

# ITER Conductors from Design, through Specification, Qualification, Production and Test

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# Outline

The birth of the ITER conductor

The success oriented design

Learning to accept degradation

The challenge of large scale manufacture

The last minute R&D

The cost issue

The lessons learned (by whom?)

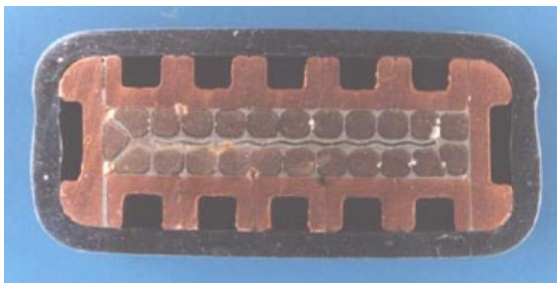


# Roll back to the late eighties – TF

For Toroidal Field Coils, the LCT project in Oak Ridge boosted the R&D, with reference operating current  $<20\text{kA}$  and peak field  $\approx 7\text{T}$ : the *forced flow cooling* proved to be superior (mechanical stiffness, electrical insulation).

After the JET operation, the size and field requirement for the “Next Step” Tokamak became prohibitive for NbTi (T7, Tore Supra). The era of *Nb<sub>3</sub>Sn* for TF coils, pioneered by T15 and TRIAM, was about to start.

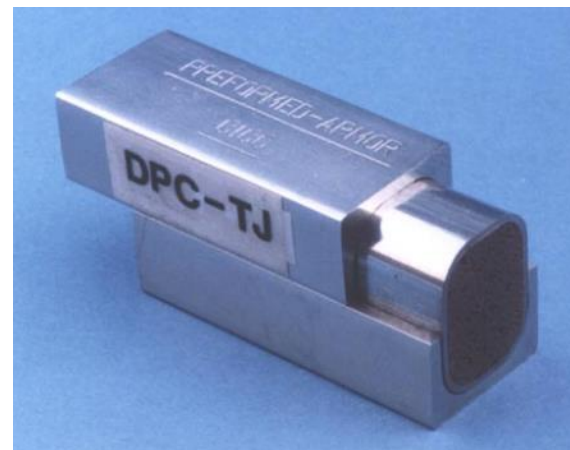
A flat cable, soldered, Nb<sub>3</sub>Sn react&wind TF prototype was made by JAEA after the LCT.



# Roll back to the late eighties – PF

In the Demonstration Poloidal Coils (DPC, Naka), about 6 years after LCT, all conductors were “cable in conduit”: NbTi with insulated strands (DPC-U), Nb<sub>3</sub>Sn with *react&wind/steel* (DPC-EX and DPC-JT) and *wind&react/Incoloy* (US-DPC). The design operating current was <20kA.

The NbTi Polo conductor/coil in Karlsruhe was designed for very large field transient, up to 1000 T/s (this requirement vanished in the nineties).



# ITER CDA 1988-1990 – The precursors

The European NET project run in parallel with ITER CDA, substantially with identical design, promoting relevant R&D activities, including the manufacture and test of three short length Nb<sub>3</sub>Sn CICC prototypes in the 40kA class. The requirement of **40kA / 12T**, wind&react, was a new challenge on the field.

The test of such high current / high field conductors was not obvious. FENIX (Livermore, 1990) suffered from large noise from the direct power supply. SULTAN was first operated as split coil with superconducting transformer, 1992.

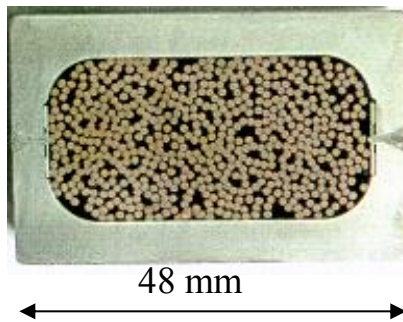
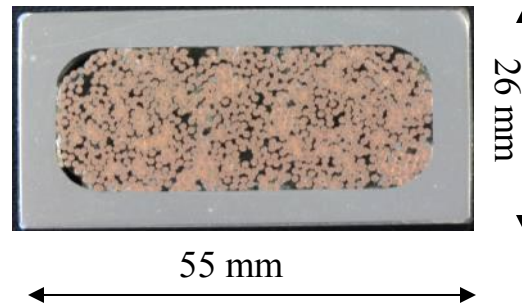
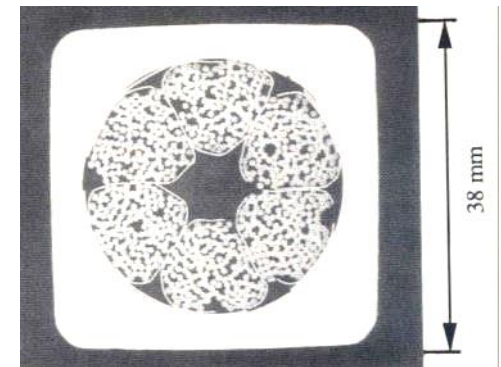


ABB – 1990  
Laser welding



LMI – 1992  
Extruded conduit

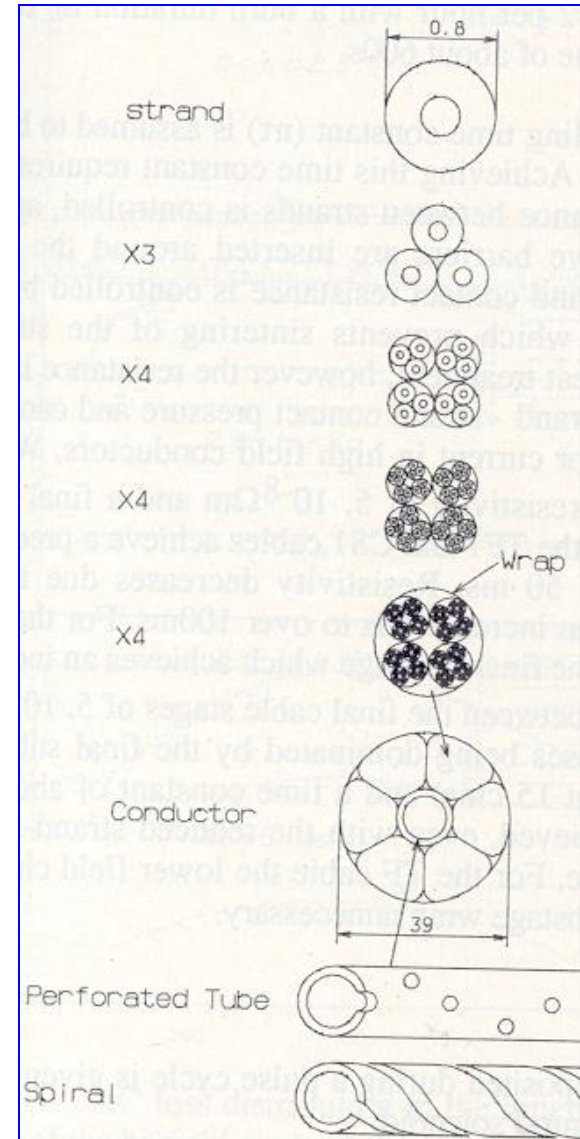
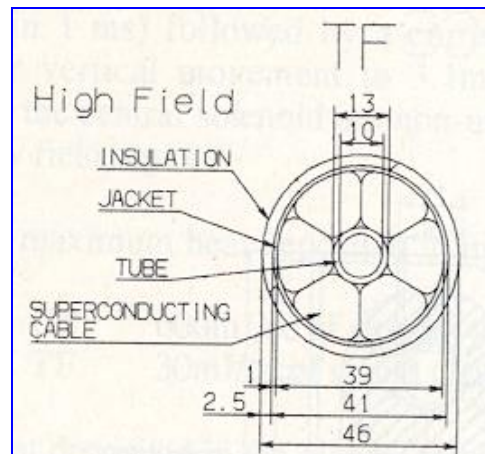


CEA – 1992  
Central hole

# ITER EDA 1992-1999

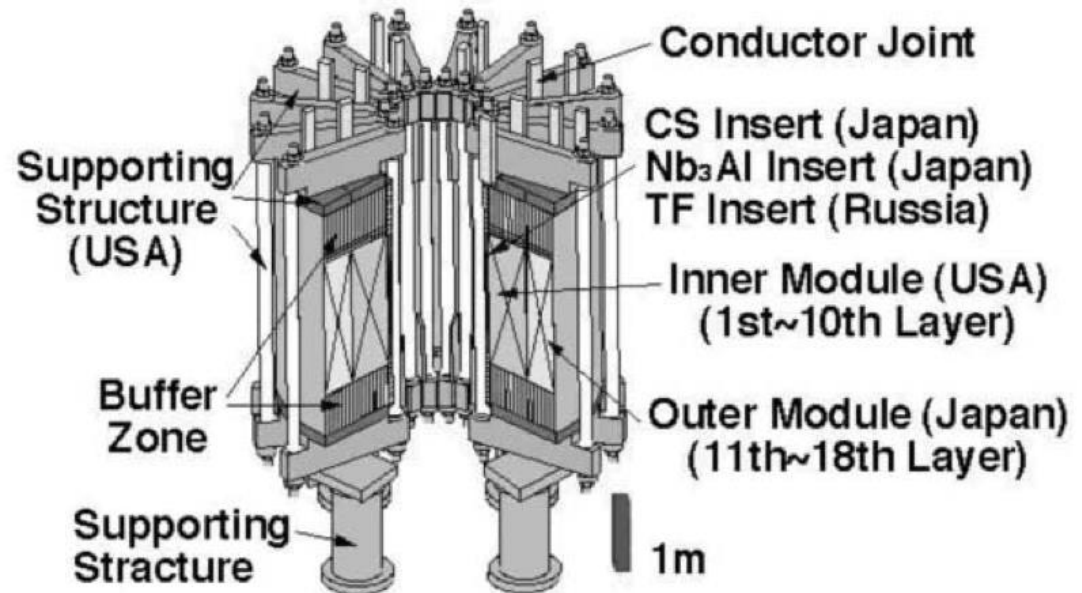
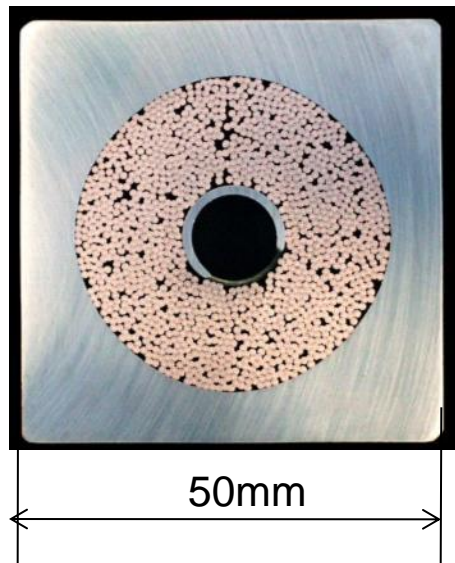
The French management of ITER EDA, eager to start construction, froze in 1992 the design of the ITER conductors, upgrading the CEA prototype of 1992. The same basic layout was retained for the DC coil (TF 68kA) and pulsed coils, CS (Nb<sub>3</sub>Sn) and PF (NbTi). Although the scope of the 1992 tests was very limited, no further conductor prototype test was carried out till 1999, jumping straightaway to the Model Coil Test.

Success  
oriented  
design



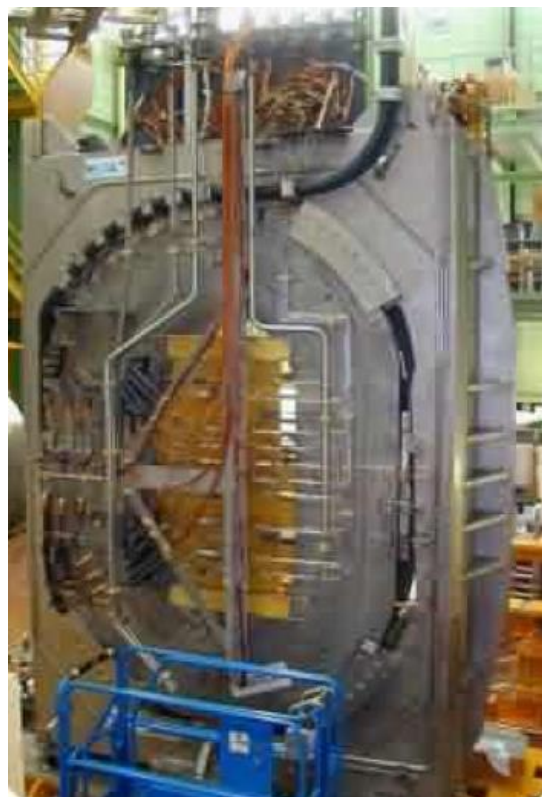
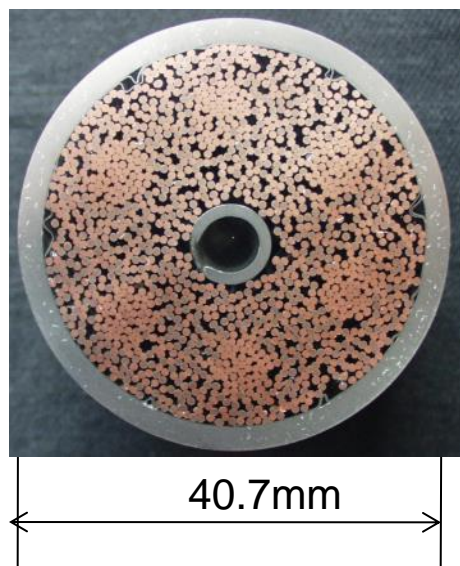
# The ITER Model Coils - CSMC

The Central Solenoid Model Coil (CSMC, Naka 2000) used full size CS conductor in a reduced size solenoid, for 13T @ 45kA. It used the **Incoloy 908®** jacket for mitigation of thermal strain, with extensive R&D to control the SAGBO. It reproduced the graded, layer winding and the **wind-react-transfer-insulate** method with pre-preg electrical turn insulation and final VPI.



# The ITER Model Coils - TFMC

The Toroidal Field Model Coil (TFMC, Karlsruhe 2001) used full size TF conductor in a small size, pancake wound race-track coil. It used **steel jacket**. It aimed to verify the **wind-react-transfer-insulate** method on a non-circular shape. The peak field,  $<9T$ , was not relevant for ITER.





Mandatory for small coils  
Electrical insulation issue



Suitable for large coils  
Low thermal strain  
Cheaper tooling cost



Wind & React	Wind-React-Transfer	React & Wind
Complete Conductor Assembly	Complete Conductor Assembly	Pre-assemble Cable (no steel)
Apply dry Insulation	Apply temp. Spacers	Coil on av. Diameter
Wind in Final Shape	Wind in Final Shape	Heat Treat
Heat Treat	Heat Treat	Uncoil to complete conductor assembly
Pot by VPI	Un-spring to apply dry insulation	Apply dry insulation
	Re-compose the coil	Wind in Final Shape
	Pot by VPI	Pot by VPI



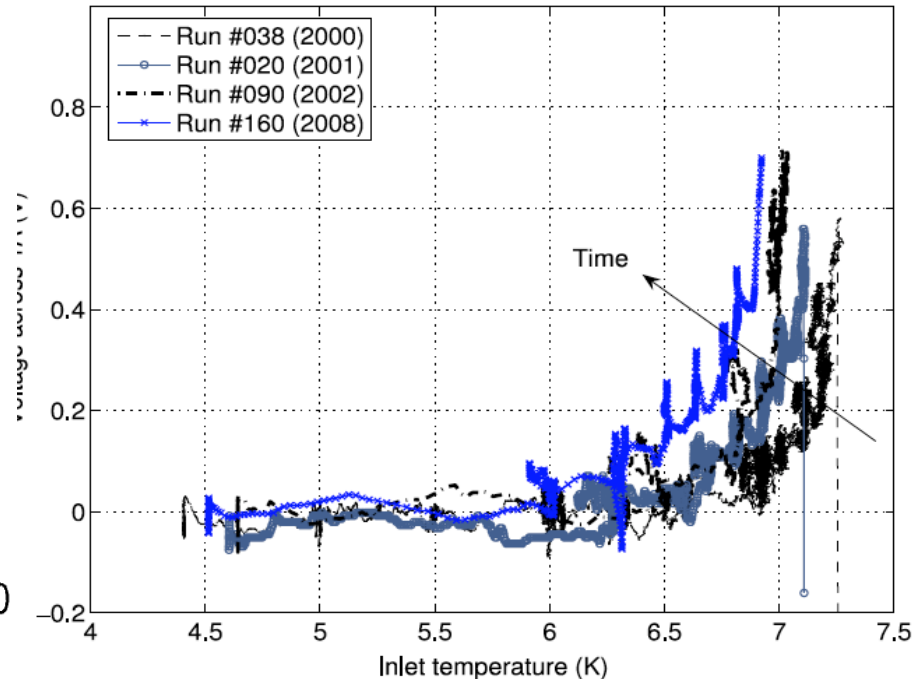
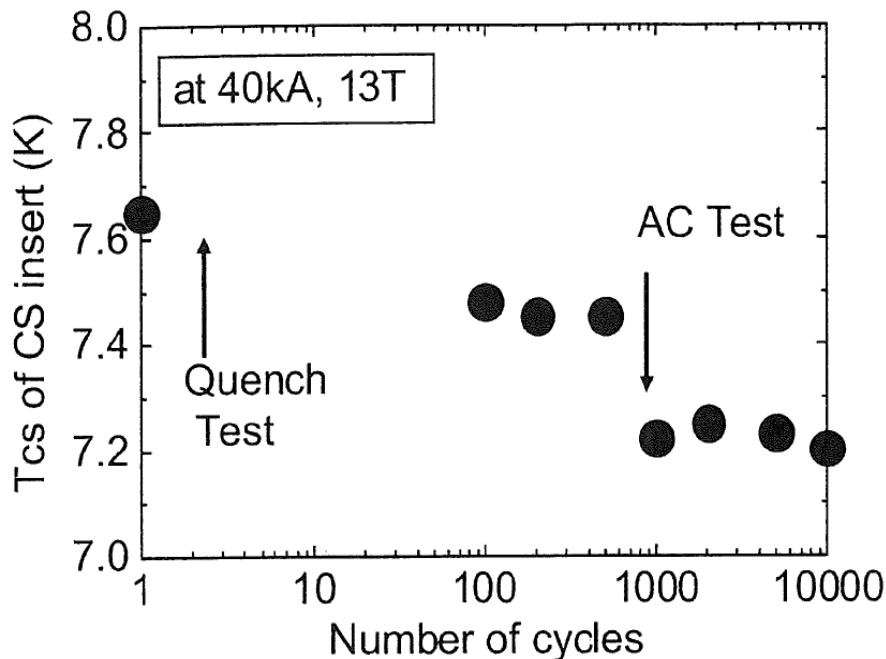
Mandatory for use of Incoloy (SAGBO issue)  
Suitable for large coils, High tooling cost



# The first Test Results – Red Alert

The first test results of the Model Coils (CSMC-2000 and TFMC-2001), Insert Coils (CSI-2000, TFI-2003) and conductor tests (1999-2000) raised a red flag:

- The performance was substantially lower than predicted by the scaling law
- The performance worsened continuously upon cyclic loading
- The superconducting transition was very broad, with very low  $n$  index



# Feedback after Model Coil Test?

Although Neil Mitchell made in 2002 a very critical review of the test results, the Model Coils were advertised, mostly in EU and JA as success stories.

In the uncertain situation of the project (EDA closed, but construction far from approval), it was considered wise to keep low profile on the performance loss.

ITER decided to “*live with the problem*” rather than “*solve the problem*”.

What happened to the ITER conductors from 2000 to 2006?

- *As soon as the US quit ITER in 1999, the Incoloy 908 was replaced by steel as conduit material, with higher thermal strain and 30% lower  $I_c$*
- *The design temperature margin dropped from 2K to 0.7K*
- *The spec for the strand  $J_c$  was increased by about 27%*
- *The central hole and the void fraction were reduced*
- *The non-cu cross section increased by 7%*



# The TFAS conductor test - 2006

The “advanced  $Nb_3Sn$  strands”, with  $J_c @ 12T/4.2K > 700 A/mm^2$  (compared to 550 in the Model Coils) were qualified in 2003-2005. The TFAS samples, tested in 2006, just before the ITER Organization entered in force, are *TFMC-type conductors with advanced strands to check the retention of strand properties in the CICC.*

The test results of the four TFAS conductors, with electromagnetic and thermal cycles, was disappointing, with initial performance lower than extrapolated from the TFMC and dramatic worsening with cyclic loading.

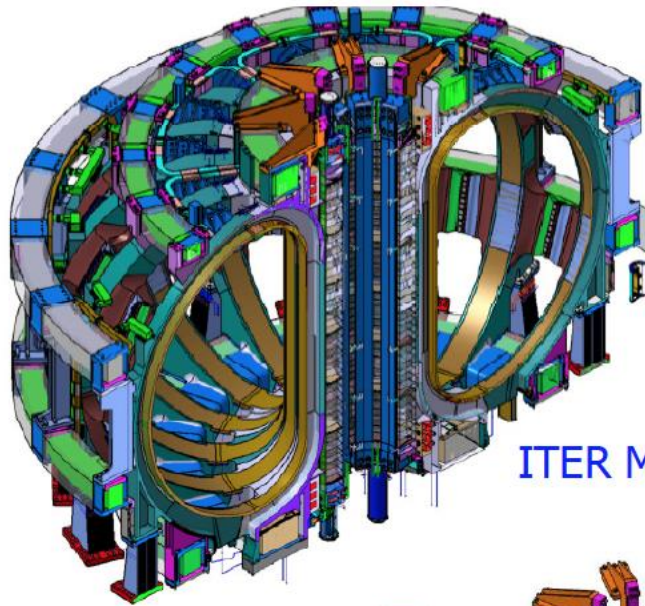
	ITER spec	TFMC	OST	EAS	OKSC	OCSI
Before cyclic load	<b>5.7 K</b>	5.52 K	6.63 K	4.93 K	5.29 K	5.77 K
After cyclic load	<b>5.7 K</b>	-	5.81 K	4.72 K	<b>5.09 K</b>	<b>5.53 K</b>
3 <sup>rd</sup> Campaign after warm up	<b>5.7 K</b>	-	<b>5.44 K</b>	<b>4.57 K</b>	-	-

## The ITER construction agreement is signed in Nov. 2006

- The magnet and conductor design is frozen, with last update in 2004.
  - The conductor procurement is on the critical path and must start immediately.
  - The available test results suggest non-adequate performance.
- 
- As most of the ITER components, the conductor is an *in-kind procurement*. The sharing of the the procurement among the DA is agreed since 2007 and cannot be changed. A *Procurement Arrangement* (PA) is signed between IO and each DA. The object of the PA is the assembled conductor (*no split for strand, cable, jacket*, etc.). The value of the PA (credit) is not correlated with the actual expenditure by the DA.
  - IO issued a *functional* specification for the strand ( $J_c$  *non-copper @12T, 4.2K  $\geq 700$  A/mm<sup>2</sup>*) and a *blue-print* specification for cabling and jacketing. A performance minimum, e.g.  $T_{cs} \geq 5.7K @ 68$  kA, 10.78 T for TF conductor, is imposed by IO to the DA as acceptance test for the conductor (but the DA cannot impose a CICC acceptance test to his suppliers...).



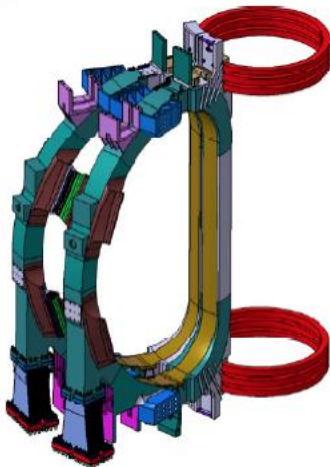
# Key data of ITER Magnet System



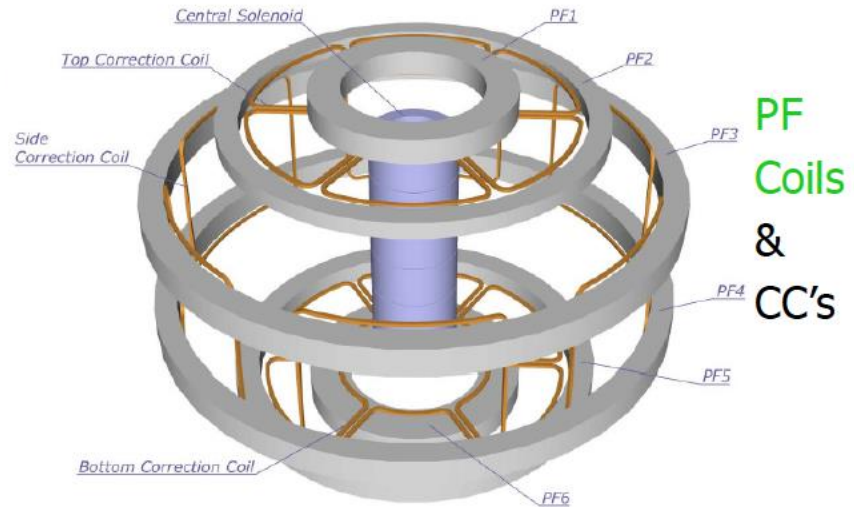
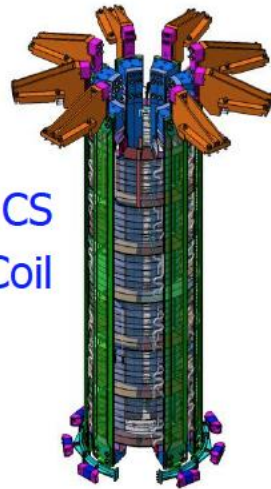
ITER Magnet System

- The ITER magnet system is made up of
  - 18 Toroidal Field (TF) Coils, } Nb<sub>3</sub>Sn
  - a 6-module Central Solenoid (CS), }
  - 6 Poloidal Field (PF) Coils, } NbTi
  - 9 pairs of Correction Coils (CC's).

Pair of TF Coils



CS Coil



# Scope of the ITER Conductor Procurement

Coil	Total Length (km) [Weight (t)]	SC Strand Type	SC Strand Weight (t)	Jacket Type	Jacket Material	Jacket Weight (t)	ITER Credit [kIUA (M€)]	ITER Credit Sharing (%)					
								CN	EU	JA	KO	RF	US
TF	88 (826)	Nb <sub>3</sub> Sn	384	round-in round	Mod. 316LN	185	215 (323)	7.5	20	25	20	20	7.5
CS	42 (728)	Nb <sub>3</sub> Sn	122	round-in square	JK2LB or Mod. 316LN	530	90 (135)	–	–	100 (paid by EU)	–	–	–
PF	65 (1224)	NbTi	224	round-in square	316L	900	81 (122)	67	13 (PIA w. RF)	–	–	20 (PIA w. EU)	–
CC/ Feeder	10/ 3.5	NbTi	21	square/ round	316L or LN	22	2.13 (3)	100	–	–	–	–	–

The **250 t of NbTi strand** (in coil) is a fraction of the world wide yearly production.

The **> 500 t of Nb<sub>3</sub>Sn strand** (in coil) compares to a yearly production < 10 t

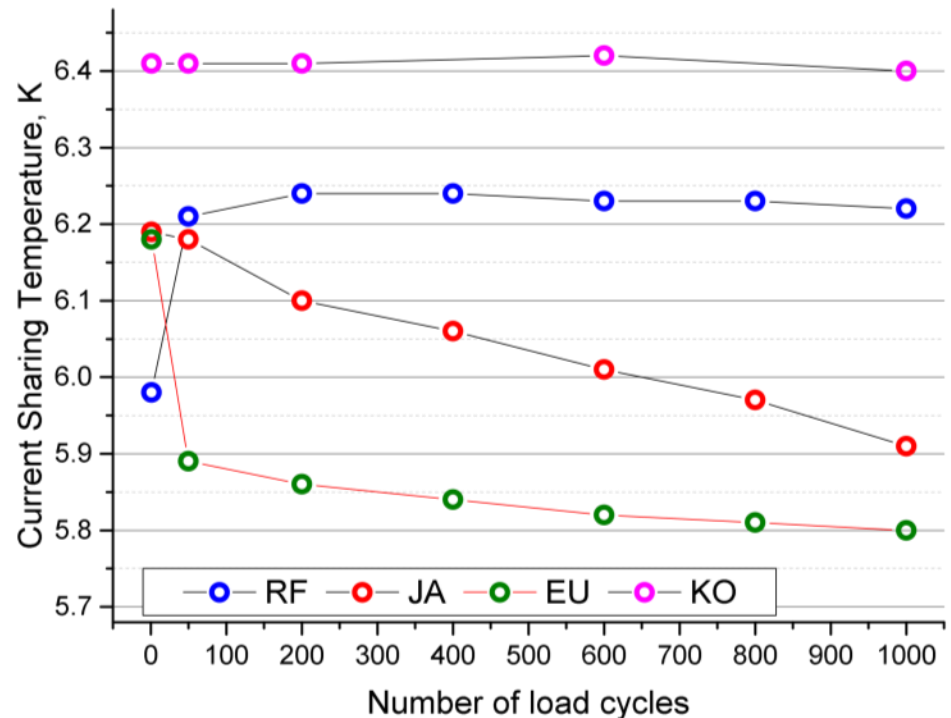


# The TF conductor in 2007

While the strand procurement contracts are being signed by the Domestic Agencies, 12 TF prototype conductors from six strand suppliers are manufactured and tested. The only “free” parameters are the *void fraction* and the *cable pitches* because the strand diameter, # of strands and cable diameter are frozen.

The IO conclusion from the 12 TF prototype conductors of 2007 is that a *“long pitch sequence”* and *29% void fraction help mitigating the degradation*.

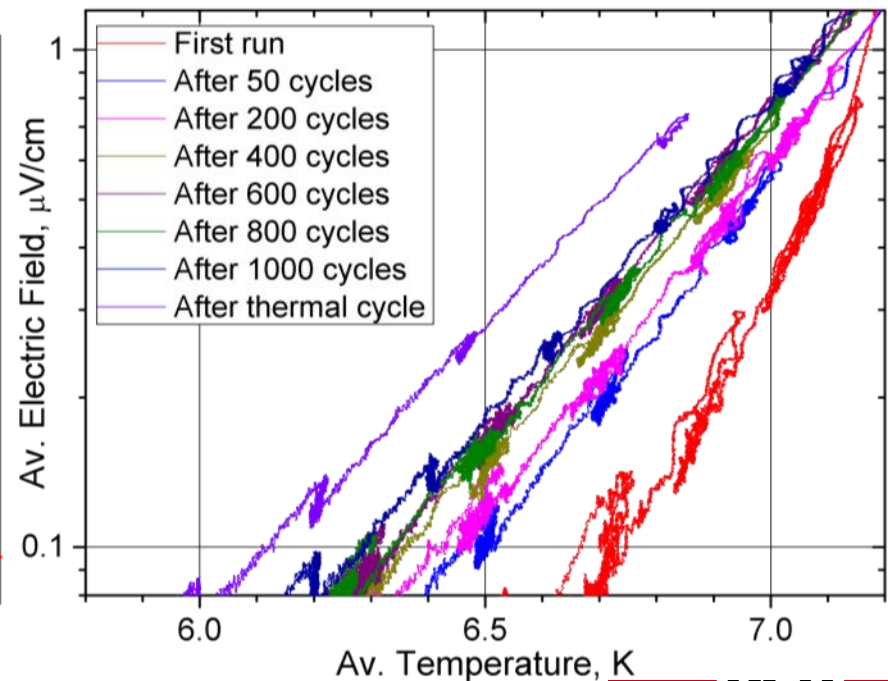
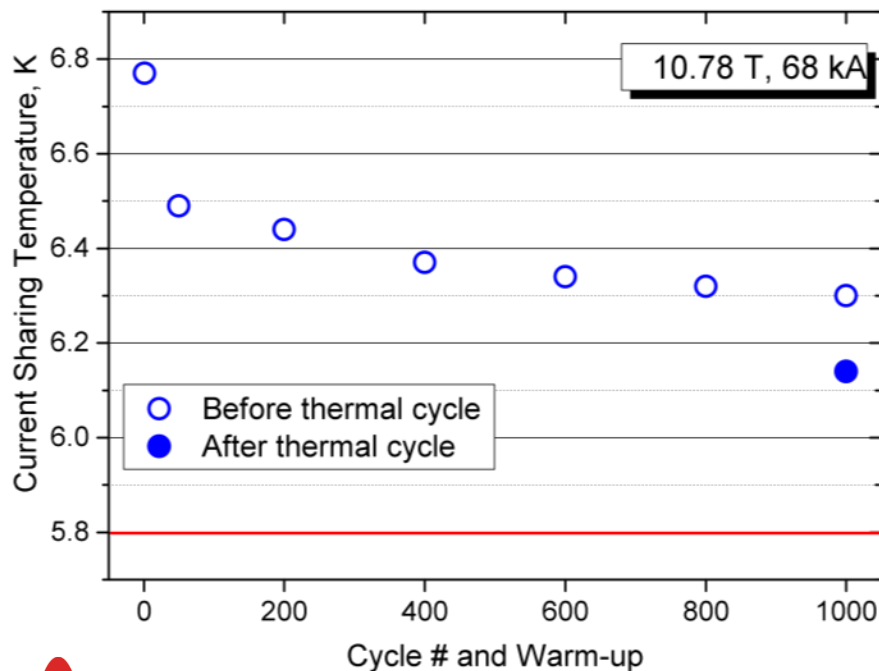
The CICC performance is dictated by the strand  $J_c$  and by the sensitivity of the various strand to the transverse load (but this cannot be exploited as the strands are accepted based only on the free standing  $J_c$  performance).





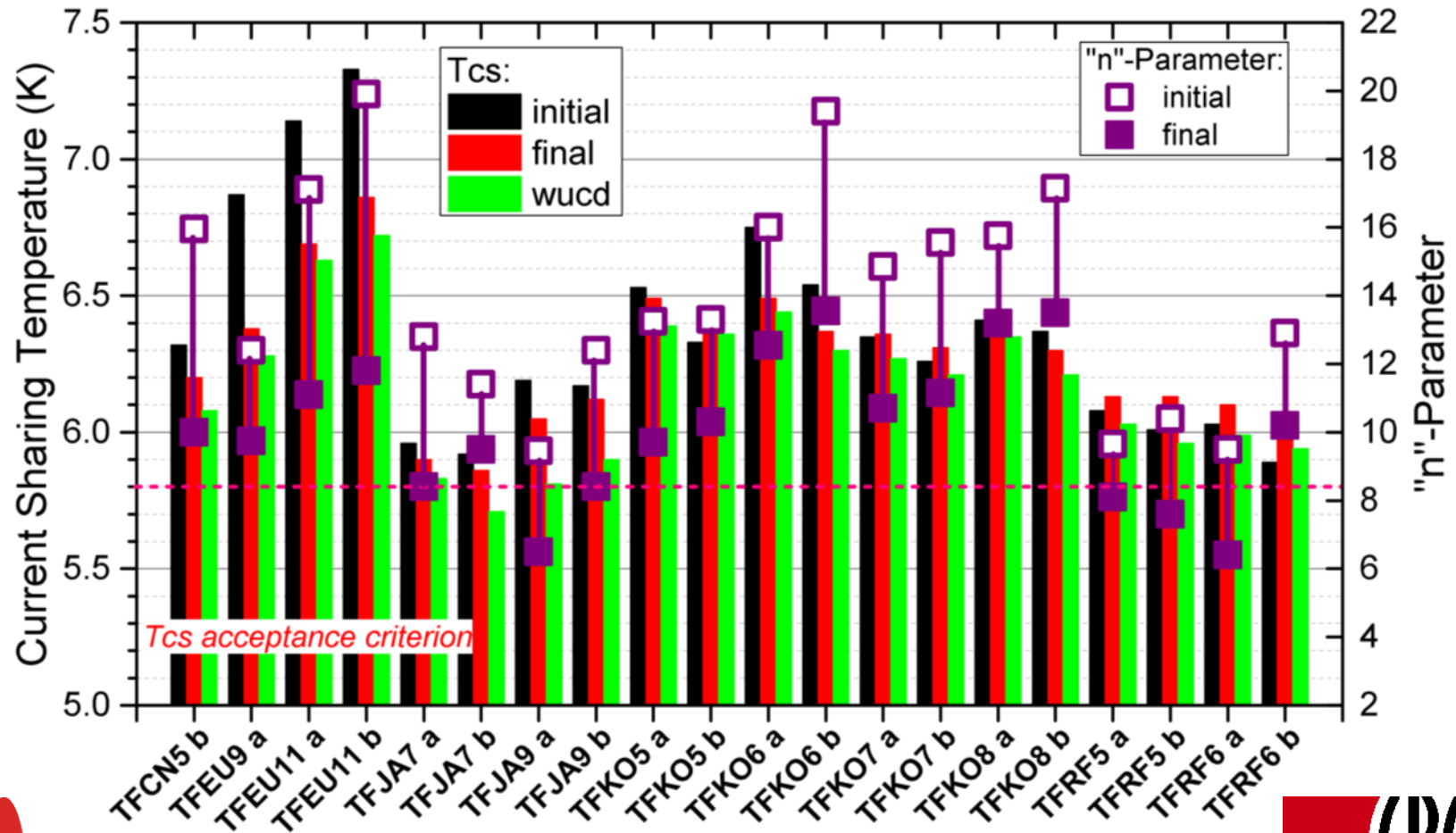
# The TF conductor performance 2009 - 2015

The crucial test is the  $T_{cs}$  at the nominal operating conditions, 68kA and 10.79T background field, after 1000 load cycles, before the thermal cycling. The initial performance is always below the one predicted by the scaling law. The typical behavior upon cyclic loading is a drop of  $T_{cs}$  by  $0.3 \div 0.6$  K. The drop represents an increase of filament breakage with a broadening of the transition or decrease of the  $n$ -index. For the same cable layout, some strands are less sensitive to cyclic load degradation.



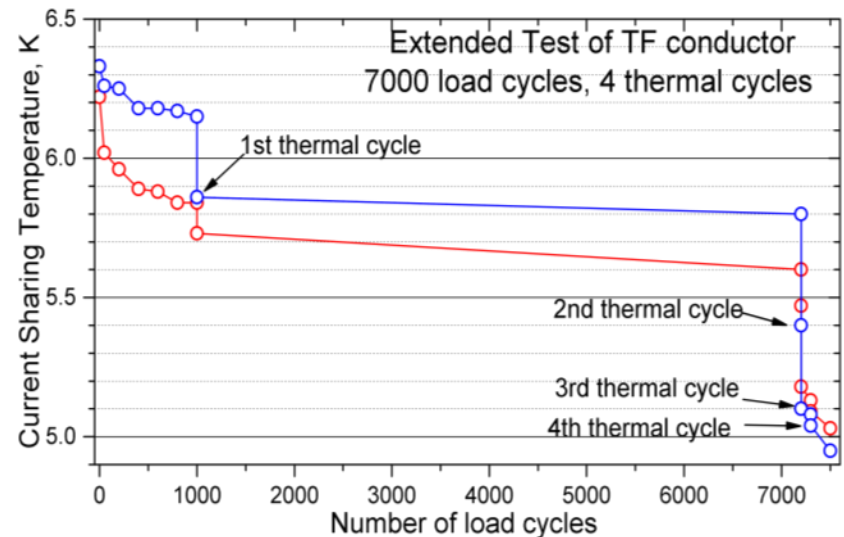
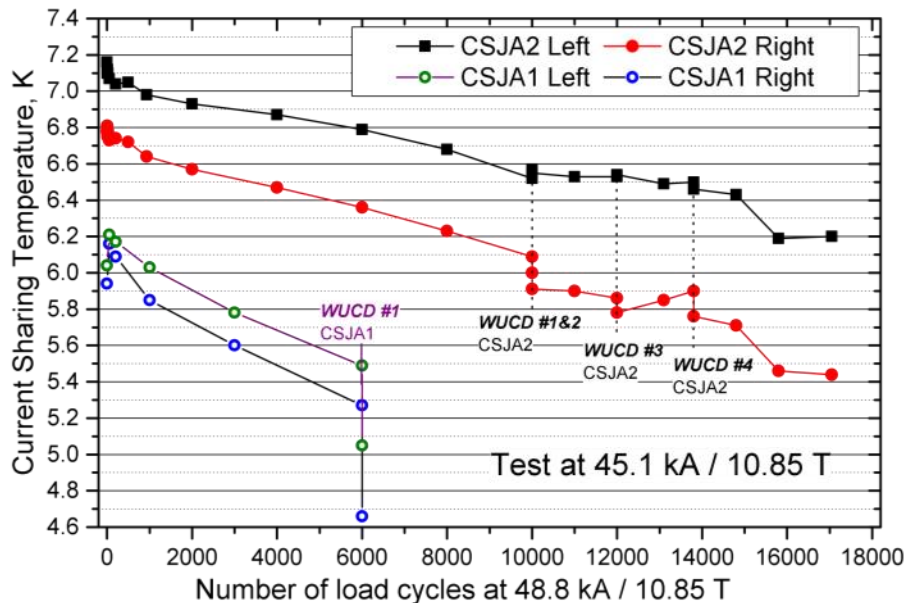
# The TF conductor performance - Summary

The large performance drop (even higher than in the Model Coils) is offset by overdesign, with actual strand  $J_c$  up to 30% larger than specified: not a problem for internal-Sn strand, but marginal for bronze strand.



# The CS conductor in 2010 - 2011

The qualification of the CS conductor started in late 2010. The first two samples, CSJA1 and CSJA2, had the same “long pitch sequence” as the TF conductors. The ITER CS requirement is for **60 000** load cycles. The test in SULTAN is foreseen for 10000 cycles (compared to 1000 cycles for TF)

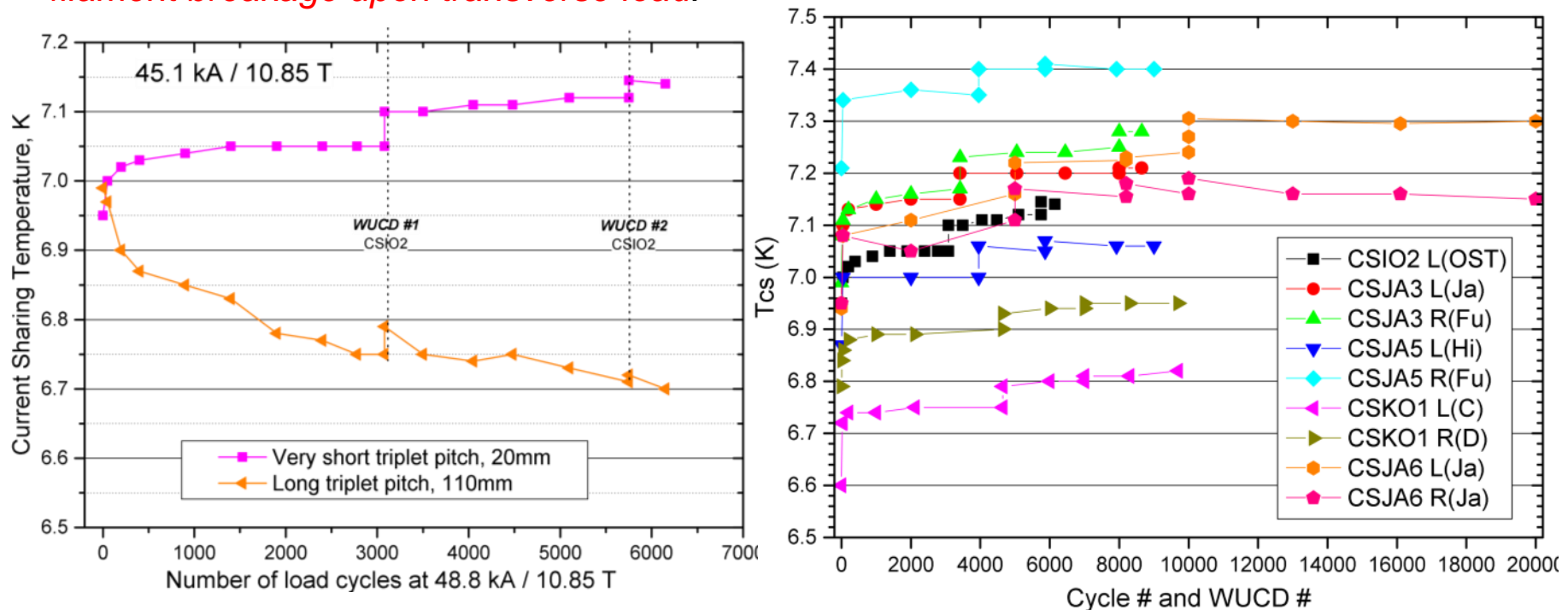


The degradation does not stop at 1000 cycle. The combination of load cycles and thermal cycles leads to dramatic performance loss in both CS and TF conductors. The US, responsible for the delivery of the CS, requests an urgent R&D to address the issue.



# The breakthrough of CS conductor in April 2012

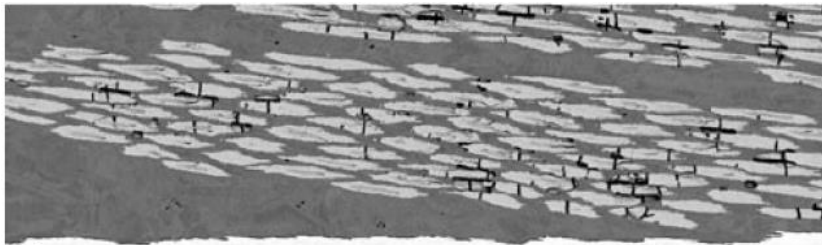
In the CSIO2 sample, one conductor has “short”, 20/45/78/155/423 mm, and the other “pseudo-long”, 110/117/125/139/352 mm pitches sequence, with quasi parallel strands. The direct comparison leads to the dramatic conclusion, verified on nine strands, bronze and internal-Sn, that *the “very short” pitch (in the triplet) prevents strand bending and filament breakage upon transverse load.*



The “very short” pitch is retained in the CS conductor spec, but it was considered “too late” to apply the “very short” pitch to the TF conductor.

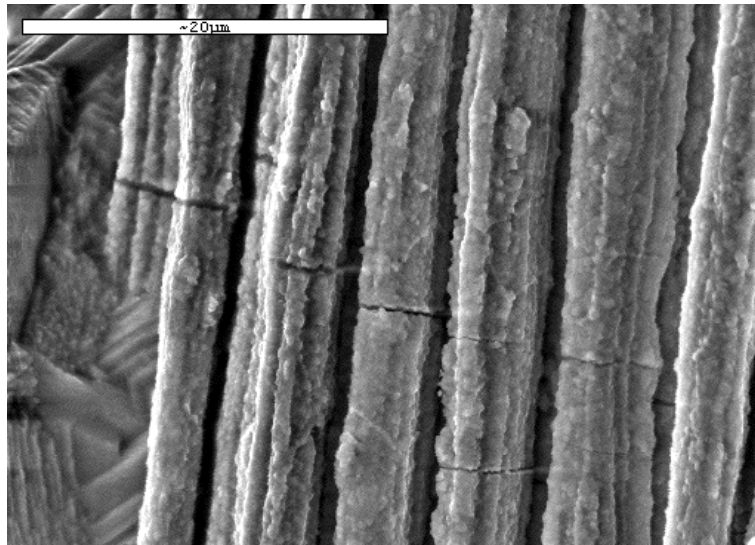
# Summary on Performance of ITER Nb<sub>3</sub>Sn CICC

The reason of the cyclic load degradation is due “*filament breakage (ratcheting) upon transverse load*”. Very short triplet pitch drastically mitigates the effect.



↑ **Cracks at bending, Jewell 2003**

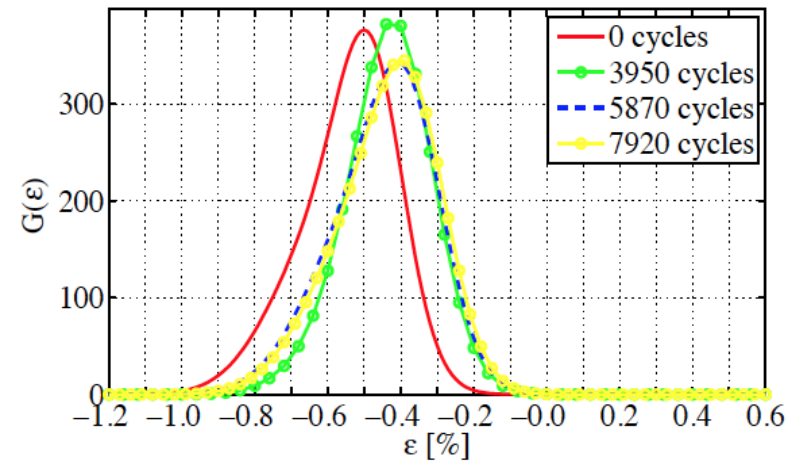
↓ **Bochvar 2002**



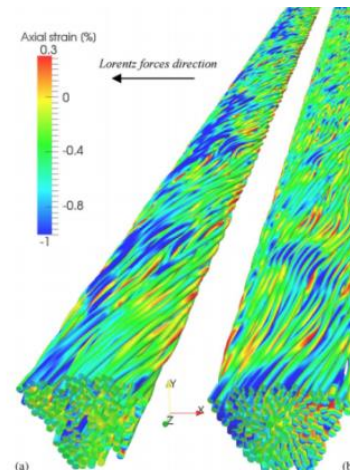
Pierluigi Bruzzone

ITER Conductors

The reason for missing the expected performance is largely due to “strain distribution”: the compressive “tail” of the distribution dictates the performance.



↑ **Calzolaio 2012**



← **Bajas 2011**

FCC, Washington March 2015

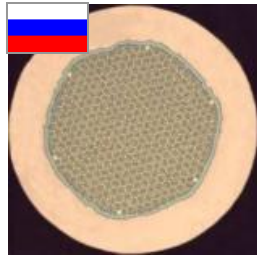
# Procurement Status: the Strand

Nine suppliers for Nb<sub>3</sub>Sn strand, two suppliers for NbTi strand

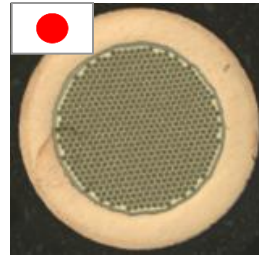
## Nb<sub>3</sub>Sn/TF Conductor



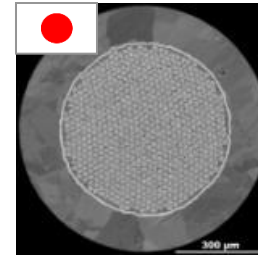
**BAS** (Br)



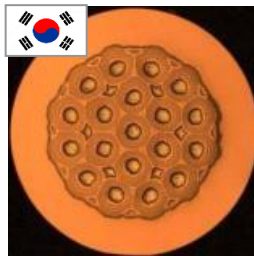
**ChMP** (Br)



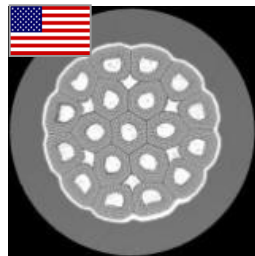
**Hitachi** (Br)



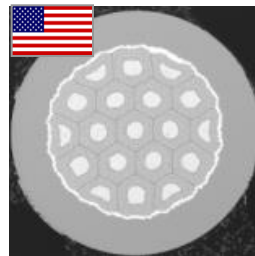
**Jastec** (Br)



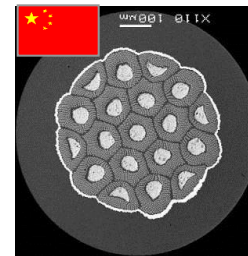
**KAT** (IT)



**Luvata** (IT)

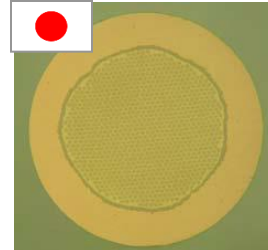
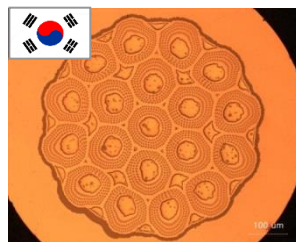
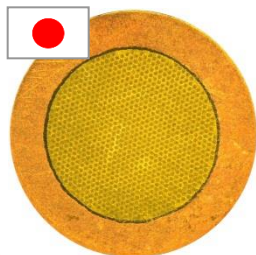


**OST** (IT)



**WST** (IT)

## Nb<sub>3</sub>Sn/CS Conductor



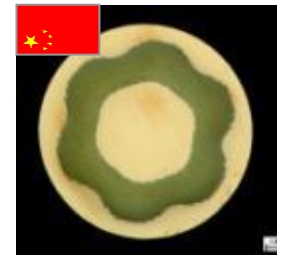
## Nb-Ti/PF1&6



**Type 1: 1.6:1**  
**ChMP** (RF)

## Nb-Ti/PF2-5

**CC, MB&CB**



**Type 2: 2.3:1**  
**WST** (CN)



# Procurement Status: the Strand

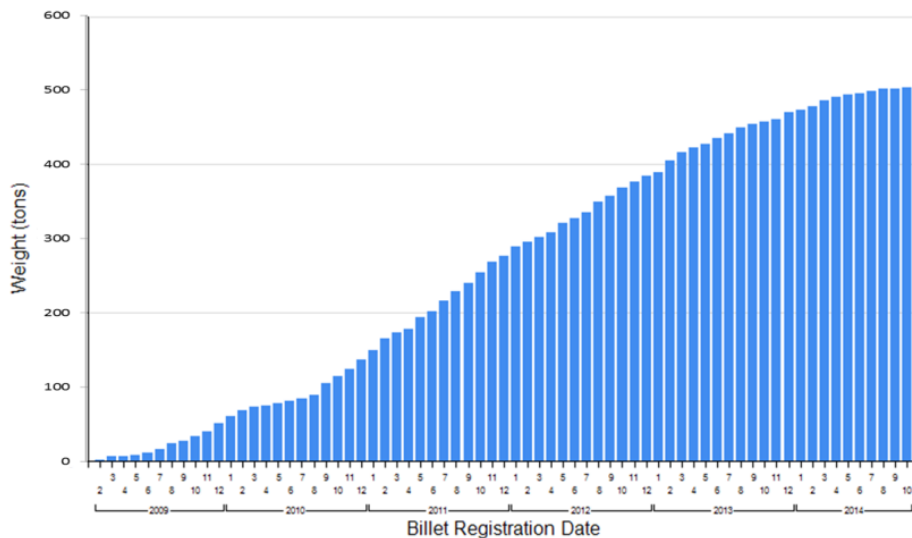
TF Conductor – **505 t** of strand are already registered in the data base, versus 384 t required for the TF coils. Despite the outrageous cost, the DA have placed order exceeding the needs by over 30% !

CS Conductor - **>60 t** of strand are already registered in the data base, about 40% of the total need.

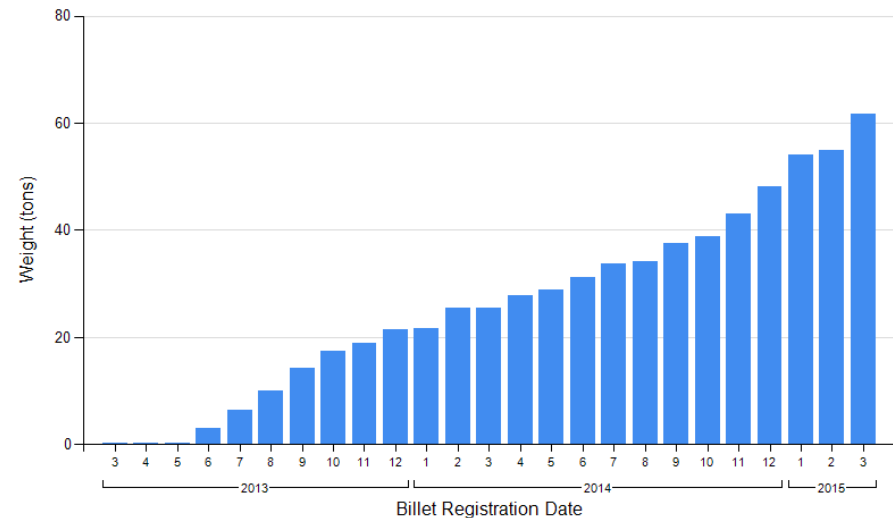
NbTi Conductors- **≈ 245 t** of strand for PF, CC and busbar are registered in the data base, out of 300 t needed.

The yearly production of Nb<sub>3</sub>Sn strand exceeded 100 t.

### TF Strand Production Dashboard



### CS Strand Production Dashboard



# The Cable – Production in progress

Each DA with a conductor PA has his own cable supplier(s)

- *EU: TRATOS Cavi, Italy (TF, PF)*
- *RF: VNIKP, Podolsk (TF, PF)*
- *KO: Nexans Korea (TF)*
- *US: New England Wire Technology, NH (TF)*
- *China: Boasheng (TF)*
- *China: Changtong (PF)*
- *China: ASIPP (CC)*
- *Japan: Hitachi Cable (TF)*
- *Japan: Mitsubishi Cable (CS)*
- *Japan: Furukawa (CS)*
- *Japan: Nexans Korea (CS)*



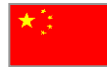
*The spread among 11 suppliers, with very demanding duplication of qualification procedures and tooling, is not driven by the overall amount of cable ( $\approx 200\text{km}$  over 6-7 years)*



# The Jacketing – Production in progress

**JA, CN, RF, EU and US** have built **800-1000 m long jacketing lines**, while **KO** is subcontracting jacketing work to **EU supplier**.

All jacketing lines have been commissioned and are **operational**.



TF & CS  
Jacketing  
at **NSE**



TF, PF, CC & Feeder  
Jacketing at **ASIPP**



TF Jacketing  
at **IHEP**



TF & PF Jacketing  
at **Criotec**



TF Jacketing  
at **HPM**

*Jacketing lines are very expensive. Setting up five manufacturing facilities (to be dismantled after the ITER production) is dictated by the strategic interest of the DAs.*



# Status of Conductor Delivery

The challenge of the large scale manufacture, including the logistic, qualification and quality assurance aspects, is successfully mastered by the IO and the DAs.

At the time being, the rate of conductor delivery to the winding companies largely exceeds the needs. **The conductor is not on the critical path** and the storage rooms at the winding companies are full.

For TF coils, **112 out of 126** conductor unit lengths are completed.

For NbTi conductors, **56 out of 93** conductor unit lengths are completed.

For CS, **8 out of 49** conductor unit lengths are completed.



# The Cost Issue – is the design cost effective?

The ITER magnets are all pancake wound, i.e. **no conductor grading**. Mostly for the Nb<sub>3</sub>Sn coils (TF and CS), the lack of grading is very expensive. The amount of Nb<sub>3</sub>Sn strand is almost doubled compared to a graded, layer wound design.

For Nb<sub>3</sub>Sn, the lower-than-predicted performance (strain distribution issue) and the cyclic load degradation (filament breakage) led to **substantial overdesign**. Less than 50% of the strand J<sub>c</sub> is retained in the CICC.



# The Cost Issue – is the procurement cost effective?

Over decades, the suppliers claimed that the high price for Nb<sub>3</sub>Sn strand was due to the small scale production. Although the production was upgraded by over an order of magnitude, the strand suppliers (with few exceptions), helped by the non-competitive procurement, maintained high price. The expected drop of Nb<sub>3</sub>Sn strand price was totally missed.

The cabling of ITER conductor is much more expensive than ordinary cable products. The mechanism of procurement sharing and the lack of interest from traditional large cabling companies prevented competition.

The choice of JK2LB™ (Mo steel) for the CS conduit turned to be very expensive. The jacketing by pull through method is intrinsically expensive. The lack of a market outside ITER and the will of each DA (except Korea) to have his own jacketing line skyrocketed the price of jacketing. Despite the high price of Nb<sub>3</sub>Sn strand, the price of the CS conductor is not dominated by the strand!



# Do the Fusion Conductors need to be cheap?

In ITER, similar to other “big science projects”, the cost is an issue because it exceeds the agreed budget. As long as the stakeholders agree to increase the budget, there is *no need for the ITER conductors to be cheap*.

In future devices, aimed to demonstrate the commercial feasibility of fusion, the benchmark for the cost will be the market price of the kWh. The target price for the fusion magnets of DEMO is in the range of 500M\$, *one order of magnitude cheaper compared to ITER*.

A radical cost-effective design approach will be not sufficient for DEMO. The stimulation of industrial competition and an aggressive procurement are essential. So far, the “ITER conductors” have been an excellent business (over 1B\$) – in future, *“fusion energy” must become the business*.



# Conclusion or “lessons learned” - 1

The long history of the ITER conductor suffered of *insufficient R&D* and inadequate reactions to inadequate performance. Overdesign was used instead of design improvement. Last minute R&D was successful for CS.

Due to the in-kind procurement scheme (strand with very different  $J_c$  and different sensitivity to transverse load degradation), the TF conductors have *a broad range of performance,  $\Delta T_{cs} > 1K$*  but the TF system performance will be dictated by the worst performing conductor.

The CS conductor with very *short triplet pitch withstands 10000 load cycles without degradation* (a small performance loss may start after 15000 load cycles). The large performance spread, with  $\Delta T_{cs} = 0.6K$ , is solely due to the strand performance (Bronze > Int. Sn).



## Conclusion or “lessons learned” - 2

The *poor cost effectiveness of the design* is tolerable in ITER but cannot be accepted in future fusion devices, aimed to deliver electricity at competitive prices. The change of approach from “big science” to “marketplace” is **THE** big challenge for the future.

The “forced sharing” of the procurement, the “credited value” instead of real cash, the unnecessary duplication of large equipment, the lack of market for jacketing and the heavy management (IO/DA/PA/companies) are the reasons for the *poor cost effectiveness of the procurement*.

The technical (upgrade of Nb<sub>3</sub>Sn strand, qualification and tests) and logistic challenges of *the large scale manufacture are successfully mastered by the IO and DAs*. The conductor procurement is not on the critical path of the ITER project.

