TOWARDS DIGITAL TWINS OF FUSION SYSTEMS

OV: Overview

Achievements of the E-TASC initiative

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Background. Bridging the gap to next-step devices – while saving valuable time and resources – requires more than semi-empirical models, which struggle to **predict plasma behavior in unexplored parameter regimes**. Instead, validated simulation tools are essential, leveraging high-fidelity exascale computing and multi-fidelity models, including AI-based surrogates. To address these challenges, the "**EUROfusion Theory and Advanced Simulation Coordination (E-TASC)**" initiative was launched in 2021 [1]. It includes 15 TSVV (Theory, Simulation, Verification, and Validation) projects supported by 5 Advanced Computing Hubs. This "team of teams" has made substantial progress toward developing digital twins of fusion systems, with **key scientific achievements** to be presented.

Predicting MHD transients in next-step devices. MHD-induced transients pose a significant risk to the operation of tokamak-based fusion power plants. Disruptions have been extensively studied using state-of-the-art codes such as JOREK and DREAM. Research on disruption mitigation via shattered pellet injection has identified the mechanism by which it reduces the global vertical force [3,a]. Additionally, runaway electron dynamics and their impact on mitigated disruptions in JET, ITER, and DEMO have been analyzed [4,b,c]. Also, new insights have been gained into the control of H-mode pedestal instabilities (e.g., ELMs) via external magnetic perturbations or X-point radiators [d].

Predicting core performance. In recent years, it has become increasingly evident that a nonlinear interplay exists between turbulence, energetic particles, and MHD modes in the plasma core. Key findings based on comprehensive gyrokinetic (GK) simulations highlight the turbulence suppression by energetic particles, the interaction between turbulence and Alfvénic modes in high-beta plasma regimes, and the operational limits imposed by kinetic ballooning modes (KBM) [5]. The results [e] include global fully GK simulations demonstrating generation of zonal flows by Toroidal Alfvén Eigenmodes in JET plasmas [6], self-consistent nonlinear growth of a magnetic island and its interaction with turbulence in a toroidal geometry [7], nonlinear excitation of Alfvénic modes by the ambient turbulence in W7-X [8]. The implications for ITER operation will be discussed.

Predicting L-H transitions and ELM-free regimes. GK edge turbulence simulations have been used to characterize ion- and electron-scale pedestal turbulence across L, H, I, and EDA-H modes, highlighting key players such as KBM proximity, the effects of ExB and magnetic shear, the role of impurities and confirming the relevance of slab and toroidal ETG modes. Additionally, to gain deeper insights into L-H transitions, a multi-fidelity hierarchy of models – ranging from ASTRA-TGLF to flux-driven fluid and GK codes – has been employed to demonstrate and compare the profile steepening following with increased input power crucial to L-H transition modeling [9,10]. This range of models has been exploited to identify the impact of missing physics at each level of the hierarchy and to guide future developments in both fluid and kinetic edge modeling.

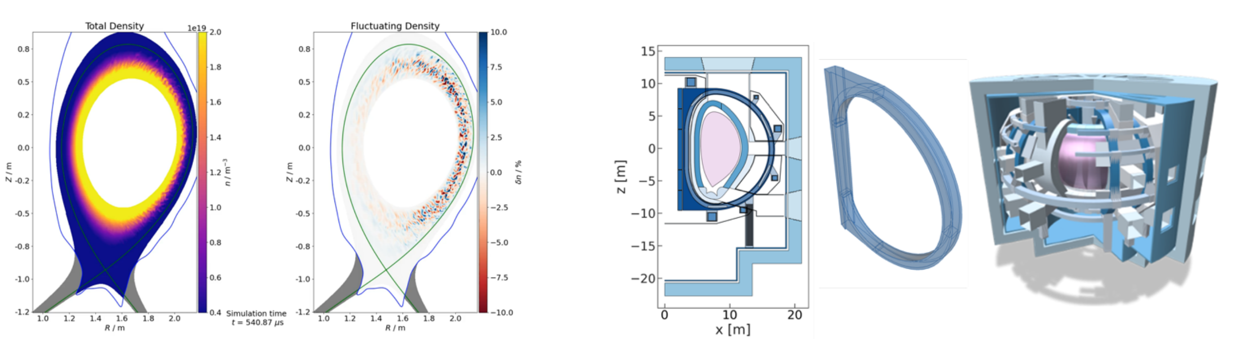

Fig. 1: Examples for important steps towards digital twins of partial or complete fusion systems: [Left] Turbulent transport in AUG, simulated with the fast full-f gyrokinetic GENE-X code. [Right] BLUEMIRA-generated CAD for DEMO: 2-D cross section, TF coil, and whole reactor 3D CAD.

Predicting plasma exhaust physics. To overcome the limitations of edge "mean-field" codes like SOLPS-ITER, a complementary suite of full-f fluid and GK codes with advanced modeling and magnetic geometry capabilities has been developed and validated [11]. Notably, the GENE-X code – a grid-based GK edge turbulence code in X-point geometry – achieved a 50x speedup [12], reducing its computational cost to that of a fluid code [see Fig. 1]. The SOL fall-off widths predicted by GENE-X have been successfully validated against TCV-X21 experiments [13]. Significant efforts have also been dedicated to enhancing fluid turbulence codes by incorporating divertor physics in a self-consistent manner. This breakthrough has enabled, for the first time, turbulence modeling in power-plant-relevant regimes such as divertor detachment, revealing a strong response of turbulent transport and SOL width to divertor dissipative conditions [14,f].

Predicting plasma-wall interactions in DEMO. Scoping studies with state-of-the-art codes have provided design- and safety-relevant estimates for DEMO [g,h]: (i) tungsten erosion in the main chamber is highest around the mid-plane, dominated by fast charge-exchange neutrals, while tungsten re-deposition is pronounced in the divertor; (ii) dust mobilized from the divertor floor evaporates at separatrix and redeposits predominantly in divertor corners; (iii) neutron-induced material damage leads to many-fold increase of tritium retention and respective reduction of permeation, with simulations for divertor monoblocks highlighting the role of 3D simulations for proper description of outgassing fluxes; (iv) material melting simulations are enhanced with a state-of-the-art thermionic electron emission model derived from kinetic simulations, and particular scenarios of transient vertical displacement events are identified that provide high heat loads on wall elements, with risks of material melting and melt splashing. The established modeling framework [15] guides the design of future machines in unexplored parameter regimes.

Assessing the potential of negative triangularity tokamaks. The differences between negative and positive triangularity (NT, PT) tokamaks were studied systematically. GK simulations of idealized and experimental equilibria have revealed that NT generally improves core plasma confinement (in conventional aspect ratio tokamaks), with these benefits scaling well to larger devices [16,17]. Edge turbulence analysis indicates that NT will have better power exhaust than PT H-mode, due to a wider scrape-off layer width and no ELMs [18]. An NT power plant may also optimize very differently than PT. MHD calculations show that NT plasmas are less vertically stable, encouraging lower elongation, while 0D power balance calculations motivate reducing auxiliary heating, exploiting the lack of an L-H power threshold. Fast particle transport and Alfvénic modes show little difference between NT and PT plasma shapes.

Designing optimized stellarators. GK core turbulence codes have successfully reproduced the zonal flow frequency spectra measured in W7-X standard ECRH plasmas and, coupled to transport solvers, the profile shape of several W7-X scenarios. Additionally, the role of impurities on reducing or enhancing heat fluxes in W7-X, LHD, and ITER have been comprehensively investigated [19] as well as the Alfvénic activity in W7-X with global gyrokinetic codes [20]. – Significant breakthroughs in general stellarator optimization include the concept of piecewise omnigenous stellarators, discovering new stellarators with excellent neoclassical confinement [21]. In addition, compact stellarator-tokamak hybrids [22] and QI designs with improved properties compared to W7-X, such as better fast-particle confinement, have been developed [23,24,i].

Towards digital twins of fusion systems. The activities described above pave the way for realistic virtual representations of partial or complete fusion systems. In the realm of integrated plasma modeling, a newly developed High-Fidelity Plasma Simulator has been applied to analyze JET D-T plasmas and the ITER 15 MA scenario, targeting record fusion power. Additionally, Pulse Design Tool prototypes have been employed to study discharges from three key experiments: AUG, TCV, and WEST. On the engineering front, the BLUEMIRA framework has integrated critical systems with parametric space-saving CAD — including the magnets, vacuum vessel, first wall, blanket, coil support structures, and cryostat — combined with systems codes (e.g., PROCESS) and mid-fidelity physics models. Applications to DEMO design [see Fig. 1] will be presented.

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