R008-01
C 会場 ：9/25　PM1 （13:45-15:30）
13:45～14:00

スーパーコンピューター富岳における磁気流体コード CANS+ の性能チューニングと超高解像度磁気圏シミュレーション

#松本　洋介 [1)]
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Performance tuning of the MHD simulation code on Fugaku and super-high-resolution global magnetospheric simulations.

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We have developed a global magnetohydrodynamic (MHD) simulation model of the magnetosphere using the public MHD code CANS+ (Matsumoto et al., 2019; Matsumoto and Miyoshi, 2022). This model was developed to virtually observe the soft X-ray emission by the charge exchange process between the high-charge state ions in the solar wind and the Earth's exosphere and for upcoming X-ray imaging missions of GEO-X and SMILE.

On the other hand, we recently started a project called "Elucidation of Solar-Terrestrial Environment with Simulation and AI" on the Supercomputer Fugaku. In this project, we plan to conduct different simulation models of the solar convection zone, the solar corona, the solar wind, and the Earth's magnetosphere. Using Fugaku's huge computational resources, we examine super-high-resolution MHD simulations to examine turbulence in the plasma sheet and particles' turbulent transport to the inner magnetosphere. The numerical resolution approaches the limit of the MHD approximation with a few hundred kilometers (0.04 the Earth's radius) of the computational cell.

In this presentation, we report performance tuning results of the CANS+ code on Fugaku, its application to the super-high-resolution global MHD simulations, and turbulent natures in the magnetosphere. We also discuss the possibility of remote imaging of the soft X-ray emission reflecting the turbulent structure around the magnetopause.

R008-02
C 会場 ：9/25　 PM1 （13:45-15:30）
14:00～14:15

電流源を含む陽的高次 FDTD 法における数値誤差の修正

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([1] 名大工学研究科,([2] 名大 ISEE

Correction of Numerical Errors in Higher-Order Explicit Finite-Difference Time-Domain Method with Current Sources

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This study proposes a correction of numerical errors in the Finite-Difference Time-Domain (FDTD) method with the time-development equations using higher-order differences and including current sources. The FDTD method (Yee 1966) is a numerical method for solving the time development of electromagnetic fields by approximating Maxwell's equations in both space and time with the finite difference of the second-order accuracy. FDTD(2,4) uses the fourth-order spatial difference (Fang 1989; Petropoulos 1994).

Although numerical errors in the phase velocity of FDTD(2,4) are smaller than that of FDTD(2,2), the Courant condition of FDTD(2,4) is more restricted than that of FDTD(2,2). Recently, a numerical method has been proposed to relax the Courant condition and reduce the numerical errors in the phase velocity (Sekido & Umeda 2023). However, it has been found that there arises a large numerical error in the charge conservation law if the time-development equations including current sources are discretized with a higher-order finite difference in space. In the present study, the numerical error is suppressed by adding correction terms to the time-development equations of a higher-order FDTD.

本研究では、電流源を含む FDTD (Finite-Difference Time-Domain) 法において、時間発展式に高次精度差分を用いた際に生じる数値誤差の修正を行った。FDTD 法は、電磁界の時間発展を解く数値計算手法であり、空間と時間ともに 2 次精度の差分で Maxwell 方程式を近似することで求められる (Yee 1966)。不連続波形で数値振動が発生するほか、連続波形でも傾きが大きいと数値振動や振幅の減衰が起こるといった欠点が存在する。これらの欠点を改善するため、空間微分項の差分精度を 4 次精度とした FDTD(2,4) 法が提案された (Fang 1989; Petropoulos 1994) が、Courant 条件がより厳しくなるという問題を抱えていた。そこで、FDTD(2,4) の時間発展式に高階微分項を追加することで、Courant 条件を緩和しつつ位相速度誤差を抑えた手法を新たに開発した (Sekido & Umeda 2023)。しかし、電流源を含む時間発展式の空間差分を高次精度化したときに電荷保存則において数値的な誤差が生じ、静電場の残留が生じることが明らかとなった。FDTD(2,2) ではこのような残留は発生しないことから、本研究では FDTD(2,4) の時間発展式に修正項を追加することにより、電荷保存則における数値的な誤差を抑制することに成功した。

R008-03
C 会場 ：9/25　 PM1 （13:45-15:30）
14:15～14:30

#梅田　隆行 [1), 尾崎　理玖 [1)]
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A new integrator for relativistic equations of motion for charged particles

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Numerical methods for solving the relativistic motion of charged particles with a higher accurately is an issue for computational physics in various fields. The classic fourth-order Runge-Kutta method (RK4) has been used over many years for tracking charged particle motions, although RK4 does not satisfy any conservation law. However, the Boris method has been used over a half century in particle-in-cell plasma simulations because of its property of the energy conservation during the gyro motion.

In the present study, a new method for solving relativistic charged particle motions has been developed, which conserves both boosted Lorentz factor and kinetic energy during the gyro motion. The new integrator has the second-order accuracy in time and is less accurate than RK4. The new integrator is also extended to the fourth-order method by combining RK4.

R008-04
C 会場 ：9/25　 PM1 （13:45-15:30）
14:30〜14:45

量子コンピュータシミュレータ Qiskit を用いた無衝突プラズマ 6 次元 Boltzmann-Maxwell 系のセルフコンシステントな量子計算アルゴリズムの開発

#樋口　颯人 [1), ピダーセン　珠杏 [2), 吉川　顕正 [3)
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Self-Consistent Quantum Calculations of the 6D Boltzmann-Maxwell System in Collisionless Plasmas Using Quantum Computer

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The space plasma environment, extending from the Sun to the magnetosphere-ionosphere-atmosphere, includes regions of frozen conditions, zones of anomalous resistance caused by electromagnetic turbulence, interconnected regions characterized by weakly ionized gas systems in strong magnetic fields, coupled neutral-atmosphere chemical processes, and pure neutral-atmosphere collision systems. Owing to their complex interactions, an inclusive understanding and forecasting of the space environment remains an elusive goal, even with the advancements in high-performance instrumentation and in-situ observation of satellites. Therefore, it is imperative to develop space plasma simulations capable of providing comprehensive insights, ranging from local spatial domains to the global schematic.

Historically, the development of space plasma simulations has been constrained by computational time, memory capacity, and data storage limitations, resolving complex phenomena with restricted physics at local space scales.

In recent years, advances in quantum computing, both software and hardware, have demonstrated numerous advantages of quantum algorithms, such as those represented by (e.g. Shor [1994]). Following Google's achievement of quantum supremacy in 2019 (Arute et al., [2019]), the pragmatic implementation of quantum computing in plasma simulation, weather forecasting, fluid simulation, and various fields is attracting interest. Among them, the quantum lattice Boltzmann method is constructed by considering the streaming operation as Quantum Walk(Aharonov et al., [1993])(Succi et al., [2015]). Then Todorova et al. developed a quantum algorithm for the collisionless Boltzmann equation using the discrete velocity method, describing propagation in discrete real space and discrete velocity space with quantum walks (Todorova and Steijl, [2020]).

We have improved the quantum algorithms presented at JpGU2023(Higuchi, et al.,[2023]) and developed a quantum algorithm for the 6D Boltzmann-Maxwell equations for collisionless plasmas without the uniform velocity condition and the vacuum condition in Maxwell's equations. By implementing a quantum algorithm that computes the velocity moment into (Higuchi, et al.,[2023]), the collisionless Boltzmann-Maxwell system becomes self-consistent as a simulator. Thus, our simulator obtains MHD quantities based on the Boltzmann equation. In other words, it can be called a quantum algorithm for the MHD equation using the Boltzmann method. Furthermore, although there was a measurement problem of the 6D distribution function on the side (Higuchi, et al.,[2023]), this problem was solved by obtaining 3D MHD quantities.

In this presentation, we will explain the above quantum algorithm, compare quantum numerical results to classical results, and discussed with those, with a view to the future.

太陽から磁気圏、イオン圏、大気圏に至る宇宙プラズマ環境は、フローズイン状態、電磁乱流による抵抗異常、強磁場弱電離気体系、中性大気ケミカル結合系、純粋な中性大気衝突系などの相互接続領域を含んでいる。これらの複雑な相互作用により、宇宙環境の包括的な理解と予測は、高性能な計測機器や人工衛星によるその場観測が進歩した現在でも、遥か遠い将来的な目標とされる。そのため、局所的な空間領域からグローバルな領域に至るまで、包括的な洞察を提供することができる宇宙プラズマシミュレーションの開発が不可欠となる。これまで、宇宙プラズマシミュレーションの開発は、計算時間、メモリ容量、データストレージの制約を受け、局所的な空間スケールで制限された物理を持つ複雑な現象を解明できなかった。

近年、ソフトウェア・ハードウェアを問わず、量子コンピューティングの進歩により、(e.g. Shor [1994]) に代表される量子アルゴリズムには数多くのメリットがあることが証明されている。2019 年に Google が量子優位性を達成したことを受け (Arute et al., [2019])、プラズマシミュレーション、天気予報、流体シミュレーション、様々な分野での量子コンピューティングの実用化が注目されている。その中でも、ストリーミング操作を量子ウォークと考え、量子格子ボルツマン法が構築された (Aharonov et al., [1993])(Succi et al., [2015])。そして Todorova らは、量子ウォークで離散実空間と離散速度空間の伝播を記述する、離散速度法を用いた無衝突ボルツマン方程式の量子アルゴリズムを開発した (Todorova and Steijl, [2020])。

我々は、JpGU2023 で発表した (Higuchi, et al.,[2023]) を改良し、速度の一様条件、Maxwell 方程式の真空条件なしの無衝突プラズマの 6 次元 Boltzmann-Maxwell 方程式の量子アルゴリズムを開発した。(Higuchi, et al.,[2023]) に速度モーメントを計算する量子アルゴリズムを実装し、無衝突 Boltzmann-Maxwell 系はシミュレータとしてセルフコンシステントになる。これにより、本シミュレータは Boltzmann 方程式に基づいた MHD 量を得る。つまり、それはボルツマン法を用いた MHD 方程式の量子アルゴリズムと呼ぶこともできる。また、(Higuchi, et al.,[2023]) では 6 次元分布関数

の測定問題があったが、3 次元 MHD 量を得ることでそれは解決された。

本発表では上記の量子アルゴリズムを解説し、得られた量子数値結果を元に、古典アルゴリズムによる数値計算との比較・考察を行い、今後の展望を踏まえて話す予定である。

R008-05
C 会場 ：9/25 PM1 （13:45-15:30）
14:45～15:00

低域混成波高調波の励起および非線形発展に関するパラメーター依存性

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Parameter dependence of excitation and non-linear development of harmonic lower hybrid waves

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The harmonic structure of lower hybrid waves (or harmonic lower hybrid waves) is a characteristic structure in the wavenumber-frequency ($k - \omega$) spectrum resulting from non-linear wave-wave interactions of large amplitude lower hybrid waves. In the simplest case, harmonic lower hybrid waves can be generated at a specific wavenumber and frequency, (mk_1, $n\omega_1$), due to the lower hybrid wave with (k_1, ω_1). In recent years, increasing attention has been paid to the harmonic lower hybrid waves because of their possibility to efficiently accelerate background ions in the polar region. In order to clarify this, general conditions for generating the harmonic lower hybrid waves should be investigated, but not yet.

In this meeting, we report the parameter dependence of excitation and non-linear development of the harmonic lower hybrid waves driven by ring-like energetic ions. We mainly focus on two parameters: the ratio of the electron plasma frequency to electron cyclotron frequency and the ratio of the ring velocity of energetic ions to the Alfven velocity. The favorable condition of generating the harmonic lower hybrid waves is discussed.

R008-06
C 会場 ：9/25　 PM1 （13:45-15:30）
15:00〜15:15

月局所磁化領域周辺の静電プラズマ環境に関する粒子シミュレーション

#早稲田　卓 [1), 三宅　洋平 [2), 中園　仁 [3)
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Plasma Particle Simulations on Electrostatic Environment near Lunar Local Magnetization Regions

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In airless planetary bodies such as the Moon, the solar wind plasma precipitates directly onto the surface. The plasma charge deposition on the surface and the photo-emitted electron current determine the dayside, near-surface electrostatic environment. In general, orbital observations by a number of lunar exploration satellites suggest that the day side of the Moon is positively charged. Although the Moon has no global intrinsic magnetic field like the Earth, it is widely known that there are locally magnetized crusts (magnetic anomaly). The influence of these magnetic anomalies on the plasma and wave environment above has been intensively discussed for many years, whereas the near-surface electrostatic environment, including the contribution of photoelectrons, inside and directly below the magnetized regions, has not been fully addressed.

For large magnetic anomalies with a spatial scale comparable to the ion inertia lengths, it is not practical to perform three-dimensional simulations of the electrostatic environment taking into account the photoemission effect. This study focuses on a small-scale magnetization region on the Moon to elucidate its electrostatic environment as well as the contributions of photo-emitted electrons to the environment.

Our preliminary simulation results have identified a pronounced charge separation effect resulting from the difference in electron and ion inertia, as previously reported. This leads to a higher surface potential, e.g. 60 V, below the mini-magnetosphere than that predicted for the outside. The simulations also suggest the effect of photoelectrons of moderating the intense positive charge below the mini-magnetosphere, which differs from the conventional view on the photoelectron effect as a major source of positive surface charging.

月を始めとする大気が希薄な固体天体では、太陽風などの宇宙プラズマが直接表面に降り注ぐ。プラズマの降り込みによる天体表面への電荷蓄積や、光電効果による光電子電流が表面近傍での静電気環境を決定づける。一般に月探査機による軌道上観測では月昼側は正に帯電していることが示唆されている。月には地球のような固有磁場は存在しないが、これまでの観測により局所的に磁化された地殻 (磁気異常) が存在することも明らかとなっている。この磁気異常が上空のプラズマ・波動環境に及ぼす影響は長年活発に議論されてきたが、磁化領域の周囲、内部、および直下の光電子の寄与を含む月面帯電環境の検討は、シミュレーションを活用した数値アプローチを含め、十分に検討されてきたとは言い難い。

軌道上から観測可能なイオン慣性長程度の空間サイズの磁気異常に対し、表層の光電子環境を考慮した 3 次元シミュレーションを実施するのは計算コスト面から現実的ではない。そこで本研究では、地中に小規模な双極子磁場を持つ月面に対し上空から太陽風プラズマが降り注ぐ状況を想定したシミュレーションを実施し、磁化領域の月面付近の静電気環境、および光電子放出の寄与についての解析を行い、局所磁化領域での帯電環境の定性的な理解を目的とした。

その結果、小規模磁化領域においても先行研究で示されているようなイオンと電子の質量比による荷電分離を確認でき、月面電位は 60V ほどと非磁化領域に比べて、高い電位を有することが判明した。また、従来は月面の正帯電の原因そのものであるとされていた光電子電流が、当該状況においては逆に局所磁化領域の顕著な正帯電を緩和する働きを行う可能性があることが分かった。

R008-07
C 会場 ：9/25　 PM1 （13:45-15:30）
15:15～15:30

宇宙プラズマ中の低域混成周波数付近におけるアンテナインピーダンス特性に関する粒子シミュレーション

#草地　恒史郎 [1), 三宅　洋平 [1), 臼井　英之 [1), 小嶋　浩嗣 [2), 栗田　怜 [2), 深澤　伊吹 [2)
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Particle Simulation on Antenna Impedance Characteristics near the Lower-Hybrid Resonance Frequency

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For the plasma wave observations in space, the electric field sensor based on a dipole antenna is commonly put in use onboard scientific satellites. The electrical properties of the dipole antenna in space are different from those on the ground due to the dispersive nature of space plasma. Since the observed wave data are calibrated taking into account the antenna characteristics, it is important to understand them quantitatively for correct interpretation of the observational data. The solar-terrestrial physics community in Japan has organized a new polar ionosphere-mesosphere mission FACTORS, one of whose objectives is to observe and elucidate the ion-mode plasma wave processes that cause ion heating and acceleration. Thus, we have initiated numerical investigations of the antenna characteristics in a low-frequency range where the ion dynamics are involved. It is reported that previous chamber experiments detected a lower-hybrid resonance feature in the measured impedance data [1]. In this study, we apply the particle-in-cell (PIC) method to the analysis of antenna impedance in such a low-frequency range [2]. The PIC simulation is advantageous to include plasma kinetic effects.

In the simulation, we place a dipole antenna in the center of a three-dimensional simulation box domain filled with a large number of plasma particles. We evaluate the antenna impedance by using the delta-gap feeding technique [3]. In the simulation results, we observed an impedance resonance near the lower hybrid resonance frequency: ω LHR (Figure). To clarify the relationship between the impedance resonance and relevant plasma wave modes, we derived dispersion relations from the simulation. We found that the impedance resonance frequency coincides with the frequency at which a lower hybrid wave blanch intersects the particular wavenumber k_half where the antenna behaves as a half-wave dipole. In addition, we found that the dependence of the antenna impedance on plasma conditions such as ion temperature and magnetic field strength. Our preliminary simulations have also identified similar impedance resonances relevant to the electrostatic ion cyclotron harmonic waves, which are, however, pronounced in different simulation configurations. We will discuss necessary physical conditions under which these impedance resonances are prominent.

References

[1] A. Kumamoto, K. Endo, and Y. Ishigaya, “Experiment of lower hybrid resonance detection by wideband impedance probe for measurement of ion composition and electron number density”, Proceedings of 2017 Symposium on Laboratory Experiment for Space Science, SA6000095011 (2017).

[2] Y.Miyake, H.Usui, H.Kojima, Y.Omura, and H.Matsumoto, “Electromagnetic particle-in-cell simulation on the impedance of a dipole antenna surrounded by an ion sheath.”, Radio Science, 43(03):1-14 (2008)

[3] Raymond Luebbers, Li Chen, Toru Uno, and Saburo Adachi, “Fdtd calculation of radiation patterns, impedance, and gain for a monopole antenna on a conductiong box”, IEEE Transactions on Antennas and Propagation, Vol. 40 No. 12, pp. 1577-1583 (1992).

宇宙環境におけるプラズマ波動観測では、ダイポールアンテナを基本とした電界センサーが観測器として広く 用いられている。宇宙空間では、プラズマ媒質の分散性からアンテナの電気特性が地上とは大きく異なることが 知られている。観測された波動データはアンテナ特性を考慮して較正が行われていることから、アンテナの宇宙プ ラズマ中特性の定量的な理解は、観測データの正しい解釈につながるとして現在まで研究が進められてきた。 日本の太陽地球物理コミュニティが組織する探査計画の中に電離圏・中間圏探査計画「FACTORS」があ り、その探査ミッションの一つに、イオンモードに関するプラズマ波動に関連した粒子加速・加熱過程の調査があ る。したがって我々は、イオン運動が関連する低周波領域でのアンテナ特性について数値シミュレーションを用い た研究を進めてきた。過去のチャンバー実験では、測定されたインピーダンスデータに低域ハイブリッド共振の特 徴が検出されたことが報告されている [1]。シミュレーションには、プラズマの運動論に基づいた PIC(Particle − in − cell) 法 [2] を採用した。

本研究では、一様な磁化プラズマ中を模した三次元シミュレーション空間の真ん中にダイポールアンテを設置 し、デルタギャップ給電法 [3] を用いてアンテナインピーダンスの周波数特性を算出した。シミュレーションの結 果、我々は低域混成周波数 (ω LHR) 付近で特徴的なインピーダンス共振を観測した (図)。このインピーダン ス共振とプラズマ波動を関連づけるため、我々は波動分散関係をシミュレーション値から導出した。その結果、 インピーダンス共振が起きた周

波数は、波動分散関係上の半波長ダイポールアンテナとみなせる波数 k_half に 対応した LHR 波のブランチの周波数とよく一致することが確認された。加えてアンテナインピーダンス特性には、 イオン温度、磁場強度のようなプラズマ環境の依存性があることが考察された。上記に加え、静電イオンサイク ロトロン高調波に対応したインピーダンス共振も異なる計算条件で確認されている。それぞれの波動に対するイ ンピーダンス共振の条件についての研究の進歩を報告する。

参考文献

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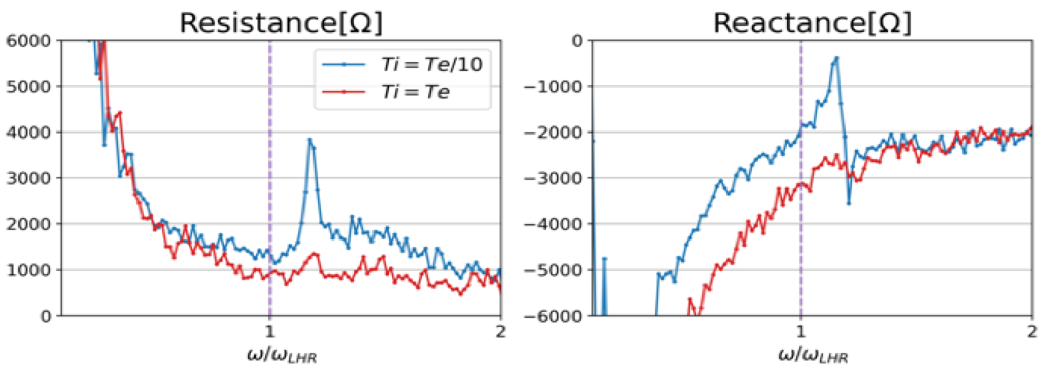

R008-08
C 会場 ：9/25　 PM2 （15:45-18:15）
15:45～16:00

#寺境　太樹 [1), 天野　孝伸 [1), 松本　洋介 [2)]
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Electron pre-acceleration in shock transition regions of weakly magnetized perpendicular shocks

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One of the long-standing issues regarding cosmic ray acceleration by the Fermi process at astrophysical shocks is the electron injection problem. Some population of the electrons must be pre-accelerated before the Fermi process because low-energy electrons cannot resonate with MHD-scale waves in the shock downstream. It is believed that this acceleration takes place in the shock transition region (a thin layer with a thickness of ion gyro-radius).

We investigate the electron pre-acceleration by Weibel instability, which is known to be the dominant instability for non-relativistic, high-Mach number shocks. We use 2D and 3D particle-in-cell simulations to show that Weibel instability can amplify the magnetic field efficiently when there is a strong enough background magnetic field to magnetize the electrons but not the ions.

The 2D simulation shows clear evidence of magnetic reconnection and associated electron acceleration. This result is consistent with previous shock simulations, which indicate that the Weibel instability determines the dynamics of shocks with these parameters.

In the 3D simulation, we find the same efficient magnetic field amplification. However, the structure in the nonlinear stages is much more turbulent than in 2D.

This scenario applies to nonrelativistic shocks with Alfven Mach-numbers of 100s, which is a typical value for young supernova remnants believed to accelerate a significant portion of galactic cosmic rays.

R008-09
C 会場 ：9/25　 PM2 （15:45-18:15）
16:00〜16:15

Kinetic Alfvén wave により捕捉された電子の非線形運動についての理論・数値的考察

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Theory and simulation of the nonlinear motion of electrons trapped by kinetic Alfven waves

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The kinetic Alfven wave (KAW) is a type of dispersive Alfven wave with a long wavelength parallel to the magnetic field line and a perpendicular wavelength comparable to the ion Larmor radius. KAWs carry an electric field component parallel to the magnetic field line δE_{jj} and accelerate electrons along the magnetic field line through Landau resonance [e.g., Hasegawa, 1976; Kletzing, 1994; Artemyev et al., 2015]. KAWs are often observed in the terrestrial magnetosphere during substorms [e.g., Stasiewicz et al., 2000], and it has been pointed out that a few keV electrons produced by KAWs cause the auroral brightening during the substorm expansion phase [e.g., Keiling et al., 2002; Duan et al., 2016]. At the equatorial region in the L-shell of 9, where electrons are accelerated by KAWs, the plasma β is $m_e/m_i < \beta < 1$. A parallel magnetic field component, δB_{jj}, which depends on the plasma β [Schekochihin et al., 2009], becomes approximately 8% of a background magnetic field B_0 and is considered to be a non-negligible value in the electron acceleration process of KAWs. The electron acceleration by KAWs has also attracted attention as an electron acceleration process in the Jovian magnetosphere [e.g., Saur et al., 2018; Damiano et al., 2019]. While it has increased the importance of the electron acceleration process by KAWs in magnetized planets, there are still unresolved questions regarding the details of the process, such as the effect of δB_{jj} on the process, the conditions determining the efficiency of the electron acceleration, and the upper energy limit of the accelerated electrons.

In this study, we apply the second-order resonance theory, which has been applied to the electron acceleration processes by coherent whistler mode waves [e.g., Omura and Katoh, 2008; Hsieh and Omura, 2017; Kitahara and Katoh, 2019], to the electron acceleration process by KAWs. We calculate the conditions for the Landau resonance and estimate the amount of energy gained through the Landau resonance. If only δE_{jj} is considered, we can describe the motion of electrons trapped by KAWs as the balance between a simple harmonic motion of the wave phase as viewed from the electron ψ and the inhomogeneity ratio S due to the background magnetic field gradient. This is similar to the theory of the nonlinear motion of resonant electrons interacting with coherent whistler mode waves. Furthermore, when both δE_{jj} and δB_{jj} are considered, the motion of the trapped electrons is described by the balance between the superposition of two simple harmonic motions of ψ and 2ψ and the inhomogeneity ratio S. Here, the magnitude of the 2ψ oscillation is about $\delta B_{jj}/B_0$ relative to the ψ oscillation.

We apply the above discussion to the test particle simulation results for the electron acceleration process by KAWs in the terrestrial magnetosphere in the L-shell value equal to 9 [Saito et al., P-EM17-P08, JpGU Meeting, 2023]. We have confirmed that trapped electrons are detrapped from the KAW at the time when S exceeds 1. In addition to the above theoretical considerations and results, we discuss the amount of energy gained through the trapped/detrapped process and the contribution of δB_{jj}.

分散性 Alfvén 波の一種である kinetic Alfvén wave(KAW) は、磁力線垂直方向の波長がイオン Larmor 半径程度の電磁波動である。KAW は磁力線平行方向の電場 δE_{jj} を持ち、電子やイオンを磁力線平行方向に加速することが知られており、特に KAW の位相速度と同程度の磁力線平行方向の速度を持つ粒子と Landau 共鳴する [e.g., Hasegawa, 1976; Kletzing, 1994; Artemyev et al., 2015]。KAW は地球磁気圏のサブストームと関連があると考えられており [e.g., Stasiewicz et al., 2000]、KAW が電子を磁力線平行方向に数 keV 程度のエネルギーまで加速し、オーロラ増光を引き起こすことが指摘されている [e.g., Keiling et al., 2002; Duan et al., 2016]。さらに、KAW による電子加速が生じる地球磁気圏 L = 9 では、プラズマ β が $m_e/m_i < \beta < 1$ であり、プラズマ β の値に依存する KAW の磁力線平行磁場成分 δB_{jj}[Schekochihin et al., 2009] は、背景磁場 B_0 に対して 8% 程度となり、KAW の電子加速過程において無視できない値になると考えられる。木星磁気圏においても KAW による電子加速は重要な加速機構として注目され [e.g., Saur et al., 2018; Damiano et al., 2019]、磁化惑星における KAW による電子加速過程の重要性が高まる一方で、δB_{jj} が電子加速に与える影響や、電子加速が効率的に生じる条件、加速された電子のエネルギー上限といった、電子加速過程の詳細につ

いては未解決の問題が残されている。

本研究では、KAW による電子加速過程に対して、coherent whistler mode wave による電子加速過程の研究で用いられてきた 2 次共鳴理論 [e.g., Omura and Katoh, 2008; Hsieh and Omura, 2017; Kitahara and Katoh, 2019] を導入することで、Landau 共鳴における非線形効果を考慮した位相空間上での電子軌道の導出と、共鳴を通して電子が得るエネルギー量の推定を試みる。KAW の電子加速過程も、whistler mode wave の過程と同様の議論が可能である。KAW の δE_{jj} のみを考慮した場合、KAW に捕捉された電子の速度位相空間上の運動は、KAW の位相速度 v_{phjj} の周りの、電子から見た KAW の位相ψについての単振動と背景磁場勾配に起因する不均一性因子 S のバランスで記述される。一方で、KAW の δB_{jj} も考慮に入れた場合、KAW に捕捉された電子の運動は、v_{phjj} の周りで、KAW の位相ψと 2ψの 2 つの単振動の重ね合わせと不均一性因子 S のバランスで記述される。ここで、2ψの振動の大きさはψの振動に対して $\delta B_{jj}/B_0$ 程度である。さらに、地球磁気圏 L = 9 での KAW による電子加速過程に関するテスト粒子計算結果 [Saito et al., P-EM17-P08, JpGU Meeting, 2023] に対して、以上の議論を適用することで、不均一性因子 S が 1 を越えたタイミングで、KAW に捕捉されていた電子が非捕捉電子の軌道に遷移することが確認できた。本発表では、以上の理論検討や結果に加えて、共鳴過程を通して電子が得るエネルギー量や、KAW と電子の Landau 共鳴における δB_{jj} の寄与について議論する。

R008-10
C 会場 ：9/25　PM2 （15:45-18:15）
16:15〜16:30

電子・陽電子プラズマにおけるフィラメント不安定

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Filamentation Instability in Electron-Positron Plasmas

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The nonlinear interaction between electromagnetic waves and plasmas attracts significant attention in astrophysics because it can affect the propagation of Fast Radio Bursts (FRBs), which are luminous millisecond-duration radio pulses. The filamentation instability (FI), which is a kind of four wave interactions, is considered to be dominant near FRB sources, and its non-linear development may also affect the inferred dispersion measure of FRBs. In this study, we carry out fully kinetic particle-in-cell simulations of the FI in unmagnetized electron-positron plasmas. Our simulations show that the FI generates transverse density filaments, and that the electromagnetic wave propagates in near vacuum between them, as in a waveguide. The density filaments keep merging until force balance between the wave ponderomotive force and the plasma pressure gradient is established. We estimate the merging time-scale and discuss the implications of filament merging for FRB observations in this talk.

R008-11
C 会場 ：9/25　 PM2 （15:45-18:15）
16:30～16:45

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Effect of the magnetized parameter on particle acceleration in 2D Alfven turbulence

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Coherent large amplitude MHD waves are ubiquitous in space, and they are considered to play crucial roles in the acceleration of high energy cosmic rays. A number of models of large amplitude Alfven generation accompanying cosmic ray acceleration have been proposed so far [1-3]. In 2009, by 1D simulation, Matsukiyo and Hada [4] showed that a relativistic Alfven wave in a pair plasma is unstable to form the coherent standing wave form which consists of counter propagating Alfven waves. Recent studies have also shown that when the amplitude of the two counter-propagating Alfven waves exceeds critical amplitude any particles irreversibly gain relativistic energy within a short time regardless of their initial energy [5].

In this study, we investigate the particle acceleration in 2D Alfven wave turbulence where the long-time evolution of parametric instability could be different from that in 1D. It is clarified that the particle acceleration process strongly depends on the magnetized parameter (σ) due to the difference in the rate of decay process. In this talk, we discuss the effect of σ on particle acceleration in 2D Alfven turbulence.

[1] B. Zhang, ApJ. 836, L32 (2017).
[2] P. Kumar and P. Bosnjak, MNRAS. 494, 2385 (2020).
[3] X. Li, A. M. Beloborodov and L. Sironi, ApJ. 915, 101 (2021).
[4] S. Matsukiyo and T. Hada, ApJ. 692, 1004 (2009).
[5] S. Isayama, K. Takahashi, S. Matsukiyo and T. Sano, ApJ. 946 68 (2023).

R008-12
C 会場 ：9/25　 PM2 （15:45-18:15）
16:45～17:00

#凡　雨萌 [1), 松清　修一 [2), 銭谷　誠司 [3)
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Microscale fluctuations in a magnetic island in collisionless reconnection

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(1Kyushu University,(2Faculty of Engineering Sciences, Kyushu University,(3Space Research Institute, Austrian Academy of Sciences

Magnetic reconnection is a fast magnetic energy releasing process. It is widely observed in space and laboratory plasma such as solar flares, CME, substorms, tokamak devices etc. In the process of magnetic reconnection, magnetic energy is converted into the thermal and kinetic energy of plasma. When there are two or more X-points, magnetic island is formed. Inside a magnetic island one can often observe nonthermal particles as well as a variety of electromagnetic fluctuations. The origin of microstructures and nonthermal particles in a magnetic island has not been fully understood and extensively studied by using numerical simulations.

We conducted 2d PIC simulations of magnetic reconnection without guide field using periodic boundary conditions. The system size is $L_X*L_Y=25.6d_i*12.8d_i$ in which two Harris current sheets are distributed along $Y=L_Y/4$ and $Y=(3L_Y)/4$. We focus only on the lower half system, $0 \leq L_Y \leq 6.4d_i$, hereafter. Ion to electron mass ratio is $m_i /m_e=100$, and the ratio between the background density and current sheet density $n_b /n_0=0.2$, initial temperature ratio $T_i /T_e= 4$ for both background and current sheet particles.A perturbation of magnetic flux is added in an initial Harris sheet condition to trigger a reconnection at (X, Y) = (0, $3.2d_i$). In the development of magnetic island, micro-scale fluctuations are grown along the current sheet. We focus them here and their generation mechanism is discussed by carefully estimating parameters of local plasma. The result here is compared with the micro-fluctuations observed by Lu et al. (2011).

R008-13
C 会場 ：9/25 PM2 （15:45-18:15）
17:00～17:15

#星野　真弘 [1)]
[(1] 東大・理

Energy Partitioning of Thermal and Nonthermal Plasmas in 3D Magnetic Reconnection

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In our space and astrophysical collisionless plasmas, nonthermal particles whose energies are much higher than the thermal temperature are often observed, yet our understanding of the energy partitioning between thermal and nonthermal particles remains to be elucidated. In this presentation. we discuss the energy partitioning during magnetic reconnection by using PIC simulations. We have investigated the energy partitioning for hot plasmas in plasma sheet as a function of plasma sheet temperature from nonrelativistic to relativistic reconnection. For simplicity, we have assumed a pair plasma, and analyzed the hot plasmas heated by reconnection by fitting a model function composing of Maxwellian and kappa distributions. It was found that the nonthermal energy density can occupy more than 90% of the total kinetic plasma energy density in relativistic reconnection, and furthermore the efficiency of the nonthermal particle acceleration can be enhanced for three-dimensional system. However, the nonthermal particle acceleration efficiency decreases with decreasing the plasma sheet temperature.

R008-14
C 会場 ：9/25 PM2 （15:45-18:15）
17:15～17:30

テアリング不安定性の磁気流体線形理論から見た高速磁気再結合過程のトリガ問題

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Triggering problem of fast magnetic reconnection process in MHD linear theory of tearing instability

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Recently, a new MHD linear theory of tearing instability in 1D current sheet was proposed by largely improving the classical FKR theory (PhFl1963) and modern LSC theory (PoP2007), which is called as modified LSC theory. According to the new theory, the critical condition of the instability depends on the resistivity, viscosity and upstream boundary condition. Simply, when the resistivity and viscosity are fixed in the plasma, the relation of the upstream boundary and the thickness of current sheet simply determines whether the instability starts on the linear growth stage or not. That will be significantly suggestive for the controversial triggering problem of the fast magnetic reconnection in solar flares and geomagnetic substroms, where 3D current sheet is destabilized by tearing instability.

R008-P01
ポスター１：9/24　PM1/PM2 （13:45-18:15）

太陽コロナ中の非対称磁気リコネクション

#近藤　光志 [1)]
(1 愛媛大・RCSCE

Asymmetric magnetic reconnection in the solar corona

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(1Research Center for Space and Cosmic Evolution, Ehime University

Asymmetric magnetic reconnection plays crucial role in a lot of situations in the space plasma. We have shown using MHD simulations that the asymmetric magnetic reconnection is significantly different with the symmetric one, and we have verified our previous simulation results (models) using the in-situ observation in the magnetosphere. Next stage, we apply them to the solar corona phenomena. In this study, we show the asymmetric reconnection seen in the solar corona on the basis of our simulation models.

R008-P02
ポスター１：9/24　PM1/PM2（13:45-18:15）

非相対論的高マッハ垂直衝撃波における電子サーフィン加速効率の上流速度依存性について

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Upstream velocity dependence of the electron surfing acceleration efficiency in non-relativistic high Mach perpendicular shocks

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One of the most important problems with cosmic rays is the electron injection problem. This problem is that an unresolved acceleration mechanism for electrons to gain energy to enter the diffusive shock acceleration (DSA) is needed. Currently, the mechanism combining the shock drift acceleration (SDA) and the shock-surfing acceleration (SSA) is proposed. In particular, the Buneman instability is the key mechanism in the SSA. This is an electrostatic two-stream instability of cold electrons and ions, which excites a coherent electrostatic field in the shock transition region, leading to the electron acceleration.

The supernova remnant shocks, which are considered to be the main source of the galactic cosmic rays, have speeds of several thousands km/s (about 1% of the speed of light). However, current Particle-In-Cell (PIC) simulations have been conducted with the parameters of several tens of percent of the speed of light due to computational resource limitations. Under a fixed Alfven Mach number, decreasing the shock wave speed to the speed of light (V/c) corresponds to increasing the ratio of the electron plasma to gyro frequencies. This ratio is known to affect the saturation process of the Buneman instability. The Debye length consequently becomes small for large frequency ratios (=V/c<<1), increasing computational resources. Therefore, the simulations of high Mach number shocks have not been conducted with such large frequency ratios.

We have examined 1D PIC simulations of high Mach number shocks and found that lowering V/c tends to make the Buneman instability grow at higher amplitudes and result in higher electron acceleration efficiencies. In this study, we also examine 2D PIC simulations of high Mach non-relativistic perpendicular shock using the supercomputer Fugaku. We report the results of the Buneman instability growth under various frequency ratios. We discuss electron heating and acceleration efficiencies under such high frequency ratios, and resulting electron reflection ratio at the shock front in quasi-perpendicular shocks, which are recently actively studied by 2D PIC simulations.

超新星残骸における無衝突衝撃波は銀河宇宙線の加速源として考えられているが、その加速メカニズムについては解明されていない。大きな問題の一つとして電子の注入問題があるが、現在では電子が衝撃波統計加速（DSA）に入るエネルギーを得るために、衝撃波ドリフト加速（SDA）と衝撃波サーフィン加速（SSA）を組み合わせた電子加速機構が考えられている。このうち SSA での電子加速に大きく関わるのが Buneman 不安定性である。これは電子・イオンの 2 流体不安定性で、衝撃波遷移領域にコヒーレントな電場を励起し、電子の加速へと繋げる。一方、超新星残骸衝撃波速度はおよそ数千 km/s（光速の 1 %程度）であると考えられているのに対し、これまでの Particle-In-Cell（PIC）シミュレーションでは計算資源の制約により光速の数十%程度のパラメタで行われている。マッハ数一定の下で光速に対する衝撃波速度（V/c）を小さくすることは電子プラズマ/ジャイロ振動数比を大きくすることに相当し、この振動数比の大きさは Buneman 不安定性の飽和過程に対し影響を及ぼすことが知られている。また、大きな振動数比（= V/c<<1）ではデバイ長が相対的に小さくなり、その結果計算量は増大する。そのため大きな振動数比の下での高マッハ衝撃波での計算は行われていなかった。

これまで我々が行った 1 次元 PIC 計算により、V/c を下げることによって Buneman 不安定性がより大振幅へと成長し、コヒーレントな電子ホール、及び高い電子加速効率が見られた。そこで、本発表ではスーパーコンピューター「富岳」を用いた高マッハ数垂直衝撃波の 2 次元 PIC シミュレーションを行った結果を報告する。これまで行われていない非相対論的衝撃波速度での Buneman 不安定性について、そのパラメタ依存性や多次元性の効果を含めた解析結果を報告する。現在、無衝突衝撃波による電子加速について斜め衝撃波の研究が盛んに行われており、この垂直衝撃波での結果を元に斜め衝撃波における電子の反射効率について議論を行う。

R008-P03
ポスター１：9/24　PM1/PM2 （13:45-18:15）

1 次元 PIC 計算による大型レーザー実験における無衝突衝撃波生成機構の解明

#忍田　昂太郎 [1), 松清　修一 [1), 諫山　翔伍 [1), 坂和　洋一 [2), 山本　直嗣 [1), 森田　太智 [1), 山崎　了 [3), 田中　周太 [3), 竹崎　太智 [5), 富田　章久 [6), 境　健太郎 [4), 中山　学 [1), 塩田　珠里 [3), 花野　正浩 [2), 鈴木　悠斗 [2), 前之園　凱夫 [1), 金定　功樹 [1), 村本　裕耶 [1), 佐藤　弓真 [1), 矢倉　彰真 [3)
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1D PIC simulation of collisionless shock formation in high-power laser experiment

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It is known that a collisionless shock plays a role of energy converter in space. While it produces cosmic rays and large amplitude waves, detailed mechanism of the energy conversion has been unresolved so far. We have used Gekko XII high-power laser in the Institute of Laser Engineering at Osaka University to investigate microstructure of a collisionless shock. In the experiment a solid target surrounded by magnetized uniform gas is irradiated by the Gekko laser. The target plasma sweeps the ambient gas plasma so that a shock is formed in the gas plasma. However, the process of shock formation has not been well understood. Therefore, this study aims to resolve the mechanism of collisionless shock formation in the experiment by utilizing one-dimensional full particle-in-cell simulation.

The experimental circumstance is mimicked as follows. Initially, a homogeneous gas plasma at rest is distributed in space (-0.3 L <x <0.7 L). Then, a dense target plasma having bulk velocity V0 is injected at x=0 for a finite time (=tau). This target plasma plays a role of a piston to initiate a shock in the gas plasma. The gas plasma is magnetized along B0 which is applied in z-direction. The number of spatial grid is 90,000. The number of super-particles per cell is 128 for each species. The ion-to-electron mass ratio is 100 for the gas ions and 200 for the target ions. The ratio of electron density of the gas plasma to the target plasma is 1/7. The electron plasma to cyclotron frequency ratio in the gas plasma is 20. We performed a number of runs with different ambient magnetic field strength as well as the injection time of the target plasma. The dependence on the above parameters in the mechanism of shock formation will be reported.

我々は現在、激光 12 号レーザー（大阪大学レーザー科学研究所）を用いて無衝突衝撃波を生成する実験的研究に取り組んでいる。無衝突衝撃波は宇宙におけるエネルギー変換器の役割を担っており、宇宙線や大振幅波動の生成源として知られているが、エネルギー変換機構の詳細は未解明である。実験では、磁化した検査空間に設置した平板ターゲットに高出力レーザーを照射し、ターゲット由来の高速プラズマ流が背景ガスプラズマを圧縮して衝撃波を生成する。実験時の衝撃波の生成過程はよく理解されておらず、本研究では、実験環境を模した１次元フル粒子シミュレーションを用いて磁化プラズマ衝撃波の生成機構を理解する。

　初期（t=0）に１次元空間（-0.3L<x<0.7L）に静止したガスプラズマ（イオン価数 1）を配置し、有限の速度 V ⊠を持ったターゲットプラズマ（イオン価数 6）を x=0 から有限時間（=τ）注入することでガスプラズマ中に衝撃波を生成する。背景磁場として z 方向に B ⊠を印加しており、境界条件は反射境界とした。90000 の空間グリッドそれぞれに 128 の超粒子を粒子種ごとに配置している。電子に対するイオン質量比はガスイオンを 100、ターゲットイオンを 200、ガスとターゲット電子の密度比は 1:7、ガスプラズマの電子プラズマ周波数と電子サイクロトロン周波数の比は 20 とした。背景磁場強度（B ⊠）とターゲットプラズマの注入時間（τ）を変化させた計算を行い、無衝突衝撃波の生成過程におけるパラメータ依存性について報告する。

R008-P04
ポスター１：9/24　 PM1/PM2 （13:45-18:15）

大振幅アルフベン波の多次元発展のフル粒子計算

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Full-particle simulation of multidimensional evolution of a large-amplitude Alfven wave

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In general, an Alfven wave of finite amplitude propagating along magnetic field is unstable to parametric instabilities. Heating of plasma via parametric instabilities has attracted much attention in recent years, as it is regarded as a candidate mechanism for solar wind acceleration. Although there have been many studies on the long time evolution of parametric instability in the one-dimensional case where the direction of wave propagation is limited to the direction of the background magnetic field, there have been few studies on the multidimensional evolution of parametric instability. In this study, we use two-dimensional full particle-in-cell simulations to investigate the long-time evolution of waves when a low-beta monochromatic Alfven wave propagating in the direction of magnetic field is used as the parent wave. When a left-hand circularly polarized wave (amplitude of 0.6 of the background field and wavenumber normalized to the inverse of the ion inertial length, 1.23) is the parent wave, a short wavelength obliquely propagating waves are first excited, followed by the decay instability along the background field. In this case, more efficient plasma heating was observed than in the 1D calculation. In the presentation, we will also report the results of simulations for a right-hand polarized parent wave and different amplitudes of the left-hand and right-hand polarized parent waves.

一般的に、磁力線沿いに伝搬する有限振幅のアルフベン波はパラメトリック不安定性を起こすことが知られている。パラメトリック不安定性を介したプラズマの加熱は、太陽風加速の候補機構と目されるなど、近年注目されている。パラメトリック不安定性の長時間発展の議論は、波動の伝搬方向を背景磁場方向に限った空間１次元の場合には多くの既往研究があるものの、多次元発展の研究例は少ない。本研究では、２次元フル粒子計算を用いて、磁力線方向に伝搬する低ベータ単色アルフベン波を親波としたときの波動の長時間発展を調べる。親波として左回り円偏波（振幅は背景磁場の 0.6、イオン慣性長の逆数で規格化した波数は 1.23）を与えた場合、初めに短波長の斜め伝搬の波が励起され、これに続いて背景磁場に沿って崩壊不安定性が起こった。このとき、1 次元計算の場合よりも効率のよいプラズマ加熱が見られた。発表では、親波として右回り円偏波を与えた場合、背景磁場に対する親波の磁場振幅を変えた場合の計算結果についても報告する。

R008-P05
ポスター１：9/24　PM1/PM2 （13:45-18:15）

相対論的電子-陽電子プラズマ中のシンクロトロンメーザー不安定性の２次元発展

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Two-dimensional evolution of synchrotron maser instabilities in relativistic electron-positron plasmas

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Synchrotron maser instability (SMI) is one of the energy conversion processes from charged particles to electromagnetic fields. It has recently attracted attention as a physical mechanism that contributes to high-intensity emissions as well as particle acceleration observed in some high energy astrophysical phenomena. Although SMI has been extensively discussed in conjunction with numerical simulations of relativistic shocks, simulation studies focusing purely on the basic processes of SMI are seldom. The purpose of this study is to understand the fundamental properties of SMI in an electron-positron plasma by using two-dimensional periodic PIC simulation. We discuss the long-term evolution of the waves and particle acceleration process when the background magnetic field is taken out of the simulation plane (Z direction) and in the simulation plane (Y direction). In the out-of-plane case, X-mode waves were excited and the system evolution is similar to the case of one-dimensional simulations. In the in-plane case, in addition to the X-mode waves, waves propagating oblique to the background magnetic field, O-mode-like waves, and R- and L-mode waves propagating parallel to the background magnetic field were observed. Obliquely propagating waves and O-mode waves have high radiation intensity, and particles are energized by these waves in both parallel and perpendicular to the background magnetic field. The results are discussed in comparison with the past relativistic shock simulations.

シンクロトロンメーザー不安定性は荷電粒子から電磁場へのエネルギー変換過程の１つであり、パルサーなどの高エネルギー天体周辺に見られる相対論的衝撃波などで発生する。高輝度放射と粒子加速の両方に寄与する物理機構として近年注目されている。これまで、相対論的衝撃波の数値実験に付随して盛んに議論されているが、不安定性の素過程に着目した周期系での計算例は少ない。本研究では、２次元周期境界における電子-陽電子プラズマ中のシンクロトロンメーザー不安定性を PIC シミュレーションにより再現し、その基本的性質を理解することを目的とする。背景磁場を計算面外（Z 方向）にとった場合と計算面内（Y 方向）にとった場合のそれぞれについて、波動の長時間発展と粒子の加速過程を議論する。背景磁場を Z 方向にとった計算では、1 次元計算と同様、X 波が励起され、電磁場や粒子分布の時間発展には１次元計算との大きな違いは見られなかった。背景磁場を Y 方向にとった計算では、X 波に加えて、背景磁場に対して斜め方向に伝搬する波動や O 波的な波動、さらに背景磁場に平行方向に伝搬する R 波や L 波の励起が確認された。また、斜め伝搬の波や O 波的な波動の放射強度が高いこと、粒子がこれらの波動によって加速され、背景磁場方向にも速度を持つことなどが分かった。既往の衝撃波系の計算例を踏まえて結果を考察する。

R008-P06
ポスター 1 ：9/24　 PM1/PM2 （13:45-18:15）

平衡および非平衡プラズマにおける協同トムソン散乱の 2 次元フル粒子シミュレーション

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Two-dimensional full particle-in-cell simulation of collective Thomson scattering in equilibrium and non-equilibrium plasmas

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Thomson scattering measurement is commonly used to measure laboratory and ionospheric plasmas. When the wavelength of the incident wave is longer than the Debye length of the plasma, it is called collective Thomson scattering. In the collective Thomson scattering the spectrum of scattered light contains the information of the collective motion of electrons in the plasma. For example, the scattered light spectrum through Langmuir waves (called the electron feature) is a function of the electron density, temperature, and specific heat ratio of the electrons, and that through ion acoustic waves (called the ion feature) is a function of the ion valence, temperature, and specific heat ratio. Therefore, the parameters of the plasma can be estimated by theoretically fitting the measured scattered light spectra.

We aim to measure the transition region of collisionless shock waves generated in high-power laser experiments by collective Thomson scattering. In general, the transition region of a collisionless shock is in a highly nonequilibrium state. But the theory of collective Thomson scattering in a non-equilibrium plasma is not well developed. In this study, we reproduce the collective Thomson scattering in equilibrium as well as non-equilibrium plasmas by using full particle-in-cell (PIC) simulation to develop a scattering theory. Although in the past PIC simulations one-dimensionality and uniformity of space are assumed, the actual experimental system is two-dimensional and the incident light has a finite beam width. In this study, we reproduce the collective Thomson scattering of incident light with finite beamwidth by two-dimensional PIC simulations and discuss the characteristics of scattered light propagating in arbitrary directions. First, we reproduce the scattering in an equilibrium plasma and compare it with theory. Next, we reproduce collective Thomson scattering in a beam-plasma system as an example of a non-equilibrium system and discuss the results.

プラズマ中の自由電子による光のトムソン散乱は、実験室プラズマや電離層プラズマの計測に用いられている。入射波の波長がプラズマのデバイ長よりも長い場合は協同トムソン散乱と呼ばれ、プラズマ電子の集団運動を反映した散乱光スペクトルが得られる。これはプラズマ波動による光の散乱ととらえることができ、例えばラングミュア波による散乱光スペクトル（電子項とよぶ）はプラズマの電子密度や温度、比熱比の関数に、イオン音波によるもの（イオン項とよぶ）はさらにイオンの価数や温度、比熱比の関数になることが知られている。このため計測される散乱光スペクトルを理論フィッティングしてプラズマのパラメータを推定することができる。

我々は、大型レーザー実験で生成した無衝突衝撃波の遷移層構造を協同トムソン散乱で計測することを目指している。一般に、無衝突衝撃波の遷移層は著しい非平衡状態にあるが、非平衡プラズマによる協同トムソン散乱の理論は未整備である。そこで本研究では、数値シミュレーションによって非平衡プラズマの協同トムソン散乱を再現し、散乱理論の構築を目指す。これまでに、空間の 1 次元性と一様性を仮定した協同トムソン散乱の PIC 計算が行われているが、実際の計測システムは 2 次元系で、入射光は有限のビーム幅を持つ。本研究では、有限のビーム幅を持つ光を入射したときの協同トムソン散乱を 2 次元 PIC 計算で再現し、任意の方向に生成される散乱光の特徴について議論する。初めに平衡プラズマにおける散乱を再現し、電子項とイオン項の特徴を理論と比較する。次に、非平衡系の例としてビームプラズマ系での協同トムソン散乱を再現してその結果を議論する。

R008-P07
ポスター１：9/24　PM1/PM2（13:45-18:15）

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(1 東大

Generation of oblique whistler waves by an energetic electron beam

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Diffusive shock acceleration (DSA) stands as the leading candidate for producing high-energy particles, such as cosmic rays believed to be accelerated at supernova remnant shocks. However, it still faces a challenge known as the electron injection problem, as it cannot efficiently accelerate electrons with low energies. Overcoming this challenge necessitates higher-frequency waves capable of scattering these low-energy electrons to confine them around the shock.

Matsukiyo et al. (2011) proposed a self-generation mechanism wherein energetic electrons reflected in the upstream region of the shock locally excite oblique whistler waves. These waves scatter the electrons back toward the shock, potentially contribute to effective confinement of electrons close to the shock. Similar oblique wave generation ahead of the shock has been observed in simulations of non-relativistic shocks with various parameter regimes (e.g., Guo et al. 2014, Kobzar et al. 2021, Bohdan in 2022). It is also interesting to note that oblique wave generation mechanisms by an electron heat flux have been discussed for different astrophysical contexts, including the solar wind (Verscharen et al. 2019), solar flares (Roberg-Clark et al. 2019), and intracluster medium (Roberg-Clark et al. 2018). Understanding the wave generation mechanism by an energetic electron beam may help to solve the injection problem.

Our study aims at improving the understanding the conditions required for wave generation and the resulting scattering efficiency. We conduct two-dimensional (2D) Particle-In-Cell (PIC) simulations with a simplified periodic model to reduce the computational costs and, at the same time, ease the theoretical analysis. Our model assumes that the plasma consists of three particle population: background ions and electrons, and a hot electron beam propagating along an ambient magnetic field.

We have confirmed that, as predicted by Verscharen et al. (2019), the system becomes unstable when the beam velocity is larger than the electron Alfven velocity. We observe that the generated waves propagate at an angle of approximately 80 degrees with respect to the background magnetic field and the wave amplitude at saturation is around 0.1 times the background magnetic field. Our ongoing investigation focuses on exploring the dependence of wave generation on the beam velocity and the plasma to cyclotron frequency ratio. This investigation aims to understand the factors determining the saturation level and scattering efficiency in a realistic system.

R008-P08
ポスター１：9/24　PM1/PM2 （13:45-18:15）

オーロラ加速領域における電気二重層の計算機シミュレーション

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[(1 名大 ISEE,[(2 名大 ISEE

Comuputer simulation on the structure of double layer in the auroral acceleration region

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Electric fields in the acceleration region of the auroral zone have been observed through local observations (Mozer et al. 1977), which is known as electric double layers. The FAST observation showed detailed multi-dimensional structures of the auroral electric double layer (Ergun et al. 2001). Recently, observations by Arase have suggested the presence of electric fields parallel to magnetic field lines in the magnetosphere at altitudes of 30,000 km (Imajo et al. 2020). Simulations of the electric fields in the auroral acceleration region have been performed by one-dimensional Vlasov equations (Newman et al. 2001). They have shown that electric double layers have been generated by a strong density depression in current-carrying plasmas. However, multi-dimensional kinetic simulations on the formation of double layers in a current-carrying plasma have not been performed over twenty years due to both computational resources and computational techniques. In the precious study, we perform two-dimensional Particle-In-Cell simulations of a current-carrying plasma with a density depression. The formation of electric double layers has been confirmed in two-dimensional current-carrying plasma for ω_{ce}/ω_{pe}=0.1-1.0. However, it has also been confirmed that the lifetime of electric double layers becomes shorter with a larger ambient magnetic field. Detailed analyses on the decay process of electric double layers will be made.

オーロラ領域において、電気二重層として知られる加速電場の存在がその場の衛星観測によって発見された (Mozer et al. 1977)。また、FAST 衛星観測によってオーロラ領域の電気２重層の詳細な多次元構造が明らかにされた (Ergan et al. 2001)。さらに、最近のあらせ衛星の観測により、高度 30000km の磁気圏においても磁力線に平行な加速電場の存在が示唆された (Newman er al. 2001)。一次元 Vlasov シミュレーションにより、加速電場の形成が研究されてきた (Newman et al. 2001)。Newman et al. (2001) は、電流を運ぶプラズマ中に強い密度降下を与えることによって電気二重層が形成されることを示した。しかし、二次元における電気二重層の形成に関する運動論的シミュレーションはこれまでに行われてこなかった。そこで本研究では、Newman et al. (2001) の強い密度降下を持つプラズマ電流モデルを、PIC シミュレーションを用いて２次元に拡張する。その結果、ω_{ce}/ω_{pe} =0.1-1.0 において電気二重層の形成が確認できた。しかし、背景磁場の強度が大きくなるにつれて電気二重層の寿命が短くなることも確認できた。電気二重層の崩壊メカニズムについての詳細な解析を行う。

R008-P09
ポスター１：9/24　PM1/PM2（13:45-18:15）

PINNsを用いたMHD現象におけるプラズマパラメータ予測

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Prediction of plasma parameters in MHD phenomena by using PINNs

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In space, satellite observations can access to microstructure of plasma phenomena. The MMS (Magnetospheric Multiscale) mission, for instance, utilizes a formation flight of four satellites to measure microscale spatio-temporal structure of a plasma. To discuss the physics of plasma phenomena, numerical simulations are commonly used for the comparison with the observational data [1,2]. In this way, the boundary conditions and initial conditions are set to be consistent with the observed data. In this case symmetry and/or planarity of the system are often assumed. However, in reality, there are observational data that cannot be explained solely by comparison with such simplified systems, and there may be still yet-to-be unexplained physics. While attempts have been made to reconstruct the two-dimensional structure of plasma directly from observational data, they assume that the plasma is in equilibrium [3,4]. However, actual plasma phenomena are multidimensional and dynamic so that it is difficult to reconstruct such spatio-temporal evolution from the observation data.

With the recent advancements in AI research, a method called Physics-informed Neural Networks (PINNs) has been proposed [5]. In this approach, unknown physical parameters are predicted from limited data to satisfy the governing equations describing physical phenomena. As a first step of this study, by using numerical simulations, we use the PINNs to predict spatio-temporal structures of MHD phenomena such as magnetic reconnection and magnetic turbulence. By using the observed data as a training data, the parameters apart from the observation points are predicted to satisfy the MHD equations. In this approach, the unknown parameters can be predicted without setting the initial and boundary conditions explicitly. Therefore, if this method is established, it is expected to greatly contribute to understand spatiotemporal behavior of MHD phenomena. In our presentation, we discuss the development status of the prediction model and prospects.

宇宙では衛星観測により、宇宙プラズマ現象のミクロ構造の情報にアクセスすることができる。MMS (Magnetospheric Multiscale) ミッションでは、4機の衛星を編隊飛行させることで、プラズマの時空間構造を計測している。観測データからプラズマ現象の時空間発展を議論する際には、通常数値シミュレーションを比較対象として用いる [1, 2]。この時、境界条件と初期条件は観測データと矛盾がないように設定されるが、構造の対称性や平面性などを仮定する場合が多い。しかし実際には、このように簡略化されたシステムとの比較からだけでは説明できない観測データも存在し、その中には、未だ明らかにされていない物理が残されている可能性がある。観測データから直接プラズマの二次元構造を再構築する試みも行われているが、これらはプラズマの平衡状態を仮定したものである [3,4]。実際のプラズマ現象は多次元かつダイナミックであり、そのような構造の時空間発展を衛星データから直接再構築する事は困難である。

近年の AI 研究の発達に伴い、Physics-informed Neural Networks (PINNs) [5] という手法が提案された。本手法では、限られた観測パラメータから物理現象を記述する支配方程式を満たすように他の物理パラメータを予測することが可能である。本研究における最初のステップとして、数値シミュレーションによって観測データを模擬し、PINNs を用いて磁気リコネクションや磁気乱流等の MHD 現象における時空間構造の予測を行う。本手法では、初期条件や境界条件を明示的に定める必要がなく、観測データのみから観測領域以外のパラメータを推定することができる。本手法を確立できれば、MHD 現象の時空間構造の解明につながると考えられる。本セッションでは、予測モデルの開発状況と今後の展望について述べる。

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R008-P10
ポスター１：9/24　PM1/PM2 （13:45-18:15）

スケール間結合現象再現に向けた連結階層 MHD-PIC シミュレーションの開発

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Development of MHD-PIC simulation for Reproducing multiscale coupling phenomena.

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The evolution of large-scale structure in the Earth's magnetosphere has been understood by assuming that the ideal MHD conditions are approximately satisfied. Global MHD simulations have reproduced the behavior of the global magnetosphere-ionosphere based on this concept, and have contributed to the understanding and prediction of plasma dynamics and space weather phenomena. However, for phenomena such as magnetic reconnection and other phenomena that involve a violation of the ideal MHD, the only way to describe the effect is to use the electric anomaly resistance and viscosity coefficient in Ohm's law, and to reproduce the phenomena, parameterization of the various coefficients based on observation facts and empirical laws is generally required. In order to reproduce the phenomena, parameterization of the coefficients based on observed facts and empirical rules is common practice. Naturally, this parameterization is not always consistent with the universality of plasma physics based on kinetic theory.For example, in the diffusion region, PIC simulation calculations have confirmed the formation of a peculiar electromagnetic field structure produced by the difference in inertial length between ions and electrons [Zenitani et al. 2016]. It has also been observed that in the nightside magnetosphere, the explosive flow structure formed by magnetic reconnection can cause secondary magnetic reconnection [Wang et al.,2014], and it has been shown that for the development of macro-scale electromagnetic field structure and plasma dynamics, the underlying plasma kinetic behavior of the underlying plasma particles is considered to be an essential contribution to the development of macroscale electromagnetic field structure and plasma dynamics.

The ideal global simulation is a first-principles three-dimensional PIC simulation of the full particle-electromagnetic field interaction evolution, but this is not possible due to computational resource constraints. In this study, we are developing a MHD-PIC coupled hierarchical simulation, in which a dynamic PIC method calculation domain is embedded in a part of the global MHD simulation, aiming at a smooth connection between micro and macro phenomena. In this presentation, we will report the current status of the development and discuss future prospects and problems.

地球磁気圏における大規模構造の発展は理想 MHD 条件が近似的に成立していると見做すことにより理解されてきた。グローバル MHD シミュレーションはこのようなコンセプトの下、大域的磁気圏-電離圏の振る舞いを再現し、宙空領域におけるプラズマダイナミクスや宇宙天気現象の理解、予測等に日々貢献している。しかしながら、磁気リコネクション現象をはじめとする理想 MHD の破れを伴う現象については、オームの法則において電気異常抵抗や粘性係数などでその効果を表現するしか手段が無く、且つ、現象の再現のためには、諸係数を観測事実や経験則に基づくパラメタリゼーションを行うことが一般的となっている。当然のことながら、このパラメタリゼーションは運動論に基づくプラズマ物理学の普遍性と常に合致するものでは無い。例えば拡散領域においてはイオンと電子の慣性長の違いから生み出される特異な電磁場構造が形成されることが PIC シミュレーション計算により確認されている [Zenitani et al.,2016] 。また夜側磁気圏においては磁気リコネクションが形成する爆発的なフロー構造は二次的な磁気リコネクションを引き起こすことも観測されており [Wang et al.,2014]、マクロスケールな電磁場構造およびプラズマダイナミクスの発展に対して、その根底に存在するプラズマ粒子の運動論的振る舞いが本質的に寄与していると考えられる。

グローバルシミュレーションの理想は第一原理である三次元 PIC シミュレーションによる完全な粒子-電磁場相互作用の発展計算であるが、計算資源の制約上不可能である。本研究ではミクロ現象とマクロ現象のスムーズな接続を目指して、グローバル MHD シミュレーションの一部領域に動的な PIC 法計算領域を埋め込んだ MHD-PIC 連結階層シミュレーションの開発を進めている。本発表では開発の現状と今後の展望、問題点について議論する予定である。

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コード間結合フレームワークに基づく宇宙環境変動－衛星帯電現象連成解析プラットフォームの開発

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Development of the Space-Weather-Aware Satellite Charging Analysis Platform based on the Numerical Code Coupling Framework

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The assessment of spacecraft charging is one of the important technical elements of space weather forecasting system. Numerical simulations based on the particle-in-cell (PIC) method are widely used for quantitative analysis of spacecraft charging processes in space environment. Due to the high computational cost for advancing the motions of a large number of plasma particles, the method allows us to simulate only phenomena of very limited temporal and spatial scales within practical computation time. This feature makes it difficult to analyze temporal evolution of a spacecraft potential in space environment that changes dynamically.

In this study, we develop a simulation platform that couples the dynamics of the Earth's magnetosphere and satellite charging simulations. The platform enables us to assess a spacecraft potential evolution in a longer time period, which can cover space environmental variations associated with space weather events. Specifically, the Earth's magnetosphere environment during space weather events is simulated by means of a global MHD simulation, and the obtained time-series data of environmental parameters will be served as an input for the spacecraft charging analysis. One of major difficulties of such coupled analysis is the large difference in temporal scales between the magnetospheric dynamics and spacecraft charging phenomena. To address the issue, we have decided to avoid coupling the MHD and PIC computations directly. Instead of PIC simulations, a single/multiple set of ordinary differential equations representing the potential evolutions of individual satellite elements are coupled with the MHD calculations, which allows us for long-time spacecraft charging predictions. The plasma currents, which are source terms of the differential equations, are evaluated based on an analytical model or current-voltage (I-V) characteristic database prepared for each satellite. Such I-V database are constructed in prior to the coupled analysis by performing a large (but manageable) number of small-scale plasma particle simulations.

From an information science perspective, we utilize in-house code-to-code coupling framework named CoToCoA (Code-To-Code Adapter) for coupling the MHD and spacecraft charging calculations. Based on the framework, the coupled analysis can be executed as a single MPI parallel program that encompass the above model calculations as its subcomponents. It is expected that the approach enables us for efficient use of modern supercomputers. The paper focuses on design details of the developed platform and their validity in terms of a coupled physical model involving different temporal and spatial scales.

宇宙環境変動に対する衛星帯電の予測評価は、宇宙天気予報における重要な技術要素の一つである。衛星帯電過程の定量的解析には、粒子（PIC）法に基づく数値シミュレーションが広く用いられる。PIC 法はその計算コストの大きさにより、現実的に利用可能な計算資源では非常に限られた時間的・空間的スケールの現象しかシミュレーションできない。このため、動的に変化する宇宙環境における長期の衛星電位時間発展を解析することは困難である。

本研究では、地球磁気圏ダイナミクスと衛星帯電シミュレーションを連成させたシミュレーションプラットフォームを開発する。当プラットフォームは、宇宙天気現象に伴う宇宙環境変動を包摂したより長期の衛星電位時間発展を評価することを目的に開発されている。じょう乱時の地球磁気圏環境をグローバル MHD シミュレーションによって再現し、得られた環境パラメータの時系列データを衛星帯電解析の入力とする。このような連成解析の大きな困難の一つは、磁気圏ダイナミクスと宇宙機帯電現象の時間スケールが大きく異なることである。この問題に対処するため PIC 計算の代替として、個々の衛星要素の電位時間発展を記述する常微分方程式の単一/複数セットを MHD 計算と連成させ、長時間の衛星帯電予測を行う。微分方程式のソース項であるプラズマ電流は、各衛星要素に対応した準解析解もしくは事前に作成した電流電圧特性データベースに基づいて評価される。

本研究では MHD シミュレーションと衛星帯電計算を結合するために、著者らが独自に開発を行ったコード間結合フレームワーク CoToCoA（Code-To-Code Adapter）を用いる。当該連成フレームワークにおいては、MHD および衛星帯電計算をサブコンポーネントとして包含する単一の MPI 並列プログラムとして実行される。当アプローチにより、開発

された連成数値予測モデルを最新のスーパーコンピュータに容易に適合させることが可能となる。本論文では、開発したプラットフォームの設計の詳細と、異なる時空間スケールを含む連成物理モデルの効率性の観点について議論を行う。

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Dynamic Load-Balancing Framework for Kinetic Plasma Simulations

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Kinetic plasma simulations have been playing increasingly important roles in the numerical modeling of collisionless and weakly collisional space, astrophysical, and laboratory plasmas. The standard numerical method for solving Vlasov or Boltzmann equation is the so-called Particle-In-Cell (PIC) scheme. The PIC scheme approximates the velocity distribution function by the superposition of computational particles that move continuously in phase space. While it has been proven useful for modeling plasma dynamics with a relatively small number of particles, it does not necessarily fit well with the conventional parallelization strategy based on the static domain decomposition on a distributed memory system. Namely, any inhomogeneity in the plasma density naturally introduces unequal computational loads among different processes, substantially degrading the parallelization efficiency. In particular, since the inhomogeneity often significantly evolves over time, the computational load balancing must be performed dynamically. Given the ever-increasing parallelism in modern supercomputers, the dynamic load-balancing capability is now a necessary feature for a parallel PIC-type code.

We have been developing a generic dynamic load-balancing framework for PIC-type plasma simulation codes. It is based on "chunking" the computational domain. In other words, the entire domain is divided into small chunks, with the number of chunks typically more than ten times larger than the number of processes. The chunks are dynamically distributed among different processes to balance the computational load. The framework automatically handles the distribution of chunks and boundary exchanges between the chunks (both particles and mesh quantities). It is designed such that an application programmer is able to implement solvers without knowing the details of parallelization and load balancing. A standard explicit PIC simulation code implemented on top of the framework has been working with good parallelization efficiency.

We report the present status of the framework and discuss future perspectives. Some of the objectives include the implementation of higher-order shape functions to the explicit PIC code with Esirkepov's density decomposition scheme and a hybrid simulation algorithm (particle ions and fluid electrons). Furthremore, migration to fully asynchronous implementation using task parallelism and Kokkos library for heterogeneous architecture (including GPUs) will be discussed.