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Symplecticity of the GORILLA guiding-center tracer and its implications for edge transport modeling

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Abstract. We demonstrate symplecticity of the flow map generated by the guiding-center tracer GORILLA [1, 2]. Since the underlying algorithm relies on a piecewise linear approximation of the Hamiltonian, usual proofs based on a twice continuously differentiable Hamiltonian [3] are not applicable. The analysis is pinned down to the critical section near the boundaries of tetrahedral elements, where the Hamiltonian vector field is discontinous. We show that it is possible to retain symplecticity of the piecewise linear system as a limiting case of a parameterized family of smooth Hamiltonian systems nearly everywhere in phase-space. Limitations are discussed for the case of the X and O-point in the magnetic field topology. The connection to Hdiv-conforming finite element discritezations and their interface conditions is pointed out [4, 5]. Globally, we verify the correct behavior of Poincaré invariants. Finally, the practical implications for edge transport modeling are elaborated. For this purpose, we analyze the footprint of magnetic field lines intersecting with the divertor of a tokamak with resonant magnetic perturbations. These footprints are shown to be in line with the expected behavior of invariant manifolds of the underlying Hamiltonian system. This demonstration of physical consistency at low-order discretization lays the basis for further developments of highly efficient edge transport solvers.

References

[1] M. Eder *et al* Physics of Plasmas **27**, 122508 (2020)

[2] M. Eder *et al* *"GORILLA: Guiding-center ORbit Integration with Local Linearization Approach"* submitted to Journal of Open Source Software

[3] Hairer, E., Lubich, C., & Wanner, G. (2006). *"Geometric numerical integration: Structure-preserving algorithms for ordinary differential equations"* (2nd ed). Springer.

[4] M. W. Scroggs et al. *DefElement: an encyclopedia of finite element definitions*, 2024, https://defelement.com

[5] Raviart, P.-A., & Thomas, J.-M. (1977). *"A mixed finite element method for 2nd order elliptic problems."* In *Mathematical aspects of finite element methods* (Bd. 606, S. 292–315).

Analytic and numerical investigation of Kelvin-Helmholtz-like instabilities in tokamaks with sheared thermal and plasma rotation profiles

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Abstract. Toroidal rotation in tokamak plasmas has been shown to stabilize several instabilities. However, for toroidal flows of the order of the ion sound speed a rotation-driven Kelvin-Helmholtz-like instability can grow [1] [2] [3]. Two main driving mechanisms for this instability have been identified [3]. The first is a drop in dynamic pressure across the mode width. The second, appearing for poloidal mode number $m > 1$, is related to the rotation-induced variation of density along the magnetic field lines. Previous analysis of the Kelvin-Helmholtz-like instability has focused on sheared rotation drive in the absence of gradients in other plasma profiles. Its main driving mechanisms are, however, sensitive to density and temperature gradients.

In this work, a large aspect ratio expansion of the ideal magnetohydrodynamic model with sonic ordered flows is employed to analyse the driving and damping mechanisms of the Kelvin-Helmholtz-like instability in the presence of strong density, temperature and pressure gradients. This analytic model is compared favorably against VENUS-MHD [4], a full magnetohydrodynamic code. Strong mode drive is observed for large rotation amplitude when the density is peaked in the core, and the temperature and rotation profiles are flat. If, on the other hand, density is held constant and the temperature gradient is increased, a stabilizing effect is observed. In cases where this stabilizes the Kelvin-Helmholtz-like instability completely, a sufficiently high density gradient can re-excite the mode.

[1] I T Chapman, N R Walkden, J P Graves, and C Wahlberg. The effects of sheared toroidal rotation on stability limits in tokamak plasmas. *Plasma Physics and Controlled Fusion*, 53(12):125002, Oct 2011.

[2] I T Chapman, S Brown, R Kemp, and N R Walkden. Toroidal velocity shear kelvin–helmholtz instabilities in strongly rotating tokamak plasmas. *Nuclear Fusion*, 52(4):042005, Mar 2012.

[3] C Wahlberg, J P Graves, and I T Chapman. Analysis of global hydromagnetic instabilities driven by strongly sheared toroidal flows in tokamak plasmas. *Plasma Physics and Controlled Fusion*, 55(10):105004, Aug 2013.

[4] S Lanthaler, J P Graves, D Pfefferlé, and W A Cooper. Guiding-centre theory for kinetic-magnetohydrodynamic modes in strongly flowing plasmas. *Plasma Physics and Controlled Fusion*, 61(7):074006, may 2019.

In search of universality: towards a statistical mechanics of collisionless plasma

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Much of existing plasma physics is done hovering in the vicinity of a Maxwellian equilibrium, which is the maximum point of the standard Gibbs entropy and is achieved dynamically by means of two-particle collisions. I would like to discuss what I believe to be the next frontier for plasma theoreticians — and, to an extent, generally for theoretical physicists concerned with complex many-body systems — and attempt to grapple with the fact that many natural plasmas are too collisionless to be Maxwellian (in the sense that their dynamics occur on shorter timescales than interparticle collisions). The central question is then whether there exist universal collisionless equilibria, or classes thereof, and what they are. What is the meaning of entropy in a collisionless system? I will discuss some simple ideas, going back to the work of Lynden-Bell in the 1960s, about the statistical mechanics of collisionless systems, leading to a class of universal collisionless equilibria — these are reminiscent of the equilibria of Fermi gases, with phase-volume conservation imposing (an infinite set of) Casimir invariants, whose effect is analogous to that of the Pauli exclusion principle. The generalised Lynden-Bell equilibria obtained in this way cover quite a wide variety of distributions — most intriguing perhaps is that they will generically feature a "nonthermal" power-law tail proportional to inverse square of the particle energy [1] — a matter of some interest, e.g., for the theory of cosmic rays and of the nonthermal particle distributions routinely measured in the solar wind. I will then outline a programme for how one might do to this statistical mechanics what Boltzmann did to Gibbs: derive a "collisionless collision integral" that describes the dynamical relaxation of a plasma towards the Lynden-Bell equilibria. It turns out that in order to make progress in this task, one must understand the structure of chaotic fluctuations in phase space. Lynden-Bell-like equilibria are recoverable under some very simplistic assumptions — roughly speaking, when these fluctuations are treated as structurally similar to a thermal noise [2]. In fact, they are more likely to behave like fully-fledged turbulence — with phase mixing ("Landau damping") and stochastic echoes conspiring to process a constant flux of energy [3]. What universal equilibria exist against such a background is a topic of ongoing research. In reassuring news for the statistical-mechanical approach, recent numerical simulations of 1D1V two-stream instability suggest that, despite all these reservations, the universal power-law tail derived in [1] does form — and indeed the relaxation to this universal equilibrium appears to be assisted by gradual breaking of the phase-volume conservation by small-scale structure of the distribution function, with a Casimirs now not conserved but slowly converging to a universal state [4].

References

[1] R. J. Ewart, M. L. Nastac, A. A. Schekochihin, *JPP* **89**, 905890516 (2023)
[2] R. J. Ewart, A. Brown, T. Adkins, A. A. Schekochihin, *JPP* **88**, 925880501 (2022)
[3] M. L. Nastac, R. J. Ewart, W. Sengupta, A. A. Schekochihin, M. Barnes, W. D. Dorland, *PRE* **109**, 065210 (2024)
[4] R. J. Ewart, P. Bilbao, Y. B. Ginat, M. N. Nastac, T. Silva, A. A. Schekochihin, in preparation (2024)

Adding parallel magnetic fluctuations to the global GENE code

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Abstract.

The inclusion of parallel magnetic fluctuations ($B_{1||}$) in global gyrokinetic turbulence codes has become more and more relevant due to their increased impact on high beta and reactor relevant scenarios, along with their potential effect on the constraint of the edge/pedestal profiles in KBM driven scenarios. However, this has been a challenge for several years due to the complexity of the model itself and it's computational cost.

While these effects have been recently added to the global GENE [1, 2] code [3], the computational cost of the full $B_{1||}$ dynamics restricts it's applicability to simple scenarios. Therefore, a long wavelength ($k_\perp \rho_s \ll 1$) approximation for parallel magnetic fluctuations was implemented for GENE in order to improve its predictive power and asses its importance for global physics without a significant increase in computational cost.

The approximation has been successfully tested showing a surprisingly good agreement with the full model even at smaller wavelengths. The impact of global $B_{1||}$ dynamics is tested on the Cyclone Base Case where a shift on the ITG-KBM transition is apparent. In cases where profiles are bound by the latter instability, this could lead to quite different profile predictions. Results of global nonlinear simulations at different β values are discussed. Research on complex high beta scenarios and edge pedestals is ongoing.

References

[1] Jenko F, Dorland W, Kotschenreuther M and Rogers B N 2000 *Physics of Plasmas* **7** 1904–1910 ISSN 1070-664X (*Preprint* `https://pubs.aip.org/aip/pop/article-pdf/7/5/1904/19273118/1904_1_online.pdf`) URL `https://doi.org/10.1063/1.874014`

[2] Görler T, Lapillonne X, Brunner S, Dannert T, Jenko F, Merz F and Told D 2011 *Journal of Computational Physics* **230** 7053–7071 ISSN 0021-9991 URL `https://www.sciencedirect.com/science/article/pii/S0021999111003457`

[3] Wilms F, Merlo G, Sheffield F, Goerler T, Bañón Navarro A and Jenko F 2024 (submitted) *Computer Physics Communications*

ICRH schemes for generating deeply trapped fast ions in Wendelstein 7-X

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Abstract. Wendelstein 7-X (W7-X) is a large, superconducting, optimized stellarator being operated in Greifswald, Germany. One of the original optimization criteria [1] is good fast-ion confinement, especially at increased plasma beta [2]. This improvement of the fast-ion confinement compared to non-optimized configurations lacking a (quasi-)symmetry is a consequence of the quasi-omnigeneous nature of W7-X which means that the toroidally trapped particles gain a poloidal drift which, on average, prevents them from drifting out radially. This optimization applies mostly to deeply trapped collisionless fast ions.

It has been shown in the past [3] that the current NBI system at W7-X does not populate these deeply trapped particle orbits in most magnetic configurations. Additionally, the maximum NBI injection energy is limited to 55 keV in Hydrogen which makes the particles not quite collisionless.

On the other hand, generating fast ions with ion-cyclotron-resonance heating (ICRH) does not suffer from such a limitation. The ICRH system is also more flexible in other regards: By choosing the ICRH frequency appropriately, the resonance can be shifted away from the usual region of high magnetic field strength and placed deliberately into a region of low field strength which favours the generation of deeply trapped fast ions. Also different magnetic field configurations, in which the generation of trapped ions is more favourable than in the standard configuration, may be chosen.

In this contribution we explore these ICRH schemes for generating deeply trapped fast ions in W7-X using the SCENIC code package [4]. We compare different magnetic configurations, with and without a shifted resonance, with regards to their potential for generating deeply trapped fast ions. Collisional and collisionless simulations are compared.

References

[1] Grieger G, Lotz W, Merkel P, Nührenberg J, Sapper J, Sturmberger E, Wobig H, the W7-X Team, Burhenn R, Erckmann V, Gasparino U, Giannone L, Hartfuss H, Jaenicke R, Kühner G, Ringler H, Weller A, Wagner F and the W7-AS Team 1992 *Physics of Fluids B: Plasma Physics* **4** 2081

[2] Drevlak M, Geiger J, Helander P and Turkin Y 2014 *Nuclear Fusion* **54** 073002

[3] Lazerson S, Kulla D, Slaby C, McNeely P, Rust N, Hartmann D and the W7-X team 2023 OPTEMIST: A neutral beam for probing quasi-omnigeneous fast ion behavior in Wendelstein 7-X *Poster presented at the 65th Annual Meeting of the APS Division of Plasma Physics, Denver, CO*

[4] Jucker M, Graves J, Cooper W, Mellet N and Brunner S 2011 *Comput. Phys. Commun.* **182** 912–925

Towards a 3D Full MHD plasma - 3D electromagnetic wall model

On the eddy and halo current coupling of JOREK with electromagnetic wall codes

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Abstract.

An adequate modelling of the electromagnetic interaction of a tokamak plasma with the surrounding conductors is paramount for the correct reproduction of its so-called *free boundary* dynamics. Simulations of the latter provide in turn useful predictions regarding the plasma evolution, the related MHD modes leading to disruptions and the electromagnetic forces acting on the vacuum vessel's components when said disruptions occur[2, 3]. The latest modelling efforts with the 3D FEM non-linear code JOREK[1] have been directed towards the eddy current coupling of a *reduced MHD* plasma model with thin and volumetric wall codes (STARWALL and CARIDDI)[4, 5]. Relying on this work, code development in the scope of free boundary modelling is currently aimed in two main directions. In particular, a *full MHD coupling* scheme has been implemented in the JOREK-STARWALL suit; the validation work and the physical features of this new coupling scheme are highlighted in this contribution. Concurrently, this work showcases the latest progress towards the generalization of the eddy current coupling scheme to a *eddy and halo current coupling*, thus accounting for both the currents induced by the plasma in the surrounding structures and the currents flowing between the plasma and said structures. Coupling JOREK's halo currents with CARIDDI's volumetric conductors will be crucial in view of the prediction of the magnitude of asymmetric sideways forces arising on conductors during disruptions in ITER-like tokamaks.

References

[1] Matthias Hölzl et al. "The JOREK non-linear extended MHD code and applications to large-scale instabilities and their control in magnetically confined fusion plasmas". In: *Nuclear Fusion* 61.6 (2021), p. 065001.

[2] VD Pustovitov, G Rubinacci, and F Villone. "On the computation of the disruption forces in tokamaks". In: *Nuclear Fusion* 57.12 (2017), p. 126038.

[3] Francisco Javier Artola et al. "Modelling of Vertical Displacement Events in tokamaks: status and challenges ahead". In: *Plasma Physics and Controlled Fusion* (2024).

[4] M Hölzl et al. "Coupling JOREK and STARWALL codes for non-linear resistive-wall simulations". In: *Journal of Physics: Conference Series*. Vol. 401. 1. IOP Publishing. 2012, p. 012010.

[5] N Isernia et al. "Self-consistent coupling of JOREK and CARIDDI: On the electromagnetic interaction of 3D tokamak plasmas with 3D volumetric conductors". In: *Physics of Plasmas* 30.11 (2023).

Boundary simulations in realistic wall geometry with the GBS code

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Abstract. The detachment regime presents a promising reduction of the heat flux reaching the divertor plates by dissipating most of the upstream heat flux to the neutral particles. In order to access detached regimes, a sufficiently high neutral pressure in the divertor has to be ensured, which can be achieved through increasing the divertor closure [1–3].

Modeling the boundary plasma and neutral dynamics while accounting for a realistic first wall geometry is thus important. The boundary region is typically studied with fluid models which are less computationally demanding than their kinetic counterparts. Spatial discretization often relies on flux-aligned grids in order to correctly resolve the anisotropic parallel transport, which comes at the cost of simplifications to the treatment of boundary conditions, e.g. by using immersed boundary conditions [4, 5].

In this work, the extension of GBS [6, 7] to handle flexible first wall geometry is described. This capability is enabled by use of curvilinear structured finite differences to allow for an accurate treatment of the boundary conditions. Grid generation and optimization leverage a spline elliptic grid generation framework originally developed in the context of isogeometric analysis applications [8]. The first simulations of baffled TCV simulations are compared to equivalent Cartesian domain cases.

References

[1] A. Q. Kuang et al. 2020. *Journal of Plasma Physics* **86**, 865860505.

[2] O. Février et al. 2021. *Nuclear Materials and Energy* **27**, 100977.

[3] G. Sun et al. 2023. *Nuclear Fusion* **63**, 096011.

[4] T. Body et al. 2020. *Contributions to Plasma Physics* **60**, e201900139.

[5] N. Rivals et al. 2022. *Contributions to Plasma Physics* **62**, e202100182.

[6] P. Ricci et al. 2012. *Plasma Physics and Controlled Fusion* **54**, 124047.

[7] M. Giacomin et al. 2022. *Journal of Computational Physics* **463**, 111294.

[8] J. Hinz, M. Möller, and C. Vuik 2018. *Computer Aided Geometric Design* **65**, 48–75.

Verification of the PICLS electromagnetic upgrade in mixed variables

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Abstract. The gyrokinetic particle-in-cell code PICLS is a full-f finite element tool to simulate turbulence in the tokamak scrape-off layer. During the previous year, the capability of PICLS was extended to encompass electromagnetic effects. Successful tests using the method of manufactured solutions were conducted on the freshly added Ampères-law-solver, and shear Alfvén waves were simulated to verify the new electromagnetic time step. However, as a code based on the $p_{||}$-formulation of the gyrokinetic equations, PICLS is affected by the Ampére-cancellation problem [4]. In order to bring higher-beta simulations within reach of our computational capacity, we implemented the mixed-variable formulation with pullback-scheme [4] in a similar fashion to, e.g., EUTERPE [2], ORB5 [1], or XGC [3]. Here, we present the corresponding verification efforts made for the different electromagnetic formulations of PICLS, using a test setup comparable to previously published results from ORB5 [5].

References

[1] A. Mishchenko et al., Pullback scheme implementation in ORB5, Computer Physics Communications 238 (2019)

[2] M. D. J. Cole, Global gyrokinetic and fluid hybrid simulations of tokamaks and stellarators, Ernst-Moritz-Arndt-University Greifswald (2016)

[3] R. Hager et al., Electromagnetic total-f algorithm for gyrokinetic particle-in-cell simulations of boundary plasma in XGC, Physics of Plasma 29, 112308 (2022)

[4] A. Mishchenko et al., Pullback transformation in gyrokinetic electromagnetic simulations, Physics of Plasmas 21 092110 (2014)

[5] A. Biancalani et al., Linear gyrokinetic particle-in-cell simulations of Alfven instabilities in tokamaks, Physics of Plasmas, Volume 23, page 012108 (2016)

Physics of the low momentum diffusivity regime in tokamaks and its experimental applicability

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Abstract. Strong $E \times B$ plasma flow shear is beneficial for reducing turbulent transport in tokamak plasmas. However, traditional methods for driving flow shear do not scale well to large devices such as future fusion power plants. Based on a large number of nonlinear gyrokinetic flux tube simulations, a novel approach to increase flow shear is studied: making the plasma "easier to push" by decreasing momentum diffusivity. By first considering a circular geometry, it is found that one can obtain low momentum diffusivity at tight aspect ratio, low safety factor, high magnetic shear and low temperature gradient. This is the so-called Low Momentum Diffusivity (LMD) regime. To drive intrinsic momentum flux, the magnetic surface is then elongated and tilted, making it up-down asymmetric. In the LMD regime, it is shown that this intrinsic momentum flux can drive strong flow shear, which can significantly reduce the heat flux. To decrease computational costs, a novel quasilinear model is proposed to efficiently calculate the momentum diffusivity and predict steady state intrinsic flow shear. Finally, the actual experimental conditions of the MAST tokamak are considered to illustrate that this strategy should allow to experimentally create significant flow shear.

Reconstructions of electron-temperature profiles from EUROfusion Pedestal Database using turbulence-based models and machine learning

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Abstract.

This study makes use of the EUROfusion pedestal database, and focuses on the electron-temperature and electron-density profiles in the edge region of H-mode ELMy JET-ILW pulses. We make systematic predictions of the electron-temperature pedestal, with engineering parameters and the density profiles as inputs. Taking a simple approach that assumes a definite local relationship between the gradients, we find that a range of power-law scalings $R/L_{T_e} = A\,(R/L_{n_e})^{\alpha}$ with α between 0.33 and 1.0 correctly capture the behaviour of the electron-temperature at the density-pedestal top when A is fit for each pulse at different points in the pedestal. For $\alpha = 1$, $A \equiv \eta_e$, a parameter known to govern the saturation of turbulence in the standard picture of slab-ETG modes. Determining η_e across the region between pedestal-density top and the separatrix yields a distribution of values that lie considerably above the slab-ETG linear threshold $\eta_{e,lin} = 0.8$. Simulations of ETG turbulence in steep-gradient regions of the pedestals of JET and other tokamaks suggest that a simple scaling exists between the turbulent heat flux and the the local values of the electron density (R/L_{n_e}) and temperature (R/L_{T_e}) gradients. Several versions of this scaling have previously been checked on a small subset of this database, and we now confirm that testing them against the entire database leads a prediction of the electron temperature within 50% of the experimental values. Based on simple arguments of the modification of critically-balanced slab-ETG turbulence with the introduction of a finite density, we provide a scaling which maximises the prediction accuracy across the database. Furthermore, we build a machine learning algorithm which, given more inputs than theory-based modelling, is able to predict the electron temperature accurately on a subset of 20% of the database, and we identify the most consequential engineering parameters for correct predictions. This result confirms the conceptual possibility of accurate prediction via models that rely on traditional theoretical understanding of turbulent transport. Finally, we present the results of simulations of ETG transport in the context of a high-collisionality reduced fluid model and discuss the transport properties of the plasma with varying density and temperature gradients, with particular concern to modelling the critical regime close to the ETG linear stability boundary.

Control of n=2 resistive wall mode in spherical tokamak

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Abstract. The Spherical Tokamak for Energy Production (STEP) is a UKAEA programme that aims to deliver a prototype compact fusion energy plant and a commercial pathway to fusion energy [1]. The low aspect ratio spherical tokamak is attractive because of its potential to achieve high-β since fusion power is $\propto \beta^2$. The resistive wall mode (RWM) is the primary instability which limits β [2], and so to maximize economic attractiveness, operation above the no-wall beta limit is desirable, where either passive or active control of n=1 and n=2 RWMs is needed, to avoid major disruptions. We use the MARS-F [3] MHD code to calculate how to stabilise n=2 RWMs, including plasma rotation effects, feedback control with sensor signal noise and low-pass frequency filtering. The results show the requirements to control the n=2 RWM are less onerous than for the n=1 RWM, and control coils for n=1 and 2 RWMs are planned in STEP. The presentation will also discuss possible passive structures needed to slow the RWM growth rate into the domain where it can be feedback controlled.

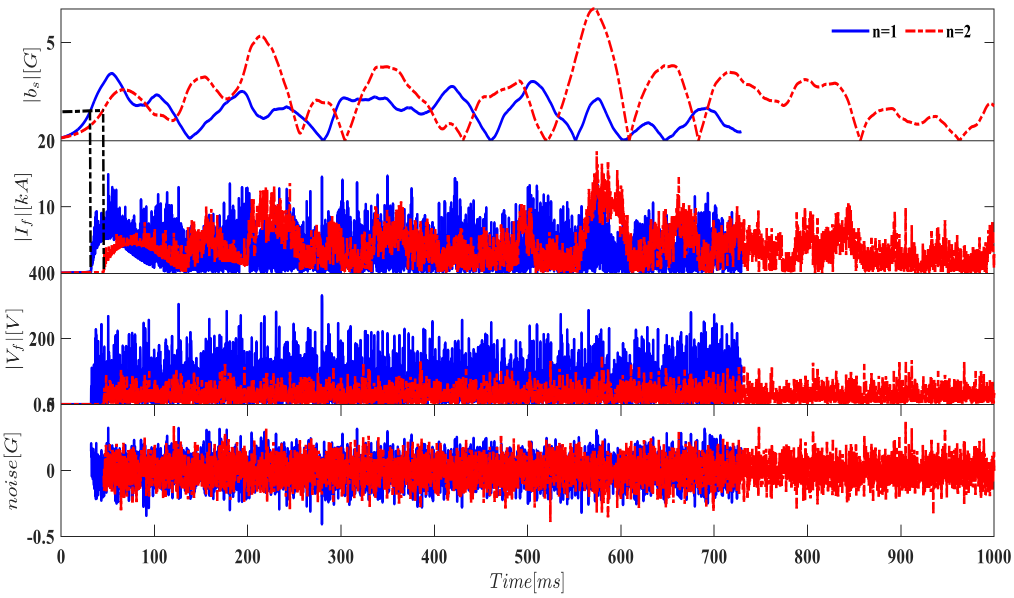

Figure 1. Feedback control results with gain value |G|=8 for n=1 (solid lines) and n=2 (broken lines) RWMs for a possible STEP scenario. b_s: sensor signal; I_f: coils current; V_f: coils voltage; *noise*: sensor noise

References

[1] Wilson H.R. et al 2020 Commercialising Fusion Energy vol **2053** pp 8–18
[2] Chu M.S. and Okabayashi M. 2010 Plasma Phys. Control. Fusion **52** 123001
[3] Liu Y.Q., Chu M.S., Chapman I.T. and Hender T.C. 2008 Phys. Plasmas **15** 112503

Study of neoclassical transport characteristics by MONTS code in the CFQS quasi-axisymmetric stellarator

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Abstract. Stellarators provide steady-state magnetohydrodynamic (MHD) equilibrium by only external coils, without relying on toroidal plasma current. On the other hand, in the case of a three-dimensional magnetic configuration without any continuous symmetry like conventional stellarators, larger neoclassical diffusion is expected in a low collisional regime [1]. In order to overcome this disadvantage, advanced stellarators have been proposed and studied. A quasi-axisymmetric stellarator (QAS) is one of those advanced stellarators, and it has a magnetic configuration embedded with axisymmetry like tokamaks [2-3]. As the first experiment device of QAS in the world, the CFQS has been designed and being constructed [4-6]. In this work, to investigate neoclassical diffusion properties in CFQS plasmas, we have been developing the Monte Carlo Neoclassical Transport Simulation (MONTS) code. At the moment, this research is also dedicated to systematically investigating the effect of axisymmetry breaking due to finite beta (the volume-averaged beta, $<\beta>$) on neoclassical transport characteristics in the CFQS. The enhancement of the finite beta leads to an increase in the neoclassical bootstrap current and variations in the major helical ripple component $B_{1,1}$ and other non-axisymmetric magnetic components. The magnetic surface is maintained at low beta ($<\beta>$=0.77%), but the surface is significantly deformed with an enhancement of axisymmetry breaking at high beta ($<\beta>$=2.03%). The neoclassical diffusion properties in CFQS have been studied for these cases. Electron and ion particle fluxes as a function of radial electric field have been investigated using the neoclassical diffusion coefficients and plasma parameters for the low beta and the high beta cases. It is found that electron roots of the ambipolar condition can provide good confinement in CFQS for the low beta and the high beta values. In order to evaluate the particle fluxes in CFQS more accurately, momentum conservation [7] in the Coulomb collisions will be taken into account. By utilizing the improved version of the MONTS code, we will investigate the bootstrap current and neoclassical parallel viscosity.

References

[1] Albert A. Galeev et al., *Physical Review Letters* **11** (1969) 511.
[2] J. Nührenberg et al., *Theory of Fusion Plasmas* (E. Sidoni et al., Eds.) (SIF, Bologna, 1994) p.3
[3] P. R. Garabedian et al., *Phys. Plasmas* 3 (1996) 2483
[4] Mitsutaka Isobe et al., *Plasma Fusion Res* **14** (2019) 34.
[5] Akihiro Shimizu et al., *Nuclear Fusion* **62** (2022) 016010.
[6] Haifeng Liu et al., *Nuclear Fusion* **61** (2020) 016014.
[7] Kimin Kim et al., *Phys. Plasmas* **19** (2012) 082503.

Universal behaviour of frequency chirping fluctuations in magnetized plasmas

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Abstract. Frequency-chirping fluctuations are ubiquitous in magnetized plasmas and are routinely observed in space and laboratory environments. Examples of the first type are whistler mode chorus and electromagnetic ion cyclotron (EMIC) waves in the Earth's magnetosphere; while fishbone oscillations and energetic particle modes (EPM) in tokamak fusion plasmas belong to the second category. In this work, we will discuss the universal process underlying these different observations; that is, the excitation and ensuing nonlinear dynamics of wave packets belonging to a dense, nearly continuous spectrum. More specifically, the wave-packets are continuously emitted and reabsorbed to maximize wave-packet growth via wave-particle interactions; leading to a renormalization of the particle distribution function. Consequences of this process are wave-particle phase locking, secular propagation of structures in the particle phase space, convective amplification of the wave packets, and linear scaling of frequency chirping rate with the wave-packet amplitude in the strong and non-perturbative drive case. It will be shown that the general theoretical framework is fully consistent with observations and numerical simulation results. Illustrative examples in each of the aforementioned cases will be presented.

Machine learning based tungsten spectroscopy in WEST Tokamak

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In the field of magnetic fusion, a shift has been operated from carbon-based materials to tungsten for the walls of several existing tokamaks and of ITER which is still under construction. Owing to the interactions of the plasma with the wall, tungsten is released and transported to confinement region as ions of different ionization stages. The presence of impurities as heavy as tungsten is a major source of power loss [1] as they have a high radiation capability. However, tungsten radiation can be used as a diagnostic tool to infer several parameters such as the ion temperature, the various ion abundancies and densities [2].

In this paper, we present two applications of deep learning to tungsten spectroscopy to analyze experimental data obtained from two shots performed in the WEST tokamak under different heating scenarios. In the first application, we investigate the correlation between Extreme UV (EUV) emission spectra and the electron temperature characterizing the magnetic surfaces. We develop a convolutional neural network (CNN) to predict the maximum electron temperature of the tungsten emission zone covered by each line of sight of the EUV system. The preliminary results show that, in most cases, the temperatures predicted by the neural network are in a reasonable agreement with those obtained by an independent system, with a mean absolute error of less than 150 eV.

The second application focuses on tomographic reconstruction. We employ a combination of an auto-encoder [3] - a neural network designed for data compression and feature extraction - and a neural network to reconstruct the emissivity profile along a line of sight, considering only the maximum electron temperature encountered by that line of sight. Thanks to its feature extraction the auto-encoder allows to obtain a continuous representation of the emissivity profiles allowing a better generalization capacity to the framework. The resulting reconstructions highlight a quasi-continuum profile typical of tungsten EUV emission. However, the neural network faces challenges in generating the high-frequency component of the desired signals. Enhancing the capturing of this missing part can be achieved by considering physics and signal processing informed constraints in the training process, thereby emphasizing attention on these emissivity fluctuations. These efforts pave the way for further improvements and applications of machine learning in spectroscopy measurement analysis.

[1] Puetterich T et al., Nucl. Fusion 50 (2010) 025012
[2] Guirlet R et al., Plasma Phys. Control. Fusion 64 (2022) 105024
[3] LeCun, Y., et al., Nature 521 (2015)