ENERGETICS

MUR DM 118 - Development of a digital twin for the operation of MW-class gyrotrons for plasma heating and current drive in fusion reactors

Funded By	Dipartimento Energia [P.iva/CF:00518460019] MINISTERO DELL'UNIVERSITA' E DELLA RICERCA [P.iva/CF:97429780584]

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Context of the research activity	The proposal aims to develop an innovative simulator for MW-class Gyrotrons, addressing challenges posed by complex time-variant multi-physics systems, integrating physical aspects into a unified computational environment using reduced order techniques for faster simulations without compromising accuracy. The ultimate goal is to build an efficient object-oriented simulator, enabling sensitivity analyses and development of control strategies. Progetto finanziato nell'ambito del PNRR – DM 118/2023 - CUP E14D23001610006

	The research project focuses on developing an innovative simulator for MW-class Gyrotrons, which are used for plasma heating in fusion reactors. These devices can only be described by complex, time-variant multi-physics systems, where electromagnetic and radio frequency aspects, thermo-fluid dynamics (thermal heat transfer by conduction, convection, radiation, and fluid dynamics), are intricately linked to all aspects related to mechanical expansions. The integration of these closely interconnected physical phenomena makes the analysis very challenging when approached using traditional methods, where individual dedicated codes describe a single physical phenomenon, and their results are made available to other simulators. One possible solution to the multi-physics problem is to couple different dedicated codes using numerical techniques (e.g., Picard iteration), linking inputs and outputs as appropriate boundary conditions and iterating on different solutions to achieve convergence. Another approach is to integrate all physical aspects into a unified computational environment, such as OpenFOAM, capable of efficiently handling all Gyrotron description models.

Objectives	The critical aspect of this approach lies in the numerical issues arising from the varying time constants of the different involved aspects and the length of simulations, which can lead to significantly high computational times, making it difficult to perform parametric or local and global sensitivity analyses with respect to various parameters. To overcome this problem, reduced order techniques will be utilized to accelerate the simulations without compromising accuracy compared to the full model built beforehand. Additionally, in case of convergence issues with the full model, a reduced model could be derived for each individual dedicated code, and then the physics represented by their reduced models could be coupled (this approach, still under development, is referred to as reduced multi-physics and offers a solution to excessively complex models from the perspective of numerical simulation). The ultimate goal of this research is to construct a time-variant simulator dedicated to Gyrotrons, utilizing the potential of the Object-Oriented modeling language such as Modelica. In this simulator, different components of the Gyrotron (Magneto-Injection gun, cavity, launcher, collector, etc.) will be represented by a specific library, and all libraries will be interconnected through connectors capable of exchanging information. The models within each library must describe the specific component and can do so using a simplified, lumped, or reduced order model derived from the previous full model. Therefore, the object-oriented simulator would be composed of multiple component libraries, whose models would be directly derived from the corresponding full-order models obtained using multi-physics codes. This would enable the creation of a simulator with reduced execution times while maintaining the accuracy of a 3D finite volume/element simulator. At the end of this research, a simulator will be available that, thanks to the Object-Oriented technique, can simulate a complex system like the Gyrotron using accurate techniques such as reduced order from full multi-physics models. Alternatively, within the component library, a less rigorous description can be adopted, depending on the needs. This way, a comprehensive simulator for a key component in future fusion reactors could be realized, capable of simulating time-variant operational transients over significant time intervals, conducting parametric and sensitivity analyses, understanding all relationships between the various involved physical phenomena, and defining the most appropriate control and optimization strategies. In conclusion, the research project will be structured as follows: 1. Definition of all relevant components and physical phenomena 2. Construction of a full-order and high-fidelity model for the Gyrotron 3. Development of reduced models for each component 4. Incorporation of these reduced models into an object-oriented simulator, where each component is represented by a library with embedded model/models 5. Time-variant operational simulations, parametric and sensitivity analyses, and definition of control and optimization strategies.

Skills and competencies for the development of the activity	The candidate should be genuinely interested in pursuing a Ph.D. and has a solid background in modeling and complex systems. Their experience and skills demonstrate a sincere commitment to research and a desire to make valuable contributions to the field.