Recent Results of ITER TF Conductor Performance Tests

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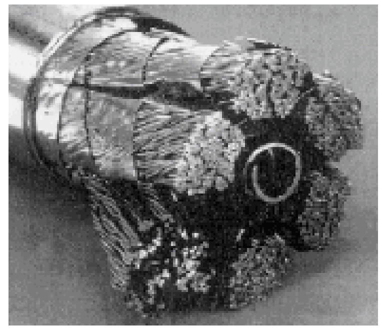
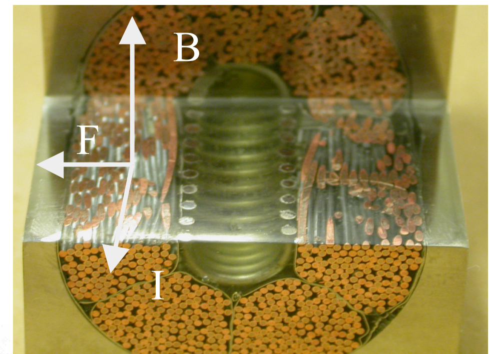
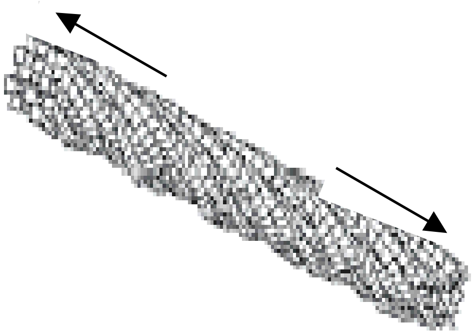
Mechanical Effects

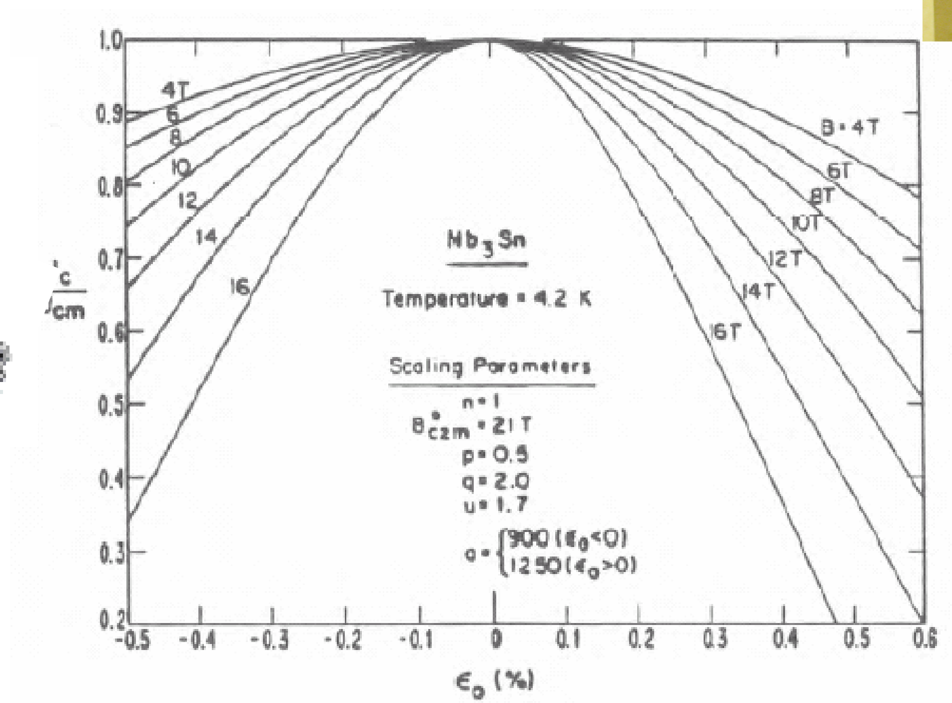
The critical properties of certain superconductors (such as Nb_3Sn) can degrade when a *strain* is applied. Various strains appear when a magnet is energized:

- Axial
- Transverse
- Bending

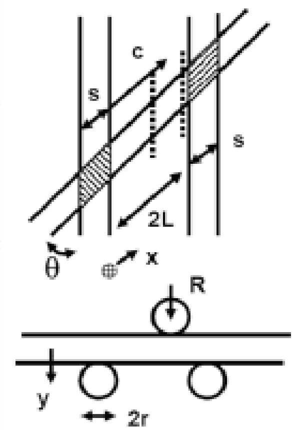






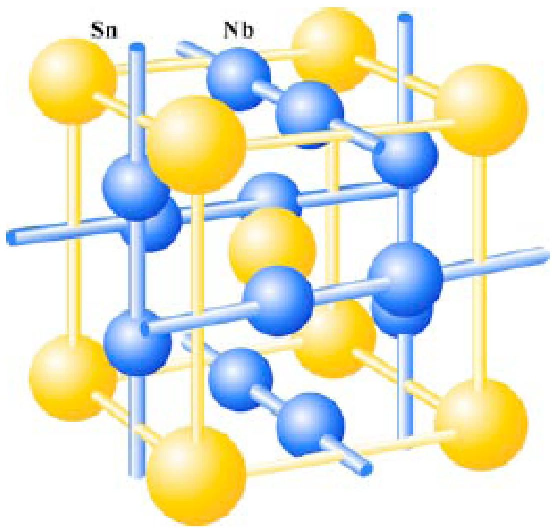


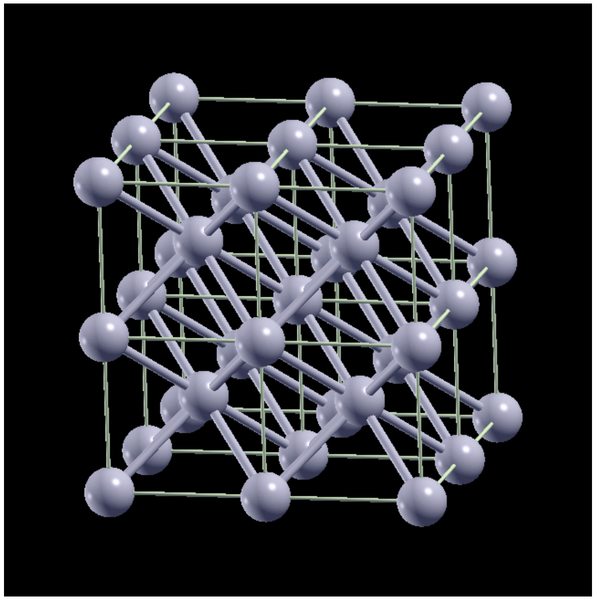
(b)

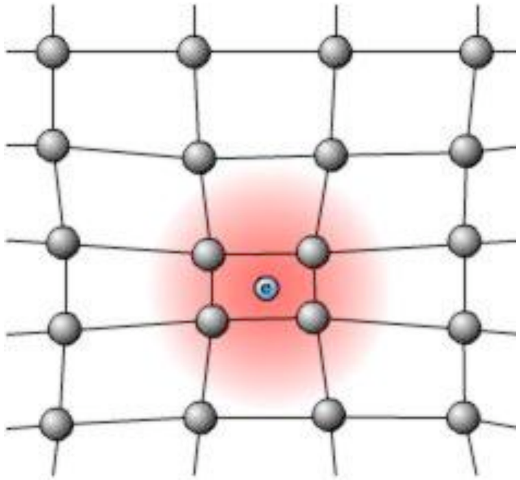


T_c Strain Sensitivity of Nb, Nb_3Sn and Nb_3Al Using Ab-Initio Techniques

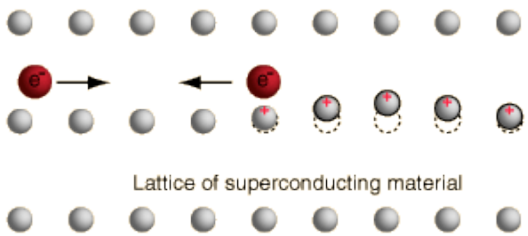
Matteo Salvetti, MIT Mechanical Engineering Graduate Student





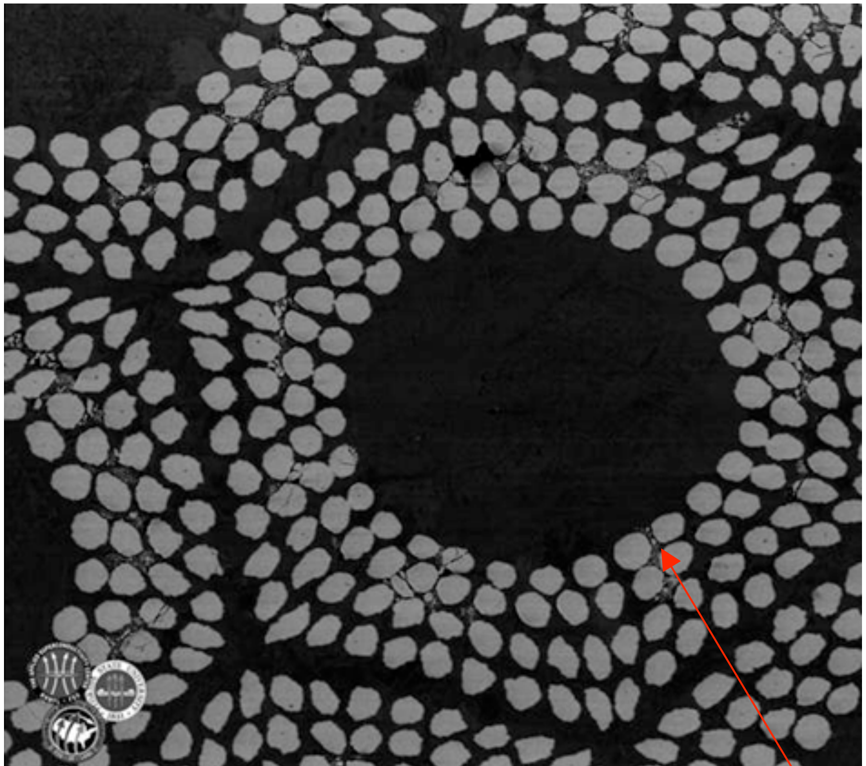


The electron-phonon (el-ph) interaction is the mechanism behind the critical temperature T_C in conventional superconductors. The presence of strain in real materials modifies the el-ph coupling and the Tc value.



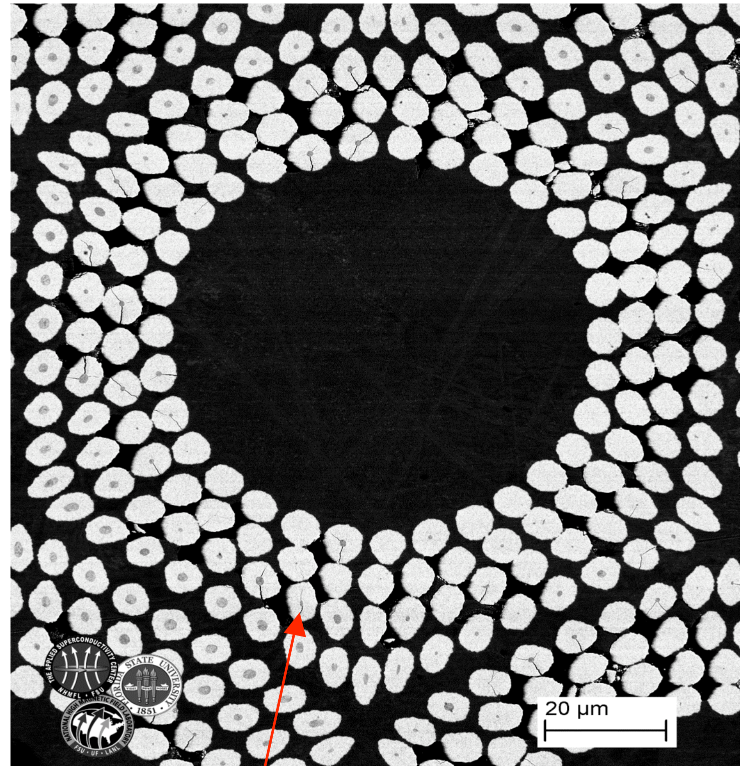
Technology & Engineering I

Photomicrographs: Strand Subelements

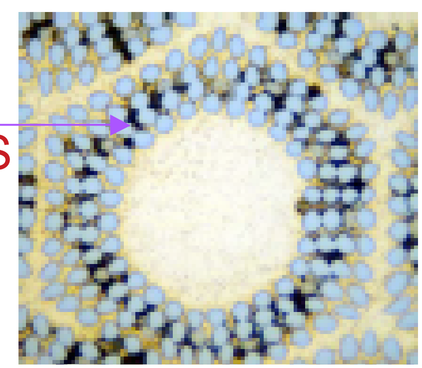


Luvata

Jewell et al, NHMFL



OST



Impressions (No quantitative analysis); grey “dust” is artifact

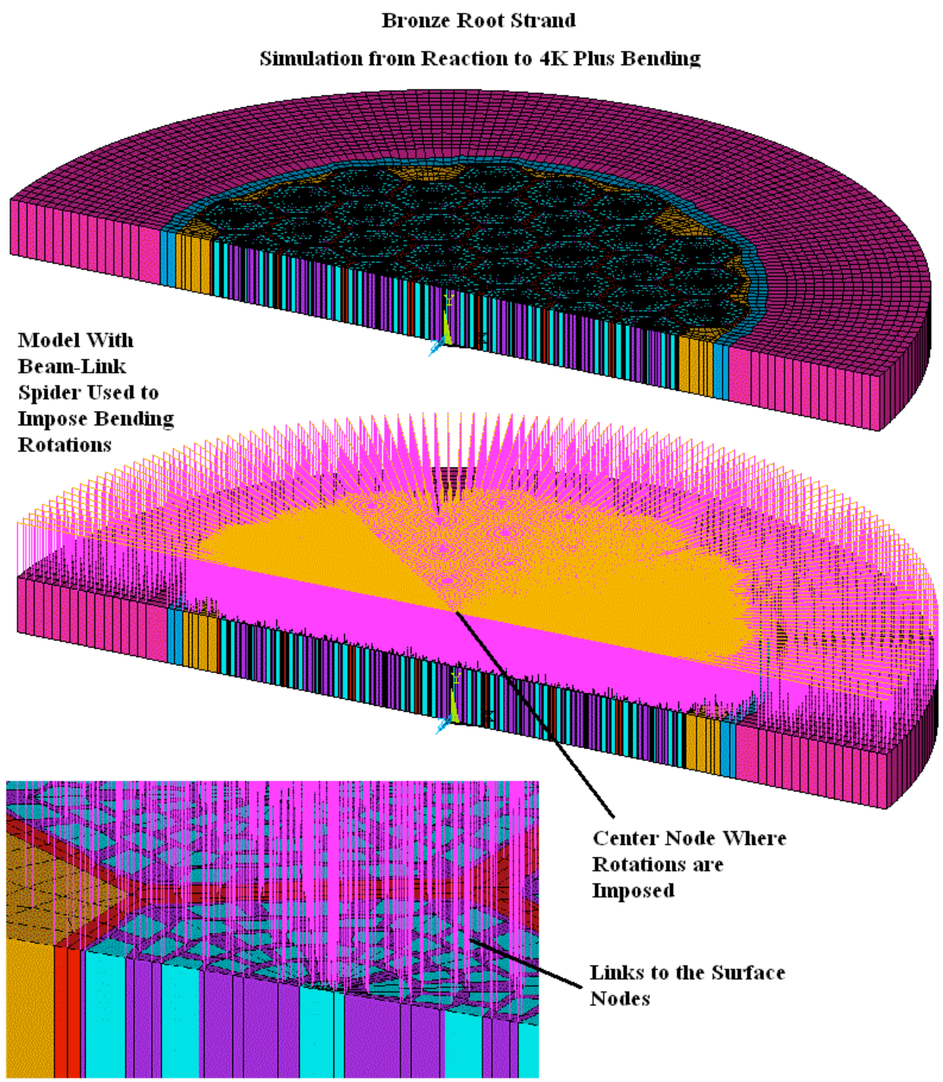
- OST still has more radial bridging than Luvata, but less than OST CS
- Subelement gaps thicker in Luvata
- OST more unreacted Nb in filament cores, (Jewell- crack initiators?)

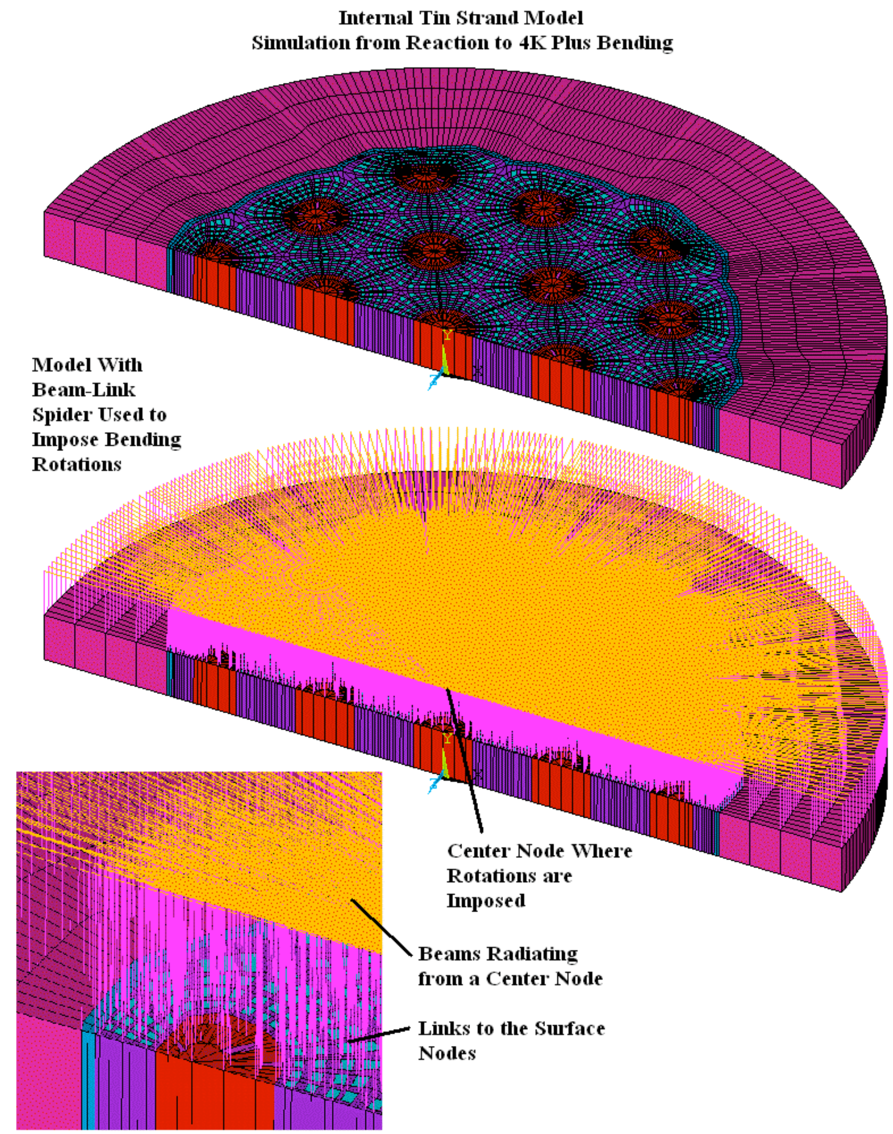
PSFC

Technology & Engineering Division

FEA Models of Strand Bending
Bronze and Internal Tin

Bronze Wire (Vac) **Peter Titus, MIT** Internal Tin Wire (OST TF)





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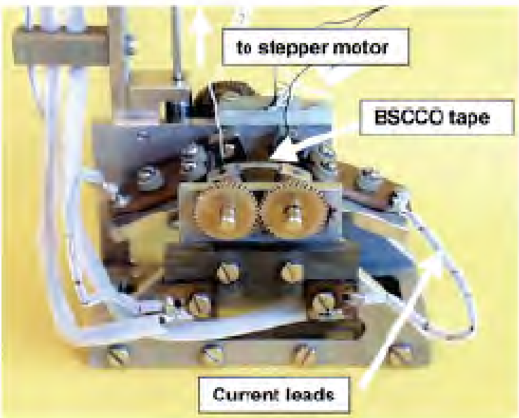
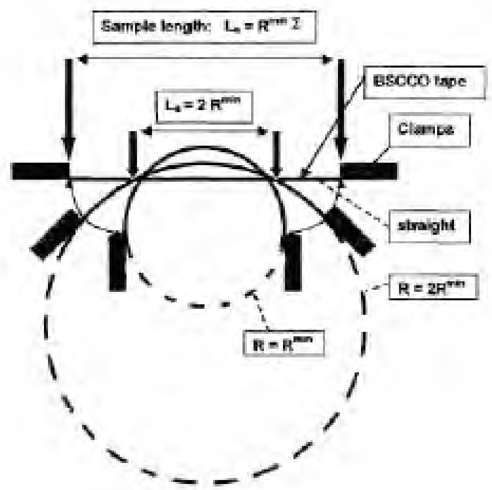
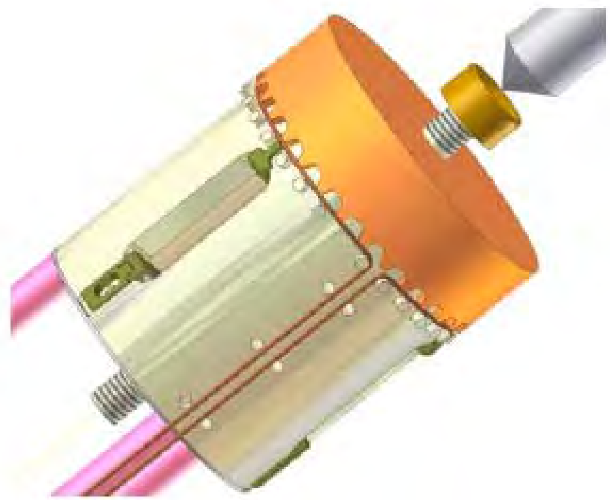
Current Experimental Work

(Pure bending of a single strand)



W. Goldacker

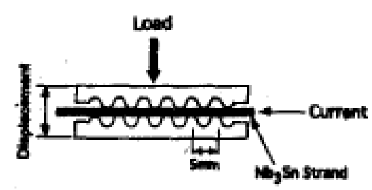




A. Nijhuis

P. Lee

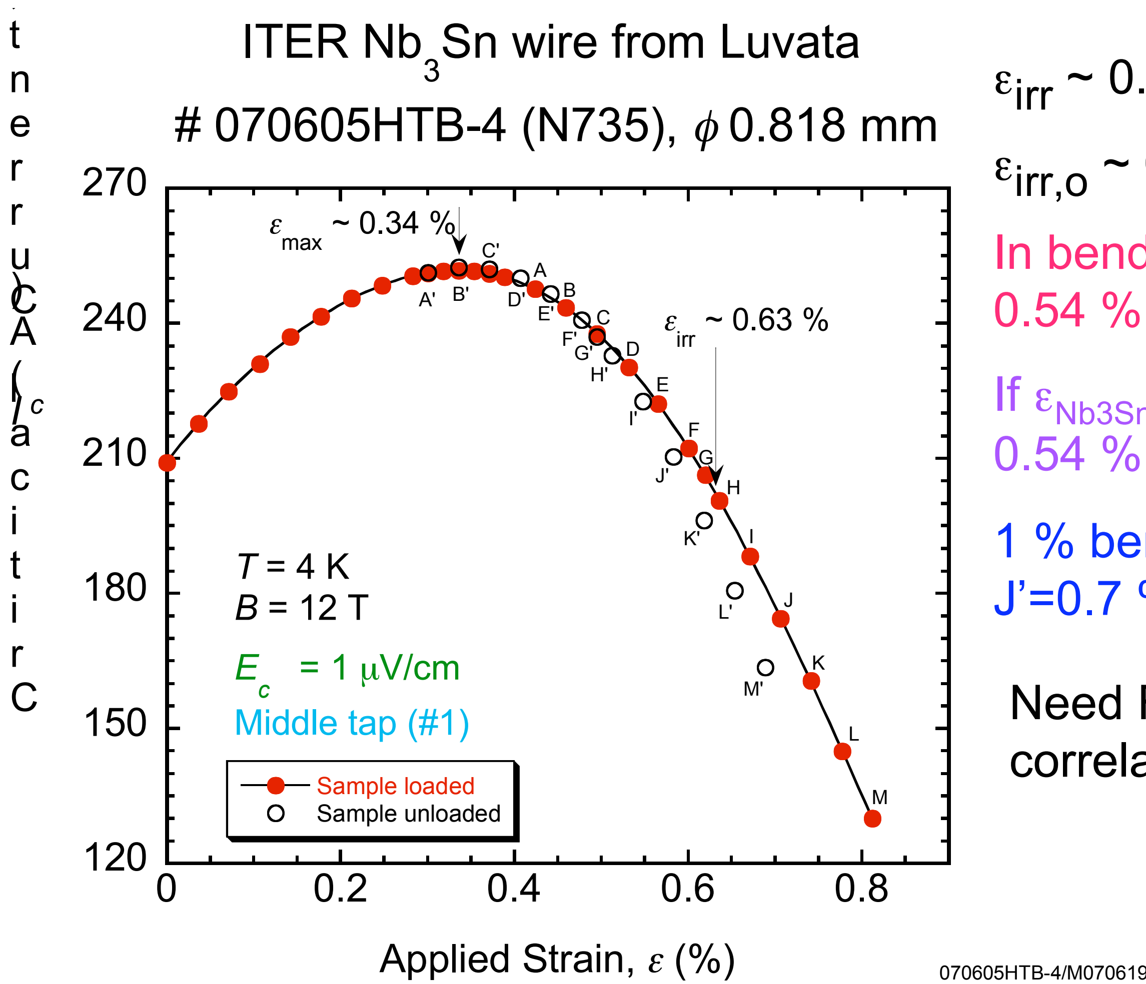
Zani et al.



Y. Nunoya

Periodic bending

Irreversible Strain Limit: Luvata Strand



ε_{irr} ~ 0.63 %

$\varepsilon_{irr,o}$ ~ 0.29 %

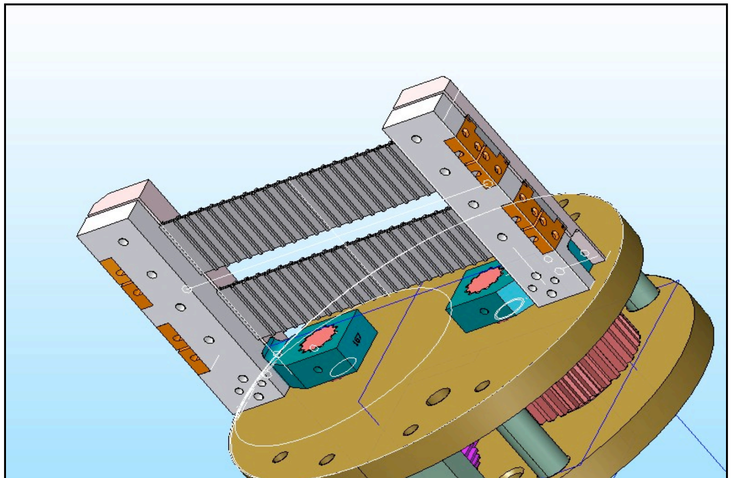
In bending, irreversibility only 1 % at 0.54 %

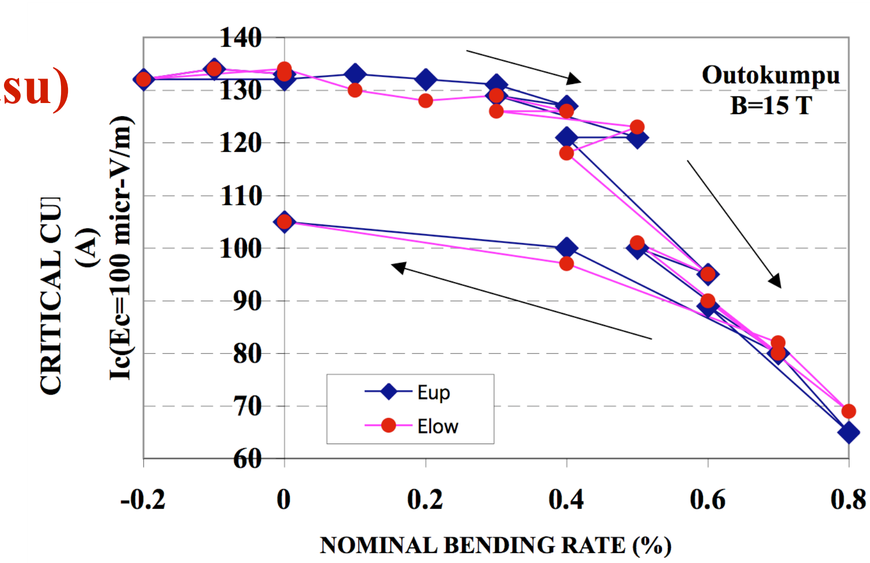
If ε_{Nb3Sn}(Ti,alloy,cool)=-0.25 %, then 0.54 % peak = 0.29 % intrinsic

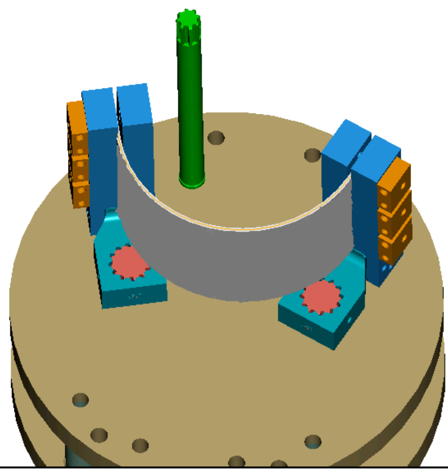
1 % bending ~ 5 % tension, ~ J'=0.7 %=0.36 % intrinsic

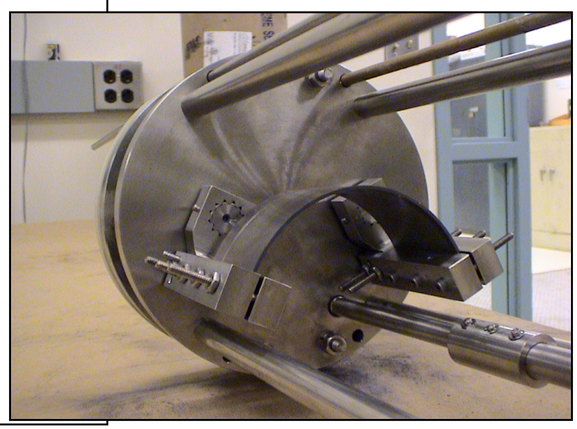
Need FEA, integration to get good correlation

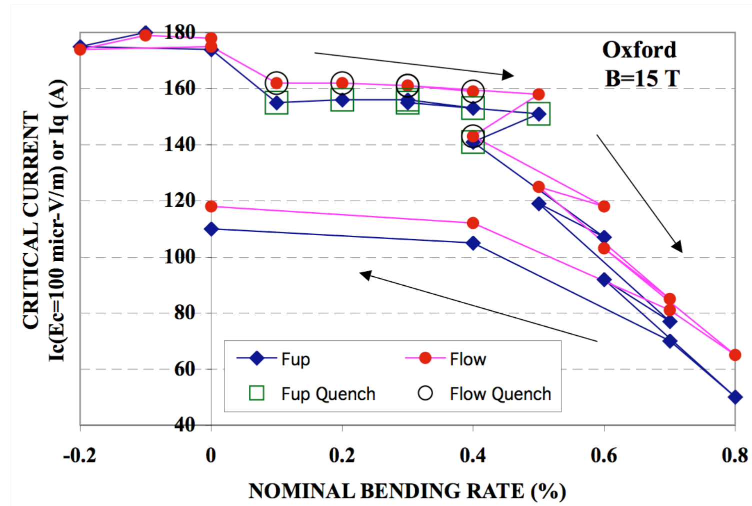
Pure-Bending Rig (Harris, Allegritti,Takayasu) - tests 4 strands at once, slotted Ti plates









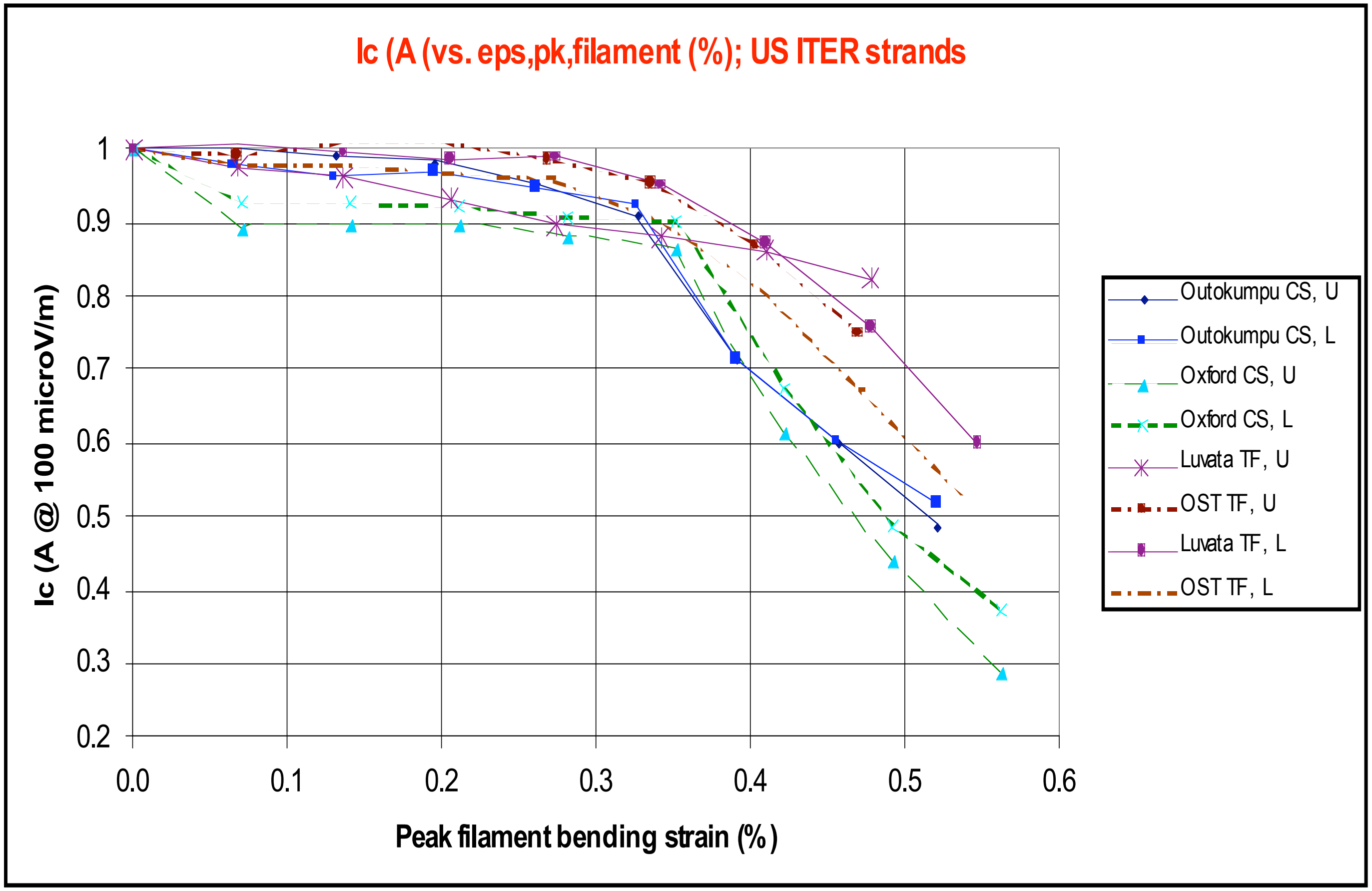


Pure bending test results of ITER Stage-I CS pre-production wires tested at NHMFL

I_c OST CS strand starts 36 % higher than OKAS; only 4 % after 2^{nd} cycle

Reversibility limits not established; simulations not attempted

Normalized I_c vs. Peak Filament ε(%)



Rank:

Insensitivity to Bending

1) Luvata TF

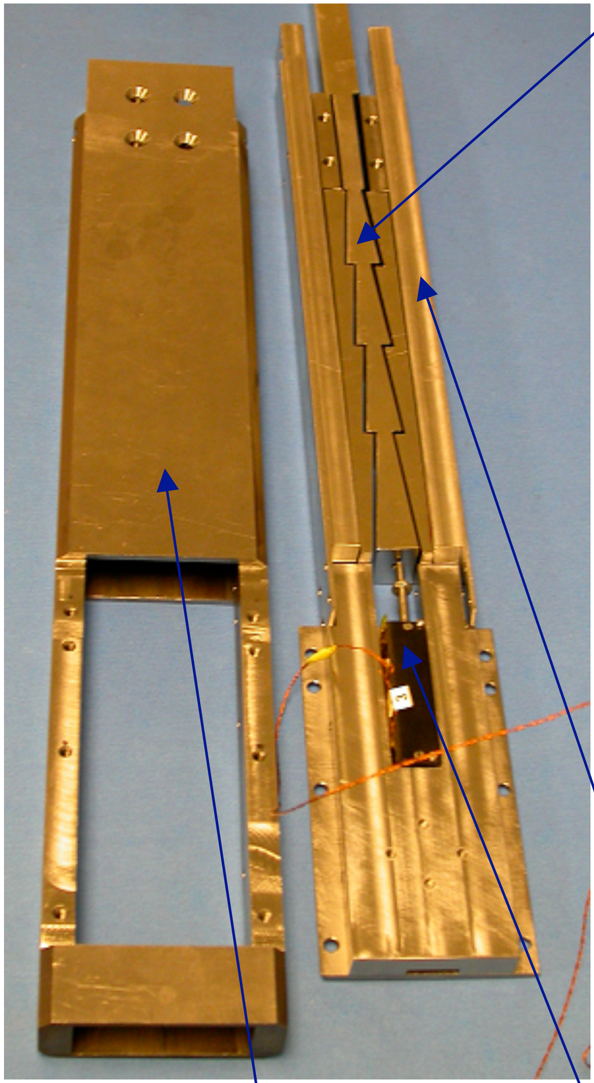
2) OST TF

3) Outokumpu CS

4) Oxford CS

Luvata/Outokumpu less sensitive than OST, but within data spread

New Experiment
(Transverse Load Cable Test)

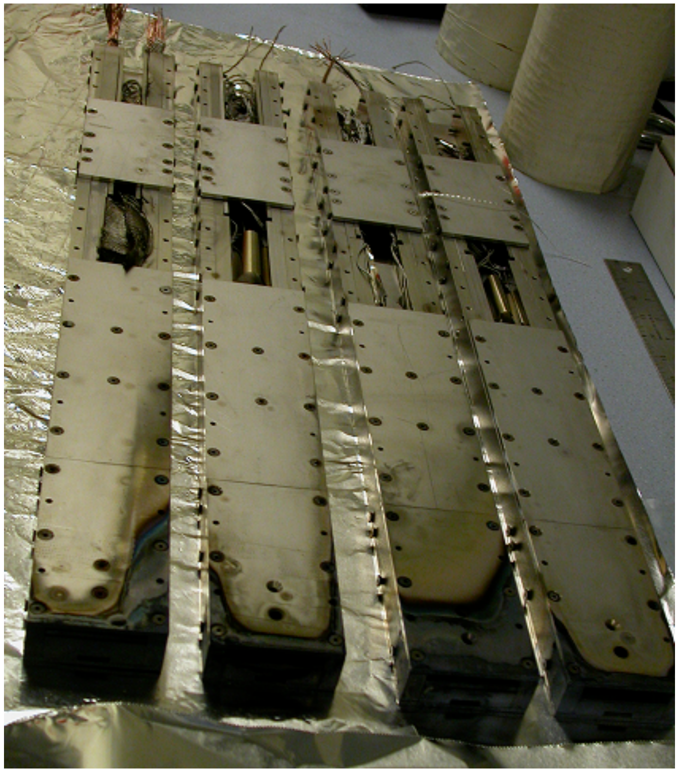


Wedge

Sample holder

Single piece case to sustain load

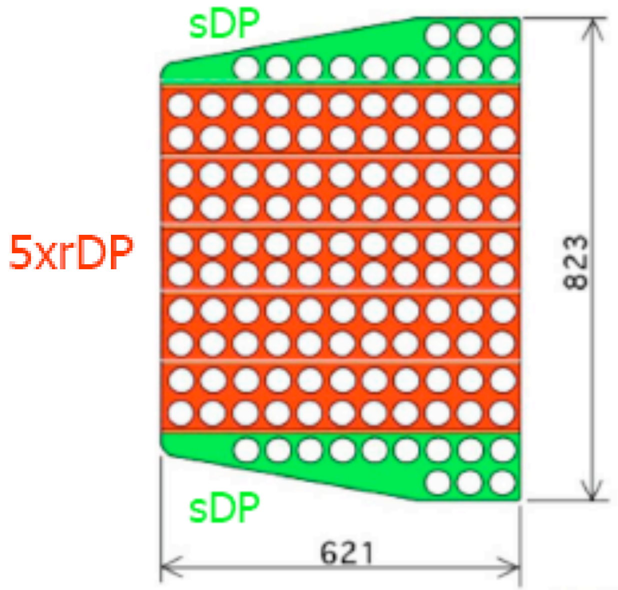
Extensometer

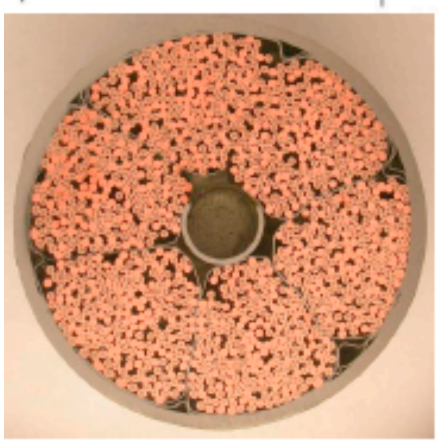


Four samples after heat treatment
Same heat treatment for single strand, 3strands, 9 strands, 45 strands cables

New probe and current leads

ITER TF Conductor





TF Conductor

- It is foreseen to manufacture 18 TF Coils + One Spare: 10 in the EU and 9 and Japan.
- Each TF Coil is made up of 5 *regular* Double Pancakes (rDP) and 2 *side* Double Pancakes (sDP).
- Each DP is wound from a single, continuous length of Cable-In-Conduit Conductor, referred to as *Conductor UL.*
- rDP Conductor UL: ~765 m.
- sDP Conductor UL: ~425 m.
- Total: 95 rDP's + 38 sDP's (plus spares).

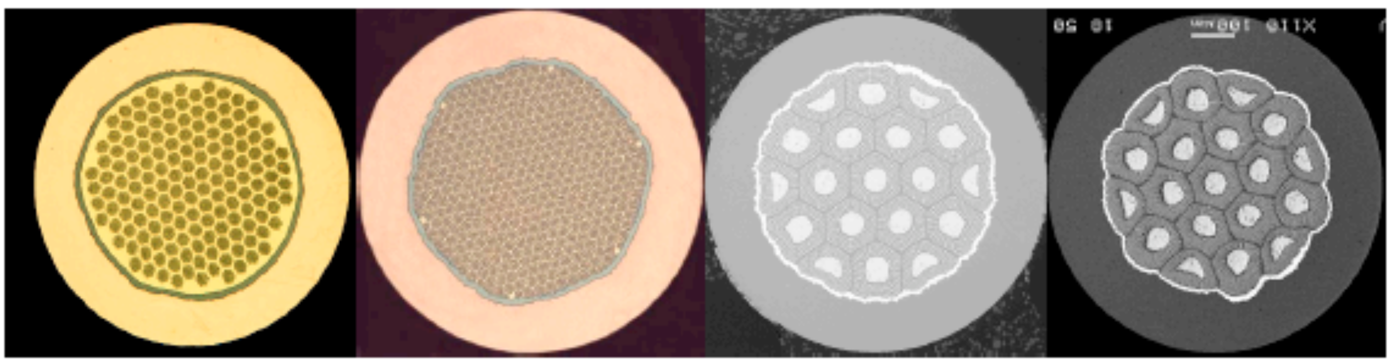
ITER TF Conductor Supply

TF Conductor	EU	JA	RF	KO	US	CN	Total
Credits (kIUA) (2007 M€)	43.4 (62)	53.7 (76)	41.5 (59)	43.4 (62)	16 (24)	16.2 (23)	215 (305)
Share (%)	20.2	25.0	19.3	20.2	7.8	7.5	100
rDP (765 m)	19	24	18	19	9	6	95
sDP (425 m)	8	9	8	8		5	38
sc weight (t)	77	95	74	77	30	29	381
Manufacturers							
Bronze	1	3	1				5
Internal Tin	2	1		1	2	1	7
Number of billets	1239	1071	614	1539	591	576	5629
Minimum number of strand acceptance tests	2479	2141	1227	3077	1183	1151	11259

- Total weight of Nb_3Sn wires: ~380 t (annual production presently estimated around 15 t).
- Total number of billets: ~5600 (similar to LHC, where it was ~6000).
- Large number of QC tests on strands (*e.g.*, as many as ~11000 I_C measurements).

ITER TF Strand Specification

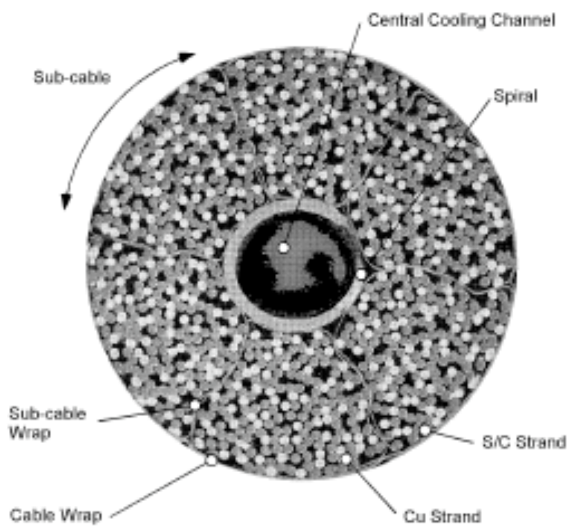
- ITER R&D has focused on two routes: Bronze and Internal Tin.
- Specifications call for
  - Diameter — 0.82 mm
  - Cu-to-Non-Cu ratio — 1:1
  - I_C at 4.2 K and 12 T (ITER Barrel) — 200–300 A
  - Hystreresis loss over ± 3 T cycle — < 1000 mJ/cm^3
  - RRR (after heat treatment) — > 100
- Most suppliers around the world are able to meet these specs.

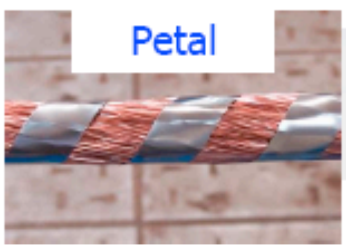


EAS (Br; EU) Boschwar (Br; RF) OST (IT; EU) NIN&WST (IT; CN)

ITER TF Cable Design

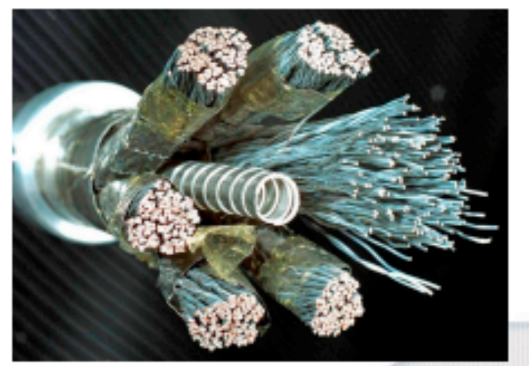
- The ITER TF cable pattern is complicated; it mixes 900 sc strands with 522 Cu strands in five stages
  - inner triplet: (2 sc + 1 Cu)
  - x 3
  - x 5
  - petal: x 5 around (3 x 4 Cu) + stainless steel wrap
  - x 6 around central cooling spiral + stainless steel wrap





Petal

Cooling Spiral

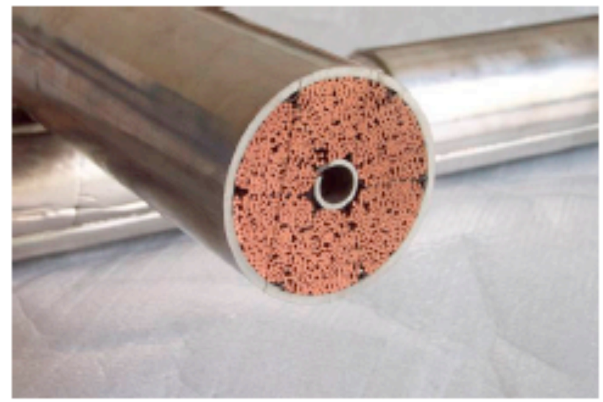


ITER TF Conductor Design

- The ITER TF cable is inserted inside a "round-in-round" stainless steel conduit made up of butt-welded, seamless tubes.

Conduit

Jacketing line



Finished conductor

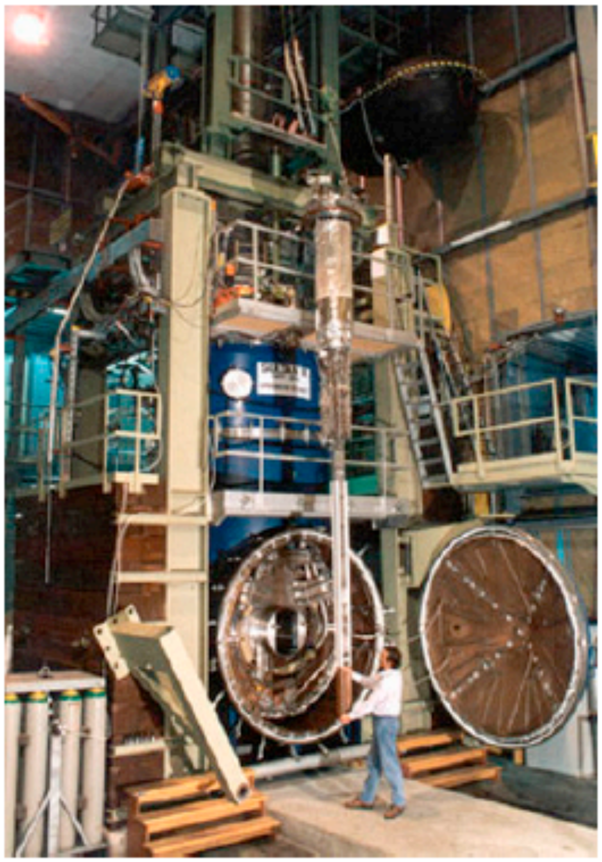
Compaction tool

(courtesy of Yu Wu, ASIPP)

- The jacketed conductor is compacted to achieve the desired void fraction.

ITER TF Conductor Testing

SULTAN Facility @CRPP
(http://crppsc.web.psi.ch/Facilities/sultan.html)



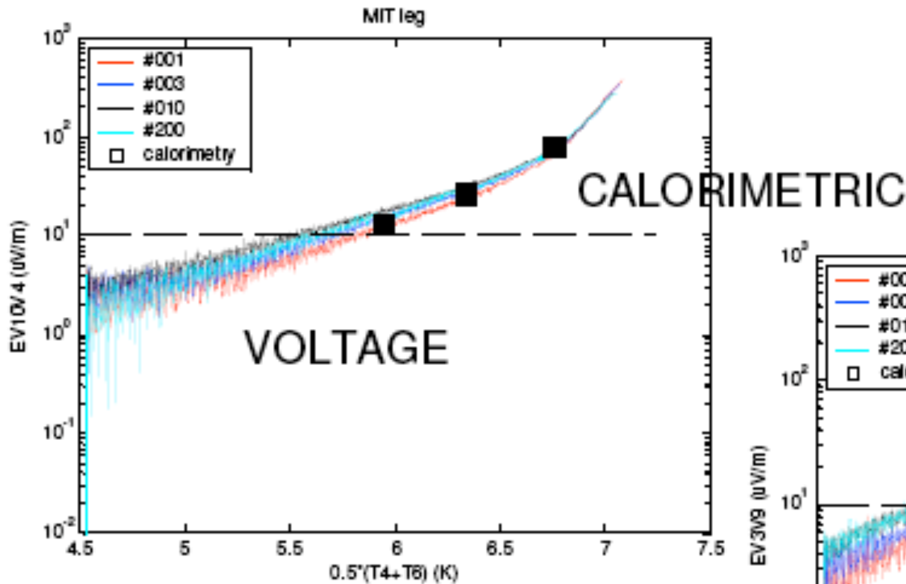
- At present, the performance of a CICC cannot be extrapolated from the performances measured on individual strands.

⇒ each strand/cable/jacket combination must be tested in a full-size conductor sample.

- Testing of full-size CICC samples requires a dedicated facility, that, ideally, should reproduce the most severe "in-coil" operating conditions.
- The only facility of this kind is SULTAN at CRPP (Centre de Recherche en Physique des Plasmas), located in Villigen, Switzerland.

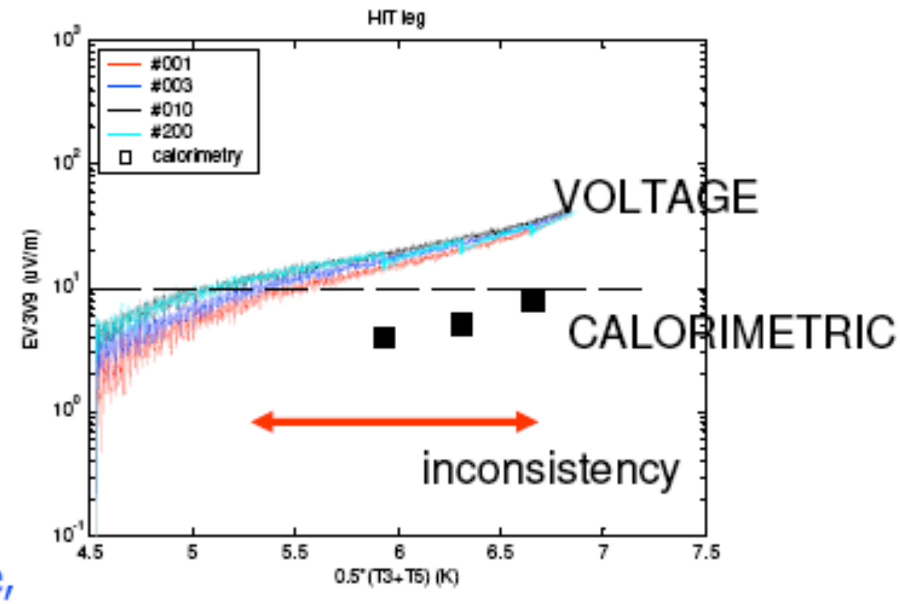
Interpretation of Test Results

- This mixture of effects can lead to significant inconsistencies between voltage and calorimetric data.



JA2 sample
(Mitusbishi leg)

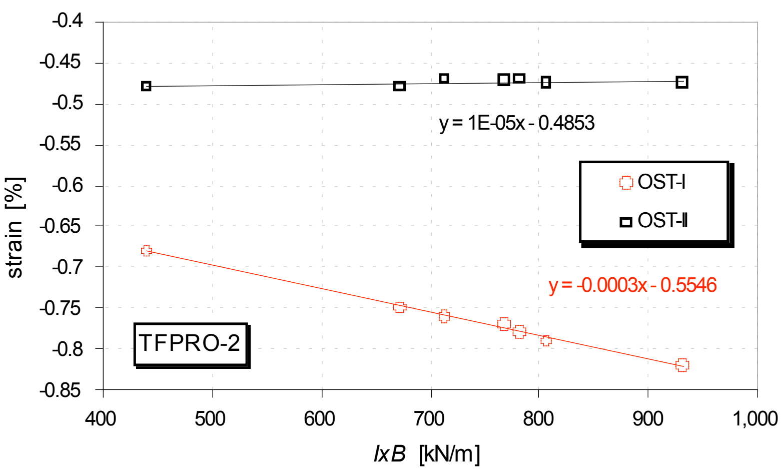
JA2 sample
(Hitachi leg)

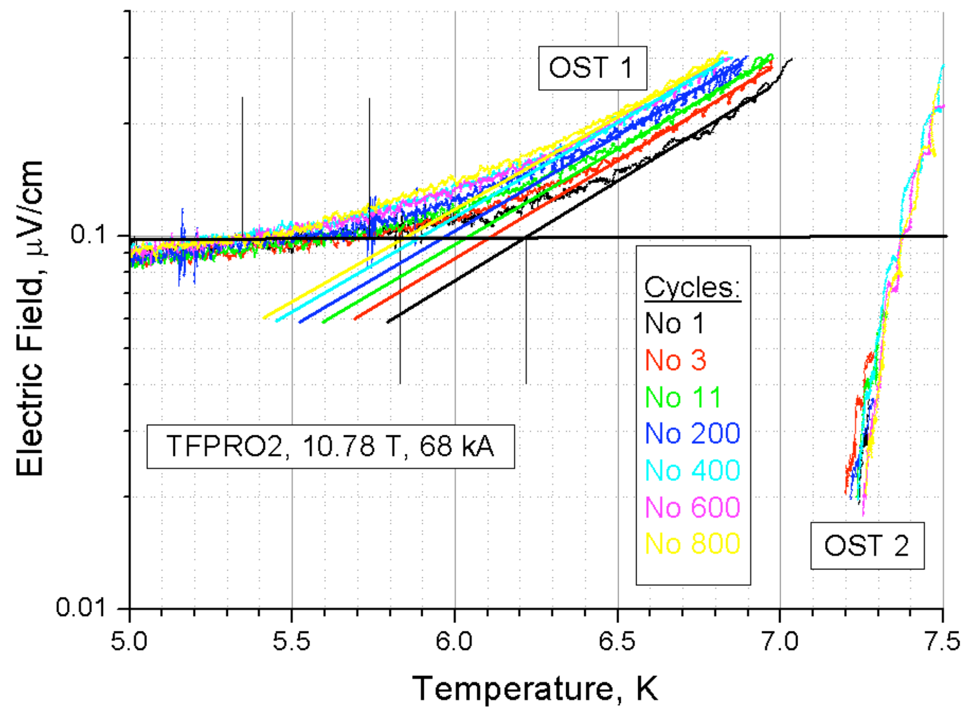


(Courtesy of D. Bessette, ITER/IO)

Cabling Pattern Affects Performance

TFPRO-2	OST-1	OST-2
J_c [A/mm^2]	1130	1070
twist pitches, L_p [mm]	45 88 127 245 470	116 182 245 415 440
L_w [mm]	7	26
void fraction, *vf*	29%	28%





OST-1: ITER reference cable pattern gives degraded T_{cs} ~6 K, *n*-value ~ 8.
OST-2: new cable layout based on TEMLOP prediction with outstanding result: T_{cs} = 7.3 K, no degradation, no *IxB* sensitivity, *n*-value similar to strand (20), maximum achievable performance.

Summary

- Significant worldwide effort has been applied to understanding effects of longitudinal, bending, and transverse compression strain on degradation of critical current of Nb_3Sn superconductors.
- Some ITER relevant Nb_3Sn strands appear more sensitive to strain than others.
- Initial short-length, full-size ITER conductor samples using baseline parameters have shown disappointing results in SULTAN Facility tests.
- Most recent tests using redefined cable twist patterns *indicates required conductor performance can be achieved or exceeded.*
- Further comprehensive qualification of ITER TF conductor samples will be performed during 2008 in SULTAN facility.