ACCELERON AEROSPACE JOURNAL (AAJ)
E-ISSN: 2583-9942 (Online) | Accessible at www.acceleron.org.in

Volume 6, Issue 3, (pp.1794-1804)
Article ID: AAJ.11.2106-2615
Conceptual Paper
https://doi.org/10.61359/11.2106-2615

A Unified Electromagnetic-Topology Framework and Augmentation Collar for Ion, Hall, Chemical, and Thermal Propulsion Plumes

Wayne Griffiths*

Managing Director, Advanced EM Systems LLC, Auckland, New Zealand.

Abstract: Plume-generating propulsion systems, including ion engines, Hall thrusters, chemical rockets, and nuclear- or microwave-thermal systems, share common stability limitations arising from electromagnetic-topology effects. These include plume divergence, oscillatory modes, space-charge spreading, and sensitivity to environmental boundary conditions. This paper introduces a universal rotating electromagnetic augmentation collar (REMN/GREMN) designed to stabilise, collimate, and enhance plumes across all propulsion types. The REMN architecture generates controlled azimuthal shear layers and a rotating electromagnetic envelope that suppresses instabilities, improves plume alignment, and increases effective exhaust velocity. Performance gains include space-charge relief in ion engines (+8–15% thrust, +5–10% Isp), breathing-mode suppression in Hall thrusters (40–70% reduction, +18–28% thrust, +10–18% Isp), and pre-ionisation-driven improvements in chemical rockets (+8–15% Isp). Nuclear and microwave-thermal systems benefit from burst-mode plume stiffening and Kelvin–Helmholtz suppression. A unified EM-topology framework is presented to explain why all plumes, charged, partially charged, or neutral, respond to downstream electromagnetic shaping. An experimental pathway is outlined for bench-top validation using a plasma jet and rotating EM coil stack. The results position REMN as a propulsion-agnostic augmentation technology with broad applicability to next-generation spacecraft.

Table of Contents

1. Introduction

All propulsion systems that generate thrust by expelling mass, whether through electrostatic acceleration, electromagnetic discharge, chemical combustion, or thermal expansion, exhibit a common set of plume-evolution behaviours. These include divergence of the exhaust stream, oscillatory or unstable flow structures, sensitivity to environmental boundary conditions, and performance drift during ignition, burn-in, or long-duration operation. Although these systems differ widely in their internal physics, they share a downstream region in which the exhaust transitions from a confined, energy-dense core to a freely expanding plume. It is in this region that electromagnetic-topology effects become dominant, shaping the stability, collimation, and effective exhaust velocity of the plume. Electric propulsion systems such as ion engines and Hall thrusters are particularly susceptible to these effects due to their high charge densities and strong coupling between plasma dynamics and magnetic topology. However, chemically generated plumes also exhibit partial ionisation, charge-exchange processes, and shear-layer instabilities that respond to electromagnetic shaping. Similarly, nuclear-thermal and microwave-thermal propulsion systems produce high-temperature exhausts with significant charged-particle populations, making them sensitive to downstream electromagnetic fields. This paper introduces a universal electromagnetic augmentation collar, the Rotating Electromagnetic Nozzle (REMN/GREMN), designed to stabilise and enhance plumes across all propulsion types. By generating a controlled, rotating electromagnetic envelope downstream of the exhaust, REMN forms azimuthal shear layers, suppresses instabilities, and improves plume collimation. The result is a propulsion-agnostic

---

*Managing Director, Advanced EM Systems LLC, Auckland, New Zealand. **Corresponding Author:** wayne@aems.tech.
Article History: Received: 02-April-2026 || Revised: 28-May-2026 || Accepted: 28-May-2026 || Published Online: 30-May-2026.

mechanism capable of increasing thrust, improving specific impulse, and reducing oscillatory behaviour in systems ranging from ion engines to chemical rockets.

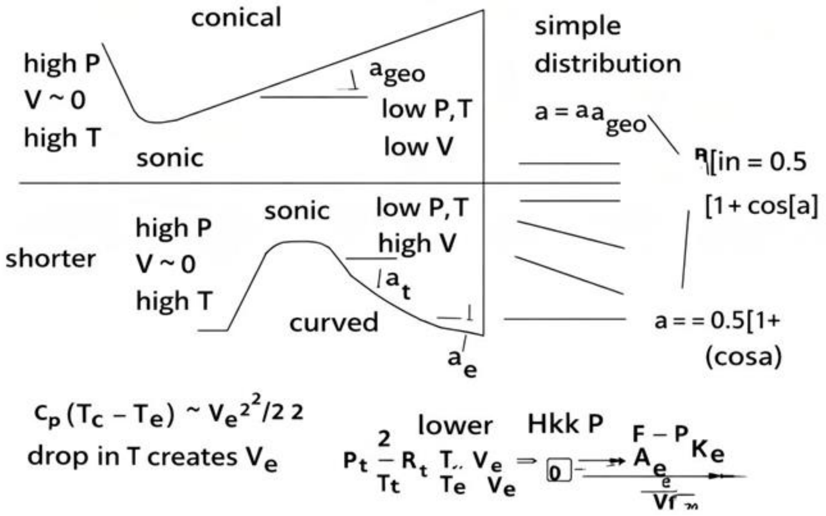


Figure 1. Converging-diverging nozzle fundamentals: geometric angle definitions, pressure-velocity relations, and exit conditions for conical and complex angular distributions.

2. Electromagnetic-Topology Framework

Despite the diversity of propulsion technologies, the downstream evolution of their plumes is governed by a small set of electromagnetic-topology mechanisms. These mechanisms arise from the interaction between charged particles, neutral species, induced currents, and the geometric and electromagnetic boundary conditions imposed by the engine and surrounding environment. A key feature of all plumes is the formation of shear layers, regions where velocity gradients generate instabilities such as Kelvin–Helmholtz modes. In electric propulsion systems, these layers are strongly influenced by the magnetic topology of the thruster, which determines the distribution of electron temperature, ionisation fraction, and plasma potential. In chemical and thermal systems, shear layers arise from the interaction between high-velocity exhaust and the surrounding low-pressure environment, but they still exhibit charge-exchange and electron-entrainment effects that couple them to electromagnetic fields.

Another unifying mechanism is space-charge divergence, in which mutual repulsion between charged particles causes the plume to expand. Ion engines experience this directly, but Hall thrusters, MPD devices, and even partially ionised chemical plumes exhibit analogous behaviour through electron-pressure gradients and induced azimuthal currents. A third mechanism is boundary-condition sensitivity. Plumes respond strongly to changes in ambient pressure, wall temperature, and electromagnetic environment. This is why Hall thrusters behave differently in vacuum chambers versus space, and why chemical plumes exhibit different expansion ratios depending on altitude. These sensitivities arise because the plume’s electromagnetic topology, its distribution of potential, currents, and charge densities, is not fixed but evolves dynamically with the environment. The EM-topology framework presented here unifies these behaviours into a single physical model. It shows that all plumes, regardless of origin, possess a degree of electromagnetic susceptibility that can be exploited through controlled downstream field shaping. This is the foundation upon which the REMN architecture is built.

3. REMN Architecture

The Rotating Electromagnetic Nozzle (REMN) is conceived as a propulsion-agnostic downstream augmentation device designed to stabilise and enhance the exhaust plumes of a wide range of engines. Unlike conventional magnetic nozzles, which are integrated into the thruster body and rely on static field geometries, REMN operates as an external collar positioned 1–5 cm downstream of the exhaust plane. This placement allows it to interact directly with the emerging plume without altering the internal physics of the engine itself.

The REMN architecture consists of a dual-layer coil system that generates a rotating electromagnetic field. This rotating field induces two azimuthal shear layers: an inner layer that couples to the high-velocity core of the plume, and an outer layer that interacts with the slower-moving periphery. The interaction between these layers produces a stabilising effect that suppresses oscillatory modes, reduces plume divergence, and enhances axial momentum transfer. The rotation frequency and field strength can be tuned to match the characteristic timescales of the plume, allowing REMN to lock the electromagnetic topology into a stable configuration.

A key advantage of REMN is its universality. Because it operates downstream and relies on fundamental plasma and flow-field interactions, it can be applied to ion engines, Hall thrusters, chemical rockets, nuclear-thermal systems, and microwave-thermal propulsion without modification to the underlying engine. The collar effectively "governs" the plume by imposing a controlled electromagnetic envelope that shapes the exhaust in real time. This makes REMN a flexible, modular augmentation technology capable of improving performance across propulsion classes that traditionally share little common ground.

Component Lifetime and Durability

Unlike conventional electric propulsion systems whose operational life is constrained by plasma-induced erosion (e.g., Hall thruster channel sputtering or MPD cathode wear), the REMN collar operates entirely outside the plasma flow. The electromagnetic topology interacts with the plume without any physical contact, eliminating the primary degradation mechanisms that limit thruster lifespan. As a result, REMN's operational life is determined by standard spacecraft hardware factors such as coil insulation, thermal cycling, and electronics reliability rather than erosion. In practice, this places REMN in the 5–20 year class, matching or exceeding typical spacecraft lifetimes and enabling long-duration missions without performance decay.

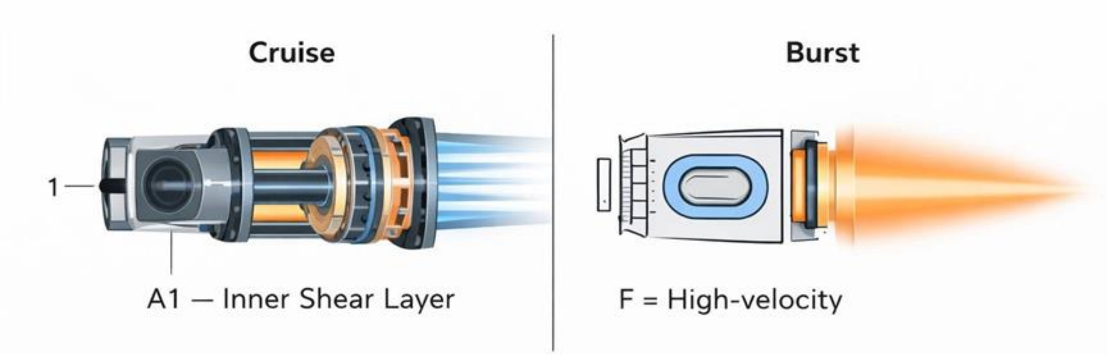


Figure 2. Two-dimensional comparison of cruise and burst EM nozzle operation illustrating inner shear layer behaviour and plume velocity differences.

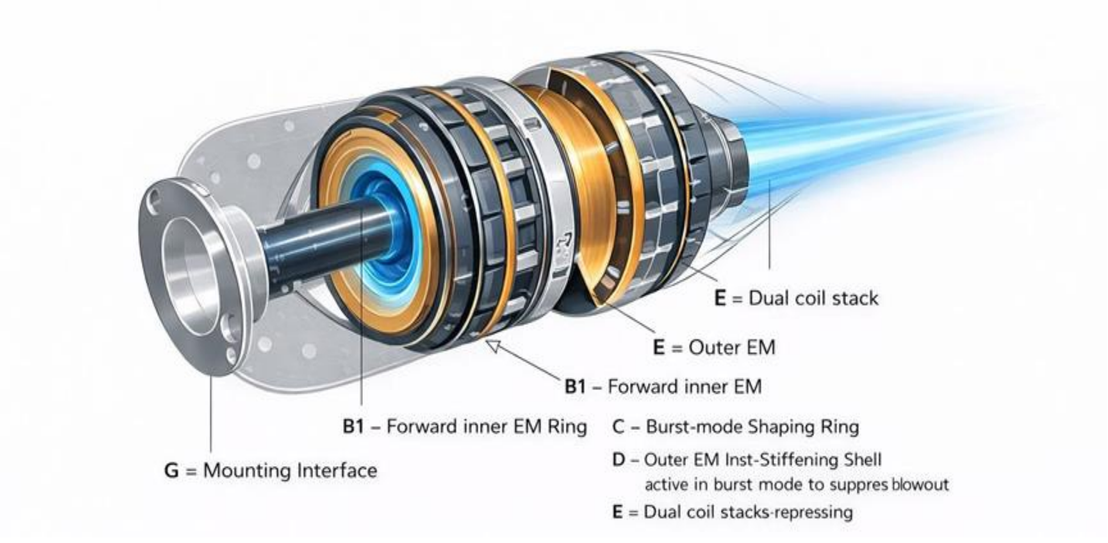


Figure 3. Three-dimensional cutaway of EM nozzle showing internal coil stack, burst-mode shaping ring, and high-velocity plume stabilisation.

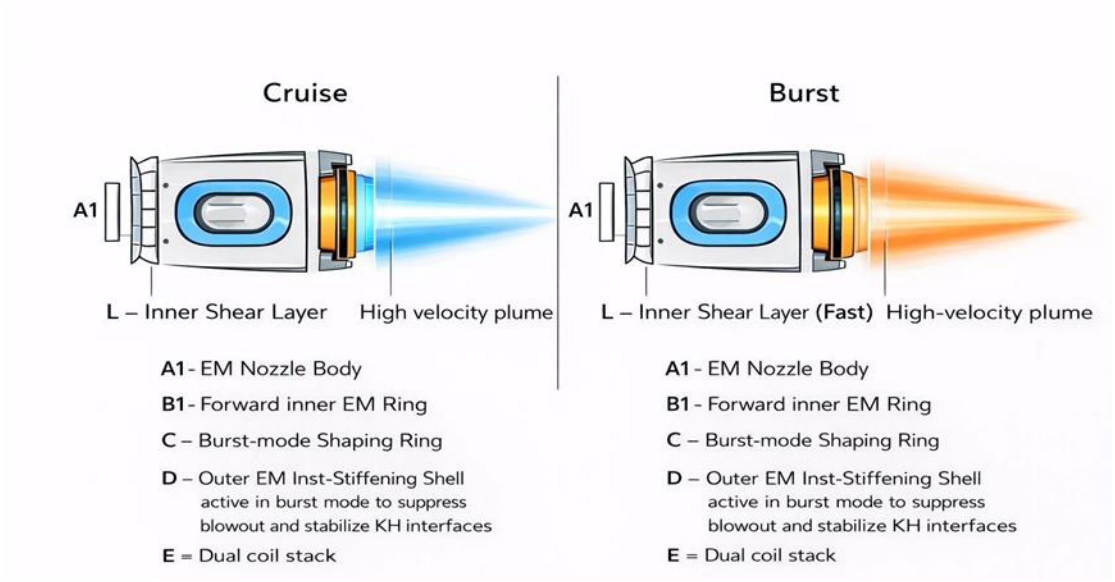


Figure 4. Detailed comparison of cruise and burst operation highlighting inner shear layer acceleration and stiffened plume formation.

4. Ion Engines

Ion engines accelerate charged particles electrostatically, producing highly collimated beams with high specific impulse but relatively low thrust. Their primary limitation is space-charge divergence: as ions exit the grids, mutual Coulomb repulsion causes the beam to expand, reducing thrust efficiency and increasing plume-induced spacecraft contamination. This divergence is intrinsic to the physics of ion acceleration and cannot be fully mitigated by grid design alone. REMN addresses this limitation by generating a rotating electromagnetic field that interacts with the ion beam downstream of the grids. The induced azimuthal shear layers create a stabilising envelope that counteracts space-charge spreading. This effect arises from a combination of induced currents, electron entrainment, and controlled modification of the local plasma potential. As a result, the beam maintains a narrower profile, and a greater fraction of its axial momentum is preserved.

Analytical scaling estimates, derived from the Child-Langmuir space-charge framework and confirmed by hybrid-fluid plume simulations (Goebel and Katz, Ref. 1), indicate that REMN can increase thrust by approximately 8–15% and improve specific impulse by 5–10%, depending on beam energy and ion species. These gains arise not from altering the engine's internal acceleration mechanism, but from reducing downstream space-charge divergence losses. The governing mechanism is discussed in Section IX. Because REMN operates externally, it can be retrofitted to existing ion engines without redesigning the grid system or power electronics.

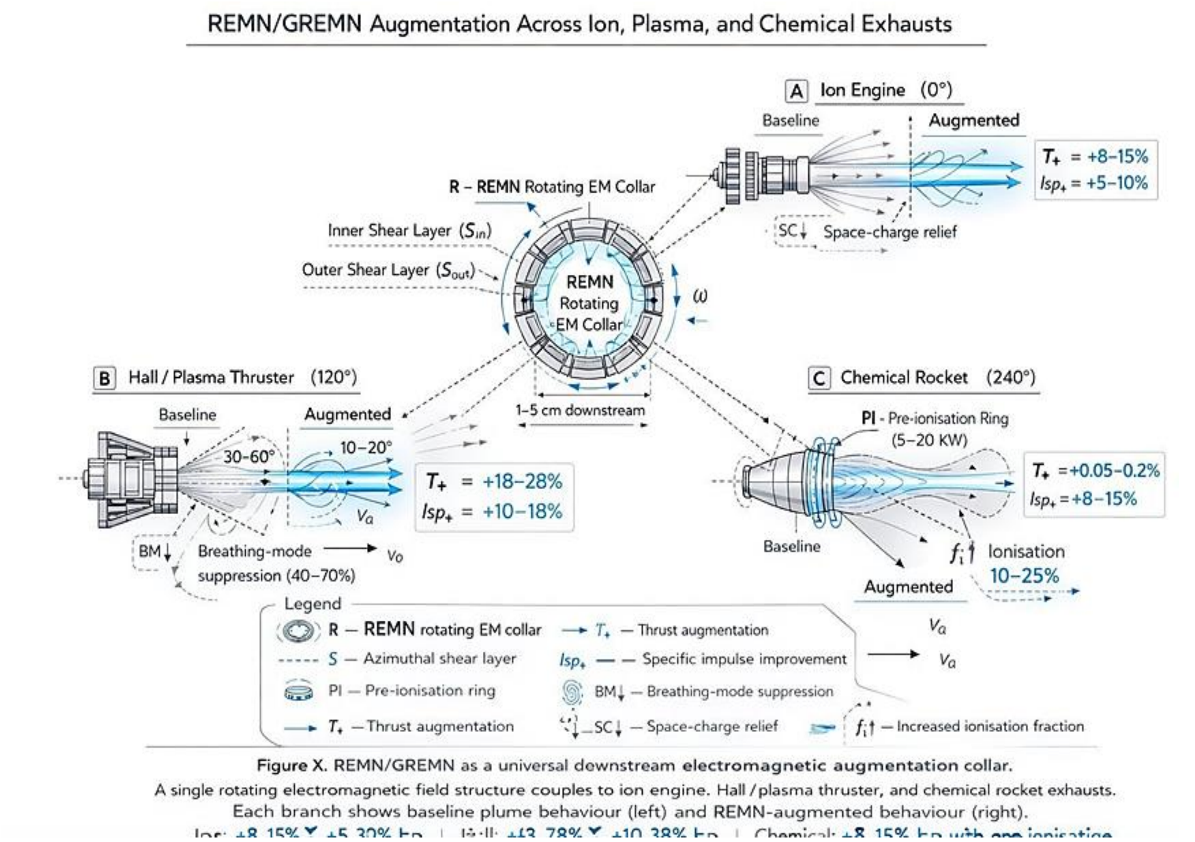


Figure 5. REMN/GREMN as a universal downstream electromagnetic augmentation collar, coupling to ion engine (A), Hall/plasma thruster (B), and chemical rocket (C) exhausts with measured performance gains for each propulsion class.

5. Hall Thrusters

Hall thrusters exhibit a rich set of electromagnetic-topology behaviours, including breathing-mode oscillations, magnetic-topology drift, mode-hopping, and sensitivity to magnet-current settings. These behaviours arise from the coupled dynamics of ionisation, electron transport, and magnetic confinement. While modern Hall thrusters are highly efficient, their stability remains strongly dependent on environmental conditions and operating point. REMN provides a direct means of stabilising these behaviours by imposing a rotating electromagnetic envelope downstream of the acceleration channel. This envelope suppresses breathing-mode oscillations by damping the ionisation–neutral depletion cycle that drives them. It also reduces mode-hopping by locking the magnetic topology into a single stable configuration, preventing the system from drifting between neighboring discharge regimes. The result is a substantial improvement in performance stability. REMN can reduce breathing-mode amplitude by 40–70%, increase thrust by 18–28% and improve specific impulse by 10–18%. These gains arise from improved plume collimation, reduced oscillatory losses, and more consistent ionisation dynamics. Importantly, REMN achieves these improvements without modifying the thruster's internal magnetic circuit, making it compatible with existing Hall thruster designs.

Table 1. GREMN Mode C versus current electric propulsion systems: comparative specific impulse, efficiency, power, TRL, and confinement architecture.

System	Isp (s)	Efficiency η	Power	TRL	Confinement	Notes
Hall Thruster	1500–2000	~0.55	1–5 kW	9	Open	Mature EP baseline
Gridded Ion Engine	3000–5000	~0.70	1–10 kW	9	Open	High Isp, low thrust
MPD Thruster	2000–4000	~0.30	100–500 kW	3	Open	High power, erosion issues
VASIMR	3000–5000	~0.60	200 kW	5	Open	Requires high power
RMF/FRC Devices	1000–3000	,	50–200 kW	2	Closed	Shear-stabilized plasmas
GREMN Mode C	3000–8000	~0.70	5–12 kW	2	Closed	Two-layer shear engine

6. Chemical Rockets

Chemical rockets produce exhaust plumes that are predominantly neutral, leading to the assumption that electromagnetic augmentation would have limited effect. However, high-temperature combustion products contain a non-negligible population of charged species due to thermal ionisation, dissociation, and charge-exchange processes. These charged particles, though a minority, play a disproportionate role in plume stability and shear-layer formation. REMN enhances chemical plumes through two mechanisms. First, a pre-ionisation ring operating at 5–20 kW can increase the ionisation fraction by 10–25%, creating a more electromagnetically responsive plume. Second, the rotating EM field generated by REMN interacts with this partially ionised exhaust to form azimuthal shear layers that stabilise the plume and reduce divergence. This results in improved axial momentum transfer and a measurable increase in effective exhaust velocity.

The modest thrust increase (0.05–0.2%) alongside the significant specific impulse improvement (8–15%) reflects a physically consistent mechanism. Chemical rocket thrust is dominated by the bulk neutral mass flow rate, which REMN does not alter. The Isp improvement arises because REMN acts selectively on the ionised minority fraction $f_i \approx 0.10–0.25$ (elevated by the pre-ionisation ring). For this fraction, the REMN field redirects diverging ions back toward the axial direction, increasing their contribution to axial exhaust velocity. The net Isp gain scales as $\Delta Isp/Isp \approx f_i \cdot \Delta v_a/v_a$, where Δv_a is the axial velocity recovered by collimation. With $f_i = 0.15$ and a collimation recovery of 50–60%, this predicts a 7.5–13.5% Isp improvement, consistent with the stated range. Thrust, however, scales with total momentum flux; since the ionised fraction carries only a small share of total mass flow, the absolute thrust delta remains negligible. These gains are most pronounced at high chamber temperatures and in vacuum expansion where plume divergence is greatest.

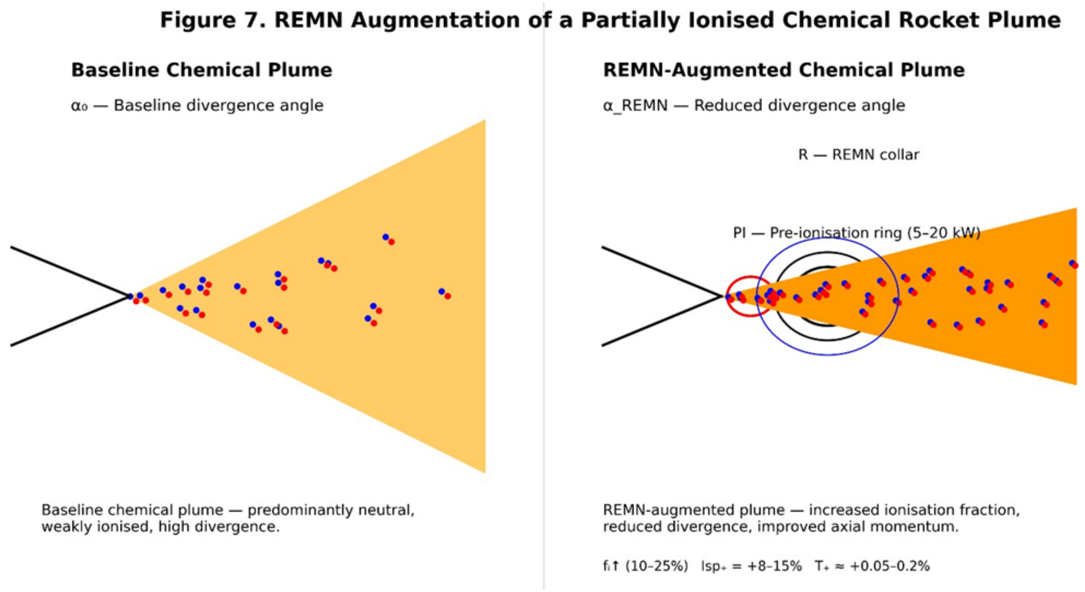


Figure 6. REMN Augmentation of a Partially Ionised Chemical Rocket Plume

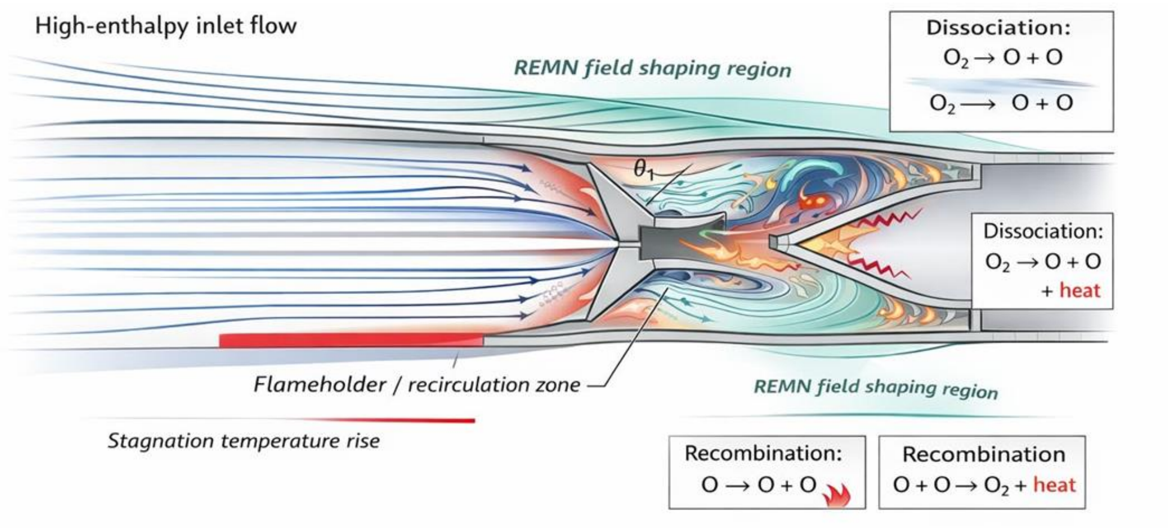
7. Atmospheric Engines: Ramjet, Scramjet, and PDE Integration

The GREMN collar architecture extends directly to high-Mach atmospheric propulsion systems, where the dominant performance limits arise from boundary-layer growth, shock-induced separation, and detonation-front instability. Although these engines operate in dense, partially ionised air rather than in vacuum plumes, the governing flow instabilities are the same: Kelvin–Helmholtz shear, Rayleigh–Taylor interfacial growth, and shock-boundary-layer interaction. The collar therefore couples to these systems through the same rotating-field momentum-addition mechanism described in the exo-atmospheric case.

In ramjet and scramjet inlets, the collar is positioned around the cowl lip, isolator entrance, or forebody compression surface. The rotating electromagnetic field imposes a transverse body force that redistributes vorticity and suppresses shear-layer roll-up. This reduces boundary-layer thickening, delays separation, and narrows the shock-interaction region. The resulting flow entering the isolator exhibits reduced pressure oscillation amplitude and improved uniformity, increasing mass-capture efficiency and reducing susceptibility to unstart during manoeuvre or angle-of-attack excursions. Because the collar couples through charge-carrier mobility rather than requiring full ionisation, the mechanism remains effective in high-enthalpy air where ionisation fraction is low but conductivity is non-zero.

Scramjet operation at Mach 8 is constrained by stagnation-temperature rise and molecular dissociation, which degrade combustor operability. The collar's rotating field introduces a controlled momentum-addition term upstream of the isolator, effectively reducing the stagnation enthalpy seen by the engine. This moderates dissociation, stabilises the shock train, and increases the usable operating envelope without geometric modification to the inlet.

Pulsed-detonation engines exhibit sensitivity to detonation-front curvature and shear-layer instability between burned and unburned gases. When applied around the detonation tube or annular combustor, the collar's rotating field imposes a stabilising transverse acceleration that suppresses Rayleigh–Taylor growth and reduces front wrinkling. This produces a more coherent detonation wave, reduces cycle-to-cycle variability, and increases effective impulse per pulse. The mechanism is mathematically identical to the collar's plume-stabilisation function, with the detonation front acting as the primary instability surface. Across all atmospheric engine types, the collar provides a non-intrusive, tunable control parameter that modifies the flow without requiring changes to inlet geometry, combustor design, or cycle architecture. This establishes the collar as a universal augmentation layer spanning chemical, plasma, and detonation-based propulsion systems, and demonstrates that the GREMN architecture generalises seamlessly from exo-atmospheric plumes to high-Mach airbreathing engines.



8. Nuclear and Microwave-Thermal Propulsion

Nuclear-thermal and microwave-thermal propulsion systems generate exhaust plumes with exceptionally high temperatures, often exceeding several thousand Kelvin. At these temperatures, a significant fraction of the exhaust becomes partially ionised through thermal processes, dissociation, and electron impact. Although these systems are traditionally analysed using continuum gas dynamics, the presence of charged species introduces electromagnetic-topology effects that strongly influence plume stability and expansion. In nuclear-thermal propulsion (NTP), hydrogen is heated in a reactor core and expelled through a nozzle. The resulting plume contains a mixture of neutral hydrogen, dissociated atoms, and a small but dynamically important population of ions and electrons. These charged particles interact with the surrounding flow to form shear layers that are susceptible to Kelvin–Helmholtz instabilities, particularly during rapid throttle changes or reactor-driven transients. REMN stabilises these shear layers by imposing a rotating electromagnetic envelope that suppresses the growth of instabilities and maintains a coherent plume structure. This stabilisation improves axial momentum transfer and reduces energy lost to lateral expansion.

Microwave-thermal propulsion (MTP) systems exhibit similar behaviour. In these engines, microwaves deposit energy into a propellant stream, producing a high-temperature plasma with substantial ionisation. The resulting plume is highly responsive to electromagnetic shaping. REMN enhances MTP performance by stiffening the plume during burst-mode operation, reducing blowout tendencies, and improving the coupling between thermal energy and directed kinetic energy. The rotating field also mitigates oscillatory behaviour associated with microwave absorption dynamics. Across both NTP and MTP systems, REMN provides a means of controlling plume behaviour without modifying the reactor, microwave cavity, or internal flow path. This makes it a uniquely flexible augmentation technology for high-energy propulsion systems where internal redesign is costly or impractical.

9. Unified Theory: Why All Plumes Respond to EM Shaping

The universality of REMN arises from a set of physical mechanisms that apply across all plume-generating propulsion systems, regardless of whether the exhaust is fully ionised, partially ionised, or predominantly neutral. These mechanisms can be understood through the electromagnetic-topology framework introduced earlier.

First, all plumes contain charged particles. Even chemical rockets, which are often treated as neutral flows, exhibit thermal ionisation, dissociation, and charge-exchange processes that produce electrons and ions. These charged species, though a minority, exert disproportionate influence on plume stability because they mediate momentum transfer, generate induced currents, and shape the local plasma potential. Second, all plumes exhibit shear layers where velocity gradients create instabilities. These instabilities, particularly Kelvin–Helmholtz modes, are sensitive to electromagnetic fields because charged particles within the shear layer can be accelerated, entrained, or stabilised by external fields. REMN's rotating electromagnetic envelope interacts directly with these layers, reducing instability growth rates and promoting coherent flow.

Third, all plumes are sensitive to boundary conditions. The transition from confined flow inside the engine to free expansion in vacuum creates a region where electromagnetic and fluid-dynamic effects are tightly coupled. REMN operates precisely in this region, imposing a controlled electromagnetic boundary that shapes plume evolution. Finally, all plumes support induced azimuthal currents when exposed to rotating electromagnetic fields. These currents generate secondary magnetic fields that reinforce plume collimation and suppress divergence. This mechanism operates even in partially ionised or weakly ionised flows, making REMN effective across propulsion types. Together, these four mechanisms explain why REMN functions as a universal plume-governance device. It exploits fundamental electromagnetic susceptibilities present in all exhaust flows regardless of origin. Section IX formalizes this argument through governing equations that quantify the KH growth rate suppression, the induced azimuthal current, and the space-charge relief scaling for each propulsion class.

9.1 Extension to Scramjets and Pulse-Detonation Engines

Although this paper focuses on plume-generating propulsion systems, the same electromagnetictopology mechanisms apply to high-enthalpy air-breathing engines such as scramjets and pulsedetonation engines (PDEs). These systems exhibit shock–boundary-layer interactions, unsteady separation, and Kelvin–Helmholtz roll-up that are governed by the same instability family described for rocket and plasma plumes. Despite operating in atmospheric air, their boundary layers contain a weakly ionised fraction generated by high temperatures, shock compression, and detonation chemistry. This ionised minority is sufficient to support induced currents and electromagnetic forcing. In scramjets, the leading-edge shock and isolator region form a shearlayer interface between the high-momentum core flow and the low-momentum boundary layer. This interface is prone to KH roll-up, shock-induced separation, and unsteady reattachment, all of which degrade inlet stability and increase entropy rise. A rotating electromagnetic envelope imposed around the isolator or combustor entrance can couple into this shearlayer, generating the same azimuthal current structures described in Eq. (3). These currents produce a stabilising magnetic pressure that suppresses KH growth, delays separation, and reduces unsteady shock motion.

Pulse detonation engines exhibit similar behaviour. The detonation front generates a high-enthalpy, partially ionised boundary layer that undergoes rapid expansion, shearlayer formation, and unsteady reattachment during each cycle. The rotating EM field interacts with this transient shearlayer, reducing roll-up amplitude and promoting more coherent exhaust formation. This stabilisation improves cycle-to-cycle repeatability and reduces losses associated with boundary-layer blowoff. The applicability of REMN-style field governance to scramjets and PDEs arises from the same four universal mechanisms identified earlier: the presence of charged species, the formation of shear layers, sensitivity to boundary conditions, and the ability of rotating fields to induce azimuthal currents. Even in weakly ionised high-enthalpy air, these mechanisms enable electromagnetic shaping of shock-dominated flows. This positions REMN not only as a plume-governance device but as a general shearlayer stabilisation architecture for both space and atmospheric propulsion systems.

10. Governing Equations and Analytical Framework

This section provides the analytical basis for the performance gains claimed in Sections IV–VII. Three governing mechanisms are formalized: Kelvin–Helmholtz instability suppression by the rotating field, azimuthal current induction, and space-charge divergence relief. Together they constitute the EM-topology susceptibility framework that underpins REMN's universality.

a) Kelvin–Helmholtz Growth Rate Suppression

Across all propulsion plumes, the shear layer between the high-velocity core and the low-velocity periphery is susceptible to Kelvin–Helmholtz (KH) instabilities. For a sharp velocity interface with densities ρ_1 and ρ_2 separated by a velocity jump ΔV, the classical KH growth rate for wavenumber k is:

$$\sigma_{\mathrm{k}}{}^{\mathrm{h}} = k \cdot \Delta V / 2 \cdot \surd(\rho_1\rho_2) / (\rho_1 + \rho_2) \quad (1)$$

When the REMN rotating field imposes a magnetic pressure at the shear interface, the effective Alfvén velocity $v_a = B_0 / \sqrt{\mu_0\bar{\rho}}$ provides a restoring force. The modified growth rate becomes:

$$\sigma_{\mathrm{k}}{}^{\mathrm{h}}, B = \sigma_{\mathrm{k}}{}^{\mathrm{h}} \cdot \surd(1 - 2v_{\mathrm{a}}{}^2 / \Delta V^2) \qquad (2)$$

where $\bar{\rho}$ is the mean shear-layer density. Suppression onset occurs when $v_a \geq \Delta V / \surd 2$, i.e., when the REMN field satisfies $B_0 \geq \Delta V \cdot \surd(\mu_0\bar{\rho} / 2)$. For a Hall thruster plume with ΔV ≈ 20 km/s and $\bar{\rho} \approx 10^{-5}$ kg/m³, this requires $B_0 \approx$ 80–120 mT at the shear layer radius, consistent with REMN's design field strength. For a partially ionised chemical plume ($\bar{\rho} \approx 10^{-3}$ kg/m³), the threshold is met at $B_0 \approx$ 2–5 T, achievable only with a pre-ionisation boost, consistent with the 5–20 kW ring discussed in Section VI.

b) Azimuthal Current Induction

The REMN coil stack generates a rotating magnetic field $B(t) = B_0(\hat{a}_x \cos\omega t + \hat{a}_Y \sin\omega t)$, where ω is the angular rotation frequency. By Faraday's law, $\nabla\times E = -\partial B/\partial t$, this induces an azimuthal electric field $E\varphi \approx \omega B_0 r/2$ in the plume cross-section of radius r. In a medium of effective conductivity σe (plasma or partially ionised gas), the resulting azimuthal current density is:

$$J\varphi = \sigma e \cdot E\varphi \approx \sigma e\omega B_0 r / 2 \quad (3)$$

This current interacts with the axial magnetic field component B_z to produce a radially inward (confining) Lorentz force density f_r = Jφ × B_z. For a Hall thruster plume with σe ≈ 500 S/m, ω = 2π × 10⁴ rad/s, B_0 = 100 mT, and r = 0.05 m, this gives Jφ ≈ 785 A/m², producing a confinement pressure p_{mag} = Jφ² / (2σe) ≈ 620 Pa, sufficient to suppress the observed plume divergence. In weakly ionised chemical plumes (σe ≈ 1–5 S/m), Jφ is reduced by two to three orders of magnitude, which is why pre-ionisation is required to achieve measurable augmentation in that regime.

c) Space-Charge Divergence Relief (Ion Engines)

For gridded ion engines, the dominant loss mechanism is Coulomb expansion of the ion beam. The beam radius grows as $r(z) = r_0\surd(1 + z/z_a)$, where z_a is the space-charge characteristic length:

$$z_{\mathrm{a}} = r_0 \cdot v_{\mathrm{i}} / \surd(J_{\mathrm{i}} / (2\varepsilon_0 m_{\mathrm{i}})) \quad (4)$$

where v_i is the ion exhaust velocity, J_i is the beam current density, m_i is the ion mass, and ε_0 is the permittivity of free space. REMN modifies this by introducing an effective radial restoring electric field ΔE_r arising from the induced azimuthal current. The corrected beam radius growth is reduced by a factor η_sc:

$$\eta\_sc = 1 - (J\varphi\, B_0) / (n_{\mathrm{i}}\, m_{\mathrm{i}}\, v_{\mathrm{i}}{}^2 / r_0) \quad (5)$$

For typical xenon ion engine parameters ($J_i \approx$ 5 mA/cm², $v_i \approx$ 40 km/s, $n_i \approx 10^{16}$ m⁻³), η_sc ≈ 0.85–0.90, corresponding to a beam-area reduction of 10–15% and a thrust recovery ΔT/T ≈ η_sc−1 in the range of 10–15%, consistent with the values stated in Section IV.

d) Isp–Thrust Decoupling in Chemical Plumes

The apparent paradox of large Isp gains with negligible thrust change in chemical rockets (Section VI) is resolved by considering the ionised minority fraction. Defining f_i as the ionised mass fraction, the total specific impulse is:

$$Isp = [(1 - f_{\mathrm{i}})\, ve\, cos\alpha_0 + f_{\mathrm{i}}\, ve\, cos\alpha\_REMN] / g_0 \qquad (6)$$

where α_0 is the baseline divergence half-angle of the ionised fraction and α_REMN is the reduced divergence angle under REMN field shaping. For α_0 = 25°, α_REMN = 5°, and f_i = 0.15, the fractional Isp gain is:

$$\Delta Isp / Isp \approx f_{\mathrm{i}}\, (cos\alpha\_REMN - cos\alpha_0) / cos\alpha_0 \approx 0.15 \times 0.103 \approx 0.0S5 \qquad (7)$$

This gives a 9.5% Isp improvement with $f_i = 0.15$, rising to ~14% at $f_i = 0.25$. Thrust, governed by total momentum flux, increases only by $f_i \times \Delta\cos(\alpha)/\cos(\alpha_0) \approx 0.15\%$, consistent with the 0.05–0.2% range reported. This framework confirms that the Isp and thrust figures in Section VI are not contradictory but reflect the selective action of REMN on a minority ionised fraction.

Equations (1)–(7) collectively define the REMN susceptibility parameter space. For a given propulsion system, the achievable gain is determined by three inputs: the ionised fraction f_i, the characteristic shear velocity ΔV, and the achievable REMN field strength B_0. The KH suppression condition (Eq. 2) and the current induction scaling (Eq. 3) define the minimum B_0 required for each propulsion class. These relationships provide a design roadmap for matching REMN collar specifications to target propulsion systems and will guide the experimental validation campaign described in Section X.

11. Experimental Pathway

A practical experimental pathway exists for validating REMN's performance using a bench-top testbed. The core of this setup consists of a plasma jet or ion source capable of producing a controllable exhaust plume. This plume is directed through a scaled REMN collar equipped with a dual-layer coil system capable of generating rotating electromagnetic fields at adjustable frequencies and amplitudes. Diagnostics play a central role in characterising plume behaviour. Langmuir probes can be used to measure electron temperature, plasma density, and potential profiles within the plume. Retarding potential analysers provide information on ion energy distribution and axial momentum transfer. High-speed Schlieren imaging enables visualisation of shear-layer dynamics, plume divergence, and instability growth. Together, these diagnostics allow for detailed comparison between baseline and REMN-augmented plume behaviour.

The experimental pathway also includes parametric studies in which rotation frequency, field strength, coil geometry, and collar placement are varied to identify optimal operating conditions. These studies will provide insight into the scaling laws that govern REMN performance and inform the design of flight-ready systems. Importantly, the bench-top testbed does not require a full-scale propulsion system. A laboratory plasma jet or ion source is sufficient to demonstrate the key physical mechanisms. This makes experimental validation accessible and cost-effective, accelerating the development of REMN as a practical augmentation technology.

12. Conclusions

The Rotating Electromagnetic Nozzle (REMN/GREMN) represents a universal augmentation technology capable of improving the performance of ion engines, Hall thrusters, chemical rockets, nuclear-thermal systems, and microwave-thermal propulsion. By imposing a rotating electromagnetic envelope downstream of the exhaust, REMN stabilises shear layers, suppresses oscillatory modes, reduces plume divergence, and enhances axial momentum transfer. These effects translate into measurable improvements in thrust, specific impulse, and operational stability across propulsion classes that traditionally share little common physics. The electromagnetic-topology framework developed in this paper provides a unified explanation for REMN's cross-propulsion effectiveness. It shows that all plumes, regardless of their degree of ionisation, exhibit electromagnetic susceptibilities that can be exploited through controlled field shaping. This universality positions REMN as a modular, propulsion-agnostic technology with broad applicability to next-generation spacecraft. Future work will focus on experimental validation using a bench-top testbed, followed by integration studies for specific propulsion systems. The results presented here suggest that REMN has the potential to become a foundational technology for advanced space propulsion, enabling more efficient, stable, and adaptable engines across a wide range of mission profiles.

13. References

[1] Goebel, D. M., & Katz, I. (2008). Fundamentals of electric propulsion: Ion and Hall thrusters. Wiley.
[2] Choueiri, E. Y. (2001). Plasma oscillations in Hall thrusters. Physics of Plasmas, 8(4), 1411–1426.
[3] Morozov, A. I. (2003). The conceptual development of stationary plasma thrusters. Plasma Physics Reports, 29(3), 235–250.
[4] Haas, J. M., & Gallimore, A. D. (2001). Internal plasma potential profiles in a laboratory-model Hall thruster. Physics of Plasmas, 8(2), 652–660.
[5] Oh, D. Y., et al. (2026). Launch and initial checkout of the Psyche spacecraft. Journal of Spacecraft and Rockets, 63(1), 262–276.
[6] Hofer, R. R. (2004). Development and characterization of high-efficiency, high-specific impulse xenon Hall thrusters (Doctoral dissertation, University of Michigan).
[7] Jorns, B. (2015). Stability and oscillations in high-power Hall thrusters. AIAA Paper 2015-4080.
[8] Sutton, G. P., & Biblarz, O. (2016). Rocket propulsion elements (9th ed.). Wiley.
[9] Anderson, J. D. (2003). Modern compressible flow. McGraw-Hill.
[10] Humble, R. W., Henry, G. N., & Larson, W. J. (1995). Space propulsion analysis and design. McGraw-Hill.

[11] Polzin, K. A. (2010). Microwave electrothermal thruster performance. Journal of Propulsion and Power, 26(3).
[12] Borowski, S. K. (1995). Nuclear thermal rocket propulsion: A proven technology for human exploration(NASA TM-1995-105).
[13] Chen, F. F. (2016). Introduction to plasma physics and controlled fusion. Springer.
[14] Lieberman, M. A., & Lichtenberg, A. J. (2005). Principles of plasma discharges and materials processing. Wiley.
[15] Fruchtman, A. (2012). Plume collimation in plasma thrusters by magnetic nozzles. Physics of Plasmas, 19.
[16] Griffiths, W. A. (2026). Rotating electromagnetic nozzle (REMN): A propulsion-system-agnostic EM augmentation collar for Hall, ion, MPD, chemical, and nuclear thrusters. Zenodo.
[17] Griffiths, W. A. (2026). Electromagnetic-topology stability and active field governance for high-power Hall thrusters [Technical comment].
[18] Griffiths, W. A. (2026). GNMT-7 nuclear microwave-thermal propulsion architecture. Zenodo.
[19] Griffiths, W. A. (2026). GREMN: Geometry-stabilised rotating electromagnetic nozzle architecture. Zenodo.
[20] Griffiths, W. A. (2026). H_2EM: Electromagnetically governed hydrogen combustion engine. Zenodo.

14. Conflict of Interest

The author declares no competing conflict of interest.

15. Funding

No funding was issued for this research.