

Magnetic Filters for Plasma Processing: A Proposed Phenomenological Framework for Retention and Stochastic Defect Scaling

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Abstract—This paper proposes a phenomenological framework for examining transverse magnetic filters (TMFs) in plasma processing. Building on the single-layer scaling discussed in Part I, it separates an assumed one-layer retention factor from the physical plasma Debye length and states the assumptions connecting a defect-event rate to accumulated roughness. A deliberately chosen layer thickness of 10 nm and effective attenuation length of 20 nm illustrate partial attenuation through a single layer; their physical realism is not established. The defect-rate closure remains symbolic. The mechanical discussion identifies the missing transfer from plasma force to solid loading, and the causal graphs describe hypotheses that would require identifiable interventions and suitable data. The framework has not been evaluated here by a completed PIC–MCC study, coupled-mechanics calculation or causal-controller test. An intended, uncompleted computational protocol is described separately. The contribution is a set of explicit modelling assumptions and limits, rather than a quantitative demonstration of manufacturing performance.

Keywords— magnetic filters; plasma etching; phenomenological modelling; stochastic defects; plasma–solid coupling; causal hypotheses.

I. INTRODUCTION

Plasma etching defines nanoscale features in semiconductor fabrication, but energetic-particle damage and non-uniform sheath dynamics can limit its performance [1, 2]. Transverse magnetic filtering offers a means of modifying electron transport and the electron energy distribution [3–5]. Its possible use in low-damage processing motivates examination of the relationship between plasma conditions and surface response [6, 7]. The discussion here concerns modelling assumptions; it does not establish a processing outcome.

Part I [3] introduced the normalised etch-performance gain

$G \equiv \frac{Y_{\text{etch}}}{Y_0}$ in the form

$$G = 1 + \alpha \left(\frac{\delta n_e}{n_0} \right)_{\max} \left(\frac{T_{e,\text{hot}}}{T_{e,\text{cold}}} \right), \quad (1)$$

Here, $\left(\frac{\delta n_e}{n_0} \right)_{\max}$ is the peak fractional electron-density perturbation, $T_{e,\text{hot}}$ and $T_{e,\text{cold}}$ are characteristic electron temperatures, and α is a fitted enhancement factor in the prior model. Equation (1) is retained as a modelling starting point; no new calibration or numerical performance estimate is supplied. Throughout this paper, temperature T is in kelvin. Electron thermal energies may be quoted as $k_B T$ in eV, with conversion to joules where an SI equation requires it.

Inductively coupled plasma systems provide a relevant processing context [8]. A resolution estimate is outside the present model because its additional parameters and dimensional calibration are not established here.

Multilayer stacks and high-aspect-ratio features motivate the proposed framework because transport, interface charging and surface damage can interact across a structure [2, 9, 10]. Defect formation also raises mechanical questions involving residual stress, interface cracking and delamination [11, 12]. Extending a single-layer model to such structures requires a composition rule and a specified plasma–solid loading model; neither follows from a one-layer attenuation factor alone. Fragile materials provide a further motivation. Halide perovskites such as formamidinium lead iodide (FAPbI₃) exhibit domain-dependent optoelectronic behaviour [13], and their processing requires attention to damage and phase stability [14, 15]. They are considered here as possible future applications. No domain-stability, impurity or transient-response outcome is calculated.

This paper states the assumptions of a one-layer retention illustration, a stochastic defect-count model and a symbolic defect-rate closure. It then identifies the missing information needed for a mechanical coupling and outlines causal hypotheses following [16]. These components have not been jointly evaluated. Section V and the Appendix describe an intended, uncompleted protocol; the worked arithmetic in Section II is the only numerical evaluation of the proposed retention factor.



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II. PROPOSED ONE LAYER RETENTION MODEL

A transverse magnetic filter can alter electron transport through the Lorentz force. The extent of energy selectivity depends on transport, collisions and geometry; it is an assumption to be tested for any particular processing case. The proposed model distinguishes characteristic hot and cold electron temperatures without treating either population as a measured distribution in this study.

Possible changes in dissociative attachment and radical production motivate the model. No reaction-rate or surface-heating improvement is inferred without a specified distribution and collision model.

In [3], the resulting behaviour was summarised by a heuristic confinement scaling,

$$\eta \propto \left(\frac{n_{H-}}{n_e} \right) \frac{B}{P_a}$$

Here, n_{H-} is the negative-ion density, n_e is the electron density, B is filter strength and P_a is activation power. This is a proportionality rather than an absolute dimensionless efficiency. The factor $\frac{B}{P_a}$ has units $T W^{-1}$, so a calibrated coefficient or explicit normalisation would be required for an equality.

For one layer, a retention factor can be included in the same uncalibrated proportionality. No rule for composing this factor over multiple layers is supplied.

The proposed relation is

$$\eta \propto \frac{n_{H-}}{n_e} \frac{B}{P_a} f_{\text{layer}}, \quad (2)$$

where

$$f_{\text{layer}} = \frac{T_{e,\text{hot}} - T_{e,\text{cold}}}{T_{e,\text{hot}}} \exp\left(-\frac{d_{\text{layer}}}{\ell_{\text{eff}}}\right), \quad (3)$$

where d_{layer} is a single layer thickness and ℓ_{eff} is an effective attenuation length. The latter is independent of the physical Debye length

$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T_e}{n_e e^2}}, \quad (4)$$

in a plasma with electron density n_e , vacuum permittivity ϵ_0 , elementary charge e and thermal energy $k_B T_e$ in joules [17]. The illustrative value assigned to ℓ_{eff} below is not a Debye length inferred from Eq. (4), a density measurement or a stated reactor pressure.

Equation (3) is a one-layer phenomenological assumption. Its thermal prefactor represents the chosen contrast between characteristic electron temperatures, and its exponential factor represents assumed attenuation over ℓ_{eff} . For positive electron temperatures, nonnegative layer thickness and $\ell_{\text{eff}} > 0$, it requires $0 \leq T_{e,\text{cold}} \leq T_{e,\text{hot}}$ to keep the retention factor within its intended range. There is no derivation here from Poisson electrostatics or a layer sum, and no justified composition rule for a stack.

For a transparent worked example, choose $d_{\text{layer}} = 10$ nm and $\ell_{\text{eff}} = 20$ nm. Then the attenuation factor is $\exp(-0.5) \approx 0.60653$. Choosing a thermal prefactor between 0.7 and 0.8 gives $f_{\text{layer}} \approx 0.42457 - 0.48522$.

These inputs deliberately illustrate partial attenuation through one layer. Their physical realism is not established, and the calculation does not imply a multilayer yield or defect reduction.

- Within the assumed closure, reducing the ratio $\frac{d_{\text{layer}}}{\ell_{\text{eff}}}$ increases retention. This mathematical dependence does not by itself determine selectivity, sputtering or defect risk.
- A physical application would need evidence for the effective length and temperature prefactor, together with a transport model appropriate to the material interfaces.

A domain size that is numerically similar to the selected layer thickness does not establish that the same effective attenuation length applies in a perovskite or another fragile material.

The worked example therefore remains a single-layer illustration. No multilayer composition, transport calculation or material-specific performance inference is made.

III. PROPOSED STOCHASTIC DEFECT MODEL

Surface roughness, micro-trenching and phase or compositional changes are distinct damage measures. A stochastic event model can organise questions about bombardment-induced displacement, but it does not establish a measured defect rate or a spatial roughness map. The following relations specify the assumptions needed to connect an event rate to an accumulated displacement scale.

A. Stochastic Bombardment Model

For a specified target or site, let defect-producing events follow a Poisson process with rate

$$\lambda_{\text{def}} = \int \Gamma_e(\mathbf{r}, E_e) \sigma_{\text{coll}}(E_e) dE_e, \quad (5)$$

Here, $\Gamma_e(\mathbf{r}, E_e)$ is an energy-resolved electron number flux, in $m^{-2} s^{-1} J^{-1}$ when energy is in joules, and $\sigma_{\text{coll}}(E_e)$ is an effective defect-producing cross section in m^2 . The integral therefore has units s^{-1} per specified target or site. Its use requires an energy distribution, cross section and target definition; no numerical cross section is assigned here.

Atomic-scale plasma processing requires control of energetic-particle interactions and variability [9]. To distinguish a rate from accumulation, define the dimensionless expected event count over an exposure interval t_{exp} as

$$\Lambda_{\text{def}} = \int_0^{t_{\text{exp}}} \lambda_{\text{def}}(t) dt,$$

which reduces to $\Lambda_{\text{def}} = \lambda_{\text{def}} t_{\text{exp}}$ for a stationary rate. Assuming uncorrelated bombardment-induced displacements with characteristic RMS magnitude a_0 , the resulting surface roughness is represented phenomenologically by

$$\sigma_{\text{def}} = a_0 \sqrt{\Lambda_{\text{def}}}, \quad (6)$$

The effective displacement scale a_0 has units of length. Equation (6) assumes independent, zero-mean displacement

contributions with a common finite mean square and no correlated surface evolution. It is a phenomenological square-root accumulation law. No numerical displacement scale or achieved roughness threshold is asserted.

An additional candidate assumption for the defect rate under TMF operation is

$$\lambda_{\text{def}}^{\text{TMF}} = \lambda_{\text{def}}^0 \exp\left(-\frac{\Delta E_{\text{trap}}}{k_B T_{\text{e,cold}}}\right) (1 - f_{\text{layer}}) \quad (7)$$

Here, ΔE_{trap} is an effective suppression-energy parameter and f_{layer} is the one-layer retention factor of Eq. (3). Equation (7) assumes that the energy-dependent and residual-retention factors can be multiplied independently. For positive cold-electron temperature, nonnegative suppression energy and a retention factor between zero and one, it has the algebraic form of a rate-reduction closure. Its parameters and physical applicability are not established. It remains symbolic and is not fitted to a PIC-MCC trend or used to report a performance percentage.

Equations (5)–(7) serve different purposes: Eq. (5) defines a candidate event rate, Eq. (6) connects event accumulation to a displacement scale under independence assumptions, and Eq. (7) proposes an uncalibrated modification to the rate. None supplies a spatial roughness distribution or a material failure criterion.

At equal exposure time and displacement scale, the roughness ratio implied by Eq. (6) is the square root of the corresponding rate ratio. A claim about spatial localisation would require a separate spatial model and cannot be inserted into that relation without further assumptions.

B. Causal Hypotheses for Defect Formation

A directed acyclic graph can state a proposed dependency structure without estimating its edges. One candidate path is $B \rightarrow \delta n_e \rightarrow \lambda_{\text{def}} \rightarrow \sigma_{\text{def}}$,

where magnetic-field strength may affect an electron-density perturbation, the defect-event rate, and the roughness metric. The expected event-count step remains implicit for a specified exposure interval. The arrows are hypotheses, not relationships inferred from data.

An intervention analysis would need a defined outcome, a specified intervention and a justified adjustment set [16]. Pressure and activation power are possible pre-intervention variables, but their sufficiency for adjustment is not established by drawing the graph.

No intervention probability, counterfactual roughness change or controller performance is estimated. The graph identifies questions for future identification and measurement.

C. Possible Application to Perovskites

Perovskite domain structure motivates a possible extension [13–15], but the present framework has no material-specific plasma, surface, or mechanical calculations. The effect of filtering on domain stability remains an open question.

For clarity, the proposed domain-factor extension of Eq. (1) is retained only in symbolic form:

$$\frac{Y_{\text{etch}}}{Y_0} = 1 + \alpha \left(\frac{\delta n_e}{n_0} \right)_{\text{max}} R_T f_{\text{domain}}, \quad (8)$$

where

$$R_T = \frac{T_{\text{e,hot}}}{T_{\text{e,cold}}},$$

and

$$f_{\text{domain}} = \frac{l_{\text{conf}}}{d_{\text{twin}}}$$

with l_{conf} denoting a proposed confinement length and d_{twin} a characteristic twin spacing. The ratio is a geometric descriptor; its adequacy as a performance multiplier is an additional assumption. No complete calibrated parameter case is available, so Eq. (8) is not numerically evaluated.

Equation (8) does not establish preservation of domain order, phase purity or optoelectronic response. Those outcomes need their own material-specific model and evidence.

IV. MECHANICAL AND CAUSAL MODELLING REQUIREMENTS

A coupled description would need to connect plasma transport, surface loading and solid response. The present framework specifies neither a completed fluid calculation nor a closed mechanical boundary-value problem. This section makes the missing coupling explicit and records the conditions under which a future causal analysis could be interpreted.

A. Plasma Force and Solid Response

Within a homogeneous isotropic solid layer with constant Lamé coefficients and no specified solid body force, the elastic displacement equation is

$$\rho_m \frac{\partial^2 u}{\partial t^2} = \mu \nabla^2 u + (\lambda + \mu) \nabla (\nabla \cdot u), \quad (9)$$

where u is the solid displacement, ρ_m is mass density, and λ and μ are Lamé constants. The coefficient of the gradient of the divergence is $\lambda + \mu$ when μ multiplies the Laplacian. If coefficients vary spatially, the elastic force must instead be written as the divergence of the full stress tensor; coefficients cannot simply be moved outside derivatives.

The Lorentz force density $J \times B$ acts on the plasma when J is the plasma current density. It cannot be placed directly into Eq. (9) as a distributed force on the substrate. The solid could respond through a specified surface traction or another justified transfer mechanism, but the required plasma-to-solid force-transfer law and loading boundary conditions are missing here. No traction law is invented or used in this paper.

Equation (9) is therefore an uncoupled solid-balance statement, not a computed mechanical result. A quasi-static approximation would set its inertia term to zero only after the loading, supports and interfaces had been specified.

The previous stress-amplification expression is withdrawn. No amplification metric, reference stress, strain field or material-specific failure threshold is evaluated.

B. Requirements for Causal Analysis

A future causal analysis could connect a controllable input, such as magnetic-field strength, to a well-defined outcome, such as the normalised gain G . Any mediating plasma and material variables would need observable definitions and a defensible causal structure. No controller or data-replay analysis has been performed for the proposed framework.

For illustration of the identification requirement, let Z denote a proposed set of pre-intervention covariates. If that set blocks all relevant backdoor paths between B and G , and the required consistency and support conditions hold, the standard adjustment identity is

$$P(G \mid do(B = b)) = \int P(G \mid B = b, Z = z)p(z)dz$$

with the corresponding sum for discrete covariates [16]. This identity does not establish that a sufficient adjustment set exists or that any intervention distribution has been estimated. Mediators on the causal path would not belong in an adjustment set for the total effect merely because they appear in a physical mechanism.

C. Questions for Manufacturing Assessment

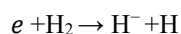
A manufacturing assessment would need to determine whether filtering changes a specified surface metric at matched processing conditions and whether any benefit persists after accounting for energy, throughput and material consumption. The present model supplies no activation power, consumables, or lifetime estimate.

For fragile materials, the corresponding questions concern surface chemistry, domain integrity and the mechanical boundary conditions. No sustainability or reliability improvement can be inferred from the illustrative retention factor alone.

V. INTENDED COMPUTATIONAL PROTOCOL

The proposed PIC–MCC protocol is incomplete. Its intended reference geometry is a two-dimensional 10 cm $\times$ 5 cm chamber at 2 mTorr with an H₂/Ar mixture specified as 80/20, a 13.56 MHz RF drive at 100 W, and a transverse field considered over 0–0.5 T. These are design inputs, not conditions of a completed evaluation. A proposed 100 $\times$ 50-cell grid over that domain has 1 mm spacing. A trial time step of 0.1 ns and proposed super particle and step counts would require convergence and stability tests before use.

The intended collision model would need to include and verify relevant channels such as elastic scattering, charge exchange, and dissociative attachment,



with each species, reaction and cross-section provenance checked. The proposed sources are the Phelps compilations for H₂ and the applicable native argon set in XOOPIC.

BOLSIG+ is a Boltzmann solver, not a cross-section database. Species coverage and attachment support have not been established for a production configuration. Dielectric interfaces and unresolved sheath scales would require justified boundary treatments and convergence checks [17]. A candidate stochastic extension for particle velocities is

$$\frac{dv}{dt} = \frac{F}{m} + \Gamma(t), \quad (10)$$

Here, v is particle velocity, F is the deterministic force, m is particle mass and Γ is acceleration noise. Its required component statistics are $\langle \Gamma_i(t) \rangle = 0$, and

$$\langle \Gamma_i(t) \Gamma_j(t') \rangle = 2D_v \delta_{ij} \delta(t - t')$$

Here, D_v is a velocity-space diffusion coefficient with units m² s⁻³; it is not an energy in eV. Its numerical value and any conversion from a thermal-energy scale require a specified stochastic model. Collision sampling and added Langevin forcing must be checked for double counting. Neither a noise-sensitivity result nor a coupled neutral-flow improvement is reported.

A. Evidence Needed for Evaluation

A completed evaluation would require preserved input decks, code and cross-section versions, initial and boundary conditions, seeds, output arrays and a documented analysis path. Numerical convergence, physical-model adequacy and comparison with relevant observations are separate requirements.

The one-layer illustration does not supply a composition rule for a stack, and the proposed mechanical discussion does not supply the surface loading. Both gaps must be resolved before evaluating multilayer yield, roughness maps or mechanically mediated defects.

B. Scope of Existing Checks

Separate vacuum and low-density solver checks are limited numerical checks. They are not a source of the withdrawn performance table or figures and do not test the retention, defect-rate, mechanical or causal claims proposed here. No qualification result is used as manufacturing evidence.

VI. DISCUSSION

The proposed framework separates a single-layer attenuation assumption from physical screening, distinguishes a defect rate from an accumulated event count, and identifies the uncompleted plasma-to-solid coupling. These distinctions limit what can be concluded from the available equations. They do not establish a multilayer gain, a roughness threshold or a mechanical reliability improvement.

The 10 nm / 20 nm illustration shows how the assumed exponential behaves when its dimensionless argument is one half. It does not show that such an effective length occurs in the intended low-pressure discharge. A material-specific use would require an independently justified value and a consistent transport description.

A. Limits of the Closures

The multiplicative assumptions in (3) and (7) need independent scrutiny. A retention factor and an event-rate modifier are not interchangeable physical observables. Correlated surface evolution, nonstationary flux, and material-dependent chemistry could invalidate the simple accumulation model.

The mechanical limitation is separate: knowing a plasma force does not determine traction on a solid. The required momentum, thermal, and interfacial transfer cannot be inferred from the elastic operator alone.

B. Limits of Causal Interpretation

A causal graph can make an assumption explicit, but an intervention estimate additionally needs identifiable effects, adequate data, and support for the intervention. No posterior, controller convergence rate, or causal performance gain follows from the schematic paths in this paper.

C. Relevance to Manufacturing

The model offers a way to organise questions about low-damage processing. Establishing practical relevance would require measurements or reproducible calculations tied to particular materials, geometries and process objectives. Energy use, throughput and lifetime must be assessed as separate outcomes.

The scope remains a proposed phenomenological framework with an illustrative calculation and an incomplete evaluation protocol.

VII. Conclusion

This paper proposes a one-layer retention closure and states the assumptions connecting defect-event accumulation to a roughness scale. The deliberately selected 10 nm layer and 20 nm effective length illustrate partial attenuation only. Equation (7) remains symbolic, and no multilayer composition rule or numerical manufacturing benefit is established.

The corrected homogeneous isotropic elastic operator is stated separately from plasma loading. The plasma-to-solid transfer law and loading conditions are missing, so no coupled stress or strain response is calculated. Causal graphs are likewise hypotheses and are not evaluated as interventions or controller results.

The principal outcome is a bounded model description: explicit assumptions, one transparent retention example, and a statement of the evidence needed for further evaluation. The intended PIC–MCC protocol is incomplete. No computational or experimental performance demonstration is claimed.

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The author gratefully acknowledges the Harmony Research Initiative for theoretical collaboration. This article develops modelling questions related to the prior plasma-filter studies [3, 18].

Appendix

This appendix records assumptions and an intended, incomplete protocol. It does not provide a derivation of the exponential retention closure or an executable reproduction package for manufacturing results.

A. Confinement Assumptions and Intended Protocol

Part I [3] motivates the use of a confinement proportionality. Its dimensional calibration and application to a specific transport problem are not supplied here.

The heuristic relation is repeated for reference:

$$\eta \propto \left(\frac{n_{H-}}{n_e} \right) \frac{B}{P_a},$$

The proportionality has the same dimensional limitation discussed in Section II. Multiplication by the one-layer factor in Eq. (3) is a proposed assumption. Neither this expression nor a layer sum derives the exponential, and no composition over multiple layers is asserted.

1) Intended PIC–MCC implementation: The proposed XOOPIC geometry and candidate inputs are listed in Section V. The 10 cm × 5 cm domain with 100 × 50 cells has 1 mm spacing. This protocol has not produced the manufacturing, mechanical or causal results previously attributed to it.

A completed setup would have to verify the leapfrog advance, time-step stability, collision probabilities, species support and cross-section data. Effective sheath and dielectric boundary treatments would need separate justification; a trial mesh or time step is not evidence of adequate resolution.

A usable record would retain input decks, code versions, random seeds, outputs and post-processing. The original computational outputs, seeds and scripts underlying earlier performance claims are not recoverable. No replacement calculation or confidence interval is presented here.

B. Stochastic Bombardment and Langevin Modelling

A candidate stochastic extension can be written as the acceleration equation

$$\frac{d\mathbf{v}}{dt} = \frac{\mathbf{F}}{m} + \mathbf{\Gamma}(t),$$

with zero-mean Gaussian acceleration noise and the component covariance stated in Section V. Its coefficient D_v has units m² s⁻³. A numerical coefficient cannot be supplied from an energy value alone without a defined mass and relaxation model.

The stochastic extension has not been calibrated against defect statistics or assessed for sensitivity. Its relationship to the collision model would need to be specified before adding it to particle trajectories.

C. Requirements for Intervention Analysis

The DAGs in Sections III and IV represent hypothesised relationships following [16]. Nodes and interventions require operational definitions, and adjustment requires a justified causal structure.

No interventional query has been evaluated. The adjustment identity states a conditional identification result; it is not evidence for a numerical probability or a completed control analysis.

Conflict of Interest

The author declares no conflict of interest.

Data and Code Availability

The worked example is reproducible directly from (3), and the explicitly selected 10 nm and 20 nm inputs. No recovered PIC–MCC production outputs, random seeds, or post-processing scripts support the previously reported manufacturing estimates. Separate vacuum and low-density solver checks are bounded numerical checks and are not the source of those withdrawn estimates or evidence for the proposed closures. The Appendix describes an intended, uncompleted protocol rather than a completed reproduction package. No new solver run, experiment, or controller evaluation was performed for this revision.

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