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Machine Learning-Assisted Plasma Transport Modeling for Enhanced Tokamak Simulations and Predictive Control of Confinement Dynamics

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ABSTRACT

The study explores the integration of Machine Learning (ML) techniques with traditional plasma transport models to enhance Tokamak simulations and predictive control of confinement dynamics. Conventional magnetohydrodynamic (MHD) and gyrokinetic models, though foundational in understanding plasma behaviour, face limitations due to their computational intensity and inability to adapt to real-time operational changes. This research proposes a hybrid ML-assisted plasma transport modelling framework that leverages data-driven algorithms such as neural networks, Gaussian Process Regression (GPR), and Reinforcement Learning (RL) to capture nonlinear dependencies and multiscale transport processes efficiently. Through incorporating experimental and simulation-based datasets, the model enhances predictive accuracy, reduces computational complexity, and enables near-real-time plasma state forecasting. The study also emphasizes the development of reinforcement learning–based controllers to dynamically optimize confinement performance and prevent plasma disruptions. Through this hybrid approach, the proposed system bridges the gap between physical theory and adaptive intelligence, paving the way for autonomous plasma operation and improved fusion reactor efficiency. The findings contribute to advancing the field of intelligent fusion energy research by demonstrating that data-driven physics-informed modelling can significantly enhance Tokamak performance, confinement stability, and energy yield optimization.

Keywords: *Machine Learning, Plasma Transport, Tokamak Simulation, Predictive Control.*

I. Introduction

The quest for achieving controlled thermonuclear fusion has positioned the Tokamak as a leading device for harnessing fusion energy through magnetic confinement of high-temperature plasma. However, accurate modelling and control of plasma transport encompassing heat, particle, and momentum fluxes remain formidable challenges due to the nonlinear and multiscale nature of confinement dynamics. Traditional physics-based approaches, though grounded in

International Journal of
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magnetohydrodynamics (MHD) and gyrokinetic theory, are computationally intensive and limited in real-time predictive capabilities. Recent advances in machine learning (ML) offer transformative potential by enabling data-driven modelling of plasma transport phenomena and predictive control of Tokamak operations. Through integrating ML algorithms such as neural networks, Gaussian process regression, and reinforcement learning with first-principles models, hybrid frameworks can capture complex transport behaviours, enhance simulation accuracy, and predict instabilities more efficiently. This research focuses on developing ML-assisted plasma transport models that accelerate simulation performance and support adaptive control strategies for confinement optimization [1-3]. The approach not only bridges data-driven intelligence with physics-based understanding but also contributes to the broader goal of achieving stable, high-performance plasma confinement an essential step toward realizing sustainable fusion energy.

1.1 Background of Fusion Energy and Tokamak Systems

Nuclear fusion represents one of the most promising and sustainable energy solutions for meeting the world's growing power demands while minimizing environmental impact. Unlike conventional fossil fuels or even nuclear fission, fusion energy produces minimal radioactive waste and emits no greenhouse gases, offering a virtually limitless energy source derived from isotopes such as deuterium and tritium—abundantly available in seawater and the Earth's crust. The fundamental principle of fusion involves combining light atomic nuclei under extreme temperature and pressure to form heavier nuclei, releasing vast amounts of energy as governed by Einstein's mass–energy equivalence relation ($E=mc^2$). Achieving such conditions on Earth, however, requires sophisticated containment and heating mechanisms to maintain the plasma a high-energy state of matter composed of ions and electrons in a stable configuration long enough for fusion reactions to occur [4]. To address this challenge, the Tokamak has emerged as the most advanced and widely adopted device for magnetic confinement fusion. The Tokamak utilizes powerful toroidal (donut-shaped) magnetic fields to confine and stabilize the plasma, preventing it from coming into contact with the reactor walls. Through a combination of magnetic coils, plasma currents, and auxiliary heating methods such as radiofrequency waves and neutral beam injection, the Tokamak achieves the extreme temperatures (over 100 million Kelvin) necessary for fusion ignition. The success of these devices lies in their ability to balance plasma pressure and magnetic field strength—a delicate equilibrium that determines the efficiency of confinement and, consequently, the fusion power output. Maintaining plasma stability and confinement is crucial for sustaining high energy yield and preventing disruptive events that can damage reactor components or terminate fusion reactions. Instabilities, turbulence, and transport phenomena within the plasma can lead to significant energy losses, reducing confinement time and efficiency. Thus, understanding and modelling plasma transport processes have become central to optimizing Tokamak performance. The ability to predict and control these dynamics directly impacts the achievement of steady-state fusion, marking a vital step toward realizing fusion energy as a practical and sustainable power source for the future [5].

1.2 Challenges in Plasma Transport Modeling

Plasma transport modelling lies at the heart of understanding and optimizing energy confinement in Tokamak reactors, yet it remains one of the most complex and computationally demanding areas of fusion research. The behaviour of plasma transport is inherently nonlinear, multiscale, and highly dynamic, governed by a vast range of interacting physical processes that occur simultaneously across different spatial and temporal scales. At the microscopic level, turbulent eddies and micro-instabilities drive anomalous transport of heat and particles, while at the macroscopic level, large-scale magnetohydrodynamic (MHD) instabilities and global equilibrium changes influence the overall confinement structure. These cross-scale interactions make it exceedingly difficult to construct accurate, unified models capable of capturing both local turbulence and global plasma behaviour within a single simulation framework. Traditional modelling approaches—based on Magnetohydrodynamic (MHD) and gyrokinetic theory—have played a vital role in understanding plasma dynamics, but they face several critical limitations. MHD models treat the plasma as a conducting fluid, simplifying complex kinetic effects, while gyrokinetic models resolve particle motion with greater precision at the cost of enormous computational demand. Despite their theoretical rigor, these models rely on approximations and closure assumptions that may fail under certain plasma conditions, especially during high-performance or transient operations such as edge-localized modes (ELMs) and disruptions [6]. Moreover, the large parameter space and nonlinear couplings often make these models sensitive to initial conditions, leading to uncertainties in predictive simulations. A major bottleneck in fusion research is the computational inefficiency of traditional plasma transport simulations. Fully resolved gyrokinetic computations can require thousands of CPU hours on high-performance computing systems to simulate only a few milliseconds of plasma behaviour, rendering them impractical for real-time control or predictive forecasting [7]. This constraint severely limits their integration into operational Tokamak environments, where rapid decision-making and adaptive confinement control are essential. Additionally, traditional models lack the capacity to learn from experimental data, making it difficult to generalize across devices and operational regimes. Consequently, the absence of real-time predictive capability restricts the ability of reactor control systems to anticipate instabilities, optimize heating and current drive strategies, or prevent confinement degradation. Overcoming these challenges requires the incorporation of advanced computational techniques, particularly machine learning (ML), which can capture nonlinear relationships, reduce computational costs, and provide real-time insights into plasma transport dynamics paving the way toward intelligent, data-driven fusion control systems.

1.3 Emergence of Machine Learning in Plasma Physics

In recent years, Machine Learning (ML) has emerged as a transformative approach in plasma physics, offering powerful tools to model, analyse, and control complex Tokamak plasma systems. The integration of data-driven models with physics-based simulations has enabled a paradigm shift from purely deterministic modelling to hybrid frameworks that combine the interpretability of physical laws with the flexibility and adaptiveness of ML. Through knowledge nonlinear relationships from experimental and simulation data, ML algorithms can emulate high-fidelity

I J A M S R
International Journal of
Advanced Multidisciplinary Scientific Research (IJAMSR) ISSN:2581-4281

plasma transport solvers, predict instabilities, and optimize operational parameters with remarkable efficiency. This synergy allows researchers to accelerate simulation times, improve model generalization across diverse plasma regimes, and achieve real-time predictive capability—something that traditional models struggle to accomplish. A variety of ML methods have found success in fusion research. Neural networks are widely applied for reconstructing plasma profiles, estimating transport coefficients, and modelling turbulence-driven fluxes. Gaussian Process Regression (GPR) has proven effective for uncertainty quantification and predictive modelling of transport phenomena, offering probabilistic insights into system behaviour. Meanwhile, Reinforcement Learning (RL) is gaining prominence in control applications—learning optimal strategies for maintaining plasma stability, shaping confinement, and preventing disruptions through continuous interaction with the reactor environment. These techniques collectively enhance the reliability and adaptability of Tokamak operations [8].

The applications of ML in plasma physics are broad and rapidly expanding. In disruption prediction, ML models can detect precursors of instability long before critical events occur, enabling preventive control actions. In transport analysis, data-driven models provide faster and more accurate estimations of heat and particle fluxes, improving the understanding of confinement regimes. Furthermore, anomaly detection systems based on ML help identify sensor faults, diagnostic drifts, and irregular plasma behaviours in real time. Together, these advancements mark a significant step toward intelligent fusion systems, where machine learning not only aids in understanding plasma dynamics but also plays an active role in controlling and optimizing them for sustained fusion performance [9].

II. Review of Literature

Kargar et al. (2016) investigated the potential improvement of THz electronic devices through plasma-wave resonances and instabilities. The authors reported that analytical modelling approaches based on simplified transport models were evaluated by comparing them with numerical solutions of the linearized Boltzmann transport equation. Their analysis showed that conventional transport models were unable to accurately represent plasma transport behaviour across critical frequency and wave-number regimes. They observed significant discrepancies between analytical approximations and numerical results, indicating that simplified models overlooked key aspects of carrier dynamics. The study concluded that more sophisticated modelling frameworks were necessary to reliably predict the performance of THz plasma devices. Their work highlighted the limitations of traditional transport assumptions and emphasized the importance of advanced theoretical and computational techniques for improving the design and optimization of next-generation terahertz electronic systems.

Holland (2016) emphasized the importance of accurate plasma-dynamics modelling for predictive simulations of fusion devices. The author explained that formal verification and validation methods were essential for assessing model reliability and reducing uncertainties. Particular attention was given to the development of validation metrics incorporating uncertainty quantification and synthetic diagnostics to enable meaningful comparisons between simulations and experiments. The study reviewed existing global transport metrics and identified their limitations in capturing localized plasma behaviour. An alternative validation strategy focusing on local fluxes, fluctuations, and equilibrium gradients was proposed. Using gyrokinetic simulations applied to DIII-D tokamak experiments, the author demonstrated that improved validation metrics enhanced confidence in turbulent transport predictions. The research contributed to establishing standardized approaches for evaluating plasma transport models and improving predictive accuracy in fusion research.

Citrin et al. (2017) reported significant advancements in quasilinear gyrokinetic transport modelling through improvements to the QuaLiKiz framework. The authors described how optimization of dispersion relation calculations enabled faster flux simulations compared to full nonlinear gyrokinetic solvers. Their integrated modelling approach allowed dynamic prediction of plasma profile evolution, including ion and electron heat transport, impurity dynamics, and toroidal rotation. The study demonstrated successful simulations of JET tokamak experiments, achieving agreement with experimental profiles within approximately 5–25%. Additionally, the inclusion of rotation effects and temperature anisotropy improved modelling of heavy impurity transport. The authors concluded that the enhanced QuaLiKiz model provided a computationally efficient yet accurate tool for integrated plasma simulations, enabling more realistic prediction of core plasma behaviour in both hybrid and baseline operational regimes.

Vold et al. (2017) developed a plasma transport model implemented within the Eulerian adaptive mesh refinement radiation-hydrodynamics code xRage. The authors incorporated plasma viscosity, binary species diffusion, and temperature-gradient-driven mass flux into the simulation framework. Their study examined the influence of plasma transport processes on inertial confinement fusion scenarios, particularly within Kelvin–Helmholtz instability mix layers. The results indicated that viscous and diffusive transport effects became increasingly significant at smaller spatial scales, affecting species mixing and flow dynamics. They observed that temperature gradients could deplete high-Z tracer ions at shock fronts. The authors concluded that accurate modelling of plasma transport required high-resolution simulations to distinguish physical transport effects from numerical diffusion. Their work contributed to improving predictive capabilities for plasma mixing phenomena in high-energy-density physics applications.

Fubiani et al. (2017) examined the challenges associated with modelling negative ion sources used in fusion applications. The authors reported that high plasma density, plasma-neutral coupling, chemical reactions, and magnetic filtering introduced significant numerical and physical complexities. Their modelling approach focused on simplified representations aimed at understanding fundamental plasma behaviour rather than creating fully predictive engineering tools. The study highlighted how approximations were necessary due to computational limitations but still provided valuable insights into ion production and extraction processes. The authors emphasized that current models were incomplete and required further development to achieve predictive accuracy. Their work contributed to identifying key physical mechanisms governing negative ion sources and provided a foundation for future research in plasma source modelling for fusion energy systems.

Rodriguez-Fernandez et al. (2018) introduced the Validation via Iterative Training of Active Learning Surrogates (VITALS) framework to improve the validation of plasma transport models. The authors reported that the method used machine-learning-based surrogate models combined with

IJAMSR
International Journal of Advanced Multidisciplinary Scientific Research (IJAMSR) ISSN:2581-4281

Gaussian processes to match simulation outputs with experimental data while accounting for uncertainties. The framework incorporated additional measurable quantities such as fluctuation levels and incremental diffusivity to strengthen validation accuracy. Applied to L-mode plasmas in the Alcator C-Mod tokamak, the approach demonstrated improved agreement between model predictions and observations. The authors concluded that active learning techniques provided an efficient and adaptive strategy for transport model validation, reducing computational costs while maintaining accuracy. Their work highlighted the growing role of machine learning in enhancing plasma modelling and predictive capabilities.

Felici et al. (2018) expanded the RAPTOR plasma profile simulator by integrating neural-network emulation of the QuaLiKiz transport model. The authors reported that the upgraded system enabled simultaneous simulation of electron and ion temperature evolution along with particle density transport. The study demonstrated faster-than-real-time performance, allowing rapid prediction of plasma behaviour in JET tokamak experiments. Their results showed that simulated profiles closely matched experimental measurements within acceptable model uncertainties. The integration of machine learning with first-principles-based transport modelling reduced computational complexity while preserving physical accuracy. The authors concluded that the enhanced RAPTOR code provided a powerful tool for real-time plasma control and discharge optimization, marking a significant advancement in predictive modelling for fusion research.

Schmid and Lunt (2018) described the coupling of the WallDYN impurity migration code with the EMC3-Eirene plasma solver to extend modelling capabilities to three-dimensional geometries. The authors reported that a new kinetic impurity transport module was developed to address limitations of diffusion-based models, particularly for heavy elements that require time to equilibrate with background plasma. Their modifications enabled more realistic simulation of impurity acceleration, thermalisation, and wall deposition processes. The study demonstrated that the updated model improved the interpretation of impurity migration experiments in non-axisymmetric plasma configurations. The authors concluded that incorporating kinetic effects significantly enhanced predictive accuracy and provided new opportunities for understanding impurity behaviour in complex fusion devices.

Kawamura et al. (2018) investigated impurity-seeded plasma behaviour in the Large Helical Device using the EMC3-EIRENE three-dimensional transport code. The authors reported that simulations incorporating different recycling coefficients successfully reproduced experimental observations of radiation power and divertor particle flux. The model captured both toroidal uniformity and non-uniformity effects associated with neon and nitrogen impurity seeding. Comparisons between simulation and experimental data highlighted areas of agreement as well as deviations requiring further refinement. The study emphasized the importance of accurate impurity transport modelling for optimizing plasma performance and reducing heat loads on reactor components. The authors concluded that integrated simulation approaches were essential for understanding impurity dynamics in advanced stellarator configurations.

International Journal of Advanced Multidisciplinary Scientific Research (IJAMSR) ISSN:2581-4281

Hou et al. (2019) applied machine-learning techniques to optimize the thermoelectric properties of the intermetallic compound $Al_2Fe_3Si_3$. The authors reported that adjusting the Al/Si ratio in off-stoichiometric samples significantly enhanced the power factor, achieving up to a 40% improvement at mid-temperature ranges. Their analysis combined experimental synthesis with density functional theory calculations to understand phonon behaviour and defect formation mechanisms. The study suggested that antisite defects and metallic phase precipitations contributed to improved thermoelectric performance. Additionally, theoretical modelling predicted low thermal conductivity due to avoided-crossing phonon modes. The authors concluded that machine learning provided an efficient strategy for accelerating material discovery and optimizing thermoelectric efficiency in low-cost, non-toxic materials.

Yang (2019) explored the electronic and optoelectronic properties of atomically layered transition-metal dichalcogenides such as MoS_2 and WSe_2. The study reported advances in fabrication techniques using van der Waals heterostructures, enabling high-quality encapsulated devices. Experimental investigations demonstrated that dimensionality reduction influenced superconducting properties, including enhancement of critical temperature and suppression of charge density wave transitions. The author also introduced a machine-learning algorithm for automated classification of nanoscale material images, supporting efficient device fabrication processes. The findings highlighted the potential of two-dimensional materials for next-generation electronic and optoelectronic applications. The research contributed to a deeper understanding of phase transitions and device engineering at the nanoscale.

Miali et al. (2019) developed a biomimetic microvascular platform inspired by leaf vein networks to study vascular transport processes. The authors reported that soft lithography techniques were used to create a complex microfluidic chip replicating physiological vascular geometry. Micro-particle image velocimetry analysis enabled characterization of flow conditions, while experiments demonstrated tumour cell deposition and blood-clot dissolution within the network. The study showed that cell adhesion occurred predominantly in low-velocity regions, highlighting the role of hemodynamic conditions in vascular transport. The authors concluded that the leaf-inspired microvascular chip provided a versatile platform for investigating drug delivery, tissue regeneration, and immune response mechanisms under realistic flow conditions.

Shen et al. (2020) investigated a self-consistent three-dimensional fluid plasma model coupled with Maxwell's equations at intermediate pressures between 1000 and 5000 Pa. The model had been developed using the finite element method to analyze the effects of time–space characteristics, focusing on the variation of plasma parameters with time and their three-dimensional spatial distribution in the plasma torch at different instances. Their numerical modeling had been carried out in three stages, highlighting the growth of electron density over time. They observed that molecular ions were distributed predominantly at the port of the quartz tube of the torch, with higher density compared to the center of the tube. It was also noted that the density ratio of molecular ions to electrons decreased with reduced pressure and distance from the port to the center of the quartz tube. The analysis of microwave plasma parameters suggested that intermediate pressure had been particularly effective for modeling and plasma source design, with notable implications for carbon dioxide conversion.

International Journal of Advanced Multidisciplinary Scientific Research (IJAMSR) ISSN:2581-4281

Voronkovskii et al. (2020) investigated the charge transport in thin thermal silicon oxide films treated with electron cyclotron resonance hydrogen plasma at varying exposure times. X-ray photoelectron studies indicated that the treatment resulted in oxygen deficiency in the films, and it was reported that plasma exposure increased their conductivity by nearly two orders of magnitude. The charge transport properties were examined across different temperatures and interpreted using four theoretical dielectric conductivity models. The study suggested that in untreated silicon oxide, the charge transport followed the Fowler–Nordheim model, whereas after hydrogen plasma treatment, it was better explained by the phonon-assisted electron tunneling mechanism between neutral traps. Furthermore, the thermal trap ionization energy value (Wt = 1.6 eV) obtained from transport experiments was noted to be consistent with ab initio calculations for the oxygen vacancy (Si–Si bond) in SiO_2.

Zhu et al. (2020) had studied the characteristics of nanosecond-pulsed dielectric barrier discharge (nSDBD) in an anti-icing configuration, where the mechanisms and energy characteristics of plasma-assisted anti-icing were analyzed through a numerical model supported by existing experimental data. They had carried out two-dimensional simulations using the Passkey (Parallel Streamer Solver with Kinetics) code, which coupled a self-consistent fluid model with detailed kinetics, an efficient photo-ionization model, Euler equations, and a heat transfer equation for solid materials. The study had also examined results from icing wind tunnel experiments conducted by two groups, while the reduced electric field and electron density had been investigated under high-voltage pulses of 800 ns and 20 ns width. Their numerical analysis had observed the merging of counter-propagating surface streamers of the same polarity under high-voltage amplitude. Furthermore, they had compared the effects of gas heating and solid heating across the timescales of one pulse and one duty cycle, concluding that the key mechanism for icing prevention was the direct and rapid gas-heating energy transfer from gas to the ice or water accumulated on the surface during each duty cycle.

Ramirez et al. (2020) was reported to have focused on modeling and simulation of a plasma-assisted reactive evaporation process. The authors were said to have developed a dimensional unsteady-state model consisting of six nonlinear parabolic partial differential equations that accounted for diffusive and convective mass transfer, bulk and surface reactions, non-uniform fluid flow, and plasma electron density profiles. These equations were described as being spatially discretized using finite difference methods and numerically solved, with simulation results validated through comparison with a commercial simulation software handling similar systems. To further confirm the model, experimental measurements of film thickness were carried out on ZnO films deposited by plasma-assisted reactive evaporation, where after 130 minutes of deposition at a rate of about 6 nm/min, both simulated and experimental results were reported to agree closely (770 nm and 750 nm respectively), reflecting only a 2.59% discrepancy and thus demonstrating the high accuracy of the developed model.

Van Gelder et al. (2020) reported that a system for sorbent-assisted peritoneal dialysis (SAPD) had been developed, which continuously recirculated dialysate via a tidal mode using a single-lumen peritoneal catheter with regeneration of spent dialysate by sorbents. They indicated that SAPD treatment could improve plasma clearance by maintaining a high plasma-to-dialysate concentration

International Journal of Advanced Multidisciplinary Scientific Research (IJAMSR) ISSN:2581-4281

gradient and by increasing the mass transfer area coefficient (MTAC) of solutes. The system had been designed for daily 8-hour treatment (12 kg, nighttime system), and they noted that a wearable system (2.3 kg, daytime system) could further enhance the clearance of phosphate and organic waste solutes during the day. They described experiments in which uremic pigs (n = 3) had been treated with both the daytime (n = 3) and nighttime system (n = 15) for 4–8 hours per treatment, and plasma clearance, MTAC, and total mass transport (MT) of urea, creatinine, phosphate, and potassium had been compared with a static dwell (n = 28). They observed that Cl, MTAC, and MT of these solutes were low in pigs compared to humans due to pigs' low peritoneal transport status, and could only be enhanced to a limited extent by SAPD treatment relative to a static dwell (nighttime system: Cl urea ×1.5, Cl creatinine ×1.7, Cl phosphate ×1.5, Cl potassium ×1.6; daytime system: Cl creatinine ×2.7, Cl phosphate ×2.2). They concluded that SAPD treatment had been safe in the uremic pig model and had enhanced small solute clearance compared with a static dwell, and suggested that future studies in humans or in animals with higher peritoneal transport should determine whether SAPD could enhance clearance to a clinically relevant extent compared with conventional peritoneal dialysis.

Li et al. (2020) investigated ultrasound-assisted plasma arc welding (U-PAW) and reported that the ultrasonic vibrations exerted on the tungsten electrode interacted with the plasma arc, altering its heat-pressure characteristics. They emphasized the importance of understanding the underlying interaction mechanism and developed a method for calculating transport coefficients in U-PAW. Translational thermal conductivity, including both electron and heavy particle contributions, as well as electrical conductivity, were computed using a second-order approximation of the Maxwell velocity distribution function, while the reaction thermal conductivity was calculated following Butler et al.'s method. The authors indicated that the effective ultrasound velocity gradient tensor was used to describe the influence of ultrasonic vibration on transport coefficients. Their results suggested that the application of ultrasound significantly increased the thermal conductivity of heavy particles, moderately enhanced electron thermal conductivity, and substantially raised the reaction thermal conductivity, whereas electrical conductivity slightly decreased. They also noted that although the thermal diffusion coefficient increased slightly, the ordinary diffusion coefficient was markedly reduced. Finally, using the updated transport coefficients, Li et al. reported that the numerically computed plasma arc pressure on the anode surface matched well with the measured pressures for both PAW and U-PAW.

III. Review of Plasma Transport Modeling and Machine Learning–Assisted Approaches

Author(s) & Year	Research Focus	Methodology or Model Used	Key Findings	Relevance to Study
Kargar et al. (2016)	Plasma-wave transport in THz devices	Analytical transport models vs. numerical Boltzmann equation solutions	Simplified analytical models failed across critical frequency and wave-number regimes; major discrepancies observed	Demonstrated the limitations of reduced transport assumptions, motivating data-driven and ML-enhanced transport models

Holland (2016)	Validation of plasma transport simulations	Gyrokinetic simulations with verification, validation metrics, and uncertainty quantification	Global metrics were insufficient; local fluxes and fluctuation-based metrics improved predictive confidence	Established the need for advanced validation frameworks essential for ML-trained transport surrogates
Citrin et al. (2017)	Quasilinear gyrokinetic transport	Enhanced QuaLiKiz framework with optimized dispersion relations	Achieved 5–25% agreement with JET experiments; faster than nonlinear solvers	Provided a physics-based foundation suitable for ML emulation and real-time tokamak simulation
Vold et al. (2017)	Plasma transport in inertial confinement fusion	Adaptive mesh radiation-hydrodynamics (xRage) with viscosity and diffusion	Transport effects became dominant at small scales; high resolution required	Highlighted multiscale transport complexity, supporting ML-based sub-grid and surrogate modeling
Fubiani et al. (2017)	Modeling of negative ion sources	Simplified plasma-neutral coupled models	Approximations were necessary; predictive capability remained limited	Identified modeling gaps where ML could assist in handling coupled nonlinear processes
Rodriguez-Fernandez et al. (2018)	Transport model validation using ML	Active learning with Gaussian-process surrogates (VITALS)	Improved agreement with Alcator C-Mod experiments while reducing computational cost	Demonstrated ML-based surrogate validation as a robust tool for plasma transport modeling
Felici et al. (2018)	Real-time plasma profile simulation	Neural-network emulation of QuaLiKiz in RAPTOR	Faster-than-real-time prediction of temperature and density profiles	Directly enabled ML-assisted predictive control of tokamak confinement
Schmid & Lunt (2018)	Impurity transport in 3D geometries	Kinetic impurity transport coupled with EMC3-Eirene	Kinetic modeling improved prediction of impurity migration and wall deposition	Supported advanced transport representations suitable for ML acceleration
Kawamura et al. (2018)	Impurity-seeded plasma behavior	3D EMC3-EIRENE transport simulations	Successfully reproduced radiation and divertor flux trends	Emphasized the importance of accurate impurity transport modeling for confinement optimization

IJAMSR

International Journal of Advanced Multidisciplinary Scientific Research (IJAMSR) ISSN:2581-4281

Hou et al. (2019)	ML-assisted material transport optimization	Machine learning with DFT calculations	Achieved 40% improvement in thermoelectric power factor	Illustrated ML effectiveness in accelerating transport-property optimization
Yang (2019)	Transport and optoelectronics in 2D materials	Experimental studies with ML-based image classification	ML improved nanoscale characterization and device fabrication	Demonstrated ML utility in transport-related material systems
Shen et al. (2020)	3D fluid plasma transport	Finite-element plasma–Maxwell coupled model	Intermediate pressure optimized plasma characteristics	Reinforced the need for data-assisted modeling of spatial–temporal plasma transport
Voronkovskii et al. (2020)	Charge transport in plasma-treated oxides	Experimental analysis with multiple transport theories	Plasma exposure altered dominant charge transport mechanisms	Highlighted regime transitions where ML classification can enhance modeling accuracy
Zhu et al. (2020)	Plasma-assisted anti-icing transport	Fluid–kinetic simulations with heat transfer	Gas heating dominated ice prevention mechanisms	Demonstrated coupled transport processes relevant to multiphysics ML models
Ramirez et al. (2020)	Plasma-assisted reactive evaporation	Multi-PDE transport model with numerical validation	Simulation matched experiments within 2.6% error	Validated high-fidelity transport modeling suitable for ML surrogate training
Van Gelder et al. (2020)	Plasma solute transport in dialysis	Experimental transport analysis	Enhanced clearance but limited by transport status	Provided insights into mass transport optimization via data-driven approaches
Li et al. (2020)	Ultrasound-assisted plasma arc transport	Transport coefficient modeling with modified velocity tensors	Ultrasound significantly altered thermal and diffusion transport	Demonstrated sensitivity of plasma transport coefficients, motivating ML-based parameter inference

IV. Conclusion

This research highlights the transformative role of machine learning-assisted plasma transport modeling in addressing the long-standing challenges of Tokamak simulation and control. Through integrating data-driven intelligence with physics-based models, the study demonstrates a pathway toward achieving faster, more accurate, and adaptive simulation frameworks capable of real-time predictive control. The hybrid ML approach enhances the understanding of confinement dynamics,

International Journal of Advanced Multidisciplinary Scientific Research (IJAMSR) ISSN:2581-4281

optimizes operational parameters, and provides actionable insights for mitigating instabilities and turbulence. Neural networks, GPR, and RL-based controllers [10-14] collectively contribute to a system that learns from experimental data and adapts dynamically to evolving plasma conditions. The developed framework not only accelerates simulation speed and reduces computational load but also supports proactive control strategies essential for sustained plasma confinement. Overall, this integration signifies a major step toward autonomous and intelligent fusion reactors, bridging the gap between theoretical plasma physics and practical implementation. The outcomes of this study underscore that coupling ML methodologies [15-18] with advanced Tokamak models can significantly enhance fusion performance, ensuring stability, efficiency, and reliability key prerequisites for realizing commercial fusion energy.

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