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Resonant Domain Wall Dynamics in a Three-Dimensional Magnetic Nano Double Helix

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ABSTRACT

The extension of magnetic nanostructures to three dimensions (3D) has been predicted to result in phenomena such as non-reciprocal collective dynamics and ultra-fast motion of textures. However, while first indications of dynamics in 3D have been explored in microstructures, the experimental investigation of magnetization dynamics in complex-shaped 3D nanostructures remains challenging. Here, 3D nanoprinted cobalt double-helix nanostructures are investigated with time-resolved X-ray microscopy at nanoscale spatial and picosecond temporal resolution to study their magnetization dynamics. Within the helices, the dynamics of coupled domain walls are observed, and a clear resonant response identified. Micromagnetic simulations confirm that the experimentally observed resonance arises from a harmonic oscillatory mode of the coupled domain walls and predict additional higher-frequency modes, revealing a rich dynamic spectrum. By systematically varying the helix geometry in simulations, we find that the resonant modes can be engineered. This geometrical control promises an alternative to conventional tuning strategies based on tailored magnetic anisotropies, DC bias, or externally applied fields. Together, these experimental and simulated results of magnetization dynamics in complex 3D nanostructures provide a pathway for programmable functionalities, relevant for potential technologies including information processing architectures based on tunable spin texture dynamics.

1 | Introduction

Magnetization dynamics, from controlled spin wave emission to the manipulation of nanoscale magnetic textures, offer a number of technological opportunities. These include low-energy infor-

mation processing with magnonics [1, 2], emerging approaches to non-traditional computing based on non-linear behavior such as in coupled spin torque oscillators [3, 4], and the use of stochastic motion of topological spin textures for probabilistic and neuromorphic computing architectures [5]. In order to realize

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this potential, careful control of local material properties is key, which so far has relied on the precise growth of thin film heterostructures, or the growth of high-quality crystalline materials with tailored anisotropies and symmetries. Indeed, by controlling the crystalline symmetry of a system, introducing, for example, chirality, phenomena such as chirality-induced non-reciprocal motion of magnetic textures [6] can be achieved.

The extension to three dimensions offers a promising route to achieve exotic phenomena, without the need for such precise material control. When it comes to static configurations, for example, 3D geometries have been shown to promote the formation of topologically non-trivial spin textures such as Bloch points [7, 8], spin spirals [9], and skyrmions [10, 11] in otherwise simple ferromagnetic materials without the need for intrinsic crystalline chirality. In addition, the combination of chiral materials with curved geometries has been predicted to lead to the stabilization of topological supercoiled helical textures [12] and to promote the stabilization of 3D hopfion textures [13, 14].

3D spin systems furthermore provide opportunities to go beyond the physics of planar systems in terms of dynamics, with more complex 3D modes [15], 3D magnonic crystals [16, 17], and non-reciprocity induced by the curving of films [18]. In terms of nanostructuring, the evolution from flat nanostrips to cylindrical nanotube and nanowire architectures was predicted to lead to ultrafast domain wall motion [19] and even non-reciprocal spin wave propagation [18] in conventional ferromagnetic systems. Subsequent experiments in permalloy nanowires confirmed these predictions, demonstrating high domain wall velocities [20]. More recently, with improvements in advanced fabrication techniques such as two-photon lithography and additive manufacturing, the study of more complex 3D architectures in the micro and mesoscale has become possible, with exciting implications for magnetization dynamics. Indeed, the introduction of geometric chirality and torsion in complex 3D microstructures has led to the realization of non-reciprocal spin wave propagation [21] and diode-like domain wall motion [22]. When these microstructures are extended to 3D lattices, it opens the possibility to explore the influence of frustration on coherent spin waves [23], as well as the presence of surface and bulk magnonic modes in artificial lattices with submicron periodicity [24].

However, while recently established for microsystems, the exploration of magnetization dynamics on the *nanoscale* using complex 3D geometries remains in its early stages, primarily due to the demanding requirements in advanced nanofabrication and characterization capabilities. In the terms of fabrication, the filling of templates formed using self-assembly or porous materials with electrodeposition has enabled the realization of nanowire networks [25] and 3D architectures such as magnetic gyroids [26].

For the creation of designed complex 3D magnetic nanostructures, a number of fabrication approaches have been developed, that can broadly be divided into two main strategies: the coating of non-magnetic scaffolds and the direct writing of magnetic materials. In the first case, complex 3D geometries can be achieved through multi-photon lithography, in which a photoresist scaffold is written layer-by-layer and subsequently coated with a magnetic material [27, 28]. The method used to

deposit the magnetic material plays a critical role in defining the final magnetic structure. Directional techniques like evaporation [29] or sputtering [30] can produce half-shell geometries. By rotating the substrate in a specific fashion during deposition, these methods can also yield tubular-like structures. In contrast, conformal coating techniques, such as electrodeposition [31] or atomic layer deposition (ALD) [32], allow the realization of tube-like or fully enclosed 3D structures.

In contrast to scaffold-based approaches, focused electron beam induced deposition (FEED) offers remarkable flexibility: it can directly write solid 3D magnetic structures, eliminating the requirements for a non-magnetic scaffold [33], or alternatively grow complex non-magnetic scaffolds that are subsequently coated with magnetic material via directional or conformal deposition [34]. In FEED, a precursor gas is introduced near the substrate while a focused electron beam from a Scanning Electron Microscope (SEM) traces the desired 3D shape, initiating a local chemical vapor deposition process. This enables the controlled growth of free-standing magnetic nanostructures with high spatial precision and the definition of arbitrary geometries by design. These fully magnetic 3D architectures therefore provide a unique platform to investigate phenomena shaped by curvature, broken symmetries, and structural complexity, and have been widely explored in the context of static magnetization states [8, 35–37].

First investigations into the dynamics of FEED nanostructures have begun to probe the response of such systems to external stimuli, such as in artificial spin-ice clusters [38], and in patterned 3D nanogeometries like nanowires and nano volcanoes, where the geometry itself supports multiple spin-wave resonant modes [39, 40]. However, the dynamics of such complex 3D nanostructures remain challenging to characterize, as most studies rely on frequency-domain techniques like micro-focused Brillouin light scattering (μ -BLS) or indirect inference from hysteresis loops (measured, for example with Magneto-Optic Kerr Effect). In these approaches, spatial resolution is often limited, and the extremely small volume of individual nanostructures pushes measurements to the sensitivity and resolution limits of current instrumentation.

Here, we harness FEED 3D nanoprinting and X-ray microscopy to investigate the magnetization dynamics of coupled magnetic domain walls in magnetic nano double helices with spatially separated strands. By combining advanced 3D nanoprinting together with high spatial and temporal resolution X-ray imaging, we directly probe localized domain wall dynamics at GHz frequencies within these 3D chiral nanoconduits. By varying the excitation frequency, we identify a resonant mode where the domain wall dynamics are locally enhanced. By comparing with micromagnetic simulations, we identify the nature of the experimentally observed resonance to be an out-of-phase oscillatory motion of individual domain walls in each helix strand, indicating that the oscillation is driven by the magnetostatic coupling between domain walls. Simulations further reveal higher frequency modes beyond the experimentally accessible range, including a breathing mode and an intrinsic spin wave mode of the double helix, demonstrating that the system supports a diverse range of dynamic behavior. Finally, we show with simulations that the frequency and character of these modes can be tuned by modifying the helix geometry. By establishing tunable magnetization dynamics in a fully 3D geometry, our results not

only highlight the double helix system as a promising platform for magnetization dynamics, but establish a route to explore dynamic magnetic phenomena in more intricate 3D geometries at the nanoscale [33, 41, 42].

Magnetic double helices offer the possibility to create chiral and topological magnetic nanotextures that arise purely due to the non-trivial geometry. This rich landscape of textures occurs as the structure naturally combines two key aspects: (i) intrastructural interactions including exchange interaction, shape anisotropy and chirality, that promote the formation of axial magnetic domains within the individual helical strands, and (ii) interstructural interactions, i.e. exchange or magnetostatic coupling of the two helical strands (depending on whether the strands are separated or not). The competition between these intra- and inter-structure effects leads to the emergence of non-trivial spin-textures, that depend strongly on the nature of the system. For the case where the strands of the double helix overlap and are exchange coupled, the chiral geometry leads to the formation of chiral domain walls [9], and skyrmion-like textures [10]. When the helical strands are spatially separated, but closely intertwined, the strong magnetostatic interaction between them leads to highly coupled bound domain wall pairs that result in topological textures forming in the magnetic field induction, consisting of vortices in the magnetization and antivortices in free space [43].

These strongly coupled domain walls (referred also as “locked domain walls” or the “locked state”) form naturally following the application of a saturating magnetic field perpendicular to the double helix’s long axis (Figure 1a). Upon removal of the field, the magnetic moments relax into the curvature-preferred direction, forming pairs of head-to-head and tail-to-tail transverse domain walls in neighboring strands. These domain walls initially align with the applied field, as preferred by the curvature-induced chirality of the system [44], forming an “unlocked” domain wall configuration (Figure 1b). In the case of helices with high torsion and low curvature (Section S1), strong magnetostatic interactions between the domain walls overcome the curvature induced Dzyaloshinskii-Moriya interaction (DMI), reorienting the domain walls to form a “locked” state, shown in Figure 1c. Similar pairs of coupled domain walls in 2D systems [45] have previously been observed to exhibit harmonic dynamic oscillations [46, 47]. The double helix nanostructure, therefore, represents an opportunity to realize a nanoscale domain wall harmonic oscillator in three dimensions, where the design of the chiral geometry offers a route to geometrically tune the dynamics.

2 | Experiments

2.1 | Observation of Coupled Domain Wall Dynamics Under Single-Frequency Excitation

To investigate the dynamics of the locked domain walls within the double helices, we first evaluated the magnetostatic interaction energy as function of wall separation. The resulting energy profile exhibits a well-defined potential minimum with an approximately parabolic shape near equilibrium. In this regime, the effective interaction can be described by a quadratic potential, rendering the system formally equivalent to a simple harmonic

oscillator (Section S1). In this case, the dipolar interaction not only pins the domain walls, suppressing free motion along the nanowires, but also provides an effective restoring force [46, 48]. Under these conditions, the oscillatory response within the double helix can be understood as follows: a magnetic field applied along the helix axis displaces the two domain walls in opposite directions (Figure 1d). When this field is modulated, the domain walls oscillate about a central equilibrium position with a phase difference of π (Figure 1e). This allows the dynamics to be described by a simple harmonic oscillator model, yielding a well-defined main resonant oscillatory mode of the domain walls.

To experimentally study such an oscillation, a set of cobalt nano double helices were fabricated making use of the f3ast software for 3D nano-printing [33, 41] (Figure 1f), with the helical radius (75 ± 20 nm), pitch (1800 ± 50 nm) and nanowire thickness (100 ± 15 nm) designed to promote the formation of locked domain walls within the system [43]. To apply the radio frequency (RF) magnetic field along the long axis of the double helix, the structures were fabricated on top of a Cu microwave antenna on an X-ray transparent silicon nitride (Si_3N_4) membrane, such that the long axis of the helix is parallel to the Oersted field of the stripline. A SEM image of a series of cobalt nano helices grown on a Cu stripline is given in Figure 1g (Section S2).

To map the static magnetic configuration, we employed Scanning Transmission X-ray Microscopy (STXM), where the X-ray beam is focused to a spot size of 30 nm and the absorption of the X-rays is acquired as the sample is scanned through the nanofocused beam. Measurements were carried out at the MAXYMUS beamline of the BESSY II electron storage ring operated by the Helmholtz-Zentrum Berlin für Materialien und Energie [49]. The magnetic configuration of the sample was imaged by harnessing X-ray magnetic circular dichroism (XMCD) (Section S3). Specifically, STXM images were acquired using monochromatic X-rays, tuned to the Co L_2 absorption edge at nominal photon energy of 793.65 eV, with right- and left-circular polarization. The resulting XMCD contrast, obtained from the difference between the two polarizations, provides the projection of the magnetization along the X-ray propagation direction $\vec{k}$ (leading to a black/white contrast as indicated in Figure 1c). To probe the axial magnetic domains of the helical strands, the sample was tilted by 30° relative to the X-ray wave vector $\vec{k}$ (Figure 2a).

By applying different magnetic-field initialization protocols, we generated distinct remanent states, as evidenced by static XMCD images, and gained insight into the dynamics of the coupled domain walls by comparing static and dynamic images obtained after each initialization. First, we applied a magnetic field (~ 200 mT) parallel to the long axis of the helices. At remanence, the resulting static XMCD image shows a dominant uniform dark contrast across the structure, indicating a uniform axial magnetization and indicating that the double helix was in a single domain “parallel” configuration (Figure 2b). Next, we applied a magnetic field perpendicular to the long axis of the helix. At remanence (Figure 2c), we observed alternating dark and bright contrast along the double helix, indicating a multidomain state. In the region highlighted by the red arrow, both strands of the helix can be seen to change contrast, consistent with

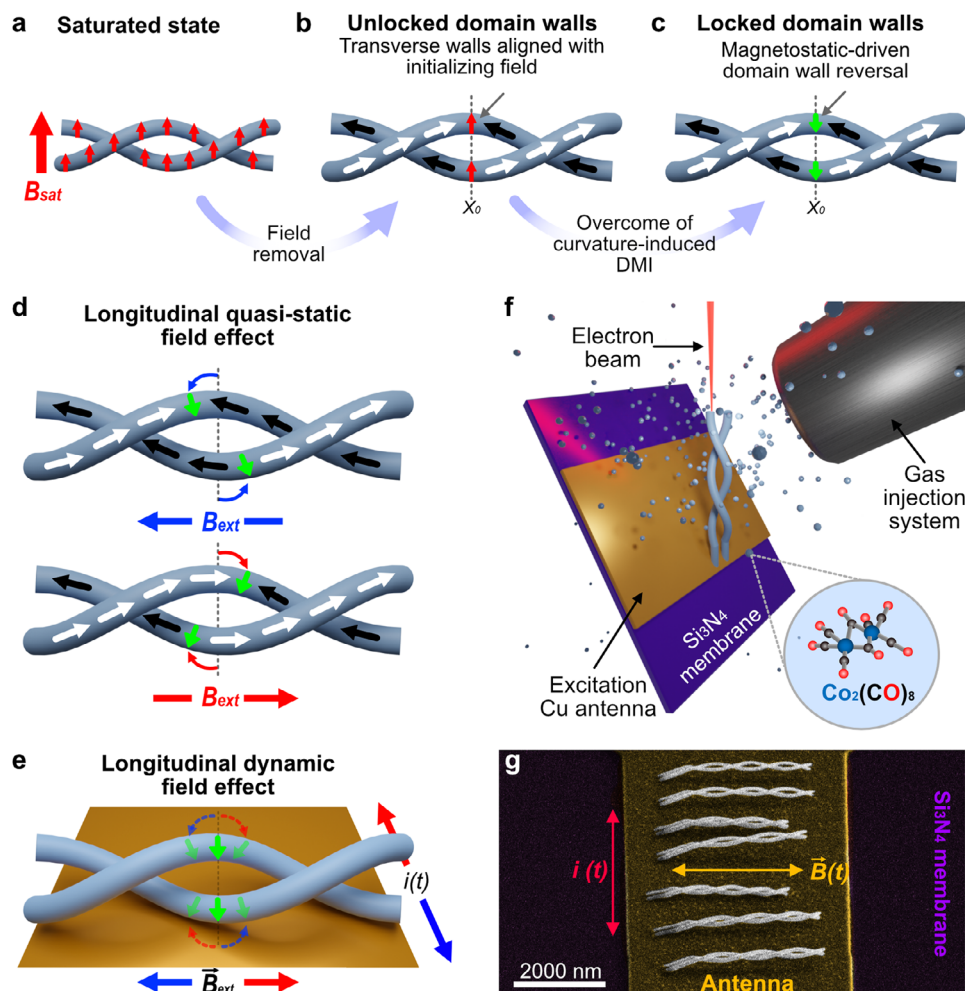


FIGURE 1 | Magnetic nano double-helices: domain wall formation, excitation mechanism, and direct nano printing: a) Domain wall formation in double helices: Saturating field applied perpendicular to the double helix axis. b) Magnetic moments relax into the curvature preferred direction, forming transverse domain wall pairs aligned with the initial field. c) For specific pitch/torsion, the curvature-induced DMI is overcome and the domain walls reverse, yielding highly coupled domain wall pairs. d) The quasi-static response of the coupled domain walls under small unidirectional magnetic fields along the main axis of the helix is shown, with the domain wall in each nanowire propagating in opposite directions with respect to x_0 , as indicated by the colored arrows. e) Expected response of the coupled domain walls under a continuous oscillatory excitation is depicted, where the domain walls oscillate in an antiphase manner with respect to each other in accordance with the external magnetic field. f) Focused electron beam induced deposition (FEBID) schematic for nanoscale 3D printing of a cobalt double nano-helix. g) SEM image featuring the lateral view of the free-standing nano double helices, taken at 40° observation angle. Here, the Cu stripline antenna fabricated on an X-ray transparent membrane acts as the substrate for the nanostructures.

the presence of a head-to-head and tail-to-tail domain wall pair, indicating the successful initialization of the coupled domain wall configuration. A separate single domain wall is also present in the structure; however, it lies outside the scope of this study (for more information see Section S4).

To excite the magnetic configuration, a sinusoidally modulated current was sent through the microwave antenna generating an oscillating RF Oersted field (~ 6.6 mT) parallel to the long axis of the double helices (Section S5). To track the dynamic response of the magnetic configuration, time-resolved STXM was performed (TR-STXM), where the time structure of the synchrotron X-rays is harnessed to probe the dynamic response of the magnetization with sub-100 ps temporal resolution [49] (Figure 2d) (Section S6). TR-STXM measurements of the single domain and coupled domain walls configurations are shown in Figure 2e,f, respectively. When comparing the dynamic images for the two

initialized configurations, we observe a remarkable difference: no significant dynamic signal is observed in the parallel state, whereas a pronounced dynamic signal is observed localized in the region of the multidomain wall configuration. This observation of strong dynamics in the vicinity of the coupled domain walls indicates that the pairs of domain walls can be effectively excited by the longitudinal RF magnetic field, producing a response that is significantly stronger than in regions without domain walls.

To obtain a quantitative representation of the strength of the magnetization dynamics within the structure, a discrete fast Fourier transform (FFT) was applied to the dynamic image stack across the excitation cycle. Here, the FFT magnitude indicates the local strength of the dynamic magnetic response. In the case of the parallel state (Figure 2g), the FFT magnitude is small and uniform across the entire field of view, consistent with the lack of dynamics observed in the dynamic scans. In contrast, the FFT magnitude

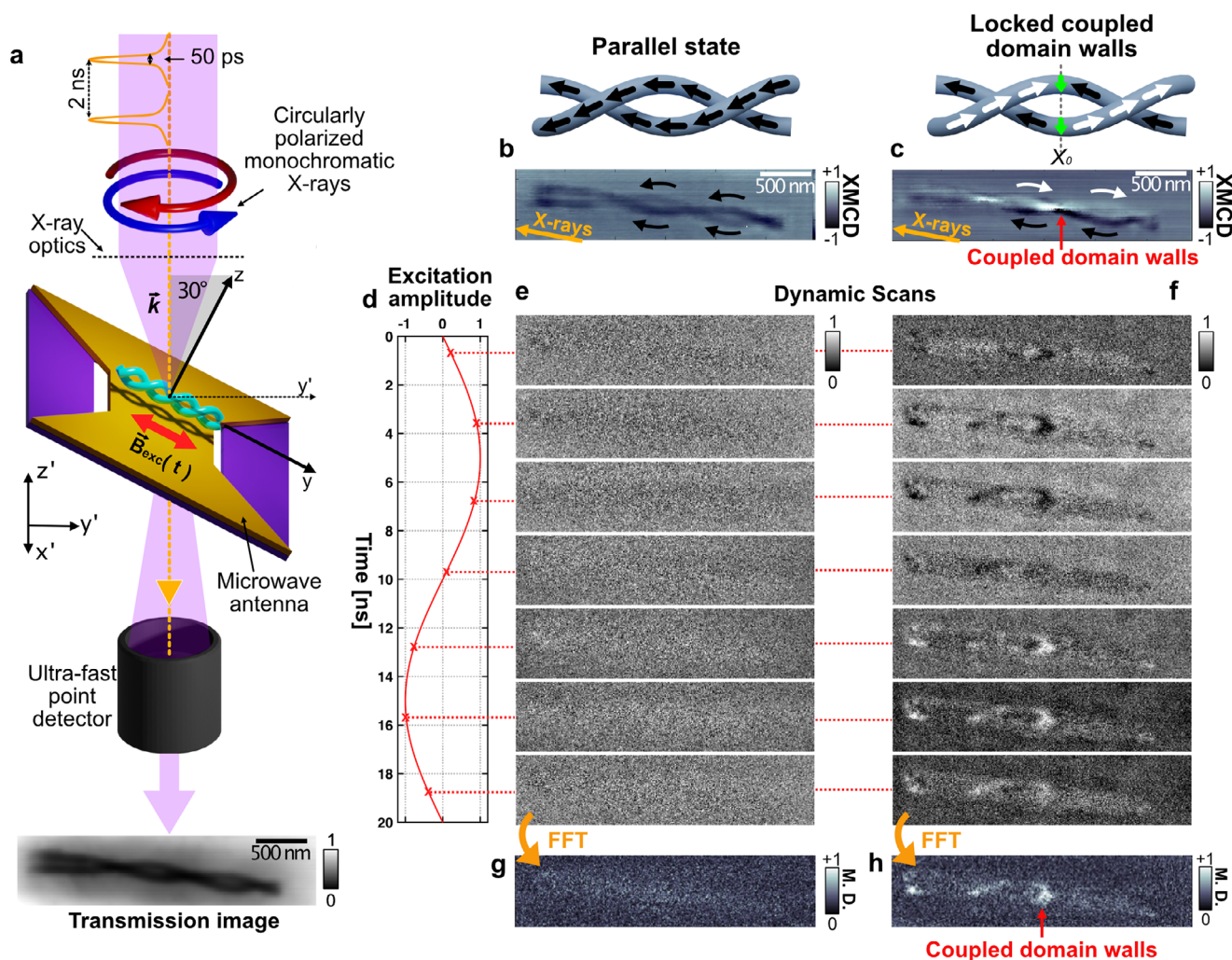


FIGURE 2 | Probing the dynamic response of the possible magnetic configurations in the double-helix system using time-resolved soft X-ray microscopy: a) Schematic of the scanning transmission X-ray microscopy setup used to measure the samples, mounted at 30° to allow visualization of the double helix with nanoscale resolution and axial magnetic sensitivity. b) Static XMCD and schematic corresponding to the parallel single domain configuration. c) Static XMCD and schematic corresponding to the coupled domain walls state. d) Sinusoidal excitation of 1.7 GHz was applied via the microwave antenna, with time-resolved scans across 7 phase channels spaced equidistantly in phase. Illustrative schematic only; the absolute phase with respect to the excitation is not known. e) Dynamic images of the single domain configuration, displaying a uniform variation in the complete field of view across the excitation. f) Dynamic scans of the coupled domain walls, which shows an enhanced response in the positions of the domain walls. g) Normalized magnitude of dynamics (M.D.) of the discrete Fourier transform (FFT) across time of the single domain configuration. The low intensity indicates minimal dynamics in the system. h) Normalized M.D. of the FFT for the coupled domain wall configuration. The brighter areas in the region of the domain walls indicate the presence of dynamics in the region of domain walls.

for the multi domain wall configuration (Figure 2h) exhibits a stronger signal forming a distinct pattern in the region of the coupled domain walls, demonstrating that we were able to probe their dynamics in the 3D FEBID structure experimentally. Such dynamics were observed in repeated experiments, demonstrating that the dynamics could be realized in a reproducible way. Once the excitation was removed, the coupled domain walls remained at their initialized positions, confirming that the domain wall configuration remained stable during and after the excitation. As well as the FFT magnitude, phase information can also be retrieved. While this phase does not provide the absolute phase relative to the excitation, it enables the determination of relative phase shifts and the accurate identification of regions with strong dynamics within the sample for subsequent analysis.

2.2 | Frequency-Dependent Response of Coupled Domain Walls in the 3D Nano Double Helix

Having confirmed that we were able to excite the coupled domain walls and distinguish their dynamics from those of the parallel configuration, we next investigated the nature of these dynamics. Specifically, to determine whether the state could be modelled as that of a simple harmonic oscillator [46, 50], we sought evidence of resonant behavior in the double helix. We measured the magnetization dynamics in the helices for a variety of different excitation frequencies, making sure to maintain the same power of excitation at all frequencies. Dynamic projections were measured, focusing on the region of the double helix containing the pair of coupled domain walls (Figure 3a).

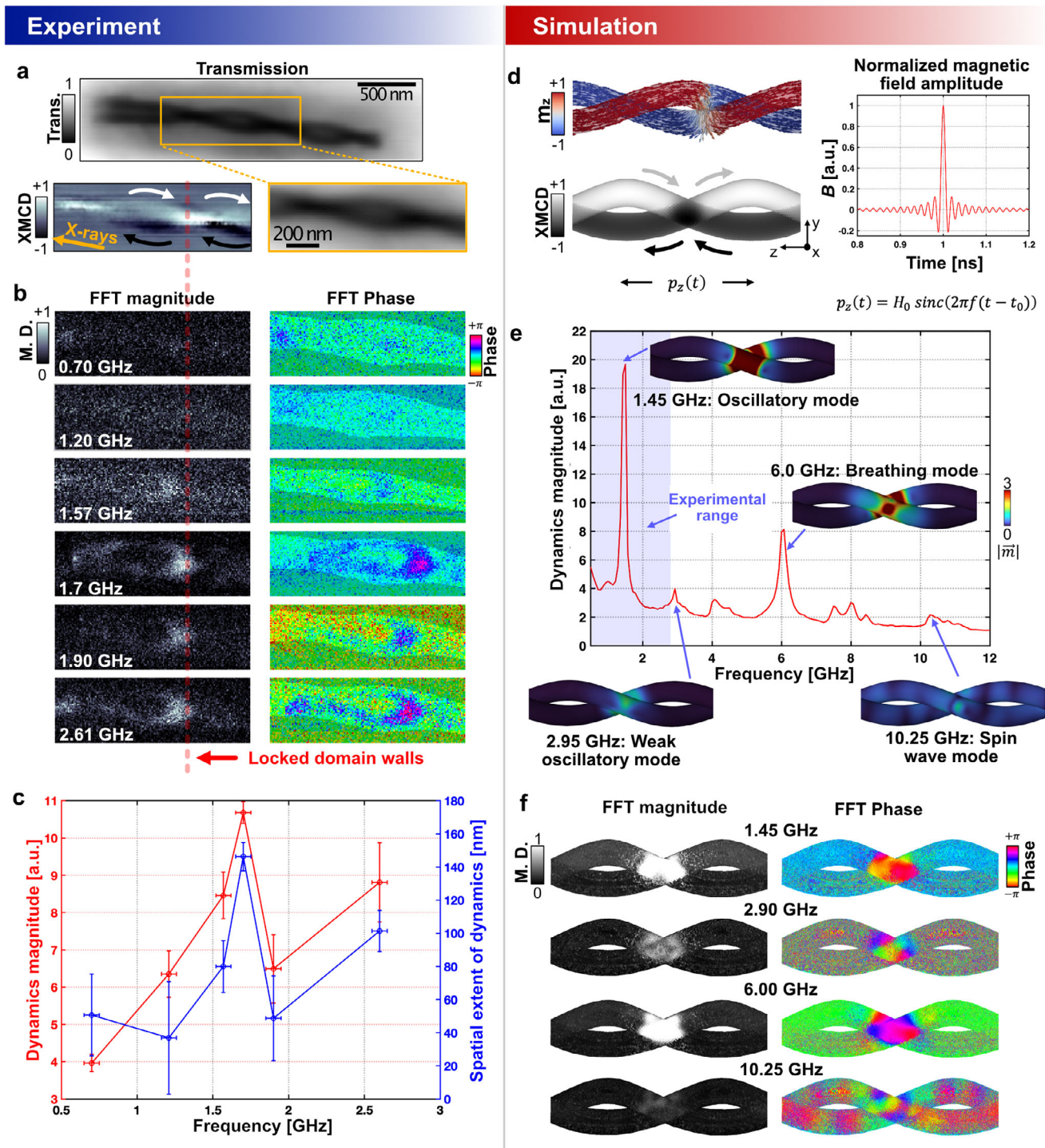


FIGURE 3 | Experimental and simulated frequency dependent behavior of coupled domain walls in the 3D nano double helix: a) Transmission image of the zoomed-in region where the coupled domain walls are located, as confirmed by the correspondent XMCD image. b) FFT magnitude and phase as a function of the excitation frequency, indicating the position of the coupled domain walls. Measurements were performed over a frequency range of 0.7 to 2.61 GHz. M.D. stands for "Dynamics magnitude". c) Dynamics magnitude, associated with the tilting of individual magnetic moments relative to $\vec{k}$, and spatial extent of dynamics, which reflects the overall dynamics of the locked domain walls, as a function of frequency. d) The locked domain wall configuration in the 3D mesh is excited by a sinc pulse magnetic field along the helix's main axis, with simulated XMCD used to validate the experimental response. e) Simulated spectrum from 0 to 12 GHz, with the experimental frequency range and the corresponding resonant mode frequencies highlighted, alongside with the FFT magnitude of the magnetization amplitude $|\vec{m}|$. f) FFT dynamics magnitude and phase of the simulated dynamics allowing comparison with experimental data.

First, we observed that the strong dynamics remained consistently localized in the vicinity of the domain walls across all measured frequencies, as indicated by both magnitude and phase scans in Figure 3b. This localization suggested that the oscillation occurred around an equilibrium position, with the equilibrium domain wall positions remaining largely unchanged regardless of the driving frequency. Second, when we extracted the magnitude of the dynamics in the vicinity of the domain walls and plotted this as a function of frequency (red plot in Figure 3c), we observed a peak at 1.7 GHz, suggesting the presence of a resonant frequency within the measured range. Finally, the spatial extent of the dynamics in the region of the domain walls (blue curve in Figure 3c) also peaked at 1.7 GHz, again indicating the enhancement of dynamics in the system at that particular frequency. Notably, the response also displays an increase in magnitude at higher frequencies: both magnitude and spatial extent increase again near 2.61 GHz, indicating the possibility of another resonance.

3 | Micromagnetic Simulations

3.1 | Resonant Mode Confirmation and Emergence of Higher-Frequency Modes

After having experimentally observed resonant domain wall dynamics in the double helices, we next performed finite element micromagnetic simulations to gain insight into the nature of the dynamics. To interpret the experimental spectra, we used the software *magnum.pi* [51] to simulate a finite-size scaled-down version of the nanostructure to investigate the dynamic response within feasible computational resources. Curvature-induced effects are inherently captured by the explicit simulation of the curved geometry, and thus no DMI terms were introduced explicitly. For comparison, we nevertheless calculated the corresponding effective DMI terms, together with further details on the material parameters, which are provided in Section S7. The locked domain wall state was initialized by applying a magnetic field perpendicular to the helix's long axis and is shown in Figure 3d, along with the simulated XMCD. To excite dynamics at a broad range of frequencies, a spatially homogeneous sinc magnetic field pulse was applied parallel to the long axis of the double helix, with field amplitude $H_0 = 50$ mT and a frequency window of $f = 20$ GHz (Section S8).

The dynamic response of the locked domain wall state is characterized by several resonances, as shown in the simulated frequency spectrum in Figure 3e, with the corresponding spatial distribution of the dynamics shown for the four most unique spin excitations (Section S9). Within the experimentally probed frequency range (up to 2.61 GHz in Figure 3e), a pronounced peak at 1.45 GHz dominates the spectrum. This mode corresponds to the characteristic oscillatory motion of the two locked domain walls, where the individual domain walls move with opposite phase with respect to each other around an equilibrium position, resembling a simple harmonic oscillator (Figure 1e; see Sections S9 and S10). A weaker oscillatory mode appears at 2.9 GHz, consistent with the enhanced response observed near 2.6 GHz in our experiments. When we visualize the FFT magnitude and phase of the simulated dynamic XMCD, the locations and shapes of the enhanced dynamics can be directly compared

with the experimental images. In particular, the lower-frequency dynamics (Figure 3g, shown for $f = 1.45$ GHz) closely resemble the experimental observations at 1.7 GHz in both magnitude and overall spatial pattern. We note that there is a slight difference between the experimental and simulated dynamic projections, which is due to the position of the domain wall (See Section S11). These strong spatial similarities, combined with the closely matched resonant frequencies (1.45 to 1.7 GHz), indicate that the experimentally measured resonant dynamics correspond to the predicted harmonic oscillatory mode of the locked domain walls.

In addition to these experimentally observed oscillatory modes, the simulated dynamic spectrum reveals several higher-frequency resonances that lie outside the experimentally accessible frequency range. We observe a resonance at 6.0 GHz, associated with a breathing motion of the coupled domain wall texture. This mode exhibits maximum intensity at both the inner radius and the outermost part of the helix, indicating a qualitatively different dynamic behavior. Additionally, a mode at 10.25 GHz is attributed to a natural spin wave resonance of the full double helix structure (see Sections S9 and S10), highlighting the double helix potential as a platform for hosting spin waves that interact with non-trivial spin textures.

3.2 | Engineered Magnetization Dynamics Through Geometric Tuning of the Double Helix

Having identified the resonant dynamic modes of the coupled domain wall state within the double helix, we next explored whether the 3D geometry of the double helix can be leveraged to control the dynamic behavior of the magnetization. Rather than establishing one-to-one quantitative relationships between frequency and geometry, our aim is to identify the overall influence of geometry on the modes and the trends. Using the scaled model introduced previously (see Section S12 for more details), we systematically varied the geometrical parameters of the double helix – these include the helical diameter D_{He} , the helix pitch P_{He} , inter-helix distance d_{He} and nanowire diameter D_{nw} – as illustrated in Figure 4a. The scaled-down parameters were chosen such that, upon rescaling to experimental dimensions, they remain within the fabrication capabilities of FEBID [52], ensuring that the resulting trends remain directly relevant to experimentally accessible structures.

We first examined the influence of the helix diameter (Figure 4b), which predominantly affects the magnetostatic coupling between the coupled domain walls. As the helical diameter increases, the resonant frequencies of both the oscillatory and breathing modes decrease. This trend can be understood by considering the role of magnetostatic coupling as the restoring force of the oscillation: larger diameters reduce the coupling between the domain walls, weakening the effective restoring force of the system and thereby lowering the resonant frequency of the coupled oscillator. Conversely, smaller helical diameters strengthen the coupling between the walls, making them more tightly bound and “stiffer”, which results in higher resonant frequencies.

A different behavior was obtained when varying the helix pitch P_{He} (Figure 4c). By varying the double helix pitch, while keeping the inter-helix distance d_{He} constant (and thus the magnetostatic

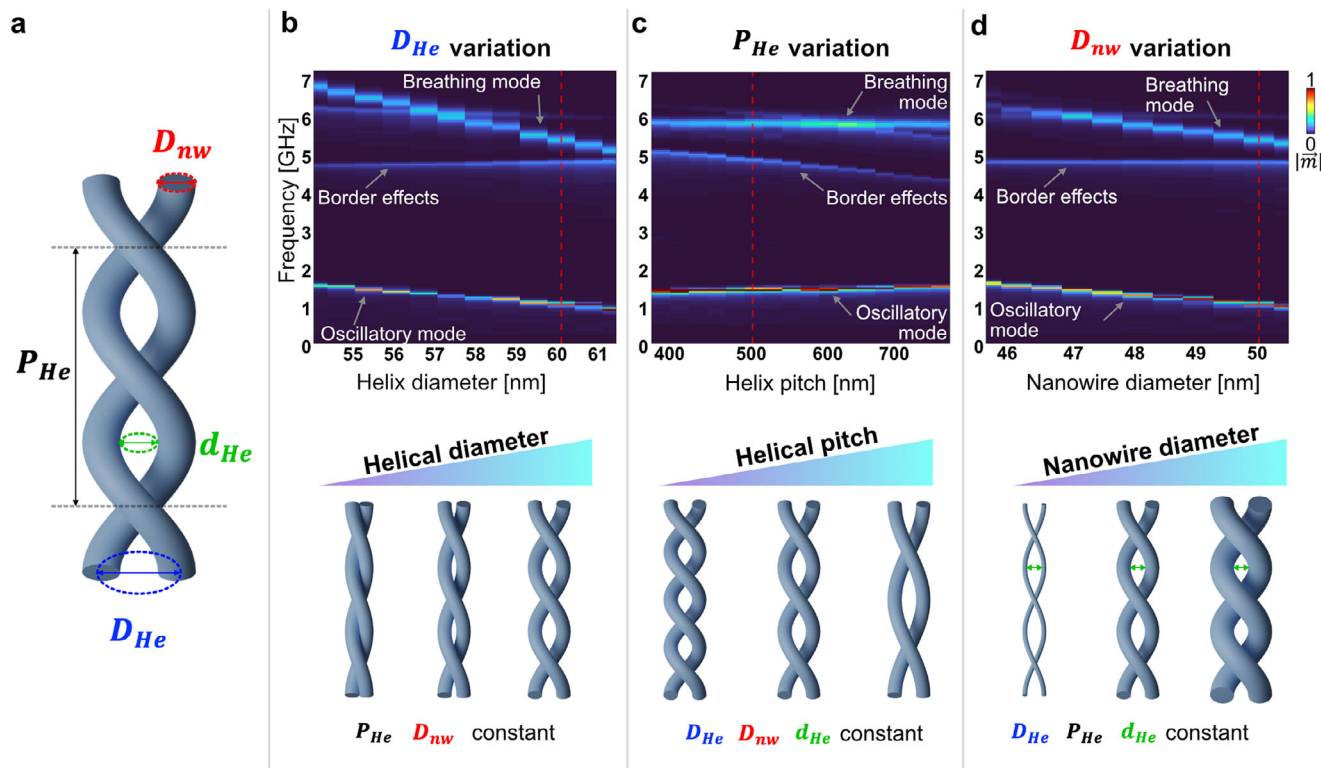


FIGURE 4 | Geometrical tuning of resonant modes of coupled domain walls in the 3D nano double helix: a) Schematic illustrating the geometrical parameters of the scaled-down system used to investigate the control of resonant modes: helical diameter D_{He} , the helix pitch P_{He} , inter-helix distance d_{He} and nanowire diameter D_{nw} . b) Frequency spectra as a function of helical diameter D_{He} , with schematic examples. c) Frequency spectra as a function of helix pitch P_{He} with schematic examples. d) Frequency spectra as a function of nanowire diameter D_{nw} , keeping the inter-helix distance d_{He} constant, schematic examples included.

coupling), we effectively change only the curvature and torsion of the system. In this case, the resonant frequencies of both the oscillatory and breathing modes remain largely unchanged, indicating that the dynamics of the coupled domain walls are not strongly affected by the curvature.

Finally, we considered the influence of the diameter of the nanowires D_{nw} . As D_{nw} increases, keeping the inter-helix spacing constant, the resonant frequencies of both the oscillating and breathing modes decrease. This can be understood again in the context of the magnetostatic interaction: in thicker nanowires, the magnetization tends to curl parallel to the surface to reduce surface charges, forming a domain wall with a more azimuthal configuration (vortex-like domain wall) that weakens the magnetostatic coupling, similar to the effect of larger helix diameters (see Section S13). When we move to thinner nanowires, which exhibit stronger shape anisotropy, the domain walls are narrower with less curling of the magnetization, resulting in stronger inter-domain wall coupling, and higher resonant frequencies.

The effects of helix diameter, pitch, and nanowire thickness on the resonances reveal that the magnetostatic coupling between coupled domain walls is the dominant tuning mechanism. This interaction not only pins the walls, preventing free motion along the nanowires, but also acts as an effective restoring force, allowing precise control over the dynamic response. This allows to confirm an analogy with a simple harmonic oscillator, with a well-defined main resonant oscillation mode of the domain

walls. In this context, the resonant frequency is mainly governed by the nanowire and helical diameter through their effect on the magnetostatic coupling. The harmonic oscillator description can be applied only when this coupling is strong enough to confine the domain walls within a shared potential well, a regime that can be straightforwardly realized using FEBID-fabricated geometries. The helical pitch, while not directly visible in the spectra, indirectly constrains the curvature and torsion required to stabilize the coupled-wall state (see Section S14).

The simulation results presented here are promising and indicate that the resonant frequencies of the double-helix modes can be finely tuned purely through geometric parameters, without the need of external bias currents, voltage-controlled magnetic anisotropy, or modifications of intrinsic material anisotropies. This stands in contrast to established planar nanoresonators based on spin transfer torque effects [53–56] or in resonant domain walls in planar nanowires [57], where frequency tuning typically requires sophisticated electronic circuitry or constrained material engineering.

Geometry-only tuning of resonant frequencies has so far been explored only in a limited number of experimental studies [58–60], highlighting a clear opportunity for further work in this direction. In order to explore the geometric tuning of dynamics in the double helices, a systematic approach is required. On the sample side, this involves fabricating double helices with controlled modulations of the geometry, readily accessible by

FEBID. On the characterization side, TR-STXM operated in the low- α mode of a synchrotron source (X-ray pulses of ~ 15 ps duration) would provide access to the high-frequency regime, while retaining the nanoscale spatial resolution needed to directly confirm the magnetic state. Owing to the discretized nature of this technique, the accessible frequency range would be limited to a set of discrete excitation frequencies [49]. This could be complemented by lab-based techniques such as micro-focused Brillouin light scattering [61], which offer access to a more continuous frequency space at the expense of spatial resolution and direct magnetic state confirmation. For full vectorial, 3D dynamic imaging of the resonances, time-resolved X-ray laminography [62] would be particularly well suited.

While the present study is focused on the fundamentals of the dynamics, the results point to several promising opportunities that arise from the intrinsic differences between the double helix and well-established resonators based on spin-torque nanoo oscillators or domain walls in planar wires. In contrast to planar systems, where coupled domain-wall states typically require multistep preparation involving separate nucleation and field-driven positioning [48], the 3D geometry of the helix intrinsically defines both the nucleation and spatial arrangement of the coupled walls, greatly simplifying state preparation and control. Moreover, the prospect of tuning the resonant frequencies purely through geometry –without relying on external bias or engineered material anisotropies– represents a particularly attractive and conceptually simple control mechanism. Looking ahead, these geometry-driven properties also provide a route toward geometric tunability, for example through integration with strain-engineered substrates, where controlled deformation of the helix could enable continuous adjustment of resonant frequencies, opening opportunities for applications in mechanically reconfigurable 3D magnonics, adaptative radio-frequency components or strain-tunable magnetic sensors.

From a broader perspective, by demonstrating that FEBID-grown 3D nanostructures can host stable and well-defined magnetization dynamics, this work opens new avenues for exploring dynamical effects unique to intricate 3D geometries. Among these opportunities are the investigation of anisotropic domain-wall propagation driven by the geometric chirality [21], as well as access to fast magnetization regimes in which 3D systems benefit from topological protection and reduced susceptibility to Walker breakdown [63, 64]. Overall, these results highlight the double helix as a compelling system for geometry-driven magnetization dynamics and emphasize the potential of 3D magnetic nanoarchitectures beyond planar systems.

4 | Conclusions

In conclusion, we have investigated the fundamentals of the dynamics of magnetic domain walls in a 3D double helix nanostructure, revealing the presence of resonant dynamics that can be tuned via the 3D geometry. Specifically, we have fabricated 3D magnetic nano double helices using FEBID 3D nano printing and directly imaged the dynamic response to an RF magnetic field using time resolved STXM. In this way, we observed the presence of resonant dynamics in the GHz range. With micromagnetic simulations, we identified the measured

resonance as an oscillatory mode where the bound domain walls behave like a simple harmonic oscillator driven by the interhelix magnetostatic coupling. By varying the 3D geometry to modulate the magnetostatic coupling between walls, we show that the resonant dynamics in these nanoarchitectures are tunable, highlighting the double helix as a promising platform for geometrically engineered magnonic devices.

Until recently, studying magnetization dynamics in complex 3D nanoarchitectures has been limited by the difficulty of combining suitable geometries with appropriate materials. Our results show that FEBID nanofabrication allows us to access measurable magnetization dynamics in complex 3D nanostructures. This approach provides a straightforward means to prototype and investigate magnetization dynamics in complex 3D nanoarchitectures. The resonant dynamic response of the coupled domain walls positions them as promising stable and reconfigurable building blocks for future 3D spintronic and magnonic technologies.

Going forward, structural chirality could be harnessed to introduce non-reciprocal effects [21] while networks of interconnected helices may provide a route to tunable collective dynamics in fully 3D environments [65]. Additionally, combining FEBID with additive techniques such as electrodeposition [34] and selective chemical vapor depositions [66] will further expand the design space, enabling hybrid complex 3D heterostructures with tailored magnetization dynamics responses, ranging from magnetic nanotube arrays to superconducting-magnetic [67] heterostructures. Such direct-write approaches provide a pathway toward the integration of complex 3D nanoarchitectures into functional computing platforms.

Author Contributions

Claire Donnelly and Amalio Fernández-Pacheco conceived the project. The striplines for excitation were fabricated and characterized by Simone Finizio. The samples were fabricated by Claire Donnelly and Pamela Morales-Fernández with the support of Amalio Fernández-Pacheco and Markus König. The samples were annealed by Pamela Morales-Fernández. The synchrotron measurements were performed by Pamela Morales-Fernández, Claire Donnelly, Sandra Ruiz-Gómez, and Elina Zhakina, with support from Aurelio Hierro-Rodríguez, Naëmi Leo, Sebastian Wintz, Markus Weigand, and Simone Finizio. Micromagnetic simulations were performed by Iason Konstantinos-Douveas and Claas Abert with the support of Claire Donnelly, Pamela Morales-Fernández, and Dieter Suess. The data analysis was performed by Pamela Morales-Fernández and Claire Donnelly with the support of Amalio Fernández-Pacheco, Claudia Fernández-González, and Luke Alexander Turnbull. The results have been interpreted by Pamela Morales-Fernández, Claire Donnelly, and Amalio Fernández-Pacheco with the support of Iason Konstantinos-Douveas, Claas Abert, and Sandra Ruiz-Gómez. The manuscript was written by Pamela Morales-Fernández and Claire Donnelly with contributions of all authors.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data will be made available in a repository upon publication of this manuscript.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File 1: adma72811-sup-0001-SuppMat.docx.

Supporting File 2: adma72811-sup-0002-VideoS1.mp4.

Supporting File 3: adma72811-sup-0003-VideoS2.mp4.

Supporting file 4: adma72811-sup-0004-VideoS3.mp4.