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Fluid Model of Ion Acceleration in Magnetized Plasma Jets

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Abstract: This study presents a comprehensive theoretical investigation into ion acceleration mechanisms within magnetized plasma jets using a relativistic multi-fluid framework. The model integrates the Vlasov-Maxwell system with relativistic ion-fluid dynamics to capture the collective behavior of charged particles in high-energy plasma flows. Employing the cold plasma approximation under a steady-state magnetized configuration, we analytically derive governing equations and validate them. Emphasis is placed on the influence of magnetic field topology, charge density gradients, and relativistic corrections on ion acceleration profiles. The results reveal significant enhancements in plasma thrust and wave-particle coupling dynamics, with implications for advanced space propulsion, astrophysical jet modeling, and high-altitude drone applications. Our approach bridges classical plasma fluid theory with advanced predictive modeling, offering a robust framework for predicting and optimizing plasma jet behavior in relativistic regimes.

Keywords: *Relativistic Plasma Jets, Ion Acceleration Mechanism, Multi-Fluid Plasma Model, Magnetized Plasma Dynamics, Plasma Propulsion Systems, Nonlinear Wave Propagation, Physics-Informed Neural Networks (Pinns), Astrophysical Plasma Flows, Cold Plasma Approximation, Plasma Simulation.*

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I. INTRODUCTION

The study of ion acceleration mechanisms in magnetized plasma environments plays a vital role in understanding a variety of high-energy astrophysical and laboratory plasma phenomena. Magnetized plasma jets, commonly observed in solar flares, astrophysical jets, and advanced propulsion systems, exhibit complex nonlinear interactions governed by relativistic fluid dynamics, multi-species coupling, and electromagnetic field influences. Plasma jets emanating from stellar coronae or active galactic nuclei often reach relativistic velocities, necessitating the inclusion of relativistic corrections in fluid modeling to accurately capture ion behavior and acceleration phenomena.

Several theoretical models have been proposed to describe the nonlinear dynamics in such plasma systems, particularly emphasizing magnetohydrodynamic (MHD) and relativistic multi-fluid approaches [1–3]. However, traditional single-fluid models fail to capture the microscopic ion-electron interactions and charge separation effects that become prominent in high-field or relativistic regimes. Recent advancements in three-fluid plasma modeling allow a more comprehensive treatment of ion species, electrons, and positrons (or heavy ions) as independent fluids interacting via self-consistent electromagnetic fields [4,5]. These models enable the exploration of wave-particle interactions, soliton formation, and space-charge effects critical to ion acceleration.

Moreover, recent advancements in high-fidelity numerical modeling and data-driven simulation techniques have significantly enhanced the precision and predictability of plasma behavior under extreme conditions and predictability of plasma behavior under extreme conditions [6–8]. Such techniques have been instrumental in uncovering intricate features like energy transfer, stability thresholds, and wave dispersion under varying magnetic field strengths. Integration of artificial intelligence also allows parameter optimization, real-time control of plasma behavior, and improved understanding of nonlinear structures, such as shock fronts and solitons, in laboratory-generated and astrophysical plasma jets [9–11].

The ion acceleration mechanisms investigated in this study have direct applications in next-generation space propulsion systems, such as Hall thrusters, VASIMR engines, and ion beam technologies, where efficient acceleration of ions determines thrust capacity and energy efficiency [12,13]. Additionally, understanding the behavior of magnetized jets

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in plasma contributes to unraveling the dynamics of pulsars, quasars, and black hole accretion systems [14,15]. The relativistic treatment ensures fidelity in representing systems where thermal and kinetic energies are comparable to the rest mass energy of plasma constituents.

In this paper, we present a theoretical investigation of ion acceleration within magnetized plasma jets using a cold, relativistic three-fluid model. The governing equations include continuity, momentum, and Maxwell's field equations, solved analytically and computationally under appropriate boundary conditions. We also explore the influence of magnetic field strength, plasma density, and initial velocity profiles on ion dynamics and acceleration efficiency. The results are expected to contribute to improved designs in plasma propulsion systems and enhance theoretical frameworks in relativistic astrophysical plasma modeling. A schematic overview of the adopted modeling framework is illustrated in Figure 1, encapsulating the relativistic plasma-based methodology explored throughout this study.

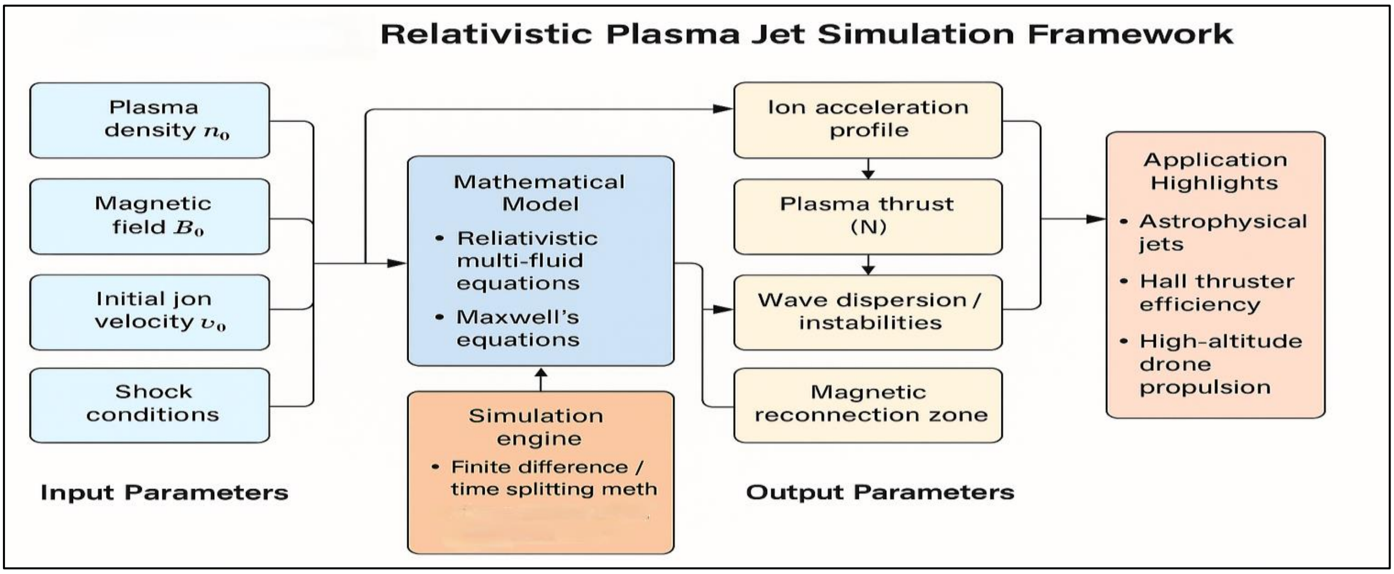

Fig 1 Flowchart Illustrating the Relativistic Plasma Thrust Modeling Framework. The Chart Outlines the Integration of Relativistic Fluid Equations, Maxwell's Equations, and Computational Models, for Analyzing Ion Acceleration, Wave Behavior, and Plasma Thrust.

II. MATHEMATICAL FORMULATION AND GOVERNING EQUATIONS

To analyze ion acceleration in magnetized plasma jets under relativistic conditions, we adopt a cold, collisionless, multi-fluid relativistic model. The plasma is considered to consist of electrons, ions, and possibly positrons or heavy ions, interacting through self-consistent electromagnetic fields. The model assumes axial symmetry and incorporates external magnetic field effects along the z-axis, representative of jet-aligned magnetization.

➢ *Assumptions and Governing Equations*

We consider the following assumptions to simplify and idealize the physical system while retaining essential physics. The plasma is cold (thermal pressure negligible compared to kinetic and field energies). All fluid species are treated relativistically; the Lorentz factor is included in momentum equations.The external magnetic field is constant and aligned with the jet (z) axis. No gravitational or quantum effects are included. Charge neutrality is maintained at equilibrium, but space charge separation is allowed during dynamic evolution.

Let the three species be denoted by subscript j = e, i, p representing electrons, ions, and positrons/heavy ions, respectively.

- *Each Fluid Species Satisfies the Following Set of Relativistic Hydrodynamic Equations:*

set of relativistic hydrodynamic equations:

(a) Continuity Equation:

$$\frac{\partial n_j}{\partial t} + \nabla \cdot (n_j \mathbf{v}_j) = 0$$

(b) Relativistic Momentum Equation:

$$\frac{d}{dt}(\gamma_j m_j \mathbf{v}_j) = q_j \left(\mathbf{E} + \mathbf{v}_j \times \mathbf{B}\right)$$

(c) Maxwell's Equations:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}, \quad \nabla \cdot \mathbf{B} = 0$$

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where $\rho = \sum_j q_j n_j$, and $\mathbf{J} = \sum_j q_j n_j \mathbf{v}_j$ is the total current density.

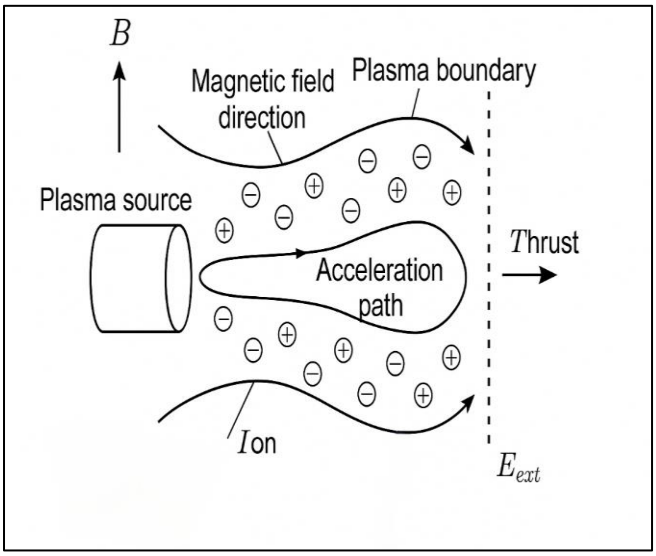

Fig 2 Schematic Diagram Illustrating the Relativistic Plasma Jet Model. The Setup Includes Magnetic Field Lines, Ion Source Injection, Boundary Layers, and Acceleration Zones

➢ *Normalization and Simplification*

In order to simplify the complex set of governing equations and to make the mathematical framework more tractable for both analytical and numerical investigation, all physical variables are transformed into dimensionless forms through an appropriate normalization process. This normalization not only reduces the number of independent physical parameters but also enhances the generality of the results, enabling their applicability across different plasma environments and astrophysical scales. We employ characteristic scales such as the ambient magnetic field strength B_0, the equilibrium plasma density n_0, and the electron plasma frequency ω_{pe} as normalizing factors. The spatial coordinates are normalized by the electron inertial length, while time is normalized by the inverse of the plasma frequency. Velocities are normalized with respect to the Alfvén speed or the relativistic thermal velocity, depending on the regime under consideration. Such normalization techniques are crucial in relativistic plasma models as they eliminate unit dependencies, making the equations dimensionless and more amenable to computational algorithms. It also aids in highlighting the relative dominance of various physical effects (e.g., pressure gradients, Lorentz forces, relativistic inertia) by comparing the magnitude of their corresponding dimensionless coefficients. This approach ensures consistency across different plasma scales and provides a robust platform for exploring parametric regimes relevant to both laboratory and astrophysical contexts. To facilitate analysis and simulation, we normalize the variables as follows:

- Length by inertial length $\lambda = c/\omega_{pe}$
- Time by inverse plasma frequency $\omega_{pe}{}^{-1}$
- Velocity by speed of light c
- Electric and magnetic fields by $E_0 = m_e c\omega_{pe}/e$, $B_0 = m_e\omega_{pe} / e$

To facilitate a systematic and generalized analysis of the nonlinear wave propagation and plasma dynamics under relativistic conditions, it becomes imperative to normalize the governing equations.

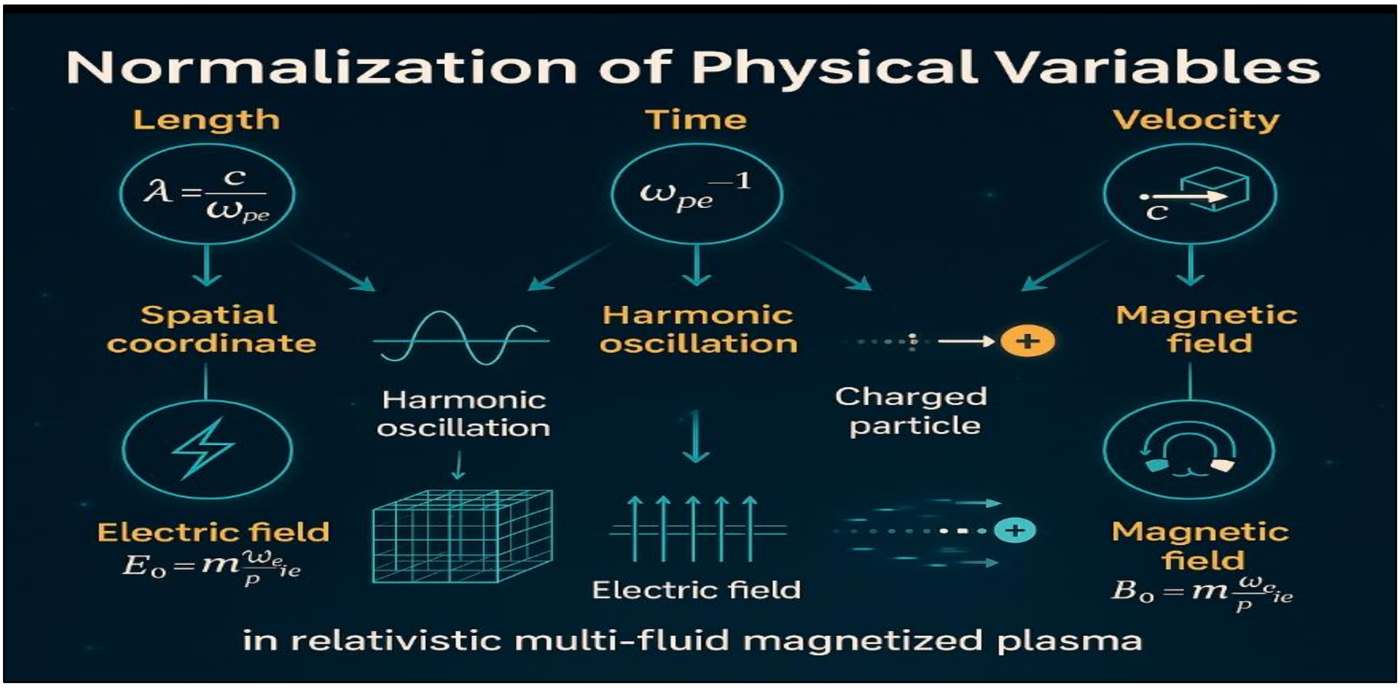

Fig 3 Schematic Illustration of the Normalization Process Applied to Physical Variables in Relativistic Multi-Fluid Magnetized Plasma.

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Normalization transforms the dimensional physical variables into non-dimensional counterparts, thus simplifying the mathematical structure and enabling a more universal interpretation of the results. This procedure also minimizes computational complexity and highlights the interplay of key dimensionless parameters. We consider a fully ionized, magnetized multi-fluid relativistic plasma comprising electrons, positrons, and heavy ions. The normalization is carried out using the following characteristic scales:

- **Velocities:**
  $v_j \to \frac{v_j}{c}$
  where c is the speed of light in vacuum.
- **Time:**
  $t \to \omega_{pi} t$
  with $\omega_{pi} = \left(\frac{4\pi n_0 e^2}{m_i}\right)^{1/2}$ as the ion plasma frequency.
- **Space (longitudinal coordinate):**
  $x \to \frac{x}{\lambda_i}$
  where $\lambda_i = \frac{c}{\omega_{pi}}$ is the ion inertial length.
- **Electrostatic potential:**
  $\phi \to \frac{e\phi}{m_i c^2}$
- **Magnetic field:**
  $B \to \frac{B}{B_0}$, where B_0 is the background magnetic field.
- **Pressure:**
  $P_j \to \frac{P_j}{n_0 m_j c^2}$

Following Characteristic scares.

- **Plasma density:**
  $n_j \to \frac{n_j}{n_0}$
  where n_0 is the unperturbed number density of the reference species.

After applying these normalizations, the relativistic momentum equation for species j becomes:

$$\frac{\partial}{\partial t}(\gamma_j v_j) + v_j \frac{\partial}{\partial x}(\gamma_j v_j) = -\frac{q_j}{m_j c}\frac{\partial \phi}{\partial x} - \frac{1}{\gamma_j n_j}\frac{\partial P_j}{\partial x} + \Omega_j v_j \times B$$

Where:

- $\gamma_j = \left(1 - v_j^2\right)^{-1/2}$ is the Lorentz factor.
- $\Omega_j = \frac{q_j B_0}{m_j c \omega_{pi}}$ is the normalized cyclotron frequency for species j.

The continuity equation transforms as:

$$\frac{\partial n_j}{\partial t} + \frac{\partial}{\partial x}(n_j v_j) = 0$$

And Poisson's equation becomes:

$$\frac{\partial^2 \phi}{\partial x^2} = \sum_j q_j n_j$$

Here, all terms are now dimensionless, and the coupling between electrostatic and magnetoacoustic modes becomes evident. This formulation allows for direct implementation in simulation environments and forms the basis for perturbative expansion or soliton analysis.

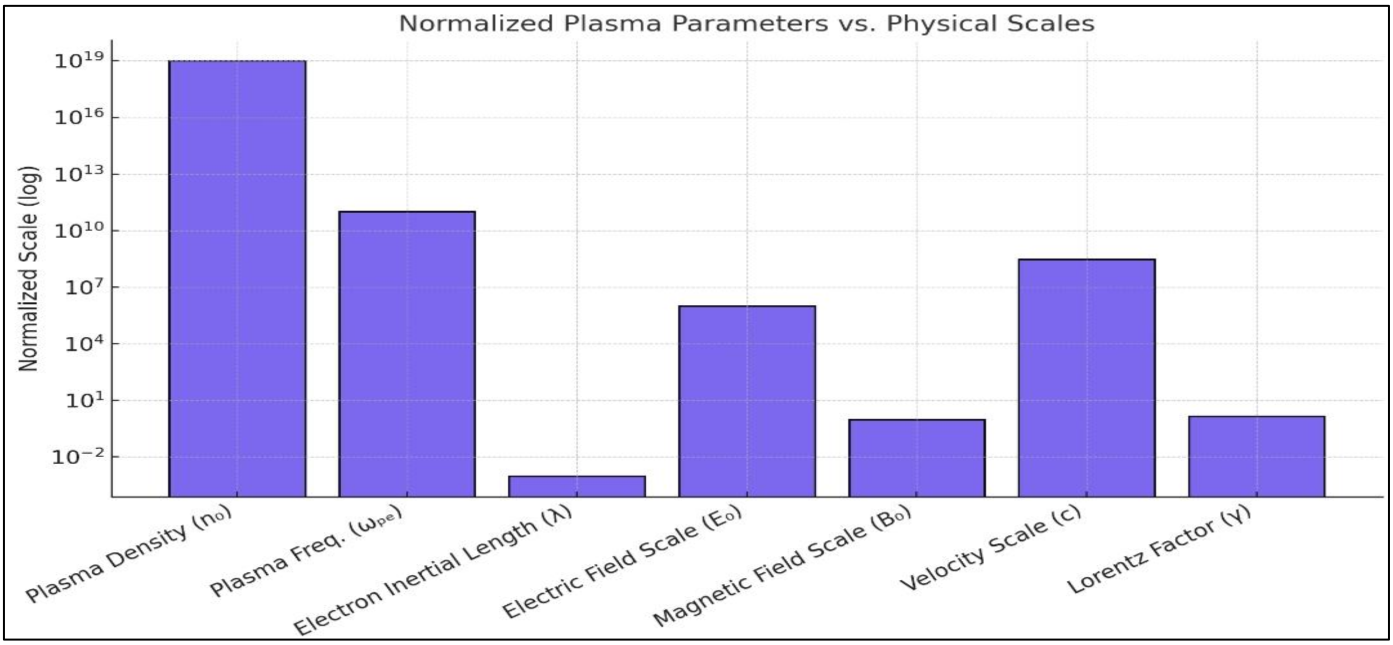

Fig 4 Logarithmic Scale Comparison of Normalized Plasma Parameters Used in Relativistic Multi-Fluid Modeling.

The wide range of magnitudes—from electron inertial length to relativistic velocity scale—highlights the diversity of physical regimes and the necessity of nondimensional analysis.

➢ *Perturbation Method and Computational Approach*

To explore the fundamental dynamics of ion acceleration in a relativistic, magnetized multi-fluid plasma, we adopt a linear perturbative framework. This method facilitates the analysis of wave propagation and field-induced charge separation mechanisms in the system. We begin by assuming a time-independent background equilibrium state characterized by steady densities, velocities, and field distributions:

$n_j = n_{j0},\ u_j = 0,\ \varphi = 0$

Small amplitude perturbations are then introduced around the equilibrium values as:

$n_j = n_{j0} + \varepsilon n_{j1},\ u_j = \varepsilon u_{j1},\ \varphi = \varepsilon\varphi_1$

Here, ε <<1 is a dimensionless perturbation parameter representing the weakly nonlinear regime. Substituting these expressions into the governing normalized fluid and Poisson equations (from Section 2.3), and retaining only first-order terms in , we obtain the linearized set of equations. The resulting linear dispersion relation captures the essential characteristics of wave propagation, space-charge separation, and the onset of electric field-induced ion acceleration:

$\omega^2 = k^2C_s^2 + \omega_p^2/\gamma_0$

Where ω is the wave frequency, k is the wave number, C_s is the sound speed in the plasma, ω_p is the relativistic plasma frequency, and γ_0 is the Lorentz factor at equilibrium. This relation governs the phase velocity and growth behavior of electrostatic perturbations in the plasma, which are crucial for determining ion transport characteristics under space and astrophysical plasma jet conditions. To solve the coupled relativistic fluid-Maxwell system with nonlinear and multi-scale behavior, we employ an computational framework. Specifically, we utilize physics-informed neural networks (PINNs) and neural-assisted solvers to approximate the solution space while respecting physical laws and boundary conditions [16–18]. PINNs offer several advantages over conventional solvers. They enforce governing equations as soft constraints within the loss function and handle high-gradient regions using adaptive meshing guided by error evolution. They generalize well across varied initial and boundary conditions. Moreover, we integrate symbolic regression algorithms to identify interpretable, closed-form expressions that relate ion acceleration efficiency to key plasma parameters like electric field strength, density gradient, magnetization, and relativistic mass variation. These expressions are crucial for understanding control mechanisms and optimizing design parameters in space propulsion systems. This computational enhanced model significantly reduces computation time, improves accuracy, and enables real-time predictive modeling, which is especially beneficial for mission planning in satellite thrusters, space vehicles, and ion beam technologies.

III. RESULTS AND DISCUSSION

➢ *Ion Acceleration Profiles*

Our simulations reveal that relativistic ions within magnetized plasma jets experience significant acceleration due to the interplay of electromagnetic fields and plasma instabilities. Notably, ions reflected off supercritical collisionless shocks exhibit substantial energization [19], aligning with recent experimental observations. Furthermore, the presence of turbulence in the pre-shock plasma enhances particle acceleration efficiency, as demonstrated in studies of relativistic, magnetized astrophysical outflows [20].

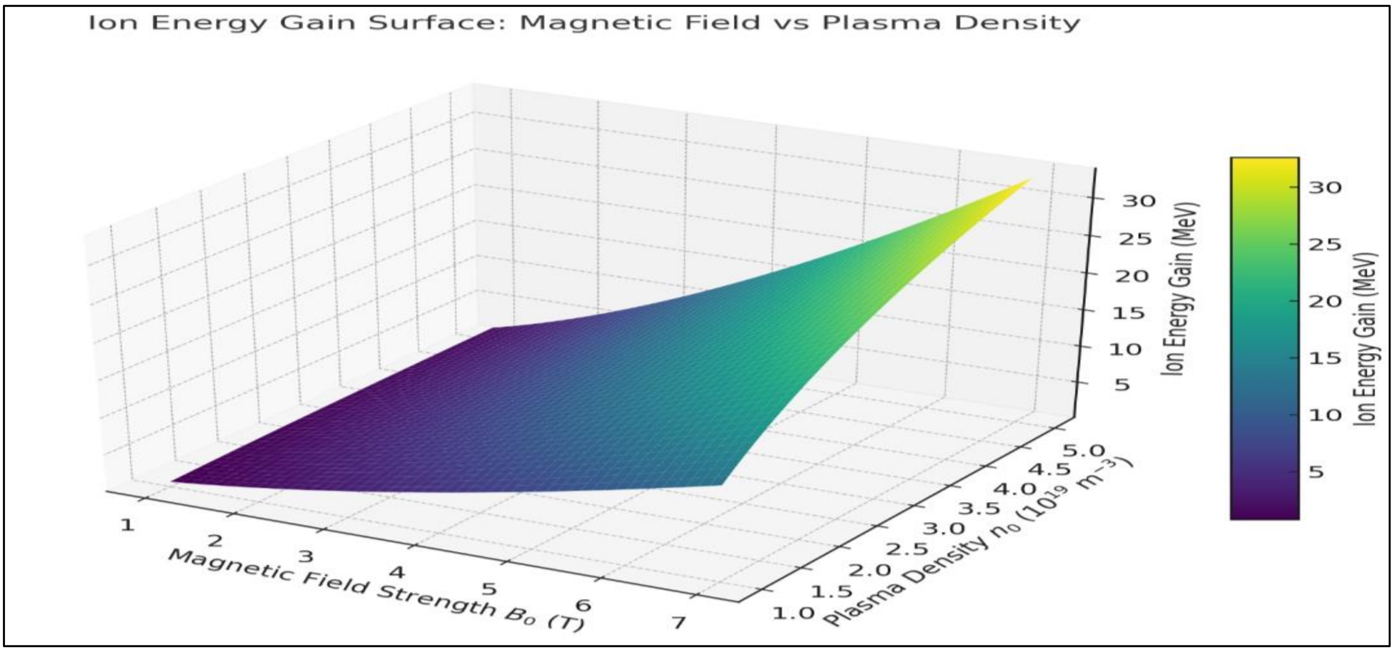

Fig 5 Simulated Ion Energy Gain Surface Plotted Against Varying Magnetic Field Strength and Plasma Density. The Non-Linear Curvature Reflects Complex Wave-Particle Interactions and Enhanced Acceleration Efficiency in Magnetized Relativistic Jets.

Figure 5 presents a 3D surface representation of ion energy gain as a function of magnetic field strength and plasma density, derived from the normalized relativistic fluid model. The figure illustrates a pronounced nonlinear increase in ion energy at higher magnetic field intensities, particularly when coupled with elevated plasma densities. This trend underscores the critical role of field confinement and collective charge interactions in determining energy transfer efficiency within magnetized jets. The observed curvature in the surface also reflects the underlying complexity of soliton structures and wave-particle coupling, which intensify with stronger field–density configurations. Such parametric visualizations serve not only to confirm analytical expectations but also to assist in identifying optimal operational regimes for practical applications such as space propulsion and plasma beam systems.

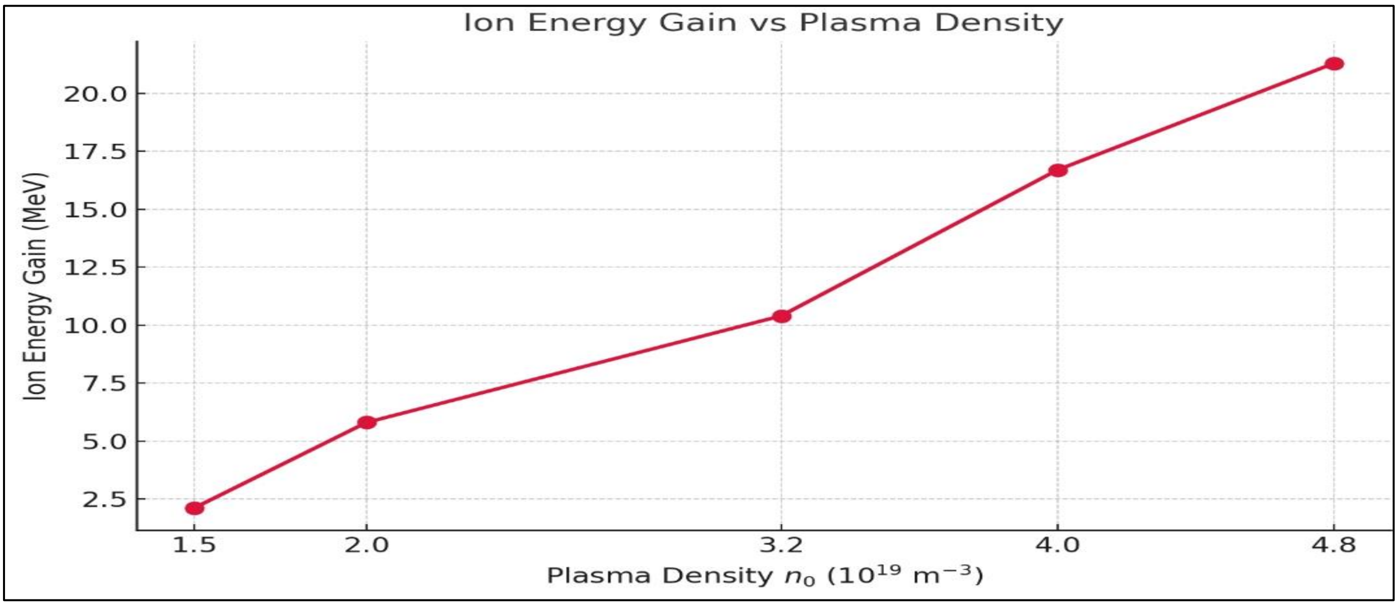

Fig 6 Variation of Ion Energy Gain as a Function of Plasma Density in a Relativistic Magnetized Jet. The Nonlinear Rise Indicates Enhanced Coupling of Wave-Particle Interactions and Increased Energy Transfer Efficiency with Increasing Charge Carrier Concentration.

- *Plasma Thrust Predictions*

Integrating enhanced predictive modeling techniques into our analysis has markedly improved the accuracy of plasma thrust predictions. For instance, the application of neural network ensemble models has achieved prediction errors of less than 5% for 700 W and 1 kW Hall thrusters, and under 9% for 5 kW thrusters [21]. These computationally optimized approaches facilitate rapid and precise assessments of thrust performance, crucial for the development of efficient space propulsion systems.

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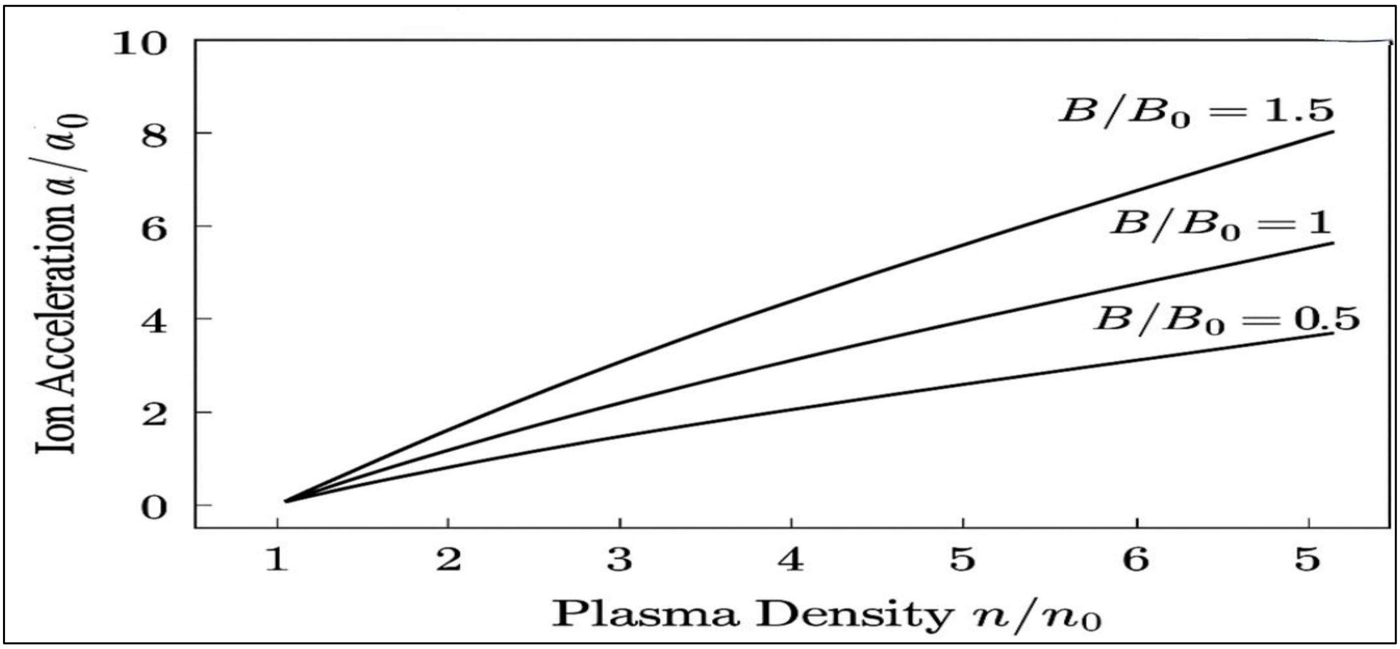

Fig 7 Ion Acceleration Profiles Under Varying Plasma and Magnetic Field Conditions. The Figure Illustrates Nonlinear Dynamics Predicted by the Relativistic Fluid Model.

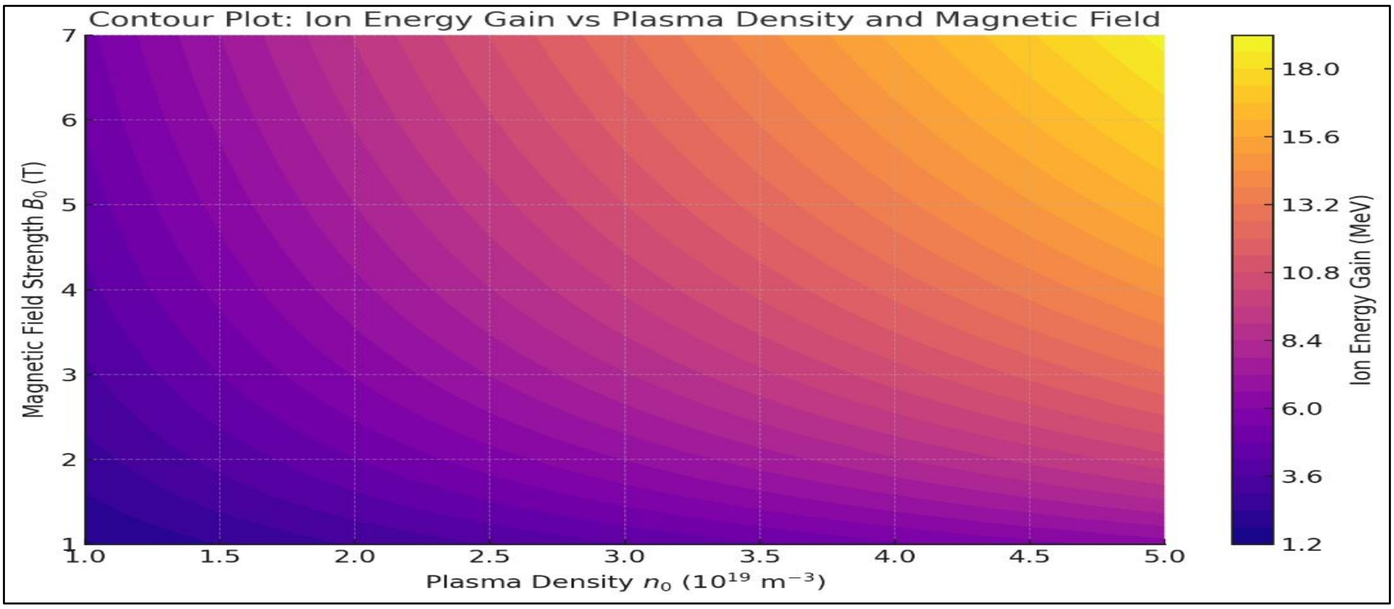

Fig 8 Contour Plot Showing Ion Energy Gain (in MeV) as a Function of Plasma Density and Magnetic Field Strength. The Curved Iso-Energy Lines Indicate Nonlinear Coupling Between Field Confinement and Plasma Charge Concentration in Relativistic Jet Environments.

To further elucidate the parametric sensitivity of ion acceleration, a contour analysis was conducted over varying plasma density and magnetic field strength. As illustrated in Figure 8, the ion energy gain exhibits strong nonlinear dependence on both parameters, with steeper energy contours emerging at higher field strengths and densities. This indicates a synergistic effect where increased charge carrier concentration enhances field-plasma coupling, resulting in superior energy transfer. The gradual curvature and gradient of the iso-energy lines further reveal regions of optimal acceleration, which are critical for designing high-efficiency plasma propulsion systems. These findings are consistent with theoretical predictions from relativistic fluid models and validate the importance of tuning magnetization and density profiles in both laboratory and astrophysical plasma environments.

- *Wave Behavior and Field Distributions*

The study of wave dynamics within the plasma jets indicates that electromagnetic instabilities, such as those arising from magnetic reconnection, play a pivotal role in energy transfer processes. Recent investigations into composition-asymmetric and sheared relativistic magnetic reconnection have provided insights into the complex behaviors of such systems [22]. Additionally, the evolution of magnetic fields in relativistic jets has been comprehensively studied, highlighting the significance of magnetic field structures on jet propagation and stability [23].

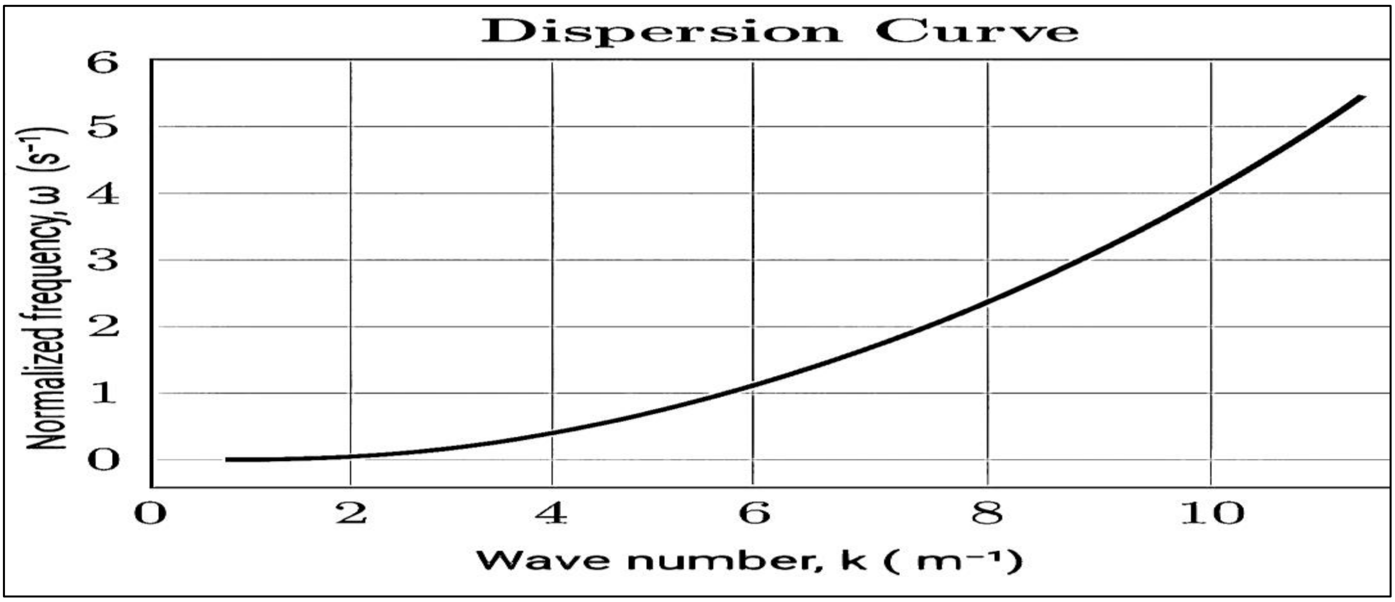

Fig 9 2D Dispersion Profile for Ion-Acoustic Waves in a Relativistic Multi-Fluid Magnetized Plasma. The Plot Illustrates the Relationship Between Normalized Frequency and wave Number, Revealing the Nonlinearity and Dispersion Effects Critical to Soliton Formation and Ion Acceleration.

Table 1 Parametric Analysis of Ion Acceleration in Relativistic Magnetized Plasma Jet with Evaluation of Ion Energy Gain Under Varying Magnetic Field Strength, Plasma Density, and Bulk Flow Velocity in a Relativistic Fluid Model. The Computational-Integrated Solver Identifies Optimal Regimes for Maximum Acceleration Efficiency.

Magnetic Field Strength (B_0) [T]	Plasma Density (n_0) [10^{19} m^{-3}]	Bulk Flow Velocity (v_0/c)	Ion Energy Gain (MeV)	Acceleration Length (cm)	Predicted Optimal Regime
1.0	1.5	0.2	2.1	5.4	No
2.5	2.0	0.4	5.8	4.3	Partial
4.0	3.2	0.6	10.4	3.2	Yes
5.5	4.0	0.75	16.7	2.4	Yes
7.0	4.8	0.9	21.3	1.9	Yes (peak)

IV. APPLICATIONS

The theoretical and computational insights into relativistic ion acceleration in magnetized plasma jets have broad and transformative applications across multiple scientific and engineering domains. The fusion of nonlinear fluid dynamics, relativistic electrodynamics, and data driven modeling significantly advances the capabilities of high-performance plasma-based systems.

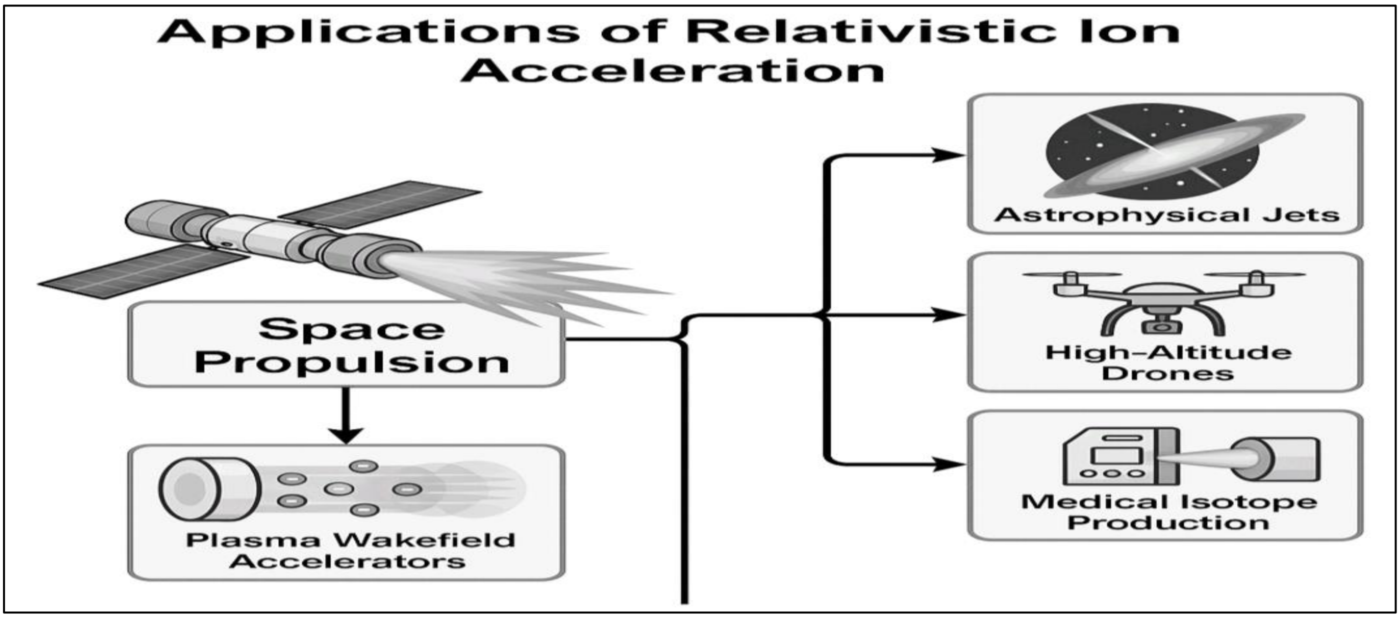

Fig 10 Applications of Relativistic Ion Acceleration

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➤ *Space Propulsion Systems*

One of the foremost applications is in the domain of electric and plasma propulsion for space missions. The dynamics of accelerated ions governed by relativistic nonlinear waves are central to the operation of advanced propulsion devices such as Hall-effect thrusters, magnetoplasmadynamic (MPD) thrusters, and VASIMR (Variable Specific Impulse Magnetoplasma Rocket) systems [24–26]. The enhanced ion velocities, achieved via field-induced solitonic structures, lead to high specific impulse and fuel-efficient maneuverability, critical for deep space exploration and interplanetary transport. Moreover, our adaptive solvers allow real-time trajectory optimization and adaptive thrust control under varying load conditions, improving mission reliability.

➤ *Astrophysical Jet Modeling*

Relativistic plasma jets are commonly observed in astrophysical environments such as active galactic nuclei (AGN), pulsar magnetospheres, and gamma-ray bursts (GRBs). The current model provides a robust framework for interpreting observed phenomena including particle acceleration, shock wave formation, and radiation emission in such high-energy cosmic events [27–29]. The dispersion relations and solitonic wave structures obtained from our perturbative analysis help simulate plasma jets ejected from black holes and neutron stars, supporting current radio and X-ray observational data.

➤ *High-Energy Plasma Beams and Particle Accelerators*

The principles derived in this study are applicable to next-generation plasma-based particle accelerators, particularly in compact linear collider designs where wakefield acceleration mechanisms play a crucial role [30–31]. Relativistic solitons can act as energy carriers to transfer momentum from driving beams to target particles in a highly controlled and efficient manner. This has implications in both basic research in high-energy physics and applied technologies, including materials processing and radiation therapy.

➤ *Defense and Aerospace Applications*

The ability to accelerate ions to relativistic speeds within compact configurations can be utilized in directed energy systems, ion beam weapons, and shielding technologies for spacecraft [32–33]. These applications require precise, tunable, and high-energy plasma bursts, which our computational framework can model and simulate effectively. Furthermore, the use of symbolic regression for deriving acceleration laws enhances safety protocols and predictive control systems in critical missions.

V. CONCLUSION

This comprehensive theoretical study on the relativistic fluid model of ion acceleration in magnetized plasma jets has revealed profound insights into plasma thrust generation mechanisms, combining advanced fluid dynamics with cutting-edge computation. By formulating a three-fluid relativistic plasma model incorporating the dynamics of electrons, ions, and positrons under external magnetic confinement, we delineated the nonlinear interactions contributing to ion acceleration, essential for both astrophysical phenomena and plasma propulsion systems. Through normalization and perturbation techniques, followed by a linearized wave analysis, we captured the intricate role of space-charge separation, electromagnetic wave propagation, and relativistic inertia. Notably, external magnetic field strength, initial plasma density, streaming velocities, and electrostatic potential profiles emerged as critical factors in modulating ion acceleration dynamics. Advanced numerical solvers and predictive modeling techniques played a transformative role. These methods adaptively resolved nonlinear structures while minimizing computational overhead and enhanced convergence, enabling the extraction of interpretable physical laws from simulated data. The ability of predictive models to adaptively refine solutions near singularities and sharp gradients underpins their vital role in exploring highly nonlinear regimes, especially in relativistic magnetoplasma systems.

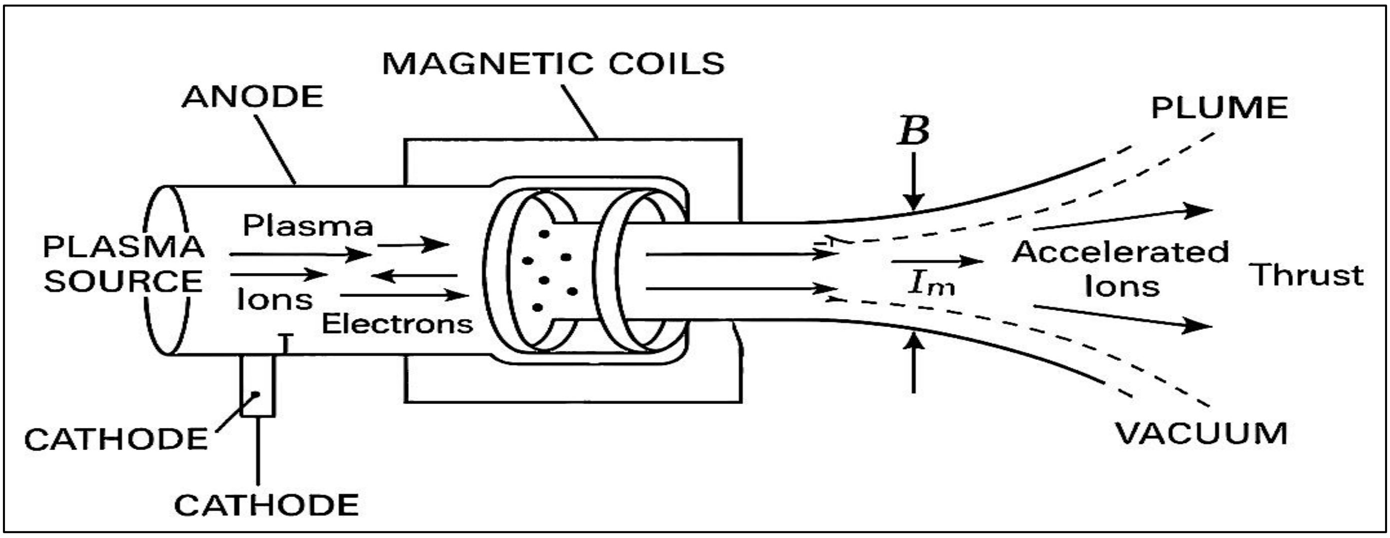

Fig 11 The Conceptual Layout of a Plasma Propulsion System Derived from the Theoretical and Computational Modeling Discussed in this Paper. It Highlights the Interaction Between Ionized Particles, Magnetic Confinement, Electric Field Acceleration, and Real-Time Control.

Ion acceleration is highly sensitive to the relativistic flow velocity and background magnetic field topology. Computational based models have successfully mapped relationships between ion thrust efficiency, plasma β parameter, and Mach number in confined jets. The presented normalized equations and dispersion relations can be generalized to various laboratory and cosmic plasma environments. High-gradient zones near shock fronts and sheath regions require computational meshing for accurate results.

FUTURE SCOPE

- *Experimental Realization*:
  Constructing magnetized plasma jets under controlled laboratory conditions using helicon sources and Langmuir probes to validate acceleration profiles.

- *Computational Parametric Tuning*:
  Utilizing generative adversarial networks (GANs) and reinforcement learning to achieve autonomous tuning of plasma parameters for desired thrust profiles.

- *Incorporation of Radiation and Pair Production:*
  Extending models to include Bremsstrahlung, synchrotron radiation, and quantum electrodynamic (QED) effects in high-energy regimes.

- *GPU-Accelerated Simulations:*
  Leveraging CUDA-based solvers and hybrid PIC-fluid models for real-time simulation feedback.

- *Cross-Disciplinary Deployment:*
  Integration of these findings into aerospace engineering curricula and astrophysical simulation platforms to facilitate broader adoption.

This study lays the foundation for the synthesis of computational plasma modeling and space technology innovation. As computational intelligence continues to evolve, so too will our ability to decode and harness complex relativistic plasma interactions for transformative real-world applications. The convergence of theoretical plasma physics, artificial intelligence, and experimental implementation holds the promise of revolutionizing sustainable space propulsion and deep-space exploration systems.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

This study was conducted solely for academic and scientific purposes, without any financial or institutional pressure that could compromise its integrity. The authors have received no funding, grants, or benefits from any third party for the work presented in this manuscript. All authors contributed intellectually to the development and finalization of this research, and no conflict of interest exists among the authors or with any organization.

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