Theory of Fusion Plasmas

Joint Varenna–Lausanne International Workshop

21–25 September 2026

Villa Monastero, Varenna, Italy

Book of Abstracts

EPFL
Swiss Plasma Center

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Swiss Plasma Center, Ecole Polytechnique Fédérale de Lausanne
“Piero Caldirola” International Centre for the Promotion of Science and International School of Plasma Physics (ICPC)
Istituto per la Scienza e la Tecnologia dei Plasmi – CNR, Milan
Università degli Studi di Milano-Bicocca

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General Information

Organised by

Swiss Plasma Center
Ecole Polytechnique Fédérale de Lausanne

"Piero Caldirola" International Centre for the Promotion of Science and International School of Plasma Physics (ICPC)
Prof. E. Sindoni, Honorary President – Prof. G. Gorini, President

Istituto per la Scienza e la Tecnologia dei Plasmi – CNR, Milan

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Programme

Sunday, 20 September 2026

16:00–19:00 Registration at Villa Monastero

Monday, 21 September 2026

Session 1: Fundamental Theory of Turbulence and Transport

09:00–09:10 Welcome — J.P. Graves and P. Helander

09:10–09:55

A. Schekochihin

Tutorial: "As simple as possible but not simpler": physics of turbulence and transport in fusion plasmas via reduced fluid models (I1)

09:55–10:40

G. O. Acton, E. Rodríguez, G. Roberg-Clark, Alessandro Zocco

Computational and Theoretical Advances for Zonal Flows in Stellarators (I2)

10:40–11:10 Coffee break

11:10–11:55

K. Zhang, W. Zholobenko, A. Stegmeir, M. Faitsch, K. Eder, C. Pitzal, F. Jenko, ASDEX Upgrade team

Exploring Tokamak Boundary Turbulence with GRILLIX Simulations: From L-Mode to H-Mode and the Quasi-Continuous Exhaust Regime (I3)

11:55–12:40

P. J. Costello, G. G. Plunk

Constrained optimal modes: tightening thermodynamic bounds on the linear growth rate of microinstabilities (I4)

12:40–12:50 Group photo (Villa Monastero garden)

12:50–15:00 Lunch

Session 2: Tokamak Plasma Regimes

15:00–15:45

N. Rivals, N. Fedorczak, H. Yang, E. Havlickova, E. Geulin, R. Nouailletas, D. Moiraf, L. Meng, C. Guillemaut, J.P. Gunn, P. Hennequin, J. Morales, P. Manas, L. Fevre, J. Gaspar, A. Ekedahl, J. Gerardin, Y. Corre, P. Maget, M. Bernert, S. Henderson, H. Reimerdes, E. Tsitrone, N. Vianello, E. Serre, G. Ciraolo, the EUROfusion Tokamak Exploitation Team, the WEST team

Understanding of the X-Point Radiator regimes in tokamaks through an example in the WEST device (I5)

15:45–16:30

F. Maiden, S. Freethy, V. Shevchenko, R. Vann

The theory behind solenoid-free microwave driven start-up in tokamaks (I6)

16:30–17:00 Coffee break

17:00–17:45

J. W. Burby

Statistical equilibrium model for stellarators (I7)

19:30 Welcome Party (Blanco Lounge Bar, Varenna)

Tuesday, 22 September 2026

Session 3: Fast Ions, Runaways and Heat Transport in Stellarators

09:00–09:45

T. E. Foster, F. I. Parra, R. B. White, J. L. Velasco, I. Calvo, E. J. Paul
Analytical formulas for alpha-particle orbits in stellarators (I8)

09:45–10:30

M. Fitzgerald
Conservation and destruction of alpha particle invariants in optimized stellarators. (I9)

10:30–11:00 Coffee break

11:00–11:45

I. Ekmark, M. Landreman
Runaway electrons in stellarators: Unlikely or unavoidable (I10)

11:45–12:30

H. Thienpondt, J. M. García-Regaña, I. Calvo, M. Wappl, S. Bozhenkov
Nonlinear critical gradients in W7-X: Insights from massive gyrokinetic simulations and experimental measurements of turbulent heat transport (I11)

12:30–14:30 Lunch

Posters

14:30–16:00 Poster session 1

16:00–16:30 Coffee break

16:30–18:00 Poster session 2

Wednesday, 23 September 2026

Session 4: Microturbulent Transport and Gyrokinetics in Tokamaks

09:00–09:45

Haomin Sun, Plamen Ivanov, Justin Ball, Stephan Brunner
The unusual dynamics of turbulent transport in spherical tokamaks with large field line pitch angle (I12)

09:45–10:30

L. De Gianni, P. Donnel, X. Garbet, Y. Sarazin, R. Bigué, G. Dif-Pradalier, V. Grandgirard, K. Obrejan, M. Protais, J.Y. Ng, Y.Cho, Z.Qu
Understanding Trapped Electron Modes in negative triangularity (I13)

10:30–11:15

S. Y. Liu, P. Y. Jiang, P. F. Liu, G. Y. Fu
Development of the Gyrokinetic-MHD Hybrid Code cuGMEC and Its Nonlinear Simulations of Alpha Particle-driven Alfvén Eigenmodes in ITER (I14)

11:15–11:35 Coffee break

11:35–12:20

S. Choudhary, M. G. Krishna, J. Chowdhury, A. K. Singh, T. Hayward-Schneider, E. Lanti, R. Ganesh, L. Villard
Gyrokinetic Transport in flat-Temperature Tokamak Plasmas (I15)

12:20–13:05

J. McClenaghan, K. E. Thome, T. F. Neiser, J. Candy, F. D. Halpern, T. H. Osborne, S. Saarelma
Integrating Gyrokinetic Flux Predictions with Ideal MHD Stability Boundaries (I16)

13:05– Lunch

19:30 Conference dinner (Ristorante La Breva, Lierna)

Thursday, 24 September 2026

Session 5: Stellarator Optimisation

09:00–09:45

J. L. Velasco, V. Fernández-Pacheco, I. Calvo, E. Sánchez, J.M. García-Regaña, J. A. Alonso, D. Carralero, R. Gaur, H. Liu, M. Padidar, G. Yu, C. Zhu
Tutorial: New avenues for stellarator design enabled by piecewise omnigenity (I17)

09:45–10:30

W. Sengupta, N. Nikulsin, S. Buller, R. Madan, A. Brown, E.J. Paul, R. Nies, A.A. Kaptanoglu, S.R. Hudson, A. Bhattacharjee
Periodic Korteweg-de Vries soliton potentials generate quasisymmetric magnetic field strength in both vacuum and finite plasma-beta equilibrium (I18)

10:30–11:00 Coffee break

11:00–11:45

A. Goodman, G. Plunk, P. Xanthopoulos, Carolin Nührenberg, Joachim Geiger, Craig Beidler, Håkan Smith, Michael Drevlak
Searching for SQuIDs: Developments in the optimisation of Stable Quasi-Isodynamic Designs (I19)

11:45–12:30

P. Jurašić, S. R. Hudson, A. Merlo, E. Laude
Designing stellarator island divertors by controlling the island flux (I20)

12:30–14:30 Lunch

Posters

14:30–16:00 Poster session 3

16:00–16:30 Coffee break

16:30–18:00 Poster session 4

Friday, 25 September 2026

Session 6: Fast Ion and Nonlinear Physics in Tokamaks

09:00–09:45

Huishan Cai
Cross-scale Interaction between Microturbulence and Fishbone in Fusion Plasmas (I21)

09:45–10:30

D. Korger, E. Poli, F. Zonca, M. V. Falessi, R. Stucchi, A. Bottino, T. Hayward-Schneider
A nonlinear Schrödinger equation for the description of geodesic-acoustic-modes in tokamaks (I22)

10:30–11:00 Coffee break

11:00–11:45

J. Wang, Y. Todo, A. Bierwage, R. Seki, Z.X. Wang, N. Tsujii, Z. Cheng, H. Wang, P. Su
Comprehensive simulations of bursting shear Alfvén waves in tokamaks and their control via phase space engineering with ICRF waves (I23)

11:45–12:30

E. G. Devin, V. N. Duarte
Nonlinear evolution of strongly driven perturbative kinetic instabilities (I24)

12:30–12:45 Closing session

List of Invited Speakers

I1 A. Schekochihin — Tutorial: "As simple as possible but not simpler": physics of turbulence and transport in fusion plasmas via reduced fluid models

I2 G. O. Acton, E. Rodríguez, G. Roberg-Clark, Alessandro Zocco — Computational and Theoretical Advances for Zonal Flows in Stellarators

I3 K. Zhang, W. Zholobenko, A. Stegmeir, M. Faitsch, K. Eder, C. Pitzal, F. Jenko, ASDEX Upgrade team — Exploring Tokamak Boundary Turbulence with GRILLIX Simulations: From L-Mode to H-Mode and the Quasi-Continuous Exhaust Regime

I4 P. J. Costello, G. G. Plunk — Constrained optimal modes: tightening thermodynamic bounds on the linear growth rate of microinstabilities

I5 N. Rivals, N. Fedorczak, H. Yang, E. Havlickova, E. Geulin, R. Nouailletas, D. Moiraf, L. Meng, C. Guillemaut, J.P. Gunn, P. Hennequin, J. Morales, P. Manas, L. Fevre, J. Gaspar, A. Ekedahl, J. Gerardin, Y. Corre, P. Maget, M. Bernert, S. Henderson, H. Reimerdes, E. Tsitrone, N. Vianello, E. Serre, G. Ciraolo, the EUROfusion Tokamak Exploitation Team, the WEST team — Understanding of the X-Point Radiator regimes in tokamaks through an example in the WEST device

I6 F. Maiden, S. Freethy, V. Shevchenko, R. Vann — The theory behind solenoid-free microwave driven start-up in tokamaks

I7 J. W. Burby — Statistical equilibrium model for stellarators

I8 T. E. Foster, F. I. Parra, R. B. White, J. L. Velasco, I. Calvo, E. J. Paul — Analytical formulas for alpha-particle orbits in stellarators

I9 M. Fitzgerald — Conservation and destruction of alpha particle invariants in optimized stellarators.

I10 I. Ekmark, M. Landreman — Runaway electrons in stellarators: Unlikely or unavoidable

I11 H. Thienpondt, J. M. García-Regaña, I. Calvo, M. Wappl, S. Bozhenkov — Nonlinear critical gradients in W7-X: Insights from massive gyrokinetic simulations and experimental measurements of turbulent heat transport

I12 Haomin Sun, Plamen Ivanov, Justin Ball, Stephan Brunner — The unusual dynamics of turbulent transport in spherical tokamaks with large field line pitch angle

I13 L. De Gianni, P. Donnel, X. Garbet, Y. Sarazin, R. Bigué, G. Dif-Pradalier, V. Grandgirard, K. Obrejan, M. Protais, J.Y. Ng, Y.Cho, Z.Qu — Understanding Trapped Electron Modes in negative triangularity

I14 S. Y. Liu, P. Y. Jiang, P. F. Liu, G. Y. Fu — Development of the Gyrokinetic-MHD Hybrid Code cuGMEC and Its Nonlinear Simulations of Alpha Particle-driven Alfvén Eigenmodes in ITER

I15 S. Choudhary, M. G. Krishna, J. Chowdhury, A. K. Singh, T. Hayward-Schneider, E. Lanti, R. Ganesh, L. Villard — Gyrokinetic Transport in flat-Temperature Tokamak Plasmas

I16 J. McClenaghan, K. E. Thome, T. F. Neiser, J. Candy, F. D. Halpern, T. H. Osborne, S. Saarelma — Integrating Gyrokinetic Flux Predictions with Ideal MHD Stability Boundaries

I17 J. L. Velasco, V. Fernández-Pacheco, I. Calvo, E. Sánchez, J.M. García-Regaña, J. A. Alonso, D. Carralero, R. Gaur, H. Liu, M. Padidar, G. Yu, C. Zhu — Tutorial: New avenues for stellarator design enabled by piecewise omnigenity

I18 W. Sengupta, N. Nikulsin, S. Buller, R. Madan, A. Brown, E.J. Paul, R. Nies, A.A. Kaptanoglu, S.R. Hudson, A. Bhattacharjee — Periodic Korteweg-de Vries soliton potentials generate quasisymmetric magnetic field strength in both vacuum and finite plasma-beta equilibrium

I19 A. Goodman, G. Plunk, P. Xanthopoulos, Carolin Nührenberg, Joachim Geiger, Craig Beidler, Håkan Smith, Michael Drevlak — Searching for SQuIDs: Developments in the optimisation of Stable Quasi-Isodynamic Designs

I20 P. Jurašić, S. R. Hudson, A. Merlo, E. Laude — Designing stellarator island divertors by controlling the island flux

I21 Huishan Cai — Cross-scale Interaction between Microturbulence and Fishbone in Fusion Plasmas

I22 D. Korger, E. Poli, F. Zonca, M. V. Falessi, R. Stucchi, A. Bottino, T. Hayward-Schneider — A nonlinear Schrödinger equation for the description of geodesic-acoustic-modes in tokamaks

I23 J. Wang, Y. Todo, A. Bierwage, R. Seki, Z.X. Wang, N. Tsujii, Z. Cheng, H. Wang, P. Su — Comprehensive simulations of bursting shear Alfvén waves in tokamaks and their control via phase space engineering with ICRF waves

I24 E. G. Devin, V. N. Duarte — Nonlinear evolution of strongly driven perturbative kinetic instabilities

Monday

Monday, 21 September 2026 — invited talks

Session 1: Fundamental Theory of Turbulence and Transport

I1 A. Schekochihin — Tutorial: "As simple as possible but not simpler": physics of turbulence and transport in fusion plasmas via reduced fluid models

I2 G. O. Acton, E. Rodríguez, G. Roberg-Clark, Alessandro Zocco — Computational and Theoretical Advances for Zonal Flows in Stellarators

I3 K. Zhang, W. Zholobenko, A. Stegmeir, M. Faitsch, K. Eder, C. Pitzal, F. Jenko, ASDEX Upgrade team — Exploring Tokamak Boundary Turbulence with GRILLIX Simulations: From L-Mode to H-Mode and the Quasi-Continuous Exhaust Regime

I4 P. J. Costello, G. G. Plunk — Constrained optimal modes: tightening thermodynamic bounds on the linear growth rate of microinstabilities

Session 2: Tokamak Plasma Regimes

I5 N. Rivals, N. Fedorczak, H. Yang, E. Havlickova, E. Geulin, R. Nouailletas, D. Moiraf, L. Meng, C. Guillemaut, J.P. Gunn, P. Hennequin, J. Morales, P. Manas, L. Fevre, J. Gaspar, A. Ekedahl, J. Gerardin, Y. Corre, P. Maget, M. Bernert, S. Henderson, H. Reimerdes, E. Tsitrone, N. Vianello, E. Serre, G. Ciraolo, the EUROfusion Tokamak Exploitation Team, the WEST team — Understanding of the X-Point Radiator regimes in tokamaks through an example in the WEST device

I6 F. Maiden, S. Freethy, V. Shevchenko, R. Vann — The theory behind solenoid-free microwave driven start-up in tokamaks

I7 J. W. Burby — Statistical equilibrium model for stellarators

I1

Tutorial: "As simple as possible but not simpler": physics of turbulence and transport in fusion plasmas via reduced fluid models

A. Schekochihin[1]

[1] University of Oxford and Merton College

In the early days of fusion physics, when the crucial role to be played by Larmor-scale turbulent transport started to be realised but computing power was insufficient for any kind of quantitative modelling, the focus necessarily had to be on the qualitative understanding of the physics, and the first glimmers of such an understanding emerged from considerations of maximally simplified models – usually describing plasma dynamics in terms of a few fluid fields in a slab-like box, with equilibrium profiles and field-line geometry parametrised in terms of a few coefficients constant across that box. The advent first of gyrofluid and then of gyrokinetic computations on ever more powerful machines shifted the community's priorities towards perfecting the ever more realistic, largely brute-force (inasmuch as affordable), quantitative modelling – the emphasis that continues today, now increasingly in the context of providing learning data for hoped-for superior AI-assisted modelling systems. If, however, AI (perhaps human-assisted, if ever more lightly) is to take over not just quantitative prediction and optimisation of machine performance but also (much of) the code development required for it, there is perhaps some bandwidth opening up for theoreticians to revisit the analogue approach, re-embracing our ability to think in simple terms and to anticipate complicated outcomes based on physical intuition developed from minimal models (indeed it is worth asking in this context whether we currently have any real physical understanding of turbulence in fusion devices that is based on anything other than such models). In this tutorial talk, I will attempt to share some experience of taking such an approach, which has brought our group at Oxford some notable findings across a number of physical problems that have long been of interest to the students of fusion-relevant turbulence: the mechanism of the Dimits transition [1,3], the reasons for extreme electromagnetic transport in high-beta regimes [8,9], the nature of turbulence in the presence of flow shear [5,13], the saturation of electron-scale turbulence far from [2,4] vs. close to [12] its threshold, the emergence of transport barriers [10], high- and low-transport states as well as some unexpected subcritical regimes of interchange turbulence [11], etc. While my message is that many things can be understood, at least on a conceptual level, in fairly simple terms, one does of course learn some lessons on the way as to the dangers of oversimplification and the need to keep an eye on the geometrically and physically complex reality [6,7,9]. How the basic ingredients of the complicated turbulent mix present in actual machines emerge, what physical elements are necessary for what outcomes, how they interact, how to make models simple enough for human (or easy computational) grasp while keeping the proverbial baby firmly separated from the vast quantities of discarded bathwater – these are questions that may have renewed relevance for a generation of fusion researchers whose professional and intellectual survival will hinge on their ability to understand, assess, and direct the output of vast modelling frameworks no less complex and (potentially) unreliable than the confined plasma itself.

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[1] P. G. Ivanov, A. A. Schekochihin, W. Dorland, A. R. Field, and F. I. Parra, "Zonally dominated dynamics and Dimits phase transition in curvature-driven ITG turbulence," J. Plasma Phys., 86, 855860502 (2020) [arXiv:2004.04047]

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static drift-kinetic turbulence," J. Plasma Phys. 89, 905890406 (2023) [arXiv:2303.14834]

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[10] R. Dutta, Y. Zhang, P. G. Ivanov, D. Kennedy, R. Nies, and A. A. Schekochihin, "Transport barriers in double-diffusive plasmas," J. Plasma Phys., in preparation (2026)

[11] W. A. Clarke, A. A. Schekochihin, T. Adkins, P. G, Ivanov, M. A. Barnes, D. N. Hosking, and J. Squire, "Transitions from high to low transport and spontaneous imbalance in interchange-driven Alfvénic turbulence," Plasma Phys. Control. Fusion, in preparation (2026)

[12] L.-P. Turica, T. Adkins, P. G, Ivanov, R. Nies, and A. A. Schekochihin, "Saturation of electron-temperature-gradient turbulence near threshold," J. Plasma Phys., in preparation (2026)

[13] D. Fedeli, P. G. Ivanov, and A. A. Schekochihin, "Nature and dynamics of long-lived solitary structures in temperature-gradient-driven plasma turbulence embedded in a shear flow," in preparation (2026)

I2

Computational and Theoretical Advances for Zonal Flows in Stellarators

G. O. Acton[1], E. Rodríguez[1], G. Roberg-Clark[1], Alessandro Zocco[1]

[1]Max-Planck-Institut for Plasma Physics, Wendelsteinstraße 1, 17491 Greifswald, Germany

Zonal flows play a central role in regulating turbulence and improving confinement in magnetically confined fusion plasmas. Their accurate prediction is essential for the development of reliable turbulence models and the optimisation of future fusion reactors. In stellarators, however, the intrinsically non-axisymmetric magnetic geometry introduces additional complexity: local variations in magnetic structure modify turbulent dynamics and enhance cross-field mode coupling, complicating the generation, evolution, and saturation of zonal flows.

In this work, we introduce a systematic ordering of the amplitudes of interacting modes that identifies distinct nonlinear regimes governing zonal-flow dynamics. These are classified as weak, strong, and fully developed, according to the structure of the underlying mode coupling, and their relationship to existing theoretical descriptions is established. Within this unified framework, we investigate the mechanisms responsible for zonal-flow generation and the processes that determine their saturation across a range of stellarator magnetic configurations.

In the weakly nonlinear regime, the temporal evolution and phase-space structure of zonal flows are described using a truncated spectral representation and validated against direct numerical solutions. Beyond this regime, as turbulence becomes strongly nonlinear, a minimal-mode saturation model can still be used to capture the essential qualitative dynamics. This framework provides a systematic interpretation of zonal-flow generation, destabilisation, and saturation under different ordering assumptions. To this end, it demonstrates that the toroidal secondary mode [1] (which is be captured by this minimal model) plays a significant role in the saturation process over a broad range of stellarator geometries.

Finally, we present advances in numerical capability through the development of a full-flux-annulus formulation of the gyrokinetic code stella [2], enabling efficient and accurate simulations of turbulence with kinetic electrons in general magnetic geometries. Together, the theoretical framework and numerical developments presented here provide complementary tools for advancing the understanding and predictive modelling of stellarator turbulence.

References:

[1] R. Nies, F. I. Parra, M. Barnes, N. Mandell, and W. Dorland, Phys. Rev. (2026)

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[3] G. Acton, E. Rodríguez, G. Roberg-Clark, A. Zocco, Arxiv (2026)

I3

Exploring Tokamak Boundary Turbulence with GRILLIX Simulations: From L-Mode to H-Mode and the Quasi-Continuous Exhaust Regime

K. Zhang[1], W. Zholobenko[1], A. Stegmeir[1], M. Faitsch[1], K. Eder[1], C. Pitzal[1], F. Jenko[1], ASDEX Upgrade team[2]

[1] Max Planck Institute for Plasma Physics

[2] See author list of T. P¨utterich et al, 2026 Nucl. Fusion 66 116002 https://doi.org/10.1088/1741-4326/ae61c8

The H-mode in tokamaks brings fusion performance within reach but faces two major challenges: damaging ELMs and excessive divertor heat loads. Recent results from various tokamak experiments identified an ELM-free H-mode—the quasi-continuous exhaust (QCE) regime—combining high pedestal pressure, reactor-relevant separatrix density, and a broadened SOL heat width [1], making it promising for a fusion reactor [2]. We present a first-principles, turbulence-based explanation for QCE performance. Using the GRILLIX code, we perform global simulations across the pedestal and SOL in realistic AUG geometry. These results reveal a quasi-coherent mode (QCM) [3] spanning the separatrix and launching ballistic, filamentary blobs into the SOL, reproducing mean profiles, fluctuation spectra, and mode structure seen in experiments.

Our results show that the QCM resides within a broad Er well whose width accommodates the QCM's radial autocorrelation length and enables sufficient E×B transport to narrow the pedestal. The width of the Er well is self-organized electromagnetically through the Maxwell stress generated by the QCM, which depletes the turbulent drive for zonal flow. Simulations and analytical investigation consistently demonstrate that the QCM is driven by a kinetic ballooning mode (KBM), in which the notable stabilization by finite-Larmor-radius effects prevents the transport from degrading the H-mode-like confinement. The destabilization of resistivity remains prominent only near the X-point, where it triggers a resistive X-point mode (RXM) [4]. In the SOL, the interaction between the KBM and RXM ejects blobs whose radial propagation enhances heat exhaust and decouples the SOL temperature fall-off from the pedestal-foot gradient. Together, these dynamics outline a pathway to self-sustained, ELM-free H-mode confinement with manageable heat exhaust.

References:

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[2] M. Faitsch et al., Nucl. Fusion 63, 076013 (2023).

[3] J. Kalis et al., Nucl. Fusion 64, 016038 (2024).

[4] J. R. Myra et al., Physics of Plasmas 7, 4622 (2000).

I4

Constrained optimal modes: tightening thermodynamic bounds on the linear growth rate of microinstabilities

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The required size of a future, economically viable tokamak or stellarator power plant is largely dictated by the expected outward turbulent transport of heat and particles in the confined plasma. This turbulence occurs on spatial scales comparable to the gyro-motion of particles in the magnetic field and is best described by gyrokinetic theory. Our under standing of the onset of this turbulence relies primarily on linear stability analyses, where the micro-scale instabilities of the gyrokinetic system can be studied analytically in simple limits, or modelled with expensive gyrokinetic simulations. In recent years, a complementary approach to such analyses has been developed, in which the growth rate of microinstabilities is bounded from above by the growth of optimal modes: perturbations that achieve the maximum allowable extraction of free energy from the plasma gradients [1, 2]. Until now, optimal modes have provided an upper bound on the instantaneous growth of any perturbation, which includes, but is not limited to, linear instabilities. Here we present an extension of optimal-mode theory by seeking perturbations that maximise the extraction of free energy from the plasma gradients subject to constraints that are also satisfied by the linear instabilities, namely the linear evolution equations for the moments of the distribution function. This allows for a systematic tightening of the constrained optimal growth rate toward the linear growth rate by increasing the number of moment constraints. With an eye towards understanding and practical applications, we seek a minimal set of constraints for which the optimal growth rate captures the key dependencies of the linear growth rate on plasma parameters and magnetic geometry. We derive the system of ordinary differential equations that govern these minimally constrained optimal modes and compare their numerical solutions with the output of linear gyrokinetic simulations, demonstrating that the upper bound exhibits similar dependencies on plasma gradients and magnetic geometry to the linear growth rate. Because the computational cost of evaluating the optimal growth rate is low, we explore the potential applicability of this method to the optimisation of stellarator magnetic geometry for reduced turbulent transport.

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I5

Understanding of the X-Point Radiator regimes in tokamaks through an example in the WEST device

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[10]See http://west.cea.fr/WESTteam

In future, reactor-scale tokamaks the unmitigated heat flux deposited on the machine wall in the divertor region (divertor targets) poses a serious challenge for both survivability of materials and core plasma performance degradation due to impurity pollution and radiation.

The X-Point Radiator (XPR) regime, which is triggered by voluntarily injecting light impurities from the edge, and features strongly reduced divertor heat fluxes, brings a potential solution. It has been observed in almost all tokamak devices (see [1] and references therein), and while the properties of the plasma reaching the surfaces at the divertor plates may differ from one machine to the other, they all commonly share observations of the formation of a characteristic toroidal radiation ring (MARFE) near the X-Point.

The physics mechanisms of the XPR formation and stability conditions are investigated using time-dependent SOLEDGE3X simulations with drifts, using the WEST [3] device as an example. Parallels are drawn with the well-known simplified 0-D model from Stroth et al. [2], and new elements are presented on the dynamics of the onset as well as 2D spatial considerations. The localization of the X-Point MARFE above the X-Point is studied, showing that strong poloidal asymmetries can exist even in closed field lines. The onset dynamics is understood to be initially driven by the formation of ExB-driven vortex at the X-Point followed by a thermal instability forming the MARFE. The impact on stability of the direction of the toroidal magnetic field (hence the ExB flow direction) is highlighted in simulations, with the MARFE in reversed magnetic configuration being much less stable, and often leading to radiative collapses, as observed in WEST experiments. Findings form this study are also in accordance with observations and studies from other devices.

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I6

The theory behind solenoid-free microwave driven start-up in tokamaks

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Solenoid-free start-up of tokamaks offers the opportunity to remove the solenoid from tokamak power plants, decreasing the cost and size of the device. Microwaves can be used in lieu of the solenoid as they can both ionise the plasma and initiate a plasma current. This has been demonstrated experimentally [1, 2, 3, 4, 5, 6] and possible theories for the current drive have been proposed. However, present-day expertise on the theory behind solenoid-free wave driven start-up of tokamaks, particularly in Europe is limited. We present an introduction to the different current drive mechanisms introduced in the literature including the pressure driven [7, 8], preferential confinement [7, 9] and trapped particle precession [1] currents as well as induction due to ramping poloidal field coils. Two new current drive mechanisms are also introduced. The first is that if a localised absorption region due to electrons Bernstein waves is assumed, the current drive above and below the absorption region in open field lines is in opposite directions. The second is that the current driven by an accumulation of electrons in the co-current direction is determined by the increase in the vacuum magnetic field due to the poloidal field coils. These current drive mechanisms are compared to experimental results from MAST [4, 10] and it is found that the new mechanisms play an important role.

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I7

Statistical equilibrium model for stellarators

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Standard stellarator equilibrium modeling assumes the nominal plasma state in a stellarator satisfies ideal force balance. However, the partial differential equations (PDE) describing ideal force balance suffer from well-known mathematical deficiencies in three dimensions. The typical response to these deficiencies is development of new solver strategies, for instance through introduction of numerical magnetic relaxation effects that allow for formation of islands. An alternative response is to doubt suitability of the ideal force balance model itself. I will describe a new approach to equilibrium modeling in stellarators based on including Maxwell Reynolds stress using a Taylor hypothesis. The new approach replaces the usual Lagrangian for three-dimensional equilibria with its average over short-scale, nonideal fluctuations. This introduces a frozen-in magnetic variance tensor encoding second-order statistics of short-scale magnetic fluctuations. The Euler-Lagrange equations for the mean Lagrangian are elliptic due to the presence of Maxwell Reynolds stress, in contrast to the mixed hyperbolic-elliptic type inherent to standard ideal force balance. Asymptotic boundary layer analysis shows that Maxwell Reynolds stress also naturally regularizes singularities that typically appear at rational surfaces. A 3D solver for the new model in a toroidal annulus demonstrates robust convergence under radial mesh refinement without formation of singularities. This equilibrium model explicitly exposes magnetic topology as a an adjustable model parameter. The model remains elliptic regardless of whether the chosen magnetic topology is integrable or non-integrable.

Tuesday

Tuesday, 22 September 2026 — invited talks

Session 3: Fast Ions, Runaways and Heat Transport in Stellarators

I8 T. E. Foster, F. I. Parra, R. B. White, J. L. Velasco, I. Calvo, E. J. Paul — Analytical formulas for alpha-particle orbits in stellarators

I9 M. Fitzgerald — Conservation and destruction of alpha particle invariants in optimized stellarators.

I10 I. Ekmark, M. Landreman — Runaway electrons in stellarators: Unlikely or unavoidable

I11 H. Thienpondt, J. M. García-Regaña, I. Calvo, M. Wappl, S. Bozhenkov — Nonlinear critical gradients in W7-X: Insights from massive gyrokinetic simulations and experimental measurements of turbulent heat transport

I8

Analytical formulas for alpha-particle orbits in stellarators

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In stellarator reactors, the energetic alpha particles produced by D–T fusion will have a relatively large normalized gyroradius $\rho_\star$ (up to ~3%). This has motivated concerns (e.g. [1,2]) about the accuracy, for fusion-born alphas, of results derived from an asymptotic expansion in $\rho_\star \ll 1$, such as conservation of the second adiabatic invariant (J), orbit-averaged drift-kinetic equations, and the guiding-centre model. In this talk, we demonstrate—by comparing analytical calculations with ASCOT5 [3] simulations—that expansion in $\rho_\star \ll 1$ can accurately describe alpha-particle orbits in reactor-scale stellarators. These calculations are more involved than for lower-energy particles because good agreement with simulations often requires higher-order (in $\rho_\star$) corrections, and because resonant and non-resonant orbits require different asymptotic treatments.

As examples, we discuss two types of resonant orbit that could degrade alpha confinement in stellarator reactors. First, passing orbits containing wide 'drift islands' can arise near rational surfaces, even when the magnetic field possesses nested flux surfaces [4]. The width of these drift islands scales as $(\rho_\star \delta / s)^{1/2}$ (δ is the deviation from omnigeneity and s is the magnetic shear), so they can be large in low-shear stellarators that are insufficiently omnigeneous. We derive formulas for the drift-island shape by expanding in $\rho_{star}^{(1/2)} \ll 1$. Second, for trapped alphas in quasi-axisymmetric stellarators with a low rotational transform iota, resonance between the bounce motion and toroidal precession can violate conservation of J and generate wide resonance islands [5,6]. We argue that this occurs when iota $\sim \rho_\star^{1/2}$, and by adopting this ordering we derive a new invariant replacing J that determines the island shape. Our analytical formulas allow the alpha orbits in a given equilibrium to be computed rapidly, which could facilitate optimization for improved alpha confinement.

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I9

Conservation and destruction of alpha particle invariants in optimized stellarators.

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It has long been understood that alpha particle equilibrium in tokamaks relies on the existence of approximate symmetries in time, gyroangle and toroidal angle. These symmetries lead to invariants, and invariants lead to an integrable Hamiltonian system for the guiding centre motion and ultimately alpha confinement. Toroidal canonical momentum P_ζ, at least on paper, is exactly conserved in a tokamak. Deviations from toroidal symmetry in tokamaks caused by ripple, instabilities, and error fields are the principal cause of anomalous fast ion transport observed in current experiments and are well understood as a perturbation to the equilibrium Hamiltonian. Outside the guiding centre picture, deviations in gyro symmetry are known to be responsible for both adiabatic and non-adiabatic changes in magnetic moment μ. Less well known are analogous changes in second invariant $J_\parallel$. Both effects were studied by Hastie [1,2]

The Taylor Hamiltonian governing guiding centre motion depends on the magnetic field B only through the modulus [3]. Stellarators have many attractive features for a fusion reactor, and recent work on quasi-symmetry demonstrates magnetic equilibria approaching global symmetry in the modulus in B [4], and accompanying claims on confinement in comparison to tokamaks in absence of experimental demonstration.

Adiabatic and non-adiabatic changes in P_ζ in stellarators have attracted little attention, with alpha particles the most susceptible. These effects are absent in guiding centre codes and optimizations widespread in the stellarator community.

Using a deviation from the procedure introduced by Littlejohn [5], we have found a way to express the exact particle motion as the usual guiding centre motion plus a fictitious magnetic field perturbation due to all higher order terms in ρ^*_α. We have clarified that all changes to the adiabatic invariants can be thought of as coherent kicks from this quasi field, and these errors will accumulate for resonant particles in the usual way as for other perturbing fields. This quasi field scales as ρ^*_α^2 times the equilibrium field and has a slowly varying piece which is set by the magnetic field line torsion times the magnetic moment. Crude estimates lead one immediately to require at least that $\rho^*_\alpha<0.1$. Resonant orbits in a 'precise' QA stellarator will be presented as an example.

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I10

Runaway electrons in stellarators: Unlikely or unavoidable

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One of the major challenges for development of tokamak reactors is disruptions caused by plasma instabilities, which can give rise to significant generation of runaway electrons. The generation is exponentially sensitive to the initial plasma current [1]. For reactor scale tokamaks with plasma currents of several MAs, a significant fraction of the initial plasma current can be converted into runaway current. Due to the lack of an externally driven plasma current and large-scale instabilities, disruptions are not anticipated to be a concern in stellarators. However, there can be significant bootstrap currents, driven by radial pressure gradients, possibly on the order of MAs [2]. The bootstrap current would disappear should there be a sudden loss of thermal confinement, for instance due to impurities entering the plasma. However, as the total plasma current cannot change instantaneously due to the self-inductance, an electric field will be induced to maintain the current that could be sufficiently high for runaway electron generation. Thus, runaway electrons could be a concern also for stellarators.

To study if runaway electrons risks being a concern in stellarators, we have implemented a stellarator plasma model in the runaway electron simulation code DREAM [3]. DREAM is one of the primary tools for studying runaway electrons in tokamaks. By implementing flux surface averaging for stellarator configurations as well as allowing non-axisymmetric fields in the implementation of Faraday's and Ampere's Laws, we are able to utilize the state-of-the-art runaway electron modelling capabilities of DREAM also for stellarators.

The possibility of runaway electrons in stellarators has been studied by exploring the effects of the initial plasma current, temperature decay rate and final equilibrium temperature. The temperature decay rate affects the seed generation, especially through impacting the hot-tail mechanism, while the final equilibrium temperature and the initial plasma current affect the avalanche generation. Our results predict that there can be significant runaway generation if two out the following three conditions are fulfilled: large initial plasma current, low final temperature, and fast thermal loss. Compared with a tokamak, our simulations predict the avalanche multiplication to be weaker during a disruption in a stellarator, even for stellarators of high plasma currents, which is explained by the stronger elongation of stellarator plasmas [4]. Thus, the combination of lower plasma currents and stronger elongation likely limits the risk of significant runaway generation, suggesting that runaway electrons will be less of a concern in stellarators with compared with tokamaks.

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I11

Nonlinear critical gradients in W7-X: Insights from massive gyrokinetic simulations and experimental measurements of turbulent heat transport

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Understanding under which conditions turbulent heat losses are minimized in magnetically confined fusion devices is crucial for achieving efficient and sustained plasma confinement. The Wendelstein 7-X (W7-X) stellarator exhibits a pronounced reduction of turbulent heat transport with increased density peaking, a behavior predicted by nonlinear gyrokinetic simulations [1] and confirmed experimentally [2]. Motivated by these findings, this work [3] presents an extensive and systematic comparison between nonlinear gyrokinetic simulations and experimental heat flux measurements across multiple operational campaigns, magnetic configurations, heating schemes, and fueling methods of the Wendelstein 7-X stellarator.

More than one thousand nonlinear electrostatic flux-tube simulations have been performed with the gyrokinetic code stella, resulting in one of the largest nonlinear gyrokinetic datasets ever assembled for a stellarator. Direct comparison with hundreds of experimental data points reveals robust, configuration-independent trends. First, a reduction of ion heat transport with increasing density peaking (i.e. larger a/L_n) is observed, with a density-gradient threshold for turbulence reduction at approximately $a/L_n = 1.0$. Second, the ion and electron heat fluxes exhibit strong dependencies on their respective temperature gradients, a/L_{Ti} and a/L_{Te}, allowing the identification of nonlinear critical temperature gradients around $a/L_{Ti} = 0.7$ and $a/L_{Te} = 1.6$. Notably, neither of these trends display a clear dependence on the magnetic configuration.

These results improve our understanding of turbulent transport in stellarators and raise new questions of how magnetic geometry affects turbulence, or whether its influence may, in some cases, be weaker than expected.

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Poster session 1 — Tuesday

P1 K. Aleynikova — Kinetic ballooning modes and electromagnetic stability in W7-X

P2 O. Anuaruly, J. Ball, S. Brunner — Gyrokinetic investigation of zero magnetic shear regions in tokamaks

P3 Wayne Arter — Simplest Models of Tokamak MHD

P4 J. Ball, S. Barreca, S. Brunner, J. Loizu — Gyrokinetic analysis of internal transport barriers in stellarators

P5 T. Barberis, V. Duarte — Reduced model of the interaction between microturbulence, energetic particles and energetic particle driven modes

P6 Andrew Brown, Yi-Min Huang, Amitava Bhattacharjee — MHD Equilibria via Voigt Regularization

P7 A. Cardinali, C. Castaldo, F. Napoli, W. Bin, P. Buratti, B. Moshref, R. Gatto, M. Guerini Rocco — Analysis of the electromagnetic and electrostatic instability induced by runaway electrons in a magnetized plasma

P8 S. Cavallero, V. N. Duarte, T. Barberis, F. Porcelli — Nonlinear saturation of Axisymmetric (n=0) modes driven by Energetic Particles in Tokamaks

P9 F. Ceccherini, L. Galeotti, A. Evangelias, H. Betar, C. Hue, J. Ortiz Luengo, G. Antar — Stellarator design points and optimized equilibria for compact high-field nuclear fusion reactors

P10 L. Galeotti, F. Ceccherini, C. Hue, J. Ortiz Luengo, A. Evangelias, H. Betar, G. Antar — Application of ECRH and NBI in compact high-field stellarator nuclear fusion reactors

P11 M. Evans, M. Barnes, P. Ivanov — Minimal Model for Floquet Modes in a Tokamak

P12 M. Francisquez, G. Wilkie, A. Maan, A. Hoffmann, D. Boyle, R. Majeski, G. W. Hammett — Validation and benchmarking of gyrokinetics in low-recycling lithiated conditions with Gkeyll and XGC

P13 K. Fujita, S. Satake — Effect of magnetic drift on the stability structure of the ambipolar condition in nonaxisymmetric plasmas

P1

Kinetic ballooning modes and electromagnetic stability in W7-X

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High-performance stellarator plasmas increasingly operate in regimes where electromagnetic effects become essential for confinement. Under these conditions, kinetic ballooning modes (KBMs), driven by finite-beta effects and pressure gradients, may become the dominant electromagnetic instability, linking ideal ballooning physics with kinetic microturbulence.

This contribution presents a combined theoretical, numerical, and experimental overview of KBMs in W7-X stellarator. To introduce the underlying physics, the discussion briefly revisits the ballooning instability framework in tokamaks before extending it to the three-dimensional magnetic geometry of stellarators, where magnetic configuration strongly influences stability.

Gyrokinetic simulations are used to investigate the evolution of the microinstability spectrum with increasing beta. While finite beta can stabilize electrostatic turbulence, sufficiently strong pressure gradients destabilize KBMs. Particular emphasis is placed on identifying KBM thresholds and on understanding the influence of magnetic geometry, including rotational transform, mirror ratio, and magnetic shear.

The theoretical predictions are compared with observations from high-performance W7-X plasmas, where coherent electromagnetic fluctuations with characteristics consistent with KBMs are observed. Together, simulations and experiments suggest that KBMs may represent an important electromagnetic stability boundary for high-beta stellarator operation. These results highlight the value of linear stability maps for identifying KBM-prone scenarios and demonstrate the importance of incorporating KBM physics into profile optimization and future stellarator reactor design.

P2

Gyrokinetic investigation of zero magnetic shear regions in tokamaks

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Hybrid and advanced tokamak operating scenarios are considered promising candidates for future burning-plasma operation. A distinctive feature of these scenarios is a core region with low magnetic shear, which can improve confinement through the formation of Internal Transport Barriers (ITBs) and suppression of sawtooth activity by magnetic flux pumping. Previous studies [1,2] have shown that regions of low and zero magnetic shear support ultra-long turbulent eddies that extend far along magnetic field lines. At rational surfaces, where the parallel connection length is finite, these eddies can self-interact and strongly modify the turbulent state. In this work, we investigate the effects of self-interaction on trapped-electron-mode (TEM) turbulence under realistic electron-ITB conditions in the TCV tokamak. It is shown that in contrast to the ITG-driven turbulence regime [3], rational surface q = 2 does not lead to the stabilization of turbulence, which is consistent with experimental observation [4]. We further show that self-generated turbulent currents in low-shear regions can modify the magnetic geometry through the formation of steady zonal current sheets. An analytical treatment of self-interaction in slab geometry is developed to investigate the effects of the finite connection length on the mode structure near rational surfaces.

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P3

Simplest Models of Tokamak MHD

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A minimal model for tokamak MHD was proposed [1] consisting of a helical mode interacting with a toroidally symmetric background, abbreviated ANAC for "Axisymmetric Non-Asymmetric Coupling". Recently the more mathematical aspects of ANAC and the related ANAET model (where ...ET denotes "Extra Terms") were explored for general application to sudden rapidly growing transient behaviour [3], whereat ANAC/ET was found to be simpler than most models invoked to describe e.g. neuronal spiking in the human brain. Indeed, as a third order ordinary differential equation with 7 terms and 3 explicit parameters, the simplified ANAET model has the same complexity as the well-known Lorenz model. One of the ANAET model's notable features is its ability to produce spikes in the helical mode as part of a quasi-regular biperiodic temporal oscillation, spikes that lead to sudden collapses in the symmetric background. Such solutions make ANAC/ET strong candidates to become surrogate models for sawtoothing behaviour in tokamaks, and also to represent major disruptions using the 'overtopping' mechanism [2, 4]. Recent work on reducing the ANAET model dissipation (effective resistivity), of including stochastic perturbations, and of the insights gained from the results, will be described. Work funded by the EPSRC[grant number EP/W006839/1].

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P4

Gyrokinetic analysis of internal transport barriers in stellarators

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We study so-called “internal island” discharges in W7-X [1], which have achieved the highest plasma performance to date. In these discharges, instead of using the iota=1 surface to define the edge of the plasma with the 5/5 island chain, iota=1 is moved inside the plasma where it sometimes causes an internal transport barrier. We show that turbulent self-interaction on such integer surfaces can directly affect heat transport [2]. Additionally, we demonstrate that a symmetry of the local gyrokinetic model is broken when iota is almost (but not exactly) a rational number and magnetic shear is low [3]. This can drive intrinsic rotation due to turbulent momentum transport. Nonlinear gyrokinetic simulations indicate this mechanism is significantly stronger than all other drives of intrinsic rotation. It also intrinsically transports electric current, pulling iota towards rational values and potentially aiding non-inductive current drive [3,4]. This is likely important in the triggering of internal transport barriers in both stellarators and tokamaks.

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P5

Reduced model of the interaction between microturbulence, energetic particles and energetic particle driven modes

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We present a reduced framework to describe the multiscale interaction between thermal plasma microturbulence, energetic particles generated by auxiliary heating, and the macroscopic instabilities that these particles can drive. Our approach focuses on how microturbulence regulates the saturation amplitude of energetic-particle-driven modes, such as shear Alfvén waves, through scattering-dominated nonlinear dynamics, where effective particle scattering balances wave dissipation. At the same time, energetic-particle-driven modes can modify the underlying microturbulence via nonlinear couplings and zonal mode excitation, introducing a feedback loop that can reduce turbulence levels and, in turn, lower the mode saturation amplitude. This interplay may lead to improved thermal plasma confinement and reduced energetic particle transport. The proposed framework provides a tractable way to capture the essential physics of this coupled system and to explore the mutual interaction between turbulence, energetic particles, and macroscopic instabilities.

P6

MHD Equilibria via Voigt Regularization

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Voigt-regularized MHD (VMHD) is investigated as a potential tool for the computation of 3D stellarator equilibria with magnetic islands and stochasticity. VMHD admits modified energy and magnetic helicity which provably prevent the formation of singular structures during relaxation. Numerical results in 2D test problems for forced and spontaneous magnetic reconnection show that VMHD relaxation provides ~40-60-fold speedup compared to ideal relaxation (Phys. Plasmas 32, 062507 (2025)). Asymptotic analysis of linear-phase and nonlinear evolution in the Hahm-Kulsrud-Taylor problem is supported by numerics. Additional dissipation terms provide a modest additional speedup without changing the final equilibrium (https://arxiv.org/abs/2603.02432). Preliminary results in shaped, toroidal geometry are presented.

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P7

Analysis of the electromagnetic and electrostatic instability induced by runaway electrons in a magnetized plasma

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The detection and analysis of the electromagnetic effects of a fast electron beam in a thermally equilibrium and magnetically confined plasma are an important precursor to characterizing the evolution of the discharge and a possible mitigation of the disruption that could be an unpleasant consequence of the generation of a runaway beam. To this end, a locally valid electromagnetic dispersion relation with relativistic effects has been derived based on fluid theory and solved in the complex frequency domain. A self-consistent evaluation of the frequencies of the destabilizing modes and their growth rate as well as their radial position can be established as a function of the plasma parameters (density and magnetic field, energy of the beam) and parameters of the destabilized wave (parallel and perpendicular wave vector). Subsequently, the dynamics (propagation and possible reabsorption) of the unstable wave can be studied using WKB or full-wave techniques, depending on the applicability of these approximate techniques. An application of the theory to data collected during the runaway study campaigns on the FTU tokamak is also presented.

P8

Nonlinear saturation of Axisymmetric (n=0) modes driven by Energetic Particles in Tokamaks

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Axisymmetric (n=0) perturbations in magnetically confined plasmas include distinct global oscillatory modes occurring in the Alfvénic frequency range, such as Global Alfvén Eigenmodes and Vertical Displacement Oscillatory Modes, both of which can couple resonantly to energetic particles and undergo nonlinear saturation in the presence of fast-ion drive. This is particularly relevant in NBI or ICRH-heated plasmas, where fast ion populations provide a source of resonant drive for low-n Alfvénic activity, motivating a quantitative test of whether the observed amplitudes are compatible with energetic-particle-driven nonlinear saturation.

In this work, we develop an analytical framework for the nonlinear saturation of generic n=0 modes by energetic particles. Starting from reduced and hybrid MHD descriptions, we derive the mode structure and the corresponding wave-particle coupling coefficients in a form suitable for the weakly nonlinear theory of marginally driven instabilities. This allows us to extract explicit scaling relations for the nonlinear saturation level, the dependence on equilibrium parameters, and the role of the resonant particle population.

The resulting framework provides predictive expressions for the coupling strength, the saturation amplitude scalings, and the expected order of magnitude of the relative magnetic field perturbation amplitude in the weakly nonlinear regime. These scalings are designed to connect analytic theory with experimentally accessible quantities, enabling direct comparison with observations of axisymmetric fluctuations in present-day tokamaks and offering a route to assess whether their measured saturation levels are consistent with energetic-particle-driven nonlinear dynamics.

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P9

Stellarator design points and optimized equilibria for compact high-field nuclear fusion reactors

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Renaissance Fusion approach to a stellarator nuclear fusion reactor is based on the combined paradigm of a compact and high-field configuration. We leverage proprietary technologies based on laser engraved current patterns on cylindrical coil leading to considerable manufacturing simplification. We present a series of reactor designs, with different stellarator symmetries, aspect ratios, and plasma-to-magnetic pressure ratios, targeting an on-axis magnetic field of order 10 T and a major radius of up to 7 m. The applied scaling laws are reviewed and discussed. A selected subset of the scenarios is further investigated by generating the corresponding optimized 3D equilibrium. They are obtained by the inclusion of objective functions, which address key features such as geometry, stability, and quasi-symmetry. The magnetic field and geometrical properties of the compact and high-field stellarators are discussed, with particular emphasis on the role of quasi-symmetry as well as on the specific optimization techniques and metrics that have been implemented. An outlook for the next steps along the project roadmap is provided.

P10

Application of ECRH and NBI in compact high-field stellarator nuclear fusion reactors

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In a stellarator nuclear fusion reactor, actuators such as electron cyclotron resonance heating (ECRH) and neutral beam injection (NBI) are of fundamental relevance to reach and sustain the required fusion conditions. By injecting fast ions and radio frequency waves in the electron cyclotron range, it is possible to increase and maintain plasma temperature. Moreover, they can affect the plasma profiles, hence gradients which would modify turbulence dynamics and eventually dictate the reactor's confinement properties. Renaissance Fusion is pursuing the design of a compact and high-field stellarator with possible high-beta operational scenarios. We present results of ECRH and NBI studies on a selected list of compact and high-field stellarators, which were obtained by combining reduced model scaling laws and the corresponding 3D optimized equilibria. In particular, the role of the bootstrap current combined with the external sources is investigated as it can dictate the preferable quasi-symmetry type for compact stellarators. The application of the coupling of ECRH and NBI to gyrokinetic codes for the study of turbulent transport in the investigated regimes is also discussed.

P11

Minimal Model for Floquet Modes in a Tokamak

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It is widely known that cross field E × B shear stabilises ion temperature gradient (ITG) turbulence in magnetised plasma via deforming eddies to small scales. However, in the presence of a sheared magnetic field, this effect can be negated for turbulence moving at a known constant rigid body speed. Due to variation in curvature along a given magnetic field in a tokamak, our instantaneous growth rates for these modes oscillate periodically in time. However our growth rates averaged over the period of the rigid body rotation are constant complex numbers. This behaviour is characteristic of Floquet modes, which have been heavily studied and are seen in an a range of physically important systems.

We perform the transform as seen in [1] before collapsing to two dimensions and integrating to produce fluid equations by taking the approximations of [2]. We then impose the geometry of large-aspect ratio circular flux surfaces. We form a system of equations which we then study linearly. At sufficiently high flow shear, we find our linear modes are completely suppressed. However, we find that maximum linear growth rates and non-linear heat flux do not decrease monotonically, as they would without magnetic shear. We use both a change of variables and qualitative models to explore this effect and predict the point at which complete suppression of turbulence happens.

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P12

Validation and benchmarking of gyrokinetics in low-recycling lithiated conditions with Gkeyll and XGC

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Liquid lithium (Li)-coated plasma-facing components (PFCs) may offer an alternative approach to power exhaust in tokamaks. Lithium (Li) suppresses hydrogenic recycling, producing hot scrape-off-layers (SOL) and flat edge temperatures with weaker turbulent transport. Such high temperatures are supported by drastically lower SOL densities, reducing heat loads on PFCs that are anyway protected by liquid Li, which can be replenished as it evaporates. These regimes are inherently kinetic; the SOL collisionality is low and distribution functions are non-Maxwellian. We present gyrokinetic simulations of low- and high-recycling discharges in the Lithium Tokamak Experiment-beta (LTX-beta) at PPPL with the Gkeyll and XGC gyrokinetic solvers. LTX-beta can operate with nearly complete Li coating of PFCs and has reproduced the predicted flattening of temperature profiles. Gkeyll and XGC employ different models and algorithms, e.g. Gkeyll is a continuum code with a simplified collision operator, whereas XGC is a particle-in-cell code with a Fokker–Planck collision operator. This work benchmarks the two tools and validates them through comparisons with experimental profiles, fluctuation measurements and Lyman-alpha diagnostics. This benchmark and validation effort increases confidence in using such tools to explore candidate low-recycling fusion pilot plants.

P13

Effect of magnetic drift on the stability structure of the ambipolar condition in nonaxisymmetric plasmas

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In non-axisymmetric plasmas, the ambipolar condition may have multiple roots. In such cases, the evolution of the ambipolar electric field can be described by the dynamics in a bistable potential, where the relative depth of the potential wells primarily determines the realized root [1, 2]. The negative and positive roots, usually referred to as the ion root and electron root, respectively, correspond to the positions of the potential minima, while the middle unstable root corresponds to the local maximum of the potential.

According to the definition of the potential function, the relative stability between the ion root and electron root depends on the profile of the radial current in the interval between the two roots. In conventional local neoclassical simulations, a steep potential barrier is formed due to a sharp peak in the ion flux within this interval. However, it has been shown that the ion flux in a non-axisymmetric system strongly depends on the orbit model in the small radial electric field region. Particularly, the inclusion of magnetic drift prevents orbit resonance and significantly suppresses the ion flux peaking in this region [3-5]. Consequently, the magnitude of the radial current is also suppressed, and the potential landscape is modified significantly. Depending on the conditions, the choice of the orbit model may even alter the selected root.

In this study, we demonstrate this effect by comparing simulation results using orbit models with and without magnetic drift. This effect provides a plausible explanation for the discrepancies between simulation results obtained using different orbit models, as well as between simulations and experimental observations of ambipolar radial electric field profiles. Furthermore, the lowered potential barrier suggests that the ambipolar electric field may be more susceptible to fluctuations than previously expected, indicating the potential relevance of noise-induced state transitions. This susceptibility also raises the possibility of controlling the ambipolar electric field profile through noise-induced transitions. For example, if a transition from an ion root to an electron root could be induced in the core region, even transiently, impurity ions could be efficiently exhausted from the core. Thus, our findings have significant implications for both device design and operation.

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Poster session 2 — Tuesday

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P14

Resonant staircase formation and zonal flow amplification in tokamak turbulence: the role of negative mass instability and mode synchronization

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Transport barriers play a key role in the so-called Low-to-High confinement transition scenario in tokamaks. Their generation depends on the amplification of zonal flow to sufficiently large amplitudes. The amplification of zonal flows in gyrokinetic tokamak turbulence is often correlated to the formation of the so-called "E x B stair-case structures", which, both numerically and experimentally, manifest themselves as precursors of the formation of macroscopic transport barriers [1]. Staircase structures appear as a result of spontaneous structural self-organization where initially smooth radial profiles of density, temperature, or velocity break up into a quasi-regular, step-like pattern. Their complex interplay with the formation of transport barriers is still matter of investigation.

We show that E × B staircase solutions can form in nonlinear simulations of low frequency turbulence driven by trapped ion and electron modes, when energetic ion populations are taken into account, and we discuss how this process can induce the amplification of large amplitude zonal flows [2]. To this end we rely on a reduced model (which we refer to as "particle-mode" model [3]), based on a double gyro-average over both the fast cyclotron phase and the bounce (or transit) phases. This model allows us to show that interaction between trapped particle modes and energetic particles is mediated by a Fourier mode synchronization [2-4].

Here, thanks to formal analogies that the 'particle mode model' allows us to identify with the model discussed by Dodin et al. [5], we identify the E × B staircase solution as a saturated state of the negative mass instability [2].

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P15

Analytical approximation of the velocity distribution through the collisional layer

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Sputtering erodes the target and sources the plasma with heavy impurities corresponding to the target material (typically tungsten). The overall sputtering is determined by the distribution of kinetic energy and impact angle of ions at divertor targets [1]. However, this information is not a direct output of Scrape-Off Layer transport models, as they cannot resolve the plasma-wall boundary layers.

If the plasma is sufficiently collisional, as is assumed in Braginskii fluid models, the ion distribution function is a Maxwellian. There is a thin collisional layer next to the target in which an ion collides one last time before reaching the target, and the ion distribution becomes non-Maxwellian [2]. The characteristic size of this layer is a mean free path along the magnetic field. There are even smaller boundary layers, the magnetic presheath [3] and Debye sheath, in which the ion Larmor motion is strongly distorted until ions are pulled off their gyro-orbit and accelerated to the wall. The characteristic sizes of these layers are the ion gyro-radius and the Debye length, respectively. Numerical solutions of the plasma-wall boundary using particle-in-cell codes are extremely expensive, due to the vast difference in length and time scales associated with the different boundary layers. Direct steady-state solvers, such as CLOVER [2] for the collisional layer and GYRAZE [4] for the magnetic presheath and Debye sheath, allow for faster calculations of the velocity distribution at the target.

Here, we develop an analytical approximation to the distribution function passing through the collisional layer, benchmarked against CLOVER. There are 5 numerically determined parameters, which are fixed by: quasineutrality, the kinetic Chodura condition, ion flux conservation, the parallel momentum equation, and energy flux conservation. A good agreement with the CLOVER distribution functions is found. This analytical model can be coupled with an analytical model of the target distribution function predicted by GYRAZE (an extension of reference [5]) to give a fully analytical approximation for the distribution function at the target.

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P16

Continuous linear to nonlinear analytic treatment of tearing and double tearing modes with toroidal effects and fast particles

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A new tractable analytic calculation is presented for tearing modes that is valid from linear growth to nonlinear saturation in an initially axisymmetric torus. It is shown that the nonlinear harmonics in the plasma displacement help to recover the algebraic growth obtained in the seminal nonlinear calculation of Rutherford et al [1]. The nonlinear equation with toroidal and shaping effects smoothly joins to the Glasser-Greene-Johnson [2] dispersion relation for linear tearing modes, and as such, it is found that the unadulterated nonlinear equations are not singular in the limit of vanishing island width. The unified treatment developed here, which also includes neoclassical bootstrap effects, comes with a number of additional advantages, including a path to obtaining the full evolution of double tearing modes in equilibria with reverse sheared q-profiles, and the inclusion and kinetic corrections associated with fast ions.

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P17

Bootstrap current beyond the near omnigenous asymptotic model

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Configurations close to omnigenity (quasisymmetry/isodynamicity) are handled as prime candidates for future stellarator reactors. Some of these devices rely on the island divertor at the edge for proper operation and require very accurate control of the rotational transform ι. Modern stellarator optimization therefore often aims at minimizing the bootstrap current, inducing a need for fast and accurate proxies. Asymptotic formulas for the long mean free path regime such as the Shaing-Callen formula [1] describe well the ideal omnigenous configuration, but fail to accurately capture the departure from omnigenity. In the case of only slight violations, the correction formula derived in [2] and its generalized form, implemented in the code rabe, allow to provide proxies for the bootstrap current also in such non-ideal configurations. At low collisionalities ν_* it predicts the mono-energetic bootstrap coefficient to deviate from the Shaing-Callen limit like $\Lambda_A/\sqrt{\nu_*} + \Lambda_B/\nu_*$ with geometrical constants $\Lambda_{A,B}$ scaled by the violation of omnigenity. In this report we extend our study of the bootstrap current beyond the valid scope of this asymptotic model. We target piecewise omnigenous configurations [3], which have emerged as another promising design for a stellarator reactor and which significantly depart from the classical picture of omnigenity. Recent calculations [4] indicate that also in case of imperfect piecewise omnigenity, the bootstrap current exhibits a growth similar to the asymptotic model. We will continue those calculations to even lower collisionalities using the code NEO-2 [5] to better understand the form of this growth and its physical mechanism. Some other aspects like fast precession and the residual effect of bootstrap resonances will be considered as well.

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P18

Runaway-Electron Avalanches as a Branching Markov Process

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Runaway-electron dynamics in plasmas involve the combination of several processes acting across different scales: electric-field acceleration, collisional slowing-down, pitch angle scattering, radiative energy losses, and secondary generation through knock-on collisions. In this work, we present a stochastic framework for runaway-electron dynamics, in which electrons are described by processes in momentum space [1], and where multiplication events are accounted for in a branching-population description [2]. This viewpoint provides a unified language for seed formation, avalanche growth and loss mechanisms through a probabilistic approach.

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P19

Driftless Star: an end-to-end pipeline for transport-consistent stellarator optimization

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Stellarator design is fundamentally an optimization problem. The 3D boundary shape that produces closed flux surfaces also sets neoclassical and turbulent transport, bootstrap current, and stability. Evaluating one candidate today requires chaining several expensive, independently developed codes with a human expert judging convergence at each handoff: the central bottleneck to searching the design space at scale. We present Driftless Star, an open-source workflow that maps a stellarator boundary to transport-consistent plasma profiles in a unified, reproducible pipeline, chaining three-dimensional ideal-MHD equilibrium, a Boozer-coordinate transform, neoclassical and gyrokinetic transport, and one-dimensional profile and power-balance evolution. Every stage is modular and swappable and a closed outer loop iterates the transport-evolved pressure back into the equilibrium to continue the convergence cycle. The pipeline is also a natural substrate for AI-accelerated design: support for swappable neural surrogates enables the replacement of costly physics stages and large language model agents can orchestrate the chain, automate the expert judgment, and autonomously search for improved geometries.

P20

Dynamics of ion temperature gradient modes in burning plasma conditions in the presence of energetic particles

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We investigate the interaction between energetic particles (EPs) and ion temperature gradient (ITG) modes using the global gyrokinetic particle-in-cell ORB5 code. This work expands the parameter space to a broader range of EP temperatures, explicitly focusing on the burning plasma regime and introducing a wider variety of EP distribution functions. While direct dispersion relation modification (DDRM) stabilizes ITG modes at intermediate EP temperatures, our results demonstrate that the dilution effect (DE) independent of temperature becomes dominant over DDRM in the burning plasma regime (Tf > 50 Ti). Furthermore, our extension to slowing-down EP distributions shows a complete absence of DDRM-related stabilization compared to a Maxwellian one. To validate these findings for future reactor operations, we analyze an ITER pre-fusion operation scenario, comparing EP stabilization against electromagnetic and kinetic electron effects. In this context, EP stabilization is found to be weak, while ITG suppression is heavily dominated by electron Landau damping and β-stabilization. Overall, these results provide better understanding of EP-ITG interactions over a wider range of EP parameters relevant to burning plasma regime which is important for predicting turbulence and confinement in future devices such as ITER.

P21

kobra: a new Vlasov code with AMR

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The interaction between plasma and the wall in fusion devices can be treated as a collisionless process. In modeling this low-density region, conventional particle-in-cell (PIC) methods are limited by statistical noise due to insufficient sampling of velocity space. To overcome this, we introduce kobra, a new grid-based, finite-volume, 3D-3V Vlasov code that utilizes adaptive mesh refinement (AMR) which is free from statistical error.

Our current implementation solves the Vlasov-Poisson system across the entire phase space. We have verified the accuracy of kobra by replicating the analytic growth and damping rates for key electrostatic benchmarks: strong and weak Landau damping, and the two stream instability [1,2,5,7]. Additionally, we have employed a floating boundary potential which allows us to simulate the plasma wall interaction and reproduce the analytic results of a Schwager-like plasma sheath [6]. Finally, we have demonstrated computational efficiency gains using AMR, where refinement is guided on a per-cell basis by the first two truncation error terms [4].

As we move to reproduce the seminal work by Chodura on the edge plasma transition layer (a 1d3v problem), we first verify kobra's capabilities in higher dimensions with a constant magnetic field [3]. This is done by benchmarking the Dory-Guest-Harris instability, a 1d2v problem with a constant magnetic field [8]. These results demonstrate kobra's capability to model higher-dimensional plasma dynamics, highlight the computational advantages of our AMR framework, and provide a foundation for future simulations of fusion edge environments.

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P22

Full-F Gyrofluid Vortex interaction with arbitrary wavelength Polarization

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Magnetized plasma turbulence is fundamentally governed by the interaction of coherent vortical structures, whose dynamics determine energy transfer, transport, and self-organization across a wide range of spatial scales [1–3]. While vortex interactions have previously been investigated within δF gyrofluid models [4], the extension to finite-amplitude Full-F gyrofluid formulations remains challenging due to the nonlinear polarization equation, whose variable-coefficient structure precludes the simple Poisson inversion employed in conventional approaches [5–7].

In this work, we develop a Full-F/Full-K gyrofluid framework for studying vortex interactions in magnetized plasmas. We formulate a robust numerical strategy for reconstructing the ion gyrocentre density from prescribed finite-amplitude electron density and electrostatic potential fields. The method combines a background–fluctuation decomposition with a conservative finite-volume discretization and a regularized iterative inversion of the nonlinear polarization equation, providing a stable and accurate treatment even for vortex configurations containing closed potential contours.

Furthermore, we derive analytical interaction kernels describing gyrofluid vortex dynamics. Starting from the local Padé finite-Larmor-radius (FLR) polarization response, we obtain a generalized point-vortex interaction kernel that regularizes the singular Euler interaction at ion-gyroradius scales while recovering the classical logarithmic behavior at large separations. The analysis is extended to finite-core vortices, yielding analytical expressions for interaction energies and orbital frequencies suitable for direct comparison with numerical simulations.

The presented framework establishes the Full-F counterpart to earlier δF gyrofluid vortex studies. By consistently incorporating finite-density fluctuations, nonlinear polarization, and FLR effects, it provides the numerical and analytical foundation for future investigations of vortex merger, co-rotation, filamentation, and finite-amplitude drift-wave turbulence in Full-F gyrofluid simulations.

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P23

Second stability region for gyrokinetics and the L-H transition

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In spite of enormous progress in modeling and simulating the L-H transition, there is no consensus on the underlying physical mechanism — surprising for a phenomenon so robustly attainable in tokamak experiments. We speculate that this is, in part, because many such simulations use a fixed magnetic field. As we show in [1], the equilibrium field in an actual tokamak plasma responds to changes in the pressure gradient: as the latter grows, the Shafranov shift increases and the local magnetic shear on the outboard side of the torus tends to decrease, a circumstance instrumental in establishing the ”second stability region” for MHD ballooning modes [2]. In addition, a steeper pressure gradient drives more bootstrap current, which also affects the magnetic field and tends to reduce the global magnetic shear in the H-mode pedestal. Using the well-known s-α model for the magnetic geometry [3], we show that a second-stability region exists for linear gyrokinetics as well, accessed when the collisionality is sufficiently small and $\alpha_{\mathrm{MHD}} \gtrsim 1$. Electrostatic simulations of more realistic L- and H-mode geometries show that the combined action of the Shafranov shift and bootstrap current is sufficient to reduce transport levels by well over an order of magnitude. Finally, we calculate the transport along a path connecting the L- and H-mode equilibria, finding non-monotonic behavior as a function of the pressure gradient, mirroring results found on DIII-D for an internal transport barrier [4]. The peak energy flux along this path is shown to be of the same order of magnitude as that triggering the L-H transition for typical plasma parameters. We suggest that a transport simulation in which the magnetic geometry evolves self-consistently with the plasma profiles should exhibit a bifurcation as the heating power is increased.

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P24

Global Fluid Turbulence Simulations of W7-X Internal Magnetic Island Configurations

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Edge turbulence is a decisive factor in global plasma confinement, yet it remains significantly underdeveloped in both analytical theory and numerical simulations. This is especially true for stellarators when compared to tokamaks, due to the increased complexity of 3D geometries and the presence of magnetic islands. With the objective of reducing the gap, the fluid turbulence code GRILLIX has been recently extended to support 3D geometries [1] and, in particular, Wendelstein 7-X (W7-X). Thanks to its Flux Coordinate Independent (FCI) approach [2] it is able to self-consistently model plasma transport and the radial electric field in topologies with magnetic islands.

While the magnetic islands in W7-X typically form the basis of the island divertor concept, the highest confinement for typical ECRH plasmas is achieved in limiter configurations featuring internal magnetic islands, in particular the so-called FMM configuration [3]. A prominent characteristic of the FMM configuration is the "W-shaped" perpendicular flow profile measured by Doppler Reflectometry (DR) inside the islands, which leads to increased shear [4]. Concurrently, DR measurements show a substantial reduction in the density fluctuation amplitude in this region when compared to similar plasmas in island divertor configurations. The neoclassical models typically employed in calculating W7-X's radial electric field are local, and the previously available turbulence models rely on flux surface coordinates, thus, neither can capture the effect of the magnetic islands on the perpendicular flows.

This work aims to validate the new capabilities of GRILLIX by modelling W7-X's 5/5 magnetic island chain in limiter configurations. The simulations successfully match the experimental plasma profiles and reproduce the characteristic "W-shaped" perpendicular flow observed in FMM. The calculated density profiles are further used as input to a synthetic DR diagnostic, allowing the investigation of the effect of the local density profile on the DR measurements. To study the impact of the island size on the radial electric field, a scan was conducted in a simplified circular toroidal geometry with superimposed islands for two device sizes. It reveals a critical island width at which strong E x B flows develop [5], significantly increasing the electric field shear and leading to localized turbulence suppression.

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P25

Reduced Magnetohydrodinamics studies on tungsten transport inside magnetic islands

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The accumulation of tungsten in the plasma core is one of the major concerns for present-day tokamaks and future fusion reactors. Experimental observations in JET have shown that the onset of a neoclassical tearing mode (NTM) can strongly modify tungsten transport and promote impurity redistribution toward the plasma center [1]. While integrated modelling can reproduce this behaviour through enhanced transport inside the island, the fundamental mechanisms governing impurity behaviour within reconnecting magnetic structures remain only partially understood.

In this work, we investigate the dynamics of a localized tungsten population embedded in a reconnecting magnetic configuration using reduced MagnetoHydroDynamics (RMHD) simulations and modelling the impurity transport via passive scalars. Different initial impurity distributions are considered, including perturbations aligned with the neutral line, centered on the X-point, and located outside the island separatrix. The evolution is followed from the linear growth phase of the instability up to the nonlinear saturated regime.

The simulations show that tungsten does not immediately fill the magnetic island after reconnection. Instead, the impurity distribution initially preserves its coherence and subsequently undergoes stretching, oscillation and fragmentation. Depending on the initial location, the impurity may penetrate the island through the X-point region or remain confined within a limited portion of the island volume. The observed dynamics are qualitatively robust against variations of the ion sound Larmor radius (ρ_s).

These results indicate that the fluid dynamics developing inside the magnetic island strongly influence the way tungsten accumulates within the island itself. Understanding these internal transport mechanisms is therefore an essential step toward a physics-based description of the subsequent redistribution of tungsten on larger spatial scales.

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P26

Interpretation of the Dimits shift as a phase transition

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Micro-turbulence is one of the primary drivers of heat and particle transport in tokamaks, leading to reduced confinement performance. In particular, Ion Temperature Gradient (ITG) instability plays an important role in ion heat and particle transport. In the present work, the transition between a highly turbulent regime and a zonal flow dominated regime is investigated for ITG turbulence, using the local, gradient driven version of the gyrokinetic code GENE [1] considering electrostatic turbulence and assuming adiabatic electrons for simplicity. We propose an interpretation of the Dimits shift [2] as a thermodynamic phase transition between a disordered, turbulent phase, and an ordered zonal flow dominated phase, using the zonal to total free energy fraction as the order parameter. A precise scan of the ion temperature gradient $R/L_{T,i}$ is performed to highlight the two phases: at large $R/L_{T,i}$, the system exhibits high heat flux characteristic of fully developed turbulence, whereas at lower $R/L_{T,i}$ the heat flux is strongly suppressed and quasi null. To probe the nature of the transition, chained simulations are performed using the Cyclone Base Case parameters with the control parameter $R/L_{T,i}$ varied. Starting from a high $R/L_{T,i}$ (turbulent phase), the ion temperature gradient is gradually decreased to reach the zonal flow dominated state. Then, $R/L_{T,i}$ is increased back to higher values to achieve the transition back to the disordered turbulent phase. Comparing these simulations to independent runs at each value of $R/L_{T,i}$, reveals a hysteresis for the zonal to total free energy fraction, which plays the role of the order parameter. The mechanism for the hysteresis seems to be that once established, zonal flows persist at higher temperature gradients and continue to suppress turbulence, resulting in different thresholds for the turbulent to zonal and zonal to turbulent transitions.

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Wednesday

Wednesday, 23 September 2026 — invited talks

Session 4: Microturbulent Transport and Gyrokinetics in Tokamaks

I12 Haomin Sun, Plamen Ivanov, Justin Ball, Stephan Brunner — The unusual dynamics of turbulent transport in spherical tokamaks with large field line pitch angle

I13 L. De Gianni, P. Donnel, X. Garbet, Y. Sarazin, R. Bigué, G. Dif-Pradalier, V. Grandgirard, K. Obrejan, M. Protais, J.Y. Ng, Y.Cho, Z.Qu — Understanding Trapped Electron Modes in negative triangularity

I14 S. Y. Liu, P. Y. Jiang, P. F. Liu, G. Y. Fu — Development of the Gyrokinetic-MHD Hybrid Code cuGMEC and Its Nonlinear Simulations of Alpha Particle-driven Alfvén Eigenmodes in ITER

I15 S. Choudhary, M. G. Krishna, J. Chowdhury, A. K. Singh, T. Hayward-Schneider, E. Lanti, R. Ganesh, L. Villard — Gyrokinetic Transport in flat-Temperature Tokamak Plasmas

I16 J. McClenaghan, K. E. Thome, T. F. Neiser, J. Candy, F. D. Halpern, T. H. Osborne, S. Saarelma — Integrating Gyrokinetic Flux Predictions with Ideal MHD Stability Boundaries

I12

The unusual dynamics of turbulent transport in spherical tokamaks with large field line pitch angle

Haomin Sun[1], Plamen Ivanov[2], Justin Ball[1], Stephan Brunner[1]

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We present two unconventional dynamics of turbulent transport in spherical tokamaks characterized by large magnetic field line pitch angles.

First, we elucidate a novel interaction between mean E×B flow shear and Ion-Temperature-Gradient (ITG) turbulence. In contrast to the well-established stabilizing role of strong E×B shear in conventional aspect-ratio tokamaks, our work reveals a mechanism through which it can actively enable ITG turbulence. High-fidelity nonlinear gyrokinetic simulations, supported by a fluid model, demonstrate that the underlying physics originates from the Dimits regime persisting across an extended range of temperature gradients. In this situation, the mean E×B shear disrupts the zonal flow structures inherent to the Dimits regime before it can completely quench the turbulence, thereby facilitating the destabilization of ITG turbulence. This mechanism is further confirmed in realistic MAST-U equilibria.

Second, we report the achievement of a negative turbulent Prandtl number within finite-β modified microturbulence. Through the implementation and benchmarking of the full electromagnetic toroidal angular momentum flux, we show that a negative Prandtl number—capable of driving intrinsic flow shear without external momentum input or magnetic flux surface tilt—is attainable in spherical tokamaks. The underlying physics is tied to the decoupling of the parallel velocity moment from the electrostatic potential as plasma β increases. This finding not only demonstrates a new route to achieving a negative Prandtl number, but also reveals a new potential way to generate intrinsic rotation in future large spherical tokamaks.

Collectively, our works uncover unique turbulent transport phenomena intrinsic to the spherical tokamak geometry, with direct applications to confinement and stability predictions.

I13

Understanding Trapped Electron Modes in negative triangularity

L. De Gianni[1], P. Donnel[1], X. Garbet[1,2], Y. Sarazin[1], R. Bigué[1,3], G. Dif-Pradalier[1], V. Grandgirard[1], K. Obrejan[1], M. Protais[1], J.Y. Ng[2], Y.Cho[2], Z.Qu[2]

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Good plasma confinement is essential for harnessing fusion energy. Negative triangularity (NT) has been shown to reduce turbulent transport, thereby improving confinement. While the impact of NT on ion temperature gradient (ITG) instabilities remains unclear, both experiments and simulations consistently indicate its beneficial effect on trapped electron mode (TEM) instabilities [1] [2]. A full understanding of the physical mechanism underlying TEM stabilization by NT is crucial for extrapolating towards reactor-relevant regimes. In this contribution, we present the first modeling-based explanation for the linear stabilization of TEMs by NT. Linear stability is investigated using a reduced semi-analytical model [3] [4], through which Finite Mode Width (FMW) effects are identified as the main mechanism responsible for stabilization. This effect consists of the poloidal localization of the linear modes — the ballooning character of the instability. It enhances the contribution of deeply trapped electrons, which are shown to favor stabilization in NT configurations. In any case, linear stabilization remains weak. We therefore explore nonlinear effects by means of flux-driven global simulations with the GYSELA code [5] in TEM-dominated turbulence. Importantly, such simulations do not assume any scale separation between fluctuations and mean profiles, hence capturing turbulence self-organization from eddy size to large scale flows. In TCV-like highly shaped configurations, turbulent heat fluxes are found to be lower in NT than in PT in the outer half of the tokamak ($0.5 < r/a < 1$), in qualitative agreement with the experiments. Zonal flows (ZF) are likely responsible for the reduced heat fluxes, their drive and shear being higher in NT than in PT. The major novelty of the simulations lies in the use of poloidally non-uniform boundary conditions. This feature enables the development of poloidal asymmetries in the region close to the boundary, making the latter more realistic compared to simulations with poloidally uniform boundary conditions.

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I14

Development of the Gyrokinetic-MHD Hybrid Code cuGMEC and Its Nonlinear Simulations of Alpha Particle-driven Alfvén Eigenmodes in ITER

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We report the development of cuGMEC [1], a high-performance GPU-accelerated gyrokinetic-MHD hybrid code implemented in CUDA C++, along with nonlinear simulation results for the ITER steady-state scenario (#131041). In cuGMEC, electrons are treated as a fluid, while energetic particles (EPs) and thermal ions are described by gyrokinetic equations solved using the Particle-in-Cell (PIC) method. Compared with the CPU version [2,3], additional equations and terms have been incorporated, and all nonlinear terms have been implemented to make the physical model more self-consistent. Spatial and temporal discretizations are performed using five-point central differencing and fourth-order Runge-Kutta methods, respectively. A field-aligned coordinate system is used to enhance grid resolution, while shifted metric coordinates and a staggered grid are employed to improve numerical stability. The hybrid model is verified through benchmarks against theoretical predictions and other codes. Several optimizations are applied to both the MHD and PIC components. Tests on NVIDIA GPUs show favorable scaling and acceleration. For ITER simulations, we first scan the toroidal mode number and obtain growth rates and frequencies that agree well with GTC results [4]. We then conduct fully nonlinear full-torus simulations with multiple toroidal mode numbers, ranging from $n = 0$ to $n = 40$. Simulating 20,000 time steps, corresponding to 0.37 ms, takes only 4.8 hours on 8 A800 GPUs, using 7.9 million grid points and 4.5 billion particles. During the linear phase, modes with $n \sim 30$ exhibit the highest growth rates and saturate first. However, in the nonlinear phase, lower-n modes are excited and ultimately dominate in amplitude. By $t = 0.37$ ms, the alpha particle distribution function shows significant flattening. More details on the nonlinear ITER simulations will be presented.

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I15

Gyrokinetic Transport in flat-Temperature Tokamak Plasmas

S. Choudhary[1], M. G. Krishna[1], J. Chowdhury[1], A. K. Singh[1], T. Hayward-Schneider[2], E. Lanti[3], R. Ganesh[1], L. Villard[4]

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Transport in toroidal plasmas is widely believed to be driven by drift-wave instabilities that arise from radial gradients in temperature and density. Among these, temperature-gradient-driven modes, such as the ion temperature gradient (ITG) and the trapped electron mode (TEM), often dominate and are key drivers of microturbulence in tokamak plasmas. To suppress conventional temperature-gradient-driven turbulence (e.g., ITG/TEM), experiments such as Lithium Tokamak Experiment (LTX) employ lithium coatings on the tokamak's inner walls, enabling plasmas with experimentally reported flat T profiles [1,2]. This motivates a

key question: for $\eta \sim 0$, what instabilities dominate and lead to transport? To answer this, we perform global gyrokinetic simulations with LTX-like equilibria and find that the trapped-electron-driven Ubiquitous Mode (UM) persists, providing a candidate mechanism for turbulence and transport.

The ubiquitous mode (UM), primarily driven by trapped electrons, has been studied in circular tokamak geometries using ad hoc equilibria [3] and, more recently, for reconstructed LTX-like plasma equilibria [4]. To assess how UM competes with temperature-gradient-driven turbulence as η increases, the effect of finite η temperature non-uniformity has also been examined to understand the mode interactions in regimes where ITG may be present [5]. In the LTX-focused studies, equilibrium was obtained using the CHEASE code [6], with profiles and parameters consistent with LTX measurements [2]. However, the transport behaviour of the UM in advanced magnetic configurations remain largely unexplored. In this work, we investigate the UM in advanced configurations such as negative triangularity (NT) and reversed magnetic shear (RS) while also assessing the impact of kinetic passing electrons. Simulations are performed using the global gyrokinetic code ORB5 [7]. We first conduct a linear analysis using global electrostatic simulations to quantify how kinetic passing electrons, negative triangularity, and magnetic shear reversal affect the mode growth rates. We then perform nonlinear simulations to examine the resulting turbulence and associated transport characteristics in these configurations. RS is observed to enhance the growth rates of UM due to the contribution of magnetic drifts. However, the mode is observed to be stabilised in the region of negative shear. Meanwhile, we find that NT reduces the growth rates of UM and has little effect on the zonal flows shear rate, nonetheless, a reduction in particle diffusivity is observed.

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I16

Integrating Gyrokinetic Flux Predictions with Ideal MHD Stability Boundaries

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Accurate prediction of pedestal height and width in tokamaks remains a critical issue as it strongly influences the predicted plasma performance of all future reactors. We present an integrated pedestal-stability workflow that combines equilibrium scans with magnetohydrodynamic (MHD) stability analysis using ELITE and GATO and gyrokinetic transport predictions using CGYRO/QLGYRO. The workflow reproduces the characteristic kinetic ballooning mode (KBM) first- and second-stability structure previously identified in gyrokinetic pedestal studies. Applied to spherical tokamaks (STs), the workflow shows good agreement with past studies when low-n peeling stability is included, emphasizing the importance of resolving low-n physics in ST pedestals. Extending the analysis to SPARC-like, high toroidal field plasmas, the KBM and microtearing mode (MTM) heat fluxes are found to increase strongly with toroidal field, suggesting that access to the KBM second-stability region may become significantly more difficult in high toroidal field devices. Comparison with global ELITE finite-n analysis at SPARC parameters suggests that the H-mode pedestal lies in an intermediate regime bounded by local KBM second stability on one side and global finite-n ballooning instability on the other, consistent with the EPED picture once global effects are included.

Thursday

Thursday, 24 September 2026 — invited talks

Session 5: Stellarator Optimisation

I17 J. L. Velasco, V. Fernández-Pacheco, I. Calvo, E. Sánchez, J.M. García-Regaña, J. A. Alonso, D. Carralero, R. Gaur, H. Liu, M. Padidar, G. Yu, C. Zhu — Tutorial: New avenues for stellarator design enabled by piecewise omnigenity

I18 W. Sengupta, N. Nikulsin, S. Buller, R. Madan, A. Brown, E.J. Paul, R. Nies, A.A. Kaptanoglu, S.R. Hudson, A. Bhattacharjee — Periodic Korteweg-de Vries soliton potentials generate quasisymmetric magnetic field strength in both vacuum and finite plasma-beta equilibrium

I19 A. Goodman, G. Plunk, P. Xanthopoulos, Carolin Nührenberg, Joachim Geiger, Craig Beidler, Håkan Smith, Michael Drevlak — Searching for SQuIDs: Developments in the optimisation of Stable Quasi-Isodynamic Designs

I20 P. Jurašić, S. R. Hudson, A. Merlo, E. Laude — Designing stellarator island divertors by controlling the island flux

I17

Tutorial: New avenues for stellarator design enabled by piecewise omnigenity

J. L. Velasco[1], V. Fernández-Pacheco[1], I. Calvo[1], E. Sánchez[1], J.M. García-Regaña[1], J. A. Alonso[1], D. Carralero[1], R. Gaur[2], H. Liu[3], M. Padidar[4], G. Yu[3], C. Zhu[3]

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Stellarators achieve levels of neoclassical transport comparable to tokamaks by means of a careful design of their magnetic field. In most reactor candidates, this is done in a way that generalizes the axisymmetry of the tokamak. In quasisymmetric stellarators [1], the magnetic field strength B on the flux-surface has a symmetry -toroidal, as the tokamak, poloidal or helical. Omnigenity [2] can in turn be understood as a generalization of quasisymmetry. Although an omnigenous field B does not have a symmetry, its contour levels still have to satisfy strong topological constraints: they have to close toroidally, poloidally (in quasi-isodynamic fields) or helically. In all these cases -axisymmetric, quasisymmetric, and omnigenous fields-, the second adiabatic invariant J is constant on each flux surface, which guarantees the confinement of all particle orbits in the absence of collisions and turbulence. This talk will trace the development of the ideas outlined above and will present the notion of piecewise omnigenity [3, 4, 5] as an extension of them. This concept broadens the notion of omnigenity by allowing J to be constant on each flux surface only piecewisely, thus relaxing the aforementioned topological constraints.

The rest of the talk will illustrate how the concept of piecewise omnigenity enlarges the space of reactor candidates, and how this is already being exploited by the stellarator community. Piecewise omnigenous configurations far from quasisymmetry or quasi-isodynamicity have been shown to satisfy the standard set of physics criteria required for a viable reactor candidate [6]. Piecewise omnigenity can also be combined with quasi-isodynamicity [7], leading e.g. to more compact magnetic configurations [8], or with quasi-axisymmetry [9], enabling some level of bootstrap current control. More generally, once omnigenity is removed as a target, modern optimization techniques have allowed to find [10] novel theoretically-predicted [5] fields.

The development of the concept of piecewise omnigenity occurs at a time when the stellarator community is undertaking the design of a number of new devices of varying size. We will close this talk showing examples in which piecewise omnigenity is a relevant ingredient [11, 12].

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I18

Periodic Korteweg-de Vries soliton potentials generate quasisymmetric magnetic field strength in both vacuum and finite plasma-beta equilibrium

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Quasisymmetry (QS) is a hidden symmetry of the magnetic field strength, B, that enables effective confinement of charged particles in a fully three-dimensional (3D) toroidal plasma equilibrium, usually modeled by ideal magnetohydrostatic (MHS). The nonlinear, overdetermined nature of the QS-MHS system severely obscures our understanding of the interplay between 3D shaping, equilibrium properties such as pressure and magnetic shear, and B. Analytical progress has been made through various asymptotic expansions, such as expansion in distance from the axis and expansion in aspect ratio. However, a more complete theory is desirable. Using a combination of analysis and data-driven regression on a large dataset of numerically optimized quasisymmetric stellarators, we demonstrate that B has a hidden lower dimensionality on a magnetic flux surface, with connections to the theory of periodic solitons for both vacuum and finite-beta MHS equilibria. We show that B on a flux surface is determined by three or at most four flux functions, each of which determines a critical value of the derivative of B along the field line. Our results are valid throughout the entire toroidal volume and are consistent with the various asymptotic limits. Leveraging the global perspective, we go beyond near-axis solutions and demonstrate the key role of the rotational transform profile in solving the overdetermined QS-MHS system. Finally, we deduce an upper bound on the maximum toroidal volume that can be quasisymmetric and verify it for the Landreman-Paul configuration. As the maximum volume is approached, the period of B diverges as B tends to a 1-soliton reflectionless potential. We discuss the implications of the maximum volume for flux surface shapes.

I19

Searching for SQuIDs: Developments in the optimisation of Stable Quasi-Isodynamic Designs

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Quasi-isodynamic (QI) stellarators are uniquely attractive fusion reactor candidates due to their low neoclassical transport and small toroidal currents [1], the latter offering uniquely robust plasma stability. In addition to being QI, a stellarator reactor configuration must be resilient to magnetohydrodynamic (MHD) instabilities and turbulent transport, the latter of which has limited the performance of Wendelstein 7-X [2], itself a roughly QI stellarator. Recent developments in stellarator optimisation have uncovered a new class of stellarators known as "SQuIDs" (Stable Quasi-Isodynamic Designs) [3] which satisfy these two conditions, along with excellent QI quality. The findings from Kappel et al. [4] can be included in the SQuID design process, yielding SQuIDs which can be realized by a set of relatively simple electromagnetic coils. Their small net toroidal currents, along with their optimised rotational transform profiles, make these configurations compatible with an edge island divertor. More recent additions to the SQuID family include an electron root — a region of outward-pointing radial electric field — which may result a transport barrier akin to an H-mode sitting at the plasma radius of the designer's choosing [5]. An inward particle pinch can also be added to these SQuIDs [6], resulting in further improved fusion power output and plasma confinement, the latter owing to the TEM- and ITG-stabilising maximum-J property enjoyed by these SQuIDs.

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I20

Designing stellarator island divertors by controlling the island flux

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The island divertor concept has been demonstrated to be a reliable method for controlling the heat and particle loads onto the vacuum vessel in stellarators. We present a variational method for designing the current-carrying coils that achieves a magnetic island with a prescribed location and (reconnected) island flux. The magnetic field line action is given by $S[\mathbf{x}] \equiv \oint \mathbf{A}(\mathbf{x}) \cdot d\mathbf{l}$, with $\mathbf{x}$ a periodic trial curve, the magnetic vector potential $\mathbf{A}$, and $d\mathbf{l}$ the infinitesimal line segment. The variation induced by a variation, $\delta\mathbf{x}$, is $\delta S = \oint \delta\mathbf{x} \cdot d\mathbf{l} \times \mathbf{B}$, which shows that stationary curves are tangential to the magnetic field. The reconnected flux inside the island is given by the difference in the action of the minimizing (X) and minimax (O) periodic field lines, $\psi \equiv S[\mathbf{x}_X] - S[\mathbf{x}_O]$. With a change in the coil geometry, the action changes by $\delta S = \oint \delta\mathbf{A} \cdot d\mathbf{l} + \oint \delta\mathbf{x} \cdot \nabla\mathbf{A} \cdot d\mathbf{l} + \oint \mathbf{A} \cdot \delta d\mathbf{l}$, where the first term results from the change in vector potential and the other terms result from the change in the periodic field line geometry, $\delta\mathbf{x}$, which is determined by the second variation of the action [1]. We have implemented this method to design the coils so that magnetic island divertors are obtained in next-generation stellarator designs. Our implementation employs automatic differentiation to allow arbitrary trial curve and coil parameterizations. We reformulate the bilevel optimization as a single-level optimization of the island flux subject to the Karush–Kuhn–Tucker (KKT) conditions (stationarity condition of the magnetic action), where both the trial curves and coil parameters are adjusted simultaneously.

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Poster session 3 — Thursday

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P37 B. Rofman, A. Mishchenko, E. Lanti, A. Bottino, T. Hayward-Schneider, A. Biancalani, B.F. McMillan, S. Brunner, L. Villard — Nonlinear interactions between energetic particles, Alfvén eigenmodes and ITG driven turbulence in global, gyrokinetic, electromagnetic simulations

P38 J. Ruiz Ruiz, M. Barnes, J. Garcia, M. R. Hardman, S. Mazzi, B. S. Patel, F. I. Parra, A. A. Schekochihin — Assessing the effect of alpha-particle-driven modes on the fusion power gain in a burning plasma

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P27

Kinetic modeling of emissive plasma sheath

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The interaction between a plasma and an emissive solid surface leads to the formation of a complex electrostatic sheath, strongly influenced by secondary electron emission. When the emission coefficient γ, defined as the ratio between the number of emitted secondary electrons and the number of incident electrons, becomes larger than unity, the sheath structure can adopt different equilibrium regimes, such as the SCL sheath, also known as the space-charge-limited sheath, or the inverse sheath, which exhibit distinct physical properties. Conversely, when secondary electron emission remains weak, the sheath is referred to as a classical sheath. These different sheath regimes have been studied theoretically [1] and numerically [2] for many years. More recently, Campanell and Umansky [3] modeled the classical, SCL and inverse regimes using a kinetic description. However, the physical mechanisms allowing one to precisely distinguish the onset of these different regimes are still not fully understood, and their experimental observation remains an open issue [4]. In the context of edge plasmas and tokamak divertors, understanding sheath formation is also essential in order to better describe the particle and energy fluxes reaching the walls. The magnetic field, especially when it is oblique with respect to the surface, modifies the trajectories of charged particles and may influence both the sheath structure and the impact conditions at the wall. In this framework, this work aims to develop a kinetic model to study plasma sheath formation and, ultimately, to reproduce the different regimes associated with secondary electron emission. A new code, K-A2 MON, is currently being developed based on the architecture of the AMON code. It relies on a Vlasov–Poisson description and will first be validated on simple configurations before progressively introducing secondary electron emission, collisions and an oblique magnetic field. The objective is to improve the understanding of the existence conditions of the different sheath regimes and of the transition mechanisms between them. The kinetic results will also be compared with experimental measurements obtained at the PIIM laboratory, in order to identify the physical parameters governing the formation of emissive sheaths and to contribute to the interpretation of these experiments.

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P28

Fast ITG eigenmode-eigenfrequency prediction in general geometry

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Heat losses associated with microturbulence-induced transport are the dominant limiting factor on energy confinement in tokamaks and modern neoclassically-optimised stellarators. Such transport can be traced back to several pressure-gradient driven microinstabilities, among the most ubiquitous of which is the ion-temperature-gradient (ITG) mode.

These microinstabilities display a sensitivity to the toroidal magnetic geometry, which permits potential optimisation for a microturbulence-robust configuration. While recently ITG optimisation efforts based on linear [1] and non-linear [2] gyrokinetic simulations have been successful, they are generally deemed too computationally expensive for exhaustive scans in geometry-space, motivating the need for faster alternative proxies.

Within the tokamak community well-known reduced transport models like TGLF [3] and QuaLiKiz [4] may provide fast predictions for anomalous heat losses, however, these models have poor predictive power for low magnetic shear [5] or strong plasma shaping in edge regions [6].

Here we present a semi-analytical reduced model predicting unstable ITG eigenfrequencies and eigenmodes based on an asymptotic expansion of the gyrokinetic Vlasov-Poisson system under small transit frequency and adiabatic electron approximations. The model retains both kinetic and full-Larmor radius effects for ions, does not enforce an a priori ansatz for the mode structure, and is valid in arbitrary geometry.

We test the model versus high-fidelity flux tube GENE [7] simulations, probing for suitable geometric sensitivity capabilities in both positive/negative and high/low-shear s-α tokamaks, as well as its wider applicability to non-axisymmetric geometries in both the LHD and W7-X stellarators. In the s-α case, we find close quantitative agreement at conventional positive shear down to s $\sim$0.3, with agreement further decreasing towards large negative shear. At small-|s| the model predicts eigenmodes to be localised away from the outboard midplane at finite ballooning angle, in agreement with GENE simulations. For stellarator geometries, the eigenfrequency spectrum is obtained to within 25% accuracy for LHD, with eigenmode predictions closely reproducing the mode widths found by GENE, although lacking their finer oscillatory substructure. For W7-X the agreement between the model predictions and GENE deteriorates, especially at long wavelengths. These observed discrepancies for both W7-X and negative shear tokamaks are associated with the increased significance of parallel streaming effects, which may no longer be treated as asymptotically small.

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P29

An improved knock-on operator for runaway avalanche modelling

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Large-angle collisions (equivalently, knock-on collisions), while usually subdominant with respect to small-angle collisions in plasmas, can cause an exponential growth of the Runaway Electron (RE) population [1], the so-called runaway avalanche. In reactor-scale Tokamak disruptions RE generation is expected to be dominated by avalanches [2], which can turn a small seed population into a multi-megaampere RE beam whose interaction with the first wall could lead to destructive results [2]. Mitigating mechanisms such as enhanced radial transport can counterbalance this effect [3], but they are highly sensitive to the avalanche growth rate. Accurate modelling of the underlying physical mechanism is therefore essential to be able to correctly reproduce experimental data and to ensure predictive capabilities for future machines. This contribution describes the effort has been done to integrate the most complete avalanche model available to date in the drift-kinetic codes LUKE [4] and DREAM [5]. Such a model, originally developped by Embréus [6], was derived from the linearised Boltzmann operator in the case of knock-on collisions, and presents a variety of challenges both from the analytical and from the numerical point of view. Its implementation in the code has been tested for a variety of numerical and physical parameters to ensure robustness, and benchmarks have been obtained against known simplified limits, the Rosenbluth-Putvinski and the Chiu-Harvey models. Cross-tests have been carried out between the implementations in the two codes, as their similar analytical frameworks allowed for natural comparison between the simulation results. Three regimes of interest have been identified where the improved operator might have a significant effect on the runaway population, and a characterization of the relevant parameters will be discussed.

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P30

Direct optimization of steady-state plasma profiles in stellarators

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Recent advances in stellarator optimization have strengthened the case for stellarators as candidates for fusion power plants. As we push for high-performing reactor designs, the importance of accessing plasma scenarios for different candidate geometries increases. Accessing the effect of geometry and initial plasma conditions on the steady-state plasma profiles is currently achieved via multiple evaluations of local radial transport simulations using codes like NTSS [1] and trinity3D [2]. These codes are often coupled with neoclassical and turbulent codes for flux evaluation, which can make multiple iterations expensive for traditional finite difference-based optimizations. Leveraging auto-differentiable frameworks to perform such simulations can help improve efficiency in plasma scenario optimization. In tokamaks, the code TORAX [3] has shown that steady-state profile sensitivity against initial plasma conditions is efficiently obtained using an auto-differentiation framework like JAX. In this work, we show that for stellarators this can also be achieved with NEOPAX [4], a differentiable JAX code that solves the relevant local radial transport equations for stellarators. Steady-state density, temperature, and electric field sensitivities with respect to geometry and initial plasma parameters can be obtained from a single transport simulation. These sensitivities enable efficient gradient-based stellarator optimization targeting desired plasma profile shapes, reduced bootstrap current, and enhanced fusion power.

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P31

Theory of nonlinear zonal flow dynamics in toroidal geometry

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The toroidal geometry of tokamaks and stellarators has long been known to play a crucial role in the linear physics of zonal flows, leading to the Rosenbluth-Hinton residual [1] for stationary ZFs and the rapidly oscillating geodesic acoustic modes [2]. However, descriptions of the nonlinear ZF dynamics due to the interaction with drift-wave turbulence typically resort to simplified models of the geometry which do not include toroidicity. We show that the toroidal geometry in fact substantially modifies the nonlinear physics of both short- and long-wavelength zonal flows. First, we develop a theory of short-wavelength zonal flows by generalising the secondary instability theory of [3] to toroidal geometries, revealing a new nonlinear branch of propagating zonal flows, the toroidal secondary mode (TSM) [4]. Second, we develop a gyrokinetic theory of the nonlinear stresses governing the evolution of near-stationary long-wavelength zonal flows. We show that their saturation is governed by a balance between the zonal flow drive through perpendicular stresses and the damping through parallel stresses, generalising the fluid theory of [5] to gyrokinetics. The theory is verified through extensive gyrokinetic simulations using the code stella [6], and we consider the implications of our findings for the saturation of turbulence in the regimes of strongly-driven [7] and near-marginal (Dimits [8]) turbulence.

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P32

On the Shafranov shift in stellarators

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As first shown by Shafranov, toroidal plasmas in magnetohydrodynamic equilibrium tend to expand in major radius when the pressure is increased. The Shafranov shift is of considerable practical importance in stellarators, because it sets a limit on the achievable pressure - an MHD equilibrium limit rather than a stability limit.

Most previous treatments of the Shafranov shift have focused on special cases, usually by calculating the shift in specific geometries, either by analytically or numerically. By contrast, we introduce a measure of the average Shafranov shift, which can be easily calculated in any stellarator with large aspect ratio. Moreover, generally valid upper bounds on the Shafranov shift can be derived. These results enable a general discussion of the Shafranov shift in entire classes of stellarators rather than individual cases.

Focusing on omnigenous stellarators, we find that the average Shafranov shift mostly scales with the aspect ratio and rotational transform in the same way as in classical stellarators, but there is an additional dependence on the rotational transform per field period. If this quantity can be made to be large, as in the case of quasihelical symmetry, the Shafranov shift becomes correspondingly smaller. In quasi-isodynamic devices, it can also be minimised by reducing the poloidal variation of the magnetic field strength. As a result, recently optimised quasi-isodynamic designs have a Shafranov shift that is only about half as large as that in W7-X, and it is yet smaller in quasi-helically symmetric configurations.

P33

The role of different nonlinearities in two-dimensional fluid ITG models

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The nature of the turbulent energy cascade of various simple two-dimensional fluid models of ion temperature gradient driven turbulence is studied in some detail. In order to clarify the mechanisms of injection and dissipation, on top of which a nonlinear cascade picture can be developed, linear terms related to finite Larmor radius corrections, and small and large scale dissipation terms are considered, and their effects on growth rate and the mixing length are characterized. Then, the effects of different nonlinearities, and their implications are considered, especially in terms of zonal flow dynamics and the resulting turbulent cascade.

In a minimal two-field toroidal ITG model, zonal flows dominate without the diamagnetic nonlinearity, preventing high transport. When included, zonal flows dominate only near marginality (per the Dimits shift [1]), while far from marginality, an inverse cascade with streamers emerges, requiring large-scale dissipation for saturation. Furthermore, we use the potential vorticity for ITG given by Ref. [4] and derive a more complete system with four nonlinearities that conserves potential vorticity. Unlike the simpler models, this system exhibits a well-behaved heat flux while retaining proper zonal flow dynamics (and destabilization). The turbulent cascade of this system is studied and compared to the initial system demonstrating the role of higher order terms in the pressure equation.

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P34

Gradient-driven instabilities in 2D models for tokamak edge

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Tokamak edge plasmas are frequently modeled employing kinetic or fluid equations that assume axisymmetry, that is, physical quantities depend only on the radial and poloidal coordinates, and are independent of the toroidal angle. In these models, turbulent transport due to non-axisymmetric fluctuations is included through ad-hoc diffusion and pinch coefficients. These 2D edge models have been crucial to interpret experimental results, to explain poloidal asymmetries and to study detachment. It has been observed that the inclusion of the radial and poloidal components of the perpendicular drifts in the equations is necessary to reproduce the experimentally observed poloidal variation of density and temperature. In this poster, we show that the inclusion of these drifts leads to novel branches of the Ion-Temperature-Gradient (ITG) and Parallel Velocity Gradient (PVG) instability. These new branches are driven unstable by the poloidal projection of the temperature and velocity gradients, unlike the usual ITG and PVG instabilities, driven by the radial component of these gradients. We will describe the instability in the fluid and kinetic limits, and we will discuss its relevance for edge cross-field transport.

P35

Stellarator-Tokamak Hybrid configurations for representative TCV discharges

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The stellarator-tokamak hybrid concept aims to combine tokamaks' large plasma volume (compactness) and coil simplicity with the stability and operational advantages (steady-state, vacuum flux surfaces) of stellarators. Generating rotational transform in part with external coils (ι_{ext}) effectively allows for reducing the required plasma current (typically ohmic), thereby diminishing the effect of current-driven instabilities. Experimentally, this idea has already been proven to drastically mitigate disruptions in the CTH device, with ι_{ext} values on the order of 10% of the total ι [1], and, more recently, to mitigate neoclassical tearing modes on J-TEXT [2]. These configurations, however, were not optimized for low neoclassical transport. On the other hand, theoretical work has shown the existence of quasi-symmetric (QA) ideal MHD solutions as perturbations of axisymmetric equilibria [3][4]. Numerical optimization has also been conducted to produce hybrid equilibria with reduced neoclassical transport [5], and compatible coil sets have been identified [6,7,8].

For the Tokamak à Configuration Variable [9], we seek to investigate whether QA hybrid configurations are attainable, identify possible coil configurations, and explore their benefits over the standard tokamak operation. Initially, a double-null plasma discharge from a 2020 campaign was selected, and QA hybrid fixed-boundary equilibria were obtained through numerical optimization using SIMSOPT [10]. The cost function to minimize balances gains in external iota and quasi-axisymmetric penalty. Various levels of external iota were achieved, and a compatible filamentary coil set was explored. The investigation was further extended to include different plasma shapes characteristic of TCV's unique flexibility, such as positive and negative triangularity single-null equilibria.

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Convective-diffusive modeling of anomalous particle and energy transport in 2D interchange-dominated simulations.

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In mean-field plasma edge codes such as SOLPS-ITER [1] and SOLEDGE3X [2], anomalous particle and energy fluxes are typically modeled using convective–diffusive approaches with ad hoc transport coefficients. Recently, Reynolds-averaged Navier–Stokes-like models (RANS) have been introduced to describe these coefficients self-consistently by relating them to turbulence characteristics such as turbulent ExB kinetic energy k_E, enstrophy ξ_E, ..., through additional transport equations.

Earlier proposed RANS-models [3] assumed that the transport could be described by the gradient-diffusion hypothesis. We investigate this assumption for the turbulent transport occurring in 2D interchange dominated simulations by applying the correlation based diffusion approach [4]. This approach allows to decompose the time-averaged flux in diffusive and convective contributions and residual terms. It is observed that the sum of the convective and diffusive contributions recovers well the total transport over the main part of the domain. This supports the earlier made assumption. The decomposition further reveals that the convective velocity corresponds to the anomalous curvature pinch [5], while the particle diffusivity scales with the turbulent ExB kinetic energy and the autocorrelation time. The heat diffusivity is found to be approximately 3/2 of the particle diffusivity.

Based on these observations the earlier proposed $k_E - \xi_E$ model is further developed as it allows one to use a $\tau_{Corr} \sim 1/\sqrt{\xi_E}$ scaling for the autocorrelation time instead of the $\tau_{Corr} \sim \rho_L/\sqrt{k_E}$ scaling implied by the k_E model for describing the diffusion coefficient. It is shown that a more accurate submodel for the viscous dissipation of enstrophy is obtained by using the upper bound scaling derived by Alexakis et al. [6]. Lastly, we revisit the proposed closure by Dekeyser et al. [3] of the ensemble averaged parallel flux $\overline{\phi' j'_\parallel}$, which arises due to the correlation between potential and parallel current fluctuations and which is thought to be the dominant k_E transport term, as it may be improved by incorporating the enstrophy.

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P37

Nonlinear interactions between energetic particles, Alfvén eigenmodes and ITG driven turbulence in global, gyrokinetic, electromagnetic simulations

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A burning plasma is a self-organizing multi-scale dynamical system. For future reactors, it is essential to understand the stability of such systems, and the relevant parameters that determine the resulting anomalous transport. By nature, such systems exhibit emergent phenomena and require a step-by-step approach to untangle the combined effects.

Previously [1] we investigated a scenario with a circular MHD equilibrium using the global, electromagnetic, gyrokinetic code ORB5 [2]. We designed the scenario such that the bulk ions drive an Ion temperature gradient (ITG) turbulence and the energetic particles excite Toroidal Alfvén Eigenmodes (TAEs). For each instability, we found a dominant representative single toroidal mode, e.g. n=2 for the TAE. And used them to study the nonlinear saturation of the system for each instability separately. Both instabilities self-generate zonal structures as they nonlinearly saturate. In these cases, the E x B shearing rate produced by the zonal flows, decorrelates the turbulent eddies and limits the transport. However, in the TAE cases, another axisymmetric but not zonal Alfvén Eigenmode is nonlinearly excited and drives ten times the particle flux than before.

In the present work we perform large-scale simulation which include a wide range of toroidal modes simultaneously. The system is free to evolve self-consistently, allowing us to study the direct and indirect coupling between the energetic particles, TAEs, ITGs and the resulting turbulence. We analyze the self-generated zonal structures, which function as nonlinear coupling channels between the two coexisting instabilities. We compare the resulting system to the single mode results and to cases where the n=0 plasma response is artificially filtered out. Which allows us to study the wave-wave coupling between an ITG drift wave and an Alfvén eigenmode peaking at similar radial location.

Another key element are the energetic particles, which excite Alfvén eigenmodes, add significant pressure to the magnetic equilibrium and act as a kinetic mesoscale due to their large orbit widths. We first separate and then combine the different effects to study their impact on the resulting turbulent fluxes.

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Assessing the effect of alpha-particle-driven modes on the fusion power gain in a burning plasma

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Energetic particles will be ubiquitous in next-generation burning plasmas, where 3.5 MeV alpha particles produced by the DT reaction will provide the dominant self-heating. Understanding how alpha particles affect plasma confinement is therefore essential for predicting fusion performance. Alpha particles can destabilise Alfvén modes, which may drive significant alpha-particle transport. Recently, theory, numerical simulations, and experiments have suggested that Alfvén modes can suppress turbulence through zonal-flow generation, potentially improving confinement. In this work, we address the net impact of alpha-particle-driven Alfvén modes on the fusion power gain. We solve the one-dimensional power-balance equations for the thermal plasma and the alpha particles using heat fluxes calculated from local, nonlinear gyrokinetic simulations (CGYRO) corresponding to a recently analysed, ICRH-heated JET plasma [1]. We find that increasing the alpha-particle drive reduces the thermal heat fluxes, consistent with turbulence suppression by Alfvén-mode-driven zonal flows, but also leads to substantial alpha-particle transport. Overall, when alpha-particle transport and Alfvén-mode-induced turbulence stabilisation are both included, the fusion power gain is reduced relative to the ideal slowing-down case without turbulence stabilisation. These results suggest that, in burning plasmas, the confinement benefits of Alfvén-mode-driven zonal flows may be outweighed by enhanced alpha-particle transport.

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Understanding the sensitivities of the radial electric field between favorable and unfavorable configurations using SOLEDGE3X simulations

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Since its discovery on the ASDEX tokamak in 1982, the L–H transition has been the subject of extensive research, yet it remains not fully understood. One of the key parameters seen to influence the transition to H-mode is the depth of the radial electric field well. A deeper Er well is associated with stronger (ExB) flow shear near the plasma edge, which can suppress turbulent transport and contribute to the formation of the edge transport barrier characteristic of H-mode. However, the exact mechanisms and processes leading to the formation and dynamics of the Er well are also not fully understood. As a result, considerable attention has been devoted to studying the mechanisms that generate it and how it responds to changes in plasma conditions. Particularly, the magnetic configuration has been seen to greatly affect the Er well. In this context, we define favorable and unfavorable magnetic configurations based on the relative direction of the ion magnetic drift with respect to the X-point, where in the former it is towards it, while in the latter it is away from it. This terminology comes from the ease of access to the H-mode, where it was seen that in unfavorable configurations a higher power threshold (2-3 times more) is required to access it. Experimental observations on several tokamaks have shown that deep Er wells are recorded in favorable configurations, while they tend to be shallow in the unfavorable ones [1][2]. This work, tries to understand these results through numerical simulations using the SOLEDGE3X code. The conducted simulations till date, have been WEST cases, using the code's mean-field transport mode, with neutrals, at varied plasma currents. Results have shown agreement with experiments where the Er well in the outboard midplane is present in the favorable configuration, but tends to disappear in the unfavorable configuration. However, no significant changes have been recorded while varying plasma current. In SOLEDGE3X, Er is calculated using the vorticity equation, which is obtained by expanding the terms of the current balance. The main differences between configurations were seen in the diamagnetic current contribution, which can be explained through asymmetries in the poloidal distribution of pressure and flows. The simulated poloidal pressure profiles indeed show asymmetries between configurations, which, when used in a simplified theoretical model, reproduce qualitatively the favorable/unfavorable Er well discrepancies.

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Poster session 4 — Thursday

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P51 F. Zonca, L. Chen, M. Falessi, Z. Qiu, G. Wei — On the kinetic continuous spectrum in toroidal plasmas

P40

Plasma transport in a chaotic magnetic field using an MHD model

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Magnetic reconnection is responsible for a significant part of tokamak plasma loss of confinement. This is well identified for magnetic islands [1] through the temperature profile flattening [2]. In addition, when magnetic islands overlap the magnetic field becomes stochastic. The stochasticity of the magnetic field lines brings them to travel over the whole radial width of the plasma so it could be expected to act similarly on particles themselves and result in a high radial transport. The same physics plays out at smaller scales due to the magnetic fluctuations caused by turbulence [3]. Turbulent electrostatic transport is usually considered dominant in the core, but can be supplemented by electromagnetic perturbations ($\tilde{B}/Bo \geq 10^{-4}$) in future tokamaks with higher β. Moreover, stochasticity is expected in electromagnetic regimes even at low β [4].

We investigate the transport in a stochastic magnetic field with a simulation of a turbulent plasma including electromagnetic perturbations. The plasma is simulated with Reduced MagnetoHydroDynamic (RMHD) equations in a non-linear regime. A pressure gradient feeds the resistive interchange instability, which non-linearly evolves into a turbulent steady state including Turbulence Driven Magnetic Islands (TDMI) [3].

The stochastic magnetic field, apparently uniform in a poloidal cut, hides topological structures [5] that are shown to be relevant for the transport. The Finite-Time Lyapunov Exponent (FTLE)[5], which characterizes the spreading rate of field lines, exhibits sheets of high values (sometimes described as "ridges" over a 2D cut). We show that the pressure gradient magnitude $|\nabla P|$, which characterizes the pressure transport, is statistically higher where the FTLE is higher. Indeed, a linear correlation between the average $|\nabla P|$ and FTLE is found at every time during the saturation phase. Statistically, the transport appears to be reduced by the stochastic magnetic field. However, in this simulation, it appears that the FTLE is not directly responsible for $|\nabla P|$ structures. Instead a simultaneous advection of the magnetic flux and pressure is proposed as the reason for the correlation.

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Nonlocal integral kernels for ICRH – Progress with the implementation into PSYDAC

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Recently, nonlocal integral kernels in configuration space have been derived for describing the interaction of radio-frequency waves and a warm plasma [1, 2]. In contrast to the more widely used Fourier approach, this method enables the use of finite elements for the numerical discretization, allows local mesh refinement around the ICRH resonance and mode conversion layers, and can more straightforwardly be interfaced with antenna models based on e.g. CAD models. The current focus is on the temperature effects on wave dispersion along the magnetic field and the associated non-locality: we address the fundamental cyclotron and the Landau interactions. Finite-Larmor-radius contributions will come later to model harmonic heating and mode conversion effects.

This contribution gives an overview of the theory and focuses on illustrating the progress of implementing the nonlocal integral kernels into the PSYDAC library, a Python library for isogeometric analysis [3]. It has been used in the past to solve the wave equation in the ICRH and ECRH range of frequencies using a cold-plasma model [4–6]. The library makes use of finite-element exterior calculus and various differential operators (such as the curl-curl operator) are discretized straightforwardly by PSYDAC while SymPDE provides an easy-to-use interface for formulating the equations. Since PSYDAC uses tensor-product B-splines, the challenge is implementing the nonlocal integral kernels, which is uncommon for FEM methods as they are usually employed for discretizing local (point-wise) models.

First numerical results in simple slab geometry will be presented

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P42

Guiding center motion in self-consistent axisymmetric mirror equilibria

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Modeling gyrokinetic instabilities and turbulent transport in fusion plasmas requires a detailed understanding of the guiding center trajectories of individual particles [1]. In contrast to toroidal plasmas, high-performance mirror plasmas are non-Maxwellian and cannot be adequately described by isotropic ideal magnetohydrodynamic (MHD) equilibria [2]. The presence of parallel electric fields, axial variations in the E-cross-B drift, anisotropic pressure, and high β present unique challenges in accurately capturing the drift resonances that drive microinstabilities. In this work, we present an analytical framework to calculate the electrostatic potential and magnetic drifts in axisymmetric mirror geometry such that they are consistent with Hall-MHD equilibria with arbitrary parallel flow, rotational flow, and anisotropic ion temperature. We show that the axisymmetry of the system and the absence of an azimuthal magnetic field greatly simplifies the problem. Knowledge of the local field line shape as well as profiles of a small number of quantities along the field line are sufficient to compute the electrostatic potential, perpendicular gradient of the magnetic field strength, and perpendicular gradient of the electrostatic potential in a straightforward fashion. Moreover, the magnetic field structure guarantees that the classical drift equations coincide with the low-flow Hamiltonian drift equations [3] since $B = B_{\parallel}^{*}$. We compute these quantities with a variety of example analytic distribution functions representative of mirror systems and then analyze the guiding center motion of the constituent charged particles.

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Adjoint-based trust region method with DGSEM discretization for MRxMHD in HKT slab geometry

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In this work, we develop a novel PDE-constrained optimisation framework for computing MRxMHD equilibria in Hahm-Kulsrud-Taylor(HKT) slab geometry. The Beltrami field is discretised using the weak formulation of the discontinuous Galerkin spectral element method (DGSEM) [1] . The force balance condition is enforced as a DG consistent weak residual defined on plasma interfaces and a trust-region method is developed to find the root of the residual. To solve the corresponding shape-optimization problem efficiently, we derive an adjoint method for the Jacobian of the residual with respect to the interface geometry. The proposed method is designed as a more robust and versatile numerical alternative to the global mixed Fourier method often used in community codes such as the stepped pressure equilibrium code [2] . The local DGSEM structure is well-suited for complex geometries and the real force residual, as well as, adjoint sensitivity and the trust-region method target to improve the numerical robustness of the shape optimisation problem. Future work will include 3D stellerator geometry and modelling of extended MRxMHD [3] for richer physics.

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Solving the phase-space relaxed MHD model: from cross-field flow to the weak ideal Ohm's law

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Relaxed magnetohydrodynamics offers a route to three-dimensional equilibria that admit magnetic islands and chaotic field regions, sidestepping the current singularities that afflict ideal-MHD models on rational surfaces [1]. The multi-region relaxed MHD underlying the SPEC code [2] achieves this through Taylor-relaxed volumes [3] separated by ideal interfaces, but in its standard form permits only field-aligned flow, with cross-field flow recoverable only through a toroidal-angular-momentum constraint meaningful in axisymmetry alone [4]. The phase-space action principle of Dewar et al. [5] resolves this limitation in a conceptually appealing way: by formulating relaxation directly on the phase-space Lagrangian, it admits a kinematically constrained cross-field flow in arbitrary geometry without any ad hoc symmetry-dependent constraint, while simultaneously enforcing cross-helicity conservation and recovering the ideal-MHD force balance from its Euler-Lagrange equations. The result is a relaxed equilibrium model that retains the topological freedom of Taylor relaxation yet supports the cross-field flows expected on neoclassical grounds - a combination that no earlier relaxed model provides. Despite its appeal, the steady-state form of this theory has never been solved, and its mathematical structure in general geometry has remained largely unexplored. In this talk I introduce the Dewar model and its physical motivation, characterize the steady-state solution space, and show that a geometric solvability condition governs which flows are admissible; using this, I present the first equilibria of the model in slab, cylindrical, and toroidal geometry, in which cross-field flow is found to couple strongly to magnetic-island structure. I close by introducing the more recent model of Dewar & Qu [6], which pushes the phase-space Lagrangian framework a step closer to ideal MHD by weakly enforcing the ideal Ohm's law through an augmented-Lagrangian optimization scheme.

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P45

Stellarator Coil Optimization for Beta-Resilient Divertor Island Positioning

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Finite plasma pressure leads to a Shafranov shift of the magnetic axis and can thereby displace the o-point of a radially outward magnetic island in a stellarator. For island-divertor configurations, this displacement shifts the strike line at which the plasma intersects the divertor target, potentially moving it outside the region of effective divertor coverage.

Here, we show how stellarator coils can be optimized to make the island o-point position resilient to finite-beta effects. Although demonstrated for divertor-relevant island positioning, the approach is general and can be applied to other equilibrium-dependent target quantities.

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Electron-temperature-gradient turbulence and secondary-instability saturation with large density gradients

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In magnetic-confinement-fusion devices, turbulent transport is an essential constraint on the confinement of the plasma. In tokamak edge-pedestals formed in the high-confinement mode of operation (H-mode), electron-scale turbulence is found to be the main source of anomalous transport, and the parameter $\eta_e = L_{ne}/L_{Te}$ is strongly correlated with the structure of the pedestal [1]. Here, L_{ne} and L_{Te} are the equilibrium gradient length scales of the electron density and temperature, respectively.

Using a model for electron-scale, collisional, drift-kinetic turbulence [2], we investigate the dependence of the nonlinear heat transport on η_e. Linearly, this model describes unstable drift waves driven by the electron-temperature gradients of the underlying equilibrium. The inclusion of a finite density gradient affects the linear modes by inducing a drift that changes the relative phase between the perturbed electron temperature T_e and electron-density n_e, suppressing the instability.

We study the nonlinear behaviour of this system using simulations in shear-less slab geometry with periodic boundary conditions [3]. The suppression of the instability by finite ηe quenches the heat transport in the nonlinearly saturated state. This is also accompanied by a qualitative change in the turbulence: the decoherence of waves caused by the density-gradient drift increases the injection-scale anisotropy, which manifests itself by a longer radial coherence of streamers. In the marginal limit, where η_e approaches $\eta_{e,\mathrm{crit}}$, the critical value for linear stability, the system saturates in a streamer-dominated low-Reynolds-number state that is nearly monochromatic around the injection scale, imitating the linear solution.

We find that the critically balanced turbulent cascade in the weakly suppressed limit ($\eta_e \to \infty$) competes with a secondary instability of the outer-scale modes, and, in the marginal limit ($\eta_e \to \eta_{e,\mathrm{crit}}$), the secondary instability becomes the dominant means of free-energy transfer to small scales, suppressing the streamer and reducing turbulent transport. By describing the system in the intermediate stages and identifying the ηe value at which the radial correlation length of streamers diverges, obtain a full description of the transition our system undergoes, alongside a physical basis for stiff marginal ETG-driven transport.

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P47

Kinetic solutions to the stationary collisionless magnetised plasma sheath

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Gyrokinetic codes are routinely used to simulate fusion plasmas, including the edge and the scrape-off layer of a fusion device. However, they are not appropriate for representing the thin plasma-wall boundary layer (the "magnetised sheath") comprising the magnetic presheath and the Debye sheath, where the approximations of circular ion gyro-orbits and quasineutrality respectively fail. To provide realistic plasma-wall boundary conditions to these gyrokinetic codes but also to enable fundamental studies of this region, a kinetic code is being developed to solve for the steady state of the collisionless magnetised sheath for arbitrary magnetic field incidence angles and finite ratios of ion gyroradius to Debye length.

For a given electrostatic potential profile, discretized on a finite element basis, the ion density projected onto each element is calculated by summing the contributions of a set of particle trajectories whose initial conditions are sampled from a given incoming distribution function.

Electrons can be modeled adiabatically, or using a parallel streaming model, or fully kinetically via the same density deposition scheme as for the ions, thus accounting for finite Larmor radius (FLR) effects.

The electrostatic potential profile is then corrected until it satisfies Poisson's equation, which is then used to obtain the next estimate of the densities. This iterative procedure converges to the stationary solution in 20 to 30 iterations, using 1 to 10 CPU-hours, thus bypassing a much more computationally expensive time evolution.

An extension to this method adding charge-exchange collisions and ion sources is being implemented, allowing for self-consistent plate-to-plate simulations, without requiring to specify the incoming distribution function at the entrance of the magnetic presheath.

Additionally, work on implementing a second spatial direction, tangential to the target and perpendicular to the magnetic field, will be initiated to ultimately account for the effects of turbulent ExB fields on the ion transport to the wall, and possibly surface roughness.

This work is being carried out in the framework of the EUROfusion TSVV-C project.

P48

3D JOREK simulations of runaway electron benign termination on TCV

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Low-Z benign termination, achieved by injection of low-Z materials (hydrogen or deuterium), could reduce the damage of a strong runaway electron (RE) beam by evenly dispersing the REs over a large 'wetted' area on the wall through large-scale MHD instabilities in the recombined plasma [1]. This method has been investigated experimentally on JET, DIII-D, TCV, and WEST [2-4]. These experiments reveal the roles of the neutral pressure, the RE current amplitude, and the isotope effect in the benignness of the termination. Particularly, the lower and upper limits of the neutral pressure for an ideal RE mitigation scenario have been found [3,4]. To capture the physics behind the experimental results, this work aims to reproduce the expulsion of a plateau RE beam on TCV using the 3D MHD code JOREK [5,6,7]. The MHD model on JOREK can be coupled self-consistently with the neutrals, impurities, and various other physical fields, including a fluid or kinetic description of the REs. In JOREK simulations, the growth of MHD modes, the RE deconfinement, and the plasma dynamics as thermal electrons take over the RE current can be captured much more intuitively than in experimental diagnostics. The modelling of TCV RE termination would contribute to the further understanding of the low-Z injection mitigation and help extrapolate this method to larger tokamaks.

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P49

Impacts of effective diffusion caused by electron temperature gradient turbulence

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Cross-scale interactions of the electron temperature gradient (ETG) turbulence and ion-gyroradius-scale fluctuations have potential influences on anomalous transport phenomena in fusion plasmas. We have developed an effective diffusion model for the cross-scale interaction of the trapped electron mode (TEM) and the ETG turbulence [1] which has also been validated by detailed analyses of the multi-scale gyrokinetic simulation results. Recently, we have applied the effective diffusion model to a variety of drift waves and zonal flows and have found enhancement of the isotope effect in TEM turbulent transport, strong stabilization of the micro-tearing mode, selective damping of sub ion-gyroradius-scale zonal flows, and faint destabilization of the ion temperature gradient mode, which are consistent with multi-scale turbulence simulation results.

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P50

Nonlinear frequency chirping of energetic-particle-driven geodesic acoustic modes

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Geodesic acoustic modes are zonal (i.e. axisymmetric) flows with the characteristic frequency of the order of magnitude of the sound frequency. GAMs can become unstable by taking the free energy of a population of energetic particles (EP), via inverse Landau damping. These so-called EGAMs can redistribute the EP population, thus affecting the heating efficiency.

In this work, we investigate the nonlinear dynamics of EGAMs by means of global gyrokinetic simulations with the particle-in-cell code ORB5. In particular, we study the nonlinear evolution of the frequency, known as "frequency chirping". Phase Space Zonal Structure (PSZS) diagnostics are also employed to investigate the underlying phase-space dynamics. By identifying the resonance energy from the phase-space distribution and reconstructing the corresponding mode frequency, an independent estimate of the frequency evolution is obtained. The reconstructed frequencies show good agreement with those extracted directly from continuous wavelet transform analysis of the electric-field signal. This demonstrates a direct correspondence between observable frequency chirping and the nonlinear evolution of resonant energetic particles in phase space.

We also show the results of simulations of EGAMs and ion-temperature-gradient mode turbulence, thus shedding light on how turbulence and EGAMs can nonlinearly interact.

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On the kinetic continuous spectrum in toroidal plasmas

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At low frequencies comparable to characteristic thermal-particle frequencies, kinetic effects modify the compressional response in high-temperature toroidal plasmas, with important consequences for the stability of drift Alfvén waves (DAWs) driven by both thermal free energy and resonant energetic particles (EP) [1].

Using linear gyrokinetic theory, we analyze the shear Alfvén wave (SAW) and slow sound wave (SSW) continuous spectra and show how mode polarization and dispersion are altered by Landau damping and kinetic compressibility, including finite parallel electric field effects.

Floquet solutions [2,3] can be constructed for general tokamak geometries, and the renormalized plasma response is expressed analytically in quadrature form. At short wavelengths the formulation recovers the kinetic Alfvén wave (KAW) dispersion and damping, providing a robust test case for gyrokinetic codes.

Within the fishbone-like dispersion relation framework [4,5], the theory yields a compact description of resonant low-frequency DAW excitation by EP and clarifies why Alfvénic polarization is preferentially excited.

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Friday

Friday, 25 September 2026 — invited talks

Session 6: Fast Ion and Nonlinear Physics in Tokamaks

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Cross-scale Interaction between Microturbulence and Fishbone in Fusion Plasmas

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Global gyrokinetic simulations are performed for the first time to investigate cross-scale interactions between electromagnetic ion temperature gradient (ITG) turbulence and fishbone instability in tokamak plasmas. The investigation of fluctuation response in the multiscale simulation including both instabilities indicates a strong impact of fishbone on ITG turbulence. Detailed analysis reveals that fishbone-driven zonal radial electric fields at nonlinear saturation significantly suppress electromagnetic ITG turbulence, reducing ion thermal transport close to the neoclassical level. The simulation results agree well with experimental observations that turbulence suppression during fishbone bursts. These findings advance understanding of multiscale interactions that enhance thermal confinement in fusion plasmas.

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I22

A nonlinear Schrödinger equation for the description of geodesic-acoustic-modes in tokamaks

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The geodesic-acoustic-mode (GAM) is a plasma oscillation observed in fusion reactors with toroidal geometry and is recognized to be the nonstationary branch of the zonal flows [1]. Prior studies [2] have established that as a direct consequence of nonlinear gyrokinetic theory, the GAM dynamics is well described by an equation of Schrödinger type—i. e. an equation whose linear contribution is exactly of the same form as the linear Schrödinger equation, while the nonlinear dynamics necessitates an integro-differential expression.

The presented work takes a closer look into the nonlinear contributions by deriving approximate, but well-defined analytic expressions from the (exact) integro-differential operators, using a state-of-the-art gyrokinetic framework [3]. In accordance with prior numerical studies [4, 5] a cubic nonlinearity is retrieved. The nonlinearity is found to act on a similar time scale as that characterizing the linear dispersion.

The cubic term stems from an interaction of quadratic structures generated by the GAMs (with oscillation frequencies that are either zero or twice the GAM frequency) with the GAM itself. Comparisons with gyrokinetic simulations using the global particle-in-cell code ORB5 [6] show very good quantitative agreement with the analytical theory.

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I23

Comprehensive simulations of bursting shear Alfvén waves in tokamaks and their control via phase space engineering with ICRF waves

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Recurrent bursting Alfvénic instabilities can severely degrade energetic-particle (EP) confinement and impose transient loads on plasma-facing components. We recently reported the first comprehensive simulations of ICRF-heated tokamak plasmas on the slowing-down timescale with the kinetic-MHD hybrid code MEGA, where shear Alfvén wave induced minority ion transport is self-consistently retained during high-energy-tail formation [1]. Both bursting and non-bursting toroidal Alfvén eigenmodes (TAEs) were obtained: on-axis or inboard ICRF resonance yields bursting TAEs, which appear as a set of radially separated discrete modes at distinct, nearly fixed frequencies without chirping, whereas outboard heating always produces a single broad structure whose harmonics share nearly the same frequency, independent of RF power.

This work clarifies the mechanism through EP phase-space analysis. The deeply trapped ICRF-accelerated minority ions resonant with a fixed-frequency TAE occupy a highly localized region of (E, μ) phase space. For on-axis/inboard heating, TAE transport carries these ions away from the RF layer, so replenishment is weak. The resulting discrete TAEs keep the resonances isolated, free energy accumulates, and once the growing amplitudes force neighboring resonance islands to overlap, a burst is triggered, consistent with the resonance-overlap (Chirikov) avalanche picture [2]. For outboard heating, the resonant ions stay close to the RF layer, where the strong velocity-space diffusion sharply raises the replenishment rate νeff and restores them faster than the wave flattens the local gradient, suppressing isolated phase-space structures. This high-νeff picture also explains why the non-bursting state sustains a higher EP beta than the bursting one, which a critical-gradient argument alone cannot.

Building on this mechanism, we report for the first time simulations in which an on-axis-driven bursting state is suppressed by an additional low-field-side ICRF wave. The auxiliary wave introduces velocity-space diffusion where the burst-transported ions accumulate, driving the resonant population into the high-νeff regime and mitigating the bursts. To our knowledge this is the first comprehensive simulation to demonstrate phase-space engineering of energetic ions [3] for the control of bursting Alfvénic activity in magnetic confinement fusion.

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I24

Nonlinear evolution of strongly driven perturbative kinetic instabilities

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The kinetic destabilization of discrete, weakly damped modes, e.g., toroidal Alfvén eigenmodes, results in both diffusive and convective transport of energetic particles and has important implications for the confinement of burning plasmas [1]. In scenarios where fast relaxation events result in very rapid redistribution of fast ions or rapid changes to the mode resonance conditions, these modes can be very strongly driven and grow to large amplitudes. For example, strong Alfvén eigenmode activity has been observed in both JET [2] and JT-60U [3] directly following sawtooth crashes. While wave saturation levels have been established in the strongly driven regime [4,5], no analytical description of the instability evolution has been developed. We examine the dynamical evolution of a strongly driven kinetic instability at a single resonance in the presence of collisional and dissipative processes. The wave evolution is found to occur in two phases: first, linear growth driven by the unstable distribution gradient, then slower nonlinear evolution driven by the balance of the wave drive and dissipation. In the second phase of evolution, under realistic conditions, we find that the distribution evolves time locally with the evolution of the mode. By exploiting this time locality, we construct a piecewise-continuous solution for the time evolution of the mode amplitude. This result agrees closely with nonlinear kinetic simulations performed using the BOT code [6]. This work is based on Devin and Duarte, 2025, arXiv:2510.08735.

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