

Review

Research Progress of Non-Invasive Magnetic Resonance Imaging in Lithium-Ion Battery Detection

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Abstract

Non-invasive magnetic resonance imaging (MRI), as an extension of nuclear magnetic resonance (NMR) technology, enables detailed characterization of lithium-ion batteries (LIBs) in model systems. This review summarizes the fundamental principles of MRI and its applications in liquid/solid electrolytes, electrodes, and limited commercial diagnostics. Key capabilities include quantifying ion diffusion coefficients and mobility numbers in electrolytes, visualizing dendrite growth in lithium metal, and tracking lithium distribution in porous electrodes such as graphite and LiCoO₂. However, spatial and temporal resolution (typically 10–100 μm with acquisition times ranging from minutes to hours) and metal-induced shielding effects severely limit direct imaging in complete commercial batteries. Indirect methods like magnetic field imaging (MFI) show potential for defect detection. Future work should focus on sequence optimization and multimodal fusion, while emphasizing MRI's primary role in fundamental research rather than conventional industrial testing.

Keywords: magnetic resonance imaging; lithium-ion batteries; non-destructive evaluation; electrochemical dynamics; performance enhancement; defect identification

1. Introduction

Lithium-ion batteries (LIBs) are the core technology for modern energy storage, powering portable electronics, electric vehicles (EVs), and renewable energy grids. Commercial batteries currently achieve specific energy densities of 250–300 Wh kg^{−1} [1]. However, to meet the demands of long-range EVs (>500 km per charge) and rapid charging (<15 min to 80% charge), next-generation LIBs must achieve >400 Wh kg^{−1} energy density while maintaining >1000 cycles and enhanced safety. These targets are constrained by internal degradation processes such as ion segregation, solid electrolyte interphase (SEI) growth, and lithium dendrite formation, which typically cause high-energy-density batteries to lose 2%–5% of their capacity every 100 cycles [2–5]. Early in situ NMR studies first demonstrated the ability to quantify metallic lithium microstructures (mossy and dendritic) formed on the anode surface during cycling, providing the foundation for later MRI-based morphology analysis [6]. However, metallic components within complete batteries—such as current collectors and electrode layers—cause significant signal attenuation and artifacts due to the skin effect and differences in magnetic susceptibility. This limitation restricts MRI primarily to simplified model systems.



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Non-invasive magnetic resonance imaging (MRI) technology based on nuclear magnetic resonance (NMR) principles provides unique insights for operando characterization of LIBs without compromising battery integrity [7]. For instance, ^7Li MRI combined with pulsed field gradient NMR (PFG-NMR) has quantitatively determined lithium ion diffusion coefficients (typically 10^{-10} – 10^{-9} $\text{m}^2 \text{s}^{-1}$) and transfer numbers (commonly 0.3–0.4 in carbonate electrolytes), directly visualizing concentration polarization gradients under current polarization (reaching 100 mM mm^{-1}) [8]. This enables precise identification of performance bottlenecks, such as interfacial degradation and dendrite nucleation, thereby guiding material optimization.

Despite the expanding application of MRI/NMR in LIB diagnostics, existing reviews often lack systematic integration. Some offer broad overviews of NMR methods, while others narrowly focus on specific subfields (such as electrolyte dynamics) without addressing quantitative limitations or distinguishing NMR spectroscopy of extracted electrolytes from true MRI spatial imaging of operating cells [9].

The research and application of MRI technology in the field of lithium-ion batteries have undergone a remarkable evolution over the past two decades, progressing from proof-of-concept to in-depth diagnostics [10]. This developmental trajectory is closely intertwined with technological advancements. During the early phase (approximately the 2000s), research primarily utilized highly sensitive ^1H MRI, focusing on observing electrolyte filling and distribution at the macroscopic scale, thereby validating the feasibility of non-invasive monitoring. Subsequently, during the rapid development phase (2010s), the maturation of dedicated ^7Li probes and sequences enabled researchers to directly visualize core processes within operating batteries [11]. These included lithium ion concentration gradients, preliminary morphologies of lithium metal deposition, and ion diffusion within porous electrodes. This marked MRI's transformation from an "observer" to a "quantitative analytical tool." In recent years, the field's focus has shifted toward overcoming imaging bottlenecks in achieving higher spatio-temporal resolution and capturing complex systems [12,13]. This advancement stems from synergistic breakthroughs in three key areas: the application of ultra-high-field magnets significantly enhances signal-to-noise ratio and sensitivity; the integration of ultrafast imaging sequences with advanced reconstruction algorithms has enabled the capture of internal battery dynamics (e.g., dendrite growth, ion migration during rapid charge/discharge); at the same time, these advances have improved the experimental relevance of MRI-derived methods to commercial-format cells and broadened their diagnostic scope, although substantial barriers still prevent routine industrial deployment [14]. Against this backdrop of the latest technological evolution, this review systematically organizes and critically evaluates the comprehensive landscape, existing challenges, and future opportunities of MRI in revealing intrinsic battery mechanisms and enhancing engineering application performance [14]. Very recently, Lin et al. provided a comprehensive overview of MRI principles and applications in LIBs [15]. Building upon this work, the present review further focuses on non-invasive MRI for commercial battery diagnostics, incorporating the latest 2024–2025 operando and 3D MR microscopy studies.

Different from prior reviews that mainly summarize MRI principles and representative applications across electrolytes, electrodes, and full cells, the present review places particular emphasis on the translational gap between model-system MRI studies and commercial-cell-relevant diagnostics. Specifically, this review contributes in three aspects. First, it separates direct nucleus-resolved MRI of simplified electrochemical systems from indirect magnetic-field-based methods applied to commercial-format cells, thereby clarifying the different physical observables, diagnostic capabilities, and interpretation limits of these approaches. Second, it re-examines macro-scale techniques such as inside-out MRI and magnetic field imaging from the perspective of industrial relevance, including

defect localization, current heterogeneity assessment, and compatibility with packaged cells. Third, rather than treating commercial diagnostics as a straightforward extension of laboratory MRI, this review critically discusses why metal shielding, inverse-problem ambiguity, cost, and throughput jointly constrain industrial translation. In this sense, the unique value of this review lies not only in updating recent MRI studies, but also in providing a critical framework for assessing when MRI-derived methods are scientifically informative, when they are engineeringly realistic, and when complementary techniques remain necessary.

This review critically addresses these gaps through a structured “principles-applications-bottlenecks-frontiers” framework. Detailed physical principles of NMR/MRI are presented in Section 2, followed by their applications in LIB characterization, bottlenecks, and future directions [16–20] (Figure 1).

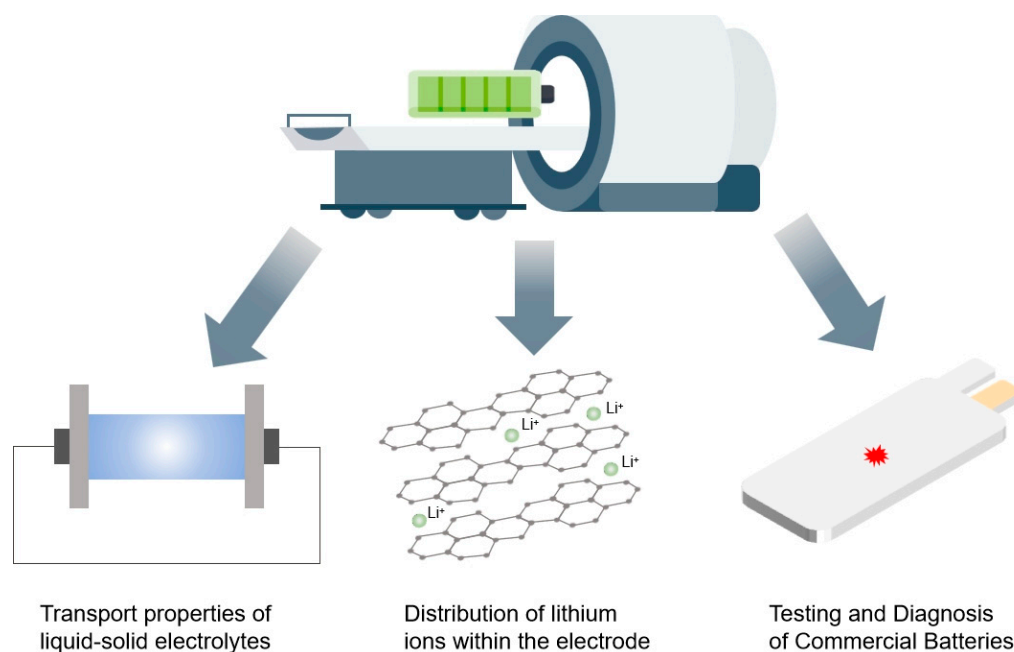


Figure 1. Application of MRI Technology in LIBs: A Summary Focusing on Fundamental Understanding of Model Systems and Limitations in Commercial Battery Packs [15].

2. Principle of Magnetic Resonance Imaging Technology

2.1. The Basic Principles of Nuclear Magnetic Resonance

Building on the foundational principles outlined above, Section 2 examines the physical mechanisms underpinning MRI in LIB systems, with emphasis on limitations imposed by low ^7Li sensitivity and conductive artifacts, as evidenced by recent operando studies. Understanding the fundamental physics of NMR and MRI is crucial for evaluating their application value in LIB diagnostics. Recent advances in MRI hardware and sequences have been systematically summarized by Lin et al. [15], highlighting the critical role of ultra-high-field magnets and ultrafast imaging for battery applications. These principles not only govern signal generation and spatial encoding but also impose inherent limitations—such as low sensitivity to ^7Li and rapid signal decay in the solid phase—that profoundly affect the spatiotemporal resolution and quantitative accuracy of in situ studies. Unlike general MRI applications, LIB systems present unique challenges due to conductive components, multiphase environments, and rapid electrochemical dynamics. This section critically examines these principles within the LIB context, highlighting quantitative bottlenecks reported in the literature and identifying critical gaps—such as the lack of robust correlation models

between relaxation parameters and degradation mechanisms—to guide future progress toward industrial translation [21].

As early as 1924, Pauli predicted that certain atomic nuclei have the properties of spin and magnetic moments, and that they can split energy levels in a magnetic field [22]. In 1946, American scientists Bloch and Purcell respectively found that electromagnetic waves in the radio frequency (RF) region can interact with magnetic nuclei (or magnetic nuclei or spin nuclei) exposed to strong magnetic fields, causing magnetic nuclei to have a resonance transition of nuclear spin levels in the external magnetic field [23,24]. They call the absorption of RF radiation by this atom NMR, and the spectrum produced is called the NMR spectrum.

The principle of NMR is mainly a physical phenomenon in which low-energy electromagnetic waves with frequencies above 60 megahertz (wave lengths at the nanometer level) interact with the nucleus of matter [25].

The foundational work on solid-state NMR of cathode materials for lithium-ion batteries was comprehensively reviewed by Grey and Dupré, establishing the framework for interpreting paramagnetic shifts and local structure in layered oxides and spinels [26].

Most atomic nuclei possess non-zero spins, which are characterized by their spin quantum number I . Such nuclei exhibit intrinsic magnetic moments, with examples including ^1H , ^7Li , ^{13}C , and ^{19}F , among others. When these nuclei are placed in a static magnetic field denoted as B_0 , they undergo spin polarization. Specifically, nuclear spins process around the field at a defined frequency—a motion referred to as “Larmor precession” (Figure 2)—which can be described by the following equation.

$$\omega_0 = \gamma B_0 \quad (1)$$

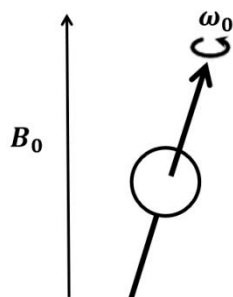


Figure 2. Larmor precession and relaxation processes in NMR. In lithium-ion batteries, the low gyromagnetic ratio of ^7Li and the short solid-state T_2 pose significant sensitivity challenges, resulting in reduced signal-to-noise ratios and extended acquisition times [15].

Among these, ω_0 is the precession frequency, and γ is the gyromagnetic ratio, which is an intrinsic property of the atomic nucleus.

The gyromagnetic ratio (γ) is nucleus-specific; particularly for ^7Li at the core of LIBs, its γ value is only about 16% of ^1H , resulting in a signal-to-noise ratio (SNR) reduction of approximately 4-fold at the same field strength. This fundamentally prolongs battery MRI acquisition times, typically requiring several hours to accumulate sufficient ^7Li signal [27–29].

Nuclei in different chemical environments exhibit different precession frequencies due to the “shielding effect” of surrounding electrons, allowing NMR experiments to distinguish nuclei in different local chemical environments. In the non-equilibrium state, the magnetization vector deviates from the z axis due to the disturbance of the pulse, causing the longitudinal component (M_Z) to decrease and the transverse component (M_{XY}) to increase [30]. When the system is no longer disturbed, it will spontaneously return to

equilibrium, M_Z spontaneously recovers, and M_{XY} naturally disappears. The recovery process of M_Z is called longitudinal relaxation, and the recovery process of M_{XY} is called transverse relaxation.

$$M_Z = M_0 \left(1 - e^{-\frac{t}{T_1}} \right) \quad (2)$$

$$M_{XY} = M_0 e^{-\frac{t}{T_2}} \quad (3)$$

T_1 and T_2 denote the longitudinal and transverse relaxation times, respectively.

In LIBs, solid-phase components (such as electrode active materials and solid-state electrolytes) typically exhibit extremely short T_2 relaxation times (<1 ms), causing signals to decay rapidly before the spatial encoding gradient is fully applied. This severely limits the resolution of microstructural features such as cracks or grain boundaries. Studies indicate that metallic lithium deposits exhibit a distinctive Knight shift (~270 ppm) distinguishable from embedded lithium species, enabling chemical species identification during operational in situ imaging [6].

To overcome these limitations rooted in physics, research frontiers are advancing along several complementary paths. To address the sensitivity challenge, the development of dedicated ultra-high field (>7 T) MRI systems is crucial. Increasing the main magnetic field strength (B_0) not only boosts the SNR proportionally but also can effectively shorten T_1 , allowing for faster pulse repetition and accelerated imaging [31]. Confronting the challenge of rapid signal decay in solids, the development of ultrafast and robust pulse sequences is paramount. Techniques such as zero echo time or single-point imaging can capture signals from species with very short T_2 . Integrating solid-state NMR methodologies like magic-angle spinning with imaging sequences offers the potential to average anisotropic interactions, thereby significantly improving resolution for solids [32]. Concurrently, developing indirect detection strategies and chemical exchange saturation transfer techniques that target high- γ nuclei like ^1H or ^{19}F provides an alternative pathway to probe environments or processes involving low- γ nuclei like lithium.

2.2. Spatial Resolution Generation of MRI

Building upon these fundamental interactions, spatial coding transforms chemical sensitivity into imaging capability. However, in LIBs, it introduces additional constraints due to material heterogeneity and conductivity. Achieving the micrometer-scale resolution required for resolving dendrites or ionic gradients necessitates strong gradients, which exacerbate artifacts within conductive battery structures. NMR spectroscopy distinguishes nuclear spins by leveraging local chemical environment effects (e.g., electron density variations modulating shielding and resonance frequencies). In contrast, MRI extends this principle by introducing magnetic gradient coils to impose spatial encoding on nuclear spins, enabling anatomical resolution. These coils generate linear magnetic field gradients along all three spatial dimensions, creating a position-dependent magnetic field distribution. From the Larmor relation ($\omega = \gamma B$), a nucleus' resonance frequency scales with the local magnetic field strength B . For identical nuclear species, resonance frequency differences in MRI arise from two sources: (1) intrinsic chemical shifts (reflecting electron density/bonding environments, central to NMR) and (2) extrinsic spatial variations induced by gradient fields. In traditional MRI, chemical shift-driven frequency differences are often treated as image artifacts [33], as spatial resolution (not chemical specificity) is prioritized; thus, spatial encoding becomes the dominant mechanism for mapping nuclear spin densities to discrete voxels.

A canonical multi-slice spin-echo MRI pulse sequence combines a spin-echo module with three orthogonal gradient pulses, each serving a specialized role: the slice-selective gradient G_s defines the imaging plane by exciting spins within a specific layer; the frequency-

encoding gradient G_f encodes horizontal/vertical positions via resonance frequency differences; and the phase-encoding gradient G_p encodes positions through precession-induced phase shifts. Collectively, these gradients enable unambiguous spatial encoding of nuclear spin densities, distinguishing individual voxels. Neglecting relaxation effects, the MR signal $S(k, x, y)$ from a voxel is governed by spin density $\rho(x, y)$ and gradient-induced phase $G(x, y)$, expressed as $S(k, x, y) \propto \rho(x, y)$. This framework illustrates how gradient coils transform NMR's chemical sensitivity into MRI's spatial resolution—a cornerstone of modern biomedical imaging.

$$S(k, x, y) = k\rho(x, y, z) \exp(i\omega(x, y, z)t + \varphi(x, y, z)) \quad (4)$$

Here, $\rho(x, y, z)$ denotes the nuclear spin density within a voxel, k represents a proportionality constant relating this spin density to the MR signal intensity, $\omega(x, y, z)$ specifies the statistically averaged Larmor precession frequency of atomic nuclei within that voxel, and $\varphi(x, y, z)$ describes the phase of nuclear spin precession. While phase effects were often simplified or overlooked in preliminary discussions, they play a critical role in MRI spatial encoding [34]. By jointly leveraging differences in both precession frequency and phase, MRI achieves unambiguous differentiation of nuclear spins within individual voxels across three-dimensional space—a capability foundational to resolving anatomical structures at the microscopic level.

MRI spatial encoding is achieved through three steps (Figure 3): Slice selection selectively excites a thin slice by applying gradient fields in specific directions in conjunction with radiofrequency pulses. Within the selected slice, frequency encoding linearly correlates spatial position with resonance frequency by applying gradient fields during signal readout. Phase encoding assigns unique phase information to each spatial position by applying a series of gradient pulses with increasing intensity. Signals acquired through these three encoding steps are processed via Fourier transform to reconstruct two-dimensional or three-dimensional images.

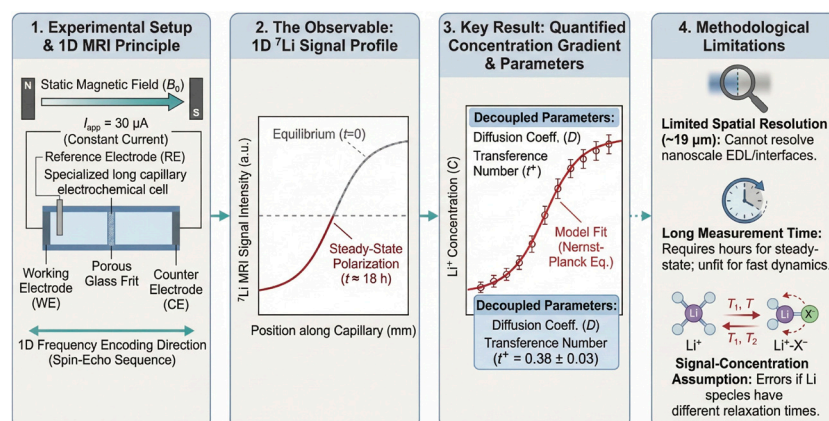


Figure 3. In situ ^7Li MRI of Li^+ concentration gradients in liquid electrolytes.

In battery applications, the high gradient switching rates required to achieve micrometer-scale resolution (10–100 μm) induce strong eddy currents in conductive components (e.g., Al/Cu current collectors). This leads to distortion of the main magnetic field B_0 and dynamic image artifacts, reducing actual resolution by up to 50%. Quantitative studies report that phase errors caused by dynamic field distortion are equivalent to several pixels, complicating ion mapping.

Frequency encoding spatial resolution is fundamentally governed by the transverse relaxation time T_2^* of the free induction decay (FID) signal. In the context of NMR spectroscopy, the FWHM of spectral peaks follows $FWHM \propto 1/T_2^*$: shorter T_2^* values induce

significant peak broadening, which complicates the differentiation of signals originating from spatially proximate atomic nuclei [35]. This broadening directly limits the achievable resolution in frequency encoding workflows.

High-strength frequency-encoding gradients (G_f) introduce a critical trade-off: while they amplify static magnetic field inhomogeneities to accelerate spin dephasing and signal decay (theoretically increasing frequency resolution ($\Delta\omega_k$), resolution enhancement is constrained by coupled effects of field distortions, eddy currents, and intrinsic tissue relaxation. Notably, even ultra-strong gradients cannot overcome the complexity of these interacting factors. For a given sample, the upper bound of frequency encoding resolution is ultimately dictated by the intrinsic physical properties of the material (e.g., molecular mobility, magnetic susceptibility contrasts) [36].

Following slice selection, frequency encoding resolves one spatial dimension by leveraging position-dependent Larmor frequencies, which are subsequently decoded via Fourier transformation. However, extending this approach to the second spatial dimension is infeasible—unlike the first dimension, the frequency distribution across the remaining axis cannot be predetermined for Fourier-based reconstruction. To address this gap in the spatial encoding framework, phase encoding is introduced as a complementary strategy.

Phase encoding assigns unique phase shifts to spatial positions through incrementally varied gradient pulses, enabling reconstruction via Fourier transformation while preserving chemical shift information. This supports techniques such as chemical shift imaging (CSI). In battery applications, the strong gradients required for 10–100 μm resolution induce eddy currents in metallic components, causing up to 50% resolution loss and necessitating specialized sequence optimization [37].

The spatial resolution Δy and field of view FOV_y are given by:

$$\Delta y = \frac{1}{2\gamma G_{p\max} \tau} \quad (5)$$

$$FOV = N_p \Delta y \quad (6)$$

A defining attribute of phase encoding is its decoupling from instantaneous precession frequencies: unlike frequency encoding, it modulates spin phase without altering Larmor frequencies during acquisition. This preserves frequency variations arising from chemical environments, enabling the acquisition of spatially resolved NMR spectra—a technique termed CSI. By retaining both spatial and chemical contrast, CSI facilitates applications ranging from metabolic profiling in medical imaging to molecular structure analysis in chemical research [5], underscoring phase encoding's unique role in hybrid spatial-chemical MRI workflows.

The concept of k-space is fundamental to understanding MRI acceleration strategies. The central region of k-space encodes low spatial frequencies (image contrast and structure), while peripheral regions encode high spatial frequencies (edge sharpness). This property enables accelerated imaging through techniques such as compressed sensing, which leverages k-space sparsity to reconstruct high-fidelity images from undersampled data. In battery MRI, compressed sensing has achieved 5–10-fold acceleration, enabling near-real-time monitoring of processes such as lithium deposition [7] (Figure 4).

The signal-to-noise ratio of an MRI system is proportional to the main magnetic field strength B_0 , while spatial encoding capability depends on the strength and switching rate of the gradient coils.

The application of spatial encoding gradients in LIB faces significant practical challenges. Induced eddy currents in metallic current collectors and interfacial magnetic susceptibility contrast cause field distortion, reducing resolution by up to 50% and in-

roducing difficult-to-correct artifacts. Quantitative analysis further reveals phase errors spanning multiple voxels, complicating the accurate mapping of ion transport or current heterogeneity. Although compressed sensing and deep learning reconstructions achieved 5–10-fold acceleration in proof-of-concept studies, systematic validation under commercial battery geometries and operational conditions remains scarce in the literature. This highlights a critical gap: the absence of standardized protocols for artifact mitigation and quantitative inversion currently hinders translation from laboratory demonstrations to industrial real-time diagnostics. Future progress requires hardware–algorithm co-design tailored to battery-specific constraints.

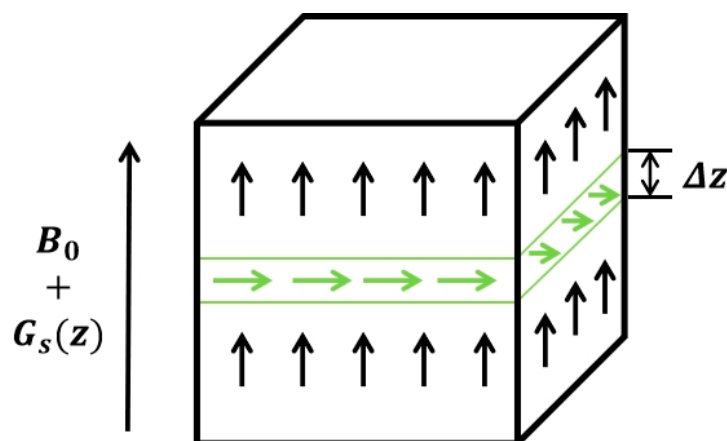


Figure 4. Slice selection in spatial encoding for MRI. In conductive cell environments, gradient-induced eddy currents cause severe field distortion, limiting practical resolution and necessitating specialized sequence optimization [15].

These physical considerations define the main acquisition and encoding constraints discussed in the following application sections [5].

3. Application of MRI in Lithium-Ion Battery Detection

3.1. Micro-Scale Applications: Intrinsic Properties of Electrolytes and Electrode Materials and Interfacial Processes

3.1.1. Transport Properties and Ionic Distribution of Liquid Electrolytes

The transport properties and ionic distribution of liquid electrolytes play a pivotal role in determining the performance of LIBs. Suboptimal ionic transport in electrolytes poses a critical limitation on the fast-charging capabilities of LIBs, manifested as ohmic and concentration polarization under high-current operation [7]. This necessitates accurate evaluation and monitoring of lithium-ion transport capacity in electrolytes. These studies are typically performed in simplified model electrochemical cells to avoid metal-induced artifacts.

Lithium-ion transport mechanisms in electrolytes are governed by two distinct processes: diffusion driven by concentration gradients and migration induced by electric field forces [38]. The battery's operational efficiency and cycle life have been found to be significantly influenced by the relative contributions of these transport mechanisms. Critical transport parameters requiring precise characterization include ionic conductivity (σ), diffusion coefficient (D), and transference number (t), which collectively determine the electrolyte's electrochemical performance (e.g., Romanenko et al.) [39]. The PFG-NMR technique enables precise determination of ionic diffusion coefficients by directly measuring self-diffusion processes [40]. Conversely, lithium transference numbers are typically evaluated through DC polarization measurements, though their accuracy remains questionable due to parasitic reactions, ion pair formation, and questionable assumptions regarding dilute solution conditions [41]. MRI has emerged as a powerful tool for spatially

resolving lithium-ion (Li^+) distributions within operational electrochemical cells under polarization conditions.

These applications demonstrate MRI's ability to quantify ion transport and microstructural evolution. However, persistent challenges in resolution and acquisition time are discussed in Section 4, alongside emerging solutions [42–45].

Building on these foundational 1D MRI studies, subsequent work by Romanenko et al. integrated ^7Li MRI with PFG-NMR to achieve spatially resolved diffusion coefficients, revealing the concentration-dependent nature of ionic transport parameters near electrode interfaces [46] (Figure 5).

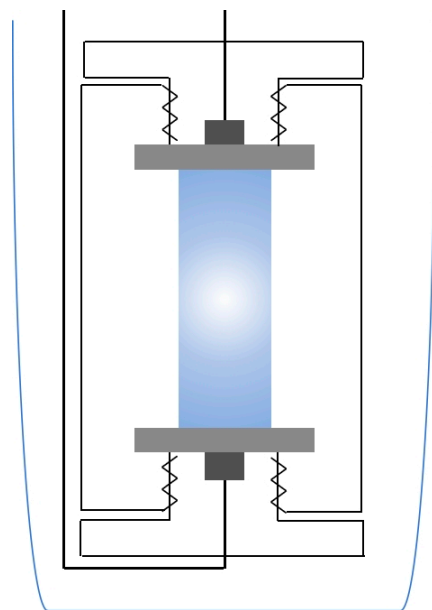


Figure 5. Operando ^7Li MRI in a lithium metal symmetric cell.

For liquid-electrolyte studies, the main limitations are application-specific rather than generic. Current spatial resolution remains insufficient for resolving nanoscale double-layer structure or early SEI evolution, acquisition times are still too long for many fast transient processes, and quantitative concentration mapping can be biased when multiple lithium environments with different relaxation behavior contribute to the measured ^7Li signal.

Several strategies have been adopted in the literature to reduce this ambiguity. One approach is calibration against standards or reference electrolytes with known lithium concentration under matched sequence conditions. A second approach is to combine MRI with complementary techniques such as PFG-NMR, spectroscopy, or electrochemical modeling, so that concentration profiles are constrained by independently measured transport parameters. A third approach is to perform relaxation-aware quantification, for example by using multi-echo acquisition, T_1/T_2 correction, or spectral decomposition to separate lithium environments with different relaxation behavior. Therefore, in battery MRI, signal intensity should be interpreted as a concentration-sensitive observable rather than an intrinsically concentration-equivalent quantity unless explicit calibration and relaxation correction are available.

These limitations do not negate the value of MRI for electrolyte transport studies, but they do confine its strongest contributions to model-cell systems and mechanism-oriented investigations rather than direct simulation of all practical charging conditions.

MRI has enabled visualization of lithium-ion (Li^+) distributions within operational electrochemical cells under applied current, while simultaneously detecting ion concentration gradients induced by polarization conditions. When coupled with mass transport modeling, this technique permits concurrent determination of diffusion coefficients and

ionic transference numbers. The first successful observation of Li^+ distribution in polarized electrolytes was achieved, using one-dimensional spin-echo frequency-encoded MRI. Through systematic collection of concentration gradients at varying current densities and subsequent fitting to established mass transport models, the researchers quantitatively determined Li^+ transference numbers in a specific electrolyte system (1M LiPF_6 in EC/DEC/PMMA) [47–50].

However, the concentration-dependent nature of ionic transport parameters necessitates consideration of spatial heterogeneity under concentration gradients. This phenomenon was systematically investigated by scientist, who developed an integrated ^7Li MRI/PFG-NMR approach to obtain spatially resolved Li^+ diffusion coefficients. Their measurements near electrode interfaces revealed an inverse correlation between local Li^+ concentration and diffusion parameters: regions with elevated Li^+ concentrations (anode-proximal zones) exhibited reduced diffusion coefficients under polarization, consistent with static electrolyte measurements at equivalent concentrations.

The pure-phase encoding imaging methodology has been demonstrated to effectively mitigate susceptibility-induced artifacts, enabling high-resolution visualization of thinner battery configurations through reduced lithium-ion migration paths and accelerated concentration gradient equilibration [51]. MRI analyses have conclusively revealed identical spatial distributions for anions and cations within the electrolyte system, consistent with local charge neutrality principles. The enhanced sensitivity of ^{19}F nuclear detection has been exploited to improve SNR while significantly reducing experimental acquisition times.

A pseudo-3D experimental protocol combining phase-encoded spin-echo chemical shift imaging with diffusion-weighted pulses has been implemented to simultaneously map lithium-ion distributions and spatially resolved diffusion coefficients across entire electrolyte domains [52]. This multimodal approach has further validated the concentration-dependent correlation of diffusion parameters, underscoring the necessity of incorporating concentration-dependent diffusion coefficients and transference numbers in quantitative transport modeling to ensure predictive accuracy. Simultaneous electrochemical impedance spectroscopy and MRI measurements have been demonstrated to correlate integral impedance changes with spatially resolved electrolyte depletion and dendrite growth in the same cell, avoiding sample replacement artifacts [49].

Furthermore, cryogenic investigations have revealed electrolyte salt depletion during cycling processes, with diffusion limitations predominantly localized at the anode-electrolyte interface [53]. The ^{19}F MRI technique has emerged as a powerful diagnostic tool for extracting ion transport parameters in concentrated electrolyte systems and developing refined mass transport models [54]. Frequency-encoded MRI methods provide valuable insights but exhibit susceptibility-induced artifacts near electrode interfaces, necessitating complementary techniques for interfacial studies [55,56].

A critical methodological caveat is that ^7Li MRI signal intensity should not be interpreted as a direct concentration proxy without additional constraints. In principle, the detected signal depends not only on the number density of lithium nuclei, but also on relaxation weighting, acquisition parameters, and the visibility of different lithium environments. More specifically, the observed ^7Li intensity is influenced by T_1 recovery, T_2 or T_2^* decay, flip angle, echo time, repetition time, line broadening, and possible partial signal loss from short- T_2 or low-mobility species. As a result, two regions with similar lithium concentration may produce different signal intensities if their local environments differ in mobility, coordination structure, interfacial interactions, or exchange behavior. This problem becomes especially important in systems where multiple lithium populations coexist, such as bulk electrolyte Li^+ , interfacial Li species, partially immobilized Li near separators or electrode surfaces, and inactive or plated lithium with distinct relaxation characteristics.

3.1.2. Interfacial Evolution and Volume Transport Properties of Solid-State Electrolytes

Solid-state electrolytes (SSEs) present even greater MRI challenges than liquid systems due to their extremely short T_2 relaxation times (<1 ms). Recent studies using 3D ^7Li MRI, have revealed severe lithium heterogeneity and crack propagation in LGPS electrolytes after cycling, attributed to interfacial lithium depletion [57]. This degradation can be mitigated by PEO coating, improving cycling stability by approximately 38%. However, acquiring 3D images still requires up to 70 h, and signals from bulk lithium, grain boundaries, and degradation products overlap significantly, limiting quantitative analysis at the nanoscale [35,36]. SSEs, as critical components of all-solid-state lithium-ion batteries (ASSLIBs), exhibit interfacial stability and bulk transport characteristics that crucially determine cell energy density, rate capability, and cycling longevity. Non-invasive MRI characterization has emerged as a powerful tool for investigating these phenomena, offering unique insights despite facing significant signal attenuation challenges in model solid-state systems [5,37].

Beyond interfacial evolution, the bulk transport properties of SSEs critically influence battery performance. MRI methodologies have been effectively employed to quantify lithium diffusion coefficients and transference numbers in SSEs essential parameters for understanding ionic transport mechanisms under diverse operational conditions. Romanenko demonstrated this capability through a combined ^1D - ^7Li MRI/PFG-NMR approach, achieving spatially resolved measurements of Li^+ diffusion coefficients [7]. Their findings revealed an inverse correlation between Li^+ concentration and diffusivity in polarized systems: anode-proximal regions with elevated Li^+ concentrations exhibited reduced diffusion coefficients, consistent with static electrolyte measurements at equivalent concentrations.

Low-temperature operation presents additional challenges, where restricted ionic mobility in SSEs significantly compromises battery performance. MRI has proven particularly valuable for investigating these cryogenic transport limitations and monitoring electrolyte salt depletion during cycling. Such analyses provide critical insights for developing SSE materials with enhanced temperature resilience.

The non-invasive nature of MRI characterization offers unique advantages for probing both interfacial dynamics and bulk transport phenomena in SSEs. This technique enables fundamental understanding of all-solid-state lithium-ion battery (ASSLIB) behavior across operational extremes, providing crucial scientific foundations for designing next-generation batteries with improved energy density, safety profiles and cycle life [50]. Continuous advancements in MRI resolution and sequence design are anticipated to drive further breakthroughs in ASSLIB technology development.

Notably, MRI applications extend to polymeric SSE systems, which exhibit transport characteristics analogous to liquid electrolytes. Researchers have developed novel experimental protocols where concentration gradient equilibration between adjacent SSE samples with varying initial ionic concentrations is systematically monitored. Through temporal analysis coupled with transport modeling, apparent diffusion coefficients can be precisely determined, enabling quantitative comparison of different SSE formulations [55,56].

Compared with liquid electrolytes, MRI studies of solid-state electrolytes face a more severe combination of relaxation and interpretation constraints. Many inorganic SSEs exhibit extremely short T_2 values, which render standard sequences ineffective and make three-dimensional imaging prohibitively slow. In addition, overlapping ^7Li signals from bulk phases, grain boundaries, and degraded regions complicate quantitative decomposition, while current spatial resolution remains far too coarse to resolve nanoscale interfacial layers. These limitations mean that most MRI studies of SSEs remain qualitative or semi-quantitative and are largely restricted to simplified particle, thin-film, or model-cell systems [51] (Figure 6).

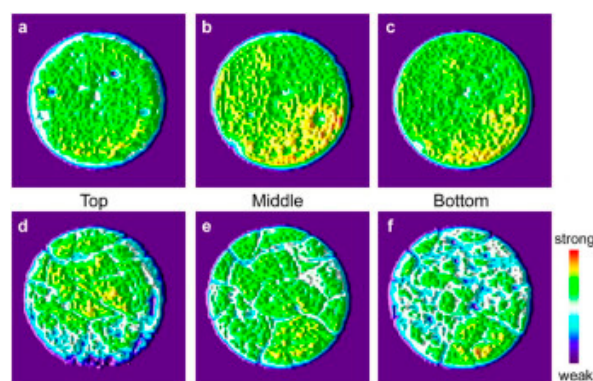


Figure 6. Summary of MRI applications in LIBs across scales, from electrolyte transport to full-cell diagnostics. The images display 2D cross sections of the pristine and the cycled $\text{Li}_{10}\text{GeP}_2\text{S}_{12}$ electrolytes in a symmetric $\text{Li}_{10}\text{GeP}_2\text{S}_{12}/\text{Li}$ cell: (a) top cross section, (b) middle cross section, and (c) bottom cross section of the acquired 3D ^7Li MRI image of the pristine $\text{Li}_{10}\text{GeP}_2\text{S}_{12}$ pellet; (d) top cross section, (e) middle cross section, and (f) bottom cross section of the $\text{Li}_{10}\text{GeP}_2\text{S}_{12}$ pellet after 3 days of electrochemical cycling. The color bar indicating the relative Li signal intensity is shown on the bottom right [15].

3.2. Mesoscale Applications: Visualization of Internal Processes in Laboratory Cells

Dendrite growth on lithium metal anodes is a critical issue leading to battery failure and safety hazards. MRI provides a unique tool for non-invasive, in situ investigation of lithium deposition morphology and chemical evolution [7]. However, during the charge–discharge process, lithium metal tends to grow into mossy or dendritic structures, which can lead to battery overheating, failure, and even fire or explosion.

Multidimensional ^7Li MRI with chemical shift imaging has enabled the first non-invasive characterization of lithium deposition morphology and chemical speciation. This technique correlates spatial location with the chemical environment of lithium, distinguishing bulk lithium from deposited structures [58].

As shown in Figure 7, indirect ^1H MR microscopy of the electrolyte provides clear visualization of the transition from mossy to dendritic structures at Sand's time, as well as the formation of dead lithium and gas evolution [59].

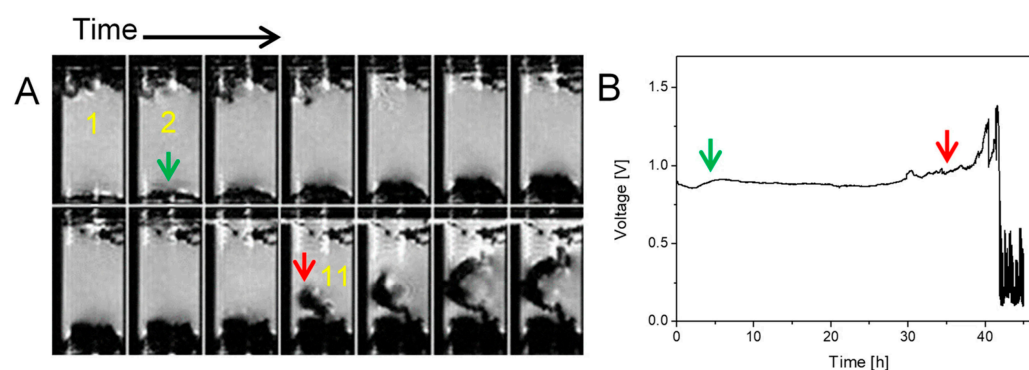


Figure 7. Time-lapse 3D ^1H MR images (electrolyte signal shown as negative for deposited Li) revealing the mossy-to-dendritic transition at Sand's time and formation of dead lithium. (A) Cross-sectional images of a symmetrical Li cell charged at $1.5 \text{ mA}/\text{cm}^2$ (200 min/frame). The numbers above each image indicate the frame number. Pre-existing dendrites at the top cathode result from prior countercurrent charging. Mossy Li grows until 35 h (frame 11), followed by dendritic growth. Red and green arrows indicate the observed and Sand's time-predicted onset of dendrites, respectively. (B) Corresponding voltage profile [59].

The same technique further reveals that dendrite growth is significantly more uniform in series-connected cells than in parallel configurations (Figure 8) [60].

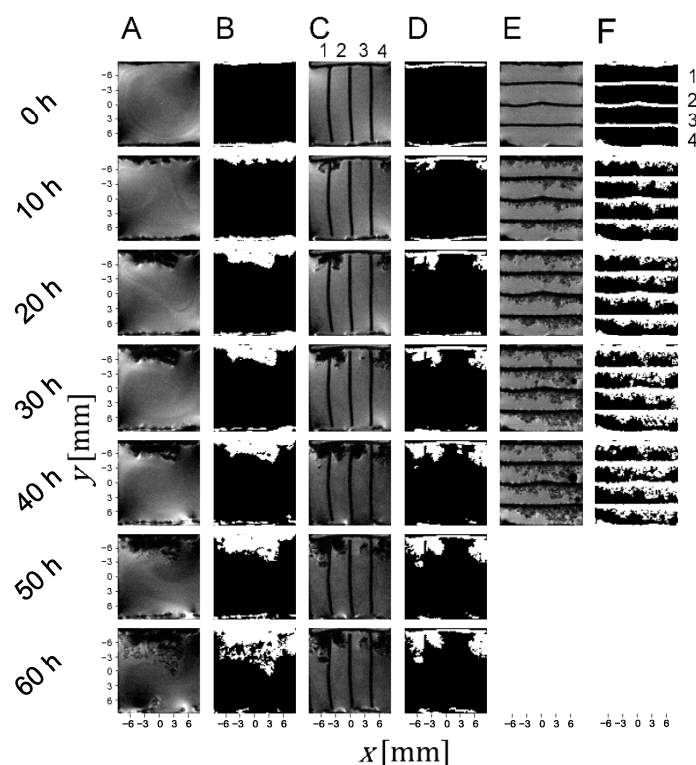


Figure 8. 3D MR microscopy comparison of dendrite growth in single, parallel, and series lithium symmetric cells, confirming theoretical predictions of uneven growth in parallel circuits. (A) MRI scans of a single electrolytic cell capturing dendritic growth over time. (B) Corresponding inverted threshold images of the single cell, highlighting the dendrites and electrodes against the cell background for clarity. (C) MRI scans of electrolytic cells connected in parallel. (D) Corresponding inverted threshold images of the parallel cells. (E) MRI scans of electrolytic cells connected in series. (F) Corresponding inverted threshold images of the series cells. The numbers (1–4) next to the cells in parallel and in series indicate the specific cell indices [60].

The study yielded revealing findings: two-dimensional MRI images demonstrated a significant enhancement of lithium metal signals on the electrode surface after charging, attributed to the formation of “mossy” or dendritic lithium with a larger specific surface area [59–61]. This visually confirmed the microstructural evolution of deposited lithium. More importantly, chemical shift dimension analysis revealed a key mechanism: the deposited lithium signal exhibited broadening and a shift toward lower fields compared to the resonance peak (~ 274 ppm) of bulk metallic lithium. This phenomenon was interpreted as a change in the growth direction of certain lithium metal microstructures (e.g., dendrites) relative to the main magnetic field, thereby altering their local magnetic susceptibility shielding effect. This finding provides direct evidence for identifying dendrite orientation from an NMR perspective [62]. The application of this technique is constrained by its spatial resolution ($240\ \mu\text{m} \times 160\ \mu\text{m} \times 2.4\ \text{mm}$ at the time), making it difficult to precisely resolve the fine morphology of dendrites. Additionally, quantitative interpretation of complex susceptibility effects still requires simulation modeling, and data acquisition and processing remain time-consuming (Figure 9).

The first successful observation of Li^+ distribution in polarized electrolytes was achieved, using one-dimensional spin-echo frequency-encoded MRI. With the use of high-resolution MRI technology, researchers are able to observe in detail the deposition and dissolution behavior of lithium metal during the charge–discharge process [41]. Chandrashekar et al. observed, using ^7Li MRI technology, that lithium metal forms a larger surface area on the anode surface after charging, due to the skin effect. These findings

indicate that the morphological changes of lithium metal directly affect the safety and performance of batteries.

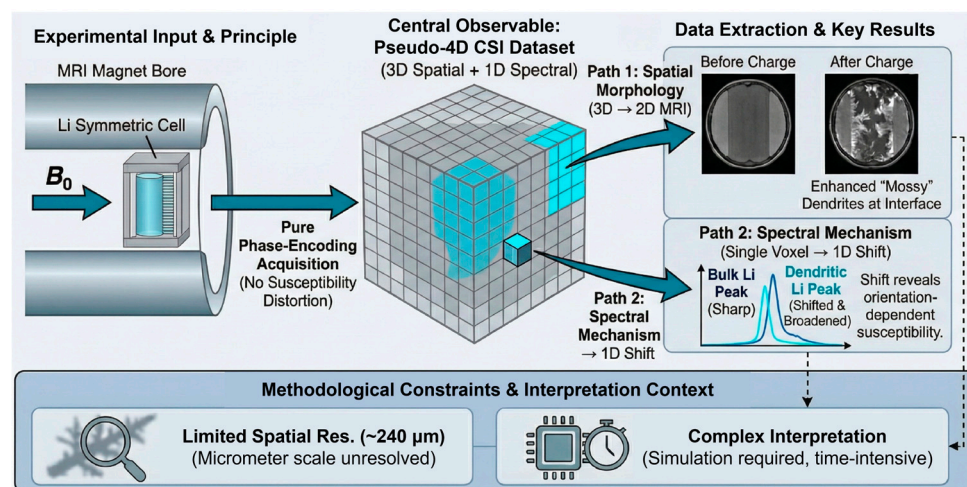


Figure 9. Operando ^7Li MRI time-series imaging of lithium dendrite growth in a lithium metal anode during galvanostatic cycling in a symmetric cell.

The spatial distribution and diffusion kinetics of lithium ions within porous electrode materials critically determine the charge/discharge performance and cycling stability of LIBs. MRI technology has provided spatially resolved insight into lithium transport mechanisms through visualization of ion distributions within electrode architectures [63].

In a comprehensive study by Tang, the stray field magnetic resonance imaging (STRAFI) NMR probe with strong magnetic field gradients was employed to investigate lithium distribution dynamics in both cathode materials (LiCoO_2 and LiFePO_4) and graphite anodes during electrochemical cycling. The initial charging phase revealed relatively uniform lithium distribution across graphite anodes, which subsequently developed steep concentration gradients near the separator interface as charging progressed. Complementary research, utilizing in situ NMR spectroscopy coupled with compressed sensing single-point ramped imaging with T_1 enhancement-MRI (CSSPRITE-MRI) demonstrated distinct lithium intercalation behavior in thick graphite electrodes: lithium ions were observed to initially accumulate at surface layers before progressively inserting into the graphite structure [64–66]. These findings provide fundamental insights for refining lithium transport models in porous electrodes and optimizing battery design parameters.

Peklar et al. demonstrated the power of indirect ^1H MR microscopy for visualizing dendrite growth in real time. Using 3D ^1H MRI of the electrolyte, they observed the transition from mossy to dendritic structures at Sand's time, the formation of dead lithium, and gas evolution in symmetric lithium cells [59]. The same group further showed that battery configuration (single, parallel, or series) significantly affects dendrite uniformity [60].

The non-invasive nature of MRI has proven particularly valuable for studying morphological evolution in lithium metal electrodes, microstructure development, and diffusion kinetics in porous electrodes. These investigations have significantly advanced our understanding of internal battery processes while providing critical scientific foundations for developing safer and more efficient energy storage technologies [67–69]. With continued improvements in resolution and acquisition speed, MRI may support more detailed and temporally resolved observation of internal battery processes, thereby contributing to a better understanding of lithium-ion battery behavior.

For electrode studies, the main challenge is not only low sensitivity but also signal ambiguity caused by metal-induced skin-depth effects, susceptibility mismatch, and multiphase averaging in porous architectures. These issues make dendrite quantification

and active/inactive lithium discrimination substantially more difficult than simple image visualization would suggest [70].

3.3. Macro-Scale Applications: Indirect and Complementary Magnetic Techniques for Commercial-Format Cells

Direct MRI of fully packaged commercial-format cells is fundamentally hindered by metallic casings, multilayer current collectors, and associated skin-effect and eddy-current artifacts, which severely limit radiofrequency penetration and spatial encoding. As a result, commercial-cell diagnostics have increasingly relied on indirect magnetic approaches that sense external field perturbations rather than internal nuclear spin signals [65].

Inside-out MRI (io-MRI) circumvents the Faraday shielding of metal casings by immersing the battery in a ^1H -rich detection medium and imaging the medium rather than the cell itself [45]. Internal currents induce phase shifts in the surrounding medium, enabling reconstruction of surface magnetic field maps, though deriving internal 3D current distributions remains an ill-posed inverse problem requiring simplified models [46].

Similarly, MFI employs sensitive sensors such as AMR sensors to map surface magnetic fields, detecting manufacturing defects like electrode misalignment or poor soldering in simplified setups. Research indicates that impacted batteries exhibit distorted current “hotspots” indicating structural failures such as deformation or delamination [47]. It is important to emphasize that io-MRI and MFI are fundamentally different from conventional NMR/MRI. They do not acquire internal nuclear spin signals but instead rely on external magnetic field mapping and inverse modeling. Computed tomography (CT) and MFI provide complementary information, but unlike conventional MRI/NMR they do not rely on direct detection of internal nuclear spin signals [48].

The practical value of io-MRI and MFI does not lie in replacing conventional MRI, but in extending magnetic diagnostics to commercial-format cells that are otherwise inaccessible to direct RF-based interrogation. In this context, these methods are valuable because they enable non-contact assessment of current heterogeneity, state-dependent field perturbations, and selected manufacturing defects without disassembling the cell. This application-oriented perspective is particularly important for commercial-format cells, where packaging realism is often more relevant than microscopic chemical resolution.

Reconstructing three-dimensional internal current distributions from two-dimensional surface magnetic field data represents a typical ill-posed inverse problem, necessitating strong prior assumptions that may compromise result accuracy [49]. Spatial resolution is typically limited to $\sim 400\ \mu\text{m}$, with poor depth sensitivity incapable of detecting micrometer-scale early-stage defects. Validation is often confined to simple batteries with known issues, lacking verification for complex real-world structures [50,51]. Furthermore, high-field systems are costly and bulky, lacking portability for field diagnostics, while low-cost MFI variants sacrifice accuracy. These methods remain surface-sensitive and cannot replace direct internal imaging. At the current technological stage, MRI remains unsuitable for routine industrial battery testing or production line quality control. Reliable defect localization requires integration with other NDT methods like X-ray CT or ultrasound, as CT provides structural details absent in magnetic techniques.

From an industrial perspective, the realistic role of these techniques is therefore selective rather than universal. They may be useful in failure analysis, laboratory validation of defect-sensitive current maps, low-throughput quality auditing, and mechanism-oriented evaluation of commercial-format prototype cells. By contrast, routine inline inspection in gigafactory environments would require much higher throughput, lower cost, simpler calibration, and more robust inversion than current io-MRI/MFI workflows can provide. Accordingly, these methods are better viewed as complementary diagnostic tools for

research, validation, and targeted troubleshooting, rather than as stand-alone replacements for established industrial inspection standards [66,67].

In situ NMR spectroscopy has also been used to reveal lithium-silicide phase transformations in nano-structured silicon anodes, distinguishing amorphous-to-crystalline transitions that are critical for practical cycling strategies [68–70]. The resolution, spatio-temporal scales, and advantages and disadvantages of various MRI techniques are summarized in Table 1.

Table 1. Comparison of Major MRI/NMR Techniques for Lithium-Ion Battery Investigation.

Technique	Primary Measurable Parameters	Typical Spatial Resolution	Typical Temporal Resolution	Applicable Scale	Key Advantages	Key Limitations
$^7\text{Li}/^1\text{H}$ MRI [22–25]	Li^+/H^+ concentration distribution, chemical environment mapping	10–100 μm	Minutes–Hours	Micro-, Meso-scale	Chemical specificity, 3D spatial encoding, non-invasive.	Low intrinsic sensitivity for ^7Li ; relaxation-dependent quantification; severe artifacts near metal.
PFG-NMR [37]	Ionic self-diffusion coefficients, transport properties.	N/A (bulk measurement)	Seconds–Minutes	Micro-scale (bulk properties)	Highly accurate for diffusion coefficients; model-free for self-diffusion.	No inherent spatial resolution; requires correlation with electrochemical models for applied fields
CSI [1]	Spatially resolved chemical spectra, distribution of different nuclei/species.	100 μm –1 mm	Hours	Meso-scale	Simultaneous spatial and spectroscopic information; identifies chemical states.	Very long acquisition times; low signal-to-noise ratio; limited spatial resolution.
MFI/Surface-Scan MRI [37]	External magnetic field perturbations, internal current density reconstruction, defect location	1–10 mm; limited depth resolution	Seconds–Minutes	Macro-scale	Fast, truly non-invasive, compatible with commercial packaged cells; no strong magnetic field required.	Poor depth resolution; current reconstruction is an ill-posed inverse problem.
Operando MRI [64]	Dynamic processes: ion transport, plating/stripping, phase transformations.	10–500 μm	Minutes–Hours	All scales	Provides direct in situ correlation between structure/chemistry and performance.	Complex cell design required; trade-off between temporal resolution and data quality.

The study quantitatively characterized the nonlinear behavior of current distribution, where the spatial distribution pattern of current is not linearly related to the magnitude of the applied total current. For instance, at low discharge depths, the distribution patterns for smaller discharge currents (e.g., <75 mA) exhibit significant differences compared to those at higher currents. This reveals complex reconfiguration of charge transport pathways as electrode materials approach electrochemical saturation or depletion [71]. Crucially, this technique demonstrates acute diagnostic sensitivity to early mechanical damage: impacted batteries exhibit markedly distorted current distribution maps, enabling localization of abnormal current “hotspots” arising from internal structural failures (e.g., electrode deformation, interfacial delamination). This facilitates intuitive spatial early warning of potential safety hazards (Figure 10).

A more realistic pathway toward industrial translation is integration into multimodal diagnostic workflows rather than independent deployment. In such workflows, MRI-derived magnetic methods could serve as function-sensitive screening tools for identifying

abnormal current redistribution or magnetic anomalies, whereas X-ray CT would remain more suitable for resolving structural defects such as misalignment, folding, or internal fracture, and ultrasound or EIS could provide faster state-screening at lower cost. Under this framework, io-MRI and MFI would contribute complementary information that is difficult to obtain from purely structural or purely electrical methods, but their outputs would need to be interpreted jointly with other modalities to approach industrial reliability standards.

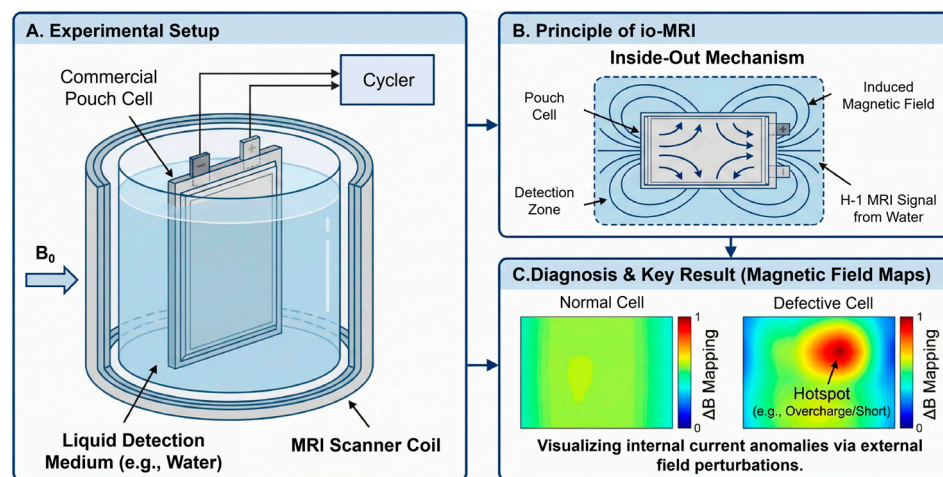


Figure 10. Non-invasive Current Mapping in Commercial Pouch Cells via io-MRI.

In addition to the ill-posed inverse problem, the shielding of high-frequency signals by metallic components (skin effect) and the high cost of superconducting magnets mean that MRI/MFI is not a viable tool for online production line monitoring [72]. Its value lies primarily in providing a non-invasive benchmark for laboratory mechanism studies rather than general industrial battery testing [73]. These factors constitute core obstacles to its adoption in production line online monitoring or rapid on-site diagnostic scenarios. While these applications demonstrate MRI's potential, persistent bottlenecks (Section 4) and future frontiers (Section 5) must be addressed for industrial translation.

To further clarify the specific role of MRI-derived methods within the broader non-destructive testing ecosystem, a comparative evaluation against other major diagnostic techniques is presented in the following section.

4. Recent Research Advances in MRI Techniques

4.1. Comparative Positioning of MRI Among Major Non-Destructive Diagnostic Techniques

Although MRI offers unique chemical sensitivity and operando capability, its practical value in lithium-ion battery diagnostics can only be properly understood when compared with other non-destructive techniques that probe different physical observables. X-ray CT, neutron imaging, ultrasound, magnetic field imaging, and electrochemical impedance spectroscopy each provide distinct combinations of spatial resolution, temporal resolution, chemical selectivity, penetration depth, cost, and industrial accessibility [53]. Therefore, the key question is not whether MRI is globally superior, but under which diagnostic objectives MRI provides uniquely informative data and under which conditions alternative techniques are more appropriate. Table 2 summarizes these trade-offs, and the following discussion positions MRI within this broader non-destructive testing landscape [54,55].

MRI should be preferred when the diagnostic target is closely linked to chemical state, ion transport, or operando redistribution of lithium-containing species. Unlike X-ray CT and ultrasound, which primarily capture structural or mechanical contrasts, MRI can provide nucleus-specific information and spatially resolved insight into concentration gradients, plating/stripping behavior, and selected interfacial processes. This makes MRI

particularly valuable in mechanism-oriented studies where the central question concerns how lithium moves, accumulates, or becomes inactive during cycling, rather than merely whether a structural defect is present.

Table 2. Comparative positioning of MRI and other major non-destructive diagnostic techniques for lithium-ion batteries.

Technique	Spatial Resolution	Temporal Resolution/Scan Time	Relative Cost	Key Advantages	Key Limitations
Direct MRI/operando NMR-MRI [6]	10–100 μm	Minutes to hours	High	Non-invasive, operando, chemical specificity (e.g., ^7Li speciation), quantitative ion transport	Low sensitivity to ^7Li , long acquisition, artifacts in conductive cells
X-ray Computed Tomography [8]	<1–10 μm	Seconds to minutes	High	High resolution, 3D structural imaging, fast	Radiation damage risk, limited chemical contrast, ex situ preference
Neutron Imaging/Tomography [1]	10–100 μm	Minutes to hours	Very High (facility-based)	Excellent lithium contrast, deep penetration	Limited access, low temporal resolution, radiation
Ultrasonic Imaging/Acoustics [71]	50–500 μm	Seconds to minutes	Low–Medium	Fast, low-cost, sensitive to defects/gas evolution	Lower resolution, limited chemical info, interpretation challenges
Magnetic Field Imaging (MFI) [37]	Macroscopic (~mm)	Seconds	Medium	Fast, non-invasive defect/current mapping	Poor spatial resolution, surface-sensitive only
Electrochemical Impedance Spectroscopy (EIS) [73]	None (bulk)	Seconds to minutes	Low	Fast, sensitive to interfaces/kinetics	No spatial information, model-dependent

By contrast, MRI is not the preferred choice when the primary task is rapid structural screening, high-throughput defect inspection, or low-cost routine diagnosis of commercial cells. In such cases, X-ray CT offers superior three-dimensional structural resolution, ultrasound provides faster and more economical defect-sensitive screening, and EIS enables quick bulk assessment of interfacial kinetics despite the absence of spatial resolution. Neutron imaging remains uniquely valuable when deep lithium contrast is required, although its facility dependence and limited accessibility prevent routine use. Therefore, MRI should not be framed as a universal replacement for alternative NDT techniques, but as a complementary method whose advantages emerge only for specific diagnostic questions.

From a practical standpoint, the selection of NDT methods should follow the nature of the question being asked. If the goal is to identify structural defects such as cracks, layer misalignment, or deformation, CT is generally more suitable. If the goal is to detect gas generation, delamination, or rapid state changes at relatively low cost, ultrasound is often more realistic. If the goal is to monitor bulk electrochemical response or interfacial kinetics without spatial mapping, EIS remains efficient. MRI becomes most informative when one needs non-destructive, spatially resolved, and chemically meaningful information about lithium transport or reaction heterogeneity. This diagnostic logic also explains why multimodal combinations are often more powerful than any single method alone.

4.2. Core Technical Bottlenecks and Quantitative Interpretation Challenges

Despite substantial methodological progress, MRI-based battery diagnostics remain constrained by a limited set of recurring technical bottlenecks that cut across electrolyte,

electrode, and full-cell studies. These bottlenecks are best understood as system-level constraints rather than isolated limitations of individual experiments.

First, low intrinsic sensitivity of ^7Li and rapid signal decay in solids remain fundamental obstacles. Compared with ^1H , ^7Li provides substantially weaker signal intensity, while many solid-state battery components exhibit extremely short transverse relaxation times. This combination restricts detectable signal windows, prolongs acquisition, and forces a trade-off among spatial resolution, temporal resolution, and chemical specificity.

Second, conductive battery architectures introduce severe encoding artifacts. Metallic casings, current collectors, and susceptibility discontinuities generate shielding, eddy currents, and local field distortions, which degrade spatial encoding and complicate quantitative reconstruction. These effects are especially pronounced in commercial-format cells and explain why many direct MRI studies still rely on simplified laboratory configurations.

Third, MRI in batteries is constrained by a persistent spatiotemporal trade-off. Protocols capable of resolving concentration gradients, lithium deposition, or chemical-state heterogeneity often require acquisition times ranging from minutes to hours, whereas many electrochemical processes of practical interest evolve on much shorter timescales. Conversely, faster acquisition strategies typically sacrifice either spatial fidelity or quantitative reliability.

Fourth, quantitative interpretation remains nontrivial even when high-quality images are acquired. MRI signal intensity does not always map directly onto lithium concentration, particularly in systems containing multiple lithium environments with different relaxation behavior, mobility, or detectability. In indirect magnetic approaches such as io-MRI and MFI, the inverse reconstruction of internal current or defect distributions introduces an additional layer of model dependence and uncertainty. This ambiguity is particularly important in electrolyte and interfacial studies, where different lithium environments may exhibit markedly different relaxation behavior, mobility, and detectability under the same pulse sequence. Consequently, rigorous quantification requires either explicit calibration, relaxation correction, or multimodal constraints rather than simple intensity-based extrapolation alone.

Taken together, these challenges indicate that the future of MRI in battery diagnostics depends not only on better hardware, but also on experimentally validated, application-specific frameworks that connect magnetic resonance observables to electrochemical reality.

4.3. Real-Time Monitoring of Current Distribution

Gunnarsdóttir et al. demonstrated an MRI-based method for rapid assessment of internal current distribution in commercial pouch cells by measuring magnetic field maps during operation. This technique revealed SOC-dependent and damage-induced changes in current patterns. Noninvasive in situ NMR further quantifies dead lithium and corrosion during rest periods (Figure 11), showing continuous Li dissolution even without current flow [74].

Ultimately, they conducted experiments on healthy and mechanically stressed batteries at different charge/discharge current rates, observing significant differences in current distribution with changes in SOC and after battery stress [75]. They also found that the non-linearity and asymmetry of current distribution could be mapped out at different SOC levels, with correlations existing between current flow hotspots and charge storage hotspots [76]. When switching from charging to discharging, the current distribution could become significantly asymmetric, and the current distribution may be non-linearly related to the total applied current. An interesting symmetry in current distribution was observed between fully charged and nearly fully discharged states.

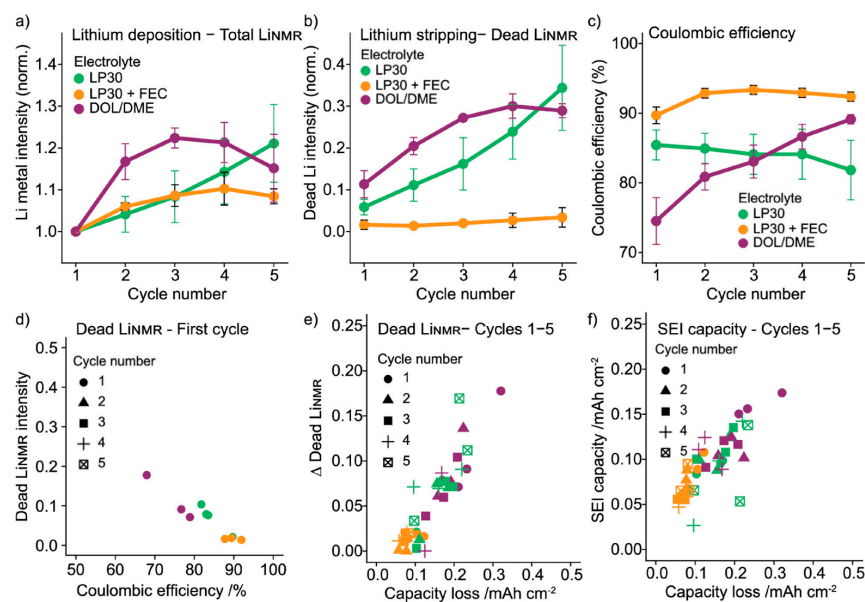


Figure 11. In situ ⁷Li NMR spectra distinguishing bulk Li, dead Li, and SEI components via magnetic susceptibility effects [74].

The MRI-based technique for non-destructive assessment of current distribution in LIBs revealed the asymmetry in current distribution between charging and discharging, which evolves with changes in SOC [77]. The behavior during full SOC charging and high DOD (depth of discharge) discharging showed significant similarities, potentially indicating less and less pronounced disturbance of the active material. Overall non-linear behavior in current distribution was also observed. When the battery was damaged, significant changes in current distribution were also noted (Figures 12–14).

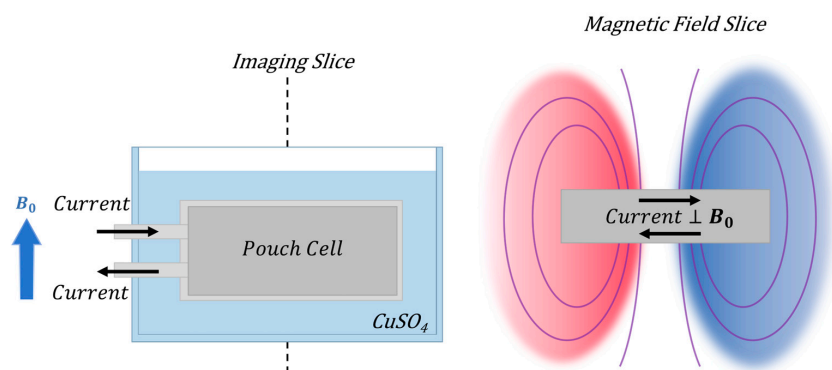


Figure 12. Cell position and orientation of imaging slice, as well as indication of the detected volume.

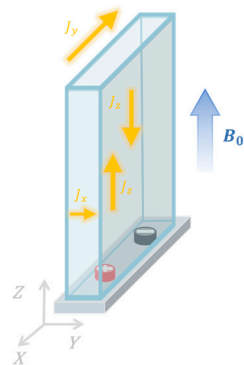


Figure 13. Current distribution elements inside the battery and cell orientation [51].

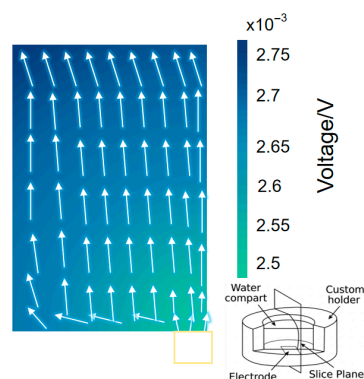


Figure 14. Results from a current distribution calculation, considering an ideal rectangular electrode assembly and negligible effects from non-uniform charge states. The yellow box outlines the ideal rectangular electrode assembly, and the arrow indicates the direction of the current flow [51].

4.4. Diagnosis of Battery Defects

MRI technology, owing to its non-invasive nature and sensitivity to internal magnetic and compositional heterogeneity, offers useful capabilities for investigating selected internal defects in LIBs [78]. This technology is capable of providing detailed images of the internal structure of batteries, including electrodes, separators, electrolyte distribution, as well as potential internal short circuits and inhomogeneities in electrode materials.

MRI has shown potential as a non-destructive tool for laboratory-scale inspection of lithium-ion batteries [19]. By detecting changes in the internal magnetic fields of batteries, MRI can directly map the internal current distribution, thereby identifying internal defects that affect battery performance. This non-invasive detection method not only avoids physical damage to the battery but also provides high-resolution images of the internal structure, including the distribution of electrodes, separators, and electrolytes. Moreover, MRI can reveal microscopic defects within the battery, such as inhomogeneities in electrode materials and internal short circuits, which are often difficult to detect using traditional destructive testing methods [79].

Felix Brauchle and colleagues proposed an improved MFI and current reconstruction method for detecting and locating defects in lithium-ion battery production [80]. Based on anisotropic magneto resistance (AMR) sensors, this method scans the magnetic field in a 2D plane above the battery to detect defects that affect current distribution. Experimental batteries with manufacturing defects, such as missing welds, notches, and cracks, were prepared and inspected using the MFI and current reconstruction method. The results indicated that the method could observe many types of defects, although not all defects were detectable.

Furthermore, the combination of CT and MRI can enhance the accuracy of detecting internal structures and defects in batteries. By comparing the results of CT scans and MRI inspections, internal defects such as misaligned electrodes and stacking faults (electrode folding) can be more accurately identified [81].

Fault simulation batteries are specifically designed to simulate faults that may occur during battery manufacturing. By studying, a better understanding of how these faults affect battery performance can be achieved, and effective detection and diagnostic methods can be developed.

Mingyu Lee and colleagues utilized non-invasive, in situ MRI technology to study LIBs simulating various faults, including lead tab connection faults, electrode misalignment and stacking faults [82]. Through high-speed, spatially resolved MFI scanning, researchers were able to derive current distribution patterns from batteries with different tag positions and collect current maps to identify potential battery faults.

An improved MFI analysis method was employed in the study, which directly identified defect points with abnormal current flow inside the battery by interfering with the magnetic field of a plate carrying reverse current. This method was able to detect and localize several internal defects, indicating its usefulness as a non-invasive approach for battery fault diagnosis in controlled test configurations [83–86] (Figure 15).

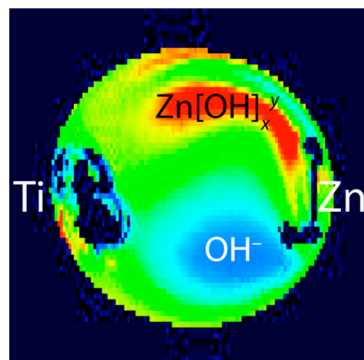


Figure 15. In situ MRI relaxation maps visualizing the distribution of Zn(OH)_x^{y-} (green), OH^- (red), and Zn (blue) in an alkaline zinc electrochemical cell during discharge [86].

Table 3 summarizes landmark achievements of magnetic resonance imaging (MRI) technology in cross-scale battery characterization, highlighting key techniques, research findings, and their contributions to electrolyte kinetics, interfacial processes, and full-cell diagnostics. For instance, early studies achieved visualization of specific species gradients in model electrochemical cells, while subsequent advancements enabled non-destructive imaging of commercial pouch batteries.

Table 3. Landmark MRI studies across battery scales.

Reference	Technique	Key Finding	Research Scale
J. E. Green et al., 2015 [10]	1D ^7Li MRI + Modeling	First visualization of Li^+ concentration gradient under polarization; enabled transference number determination.	Micro (Electrolyte)
Chandrashekar et al., 2012 [47]	^7Li MRI	Localized high-surface-area “mossy” lithium formation on anode due to skin effect.	Micro (Interface)
R. Khanna et al., 1998 [11]	3D ^7Li MRI (FLASH)	Revealed microscopic inhomogeneity and mossy morphology of Li metal deposits.	Micro/Meso (Electrode)
Tang et al., 2019 [78]	STRAFI NMR	Mapped Li^+ intercalation kinetics and concentration gradients in thick electrodes.	Meso (Electrode)
Britton et al., 2013 [86]	MRI relaxation maps	In situ, real-time visualization of Zn(OH)_x^{y-} , OH^- , and Zn distribution in an alkaline zinc electrochemical cell during discharge; demonstrated species-specific gradients and electrochemical processes	Micro (Electrolyte/Interface)

Table 3. *Cont.*

Reference	Technique	Key Finding	Research Scale
Romanenko et al., 2020 [22]	Surface-Scan MRI	Achieved non-destructive imaging and diagnosis of internal state in packaged commercial cells.	Macro (Full Cell)
Mohammadi et al., 2020 [37]	MFI (based on ^1H MRI)	Mapped nonlinear, SOC-dependent internal current distribution in commercial pouch cells.	Macro (Full Cell)
Brauchle et al., 2023 [64]	MFI (based on AMR sensors)	Enabled non-invasive detection and localization of manufacturing defects.	Macro (Quality Control)

MRI technology has provided useful information for detecting selected internal defects and for studying fault-simulated LIB configurations [38,87,88]. Through these studies, a deeper understanding of the physicochemical processes inside batteries can be achieved, offering guidance for battery design and manufacturing, as well as new perspectives for battery health monitoring and performance optimization [89].

5. Summary

Non-destructive testing of batteries is critical for their applications in portable devices, transportation, and energy storage grids. MRI-based techniques, such as those described by Markert et al., enable rapid assessment of current distribution within commercial battery designs by measuring magnetic field distributions during operation. This reveals nonlinear and asymmetric current flows that emerge with changes in SOC and during battery damage. Furthermore, MRI-particularly methods like the MFI enhanced by Brauchle et al.-plays a vital role in non-invasively detecting and localizing internal defects such as electrode misalignment, cracks, and welding failures. Integration with CT further enhances diagnostic accuracy. These developments highlight the usefulness of MRI for providing non-invasive and spatially resolved information about the internal state of lithium batteries.

Beyond summarizing representative MRI studies, this review highlights a central distinction that is often underemphasized in the literature: direct MRI of simplified electrochemical systems and indirect magnetic diagnostics of commercial-format cells are not merely different implementations of the same technique, but fundamentally different measurement paradigms with different observables, strengths, and interpretation limits. From this perspective, the main contribution of MRI to commercial battery diagnostics at the present stage is not routine industrial deployment, but the provision of function-sensitive, non-destructive information that complements structural and electrochemical methods.

The spatiotemporal limitations of current MRI systems restrict real-time monitoring of fast processes such as lithium plating. Future efforts should prioritize hardware–algorithm co-design, including compressed sensing and AI-assisted reconstruction, to improve the interpretability and practical relevance of MRI-derived diagnostics.

Future progress will likely depend on tighter integration of MRI with multimodal sensing, data-driven reconstruction, and standardized model systems that improve the interpretability and translational relevance of magnetic resonance-based diagnostics. Through physics-informed machine learning, this approach can construct high-fidelity digital twins of battery internal states. Concurrently, methodological research must anchor to standardized, industry-relevant battery specifications-rather than diverse homemade cells-to establish comparable, reproducible datasets and evaluation benchmarks.

Non-invasive magnetic resonance imaging offers a unique research window into the internal mechanisms of lithium-ion batteries, yet its widespread application still faces multiple challenges. Overall, the field appears to be moving from proof-of-concept demonstrations toward a stage that places greater emphasis on integration, validation, and application relevance. Future progress hinges on confronting the inherent physical limitations of MRI technology, actively integrating interdisciplinary approaches such as computational imaging and information fusion, and aligning research objectives with industry's core demands for reliability, safety, and cost-effectiveness.

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