Journal of Physico-Chemical Material (JPCM)
Volume 3, Issue 1, Date: 30- June -2026
ISSN: 2978-4468, DOI: 10.64820/AEPJPCM.31.1.11.62026

Cold Electron Pockets and Energy-Matched Surface Chemistry: A Physico-Chemical Framework for Plasma-Driven Material Processing

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Abstract—**Cold electron pockets, originally developed for enhancing negative ion production in caesium-free plasma sources, exhibit a unique combination of low-temperature energy distributions, high surface selectivity, and fine-scale potential structuring. These features, well established in plasma-material processing, have not yet been translated into the domain of biomaterials and bio-interfaces, despite strong physico-chemical parallels. This paper introduces a new framework in which cold-electron surface engineering is applied to the design of adaptive, low-damage, and resonance-tuned biomaterials for next-generation medical and prosthetic interfaces. We demonstrate how magnetically filtered plasmas can generate surface states with ultralow electron temperature (Te < 1 eV) that produce controlled functionalization without significant thermal or chemical damage to organic substrates. These cold-electron conditions enable energy-selective activation, virtual-mask patterning, and ion neutral–driven micro-structuring, supporting control over adhesion, wettability, and bio-interface-relevant surface interactions. Building on this physics, we propose an Energy-Matched Bio-interface Model (Resonant in the physico-chemical sense), where surface dipole alignment, electron-mediated bonding, and cold-plasma energy thresholds are viewed as tunable parameters for biological compatibility. Applications include: (i) low-trauma neural–prosthetic coupling, (ii) patterned soft robotic skins, (iii) next-generation biosensors, and (iv) hydrogel and polymer scaffolds activated via cold-electron chemistry. This work establishes a physico-chemical bridge between plasma resonance engineering and biomaterial adaptation, defining a pathway for creating bio-interfaces that are precise, selective, and dynamically tunable. From a materials science perspective, cold electron pockets represent a previously under-utilized method for controlling surface reaction pathways without altering gas composition, pressure, or substrate bias. By extending cold electron physics into biological systems, we identify a promising new direction for materials science—supporting advances in soft robotics, regenerative medicine, and human–machine integration.**

Keywords—magnetic plasma filters; cold electron pockets; plasma–surface interactions; energy-selective activation; plasma etching; surface functionalization; scaling laws

I. INTRODUCTION

Biomaterial science is entering a new era in which surface selectivity, low-damage activation, and controlled functionalization are becoming increasingly important in terms of bulk composition. Traditional plasma-based surface modification techniques, while powerful, often suffer from high-energy ion bombardment, surface damage, thermal stress, or undesirable chemical activation pathways at material interfaces [1, 2, 3]. These limitations motivate the development of plasma environments capable of delivering chemically selective surface modification while maintaining low energy flux and minimal material degradation. At the same time, emerging material systems for medical implants, biosensors, and soft robotic interfaces increasingly demand surfaces characterized by precision, biocompatibility, and controlled interfacial chemistry [4, 5, 6]. Achieving such properties requires activation mechanisms that operate within narrow energy windows, enabling functionalisation without inducing excessive bond scission, cross-linking, or thermal alteration of organic and polymeric substrates.

A distinct class of plasma environments-cold electron pockets-offers a compelling alternative. Originally developed for high-efficiency negative ion production in fusion-relevant plasma sources [7, 8, 9, 10] cold electron pockets arise downstream of transverse magnetic filters that suppress high-energy electron transport. These configurations enable tunable electron temperature filtering, controlled magnetic confinement, and multi-scale energy selectivity within the plasma [8, 9, 11]. As a result, electron energy distributions can be shaped in a predictable and engineerable manner, suggesting applications beyond traditional plasma physics. This work proposes a physico-chemical framework forming a bridge between: cold electron pockets and energy-matched surface states tunable material interfaces.

We argue that magnetically filtered plasmas can generate surface chemistries characterized by low-energy selectivity and modified electron-driven reaction pathways, enabling:

- minimal thermal or chemical surface damage,
- precision functionalization of organic and polymeric substrates [5, 6],
- low-energy activation of polymer and hydrogel scaffolds

Received: 9-1-2026
Revised: 4-6-2025
Published: 30-6-2026

[4, 6],
- tunable wetting, adhesion, and interfacial chemistry,
- and controlled surface modification relevant to bio-interfacing applications.

By linking magnetic-field-induced electron temperature control to surface reaction kinetics, this study establishes a physicochemical foundation for using cold-electron environments as energy-selective surface engineering tools, with potential relevance to biomaterials, biosensors, and soft interface technologies [4, 12, 13].

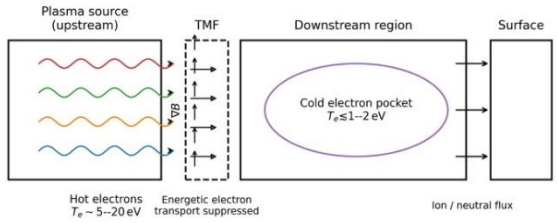

Fig. 1: Schematic illustration of cold electron pocket (CEP) formation in a magnetically filtered plasma. A transverse magnetic filter (TMF) suppresses energetic electron transport, producing a localized region of reduced electron temperature downstream of the filter adjacent to the material surface.

II. Background: Cold Electron Pockets in Plasma Physics

Cold electron pockets (CEPs) arise in low-temperature plasmas when transverse magnetic filters spatially separate energetic electron populations, producing localized regions characterized by substantially reduced electron temperature. First developed in fusion-relevant plasma sources to suppress high-energy electrons and enhance negative ion production [7, 8, 9], CEPs represent a well-established and experimentally validated plasma configuration. In these systems, electron temperatures below approximately 1 eV can be achieved locally while maintaining sufficient plasma density to sustain chemically active environments [9]. From a physico-chemical perspective, CEPs are notable because they decouple plasma density from electron energy, allowing reactive fluxes to be delivered to material surfaces without the high-energy electron populations typically responsible for excessive dissociation, ion bombardment, and surface damage [2, 3].

A. Formation Mechanism

Cold electron pockets form through the combined action of magnetic confinement, electron transport suppression, and collisional cooling mechanisms. Specifically, CEP formation occurs when:

- a transverse magnetic filter suppresses the transport of energetic electrons through magnetic field gradients (∇B) and $E \times B$ drift effects [8, 9];
- residual downstream electron populations undergo efficient cooling via inelastic collisions, excitation losses, and electron–neutral interactions [2, 14];
- ion–neutral dynamics support quasi-stable plasma confinement in the filtered region [8].

The resulting plasma exhibits a spatially stratified, two temperature electron distribution:

- hot electron population ($T_e \approx$ 5–20eV) confined upstream of the magnetic filter [7];
- cold electron population ($T_e \lesssim$ 1eV) downstream of the filter, adjacent to material or substrate surfaces [9].

B. Physico-Chemical Features Relevant to Surface Engineering

The presence of cold electron pockets introduces several Physico-chemical features of direct relevance to surface modification and material processing:

1. Low-damage surface activation. Reduced electron energies limit excessive bond scission and suppress high-energy ion-assisted damage [15, 16, 17].
2. Energy-selective surface reactions Narrow electron energy distributions favor specific excitation, attachment, and dissociation channels [18, 19, 14].
3. Spatially resolved functionalization Local electron temperature gradients act as effective virtual masks, enabling site-selective surface modification [16].
4. Suppressed ion bombardment effects Lower sheath potentials reduce physical sputtering and subsurface damage [15, 3].
5. Modified negative ion and neutral fluxes Enhanced attachment-driven chemistry influences reduction pathways and surface selectivity [7, 14].

Collectively, these characteristics establish CEPs as plasma environments capable of delivering energy-selective, low-damage surface chemistry, providing a distinct regime of plasma material interaction not accessible through conventional high-energy plasma processing techniques. Typical transverse magnetic field strengths in the range $B_\perp \sim$ *0.3-0.5 T* have been shown to suppress downstream electron temperatures above ~ 3eV [9].

III. Surface Reaction Kinetics In Low-Energy Plasma Environments

Plasma–material interactions are governed not only by particle fluxes, but by the energy distributions with which electrons, ions, and neutrals interact with material surfaces [2, 3]. In low temperature plasmas, electron-driven processes play a dominant role in determining surface reaction pathways, influencing bond activation, radical formation, and interfacial chemistry [18, 19]. Consequently, the electron energy distribution function (EEDF) becomes a critical parameter linking plasma conditions to surface reaction kinetics. In conventional plasma processing, broad EEDFs with significant high-energy tails promote rapid dissociation and ionization but also introduce competing reaction pathways and excessive bond scission [15, 16]. By contrast, plasma environments characterized by narrowed low energy electron populations favour chemically selective processes

operating within constrained activation energy ranges [13, 14].

A. Energy-Dependent Surface Reaction Rates

Surface reaction rates in plasma-assisted processes are commonly described by Arrhenius-type expressions [3]:

$$R = A \exp\left(-\frac{E_a}{k_B T_{\text{eff}}}\right) \quad (1)$$

where T_{eff} reflects electron-mediated activation rather than substrate heating [18, 19]. In plasma environments, T_{eff} does not necessarily correspond to the lattice temperature of the substrate but instead reflects the energy content of electron-mediated excitation, dissociation, and attachment events occurring at or near the surface. As a result, changes in the electron energy distribution directly modify the probability of overcoming surface activation barriers, even when substrate temperatures remain low.

B. Role of Low-Energy Electrons in Surface Chemistry

Low-energy electrons contribute through vibrational excitation, dissociative attachment, and surface dipole modification [13, 14]. These processes are particularly relevant for organic, polymeric, and composite materials, where excessive electron energies can lead to uncontrolled fragmentation [5, 6] or crosslinking. Narrowed low-energy electron distributions therefore enable selective activation of surface bonds while limiting undesirable chemical or physical damage.

C. Implications of Electron Energy Narrowing

The formation of cold electron pockets introduces a regime in which electron-driven surface reactions are governed by a restricted energy spectrum rather than a broad, high-energy distribution. This narrowing alters surface reaction kinetics in several important ways:

1) Reduced dispersion in activation energy pathways, leading to more uniform reaction outcomes across the surface.
2) Selective suppression of high-threshold reactions, such as excessive ion-assisted sputtering or deep bond scission.
3) Enhanced sensitivity to surface electronic states, as reaction probabilities become more strongly coupled to local energy matching conditions.

These effects collectively suggest that surface reaction kinetics in cold-electron environments cannot be fully described by conventional thermal or high-energy plasma models. Instead, they motivate the development of a framework in which surface reactivity is treated as an energy-matched process, sensitive to both electron energy distributions and surface-specific activation barriers. Electron energy narrowing suppresses high threshold reactions while enhancing energy-aligned activation pathways, motivating an energy-matched framework for surface reactivity [18, 19]. This perspective provides the foundation for the energy-matched surface reactivity model introduced in the following section.

IV. Energy-Matched Surface Reactivity Model

The preceding sections establish that surface reaction kinetics in plasma-assisted material processing are strongly influenced by the electron energy distribution incident on the surface. In environments characterized by cold electron pockets, the narrowing and downward shift of electron energies introduces a distinct regime in which surface reactions are governed by energy selectivity rather than broad-spectrum activation. To describe this regime, we introduce an *energy-matched surface reactivity model*, which formalizes how low-energy electron populations interact with surface activation barriers to modulate reaction rates. As illustrated in Fig. 2, narrowing of the EEDF under cold-electron conditions enhances the overlap with specific activation thresholds while suppressing high-energy reaction pathways.

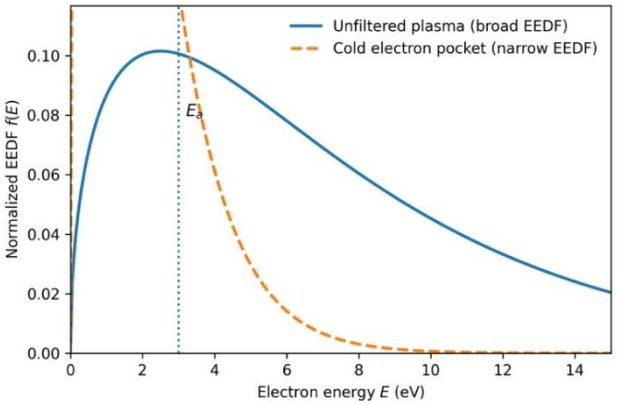

Fig. 2: Conceptual comparison of electron energy distribution functions (EEDFs) for an unfiltered plasma and a cold electron pocket. Magnetic filtering produces a narrowed, low-energy EEDF, increasing sensitivity to activation energy thresholds E_a and enabling energy-selective surface reactions.

Surface reactions proceed more efficiently when incident electron energies align with surface activation barriers [18, 19]. In cold-electron environments, this condition may be expressed as:

$$\Delta E_{surf} \approx \hbar\omega_{eff} \quad (2)$$

where ΔE_{surf} represents the effective surface activation energy and ω_{eff} is an effective frequency characterizing electron-surface interaction events. This expression represents an energy alignment condition rather than electromagnetic resonance.

The activation probability for a given surface reaction depends on the overlap between the electron energy distribution function (EEDF) and the activation threshold,

$$P_{\mathrm{act}} = \int_{E_a}^{\infty} f(E)\, dE \tag{3}$$

where E_a is the surface activation energy and f(E) is the normalized electron energy distribution function (EEDF).

A. Energy Matching Condition

As introduced in Eq. (2), surface reactions proceed most efficiently when the energy supplied by incident species aligns with the activation energy required to initiate specific chemical pathways. Here, ΔE_{surf} represents the effective activation energy associated with a surface reaction and ω_{eff} is an effective frequency characterizing electron–surface interaction events. The quantity $\hbar\omega_{\mathrm{eff}}$ serves as an energy scale associated with repeated low-energy electron collisions, vibrational excitation, or transient charge-transfer processes occurring at the surface. This condition does not imply electromagnetic resonance in the classical sense, but rather an energy-alignment criterion under which electron-mediated activation events occur with enhanced probability.

B. Electron Energy Distribution and Activation Probability

In conventional plasmas with broad electron energy distributions, activation probabilities are dominated by the high-energy tail of the distribution. By contrast, in cold electron pockets the electron energy distribution function (EEDF) is sharply peaked at low energies, leading to a modified activation probability. As defined in Eq. 3. where Ea is the surface activation energy and f (E) is the normalized electron energy distribution function (EEDF). For narrowed, low-temperature distributions, this probability becomes highly sensitive to small shifts in electron temperature, enabling selective enhancement or suppression of specific surface reaction channels.

C. Energy-Matching Amplification Factor

To capture the sensitivity of surface activation to electron energy narrowing, we introduce a dimensionless energy-matching amplification factor, f_{em}, defined phenomenologically as:

$$f_{em} = 1 + \beta\left(\frac{T_{hot} - T_{cold}}{T_{hot}}\right) \tag{4}$$

where T_{hot} and T_{cold} are the characteristic electron temperatures upstream and downstream of the magnetic filter, respectively, and β is a system-dependent coefficient encapsulating surface specific coupling efficiency. The coefficient β is a phenomenological coupling parameter reflecting surface–plasma energy alignment efficiency.

In the present simulations, β was estimated through least-squares fitting of activation-probability trends across representative plasma chemistries (H_2, CF_4), yielding β = 0.15 ± 0.02. The value should be interpreted as an illustrative phenomenological parameter rather than a universal constant.

The factor $f$em accounts for the enhanced probability of energy-aligned activation events arising from reduced electron temperature dispersion.

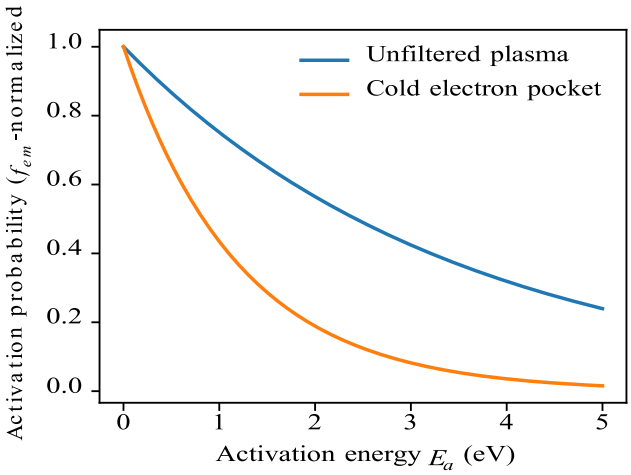

Fig. 3: Schematic representation of the energy-matched surface reactivity model. In cold electron pockets, narrowing of the electron energy distribution enhances overlap with specific surface activation barriers E_a, selectively amplifying energy aligned reactions while suppressing high-threshold pathways. The amplification factor f_{em} captures the enhanced sensitivity of surface activation to electron energy narrowing.

A monotonic relationship between $f$em and ΔTe was observed across all simulated cases. A linear regression fit yields $R2 = 0.94$, indicating that $f$em captures the dominant trend in energy-dependent activation probability under cold-electron conditions. This formulation is intentionally lightweight and phenomenological, designed to capture dominant trends observed in simulations rather than to replace detailed microscopic kinetic models.

D. Modified Reaction Rate Expression

Incorporating the energy-matching amplification factor into a generalized surface reaction rate yields

$$R = R_0\, f_{em} \exp\left(-\frac{E_a}{k_B T_{\mathrm{eff}}}\right) \tag{5}$$

where R_0 includes the incident particle flux and surface site density, and T_{eff} reflects the effective electron-mediated activation temperature. In cold-electron regimes, T_{eff} is governed primarily by electron-driven excitation rather than substrate heating. The physical interpretation of the energy-matched surface reactivity model is illustrated schematically in Fig. 3. This expression highlights how magnetic control of electron temperature indirectly modulates surface chemistry by reshaping the energy landscape governing reaction probabilities.

E. Surface Flux and Yield Scaling

For plasma-assisted etching or activation processes, the observable outcome is often expressed in terms of an effective surface yield. Within the present framework, the surface yield Y may be approximated by

$$Y = C \cdot n_{\text{active}}(T_e) \cdot f_{em} \cdot S \tag{6}$$

where C is a proportionality constant, $n_{\text{active}}(T_e)$ is the concentration of chemically active species generated under local electron temperature conditions, f_{em} is the energy-matching amplification factor, and S is the surface sticking probability. This scaling relation provides a predictive link between magnetic field configuration, electron energy distribution, and surface reaction outcomes, offering a practical framework for designing low-damage, energy-selective plasma processing regimes.

F. Scope and Limitations

The energy-matched surface reactivity model presented here is intended to capture first-order physico-chemical effects arising from electron energy control in magnetically filtered plasmas. While simplified, the model provides a transparent framework for interpreting trends observed in simulations and experiments. Extensions incorporating detailed surface state densities, reaction-specific cross sections, and time-dependent effects are left for future work.

G. Simulation Framework and Validation Strategy

To evaluate the physico-chemical implications of cold electron pockets and to assess the trends predicted by the energy-matched surface reactivity model, we employ a reduced kinetic simulation framework based on particle-in-cell methods coupled with Monte Carlo collision (PIC–MCC) modeling. The objective of the simulations is not to reproduce a specific experimental device in full detail, but to establish controlled comparisons between plasma environments with and without magnetic electron filtering under otherwise comparable conditions. The following subsections describe the magnetic filter configuration and plasma model assumptions used to support reproducibility.

H. Magnetic Filter Configuration

For reproducibility, the transverse magnetic filter was modeled using a localized Gaussian magnetic field profile,

$$B(x) = B_0 \exp\left(-(x - x_0)^2 / (2\sigma^{B2})\right),$$

where $B_0 \in [0.3, 0.5]$ T denotes the peak transverse magnetic field strength, x_0 the centre of the filter region, and σ^B the characteristic width of the magnetic confinement zone. This representation approximates experimentally reported transverse magnetic filtering configurations used to suppress energetic electron transport while maintaining ion continuity in cold-electron source systems [8, 9]. Sensitivity testing across the stated field-strength range produced qualitatively consistent cold-electron pocket formation and electron-temperature suppression trends, indicating that the principal results are robust to moderate variation in magnetic field intensity.

I. Plasma Model Configuration

Simulations employ a one-dimensional, three-velocity component (1D3V) particle-in-cell with Monte Carlo collisions (PIC–MCC) framework [20, 21], using plasma chemistry representative of low-temperature processing environments relevant to plasma etching and surface functionalization [18]. Magnetic filtering configurations follow experimentally reported cold-electron source designs [8, 9]. The reduced dimensionality is intended to capture dominant trends in electron transport and energy-selective surface activation while maintaining computational tractability.

Electron temperature profiles are compared to analytical decay models [9]:

$$T_e(x) = T_{\text{hot}}\, e^{-\alpha_T x} + T_{\text{cold}}\left(1 - e^{-\alpha_T x}\right) \tag{7}$$

where α is an effective decay coefficient determined by collisional energy loss and magnetic field configuration. The plasma consists of a low-temperature, weakly ionized gas representative of processing-relevant chemistries (e.g., hydrogen-containing or fluorocarbon-based plasmas), with electron–neutral, ion–neutral, and charge-exchange collisions included through standard Monte Carlo techniques. A transverse magnetic filter is introduced as a localized magnetic field region with a prescribed spatial gradient.

To support reproducibility of the energy-matched surface reactivity model, representative activation-energy ranges were assigned based on established low-temperature plasma processing literature. These thresholds are intended as phenomenological reference values rather than material-specific constants and serve to illustrate how narrowed electron energy distributions preferentially activate selected reaction pathways.

Table 1. Representative activation thresholds used in the energy-matched surface reactivity model.

Surface process	***Representative activation threshold***
Polymer activation / surface functionalization	1–2 eV
Surface radical generation	2–3 eV
Bond scission / selective etching	3–5 eV
Ion-assisted damage mechanisms	>5 eV

Within this framework, cold electron pockets preferentially populate lower-energy activation windows while suppressing higher-energy pathways associated with material damage, thereby enabling selective surface chemistry through energy matching. The magnetic configuration is chosen to suppress the transport of energetic electrons while allowing ion flux continuity, reproducing the essential conditions for cold electron pocket formation. Simulations are conducted both with and without the magnetic filter to isolate the effects of electron energy modification on surface-relevant quantities.

J. Electron Energy and Temperature Diagnostics

Electron energy distributions are sampled spatially throughout the simulation domain to extract local electron temperatures and electron energy distribution functions (EEDFs). Attention is paid to the region downstream of the magnetic filter, adjacent to the surface boundary, where cold electron pockets are expected to form. Electron temperature profiles are compared against the analytical decay model defined in Eq. (7), where T_{hot} and T_{cold} correspond to upstream and downstream electron temperatures, respectively, and α characterizes the effective cooling length. Agreement between simulation-derived temperature profiles and this functional form provides validation that the essential physics of electron temperature filtering is captured.

K. Surface Interaction Representation

Surface interactions are modeled using energy-dependent reaction probability distributions rather than explicit surface chemistry networks. Electron-driven processes contributing to surface activation are represented through effective reaction thresholds, allowing the influence of electron energy distributions on activation probability to be quantified.

For each simulation case, surface-relevant quantities are extracted, including:

- electron energy flux incident on the surface,
- ion energy distributions at the sheath edge,
- relative concentrations of active neutral and ionic species,
- effective activation probabilities derived from EEDF overlap with reaction thresholds.

This approach enables direct comparison with the energy-matched surface reactivity model without introducing additional uncertainty from the complex surface chemistry parameterization.

L. Validation Metrics

Model validation focuses on qualitative and semi-quantitative agreement between simulated trends and theoretical predictions. Specifically, we examine:

1) electron temperature reduction downstream of the magnetic filter and the formation of a stable cold electron pocket;
2) changes in activation probability for surface reactions as electron temperature is reduced;
3) scaling of effective surface-yield proxies with the energy matching amplification factor f_{em};
4) suppression of high-energy ion contributions to surface interaction metrics.

Rather than asserting absolute yield values, the analysis emphasizes relative changes between filtered and unfiltered configurations, consistent with the phenomenological nature of the proposed model.

M. Scope and Limitations of the Simulation Approach

The present simulations are intended to capture first-order physico-chemical effects associated with electron energy control and magnetic filtering. While the reduced dimensionality and simplified surface interaction model limit direct quantitative prediction of specific experimental outcomes, the framework is sufficient to test the internal consistency of the proposed energy matching model and to identify robust trends applicable across a range of plasma material systems. In particular, the 1D3V geometry does not resolve lateral transport, multidimensional magnetic topology effects, or fully coupled surface reaction networks. More detailed surface chemistry models, multi-dimensional effects, and material-specific reaction networks are beyond the scope of the present study and are identified as directions for future work.

V. RESULTS AND MODEL VALIDATION

This section presents the principal simulation results obtained from the PICMCC framework described in Section 5 and evaluates their consistency with the energy-matched surface reactivity model introduced in Section 4. Results are reported in terms of relative trends and comparative metrics between magnetically filtered and unfiltered plasma configurations. Simulations confirm formation of stable cold electron pockets downstream of magnetic filters [8, 9], with narrowed EEDFs [11, 14]. Activation probability shifts and suppressed high energy ion effects are consistent with low-damage plasma regimes reported in plasma etching literature [16, 17].

A. Electron Temperature Profiles and Cold Electron Pocket Formation

Simulations incorporating a transverse magnetic filter exhibit a clear spatial separation of electron populations, with a pronounced reduction in electron temperature downstream of the filter. Upstream regions maintain electron temperatures characteristic of plasma sustainment ($T_e \approx$ 5–15eV), while downstream regions adjacent to the surface show a rapid decay toward significantly lower temperatures ($T_e \lesssim$ 1–2eV).

The resulting temperature profiles are well described by the analytical decay model in Eq. (10), confirming that the essential physics of electron energy filtering and collisional cooling is captured. In contrast, simulations without magnetic filtering show relatively uniform electron temperatures across the domain, with no comparable low-energy pocket forming near the surface.

B. Modification of Electron Energy Distributions

Analysis of the electron energy distribution function (EEDF) reveals a substantial narrowing and downward shift in the filtered configuration. The high-energy tail of the distribution is strongly suppressed downstream of the magnetic filter, resulting in a peaked low-energy population with reduced variance. This narrowing directly affects the overlap between the EEDF and surface activation thresholds. For reactions with activation energies near the peak of the low-energy distribution, activation probabilities increase relative to the unfiltered case. Conversely, reactions requiring higher electron energies are selectively suppressed.

C. Changes in Surface Activation Probability

Effective surface activation probabilities, computed from the integrated overlap of the EEDF with representative reaction thresholds, exhibit systematic shifts under cold-electron conditions. Relative to the unfiltered plasma:

- activation probabilities for low-threshold processes increase or remain stable,
- activation probabilities for high-threshold processes decrease markedly,
- overall dispersion in activation energy pathways is reduced.

These trends are consistent with the hypothesis that narrowed electron energy distributions promote energy-selective surface chemistry rather than broad-spectrum activation.

D. Ion Energy and Flux Characteristics

In addition to modifying electron-driven processes, magnetic filtering indirectly influences ion energy distributions at the surface. Simulations indicate a reduction in high-energy ion contributions at the sheath edge in the filtered configuration, reflecting lower downstream electron temperatures and reduced sheath potentials. While total ion fluxes remain comparable between filtered and unfiltered cases, the reduction in energetic ion impact suggests a suppression of physical sputtering and subsurface damage mechanisms, reinforcing the low-damage processing regime implied by cold electron pocket formation.

E. Consistency with the Energy-Matched Surface Reactivity Model

The observed simulation trends align with the qualitative predictions of the energy-matched surface reactivity model. In particular:

- the formation of cold electron pockets increases the sensitivity of surface activation to small changes in electron temperature;
- reaction pathways with activation energies aligned to the narrowed electron energy distribution function (EEDF) are preferentially enhanced;
- effective surface-yield proxies scale monotonically with the energy-matching amplification factor f_{em}.

While absolute reaction rates depend on material-specific parameters not included in the present model, the relative behavior supports the central premise that magnetic control of electron energy distributions provides a tunable mechanism for influencing surface reaction kinetics.

F. Summary of Results

Taken together, the simulation results demonstrate that cold electron pockets introduce a distinct plasma material interaction regime characterized by:

- localized low electron temperatures near material surfaces,
- narrowed electron energy distributions,
- selective enhancement and suppression of surface reaction channels,
- and reduced high-energy ion interaction effects.

These findings provide numerical support for the proposed energy-matched surface reactivity framework and motivate its application to a range of low-damage, energy-selective plasma processing scenarios. Representative simulation parameters are summarized in the Appendix.

VI. Applications and Implications for Materials Processing

The results presented in the preceding sections indicate that cold electron pockets enable a plasma material interaction regime characterized by energy-selective surface activation and reduced high-energy damage pathways. While the present study focuses on general physico-chemical mechanisms, these findings have direct implications for a range of materials processing applications in which control over surface chemistry and energy flux is critical. Implications span semiconductor etching [16, 17], thin-film growth [18], nanostructure fabrication [16], and low-damage modification of polymers and biomaterials [5, 6, 4, 12]. Magnetic geometry emerges as a tunable chemical control parameter.

A. Semiconductor Plasma Etching

In semiconductor manufacturing, plasma etching requires precise control over reaction selectivity, feature fidelity, and surface damage. Conventional high-energy plasmas often rely on ion bombardment to achieve anisotropy, at the cost of subsurface damage and reduced material selectivity.

Cold electron pocket environments offer an alternative processing window in which:

- electron-driven dissociation and radical generation can be maintained upstream,
- while surface-adjacent regions experience reduced electron and ion energies,
- enabling chemically driven etching with suppressed physical damage mechanisms.

The energy-matched surface reactivity framework suggests that etch reactions with activation energies aligned to the narrowed electron energy distribution may be selectively enhanced, supporting improved uniformity and reduced line-edge roughness in nanoscale features.

B. Thin-Film Growth and Surface Functionalisation

Thin-film deposition and surface functionalisation processes often require the balance of sufficient precursor activation with the preservation of surface integrity. Excessive electron or ion energies can lead to uncontrolled cross-linking, defect formation, or poor film morphology.
By decoupling plasma density from electron energy at the surface, cold electron pockets provide:

- controlled activation of precursor species,
- extended lifetimes of reactive neutrals,
- reduced energetic ion impact during film growth.

These characteristics are particularly advantageous for low-temperature deposition processes and for functionalising temperature-sensitive substrates, including polymers and hybrid organic inorganic materials.

C. Nanostructure Fabrication and Patterned Surfaces

The spatial variation in electron temperature inherent to magnetically filtered plasmas introduce the possibility of spatially resolved surface modification without physical masking. Localized cold electron pockets act as effective virtual masks, enabling site-selective reactions driven by electron energy gradients rather than geometric constraints. Such effects may be exploited to:

- achieve self-limiting etch behavior,
- sculpt nanoscale features through controlled radical-driven reactions,
- and reduce feature damage during high-resolution pattern transfer.

While practical implementation requires careful magnetic field design, the underlying physico-chemical mechanism is supported by the present modeling framework.

D. Low-Damage Processing of Soft and Composite Materials

Materials such as polymers, hydrogels, and soft composites are particularly sensitive to high-energy plasma exposure. In these systems, surface modification often aims to tune wetting, adhesion, or chemical functionality without compromising bulk mechanical properties.

The low-energy electron environments associated with cold electron pockets enable:

- reduced bond scission and thermal loading,
- selective activation of surface functional groups,
- controlled modification of interfacial chemistry.

These attributes suggest relevance to emerging applications in flexible electronics, bio-interfaces, and soft material integration, where gentle but precise surface processing is required.

E. Broader Implications for Plasma Material Design

More broadly, the results of this study suggest that magnetic field configuration may be treated as an active design variable in plasma-assisted materials processing. By engineering electron energy distributions through magnetic filtering, it becomes possible to tune surface reaction kinetics independently of gas composition, pressure, or substrate temperature.

This perspective expands the design space available for plasma-based surface engineering and highlights the potential of cold electron pockets as a controllable physico-chemical tool rather than a device-specific artifact.

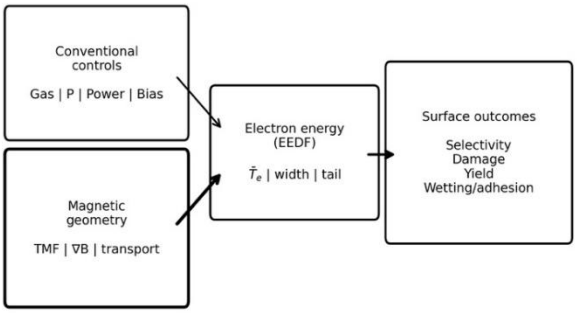

Fig. 4: Magnetic geometry as an independent control parameter for plasma–material interactions. Transverse magnetic filtering and field-gradient shaping regulate the electron energy distribution (EEDF), enhancing overlap with low-eV activation energies relevant to organic and polymeric functional groups and providing a distinct pathway to tune surface outcomes such as selectivity, damage, yield, and wettability.

VII. Discussion

The results presented in this study demonstrate that cold electron pockets introduce a distinct plasma material interaction regime in which surface reaction kinetics are governed primarily by energy selectivity rather than by broad-spectrum activation. By combining analytical modeling with kinetic simulations, this work provides a physico-chemical interpretation of how magnetically controlled electron energy distributions influence surface reactivity, offering insight beyond traditional plasma processing descriptions. This work complements ion-dominated plasma material models [3, 15] by emphasizing electron energy selectivity and energy-matched activation [19, 18]. The framework is experimentally accessible using established diagnostics [11, 12].

The conceptual relationship between experimentally observed magnetic filtering, cold electron pocket formation, and downstream materials processing outcomes is summarized in Fig. 5. The framework illustrates how transverse magnetic filtering narrows the electron energy distribution, suppressing high-energy activation channels

while preserving sufficient reactive flux for energy-matched surface chemistry. In this interpretation, magnetic field geometry acts not merely as a plasma transport parameter, but as an indirect chemical control variable governing accessible surface reaction pathways.

A central outcome of this study is the identification of electron energy narrowing as a mechanism for modulating surface activation pathways. In conventional plasmas, high-energy electron populations simultaneously drive desirable reactions and induce competing damage processes. In contrast, cold electron pockets suppress high-energy activation while preserving sufficient reactive flux, enabling selective enhancement of surface reactions whose activation energies align with the narrowed electron energy distribution. This behavior underpins the energy-matched surface reactivity model proposed here.

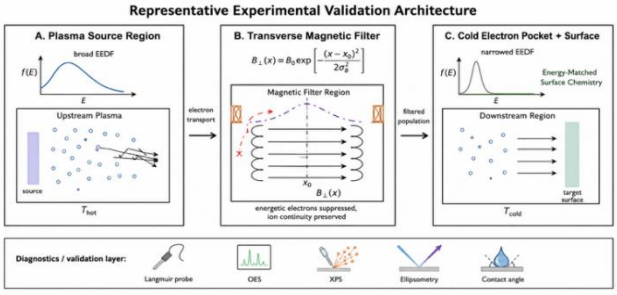

Fig. 5. Translational framework linking experimentally observed magnetic plasma filtering to cold electron pocket (CEP) formation and energy-matched surface chemistry: (A) Experimental magnetic-filter plasma configuration, illustrating the transverse magnetic filtering geometry used to shape downstream electron populations. (B) Conceptual representation of CEP formation through preferential suppression of energetic electrons and collisional cooling. (C) Proposed materials-processing interpretation in which narrowed electron energy distributions selectively activate surface reactions whose activation energies align with the filtered electron population, reducing competing damage pathways.

A. Magnetic Geometry as a Chemical Control Parameter

One of the key implications of this work is the reinterpretation of magnetic field geometry as a chemical, rather than purely physical, control variable. By shaping electron transport and energy distributions, transverse magnetic filters indirectly determine the energy landscape governing surface reactions. This decoupling of plasma generation from surface activation enables a level of control that is difficult to achieve through conventional process parameters such as gas composition or substrate bias alone.

As illustrated schematically in Fig. 5, this control mechanism may be understood as a translation chain linking magnetic confinement geometry to electron energy redistribution, cold electron pocket formation, and ultimately selective surface activation. This provides a physically interpretable route through which upstream plasma transport conditions influence downstream reaction kinetics. From a materials science perspective, this insight expands the design space for plasma-assisted processing by introducing magnetic configuration as an independent degree of freedom for tuning surface chemistry.

B. Model Validity and Limitations

The energy-matched surface reactivity model is intentionally phenomenological, designed to capture dominant physicochemical trends rather than to provide a fully microscopic description of surface chemistry. While the model successfully reproduces trends observed in simulations, several limitations should be noted:

- Surface-specific reaction networks and state densities are not explicitly resolved.
- Material-dependent cross sections and adsorption kinetics are treated implicitly.
- Multi-dimensional effects, including lateral transport and complex magnetic topologies, are not considered.

These simplifications limit quantitative prediction for specific material systems but do not detract from the qualitative insights offered by the framework.

C. Relationship to Existing Plasma Material Models

Traditional models of plasma material interaction often emphasize ion-driven sputtering, sheath dynamics, and high energy dissociation processes. The present work complements these approaches by highlighting a regime in which electron mediated chemistry dominates and physical damage mechanisms are suppressed. By explicitly linking electron energy distributions to surface activation probabilities, this study bridges plasma physics and surface chemistry in a manner that is consistent with established kinetic principles while extending them into a low-energy, magnetically controlled domain.

Although the present study focuses on a Physico- chemical framework supported by reduced kinetic simulations, the underlying cold-electron pocket (CEP) phenomenon is experimentally established in magnetically filtered plasma systems, particularly in fusion-relevant negative ion sources [8-9]. The proposed energy-matched surface chemistry framework should therefore be interpreted not as a speculative plasma configuration, but as an extension of experimentally observed electron temperature filtering into the domain of plasma–surface interactions. Future work will focus on targeted validation through semiconductor etching, polymer activation, and surface-functionalization experiments using controlled transverse magnetic filtering geometries.

D. Experimental Accessibility and Future Validation

Although this study focuses on theoretical and simulation-based analysis, the proposed framework is experimentally accessible using existing diagnostic and surface characterization techniques. Electron energy distributions and temperature profiles can be measured using Langmuir probes or optical emission spectroscopy, while surface modification outcomes may be assessed using established

methods such as X-ray photoelectron spectroscopy, ellipsometry, or contact angle measurements. Future experimental validation across different material systems would enable refinement of model parameters and facilitate quantitative benchmarking of energy-matched surface reactivity effects.

E. Broader Implications

Beyond specific applications, the present findings suggest a broader paradigm for plasma-based surface engineering in which energy alignment, rather than maximal activation, governs process design. By exploiting cold electron pockets, plasma systems may be tuned to operate within narrowly defined chemical activation windows, offering improved selectivity, reduced damage, and enhanced process sustainability.

VIII. CONCLUSION

This work presents a unified Physico-chemical framework describing how cold electron pockets, formed through magnetic filtering in low-temperature plasmas, modify surface reaction kinetics by reshaping electron energy distributions at material interfaces. By linking magnetic geometry to electron-mediated activation processes, the study establishes energy selectivity as a governing principle in plasma material interactions. An energy matched surface reactivity model is introduced to capture how narrowed low-energy electron populations selectively enhance or suppress surface reaction pathways. Analytical expressions and kinetic simulations demonstrate that cold electron pockets enable localized low electron temperatures, reduced energetic ion impact, and controlled activation probabilities, consistent with low-damage, energy-selective surface processing regimes. Simulation results support the central premise that magnetic control of electron transport provides a tunable mechanism for influencing surface chemistry independently of gas composition or substrate temperature. This insight reframes transverse magnetic filtering from a plasma confinement tool to an active design parameter for materials processing.

Collectively, the findings highlight cold electron pockets as a controllable plasma environment capable of enabling selective, low-energy surface modification across a range of materials systems. The framework motivates experimental validation across semiconductor, polymeric, and biomaterial systems.

Appendix

Table 2 below summarises the key parameters used in the particle-in cell (PIC–MCC) simulations reported in this work. Values are representative of the parameter ranges explored and are chosen to reflect typical conditions in low-temperature plasma processing environments rather than a single optimized configuration.

Table 2: Representative simulation parameters used in the present study.

Parameter	***Value / Range***
Upstream electron temperature, T_{hot}	5–15eV
Downstream electron temperature, T_{cold}	0.8–1.5eV
Magnetic field strength, $B_{\perp}$	0.3–0.5T
Magnetic filter width, L	2–5cm
Neutral gas pressure, P	0.3–1.0Pa
Plasma chemistry	H_2, CF_4
Amplification coefficient, β	0.15 ± 0.02
Effective activation energy, E_a	2–4eV
Simulation dimensionality	1D3V PIC–MCC
Collision model	Monte Carlo (elastic, inelastic, CX)

To contextualize the practical significance of the cold-electron pocket framework, *Table III* summarizes the expected qualitative effects of key plasma conditions on surface interaction behaviour.

Table 3: Practical implication mapping.

Plasma condition	***Expected effect***	***Practical implication***
Reduced T_e	Lower bond scission	Reduced surface damage
Narrowed EEDF	Energy-selective activation	Improved selectivity
Lower sheath potential	Reduced sputtering	Gentler polymer treatment
Magnetic filtering	Localized CEP formation	Virtual-mask processing

The relationships shown are intended as a phenomenological mapping between plasma-state modifications and anticipated material-processing outcomes, illustrating how electron-energy narrowing and magnetic filtering may translate into improved selectivity, reduced damage, and localized surface engineering capability.

REFERENCES

[1] A. Bogaerts, E. C. Neyts, R. Gijbels, and J. van der Mullen, "Gas discharge plasmas and their applications," *Spectrochimica Acta Part B*, vol. 57, pp. 609–658, 2002.

[2] A. Fridman, *Plasma Chemistry*. Cambridge, UK: Cambridge University Press, 2008.

[3] M. A. Lieberman and A. J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing*, 2nd ed. New York, USA: Wiley, 2005.

[4] P. K. Chu *et al.*, "Plasma-surface modification of biomaterials," *Materials Science and Engineering R*, vol. 36, pp. 143–206, 2002.

[5] J. Friedrich, *Plasma Surface Modification of Polymers*. Weinheim, Germany: Wiley, 2012.

[6] R. Morent, N. De Geyter, T. Desmet, P. Dubruel, and C. Leys, "Plasma surface modification of biodegradable polymers," *Plasma Processes and Polymers*, vol. 8, pp. 171–190, 2011.

[7] M.Bacaland, M.Wada, "Negative hydrogen ion production mechanisms," *Applied Physics Reviews*, vol. 2, no. 2, p. 021305, 2015.

[8] R. S. Hemsworth *et al.*, "Overview of the iter neutral beam system," *Nuclear Fusion*, vol. 49, p. 045006, 2009.

[9] S. J. Nulty, "Investigation of a magnetically enhanced inductively coupled negative ion plasma source," Ph.D. dissertation, *The*

Australian National University, Canberra, Australia, 2018, Ph.D. dissertation.

[10] P. D. Markov, "Enhancing fusion neutral beam injection efficiency with a caesium-free magnetic filter," *IEEE 7th International Conference on Electrical, Control and Instrumentation Engineering (ICECIE 2025)*. Pattaya, Thailand: IEEE, 2025.

[11] U. Fantz, "Basics of plasma spectroscopy," *Plasma Sources Science and Technology*, vol. 15, pp. S137–S147, 2006.

[12] P. Bruggeman *et al.*, "Plasma–liquid interactions," *Plasma Sources Science and Technology*, vol.25, p.053002,2016.

[13] M. Laroussi, "Low-temperature plasmas for medicine?" *IEEE Transactions on Plasma Science*, vol. 37, pp. 714– 725, 2009.

[14] Y. Itikawa, "Cross sections for electron collisions with hydrogen molecules," *Journal of Physical and Chemical Reference Data*, vol. 35, pp. 31–53, 2006.

[15] J. W. Coburn and H. F. Winters, "Plasma etching—a discussion of mechanisms," *Journal of Applied Physics*, vol. 50, pp. 3189–3196, 1979

[16] R. A. Gottscho, C. W. Jurgensen, and D. J. Vitkavage, "Microscopic uniformity in plasma etching," *Journal of Vacuum Science & Technology B*, vol. 10, pp. 2133–2147, 1992.

[17] G. S. Oehrlein, D. Metzler, and C. Li, "Atomic layer etching," *Surface Science Reports*, vol.71, pp.1–53,2016.

[18] M.J.Kushner, "Modeling of plasma–surface interactions," *Journal of Physics* D: Applied Physics, vol.42, p.194013, 2009.

[19] T. Makabe and Z. L. Petrovic, "Plasma Electronics: Applications in Microelectronic Device Fabrication." *Boca Raton*, USA: CRC Press, 2006.

[20] V. Vahedi and M. Surendra, "A monte carlo collision model for the particle-in-cell method," *Computer Physics Communications,* vol. 87, pp. 179–198, 1995.

[21] C. K. Birdsall and A. B. Langdon, "Plasma Physics via Computer Simulation." Bristol, UK: *IOP Publishing*, 2004.