Evaluation of the Current Sharing Temperature and the n value of the ITER Toroidal Field Model Coil

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Contents

Introduction

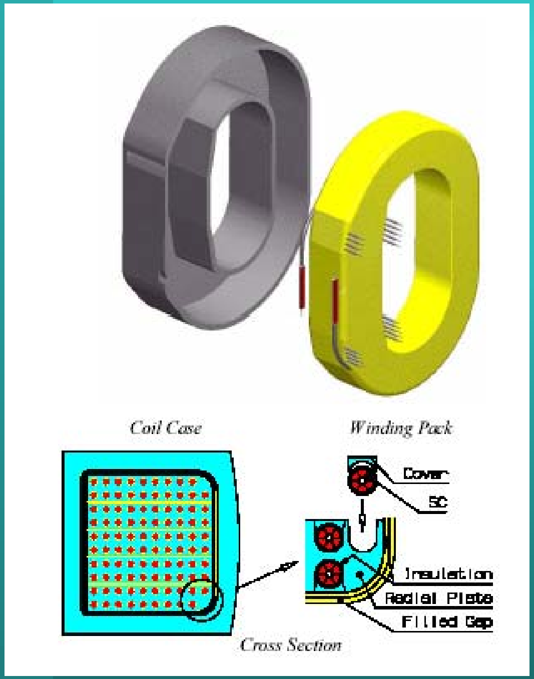
- **The Toroidal Field Model Coil (TFMC) is part of the L2 large task R&D activities in the frame of ITER**
- **The TFMC was constructed in collaboration between EU industries (AGAN) and laboratories, coordinated by EFDA**
- **The TOSKA facility at the Forschungszentrum Karlsruhe is the test bed for the TFMC**
  - **Test phase I in summer and fall 2001: TFMC as single coil**
  - **Test phase II second half of 2002: TFMC + LCT**

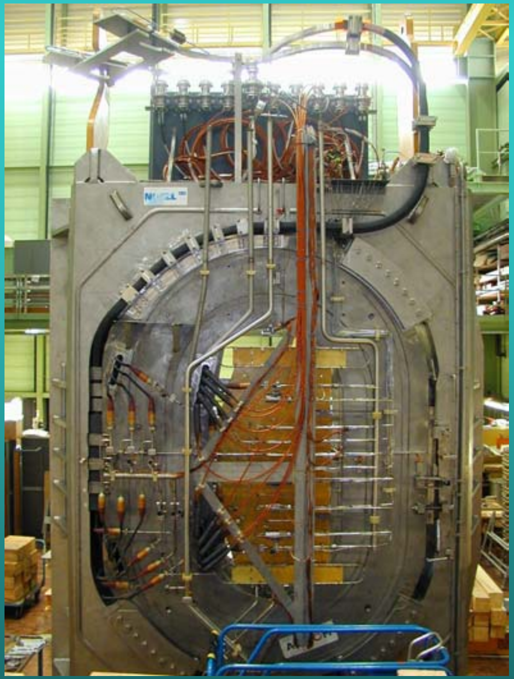
Introduction

- **Main goal of the test programme**
  - **Demonstration of the feasibility and the mechanical integrity of the design**
  - **Determination of the operation limits by evaluation of the current sharing temperature T_{CS} of the conductor has also been a substantial aim of the program**
- **Magnets made with CICC allow to explore the margin by slowly increasing the temperature of the magnet which is at constant current up to the take-off regime**
- **T_{CS} is reached by definition if the electric field along the conductor reached 10 μV/m. It is then possible to compare this T_{CS} to the one given by available models**

Introduction

- **TFMC is a racetrack coil made of 5 double pancakes with inner and outer joints**



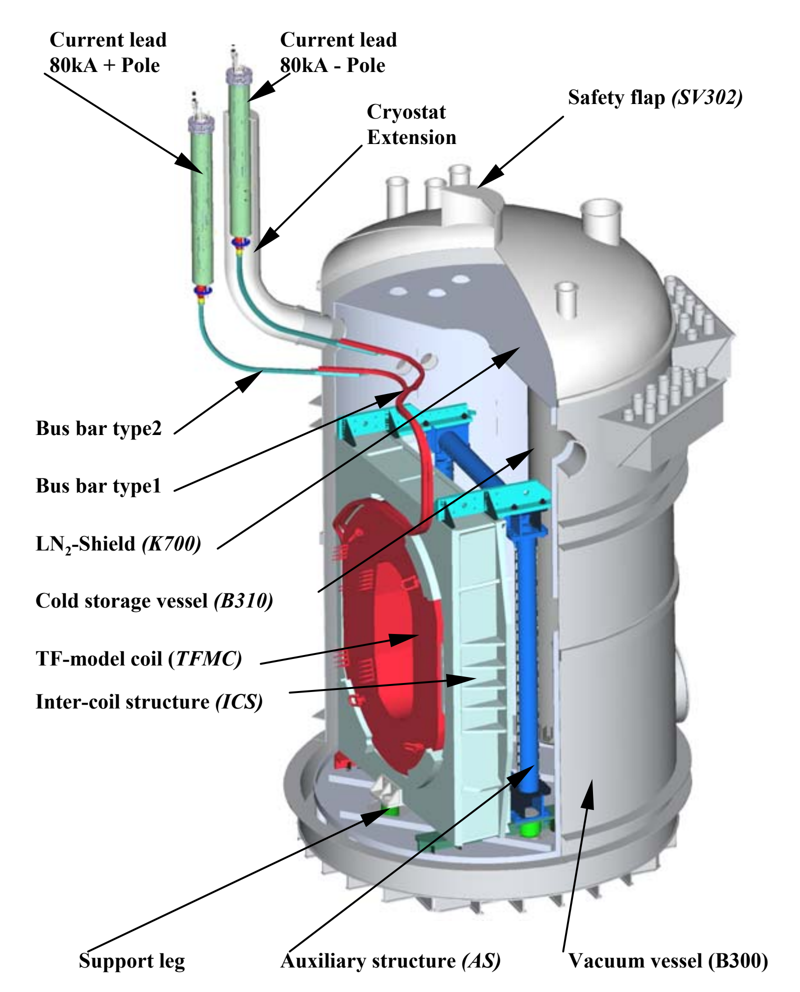


Introduction

- **TFMC conductor is a Nb_3Sn CICC with central hole, jacketed with stainless steel. Two conductors are inserted in spirally wound grooves of a stainless steel radial plate**

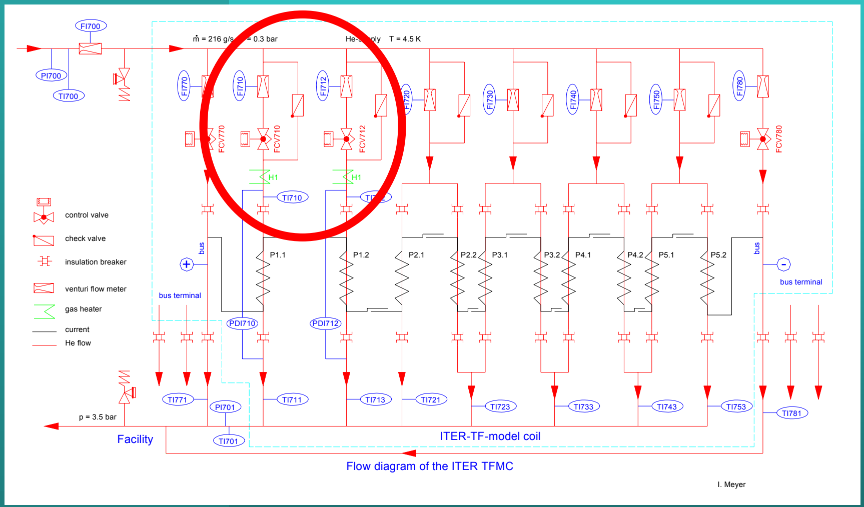
Introduction

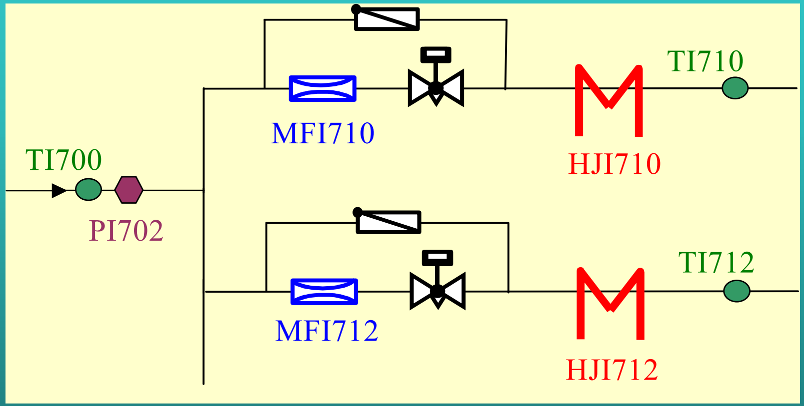
- TOSKA is the test bed for the TFMC



Introduction

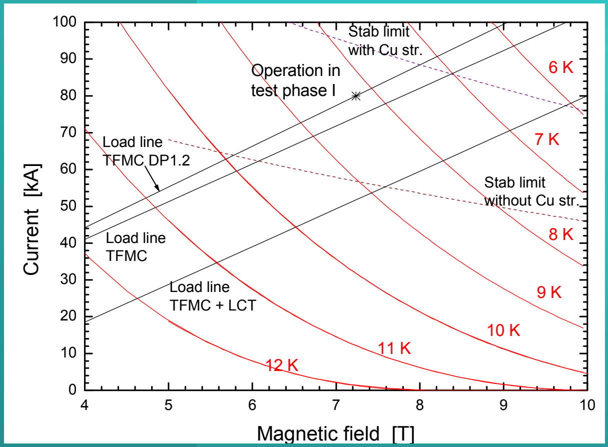
- **Pancakes 1 and 2 are equipped with heaters at their inlets to increase the helium temperature**



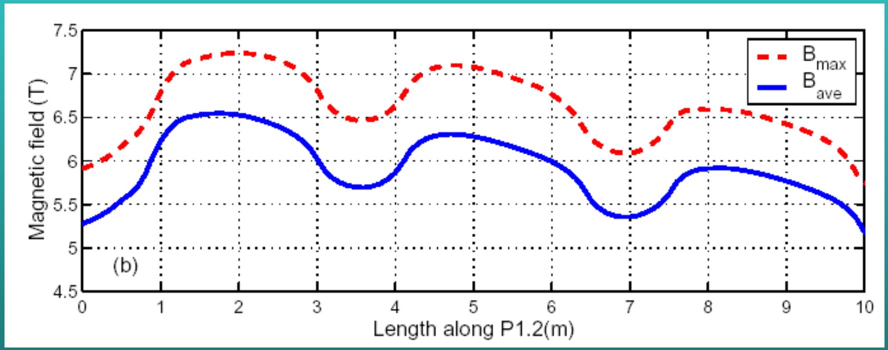


Introduction

- **Load line of the TFMC**

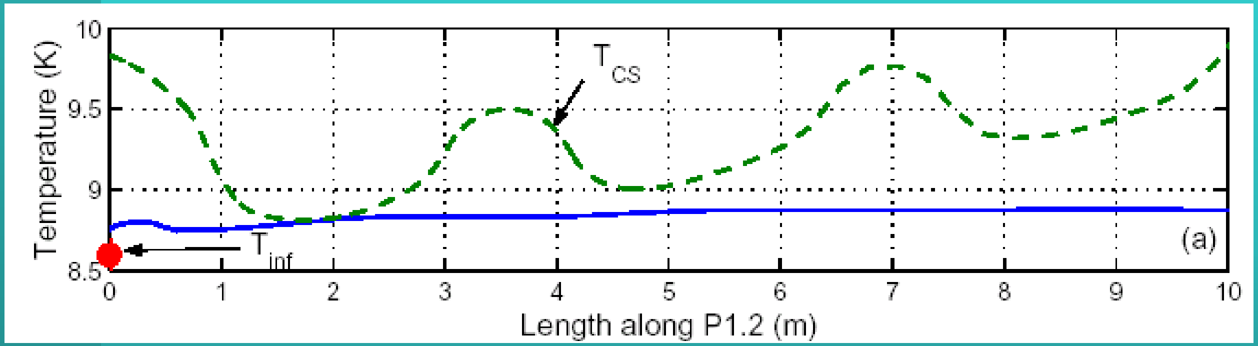


- **Proximity of the joint region, where the current distribution is non-uniform from the high field region (about 1.5 m)**



Introduction

- **Much effort was done before the experiment to show that is was possible to quench the conductor without quenching the joint**



This was successfully demonstrated in test phase I

Exploration of TFMC limits

- **Test phase I included a number of items starting from the achievement of the nominal operating current I = 80 kA. Here we concentrate on the measurement of T_{CS} at different transport currents I**
- **Calculation of the expected T_{CS} should be easily performed using the following formula**

$$I_{op} = S_{noncu}\, J_C(B, T_{CS}, \varepsilon)$$

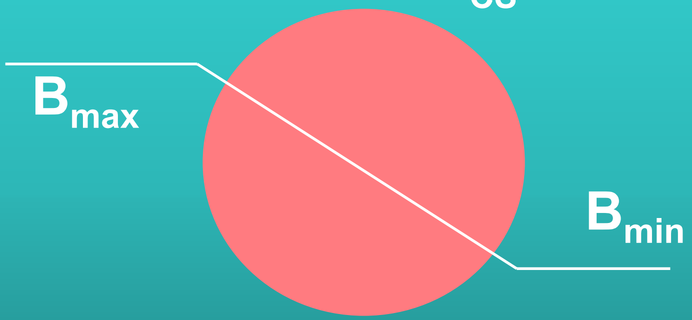
In practice, difficulties have to be pointed out in this evaluation which is now essential for all Inserts and Model Coils tested in the framework of ITER

Exploration of TFMC limits

- **Critical current density $J_c(B,T,\varepsilon)$**
  - All the billets were tested at 12 T and 4.2 K and one representative strand sample tested at variable field and temperature
  - T_{cs} tests of the TFMC were performed at field levels from 5 to 7 T and temperatures from 8.5 to 11 K
  - Within this range, only a few data are available for the basic strand

Exploration of TFMC limits

- **Magnetic field B**
  - In TFMC, the conductor self field is not negligible: 7.24 T on the inner side and 5.9 T on the outer side of the conductor. The difference in T_{CS} is in the order of 0.5 K



  - Practically, the corresponding T_{CS} can be calculated by integrating the electrical field over the CICC cross section

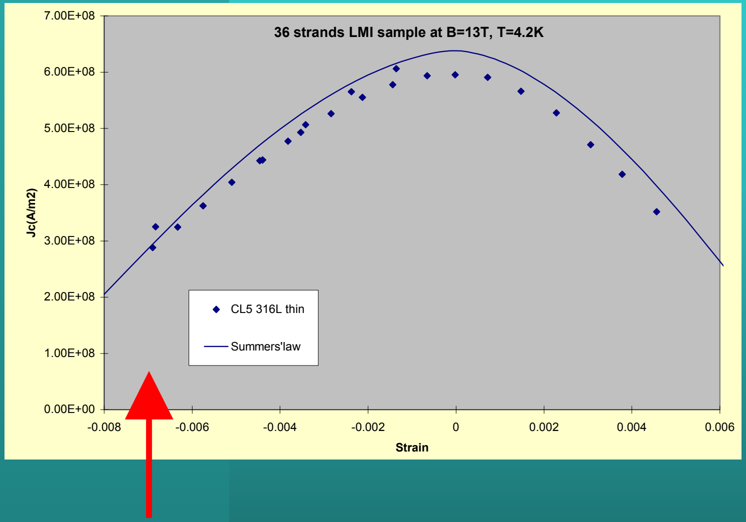
$$E = E_C/S \int (J_{OP}/J_C(B,T,\varepsilon))^n dS$$

Exploration of TFMC limits

- **Consideration on the strain ε**
  - **For Nb_3Sn, both J_C and T_{CS} are very sensitive to longitudinal strain ε**
  - **In the TFMC conductor, the filaments are put in compression load to a high value of the so-called thermal strain**
  - **No direct measurement performed on any full size conductor; the exact strain of the Nb_3Sn filaments in such a conductor is unknown**

Exploration of TFMC limits

- **Consideration on the strain ε**
  - **The only set of data available comes from a mechanical experiment performed on sub-size (36 strands) conductors with different kinds of jacket**



→ The bonded model is appropriate to describe the situation

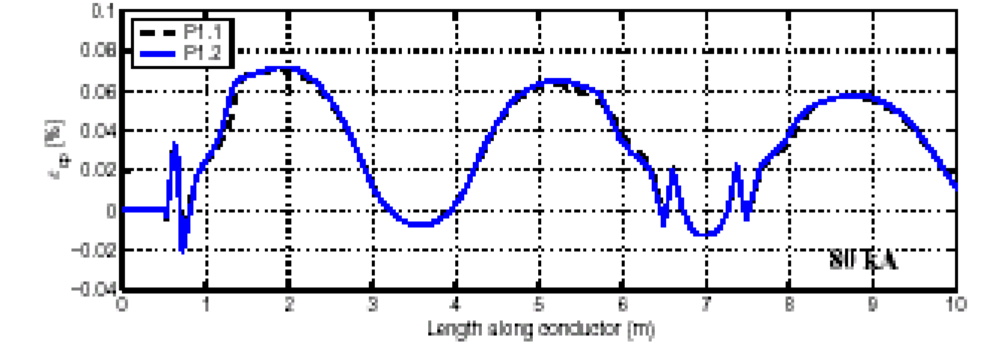
→The expected strain, according to this model, should about –0.7%

→For the full-size conductor, however, the relaxed fully-bonded model seems to describe better the situation

This model will be used in the analysis

Exploration of TFMC limits

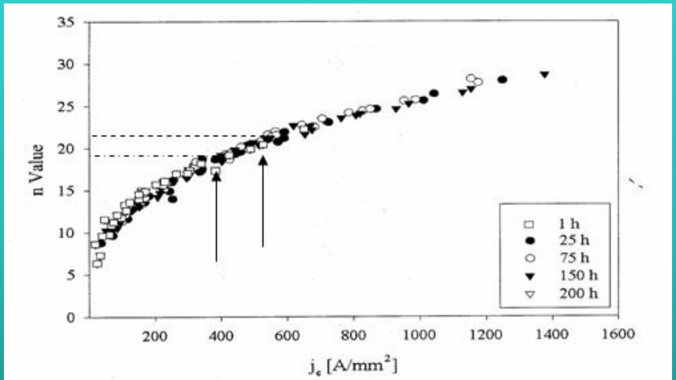
- **Consideration on the strain ε**
  - **The strain ε in the Nb_3Sn filaments is: $\varepsilon = \varepsilon_o + \varepsilon_{op}$, where ε_o is the strain at zero current and ε_{op} is the applied strain due to coil deformation under electromagnetic load coming from FEM computations**



  - **ε_o may be composed of $\varepsilon_{ht} + \varepsilon_{deg}$ where ε_{ht} comes from the relaxed fully-bonded model and ε_{deg} denotes an additional compression (or degradation)**

Exploration of TFMC limits

- **Consideration on the n value and current distribution**
  - **n value is decreasing with the critical current and precisely, the limit explorations are performed at low critical current**

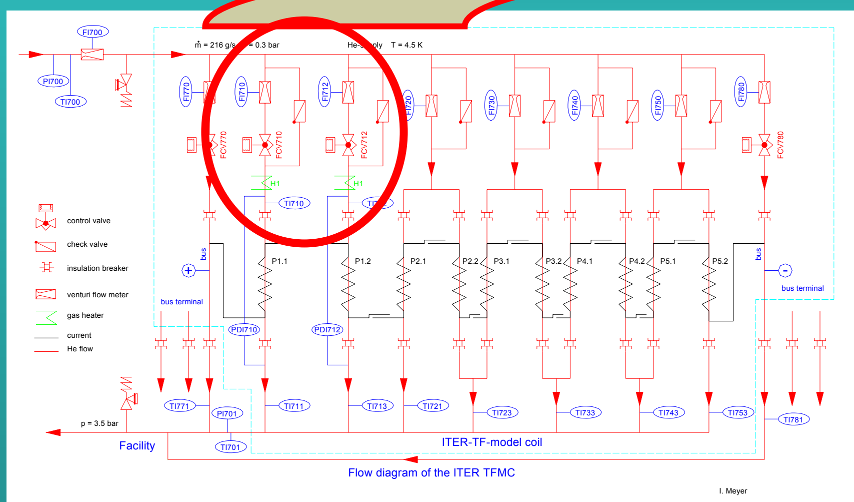


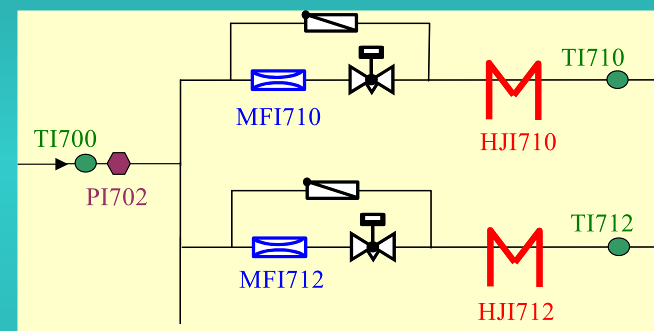
  - **In the joint region, the current distribution is highly non-uniform. Take-off characteristic is strongly influenced by the redistribution process taking place between the joint and the high field point and cannot inform us about the strand n value**

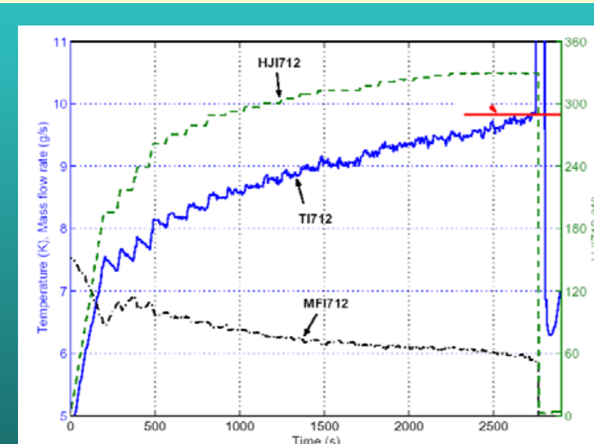
Description of experiment and results

- **Experimental procedure**
  - Current ramping and plateau
  - He entering the DP1.2 pancake (at the inner joint) slowly heated up to the quench
  - The neighbouring pancake DP1.1 in the same radial plate (and connected to the same inner joint) also heated to approximately the same level to limit the thermal exchange between the two

Description of experiment and results

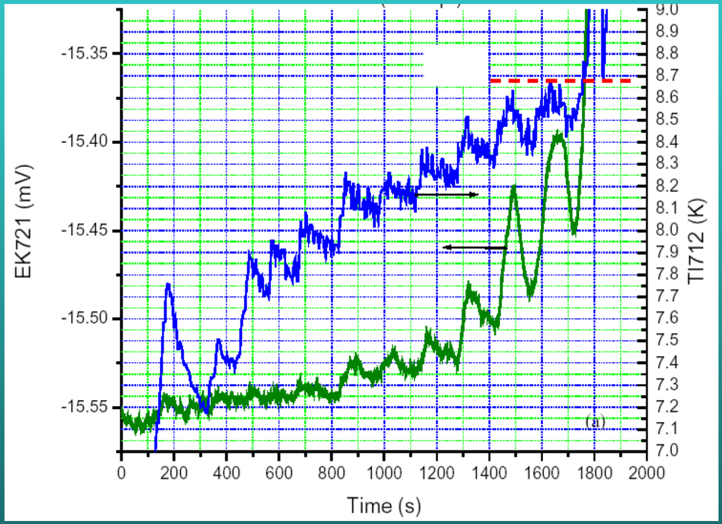






Description of experiment and results

- **Experimental procedure**
  - The voltage drop over DP1.2 measured using co-wound voltage taps
  - Temperature is measured at inlet and outlet of pancake DP1.2
  - No instrumentation is inside the winding



Voltage drop along pancake DP1.2 and inlet temperature vs time

Description of experiment and results

- **Rough data analysis**

Nine quench experiments were performed, but among them only a few are really usable and trustable because of measuring accuracy problems encountered on these low level voltage signals.

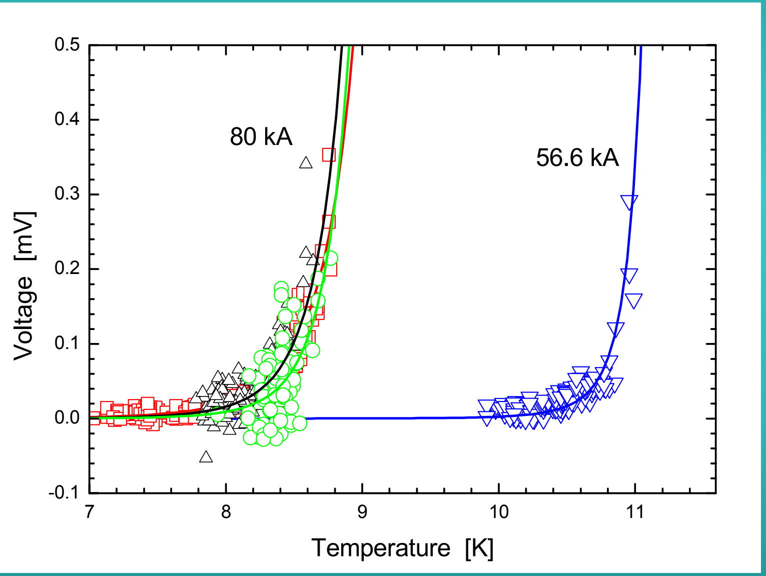
Expressing J_C as a function of T_C, one gets

$$U/U_0 = ((T^*-T)/(T^*-T_0))^{-n}$$

where T* is a free parameter but has to be not much larger than T_0.

From the fits, it is possible to derive the n value but not T_{CS}.

n = 7.5 (80 kA), n = 5 (56.6 kA)



Voltage along pancake DP1.2 vs inlet temperature for different conductor currents of the TFMC

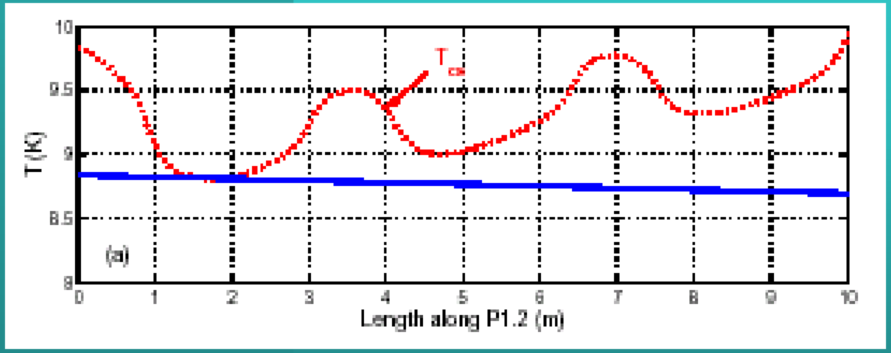
To evaluate both the T_{CS} and ε and to look for a (possible) degradation of the TFMC conductor, more physical models are needed

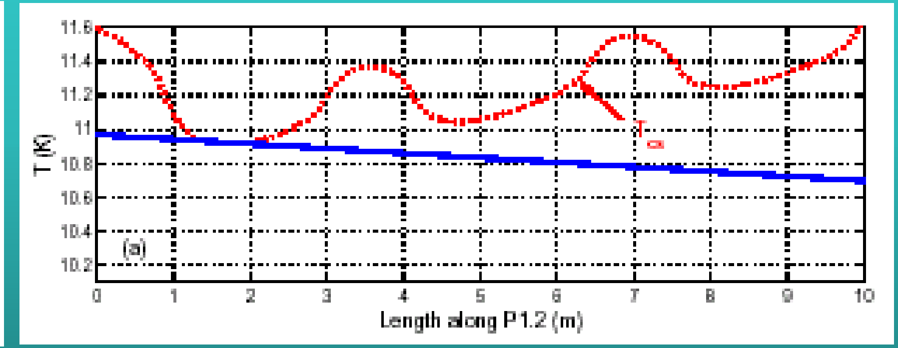
Analysis results

- Two different models were used to evaluate T_{CS}
  - Analysis using the Multi-Mithrandir M&M code
    Transient thermohydraulic code
  - Analysis using the ENSIC code
    Electric + steadystate thermohydraulic code
- In the following analysis, we have used both the last 80 kA and 56.6 kA experiments

Analysis using the M&M code

- **Thermohydraulic model of the TFMC was to compute the temperature profile along the conductor starting from the heater, modelling the DP1 inner joint and ending in the DP1.1 and DP1.2 conductors**



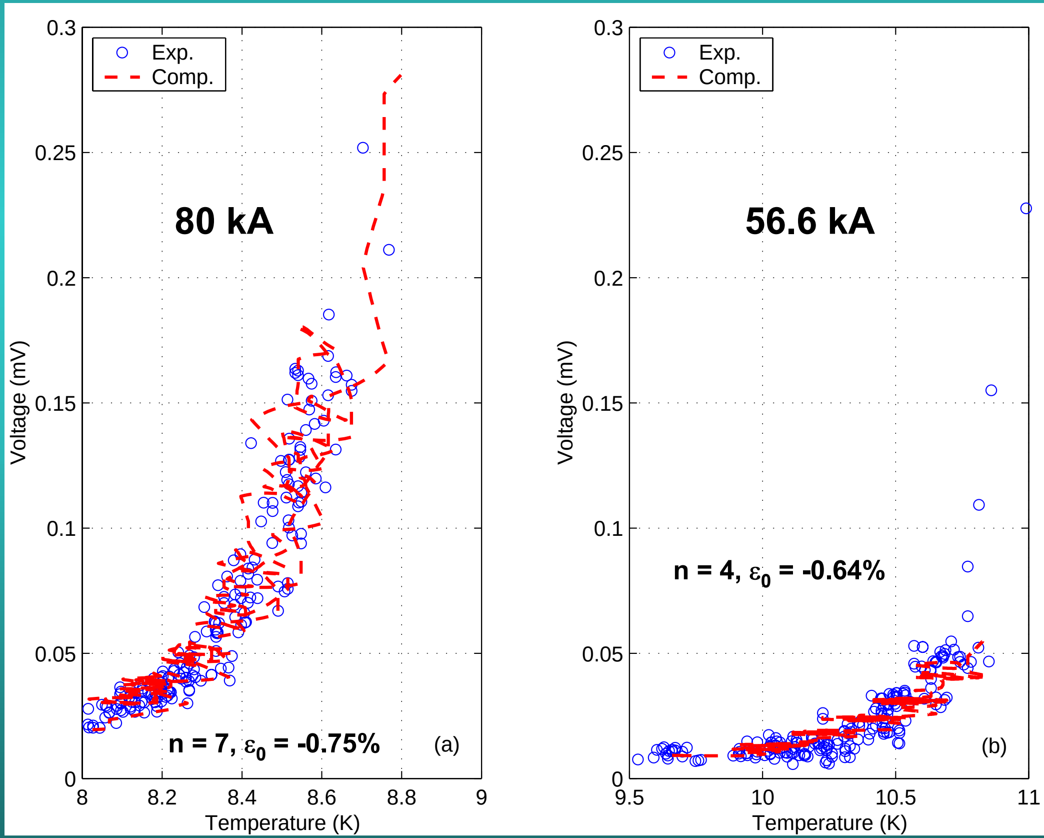


- **Difference between T_{inlet} and T_{CS} is within ± 0.2 K for the runs performed in the experiment**

Analysis using the M&M code

- **M&M code modified to be able to model the operational strain ε_{op} in the conductor**
- **The "actual" critical parameters (n, ε) are obtained from the best-fit of U-T_{in} curves (using the experimental $T_{in}(t)$ as boundary condition)**

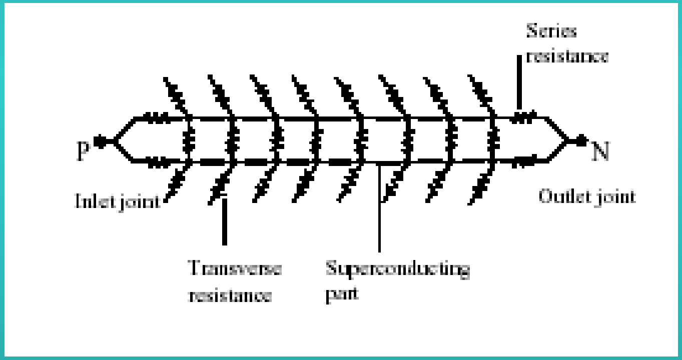
Analysis using the M&M code



Data and fit results for 80 kA and 56.6 kA

Analysis using the ENSIC code

- The electrical network model ENSIC (CEA)
  - Realistic modeling of the joints

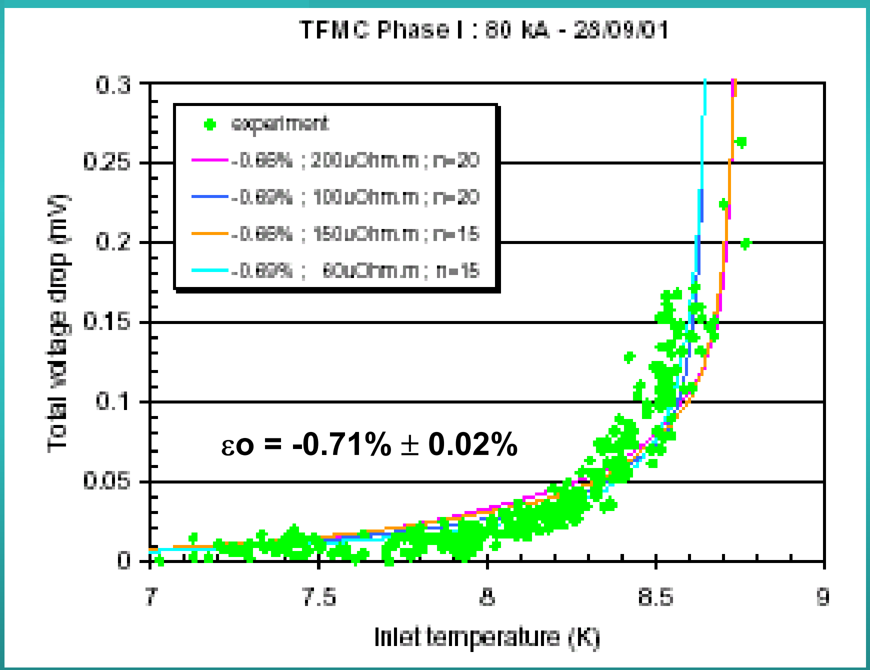


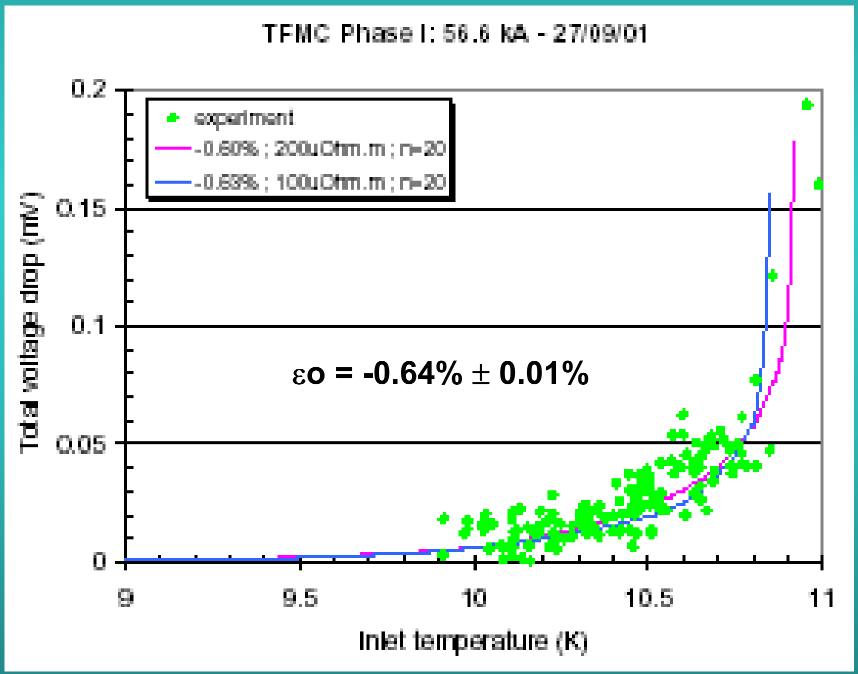
  - Simplified steady state thermo-hydraulic model
  - Calculating the temperature profile along the conductor length from the inlet temperature
  - Joule heating in the joints and in the regular conductor,heat exchange with the adjacent pancake and in the inner joint are neglected

Analysis using the ENSIC code

- Parameters n_{strand}, ρ_{t_cond}, and ε_o adjusted to best fit the U-T_{in} curves
- ENSIC computes at peak field both the local average electric field in the cable and the local temperature

Analysis using the ENSIC code





Data and fit results for 80 kA and 56.6 kA

Conclusions from analysis

- Comparing the ε_o results of M&M and ENSIC, they are different

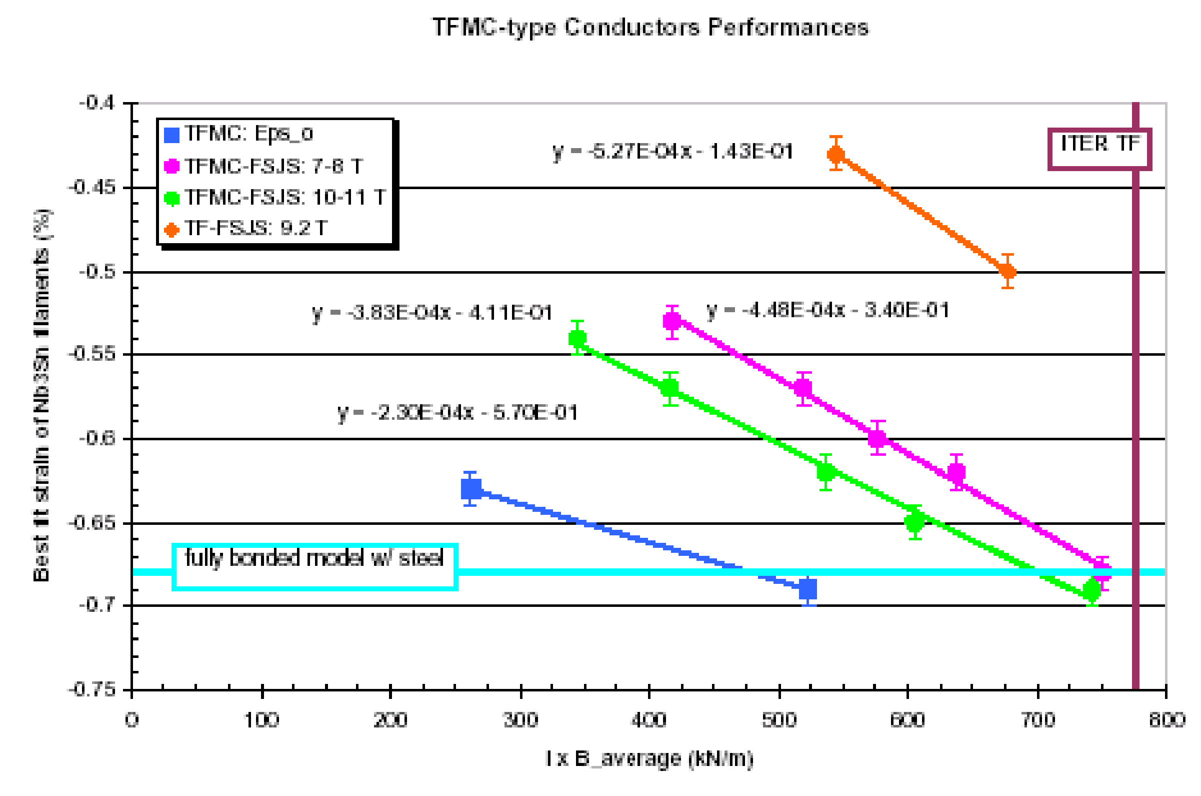
	Expectation	Model		Expectation	Model	
		M&M	ENSIC		M&M	ENSIC
Current [kA]	56.6			80		
ε_0 [%]	-0.61	-(0.64 – 0.67)	-(0.61±0.01)	-0.61	-0.75	-(0.71±0.01
n	15 – 20	4 – 5	N/A	15 – 20	7	N/A

- This may be explained by differences in the models and by the corrected J_C at lower magnetic field used in the ENSIC code

Conclusions from analysis

- The TFMC cable appears to be characterized by n values (4-7) much smaller than those of the strand (15-20), and decreasing for decreasing current (i.e., increasing temperature)
- A degradation with respect to the measured strand properties is needed to explain the TFMC conductor behavior as a collection of strands carrying a uniform current at the average field
- This strand degradation increases with operating current

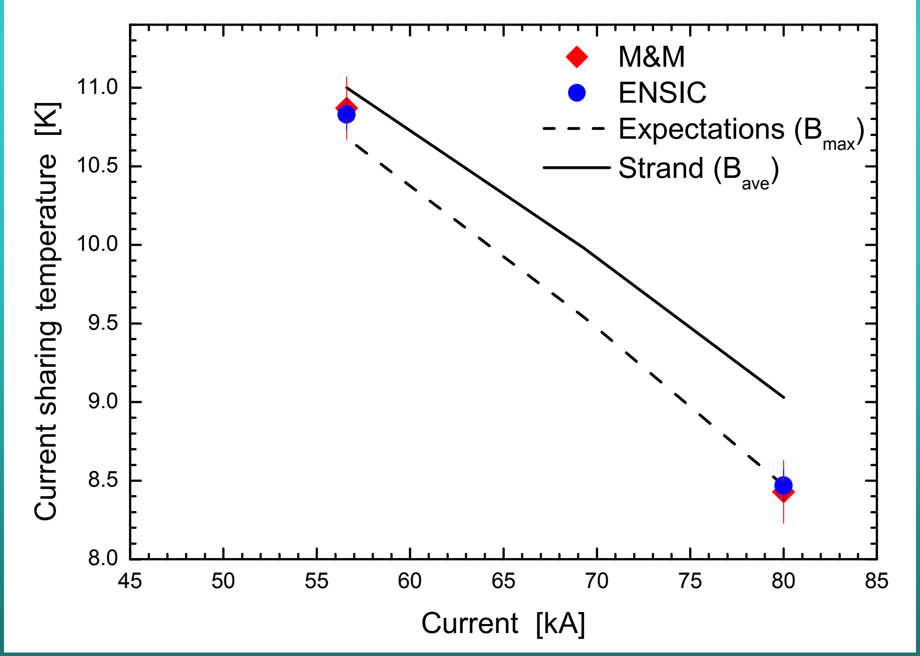
Conclusions from analysis



Best fit strain vs Lorentz force for TFMC and comparison to FSJS results

Conclusions from analysis

- **Comparing the T_{CS} results of M&M and ENSIC, they are quite similar at 10 μV/m criterion**



Conclusions from analysis

- **The local temperature at an electric field of 10 μV/m (cable T_{CS}) is compared to the expected T_{CS} from strand properties, calculated with the expected ε_o = -0.61%**
- **Looking to T_{CS}, the conductor performances look as expected from strand properties**

	Expectation	Model		Expectation	Model	
		M&M	ENSIC		M&M	ENSIC
Current [kA]		56.6			80	
T_{CS} [K]	10.68	10.87[(a)] – 10.90 [(b)]	10.83±0.1	8.47	8.33[(a)] – 8,41[(b)]	8.43±0.1

Conclusions from analysis

- **This result is quite surprising, since we use degraded strand performances (see ε_o), and moreover the current distribution is not uniform among strands**
- **Such a result comes in fact from the high magnetic field gradient across the cable section ($\Delta B/B = \pm 10\%$), indeed T_{CS} has been calculated, as usually, at the maximum field in the section, while the code is taking into account the field gradient**

Summary

- The quench experiments performed on the TFMC were a first very interesting opportunity to explore the limits of large stainless steel jacketed CICC such as the one which is needed for the TF system of ITER
- The TFMC performance is in agreement with the expectations and demonstrated the capacity of such conductors for ITER. However, a refined analysis showed that there is a degradation of strand performances which increases as I×B increases. The apparent “good” coil performances are due to the high field gradient across the cable

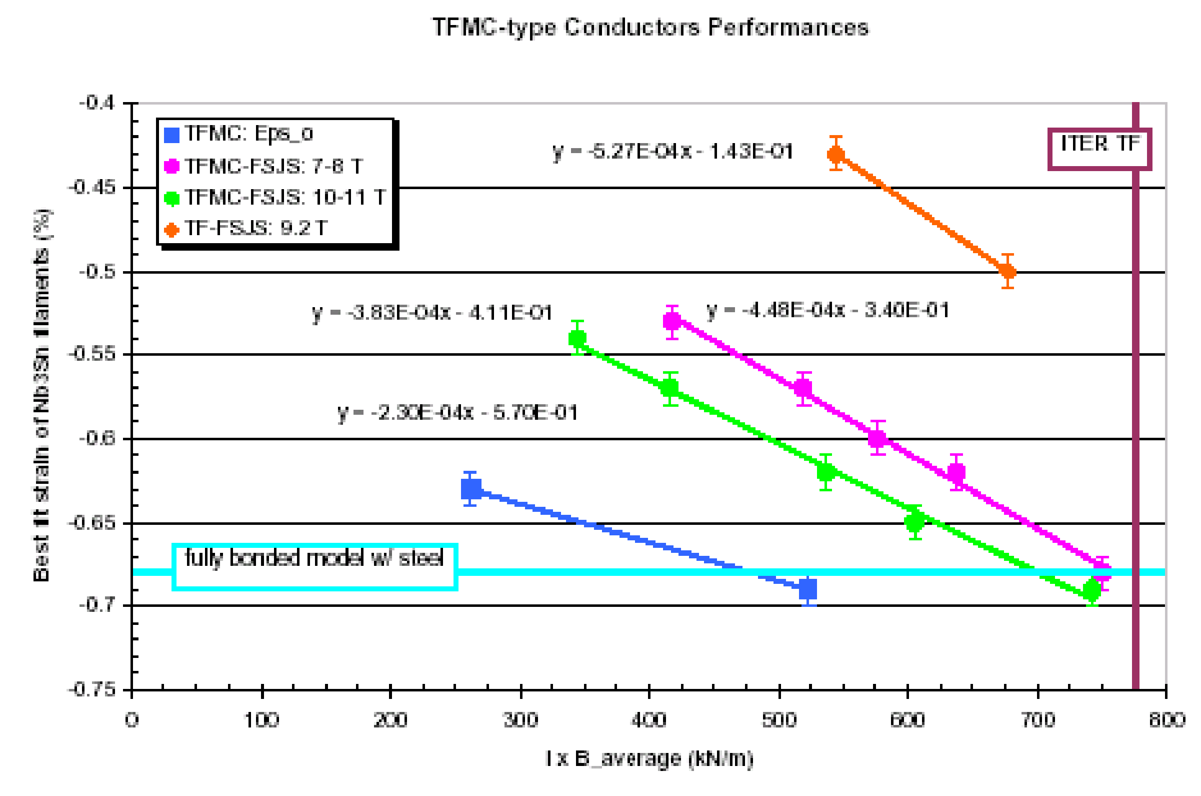
Summary

- **Since the TFMC operated at low magnetic field, an error bar on J_c is paid by a significant error on ε (10% on J_c results in 0.05% (absolute) on ε). Therefore, one needs first a better characterization of the strand under TFMC operating conditions, and second to confirm these results in Phase II operation**

Summary

- The predictions for the ITER TF coil require a significant extrapolation in I×B (max. realized in TFMC is so far 525 kN/m, and 775 kN/m is expected in the ITER TF). From the present knowledge, the extrapolations should lead to about -0.75 - -0.80% for $\varepsilon_{ht} + \varepsilon_{deg}$, which is quite high. However, this extrapolation has to be taken with caution taking into account all the error bars and the only 2 available data points

Summary



Best fit strain vs Lorentz force for TFMC and comparison to FSJS results