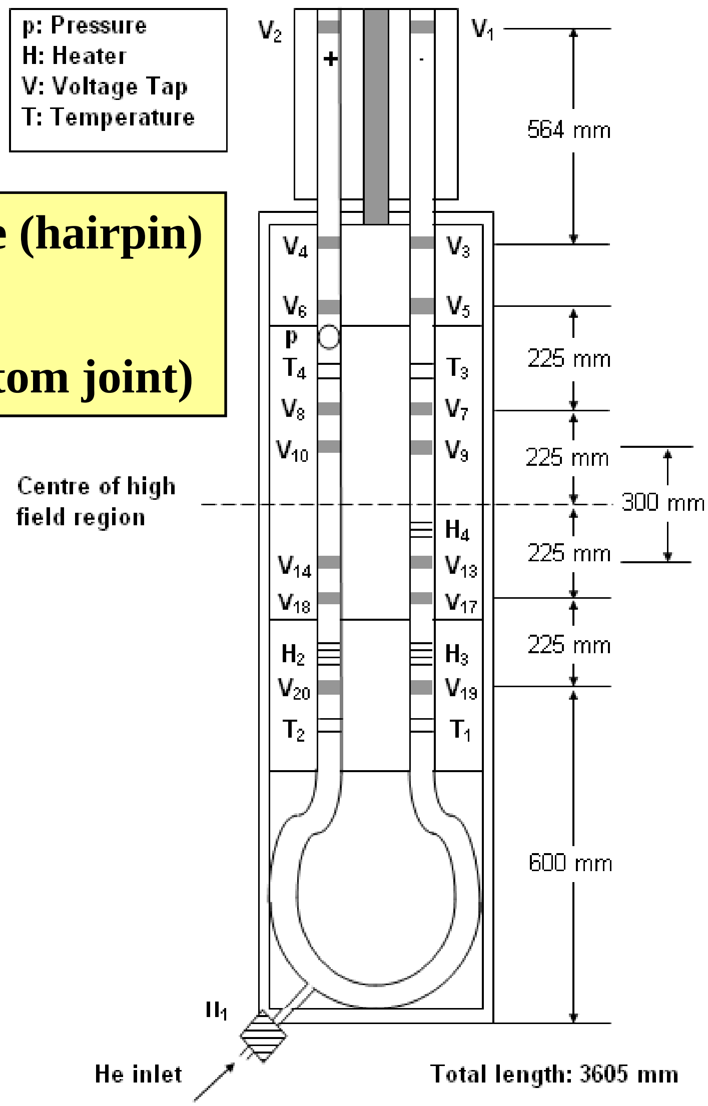
Using strand scaling relations (interpolation) and the measured strand data the “potential” DC performance of various CIC conductors has been estimated. In the estimation of the “potential” T_{cs} or I_c it has been supposed that the current distribution is uniform.

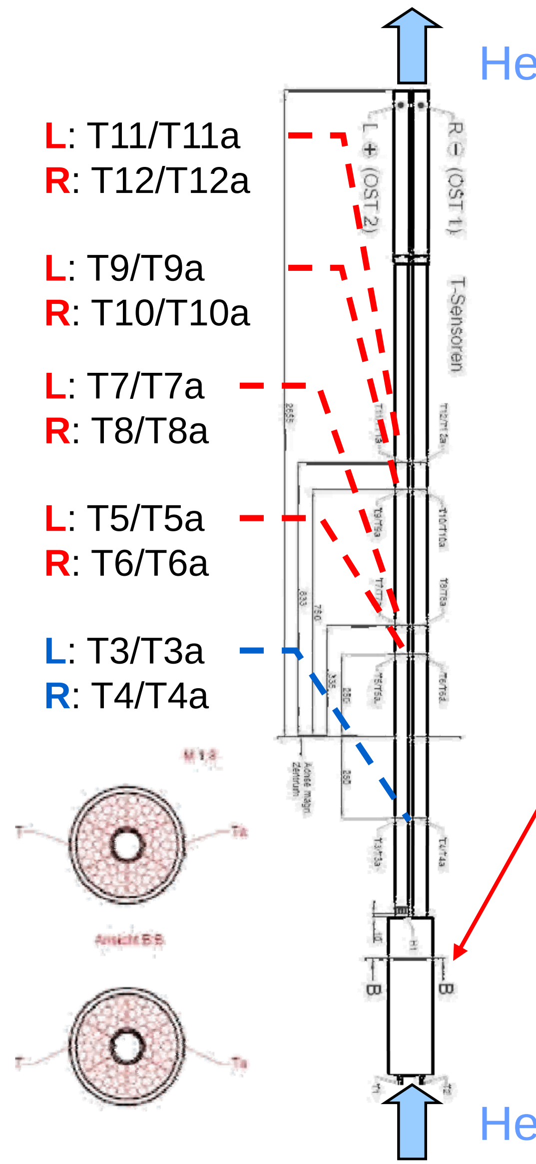
The performance of the SULTAN samples is compared to this “potential” performance.

SULTAN Samples

Sub-size (hairpin) samples

(No bottom joint)



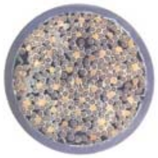


Full-size samples

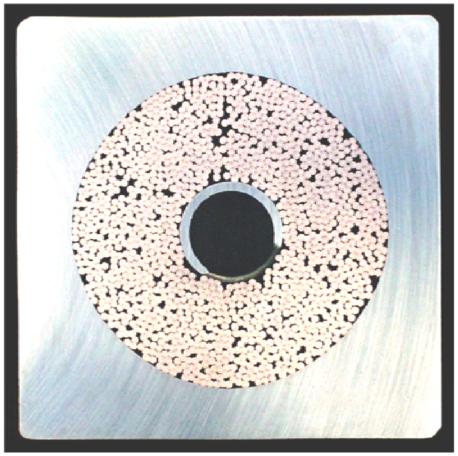
(With bottom joint)

NbTi CIC Conductors

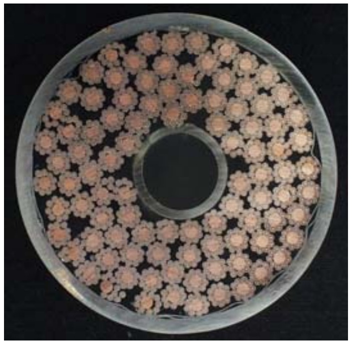
NbTi #3



PFIS R

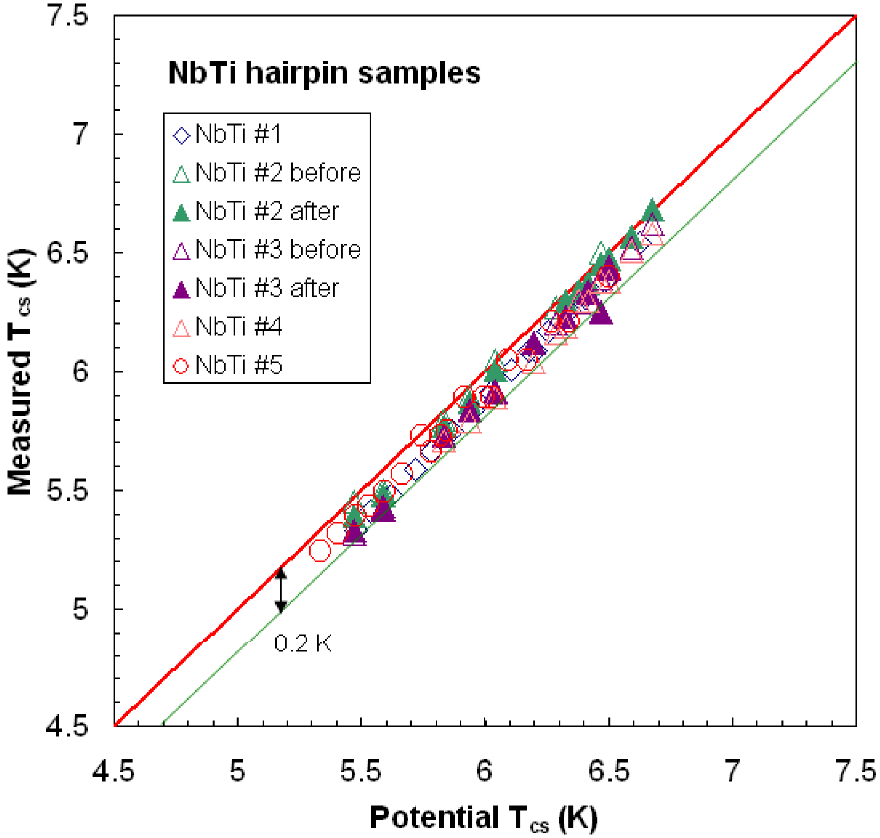


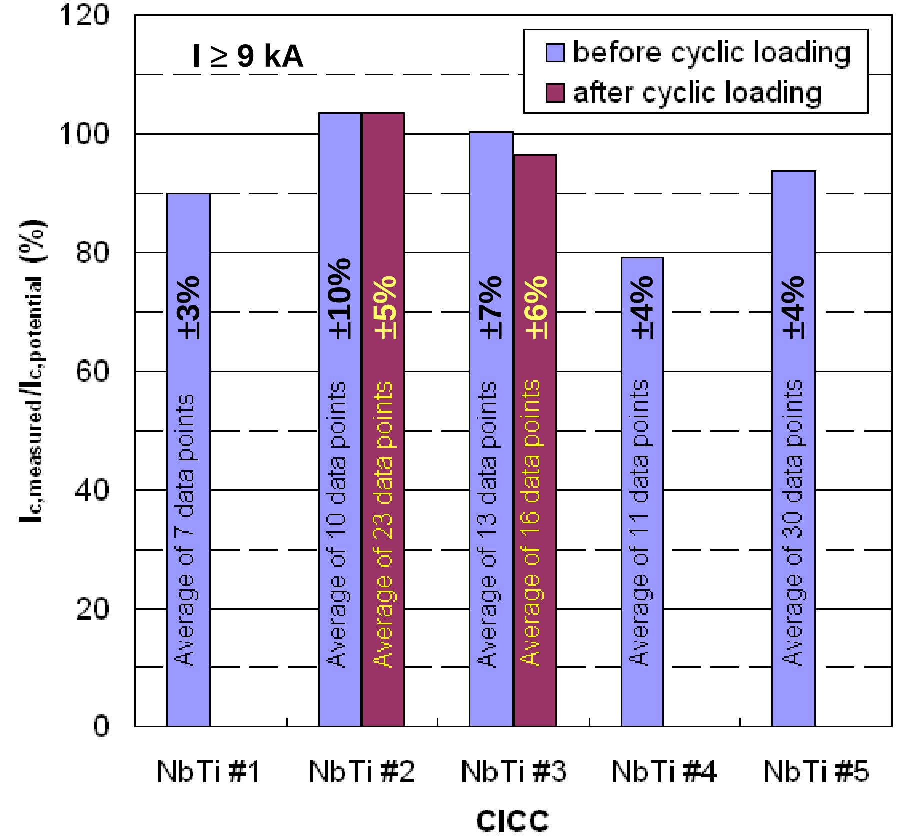
LCJ



CICC	Strand	Coating	Cable pattern	N_{NbTi}
NbTi #1	A	Ni	(1NbTi+7Cu)×3×4×4	48
NbTi #2	B	SnAg	(1Cu+6NbTi)×3×4×4	288
NbTi #3	B	Ni	(1Cu+6NbTi)×3×4×4	288
NbTi #4	B	Ni & wraps	(1Cu+6NbTi)×3×4×4	288
NbTi #5	C	Ni	(1Cu+6NbTi)×3×4×4	288
PFIS L	D	Ni & wraps	(3×4×4×5)×6 NbTi	1440
PFIS R	D	Ni	(3×4×4×5)×6 NbTi	1440
LCJ	D	Ni	(1Cu+9NbTi)×4×4×6	864

Results of NbTi Sub-size Conductors

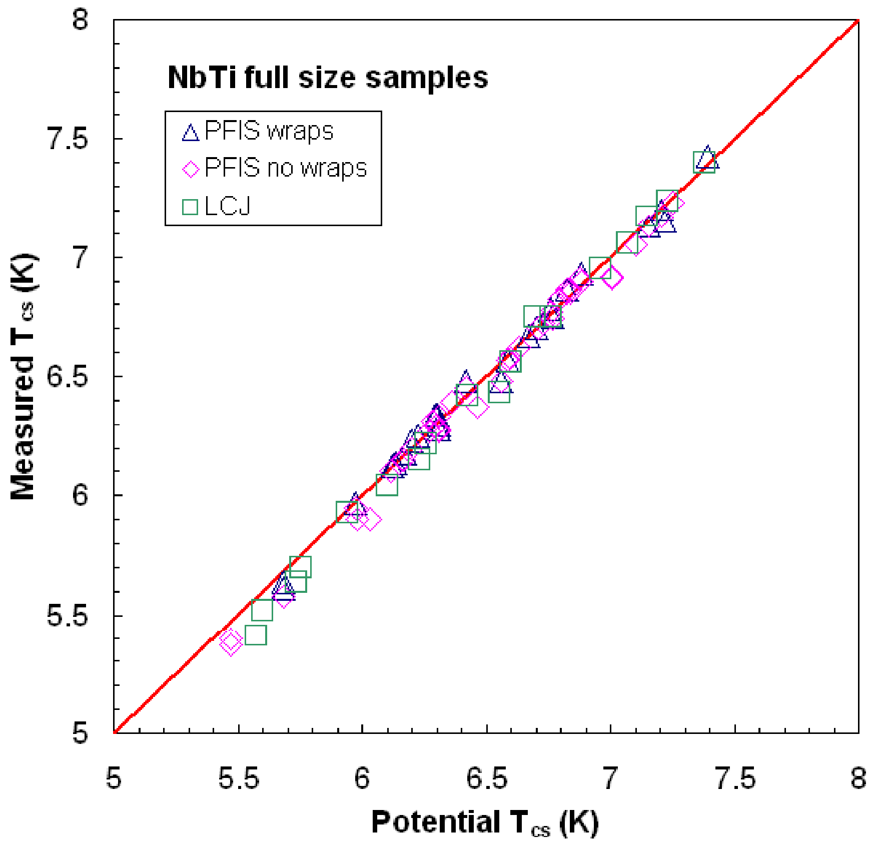


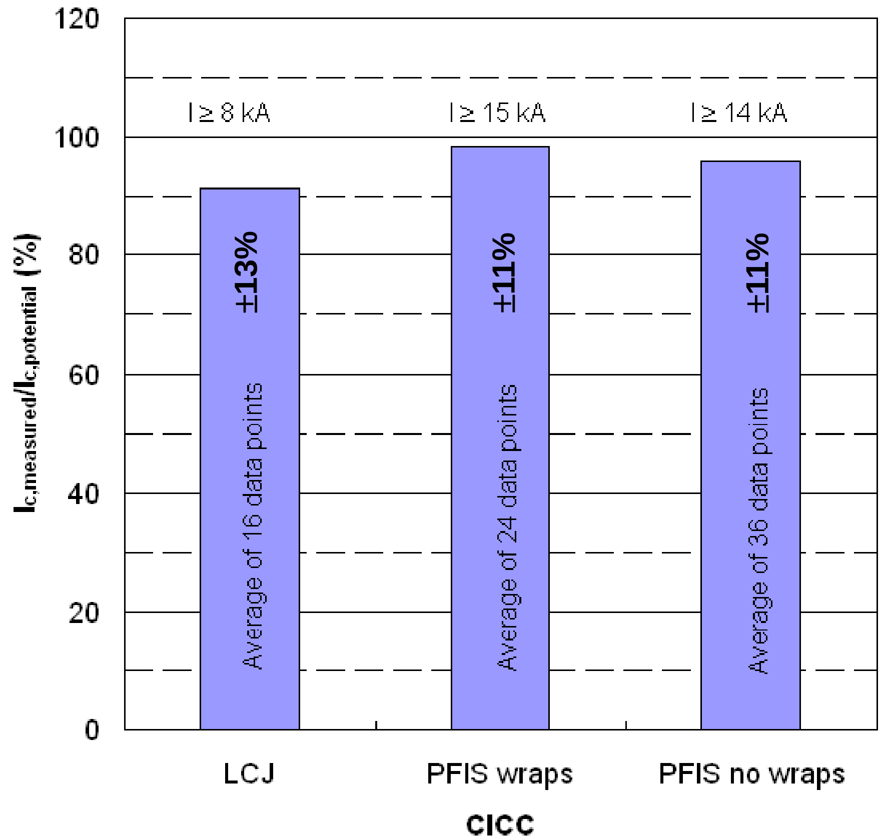


Measured T_{cs} values of NbTi hairpin conductors are very close to the "potential" T_{cs}. Deviations are of the order of 0.1 K. Cyclic loading does not affect the T_{cs}.

4 out of 5 conductors reach more than 90% of the "potential" I_c.
NbTi #4 (wraps): ≈80% of "potential" I_c.
$n_{cable} \approx n_{strand}$

Results of NbTi Full-size Conductors





Measured T_{cs} values of NbTi full-size conductors are in very good agreement with the "potential" T_{cs}. Deviations are typically less than 0.1 K.

All NbTi full-size conductors reach more than 90% of the "potential" I_c.

Summary NbTi CIC Conductors

- **No significant cyclic load degradation.**
- **In 4 out of 8 conductors more than 95% of the "potential" I_c is reached.**
- **In 7 out of 8 conductors more than 90% of the "potential" I_c is reached.**
- **In NbTi #4 (wraps) only ≈80% of the "potential" I_c is reached.**

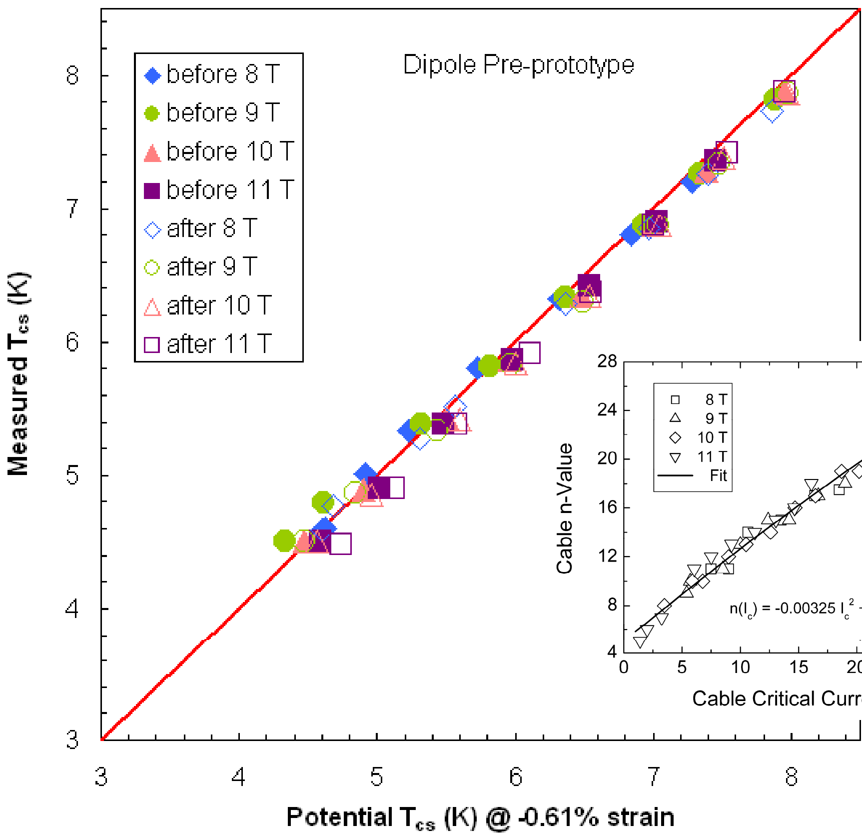
The deviations from the potential I_c include:

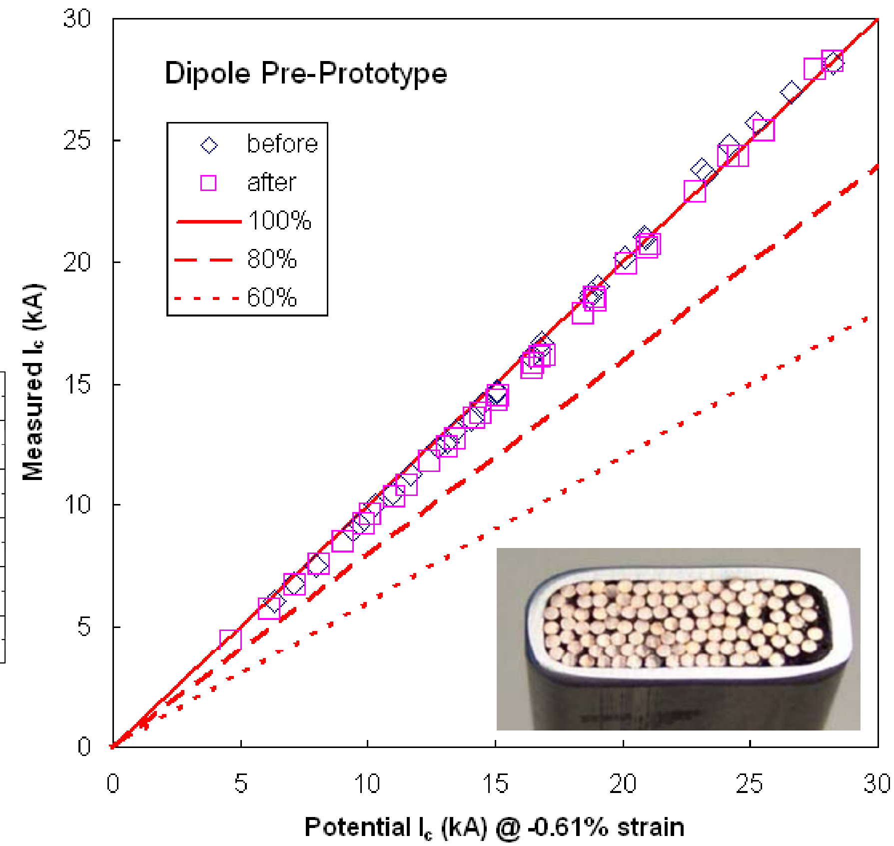
- **Accuracy of the strand measurements (Strand B, ±0.02 K, ±5% in I_c @ 6 K, 6 T).**
- **Errors in strand scaling parameters (ΔI_c typically below 8%, <6 T underestimation, >6 T overestimation of I_c).**
- **Accuracy of the SULTAN temperature measurements before 2006 (±0.05 K, NbTi #3, ±10% in I_c @ 6 K, 6 T).**
- **Uncertainty in the "potential" I_c, which is based on a completely uniform current distribution and the assumption that each strand is found with the same probability at any position in the cable cross-section.**

Nb_3Sn Sub-size CIC Conductors

CICC	Strand	Dimensions (mm)	Twist Pitch (mm)	Cable pattern	N_{sc}
VAC Sub-size	VAC CSMC	14.5 / 12.5 14.52 / 12.52	51/76/136/167 167	3×3×4×4 29 (braid) × 5	144 145
Dipole Pre-Prototype	OST 7730-2, -3	18.4 × 7.7 Jacket 16.4 × 5.7 Cable	58/95/139/213	3×3×3×4 24 Cu	84
PITSAM 1	OST dipole	21.1 × 9.5 Jacket 17.9 × 6.3 Cable	58/95/139/213	3×3×4×4	144
PITSAM 2	OST dipole	12.6 × 12.6 Jacket 9.1 × 9.1 Cable	58/95/139/213	3×3×3×4 60 Cu	48
PITSAM 3	OST dipole	15.4 × 10.5 Jacket 11.9 × 7 Cable	58/95/139/213	3×3×3×4 60 Cu	48
PITSAM 5	OST dipole	12.57 × 12.57 Jacket 9.1 × 9.1 Cable	34/95/139/213 83/140/192/213	3×3×3×4 60 Cu	48

Dipole Pre-Prototype





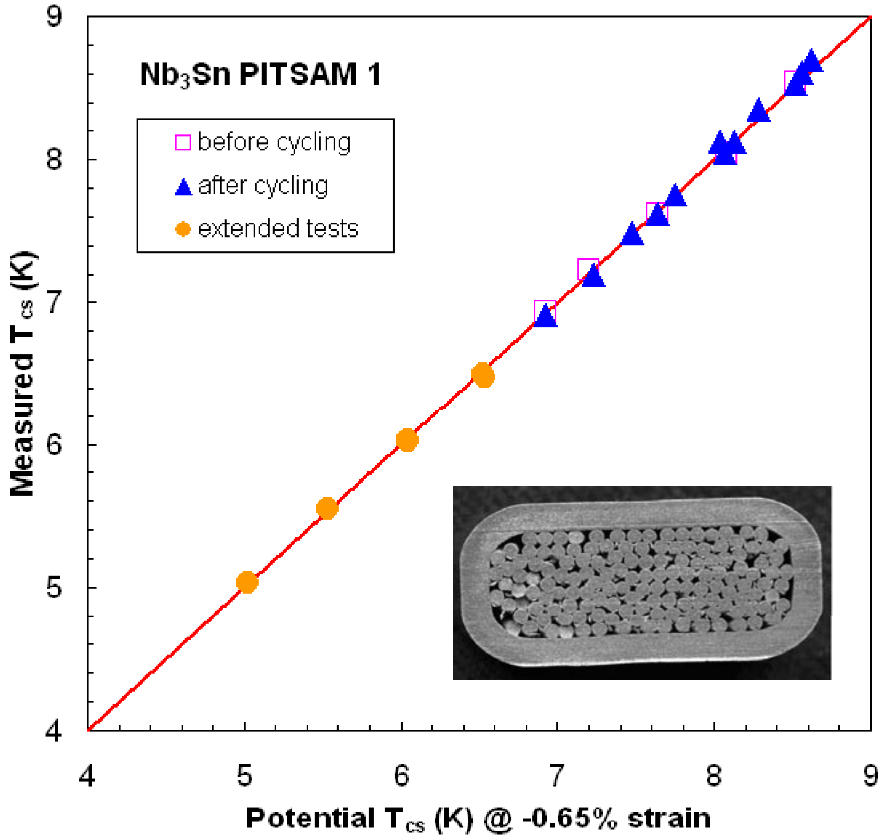
Measured T_{cs} values are close to the "potential" T_{cs} for $\varepsilon = -0.61\%$.

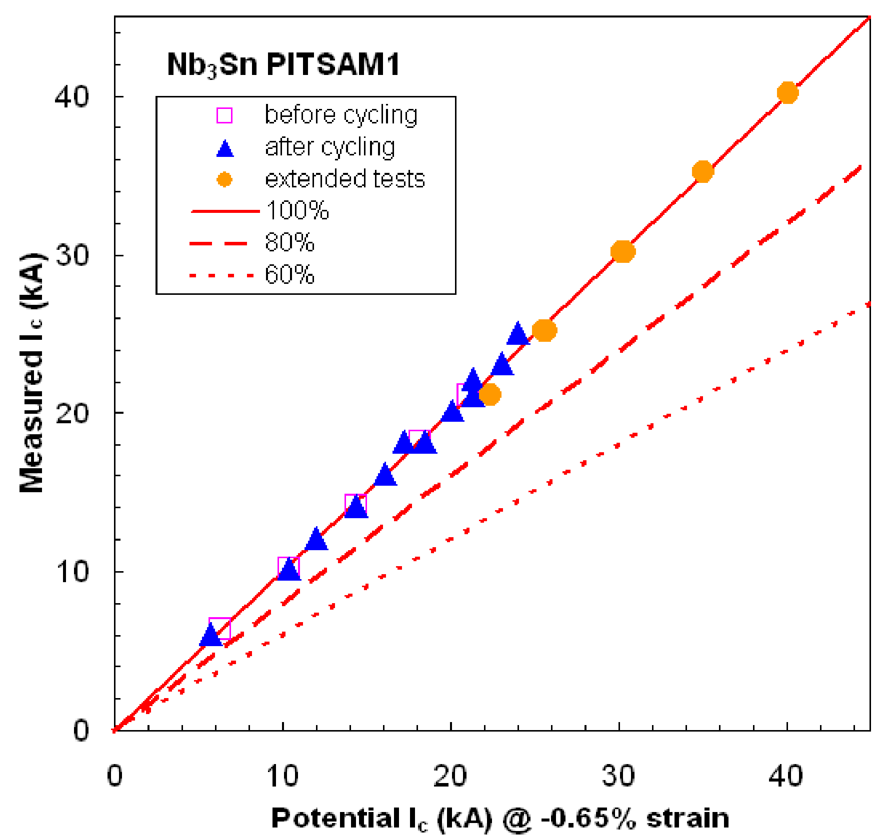
Cable n values above 20 for I_c values higher than 20 kA.

All measured I_c values are close to the "potential" I_c for $\varepsilon = -0.61\%$ (no BI dependent extra strain required).

Negligible cyclic load degradation.

PITSAM 1



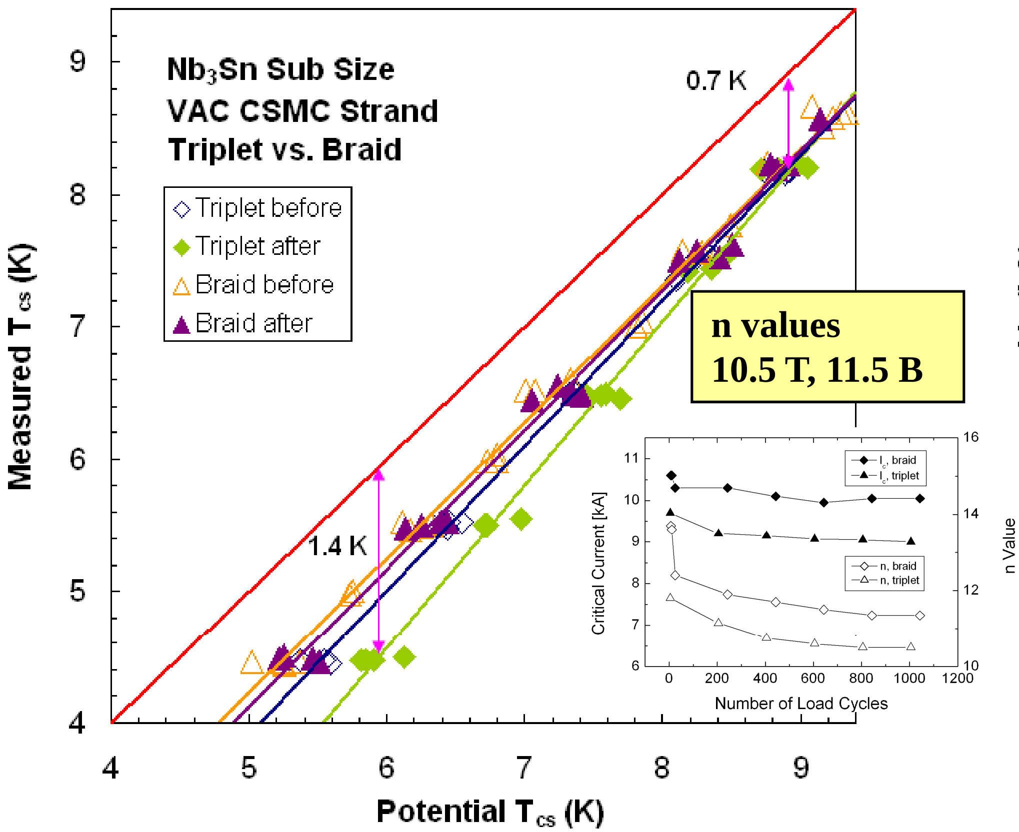


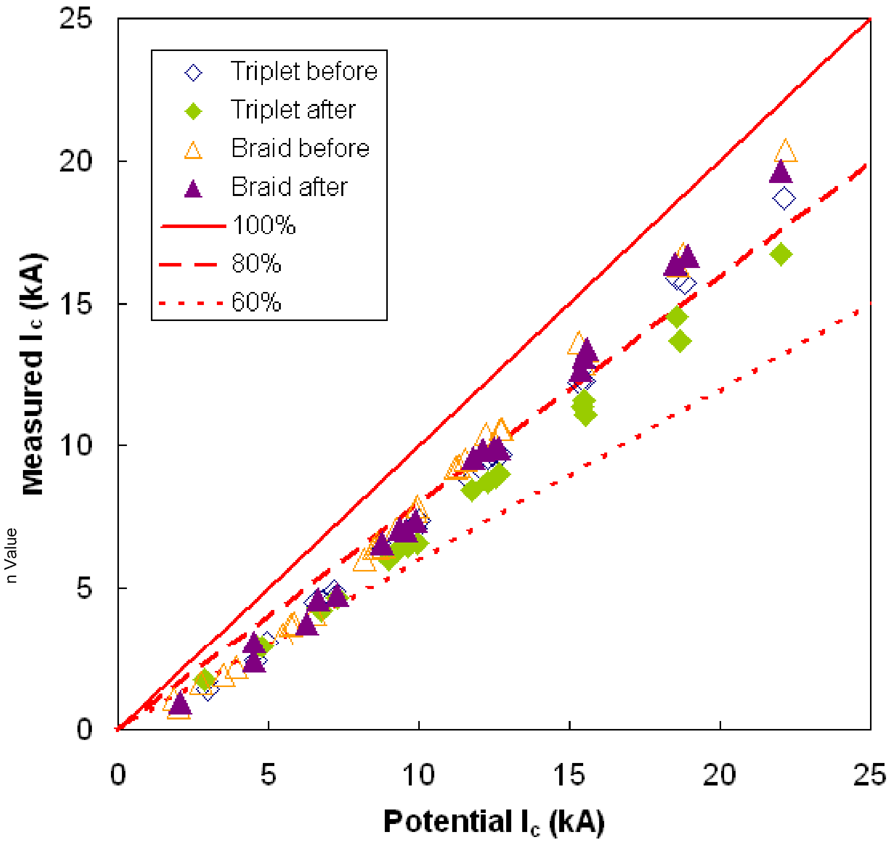
Measured T_{cs} values are close to the "potential" T_{cs} for <u>ε = -0.65%.</u>

Again the cable I_c is close to the "potential" I_c for a single ε value.

In the further considerations a strain of -0.65% is used to calculate the "potential" T_{cs} or I_c values.

VAC Nb_3Sn: Triplet versus Braid

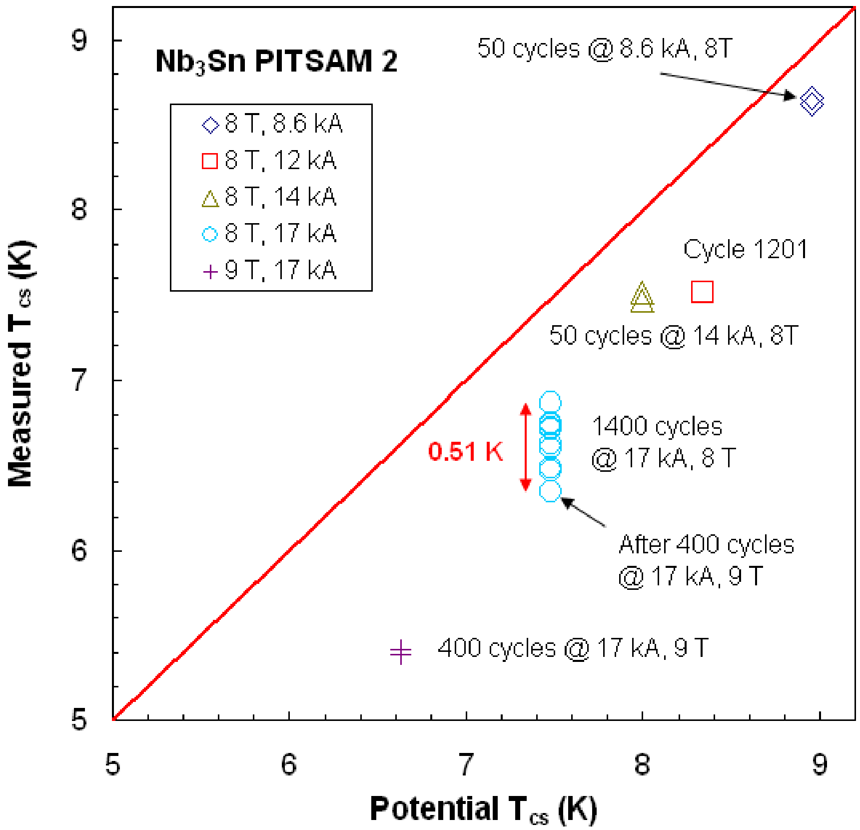


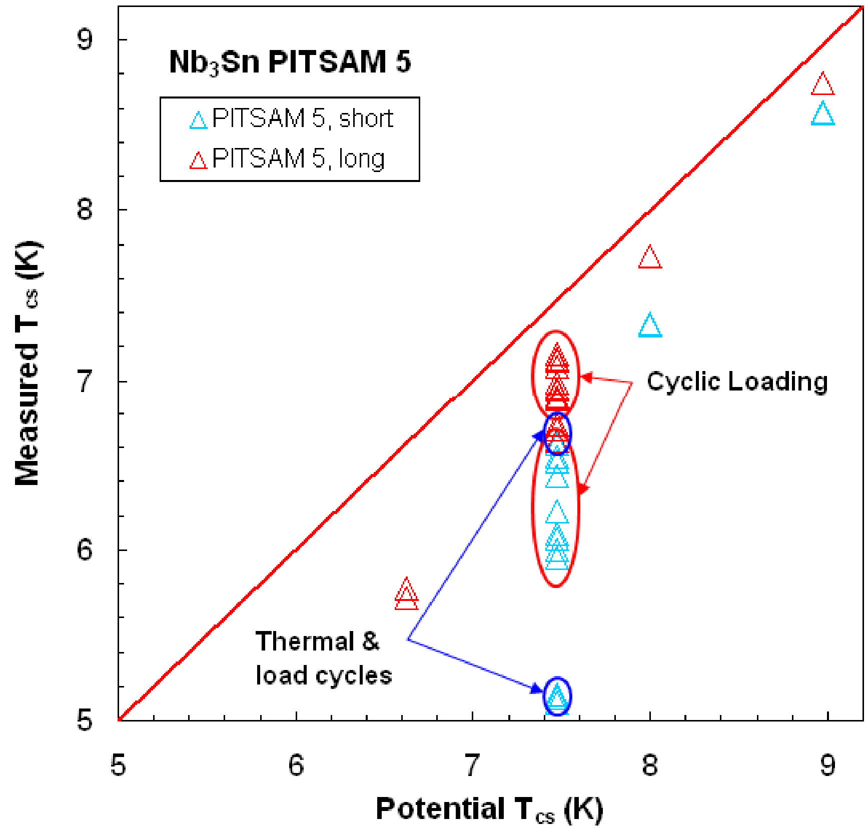


Braid results are closer to the "potential" T_{cs} and I_c values. Moreover, the triplet CICC shows reduced performance after cyclic loading.

Braid: $I \geq 15$ kA I_c^{cable}: 80-90% I_c^{pot}
Triplet: $I \geq 15$ kA I_c^{cable}: ≈75% I_c^{pot}
(after cyclic loading)
ε: -0.75 to -0.90% would fit the data

Effect of Load and Thermal Cycles

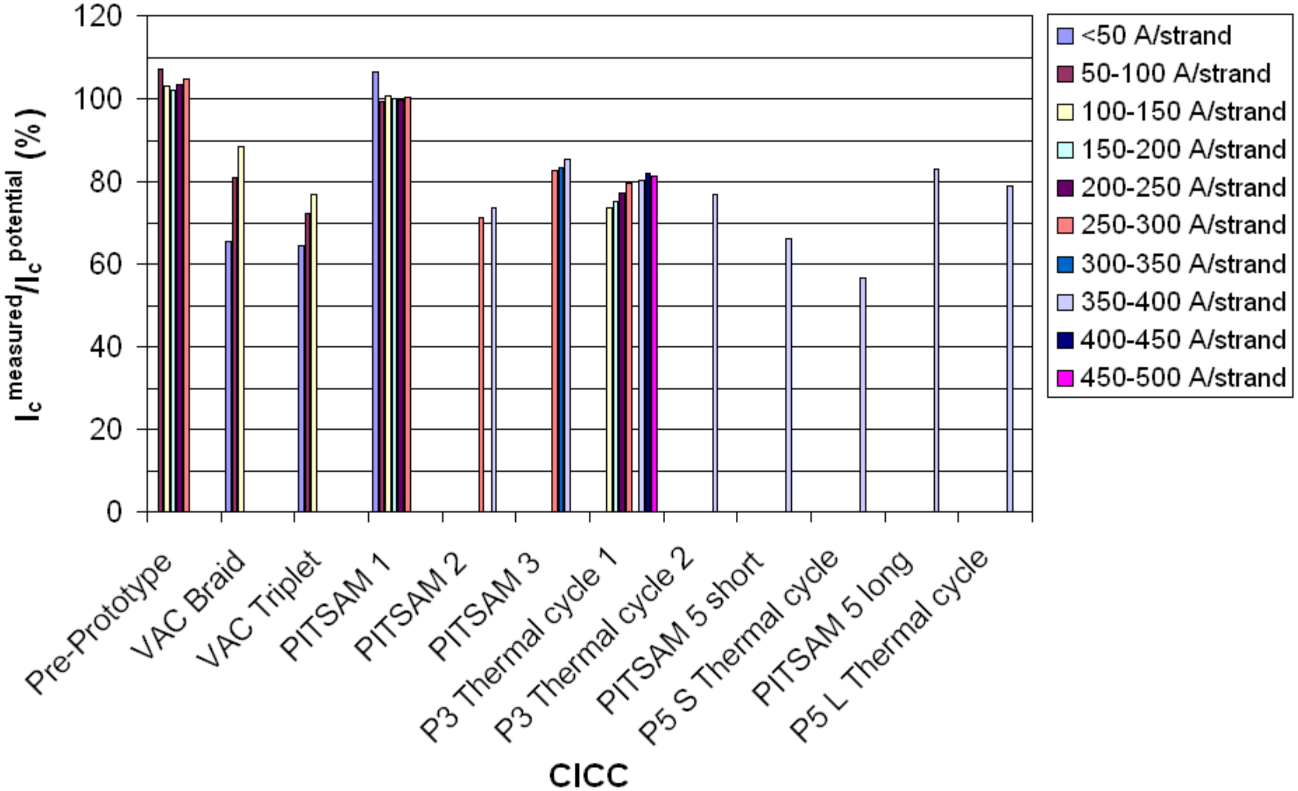




Considerable performance loss of PITSAM 2 (square conductor) during cyclic loading.

CICC half length with long twist pitches shows better performance and less sensitivity to load and thermal cycles. Behavior of PITSAM 3 (aspect ratio: 1.7) is comparable to that of PITSAM 5 long.

Summary: Nb_3Sn Sub-size CIC Conductors



Pre-Prototype and PITSAM 1 reach the "potential" performance.

VAC braid, PITSAM 3 and PITSAM 5L reach ≈80% of the "potential" performance.

VAC Triplet, PITSAM 2: ≈70%

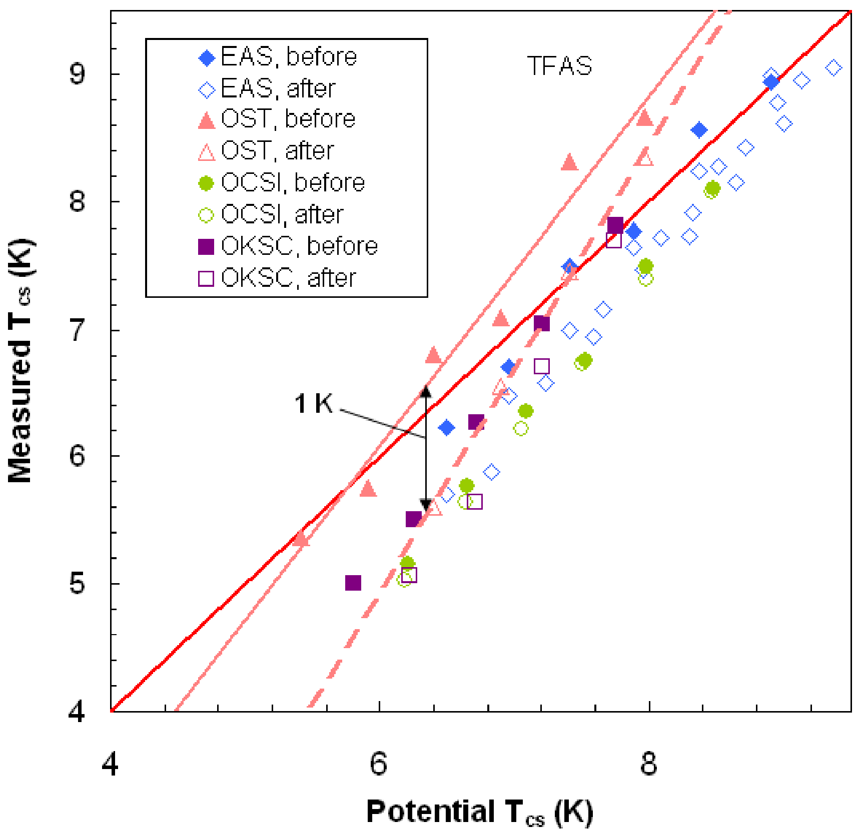
PITSAM 5S: ≈55%

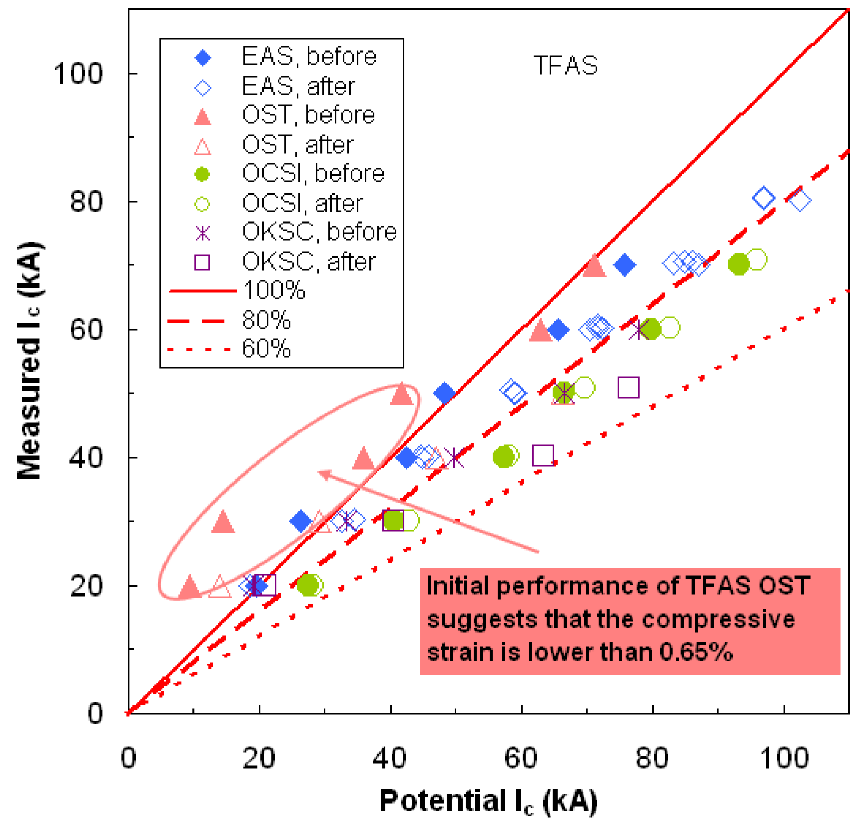
Pre-Prototype and PITSAM 1 are characterized by good performance and negligible cyclic load degradation. The complete data set can be described by a single value of strain. A rectangular shape seems to be advantageous. Low performance is accompanied by sensitivity to cyclic and thermal loads.

Nb_3Sn Full-size CIC Conductors

CICC	Strand	Dimensions (mm)	Twist Pitch (mm)	Cable pattern	N_{sc}
TFAS 1	L: EAS R: OST2	40.4, 37.2	45/87/126/166/415	3×3×5×4×6 (2sc+1Cu)×3×5×6	1080 720
TFAS 2	L: OCSI R: OKSC	40.4, 37.2	45/87/126/166/415	3×3×5×4×6 (2sc+1Cu)×3×5×6	1080 720
TFPRO 1	L: EAS R: EAS	43.45×43.45, 40.25 42.05×42.05, 38.85	45/87/126/245/460	(2sc+1Cu)×3×5×5+C)×6 C: 3×4Cu	900 900
TFPRO 2	L: OST2 R: OST1	41.45×41.45, 38.25 42.05×42.05, 38.85	116/182/245/415/440 45/87/126/245/460	(2sc+1Cu)×3×5×5+C)×6 C: 3×4Cu	900 900
JATF 1	L: Mitsubishi R: Hitachi	43.9×43.9, 40.6 43.9×43.9, 40.6	45×85×130×250×450	(2sc+1Cu)×3×5×5+C)×6 C: 3×4Cu	900 900
JATF 2	L: Hitachi R: Mitsubishi	42.7×42.7, 39.3 42.7×42.7, 39.3	45×85×130×250×450	(2sc+1Cu)×3×5×5+C)×6 C: 3×4Cu	900 900
JATF 3	L: JASTEC R: Furukawa	42.65×42.65, 39.3 42.65×42.65, 39.3	80×142×178×300×420	(2sc+1Cu)×3×5×5+C)×6 C: 3×4Cu	900 900
KOTF	L: KAT R: KAT	43.7×43.7, 40.5 43.7×43.7, 39.9	42×80×125×240×450	(2sc+1Cu)×3×5×5+C)×6 C: 3×4Cu	900 900
RFTF NEFFS	Bochvar Bochvar	43.7×43.7, 40.5 43.7×43.7, 40.5	45×84×124×250×453 Void f: L33%, R32%	(2sc+1Cu)×3×5×5+C)×6 C: 3×4Cu	900 900
TFUS 1 Alternate	L: Luvata R: Luvata	43.8×43.8, 40.2 43.8×43.8, 40.3	45×86×127×254×457 25×127×254×457	ITER pattern {[(6sc+1Cu)×6+C1]×5+C2}×6	900 1080

TFAS Nb_3Sn Full-Size Conductors

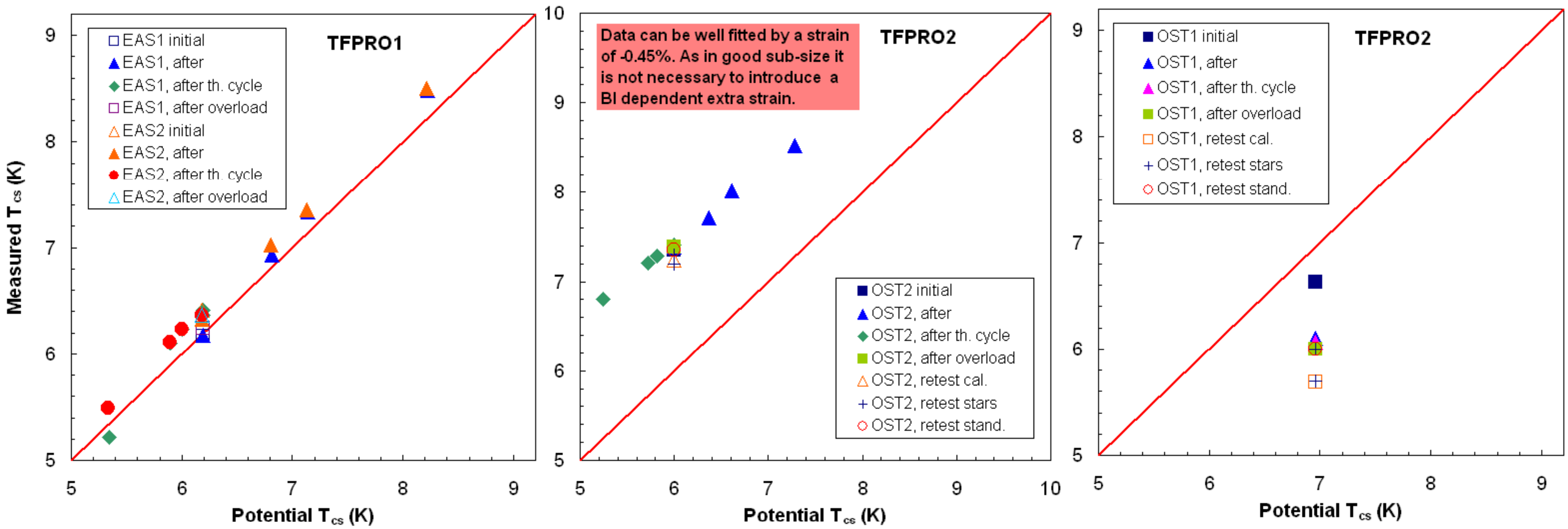




TFAS OST shows the most pronounced reduction of T_{cs} after cyclic loading. Smaller effects for TFAS EAS and OKSC. Nearly unchanged values for TFAS OCSI.

I_c values after cyclic loading reach ≈80% of the "potential" I_c. TFAS OKSC after cyclic loading $I_c \approx 0.7\ I_c^{potential}$

TFPRO 1 & 2

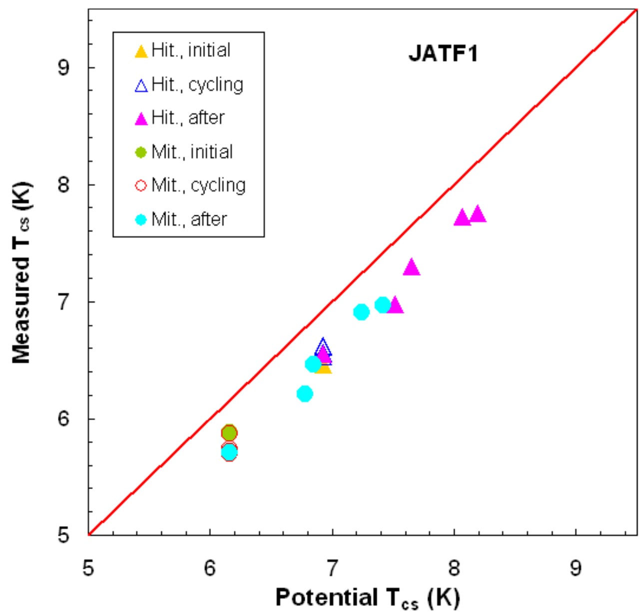


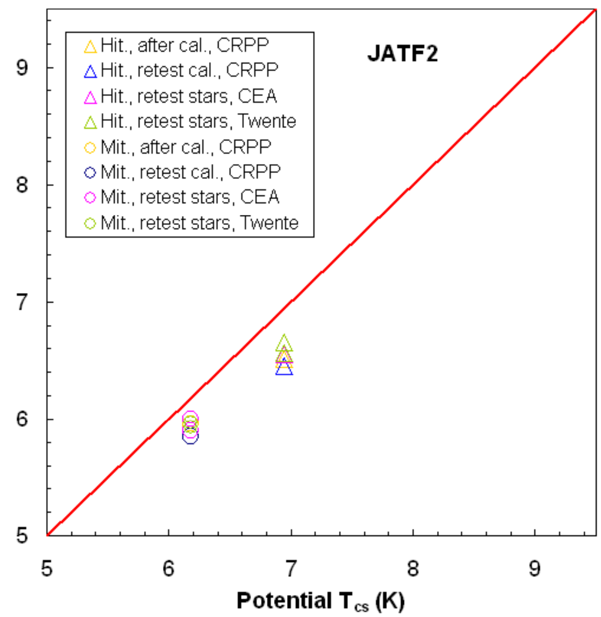
Both legs of TFPRO1 are close to the "potential" T_{cs}. The data suggest that the strain is close to -0.6%. Cyclic load effects are negligible.

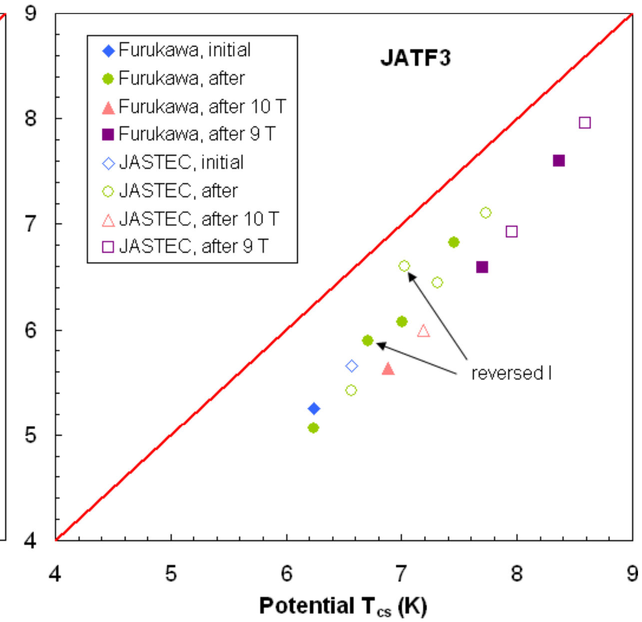
The T_{cs} values measured for TFPRO2 OST2 are far above the "potential" T_{cs}. No evidence for cyclic load degradation.

TFPRO2 OST1 showed a pronounced cyclic load degradation. The lowest T_{cs} value in the plot corresponds to ≈65% of the "potential" I_c.

JATF 1, 2 & 3







JATF1: Negligible cyclic load effects. Measured T_{cs} values slightly below the "potential" T_{cs}. Both the Hitachi and the Mitsubishi leg reach more than 80% of the "potential" I_c.

JATF 2 results are in line with the test of JATF 1.

Hitachi: ≈85% of I_c^{pot}

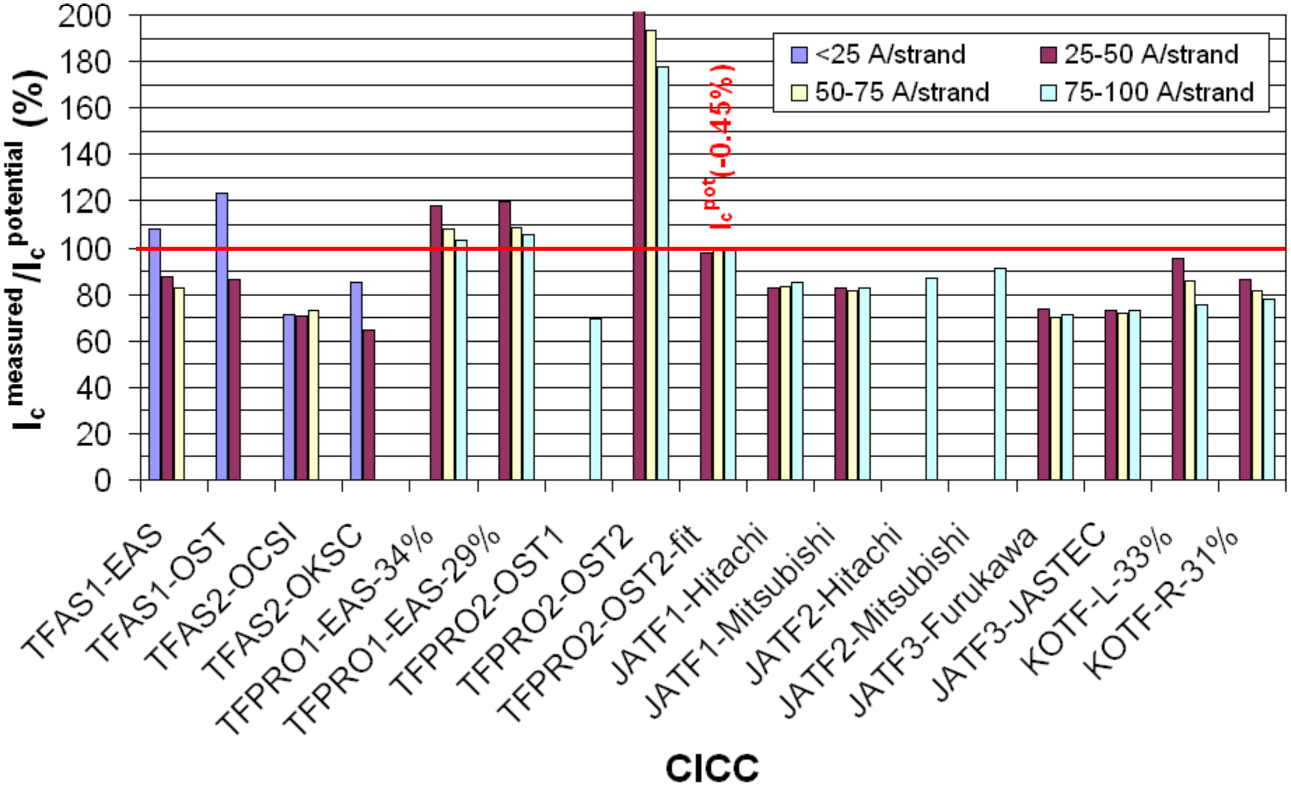
Mitsubishi: ≈90% of I_c^{pot}

JATF 3: T_{cs} of both legs is well below the "potential" T_{cs}.

Evidence for cyclic load degradation.

I_c of both legs ≈70% of I_c^{pot} (after cyclic loading)

Summary: Nb_3Sn Full-size CIC Conductors



TFAS1-EAS, OST & OKSC:

Ratio depends on current. Extra strain or degradation and lower strain.

TFPRO1:

Both legs are close to the I_c^{pot}. Strain is lower than -0.65%.

TFPRO2-OST2:

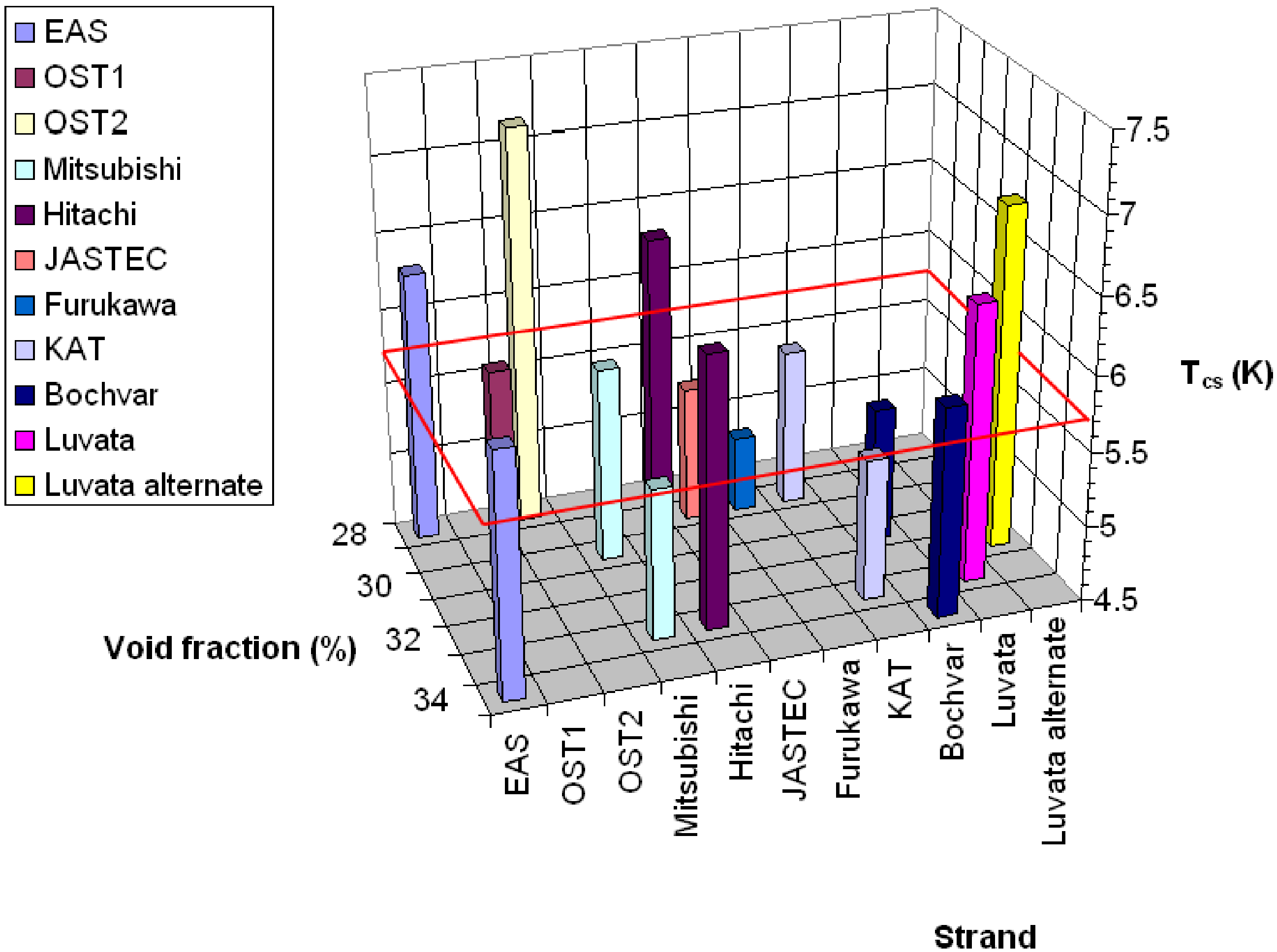
Data are consistent with $\varepsilon \approx$-0.45%.

Both legs of TFPRO1 and TFPRO2-OST2 reach I_c^{pot}.

JATF 1 & 2 Hitachi as well as Mitsubishi are close to I_c^{pot}.

All 4 TFAS legs, TFPRO2-OST1, JATF3-F & J, and KOTF-L & R: I_c^{cable} is below I_c^{pot}.

ITER TF Conductors



Statistics

$T_{cs} \geq 6.5$ K

3 CIC conductors

6 K $\leq T_{cs} \leq 6.5$ K

4 CIC conductors

5.5 K $\leq T_{cs} \leq 6$ K

5 CIC conductors

$T_{cs} \leq 5.5$ K

4 CIC conductors

Summary

- For NbTi sub- and full-size conductors, a good agreement of measured T_{cs} (I_c) with the "potential" values has been found. No evidence for cyclic load degradation in the two tested sub-size conductors.
- Nb_3Sn sub-size: Dipole pre-prototype and PITSAM 1 show excellent agreement with "potential" T_{cs} and I_c. Data can be described without a load-dependent extra strain. These two conductors are not sensitive to cyclic loading.
- VAC triplet, PITSAM 2, PITSAM 5 short showed reduced performance after cyclic loading and/or thermal cycles. T_{cs} and I_c are below the "potential" values.
- Nb_3Sn full-size: For TFAS1-EAS & OST, TFAS2-OCSI & OKSC, TFPRO2-OST1, JATF3 Furukawa & JASTEC and KOTF, the measured T_{cs} values (I_c) are below the "potential" values. Most of these conductors are sensitive to cyclic loading.
- "Potential" values have been reached in TFPRO1-EAS1 & 2, TFPRO2-OST2. JATF1 & 2 (Hitachi and Mitsubishi) are close to the potential values.
- ITER conductors: 7 out of 16 reach T_{cs} values of 6 K or above, 5 conductors are in the vicinity of the 5.7 K criterion.

There remain doubts if the potential of the strands is fully used in all conductors.