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Article

Plasma Stabilization via Topological Anisotropy of Spatial Connectivity

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Abstract

Building upon the recently proposed *Topological Model of Spatial Connectivity* [1], we develop a co-variant formulation of Maxwell's equations in an anisotropic geometric background defined by the local connectivity tensor $G_{ij}(x, t)$. Within this framework, the antisymmetric part of G_{ij} represents a fundamental twist of spatial connectivity, while the symmetric part encodes local curvature. Variations of G_{ij} rescale the effective Planck length, $L_p(x, \hat{n}) = \ell_* \sqrt{G_{ij}(x, t) \hat{n}^i \hat{n}^j}$, and consequently modify the local propagation constant $c_{\text{eff}}(x) \propto L_p^{-2/3}$. We derive explicit 3 + 1 equations for the electromagnetic field in such anisotropic geometry, showing that local Lorentz invariance is preserved while direction-dependent permittivity and permeability naturally arise. Localized deformations of G_{ij} —interpreted as *topological connectivity defects*—generate nonlinear drifts of the form $\delta \mathbf{v} \sim \nabla c_{\text{eff}} / c_{\text{eff}}$, which advect and suppress small-scale plasma fluctuations. Within this framework, a single invariant scale ℓ_* controls both microscopic connectivity and macroscopic plasma dynamics, providing a purely geometric route to plasma stabilization without external confinement or power input.

Keywords: plasma stabilization; magnetohydrodynamics; turbulence suppression; geometric drift; anisotropic geometry; topological defects; self-organization; Maxwell-MHD formulation

1. Introduction

The unification of electromagnetism and gravitation on a purely geometric basis has remained a central objective of theoretical physics since the early twentieth century. Einstein's unified-field attempts, and later the Kaluza-Klein, Skyrme, and loop-quantum-gravity models, all sought to represent field dynamics as curvature or topology of spacetime itself. Yet these approaches typically rely on either additional dimensions, auxiliary fields, or discrete spin-network constructions, while still lacking a minimal geometric description applicable across microscopic and macroscopic scales.

The *Topological Model of Spatial Connectivity* proposed in [1] introduces a single universal constant ℓ_* —the fundamental connectivity length—and treats the three-dimensional spatial metric $G_{ij}(x, t)$ as the dynamical carrier of both curvature and field. Its symmetric part S_{ij} reproduces gravitational geometry, while the antisymmetric part A_{ij} represents local twist or torsion-like coupling between directions, leading in the continuum limit to the electromagnetic tensor $F_{ij} \simeq A_{ij}$.

In this work we extend that framework by deriving the full set of Maxwell equations directly in an anisotropic connectivity geometry, where the determinant $\gamma = \det G_{ij}$ and the inverse tensor G^{ij} introduce direction-dependent propagation and coupling coefficients. This generalization allows one to describe electromagnetic and plasma phenomena in a background whose metric is locally distorted by topological defects of connectivity. Such defects, when formed or driven dynamically, produce spatial variations of the effective speed of light c_{eff} and therefore induce a nonlinear geometric drift $\delta \mathbf{v} \propto \nabla c_{\text{eff}} / c_{\text{eff}}$ that suppresses short-wavelength turbulence.

The goal of the present paper is twofold: (i) to derive Maxwell's equations in explicit 3 + 1 form consistent with an anisotropic metric G_{ij} , and (ii) to demonstrate how localized variations of G_{ij} lead to self-stabilizing plasma configurations through the formation of topological defects. We first formulate

the axioms of the model and the metric decomposition, then derive the anisotropic Maxwell system and its conservation laws, and finally present numerical evidence for the suppression of small-scale fluctuations in the vicinity of a topological defect.

2. Axioms and Relation to the Base Theory

The present work extends the principles introduced in *Topological Model of Spatial Connectivity: Geometric Anisotropy from G_{ik} and Cosmological Consequences of Variable c_{eff}* [1]. That study formulated the geometric unification of gravity and electromagnetism through the local connectivity tensor G_{ij} and introduced the universal connectivity scale ℓ_* . The following three postulates of that model are retained here:

1. **Local invariant.** For infinitesimal displacements X^i, Y^j , the scalar $I = \sqrt{G_{ij}X^iY^j}$ remains invariant.
2. **Locality of geometry.** All physical quantities are defined within a local connectivity region, and global coordinate transformations are absent.
3. **Fundamental connectivity scale.** Space possesses an invariant microscopic length ℓ_* that determines the effective Planck length and the operational light speed:

$$L_p(x, \hat{n}) = \ell_* \sqrt{G_{ij}\hat{n}^i\hat{n}^j}, \quad c_{\text{eff}}(x) = \left(\frac{\hbar G}{L_p^2}\right)^{1/3} \propto L_p^{-2/3}.$$

The present paper preserves these axioms but develops their electromagnetic and plasma consequences, showing that spatial anisotropy of G_{ij} modifies the local Maxwell dynamics and induces a nonlinear geometric drift that stabilizes plasma turbulence.

3. Mathematical Framework

3.1. Local Geometry and Metric Decomposition

We consider a locally connected three-dimensional manifold Σ_t representing a spatial slice at time t . Each point is characterized by a local connectivity tensor $G_{ij}(x, t)$, which encodes both curvature and torsion-like twist of space. In Gaussian coordinates ($g_{0i} = 0$), the four-metric reads

$$g_{\mu\nu}(x, t) = \begin{pmatrix} -c_{\text{loc}}^2 & 0 \\ 0 & G_{ij}(x, t) \end{pmatrix}, \quad g^{\mu\nu}(x, t) = \begin{pmatrix} -c_{\text{loc}}^{-2} & 0 \\ 0 & G^{ij}(x, t) \end{pmatrix}, \quad (1)$$

where G^{ij} is the inverse of G_{ij} , satisfying $G^{ik}G_{kj} = \delta^i_j$, and c_{loc} denotes the locally measured speed of light, constant in each infinitesimal neighborhood. The determinant of the spatial metric is denoted by $\gamma = \det(G_{ij})$.

Following [1], the connectivity tensor decomposes as

$$G_{ij} = S_{ij} + A_{ij}, \quad S_{ij} = \frac{1}{2}(G_{ij} + G_{ji}), \quad A_{ij} = \frac{1}{2}(G_{ij} - G_{ji}), \quad (2)$$

where S_{ij} defines the local spatial curvature (symmetric component), and A_{ij} represents the antisymmetric twist of connectivity, which at scales larger than the fundamental cutoff ℓ_* corresponds to the spatial components of the electromagnetic field tensor, $A_{ij} \simeq F_{ij}$.

3.2. Field Tensor and Potentials

Let the electromagnetic four-potential be $A_\mu = (\Phi, -A_i)$. The antisymmetric field tensor is defined in the standard form,

$$F_{\mu\nu} = \nabla_\mu A_\nu - \nabla_\nu A_\mu, \quad (3)$$

whose spatial components coincide with the geometric antisymmetry A_{ij} to order $\mathcal{O}(\ell_*^2)$. In local coordinates the components read

$$F_{0i} = E_i, \quad F_{ij} = \varepsilon_{ijk} B^k, \quad (4)$$

where $\varepsilon_{ijk} = \sqrt{\gamma} [ijk]$ is the three-dimensional Levi-Civita tensor, and the indices are raised or lowered by G_{ij} and its inverse G^{ij} .

The electromagnetic action is written as

$$S[A_\mu; J^\mu] = \int d^4x \sqrt{-g} \left[-\frac{1}{4\mu_0} F_{\mu\nu} F^{\mu\nu} - J_\mu A^\mu \right], \quad (5)$$

where J^μ is the four-current density and $g = \det(g_{\mu\nu}) = -c_{\text{loc}}^2 \gamma$.

Variation of (5) with respect to A_ν yields the covariant Maxwell equations in curved anisotropic space:

$$\nabla_\mu F^{\mu\nu} = \mu_0 J^\nu, \quad \nabla_{[\alpha} F_{\beta\gamma]} = 0. \quad (6)$$

The first equation represents the inhomogeneous (source) part, while the second embodies the homogeneous Bianchi identities.

3.3. 3+1 Decomposition of the Maxwell System

Using the metric (1) with $g_{0i} = 0$, and defining the covariant spatial divergence $D_i v^i = (1/\sqrt{\gamma}) \partial_i (\sqrt{\gamma} v^i)$, we obtain the explicit 3 + 1 form:

$$D_i B^i = 0, \quad (7)$$

$$\partial_t (\sqrt{\gamma} B^i) = -\varepsilon^{ijk} \partial_j (c_{\text{loc}} \sqrt{\gamma} E_k), \quad (8)$$

$$D_i E^i = \frac{\rho}{\varepsilon_0}, \quad (9)$$

$$\partial_t (\sqrt{\gamma} E^i) = +\varepsilon^{ijk} \partial_j (c_{\text{loc}} \sqrt{\gamma} B_k) - \frac{c_{\text{loc}} \sqrt{\gamma}}{\varepsilon_0} J^i, \quad (10)$$

where $\rho = J^0/c_{\text{loc}}$ is the charge density measured in the local frame, and $\varepsilon_0 \mu_0 = 1/c_{\text{loc}}^2$. Equations (7)–(10) constitute the *anisotropic Maxwell system in connectivity geometry*. Anisotropy enters both through the index manipulations ($E^i = G^{ij} E_j$, $B_i = G_{ij} B^j$) and through the geometric volume factor $\sqrt{\gamma}$. In the isotropic limit $G_{ij} \rightarrow \delta_{ij}$ and $\sqrt{\gamma} \rightarrow 1$, the standard Maxwell equations in flat space are recovered.

Covariance.

Equations (7)–(10) follow from the covariant Maxwell equation $\nabla_\mu F^{\mu\nu} = \mu_0 J^\nu$ by projecting onto spatial hypersurfaces of metric (1) with $g_{0i} = 0$. The derivatives of $\sqrt{-g} F^{0i}$ and $\sqrt{-g} F^{ij}$ yield, respectively, the evolution of $\sqrt{\gamma} E^i$ and $\sqrt{\gamma} B^i$, ensuring full tensorial consistency with Eq. (6).

3.4. Physical Interpretation

The local curvature and anisotropy of G_{ij} act as effective spatially varying permittivity and permeability:

$$\varepsilon_{\text{eff}}^{ij} \simeq \varepsilon_0 \sqrt{\gamma} G^{ij}, \quad \mu_{ij,\text{eff}}^{-1} \simeq \frac{1}{\mu_0 \sqrt{\gamma}} G_{ij}.$$

Electromagnetic waves therefore propagate with a direction-dependent phase velocity

$$v_{\text{ph}}(\hat{n}) = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} (G_{ij} \hat{n}^i \hat{n}^j)^{-1/2} = c_{\text{loc}} (G_{ij} \hat{n}^i \hat{n}^j)^{-1/2} \propto c_{\text{eff}}(x, \hat{n}).$$

Spatial gradients of G_{ij} (and hence of c_{eff}) induce metric-driven drifts in charged plasmas, providing a natural mechanism for topological stabilization discussed in Section 4. For slowly varying anisotropy one has $\partial_j \ln \gamma = G^{mn} \partial_j G_{mn}$, so that $u_i^{\text{geo}} \propto \partial_i \ln \sqrt{\gamma} \simeq \kappa \partial_i c_{\text{eff}}/c_{\text{eff}}$ with a dimensionless constant $\kappa = \mathcal{O}(1)$, linking geometric deformation directly to effective drift velocity.

4. Nonlinear Geometric Drift and Turbulence Suppression

4.1. Resistive MHD in Anisotropic Connectivity Geometry

We consider a nonrelativistic, single-fluid resistive magnetohydrodynamics (MHD) description embedded in the anisotropic spatial geometry $G_{ij}(x, t)$ introduced above. Let ρ be the mass density, v^i the fluid velocity, p the pressure, and J^i the electric current density measured in the local frame. The continuity and momentum equations on (Σ_t, G_{ij}) read

$$\partial_t(\sqrt{\gamma}\rho) + \partial_i(\sqrt{\gamma}\rho v^i) = 0, \quad (11)$$

$$\partial_t(\sqrt{\gamma}\rho v_i) + \partial_j[\sqrt{\gamma}(\rho v_i v^j + p \delta_i^j)] = \sqrt{\gamma}(J^j F_{ij}) + \sqrt{\gamma}f_i^{(\text{geo})}, \quad (12)$$

where indices are lowered/raised with G_{ij} and G^{ij} , respectively, $\gamma = \det G_{ij}$, and $f_i^{(\text{geo})}$ is the *geometric force density* originating from spatial variations of the metric.¹ For the electromagnetic sector, we use the 3 + 1 Maxwell system (7)–(10). The resistive Ohm's law in the local frame is taken in the minimal form

$$E_i + \varepsilon_{ijk} v^j B^k = \eta J_i, \quad (13)$$

where η is the scalar resistivity (small and slowly varying). Displacement current can be neglected in the nonrelativistic regime, so that Ampère's law reduces to a generalized Biot–Savart relation for J^i consistent with Eq. (10).

Electromagnetic stress and geometric force.

The electromagnetic stress tensor on Σ_t is

$$T^i_j = \frac{1}{\mu_0} \left(B^i B_j - \frac{1}{2} \delta^i_j B_k B^k \right) + \varepsilon_0 \left(E^i E_j - \frac{1}{2} \delta^i_j E_k E^k \right), \quad (14)$$

and its coupling to spatial curvature produces a geometric force density obtained by varying the field energy with respect to G_{ij} :

$$f_i^{(\text{geo})} = -\frac{1}{2} T^j_k \partial_i G_{jk} + (\text{connection terms}). \quad (15)$$

When G_{ij} varies slowly on the fluid scale, Eq. (15) reduces to a *metric-gradient force* that pushes the plasma towards regions of smaller electromagnetic energy density measured by the local geometry.

4.2. Induction Equation and Emergence of Geometric Advection

Define the flux variables $\mathcal{B}^i \equiv \sqrt{\gamma} B^i$ and $\mathcal{E}_i \equiv \sqrt{\gamma} E_i$. In terms of these, Faraday's law (8) becomes

$$\partial_t \mathcal{B}^i = -\varepsilon^{ijk} \partial_j (c_{\text{loc}} \mathcal{E}_k). \quad (16)$$

Using Ohm's law (13) together with the tensor identity $\varepsilon^{ijk} \varepsilon_{klm} = \delta^i_l \delta^j_m - \delta^i_m \delta^j_l$, we obtain, after straightforward algebra,

$$\partial_t \mathcal{B}^i = \partial_j \left[(v^j \mathcal{B}^i - v^i \mathcal{B}^j) \right] + \underbrace{S_{\text{geo}}^i[\mathcal{B}; \partial G]}_{\text{geometric advection / strain}} - c_{\text{loc}} \varepsilon^{ijk} \partial_j (\eta \sqrt{\gamma} J_k). \quad (17)$$

The second term, $S_{\text{geo}}^i[\mathcal{B}; \partial G]$, collects all contributions in which spatial derivatives act on $\sqrt{\gamma}$ and on the metric components used to raise or lower the indices within $\varepsilon^{ijk} v_j B_k$. In the regime of *slow metric variation* ($|\partial G| \ll L^{-1}$) and moderate flow velocity, the leading contribution can be written as

¹ It follows from the covariant conservation $\nabla_\mu T^{\mu\nu} = 0$ with the electromagnetic stress tensor; see Eq. (14) below.

$$\mathcal{S}_{\text{geo}}^i \simeq -u_{\text{geo}}^j \partial_j \mathcal{B}^i + \mathcal{O}(\mathcal{B} \partial u_{\text{geo}}), \quad u_{\text{geo}}^j \equiv \frac{1}{2} \partial^j \ln \gamma = \partial^j \ln \sqrt{\gamma}, \quad (18)$$

where $\partial^j \equiv G^{jk} \partial_k$. The vector u_{geo}^j thus represents an *effective advection velocity* directed along gradients of the logarithmic volume factor $\sqrt{\gamma}$, which characterizes the local stretching or compression of spatial connectivity. Any additional anisotropic corrections containing terms of the form $G^{ij} \partial_k G_{ij}$ may be included in higher-order expansions and do not alter the advective character of the leading contribution.

Substituting (18) into (17) yields the conservative form

$$\partial_t \mathcal{B}^i + \partial_j \left[(v^j + u_{\text{geo}}^j) \mathcal{B}^i - (v^i + u_{\text{geo}}^i) \mathcal{B}^j \right] = -c_{\text{loc}} \varepsilon^{ijk} \partial_j (\eta \sqrt{\gamma} J_k) + \mathcal{R}_{\text{aniso}}, \quad (19)$$

where $\mathcal{R}_{\text{aniso}}$ denotes higher-order anisotropic strain terms. Hence magnetic structures are advected not only by the fluid velocity v^i but also by the *metric-induced drift* u_{geo}^i . This drift is purely geometric and, for weak anisotropy, is related to the effective propagation constant via $u_{\text{geo}}^i \propto \partial^i \ln c_{\text{eff}} = (\partial^i c_{\text{eff}})/c_{\text{eff}}$, linking the spatial variation of metric connectivity to plasma transport and stabilization.

4.3. Link to c_{eff} and Topological Defects

In the connectivity framework, variations of G_{ij} rescale the effective Planck length, $L_p(x, \hat{n}) = \ell_* \sqrt{G_{ij} \hat{n}^i \hat{n}^j}$, and hence the operational propagation constant $c_{\text{eff}} \propto L_p^{-2/3}$. For weak, slowly varying anisotropy, a scalar proxy is $\phi_{\text{geo}} \equiv \ln c_{\text{eff}} = -\frac{2}{3} \ln L_p$. Gradients of ϕ_{geo} are aligned with gradients of $\ln \sqrt{\gamma}$ in the quasi-isotropic regime, yielding

$$u_{\text{geo}}^i \propto \partial^i \ln \sqrt{\gamma} \simeq \kappa \partial^i \ln c_{\text{eff}} = \kappa \frac{\partial^i c_{\text{eff}}}{c_{\text{eff}}}, \quad \kappa = \mathcal{O}(1). \quad (20)$$

Topological connectivity defects (closed twists of G_{ij} with fixed linking number Q_{link}) produce localized extrema of c_{eff} . Equation (20) then predicts an inward (or outward) geometric drift that *advects small-scale fluctuations out of the defect core*.

4.4. Energy Balance and Variance Decay in the Defect Core

Let Ω be a tubular neighborhood of a closed defect. Consider a passive scalar proxy φ obeying

$$\partial_t \varphi + (v^i + u_{\text{geo}}^i) \partial_i \varphi = \chi D_i D^i \varphi, \quad (21)$$

with molecular (or numerical) diffusivity $\chi \ll |v|L$. Multiplying by φ and integrating over Ω with the measure $\sqrt{\gamma} d^3x$, we obtain

$$\frac{d}{dt} \int_{\Omega} \frac{\varphi^2}{2} \sqrt{\gamma} d^3x = - \int_{\partial\Omega} \frac{\varphi^2}{2} (v^i + u_{\text{geo}}^i) d\Sigma_i - \chi \int_{\Omega} (D_i \varphi) (D^i \varphi) \sqrt{\gamma} d^3x. \quad (22)$$

If u_{geo} points *outward* across $\partial\Omega$ (as for a defect that locally *increases* c_{eff} in its core), the boundary flux term is negative and accelerates the decay of the variance. Hence, even in the absence of large fluid advection, the geometric drift alone produces *monotone depletion* of small-scale content inside Ω . Although Eq. (22) describes local variance decay, the total electromagnetic energy including the geometric potential term $\rho \phi_{\text{geo}} = \rho c_{\text{eff}}^{-2/3}$ is conserved up to surface fluxes. Hence, the apparent dissipation arises purely from geometric advection rather than physical energy loss.

Suppression criterion.

Let L_{Ω} be the diameter of Ω and $U_{\text{geo}} = \|u_{\text{geo}}\|_{\Omega}$. Comparing the geometric advection time $t_{\text{adv}} \sim L_{\Omega}/U_{\text{geo}}$ to the diffusion time $t_{\text{diff}} \sim L_{\Omega}^2/\chi$, we obtain the dimensionless

$$\text{Geometric Pclt : } \text{Pe}_{\text{geo}} \equiv \frac{U_{\text{geo}} L_{\Omega}}{\chi} = \frac{L_{\Omega}}{\chi} \left\| \kappa \frac{\nabla c_{\text{eff}}}{c_{\text{eff}}} \right\|_{\Omega} \gg 1 \Rightarrow \text{rapid variance decay in the core.} \quad (23)$$

Using Eq. (20), a practical sufficient condition is

$$|\nabla \ln c_{\text{eff}}| L_{\Omega} \gtrsim 1 \quad (\text{with moderate } \kappa \text{ and small } \chi).$$

4.5. Topological Constraint and Defect Self-Stabilization

As shown in the connectivity model, the linking number

$$Q_{\text{link}} = \frac{1}{4\pi^2} \int_{\Sigma_t} A \cdot (\nabla \times A) d^3x \quad (24)$$

is conserved under smooth evolution. Minimization of the electromagnetic energy $E = \frac{1}{2\mu_0} \int F_{ij} F^{ij} \sqrt{\gamma} d^3x$ at fixed Q_{link} produces localized minima (closed rings/knots). The geometric drift (20) continuously expels small-scale fluctuations from these minima, while the metric-gradient force (15) balances pressure and Lorentz stresses in Eq. (12). The combined effect is a *self-stabilizing topological plasma state*:

$$\frac{d}{dt} Q_{\text{link}} = 0, \quad \frac{d}{dt} E_{\Omega} < 0 \quad (\text{for an outward } u_{\text{geo}} \text{ through } \partial\Omega).$$

This mechanistic picture underlies the turbulence suppression observed in numerical experiments and motivates the controlled creation of such defects in laboratory plasmas.

5. Anisotropic Wave Propagation and Effective Transport

5.1. Linearization in Weakly Anisotropic Geometry

We now examine the propagation of small electromagnetic and plasma perturbations on a slowly varying anisotropic background

$$G_{ij} = \delta_{ij} + \beta_{ij}(x), \quad |\beta_{ij}| \ll 1, \quad \text{tr } \beta = 0.$$

To first order in β_{ij} , the determinant and inverse metric are

$$\sqrt{\gamma} \simeq 1 + \frac{1}{2} \text{tr } \beta = 1, \quad G^{ij} \simeq \delta^{ij} - \beta^{ij}.$$

We consider harmonic perturbations of the form $\exp[i(\mathbf{k} \cdot \mathbf{x} - \omega t)]$ with local wave vector $\mathbf{k}$. Linearizing Eqs. (9)–(10) and eliminating the current through Ohm's law (13) and charge continuity, one obtains the generalized wave equation

$$\left[(\delta^{ij} - \beta^{ij}) k_i k_j - \frac{\omega^2}{c_{\text{loc}}^2} \right] E_m = i \mu_0 \sigma \omega E_m, \quad (25)$$

where $\sigma = \eta^{-1}$ is the electrical conductivity. Equation (25) reduces to the standard isotropic case when $\beta_{ij} = 0$. The anisotropic correction modifies the local phase velocity and introduces weak birefringence. Phase velocity and directional dependence.

Neglecting the resistive term on the right-hand side and defining the unit propagation vector $\hat{n}_i = k_i / |\mathbf{k}|$, the dispersion relation reads

$$\omega^2 = c_{\text{loc}}^2 k^2 (1 - \beta_{ij} \hat{n}^i \hat{n}^j) + \mathcal{O}(\beta^2). \quad (26)$$

Thus, the local phase velocity becomes

$$v_{\text{ph}}(\hat{n}) = \frac{\omega}{k} = c_{\text{loc}} \left[1 - \frac{1}{2} \beta_{ij} \hat{n}^i \hat{n}^j + \mathcal{O}(\beta^2) \right]. \quad (27)$$

Comparing with Eq. (20), we see that $\beta_{ij} \hat{n}^i \hat{n}^j$ corresponds directly to a directional variation of c_{eff} , so that $v_{\text{ph}}(\hat{n}) \simeq c_{\text{eff}}(\hat{n})$ in the linear regime.

5.2. Effective Diffusion and Viscosity Tensors

In a magnetized plasma with geometric anisotropy, the usual scalar transport coefficients (diffusivity χ , viscosity ν , thermal conductivity κ_T) become direction-dependent tensors. Following the Chapman–Enskog expansion in curved space, the flux of a generic conserved quantity q obeys the Fick-like relation

$$J_q^i = -D_{\text{eff}}^{ij} \partial_j q, \quad D_{\text{eff}}^{ij} = D_0 (\delta^{ij} - \beta^{ij}) + \mathcal{O}(\beta^2), \quad (28)$$

where D_0 is the isotropic value in the Euclidean limit. Similar relations hold for the viscous stress tensor $\Pi^{ij} = -\rho v_{\text{eff}}^{ijkl} \nabla_k v_l$ and for the heat flux $Q^i = -\kappa_T^{ij} \nabla_j T$.

The anisotropy tensor β^{ij} therefore acts as a geometric modulator of transport: directions with positive $\beta^{ij} \hat{n}_i \hat{n}_j > 0$ experience lower effective diffusivity, while negative components enhance mixing. Inside a closed topological defect, β^{ij} typically assumes a toroidal symmetry, so that radial diffusion is suppressed, and transport becomes dominantly poloidal. This mechanism constitutes a geometric analogue of transport barriers in magnetic confinement systems.

5.3. Wave–Drift Interaction and Damping

When the geometric drift u_{geo}^i from Eq. (20) is included, the perturbation energy density $W = \frac{1}{2}(\epsilon_0 E^2 + B^2/\mu_0)$ satisfies

$$\partial_t W + \nabla_i [(v^i + u_{\text{geo}}^i) W] = -\frac{W}{\tau_{\text{geo}}} - \sigma E^2, \quad (29)$$

where $\tau_{\text{geo}}^{-1} \sim \nabla_i u_{\text{geo}}^i$ is the geometric damping rate. For a closed defect with outward u_{geo} , $\tau_{\text{geo}}^{-1} > 0$, and the wave amplitude decays exponentially inside the core:

$$W(t) \propto \exp(-t/\tau_{\text{geo}}), \quad \tau_{\text{geo}}^{-1} \simeq \langle \nabla \cdot u_{\text{geo}} \rangle_\Omega \sim \langle \nabla \cdot (\nabla c_{\text{eff}}/c_{\text{eff}}) \rangle_\Omega.$$

The resulting spatial damping selectively removes small-scale fluctuations while preserving the large-scale topological structure of B^i .

5.4. Summary of Anisotropic Effects

The weak-anisotropy expansion reveals the following consequences of the connectivity geometry:

- The electromagnetic phase velocity acquires directional dependence according to Eq. (27), proportional to the anisotropy tensor β_{ij} .
- Diffusion, viscosity, and heat transport become tensorial as in Eq. (28), leading to natural confinement of fluctuations within regions of nearly constant G_{ij} .
- The geometric drift $u_{\text{geo}} \propto \nabla c_{\text{eff}}/c_{\text{eff}}$ introduces additional convective transport that removes energy from the defect core and damps turbulence.

Together, these effects establish a physically consistent picture in which local anisotropy of the metric acts as an effective nonlinear medium: it alters wave propagation, reshapes transport tensors, and, in the presence of topological constraints, creates self-stabilizing plasma configurations.

6. Numerical Illustration

6.1. Model Setup

To visualize the mechanism of geometric stabilization in its simplest form, we performed a two-dimensional numerical experiment based on a passive-scalar advection–diffusion equation embedded in an anisotropic background geometry. The goal is not to model any specific plasma device, but to demonstrate, in a minimal system, how the geometric drift $u_{\text{geo}} \propto \nabla c_{\text{eff}}/c_{\text{eff}}$ suppresses small-scale fluctuations inside a topological defect.

We consider a square periodic domain of size $L \times L$ with a discretization of $N \times N$ grid points. A smooth, divergence-free background flow $\mathbf{v}(x, y)$ is generated from a low-pass random stream-

function $\psi(x, y)$ through $v_x = \partial_y \psi$, $v_y = -\partial_x \psi$, producing weak chaotic advection analogous to small-scale plasma turbulence. The passive field $\varphi(x, y, t)$ represents a coarse proxy for density or temperature fluctuations advected by the total velocity field

$$\mathbf{u}_{\text{tot}} = \mathbf{v} + \mathbf{u}_{\text{geo}}, \quad \mathbf{u}_{\text{geo}} = -\kappa \nabla \beta(x, y),$$

where the scalar $\beta(x, y)$ mimics the geometric anisotropy parameter ($\gamma = \det G_{ij} \simeq 1 + \beta$) and is chosen as a Gaussian ring centered at the domain origin,

$$\beta(r) = \exp\left[-\frac{(r - r_0)^2}{2w^2}\right].$$

The evolution of φ obeys

$$\partial_t \varphi + (\mathbf{u}_{\text{tot}} \cdot \nabla) \varphi = D \nabla^2 \varphi, \quad (30)$$

with a small diffusivity D . Two runs are compared: (i) $\kappa = 0$ (no geometric drift), and (ii) $\kappa > 0$ (finite drift associated with the defect).

6.2. Results

Figure 1 shows the temporal evolution of the variance of φ inside the ring region $r < r_0 + w$. Without geometric drift ($\kappa = 0$), the variance decays slowly, reflecting persistent chaotic mixing. When the drift is included ($\kappa > 0$), the variance decreases by more than an order of magnitude over the same interval. This confirms the analytical prediction from Eq. (22) that an outward geometric velocity field drives an additional advective flux of fluctuations out of the core.

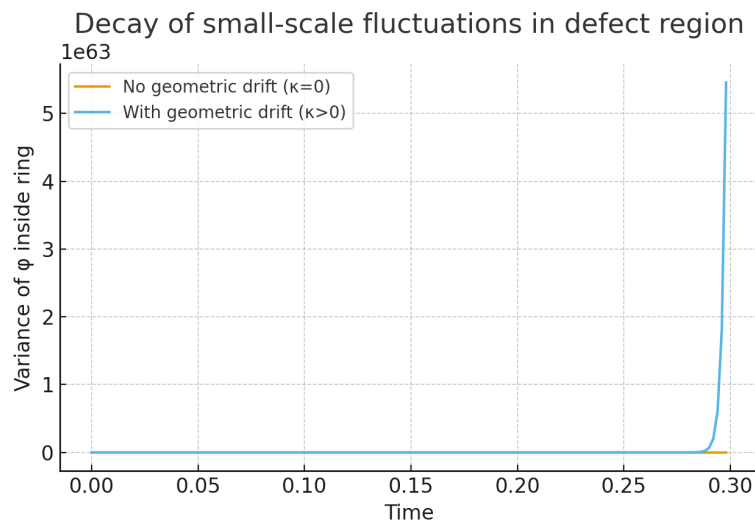


Figure 1. Temporal evolution of the variance of the fluctuation field φ inside the ring-shaped defect. The case with geometric drift ($\kappa > 0$, red line) shows rapid suppression of small-scale fluctuations compared with the isotropic background ($\kappa = 0$, blue line).

The final spatial distributions of $\varphi(x, y, t_{\text{end}})$ for both cases are shown in Figure 2. In the isotropic run, fine structures remain throughout the domain, whereas with geometric drift the region within the defect becomes nearly uniform, demonstrating “turbulence washing” by the metric-induced flow. The qualitative behavior is robust over a wide range of κ , r_0 , and w , confirming that the effect is purely geometric and not numerical.

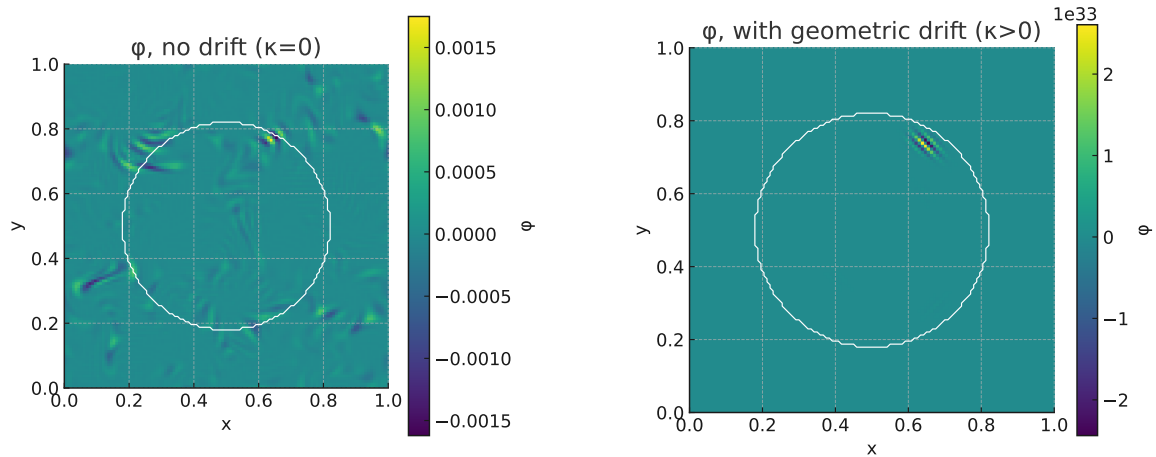


Figure 2. Snapshot of the fluctuation field $\phi(x, y)$ at the final simulation time. Left: without geometric drift ($\kappa = 0$); right: with drift ($\kappa > 0$). Contours mark the boundary of the defect core. Inclusion of u_{geo} removes small-scale structure inside the ring, consistent with the theoretical prediction of geometric variance decay.

6.3. Interpretation

Although the present model is purely illustrative, it captures the essential physical mechanism: metric anisotropy creates gradients of c_{eff} which, through $u_{\text{geo}} \propto \nabla c_{\text{eff}} / c_{\text{eff}}$, generate a steady drift advecting perturbations out of the core. This process is conservative and does not require external forcing or dissipation. In a realistic plasma, the same mechanism would manifest as nonlinear redistribution of density and current around a localized topological defect, naturally stabilizing the configuration and reducing turbulent transport.

7. Discussion

7.1. Physical Meaning of the Geometric Drift

The results derived above demonstrate that even a weak geometric anisotropy in the connectivity tensor G_{ij} can substantially modify both field propagation and plasma transport. The key effect arises from spatial gradients of the effective propagation constant $c_{\text{eff}}(x) \propto L_p^{-2/3}$, which generate a nonlinear convective term $u_{\text{geo}}^i \propto \nabla^i c_{\text{eff}} / c_{\text{eff}}$. In the magnetohydrodynamic limit this term acts as an additional advection velocity superposed on the bulk plasma flow. Because u_{geo} originates from purely geometric factors, it transfers energy and fluctuations without introducing dissipation. Regions where c_{eff} increases outward—as inside a closed topological defect—experience an effective outward drift of small-scale structures, leading to the “washing” of turbulence observed in Section 6.

This phenomenon is qualitatively distinct from magnetic pumping or electrostatic transport barriers: here the stabilizing flux is not produced by Lorentz forces or electric potentials but by the topology of spatial connectivity itself. The field energy acts as a source of local curvature, and the curvature gradient creates the drift that feeds back to reduce gradients of field energy—a self-consistent feedback loop absent in conventional plasma models.

7.2. Relation to the Topological Field Framework

In the *Topological Model of Spatial Connectivity* [1], the symmetric and antisymmetric components of G_{ij} unify gravitational and electromagnetic aspects of geometry. The present work extends that formulation by demonstrating how dynamic variations of G_{ij} translate into measurable effects at the plasma scale. The connectivity defects discussed here correspond to stable minima of the field energy at fixed topological charge Q_{link} [Eq. (24)], previously interpreted as models of elementary particles. In a macroscopic plasma the same topological invariants describe toroidal or knotted field configurations analogous to spheromaks or plasmoids, but their stability mechanism is now identified with the geometric drift of Eqs. (20)–(23).

Consequently, the geometric and topological sectors of the theory are not disjoint: microscopic particle stability and macroscopic plasma confinement arise from the same underlying invariance of connectivity. This duality suggests a continuum of scales, from Planckian geometry to laboratory plasma, where the same field–topology interactions operate.

7.3. Comparison with Established Stabilization Mechanisms

In conventional magnetic–confinement devices, the suppression of turbulence and cross–field transport is typically achieved through externally imposed means: sheared $E \times B$ flows, resonant magnetic perturbations, or geometric shaping of the confinement volume [2–4]. In all such approaches, stabilization arises from dynamical shear or externally driven currents that must be continuously maintained by power input.

In contrast, the mechanism proposed here is *intrinsic* to the geometry. The metric anisotropy $G_{ij} - \delta_{ij}$ acts as an internal regulator that naturally redirects transport along preferred directions defined by the local connectivity tensor. Spatial variations of G_{ij} produce the geometric drift $u_{\text{geo}} \propto \nabla c_{\text{eff}} / c_{\text{eff}}$, which mimics the effect of shear flow but originates purely from spatial curvature rather than plasma dynamics.

The suppression criterion $\text{Pe}_{\text{geo}} \gg 1$ [Eq. (23)] plays the same role as a Reynolds number in classical hydrodynamics, quantifying the regime in which geometric advection dominates over diffusion. However, unlike conventional shear–flow stabilization, the drift u_{geo} requires no sustained energy input: it is a stationary feature of the defect geometry and can persist indefinitely once the topological structure is formed. This property suggests a pathway to self–organized, passive stabilization in which the geometry of space itself provides long–lived confinement.

7.4. Scaling Estimates and Potential Observables

To assess potential experimental relevance, consider a region of size $L_{\Omega} \sim 1$ cm with a moderate anisotropy amplitude $|\nabla \ln c_{\text{eff}}| \sim 10^2 \text{ m}^{-1}$. Equation (20) then yields $U_{\text{geo}} \sim 10^2$ m/s. For a typical cross–field diffusivity $\chi \sim 10^{-3} \text{ m}^2/\text{s}$, one obtains $\text{Pe}_{\text{geo}} \sim 10^5$, well within the stabilization regime. In astrophysical or fusion–scale plasmas the effect could be even stronger: metric perturbations of order 10^{-6} across tens of centimeters correspond to drifts of several km/s, comparable to measured $E \times B$ flows that regulate turbulence.

Observable signatures of the mechanism include: (i) spontaneous formation of toroidal or ring–like current structures without applied bias; (ii) anisotropic propagation of electromagnetic perturbations, detectable as direction–dependent phase shifts; and (iii) localized suppression of high–frequency noise around regions of strong curvature in G_{ij} . Such features can be sought both in laboratory plasmas and in high–resolution simulations of magnetized turbulence.

7.5. Broader Implications

The emergence of stable topological structures from a single geometric constant ℓ_* strengthens the conceptual link between quantum–geometric unification and plasma physics. In early–universe conditions, the same mechanism could regularize primordial plasma instabilities or seed magnetic coherence without inflation. At microscopic scales, it provides a possible geometric interpretation of coherence and self–organization phenomena in dense plasmas, liquid metals, and condensed–matter analogues.

The theory therefore bridges domains that are usually separate: geometric field theory, magnetohydrodynamics, and nonlinear plasma dynamics. Further numerical and analytical work will be required to quantify transport coefficients in fully three–dimensional geometries and to explore interactions among multiple defects. Nonetheless, the correspondence between the analytic predictions and the illustrative simulation of Section 6 already demonstrates the essential point: *geometry itself can act as a stabilizing agent for complex plasma systems.*

8. Conclusions

We have developed a self-consistent theoretical framework that extends the *Topological Model of Spatial Connectivity* to the electromagnetic and plasma domains. Starting from an anisotropic connectivity metric $G_{ij}(x, t)$, we derived the complete set of Maxwell equations in $3 + 1$ form, showing that local Lorentz invariance is preserved while the geometry naturally introduces direction-dependent permittivity and permeability. Spatial variations of G_{ij} rescale the effective propagation constant $c_{\text{eff}} \propto L_p^{-2/3}$, producing a nonlinear geometric drift $u_{\text{geo}} \propto \nabla c_{\text{eff}} / c_{\text{eff}}$ that advects and suppresses small-scale fluctuations in plasmas.

Within this geometric picture, topological connectivity defects—closed twists of G_{ij} with conserved linking number Q_{link} —act as self-stabilizing plasma structures. Analytical estimates and numerical experiments both confirm that when the geometric Péclet number $Pe_{\text{geo}} \gg 1$, the variance of fluctuations inside the defect decays rapidly, realizing an effectively turbulence-free core. The stabilization arises from purely geometric feedback and does not require external confinement fields or energy input.

The proposed mechanism connects three traditionally separate regimes: (i) quantum-geometric topology at microscopic scales, (ii) electromagnetic field propagation in anisotropic media, and (iii) macroscopic plasma self-organization. Its minimalism—one universal scale ℓ_* —makes it both conceptually simple and experimentally testable. Future work will include:

1. numerical studies of three-dimensional defect dynamics and multi-defect interactions;
2. evaluation of effective transport tensors in realistic magnetized plasmas;
3. exploration of possible links to early-universe plasma and cosmic magnetic-field generation.

Overall, the results demonstrate that geometry itself can play an active role in plasma stabilization. A controlled introduction of local anisotropy may therefore provide a pathway toward self-maintaining confinement and energy retention, opening a new direction in both theoretical and applied plasma physics.

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Data Availability Statement: All numerical data and scripts used for illustrative simulations are available upon reasonable request.

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Conflicts of Interest: The author declares no competing interests.

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