Book of Abstracts

The International Conference on

Numerical Simulation of Plasmas

(27th ICNSP2022)

August 30 - September 2, 2022

Nagoya University, Nagoya, Japan

The conference is organaized under the auspices of Nagoya University, Kobe University, National Institute for Fusion Science, and the Program for Promoting Researches on the Supercomputer Fugaku, "Exploration of burning plasma confinement physis .

ICNSP2022 Conference Timetable (rev3.1: 1 August 2022)

- Session A: 9:00-11:00 JST (2:00-4:00 CEST, 20:00-22:00 EDT, 17:00-19:00 PDT)
- Session B: 17:00-19:00 JST (10:00-12:00 CEST, 4:00-6:00 EDT, 1:00-3:00 PDT)
- Session A' and B': Video recorded sessions for audience in different time zones
- Invited talk 30min / Contributed talk 15min (including discussion time)
- Poster session 90min
- All posters can be presented in Session 2B and 3A (both or either)

(CEST=JST-7, EDT=JST-13, PDT=JST-16)

Date (JST)	Time (JST)	Main session	Video session
30 August	8:45-9:00	Opening	
	9:00-11:00	Session 1A: Luedtke, Scott V. (LANL) Matsumoto, Yosuke (Chiba Univ.) + 3 contributed talks	
	15:00-17:00		Session 1A'
	17:00-19:00	Session 1B: Keppens, Rony (KU Leuven) + 5 contributed talks	
31 August	7:00-9:00		Session 1B'
	9:00-11:00	Session 2A: Farcas, Ionut (U. Texas) + 5 contributed talks	
	15:00-17:00		Session 2A'
	17:00-19:00	Session 2B: Ma, Jun (IPP-CAS) + Poster session	
1 September	8:30-9:00		Session 2B' (w/o Poster)
	9:00-11:00	Session 3A: Iwamoto, Masanori (Kyushu Univ.) + Poster session	
	16:30-17:00		Session 3A' (w/o Poster)
	17:00-19:00	Session 3B: Hotta, Hideyuki (Chiba Univ.) + 5 contributed talks	
2 September	7:00-9:00		Session 3B'
	9:00-11:00	Session 4A: Huang, Chengkun (LANL) + 5 contributed talks	
	15:00-17:00		Session 4A'
	17:00-19:00	Session 4B: Narita, Emi (QST) + 5 contributed talks + Closing	
3 September	7:00-9:00		Session 4B'

Oral presentations

ICNSP2022 Conference Program (rev3.1: 1 August 2022)

(CEST=JST-7, EDT=JST-13, PDT=JST-16)

30 August 2022 (Day1)

Time (JST)	#	Speaker	Title
8:45-9:00			Opening

Session 1A

Time (JST)	#	Speaker	Title
9:00-9:30	1A-1	S. V. Luedtke	VPIC 2.0: Performance-Portable Particle-in-Cell for Present and Future Supercomputers
9:30-10:00	1A-2	Y. Matsumoto	Particle-in-cell simulations for elucidating cosmic-ray accelerations in the exascale computing era
10:00-10:15	1A-3	Gahyung Jo	A New Gyrokinetic Hyperbolic Solver with Discontinuous Galerkin Method in Tokamak Geometry
10:15-10:30	1A-4	J. U. Chen	An h-adaptive HDG Scheme for Incompressible Magnetohydrodynamics
10:30-10:45	1A-5	T. Shiroto	The Structure and Structure-Preserving Discontinuous Galerkin Scheme for the Multispecies Rosenbluth-Fokker-Planck Equation

Session 1B

Time (JST)	#	Speaker	Title
17:00-17:30	1B-1	R. Keppens	When Hot Meets Cold: Recent Progress In Solar Flare Modeling
17:30-17:45	1B-2	Y. Kawazura	Ultrahigh Resolution Shearing-box Simulation of Magnetorotational Turbulence
17:45-18:00	1B-3	Dong Wu	Particle-in-cell modelling for head-on collisions of large-scale high density plasmas jets
18:00-18:15	1B-4	Xiangliang Kong	Modeling the acceleration and transport of nonthermal electrons in solar flares based on macroscopic MHD simulations
18:15-18:30	1B-5	G. Lapenta	Modeling and visualization of planetary environments using the Energy Conserving Semi Implicit method (ECSIM) and ML
18:30-18:45	1B-6	Y. Nakajima	Stability Analysis of Counter-differential Rigid-rotation Equilibria of Electrically Non-neutral Two-fluid Plasmas Using PIC Simulation

31 August 2022 (Day2)

Session 2A

Time (JST)	#	Speaker	Title
9:00-9:30	2A-1	I. Farcas	Enabling Uncertainty Quantification In Predictive Plasma Turbulence Simulations
9:30-9:45	2A-2	M. Nunami	Hyper-dimensional manifold optimization for turbulent plasma transport
9:45-10:00	2A-3	Y. Chen	Evolution of the marker distribution in gyrokinetic δf particle-in-cell simulations

10:00-10:15	2A-4	Y. Idomura	Performance portable full-f gyrokinetic simulations on exascale supercomputers
10:15-10:30	2A-5	J. H. Nicolau	Gyrokinetic Simulations Of The Helically-Trapped Electron Mode In W7-X Stellarator
10:30-10:45	2A-6	O. Koshkarov	Enabling optimizations for reduced kinetic spectral models

Session 2B

Time (JST)	#	Speaker	Title
17:00-17:30	2B-1	Jun Ma	Development of a full MHD eigenvalue code with the use of symbolic computation technique
17:30-19:00	P-1 ~ P-47		Poster session on "Remo"

1 September 2022 (Day3)

Session 3A

Time (JST)	#	Speaker	Title
9:00-9:30	3A-1	M. Iwamoto	3D PIC simulation of coherent emission from relativistic shocks
9:30-11:00	P-1 ~ P-47		Poster session on "Remo"

Session 3B

Time (JST)	#	Speaker	Title
17:00-17:30	3B-1	H. Hotta	Solar differential rotation reproduced with high-resolution magnetohydrodynamic simulations
17:30-17:45	3B-2	Taiki Jikei	Alfvén Mach number dependence on ion Weibel instability in collisionless shock transition regions: Effect of magnetized electrons
17:45-18:00	3B-3	T. Minoshima	A Quasi All-speed Scheme for MHD Flows in a Wide Range of Mach Numbers
18:00-18:15	3B-4	R. Horiuchi	Guide-field dependence of a merging process of two spherical-tokamak-type plasmoids
18:15-18:30	3B-5	J. Croonen	General geometry 2D implicit PIC model
18:30-18:45	3B-6	K. Iwata	Multidimensional study of thermonuclear burning wave triggering sub-Chandrasekhar mass Type Ia supernovae

2 September 2022 (Day4)

Session 4A

Time (JST)	#	Speaker	Title
9:00-9:30	4A-1	C. Huang	Modeling of Coherent Synchrotron Radiation Effects in High Brightness Beams via a Novel Particle-mesh Method and Surrogate Models with Symplectic Neural Networks
9:30-9:45	4A-2	T. G. Jenkins	A Kinetics-only Delta-f (KODF) Method for RF Wave Modeling in Warm Plasma
9:45-10:00	4A-3	S. Maeyama	New algorithm for solving sheared flows in local flux-tube gyrokinetic simulations

10:00-10:15	4A-4	G. Chen	An implicit, conservative and asymptotic-preserving electrostatic particle-in-cell algorithm for strongly magnetized plasmas
10:15-10:30	4A-5	H. Wang	The first nonlinear simulation of Alfvén eigenmode in CFQS
10:30-10:45	4A-6	X. Zhao	Particle energization in the vicinity of an O-point: numerical and analytical investigations

Session 4B

Time (JST)	#	Speaker	Title
17:00-17:30	4B-1	E. Narita	Machine-Learning Assistance With Nonlinear Gyrokinetic Simulations By Recognizing Wavenumber-Space Images
17:30-17:45	4B-2	T. Singh	Global Gyrokinetic Simulations of Electrostatic Microturbulence Transport Using Kinetic Electrons in LHD Heliotron
17:45-18:00	4B-3	A. Ishizawa	Saturation mechanism of ion temperature gradient driven turbulence in finite beta tokamaks studied by global gyrokinetic simulation
18:00-18:15	4B-4	Shi-Jie Liu	Calculation of collisionless pitch-angle scattering of runaway electrons with synchrotron radiation via high-order guiding-center equation
18:15-18:30	4B-5	Y. Morishita	Simulation Study of LHD Plasma Control Applying Data Assimilation System ASTI
18:30-18:45	4B-6	J. S. Kalita	UNDERSTANDING SUBCRITICAL TURBULENCE IN 3D YUKAWA LIQUIDS USING LARGE SCALE MOLECULAR DYNAMICS SIMULATIONS

VPIC 2.0: Performance-Portable Particle-in-Cell for Present and Future Supercomputers

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VPIC is a publicly available, open source, general purpose, fully kinetic and relativistic particle-in-cell simulation code for modeling plasma phenomena such as magnetic reconnection, fusion, solar weather, and laser-plasma interactions in three dimensions using large numbers of particles. In this talk, we discuss the development of VPIC 2.0, report extensive performance results, and highlight features and areas of active development. Specifically, we show the work undertaken in adapting VPIC to exploit the portability-enabling framework Kokkos and highlight the enhancements to VPIC's modeling capabilities to achieve performance at exascale. We assess the achieved performance-portability trade-off through a suite of studies on nine different varieties of modern pre-exascale hardware, demonstrating good performance on CPU and GPU platforms with a single codebase. Our performance-portability study includes weak-scaling runs on three of the top ten TOP500 supercomputers and a comparison of low-level system performance of hardware from four different vendors. Lastly, we highlight improved documentation and user-friendly features. This talk is an update on our recent paper [1].
Work performed under the auspices of the U.S. DOE by Triad National Security, LLC, and Los Alamos National Laboratory. This work was supported by the LANL ASC, Experimental Sciences, and Laboratory Directed Research and Development programs.

[1] Bird, Robert, et al. "VPIC 2.0: Next generation particle-in-cell simulations." IEEE Transactions on Parallel and Distributed Systems 33.4 (2021): 952-963.

Particle-in-cell simulations for elucidating cosmic-ray accelerations in the exascale computing era

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Using massively parallel supercomputer systems with a parallelized particle-in-cell (PIC) code is a powerful way to elucidate nonlinear phenomena including particle accelerations. Indeed, we have elucidated important acceleration mechanisms in collision-less shocks by using the Japanese flagship supercomputer system with a hundred of thousands of processor cores (e.g., Matsumoto et al., 2017).

Here we report an upgrade with an implementation of an adaptive load balancing method to our PIC code. The load imbalance among MPI processes in PIC simulations arises if particles were in-homogeneously distributed in the simulation domain as a result of time evolution. This imbalance becomes problematic when using very large numbers of MPI processes (say greater than millions of cores), and we meet this situation with the current Japanese flagship system called "Fugaku". We have adopted the recursive multi-section algorithm which have been successfully implemented into the cosmological N-body simulations (Makino, 2004; Ishiyama et al., 2009). We successfully implemented this method to the PIC code for the first time with benchmark tests of the Weibel instability and collision-less shock simulations. Benchmark tests of the Weibel instability show that this technique can maintain the workload balance in a controllable way. In addition, it also adapts to the moving injector boundary which is a standard technique for examining collision-less shock simulations.

In this presentation, we report our new PIC code and its application to collision less shock simulations by using the supercomputer Fugaku.

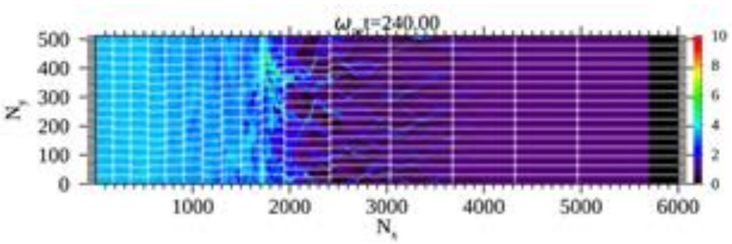

Figure: Relativistic shock simulation by using our new PIC code. Electron density as a 2D color map and the MPI subdomains surrounded by white lines are shown.

A New Gyrokinetic Hyperbolic Solver with Discontinuous Galerkin Method in Tokamak Geometry

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We develop a hyperbolic solver for the gyrokinetic equation in tokamak geometry. The new solver is based on the discontinuous Galerkin approach on a finite element mesh composed of irregular spatial and regular velocity elements together with a strong-stability-preserving time discretization method. We investigate the effects of the basis function on the conservation properties of physical quantities such as mass, kinetic energy, and toroidal canonical angular momentum in an axisymmetric configuration of toroidal plasma. It is shown that if the proper basis function is chosen, the new solver has good conservation properties of the key physical quantities in the simplified circular magnetic geometry and realistic tokamak geometry. The invariance of the canonical Maxwellian distribution function in time is confirmed. We also investigate the effect of weighting functions for the polynomial basis. The weighted basis functions show similar conservation properties to the polynomial basis; the canonical Maxwellian weighted basis shows better invariance with the lower order polynomials. The performance tests of MPI parallelization are also carried out. The results indicate that the new solver shows good performance up to a few thousand CPU cores.

[1] G. Jo, J.-M. Kwon, J. Seo, E. Yoon, Comput. Phys. Commun. 273 (2022) 108265

An h-adaptive HDG Scheme for Incompressible Magnetohydrodynamics

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Incompressible Magnetohydrodynamics (MHD) models are relevant in low Lundquist number liquid metals, high Lundquist number, large guide field fusion plasmas, and low Mach number compressible flows. Due to its complexity, it is crucial to understand the dynamics of electrically conducting flow in the presence of electromagnetic fields via simulation. However, numerical methods face several difficulties arising from wide disparate length scales, multi-physics, and divergence-free constraints, to name a few. We have addressed several of these challenges using the hybridized discontinuous Galerkin methods [1-3]
In this work, we adopt our previous work [4] which targets at developing an HDG method in solving linearized incompressible resistive MHD equations, and **equip it with h-adaptivity to efficiently solve problems with local high gradients.** Such extension is amenable, thanks to the naturally built-in mortars in HDG methods. We implement our approach in the open source library `deall.II` [5] that allows us to perform scalable local mesh refinement. To validate the effectiveness of h-adaptive HDG, we present several numerical results for both stationary and time-dependent MHD. For the first setting, we consider Hartmann flows and manufactured solution with singularity induced by non-convex domain. For the second setting, we investigate the transition from the Alfven wave resonance to forced reconnection.

[1] T. Bui-Thanh. Journal of Computational Physics, 295:114-146, 2015
[2] S. Shannon. PhD thesis, 2018.
[3] S. Muralikrishnan. PhD thesis, 2019.
[4] J. Lee, and S. Shannon, and T. Bui-Thanh and J. Shadid. SIAM Journal on Numerical Analysis, 57(4):1697-1722, 2019
[5] D. Arndt and W. Bangerth and B. Blais and T. Clevenger and M.Fehling and A. Grayver and T. Heister and L. Heltai and M. Kronbichler and M. Maier and P. Munch and J. Pelteret and R. Rastak and I. Thomas and B. Turcksin and Z. Wang and D. Wells. Journal of Numerical Mathematics, 28(3):131-146, 2020

The Structure and Structure-Preserving Discontinuous Galerkin Scheme for the Multispecies Rosenbluth–Fokker–Planck Equation

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The Fokker–Planck equation describes collisional relaxation of kinetic plasmas through inverse-square forces. The equation is originally proposed as an integro-differential equation, but Rosenbluth derived a potential formalism by using Dirac delta function; hereafter the latter is called as Rosenbluth–Fokker–Planck (RFP) equation [1]. This formulation is convenient to large-scale computation since multiple integral is hidden in the potentials.

However, development of conservative numerical methods for the RFP equation is difficult. In case of the integro-differential formulation, conservation laws can be easily derived from the mathematical symmetries of a collision kernel. The collision kernel does not appear in the potential equations explicitly, so derivation of the conservation laws had not been performed for the RFP equation. The only exception was an old work by Chacón [2]; the derivation was done by an analogy between Maxwell stress tensor, but their scheme was not applicable to multispecies system.

In this work, mathematical structure of the multispecies RFP equation and the resultant conservation laws are derived analytically. The derived structure connotes not only mathematical symmetry but also the action–reaction law as a physical principle. A discontinuous Galerkin scheme is designed so as to preserve the structure and resultant conservation laws. Numerical experiments show that the proposed scheme can preserve the conservation laws only with round-off errors, and the distribution function converges on the analytic equilibrium. On the other hand, the nonconservative counterpart loses the total energy and a fatal numerical instability is induced. For details, see our latest paper [3].

Reference

[1] M. N. Rosenbluth et al., Phys. Rev. 107, 1 (1957).
[2] L. Chacón et al., J. Comput. Phys. 157, 168 (2000).
[3] T. Shiroto et al., J. Comput. Phys. 449, 110813 (2022).

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Title:

When hot meets cold: recent progress in solar flare modeling

Abstract:

In the ERC-funded project PROMINENT [1], we study plasma processes in the solar atmosphere at unprecedented detail, using our open-source MPI-AMRVAC simulation toolkit [2], where grid-adaptivity is essential to zoom in on details that will be resolved by future observing facilities.

The most violent solar plasma process to study is the solar flare, which represents the most energetic explosion in our heliosphere. It involves a dramatic change - or reconnection - in the magnetic topology of the atmosphere, and the so-called "standard solar flare model" collects all observationally established info on flares in a cartoon. This cartoon emphasizes that macroscopic (magnetohydrodynamic) and microscopic (energetic particles) plasma physical processes dynamically interact, although most - if not all - model efforts only simulate the large *or* the small scales. I will present our *first self-consistent model of a standard solar flare* [3], where electron beam physics dynamically couples to a large-scale, multi-dimensional magnetohydrodynamic evolution of a flaring arcade. Most recently [4], we continued simulating the hour-long postflare behaviour, to ensure that *the hot meets the cold*: the first numerical demonstration of postflare coronal rain due to thermal instability!

[1] https://erc-prominent.github.io
[2] amrvac.org and Keppens et al., 2012, JCP 231, 718; Porth et al., 2014, ApJS **214**, 4; Xia et al., 2018, ApJS **234**, 30; Keppens et al, 2021, CAMWA **81**, 316
[3] W. Ruan et al., 2020, ApJ **896**, 97 (18pp) doi:10.3847/1538-4357/ab93db
[4] W. Ruan et al., 2021, ApJ Letter 920, L15 (8pp) doi:10.3847/2041-8213/ac27b0

Ultrahigh Resolution Shearing-box Simulation of Magnetorotational Turbulence

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Turbulence driven by magnetorotational instability (MRI) is believed to be the primary mechanism of angular momentum transport in astrophysical accretion flows [1]. It also sets particle heating and acceleration in the case when the plasma in the accretion flow is collisionless. However, the properties of MRI turbulence are not fully understood. The difficulty of MRI turbulence is mainly attributed to the broadband energy injection range in the Fourier space, making it difficult to resolve the inertial range [2]. In this study, we carry out an unprecedented high-resolution simulation of MRI turbulence in a local shearing box, aiming to capture the inertial range. We solve incompressible magnetohydrodynamics (MHD) using a pseudospectral MHD code CALLIOPE [3] at Fugaku, the flagship supercomputer in Japan.

The left panel of Fig. 1 shows the energy spectra obtained by the computational grids (n_x, n_y, n_z) = (4096, 8192, 2048), where x, y, and z are in radial, azimuthal, and vertical directions, respectively. One finds the break of the magnetic spectrum at $k \sim 50$ (k is the wavenumber), and beyond the break, the magnetic spectrum approaches $k^{-3/2}$. This spectral break has not been found in the previous simulations. The right panel of Fig. 2 shows the spectra of parallel and perpendicular components of magnetic and flow fields to the local mean magnetic field calculated by the method proposed by Cho & Lazarian [4]. The perpendicular and parallel components correspond to the shear-Alfvénic and pseudo-Alfvénic (high-beta limit of slow waves) fluctuations. These spectra are remarkably akin to the spectra of MRI turbulence calculated via the reduced MHD [5], supporting the validity of reduced MHD approximations in accretion disks. In the talk, we will show more in-depth analysis, including scale-dependent anisotropy and nonlinear energy transfer.

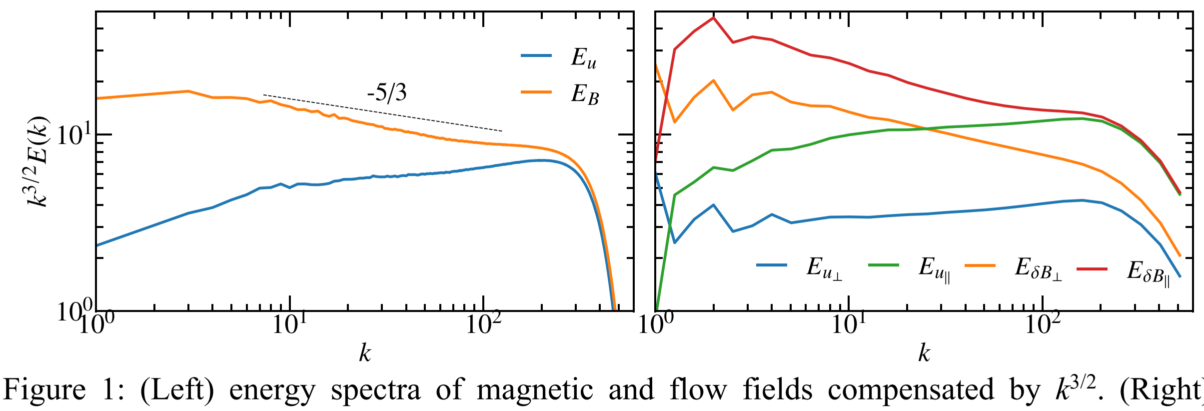

Figure 1: (Left) energy spectra of magnetic and flow fields compensated by $k^{3/2}$. (Right) decomposition of spectra to shear-Alfvén-wave like and pseudo-Alfvén like fluctuations.

[1] S. A. Balbus and J. F. Hawley, *Rev. Mod. Phys.* **70**, 1 (1998).
[2] G. Lesur and P. Y. Longaretti, *Astron. Astrophys.* **528**, A17 (2011).
[3] Y. Kawazura, *Astrophy. J.* **928**, 113 (2022).
[4] J. Cho and A. Lazarian, Mon. Not. R. Astron. Soc. **345**, 325 (2003).
[5] Y. Kawazura, A. A. Schekochihin, M. Barnes and S. A. Balbus, *J. Plasma Phys* **88**, 905880311 (2022).

Particle-in-cell modelling for head-on collisions of large-scale high density plasmas jets

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Abstract

In the double-cone ignition (DCI) inertial confinement fusion scheme, head-on collision of high density plasma jets is one of the most distinguished feature when compared with traditional central ignition and fast ignition inertial confinement fusions. However, the traditional hydrodynamic simulations become limited, due to serious plasma penetrations, mixing and kinetic physics that might occur in this process. To overcome such limitations, in this paper, we propose a new simulation method for large-scale and high density plasmas, with an ingenious kinetic-ion and kinetic/hydrodynamic-electron treatment. This method takes advantages of modern particle-in- cell simulation techniques and binary Monte Carlo collisions, including both long-range collective electromagnetic fields and short-range particle-particle interactions. Especially, in this method, the restrictions of simulation grid size and time step, which usually appear in a fully kinetic description, are eliminated. In addition, the needs of collisional coupling and state-dependent coefficients, that are usually approximately used with different forms in fluid descriptions, are also eliminated in this method. Energy and momentum exchanges among particles and species, such as thermal conductions and frictions, are modelled by "first principle" kinetic approaches. The correctness and robustness of the new simulation method are verified, by comparing with fully kinetic simulations at small scales and purely hydrodynamic simulations at large scale. Following the conceptual design of DCI scheme, the colliding of two plasma jets with initial density of 100 g/cc, initial thermal temperature of 50 eV, and counter-propagating velocity at 300 km/s is investigated by using this new simulation method. Quantitative values, including density increment, pre-heated plasma temperature, and conversion ratio from colliding kinetic energy to thermal energy, are obtained in this investigation: density increment is ∼ 3, plasma heating is ∼ 400 eV and conversion ratio is ∼ 81.2%. These values might serve as a reference for the future detailed studies.

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Modeling the acceleration and transport of nonthermal electrons in solar flares based on macroscopic MHD simulations

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Solar flares are the most powerful energy release phenomena and important sites for particle acceleration in the solar system. Although many particle acceleration mechanisms have been proposed, it remains controversial which process plays a dominant role and can explain various observational signatures of particle energization. In solar flares, HXR and radio observations provide primary diagnostics of the acceleration and transport of energetic electrons. Nonthermal looptop sources have suggested that particle acceleration takes place above the top of flare loops and the flare termination shock is one of the promising candidates as the acceleration mechanism. Here we investigate the acceleration and transport of energetic electrons in solar flares by combining a large-scale MHD simulation of a solar flare with a particle kinetic model. We find that the accelerated electrons are concentrated in the looptop region due to the acceleration at the termination shock and confinement by the magnetic trap structure, in agreement with HXR and microwave observations. Numerous plasmoids can be produced in the reconnection current sheet and interact dynamically with the shock. We find that the energetic electron population varies rapidly in both time and space due to plasmoid-shock interactions. We also present the first numerical modelling of nonthermal double coronal X-ray sources based on electron acceleration by a pair of termination shocks. Our macroscopic particle model enables detailed comparison with flare observations, and the simulations have strong implications to the interpretation of coronal nonthermal emission sources in solar flares.

[1] Kong, X., Guo, F., Shen, C., et al. 2019, ApJL, 887, L37.
[2] Kong, X., Guo, F., Shen, C., et al. 2020, ApJL, 905, L16.
[3] Kong, X., Ye, J., Chen, B., et al. 2022, arXiv:2201.02293.

Modeling and ML analysis of planetary environments using the Energy Conserving Semi Implicit method (ECSIM).

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In 2019, the USA FEMA published a report [1] stating that there were two main natural dangers that could disrupt our society: pandemic and space weather. A few months after publication of hates document we learned that it was at least 50% accurate and that's why we are meeting online and not in person. We now need to try to avoid being found unprepared also for the other threat. What is space weather? The Sun emits a solar wind made of plasma, the state of ionized gas where electrons and ions are no longer bound in atoms and behave as separate entities. These particles then interact with the planets and their magnetic field in the domain called space weather. Space weather is ripe with threats for human activities in space and for our ground infrastructure. A giant storm was observed by Carrington in 1859 and similar storms are expected to recur every 100 years on average. Every 1000 years even much stronger events are expected, statistically. Back then there was significant damage to the telegraph lines. With our much-increased reliance on the electric grid and on telecommunications compared with the age of Carrington, experts question whether our civilization could survive such an event. Predicting reliably the outcome of these events requires accurate models of the planetary space environment [2]. The current models use a fluid description where individual particles are not considered and are instead represented as a fluid, not unlike water. This description captures the macroscopic processes but not the microscopic physics that happens at the particle level. We propose here the first planetary model based on using a full particle description of electrons and ions [3]. Our model uses the new Energy Conserving Semi Implicit (ECsim) particle in cell (PIC) method [4] developed by our team. Results of a recent study of Mercury [3] will be used to visualize the role of the electrons in determining the mass an energy transfer within the system. Machine Learning (ML) techniques will be used to analyze the simulation results and extract new physics.

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Stability analysis of counter-differential rigid-rotation equilibria of electrically non-neutral two-fluid plasmas using PIC simulation

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The stability analysis of two-dimensional (2D) counter-differential rigid-rotation equilibria [1] of electrically non-neutral two-fluid plasmas with finite pressure confined in a uniform magnetic field $\boldsymbol{B}$ is presented. Recently, Experiments using non-neutral plasmas extend to apply producing and then trapping multi-component plasmas such as electron–positron pair plasmas or two-fluid plasmas consisting of a lithium ion (Li^+) and an electron (e^-) plasma. In the counter-differential rigid-rotation equilibria, the e^- plasma rotates in the same direction of $\boldsymbol{E} \times \boldsymbol{B}$ drift, while the Li^+ plasma counter-rotates overall. This counter-rotation is attributed to the contribution from the diamagnetic drift of the Li^+ plasma owing to its finite ion pressure. In addition, the non-uniform density n_e of the e^- plasma is larger than that of the Li^+ one, which means the entire plasma is in a state of non-neutral plasmas. Consequently, a bell-shaped negative potential well appears in the plasmas. The self-electric field is also non-uniform in the whole system. Nonetheless, both Li^+ and e^- plasmas exhibit corrensponding rigid rotations around the plasma axis with different angular velocities ω_{ri} and ω_{re}. To analyze the stability of the equilibria, we perform Particle-in-Cell (PIC) simulations with $\omega_{ri,e}$, $n_{i,e}$, and finite temperatures $T_{i,e}$. Data show that with some combinations of those parameters, the Li^+ and e^- plasmas are stable, as shown in figure 1. In this conference, we present these results.

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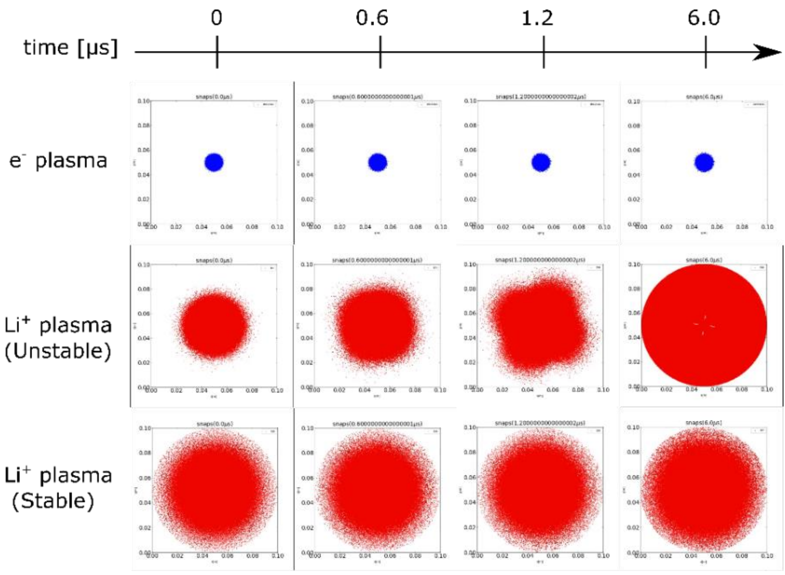

Figure 1. 2D profiles of the $\boldsymbol{e}^-$ plasma and the $\mathbf{Li}^+$ plasmas for the unstable case and stable one.

Enabling Uncertainty Quantification In Predictive Plasma Turbulence Simulations

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Gyrokinetic simulations on big supercomputers provide the gold standard for theoretically determining turbulent transport in magnetized fusion plasmas. Applications to large and costly future machines, in particular burning plasma devices like ITER, call for proper Uncertainty Quantification (UQ) in order to assess the reliability of certain predictions. However, the high computational cost of these simulations prevents straightforward applications of conventional UQ approaches. Here, we present a breakthrough, reducing the effort w.r.t. the latter by several orders of magnitude, which allows for UQ in gyrokinetic turbulence simulations of fusion plasmas. In the first part, we will show that by exploring and exploiting the fact that in most problems (i) only a subset of the uncertain parameters are important and (ii) these parameters are non-uniformly coupled, we can perform the UQ task very efficiently via our sensitivity-driven dimension-adaptive sparse grid interpolation strategy. The power and usefulness of this approach will be demonstrated in a realistic description of turbulent transport in the edge of fusion experiments. In a scenario with more that 264 million degrees of freedom and eight uncertain inputs, our approach requires a mere total of 57 high-fidelity simulations. Moreover, it intrinsically provides an accurate and efficient low-fidelity model that is nine orders of magnitude cheaper than the high-fidelity model. In certain complex simulation scenarios, however, relying on a single model might not be sufficient. To this end, in the second part of this contribution, we will discuss our recently formulated context-aware multi-fidelity Monte Carlo sampling algorithm, in which a hierarchy – instead of a single model – of high- and low-fidelity models is used to perform the UQ task. In particular, we consider data-driven low-fidelity models and address the very question of how much high-fidelity training data is required to train the low-fidelity models. This question is very relevant for machine learning-based models, for example, which, in single fidelity settings, are known to typically require large training sets. In contrast, in our context-aware algorithm we tradeoff increasing the size of training sets with using the low-fidelity models for multi-fidelity sampling, which means that small training sets are typically sufficient for training the low-fidelity models. In fact, we were able to show that low-fidelity models can become too accurate for multi-fidelity methods, which is in stark contrast to single-fidelity settings in which more training data usually implies more accuracy. We illustrate our context-aware algorithm in a plasma turbulence simulation with 12 uncertain parameters, in which, for example, only 263 high-fidelity samples are necessary to train a fully-connected feed-forward deep neuronal network model.

Hyper-dimensional manifold optimization for turbulent plasma transport

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The turbulent transport is one of the most critical issues in the magnetic fusion researches. Numerical simulation based on the gyrokinetics is the most reliable way for understanding of the transport physics. Many simulation studies indicate that the zonal flows (ZFs), which are caused by nonlinear interactions in the turbulences, are significant to determine the transport levels through the ZFs regulating the turbulences [1].

In our previous works by gyrokinetic simulations, the transport level χ can be described by certain function of the turbulent level $\mathcal{T}$ and the ZFs level $\mathcal{Z}$ with the nonlinear fitting parameters [2] as $\chi^{\text{model}} = C_1\mathcal{T}^{\alpha}/(C_2 + \sqrt{\mathcal{Z}}/\mathcal{T})$. In recent works, it has been found that there are possibilities to be able to reproduce the transport levels precisely by extending the functional forms with additional fitting parameter [3]. Furthermore, clear functional relation also exists for the time-series data of the gyrokinetic simulations [4]. To optimize the functional relation, we need to find out the global minimum point in parameter space with the dimension of the number of the fitting parameters. In this work, we propose a new approach to optimize the functional relation by focusing on the manifold formed in the hyper-dimensional parameter space of the function. As shown in Fig.1, which is the case of the ITG turbulence simulation for the LHD plasma, a manifold is clearly formed in the parameter space $\{C_1, C_2, \alpha\}$ within the certain values of the objective function, such as $G(C_1, C_2, \alpha) = \sqrt{(1/N)\sum_j(\chi_j^{\text{model}} - \chi_j^{\text{sim}})^2}$. In the proposed method, by evaluating the integral of the given objective function over the manifold $\mathcal{V}$, i.e., $\mathcal{I} = \int_{V\subset\mathcal{V}} dVG$, we can estimate the likelihood of the forms of the functional relation.

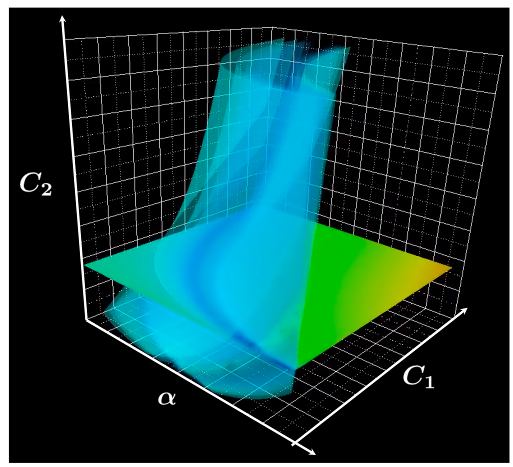

Figure 1: A manifold formed in the parameter space of the functional relation for the turbulent transport.

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Evolution of the marker distribution in gyrokinetic δf particle-in-cell simulations

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The evolution of the particle weight in a δf Particle-in-Cell simulation depends on the marker distribution that can evolve in a turbulent field due to turbulent diffusion. When Monte-Carlo methods are used to implement the test particle collision operator, or when the particle motion is not strictly Hamiltonian in a collisionless simulation, the marker distribution will evolve along the particle trajectory and in general cannot be known exactly. A two-dimensional numerical marker distribution is proposed as an approximation. It is shown to be advantageous over other common methods for evaluating the marker distribution in long time turbulence simulations. A generalized two-weight δf-method is proposed to mitigate the marker evolution problem.

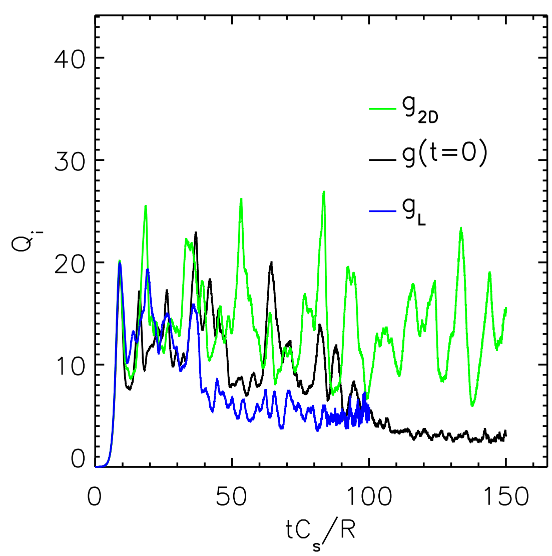

Figure 1: Ion heat flux vs time for three schemes of evaluating the marker distribution: (a) assume the marker distribution is a constant along the trajectory, evaluated during loading (black); (b) the marker distribution is assumed equal to the initially loaded distribution (blue); (c) use the numerical 2-D distribution (green). Only the simulation using the numerical marker distribution maintains a steady state turbulence and transport.

Performance portable full-f gyrokinetic simulations on exascale supercomputers

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The Gyrokinetic Toroidal 5D full-f Eulerian code GT5D [1,2] was ported on Fugaku and Summit, which are state-of-the-art exascale supercomputers based on many core CPUs and GPUs. GT5D is based on a semi-implicit finite difference scheme, in which a stiff linear 4D convection operator is subject to implicit time integration, and the implicit finite difference solver for fast kinetic electrons occupies more than 80% of the total computing cost. The implicit solver was originally developed using a Krylov subspace method (GCR), in which global collective communication and halo data communication were bottlenecks on exascale supercomputers. This issue was resolved by a communication-avoiding Krylov subspace method (CA-GMRES) [2], which reduces the number of global collective communication, and a FP16 preconditioner [3], which reduces the number of iterations and thus halo data communication. On Fugaku and Summit, the new CA-GMRES solver respectively achieved 2.8× and 1.9× speedups from the conventional GCR solver, and excellent strong scaling was obtained up to 5,760CPUs/GPUs. The dramatic improvement of computing power enabled us to perform numerical experiments with real mass kinetic electrons and with experimental data. In the talk, we will present exascale computing techniques of GT5D, and recent tokamak numerical experiments on Fugaku.

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Gyrokinetic simulations of the helically-trapped electron mode in W7-X stellarator

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This work reports the discovery of a new driftwave eigenmode in the W7-X from the first ever nonlinear gyrokinetic simulation of microturbulence in the stellarator incorporating both full flux-surface and kinetic electrons. Global simulations are necessary to study key physics of the non-axisymmetric stellarator such as linear toroidal coupling of multiple-n toroidal harmonics (e.g., localization of eigenmodes to discrete magnetic field lines, linear coupling between zonal flows and low-n harmonics etc), turbulence spreading, and secular radial drift of helically-trapped particles. In this work, global gyrokinetic simulations using the GTC code [1] find a new electrostatic helically trapped electron mode (HTEM) driven by a realistic density gradient in the W7-X. The HTEM is excited by helically trapped electrons at the toroidal section with a weak magnetic field. The linear eigenmode is localized to discrete field lines on the inner side of the torus. Nonlinear simulations find that the HTEM saturates by inverse cascade of the toroidal harmonics from a linear range of n=[100,300] to a nonlinear range of n=[0,200] and by turbulence spreading to the damped region across the whole flux-surface and in the radial direction. Zonal flows play a secondary role in the HTEM saturation. The saturated HTEM turbulence drives a large particle diffusivity comparable to the heat conductivity driven by the ion temperature gradient (ITG) turbulence [2] with similar gradient scale lengths. The HTEM can only be captured by full flux-surface simulations since helically trapped electrons residing in different flux-tubes can either drive or damp the HTEM. The full flux-surface simulations with kinetic electrons only become feasible thanks to the GTC global field-aligned mesh in real space, which reduces the number of parallel grid points by a factor of 150 in these W7-X simulations.

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Enabling optimizations for reduced kinetic spectral models

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Efficient coupling of the microscopic physics into the macroscopic system-scale dynamics (called "fluid-kinetic" coupling) is probably the most important and unresolved problem of computational plasma physics. It impacts most of plasma physics areas including space physics and fusion systems. Majority of conventional simulation tools capable of describing large scale dynamics are usually limited to simplified fluid/magnetohydrodynamics description of the plasma, because of the large spatial and temporal scale separation typical of plasmas. Yet, fluid models lack the microscopic physics, which is known to be important in many applications (e.g., reconnection, shock physics, etc.) A way forward is to build models that combine kinetic and fluid description in one consistent framework. The development of such methods can bridge the scale gap to successfully handle coupling of large-scale dynamics and microscopic processes.

In this presentation, we describe a novel simulation method, where the kinetic equation is solved using a spectral expansion of the plasma distribution function. The low-order terms in the expansion capture the large-scale dynamics of the system, while higher-order terms add microscopic physics incrementally, similar to classical fluid-moment expansion. Such a method is ideally suited for problems involving fluid-kinetic coupling, since the number of expansion terms could be adapted in space and time. Furthermore, the spectral basis itself adaptively changes in space and time, adjusting to plasma mean flow and temperature, thus making the representation of the particle distribution function very efficient. We show that our reduced kinetic model with just a $\sim (4-6)^3$ velocity-space moments agrees well with results from fully-kinetic simulations on some examples. In addition to describing the method, we will present several examples illustrating its application to various problems, including solar wind-magnetosphere interaction.

Development of a full MHD eigenvalue code with the use of symbolic computation technique

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A new full MHD eigenvalue code in toroidal geometry, named SCELT (Symbolic Computation aided Eigenvalue and Linear code for Tokamak) is constructed largely in C++ language by utilizing the symbolic computation technique for the first time. A symbolic vector analysis module is first developed to conduct the automatic derivation of the tedious linearized full MHD equations in the magnetic flux coordinate system. Furthermore, an automatic numerical discretization module is developed to implement the automatic numerical discretization. This new method has the advantage to greatly reduce the manpower and to avoid possible errors in code development. The tools provide a means of constructing matrices from differential operations and can be used for (generalized) linear problems, such as source driven and eigenvalue problems. The advantages and potential broad applications of the tools are demonstrated by the demo uses in solving the Poisson equation and tokamak equilibrium equation. The reliability of the new full MHD eigenvalue code developed with the new tools is verified by the internal kink mode and tearing mode tests.

Acknowledgments
The numerical calculations are performed on the ShenMa High Performance Computing Cluster at the Institute of Plasma Physics, Chinese Academy of Sciences. This work is supported by the National Key R&D Program of China under Grant No. 2017YFE0300402 and the National Natural Science Foundation of China under Grant Nos. 12075282 and 11775268.

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3D PIC simulation of coherent emission from relativistic shocks

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The origin of fast radio bursts (FRBs) is one of the unsolved problems in astrophysics [1]. FRBs are extremely bright and millisecond duration pulse at radio frequency. Many observations of FRBs indicate that FRBs must be coherent emission in the sense that coherently moving electrons radiate electromagnetic waves. In relativistic shocks, it is well known that coherent electromagnetic waves are excited by synchrotron maser instability (SMI) in the shock transition [2]. In the shock transition, the incoming electrons begins to gyrate due to the shock-compressed magnetic field and the ring-like momentum distribution is generated, which triggers the SMI. Previous two-dimensional (2D) particle-in-cell (PIC) demonstrates that the coherent electromagnetic waves are indeed excited in the shock transition and propagate tpward the upstream [3-5]. The SMI is also known as the emission mechanism of coherent radio sources such as auroral kilometric radiation at Earth and Jovian decametric radiation. Recently, some models of fast radio burst based on the coherent emission from relativistic shock via the SMI have been proposed [6-8] and the SMI in the context of relativistic shocks attracts more attention from astrophysics. In this study, by performing the world's first 3D PIC simulation of ion-electron relativistic shocks, we will demonstrate that large-amplitude electromagnetic waves are indeed excited by the SMI even in 3D and that the wave amplitude is significantly amplified and comparable to that in pair plasmas due to a positive feedback process associated with ion-electron coupling. Based on the simulation results, we will discuss the applicability of the SMI for FRBs in this talk.

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Solar differential rotation reproduced with high resolution magnetohydrodynamic simulations

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We carry out unprecedentedly high-resolution MHD simulations with the supercomputer Fugaku and succeed in reproducing the solar differential rotation (DR) with solar parameters [1]. The observation of the solar DR has a long history, and it is well confirmed that the solar equator region is rotating faster than the polar region. Numerical simulations have difficulty reproducing the DR. High-resolution simulations easily fall into the anti-solar DR regime with the existence of fast and small-scale turbulence. This is part of the convective conundrum, one of the most critical problems in solar physics. In this study, we use the supercomputer Fugaku which is currently the fastest computer in the world (Top 500 list, November 2020), and carry out unprecedentedly high-resolution simulations of the solar global convection zone. As a result, we achieve the first successful reproduction of the solar DR. In the highest resolution calculation, the magnetic field becomes dominant throughout the convection zone and has an important role in the angular momentum transport. In this study, a part of the convective conundrum is solved.

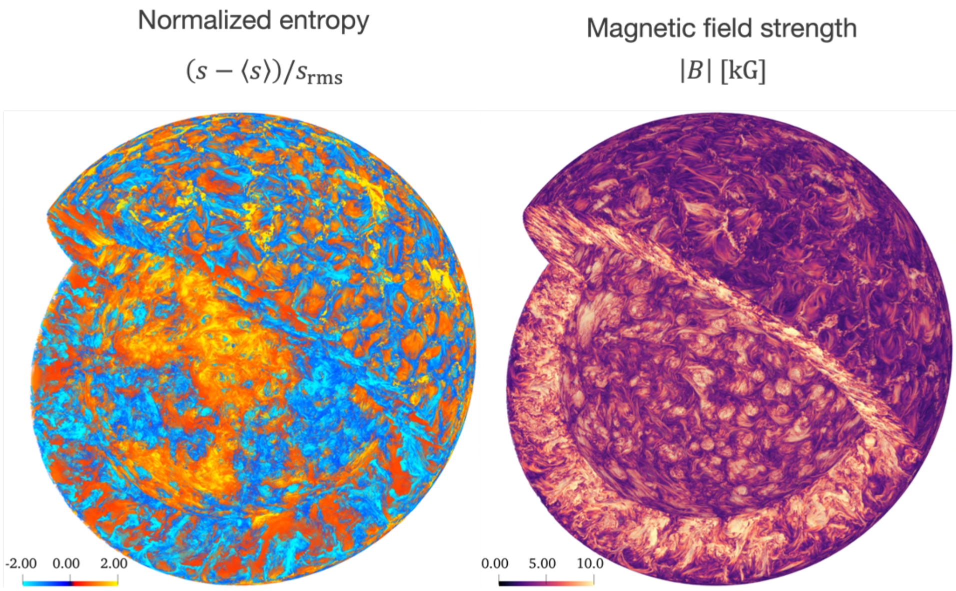

Figure 1 3D volume rendering of the result. (Left) Normalized entropy and (Right) magnetic field strength are shown.s

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Alfvén Mach number dependence on ion Weibel instability in collisionless shock transition regions: Effect of magnetized electrons

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The dynamics of collisionless shocks is an exceedingly important topic for plasma physics and astrophysics because it is related to many types of plasma instabilities and cosmic ray accelerations. In the shock transition region where the particles incoming from the upstream and particles reflected from the downstream coexist, plasma microinstabilities are excited. It is known that the Weibel instability becomes the dominant instability in non-relativistic, high Alfvén Mach number (M_A>50) shocks[1].

In these shocks, we can assume that the ions are unmagnetized. However, the response of the electrons could be drastically different depending on the Alfvén Mach number. Whether the electron frozen-in condition, which can roughly be estimated by (M_A<m_i/m_e), is satisfied could drastically change the magnetic field structure and electron heating efficiency.

In this study, we investigate the Alfvén Mach number dependence on the ion Weibel instability by theory and 2D PIC simulations. The magnetized electrons increase the growth rate of the waves, especially at long-wavelength and near parallel propagation angles. In nonlinear stages, the magnetized electrons create a strong beam-parallel magnetic field which leads to magnetic reconnection that has been observed in several 2D shock simulations[2].

By performing 2D PIC simulations with periodic boundary conditions, we confirmed the larger magnetic field generation, reconnection, and more efficient electron heating in the Weibel instability with magnetized electrons (Fig. 1).

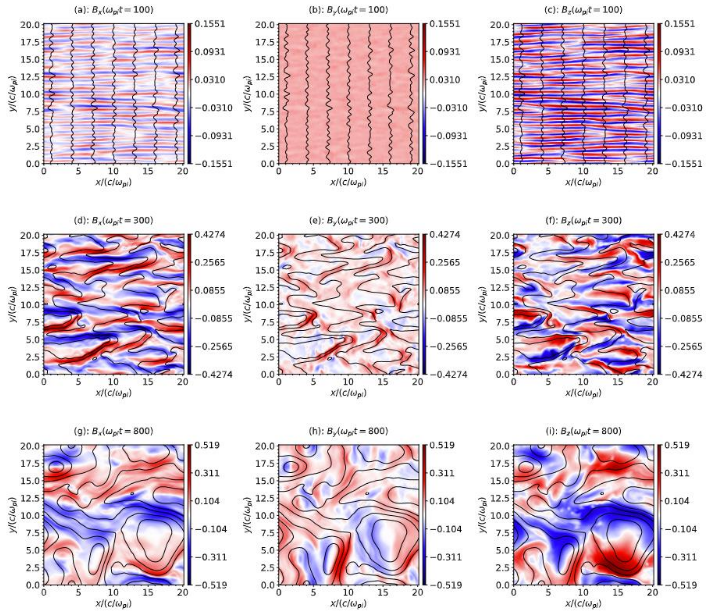

Fig. 1. Snapshots of the magnetic field. The solid lines show the in-plane magnetic field lines.

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A Quasi All-speed Scheme for MHD Flows in a Wide Range of Mach Numbers

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A magnetohydrodynamic (MHD) simulation is an indispensable tool for studying the macroscopic dynamics of laboratory, space, and astrophysical plasmas. For compressible MHD simulations, shock-capturing schemes have been developed based on the solution to the Riemann problem in one-dimensional hyperbolic conservation laws, which allows us to tackle a situation including supersonic flows. In particular, the Harten-Lax-van Leer discontinuities (HLLD) approximate Riemann solver [1] is extensively implemented in modern MHD simulation codes by virtue of its robustness and accuracy.
In practical multidimensional MHD simulations, however, familiar shock-capturing schemes may suffer from numerical difficulties, which include a numerical shock instability for high Mach number flows (known as the Carbuncle phenomena) and a degradation of the solution accuracy for low Mach number flows. Owing to these difficulties, shock-capturing schemes are available only for moderate Mach number flows. Preservation of the solenoidal condition for the magnetic field is also an issue for multidimensional MHD simulations.
We propose a new shock-capturing MHD scheme that implements two factors for shock detection and pressure correction to avoid the multidimensional shock instability and improve the accuracy of low-speed flows [2,3]. The scheme is accurate for super-Alfvenic flows; thus, we call it as a “quasi all-speed” scheme. In this talk, we will present details of the design of the scheme, benchmark test results (e.g., Figure 1), and the application of the scheme to practical MHD turbulence problems.

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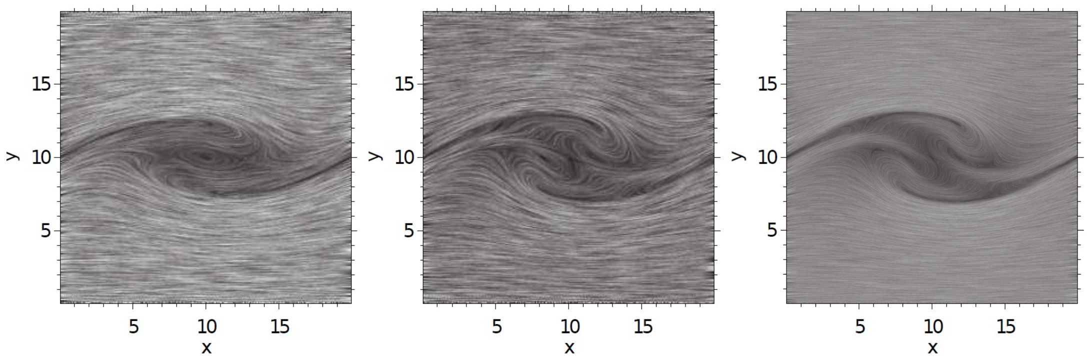

Figure 1: Stream lines in the MHD Kelvin-Helmholtz instability at a Mach number of 0.016 obtained with (left) the HLLD scheme with 256x256 grid resolution, (middle) the new scheme with 256x256 grid resolution, (right) the HLLD scheme with 1024x1024 grid resolution.

Guide-field dependence of a merging process of two spherical-tokamak-type plasmoids

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A merging process of two spherical-tokamak-type (ST) plasmoids, which are confined inside a rectangular conducting vessel, has been examined by means of two-dimensional PIC simulation [1]. Two STs are relaxed into one large ST through the merging process, while changing an equilibrium profile. Magnetic reconnection takes place at a contact point of two STs and a part of magnetic energy is transferred to the ion and electron kinetic energies first, and then dissipates into particle thermal energies in a final relaxed state. The total thermal pressure increases in the central confinement region and expands towards the edge region by changing the total confinement profile. Finally, a trapezoid-shaped pressure profile with a flat top and a hollow magnetic pressure profile are formed in the central confinement region, as indicated by red and black curves in Fig. 1. A series of simulation runs with different guide fields clarify that there appears a strong dependence of the energy partition on the guide field, as shown in Fig. 2. It is found that this strong dependence comes mainly from the difference in ion and electron dissipation mechanisms. These results are also consistent with the TS3 merging experiment [2,3].

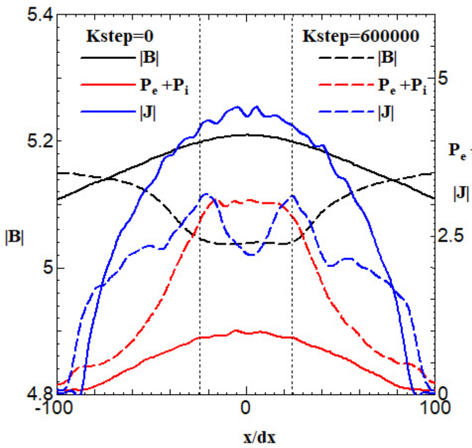

Fig. 1. Initial and final spatial profiles of absolute magnetic field, total thermal pressure, and total current density.

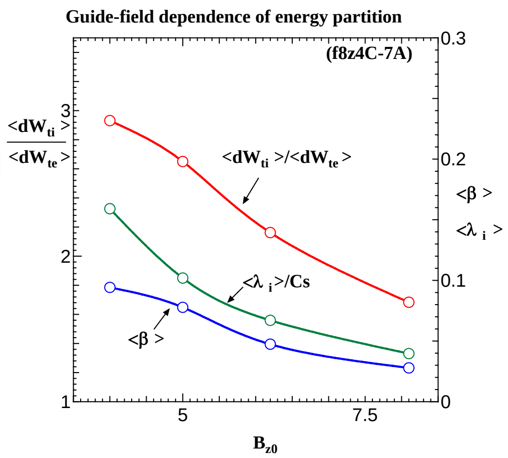

Fig. 2. Guide-field dependence of energy partition, ion Larmor radius, and plasma beta.

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General geometry 2D implicit PIC model

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Particle in cell (PIC) codes are of vital importance in the research of plasmas. They are based on first principle physics and can properly represent kinetic effects in plasmas [1]. We represent a 2 dimensional PIC code utilising a general, non-uniform grid. This allows for simulations on arbitrary geometric grid layout. This can drastically increase the efficiency of simulations which are not well suited to the commonly used cartesian grid layout, and open up the possibility for entirely new simulations. Some candidate simulations which would benefit from this include, but are not limited to: full scale tokamak simulations and expanding solar wind simulations.
The model utilises a covariant description of the electric and magnetic fields and uses the metric tensor and Jacobian tensor to create a covariant set of finite difference operators and transform the fields and grids to the desired geometry [2][3]. The particle mover is a cartesian Newtonian staggered time step mover based on the D1 scheme [4]. This adds the complexity of having to convert particle positions between cartesian and general coordinate systems when interpolating the current and fields to and from the particles. In the future a non-cartesian particle mover will be implemented to avoid this complication and open the possibility for non-analytic geometries.
The PIC implementation is fully implicit to ensure energy conservation [1]. This conservation is maintained in all orthogonal geometries, but not guaranteed in other types of geometries, though we hope to fix this in the future. Energy conservation can be crucially during instability studies to avoid numerical heating of the plasma leading to unphysical results [5]. The model uses a staggered grid layout putting the electric field in the centres of cells, and the magnetic fields on the nodes of the cells. This is based on the PIC implementation used in ECsim [6]. The model is written in python to accommodate fast iteration and small scale testing. The future goal is to implement this method in ECsim, to leverage its semi-implicit and energy conserving nature, and allow for large scale 3 dimensional HPC-optimised simulations [6].

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Multidimensional study of thermonuclear burning wave triggering sub-Chandrasekhar mass Type Ia supernovae

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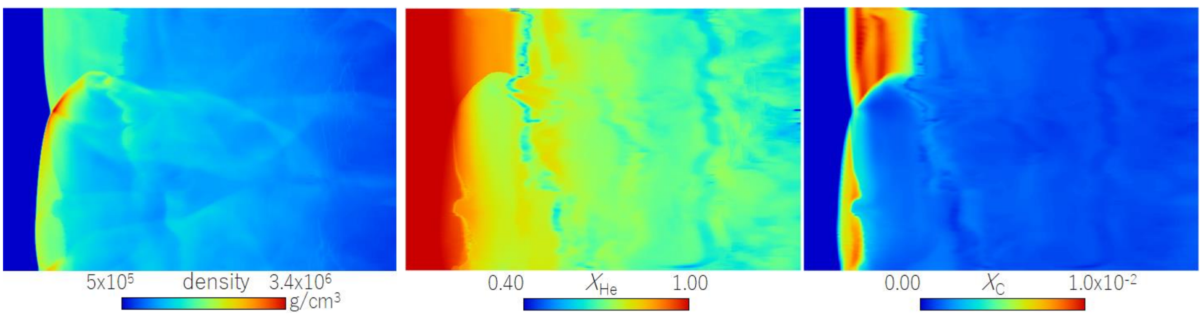
We currently study the morphologies of thermonuclear burning wave as a trigger of sub-Chandrasekhar mass Type Ia supernovae, which is expected to overcome the discrepancies with the observation that the conventional near-Chandrasekhar model suffered from.
In the sub-Chandrasekhar model, explosive burning is initiated in the helium layer on a white dwarf (WD) accreted from a companion star, as a supersonic thermonuclear burning wave (detonation). Shock wave induced by the detonation then ignites the carbon/oxygen core of the WD, which subsequently disrupts the whole WD.
However, self-consistent ignition of the helium layer has not been reproduced well, which has motivated us to begin with a 1D spherical simulation to address this issue [1]. The problem associated with the numerical methods is that detonation wave is intrinsically multi-dimensional, which can affect its minimum ignition energy required, propagation velocity, and whether it can ignite the core of the WD directly.
Therefore, we presently extend our study to 2D simulation, including a nuclear reaction network of 7 isotopes [2]. A rectangular computational domain with a uniform square spacing of 2.5×10^3 cm is adopted. Equation of state by Timmes and Arnett [3] is applied to calculate the pressure and internal energy of plasma with arbitrary degeneracy and relativity.
Fig. 1 shows the contour maps of the distributions of density, and the mass fractions of helium and carbon in the detonation propagating in the helium with the density of 5×10^5 g/cm^3 and temperature of 1.0×10^8 K. Cellular structure represented by transverse waves intrinsic to detonation appears, and a multi-stage nature of the burning process can be seen in which nickel is produced as the final product via carbon/oxygen/silicon as the intermediate products. In the conference, the physical details of this cellular detonation will be addressed associated with the likelihood of the sub-Chandrasekhar explosion.



(a) density (b) helium mass fraction (c) carbon mass fraction

Fig. 1 2D structure of helium detonation on the surface of a white dwarf
($\rho_{ini}=5 \times 10^5$ g/cm^3, $T_{ini}=1 \times 10^8$ K)

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Modeling of coherent synchrotron radiation effects in high brightness beams via a novel particle-mesh method and surrogate models with symplectic neural networks

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The self-consistent nonlinear dynamics of a relativistic charged particle beam interacting with its complete self-fields is a fundamental problem underpinning many of the accelerator design issues in high brightness beam applications, as well as the development of advanced accelerators. Particularly, synchrotron radiation induced effects in a magnetic dispersive beamline element can lead to collective beam instabilities and emittance growth, posing critical challenges for preserving the quality of a high brightness beam. We review existing numerical techniques and relevant simulation challenges of modeling synchrotron radiation effects in collective beam dynamics. A novel self-consistent code is developed based on a Lagrangian method for the calculation of the particles' radiation near-fields using wavefront/wavelet meshes via the Green's function of the Maxwell equations. These fields are then interpolated onto a moving mesh for dynamic update of the beam. This method allows radiation co-propagation and self-consistent interaction with the beam in 2D/3D simulations at greatly reduced numerical errors. Multiple levels of parallelisms are inherent in this method and implemented in our code CoSyR [1] to enable at-scale simulations of nonlinear beam dynamics on modern computing platforms using MPI, multi-threading, and GPUs. Our simulations reveal the slice emittance growth in a bend and the interplay between the longitudinal and transverse dynamics that occurs in a complex manner not captured in the 1D longitudinal static-state coherent synchrotron radiation model. Finally, we show that surrogate models with symplectic neural networks can be trained from the simulations with our first-principle method, which can lead to significant time-savings for the modeling of nonlinear beam dynamics effects that usually requires high computing cost.

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A Kinetics-only Delta-f (KODF) Method for RF Wave Modeling in Warm Plasma

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We present a new delta-f particle-in-cell method, kinetics-only delta-f (KODF), for modeling the nonlinear evolution of plasma species distribution functions in phase space.

In conventional delta-f methods, computational markers evolving along characteristic trajectories model perturbations around a known equilibrium distribution function. The computational markers need not model the equilibrium distribution (as would be necessary if one used a total-f approach); instead, a marker weight variable tracks the deviation of the distribution function from equilibrium.

In KODF, we generalize this concept to incorporate cold linear plasma waves into the known (quasi)analytic plasma behavior. The perturbations modeled by KODF PIC methods are thus nonlinear, finite-temperature perturbations atop cold linear waves whose evolution can be modeled without the noise associated with a PIC model. The KODF weight equation self-consistently tracks the deviation of the distribution function from an equilibrium upon which these evolving linear waves are superposed.

We demonstrate the implementation of KODF in the VSim particle-in-cell code. VSim's semi-implicit FDTD methods [1] are used to model the fluid behavior of cold plasma waves, and source terms that arise from these waves (e.g., from gradients of cold current or charge densities, or from quasilinear terms) appear in the KODF weight evolution equation to drive and evolve responsive warm plasma effects. We explore the noise-reduction capabilities of the KODF algorithm and its ability to model waves of interest in RF heating scenarios (e.g. mode-converted IBWs).

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New algorithm for solving sheared flows in local flux-tube gyrokinetic simulations

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Gyrokinetic simulations based on a local flux tube model are widely used in theoretical studies and experimental comparison of turbulent transport in magnetic fusion plasmas. Although the effects of background sheared flows have been implemented by using the wavenumber remap method[1] in various codes, it has been pointed out that the nearest grid point simplification can cause problems of the time discontinuity. This motivates development of new algorithms recently discussed[2-4]. All of them are based on two-dimensional coordinate transformation on the Lagrange frame moving with sheared flows. This leads deformation of simulation box in time, and therefore requires a remapping technique to keep constant resolution in the Laboratory frame. Since the remapping is a numerical procedure with data copying and dumping, it can be a source of numerical dissipation and cause a difficulty to apply mode-to-mode coupling analysis in the presence of sheared flows.

In this study, we proposed the new algorithm for solving sheared flows in local flux-tube gyrokinetic simulation, called the rotating flux tube model. It is defined by three-dimensional coordinate transformation to cancel shearing of the box by background sheared flows and shearing in the field-aligned direction in the presence of magnetic shear. This keeps radial wavenumber k_ρ in the flux coordinates (ρ,θ,ζ) constant in time, which corresponds to keeping the ballooning angle constant in the extended MHB ballooning theory[5]. The new algorithm possesses the advantages: (i) the remap procedure is not required (the associated numerical dissipation is reduced), (ii) the Floquet's generalized eigenfunction under sheared flows is properly treated by a linear simulation with a single wavenumber, (iii) mode-to-mode coupling analysis is available even in the presence of sheared flows. These advantages are demonstrated with implementing the rotating flux tube model in the local gyrokinetic code GKV[6].

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An implicit, conservative and asymptotic-preserving electrostatic particle-in-cell algorithm for strongly magnetized plasmas

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We introduce a new electrostatic particle-in-cell algorithm which extends earlier electrostatic fully implicit PIC [1] to be able to use large timesteps compared to particle gyro-period under a uniform external magnetic field. The algorithm implements a new asymptotic-preserving particle-push scheme that allows timesteps much larger than particle gyroperiods. In the large-timestep limit, the integrator preserves all the averaged particle drifts, while recovering the standard CN scheme for small timesteps [2]. The scheme allows for a seamless, efficient treatment of particles in coexisting magnetized and unmagnetized regions, conserves energy and charge exactly, without spoiling implicit solver performance. We demonstrate by numerical experiment with several strongly magnetized problems (e.g., diocotron instability, modified two-stream instability, drift instability), which shows that orders of magnitude wall-clock time speedups vs the standard fully implicit electrostatic PIC algorithm are possible without sacrificing solution quality [3].

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The first nonlinear simulation of Alfvén eigenmode in CFQS

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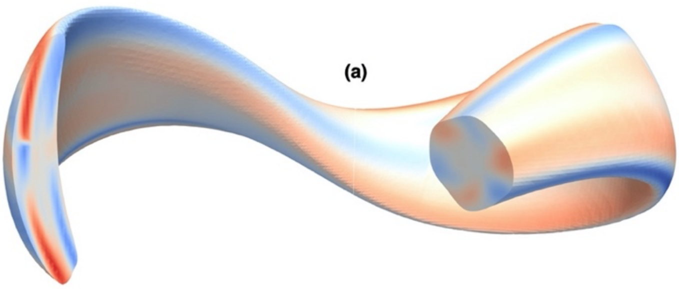
A nonlinear simulation of the Alfvén eigenmode (AE) in the Chinese First Quasi-Axisymmetric Stellarator (CFQS)[1,2] has been conducted for the first time. MEGA[3], a hybrid simulation code for energetic particles interacting with a magneto-hydrodynamic (MHD) fluid, was used in the present work. Both the m/n = 3/1 global Alfvén eigenmode (GAE) and the m/n = 5/2 toroidal Alfvén eigenmode (TAE) were found, where m is the poloidal mode number and n is the toroidal mode number. Four important results were obtained as follows. First, the instability in the CFQS in three-dimensional form was shown for the first time, as plotted in Fig. 1(a). Second, strong toroidal mode coupling was found for the spatial profiles of AEs, and it is consistent with the theoretical prediction[4]. Third, the resonant condition caused by the absence of axial symmetry in CFQS was demonstrated for the first time. The general resonant condition is $f_{mode} = Nf_{\varphi} - Lf_{\theta}$, where f_{mode}, f_{φ}, and f_{θ} are mode frequency, particle toroidal transit frequency, and particle poloidal transit frequency, respectively; N and L are arbitrary integers, represent toroidal and poloidal resonance numbers. For GAE, the dominant and subdominant resonant conditions are $f_{GAE} = 3f_{\varphi} - 7f_{\theta}$ and $f_{GAE} = f_{\varphi} - f_{\theta}$, respectively. For TAE, the dominant and subdominant resonant conditions are $f_{TAE} = 4f_{\varphi} - 9f_{\theta}$ and $f_{TAE} = 2f_{\varphi} - 3f_{\theta}$, respectively. The toroidal resonance numbers are different from the toroidal mode numbers by 2. This indicates that the 2-fold rotational symmetry affects the resonance condition. On the other hand, the subdominant resonances satisfy N = n, which is expected for the axisymmetric plasmas and most of the toroidal plasmas including stellarators. Fourth, the nonlinear frequency chirpings of AEs in CFQS were demonstrated for the first time, and the GAE case is shown in Fig. 1(b). Hole and clump structures were formed in the pitch angle and energy phase space, and the particles comprising the hole and clump were kept resonant with the GAE or TAE during the mode frequency chirping.



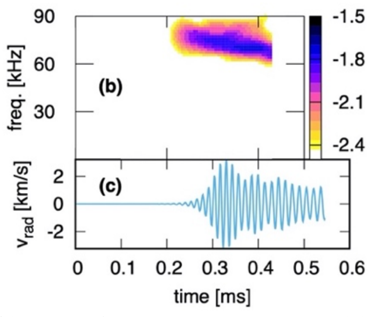


Fig. 1 (a) Radial velocity v_{rad} of GAE in three-dimensional form. (b) GAE frequency spectrum. (c) Time evolution of GAE amplitude.

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Particle energization in the vicinity of an O-point: numerical and analytical investigations

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We follow the detailed evolution of current sheets (CSs) forming in between magnetic islands as a result of an enforced large-scale merging by 2D magnetohydrodynamic (MHD) simulation. The simulation starts from four magnetic islands in magnetostatic equilibrium. The central X-point among the four islands collapses as a result of velocity perturbation and a CS is formed and gradually extending. We verify that the near-steady Sweet-Parker reconnecting CS transits to a multi-plasmoid fragmented state, when the Lundquist number exceeds about 10^4, well in the range of previous studies. Chaotic flow patters are observed inside plasmoids as shown in the left of Figure 1. Then we study the motion of the particles in a MHD snapshot at a fixed instant of time by the Test-Particle Module incorporated in the numerical code AMRVAC. We observed that the energies of particles increase in the test-particle simulation, as shown in the right of Figure 1. While the planar MHD setting artificially causes strong acceleration in the ignored third direction, it also allows for the full analytic study of all aspects leading to the acceleration and the in-plane-projected trapping of particles in the vicinities of O-points. The analytic approach uses a decomposition of the test particle velocity in slow and fast changing components [1]. We find that after an initial non-relativistic motion throughout a monster island, particles can experience acceleration in the vicinity of an O-point of sizes smaller than the proton gyroradius beyond $\sqrt{2}/2 = 0.7c$, at which speed the acceleration is at its highest efficiency.

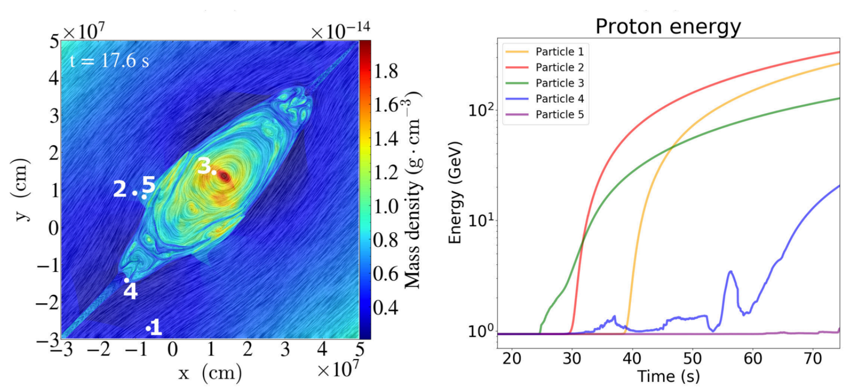

Figure 1: Left: The density distribution with magnetic field overlaid (grey) and the initial positions of 5 test particles. Right: The energy curves of the 5 test particles.

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Machine-learning assistance with nonlinear gyrokinetic simulations by recognizing wavenumber-space images

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Nonlinear gyrokinetic simulations are essential for predicting and understanding turbulent transport in magnetically confined fusion plasmas. However, it is still necessary to perform very long simulations, say, from tens of hours to weeks, even with a modern powerful large-scale supercomputer like Fugaku. We have developed a convolutional neural network (CNN) model, which assists in efficient runs of nonlinear gyrokinetic simulations [1]. The CNN model forecasts when the saturation of turbulent heat fluxes commences by recognizing a wavenumber-space image generated in an early phase of the simulation with reasonable accuracy even for unknown cases. The images fed into the model display the square of the ion perturbed distribution function $|\tilde{f}_{\mathrm{i}}|^2$ in the wavenumber-space (k_x, k_y) and they are created from the simulations with the flux-tube gyrokinetic code GKV [2]. The model is built by employing transfer learning and fine tuning techniques based on one of the state-of-the-art CNN models, EfficientNet [3]. As we have found that the characteristics of evolving processes of $|\tilde{f}_{\mathrm{i}}|^2(k_x, k_y)$ differ depending upon the dominant instability, multiple CNN models have been prepared using the images from the several simulations governed by different dominant instabilities. The best model for each simulation is selected based on the pre-performed linear stability calculation with low computational cost. The practical use of the model is as follows: The model can predict the time to saturation using the images at the very initial phase taken from the several simulations running in parallel with different initial conditions. Continuing the simulation predicted as reaching the saturation the fastest and canceling the rest, we can save computational resources in total and shorten the time it takes until saturation.

One of the primary objectives of the nonlinear gyrokinetic simulations is to calculate the turbulent fluxes of each species in the saturation phase. A predictor that forecasts the saturated turbulent fluxes just from information in the early phase could contribute to a significant reduction in the computational resources. Toward this ultimate goal, the extended CNN model is under construction.

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Global gyrokinetic simulations of electrostatic microturbulence transport using kinetic electrons in LHD heliotron

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Drift wave instabilities [1] responsible for the electrostatic turbulence transport in fusion plasma, namely, the ion temperature gradient (ITG) and trapped electron mode (TEM), are studied using gyrokinetic toroidal code (GTC) in the LHD stellarator [2]. The ITG turbulence simulations with kinetic electrons show that the kinetic effects increase the growth rate of the most dominant eigenmode by ~ 1.5 times and the turbulent transport by ~ 2.5 times as compared to the case with adiabatic electrons. The zonal flow regulates the ITG turbulence transport [3] by reducing it by almost two-folds and hence acts as a dominant saturation mechanism. The linear TEM simulations show that the electrostatic potential is localized on the low magnetic field region where the curvature is bad, just like ITG turbulence [4]. The nonlinear TEM turbulence simulations show that the main saturation mechanism is not the zonal flow but the inverse cascade of the high poloidal and toroidal harmonics to the low harmonics. The comparison of the transport levels for different pressure profiles used in this work shows that the presence of gradient in ion temperature is effective in driving the turbulence transport than the density gradient.

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Saturation mechanism of ion temperature gradient driven turbulence in finite beta tokamaks studied by global gyrokinetic simulation

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Turbulence in finite normalized pressure (beta) is electromagnetic and often exhibits non-saturation due to a lack of zonal flows in gyrokinetic simulations using radially localized flux tube geometry. The non-saturation is due to the suppression effect of magnetic fluctuations on zonal flows and is known as the run-away/non-zonal-transition [1, 2]. Our study identifies a new saturation mechanism caused by entropy/free-energy advection in real space by global gyrokinetic simulations. The convection of the entropy associated with the turbulence in the radial direction produces zonal flows at the both sides of the most active region of the turbulence to avoid the influence of the magnetic fluctuations, and then zonal-flow excitation is not suppressed, leading to a steady state of the turbulence [3].

The identification of a saturation mechanism for the ion-temperature-gradient (ITG) turbulence in finite-beta regimes is important for understanding experimentally observed trends of beta dependencies of confinement. Whereas in low-beta plasmas the zonal flow shear acts to regulate the ITG turbulence, it has often been observed that, at moderate-beta, the ITG turbulence continues to grow without reaching a physically relevant level of saturation in many local gyrokinetic simulations of turbulence. For instance, the ITG turbulence continues to grow above beta=1.2%, which is much lower than the critical beta of the kinetic ballooning mode for the CBC DIII-D parameters. The non-saturation is due to a lack of zonal flows and is known as the run-away/non-zonal-transition [1, 2], and the suppression of zonal flows stems from stochastic magnetic field produced by the turbulence.

In this work, we demonstrate a steady state of ITG turbulence at moderate-beta by global gyrokinetic simulations, and present its saturation mechanism by analysis of the nonlinear entropy/free-energy transfer [3]. The entropy transfer analysis in the toroidal mode number space shows that the ITG turbulence gets saturated by the interplay with zonal flows. The zonal flow excitation is not suppressed by the magnetic fluctuations, because the radial location of the entropy transfer to zonal flows avoids the peak of the magnetic fluctuations. The radial-shift of the entropy transfer is caused by the entropy advection in real space. The turbulent flow spreads the entropy of the ITG turbulence away from the peak of the magnetic fluctuations to the side of the peak. Thus, the radial turbulent convection of the entropy is the mechanism of the strong zonal-flow excitation in the global simulations. In addition, analysis of the entropy transfer in the wavenumber space shows that the ITG turbulence gets saturated by the interplay not only with the zonal flows but also with stable modes at low-n. Hence, these two global saturation mechanisms: the strong zonal-flow excitation by the turbulent advection of the entropy in the radial direction and the entropy transfer to low-n stable modes, are the saturation physics of the ITG turbulence at finite beta.

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Calculation of collisionless pitch-angle scattering of runaway electrons with synchrotron radiation via high-order guiding-center equation

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Recently, the collisionless pitch-angle scattering for the relativistic runaway electron (RE) in toroidal geometries such as tokamaks was discovered through a full orbit simulation approach[1], and then it was theoretically investigated that a new expression for the magnetic moment including the second-order corrections could essentially reproduce the so-called collisionless pitch-angle scattering process[2].

In this paper[3], with synchrotron radiation, extensive numerical verification of the validity of the high-order guiding-center theory is given for simulations involving runaway electrons by incorporating such an expression for the magnetic moment into our Particle Tracing Code (PTC), i.e. a high-order guiding-center simulation approach with synchrotron radiation(HGSA) is proposed. Synchrotron radiation plays an essential role in the life cycle of RE. The energy of RE first increases and then becomes saturation until the electric field acceleration is balanced by the radiation dissipation. Unfortunately the process cannot be simulated accurately with the standard guiding-center model, i.e. the first-order guiding center model. Remarkably, it is found that the HGSA can effectively produce the fundamental process of RE. Since the time scale of the energy saturation of RE is close to seconds, the computation cost becomes significant. In order to save the cost, it is necessary to estimate of the time of energy saturation. An analytical estimate is derived for the time it takes for synchrotron drag to balance an accelerating electric field and in certain test cases, the provided formula has been numerically verified. Test calculations reveal that HGSA is more favorable for exploiting dynamics of runaway electrons in tokamak plasmas.

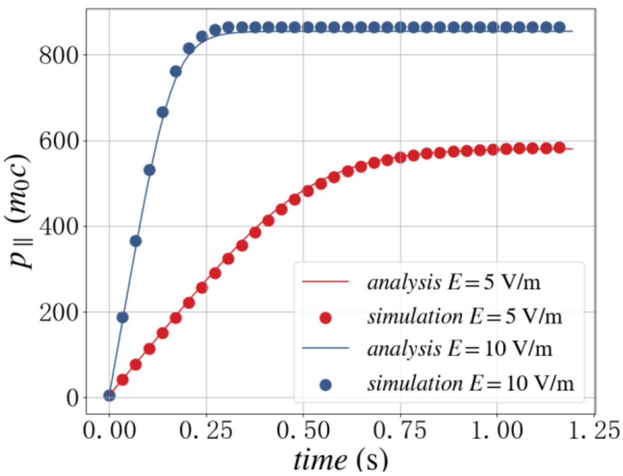

Figure. Evolution of the parallel momentum under simulations and analyzations

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Simulation Study of LHD Plasma Control Applying Data Assimilation System ASTI

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ASTI[1,2], a data assimilation system for integrated simulation of fusion plasma, is being developed to analyze, predict, and control the fusion plasma behavior. Data assimilation is a statistical estimation technique for the system state that connects simulation and observation. In the framework of data assimilation, we consider a state vector, which is a vector composed of variables representing the system state including model parameters, and treat it as a probabilistic distribution. Data assimilation optimizes the state vector to enhance the prediction capability and reproducibility of the employed system model based on the observation data. The integrated transport simulation code for helical fusion plasmas, TASK3D, is employed as the system model in ASTI. In our previous study, we have applied ASTI to some experimental data sets of the NBI-heated plasma in Large Helical Device (LHD) and investigated the validity of estimation and the prediction performance of ASTI. We have obtained good agreements in the radial profile and time evolution of density, electron temperature, and ion temperature with the experimental data sets.

In this study, we have developed a new data assimilation framework for predictive control. We construct a control algorithm for fusion plasmas using the data assimilation framework and implement it to ASTI. In the control algorithm, the control input parameters are estimated by assimilating the target states of plasma into the predicted state distribution, and the system model parameters with uncertainties are optimized by assimilating the observation results. The implemented control method keeps the prediction performance of the system model (TASK3D) and adjusts the control input parameters to achieve the target state. To investigate the effectiveness of the control method, we apply ASTI to control the virtual LHD plasma by TASK3D, assuming the appropriate transport models.

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Understanding subcritical turbulence in 3D Yukawa liquids using large scale Molecular Dynamics simulations

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Turbulence is an unsolved problem in fluid dynamics. There are two mechanisms for transition to turbulence, viz., “supercritical” and “subcritical” transition. A linearly unstable equilibrium, if perturbed infinitesimally beyond a certain critical Reynolds number, the system becomes turbulent and such transition to turbulence is called “supercritical” transition[2][3]. On the other hand, a linearly stable equilibrium also becomes turbulent, if perturbed with a finite amplitude non-linear 3D perturbation. Such transition to turbulence is called “subcritical” transition[1]. To study such subcritical transition to turbulence in a complex plasma system, we have considered a “3D” Yukawa liquid, which is simulated by using the “first principles” classical Molecular Dynamics (MD) simulation. To perform the study, we have developed a 3D MD code, called MPMD-3D [1] from the existing 2D version of the code, MPMD-2D. This code is available in both CPU and GPU parallel versions. For CPU parallelization, MPI is used to run the code across the nodes. A single GPU version of the code is developed using Open-ACC. Further, the MPI version is used to develop a multi-GPU version of the code, using both MPI and open-ACC. The multi-GPU version can run across the GPU nodes. The scaling data for 1586952 number of particles for both the MPI and the multi-GPU versions is shown in Fig.1 and it is found that the MPI version is faster than the multi-GPU version. The computations are performed using the CPU cores and P100 Tesla cards available in ANTYA cluster at IPR, Gandhinagar.

Using MPMD-3D, we demonstrate the subcritical transition to turbulence via spot formation. The spot structure [1] is shown in Fig.1. In this work we shall consider very large number of particles, and report on the performances of both the MPI and multi-GPU versions of the code and its implications on the physics of subcritical transition in 3D Yukawa liquids.

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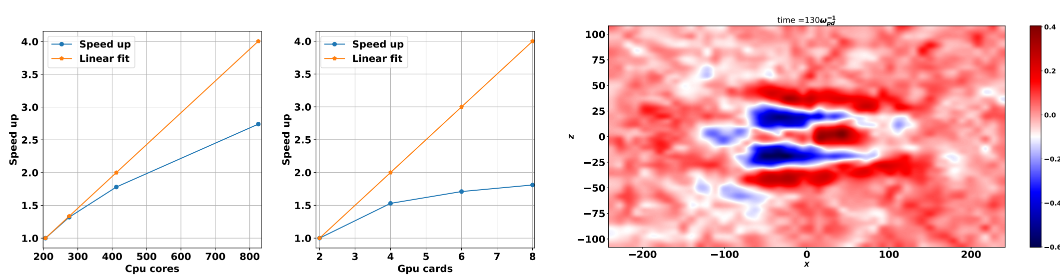

(a) (b) (c)

Figure 1: (a) Speed up diagram of the MPI version. (b) Speed up diagram of the multi-GPU version. (c) Spot structure in fluid V_x velocity field.

Poster Presentations

Poster Session (rev3.1: 1 August 2022)

#	Presenter	Title
P-1	M. Sengupta	Novel methods in device simulations of low temperature discharges and single-species plasma configurations
P-2	K. M. Verma	Scalable Multi-node Spectral Solvers on GPUs
P-3	B. S. Thapa	COMBINED EFFECT OF PHOTOELECTRIC AND THERMIONIC EMISSION ON DUST CHARGE FLUCTUATION AND ION ACOUSTIC WAVE PROPAGATION IN PLASMA
P-4	M. Honda	Multimodal convolutional neural networks for predicting evolution of gyrokinetic simulations
P-5	Mingqiang Li	RETRIEVING MAGNETIC FIELD STRUCTURE FROM MULTI-ENERGY PROTON RADIOGRAPHS USING CONVOLUTIONAL NEURAL NETWORK
P-6	T. Takizuka	Correction of Numerical Heating in Global Plasma Simulation with Particle-in-Cell Model
P-7	S. Biswas	Accuracy of a pseudo-spectral MHD solver over a grid based solver: A Comparative Study between GMHD3D code & PLUTO 4.4 code
P-8	Wenqiu Li	Numerical analysis of mode conversion characteristics of low-frequency waves in cold magnetized plasma
P-9	Jingwen Xu	Nonlinear Bidirectional Lumped-Circuit, Transmission Line and Particle-In-Cell Coupling Model
P-10	D. Gorasiya	A comparative study on denoising strategies for imaging diagnostics data from tokamak plasma experiments
P-11	S. Basnet	EFFECT OF NEGATIVELY BIASED ELECTRODE ON TWO ION SPECIES PLASMA SHEATH AND LEVITATION OF DUST PARTICLE
P-12	T. Shimizu	Linear Theory of Tearing Instability with Open Boundary Conditions
P-13	S. Baruah	SPONTANEOUS ORDERING IN LANE FORMATION DYNAMICS OF A 3D PAIR ION PLASMA
P-14	S. Chandra	Employing Symbolic Simulation technique to study the Evolution of Envelop Soliton and Associated Instability during Intense Laser Plasma Interaction
P-15	H. Miura	Growth of current tearing interchange mode under presence of two-fluid and gyro-viscous effects
P-16	Subhasish Bag	Numerical Simulations of the Expanding Magnetized Plasma in an ECR Thruster Experiment
P-17	J. Mahapatra	Role of in-plane and out-of-plane shear flow on island coalescence problem
P-18	Bo Li	Self-organized confinement in whole-plasma simulations of laboratory magnetospheres
P-19	Lei Chang	Numerical computations on the spatial non-uniformity and temporal evolution of helicon discharge
P-20	Youmei Wang	Cluster and pattern formation by charged grains under external central force and transverse magnetic field
P-21	A. Mukherjee	WAVE BREAKING FIELD OF RELATIVISTICALLY INTENSE ELECTROSTATIC WAVES IN ELECTRONEGATIVE PLASMA WITH SUPER-THERMAL ELECTRONS
P-22	R. A. Miranda	Spectral Entropy of Turbulence in Numerical Simulations of Astrophysical Plasmas, and Plasma Propulsion Devices
P-23	M. Shah	2D PIC-MCC simulations of instabilities in the magnetic filter region of low temperature plasma based negative ion sources: the effect of chamber walls
P-24	G. Barsagade	SIMULATION OF A NONLINEAR WHISTLER WAVE IN THE PLASMA
P-25	A. Paul	KINETIC PLASMA MODELLING, GPU PARALLELIZATION AND APPLICATION TO PHYSICS PROBLEM
P-26	A. Chugh	Large Scale Molecular Dynamics Study on Phase Dynamics of mixture of active and passive finite mass Yukawa particles

P-27	E. Rojas	Fluid simulations of Farley-Buneman instabilities: Model description and applications
P-28	Tong Liu	Prevention of unexpected explosive bursts during NTM control by ECCD for disruption avoidance
P-29	L. Zheng	ATEQ: Adaptive Toroidal EQuilibrium code and its applications
P-30	Hanzheng Li	Nonlinear magnetohydrodynamic effects on waveform distortion and plasma flow of off-axis fishbone instability in tokamak plasma
P-31	R. Seki	Simulations of fast-ion transport due to the Alfvén eigenmode burst in Large Helical Device
P-32	Jialei Wang	Self-consistent simulations of ICRF-induced Alfvén eigenmodes in toroidal plasmas
P-33	P. Adulsiriswad	HYBRID SIMULATION OF INTERACTION BETWEEN ENERGETIC PARTICLES AND MAGNETOHYDRODYNAMIC MODES IN THE JT-60SA INDUCTIVE SCENARIO
P-34	Wenhao Wang	Simulation of 2D electrostatic presheath potential in FRC SOL
P-35	J. Sakano	Gyrokinetic Simulation of Trapped Electron Mode in Ring Dipole Magnetic Configuration
P-36	F. A. L. Piragibe	Lagrangian Chaotic Mixing Due To Resistive Drift-Wave Turbulence In A Transition From Low-to-High Confinement In Fusion Plasmas
P-37	S. G. S. P. Costa	SPECTRAL ENTROPY OF RESISTIVE DRIFT-WAVE TURBULENCE IN A TRANSITION FROM LOW-TO-HIGH CONFINEMENT IN FUSION PLASMAS
P-38	M. Idouakass	Nonlinear Numerical Study of Energetic Particle Transport in ITER Plasmas and Comparison with Current DIII-D Results
P-39	N. Gupta	Ion Acoustic Decay Instability of Elliptical q-Gaussian Laser Beams in Plasma with Axial Density Ramp
P-40	O. Kamboj	Stimulated Raman Scattering Coupled with Decay Instability in a Magnetized Plasma with Hot Drifting Electrons
P-41	I. Khan	Effect of target front geometry in TNSA based ion acceleration
P-42	D. K. Kuri	Effect Of Laser Pulse Asymmetry On Harmonic Generation
P-43	T. Kotani	Simulation study of the harmonic structure of lower hybrid waves driven by energetic ions
P-44	A. Sahade	Magnetic Cages: a Key to Determining Whether a Flux Rope Will Erupt
P-45	M. Cécere	Sausage Modes Excitation In Coronal Loops
P-46	T. Sakaki	Feedback instability analysis of auroral growth in the dipole field configuration
P-47	J. Jansky	Numerical modeling of coplanar barrier discharge in air

Novel methods in device simulations of low temperature discharges and single-species plasma configurations

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(Dated: 17 April 2022)

A Particle-in-Cell (PIC) engine will symbiotically update mesh quantities such as plasma densities, fields etc., and advance the trajectories of computational super-particles, so that their combined evolution is the simulation of a physical plasma system.

My work so far, has specialized in the kinetic Particle-In-Cell (PIC) simulation of non-self-inductive electrostatic plasmas, motivated by open questions related to their equilibrium, waves, instabilities, turbulence and transport properties. I developed the PECXPIC package; a suite CPU-GPU parallelized, 1-3D Electrostatic Particle-in-Cell (PIC) – Monte-Carlo Collision (MCC) codes that can simulate diverse plasma configurations of laboratory experiments, plasma application devices, and space conditions.

PECXPIC is the acronym for **P**arallelized **E**lectrostatic **C**artesian '**X**'D (where X = 1, 2, or 3) **P**article-**I**n-**C**ell codes. The combination of a Cartesian mesh and an iterative Poisson solver gives these codes manoeuvrability for simulating in principle any device shape including cylindrical and toroidal geometries as well as irregular non-symmetric shapes. The same flexibility goes for electrodes, plasma sources, and spatial profiles of the loaded plasma in the simulation.

For a non-Cartesian orientation of the magnetic field vector the Cartesian particle-pusher in PECXPIC has an advanced adaptation that employs an intrinsic Cartesian transformation of the field vector at the particle's location, thus eliminating the need for a numerical approximation of the magnetic field function on the Cartesian mesh.

Device configurations that I have modelled using PECXPIC include the Hall thruster characterized by a radial inhomogeneous magnetic field[1], toroidal and partially toroidal magnetic traps having non-uniform angular magnetic fields[2–4], and linear devices that have straight uniform magnetic fields such as the cylindrical magnetron[5], the Penning discharge, and the Penning-Malmberg trap for single species plasma[6–10]. Some of these device simulations required the use of novel numerical algorithms. For example, designing a partially toroidal electrostatic-magnetic trap on the 3D mesh involved the use of numerical "pseduo-dielectric" layers to achieve the desired toroidal potential well in the trap's cavity and also isolate the biased and grounded segments of its boundary. Again, the 2D3V radial-azimuthal modelling of a Hall thruster employed an algorithm that produced a necessary virtual axial resistance for electron flow perpendicular to the simulation plane[1].

In a high level presentation I will cover these HPC and numerical aspects of my recent research activities.

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Scalable Multi-node Spectral Solvers on GPUs

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Spectral solvers are important for accurate simulations of fluid and plasma flows. However, these codes are very expensive due to intensive communication among the processors while executing *Fast Fourier Transform* (FFT) [1]. The new GPU hardware provide an efficient platform for such simulations. Fast communication via *NVSwitch* and *NVlink* have enhanced intra-node communication, thus improving the FFT efficiency significantly. Since FFT is a backbone of all spectral solvers and it takes 60-75% of the total time, we focus on making an efficient *GPU-FFT* solver. In this talk we will present the GPU implementation of our FFT and spectral solver.

Recently we created a CUDA-based multi-node GPU accelerated library for FFT (GPU-FFT) [2]. This is the first such open-source library. Here, we present scaling of our FFT library on *Selene* HPC system. We measure the *strong scaling exponent* γ and the *weak scaling exponent* γ' for a maximum grid size of 4096^3 using 512 A100 GPUs, where $T^{-1} \propto p^{\gamma}$ with T as the total time and p is the number of GPUs. For double precision (DP) R2C-C2R transforms, the strong scaling exponent, γ, for 4096^3 is 0.71. The weak scaling exponent, γ', is 0.9. We observe that 128 GPUs provide similar performance as 196608 cores of Cray XC40. Our GPU-FFT library is independent of CUDA versions and is backward compatible.

We have employed GPU-FFT library in our spectral solver. We are performing the scaling study of this solver. We will present these results in the conference. Ours is one of first multimode CUDA spectral solvers.

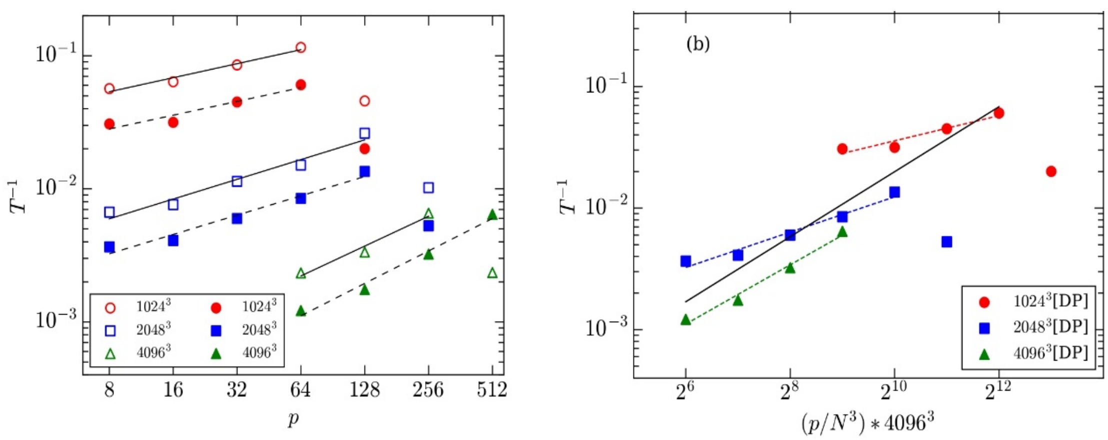

Figure 1. Strong (left) and weak scaling (right) of our GPU-FFT. The strong scaling exponent for 1024^3, 2048^3 and 4096^3 is 0.34, 0.48 and 0.71 respectively. While weak scaling exponent is 0.9. For all the figures we employ filled symbols for double precision (DP) and unfilled symbols for single precision (SP). Figure from Verma et al. [1].

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Combined effect of photoelectric and thermionic emission on dust charge fluctuation and ion acoustic wave propagation in plasma

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Abstract:

The study of dispersion relation of ion acoustic wave in ordinary plasma with dust particulates is carried out under the combined action of photoelectric and thermionic emission using kinetic theory. The dust charging process is a function of dusty plasma parameters which is significantly dominated by the secondary emission parameters such as photon flux and dust temperature. On the comparison scale, the dust temperature significantly dominates the charging parameters because of the Richardson-Dushman form of current. The dust charging coefficient corresponding to the thermionic emission is maximum and to that of ions is minimum. The mathematical analysis of dispersion relation of ion acoustic wave in dusty plasma with the modified acoustic wave velocity and charging rate is performed. The dust charge fluctuation as well as ion acoustic wave propagation is modified by the photoelectric and thermionic emission currents.

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Multimodal convolutional neural networks for predicting evolution of gyrokinetic simulations

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We have been developing a method to adequately reproduce the evolution of nonlinear gyrokinetic simulations for predicting the outcome at an early stage of the simulations with the power of deep learning techniques. A bunch of data produced by each simulation, which is hard to handle due to enormousness, is reduced to a limited amount in a manner to focus on the relatively important combination of the parameters in the wavenumber space and image the data. The series of images are fed into a convolutional neural network model, a class of artificial neural network, to make the model trained with the transfer learning and the fine tuning techniques utilized. The trained model can behave as a predictor of nonlinear gyrokinetic simulations and has shown its ability to precisely reproduce the progress of the simulations and to predict the saturation time from the limited amount of information [1,2]. A drawback of the previous models is a lack of the capability to predict the transport fluxes, especially the heat fluxes, which are the major purpose of performing nonlinear gyrokinetic simulations. This is due to the fact that the information on absolute values is lost by normalization when the data is visualized, and no inputs on them are fed into the model in the first place.

This shortcoming can be compensated for by extending the model to a multimodal model, which handles multiple kinds of input, i.e., modality, at once. Specifically, in this context the multimodal model should be developed to digest both the images from which the patterns of turbulence are to be detected and the numeric text data including the absolute values of what are associated with the intensity of turbulence or, more directly, the fluxes.

The developed multimodal model reads the images that include the cross-phase information between the pressure and the electrostatic potential fluctuations and the numeric data of the amplitudes of the pressure and potential fluctuations. Despite the very limited number of training, validation and test data, say, 155, 45 and 23, in the Cyclone base case simulation result, the model showed the high determination coefficients for the test data for predictions of the simulation time, electron and ion heat fluxes as $R^2 = 0.97$, 0.96 and 0.96, respectively.

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Retrieving magnetic field structure from multi-energy proton radiographs using convolutional neural network

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Proton radiography is a widely used diagnostic technique for high energy density (HED) plasma and is particularly useful to resolve the magnetic field structures in many interesting laser-plasma experiments. Several methods have been developed to obtain the line-integrated transverse magnetic field under many simplifying assumptions. However, the direct inversion of three-dimensional magnetic fields and the interpretation of the nonlinear regions of the proton radiographs, known as caustics, are still challenging tasks. In this paper, we present a new method to reconstruct 3D magnetic field structures in linear and nonlinear regions based on the convolutional neural network (CNN) and proton radiographs of different energies. We benchmarked the method using a Gaussian-like toroidal magnetic field as the object at various parameters. It is shown that our method is superior to the well-known feedforward neural network (FNN) in terms of accuracy and efficiency, even for small training data sets. We also demonstrate that the method can reliably retrieve the magnetic field for the linear, nonlinear, and caustic regions with a mean relative error of less than 10% and is robust for noise to the input proton radiographs.

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Correction of Numerical Heating in Global Plasma Simulation with Particle-in-Cell Model

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The numerical simulation is a powerful tool to understand underlying physics in experimental observations for various fields of plasma science, and to predict plasma natures in future experiments. The global plasma simulation is especially important for fusion plasma research. Particle-in-cell (PIC) modeling is suitable to correctly simulate the kinetic effect, which plays sometimes an essential role in the transport of fusion plasma. Electron dynamics are traced also in the PIC model. Mesh-size and time-step problems in the global plasma simulation can be overcome by introducing the "ingenious" model [1]. One of remained problems in the PIC simulation is the numerical heating. Because the electric field $\boldsymbol{E}$ is calculated self-consistently at discretized grid points, the nonphysical aliases of $\boldsymbol{E}$ arise inside a cell off a grid point. This aliasing $\boldsymbol{E}$ noise suffers the electron velocity parallel to the magnetic field $\boldsymbol{B}$, and causes the numerical heating in the parallel component of electron energy. Major source of the numerical-heating field is of the short-wavelength statistical fluctuation, whose amplitude is in inverse proportion to $N_{cell}^{1/2}$ (N_{cell}: super-particle number in a cell). Resultant numerical heating rate becomes $\mathrm{d}\ln T_e/\mathrm{d}t \sim f_A^2/N_{cell}\Delta t$ (Δt: time step) [2,3]. The aliasing factor f_A can be ~0.1 for the linear-shape PIC, and can be reduced to ~0.01 for the higher-order shaping [4].

In spite of the large numerical heating risk, it is convenient to save $N_{cell} \sim 100$ for the reasonable computation cost of multi-dimensional simulation [1]. Further reduction of N_{cell} is desirable in the pre-simulation to obtain an initial equilibrium state [5]. Therefore we propose here a method to correct the numerical heating without applying especially the higher-order shaping. Correction procedures for every time step are as follows: (i) Simply smoothed electric field parallel to $\boldsymbol{B}$ is calculated at a grid point j, $\langle \boldsymbol{E}_{\parallel}^{j} \rangle = (\boldsymbol{E}_{\parallel}^{j+1} + 2\boldsymbol{E}_{\parallel}^{j} + \boldsymbol{E}_{\parallel}^{j-1})/4$. The shortest-wavelength fluctuation is fully eliminated. (ii) Each electron velocity $\boldsymbol{V}(t)$ is advanced to $\boldsymbol{V}_{*}(t+\Delta t)$ with the original $\boldsymbol{E}$. The perpendicular component is determined, $\boldsymbol{V}_{\perp} = \boldsymbol{V}_{*\perp}$, at this step. (iii) Each electron velocity $\boldsymbol{V}_{\parallel}(t)$ parallel to $\boldsymbol{B}$ is advanced to $\boldsymbol{V}_{\#\parallel}(t+\Delta t)$ with the smoothed $\langle \boldsymbol{E}_{\parallel} \rangle$. (iv) Input and output powers in the total system are counted. Physical heating power P_{in} should be accurately evaluated. Numerical heating powers, $P_N^{(ii)}$ and $P_N^{(iii)}$, are calculated for the original $\boldsymbol{E}$ step and for the smoothed $\langle \boldsymbol{E}_{\parallel} \rangle$ step, respectively. (iv) Finally the parallel electron energy is cooled as $\boldsymbol{V}_{\parallel}^2 = \boldsymbol{V}_{*\parallel}^2 - (\boldsymbol{V}_{*\parallel}^2 - \boldsymbol{V}_{\#\parallel}^2)\, P_N^{(ii)}/(P_N^{(ii)} - P_N^{(iii)})$, so that the total excess energy due to numerical heating is fully removed in the entire system.

This correction method will be applied and tested during our development of the PIXY code [6] in the near future.

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Accuracy of a pseudo-spectral MHD solver over a grid based solver: A Comparative Study between GMHD3D code & PLUTO 4.4 code

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The theories of HydroDynamics (HD) and MagnetoHydroDynamics (MHD) are often used to analyze the HD turbulence [**1**] and magnetized plasma turbulence respectively, which are fundamental to our understanding of the behaviour of astro-plasma present in the Sun or other young stars, physics of magnetic reconnection as well as for the careful operation of complicated fusion reactors, for example Stellarators or Tokamaks [**2**]. To address these complex plasma phenomenon in astrophysical bodies as well as in laboratory scenarios, we have recently upgraded a three dimensional compressible single GPU MHD solver (G-MHD3D) to multi-node, multi-card GPU architecture using OpenAcc & MPI, in-house at Institute for Plasma Research, India and achieved substantial speed up across 32 P100 GPU cards⋆ [**Figure: 1 (a)**] [**3**]. Using this code, in a recent series of publications, novel MHD phenomena such as recurrence [**4**] of an initial MHD state [**Figure: 1 (c)**], nonlinear oscillations with linear Alfven dispersion [**4**] has been bench-marked [**Figure: 1 (b)**].

In this present work, we have used PLUTO4.4 [**5**] code to investigate several of the above said phenomena and have made a quantitative comparison of the results with those of GMHD3D code [**Figure: 1**]. It is observed that the pseudo-spectral solver GMHD3D is more superior than the grid based solver PLUTO4.4 for the above said physics issues [**6**]. The details of this comparative study will be presented.

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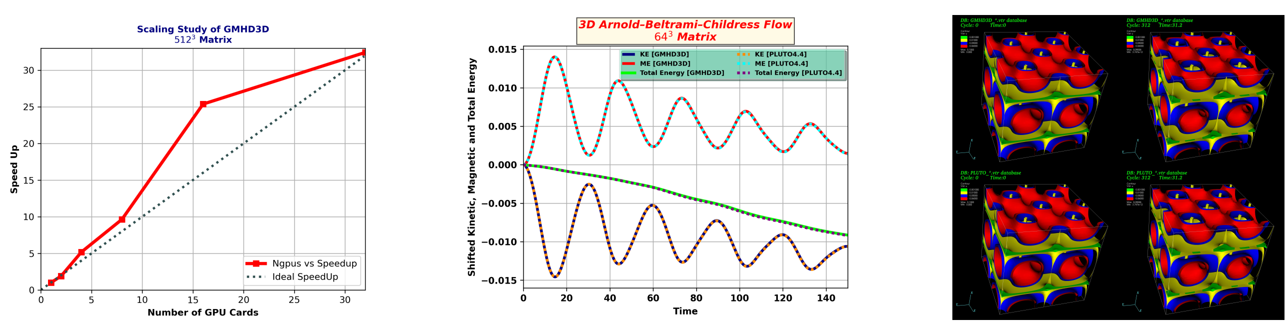

(a) (b) (c)

Figure 1: (a) Scaling study of GMHD3D code (b) Comparison between GMHD3D code and PLUTO 4.4 code for coherent non-linear oscillation problem. (c) Recurring TG flow from GMHD3D [Top row] and PLUTO4.4 [Bottom row].

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⋆Work presented here on P100 GPU cards were performed on HPC ANTYA at IPR.

Numerical analysis of mode conversion characteristics of low-frequency waves in cold magnetized plasma

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We are here to present a novel compound algorithm based method to analyze the mode conversion characteristics for low-frequency waves in cold magnetized plasma. By employing the low frequency dispersion relation (LFDR) [1], here an example solution is given under certain parameter in this paper.

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Nonlinear Bidirectional Lumped-Circuit, Transmission Line and Particle-In-Cell Coupling Model

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It is well known that the lumped-element model (LEM), distributed-element or transmission line model (TLM) and electromagnetic model are three models for electromagnetic phenomena. Each model has its own range of applications. TL models have been widely used in studying the electrostatic effects in large-area high frequency CCPs, often coupled with a global discharge model. Meanwhile, in the design of high-frequency electrode-driven plasma, the full-circuit simulation model is of high importance. Verboncoeur et al.[1] proposed to couple the PIC with an external RLC circuit. However, to the best of our knowledge there are no published studies involving this plasma-TLs-LEM coupled system due to the high complexity. In this work, a numerical scheme of TLM based on the Lax-Wendroff method was developed and the nonlinear bidirectional coupling, which among the LEM, TL model and electrostatic particle-in cell (PIC) model was realized. Stability and Accuracy have been analyzed and the numerical results were compared with the analytical ones[2]. Taking capacitively coupled plasma (CCPs) as an example, we stimulate the effects of the coaxial cable external circuit on the plasma. Three typical discharge modes are found: weak matching state, normal state and over-matching state[3,4,5]. The method can be extended without any difficulties to the numerical simulation of other plasma sources, such as Z-pinch[5].

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A comparative study on denoising strategies for imaging diagnostics data from tokamak plasma experiments

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Imaging diagnostics, which offers information about the tokamak plasma edge as well as the plasma interior, facilitates the realization of plasma shape and position, impurity distribution, and Magneto-hydrodynamics (MHD) instabilities. The tomographic reconstruction is one of the powerful tools to analyze imaging diagnostic data [1]. The imaging diagnostic, especially in the visible band, is contaminated with noises with a wide variety of origins. Hence, denoising these images relaxes the computational expenses for the tomographic reconstructions and the edge detection algorithms. In this work, we compare the performance of six different Machine-Learning based techniques (FFDNet, REDNet, MWCNN, PRIDNet, CBDNet and DnCNN) and three conventional denoising methodologies (mean, Gaussian, bilateral and Wiener filtering). ML-based methods are trained using a synthetic dataset containing a variety of images where stochastic noises of different distributions have been added [2]. Denoising is performed on a simulated noisy image of the circular tokamak plasma, in the visible range, for tangential viewing geometry. The denoising quality is observed as a function of noise magnitude. The PSNR and SSIM values are estimated for each denoising attempt as shown in Table 1. The comparison suggests that the ML-based method, MWCNN, shows promising results across different noise values while showing impressive PSNR and SSIM values (53.9 and .99 respectively). It is also observed that the ML models show poor results when the training data is not sufficient. Therefore, unlike conventional denoising methodologies, for desirable results, we need substantial diverse training data for satisfactory results. However, our results show that ML-based denoising methods perform better than widely used conventional methodologies and open up many possibilities for research requiring denoising as a precursor for plasma imaging-based diagnostics.

	FFDNet	REDNet	CBDNet	DnCNN	PRIDNet	MWCNN
PSNR	18.40	27.04	35.87	44.65	47.05	53.89
SSIM	0.7493	0.4279	0.8472	0.9568	0.9800	0.9988

Table 1: PSNR and SSIM of a given model is an average of 10 different plasma test images, which contains mixed Gaussian noise, Possian noise and Salt & Pepper noise.

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Effect of negatively biased electrode on two ion species plasma sheath and levitation of dust particle

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ABSTRACT

Using the kinetic theory, the effect of a negatively biased electrode on two ion species magnetized plasma-wall transition properties and the levitation of an isolated dust particle in the sheath region has been investigated. The plasma-wall transition characteristics: space charge density, sheath potential, phase-space evolution, and particle flux towards the electrode are found to be affected by electrode biasing. The presence of magnetic field and electrode biasing significantly affects the scale length of the Debye sheath region. The dust charging, magnitude of ion drag force, and levitation of charged dust grains in the transition region depend on the biasing voltage and size of the grains. The dust particle acquires a negative charge at the particle injection boundary and becomes positively charged close to the electrode due to electron depletion in the sheath region. The stable levitation distance from the electrode gets increased with the increase in negative voltage applied to the electrode. In addition, the concentration of xenon ions influences the dust charging process with the negative charge of the dust particle increasing as the concentration of xenon ions increases.

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Linear Theory of Tearing Instability with Open Boundary Conditions

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Tearing instability is an instability of a current sheet driven by magnetic reconnection process. Linear MHD study of the tearing instability has more than 60 years history and still now being studied, which was originated in Furth, Killeen and Rosenbluth, Phys. Fluids 1963 (FKR1963). The most essential and difficult problem to solve the theory will be that it is not easy to establish the exact equilibrium to start to solve the linear theory, from which the instability grows. For example, the equilibrium assumed in FKR1963 is exactly satisfied only in ideal-MHD limit but is not in resistive-MHD, because of the null-flow field. At this point, we are interested in the resistive-MHD. Because, in the ideal-MHD, the instability does not occur. Assuming a non-zero flow field, Loureiro (Loureiro, Schekochihin and Cowley, Phys. Plasmas 2007 (LSC2007)) drastically improved the equilibrium which is exactly satisfied in resistive-MHD. Furthermore, Shimizu improved the numerical procedures to solve the perturbation equation derived in LSC2007 and found that the perturbation equation has physically acceptable solutions even in ideal-MHD limit, i.e., zero-resistivity limit. In other words, Shimizu showed how the linear stage of tearing instability can occur in ideal-MHD limit [1]. Note that the ideal-MHD limit (η ==> 0) is different from ideal-MHD (η =0). Most previous studies including FKR1963 and LSC2007 tried to find the perturbation solution (i.e., ϕ and Ψ) which converges to zero at the infinity point of the upstream but the Shimizu's procedure is executed by assuming a kind of open boundary condition in a finite point of upstream, e.g., which are called zero-crossing solution and zero-contact solution. In this presentation, the viscosity effect is newly introduced in the LSC theory improved by Shimizu, where some varaitions of the open boundary conditions for upstream and also downstream are discussed for the applications of the MHD simulations. Finally, the perturbation solution which converges to zero at the infinity point can be deduced from the open boundary solutions.

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Spontaneous ordering in Lane formation dynamics of a 3D Pair-ion plasma

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Lane formation [1, 2] dynamics is investigated under the influence of external electric field in 3D strongly coupled pair-ion plasma (PIP) [1, 2, 3] system using Langevin dynamics (LD) simulation. The study is based on a plasma model where the ion-ion interaction is described with a screened electrostatic potential characterized by a screening parameter, and the ion-neutral background interaction is described using an overall friction force characterized by a damping factor and a zero-average stochastic collisional term that enables describing the diffusion effect. In our model, positively charged PIP particles are pulled by an external force $\overrightarrow{F_A}$ while the negatively charged particles are pulled by an external force $\overrightarrow{F_B}$. If $\overrightarrow{F_A}$ and $\overrightarrow{F_B}$ are perpendicular, as shown in Figure 1, lane formation is observed with an orientation tilted with respect to the external forces. Our setup of perpendicular external fields are realized by two crossing pedestrian lanes in which pedestrians move in only one direction. To detect the phase transition phenomena the instantaneous order parameter [1, 2, 3] and order parameter with gradient of angle of inclination ($\boldsymbol{\theta}$) are measure to monitor the influence of both constant and time varying external forces. Our study reveals that if one of the forces is time varying in nature, a periodic oscillation of the angle of inclination is observed. If both forces are oscillating with same frequency, the oscillation in the angle of inclination disappears and spontaneous formation and breaking of lanes is observed. However, in presence of forces with different oscillating frequencies flipping of lane inclination between positive and negative domain of $\boldsymbol{\theta}$ is observed. In this work, several of the above said results will be discussed in detail.

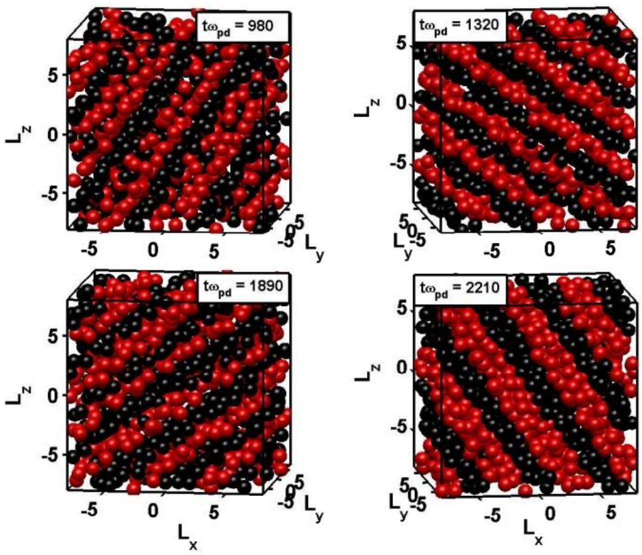

Figure 1: Typical snapshots of the 3D PIP system with perpendicular external fields show lane formation with tilted orientation.

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Employing Symbolic Simulation technique to study the Evolution of Envelop Soliton and Associated Instability during Intense Laser Plasma Interaction

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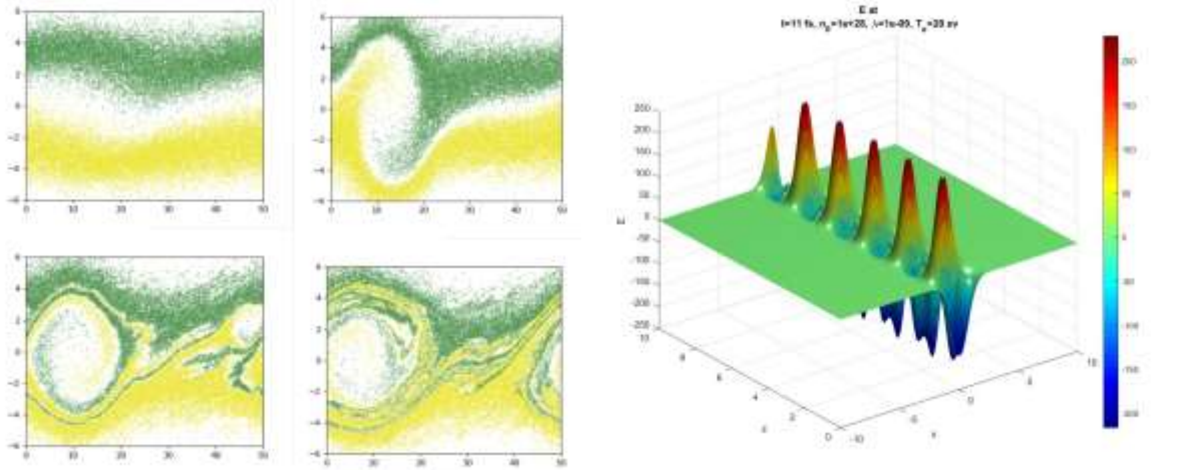
We investigated amplitude modulation and the development of envelop soliton in a quantum plasma with relativistic degeneracy pressure expressions as a powerful laser beam falls on it in this paper. We concentrated our research on the interaction of an intense laser with plasma, and we developed a novel topological formulation of issues involving a set of coupled differential equations. To arrive at the dispersion relation, we first solved the equations. We looked at phase plots using a PIC simulation and found Kelvin Helmholtz type instabilities. To learn more about the evolution of density, electric field, velocity streamlines, and subsequent amplitude modulation with various forms of nonlinearity, we used the homotopy perturbation approach. We determined the range of plasma and laser settings where nonlinearity is significant. The findings will aid in deciphering many phenomena that emerge in laser plasma interaction and plasma astrophysics, where shocks, solitons, and other phenomena in dense hot plasma may be examined at laboratory scales. The evolution of the envelop is represented in the picture below, which was created using PIC simulation and our unique Homotopy assisted Symbolic Simulation (HASS) [1-5] approach.



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Growth of current tearing interchange mode under presence of two-fluid and gyro-viscous effects

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We study a growth of Current Interchange Tearing Modes (CITM) by means of numerical simulations of extended magnetohydrodynamic simulations. The CITM has been proposed to explain an intermittent eruption of electric current toward a divertor at an edge region of a tokamak device[1,2]. We have developed a numerical model, the Scrape-Off-Layer (SOL) diffusion model, to enforce effects of plasma current being saturated in a low level outside the Last Closed Flux Surface (LCFS) (this is necessary for CITM) and verified a growth of CITM in our earlier work[3]. In this presentation we extend our numerical simulations to include some of edge plasma physics such as two-fluid effects and gyro-viscous effects.

Our numerical simulations are carried out two-dimension three-component version of the MUTSU/MINOS code which has been developed originally for simulations of instability of the Large Helical Device[4,5]. This numerical study shows that a CITM can grow under a presence of these non-ideal MHD effects. Numerical simulations with an azimuthal flow, which is a simplified model for an externally-driven flow, show that a CITM can grow even under the presence of such a flow effect, unless the externally-driven flow causes a large displacement due to the radial electric field formation associated with the flow. The results show that a CITM can be a candidate mechanism of the intermittent eruption of the current in a tokamak whether the growth is under influences of the non-ideal MHD effects or not.

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Numerical Simulations of the Expanding Magnetized Plasma in an ECR Thruster Experiment

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Magnetized plasma expansion is of great interest for advanced research in the field of electric propulsion system. Due to operational longevity and high fuel efficiency, the electrodeless plasma thrusters based on electric propulsion are far more efficient than chemical thrusters for deep space mission. Instead of a solid nozzle, a Magnetic Nozzle(MN) [1] is used to expand magnetized plasma in this system. The convergent-divergent magnetic field of the magnetic nozzle helps to convert the internal thermal energy of electrons into the directed kinetic energy of the ions. We are interested to model the expanding plasma coming out of a Compact ECR Plasma Souce (CEPS) [2] developed by Plasma Physics Laboratory (PPL), IIT Delhi. We numerically study the thrust generation mechanism for the experimental magnetic field configuration [3] in order to understand the experimental observations.

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Role of in-plane and out-of-plane shear flow on island coalescence problem

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Magnetic flux tubes are frequently observed in many plasma environment that include different astrophysical environments as well as laboratory experiments and depending on their plasma parameter, the size of flux tubes are also ranges from kinetic scale to global scale length. From different experimental, space observations, it has been understood that the interacting flux tubes are responsible for current sheet formation and magnetic reconnection that causes many eruptive/energetic events [1]. Hence, accurate numerical simulation on these interacting 3D and(or) 2D flux tubes are important for better understanding of these phenomena. In 2D, the flux tube interaction or magnetic island coalescence problem and the role of various plasma parameters on it such as guide field, asymmetric density, temperature, magnetic field, collisionality, etc. has been studies extensively using various single-fluid/two-fluid MHD, hybrid and kinetic or PIC models. One of such important parameter is shear flow, and are frequently observed in almost all the plasma environments with a wide range of flow parameters, ranging from sub-Alfvenic to super-Alfvenic scale. Effect of shear flows on island coalescence problem has been studied recently by numerical simulation using an incompressible resistive MHD model [2]. The study shows a significant change in reconnection parameters reasonably due to MHD-Kelvin-Helmholtz instability. The overall evolution of magnetic islands is also found to be severely affected [3].

A crucial question, which could be particularly important in the presence of shear flows, is the role of compressibility on the reconnection rate and related dynamics in the island coalescence. This problem is also numerically challenging. Using a fully compressible MHD code MPI-AMRVAC [4], here we report on the compressibility effects of in-plane and our-of-plane shear flow on magnetic island coalescence problem using large initial numerical grid sizes which are successively refined by AMR technique. Due to accurate numerical schemes used in MPI-AMRVAC, we have shown that it is possible to investigate the properties of microscale current sheet and other reconnection parameters. We show that the dynamics gets severely affected by super-sonic/super-Alfvenic shear flows via compressibility. Physics and numerical details of this work will be presented.

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Self-organized confinement in whole-plasma simulations of laboratory magnetospheres

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Turbulent self-organization driven by global ideal interchange modes in a dipole-confined plasma is explored with self-consistent, whole-plasma simulations using a flux-tube averaged magnetohydrodynamic model in dipole magnetic geometry [1]. We show the existence of robust particle pinch driven by ideal interchange-mode fluctuations, in which the particles are transported up the density gradient. It is found that the plasma profiles in a dipole field spontaneously relax to a marginally stable state as centrally peaked pressure and density are created by global interchange-mode transport.

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Numerical computations on the spatial non-uniformity and temporal evolution of helicon discharge

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To reveal the underlying physics of helicon discharge, numerical computations are carried out first through EMS (electromagnetic solver) and HELIC, focusing on the spatial non-uniformity, in terms of wave propagation, power deposition and impedance response; then using COMSOL Multiphysics, focusing on the temporal evolution, in terms of electron density and temperature. Several interesting findings are obtained, including for the first time the role of second-order radial density gradient, the relative superiority between parabolic and Gaussian density profiles in radius for power deposition, the spectral gap and gap eigenmode with axially periodic field, the anti-parallel wave propagation, the wave-guide feature of bright-core helicon plasma, and the opposite evolutions of density and temperature with time [1-8]. Ideas for future research are also suggested near the end of this presentation [9]. Figure 1 shows typical results.

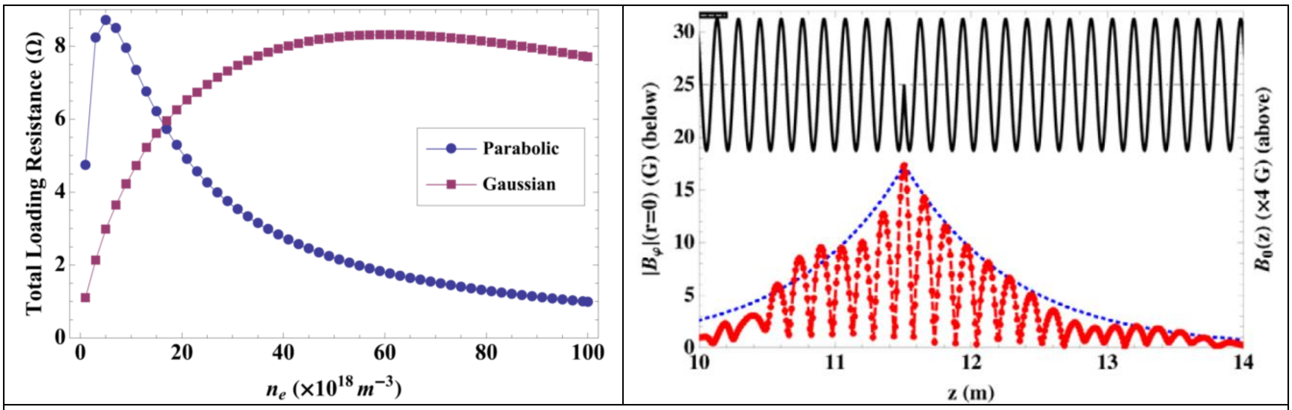

Fig. 1 Typical results of helicon plasma computations: (left) comparison between parabolic and Gaussian density profiles, (right) gap eigenmode of helicon wave.

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Cluster and pattern formation by charged grains under external central force and transverse magnetic field

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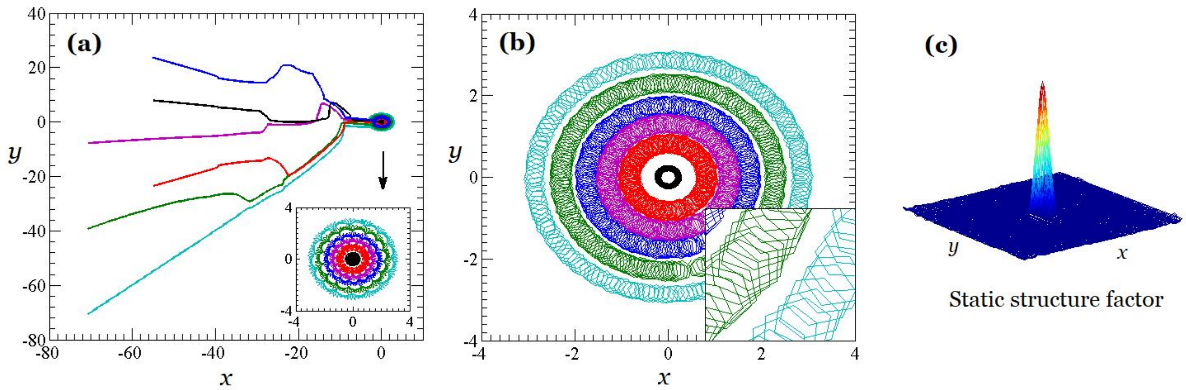
The process of cluster and pattern formation by a layer of charged grains in plasma under an external central force $\boldsymbol{F}_{ext} = -\gamma \boldsymbol{r}_i$, where $\boldsymbol{r}_i = x_i\hat{\boldsymbol{x}} + y_i\hat{\boldsymbol{y}}$, transverse magnetic field $\boldsymbol{B} = B\hat{\boldsymbol{z}}$, and a modified-Yukawa grain-grain interaction force $U_{\text{int}}(r_{ij}) = \frac{q^2}{r_{ij}}\left[\exp\left(-\frac{r_{ij}}{\lambda_d}\right) - \alpha\right]$, where r_{ij} is the distance between the grains i and j, q is the grain charge, λ_d is the background-plasma Debye length, and α (~1) is a parameter governing the attraction range of the interaction, is investigated using *molecular dynamics simulation* [1]. It is found that initially uniform-distributed Maxwellian grains tend to form small clusters that eventually aggregate into a single crystal-like disk cluster. The grain trajectories in the asymptotic quasi-stationary state of the disk cluster can be in the form of flowery spiral zonal patterns, as shown below.



(Color online.) For α=0.5, γ=0.0005, and B=0.002. (a) trajectories of typical grains during the evolution for 0<t<213600. The kinks are due to formation of metastable clusters that eventually combine into the asymptotic quasistationary state (t>213600) disk cluster shown in the inset, (b) for the intermediate stage 1140000<t<1171500, and (c) the structure factor of the asymptotic disk cluster. All parameters are normalized [1].

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Wave breaking field of relativistically intense electrostatic waves in electronegative plasma with super-thermal electrons

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The wave breaking limit of relativistically intense electrostatic waves in an unamgnetised electronegative plasma, where electrons are alleged to attach onto neutral atoms or molecules and thus forming a significant amount of negative ions, has been studied analytically. A nonlinear theory has been developed, using one-dimensional (1D) relativistic multi-fluid model in order to study the roles of super-thermal electrons, negative ion species and the Lorentz factor, on the dynamics of the wave. A generalized kappa-type distribution function has been chosen for the velocities of the electrons, to couple the densities of the fluids. By assuming the traveling wave solution, the equation of motion for the evolution of the wave in a stationary wave frame has been derived and numerical solutions have been presented. Studies have been further extended, using standard Sagdeev-pseudopotential method, to discover the maximum electric field amplitude sustained by these waves. The dependence of wave breaking limit on the different input parameters such as the Lorentz factor, electron temperature, spectral index of the electron velocity distribution and on the fraction and the mass ratio of the negative to positive ion species has been shown explicitly. The wavelength of these waves has been calculated for a wide range of input parameters and its dependence on aforementioned plasma parameters have been studied in detail. These results are relevant to understand particle acceleration and relativistic wave breaking phenomena in high intensity laser plasma experiments and space environments where the secondary ion species and super-thermal electrons exist.

Spectral entropy of turbulence in numerical simulations of astrophysical plasmas, and plasma propulsion devices

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Observational studies show that rare, large-amplitude coherent structures in turbulent plasmas are responsible for non-Gaussian fluctuations [1], multifractality [2], synchronization among scales [3], low entropy and high complexity [4]. We demonstrate the role of coherent structures detected by in-situ experiments in the interplanetary magnetic field turbulence. Then, we describe numerical simulations of magnetohydrodynamic turbulence in a Keplerian shear flow, in a regime of on-off intermittency [5]. By computing the Shannon entropy in the spectral space we show that large-scale coherent structures are characterized by low values of the spectral entropy. We will also present particle-in-cell numerical simulations of a two-dimensional model of a plasma propulsion device known as the Hall thruster. We demonstrate that the plasma in a Hall thruster displays turbulence and coherent structures arising from the ExB electron drift instability, which can affect the thruster efficiency.

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2D PIC-MCC simulations of instabilities in the magnetic filter region of low temperature plasma based negative ion sources: the effect of chamber walls

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A negative ion source is used in a neutral beam injection system in an ITER type nuclear fusion reactor. Considering plasma production, transport, and ion beam extraction, a negative ion source geometry can be divided into following sections: a driver, an expansion chamber, a magnetic filter, and an ion beam extraction system consisting of 3 grids. The Gaussian-shaped magnetic filter, perpendicular to the plasma flow is present between the expansion and extraction region, which controls the plasma flux moving towards the extraction side and virtually divides the plasma into relatively hot and cold region. A bias voltage (~ plasmas potential) is applied on the plasma facing grid with respect to the ion source chamber wall to control/reduce co-extracted electrons with negative ion beam. Understanding plasma transport in a negative ion source is a difficult task in presence of complex magnetic field configuration, which excites different drifts and instabilities and leads to anomalous plasma transport. We have used 2D-3V Particle-In-Cell Monte Carlo Collision (PIC-MCC) model to study background plasma transport across the magnetic filter using actual ROBIN (RF operated beam source in India) experimental conditions. The code is validated with experimental results. 2D simulations are carried using important hydrogen chemistry (ionization, elastic, and inelastic collisions considered) using a rectangular geometry as shown in Fig. 1. Previously, we have identified two kinds of instabilities, one at 10^5 Hz and the other at 10^6 Hz, using 2D simulations with periodic boundary conditions [2]. The 10^5 Hz frequency is recognized as E×B drift instability. In this work, we perform more realistic PIC-MCC simulations to report the effect of chamber walls on these instabilities using non-periodic boundary conditions. The plasma profiles are significantly different compared to periodic boundary conditions. We observe instabilities and asymmetry in the plasma profiles as seen in Fig. 2(ii). We have analyzed these instabilities using Fast Fourier Transform (FFT). Multiple frequencies are found between 10^5 Hz to 10^6 Hz, and one at 10^8 Hz. The frequency of fluctuations varies in space and also while changing magnetic field and bias voltage (voltage given to the boundary plate near the extraction side of negative ion source, plasma grid surface). We analyze in details the difference in the observed instabilities between the periodic and non-periodic case.

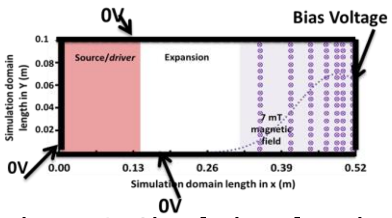

Figure 1. Simulation domain used in 2D-3V PIC-MCC simulations.

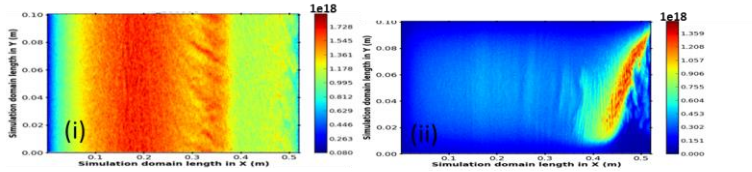

Figure 2. Snapshots of plasma density (m-3) at 24 µs using 2D-3V PIC-MCC model with 7 mT and 20 V bias voltage. (i) without wall and (ii) with wall.

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Simulation of a nonlinear whistler wave in the plasma

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The electromagnetic fluctuations in the magnetized plasma occupy the high frequency regime of the turbulence responsible for its dissipation. The mechanism underlying this process remains matter of investigation both space and large volume laboratory plasma setups. The route to transfer of energy to particles largely by kinetic mechanism is quasi-electrostatic [1]. The coexcitation of electrostatic fluctuations is observed in both linear and nonlinear regimes of the electron magnetohydrodynamic (EMHD) excitations (below electron cyclotron frequency) indicating that these modes may be largely decoupled [2]. The numerical studies are made of the electron-magnetohydrodynamic excitation in both linear and nonlinear regimes by their long-time evolution, showing that the dispersion characteristics of large amplitude nonlinear waves varies significantly only in their quasi-longitudinal propagation. For the parameters of large volume laboratory plasma setups, the relatively stronger coexisted electrostatic fluctuations are however found to be spectrally well separated from the EMHD excitations and significantly larger in the amplitude in comparison to the electrostatic field associated with the quasi-longitudinal EMHD perturbations, confirming their mutual decoupling. The Flux-corrected transport scheme [3] is used for the electron fluid equations in conjunction with forward-time and central-spatial difference for the Maxwell equations. Computations are performed on a high-performance computing cluster in order to simulate the long-time evolution with enough time and space resolution as essential for spectrally well separated electrostatic and EMHD fluctuations in the laboratory plasma regime.

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Kinetic plasma modelling, GPU parallelization and application to physics problem

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Theoretical study of high temperature space and laboratory plasmas require kinetic theory or simulations. First principle particle simulations are often the best tool for the processes involving energetic or long tailed distributions such that achieving statistical accuracy is computationally expensive. One of the numerical limitations concerns remains the resolution of the lowest frequency which roughly scales with the inverse of the execution time of the computational procedure [1] . In the recently developed solution procedure this limitation is overcome by a mode-wise resolved computation where adequate resolution is achieved in a single time-period long execution of the procedure for an electromagnetic excitation of hot nonthermal magnetized plasma [2]. The phase flux balance based vlasov simulation procedure [3,4] is benchmarked against the cold plasma dispersion relation as well as the standard kinetic results with thermal corrections. An improved numerical procedure achieves considerable numerical acceleration by employing an OpenACC based GPU implementation efficiency of which is systematically characterized with respect to the number of basic computing units. Optimization of the application has involved using CUDA/11.1.1 with Pascal 100 GPU.

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Large Scale Molecular Dynamics Study on Phase Dynamics of mixture of active and passive finite mass Yukawa particles

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Active matter is one of the most explosively evolving areas in non-equilibrium statistical mechanics[1]. Active matter consists of self propelled particles which are inherently out of equilibrium in nature owing to its ability to exchange energy with its local environment. This system is known to exhibit a collective phenomenon called Motility Induced Phase Separation or MIPS[2], where particles segregate into dense and dilute phases and these phases coexist together. However, in practice, the active and passive matter co-exist. This motivates us to study the mixture of active and passive particles and the onset of MIPS. One recent study[3] on mixture of overdamped active and passive particles with hard core interaction shows that even if the fraction of active particles is as small as 15 percent, MIPS can be observed.

Synthetic active matter such as Active Complex Plasmas with Janus particles[4], often realized in laboratory, are characterised by coupling parameter and screening parameter. In such systems, inertia cannot be neglected and interaction among the particles can be tuned from short to long range depending upon the screening parameter[5]. In our study, we investigate the role of inertia and screening parameter on the collective phenomenon of the mixtures of active and passive particles. For a fully segregated initial configuration, hard core passive particles bunch together and are surrounded by active particles which trigger crystallization of the passive core by initiating a compression wave. It is found that passive particles detrap quickly when the screening parameter is reduced.

To accurately determine MIPS phase boundary, large system size is required which increases the computational cost of the simulation. For this purpose, we have developed a parallelized GPU code, which has allowed us to study very large system sizes. The physics and numerical details of the same will be presented.

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Fluid simulations of Farley-Buneman instabilities: Model description and applications

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It is generally accepted that modeling Farley-Buneman instabilities require resolving ion Landau damping to reproduce experimentally observed nonlinear features. Particle-in-cell (PIC) simulations have reproduced most of these at a computational cost that severely affects their scalability. This limitation hinders the study of non-local phenomena that require three dimensions or coupling with larger-scale processes. We argue that a variation of the five-moment fluid system can recreate several aspects of Farley-Buneman dynamics, such as density and phase speed saturation, wave turning, and heating. Furthermore, we show that this model offers an excellent qualitative agreement with a kinetic solver. Finally, we will outline some of the applications of this new approach for studying the coupling with larger-scale phenomena, such as gradient drift instabilities, improving our interpretation of coherent backscatter from E-region irregularities, and refining conductivity estimates of Global Circulation Models.

Prevention of unexpected explosive bursts during NTM control by ECCD for disruption avoidance

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MHD@Dalian Code (MDC) [1-3] is adopted to numerically investigate the suppression of NTMs and NTM triggering explosive bursts (shown in figure 1) by ECCD in tokamak plasmas. MDC model includes both nonlinear evolving bootstrap current and EC driven current with condensation effect [4]. It is found that the ECCD with appropriate input power and switch-on time can effectively stabilize the NTM islands and NTM triggering explosive bursts [1]. Due to the existence of strong zonal magnetic field during nonlinear evolution of NTMs, the switch-on time of ECCD should be as early as possible to obtain a better effectiveness. On the other hand, the ill-advised application of ECCD may cause unexpected explosive bursts [3]. While using ECCD to control NTMs, a threshold in EC driven current has been found. Below the threshold, not only are the NTM islands not effectively suppressed but a deleterious explosive burst could also be triggered, which might contribute to major disruption for tokamak plasmas. In order to prevent this ECCD from triggering explosive bursts, three control strategies have been attempted and two of them have been recognized to be effective. Moreover, the condensation effect of ECCD may offer additional extraordinary control effectiveness. Based on the numerical results, useful suggestions are proposed for control strategy design to better control NTMs in real tokamak experiments.

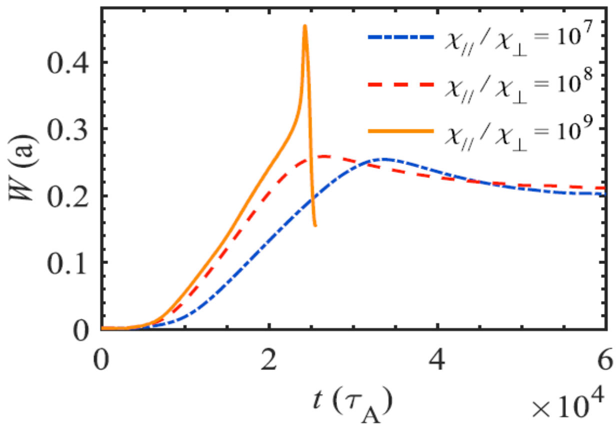

Figure 1. Temporal evolution of NTM magnetic island width under different ratio of parallel and perpendicular transport coefficients. It is noted that, with increasing the ratio, the NTM is becoming more and more unstable, and eventually lead to explosive bursts.

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ATEQ: Adaptive Toroidal EQuilibrium code and its applications

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A newly developed adaptive toroidal quilibrium code (ATEQ) is presented [1]. The code is aimed at improving the equilibrium solution near the magnetic axis and separatrix, where numerical accuracy is challenging. Comparisons with existing codes, such as TOQ, VMEC, EFIT etc., as well as the Solovev equilibrium solution with X-points, are detailed. The edge safety factor with ATEQ can reach more than 1600, while with usual equilibrium codes the value of q at the edge is numerically limited to much smaller values, such as 16. This has a significant impact for example for the peeling-ballooning stability investigation. Change of the center q value is also observed. In some cases, ATEQ finds that equilibria thought to have the center q above 1 actually have $q(0) < 1$. The convergence and comparisons with other codes are checked by the backward substitution method, i.e., the accuracy is evaluated by comparing residuals. The distinguishing features of ATEQ result from its numerical scheme. Unlike the conventional radial grid-based discretization, ATEQ uses the independent-solution decomposition method. This confers on ATEQ two distinct features: being adaptive in the radial direction and having a small matrix size in discretizing the Grad-Shafranov equation. It is because of these unique features that ATEQ is helpful to improve tokamak equilibrium solutions.

This research is supported by the U. S. Department of Energy, Office of Fusion Energy Science under Grant No. DE-FG02-04ER54742 and the US-Japan Joint Institute for Fusion Theory (JIFT) collaboration program.

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Nonlinear magnetohydrodynamic effects on waveform distortion and plasma flow of off-axis fishbone instability in tokamak plasma

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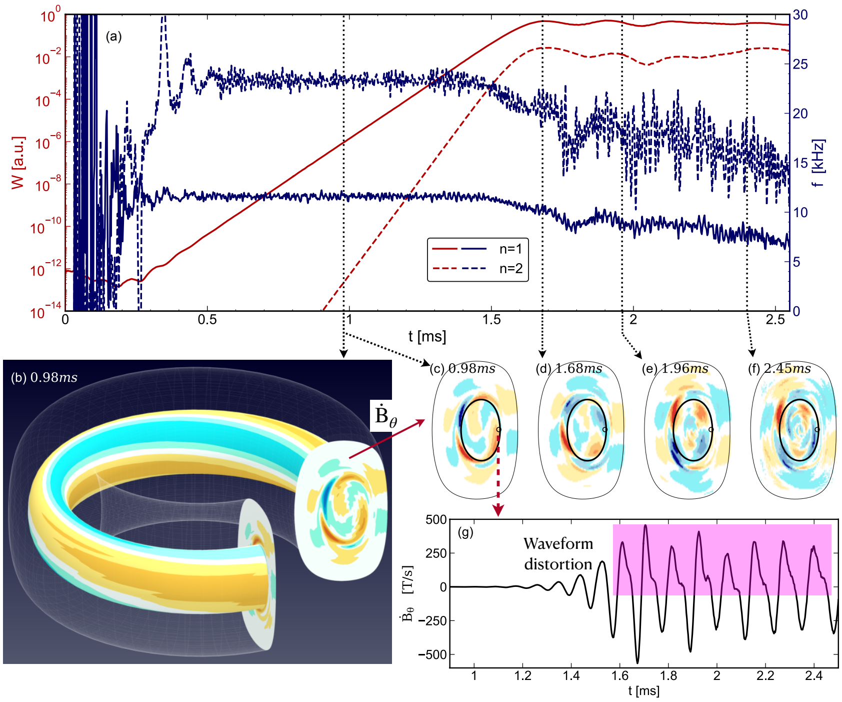
Kinetic magnetohydrodynamic (MHD) simulations have been used to examine the experimental observations of energetic particle driven off-axis fishbone mode (OFM) in tokamak plasma, including waveform distortion and plasma flow. We extended previous simulations (Li et al 2022 Nucl. Fusion 62 026013) with MHD nonlinearity. Quantitative agreement is found between the simulation and experiment results. The waveform distortion shown in figure, which is a distinctive nonlinear feature of OFM, is primarily related to the $n = 2$ harmonic, which is generated by MHD nonlinearity of $n = 1$ OFM. The two types of waveform distortion are found in different radial positions, where the mode amplitude and phase difference are important for reproducing the waveform distortion observed in the experiment. In the experiments, it was also found that resistive wall mode (RWM) can be triggered because the OFM reduced the rotation frequency. In our simulations, the nonlinear generation of zonal perturbations with $n = 0$ can significantly reduce the toroidal rotation frequency throughout the whole plasma by up to ~ -14 km/s (1.3 kHz). Additionally, simulations of classical fishbone mode were performed, and a similar waveform distortion was found for the same saturation level as that of OFM.



Simulations of fast-ion transport due to the Alfvén eigenmode burst in Large Helical Device

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The fast-ion confinement is an important issue for the prediction of the heating efficiency in a fusion reactor. The fast-ion confinement depends not only on the collisional transport but also on the fast-ion transport induced by the fast-ion driven instabilities such as Alfvén eigenmondes (AEs). Therefore, it is an important challenge to clarify the fast-ion transport due to the AEs.
In the Large Helical Device (LHD), which is one of the largest helical devices with a non-axisymmetric 3-dimensional magnetic configuration, fast-ion confinement has been investigated by using the three tangential neutral beam injectors (NBIs) and two perpendicular NBIs. The AE bursts have been observed in the LHD experiments [1,2].
A hybrid simulation code for nonlinear MHD and energetic-particle dynamics, MEGA, has been developed to simulate recurrent bursts of fast-ion driven AE instabilities including the energetic-particle source, collisions, and losses in non-axisymmetric three-dimension magnetic configurations like the LHD [3]. The multi-phase MEGA simulation, which is a combination of classical simulation and hybrid simulation for energetic particles interacting with an MHD fluid, was applied to the LHD experiments in order to investigate the AE bursts and the associated fast-ion transport and losses [4,5].The velocity distribution of lost fast ions in the MEGA simulation is in good agreement with the experimental fast-ion loss detector (FILD) measurements [5].
In the MEGA simulation of the AE burst, where multiple AEs grow suddenly, the role of each AE in fast-ion transport is not clarified. In this study, we conduct test particle simulations of fast-ion transport in the LHD using the AEs identified in the AE burst simulation. Two types of test particle simulations are performed with the different AE amplitude evolution. For the first type of simulation, the AE amplitude is assumed constant in time at the average level during the AE burst. The second type of simulation is run with the time-dependent AE amplitude following the AE burst simulation result.
The fast-ion transport due to a single AE and the synergetic effect of multiple AEs on the transport through the resonance overlap are clarified with the test particle simulations. In addition, the effect of low-frequency MHD mode on fast-ion transport is investigated.

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Self-consistent simulations of ICRF-induced Alfvén eigenmodes in toroidal plasmas

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Ion cyclotron resonance frequency (ICRF) heating has been chosen as one of the fundamental auxiliary heating systems in many present-day fusion devices. Minority ions accelerated by ICRF wave will heat the bulk plasma via Coulomb Collisions. Meanwhile, the high-energy minority ion tail developed during ICRF heating can drive a variety of Alfvén eigenmodes (AEs). The destabilized AEs, in turn, will significantly affect the ICRF heating efficiency by minority ion transport and losses. It is therefore necessary to consider AE effects during ICRF heating processes. Besides, in experiments, AEs excited by ICRF heating usually have a steady amplitude [1] while those excited by neutral beam injection (NBI) show sometimes bursting behavior [2]. Those different nonlinear states are determined by the energetic particle phase-space dynamics according to the Berk-Breizman theory [3]. One of the key elements to performing the simulations of different AE nonlinear states is including the ICRF source term in the simulation model.

In this work, we extended a kinetic-MHD hybrid code: MEGA [4] by implementing the ICRH acceleration, source, sink, and collisions. The extended MEGA code was firstly applied to an ICRF minority heating scenario in the Large Helical Device (LHD). As a first step, a hundred-millisecond classical simulation, where the MHD perturbation is turned off, was performed to obtain the minority ion distribution function in the steady state. Then, AEs driven by the minority ion tail were simulated for the first time based on the realistic phase-space distribution of ICRF minority ions via hybrid simulations where the MHD perturbation is turned on. Evaluations of AE stabilities at different RF input power and resonance layer locations in LHD will be presented. Minority ion transport in the presence of ICRF-induced AEs will also be discussed.

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Hybrid Simulation of Interaction between Energetic Particles and Magnetohydrodynamic Modes in the JT-60SA Inductive Scenario

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JT-60SA[1-2] tokamak can confine the break-even high-temperature plasma. In the inductive scenario with a lower single null (Scenario 2), the ideal MHD stability and transport codes predicted that the internal kink mode can be unstable at the plasma center ($q<1$). This mode can hinder reaching the target plasma current. Negative-ion-based neutral beam injection (N-NBI) is one of the controlling knobs in JT-60SA to control the current drive and tailoring q profile. The unstable internal kink mode can cause significant energetic-particle (EP) redistribution. Experimental and theoretical results suggest that EPs can have both stabilizing[3-4] and destabilizing effects[3-5] on the internal kink mode. The interaction between EPs and MHD modes in this scenario is investigated with MEGA[6], a kinetic-MHD hybrid code. In our simulation, the total pressure (the summation of the bulk plasma pressure and EP pressure) and q-profile are fixed. The time evolutions of the internal kink mode for the MHD, on-axis, and off-axis N-NBI cases are shown in Fig. 1a. In the MHD simulation without EP, the n=1/1 internal kink mode (red line) and other high-n modes with n=m are destabilized by the bulk plasma pressure gradient. In the hybrid simulation with N-NBI-generated EPs, the resonant EPs can transfer energy to the modes. In the on-axis NNBI case (magenta line), the linear growth rates of the modes are reduced by the dilution of the bulk plasma pressure gradient at the mode location (Fig. 1b). The dilution of the bulk plasma pressure gradient has the opposite effect in the off-axis case (cyan line) because the bulk plasma pressure gradient is steepened (Fig. 1c) within the q =1 surface. Destabilization of other MHD modes such as Alfvén eigenmodes is not observed. In the presence of multiple modes, the EP pressure profile is flattened within the q=1 surface by the stochasticity of the magnetic field at the saturation amplitude in both NNBI cases. The possibility of stabilizing the internal kink mode by the trapped EP is also investigated. In JT-60SA, the perpendicularly injected positive-ion-based NBI (P-NBI) is installed with an injection energy of 85 keV. The simulation results show that the P-NBI energy is insufficient to stabilize the internal kink mode. Instead, the n/m=1/1 precessional drift fishbone mode is destabilized when the trapped EP beta is sufficiently high.

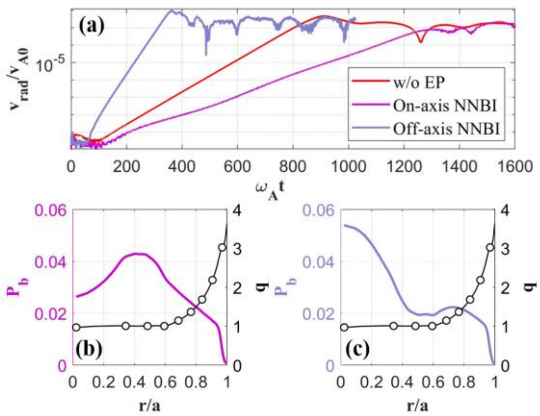

Fig. 1: (a) Comparison of the time evolution of the n/m=1/1 internal kink mode between the MHD, on-axis, and off-axis cases. The bulk plasma pressure profiles of the on-axis and off-axis NNBI cases are shown in panels (b) and (c), respectively.

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Simulation of 2D electrostatic presheath potential in FRC SOL

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The electrostatic presheath potential in the scrape-off layer (SOL) of a field-reversed configuration (FRC) could affect the turbulent transport in the SOL and the penetration of divertor biasing to the FRC confinement region. Full-f gyrokinetic simulation is needed to find the SOL equilibrium including presheath potential, which is intrinsically 2D resulting from the balance between radial and parallel transport. We have formulated an electrostatic simulation model for the SOL pre-sheath and implemented in the GTC-X code. The model has first been verified in a 1D presheath simulation on a single flux surface by recovering the parallel force balance and continuity equation. To further construct a 2D presheath, different radial boundary conditions and simulation domain size have been tested. With the absence of radial coupling between flux surfaces such as radial current, the radial electric field profile is mainly determined by the radial boundary condition at the divertor. To capture the penetration of the divertor biasing, a resistive radial current model is proposed to determine a more realistic 2D structure of the presheath potential. By including the 2D presheath as background time-independent equilibrium, we have carried out microturbulence simulation in the FRC SOL and found that the radial electric field of the presheath can reduce the ITG instability by providing a considerable E×B shearing rate.

Gyrokinetic Simulation of Trapped Electron Mode in Ring Dipole Magnetic Configuration

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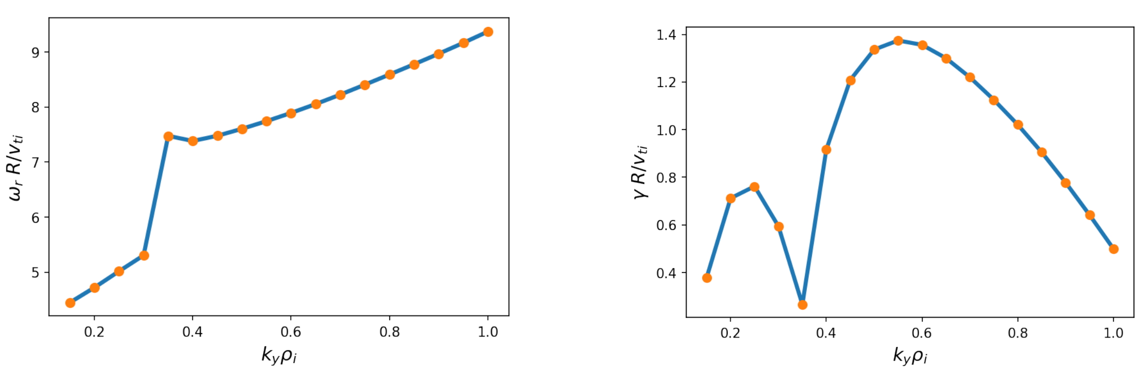
The dipole magnetic fields is ubiquitous in the universe, such as stellar and planetary magnetospheres. Being motivated from observation of plasma confinement in nature, several experimental devices using the dipole magnetic configuration are developed such as RT-1 device at the University of Tokyo [1]. So far, several simulation studies have been carried out for the dipole system, mainly focussing on the entropy mode with the maximum growth rate at $k_\perp \rho_i \sim 1$ [2].

In this study, we have investigated the trapped electron mode (TEM) which may be unstable under experimental parameters in a ring dipole magnetic configuration. We used the gyrokinetic Vlasov simulation code GKV and performed linear and nonlinear analyses. GKV code employs the five dimensional local flux-tube model along a magnetic field line. In application to the ring dipole configuration, we set the x coordinate as the radial direction on the magnetic equatorial plane, the y coordinate chosen as the toroidal angle, and the z coordinate is measured along the magnetic field line with the mirror ratio of $B_{max}/B_{min} \sim 18$. Figure 1 shows the linear frequency of TEM in the ring dipole with the density gradient $R/L_n \sim 3$ and the electron temperature gradient $R/L_{Te} \sim 5$ with no ion temperature gradient in the electrostatic limit. We have found that the unstable mode propagating in the electron diamagnetic direction has two peaks of the growth rate in the wavenumber k_y space, and that the particle flux driven by the $E \times B$ flow is inward (up-hill) in the low wavenumber region of $k_y \rho_i \sim 0.2$ in qualitative agreement with the RT-1 experiments [3].



(a) ω_r vs. $k_\perp \rho_i$ (b) γ vs. $k_\perp \rho_i$

Figure 1: Linear frequency (left) and growth rate (right) of TEM in a ring dipole configuration

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Lagrangian chaotic mixing due to resistive drift-wave turbulence in a transition from low-to-high confinement in fusion plasmas

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Coherent structures play an important role in turbulent flows in neutral fluids and plasmas. The theory of Lagrangian coherent structures has been successfully applied to understand the hidden structure of photospheric flows in the Sun [1, 2] and turbulent flows in numerical simulations of magnetohydrodynamic turbulence [3]. We report on the Lagrangian chaotic mixing properties of electrostatic resistive drift-wave turbulence in numerical simulations of a tokamak plasma modelled by the modified Hasegawa-Wakatani equations. We focus on two different regimes, namely, a regime dominated by turbulent patterns, and a regime dominated by zonal flows. A transition between these two regimes occurs by changing the value of a control parameter related to adiabaticity [4], and serves as a simplified model of the low-to-high confinement in tokamaks. Lagrangian coherent structures are detected by computing the finite-time Lyapunov exponent of the computed velocity field, and the statistics of the chaotic mixing of the two regimes are compared. These results can contribute to the understanding of turbulent transport processes in fusion plasmas.

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Spectral entropy of resistive drift-wave turbulence in a transition from low-to-high confinement in fusion plasmas

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Turbulence dominates the radial transport at the edge region of tokamak plasmas. Despite its influence on magnetic confinement in fusion experiments, it is currently poorly understood. Coherent structures have an important role for turbulent transport in fusion plasmas [1]. The spectral entropy is a useful tool from information theory that can characterize the degree of order/disorder of turbulent plasmas [2, 3]. Coherent structures are responsible for low values of the spectral entropy in observational data from space plasmas [4] and numerical simulations of magnetohydrodynamic turbulence [5,6].

We analyze numerical simulations of the modified Hasegawa-Wakatani equations [7], which provides a simplified model of the electrostatic resistive drift-wave turbulence in tokamak plasmas. We construct a bifurcation diagram of a transition from a turbulent regime to a regime dominated by zonal flows, in which turbulence is suppressed. This transition is then characterized by computing the normalized spectral entropy of the electrostatic potential. Our results show that the turbulent regime displays a high degree of entropy, and the regime dominated by zonal flows is characterized by lower values of entropy.

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Nonlinear Numerical Study of Energetic Particle Transport in ITER Plasmas and Comparison with Current DIII-D Results

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In a magnetic fusion device such as ITER, the energetic particles coming from heating mechanisms as well as coming from fusion products can destabilize Alfvén eigenmodes (AE). These AEs can lead to significant transport of energetic particles from the plasma core, thus reducing the confinement of energy in the plasma and the potential fusion yield. It is important for the future fusion devices to understand the energetic particle transport due to these modes in order to predict their importance as well as find parameters that mitigates their existence.

In this work, we numerically investigate the energetic particle driven instabilities that may exist in an ITER steady state scenario, where the energetic particles are deuterium ions coming from neutral beam injection (NBI) with a native energy of 1 MeV as well as fusion produced alpha particles with a native energy of 3.5 MeV. The investigation is done using the hybrid code MEGA [1] which treats the bulk plasma using an MHD description, and the energetic particles using a kinetic description. An ITER scenario with realistic equilibrium is used, and two energetic particle populations with characteristics consistent with integrated simulations are included.

The mesoscale AEs existing in this plasma are identified to be predominantly Toroidicity induced Alfvén Eigenmodes (TAE) with dominant $n=(15,16,17)/m=(20,21,22)$ contributions (where n and m are the toroidal and poloidal modes numbers respectively). Their effect on transport is evaluated in nonlinear simulations, and is shown to induce little energetic particle transport when studied individually (with single n simulations), and more important transport when studied in a multiple n simulation. The influence of the nonlinear generation of a zonal flow on the AE saturation is explored. The energetic particles' characteristics (e.g. beta value, spatial profile, velocity and pitch-angle distribution...) are then modified artificially in order to clarify the parameters that will most likely lead to increased or reduced AE activity and energetic particle transport. With increased NBI generated energetic ion pressure, an $n=15/m=17$ reversed shear Alfvén Eigenmode (RSAE) is shown to become important close to the q-minimum's radius.

An existing plasma in DIII-D with similarities (especially a very similar q profile) with the ITER scenario studied is also investigated. In that case, the energetic particles considered in the simulations only come from NBI. This investigation will let us compare numerical results to the experimental ones, and compare the type of AE activity present in DIII-D and expected in ITER.

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Ion Acoustic Decay Instability of Elliptical q-Gaussian Laser Beams in Plasma with Axial Density Ramp

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Abstract

Theoretical investigation on ion acoustic decay instability of an intense laser beam interacting with axially inhomogeneous plasmas has been presented. In this instability an intense laser beam interacting with an under dense plasma target resonantly decays into an electron plasma wave (EPW) and an ion acoustic wave (IAW). Using variational theory semi analytical solution to the wave equations for pump beam, EPW and IAW has been obtained. Emphasis is put on investigating the effect of self-focusing of pump beam on the power of excited daughter waves i.e., EPW and IAW.

Stimulated Raman scattering coupled with decay instability in a magnetized plasma with hot drifting electrons

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Abstract. Coupling of stimulated Raman back-scattering to decay instability with hot drifting electrons in a magnetized plasma is investigated. We consider the stimulated Raman scattering (SRS) of the laser beam in a magnetized plasma. This creates a downward shifting electromagnetic wave and a forward-moving plasma wave via parametric coupling. In this process, the plasma wave generated from SRS decays into an ion-acoustic wave and a secondary Langmuir wave with a longer wavelength that propagates backward. The amplitude of Raman instability is reduced by this energy diversion and damping of the main Langmuir wave by drifting electrons. The plasma wave is dampened resonantly at a higher rate in the presence of drifting electrons, and the stimulated Raman scattering decreases considerably.

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Effect of target front geometry in TNSA based ion acceleration

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It is well established that the interaction of a high intensity femtosecond laser pulse with a solid thick ($\sim 10\ \mu$m) target leads to proton/ion acceleration by target normal sheath acceleration (TNSA) mechanism [1-2]. There are also few reports on the enhancement of proton/ion energy by structuring the target front [3]. Here we perform a comparative study of different geometries of target front structures using two-dimensional particle-in-cell (PIC) simulations. Specifically, we investigate the proton energy spectra when the target has a semi-circular slot, a triangular slot, or a rectangular slot at the front side. We show that when the target front has a rectangular slot, ions with highest cut-off energies are obtained at the rear side.

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Effect of laser pulse asymmetry on harmonic generation

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High-intensity short-pulse laser-plasma interactions can generate high-order harmonics which has potential applications towards the production of extreme ultraviolet (XUV) pulses [1-3]. The shape of laser pulse can have a significant effect on such interactions and hence on the harmonic generation [4]. In the present work, I have numerically studied the role played by temporal asymmetry of laser pulses having unequal rise and fall time in the generation of harmonics from overdense plasmas.

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Simulation study of the harmonic structure of lower hybrid waves driven by energetic ions

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Instabilities driven by energetic ions are important issues common in space and fusion plasmas. Lower hybrid waves can be excited by energetic ions and are often observed in both plasmas. A recent observation in the Earth's magnetosphere [1] has reported unusual waves with the frequencies at the multiple of the lower hybrid resonance frequency (ω_{LH}). These unusual waves propagate perpendicular to the background magnetic field with linear polarization. Here, we define these waves as harmonic lower hybrid waves and hereafter refer to them as harmonic modes. However, the harmonic modes cannot be explained by the fluid theory because such waves propagating perpendicular to the magnetic field above ω_{LH} are evanescent. Therefore, we have performed one-dimensional, electromagnetic, particle-in-cell simulations to investigate the excitation and long-term development of the harmonic modes. We find that the harmonic modes with frequencies up to 15 times higher than ω_{LH} can be excited by energetic ions and non-linear wave-wave couplings.
We adopt an energetic-ion injection model in the simulations where energetic ions are gradually and continuously injected into a plasma. This model enables us to investigate the long-term evolution of instabilities [2]. Initial value problems, which are often solved to investigate the excitation of waves [3,4], are not suitable for our study because they only focus on the wave excitation associated with the collapse of a velocity distribution of eneregtic ions. We consider a case with a low frequency-ratio ($\omega_{pe}/\Omega_e = 0.25$) and a ring speed of the energetic ions smaller than the Alfvén speed ($v_r/v_A = 0.6$).
Simulation results show that the lower hybrid waves (hereafter referred to as the original modes) are directly excited by the energetic ions, and then the harmonic modes are excited. The harmonic modes have the wavenumbers and the frequencies at the multiples of those of the original modes. Bicoherence analysis indicates that these harmonic modes are excited by the non-linear wave-wave interactions between the original modes. Electrostatic ion cyclotron waves above ω_{LH} are also excited by the energetic ions although their amplitudes are small. We find that the electrostatic ion cyclotron waves can contribute to the excitation of the higher harmonic modes. We also investigate the dependence of ω_{pe}/Ω_e and v_r/v_A on the development of the harmonic modes.

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Magnetic cages:
a key to determining whether a flux rope will erupt

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Magnetic flux ropes (FRs) are thought to be the central structures of solar eruptions,including prominence/filament eruptions, flares, and coronal mass ejections (CMEs). Knowing whether the FR will erupt or not is, naturally, fundamental to predicting a CME event. There are several mechanisms that can decelerate and confine eruptions in the corona, including magnetic and hydrodynamic processes. We performed numerical simulations in which a FR structure is in the vicinity of a pseudostreamer (PS). We evolve this scenario, varying the PS parameters, by numerically solving the magnetohydrodynamic equations in 2.5D. The simulations consider a fully ionised compressible ideal plasma in the presence of a gravitational field and a stratified atmosphere. The PS lobe acts as a magnetic cage enclosing the FR, in this scenario we have eruptive and non-eruptive FRs. The non-eruptive cases, which initially reach higher velocities, are quickly decelerated by the magnetic cage. The cage field lines are compressed instead of adjusting to the rise of the FR, producing high magnetic pressure gradients that impulse the FR back to the surface. Also, we note for non-eruptive cases that the expansion of the FR is inhibited by the magnetic cage, keeping it overdense and less buoyant, which helps to prevent the eruption. We report that the total unsigned magnetic flux of the cage is a key parameter defining whether the FR is ejected or not.

Sausage modes excitation in coronal loops

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Quasi-periodic pulsations (QPPs) are detected in most flare events in EUV, X-ray and radio emission. A proposed model to explain these oscillations relied on magnetohydrodynamic (MHD) waves in coronal loops. In this work [1], we analyse coronal loop oscillations triggered by two types of perturbations, local and global energy depositions. We find that a local perturbation causes slow sausage modes, while a global one is responsible for the excitation of fast sausage modes.

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Feedback instability analysis of auroral growth in the dipole field configuration

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Previous works of the feedback instability in the magnetosphere-ionosphere (M-I) coupling focused on auroral structure formation and its time variation under the local approximation with a constant magnetic field line length. In the global analysis addressed by Hasegawa et.al.[1] with the non-uniform magnetic field line length and spatial dependence of the magnetic field intensity, they reported non-local characteristics of the quiet auroral arc growth. However, no simulations dealing with the time variation of auroral fine structures such as spirals or curls has been carried out in a global M-I coupling with nonuniform background electric field.

In order to describe the auroral dynamics in the global M-I coupling, we developed a novel simulation code with the flux coordinates solving the reduced magnetohydrodynamics (MHD) and two-fluid equations for the M-I coupling system. The coordinate system (Fig.1) is developed by combining the modified dipole coordinates [2] and the non-orthogonal dipole coordinates [3], providing the three advantages to conduct numerical simulations in the dipole field. First, the Jacobian changes along the magnetic field lines more gradually than that of the normal dipole coordinates. Second, a constant surface of the coordinate crossing the magnetic field lines coincides with the spherical surface of the ionosphere. Third, complexity due to the non-orthogonality of the coordinates can be avoided under the flute ordering employed for the reduced MHD equations.

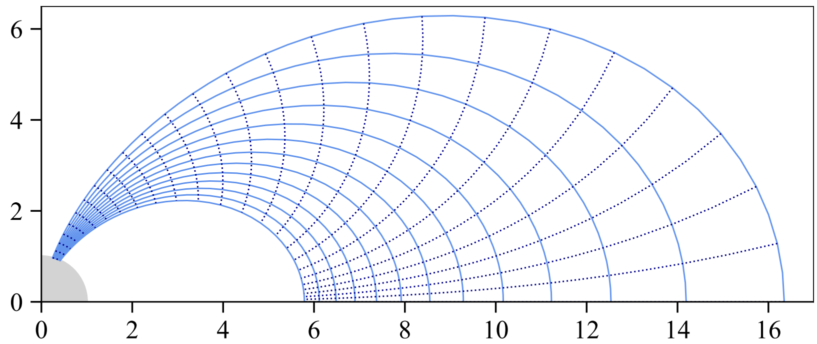

Fig. 1 A schematic of the flux coordinates at a meridian plane.

We have performed the linear analysis of the feedback instability in the dipole field and found that growth of an auroral wave packet is saturated through propagation on the ionosphere because of the effect of nonuniform field line length.

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Numerical modeling of coplanar barrier discharge in air

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The coplanar barrier discharge is a non-equilibrium low-temperature plasma. The coplanar barrier discharge driven at atmospheric pressure is currently a well established, durable and robust technology (under the name diffuse coplanar surface barrier discharge, DCSBD, see [1]) used in plasma activation treatment for multiple purposes [2–5].

The challenges in numerical simulation of such discharge lies in the modeling of the discharge itself and also of its complex interaction with dielectric surface. In [6] the ignition and propagation of surface streamer was studied and compared with experimental results using spatio-temporal distribution of electric field. The study of surface streamer propagation requires very fine mesh over large region of computational domain. That doesn't allow to study the whole discharge behavior on longer timescales. In this work we present the results using combination of coarser and finer mesh to better study events leading to the ignition of the surface streamer.

At low applied voltages the coplanar barrier discharge shows behavior close to the Townsend discharge. It is characterized by avalanches of electrons which are seeded from secondary emission by impact of ions on the dielectric surface at the cathode. The applied electric field is not disturbed by space charge effects.

When the applied voltage is increased the electron density in discharge volume is increasing in time and it eventually may lead to the avalanche to streamer transition. Such electron density increase may take a long time as it depends on the applied voltage. When the increase of electron density is slow, the accumulation of surface charge on dielectrics reduces the electric field in the discharge volume. And that prevents further increase of electron density.

For higher applied voltage the electron density in avalanche increases fast enough so that the avalanche to streamer transition appears before the electric field in the discharge volume is reduced by accumulated surface charge. Then the surface streamer ignites and propagates above dielectrics.

In conclusion it is observed that the surface streamer ignites and starts to propagate at lower applied voltages than in [6] which improves the agreement with experimental measurements.

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Amplification of nonlinear oscillations of electron beam in crossed time-periodic magnetic field

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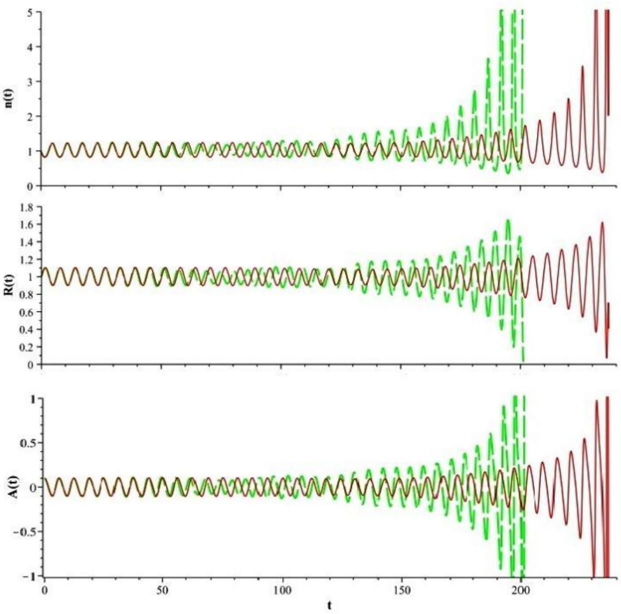
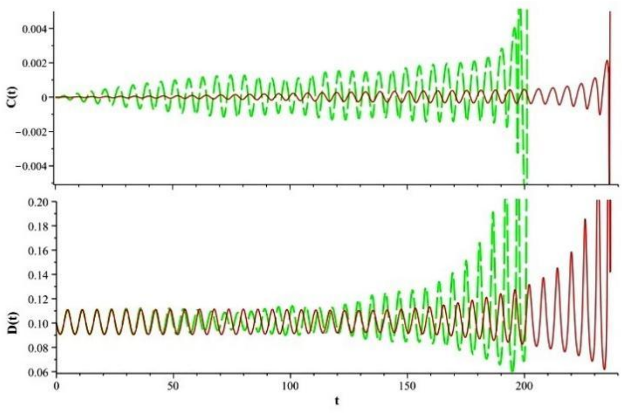
An electron beam propagating in a magnetic field that is time-periodic along the propagation direction and nearly constant in the radial direction is investigated using non-perturbative cold-fluid description. Energy/momentum exchange between the beam and the external fields can excite and amplify nonlinear electrostatic beam-mode oscillations. It is found that under appropriate conditions, the spatial structures of the beam density as well as the radial, azimuthal, and axial velocities can be self-consistently well defined [1], and they can all increase as the beam propagates, accompanied by decrease of the beam radius, as shown in the figure, where the beam density and radius are normalized by their initial values n_0 and R_0, and velocity by R_0/ω_{bp} , with ω_{bp} the beam plasma frequency. The cold, effectively Brillouin, beam [2] eventually suffers resonant collapse. The results should be relevant to particle accelerators such as cyclotrons, gyrotrons, free-electron lasers, etc., where the transverse beam size is often limited by the chamber size. The highly nonlinear amplifying beam modes may also be useful as light sources.





Evolution of the normalized e-beam density n, radius R, and velocity
$\mathbf{v} = rA(t)\mathbf{e}_r + rC(t)\mathbf{e}_\phi + rD(t)\mathbf{e}_z$
for $V_{eA}/c = 10^{-4}$ (dashed green) and 10^{-5} (solid red)
V_{eA} = electron Alfven speed

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