High Field Conductor Development for ITER

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Compulsory design choices for ITER conductors

- **Forced flow**

  The large electromagnetic loads do not allow a helium transparent winding: the largest ever bath cooled magnet is the LHD, with 930 MJ stored energy. The rigidity requirement implies monolithic, potted coils. The **forced flow** cooling option is compulsory

- **Nb_3Sn**

  The peak field for the toroidal field coils and central solenoid is 11-13 T and the amount of superconducting material is of the order of 500 t. The **Nb_3Sn** is the only high field material commercially available on large scale in a realistic procurement time

- **Large current**

  In case of quench, the large energy stored in the ITER coils must be effectively extracted to avoid damage/melting of the winding. To quickly dump the energy at reasonable voltage (= 14 kV), the number of turns must be small, i.e. the current must be large. All ITER conductors are at I_{op}> 45 kA

Selected options for ITER conductors

- **Layer/pancake**

  The selection of winding layout (either layers or stack of pancakes) affects the conductor layout. The initial design of ITER coils was by layers, with substantial optimization of conductor by **grading**. Presently, all the ITER magnets are pancake wound, what is a friendly approach for large magnet manufacture, with a penalty on the conductor cost (no grading).

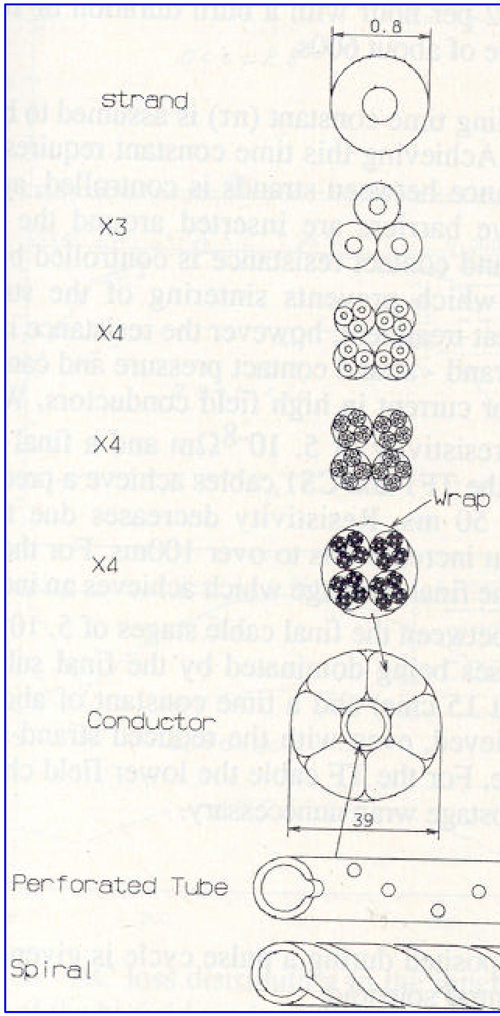
- **Monolithic / CICC**

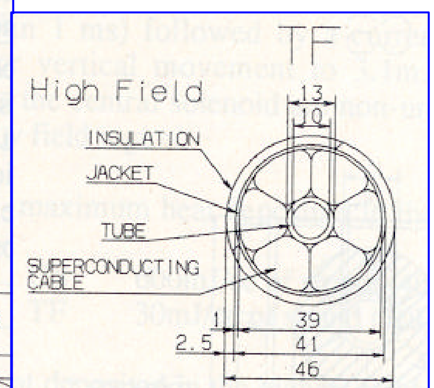
  ITER adopted since the begin the cable-in-conduit design for all the conductors, without investigating monolithic design (a traditional monolithic conductor of the ITER size would be in any case problematic because of the ac loss).

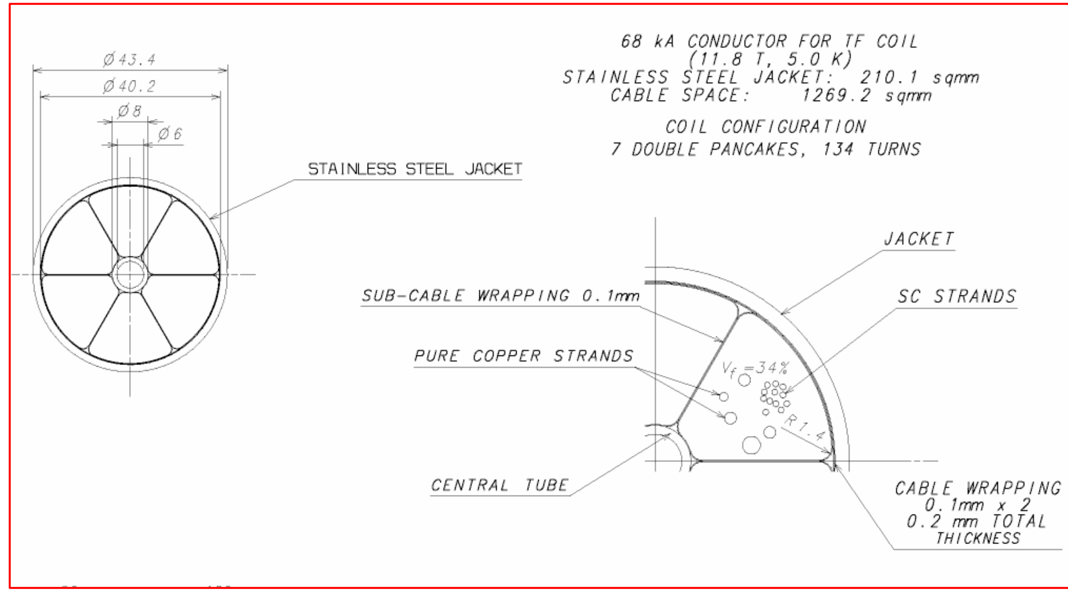
  However, the large length of the conductor sections (over 500 m) and the heat removal requirement (high mass flow rate) do not allow a plain CICC design because of the large pressure drop. A parallel, pressure reliving channel had to be added, giving raise to the **dual channel CICC**

R&D for ITER conductors ?

At first glance, the impact of 12 years of R&D on the conductor layout is not impressive







Ý **ITER 2004**

Ü **ITER 1993**

Development Area for ITER Conductors

Lab experiments

AC loss, transient stability

Prototype conductors

Strand properties

Hydraulic

Structural material characterization

Industrial activity

Strand development

Coating

Cabling

Jacketing

R&D Investigations - *Coupling Current Loss*

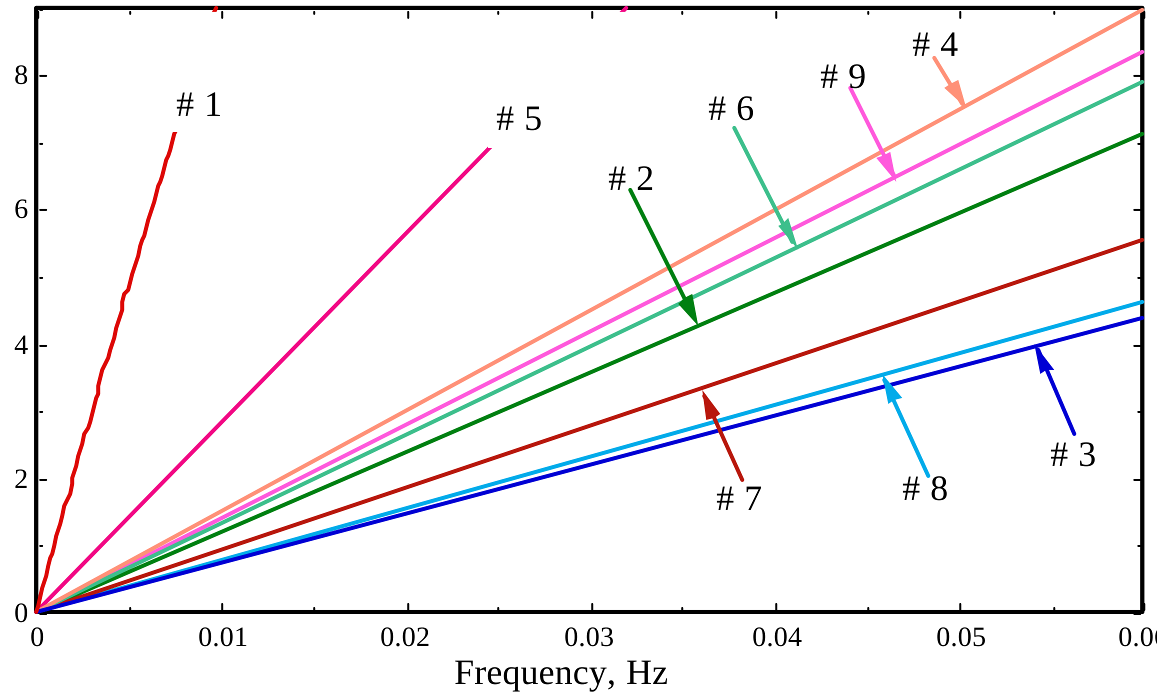
Most investigations have been carried out at: Univ. of Twente
CRPP
JAERI
Efremov

AC Loss in Nb_3Sn CICC have been investigated as a function of:

- Cr plating thickness
- Void fraction
- Conductor bending
- Electromagnetic load
- Cr vendor
- Cabling stage
- Applied transverse load
- Cyclic load

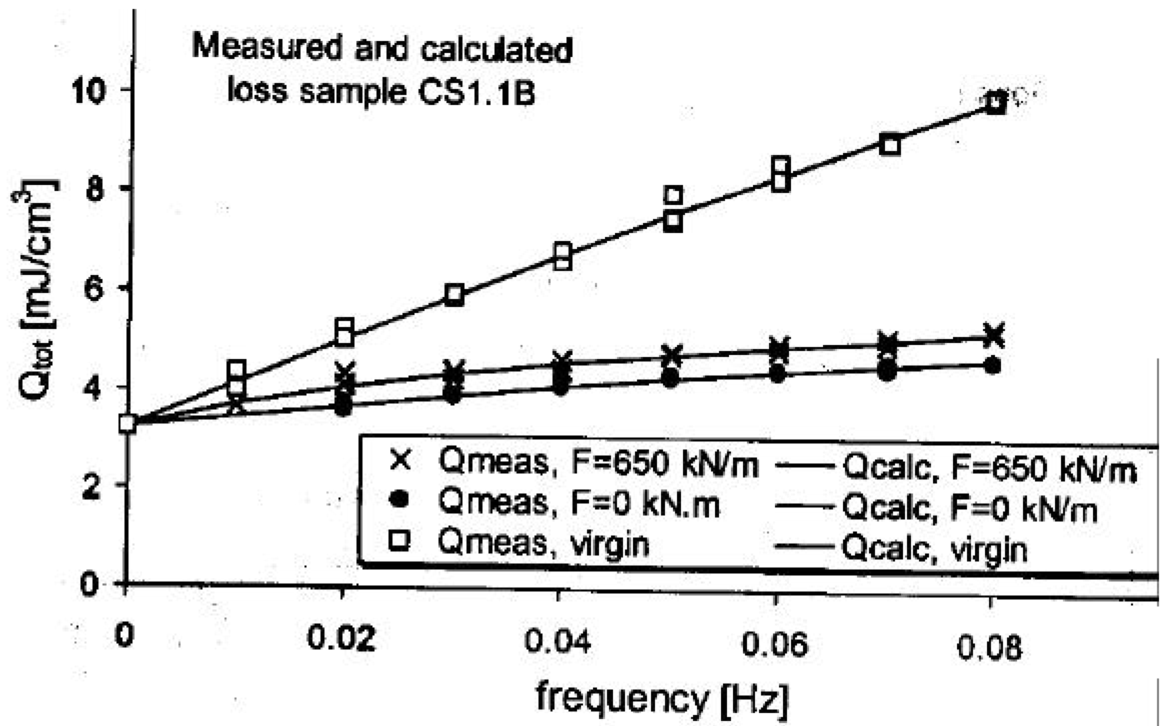
R&D Investigations - *Coupling Current Loss*

Coupling current loss vs. frequency of the ac field, normalized as mJ/cc of strand, for cables made from the same strand, but coated by **nine different Cr vendors**. For comparison, #1 is made of non-coated strands. The lowest loss (#3) is about five time smaller than the largest loss (#5)



R&D Investigations - *Coupling Current Loss*

Coupling current loss vs. frequency of the ac field, for a full size Nb_3Sn CICC (Model Coil conductor) **before any load (virgin), and after 38 load cycle** (at 0 load and full load)



R&D Coupling Current Loss -*Results and Feed-back*

- The interstrand contact resistance is of frictional nature and **evolves in time**. The interstrand coupling loss is initially high and drops quickly, after few load cycles, to the level of the interfilament loss. A number of large current loops with very long decay time constant seem to survive the cyclic load
- The ac loss for **fast field changes** (t < 1 s) is negligibly low. For **slow field changes** (t > 100 s) the loss constant is larger, but the actual power loss is not an issue.

Feed-back ? As the time constant is a function of the history and of the time scale of the field change, reliable ac loss calculations are not realistic. Generally, ac loss is not seen as a major problem for Cr plated Nb_3Sn CICC. Present ac loss estimates are conservative.

More understanding - Little feed back on design - No feed back on conductor layout

R&D Investigations - *Transient Stability*

Most investigations at:

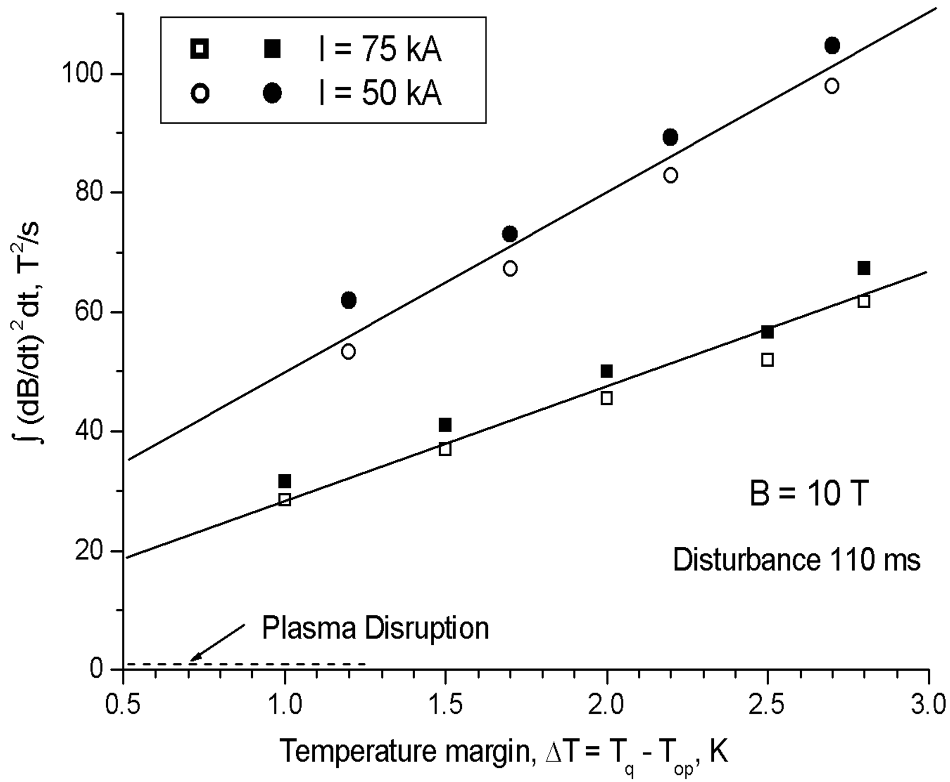
- MIT
- CRPP
- JAERI

The object of the investigations has been:

- Copper Segregation
- Energy margin
- Validation of stability models

R&D Investigations - *Transient Stability*

Transient field stability results on a Nb_3Sn CS model coil conductor at two levels of operating current. Open dots indicates recovery, full dots are for quench. The temperature margin required to withstand a plasma disruption is negligibly low



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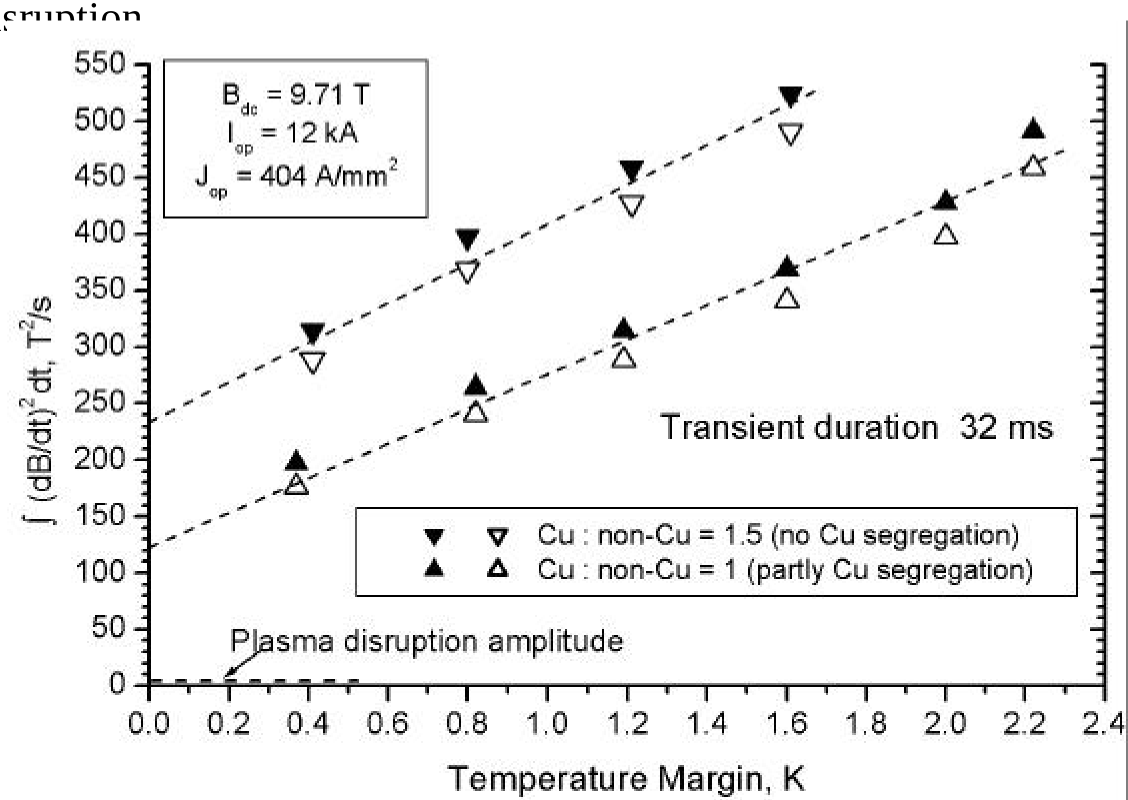
R&D Investigations - *Copper segregation*

Transient field stability results for two Nb_3Sn sub-size conductors identical except the location of the stabilizer, either fully included in the strand cross section or partly segregated. Even with segregated copper, the stability is by far better than required for plasma disruption



R&D Transient Stability -*Results and Feed-back*

- The ability to withstand very fast field transients with limited temperature margin is much better than expected. The smooth current sharing behavior, with *n* index < 10, provide an extra margin, non-accounted in the limiting current model, where a sharp transition between superconducting and normal state is retained

- In conductor with very low *n*, the amount of stabilizer in the strand plays a secondary role for transient stability. The copper cross section required for quench protection can be conveniently "segregated" as bundled Cu-wire, with marginal impact on stability

Feed-back ? The transient stability tends to disappear in the design criteria. In the conductor layout, the Cu:non-Cu ratio in the strand is reduced down to 1, with substantial cost saving (at present, the price for Nb_3Sn is independent from the Cu:non-Cu ratio)

Transient field stability is no longer an issue for fusion conductor - Cost reduction

R&D Investigations - *I_c vs. mechanical load*

Most investigations have been carried out at:

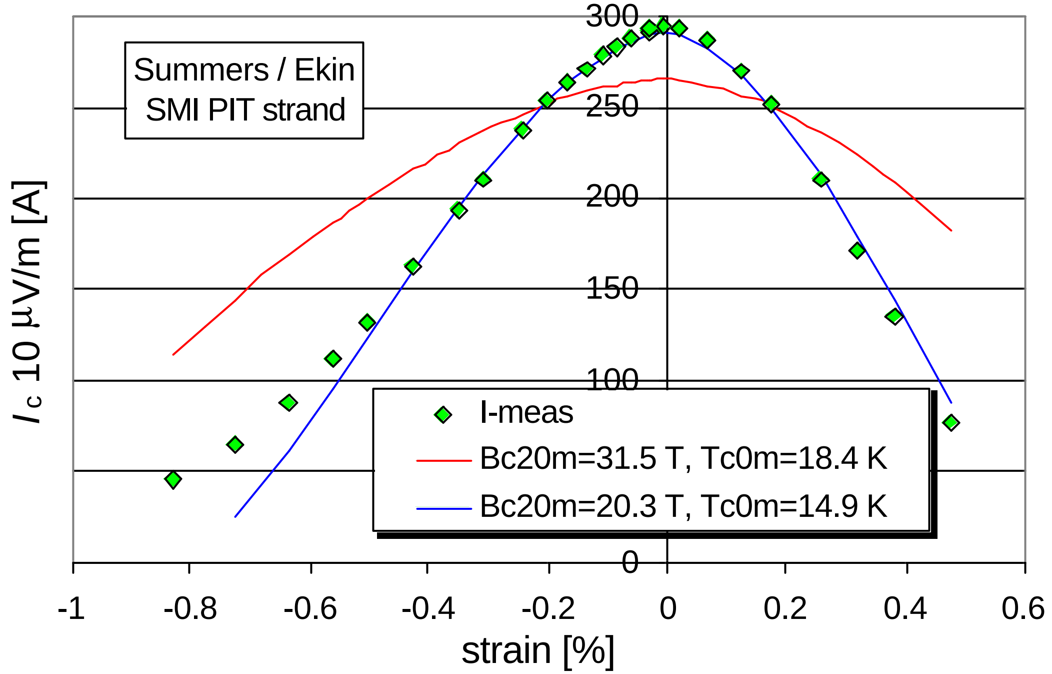
- Univ. of Twente
- FzK
- CRPP
- Durham Univ.
- NIST
- JAERI

The critical current in Nb_3Sn conductors is investigated for

- Strand I_c vs. axial strain, B, T, cyclic load
- Strand I_c vs. bending strain, cyclic load
- Subcable I_c vs. axial strain, jacket material
- Subcable I_c vs. transverse cyclic load
- Strand I_c after extraction from the CICC

R&D Investigations - *Scaling law for Nb_3Sn strand I_c*

If the Summers law is applied using realistic, physical parameters for B_{c2} and T_c, red curve, the fit is very poor. To improve the match, the critical parameters must be pushed into a non-realistic range, blue curve.



R&D DC Behavior - *Results and Feed-back*

- The applicability of the strand scaling laws is under question. Scaling parameters are replaced by fitting parameters without physical meaning. At high compressive strain, the critical current declines more severely than predicted by the "old" retained scaling law

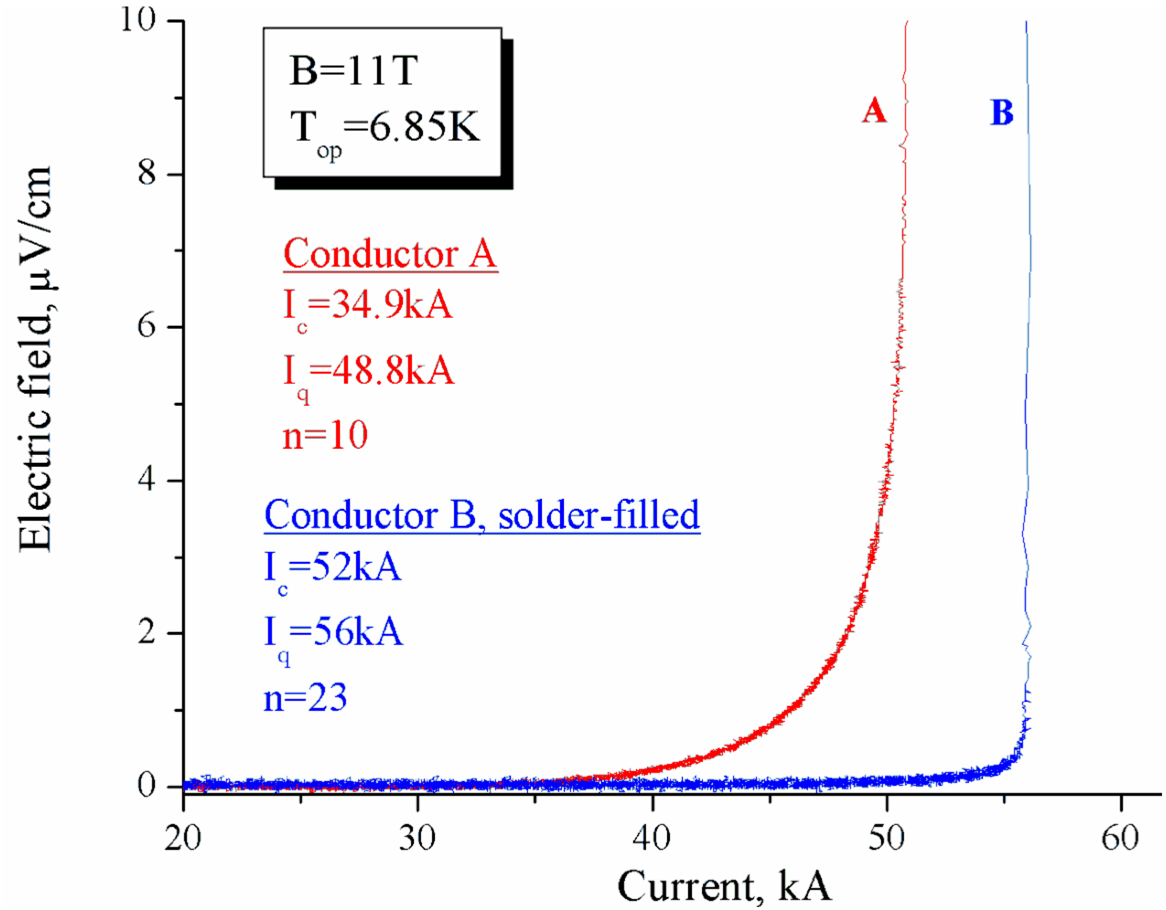
- Beside the axial strain, the transverse load from the Lorenz forces causes a further, severe performance drop in the large Nb_3Sn CICC due to the inadequate strand support. Bending and stress concentration likely induce micro-cracks in the filaments, with permanent drop of the *n* index. The damage progresses sometime with cyclic load

Feed-back ? The unexpected performance drop is balanced in the design by the increased J_c of advanced Nb_3Sn strands. No real countermeasure is taken in the conductor layout to mitigate the strain and load degradation

A heavy toll for transverse load must be paid in large Nb_3Sn CICC - We can afford it

Open issues for ITER high field conductors

The **sensitivity to mechanical loads**, both axial compressive strain and transverse load, is the main issue for Nb_3Sn CICC. In the medium-long term, the issue must be solved to exploit in full the potential of the newly developed Nb_3Sn strands. This may require a substantial design review and a deviation from the present CICC layout (likely not within the ITER project)



Pierluigi Bruzzone
High field cable development for ITER
WAMS2004, Archamps March 23 2004

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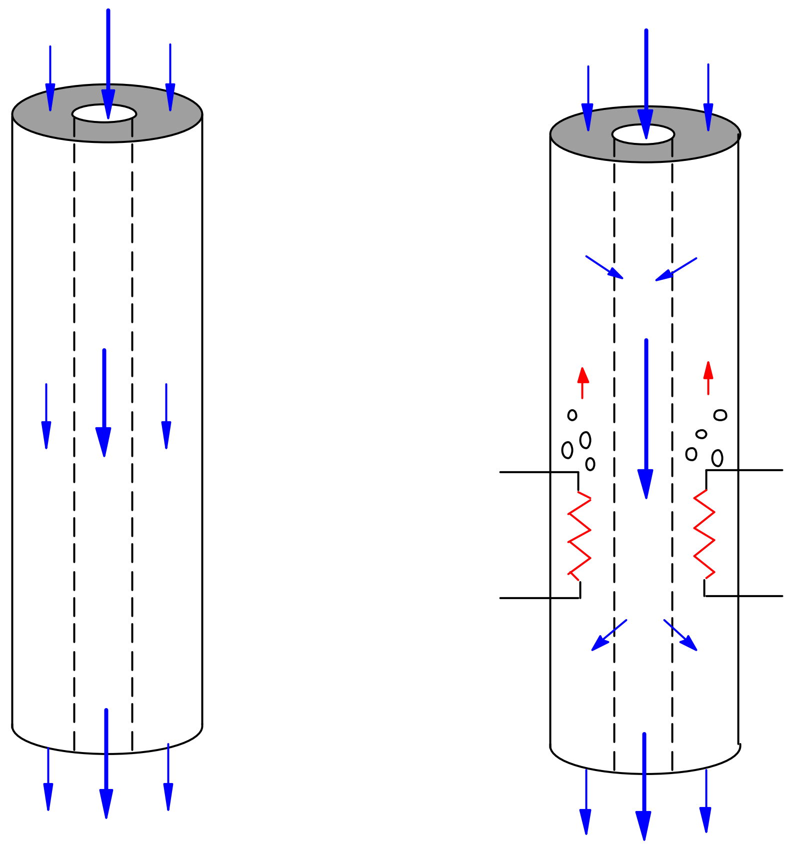
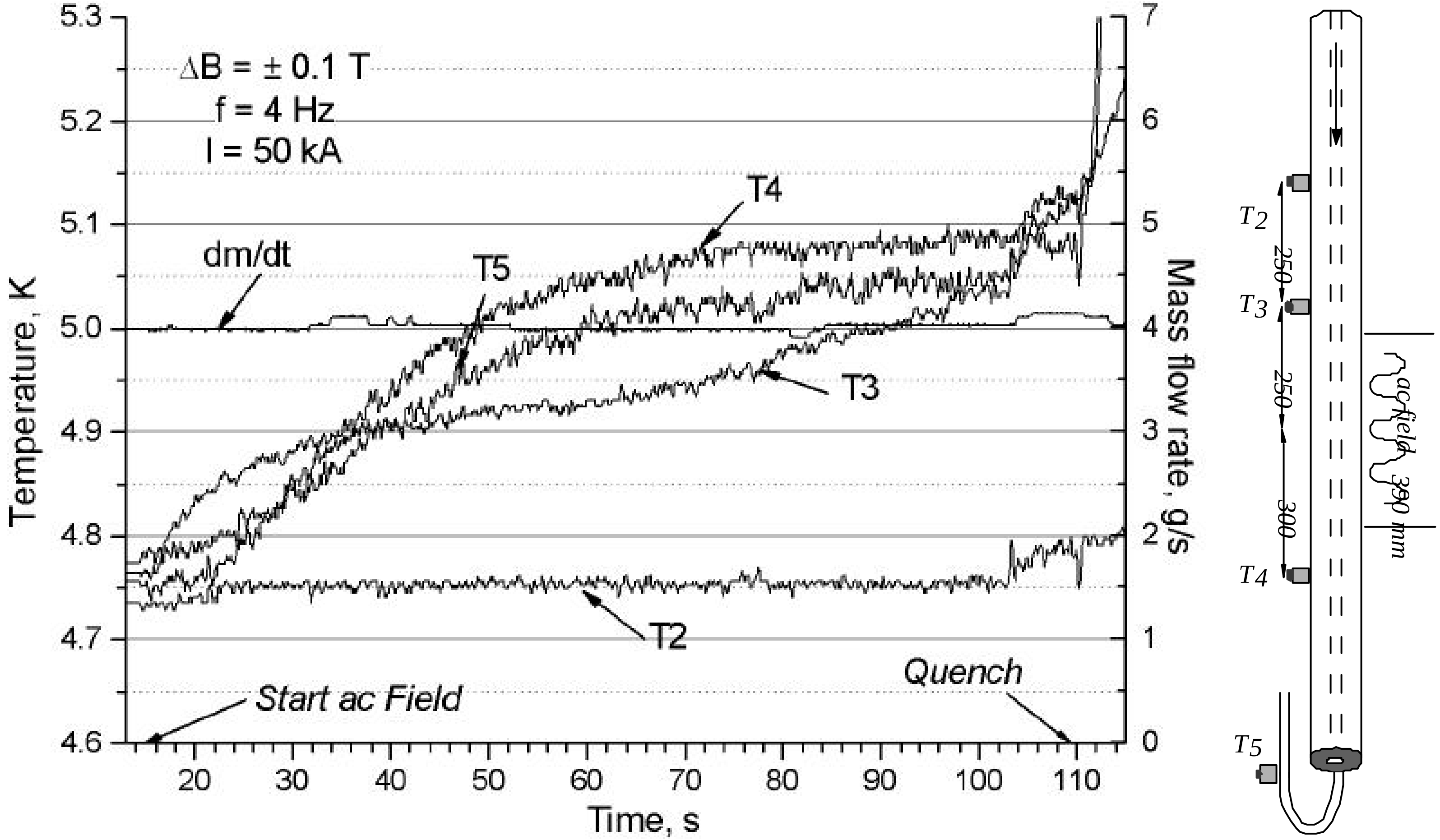
Open issues for ITER high field conductors

A **thermo siphon effect**, observed in dual channel CICC in vertical orientation with flow from top to bottom, is a big concern for the straight leg of the TF coil, where the power deposited in the strand bundle by ac loss, nuclear radiation and current sharing, may trigger local flow stagnation and thermal runaway



During an ac loss test in SULTAN with flow from top to bottom, it was observed that the local temperature increases at constant power input. The flow in the bundle area first slows down, then stagnates and eventually reverses. The heat accumulation eats up the large temperature margin and leads eventually to a quench



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Conclusion

- The R&D for high field ITER conductor has been meant as a *validation, not as an input* for the design
- Despite the efforts of the ITER team, the R&D activities suffered of lack of coordination, with un-necessary duplication and *dispersion of resources*
- The *results of R&D experiments did not confirm in full the assumptions of the design criteria*, which were in some area over-conservative (ac loss, stability) and in other area optimistic (mechanical load degradation)
- The *feed back of R&D in the design has been intentionally very limited*. The engineering margin has been largely used to balance the unexpected results
- The *interest of the industry* in the ITER conductor remains modest and insufficient to trigger internal activities in R&D and logistic (except Russia)

- There is good confidence that the ITER high field conductors will fulfill their duty. However, if we should start again from the scratch.…