Status of the Thermo-Hydraulic-ELectro-MAgnetic THELMA code and first comparison with the Stability EXperiment (SEX) database

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EFDA → Overall responsibility

ENEA → Experimental data comparison

POLITO → Thermohydraulic model

TWENTE → AC losses monitoring

UNIBO → Electric model

UNIUD → Electric model for joints

Outline

1. Code description
2. First EM tests
3. SEX data
4. Short sample measurements
5. Results and comments
6. Conclusion

Electromagnetic model

based on a distributed parameters circuit approach;

equations are derived from the magneto-quasi-static formulation of the Maxwell equations

unknowns of the problems are the values of the current in all the cable-elements (I_α)

cable element can be a single strand or a group of strands

current is a function of one spatial coordinate (ζ, which is the length of the cable axis line from the inlet of the cable to the generic cross section), and of time.

equations are derived from the induction law:

$$\sum_{\alpha=1}^{N\_ce}\int_{0}^{L\_cable}\frac{\partial i_\alpha}{\partial t}(\zeta',t)\,m_{\alpha,\gamma}(\zeta,\zeta')\,d\zeta' = -\frac{\partial V_\gamma}{\partial \zeta}(\zeta,t) - R_\gamma\left(I_\gamma(\zeta,t),T_{sc}(\zeta,t),\zeta,t\right) - \sum_{\beta=1}^{N\_ext}\frac{dI\_ext_\beta}{dt}(t)\,M\_ext_{\beta,\gamma}(\zeta) - \frac{dI}{dt}(t)\,M\_unif_\gamma(\zeta)$$

i_α is the difference between I_α and the current which would be in the cable element α if a uniform distribution (among the strands of the cable) of the transport current (I) was present, L_cable is the length of the cable, $m_{\alpha,\gamma}$ is the per unit length induction coefficient between cable elements α and γ, V_γ is the voltage of cable element γ, R_γ is a function of the tangential component of the electric field in the cable element γ with respect to the cable element axis line, T_{sc} is the temperature of the cable-elements, N_ext is the number of external coils, I_ext_β is the current in the external coil β, $M\_ext_{\beta,\gamma}$ is the per unit length mutual induction coefficient between the external coil β and the cable element γ and M_unif_γ is the per unit length mutual induction coefficient between the test coil when current I is uniformly distributed among the strands, and the cable element γ.

The **voltages** and the spatial derivative of the currents in the cable elements are connected by the transverse conductance (per unit length of the cable) matrix:

in matrix notation the equation is the following

$$\boldsymbol{V}^*(\zeta,t) = \left(\boldsymbol{G}^*(\zeta,t)\right)^{-1}\left[\frac{\partial \boldsymbol{i}^*}{\partial \zeta}(\zeta,t) + \boldsymbol{S}^*(\zeta,t)\right]$$

$g_{\lambda,\gamma}$ is the transverse conductance between cable-element λ and cable-element γ per unit length of cable, E_ext_β and E_unif take into account the magnetic coupling **of external coil β** and of **transport current** with the **currents flowing from cable-element λ to cable-element γ**.

Thermal-hydraulic description

the evolution of the current distribution of the cable depend on the strand temperature distribution T_{sc} (ζ, t).

The model has to predict the evolution of the temperature distribution along the strands, consistently with the evolution and distribution of the heat sources P_{sc}, computed in turn by the **electromagnetic part** of the code.

Due to the smallness of the conductor and lack of wrapping the temperature distribution on a given cross section should be uniform inside each cable component, and namely represented by the three quantities T_{sc} (strands), T_{jk} (jacket) and T_{He} (helium).

In the future we plan to extend the thermal-hydraulic model to a multi-channel one

The thermo-dynamic state of the helium in the single channel is described by its temperature by the helium pressure p (ζ, t), the compressible flow of the helium is assumed to occur mainly in the axial direction, characterized by a flow speed V (ζ, t).

The set of equations for the five thermal-hydraulic unknowns (T_{sc}, T_{jk}, T_{He}, p, V) is given by the standard set of modified **Euler equations** for **1D** compressible flow of the helium coolant, coupled to **1D conduction** equations for the heat transfer along the strands and, separately, along the jacket, as used and validated, in the Mithrandir and M&M codes.

Typical **boundary conditions** for this set are: inlet T_{He}, inlet and outlet p, adiabatic strands and jacket at the cable ends.

Coupling of Electromagnetic and Thermo-hydraulic models

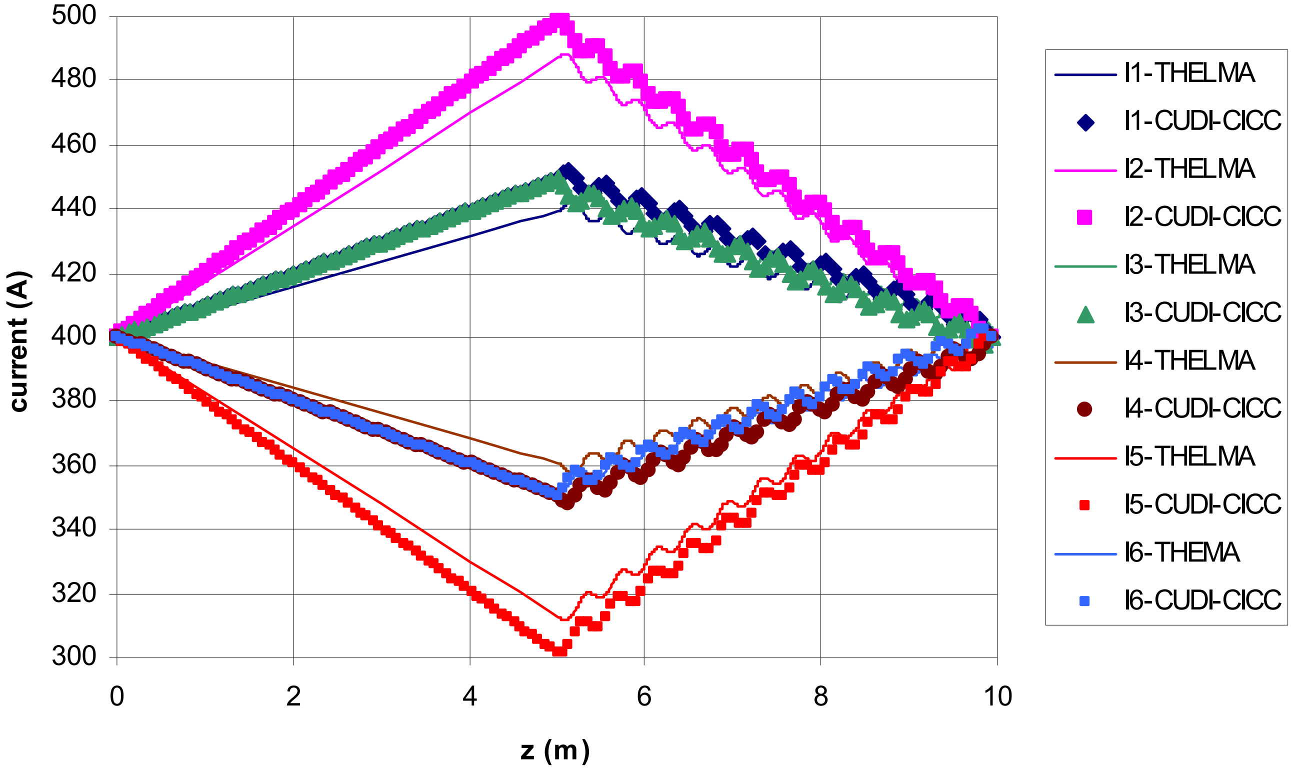
The electromagnetic and the thermo-hydraulic models need to be solved **simultaneously** due to the **temperature dependence of *E-J*** characteristics of the strand material. **In order to solve the electromagnetic step the new value of T_{sc} should be known; at the same time, in order to solve the thermo-hydraulic step the new value of the power which is dissipated in the strand (P_{sc}) should be known**

A simple coupling scheme is utilized in code THELMA: at each time step,

first the electromagnetic equations are solved with a constant temperature and P_{sc} at the new time is calculated; then the thermo-hydraulic equations are solved in correspondence of the calculated P_{sc} and the new value of the temperature T_{sc} is calculated; no iterative process to verify convergence is performed.

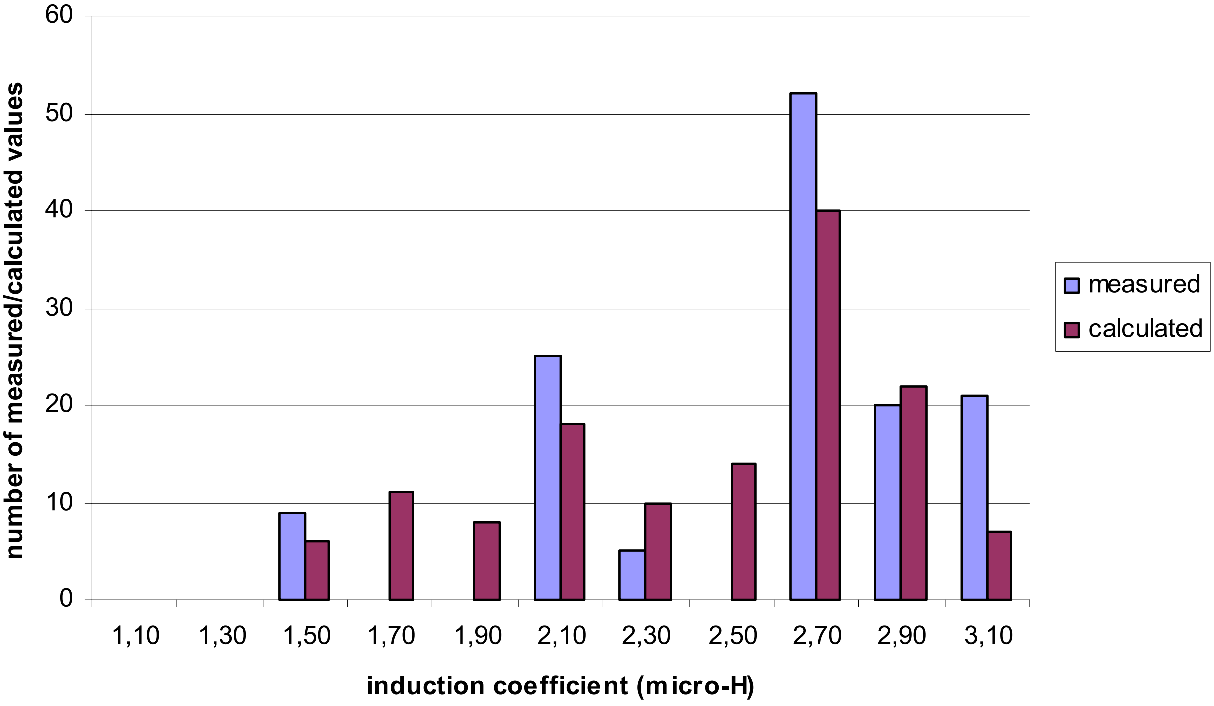
Code comparison

The section of **THELMA** dealing with the cable model was successfully **tested** by comparing it against the code **CUDI-CICC**. In one of the test cases the second half of a 10 m piece of cable is exposed to a time varying external magnetic field with a time rate of 1 T/s. Only the six last stage cable elements were considered.



Geometrical Accuracy of the Cable Model

a test with 36 **insulated copper strands** (3x3x4), having a diameter of 0.81 mm, and twist pitches of 42 mm, 83 mm and 126 mm.
The conductor outer diameter was 8.55 mm.
Test performed on two samples One rectilinear and 3 m long; the other was wounded, 13 m long.
The results of about 150 measurements performed at 1 kHz on the rectilinear sample are shown. Similar results apply for the wound sample. The similarity between the two distributions gives confidence on the accuracy of the geometrical representation of the cable.



SEX, Stability Experiment overview

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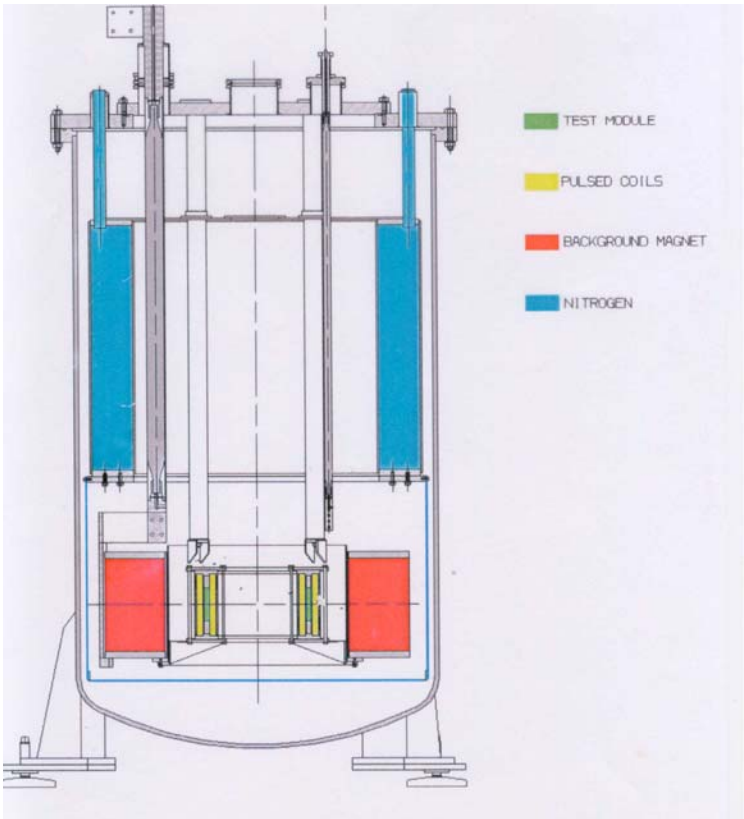
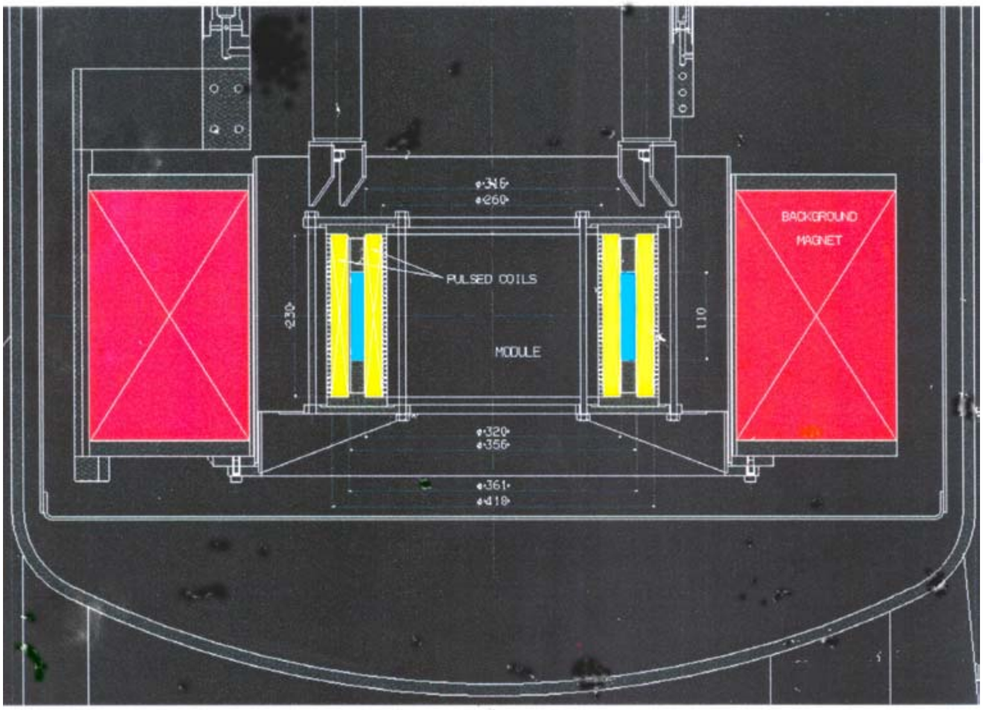
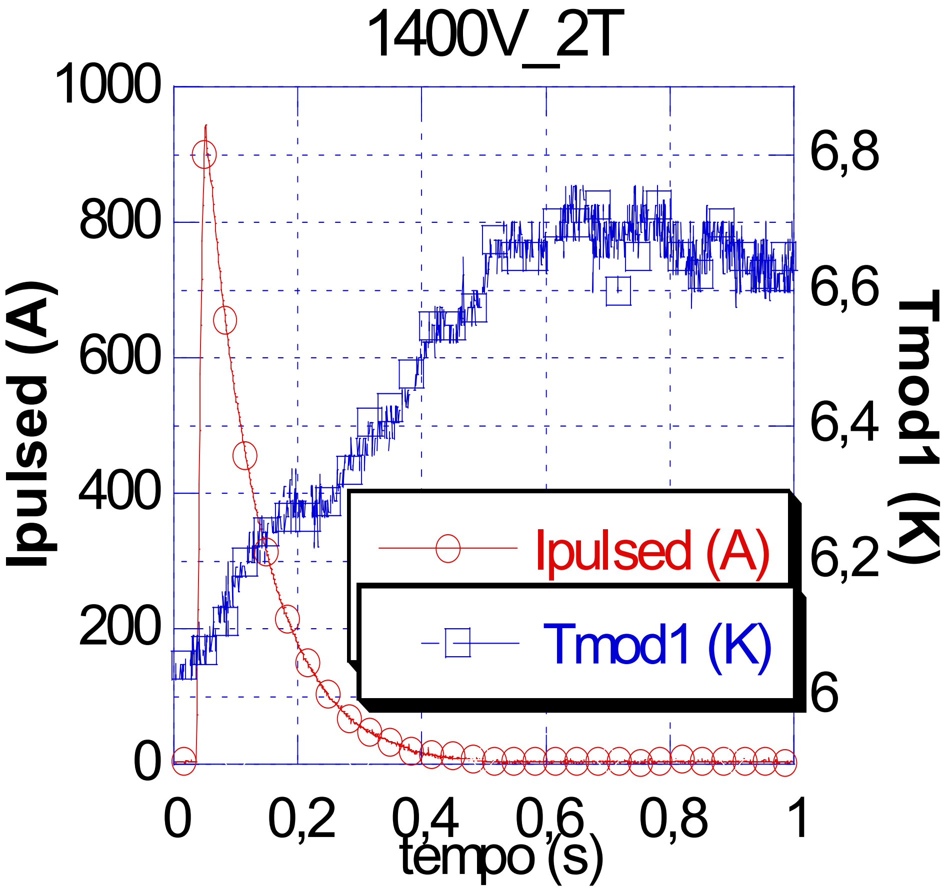




Data from **SEX**, Stability EXperiment

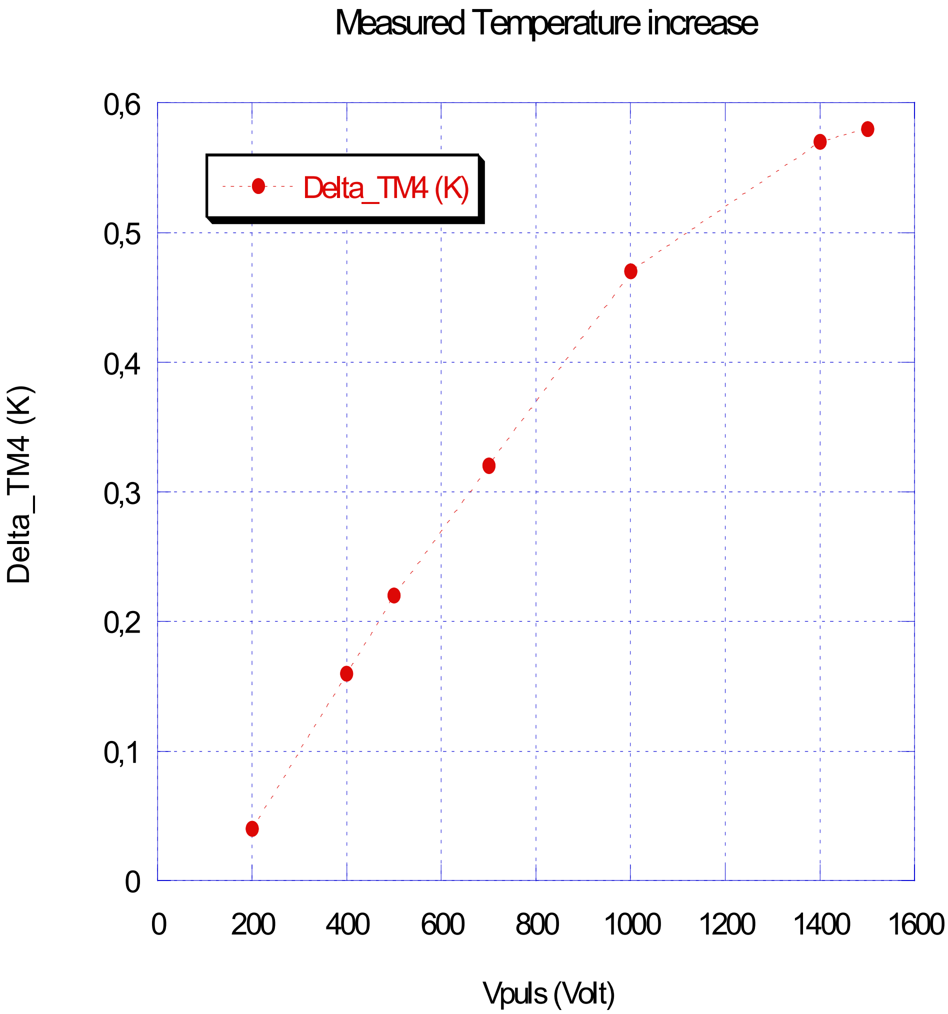
Conductor length 35 m
Three temperature sensors, located at 14.5, 17.5, 21 m

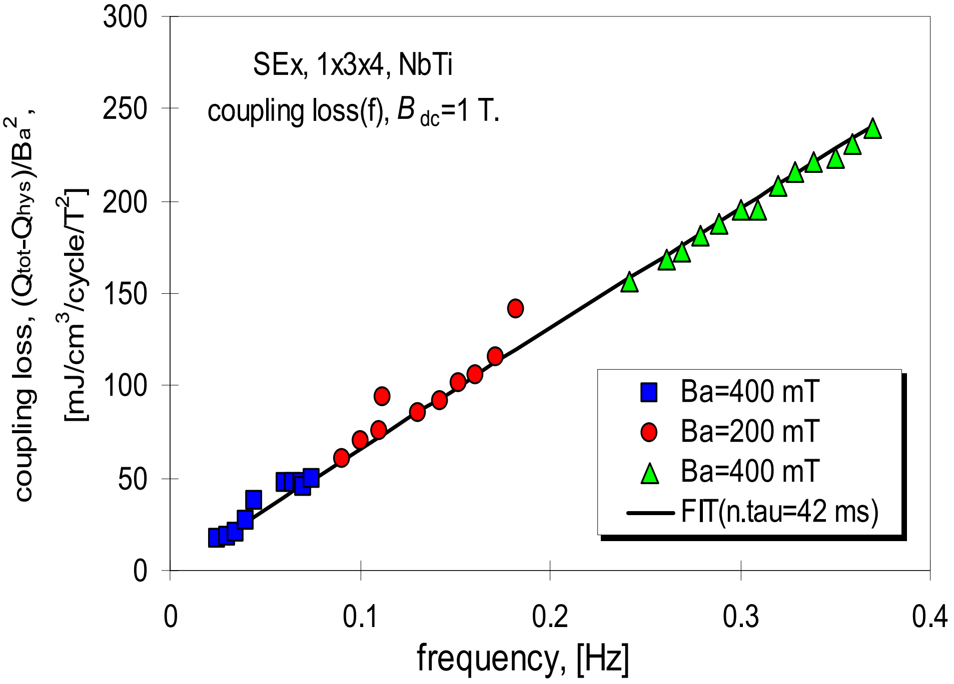


Conductor characteristics

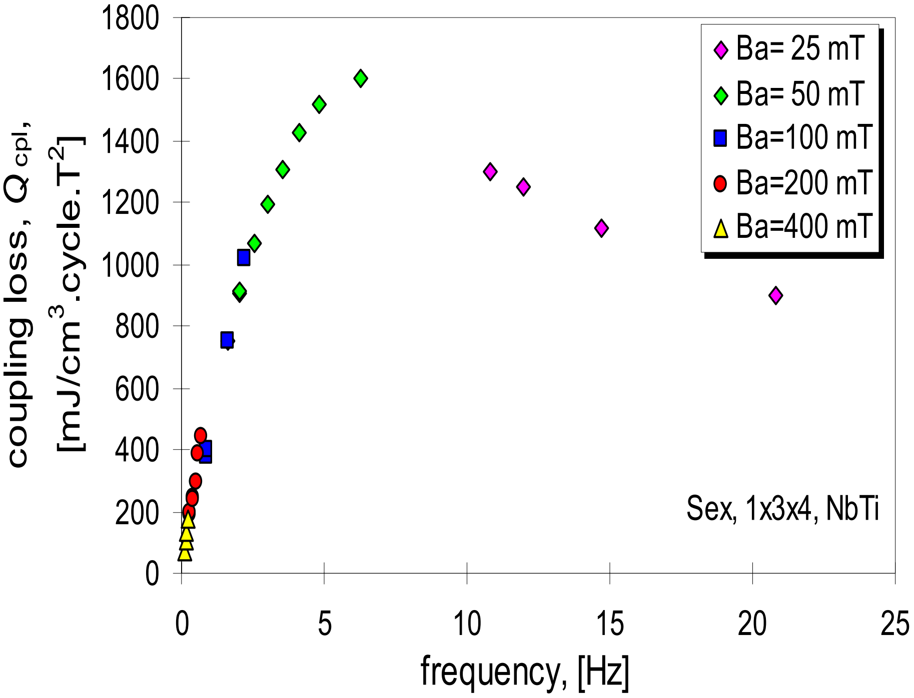
strand manufacturer	Vacuumschmelze		
strand diameter [mm]	0.60	twist pitch 1st, 2nd stage [mm]	25x40
Cu:nonCu	5.75	cable space [mm^2]	5.65
strand coating	bare copper	total strand area [mm^2]	3.39
filament twist pitch	20	void fraction [%]	40
I_c @6 T, 4.2 K, [A]	80	cable outer diameter [mm]	2.68
D_{eff} filaments [mm]	45	conduit outer dia [mm]	5.18
cable layout	1x3x4(12strands)	conduit material	CuNi
Conductor winding	Double layer	Conductor length [mm]	34.012

Data from SEX, Stability EXperiment





Coupling loss versus frequency of of the Sex conductor with amplitudes of B_a=100, 200 and 400 mT, and B_{dc}=1 T. The time constant amounts to **nt=42 ms.**



Coupling loss as a function of the frequency for all measured amplitudes B_a of the Sex conductor, with B_{dc}=0 T. The coupling loss is determined as $Q_{cpl}=(Q_{tot}-Q_{hys})/B_a^2$.

Eddy current loss in the CuNi conduit are not relevant

Contact resistance measurements

strand combination	between cabling stage	Sample #1 R_c [nΩm]	Sample#2 R_c [nΩm]	Sample #3 R_c [nΩm]
1 and 2, IS	1	171	67	119
1 and 3, IS	1	191	78	
2 and 3, IS	1	191	75	
5 and 6, IS	1	440	58	
1 and 5, IS	2	1290	55	
1 and 6, IS	2	1010	121	
2 and 5, IS	2	1260	121	
7 and 8, IB	2	1780	124	1500

The level of IS $\boldsymbol{R_c}$ in combination with the number of strands gives a rather effective indication of the inter-strand coupling loss time constant of a CICC. By using the results of a **database** available in Twente, obtained on various CICC's, it becomes clear that with such a relatively high level of IS R_c (100 nWm) **the interstrand $n\tau$ is expected to be in the range of only a few ms, which is far below 42 ms.**

The coupling loss time constant for a strand is:

$$\tau = \frac{\mu_0}{2} \cdot \left(\frac{L_p}{2\pi} \right)^2 \cdot \sigma_\perp \quad \text{[s]}, \qquad (1)$$

where *Lp* is the twist pitch and is the effective electrical conductivity in the transverse direction.
The coupling loss time constants are summarised for the strands used in reference [3]. For these strands, although not entirely similar to the one used for the SEx conductor, the ***nt*/ L_p^2 amounts to 0.098** (standard deviation 10 %). If the *nt* for the SEx strand is scaled with these data, for a twist pitch of 20 mm, an *nt* of **39 ms** is obtained

cable ID	strand pitch [mm]	$n\tau$-strand [ms]	Q_{hys} [mJ/cm^3]
# 10	8	6.45	15.97
# 13	18	26.3	15.13
# 14	15	24.5	14.94
# 15	16	24.5 / 25.0 (21.8)	13.34 / 13.81 (5.38)
# 16	16	25.4	15.02

The calculation of the **eddy current loss** in the CuNi **conduit** and in **copper matrix** show that it practically plays no role and does not contribute to the overall AC loss.

The prediction of the **interstrand** component based on a rough average R_c of 100 nΩm gave an $n\tau$ of only few ms,
together with the **intrastrand** component of 39 ms completes the overall coupling loss time constant of 42 ms obtained from the experiment.

Consequently **the main part of the coupling loss is intra strand loss, due to the combination of relatively long filament pitch and high R_c.**

Short sample comparisons between Thelma and CUDI-CICC

The 12-strand cable arrangement of the SEx cable is first simplified towards a 4-segment cable structure, **200 mm long**
The experimentally obtained inter-strand and inter triplet contact resistance measurements are used to calculate the $n\tau$ by both electromagnetic codes.

Results from **CUDI**
the nt for the last stage contribution amounts to **0.32 ms.**
The nt from the first stage (triplet) is **0.12 ms.**

Hence the overall interstrand $n\tau$ calculated by CUDI-CICC is 0.44 ms.

The $n\tau$ obtained with Thelma for the 4 sub-bundle geometry, based on the measured inter strand R_c's, is **0.44 ms**, while for the 12 strand arrangement nt=0.50 ms.

the power dissipation per meter cable length calculated by **Thelma** is reported as 1.19 mW/m.
For a direct comparison the Ra in CUDI-CICC is adjusted in such a way that the same power dissipation of 1.19 mW/m is obtained.
The pattern of the current magnitude due to the coupling currents in the four cable elements **is identical for both codes**.

However, the magnitude amounts to 1.05 A for CUDI-CICC and 1.80 A for Thelma.

Summarizing (short sample comparison)

the results of both electromagnetic codes are in agreement for $n\tau$ calculations

and seem consistent with the prediction of the proposed empirical cable and strand scaling for the coupling loss.

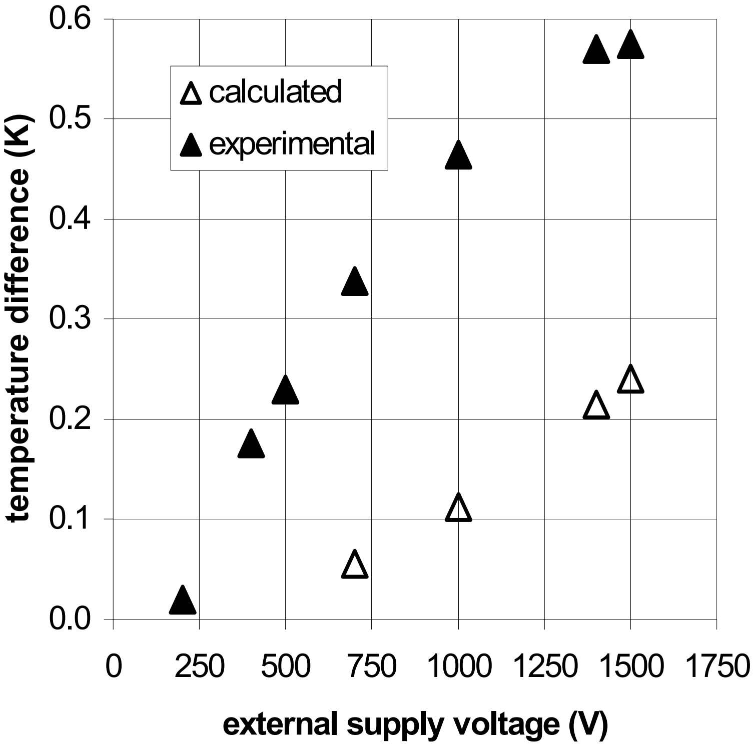
According to these results the dominant component of the coupling loss is generated inside the strands between the superconducting filaments

the inter-strand coupling currents are strongly suppressed by the large inter-strand **contact resistance** and **limited number of strands.**

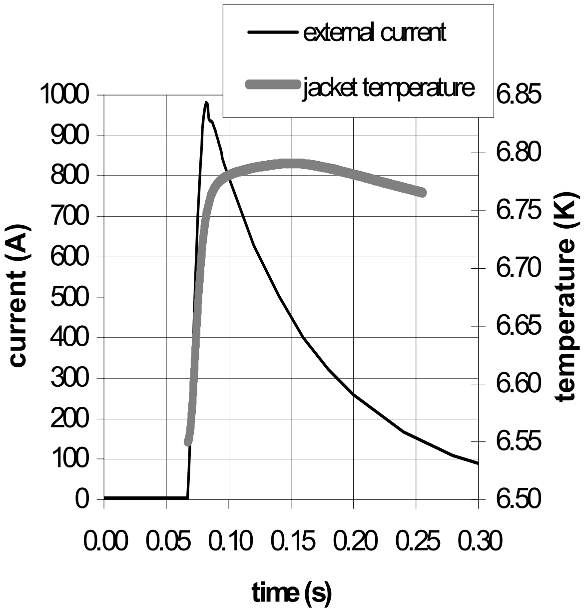
Agreement between codes for current amplitudes **has to be improved**

Results from Thelma

Two models of the cable have been considered: the first model (model a) with 12 cable elements and the second model (model b) with 4 cable-elements. In the first case each cable element represents a strand of the cable, while in the second case each cable element represents a triplet of strands.

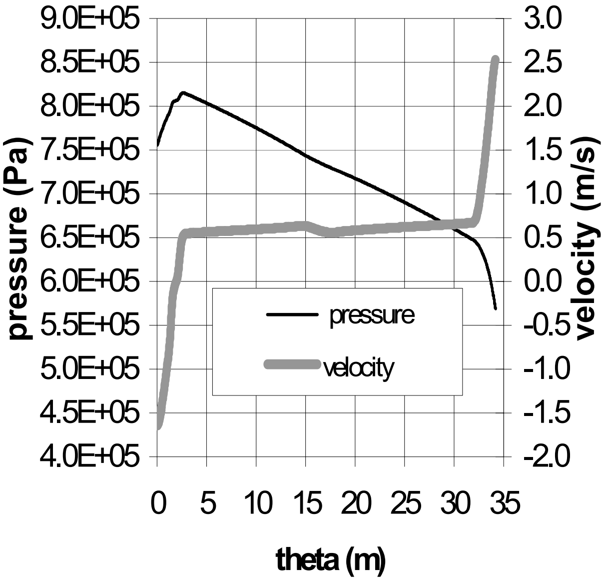


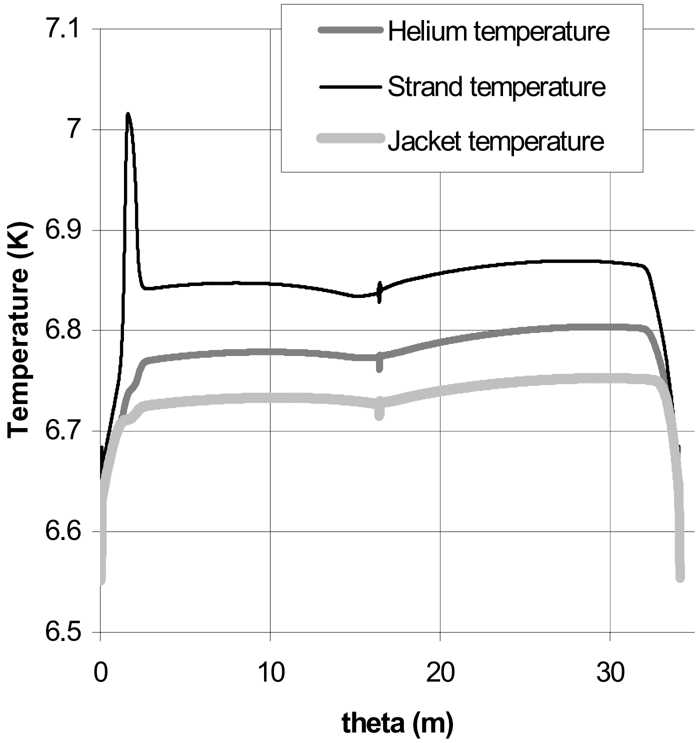
Pure inter-strand comparison model B



The maximum increase in the jacket temperature in the middle of the cable (14.52 m).

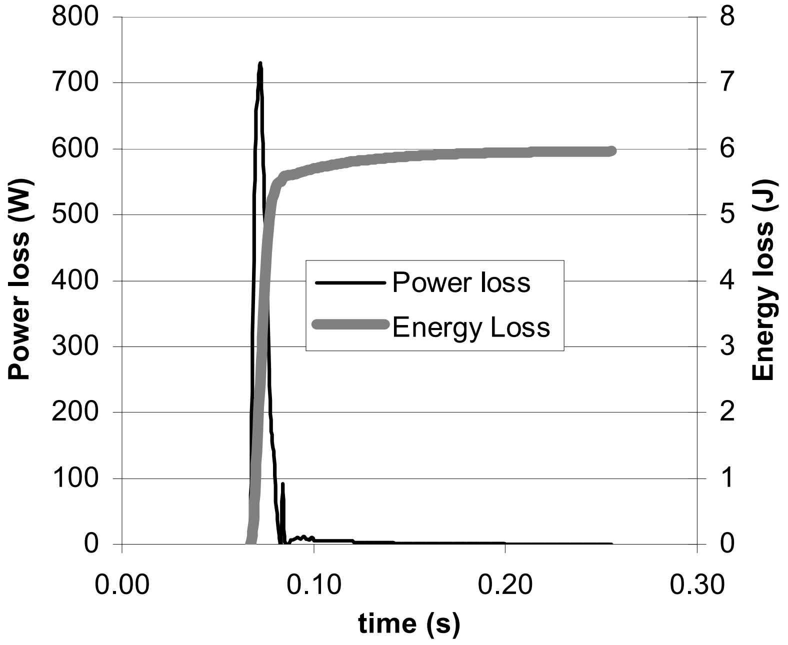
Simulations started from uniform thermo-hydraulic conditions (T=6.5 K, p = 7.55 bar) with an outlet pressure of 5.69 bar. The difference with respect to the experimental results **is more than 50%** when voltage is high, larger **(a factor of 6)** when voltage is lower. This should be due to the lack in the model of the intra-strand loss mechanism.





Helium pressure and velocity profiles at 80 ms

Helium temperature, strand temperature and jacket temperature profiles at 80 ms

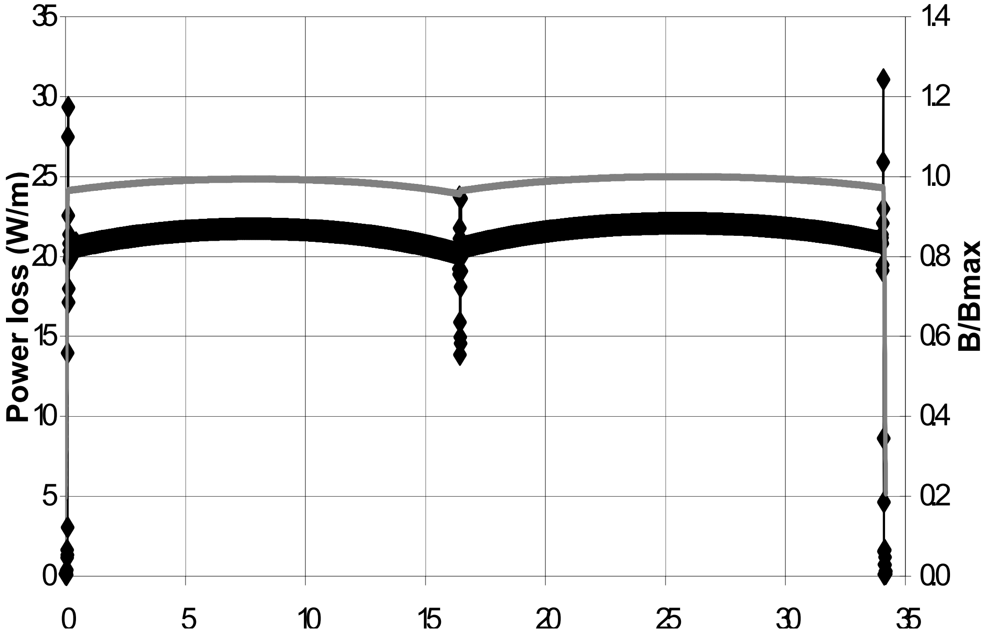


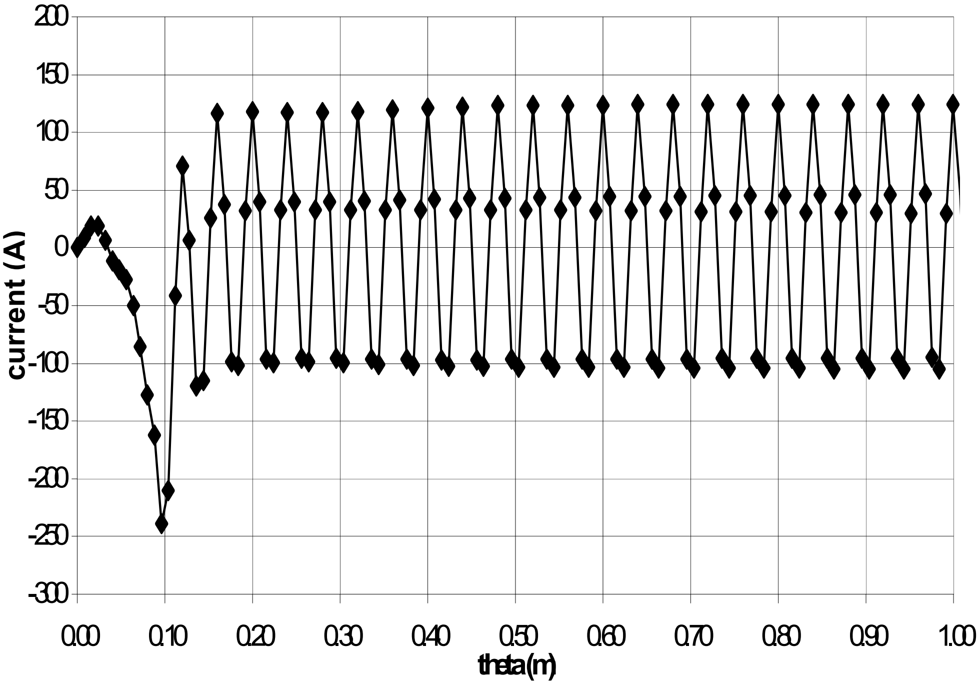
Power loss and energy loss vs. time in the 1500 V case.

The power loss distribution together with the magnetic flux density distribution.

Power loss distribution is quite similar to the magnetic flux density distribution.

The **peaks** at the inlet and outlet sections of the cable should be due to **current loops** which develop not in a twist pitch length (which are the most important source of power loss and current non-uniformity in this experimental set), but **in each half of the test coil** (a layer).





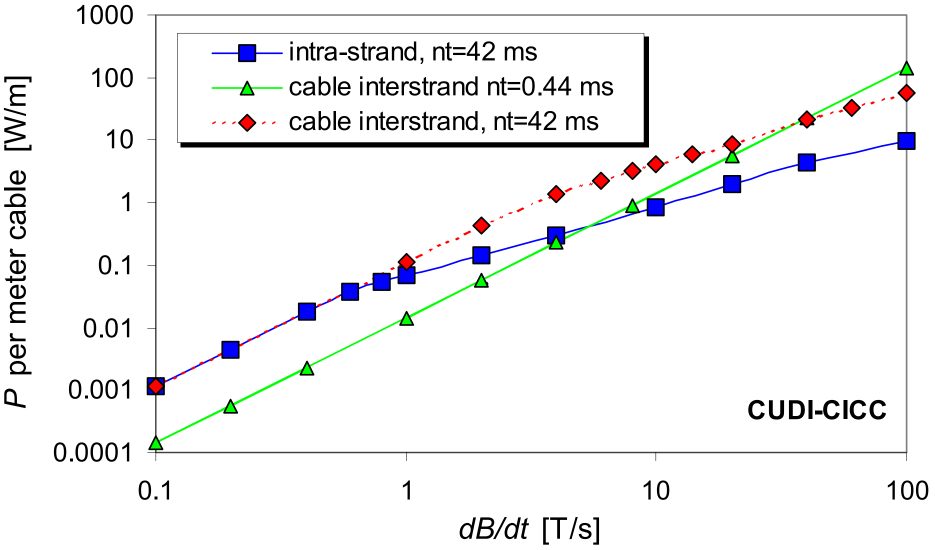
The current distribution with reference to the first strand and to the firs meter of the cable

Short sample

The difference between pure inter strand loss and pure intra strand loss is simulated with CUDI-CICC on a 4-element cable and a strand both having an *nt* of 42 ms. and a 4-element cable with realistic Rc (nt=0.44ms).

At very high field variation rates, coupling currents locally reach the **critical current** of single strands, which leads to saturation.

pure intra strand and pure inter-strand coupling loss lead to different results at high field rates, even when for both *nt* is 42 ms.



Even with such a different nτ losses contribution at **high field rates** is not only due to intra-strand because **of a strong saturation effect**

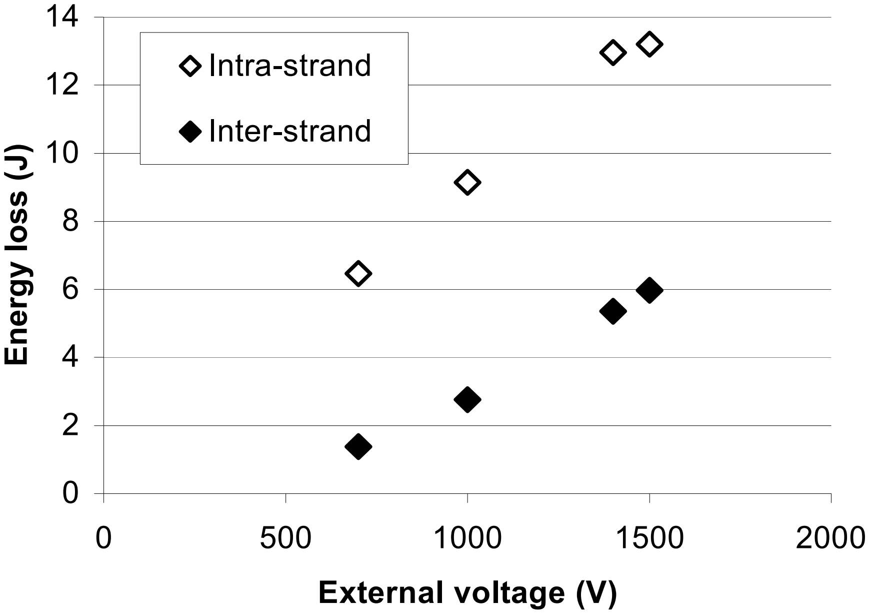
At 100 T/s the power dissipation in the 4-bundle cable model amounts to 11.5 W, while the intra strand loss has become **insignificant.**

Eddy currents are negligible

Full conductor length

To have a **first estimate** of the intra-strand coupling losses an **approximate model** of the cable has been utilized (model c).

4 cable-elements, each representing a fourth of **a strand**; the calculated power loss is multiplied for the number of the strands in the cable (12). The value of g (per unit length conductance between two adjacent cable elements) in model c, which is not a measurable quantity, has been set in order to fit the experimental value of ***n*τ of 42 ms**;



Comparison between intra-strand losses and inter-strand losses

Electro-magnetic calculations with **constant temperature (6.5 K)** has been done with **model b and model c**. It can be seen that intra strand losses are larger than inter-strand losses also in the experimental set-up, but the ratio between intra-strand losses and inter-strand losses is much lower than in the low frequency, short sample, a.c. case; This should be due to the fast change in the external field (ramp time about 10 ms) as discussed.

Saturation effect is in agreement with experimental data.

All these qualitative results are in agreement with the experimental ones.

Conclusion

First test with the new Thelma code have been performed in order to reach a agreement with experimental data.

The analysis made clear that for conductors, with high inter-strand contact resistance, high intra-strand loss and low number of strands, the intra-strand loss should be included in the model.

The very high field variation rates to which the conductor is submitted leads to coupling currents that reach locally the critical current in single strands and consequently to **saturation**. Only a qualitative comparison has been possible with experimental data showing satisfactory agreement.

Agreement with the CUDI code for short sample calculation has to be improved

Both codes seem to be in agreement with the prediction of an empirical strand and cable scaling for coupling losses.

Future developments

A intra+inter strand THELMA simulation will be performed in order to match experimental results

Joint modelling and **joint-conductor coupling** routine have been already developed and are ready to be run together with this first version of Thelma.

A more detailed em description of the strand by means of the magnetization equation will lead to a full modellization also of the **intra-strands** losses.

Code validation will continue by using **data from other experiments**, up to when the ad hoc planed SEXUP experiment, where current distribution in-homogeneity can be forced in a controlled way, will be performed.

Comparison with the only other existing ELMA code **THEA** will be performed on the basis of the SEXUP data set.

Modellization of the mechanical behaviour of the strand is currently under study