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TOWARDS DIGITAL TWINS OF FUSION SYSTEMS
Achievements of the E-TASC initiative

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Abstract

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. 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 in the paper. This includes the following topical areas: core performance in burning plasmas, magnetohydrodynamic transients, L-H transitions and ELM-free regimes, plasma exhaust, and plasma-wall interactions – with applications to both tokamaks and stellarators.

1. INTRODUCTION

As the demand for clean energy grows ever more urgent and fusion research gains momentum, high-performance computing (HPC) has become a critical enabler, accelerating the path toward practical fusion power [1]. Supercomputers allow researchers to simulate complex plasma dynamics with high precision, supporting the prediction and optimization of confinement, stability, and exhaust. As the field moves from laboratory experiments to pilot plants, HPC bridges scientific discovery and engineering application, reducing costs and shortening development timelines.

The mathematical equations governing fusion plasmas are notoriously difficult to solve analytically, due to strong nonlinearities and associated multi-scale, multi-physics effects. To address this, and in close exchange with theory and experiment, researchers rely on advanced numerical methods to solve plasma physics equations computationally. Modern supercomputers – reaching the exascale, i.e., over 10^{18} floating-point operations per second – can run detailed simulations that capture a wide range of physical processes, enabling predictions of plasma behavior under conditions beyond current experimental access.

Rigorous verification and validation of high-fidelity models lay the foundation for fast reduced models, often enhanced by modern statistical methods and artificial intelligence. These surrogate models can be deployed for high-throughput applications such as optimization, uncertainty quantification, and real-time control. Unlike semi-empirical approaches, they are grounded in first principles, greatly strengthening their predictive power. The long-term vision is the creation of digital twins of fusion systems, driving faster progress in fusion research.

In this context, the EUROfusion Theory and Advanced Simulation Coordination (E-TASC) initiative was launched in 2021 [2]. Bringing together 15 TSVV (Theory, Simulation, Verification, and Validation) projects supported by 5 Advanced Computing Hubs, this "team of teams" has made significant advances toward developing digital twins of fusion devices, with key achievements highlighted below.

2. PREDICTING CORE PERFORMANCE IN BURNING PLASMAS

In the foreseeable future, several experiments worldwide will aim to produce energy from burning plasmas. In such plasmas, energetic particles are abundant; they can destabilize Alfvén waves and generate new synergies and couplings between physical subsystems that are usually treated as independent. In burning plasmas, fine-scale turbulence and zonal flows cannot be considered separately from fast particles and Alfvén waves. Moreover, magnetohydrodynamic (MHD) instabilities such as kink modes, fishbones, or tearing modes will strongly influence plasma dynamics, turbulence, and transport. As a result, plasma profile evolution becomes a multi-scale, nonlinear problem, with its components and interactions inherently global and kinetic in nature. Global nonlinear gyrokinetic theory offers an optimal, unified framework for addressing this challenge self-consistently.

Alfvén waves destabilized by energetic particles provide a striking example of this kind of nonlinear plasma dynamics. In particular, modes that change their frequency during evolution – the so-called chirping modes – have been studied extensively with the global gyrokinetic code ORB5. Large sets of simulations, spanning a wide range of plasma and energetic-particle parameters, revealed a universal scaling: the chirping rate is proportional to the saturation amplitude of the nonlinear instability [3]. This relation also holds for other types of nonlinear waves, including whistler waves in Earth's magnetosphere and even at Mars.

Another key aspect of the burning-plasma system is electromagnetic turbulence. While low-beta plasmas are often dominated by Ion Temperature Gradient (ITG) modes, high-beta scenarios tend to exhibit Kinetic Ballooning Modes (KBMs). ORB5 simulations reproduce the characteristic dependence of linear growth rates on beta, tracing the transition from electromagnetically damped ITG modes to electromagnetically driven KBMs [4]. Nonlinearly, the turbulent heat fluxes rise in these global simulations sharply with increasing plasma beta in the KBM-dominated regime. This behavior is linked to the electromagnetic suppression of zonal-flow generation. Instead, KBM turbulence produces finger-like structures that are expelled from the linearly unstable region, accompanied by temperature profile relaxation.

Fast ions further enrich this picture. Toroidal Alfvén Eigenmodes (TAEs) destabilize zonal flows at twice their linear growth rate (beat-driven zonal flows), which in turn suppress ITG turbulence (demonstrated in JET plasma simulations [5]). In Wendelstein 7-X (W7-X) stellarator plasmas, turbulence itself can drive Alfvén waves nonlinearly [6]. Global gyrokinetic codes have also been applied to MHD dynamics [7,8] and transport, though such calculations are computationally demanding. As an alternative, reduced models are employed – e.g., the hybrid-MHD code XTOR-K for sawtooth dynamics and the ATEP code for fast-ion-driven Alfvénic transport. Applications of these tools to ITER scenario modeling are discussed in Refs. [9,10]. An overview of these many interlinked components is shown in Fig. 1.

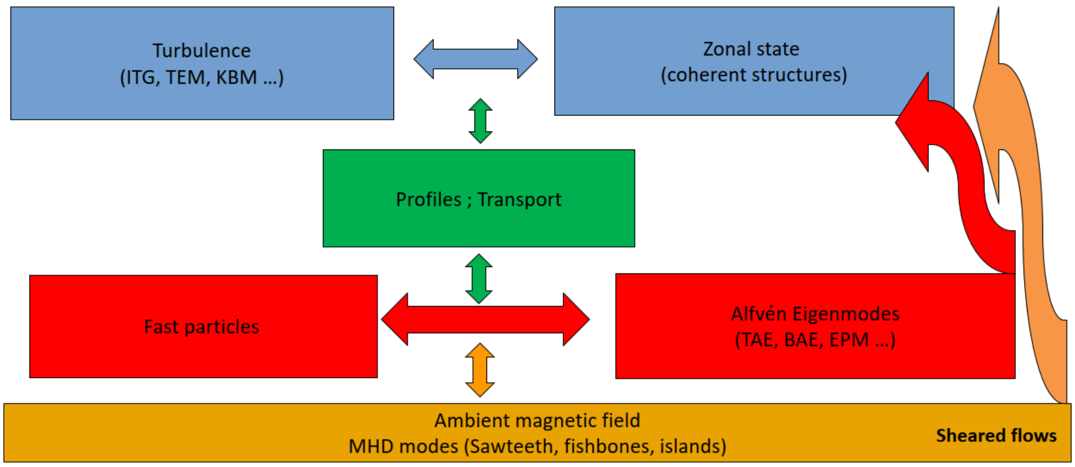

FIG. 1: Fusion plasma dynamics involve many interlinked components, with interactions that are inherently global and kinetic. Global gyrokinetic theory provides the most self-consistent framework for their description.

3. PREDICTING MHD TRANSIENTS IN NEXT-STEP DEVICES

Recent research based on the 3D nonlinear MHD code JOREK has advanced the modeling of transient instabilities in magnetically confined plasmas [11]. Studies cover edge and scrape-off layer physics, disruptions, runaway electrons (REs), core dynamics, and stellarators, with strong links to experiments. The kinetic code DREAM provides complementary results regarding REs and disruption mitigation. Predictions span ITER, DEMO, JT60-SA, SPARC, and DTT.

At the plasma edge, JOREK has reproduced natural ELM-free regimes, ELM suppression by external magnetic perturbations (RMPs), and pellet-triggered ELM dynamics [12]. Hybrid fluid-kinetic models address divertor physics, tungsten transport in RMP ELM suppressed plasmas [13], as well as X-point radiator formation and dynamics. In disruption studies, JOREK has captured key aspects of force mitigation during vertical displacement events [14]. Improved SPI modeling with DREAM and JOREK reproduces various experimental observations [15,16], and current spikes have been explained via Alfvén wave propagation and large-scale mixing [17]. A novel 3D full-f kinetic RE model in JOREK, coupled to MHD, represents a significant step forward [18]. Updated ITER studies suggest that the vertical plasma motion of elongated plasmas can reduce RE avalanches [19] which may improve RE avoidance prospects according to DREAM simulations [20]. Simulations provide a basis for RE impact studies and detailed material damage assessments.

In the core, results include flux pumping that may prevent sawteeth [21] and studies of pellet plasmoid dynamics [22]. Stellarator extensions cover nonlinear soft beta-limit behavior [23] and ECCD-driven relaxation dynamics. Computational upgrades – including GPU acceleration, enhanced hybrid fluid-kinetic frameworks, resistive wall coupling, and IMAS [24] integration – have established JOREK and DREAM as central tools for interpreting experiments and predicting transient behavior in future fusion devices.

4. PREDICTING L-H TRANSITIONS AND ELM-FREE REGIMES

To develop a predictive, physics-based description of edge turbulence, local and global gyrokinetic simulations of ion-, electron-, and multi-scale turbulence in H-, QH-, I-, and L-mode pedestals have been validated against ASDEX Upgrade and JET data. Turbulence at the pedestal top is typically dominated by ion-scale modes, such as ITG or microtearing modes, with the pedestal lying just below the KBM threshold [25-27], highlighting electromagnetic effects. Toward the pedestal foot, electron-scale Electron Temperature Gradient (ETG) modes dominate, with mixed toroidal and slab characteristics [28]. Transport levels are reasonably captured by reduced models [29], and E×B shear, magnetic shear, and impurity seeding can substantially reduce fluxes.

Regarding the generation of the radial electric field, GYSELA simulations have shown that neoclassical toroidal viscosity, driven by magnetic ripples, can dominate the flow drive once the ripple amplitude exceeds a critical threshold [30], potentially overriding turbulence-driven Reynolds stress. A comparative analysis of WEST and Tore Supra measurements reproduces the experimentally observed trend of decreasing flow with increasing safety factor q. This behavior can be understood as a competition between turbulence-driven flow (∝ 1/q) and collisional damping (∝ q) [31].

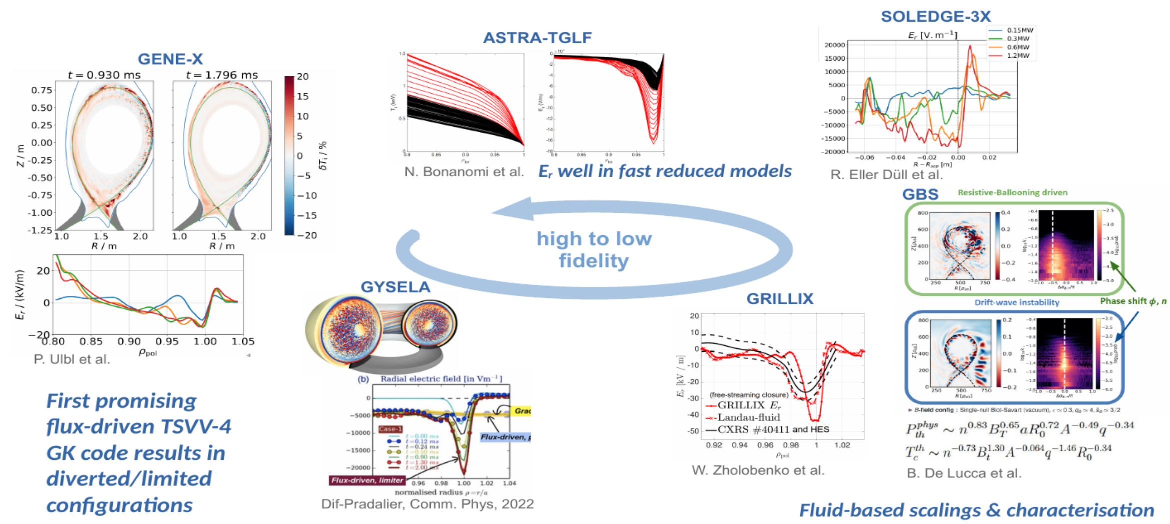

FIG. 2: Hierarchy of models employed in the L-H transition task to study power scan induced profile changes, radial electric field formation and scaling laws.

To develop an interpretative and predictive capability for the L–H transition, a multi-fidelity hierarchy of models has been established, ranging from transport codes such as ASTRA-TGLF to edge turbulence codes like GRILLIX and GENE-X (see Fig. 2). Extensive parameter scans with the GBS code have further led to a theory-based scaling law for the power threshold, $P \sim n^{0.83}B_T^{0.65}aR_0^{0.72}A^{-0.49}q^{-0.34}$, which closely matches the ITPA empirical scaling [32]. By incorporating the effects of E×B shear into these models, a critical temperature can be deduced.

In parallel, the plasma models implemented in European edge fluid codes have been improved to be able to address improved confinement regimes conditions. This effort encompasses the move from electrostatic to electromagnetic turbulence models [33] compatible with high-beta boundary plasmas as well as the implementation of advanced trans-collisional closures such as the Landau closure [34]. The capabilities of these advanced models to tackle relevant confinement regime for power plants has been demonstrated in the GRILLIX code which has been applied to the modeling of H-mode conditions in ASDEX Upgrade [35]. Excellent quantitative agreement has been recovered between simulated mid-plane profiles and experiments, demonstrating the capability of these models to capture H-mode conditions. This work also highlighted the importance of electromagnetic effects in the turbulence phenomenology observed in these conditions, especially the perpendicular transport driven by magnetic field lines fluctuations.

5. PREDICTING PLASMA EXHAUST PHYSICS

To handle heat exhaust, fusion power plants must operate in dissipative divertor regimes where most plasma momentum and energy are transferred to non-confined particles (photons and neutrals) before reaching the targets [36]. Experiments show that such regimes strongly affect scrape-off layer (SOL) turbulence transport, producing wider heat flux decay lengths [37] and far-SOL density shoulders [38]. Understanding this turbulence–density interplay is essential to predict the operational space of future machines.

Addressing this requires edge turbulence codes that self-consistently couple plasma transport with divertor physics. Major advances include realistic magnetic and wall geometries, and detailed modeling of neutral recycling and plasma–neutral interactions. These developments have enabled the first turbulence simulations of power-plant-relevant regimes, including divertor detachment [39,40] and X-point radiators [41].

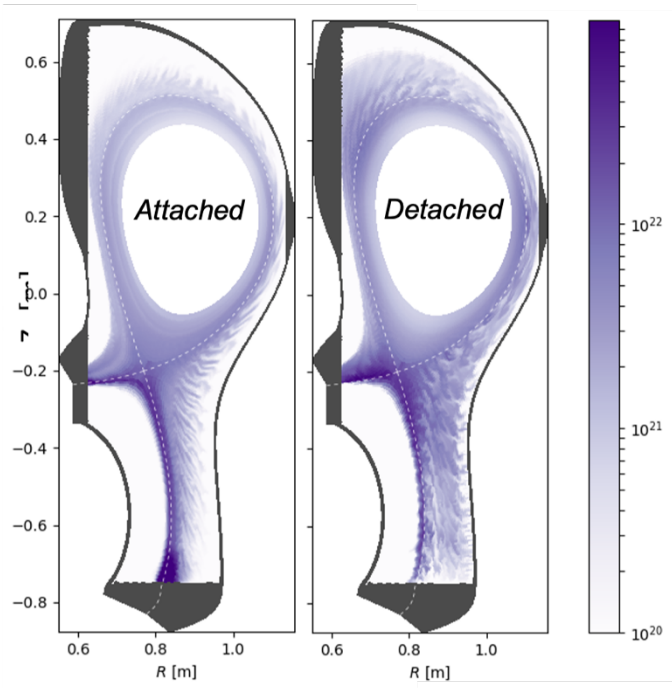

FIG. 3: Comparison of the instantaneous neutral ionization source in two TCV simulations performed with SOLEDGE3X. Left: Low-density attached case. Right: High-density detached case.

Detached-regime simulations with GBS and SOLEDGE3X (see Fig. 3) reproduce the experimentally observed SOL broadening, with heat flux decay lengths increasing up to threefold in the far SOL. While reduced parallel transport from lower temperatures plays a role, the dominant effect is enhanced turbulence – larger, faster blobs – likely expanding the operational window of detached regimes. This needs to be incorporated into mean-field models for future divertor design. Simulations of X-point radiator regimes also reveal localized turbulence modifications near the radiator, with implications for the power balance and stability of the radiative region.

To offer a high-fidelity approach to heat exhaust issues, three complementary full-f gyrokinetic turbulence codes have been developed for edge and SOL modeling. The Eulerian code GENE-X now handles X-point geometry and features a spectral velocity-space formulation that lowers costs to near-fluid levels while retaining fidelity [42]. Validation against the TCV-X21 reference case, including collisional and divertor effects, shows good agreement for SOL widths and profiles [43]. In addition, the semi-Lagrangian code GYSELA has been applied to limiter configurations [44], while the Lagrangian code PICLS has advanced SOL and core modeling through the inclusion of electromagnetic fluctuations and a nonlinear collision operator.

At the plasma–wall interface, kinetic sheath modeling has progressed on several fronts. The immersed-boundary code VOICE, based on a semi-Lagrangian scheme, was developed to enable consistent sheath boundary conditions in GYSELA. VOICE successfully reproduces established Debye-sheath physics and has been applied to study sheath self-organization and the role of non-Maxwellian distributions in determining heat-flux transmission factors [45]. In parallel, the ab-initio PIC code BIT-1 has been extended with a Dressed Cross-Section Model (DCSM) to capture ITER/DEMO-relevant collisional physics, including millions of atomic transitions. Simulations show that under such conditions, these transitions significantly reduce the suprathermal electron heat flux from the upstream region to the targets [46]. Complementary analytical and semi-analytical work has clarified the contribution of slow ions to the kinetic Bohm criterion and explored how turbulent fluctuations modify sheath dynamics under grazing-angle conditions [47].

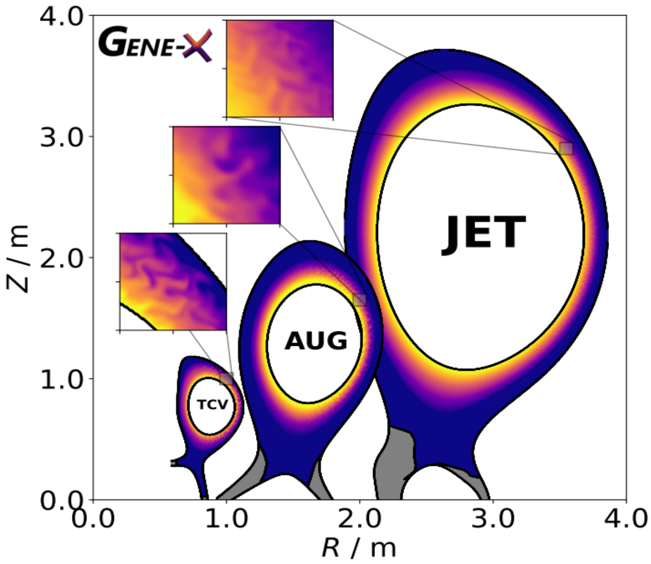

FIG. 4: Snapshot of a global gyrokinetic edge turbulence simulation with GENE-X for the JET tokamak, compared to previously simulated medium-sized tokamaks (at scale). Courtesy of P. Ulbl.

These advances highlight the rapid maturation of kinetic edge and SOL simulations toward both interpretive and predictive capability. Current work focuses on incorporating additional physics and exploiting GPU architectures to boost efficiency, enabling validation in larger devices and reactor-relevant scenarios such as detached H-mode plasmas (see Fig. 4). Notably, GENE-X has recently reproduced experimentally observed radial electric fields in cases approaching the L–H transition and in H-mode, suggesting that a first self-consistent description of the transition may be within reach.

6. PREDICTING NEUTRAL PHYSICS AND PLASMA-WALL INTERACTIONS

An important next step in edge/SOL simulation is the coupling of turbulence codes with advanced neutrals models. The EIRENE Neutral Gas Module (NGM), a Monte Carlo Boltzmann solver, is widely integrated with fluid codes such as B2.5 (as part of the established SOLPS-ITER package), EMC3, and SOLEDGE3X, and is indispensable for predicting fuel/impurity transport, plasma–surface interactions, and detachment phenomena. While fully kinetic treatments offer the highest accuracy, they are prohibitively expensive at ITER and DEMO scales. To address this, a hierarchy of fluid–kinetic hybridization (FKH) methods has been developed, where neutrals are treated partly in fluid form and optimized accordingly [48]. Alternative approaches, such as a kinetic-diffusive asymptotic approach (multilevel asymptotic-preserving Monte Carlo for kinetic-diffusive simulations of the Boltzmann–BGK equation), are also under investigation.

Algorithmic differentiation [49] reduces computational cost in optimization and uncertainty quantification studies, making large parameter scans feasible. In parallel, refined atomic and molecular (A&M) collisional–radiative models have been introduced to address the computational challenges related to the complexity and multiplicity of A&M processes. These models treat vibrationally resolved states with high resolution and account for non-stationary effects along particle trajectories. Complementary pre-processing tools ensure consistency and sensitivity control of the input data. Finally, photon transport and trapping models reveal strong opacity effects on Lyman lines, significantly influencing Dα emission in detached regimes, with important consequences for both diagnostics and ionization balance. Together, these advances establish EIRENE-NGM as a central and validated tool for reactor-scale edge plasma simulations [50].

Plasma–wall interaction (PWI) in future fusion power plants will critically affect plasma-facing component (PFC) lifetime, reactor safety, and plant availability. Therefore, one important target of E-TASC was to develop PWI modeling capabilities addressing erosion, dust, fuel retention, and transient material response, aiming to deliver a predictive framework for reactor design.

Steady-state PWI has been analyzed with the 3D Monte Carlo code ERO2.0, which now includes charge-state-resolved impurity and energy-resolved charge-exchange neutral (CXN) fluxes. First simulations for the EU-DEMO tokamak with 3D wall geometry and SOLPS-ITER edge plasma simulations [51,52] revealed critical challenges such as bridging the gap between plasma grids and wall surfaces. Results show that inner wall erosion is dominated by Ar ions, while outer wall erosion stems from high-energy CXN for the coldest far-SOL temperature conditions assumed in the modeling, underscoring the need for accurate statistical treatment. Improved assessments will follow with wide-grid SOLPS-ITER solutions for the updated EU-DEMO design [53].

In this context, validation studies of tungsten (W) erosion and migration have been carried out using 3D SOLEDGE3X–ERO2.0 simulations, which clarified the role of first-wall components (such as antenna limiters) in core contamination [54] and highlighted the need to account for fully 3D wall and magnetic geometries. Building on this approach, ERO2.0 was adapted to use fully 3D plasma backgrounds from EMC3-EIRENE, rather than the axisymmetric backgrounds previously provided by SOLPS-ITER. This new EMC3-EIRENE–ERO2.0 workflow was successfully tested at W7-X for simulating carbon (C) erosion and transport. Compared to EMC3-EIRENE alone, the coupled workflow offers a much more detailed description, since ERO2.0 incorporates the dependence of physical and chemical sputtering yields on spatially varying target conditions (ion fluxes, impact energies, and surface temperature), as well as the ionization and dissociation chain of hydrocarbons in the plasma. Initial simulations of intrinsic 12C erosion and transport were validated against spectroscopic measurements [55] and post-mortem analysis at selected marker finger locations [56], with further comprehensive validation achieved using 13C deposition data from tracer injection experiments [57].

Meanwhile, local-scale studies using Molecular Dynamics and PIC simulations [58] refine sputtering and sheath models, while dust evolution (MIGRAINe), fuel retention (TESSIM-X, FESTIM), and transient plasma–wall interactions (MEMENTO, including thermionic emission) collectively predict impurity sources, tritium retention under neutron damage, and melt-layer formation under impact of vertical displacement events, with melt splashing representing a potential source of metallic dust.

7. EXTRAPOLATING TO NEGATIVE TRIANGULARITY POWER PLANTS

Experimental results show that negative triangularity (NT) plasma shaping [59] can substantially improve tokamak energy confinement while avoiding the L–H transition typical of positive triangularity (PT). This combination could enable a power plant operating in L-mode with high confinement and fusion gain, while sidestepping the ELM-related material challenges of H-mode. Yet, no large experiments are dedicated to NT, and theoretical exploration has been limited. To address this, we applied state-of-the-art modeling tools to study turbulent transport, MHD stability, and fast-ion confinement.

Gyrokinetic turbulence simulations [60-64] show that NT confinement benefits scale favorably to higher performance plasmas in conventional aspect ratio tokamaks, due to faster magnetic drifts and finite-gyroradius stabilization around the outboard midplane [61]. In spherical tokamaks, however, NT may degrade confinement through electromagnetic turbulence [61], a prediction testable on SMART [64]. Core modeling (ASTRA-TGLF) of NT scenarios in DTT, TCV, and ASDEX Upgrade indicates that NT enables high core pressure without ELMs [65-67], though the confinement improvement is stronger in TCV and largely edge-driven [65].

Edge/SOL turbulence studies [68,69] suggest NT reduces turbulent transport, steepening separatrix gradients. While this improves confinement, it narrows the SOL, making power exhaust more challenging than PT L-mode but better than PT H-mode. The absence of an L–H transition in NT plasmas has been linked to geometry closing access to the second stability region of infinite-n ballooning modes [59]. This explains recent JET results, where NT plasmas remained in L-mode even with 25 MW heating. As NT confinement does not depend on exceeding the L–H threshold, 0-D power balance models reveal attractive low-power, high-Q scenarios well suited for burning plasma experiments [70].

Finally, MHD studies show NT plasmas are less vertically stable [71], suggesting a need for stabilizing plates [72] or reduced elongation in reactor designs. Fast-ion simulations of TCV experiments indicate that NT and PT have comparable confinement [73], with observed differences explained by diagnostic geometry.

8. DESIGNING OPTIMIZED STELLARATORS

The HELIAS concept and neoclassical optimization are the key theoretical foundations of W7-X, the flagship European stellarator. While W7-X successfully demonstrated neoclassical optimization during its initial operation phase [74], experimental campaigns highlighted the need for a deeper understanding of turbulent transport. This motivates ongoing efforts within E-TASC to incorporate turbulent transport optimization and additional design criteria into future stellarator designs.

Pioneering studies of stellarator turbulence date back more than two decades (see, e.g., [75, 76]). Within E-TASC, however, a much more extensive and coordinated effort has emerged. This includes extensive code verification campaigns (e.g., [77-79]) and experimental validation of key transport quantities, such as the zonal flow component [80], the shape of temperature and density profiles in different scenarios [81-83], and the interaction of electromagnetic turbulence across Alfvénic and ion-Larmor scales [84]. From a more fundamental perspective, research has also addressed turbulence near marginality [85], large-scale parameter scans comparing different stellarators [86], and the impact of non-trace impurity concentrations on stellarator turbulence [87].

Building on these and many other advances, recent work has pushed the frontier of stellarator optimization, yielding configurations with higher predicted performance than W7-X without increasing coil complexity. These studies also led to the discovery of new classes of optimized configurations, broadening the exploration space and reviving the concept of tokamak-stellarator hybrids. Achieving this required the development and integration of fast codes and reduced models into modern optimization suites, enabling optimization with respect to core transport physics (including novel proxies for quasi-isodynamicity, turbulence, and fast particle losses), MHD equilibrium and stability (including magnetic surface quality), and coil complexity.

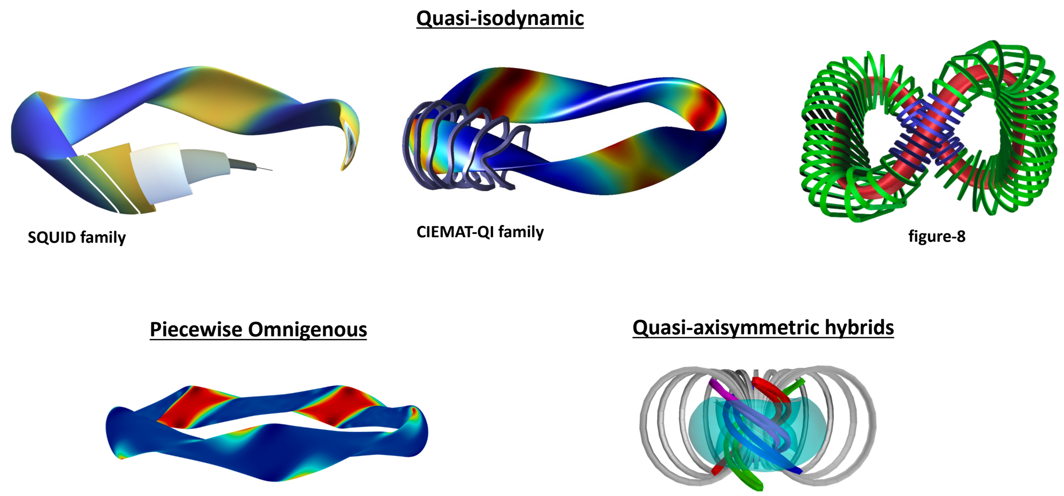

FIG. 5: A new ecosystem of optimized stellarator configurations. The 1st, 3rd, and 4th configurations have been provided, respectively, by A. G. Goodman, G. G. Plunk, and J. L. Velasco. The 2nd and 5th configurations are taken from [90] and [93].

Many of these tools have advanced the design of quasi-isodynamic (QI) stellarators for fusion reactors. Two QI families have reached unprecedented maturity: the SQUID family [88] and the CIEMAT-QI4 family [89]. Both feature ideal MHD stability up to high β, low neoclassical transport and bootstrap current, excellent fast-ion confinement, reduced electrostatic turbulence, a rotational transform compatible with an island divertor, and filamentary coils comparable in complexity to W7-X. The recent CIEMAT-QI4x design [90] exhibits a resilient edge magnetic structure – critical for island divertor operation – and is compatible with breeding blanket designs.

A new class of magnetic fields, termed piecewise omnigenous fields [91], has also been discovered. These fields differ qualitatively from omnigenous fields (including QI and quasisymmetric fields), offering tokamak-like transport of bulk species without some constraints on the spatial variation of the magnetic field strength. Piecewise omnigenous fields open an alternative pathway to stellarator reactors, with some variants compatible with an island divertor [92]. Another notable innovation is the compact stellarator-tokamak hybrid [93], which explores a previously inaccessible optimization space, potentially combining the advantages of both stellarators and tokamaks. A visual impression of these new types of magnetic configurations in provided in Fig. 5.

9. HIGH-FIDELITY INTEGRATED MODELING

Developing reliable and fast digital twins for fusion systems requires validated integrated modeling frameworks capable of capturing complex nonlinear couplings. Such frameworks are essential for optimizing current tokamak operation, preparing ITER, and guiding the design of future devices. They must integrate plasma actuators (heating, fueling, magnetic equilibrium etc.) with plasma response (current diffusion, turbulent transport etc.) while maintaining adequate accuracy.

High-fidelity modeling allows prediction of current, temperature, density, and rotation profiles over multiple confinement times, and disentangles the causality behind the observed evolution. Over the past five years, EUROfusion has coordinated knowledge exchange across European frameworks such as JETTO/JINTRAC, ASTRA, and ETS. The IMAS input/output structure has been standardized to ease benchmarks. The High-Fidelity Plasma Simulator (HFPS), an IMAS-compatible JINTRAC-based framework, has enabled modular workflows, sharing components such as Heating & Current Drive and MHD modules across frameworks. This modularity, also adopted by the ITER Pulse Design Simulator, allows switching between fast surrogate models and slower high-fidelity modules to verify physics at any stage.

Validation of advanced modules has advanced significantly [94]. In L-mode, physics-based modeling up to the separatrix has surpassed scaling laws [95,96], explained ion temperature saturation under electron heating [97]. Full radius predictive ohmic current ramp ups have shown better agreement with experiments on TCV when simultaneously modeling heat and particle [98]. Tungsten-induced radiation collapse under NBI heating has been clarified in AUG [99] and JET [100], with electron heating via ECRH or ICRH delaying collapse. These developments support attempts to automate validation using large databases.

Next steps include: enhancing HFPS modularity and synergy across European frameworks; incorporating physics-based models for pedestal and high-beta core transport, validated on multiple tokamaks; using benchmark cases – such as AUG radiative collapse, WEST long pulses, JET DT operations, and ITER 15 MA scenarios – to reinforce consistency; applying automated validation on hundreds of plasma time slices in L- and H-mode using surrogate turbulence models; and transferring validated physics to pulse design tools to better prepare ITER operation and guide future device design.

10. PULSE DESIGN TOOLS

Pulse Design Tools (PDTs) are used to design and optimize plasma discharges within machine limits. To be effective for optimization, they must run quickly. Their initial role is to verify that the target plasma geometry can be achieved with the available poloidal field coils and power supplies. The PDTs developed within E-TASC go further, coupling self-consistently to core transport solvers to check whether the desired plasma conditions can be reached with the heating and current-drive systems. The overarching goal is to coordinate and harmonize existing European PDTs by porting them across devices, developing interoperable components and frameworks, and using standardized IMAS interfaces wherever possible. Selected achievements are highlighted below.

Early current ramp-up: Specific PDTs address the evolution of the current profile in the early ramp-up phase, which is critical for hybrid and advanced scenarios. We have implemented the 1D transport solver METIS in DYON-EM, enabling calculation of P' and FF' and resolution of the free-boundary equilibrium from the breakdown phase onward. This provides a fully self-consistent description of current profile evolution at the very start of the discharge.

Applications to TCV: Two PDTs have recently been deployed on TCV. First, the transport code RAPTOR [101] was coupled to the inverse equilibrium code FBT (MEQ suite [102]) to generate feedforward coil current references that account for evolving kinetic profiles. This setup has been benchmarked (Fig. 6) and already applied in experiments. Second, the Fenix flight simulator [103], originally developed for AUG [104], was ported to TCV [105], coupled to the FGE free-boundary code (MEQ suite), and integrated with the TCV control system. This framework enables self-consistent simulations of equilibrium and kinetic profile evolution. Fig. 6 compares equilibrium reconstructions of an Ohmic L-mode discharge (64965) with results from both PDTs, using transport models calibrated for this regime.

Applications to WEST: On WEST, PDT and Flight Simulator development is carried out within the MUSCLE3 workflow framework [107], also used by ITER. First applications — coupling current diffusion and electron heat transport (NICE code) with the WEST shape controller in closed loop — successfully simulated X-point formation, with very good agreement for coil currents and plasma shape.

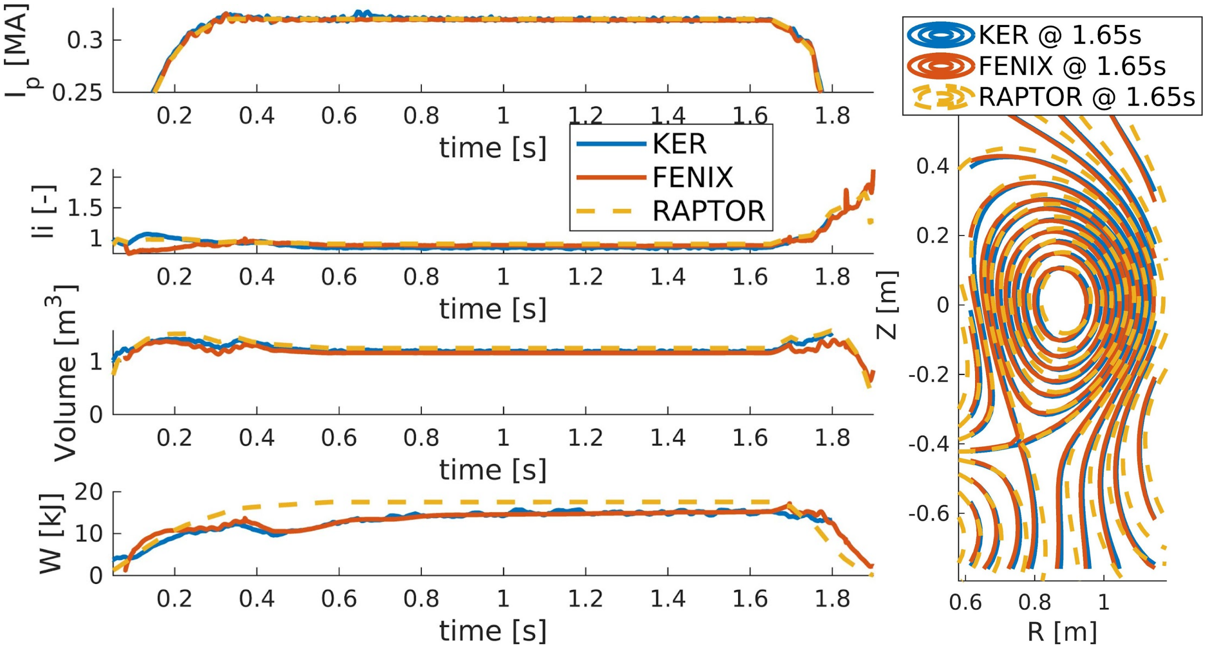

FIG. 6: Comparison of kinetic equilibrium reconstruction (KER) to results of the RAPTOR-FBT [106] and the FENIX PDTs for TCV discharge 64965. Left: Time traces of plasma current, internal inductance, plasma volume, and plasma stored energy. Right: Poloidal flux of the equilibrium for a selected time slice.

11. TOWARDS DIGITAL TWINS OF ENTIRE FUSION DEVICES

The integration of disparate subsystems is a critical stage in designing any complex device. Failing to consistently propagate model assumptions across systems and components can introduce latent incompatibilities, potentially jeopardizing the entire design. Integration is most easily visualized in the spatial layout of a fusion device: even the "best" magnet is only optimal in the context of the conditions it operates within. Each subsystem's design must account for the influence of all other parts of the machine to ensure the overall system functions as intended. Systems codes like PROCESS [108] define design limits in 0D/1D, but lack 2D/3D fidelity. BLUEMIRA, combining BLUEPRINT [109] and MIRA [110], extends these capabilities, refining assumptions and providing a modern, high-quality tokamak design framework.

Using BLUEMIRA, the team has developed a parameterized EU-DEMO design that integrates multiple aspects of device engineering. This includes automatic optimization of poloidal field coil positions and currents while accounting for remote maintenance constraints, optimization of toroidal field coil topology to minimize stored energy for a given ripple, and first wall and blanket design that addresses heat-load minimization, optional panelling, and the generation of neutronic models in OpenMC [111]. Parameterized components are converted into medium-fidelity 3D Computer Aided Design (CAD) representation (see Fig. 7) in a matter of minutes, providing rapid space envelopes and constraints for detailed design. BLUEMIRA is framework that is used to derisk design decisions early in the design process making the design team aware of higher fidelity constraints on the design at the earliest possible stage.

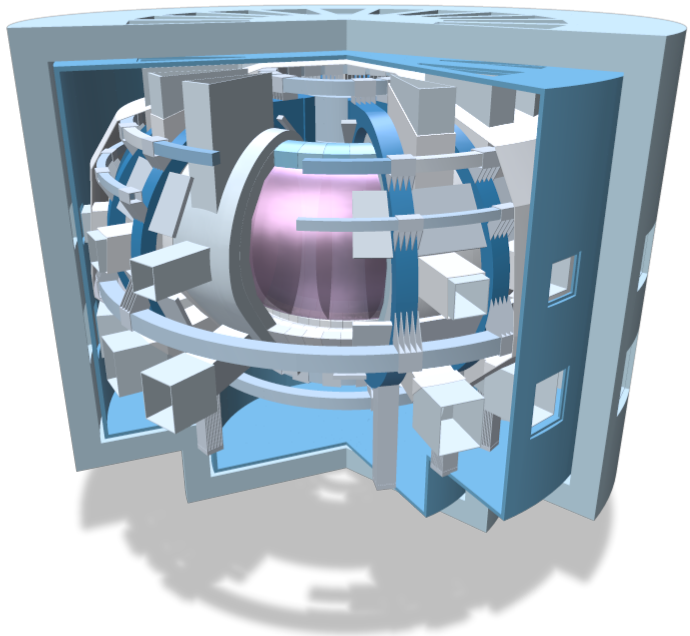

FIG. 7: 3D Computer Aided Design (CAD) representation of an entire fusion device generated by BLUEMIRA, a modern, high-quality tokamak design framework.

12. OUTLOOK

One of the central goals of high-performance computing (HPC) in fusion research is the development of digital twins [112], i.e., computational replicas of future fusion devices – including power plants – or their subsystems. Digital twins ideally integrate verified and validated multi-fidelity models, experimental data, machine learning, and rigorous uncertainty assessments to form a predictive, multi-faceted tool. They are designed to accelerate the iterative cycle of designing, building, testing, and refining fusion systems, thereby moving more rapidly toward commercial viability. Operators could use them to explore operational scenarios virtually, identify optimal settings, and predict outcomes before applying them in experiments, improving both performance and efficiency. To be effective, a digital twin must be calibrated to a level of fidelity appropriate for its intended purpose, typically by combining a spectrum of models ranging from low- to high-fidelity.

A key research thrust in this context is uncertainty quantification [113–117], which also requires improved plasma diagnostics and data processing. Enhancing data quality, including metadata, is driven by how parameter uncertainties propagate into overall model predictions. At the same time, the emerging field of multi-fidelity techniques offers powerful strategies to balance accuracy and efficiency by linking models of different fidelities within a unified framework [118–120]. This approach combines the speed and flexibility of low-fidelity models with the accuracy of high-fidelity simulations, leveraging the strengths of both.

In summary, with exascale computing power and advanced machine learning, researchers can now simulate complex, multi-scale, multi-physics plasma dynamics with unprecedented fidelity. Coupled with algorithmic advances such as uncertainty quantification and multi-fidelity modeling, these capabilities are paving the way for digital twins that can represent fusion systems with both accuracy and efficiency.

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