PLASMA PREDICTION AND SIMULATION IN SUPPORT OF REACTOR DESIGN AND OPERATION AT TOKAMAK ENERGY

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Plasma modelling and simulation remains one of the most formidable challenges in the development of viable fusion power. Advances in artificial intelligence, high-performance computing, and experimental diagnostics are gradually improving predictive capabilities. However, achieving a truly reliable and scalable simulation framework that can guide the design of commercial fusion reactors is still an ongoing pursuit. Overcoming these challenges is crucial to making fusion energy a practical and sustainable power source for the future.
A fusion power plant is not just a plasma confinement device—it includes cryogenic cooling systems, breeding blankets for fuel generation, fuel cycle and heat extraction systems for power generation. Simulating the entire plant, from plasma dynamics to thermal and structural performance, requires coupling reliable plasma models with engineering simulations, further increasing complexity.
While fusion experiments provide valuable data, real-world measurements are limited by diagnostic constraints and other limitations. Many plasma properties, such as turbulence characteristics or magnetic reconnection events, are difficult to measure directly. This limits the ability to validate models, making it challenging to improve simulation accuracy.

At Tokamak Energy we have launched a programme that aims at tackling the above challenges by designing dedicated experiments on ST40 to investigate the most urgent questions for Spherical Tokamaks in parallel to the development of simulation frameworks for the support of plasma operation and integrated plasma modelling for fusion plant design.

One of such frameworks is SOPHIA [1], a versatile tokamak plasma simulator developed by Tokamak Energy. It integrates models for the plasma, diagnostics, actuators and the plasma control system, providing a ‘control room’-grade experience to the operator. SOPHIA has been successfully deployed on the high-field spherical tokamak ST40 in the preparation of new scenarios (for both single and double-null diverted configurations), in the validation of experiments, the testing of new controllers and in the training of session leaders. The validation of SOPHIA and its physics models on ST40 enables the development of plasma scenarios in the next generation of devices, such as a spherical tokamak Fusion Pilot Plant (FPP: Tokamak Energy, supported by the US DOE Milestone-Based Fusion Development Program), to be carried out with a higher level of confidence. SOPHIA can be used to test whether a proposed design point is feasible by assessing the controllability of the design under a set of assumed realistic models for the control system, device actuators, diagnostics and plasma dynamics.
The integration of SOPHIA with existing pulse preparation and analysis tools makes it ideal for the training of new ST40 pilots and session leaders in charge of Tokamak operations. Old pulses which had been executed with pulse preparation errors, as well as newly generated errors, can both be added to SOPHIA runs, enabling a pulse database to be constructed, from which AI based virtual pilots for future fusion plants could be trained.
By design, SOPHIA is a machine-independent tool that can be deployed on other tokamaks. In this contribution, we will describe the implementation of SOPHIA on ST40 and other experimental Spherical Tokamaks as well as on Tokamak Energy’s Fusion Pilot Plant design, and report on the results of predictive scenario simulation. Using

the MATLAB/Simulink environment, SOPHIA integrates the transport code ASTRA [2], which is tightly coupled to the equilibrium code SPIDER [3], as well as models for diagnostics, actuators and the control system.

During recent campaigns on the spherical tokamak ST40, it has become clear that Internal Reconnection Events (IREs) have caused the plasma ion temperature and density to be significantly reduced, but without the plasma current collapse characteristic of a disruption. Sawtooth instabilities can have similarly deleterious effects. Databases have been collected including the instability time and type, and the physics and control current values at plasma times leading up to each type of instability. Back propagation neural networks have been used to train the Time To Reconnection *TTR* as a function of selected variables V_i for around 60 shots suitable for analysis. Suitable shots with no instability can be given a *TTR* comparable to the shot time. The stored trained network for any IRE type is able to reproduce the time to reconnection for any chosen values of the variables. In particular the differentials $dTTR/dV_i$, although often negative, are sometimes positive indicating that the onset of the IRE might be delayed by such a change. The process works both with salient physics variables, such as internal induction l_i and poloidal field b_P, and control currents, such as solenoid and poloidal field currents. It is hoped that the SOPHIA code will be able to select configurations capable of giving significant improvements in plasma stability.

Tokamak Energy Inc, the US subsidiary of the UK based private fusion company Tokamak Energy Ltd, was selected as one of eight awardees of the U.S. Department of Energy's Milestone-Based Fusion Development Program, which is supporting designing a fusion pilot plant (FPP) based on the spherical tokamak and high temperature superconducting magnets. To aid in the design of its FPP concept, Tokamak Energy will make use of a new open-source JULIA-based software suite built around the FUSE[4] framework, originally developed by General Atomics. The FUSE framework is used to rapidly produce self-consistent candidate designs of an FPP, bringing together physics and engineering codes in an automated manner, minimising the need for time consuming manual intervention by domain experts. This contribution will present applications using FUSE to identify optimum design points for an FPP with a particular focus on identifying solutions with manageable exhaust conditions. This has been achieved by the addition of new low-fidelity scrape-off layer models [5] in FUSE, improving the code's core-edge integration capabilities, as well as further developing the algorithms in FUSE responsible for constructing the divertor structure and device layout.

In parallel with the FUSE development, Tokamak Energy's system code PyTok has been integrated with the results of the open-source plasma modelling code METIS [6], originally developed by CEA.

All the above simulation platforms need reliable models for plasma performance. Indeed, the performance of a fusion reactor along with the heat loads on the walls is directly linked to plasma confinement. The dependency of confinement on magnetic field and current in a Spherical Tokamaks is still an open question with experimental results carried out in low field STs indicating a linear scaling of confinement with B [7]. ST40 allows to validate confinement models in a region of the parameter space never accessed before in Spherical Tokamaks. The impact of ST40 results on the confinement scaling and transport models used in modelling future fusion reactors will be presented along with the results of transport model validation in similarity experiments between ST40 and KSTAR analysed using the TRIASSIC [8] framework. Previous work showed good agreement between measured and TGLF predicted plasma performance in both ST40 and KSTAR hot ion mode. The direct comparison between ST40 and KSTAR plasmas will shed light on the role of aspect ratio and edge safety factor on plasma performance.

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