FUSION TECHNOLOGY DESCRIPTION

EUROfusion
TECHNOLOGY TRANSFER PROGRAMME

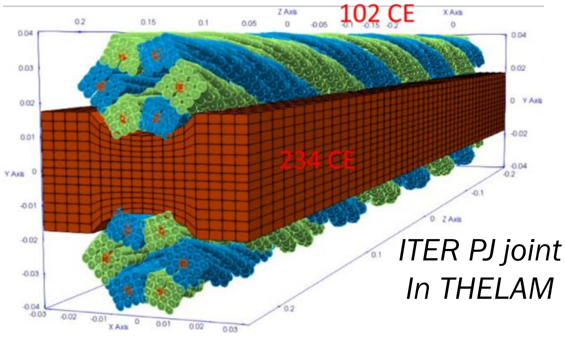
THELMA: AC-Loss & Transient Analysis for ITER Conductors and Joints

THELMA is an advanced electromagnetic simulation code, originally developed and validated for fusion applications such as ITER, where it enables accurate prediction of current distribution and AC losses in superconducting cables and joints. Its robust modeling capabilities and proven reliability make it a valuable tool for optimizing the design and safety of superconducting magnet systems, and it can be adapted for use in other sectors that employ superconducting magnets, such as medical accelerators and proton therapy gantries. Collaboration opportunities include joint R&D, model customization, and technology transfer.

Description of the technology

THELMA is a set of validated modeling codes developed at the University of Bologna to analyze large superconducting magnet systems, in particular cable in conduit conductors (CICC) and their joints, under realistic operating conditions. It is intended to analyze the working conditions of superconducting magnets during plasma scenarios, in which the currents change in time and where it is not practical to test every combination on hardware. THELMA builds a virtual replica of the conductor and of the joint, including the cabling hierarchy, the electrical contacts between strands and the local magnetic environment, and then computes how currents, voltages and losses evolve in time. In this way it becomes possible to answer design questions such as how much energy is dissipated in one pulse, whether a given joint layout produces a dangerous voltage spike, or how much current is diverted from one strand to another during a fast ramp.

THELMA has been applied and benchmarked on ITER class conductors and joint configurations. For poloidal field twin box joints (see the corresponding THELMA model in the figure) under a 15 MA plasma scenario, the code predicts a total dissipated energy of about 4.03 kJ per pulse, of which about 90 to 97 percent, is due to the transport current, with minor contributions from coupling currents.



For central solenoid dump transients, the code reproduces cases with initial currents in the range from 5 to 40 kA and a decay time constant of about 7 s, providing time profiles of losses, voltages and current sharing temperatures. In studies reproducing conductor samples similar to those tested in facilities such as SULTAN (Villigen, Switzerland), simulations were performed for field variations in the range 0.2 to 0.3 T, and the model was able to match the expected loss level when realistic contact resistances and cabling patterns were used. The expertise behind this offer comes from long term work on electromagnetic and thermal analysis of superconducting coils and joints, including circuit and finite element co-simulation, extraction of contact resistances from experiments, correlation with large conductor tests and application to both central solenoid modules, poloidal field and toroidal field coils. This know how is essential because the accuracy of the results depends on a detailed description of the conductor architecture, on realistic values of contact resistances and on a correct definition of the current waveform.

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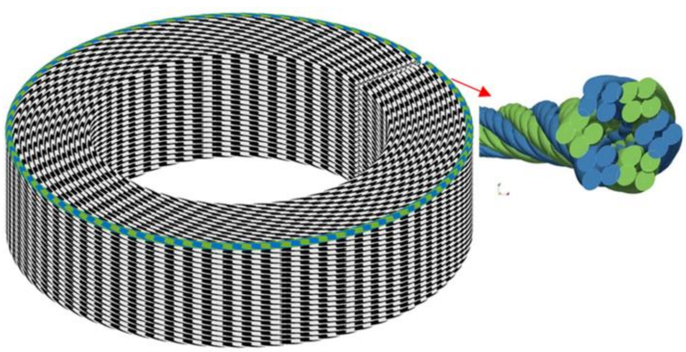
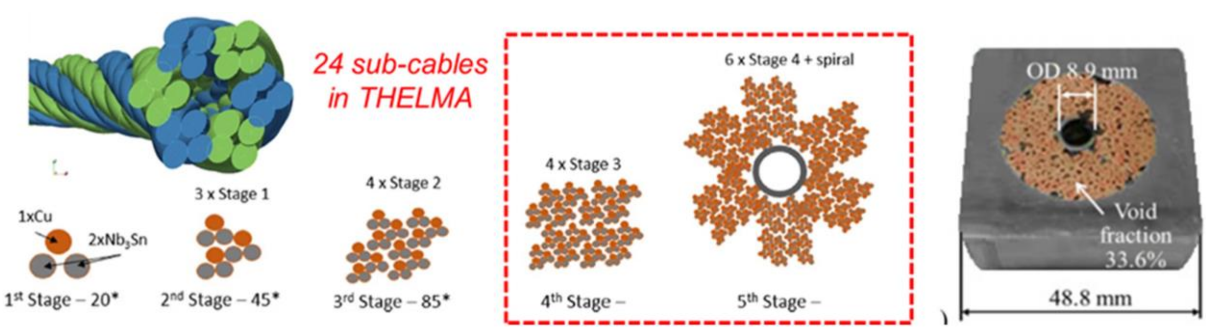
Description of the technology

For a prospective technology receiver, the usefulness of THELMA can be judged from the fact that it delivers not only the total energy per pulse, as in the examples above, but also the loss contributions from different mechanisms (coupling, hysteretic, eddy, transport), as well as strand and joint currents and voltages, and thermal indicators that can be used for quench margin assessment. It can also show the sensitivity of losses and charging to contact resistance, which is a parameter that an industrial partner can, to some extent, control during manufacturing. The present validation refers to NbTi, Nb3Sn ITER like CICC and to joints of known topology; the quality of the prediction decreases if the contact resistances or the driving waveforms are not measured or are poorly specified.

ITER CS module
In THELAM





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Innovation and advantages of the offer

THELMA innovates by enabling detailed, distributed-parameter modelling of superconducting cables, going beyond the simplified or lumped models commonly used. It discretizes cables into hundreds of strands, allowing accurate simulation of current redistribution and AC losses in complex geometries like ITER's CICCs or Rutherford cables for particle accelerator magnets. This results in quantitative agreement with experimental data, with errors typically below 20 %, and helps identify thermal hotspots and optimize cryogenic systems. Economically, THELMA reduces prototyping costs and time by providing predictive loss maps before manufacturing; advanced fitting procedures can cut simulation runtimes from about 10 days to 1 day for a full ITER CS module. The code is modular, adaptable, and transferable to other sectors like medical accelerators, offering industry benefits such as risk reduction, cost savings, and support for innovative magnet system design.

Non-fusion Applications

THELMA's potential non-fusion application domains include medical technology (proton therapy gantries, MRI/NMR systems), particle accelerators and beamlines, scientific instrumentation for high-field research, and advanced energy systems using superconducting cables. The code's ability to predict AC losses with high accuracy supports safer, more efficient magnet and cryogenic system design in these sectors.

EUROfusion Heritage

THELMA was developed to meet the demanding requirements of fusion magnet design, where accurate prediction of AC losses and current redistribution is essential for ITER and EUROfusion projects. The technology's innovation lies in its distributed-parameter modeling, enabling detailed simulation and experimental validation on large multi-strand conductors. EUROfusion investments supported advanced modeling, experimental campaigns, and integration with thermal analysis, building specialized know-how in electromagnetic and cryogenic design for fusion systems.

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