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Review Article

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Minghao Jia[1], Mu Qiao[3], Shijie Zhang[1](✉), Ruifeng Miao[1], Haifeng Quan[1], Zhenguo Gao[5], Yiqun Wang[4], Guanglei Wu[2](✉)

[1] School of Material Science and Engineering, Henan University of Technology, Zhengzhou 450001, China

[2] Institute of Materials for Energy and Environment, State Key Laboratory of Bio-fibers and Eco-textiles, College of Materials Science and Engineering, Qingdao University, Qingdao 266071, China

[3] School of Materials Science and Engineering, Zhengzhou University, Zhengzhou 450001, China

[4] College of Materials and Chemistry & Chemical Engineering, Chengdu University of Technology, Chengdu 610059, China

[5] Department of Mechanical Engineering and Research Institute for Smart Energy, The Hong Kong Polytechnic University, Hong Kong 999077, China

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[1] School of Material Science and Engineering, Henan University of Technology, Zhengzhou 450001, China;

[2] Institute of Materials for Energy and Environment, State Key Laboratory of Bio-fibers and Eco-textiles, College of Materials Science and Engineering, Qingdao University, Qingdao 266071, China;

[3] School of Materials Science and Engineering, Zhengzhou University, Zhengzhou 450001, China

[4] College of Materials and Chemistry & Chemical Engineering, Chengdu University of Technology, Chengdu, 610059, China

[5] Department of Mechanical Engineering and Research Institute for Smart Energy, The Hong Kong Polytechnic University, Hong Kong 999077, China

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Address correspondence to Shijie Zhang, shijie_zhang@haut.edu.cn, zsj562389@sina.com; Guanglei Wu, wuguanglei@qdu.edu.cn/wuguanglei@mail.xjtu.edu.cn

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Abstract: Lightweight, broadband, and highly efficient electromagnetic wave absorbers (EWAs) are increasingly demanded, yet their development remains constrained by conventional equilibrium synthesis, which limits access to the high-energy structural states required for efficient electromagnetic attenuation. Flash Joule Heating (FJH), featuring rapid electrothermal heating followed by instantaneous quenching, provides an effective route to stabilize kinetically trapped structures that are difficult to obtain through traditional processing. This review presents FJH as a platform for non-equilibrium state engineering rather than simply an ultrafast synthesis technique. By interrupting thermodynamic relaxation, FJH preserves metastable phases, abundant defects, fragmented conductive networks, and complex heterointerfaces, thereby creating multiple pathways for electromagnetic energy dissipation. These non-equilibrium characteristics offer promising solutions to persistent challenges in EWAs, including conductivity-impedance imbalance, limited polarization centers, weak interfacial dissipation, and insufficient high-frequency magnetic response. The review further discusses emerging opportunities enabled by FJH, such as kinetic-state programming, structural genome engineering, adaptive electromagnetic materials, AI-assisted materials design, and scalable manufacturing. Finally, the key challenges that remain in achieving predictive and controllable non-equilibrium materials design are outlined. More importantly, FJH is highlighted as a strategy for writing programmable non-equilibrium states, opening new directions for the design of next-generation EWAs.

Keyword: flash Joule Heating; non-equilibrium state engineering; kinetic programming; electromagnetic attenuation; adaptive electromagnetic systems

1. Introduction

The explosive expansion of high-frequency electronics, wireless communication infrastructures, and integrated intelligent devices has dramatically intensified electromagnetic interference and radiation pollution.[1-4] Particularly, the ongoing deployment of 5G technologies, together with the anticipated transition toward 6G communication systems, is further pushing electromagnetic operation toward higher frequencies, wider bandwidths, and increasingly complex signal environments. Under such circumstances, uncontrolled electromagnetic radiation can compromise the operational reliability of precision electronic systems while simultaneously raising concerns related to information security, stealth compatibility, and electromagnetic environmental safety. As a result, the development of advanced electromagnetic wave absorbers (EWAs) capable of efficiently attenuating incident electromagnetic energy has emerged as an important research focus in contemporary materials science.[5-8]

Over the past decades, tremendous efforts have been devoted to developing high-performance EWAs based on carbon materials, MXenes, magnetic nanocrystals, conductive polymers, and hybrid heterostructures.[9-16] Nevertheless, the fabrication of these materials still predominantly depends on conventional near-equilibrium approaches, such as hydrothermal reactions, chemical vapor deposition, furnace annealing, etc. Although such methods have greatly advanced compositional optimization and structural engineering of EWAs, they remain fundamentally limited by slow atomic diffusion, prolonged thermal exposure, and thermodynamically favored structural relaxation. As a consequence, materials synthesized under these conditions tend to evolve toward energetically stable configurations characterized by ordered phases, grain coarsening, and partially reconstructed interfaces. This makes it difficult to retain high-energy structural features that are particularly favorable for electromagnetic attenuation, including abundant defects, metastable electronic states, non-ideal heterointerfaces, and fragmented conductive networks. In essence, conventional synthesis restricts EWAs design within an equilibrium-governed structural framework, where achievable electromagnetic properties are strongly

bounded by thermodynamic stability.[17, 18] This limitation suggests that the future advance in EWAs are unlikely to rely solely on discovering new compositions within equilibrium regimes, but will increasingly depend on the intentional creation and stabilization of far-from-equilibrium structural states. In this sense, the key scientific challenge is gradually shifting from material selection toward structural state regulation and programming. It is precisely in this context that Flash Joule Heating (FJH) emerges as a highly disruptive synthesis paradigm.[19-21]

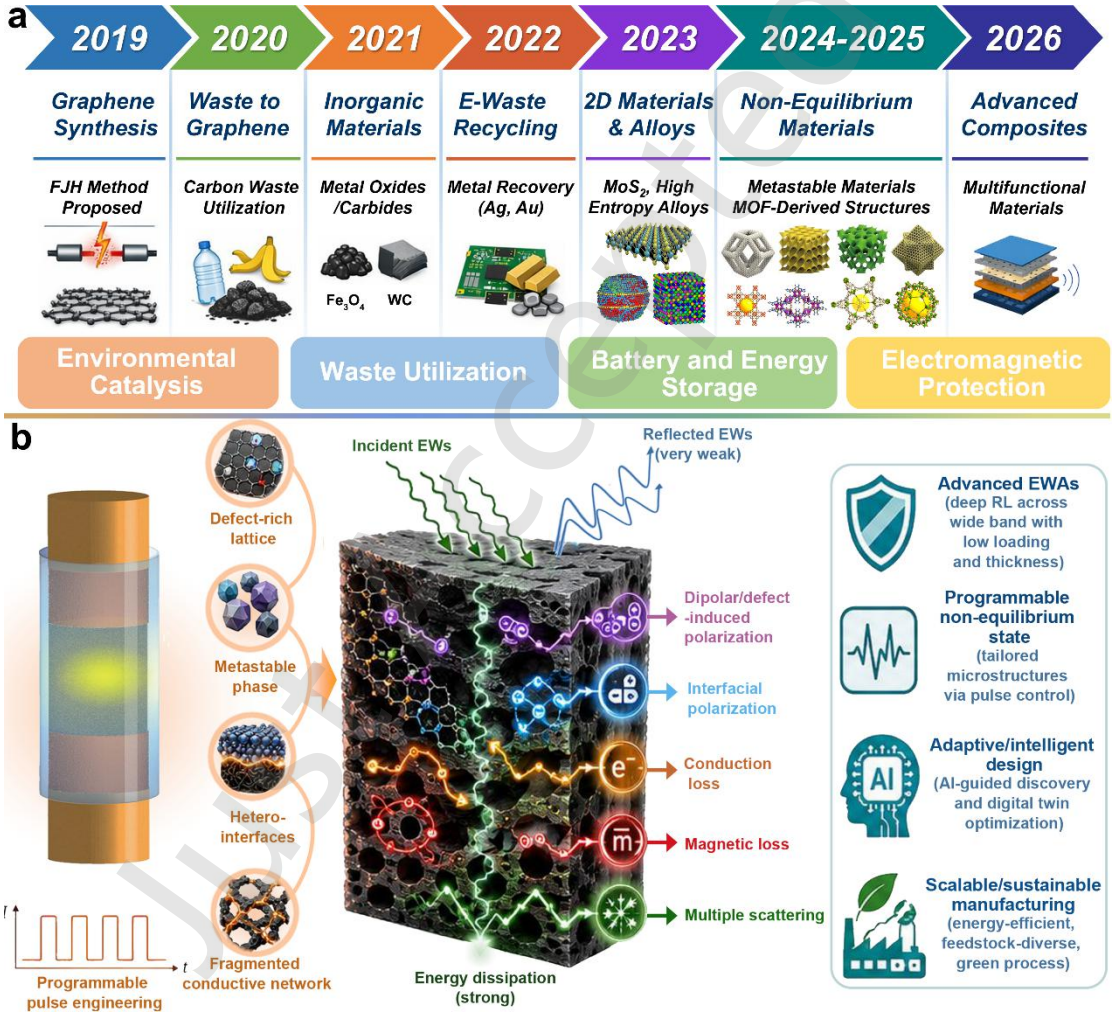

Figure 1. a) The evolution and applications of materials synthesized by FJH. b) FJH writes non-equilibrium states into matter, enabling next-generation EWAs.

Since the pioneering work by James Tour,[22] FJH has rapidly evolved from an ultrafast graphitization strategy into a versatile platform for synthesizing carbides, oxides, sulfides, metastable alloys, and various defect-engineered functional materials,[23, 24] as shown in **Figure 1a**. Through the direct discharge of high-power

electrical pulses into precursor materials, FJH can generate transient temperatures exceeding 3000 K within milliseconds, followed by ultrafast cooling that freezes the evolving structure before thermodynamic relaxation takes place. Such extreme temporal compression drives materials into a far-from-equilibrium regime, where defect formation, phase transformation, interfacial reconstruction, and conductive network evolution proceed beyond the constraints of conventional equilibrium thermodynamics. Consequently, FJH enables access to kinetically trapped structural states that are difficult or even impossible to obtain using traditional thermal processing. Such non-equilibrium configurations, including defect-rich lattices, metastable phases, amorphous-crystalline hybrids, and discontinuous conductive networks, are precisely the types of architectures capable of delivering broad polarization response, enhanced interfacial charge trapping, tunable impedance profiles, and synergistic dielectric-magnetic attenuation. Therefore, the significance of FJH for EWAs extends well beyond offering a rapid or energy-efficient synthesis route. More fundamentally, it introduces a fundamentally different strategy in which electromagnetic properties can be encoded through controllable non-equilibrium energy-time trajectories, rather than being passively determined by equilibrium structures. This suggests a profound conceptual transition that EWAs design may evolve from traditional composition/morphology optimization toward digitally programmable non-equilibrium state engineering (**Figure 1b**).

It is worth noting that FJH is not the only rapid non-equilibrium processing strategy developed in recent years. Other approaches, including microwave heating, spark plasma sintering, and laser processing, have also demonstrated unique capabilities for accelerating materials synthesis and suppressing thermodynamic relaxation. However, these techniques differ substantially in their energy-delivery mechanisms, applicable materials, processing characteristics, and achievable non-equilibrium states. A brief comparison of these approaches is summarized in **Table 1**. Among these approaches, FJH is particularly distinguished by its millisecond-scale volumetric Joule heating and ultrafast quenching, making it

especially suitable for programmable non-equilibrium state engineering in EWAs.

Table 1. Comparison of FJH and other representative processing techniques.[25, 26]

Method	Heating mechanism	Characteristic time	Typical temperature	Achievable structures	Main advantages	Limitations for EWAs
Conventional furnace	External heating	hours	~1000 ºC	Equilibrium phases, coarse grains, low defect density, homogeneous compositions	Mature, uniform	Near equilibrium
Microwave heating	Volumetric dielectric heating	min	<2000 ºC	Fine grains, localized defect structures, heterogeneous microstructures, limited metastable phases	Fast volumetric heating	Heating depends on dielectric properties
Spark plasma sintering	Pulsed DC+ pressure	min	1000-2500 ºC	Dense nanostructures, refined grains, interface-rich architectures, partially retained metastable structures	Dense bulk materials	Mainly bulk sintering and pressure required
Laser processing	Local optical heating	μs-ms	Local >3000 K	Rapidly solidified microstructures, gradient structures, amorphous/crystalline hybrids, high dislocation density	Precise local modification	Limited penetration depth and small processing area
FJH	Direct Joule heating	ms	>3000 K	Highly non-equilibrium phases, defect-rich structures, ultrafine nanocrystals, amorphous-crystalline hybrids, high-entropy/metastable phases, compositionally and structurally heterogeneous architectures	Entire-volume ultrafast non-equilibrium, kinetic trapping, scalable powders	Conductive precursors and precise pulse control

Herein, we first discuss the fundamental physics that distinguish FJH from conventional thermal processing, with particular focus on its ultrafast electrothermal characteristics and the resulting non-equilibrium structural evolution. Then how these transient states provide a powerful "surgical" tool for overcoming long-standing bottlenecks in EWAs is analyzed, including the conductivity-impedance mismatch dilemma, insufficient polarization centers, limited interfacial density, and restricted high-frequency magnetic response. Building on these discussions, several emerging opportunities enabled by FJH, ranging from kinetic programming and spatiotemporal electromagnetic regulation to adaptive intelligent materials and data-driven autonomous design are outlined. Finally, we discuss the key scientific and engineering barriers that must be addressed before FJH can mature into a universal

state-programming platform for next-generation electromagnetic matter.

2. The Physics of Non-Equilibrium State Writing in FJH

To understand why FJH has the potential to fundamentally reshape EWAs design, it is important to recognize that FJH is far more than an accelerated thermal treatment. Rather, it represents a distinct physicochemical regime in which material evolution is governed by extreme temporal compression and far-from-equilibrium energy input. In conventional furnace-based synthesis, heat is gradually transferred from an external source to the material, allowing structural evolution to proceed through relatively slow, quasi-equilibrium relaxation processes. In contrast, FJH injects electrical energy directly into the precursor through resistive heating, generating an ultrafast electrothermal shock that fundamentally changes the formation, migration, interaction, and kinetic stabilization of atoms, defects, phases, and interfaces.[27, 28]

In a typical FJH process, a high-voltage or high-current pulse released from a capacitor bank is driven through a conductive or semiconductive precursor bed. As the current passes through the resistive medium, rapid electron-phonon interactions enable nearly instantaneous conversion of electrical energy into heat via Joule heating. This internal heating mechanism bypasses the thermal lag inherent to conventional conduction, convection, and radiation, allowing heating rates on the order of 10^4-10^5 K s^{-1} and transient temperatures exceeding 3000 K within milliseconds. Once the electrical pulse ends, the system undergoes rapid cooling through radiative loss, conductive dissipation to the electrodes, and heat exchange with the surroundings, leading to an equally abrupt quenching stage.[29] As a result, the entire synthesis process is confined to an extremely short temporal window in which rapid heating, transient high-temperature excitation, and kinetic freezing occur in immediate sequence. This pronounced temporal compression fundamentally reshapes the thermodynamic and kinetic landscape of materials formation, opening reaction pathways and metastable configurations that are inaccessible under equilibrium conditions.[25, 30] In contrast to slow thermal processing, where atoms have sufficient time to diffuse, reorganize, and relax toward thermodynamically stable

states, FJH drastically limits atomic mobility in both space and time. Exactly, defects tend to annihilate, metastable intermediates readily transform into stable phases, and heterointerfaces gradually coarsen due to interdiffusion under conventional conditions,. By comparison, FJH rapidly drives the system into highly excited, far-from-equilibrium states in which bond breaking, local structural disorder, nucleation events, phase reconstruction, and charge redistribution occur in a strongly coupled and non-equilibrated manner. Before these transient configurations can relax toward equilibrium minima, ultrafast quenching effectively arrests atomic motion, locking the material into kinetically trapped states. In this sense, FJH does not simply accelerate synthesis but fundamentally interrupts thermodynamic equilibrium.

This interruption gives rise to a series of structural features that are particularly relevant to electromagnetic functionality. First, the severe mismatch between the timescale of defect formation and that of defect annihilation results in a high density of kinetically preserved vacancies, edge sites, dislocations, and lattice distortions. These non-equilibrium defects serve as localized charge asymmetry centers, effectively strengthening dipolar polarization relaxation under alternating electromagnetic fields.[31, 32] Second, the rapid thermal excursion enables transient access to metastable phases that are inaccessible under equilibrium conditions, while subsequent quenching locks these configurations in place before structural relaxation can proceed. Such metastable electronic states often exhibit modified carrier mobility, spin configurations, and dielectric response, thereby introducing additional dielectric and magnetic loss mechanisms.[33, 34] Crucially, the capability of FJH to stabilize kinetically trapped, metastable phases is supported by emerging experimental breakthroughs. Third, the explosive nucleation under extreme supersaturation, combined with the extremely short growth time, favors the formation of ultrafine nanocrystals and incomplete phase separation. This results in a high density of amorphous-crystalline interfaces, heterointerfaces, and discontinuous conductive junctions, which collectively promote Maxwell-Wagner-Sillars (MWS) polarization, interfacial charge accumulation, and enhanced multiple scattering of EWs.[35]

Overall, the non-equilibrium nature of FJH can be viewed across multiple coupled dimensions (**Figure 2**). From a thermodynamic perspective, the millisecond-scale energy input induces a pronounced electron-phonon non-equilibrium (T_e»T_p), driving the system into a transient high-free-energy state that provides the necessary chemical potential to overcome conventional thermodynamic barriers. This trajectory is then rapidly redirected into a kinetically arrested regime during ultrafast quenching, where atoms are effectively trapped in shallow metastable potential wells before reaching the global equilibrium minimum. For instance, recent experimental studies have demonstrated that ultrafast electrothermal shock can successfully freeze thermodynamically immiscible elements into single-phase high-entropy alloy nanocrystals or stabilize metastable transition metal carbides/dichalcogenides (e.g., α-MoC_x, η-MoC_x, 1T MoS_2 and WS_2) that would otherwise decompose or coarsen during slow, conventional furnace cooling.[24, 36, 37] At the structural and defect level, the extreme compression of reaction time suppresses defect annihilation, preserving a high concentration of dislocations, vacancies, and turbostratic stacking faults, thereby increasing configurational disorder and providing abundant dipolar polarization centers for electromagnetic dissipation. Finally, at the interface and strain level, the intense thermal shock generates heterogeneous strain fields and complex interfacial architectures, such as amorphous-crystalline boundaries, which further enhance MWS polarization and interfacial charge accumulation. Collectively, these synergistic non-equilibrium features transform initially ordered solids into complex architectures that are particularly well suited for broadband EWs absorption.

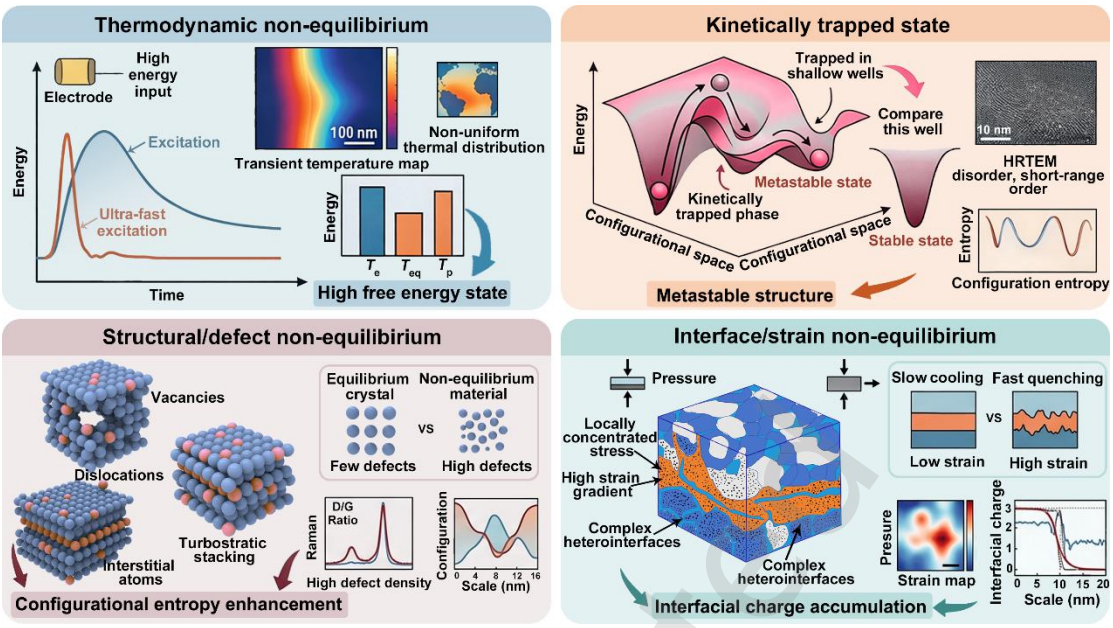

Figure 2. Four coupled dimensions of non-equilibrium state engineering during FJH, illustrating the relationships among transient thermodynamics, defect preservation, interfacial reconstruction, and strain evolution.

Therefore, the physics of FJH should not be viewed merely as ultrafast Joule heating, but more fundamentally as a controllable mechanism for inscribing kinetically frozen, far-from-equilibrium states into materials. Based on this, electrical pulse parameters are no longer mere processing conditions. Instead, they act as state-controlling variables that define the degree of departure from equilibrium, the transient structural motifs that can be accessed, and the extent to which these motifs are retained after quenching. Nevertheless, the extent to which these non-equilibrium states can be reproducibly generated still depends strongly on precursor properties, electrical pulse control, and the availability of suitable FJH equipment, highlighting the need for further quantitative process optimization.

Although the individual non-equilibrium structural features induced by FJH have been delineated, their significance for EWAs extends beyond their isolated presence. Instead, it hinges on their capacity to systematically overcome the intrinsic limitations of conventional absorbers. Fundamental bottlenecks in electromagnetic attenuation can be directly mapped to specific non-equilibrium structural features that act as physical regulators of energy dissipation.[38-40] Specifically, discontinuous

conductive networks modulate the trade-off between electrical conductivity and impedance matching, while defect-rich configurations introduce high-density polarization centers. Furthermore, metastable heterointerfaces accelerate interfacial charge accumulation, and metastable magnetic phases coupled with nanoscale magnetic disorder intensify high-frequency magnetic losses. Therefore, the core merit of FJH lies in establishing a precise structure-property paradigm wherein kinetically stabilized states are strategically translated into enhanced electromagnetic attenuation mechanisms.

3. "Surgical Tool" for Overcoming EWAs Bottlenecks

FJH generates a suite of kinetically stabilized non-equilibrium structural features rather than isolated microstructural modifications. These structural architectures establish a direct physical bridge between non-equilibrium state engineering and electromagnetic functionality. In particular, discontinuous conductive networks regulate impedance matching, defect-rich configurations provide abundant polarization centers, metastable heterointerfaces enhance interfacial relaxation, and nanoscale magnetic disorder improves high-frequency magnetic loss. Guided by this structure-property mapping, the following sections discuss how FJH functions as a "surgical tool" to overcome the four major bottlenecks in conventional EWAs.

3.1. Conductivity Modulation and Impedance Matching

Excessive electrical conductivity has long been recognized as a major obstacle in the development of high-performance carbon-based EWAs.[41-44] In most conventional systems, dielectric loss is enhanced by constructing conductive carbon networks that facilitate electron transport under alternating electromagnetic fields. The migration of charge carriers along these interconnected pathways promotes energy dissipation through conduction loss, thereby improving electromagnetic attenuation capability (**Figure 3a**).[45, 46] Nevertheless, conductivity does not correlate linearly with absorption performance. Although a certain level of electrical conductivity is necessary to generate effective conduction loss, excessive conductivity often leads to a substantial increase in complex permittivity, resulting in severe

impedance mismatch between the absorber and free space. Consequently, EWs are more readily reflected at the material surface rather than entering the absorber, which ultimately deteriorates the absorption performance. Maintaining conductivity within an appropriate range is therefore essential but remains difficult to achieve through conventional equilibrium-based synthesis routes. During prolonged high-temperature annealing, carbon structures continuously evolve toward thermodynamically favored states. The progressive graphitization process increases structural ordering, reduces defect density, and promotes the formation of highly interconnected conductive networks. While these changes improve electrical transport, they frequently push the conductivity beyond the optimal level required for balanced impedance matching and dielectric attenuation. This tendency originates from the intrinsic characteristics of equilibrium processing, where atomic diffusion and crystallite growth continuously reduce structural disorder and promote long-range ordering.[26, 47] Once conductive pathways begin to develop, further coalescence and graphitic growth become energetically favorable, making it difficult to preserve intermediate conductive states that are often more desirable for electromagnetic applications.

FJH offers an alternative pathway by introducing extreme non-equilibrium thermal conditions. The combination of ultrafast heating and rapid quenching substantially shortens the time available for structural relaxation, thereby altering the evolution of carbon frameworks. Instead of allowing graphitic domains to mature into highly ordered conductive networks, FJH freezes the structure at an intermediate stage of development. As a result, various metastable features, including partially graphitized regions, discontinuous conductive pathways, turbostratic carbon layers, lattice distortions, and irregular interlayer arrangements, can be retained within the final material. These structural characteristics can create a heterogeneous conductive network composed of both ordered and disordered regions. Localized electron transport remains active within graphitized domains, whereas structural discontinuities suppress the formation of excessively continuous conduction channels. Such a configuration is particularly beneficial for EWs absorption because it prevents

conductivity from increasing beyond the desirable range while still maintaining sufficient carrier mobility for dielectric dissipation (**Figure 3b**). The interruption of long-range charge transport effectively alleviates the excessive permittivity commonly associated with highly graphitized carbons, whereas localized conductive domains continue to contribute to conduction loss under alternating electromagnetic fields. Recently, Zhou has reported that the graphene (B-Gr) fabricated from biowaste bagasse by FJH showed excellent impedance matching than that of bagasse ash annealed through dried bagasse at 750 ºC.[48] In addition to regulating conductivity, FJH also modifies the spatial distribution of conductive domains over multiple length scales. Structural heterogeneity can be generated from atomic-scale defects and lattice distortions to nanoscale graphitic clusters and microscale conductive frameworks. The coexistence of these features could introduce diverse charge transport pathways and polarization environments, giving rise to multiple relaxation processes and more complex dielectric dissipation behavior.

From this perspective, the significance of FJH extends beyond simply generating conductive carbon frameworks. More importantly, it enables the retention of kinetically stabilized conductive architectures that cannot be readily obtained through conventional equilibrium processing. By tailoring conductive topology through non-equilibrium structural evolution, FJH potentially provides an effective strategy for balancing conduction loss and impedance matching, thereby offering new opportunities for the design of high-efficiency EWAs. However, maintaining these intermediate conductive architectures requires precise control over precursor conductivity and pulse parameters, and slight variations may lead to different conductive topologies and electromagnetic responses.

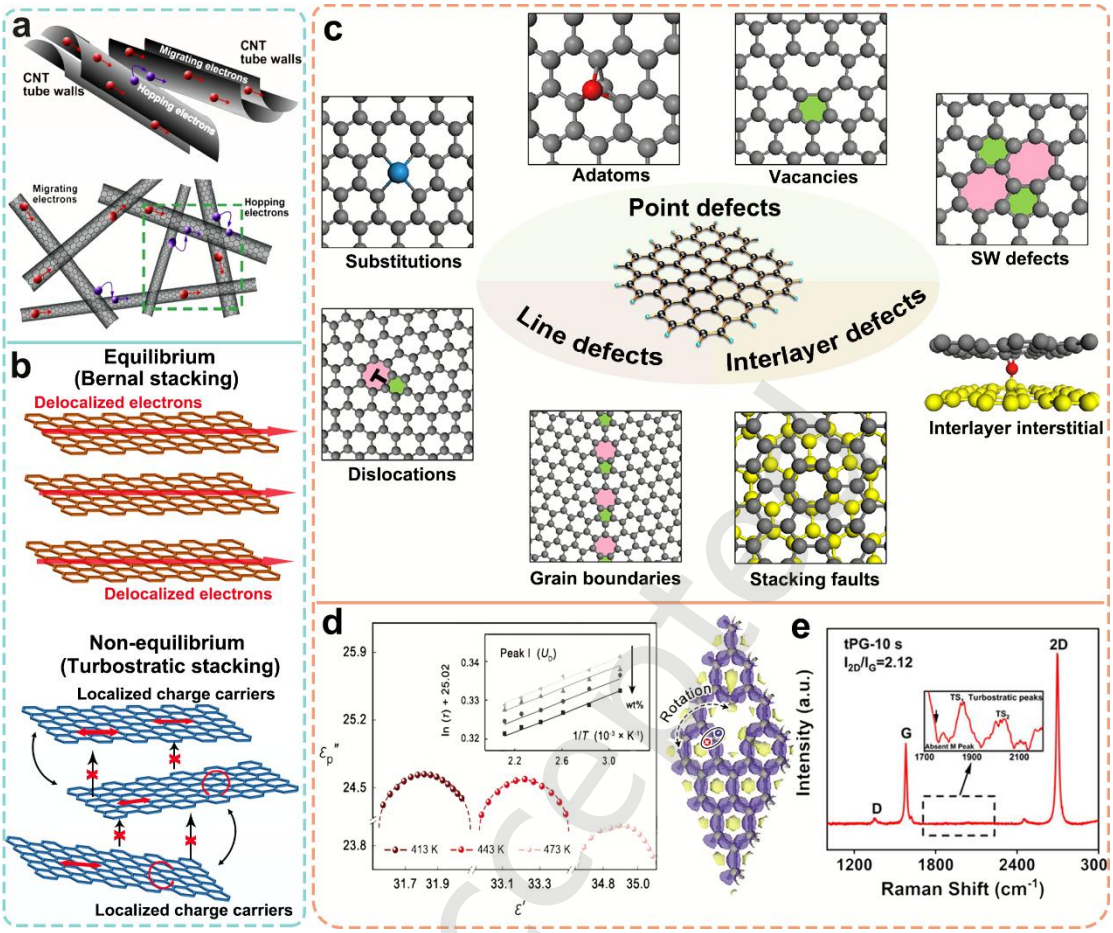

Figure 3. Representative electromagnetic dissipation mechanisms associated with conductive and defective carbon architectures. a) Electron migrating and hopping in conductive carbon networks. Reproduced with permission.[49] Copyright 2013, Elsevier. b) Charge transport behavior in equilibrium and non-equilibrium carbon frameworks generated by FJH. c) Various defect types in graphene-based carbon materials. d) Defect-induced polarization associated with vacancy structures. *Cole-Cole* plots (left) and 3D difference charge density (right) of single vacancy defect. Reproduced with permission.[50] Copyright 2020, Wiley. e) Raman spectrum of turbostratic pulse graphene (tPG). Reproduced with permission.[51] Copyright 2025, Elsevier.

3.2 Kinetically Frozen Defect Polarization

Defect polarization is widely recognized as a major source of dielectric loss in EWAs because structural imperfections can act as effective charge trapping and polarization centers.[52-54] When exposed to EWs, the disruption of local electronic symmetry around defects facilitates charge separation and dipole formation. The

repeated polarization and relaxation of these defect-associated charges dissipate electromagnetic energy in the form of heat, thereby contributing to electromagnetic attenuation.[55-57] The effectiveness of this mechanism is closely related to the density, distribution, and electronic characteristics of defects within the material. However, defect structures are inherently thermodynamically unstable and therefore difficult to preserve under conventional equilibrium synthesis conditions. Most traditional fabrication routes involve prolonged thermal treatment at elevated temperatures, where atomic diffusion continuously drives the system toward thermodynamic equilibrium.[58-60] During this process, various structural imperfections are progressively eliminated through defect recombination, lattice reconstruction, grain coarsening, and local atomic rearrangement. Vacancies may be healed by neighboring atom migration, lattice distortions are gradually relaxed, and residual strain tends to disappear as the crystal structure approaches a lower-energy configuration.[61, 62] Consequently, many electronically active defects are removed during annealing, leading to a significant reduction in the number of polarization centers available for dielectric dissipation. This behavior reflects the intrinsic nature of equilibrium processing. Structural disorder represents a higher-energy state, and thermal activation generally promotes its elimination. As a result, defect-rich configurations often exist only transiently during synthesis and are difficult to retain in the final material. The continuous reduction of defect populations limits the diversity of local electronic environments and constrains the ability to exploit defect-induced polarization for electromagnetic attenuation.

The ultrafast heating and cooling characteristics of FJH provide an effective route to overcome this limitation. During rapid thermal excitation, numerous non-equilibrium defect states can be generated, while the subsequent quenching process suppresses the atomic diffusion required for structural relaxation. Rather than evolving toward a fully ordered configuration, the material is frozen in an intermediate state containing a large population of metastable defects. This kinetic trapping effect enables the retention of structural features that are normally difficult to

preserve through conventional annealing. Experimentally, FJH has been demonstrated to generate a variety of defect-rich carbon architectures, including turbostratic graphene, atomic vacancies, dangling bonds, edge terminations, lattice distortions, heteroatom substitutions, stacking faults, disordered carbon domains, local strain fields, and short-range amorphous regions through ultrafast heating and rapid quenching.[63, 64] For graphene-based materials, these defect structures are commonly grouped into point defects, line defects, and interlayer defects according to their spatial characteristics (**Figure 3c**). The coexistence of these imperfections produces substantial variations in local charge density, electronic potential, and carrier transport behavior. Such heterogeneity creates abundant sites for charge accumulation and dipole formation, thereby strengthening polarization-related dielectric loss.[65] The contribution of these defects extends beyond a simple increase in defect concentration. Different defect species possess distinct electronic structures and relaxation characteristics. Vacancies can trap charge carriers and induce localized polarization (**Figure 3d**), heteroatom substitutions generate permanent dipoles through electronegativity differences, while lattice distortions and strained bonds create asymmetric charge distributions that readily respond to external electromagnetic fields. Because these polarization centers operate over different temporal and spatial scales, their coexistence broadens the dielectric relaxation spectrum and enables more effective electromagnetic energy dissipation across a wider frequency range.[66, 67] In addition, the high density of defects generated under non-equilibrium conditions promotes interactions among neighboring defect sites. Localized charge hopping, short-range carrier migration, and inter-defect polarization coupling become increasingly active when multiple defects are spatially correlated.[68, 69] These collective processes introduce supplementary dielectric loss channels that are rarely observed in highly ordered materials, where defect concentrations are comparatively low and local electronic environments remain relatively uniform. For instance, Chen *et al*. utilized FJH to convert hazardous distillation residue into high-value defect-engineered turbostratic pulse graphene

(**Figure 3e**).[51] Characterized by inherently disordered turbostratic stacking and an abundance of structural defects, the tPG exhibits outstanding EWs absorption performance, delivering a remarkable reflection loss of -42.0 dB and a broad effective absorption bandwidth of 3.9 GHz at a minimal matching thickness of just 1.6 mm.

On this basis, the FJH lies not simply in generating defects but in stabilizing defect-rich metastable structures that are inaccessible through equilibrium synthesis. The preservation of structurally and electronically active defect states enriches polarization mechanisms, expands relaxation pathways, and enhances dielectric dissipation efficiency. Such kinetic control over defect architecture could provide a promising framework for designing next-generation EWAs with improved attenuation capability and broadband absorption performance. It should also be noted that the type and density of kinetically trapped defects remain highly sensitive to precursor chemistry and transient thermal history, making precise defect engineering an ongoing challenge.

3.3 Metastable Interfaces and Interfacial Relaxation

Interfacial polarization represents another dominant dielectric dissipation mechanism in multicomponent EWAs because local discontinuities in electrical conductivity, dielectric constant, work function, and carrier mobility can induce substantial charge accumulation under alternating electromagnetic fields.[70-72] When EWs interact with heterogeneous materials, charge carriers tend to migrate across regions possessing different electrical properties. However, the mismatch in carrier transport behavior across adjacent phases impedes charge transfer and leads to the accumulation of charges at interfaces.[73-75] This process generates localized polarization centers that continuously respond to the alternating electromagnetic field, converting electromagnetic energy into thermal energy through relaxation processes. However, the effectiveness of interfacial polarization is highly dependent on the structural characteristics of the interfaces themselves. Conventional synthesis methods generally rely on equilibrium thermal processing, during which grain growth, atomic diffusion, and phase coarsening progressively reduce interfacial complexity. Initially

sharp phase boundaries become smoother and thicker, compositional gradients gradually disappear, and nanoscale heterogeneities are often eliminated through interdiffusion. In many cases, neighboring phases may partially merge, reducing the degree of electrical discontinuity that is essential for effective charge accumulation. As a result, the density of electronically active interfaces decreases substantially, leading to weakened interfacial polarization and diminished dielectric dissipation capability.

FJH fundamentally alters this interfacial evolution pathway by introducing an extreme non-equilibrium thermal environment. The ultrafast heating rapidly activates atomic mobility and phase transformation processes, while the subsequent rapid cooling suppresses long-range diffusion and prevents complete thermodynamic relaxation. The exceptionally short thermal duration significantly reduces the time available for grain coarsening, interface migration, and compositional homogenization. As a result, numerous transient interfacial structures generated during rapid thermal excitation can be preserved before equilibrium is established. The interfaces retained through FJH are often considerably more complex than those accessible through conventional processing routes. These non-equilibrium interfacial architectures may include metastable heterointerfaces, nanoscale phase boundaries, amorphous-crystalline junctions, compositionally heterogeneous domains, partially transformed regions, and defect-enriched interfacial layers (**Figure 4a**). Unlike equilibrium interfaces, which tend to evolve toward smooth and energetically minimized boundaries, FJH-generated interfaces frequently remain structurally abrupt and chemically heterogeneous. Such characteristics create pronounced discontinuities in electronic structure, carrier transport behavior, and local dielectric properties. Particularly important is the preservation of amorphous-crystalline hybrid interfaces, which are rarely stable under prolonged thermal treatment. These interfaces combine the high structural disorder of amorphous regions with the relatively ordered electronic environments of crystalline domains, generating strong asymmetry in charge distribution and carrier dynamics. Similarly, nanoscale heterointerfaces formed

between distinct phases often exhibit significant differences in conductivity, band structure, and carrier concentration, creating favorable conditions for charge accumulation under electromagnetic excitation. The coexistence of these diverse interfacial motifs greatly increases the overall complexity of the dielectric response.

Therefore, the central contribution of FJH to interfacial polarization engineering is the kinetic stabilization of metastable interfacial architectures with exceptionally high dielectric activity. Through the preservation of structurally abrupt, compositionally heterogeneous, and electronically asymmetric interfaces, FJH can enhance charge accumulation, broadens relaxation spectra, and promotes complex frequency-dependent dissipation behavior. This capability could establishe metastable interface engineering as a key non-equilibrium strategy for the development of next-generation high-performance EWAs. Similarly, the formation of metastable interfaces is strongly pathway-dependent, and reproducible control over interfacial structures remains difficult without precise regulation of the FJH process.

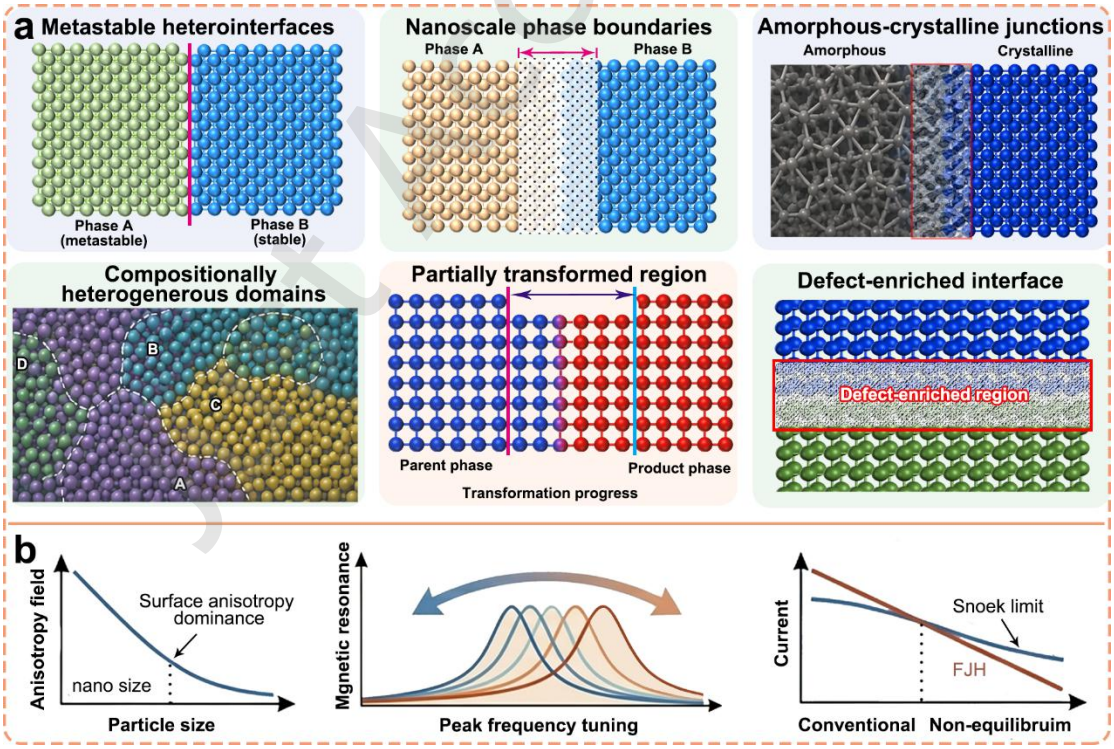

Figure 4. a) Non-equilibrium interfacial architectures through FJH. b) Magnetic properties and high-frequency characteristics.

3.4 Magnetic Disorder and Dynamic Magnetic Loss

The incorporation and precise regulation of magnetic components are essential for achieving synergistic EWs attenuation, particularly in balancing dielectric and magnetic losses over a wide frequency range.[76-78] In conventional synthesis routes, magnetic properties are frequently constrained by particle coarsening, weak interfacial interactions, and intrinsic limitations such as Snoek's limit. Alternatively, FJH could enable magnetic component engineering under extreme non-equilibrium conditions, offering unique opportunities to tailor nanocrystal size, magnetic anisotropy, interfacial magnetic coupling, etc.

According to the Landau-Lifshitz framework, the natural resonance frequency of magnetic particles is directly proportional to the effective anisotropy field (H_a).[79, 80] When the particle size decreases to the nanoscale and approaches the single-domain regime, surface anisotropy becomes increasingly significant because of the large surface-to-volume ratio. This leads to a substantial increase in H_a, thereby shifting the magnetic resonance frequency toward higher-frequency regions (**Figure 4b**), such as the X-band and Ku-band. FJH may play a decisive role in achieving such nanoscale control through its ultrafast thermal dynamics. The millisecond-scale reaction duration effectively suppresses Ostwald ripening, which normally drives particle coarsening during conventional high-temperature processing. Consequently, magnetic components such as Fe, Co, Ni, and their oxides can be retained as ultrasmall nanocrystals (< 10 nm) that are uniformly distributed throughout the matrix. Such size confinement not only enhances magnetic anisotropy, but also weakens interparticle magnetic coupling, thereby maintaining high-frequency magnetic response. Beyond particle-size control, FJH also can enable strain-mediated tuning of magnetic properties. By modulating pulse current intensity and energy input, different degrees of lattice distortion can be induced into the magnetic nanocrystals. These non-equilibrium internal strains contribute to additional magnetoelastic anisotropy, effectively increasing the overall anisotropy field. Consequently, the magnetic resonance peak can be continuously tuned from lower to higher frequencies, enabling

precise alignment with targeted electromagnetic absorption bands.

Besides, FJH can generate tightly bonded atomic-scale interfaces with strong structural integrity and electronic coupling.[25] This capability also extends to the construction of magnetic/dielectric interfaces, where intimate interfacial contact facilitates charge transfer and strengthens interfacial polarization. At the same time, the non-equilibrium nature of these interfaces could help alleviate the impedance mismatch commonly introduced by magnetic components. Through magnetic loss contributions to the imaginary part of permeability, the dielectric and magnetic responses can be better balanced, thereby suppressing surface reflection and improving electromagnetic absorption across a broad frequency range. More important, Snoek's limit restricts conventional isotropic magnetic materials because their natural resonance frequency is bound by their magneto-crystalline anisotropy.[81] To experimentally break this trade-off, recent studies have utilized non-equilibrium structural designs, such as constructing highly anisotropic microflakes, inducing massive interfacial strain, or coupling metastable magnetic/dielectric phases.[82-84] As discussed above, FJH can stabilize non-equilibrium magnetic phases, including metastable magnetic nitrides and intermetallic compounds possessing unconventional electronic structures and enhanced magnetic anisotropy. These metastable phases may provide a potential strategy for modulating magnetic resonance behavior and extending the usable high-frequency magnetic response by modifying magnetic anisotropy, domain structures, and exchange interactions.

Overall, the ability of FJH to simultaneously manipulate interfacial structure, phase composition, and charge transport provides a versatile platform for the design of next-generation EWAs. Through the combined effects of dense heterointerface construction, non-equilibrium phase stabilization, and controllable charge dynamics, FJH could enable the coordinated optimization of electromagnetic attenuation and impedance matching. This integrated non-equilibrium design strategy may ultimately promote broadband and highly efficient EWs absorption.

4. Emerging Opportunities for FJH-Derived EWAs

Building upon the unique non-equilibrium characteristics and the kinetic control capabilities described above, FJH not only provides effective routes to long-standing bottlenecks in EWAs, but also opens up a series of emerging opportunities. Current research into FJH for EWAs remains relatively sparse, focusing on turbostratic graphene,[51] amorphous/graphitic carbon,[85] carbon/alloys,[31, 86] carbide,[87] high entropy alloys/MAX/MAB compounds[35, 88, 89]. Beyond the synthesis of conventional and well-established EWAs, these opportunities point toward a paradigm shift from static structure optimization to dynamic, pathway-dependent material programming.

4.1 Kinetic Programming of Electromagnetic States

In conventional synthesis, materials inherently evolve toward thermodynamic stability through free-energy minimization. Within this equilibrium framework, parameters like temperature, atmosphere and time merely act as indirect variables influencing the pathway to equilibrium, rather than expanding the structurally stable domain. Consequently, traditional materials design focuses on optimizing equilibrium phases and compositions, offering limited opportunities to preserve transient structural states from non-equilibrium evolution. Instead of allowing gradual evolution toward equilibrium, FJH drives systems into extreme non-equilibrium states via ultrafast electrical excitation, freezing transient configurations through rapid quenching. Consequently, the final structure is dictated by kinetic pathways and temporal processes rather than thermodynamic minima. The synthesis outcome thus represents a dynamic snapshot captured during structural transformation, rather than a fixed equilibrium endpoint. This shift might enable treating electromagnetic materials as kinetically programmable systems, where electrical pulse parameters transition from mere processing conditions to active control variables.

In this kinetic programming framework, electrical pulse parameters, such as pulse amplitude, duration, waveform, and sequence regulate energy delivery, non-equilibrium depth, and the retention of transient states. Notably, the influence of

FJH parameters on electromagnetic properties has been primarily demonstrated through indirect correlations between pulse energy and resulting structural evolution. Increasing electrical input generally promotes carbon reconstruction and phase transformation, whereas insufficient energy delivery may preserve highly defective or partially transformed structures. For instance, Chen *et al.* systematically investigated the role of pulse duration in governing the structural defects of the resulting tPG.[51] Raman spectroscopy revealed that prolonged pulse duration induced a transition from highly disordered carbon toward well-developed graphene structures due to increased peak temperatures. Specifically, the I_D/I_G ratio decreased from 1.7 to 0.075, accompanied by an increase in the I_{2D}/I_G ratio from 0.20 to 2.1, indicating a substantial reduction in structural defects and enhancement of graphitic ordering. Therefore, electrical pulses can be regarded as programming inputs that define the trajectory of structural evolution rather than simply providing thermal energy. This kinetic programming strategy differs fundamentally from conventional materials engineering, where synthesis conditions are optimized mainly to obtain desired equilibrium structures. Instead, it focuses on controlling evolutionary pathways and selectively accessing metastable states that are otherwise difficult to preserve. This distinction is crucial because many advanced electromagnetic functionalities stem from temporary, metastable features. By capturing these transient states, FJH expands attainable electromagnetic architectures beyond equilibrium thermodynamic limits. This paradigm may enable continuously tunable electromagnetic states by navigating a multidimensional non-equilibrium domain, shifting away from traditional discrete phase selection. Small variations in pulse conditions can finely alter defect retention, phase evolution, interfacial reconstruction, or conductive topologies. This results in gradual modifications of electromagnetic properties rather than abrupt phase transitions, rendering electromagnetic functionality a continuously adjustable attribute rather than a fixed consequence of material composition.

Broadly, this capability transforms electromagnetic performance from a passive synthesis outcome into an actively writable property. Akin to software instructions

programming electronic systems, pulse parameters serve as digital inputs that encode structural information during non-equilibrium evolution. Consequently, electromagnetic responses are governed not just by chemical composition, but by the kinetic history. Materials with identical compositions can thus exhibit vastly different properties based on their specific pulse protocols, establishing process history as an independent design dimension. Thus, a generalized direct pulse-structure-property relationship can be tentatively established (**Figure 5a**), moving beyond traditional empirical, trial-and-error optimization. This could mark a paradigm shift from chemical-exploration-based materials discovery to kinetic-trajectory-controlled materials programming.

4.2 Toward Non-equilibrium Genome Engineering

In this work, we introduce the term "non-equilibrium structural genome" as a conceptual framework to describe the highly coupled ensemble of structural descriptors generated during FJH. Unlike the well-established concept of the materials genome, which focuses on accelerating materials discovery through the integration of composition, structure, properties, and data, the proposed framework emphasizes the collective organization of non-equilibrium structural features such as defects, metastable phases, heterointerfaces, strain fields, and conductive architectures, which evolve cooperatively during ultrafast processing. It should therefore be regarded as a conceptual hypothesis for interpreting complex non-equilibrium structures, rather than an established theoretical framework.

The structural evolution induced by FJH departs fundamentally from conventional thermal processing routes.[90, 91] In traditional equilibrium synthesis, features like defects, phase compositions, and crystallographic ordering act as independent descriptors, separately adjusted to optimize electromagnetic attenuation. This classical viewpoint forces an interpretation of structure-property relationships through isolated, single-parameter mechanisms. FJH may upend this model because its extreme thermal gradients generate highly coupled structural assemblies through synchronized non-equilibrium transformations across multiple spatial and temporal

scales.[92, 93] Here, structural configurations rarely exist as isolated entities, as the emergence of one feature inherently triggers or stabilizes another.[94] For instance, defect accumulation causes localized lattice distortions and strain concentration, while the formation of metastable phases drives compositionally heterogeneous transition zones. Similarly, amorphous-crystalline boundaries introduce disordered interfaces, and rapid elemental redistribution yields nanoscale compositional fluctuations within the matrix. The final microstructure is therefore best understood as a deeply interconnected structural network rather than a fragmented collection of components. From this perspective, these coupled architectures may be viewed as a "non-equilibrium structural genome". Rather than capturing a solitary characteristic, this proposed genome framework represents an integrated ensemble of correlated descriptors (spanning defect topology, phase distribution, interface hierarchy, and strain heterogeneity) that collectively encode the material's structural identity. Much like biological genomes orchestrate complex physiological functions through genetic networks, the electromagnetic behavior of FJH-derived absorbers emerges from the collective synergy of these intertwined structural motifs. Crucially, this genome framework aligns with the inherently multiscale nature of electromagnetic attenuation. Attenuation mechanisms like charge transport, dipolar relaxation, and magnetic resonance originate from structural heterogeneities spanning several length scales. On the atomic scale, defects regulate electronic polarization and charge trapping. Moving to the nanoscale, phase boundaries govern charge accumulation and relaxation dynamics, which then feed into mesoscopic conductive networks that define carrier transport pathways. At the macroscopic scale, these features collectively dictate wave propagation, scattering, and impedance matching. Because these multiscale contributions are tightly bound through the underlying genome, the final electromagnetic response is a macroscopic manifestation of the entire structural network.

The exceptional performance observed in FJH systems does not stem from a single dominant factor, but from the cooperative interactions among multiple

structural motifs born simultaneously during ultrafast thermal evolution. This genome framework may provide a unified lens to interpret why seemingly disparate features, such as local disorder, metastable phases, and compositional fluctuations, coexist so effectively. Collectively, these coupled structural motifs could constitute a non-equilibrium structural genome that governs the electromagnetic response of FJH-derived absorbers.

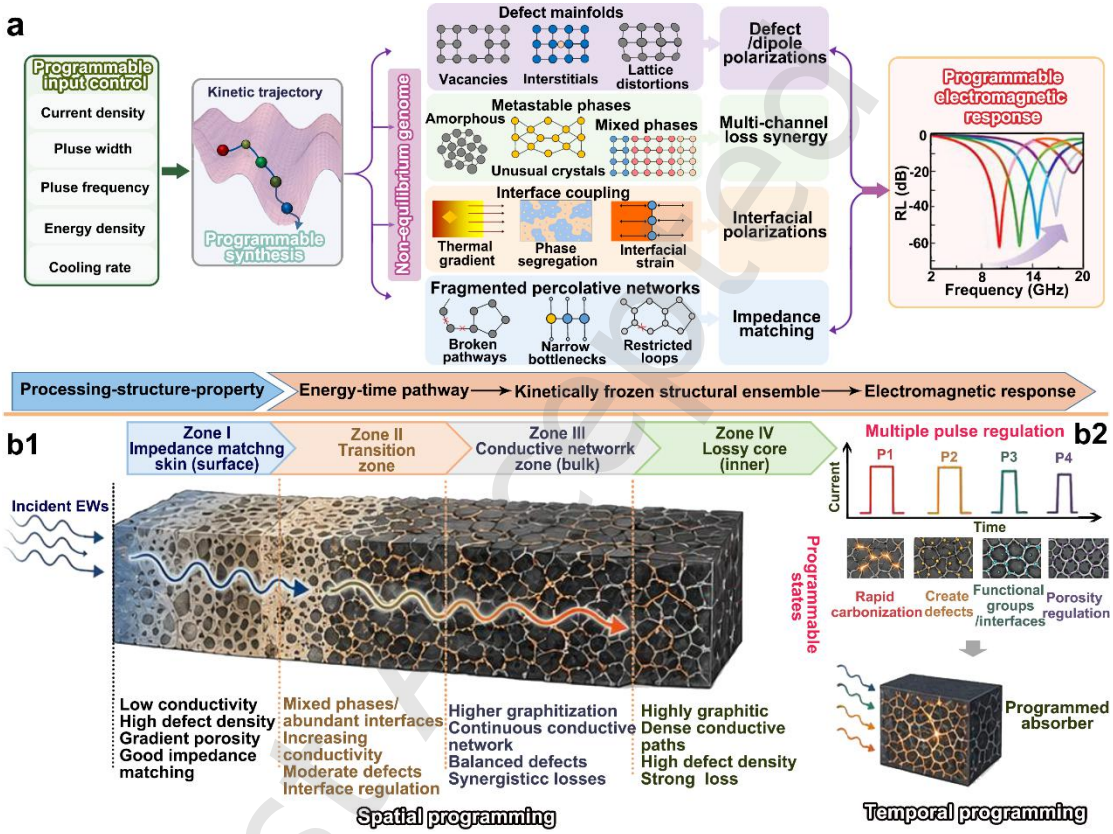

Figure 5. Schematic illustration of kinetic programming in FJH, showing how programmable pulse parameters regulate structural evolution and ultimately determine electromagnetic properties through pathway-dependent non-equilibrium states. a) Schematic illustration of the "processing-structure-property" relationship. b1-b2) Mechanisms of spatial and temporal programming of FJH.

4.3 Spatiotemporal Programming of Electromagnetic Properties

A particularly distinctive opportunity offered by FJH lies in its potential for spatiotemporal programming of material structures and electromagnetic properties. Owing to ultrafast Joule heating and rapid quenching, FJH inherently generates strong spatial and temporal variations in temperature, current density, and reaction kinetics.

In practical systems, these variations are often influenced by local current pathways, packing density, electrical contact, and heat dissipation, resulting in partially stochastic structural heterogeneity. Although such spatial non-uniformity is generally regarded as a processing challenge, it also reveals an additional degree of freedom for materials design if these energy distributions can be deliberately controlled.

If spatial energy deposition can be intentionally regulated through electrode configuration, precursor architecture, conductive pathways, or thermal boundary conditions, the resulting thermal gradients may be translated into designed structural gradients (**Figure 5b1**). Regions experiencing different thermal histories are expected to undergo distinct structural evolution pathways, including variations in graphitization degree, defect concentration, phase composition, and conductive network connectivity. Such controllable spatial gradients could provide opportunities for constructing functionally graded electromagnetic architectures. For example, a continuous transition could be established from an outer region with relatively low conductivity and favorable impedance matching to an inner region characterized by high conductivity and strong electromagnetic loss. Such "outside-to-inside" functional gradients are highly advantageous, as the low-conductivity outer layer facilitates EWs entry by minimizing reflection, while the highly lossy inner region enhances energy dissipation through conductive loss, polarization loss, and multiple scattering. Compared with conventional layer-by-layer fabrication, FJH has the potential to generate gradient structures in a single processing step, although achieving reproducible spatial gradients remains an important challenge. If spatial energy delivery can be precisely controlled, gradients in defect density, phase composition, interfacial density, and local electronic structure may also be engineered within a monolithic material. For example, intentionally designed current pathways or localized conductive additives could preferentially drive phase transformation or defect retention in selected regions, providing a possible route toward spatially defined functional domains.

Temporally, the pulsed operation of FJH introduces another highly flexible

dimension for material regulation (**Figure 5b2**). By tailoring the parameters such as pulse duration, frequency, waveform, and energy input, structural evolution may be controlled in a sequential and programmable manner. Unlike continuous heating processes that follow a single kinetic pathway, FJH allows for multi-pulse strategies that effectively decompose material evolution into sequential stages. For example, an initial high-energy pulse could be employed to rapidly establish a conductive backbone or trigger primary phase transformations, followed by subsequent lower-energy or shorter-duration pulses that introduce specific defect types, tailor surface chemistry, or optimize interfacial structures. Such staged regulation may provide opportunities to tune structural features such as conductive networks, defect populations, and interfaces, to be independently or synergistically tuned within distinct temporal windows. Different pulse combinations are expected to access different kinetic pathways, potentially leading to distinct structural distributions and corresponding electromagnetic responses. In this sense, electromagnetic properties become closely linked to the kinetic history of synthesis, the integration of spatial and temporal control unlocks an unprecedented level of design freedom. Their coupling could enable true multi-dimensional programming of material structure and functionality, in which time is elevated from a passive process variable to an active design parameter.

4.4 Toward Dynamic and Adaptive Electromagnetic Materials

The intrinsically transient, non-equilibrium, and programmable nature of FJH points to a compelling future direction, namely the transition from static electromagnetic materials to dynamic and adaptive systems. Conventional EWAs are typically designed as structurally fixed and functionally immutable materials, whose electromagnetic parameters are predetermined during synthesis and remain essentially unchanged during operation.[93, 95] While such materials can be optimized for specific frequency bands or operating conditions, their inability to respond to evolving electromagnetic environments significantly limits their versatility in real-world applications, where frequency range, incident power, and environmental conditions

are often dynamic. FJH introduces a fundamentally different paradigm by enabling post-synthesis tunability and structural reconfigurability (**Figure 6a1**). By applying additional electrical pulses, localized Joule heating, or controlled energy inputs after the initial fabrication, it becomes feasible to dynamically modify key structural features of the material, such as the connectivity and percolation state of conductive networks, the density, type, and spatial distribution of defects, the structure and electronic states of heterogeneous interfaces. Such reconfigurability enables in situ tuning of electromagnetic properties, allowing materials to adapt their absorption or shielding performance in response to changing external conditions. Moreover, the non-equilibrium structures generated by FJH inherently possess high internal energy states, including elevated defect densities, residual lattice strain, and complex interfacial charge distributions. These features render the material system highly responsive and sensitive to external stimuli (**Figure 6a2**). For instance, thermal stimuli can induce defect migration, phase transformation, or conductivity changes. Electrical bias can modulate carrier concentration, interface barriers, and local conduction pathways. Mechanical deformation can alter interfacial contact, strain fields, and percolation networks. This stimulus-responsive behavior provides a physical basis for developing adaptive electromagnetic functionalities. Importantly, the combination of programmable processing and stimuli-responsive structure creates a feedback-capable system, in which structure and function are not statically fixed but can evolve through external inputs or operational conditions. This opens the door to a new class of electromagnetic materials with closed-loop or semi-closed-loop adaptability, potentially integrating sensing, response, and functional modulation within a single material platform (**Figure 6a3**).

From an application standpoint, these capabilities may enable several emerging directions, such as the tunable electromagnetic absorbers, frequency-agile electromagnetic shielding systems, smart stealth coatings, reconfigurable electromagnetic devices. More fundamentally, this paradigm introduces time as an active and independent design dimension in electromagnetic materials science. Rather

than being defined solely by a static structure, material performance becomes a time-evolving function, dependent on both prior processing history and real-time external stimuli. It should be emphasized that the adaptive electromagnetic materials discussed here represent a forward-looking perspective based on the programmable characteristics of FJH. Although preliminary studies have demonstrated post-processing tunability under electrical or thermal stimuli, fully autonomous adaptive electromagnetic systems remain largely unexplored and require substantial future investigation.

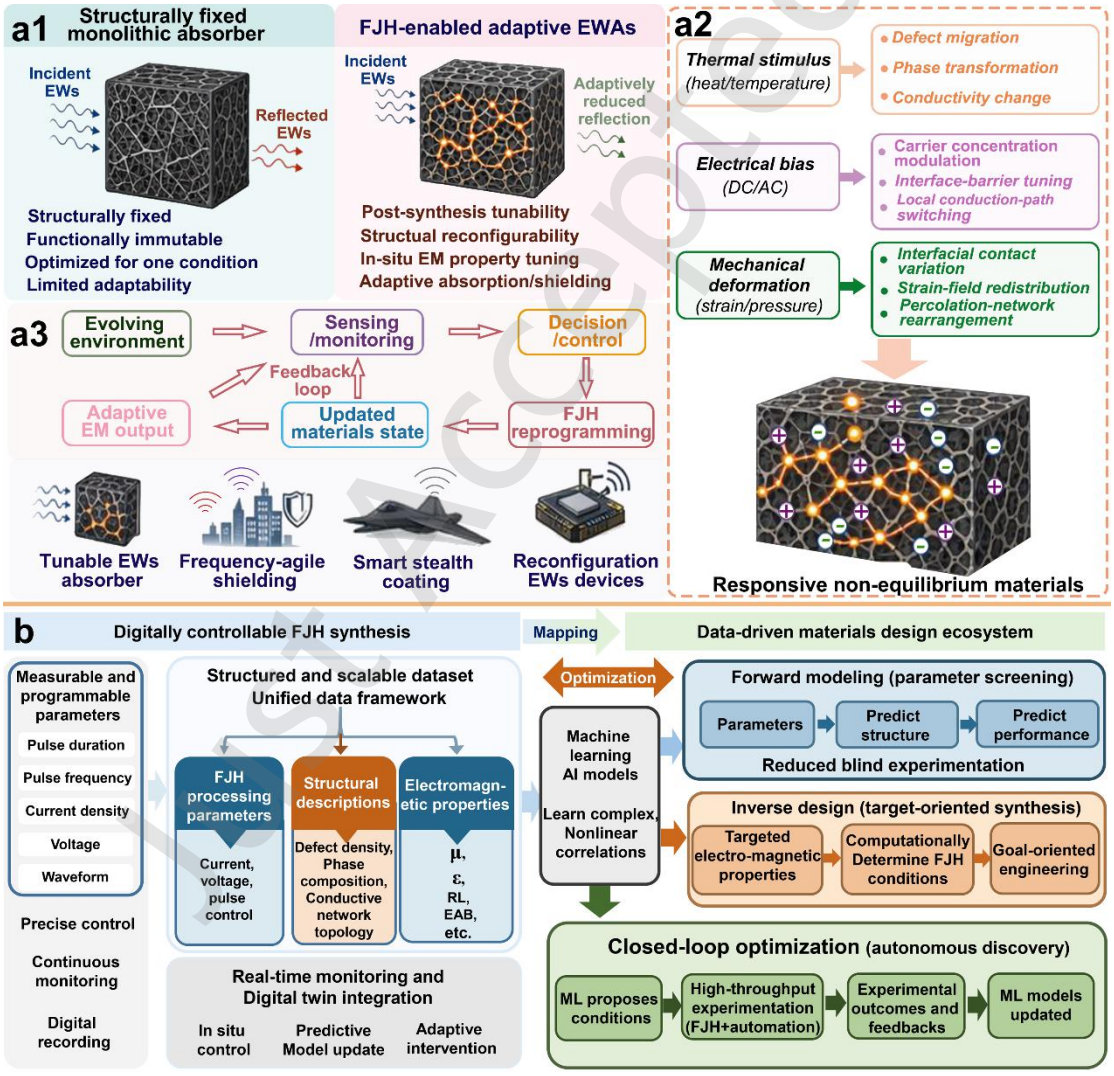

Figure 6. Conceptual framework illustrating adaptive electromagnetic materials and AI-assisted closed-loop optimization enabled by programmable FJH. a1) From static absorber to adaptive absorbers. a2) Stimulus-responsive structural evolution. a3) Feedback-capable intelligent EM functionality. b) FJH-enabled data-driven materials for high-performance

EWAs.

4.5 Data-Driven and Digitally Controlled FJH Design

Another significant opportunity enabled by FJH arises from its intrinsically digital nature (**Figure 6b**). The process is governed by a series of controllable electrical parameters, including voltage, current density, pulse duration, pulse frequency, and waveform. These parameters can be accurately adjusted, continuously monitored, and digitally recorded throughout synthesis, making FJH particularly suitable for data-driven materials design. Such approaches are often time-consuming and inefficient, especially when attempting to understand the complex relationships among processing conditions, structural evolution, and electromagnetic performance. In contrast, the digitally controllable nature of FJH enables the generation of structured datasets in which synthesis parameters, structural characteristics, and electromagnetic properties can be systematically correlated within a unified framework. This provides a foundation for establishing systematic and quantitative "process-structure-property" relationships. Based on this foundation, the integration of machine learning (ML) and artificial intelligence (AI) offers a powerful route to accelerate materials discovery and optimization. By training on experimental or simulated datasets, ML models can capture the complex and nonlinear correlations linking FJH processing parameters to structural distributions such as defect density, phase composition, conductive network topology, and further to electromagnetic responses including reflection loss, effective absorption bandwidth, etc. In addition to improving predictive capability, these approaches can help identify the dominant variables governing performance within complex multi-dimensional parameter spaces.

Within such a data-driven framework, several design strategies become possible. First, forward modeling may be established to predict structural features and electromagnetic performance based on given FJH processing parameters. This capability enables rapid screening of synthesis conditions and reducing dependence on extensive experimental trials. Second, inverse design approaches could start from

target electromagnetic properties and computationally determine the corresponding processing conditions required to achieve them. This may shift materials development from conventional empirical optimization toward performance-oriented and predictive design. Furthermore, when combined with high-throughput experimentation and automated characterization platforms, FJH could support the development of closed-loop optimization systems. In such systems, ML algorithms propose new experimental parameters based on existing data, the experimental outcomes are fed back into the model, and the optimization cycle proceeds iteratively with minimal human intervention. This self-driving workflow has the potential to dramatically accelerate the discovery and refinement of high-performance EWAs. Beyond static data analysis, the digital nature of FJH also facilitates integration with real-time monitoring and digital twin strategies. Continuous acquisition of electrical signals and process-response data during synthesis allows predictive models to be dynamically updated, enabling in situ regulation and adaptive control throughout material formation.

4.6 Scalable and Sustainable Manufacturing Platforms

Beyond its fundamental implications for materials design, FJH also offers compelling advantages in terms of scalability, manufacturing efficiency, and sustainability, positioning it as a promising platform for translating laboratory-scale innovations in EWAs into practical, real-world technologies. A defining feature of FJH is its ultrafast processing capability. The extreme temporal compression inherent to FJH not only enables high-throughput material production, but also reduces thermal budget and processing time, both of which are critical factors for industrial scalability. Equally important is the high energy efficiency of the FJH process. Unlike traditional heating methods that rely on external heat transfer (e.g., conduction, convection, or radiation) and often suffer from substantial energy loss to the surrounding environment, FJH achieves direct volumetric heating through Joule heating within the material itself.[96, 97] Electrical energy is converted into thermal energy precisely at the location where it is needed, minimizing parasitic losses and eliminating the need

for prolonged high-temperature exposure. As a result, FJH offers a more energy-efficient pathway for material synthesis, with reduced overall energy consumption and improved process sustainability. Another critical advantage of FJH lies in its exceptional versatility in precursor selection. The process has demonstrated a strong capability for transforming a wide range of low-cost, abundant, and even waste-derived feedstocks into high-value functional materials, including polymeric precursors, biomass resources, carbonaceous wastes, and other discarded organic materials. Through the rapid heating and kinetic trapping mechanisms of FJH, these otherwise low-value or environmentally problematic materials can be converted into defect-engineered carbon frameworks, conductive networks, and hybrid structures suitable for electromagnetic applications. This "waste-to-materials" approach not only reduces raw material costs but also contributes to circular economy practices and environmental sustainability by valorizing waste streams.

From a manufacturing perspective, FJH is inherently compatible with scalable and potentially continuous processing configurations. Because the process is electrically driven rather than dependent on complex chemical environments, the overall system design can be relatively simple and more readily integrated with existing electrical and automated manufacturing infrastructure. In addition, the short processing duration and programmable nature of FJH make it suitable for modular production systems in which material properties can be adjusted on demand without extensive modification of the manufacturing line. Importantly, the combination of scalability, energy efficiency, and feedstock flexibility enables the production of EWAs that are not only high-performing but also cost-effective and environmentally sustainable. This is particularly relevant for large-area or high-volume applications, such as EMI shielding, stealth technologies, and next-generation communication systems, where material cost and manufacturing throughput are critical constraints. In addition, the rapid and localized nature of FJH processing opens possibilities for on-demand and decentralized manufacturing, where materials can be synthesized or reconfigured at the point of use. This could be especially advantageous in scenarios

requiring rapid deployment, customization, or field-level adaptability. Despite these attractive prospects, large-scale implementation still faces practical challenges, including the need for conductive or suitably engineered precursors, specialized high-current pulse equipment, and standardized processing protocols to ensure reproducible material quality.

5. Challenges and Outlook

Despite the remarkable opportunities outlined above, the translation of FJH from a conceptually powerful non-equilibrium synthesis strategy into a mature platform for advanced EWAs remains at an early stage. Future advances in FJH-derived EWAs will rely not simply on expanding material demonstrations, but more importantly on overcoming several fundamental scientific and engineering barriers that continue to hinder practical technological implementation (**Figure 7**).

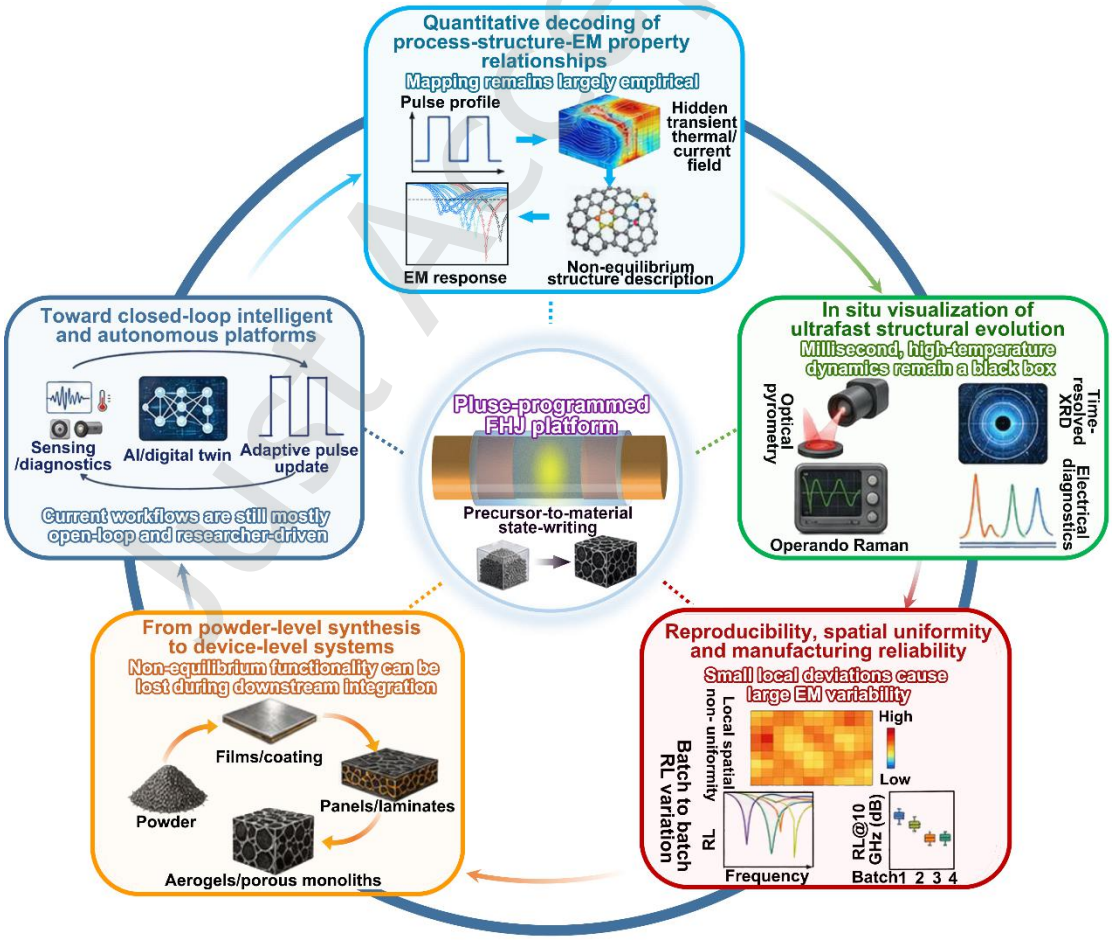

Figure 7. Key bottlenecks and future roadmap toward predictive, reliable, device-level, and autonomous non-equilibrium EWAs engineering

5.1 Quantitative Decoding of the Process-Structure-Electromagnetic Property Relationship

A major challenge in FJH research is the absence of a clear quantitative framework linking programmable electrical inputs to deterministic electromagnetic performance. Although FJH provides a highly tunable parameter space, including voltage, current density, pulse duration, waveform, pulse frequency, atmosphere, and cooling rate, how these parameters govern transient thermal behavior, atomic diffusion, defect evolution, and interfacial reconstruction is still not fully understood. At present, correlations between electrical inputs and structural characteristics, such as defect density, graphitization degree, metastable phase content, interfacial density, and conductive network topology, remain largely empirical and are often interpreted qualitatively. More importantly, the relationship between these non-equilibrium structures and electromagnetic properties, including complex permittivity, permeability, reflection loss, and effective absorption bandwidth, has not yet been systematically established.

As a result, current FJH-based material design still relies heavily on phenomenological trial-and-error optimization rather than predictive control. Although FJH is frequently described as a programmable synthesis method, the field still lacks a robust theoretical or data-driven framework capable of directly translating electrical pulse parameters into target electromagnetic responses. Addressing this issue will require the development of multiscale quantitative descriptors that can bridge electrical input, transient thermal fields, structural evolution, and final electromagnetic behavior. Such descriptors may involve real-time thermal signals, local current-distribution mapping, defect-density quantification, interfacial energy analysis, and conductive network connectivity metrics. Establishing these "process-structure-property" relationships is essential for transforming FJH from a rapid synthesis technique into a truly programmable platform for electromagnetic materials design.

5.2 In Situ Visualization of Ultrafast Non-Equilibrium Structural Evolution

A second major challenge is the lack of direct in situ or operando evidence for the ultrafast structural evolution that occurs during FJH. At present, many proposed mechanisms, including defect trapping, burst nucleation, metastable phase retention, incomplete phase separation, and transient interfacial reconstruction, are mainly inferred from ex situ characterization of the final products.[98] Although these post-synthesis analyses provide important structural information, they cannot capture the real-time pathways through which non-equilibrium structures form, evolve, and eventually become kinetically frozen.[99, 100] This limitation is particularly significant because FJH occurs within millisecond or even sub-second timescales while simultaneously reaching temperatures of several thousand kelvin. Under such extreme conditions, the key physicochemical processes take place beyond the temporal resolution and environmental tolerance of most conventional characterization techniques. Consequently, FJH remains, to some extent, a "black box" process in which the electrical input and final material state are observable, but the intermediate structural transitions governing material formation remain largely hidden. Without direct observation of these transient events, many current mechanistic explanations remain plausible but not fully validated.

Overcoming this challenge will require the development of integrated ultrafast diagnostic approaches capable of tracking transient temperature evolution, phase transformation, bond reconstruction, and current redistribution in real time. This may involve the combined use of optical pyrometry, time-resolved synchrotron X-ray diffraction, operando Raman spectroscopy, ultrafast electrical diagnostics, and multiphysics simulations to reconstruct otherwise inaccessible local reaction environments. Besides, future investigations combining ferromagnetic resonance, temperature-dependent magnetic measurements, and synchrotron-based magnetic spectroscopy will also be indispensable for quantitatively correlating FJH-induced structural evolution with magnetic anisotropy, exchange coupling, domain dynamics,

and intrinsic resonance behavior. Such multimodal characterization is crucial for transforming FJH from an empirically driven synthesis method into a mechanistically transparent non-equilibrium reaction platform, thereby enabling more reliable and rational materials design.

5.3 Reproducibility, Spatial Uniformity, and Manufacturing Reliability

Although spatial heterogeneity and thermal gradients in FJH have been highlighted here as useful for constructing gradient electromagnetic architectures, it is equally important to recognize that uncontrolled non-uniformity is a key obstacle to reproducibility and scalable production. In real FJH systems, variations in contact resistance, packing density, stochastic current pathways, and edge-related heat loss can all produce significant spatial fluctuations in current density and thermal history. Consequently, even under identical electrical input conditions, the resulting local structures may differ markedly across a single sample. For EWAs, such variations are particularly critical because electromagnetic properties are highly sensitive to subtle changes in conductive networks, defect concentration, magnetic nanoparticle size, and interfacial distribution. Minor deviations in graphitization degree or phase composition can therefore lead to pronounced changes in impedance matching behavior and reflection loss.[101, 102] In this sense, the very non-equilibrium features that enable high performance in FJH-derived materials also introduce an inherent trade-off with reproducibility, as the same ultrafast, localized reaction dynamics that generate desirable structures simultaneously make them difficult to control consistently. Addressing this issue will require a shift in focus from isolated high-performance demonstrations toward reproducible and scalable processing strategies. This includes tighter control over precursor conductivity and packing, electrode configuration, pulse energy calibration, and thermal dissipation conditions, as well as systematic spatially resolved characterization and statistical batch analysis to assess structural uniformity. Only when FJH can reliably and consistently generate targeted non-equilibrium states with high spatial fidelity will it be suitable for robust industrial-scale manufacturing of electromagnetic materials.

5.4 Bridging the Gap from Powder-Level Synthesis to Device-Level Electromagnetic Systems

Another important but often underappreciated challenge is the difficulty of transferring FJH-derived materials from laboratory-scale powders to realistic device architectures for electromagnetic applications. Most existing studies focus on producing defect-rich powders, ultrafine hybrid nanocrystals, or metastable carbon-based composites, and then evaluating their electromagnetic performance in paraffin-based test systems. However, such powder-level demonstrations are still far removed from practical requirements, which typically involve flexible films, robust coatings, lightweight aerogels, integrated shielding panels, or mechanically stable structural composites. A key issue is that many of the non-equilibrium features created by FJH, including fragile defect networks, residual internal strain, incomplete phase segregation, and delicate interfacial polarization sites, are highly vulnerable to degradation, reconstruction, or electrical disconnection during downstream processes such as grinding, dispersion, binder incorporation, film casting, hot pressing, and coating deposition. Consequently, successful non-equilibrium synthesis at the material level does not necessarily ensure preservation of the same functional advantages at the device level, leaving a substantial gap between producing a high-performance absorber powder and constructing a deployable electromagnetic system.

Overcoming this gap will require a more integrated view in which material synthesis and device construction are treated as a continuous process. Promising directions may include direct FJH writing on conductive substrates, in situ formation of functional coatings, additive manufacturing coupled with pulsed electrical programming, and binder-free monolithic architectures. Establishing such coupled processing strategies will be essential for translating the unique advantages of FJH-derived materials into usable electromagnetic devices.

5.5 Toward Closed-Loop Intelligent and Autonomous FJH Platforms

Perhaps the most forward-looking challenge for FJH is the development of intelligent closed-loop systems capable of autonomous non-equilibrium materials

discovery. Although FJH is intrinsically digital in nature, relying on electrically programmable pulse inputs, most current implementations remain open-loop: researchers select processing parameters, synthesize samples, characterize the resulting structures, test electromagnetic performance, and then refine conditions through empirical iteration. While more controllable than conventional thermal routes, this workflow is still largely guided by experience and becomes inefficient when navigating the high-dimensional parameter space of FJH. The real potential of FJH will be realized only when its digital controllability is coupled with real-time monitoring, machine learning-based prediction, and adaptive feedback control. In such a closed-loop framework, electrical pulses would no longer be predefined inputs, but dynamically adjusted signals generated through continuous interaction between experimental feedback and predictive models. Real-time indicators such as current response, voltage fluctuation, transient thermal emission, and resistance evolution could be used as indirect signatures of structural evolution. In parallel, machine learning models trained on process-structure-property datasets could infer intermediate states, including defect configurations, phase distribution, and expected electromagnetic response. Based on these predictions, subsequent pulse sequences could be autonomously updated to steer the system toward targeted functionalities. In this scenario, FJH would operate as an autonomous non-equilibrium "materials compiler", in which electromagnetic properties are not discovered through repetitive experimentation but instead are progressively encoded through adaptive electrical programming. This shift represents more than an improvement in efficiency, as it fundamentally redefines the paradigm of electromagnetic absorber design and discovery.

6. Conclusions

FJH represents far more than an ultrafast synthesis technique for EWAs. Its true significance lies in establishing a fundamentally new non-equilibrium framework for EWAs design. Through millisecond-scale electrothermal shock, transient ultrahigh temperatures, and ultrafast kinetic quenching, FJH could enable direct access to

structural states inaccessible to conventional equilibrium or near-equilibrium processing. These kinetically frozen states including dense defects, metastable phases, fragmented conductive pathways, amorphous-crystalline hybrids, and highly coupled heterointerfaces, collectively create multidimensional electromagnetic dissipation pathways capable of simultaneously optimizing impedance matching and attenuation capability. Importantly, FJH may shift EWAs development from static composition and morphology optimization toward programmable non-equilibrium state engineering. In this framework, electromagnetic functionality is no longer solely determined by equilibrium structures, but increasingly encoded through the dynamic energy-time trajectory of synthesis. Electrical pulse parameters evolve from simple processing variables into programmable state-writing coordinates that regulate defect evolution, interfacial reconstruction, conductive percolation, magnetic anisotropy, and relaxation spectra across multiple spatial and temporal scales. Consequently, electromagnetic properties become direct manifestations of kinetically programmed structural ensembles rather than passive inheritances of thermodynamic equilibrium. Beyond addressing long-standing bottlenecks in EWAs, FJH also opens opportunities for kinetic programming, non-equilibrium electromagnetic genomes, spatiotemporal electromagnetic regulation, adaptive and reconfigurable electromagnetic materials, AI-assisted autonomous synthesis, and scalable sustainable manufacturing. Collectively, these directions suggest that FJH may evolve into a universal digital platform for designing complex electromagnetic functionalities through controllable non-equilibrium physics. Nevertheless, realizing this vision still requires overcoming several key challenges, including quantitative decoding of process-structure-property relationships, operando visualization of ultrafast structural evolution, reproducible large-scale manufacturing, device-level integration, and intelligent closed-loop synthesis. Addressing these issues will require interdisciplinary advances across materials science, ultrafast diagnostics, computational modeling, machine learning, manufacturing engineering, and electromagnetic theory.

Overall, FJH offers a transformative opportunity to redefine EWAs design.

Rather than searching for optimal equilibrium materials within a limited compositional space, future research may increasingly focus on digitally programming far-from-equilibrium functional states through precisely controlled kinetic pathways. In this sense, the ultimate value of FJH lies not merely in accelerating synthesis, but in enabling a conceptual transition from "materials discovery" to "electromagnetic state writing.

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Conflict of Interest

All the contributing authors report no conflict of interests in this work.

Use of AI statement

During the preparation of this work, Google Gemini was used to assist with English language editing. In addition, Google Gemini was consulted during the preliminary conceptual design stage to explore conceptual layouts and visual references for several schematic illustrations. These preliminary concepts were used solely as design references and were not incorporated in this work. All schematic illustrations were independently designed, manually prepared, and finalized by the authors. After using this tool/service, the authors reviewed, edited, and verified all AI-assisted outputs and take full responsibility for the content of this publication.

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