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Axial and transverse stress–strain characterization of the EU dipole high J_c RRP Nb_3Sn strand

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Geneva, 20 May 2008

Introduction

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Strain sensitivity Nb3Sn strands / ITER CICC application:

- evaluate sensitivity various applied strands
- cabled conductor design (limiting peak strains).

CICC: axial strain, periodic transverse bending strain and periodic contact stress, axial and transverse stiffness.

Besides pacman disc spring for axial $I_c(\varepsilon)$ measurements, we used the TARSIS test set-up with probes for bending, contact stress and stiffness (axial & transverse).

We concentrate on results of high Jc OST RRP type of strand (EU Dipole strand, EUDIPO) and make a few comparisons with ITER type strands.

Relation cabling pattern and performance degradation in CICC.

Ic (*VI*) and strand deformation in TARSIS

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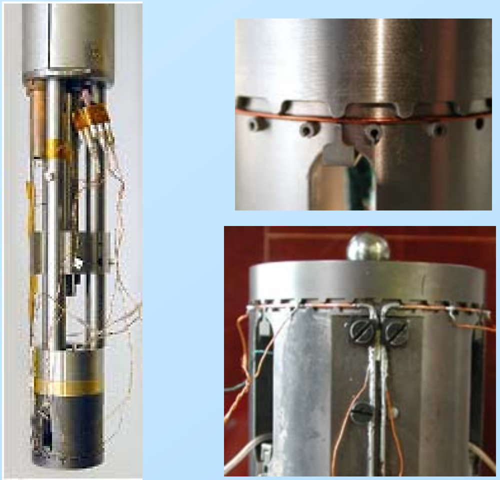
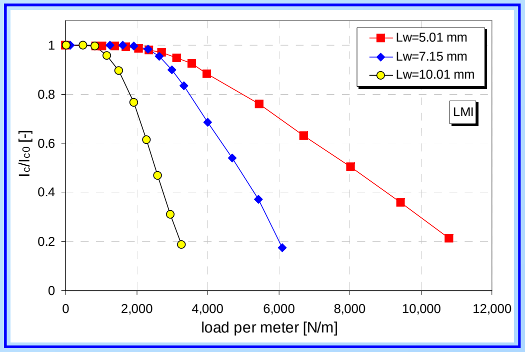
TARSIS test set-up with probes for bending, contact stress and stiffness (axial & transverse).

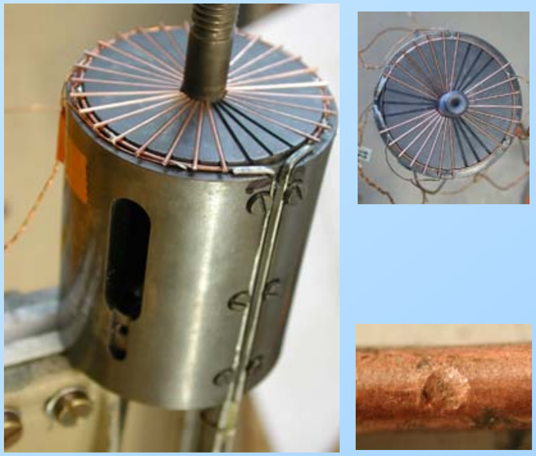
Bending between contact points, various wavelengths.

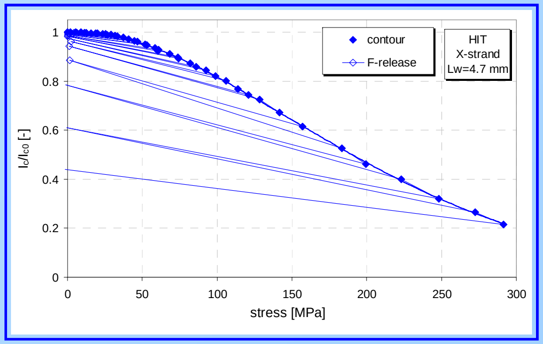




Reduced Ic vs force for SMI strand for 3 wavelengths.

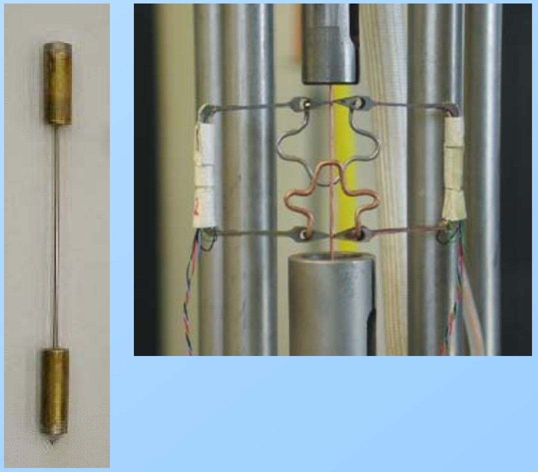
Crossing strands for contact stress characterisation.

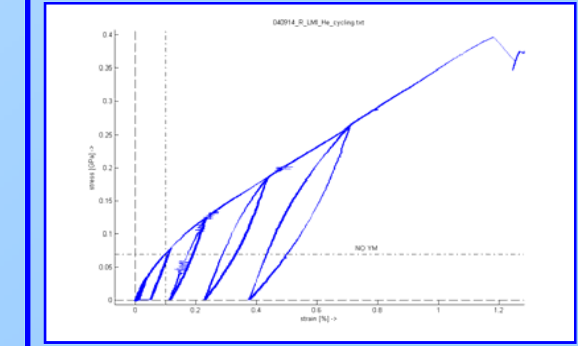




I_c vs stress for crossing strands, 11 T and 12 T for EM-LMI strand.

Strand tensile stress-strain tests at various temperatures (participation in VAMAS).





Stress-strain curve for EM-LMI (TFMC) strand

OST RRP Nb3Sn Dipole strand

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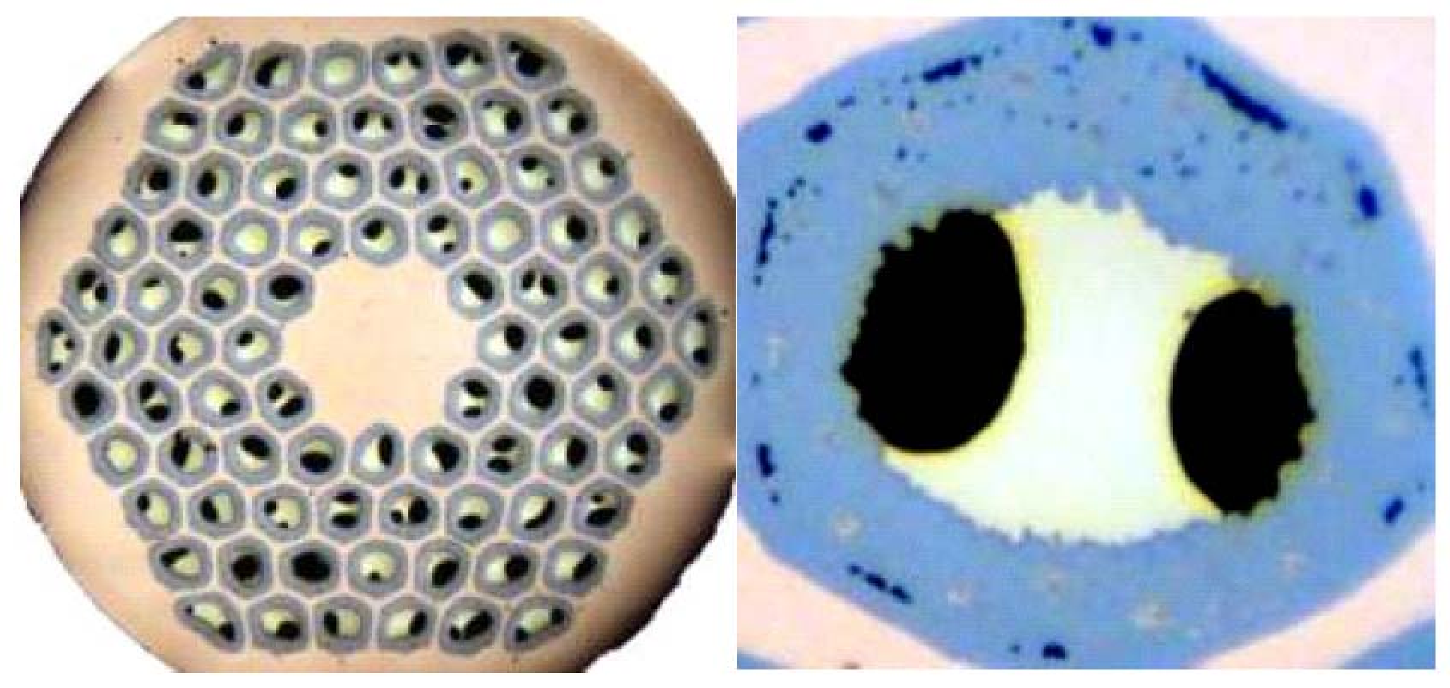
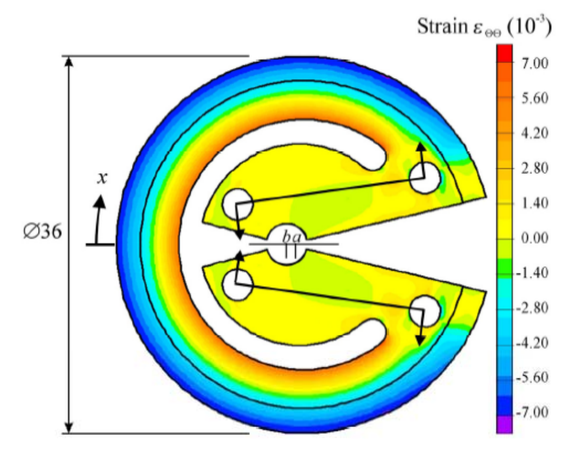


Courtesy of ENEA

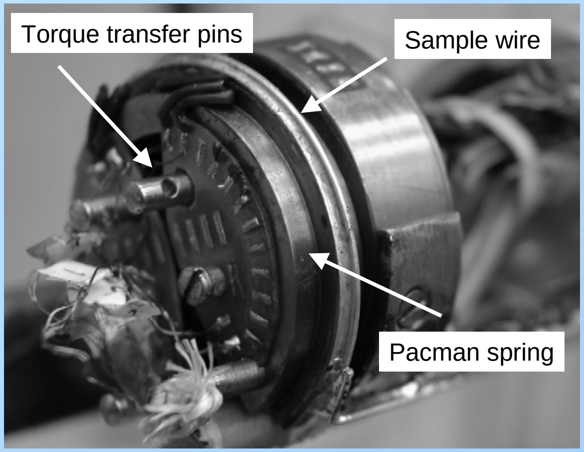
Jc>2060 A/mm2
Ternary Nb + Nb-47Ti
∅ = 0.81 mm
Cu:nonCu= 1
91 x 84 stack design
billet number 8712

A Nijhuis, Y Ilyin and W Abbas, ‘Axial and transverse stress–strain characterization of the EU dipole high current density Nb3Sn strand’
Supercond. Sci. Technol. 21 No 6 (June 2008) 065001 (10pp)

Uni-axial strain & *Ic* (Pacman)



Strand soldered on perimeter disc shaped spring



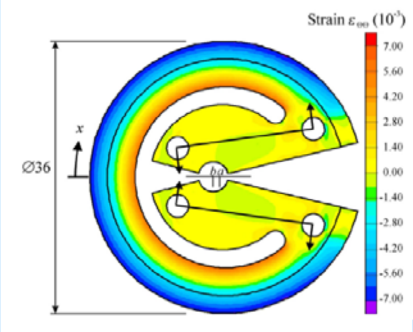
Temperature variations by placing the Pacman spring under an insulator cup, creating a helium gas volume.

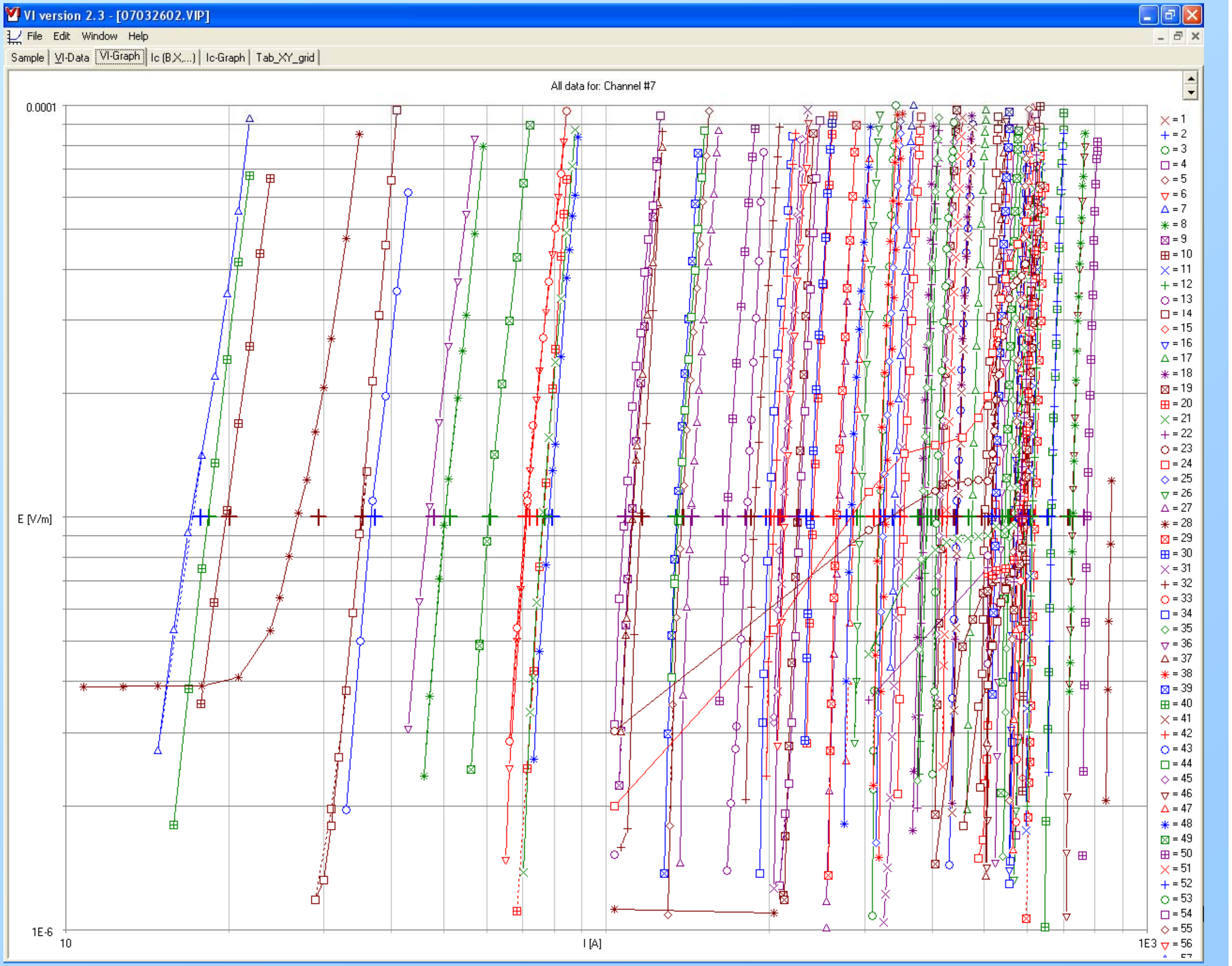
With heaters and thermometers arranged symmetrically the temperature can be balanced within ±20 mK.

Standard procedure VI curves
I =1000 A,
$\varepsilon_{\text{-appl}}$ =-0.9 to + 0.9 %
B=6 to 15 T
T=4.2 to 12 K.
First we explore the compressive strain range, then B,T dependency and finally the tensile range for irreversibility

Uni-axial *I*c-strain (OST-DIP)

VI curves for OST-dipole strand
I > 800 A,
$\varepsilon_{\text{-appl}}$ =-0.9 to + 0.9 %
B=6 to 14 T
T=4.2 to 10 K.





Uni-axial $I_c(\varepsilon,B,T)$ (OST-DIP)

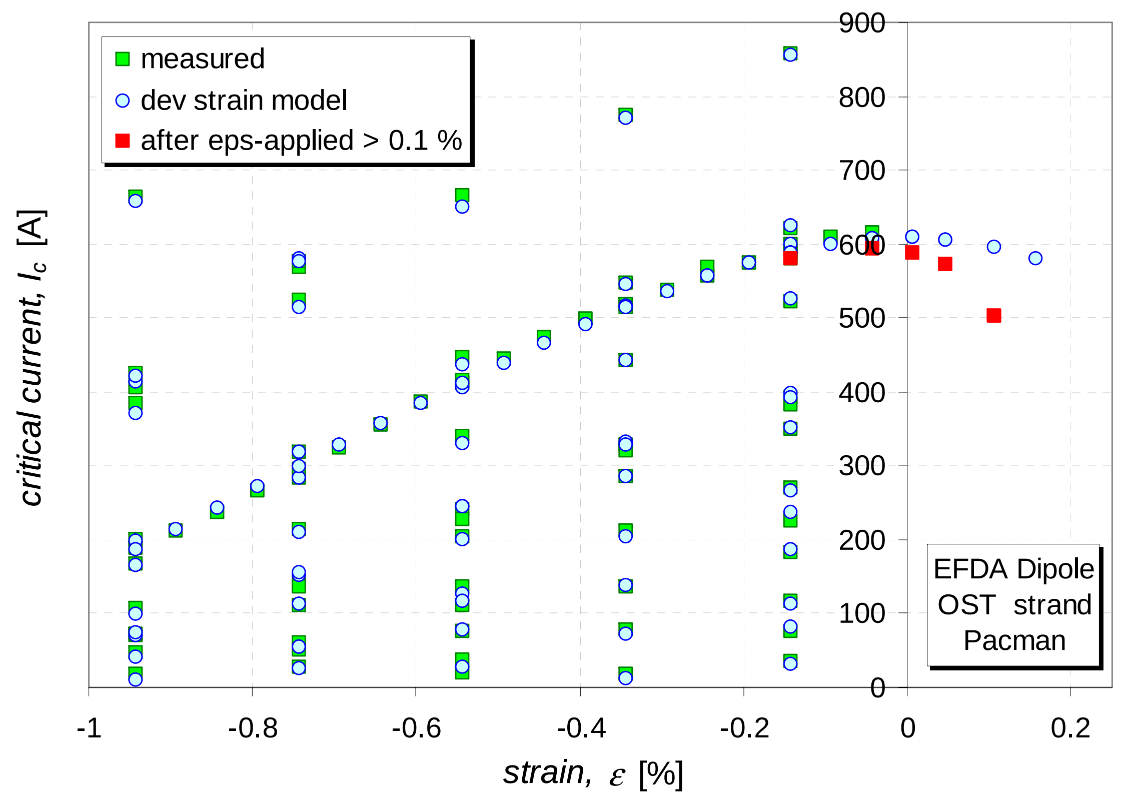
Measured I_c @ 10 µV/m
OST-dipole strand

Fit to Dev Strain Model, 30 data points required for description of entire $I_c(B\text{-}T\text{-}\varepsilon)$ space reversible behaviour
Standard: 50 data points + irreversible tensile.

OST-DIP strand degrades immediately, actually before passing zero strain (peak), red markers are after irreversible degradation

General conductor scaling parameters:

Deviatoric strain (~2nd inv.: slope)	**Ca1**	**49.05**	
Deviatoric strain (~3rd inv.: asymmetry)	**Ca2**	**13.05**	
Hydrostatic strain (~1st inv.: peak rounding)	**eps_0a**	**0.374%**	
Thermal pre-strain (axial)	**eps_m**	**-0.143%**	
Maximum upper critical field	**Bc2m(0)**	**29.40**	**T**
Maximum critical temperature	**Tcm**	**15.97**	**K**
Pre-constant [=(constant*Bc2m(0)^2)/kappa_1m(0)]	**C**	**47095**	**AT**



$I_c(B,T)$ (ε_{appl}=0)

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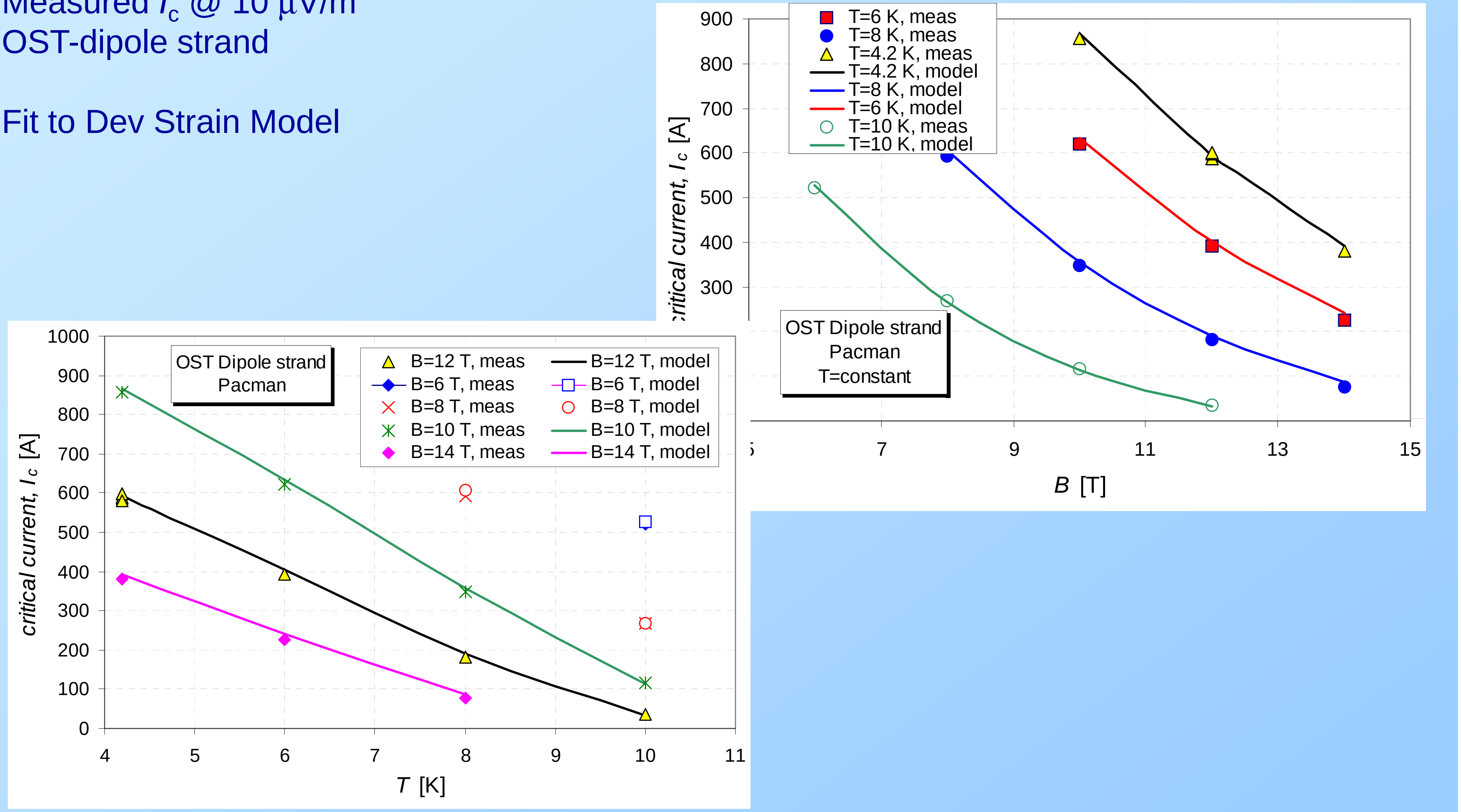
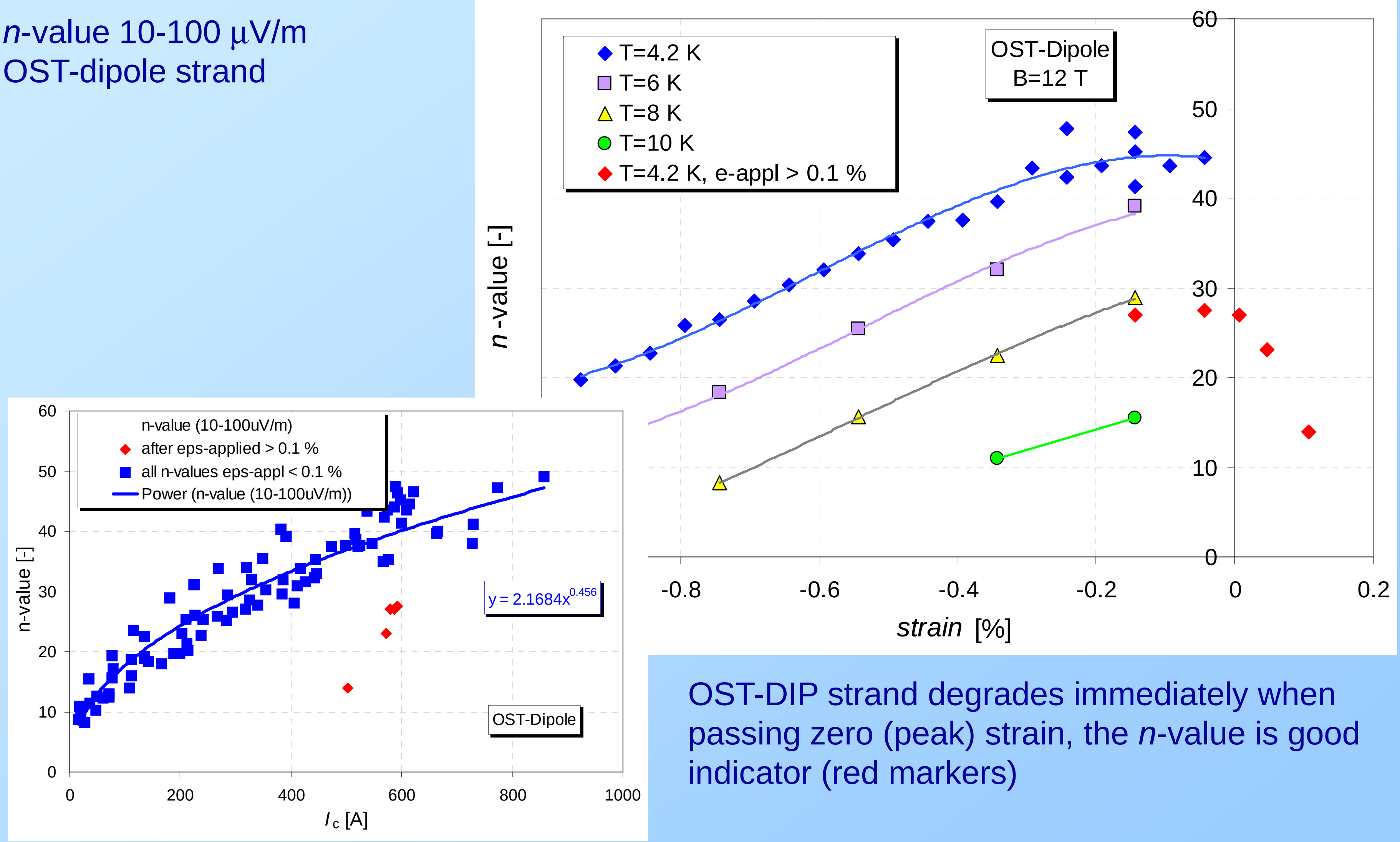
Measured I_c @ 10 µV/m
OST-dipole strand

Fit to Dev Strain Model



n-value (OST-DIP)

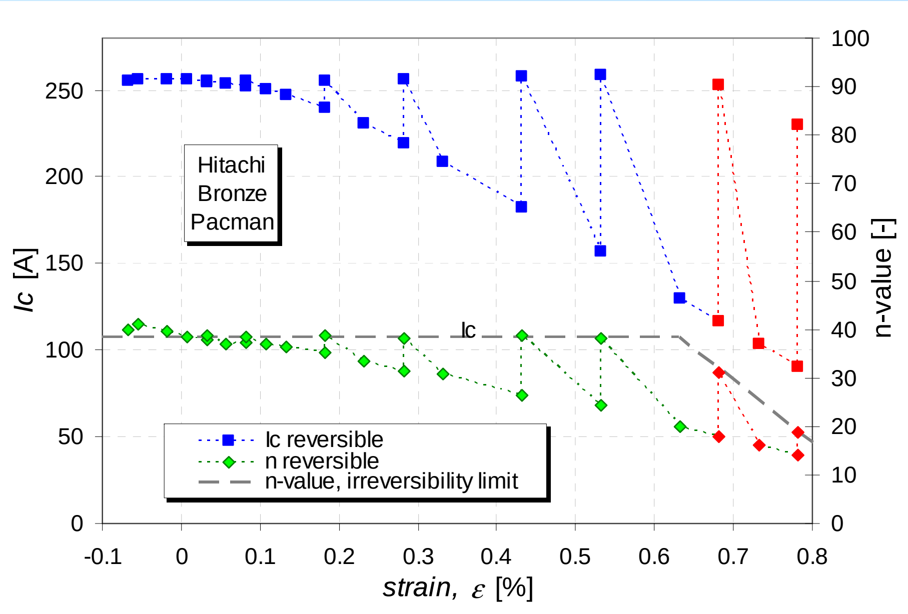
n-value 10-100 μV/m
OST-dipole strand

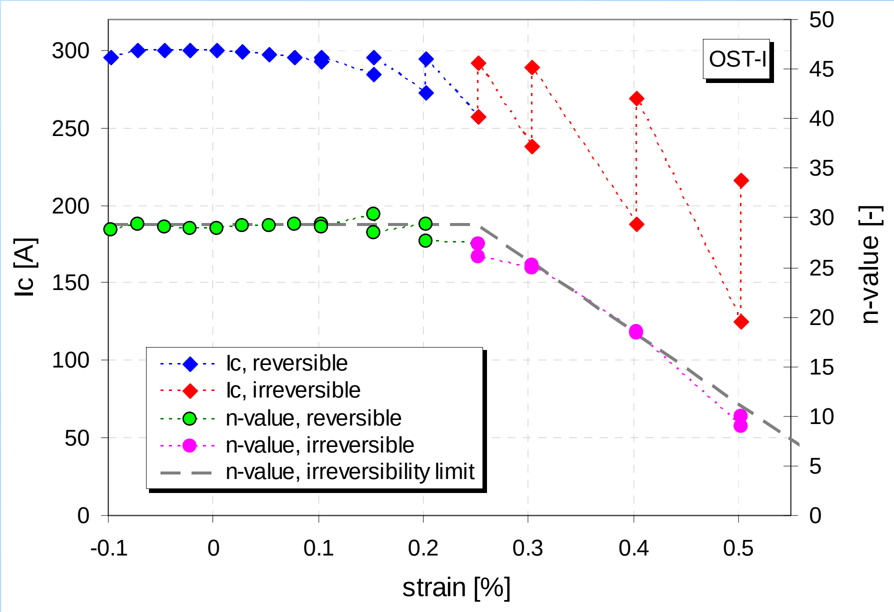


OST-DIP strand degrades immediately when passing zero (peak) strain, the *n*-value is good indicator (red markers)

Axial strain irreversibility limit

Irreversibility strain limit determined by intersection of two lines through n-values vs. strain for two ITER type of strands (Ic criterion 10 µV/m, n- value between 10 and 100 µV/m)





Hitachi bronze strand with ε_{irr}=0.63 %

OST internal tin strand with ε_{irr}=0.25 %

Strain irreversibility limit OST-DIP

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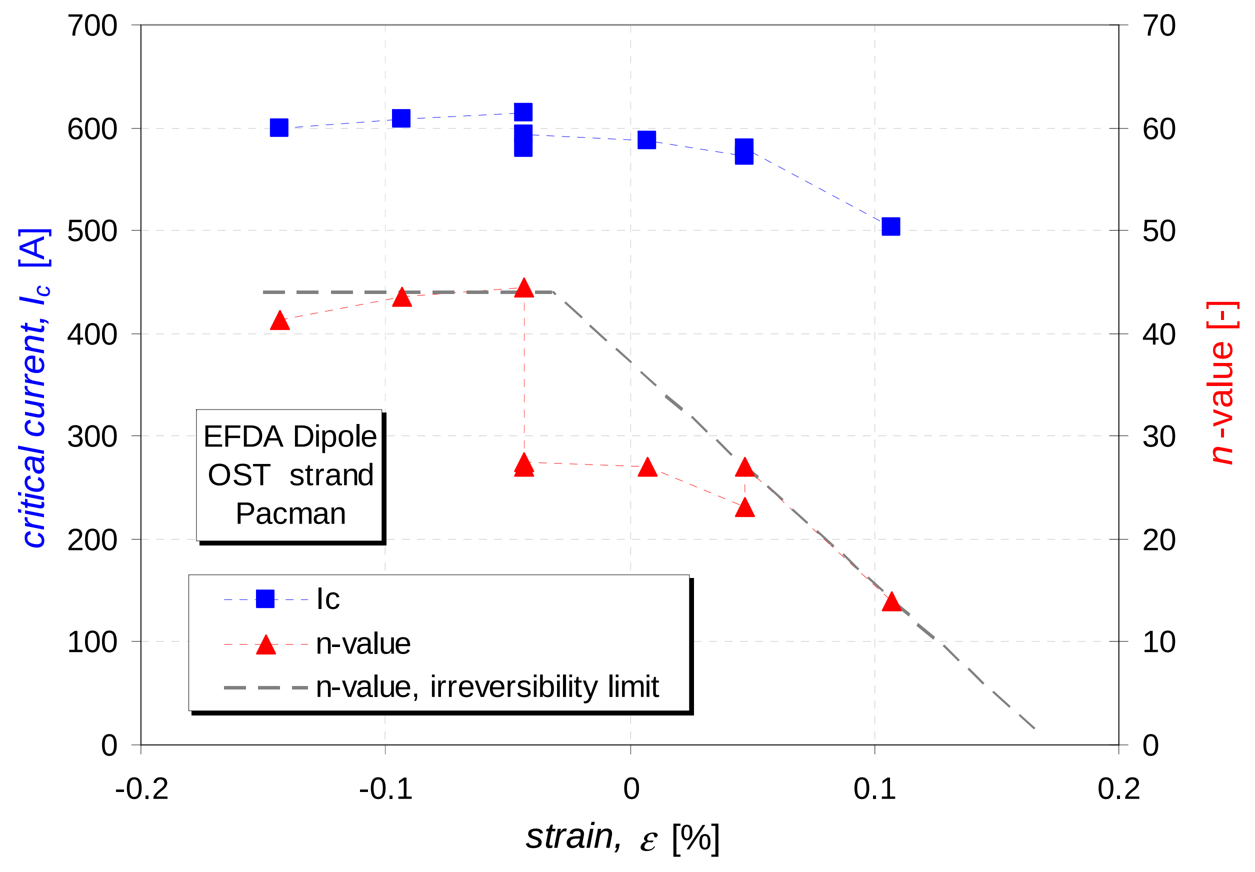
I_c & n-value
OST-dipole strand
B=12 T
T=4.2 K.



Determine irreversibility strain limit by intersection of two lines through n-values vs. strain.
For ODT-DIP ε_{irr}=-0.03 %, so irreversibility appears already before intrinsic zero axial strain is reached

Uni-axial $I_c(\varepsilon,B,T)$ (OST-DIP & HEP prototype DIP)

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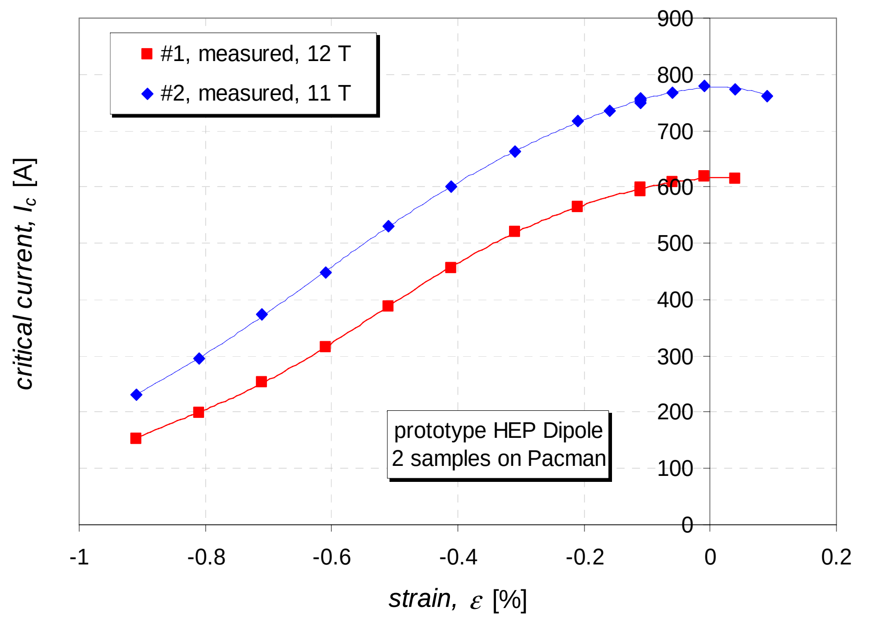
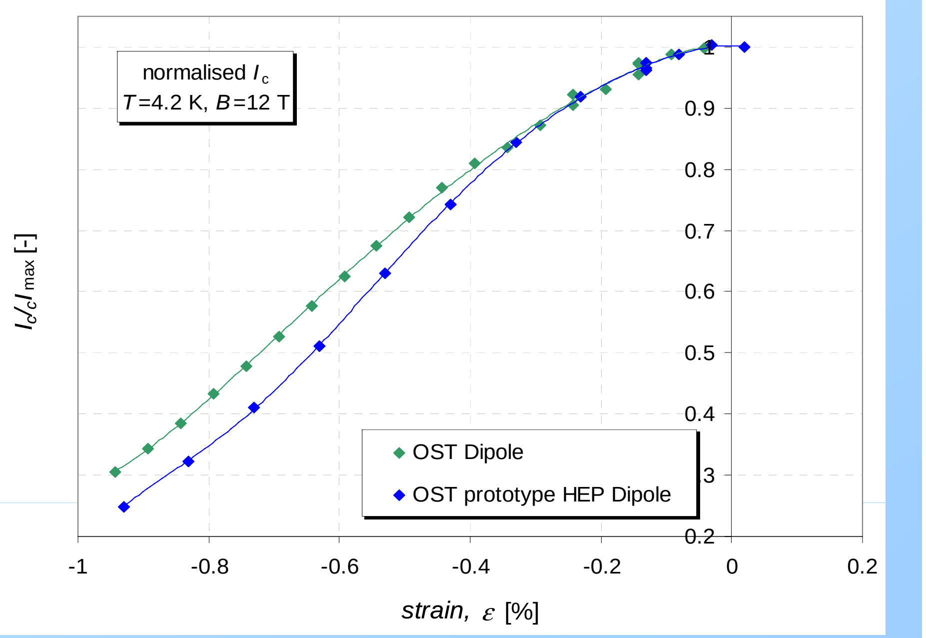


Other high Jc OST-RRP (HEP prototype DIP) strand (127 filaments) also degrades immediately when passing zero strain (peak), two samples tested.



Both types high Jc OST-RRP strands, HEP prototype and Dipole (91 filaments) degrade around zero strain (peak).
Different strain sensitivity, DIP strand less sensitive (materials not analysed).

Strain irreversibility limit OST-DIP

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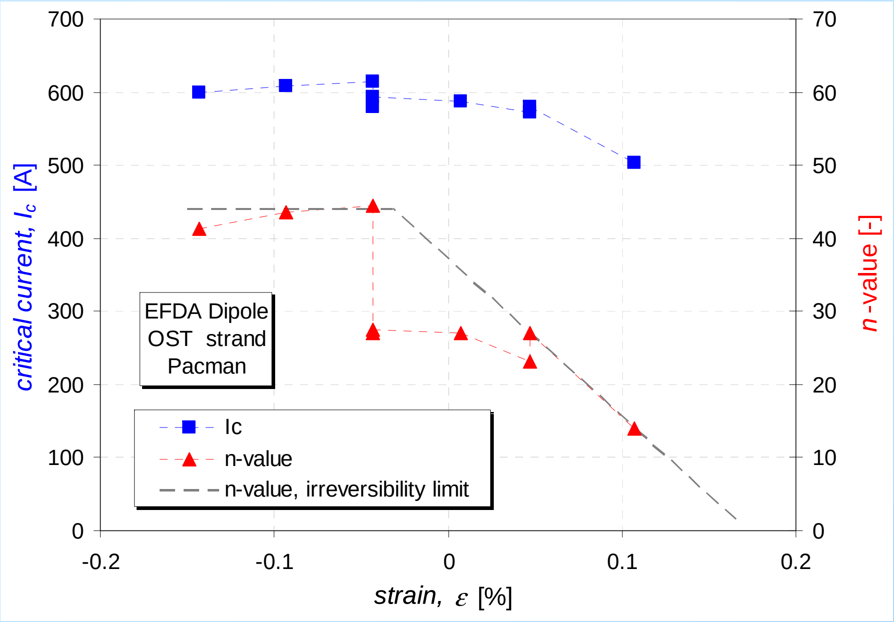
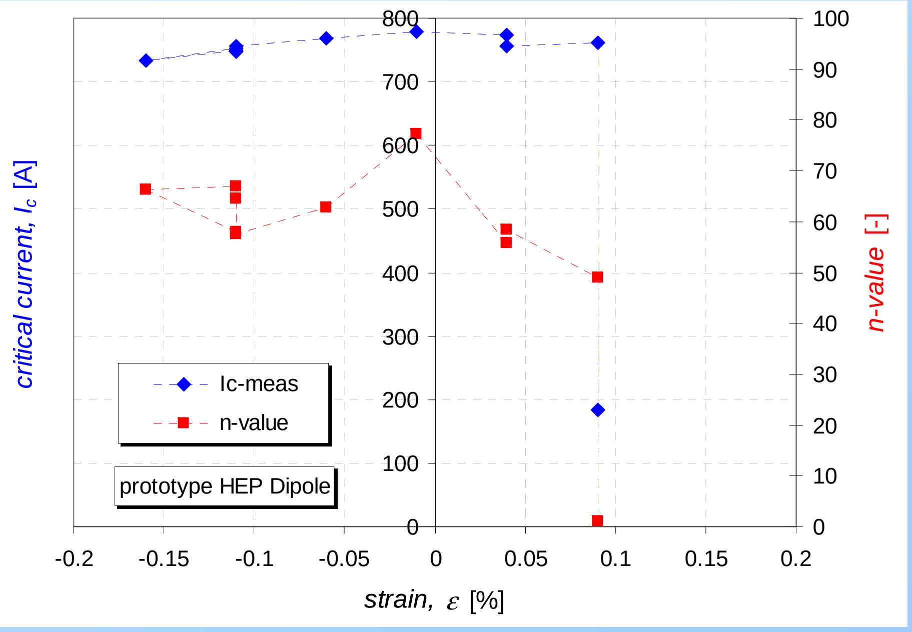


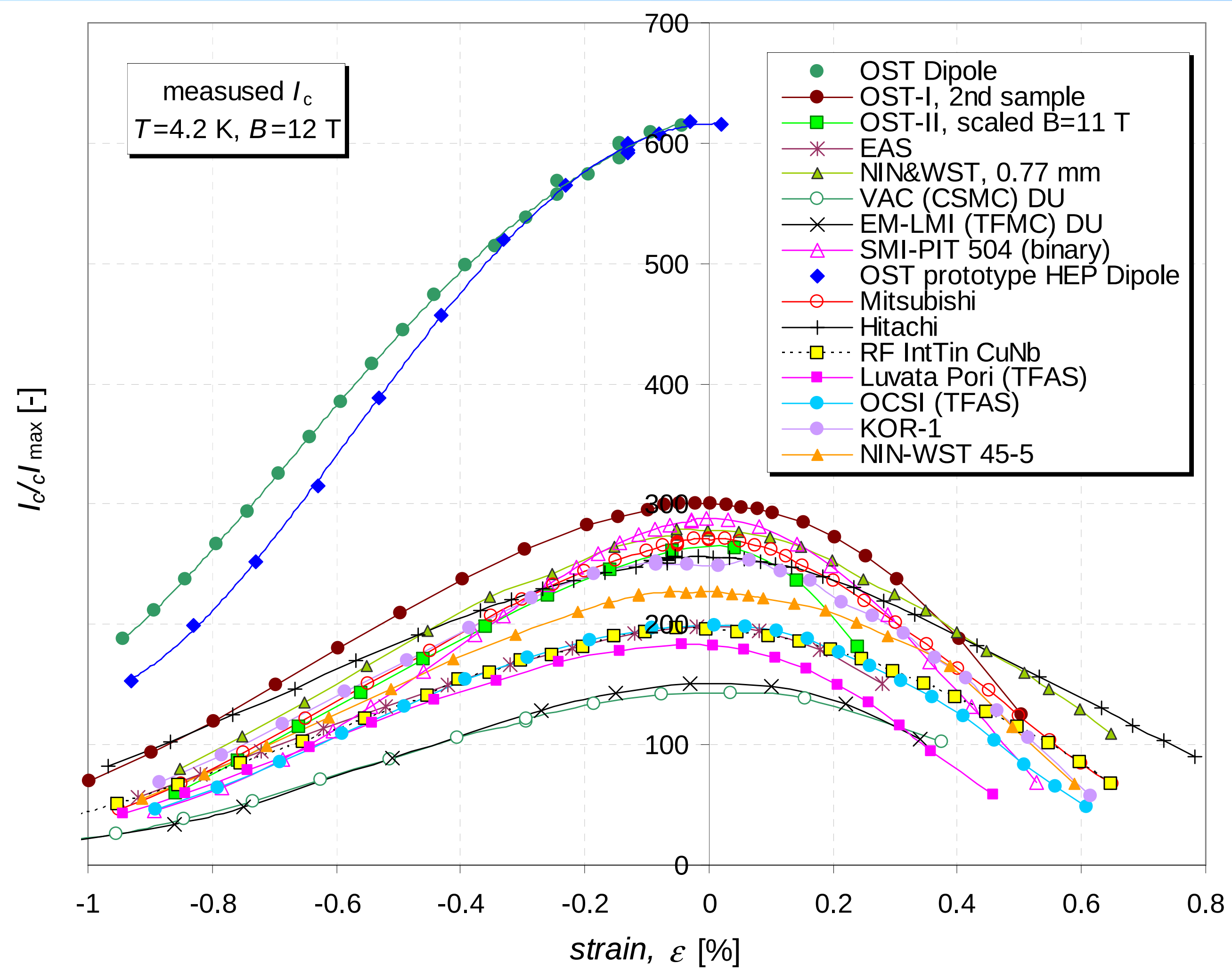


For OST-DIP ε_{irr}=-0.03 % (just before reaching peak) and prototype HEP DIP ε_{irr}= ~0.07 %

Uni-axial *I*c-strain, overview

$I_c(\varepsilon)$ @ 12 T & 4.2 K of 16 Nb_3Sn strands

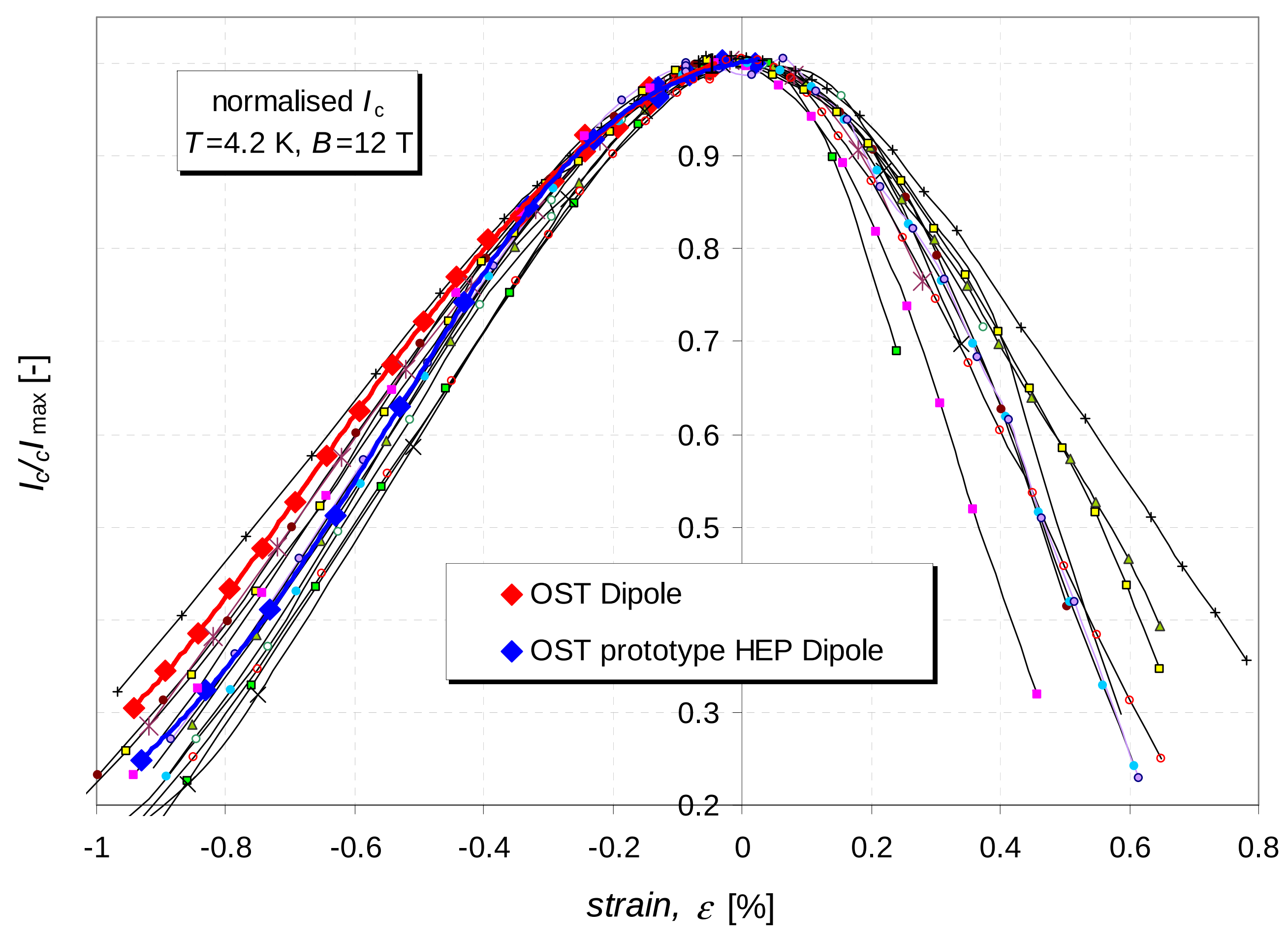
High Jc OST RRP: 600 A
ITER Advanced: 200-300 A
ITER Model Coil: 150 A



Uni-axial *I*c-strain sensitivity, overview

Normalised Ic
@ 12 T & 4.2 K

High Jc OST RRP: 600 A
ITER Advanced: 200-300 A
ITER Model Coil: 150 A



The relative strain sensitivity for strands is defined as the slope of the reduced Ic (I_c/I_{co}) vs. the strain between
-0.7 % < ε < -0.3 %.

Relative *I*c-strain sensitivity

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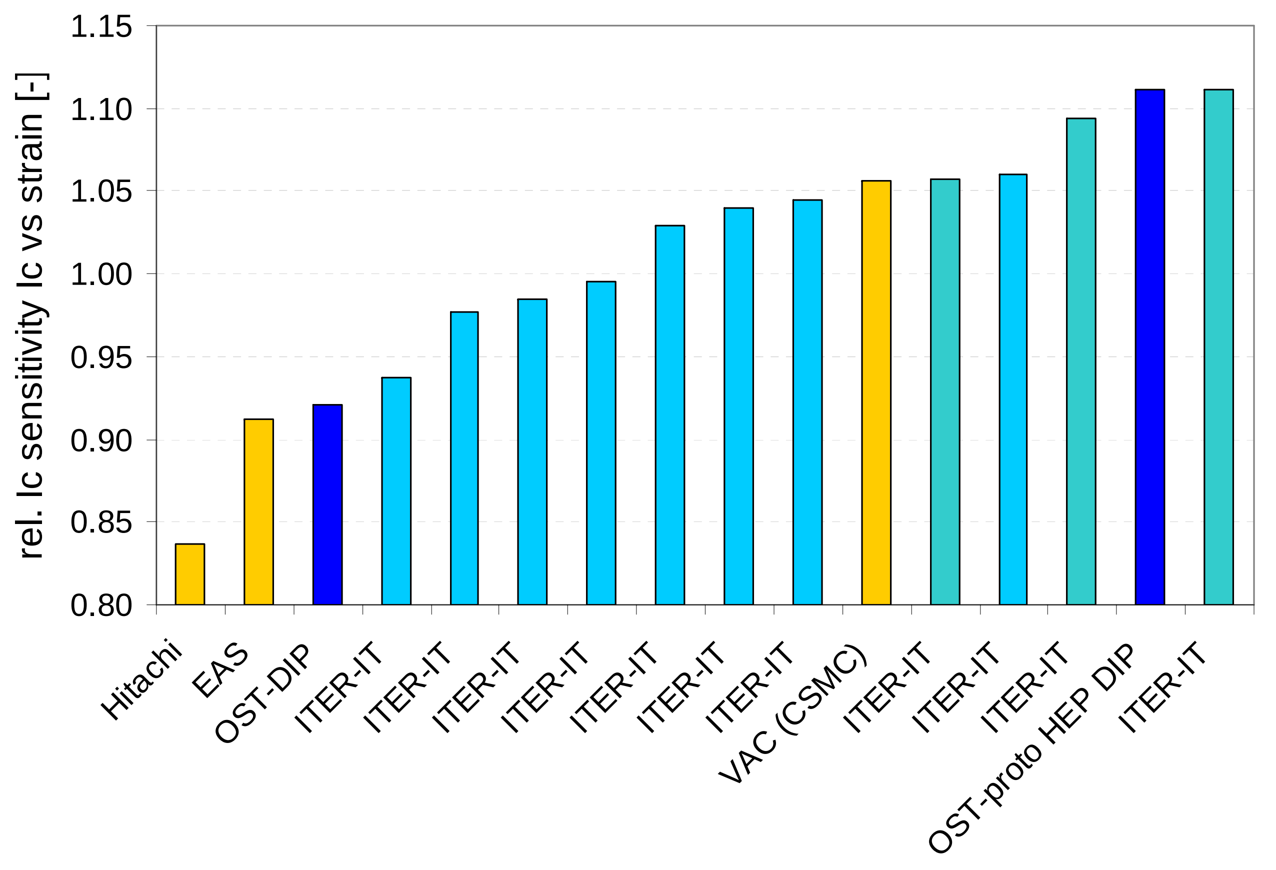
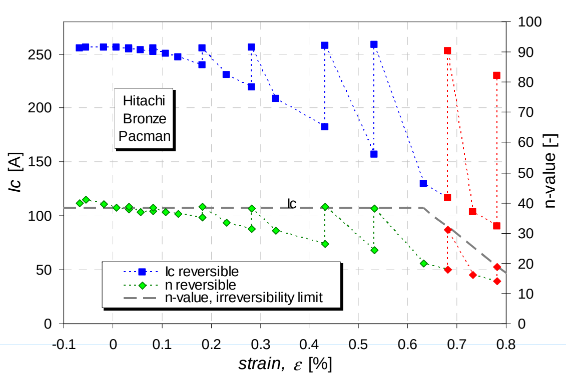
The average relative strain sensitivity of all strands is 1.01 and the stdev is 0.08.

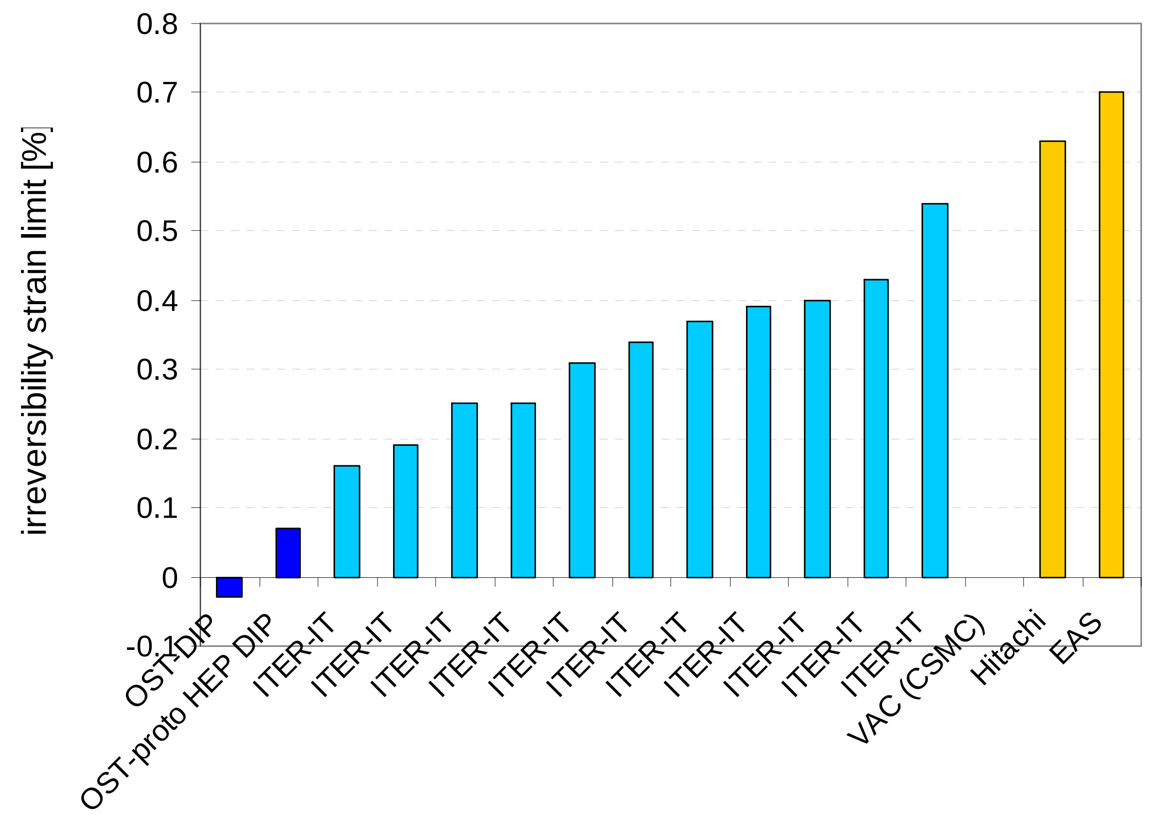
OST RRP DIP strand is least sensitive int. tin strand while the HEP prototype is one of the most sensitive. (Materials not analysed).

Recent bronze is least sensitive except (VAC-CSMC)



Irreversibility strain limit





Irreversibility strain limit for tested strands

Low limit for high Jc OST RRP type of strands (near peak) and bronze high limit.

ITER internal tin mostly between 0.2 % and 0.4 % (average 0.33 % stdev 0.11 %).

(EAS strand to be measured, here based on micrography from Matt Jewell on Twente samples)

TARSIS stress-strain results, 4.2 K

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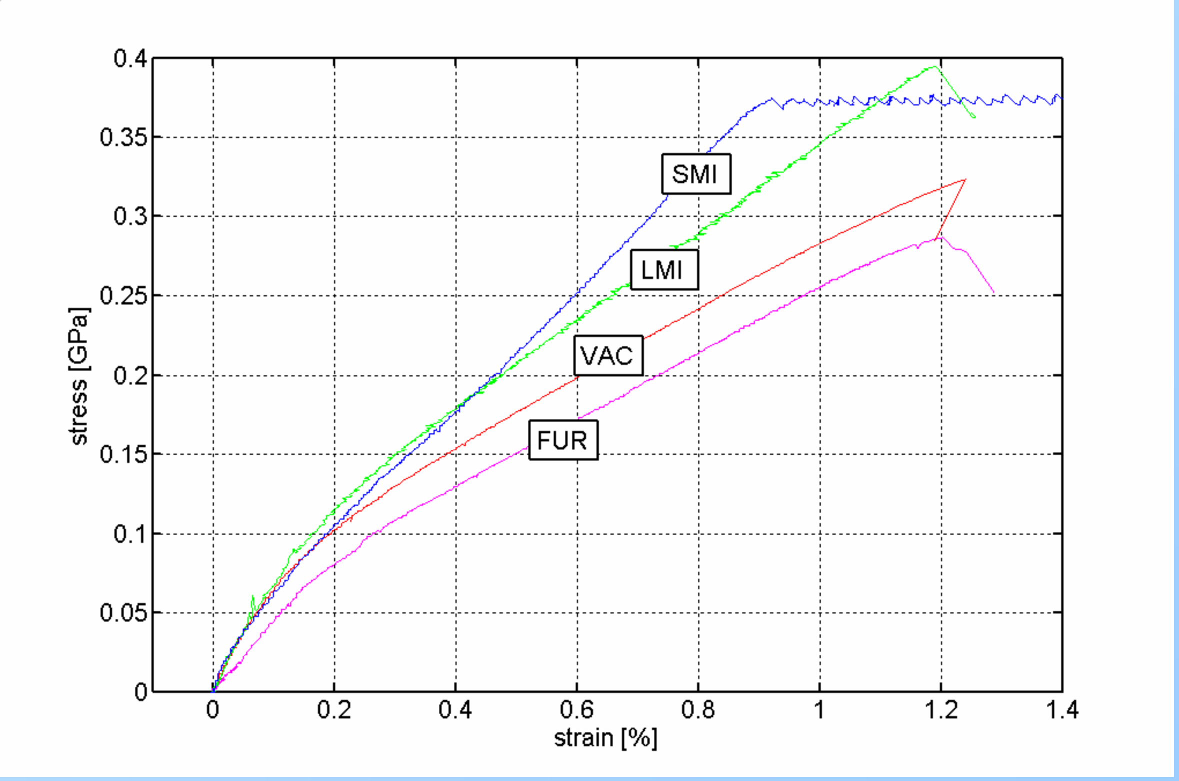
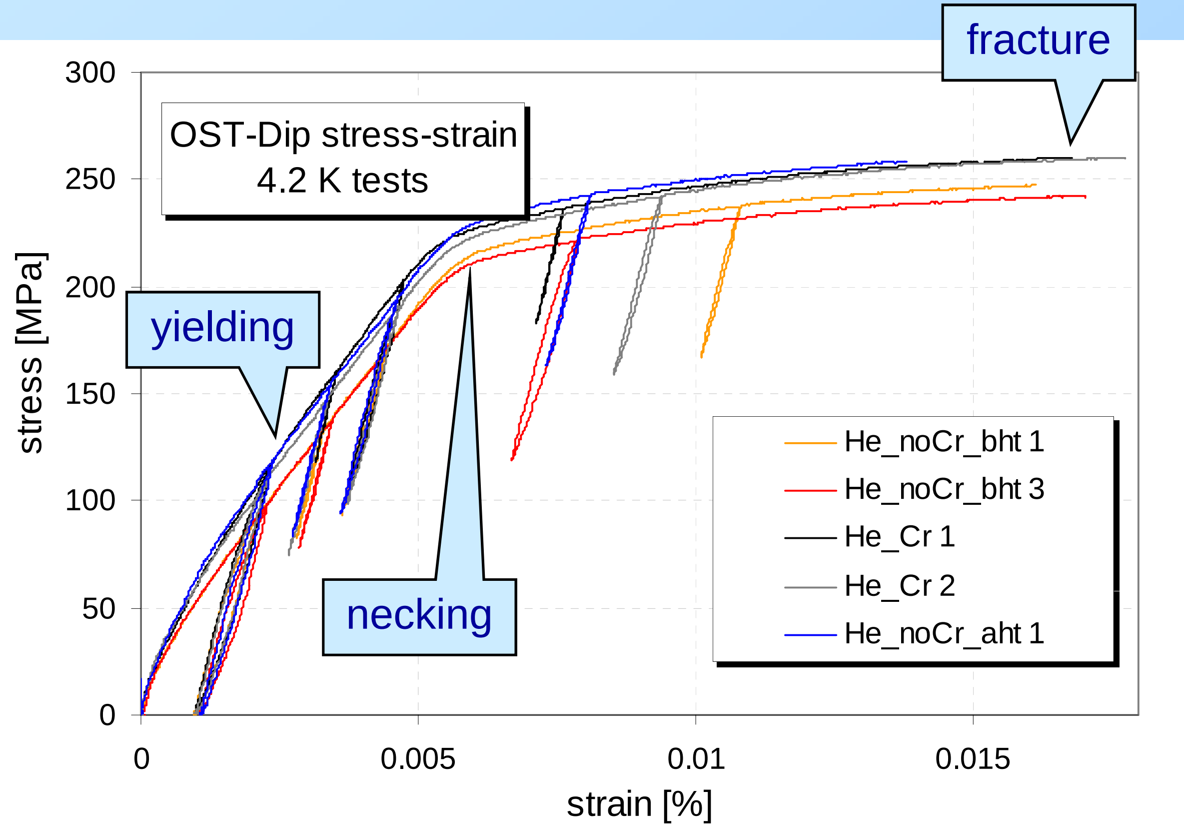


Stress-strain curves on ITER and Model Coil strands at 4.2 K: fracture: 0.9 % - 1.2 % strain

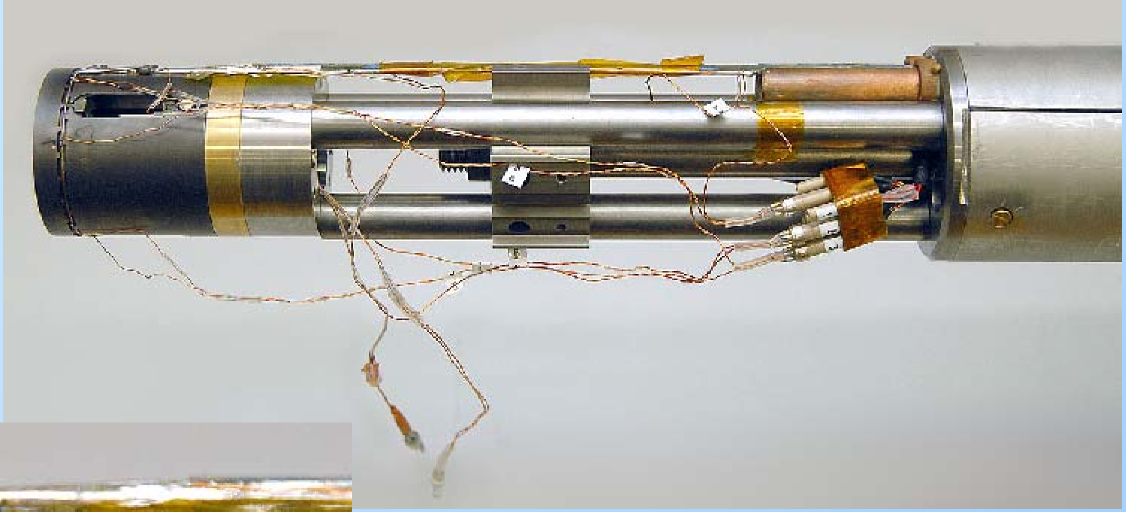
TARSIS 4.2 K stress-strain test OST-Dipole

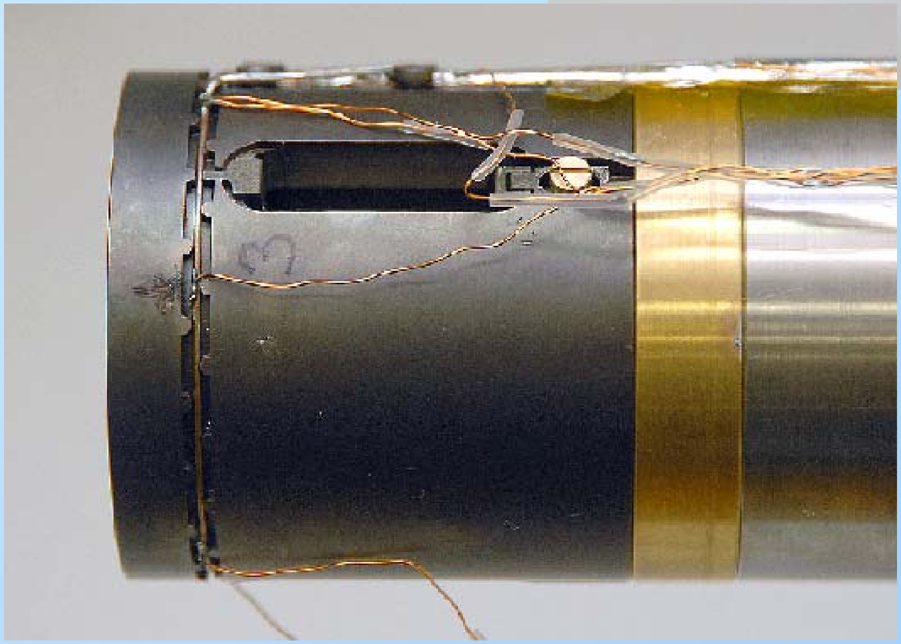


Strand failure just beyond 0.5 % strain (*T*=4.2 K).

Cr layer removed before HT: slightly weaker stiffness. Confirmed with other strand types.
All TARSIS tests are done with Cr layer removed before HT.

TARSIS bending

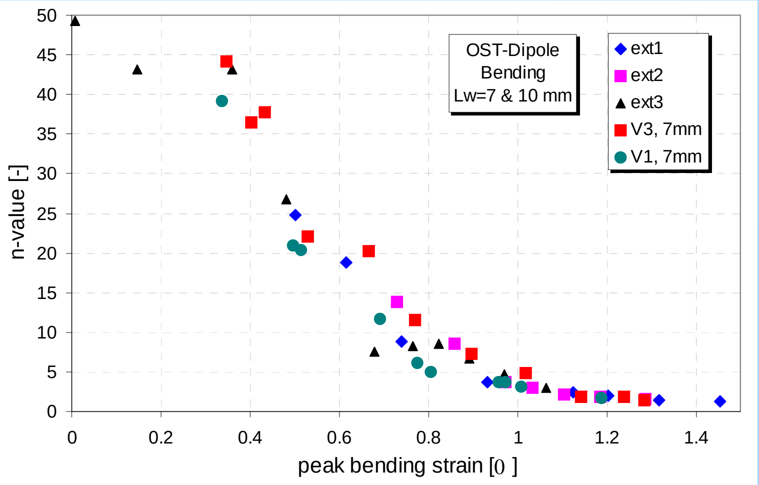


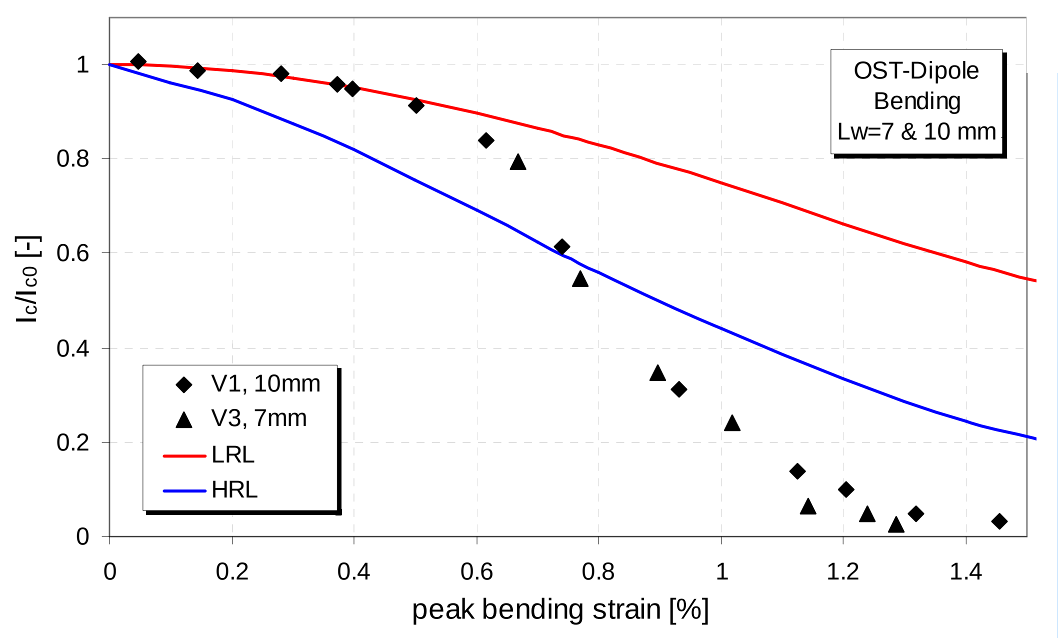


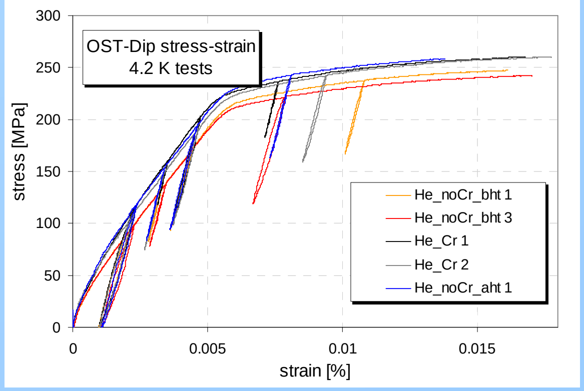
TARSIS bending test OST-Dipole

EFDA Dipole strand:
Initially following the LRL (good IF redistribution).
Failure at 0.5 % strain.

Correlation between fracture strain and deviation from bending-LRL:







TARSIS bending, results

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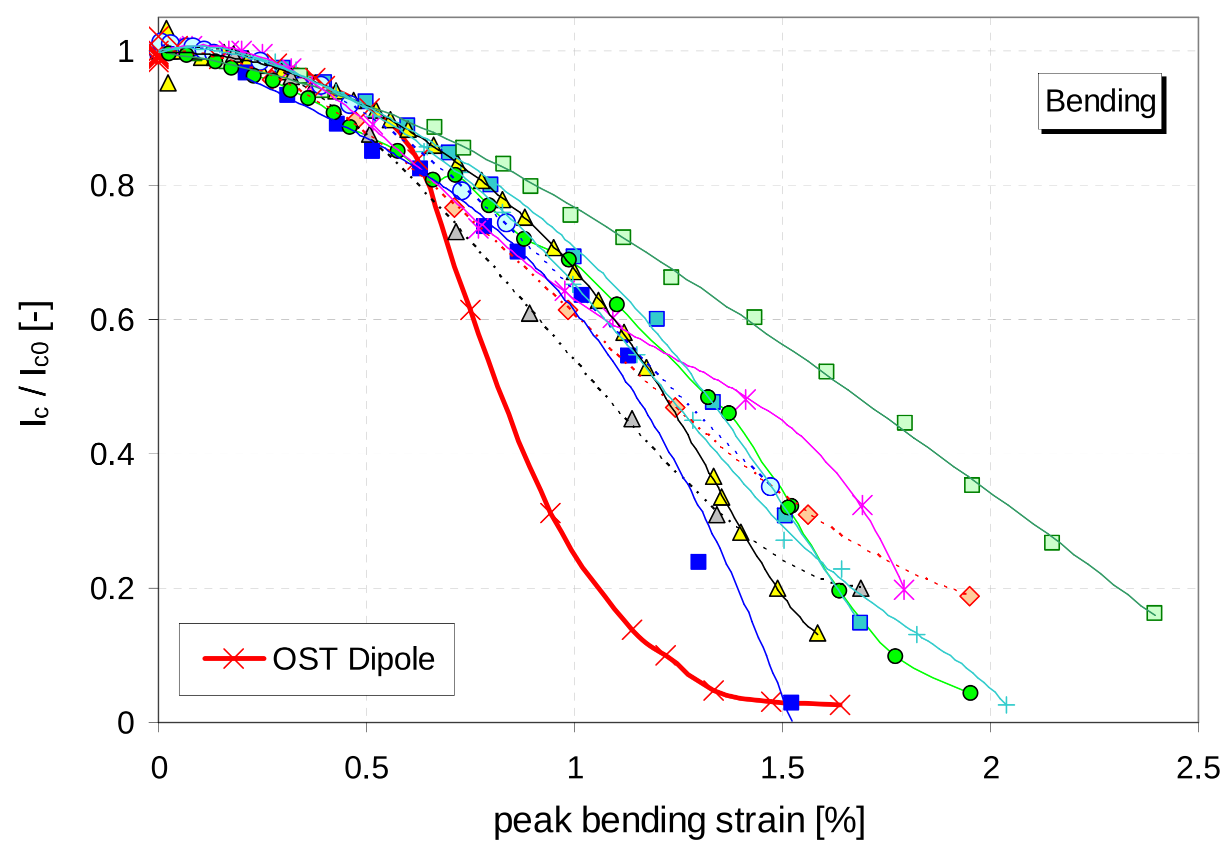

Reduced Ic vs peak bending strain for several tested strands illustrating the spread in sensitivity but in particular the high sensitivity for OST-DIP (> 0.5 %).

TARSIS crossing strands test: *Ic*

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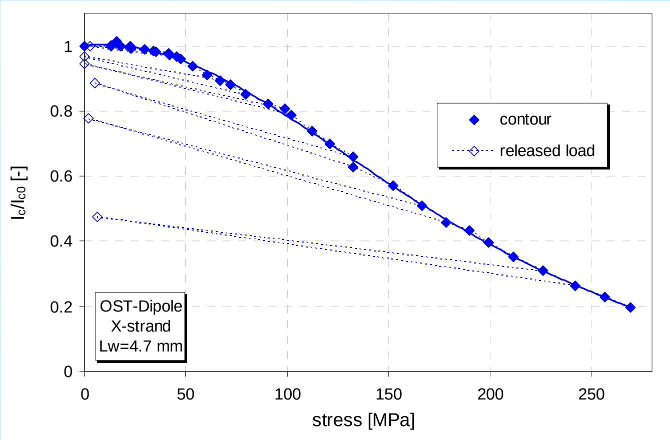
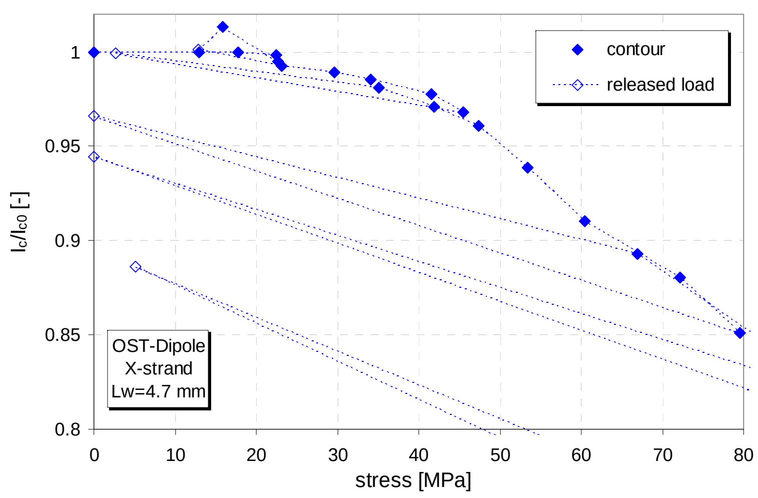
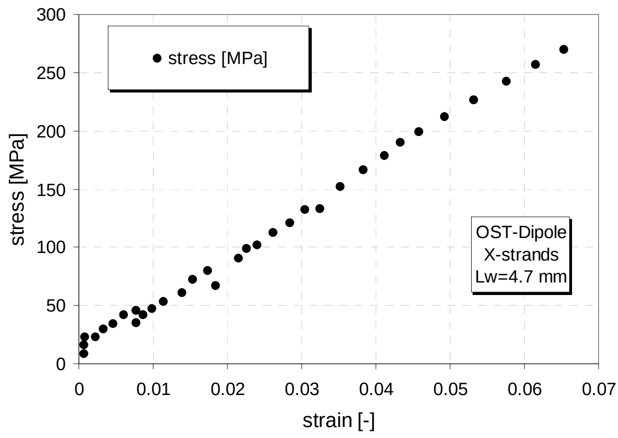
Probe for X-strands test with periodicity 4.7 mm and 90° angle.
Reacted straight X-strands, are pressed by top plate (not visible).

$I_c(\sigma)$ for OST-DIP strand also showing I_c release of load and irreversibility up to 50 MPa

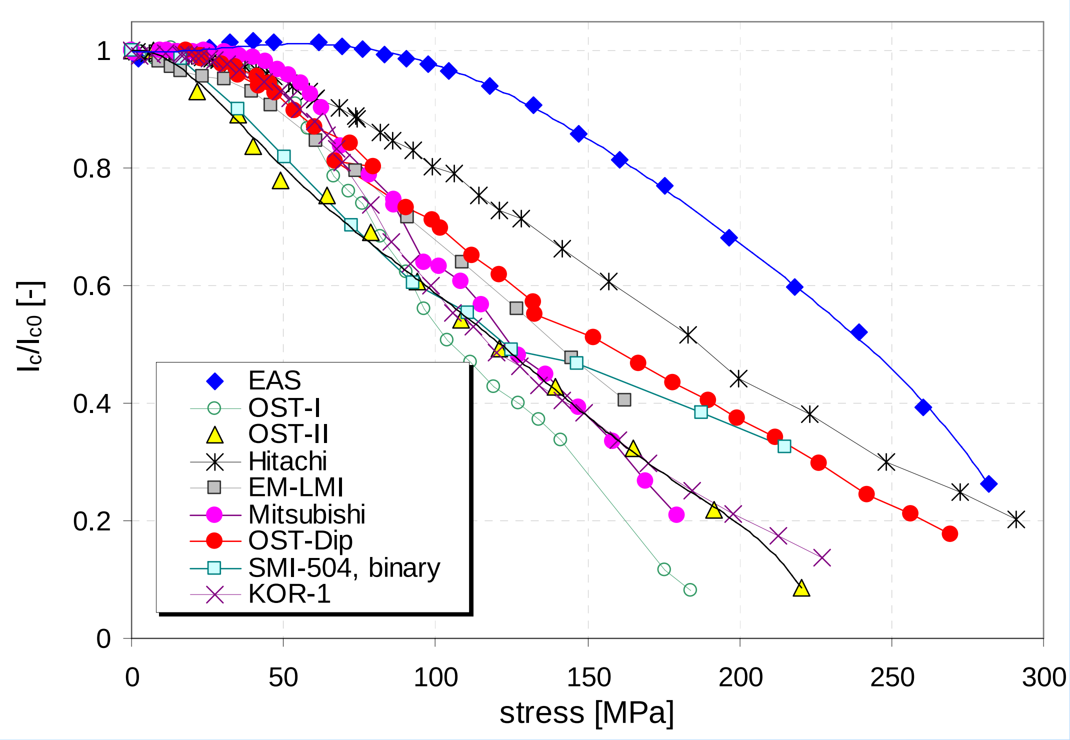


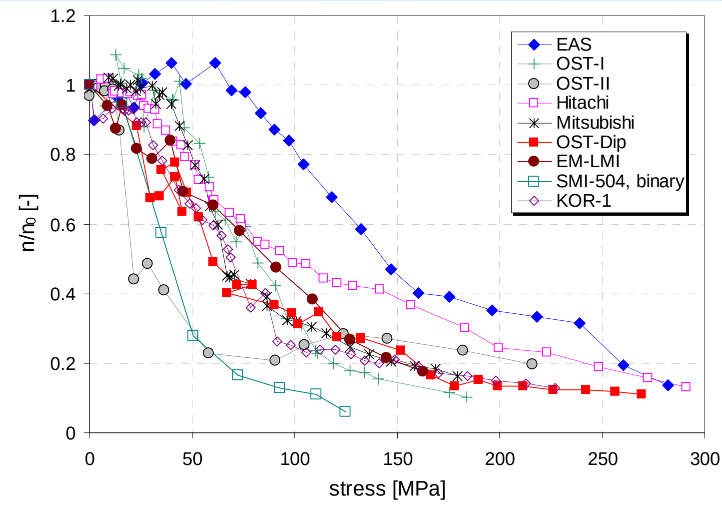


$\sigma(\varepsilon)$ transverse stiffness



TARSIS crossing strands: *Ic* and n-value





OST-II strand most sensitive to transverse contact stress (and binary SMI-PIT) followed by EM-LMI, OST-DIP, MIT and less sensitive HIT and EAS bronze strands.
n-value OST-II degrades rapidly between 10 and 30 MPa.

Influence of cabling in CICC

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Is it possible to use strain sensitive strands like the high Jc OST RRP for CICC??

Influence of cabling in CICC

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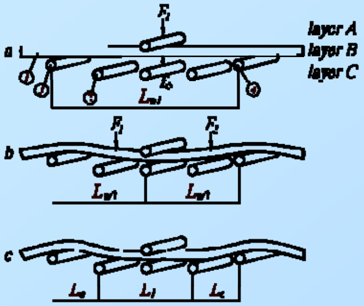
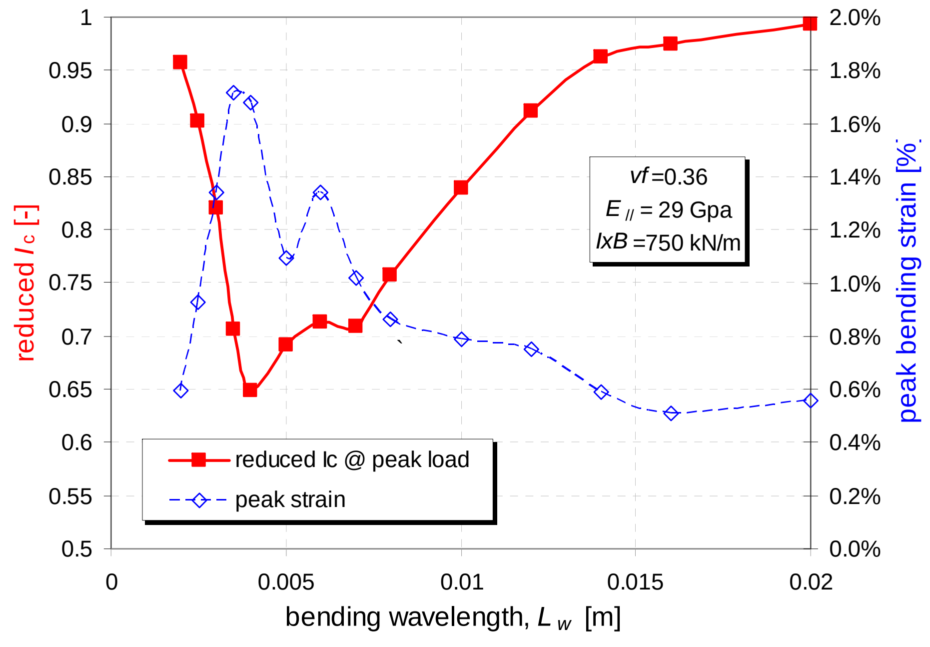
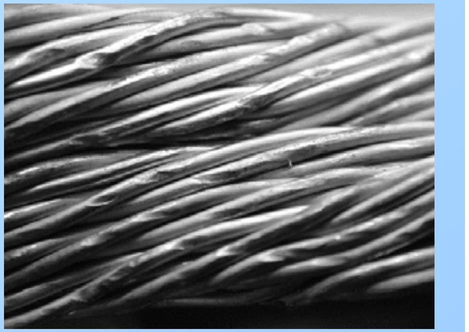
April 2006 (Barcelona), a priori TEMLOP prediction postulating influence characteristic bending wavelength (Lw), no experimental data available at that time to prove it.

A. Nijhuis and Y. Ilyin, 'Transverse Load Optimisation in Nb_3Sn CICC Design; Influence of Cabling, Void Fraction and Strand Stiffness', ***Supercond. Sci. Technol***. **19** (2006) 945-962.







August 2007: relation for Lw and Lp (1st stage twist pitch)

$$L_w = \frac{L_{p1}}{\left(N_{Lp1}\right)^2} + \frac{L_{p1}^2}{[1m]}$$

A. Nijhuis, 'A solution for transverse load degradation in ITER Nb3Sn CICCs, effect of cabling on Lorentz forces response' Supercond. Sci. Technol. 21 (2008) 054011 (15pp)

Influence of cabling in CICC

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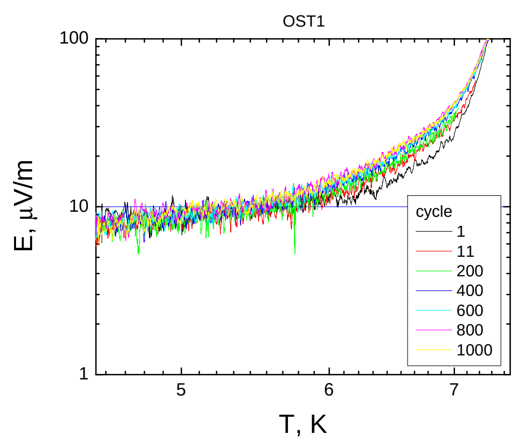
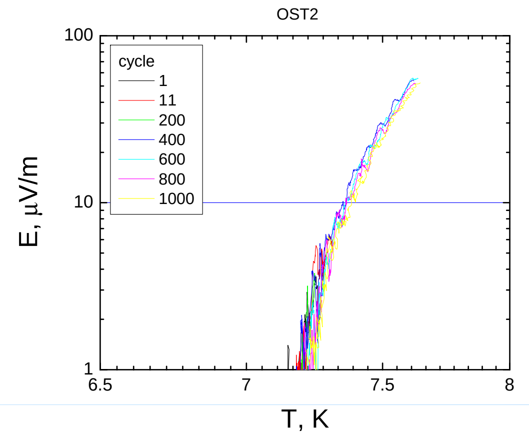
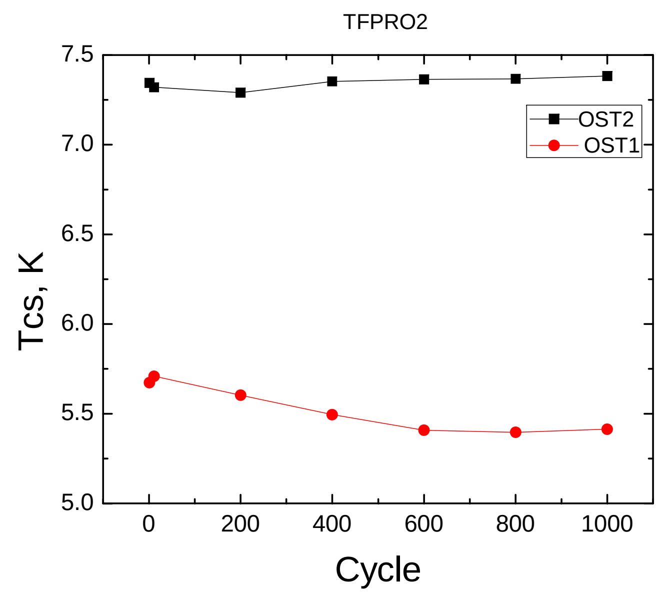
April 2007 SULTAN test first verification of a priori prediction influence bending wavelength for long pitches.



TFPRO-2 ITER reference cabling pattern



TFPRO-2 long pitches



TFPRO-2 SULTAN sample: two legs, one reference ITER cabling pattern gave Tcs= 5.5 K and very low n-value, other leg with roughly twice longer pitches gave best performance ever of Tcs=7.3 K and high n-value.

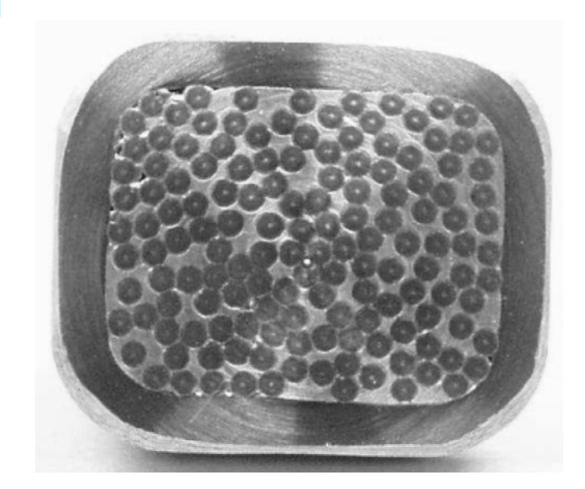
Influence of cabling in CICC

Required:

- Influence current non-uniformity induced at joints and terminations must be excluded
- Roughly similar cable design (relevant # strand layers / ratio of copper strands)

PITSAM SULTAN test of similar CICC shape but different cabling pattern PITSAM 2, 5L & 5S

Fully soldered joints



Sample	PITSAM2 (LF2)	PITSAM5 Short pitches	PITSAM5 Long pitches
EDIPO	LF2	LF2	LF2
Cable pattern	(3x3)x3x4	3x3x3x4	3x3x3x4
Sc strand number	48	48	48
Sc strand	Cr plated **OST** dipole 0.81 mm	Cr plated **OST** dipole 0.81 mm	Cr plated **OST** dipole 0.81 mm
Cu strand number	60	60	60
Twist pitch	**58/95/139/213**	**34/95/139/213**	**83/140/192/213**
Outer conductor dimensions (mm)	12.6 x 12.6	12.6 x 12.6	12.6 x 12.6
vf (%) (calculated)	30	30	30

Influence of cabling in CICC

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Dipole PITSAM 2 & 5, and ITER TFPRO2 (long pitches) Lw has been determined by:

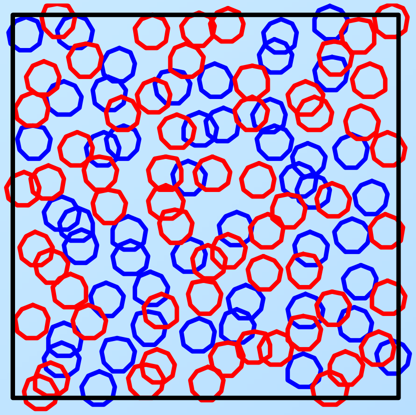
$$L_w = \frac{L_{p1}}{\left(N_{Lp1}\right)^2} + \frac{L_{p1}^2}{[1m]}$$

Conductor type	1st stage Lp	Lw [m]
PITSAM1, 2, 3, 4	0.058	0.0098
PITSAM5 Long = ITER Option II	0.083	0.0161
PITSAM5 Short	0.033	0.0048
TFPRO2/OST1 = ITER Option I *	0.045	0.007
TFPRO2/OST2, Long Lp	0.116	0.0263
USTF1 (alternate 6x1)*	0.025	0.0011

* For USTF1 the strand properties are not available so the virgin performance, and thus the degradation can not be determined. For TFPRO2/OST1 Option I influence of the joint non-uniformity can not be excluded.

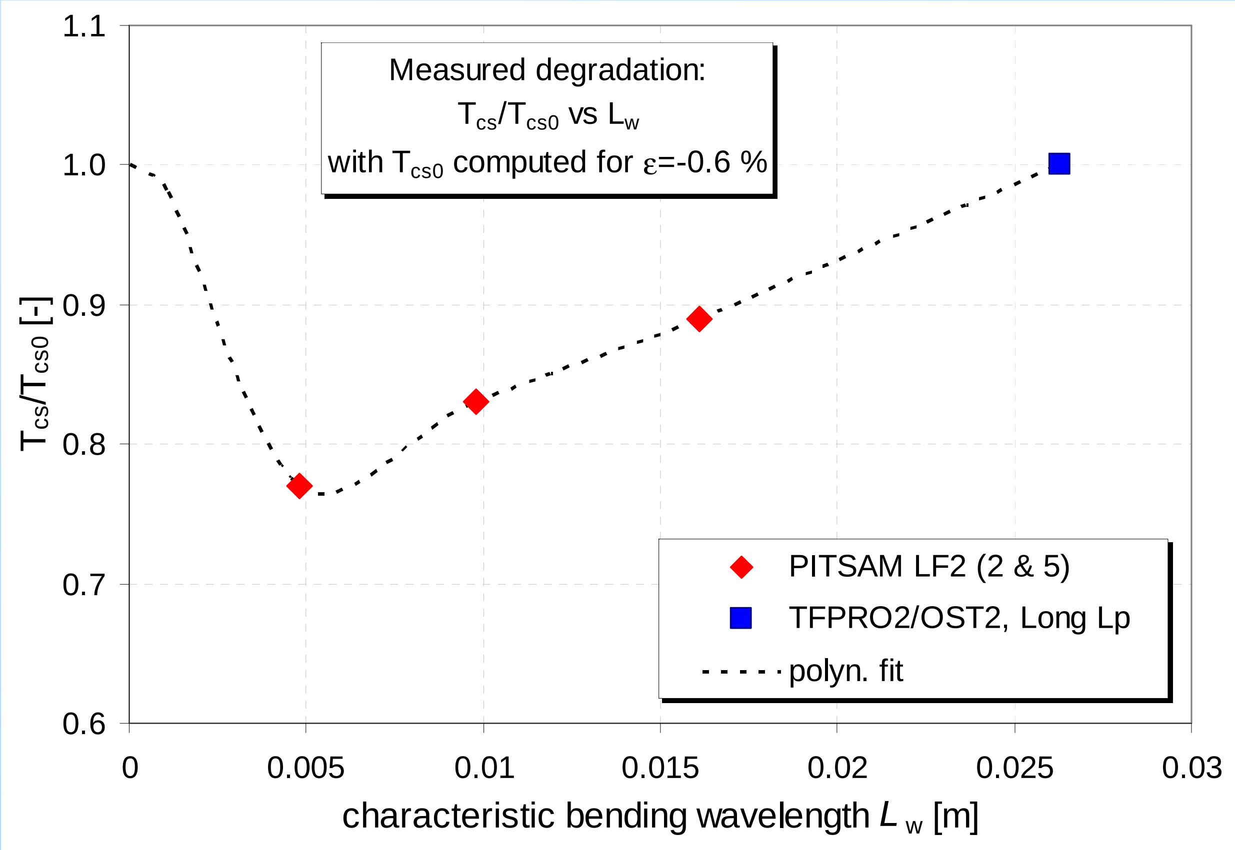
Influence of cabling in CICC

PITSAM and TFPRO2 (long pitches) performance for (virgin) zero load condition is determined by Jackpot Model (Jacket Potential) for ε=0.6 %.



JackPot model:
PITSAM 2, 5
48 SC strands
60 Cu strands

Good agreement with TEMLOP prediction.



Summary

- I_c vs. uni-axial strain, bending, contact stress and stiffness is characterised on OST RRP high Jc Nb_3Sn strands.
- Strain sensitivity $\Delta I/\Delta\varepsilon$ in the range of ITER Int tin.
- Irreversibility strain limits: ~ 0% for OST-DIP, from +0.2% to +0.4% for ITER Int tin and > +0.6% for (recent) bronze.
- Bending behaviour follows the LRL until failure strain is reached: 0.5% peak bending strain for OST DIP.
- Intermediate twist pitch length in CICC causes degraded performance: TEMLOP prediction influence pitches further confirmed.