Vittorio Di Marzo

Electromagnetic and Mechanical Design of the Central Solenoid in Tokamak Devices: from LTS to HTS configurations

Tutor: Prof. Roberto Ambrosino

Cycle: XXXVIII Year: 2025

Candidate's information

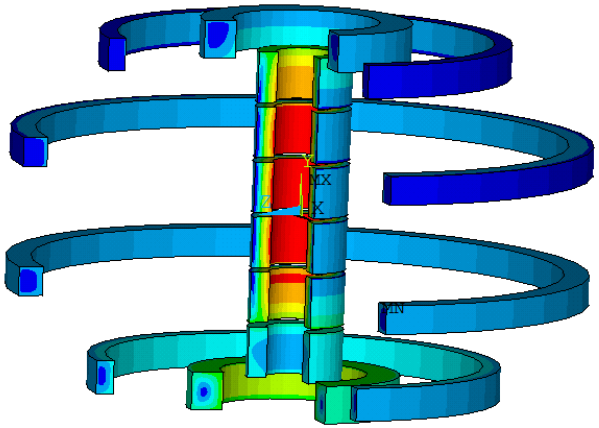
- MSc degree in Mechanical Engineering for Design and Production (July, 2022)
- Research group/laboratory: DIETI Plasma Control Group
- PhD start date: 01/11/2022
- Scholarship type: PNRR - DM 352
- Partner company: Eni S.p.A.
- Periods abroad: 6 months at Fusion For Energy (Barcellona)
- Periods in company: 6 months at Eni S.p.A. (Venice, Italy)

Summary of study activities

- **Academic courses**: Courses in the field of *Automatic Control*, *Modeling and Simulation*, *System Theory*, *Plasma Physics and Fusion*, and *Modeling and Dynamics of Fields*.
- **Specialized schools:** *National Doctoral School of Electrical Engineering (Gasparini)* and in the *4th International School on Numerical Modelling for Applied Superconductivity* (Fusion for Energy, Barcelona).
- **Seminars:** Attended >20 international seminars on plasma physics, control systems, and computational modeling.
- **Research and training periods:** *Fusion for Energy* (Barcelona, 6 months): research on HTS design for DTT Central Solenoid ; *Eni S.p.A.* (Venice, 6 months): industrial study on LTS/HTS superconducting magnets.

Research area:

- **Research field:** **Controlled thermonuclear fusion reactors** (devices aiming to reproduce on Earth the energy of the Sun, also known as “Tokamaks”).
- **Main problems tackled:**
  - **plasma control** and **power exhaust** strategies in large tokamaks (DEMO, VNS, DTT);
  - design of **superconducting magnets** for nuclear fusion applications.



Research results

- Design and testing of alternative power exhaust strategies (i.e. **plasma wobbling**);
- Electromagnetic design on new nuclear fusion facilities (i.e. **Volumetric Neutron Source - VNS**);
- Integrated **design methodology** for electromagnetic and mechanical modeling of **superconducting magnets**;

Research products

[J1]	R. Ambrosino, V. Di Marzo et al. DEMO in-vessel equatorial coils for power-exhaust and fast plasma control, **Fusion Engineering and Design**, vol.197, 2023, DOI: 10.1016/j.fusengdes.2023.114029.
[J2]	F. Romanelli, V. Di Marzo et al. Divertor Tokamak Test facility project: status of design and implementation, **Nuclear Fusion**, vol. 64, 2024, DOI: 10.1088/1741-4326/ad5740.
[J3]	E. Acampora, V. Di Marzo et al. Scenario feasibility and plasma controllability for Volumetric Neutron Source (VNS), **Fusion Engineering and Design**, vol.217, 2025, DOI: 10.1016/j.fusengdes.2025.115053.
[J4]	V. Di Marzo et al. Electromagnetic and Mechanical analyses of an explorative HTS-based Central Solenoid for the DTT Tokamak, **IEEE Transactions on Applied Superconductivity**, Special Issue on MT-29, paper accepted, 2025.
[C1]	F. Maviglia, V. Di Marzo et al. Studies on EU-DEMO In-Vessel Coils requirements and conceptual design for axisymmetric plasma control, **49th EPS Conference on Plasma Physics**, Bordeaux, France, 2023, DOI: 21.11116/0000-000E-2835-A.

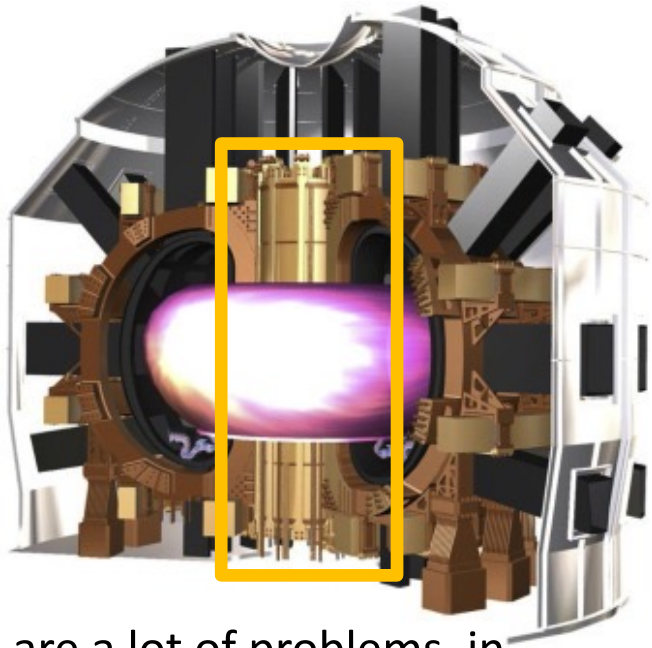
Research products

[C2]	E. Acampora, V. Di Marzo et al. Scenario feasibility and plasma controllability for Volumetric Neutron Source (VNS), **33rd Symposium on Fusion Technology,** Dublin, Ireland, Sept. 2024, DOI: 21.11116/0000-000F-F2F0-0.
[C3]	V. Di Marzo et al. Electromagnetic and Mechanical analyses of an explorative HTS-based Central Solenoid for the DTT Tokamak, **29th Magnet Technology Conference,** Boston, MA (USA), July 2025, poster session.

PhD thesis overview

Problem:

- Tokamaks represent a possible solution to get energy from nuclear fusion of particles in the state of «plasma».
- To realize this we need:
  - Extreme temperatures (both high and low).
  - High currents;
  - High magnetic fields.



Tokamak's components are subjected to very demanding conditions

A very critical component is the **Central Solenoid (CS)** (there are a lot of problems, in particular):

High currents + high fields => use of superconductors & high mechanical stresses

Fast time-varying magnetic field (in some instants) => high AC losses

PhD thesis overview

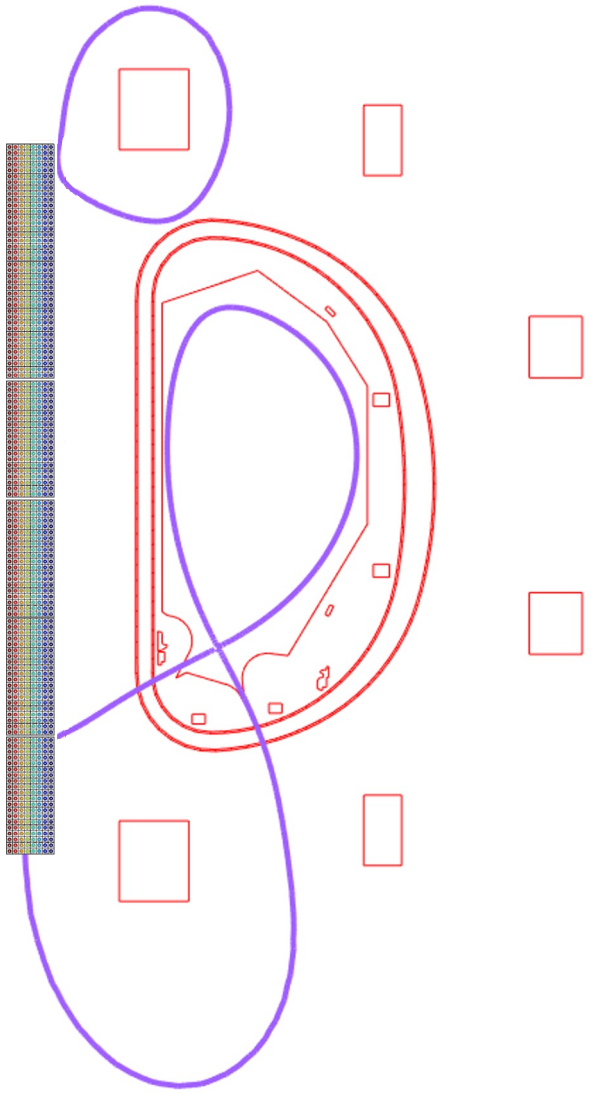
Core question:

How can we design an optimal and mechanically sound Central Solenoid while preserving electromagnetic performance?

PhD thesis overview

Objectives:

- To find **optimal configurations** (geometry, number of conductors, layout …) of Central Solenoids due to constraints (also including new innovative materials as **High Temperature Superconductors** - HTS);
- Identify the **mechanical stress field** and develop static and fatigue studies;
- Develop with the found CS geometry a **simulation of a plasma scenario** (that is a plasma discharge);
- Have a **first estimation of AC losses**;



PhD thesis overview

Methodology:

- Analysis of High and Low Temperature Superconductors **properties**;
- Identification of an optimal, feasible and robust **CS configuration** in order to **maximize the poloidal magnetic flux** in a tokamak (implemented in MATLAB);
- **Preliminary validation** of the optimal solution through **electromagnetic and mechanical simulations** in critical snapshots of the plasma scenario (implemented in ANSYS APDL);
- Development of the **electromagnetic plasma scenario**;
- First instance estimation of the **AC losses** in the conductors.

PhD thesis

- Considering the DTT Tokamak, the **Central Solenoid** is still in its **pre-design phase** (respect to other components).

Problem of the previous CS configuration:

- Full LTS CS with complex winding pack (problems in EM performances, mechanical stress, thermofluidynamics …)

Analyses of new CS configurations:

- Full HTS CS with a simpler winding pack (exploratory study);
- LTS CS with an HTS insert (current reference geometry).

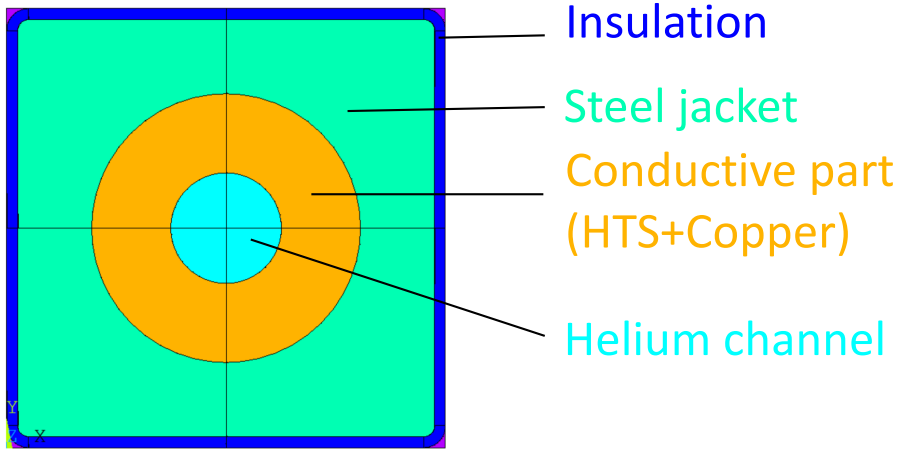
(Some) advantages of conductors with HTS tapes:

- Higher current density wrt LTS at higher fields and temperatures;
- Higher structural rigidity.

PhD thesis

First exploratory study – full HTS CS:

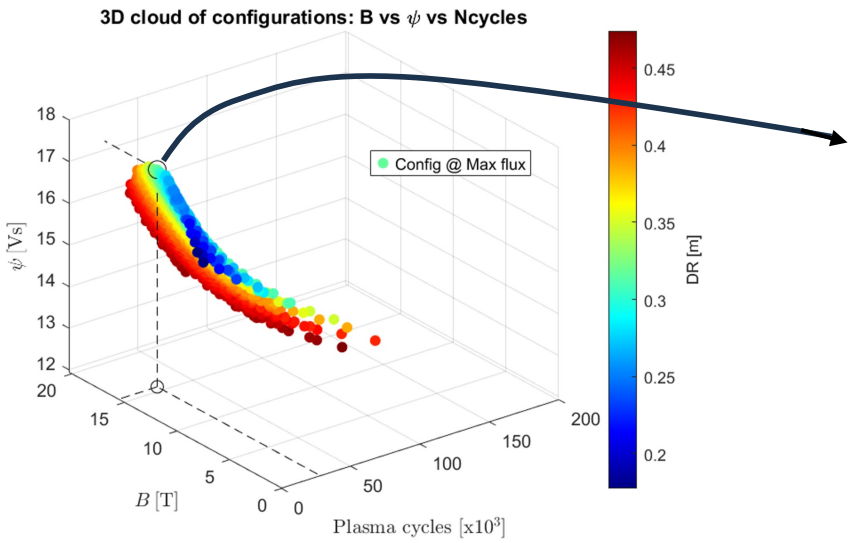
- Conductor architecture:

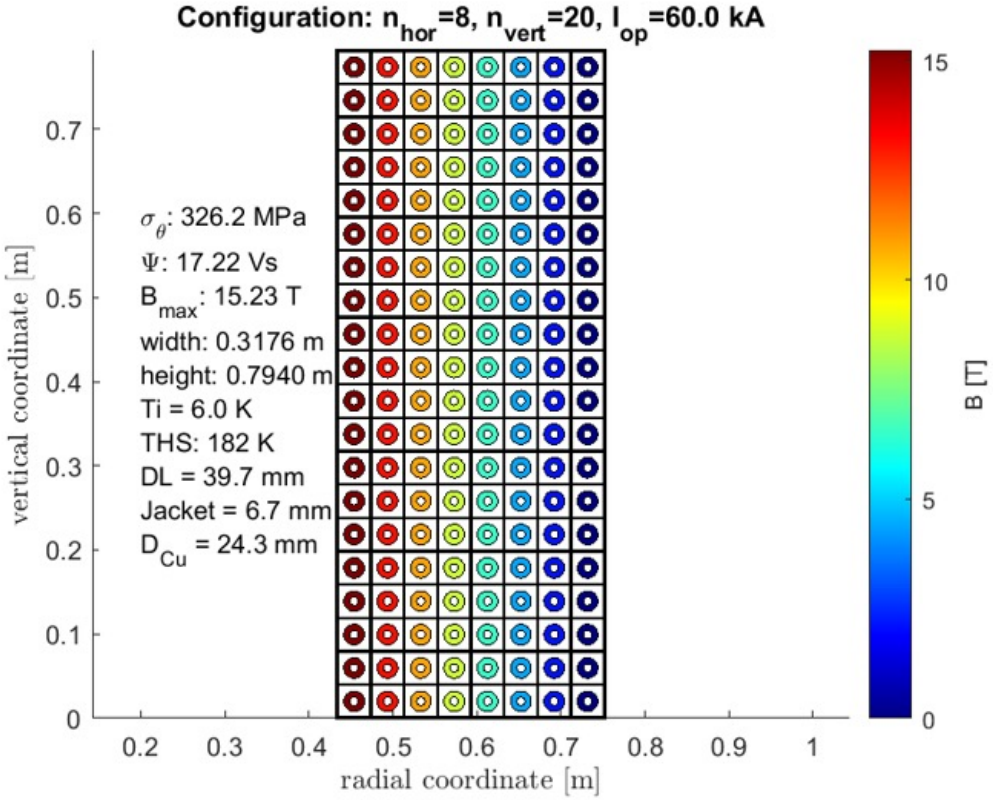


- Search of an optimal configuration:
  - Lots of possible combinations have been examined;
  - The **optimal one** is the one that survives to at least **25,000 operative cycles** that **maximizes the magnetic flux**.

PhD thesis

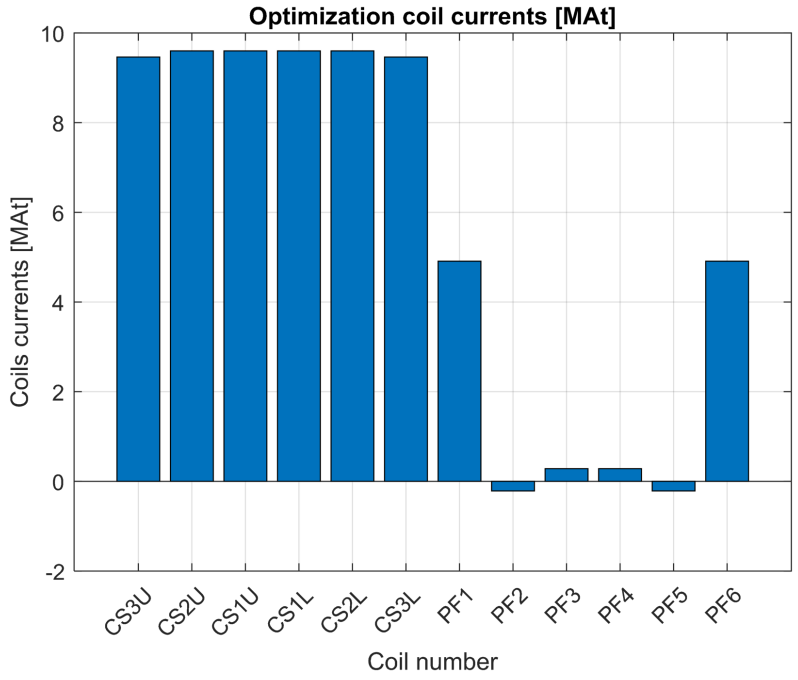
- Cloud of examined configurations:

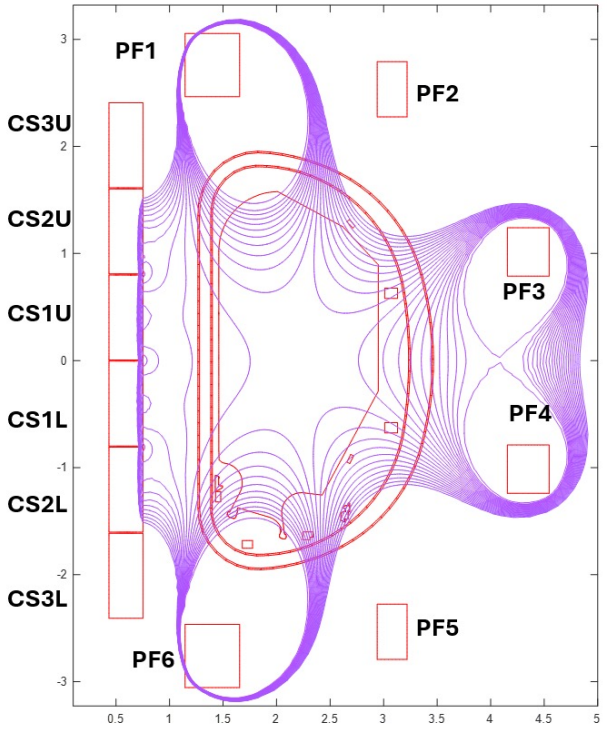




PhD thesis

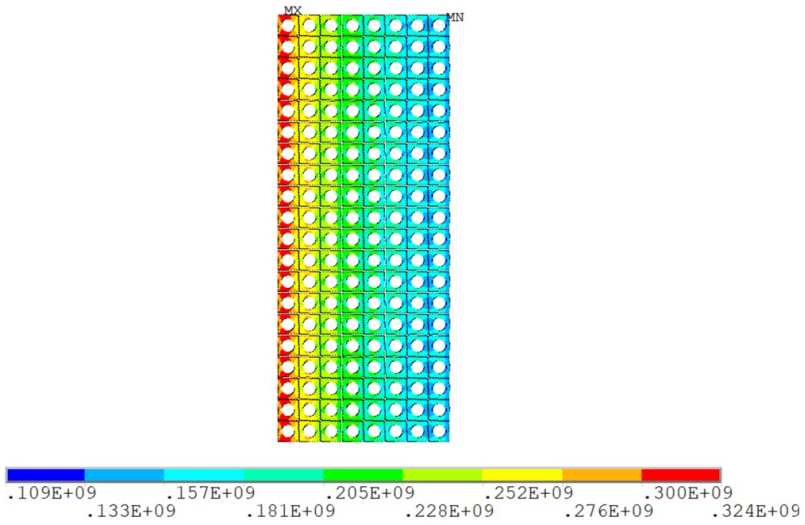
- Identification of an optimal current set capable of maximizing the flux at the beginning of the discharge:

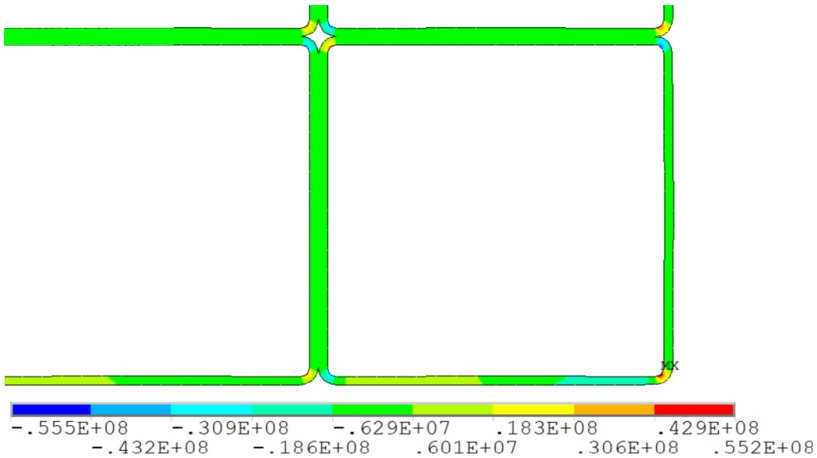




PhD thesis

- EM and mechanical analyses + assessment of conductor's jacket and insulation:

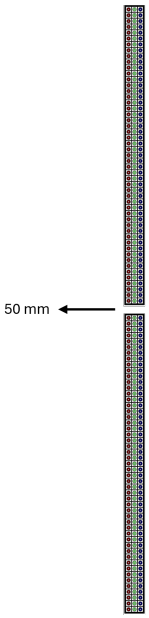


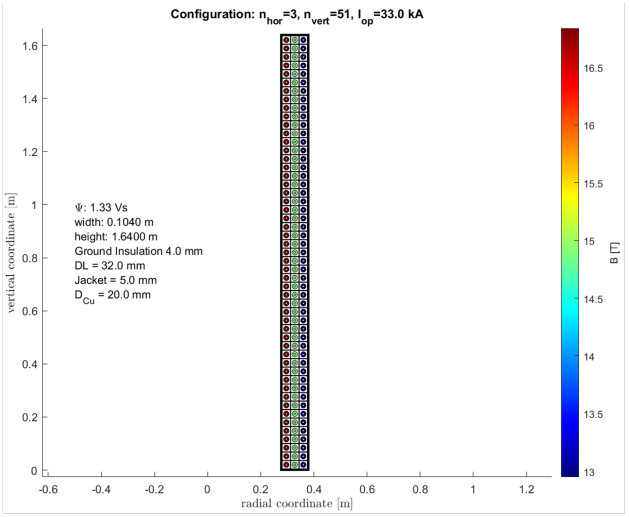


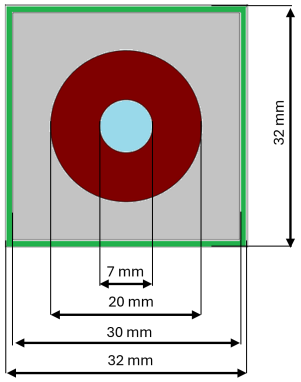
- The overall plasma scenario has not been developed because not necessary (not a reference configuration).

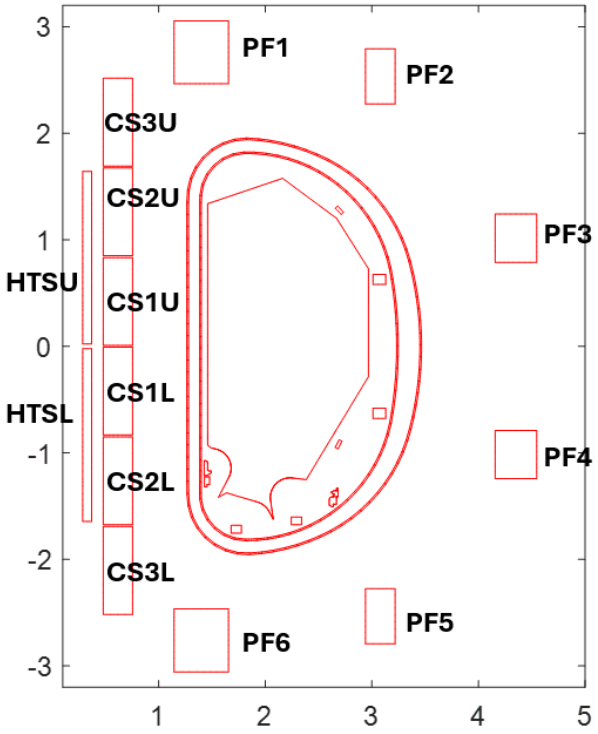
PhD thesis

Second study – Current configuration with LTS CS and HTS insert:



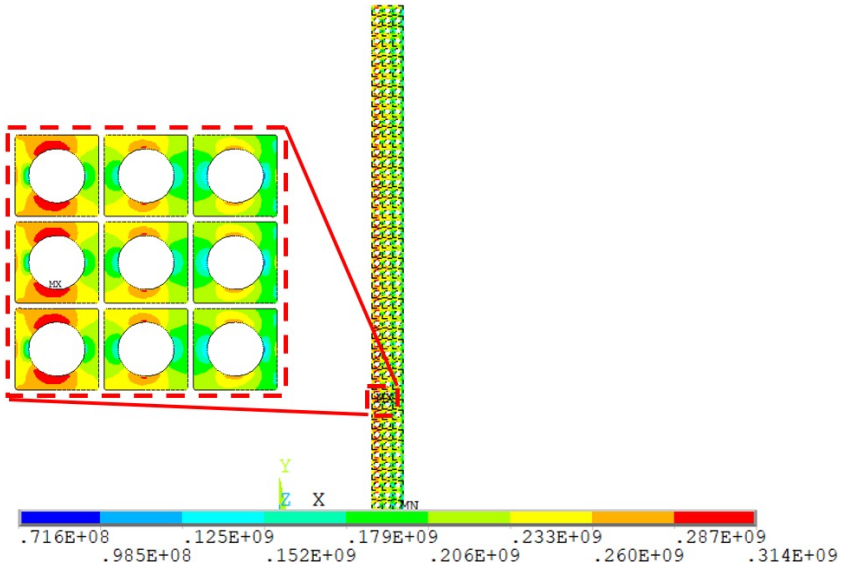


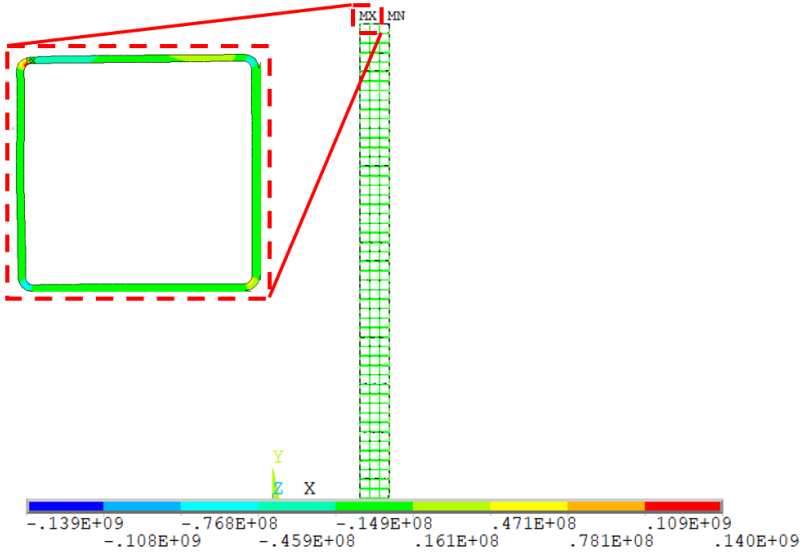




PhD thesis

- EM and mechanical analyses + assessment of conductor's jacket and insulation:





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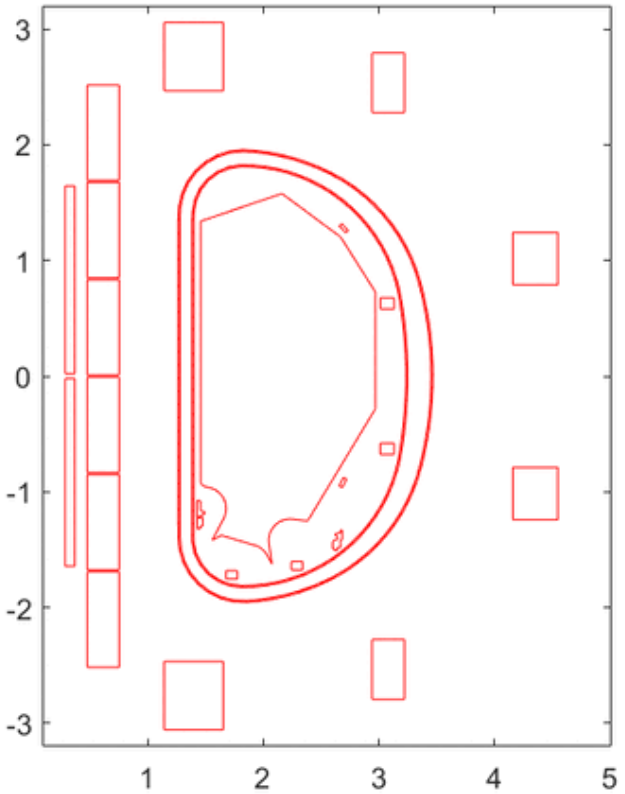
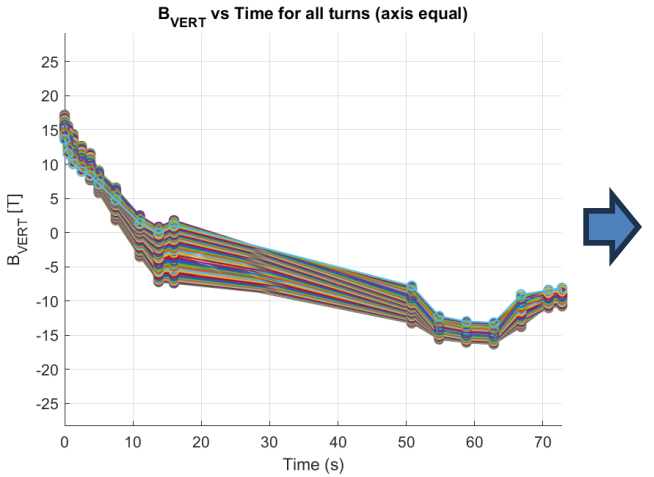
- Development of the overall plasma scenario:
  - Starting from previous current calculations, a new optimal current set has been developed for the overall plasma scenario, allowing to see the current in each superconducting conductor of the HTS insert.

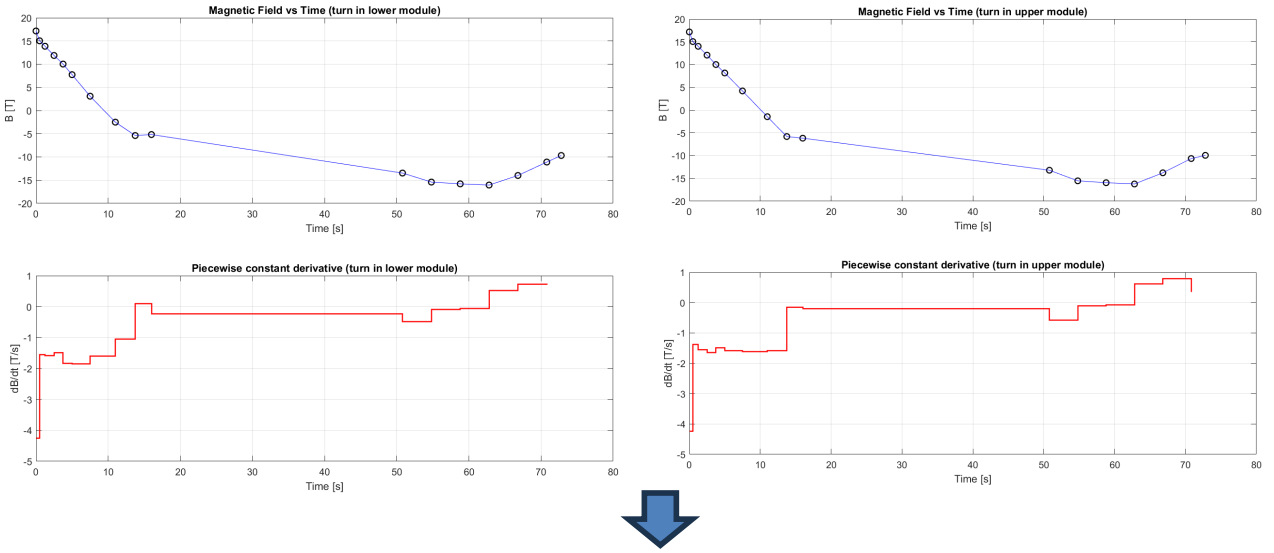


- AC losses estimation.

PhD thesis

- AC losses estimation:
  - Identification of a conductor subjected to very demanding time-varying magnetic field conditions;
  - Analytical estimation of the AC losses (hysteresis + coupling).





Turn in:	E_{hyst} [kJ/m]	E_{coupl} [kJ/m]
Upper module	6.02	2.99
Lower module	6.08	2.95

PhD thesis

Future works:

- Methodology:
- Improvement of the proposed methodology considering the following aspects:
  - fatigue analysis of the steel jacket of the HTS insert;
  - comprehensive mechanical analyses of the overall system;
  - further analyses on the conductors' insulation;
  - development of more accurate models for the evaluation of AC losses.

- Testing:
- Final validation of the proposed solution for DTT (as this pre-design phase is expected to be completed by mid next year).

Thank you for your kind attention