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Two component ferrofluids and tandem magnetic nanoparticles in nuclear medicine

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Abstract

In this article, we systematize nonlinear effects that enable *configuring* magnetic fields inside magnetic nanofluids and ferrofluids at micro- and submillimeter scales for nuclear medicine, and we propose *tandem* magnetic nanoparticles as a realistic platform for combined radionanotherapy and high-precision imaging, provided local sources of ∇B and standardized radiochemistry. We show how nonlinear magnetization $M(H)$ and field-dependent permeability $\mu(H)$ produce self-focusing of induction and "magnetic pressure"; how the normal-field (Rosensweig) instability generates periodic maps of ∇B^2 for capture and sorting; and how dipole-induced self-organization (chains, ribbons, percolation) reshapes the medium's effective anisotropy and magnetorheology. We consider nonstationary protocols (harmonic and rotating fields) that provide flow rectification and programmable orientation of structures at low Mason number, as well as inverse ferrofluids with negative magnetophoresis for label-free focusing in microchannels. We discuss feedback methods (MPS/MPI)

that enable *in situ* mapping of saturation zones, clustering, and tracer distributions. Practical guidelines are formulated: operate near presaturation, combine local flux guides/inserts with a DC gradient and a low-frequency rotating field, and use polydispersity and mixed shapes (spheres+rods) for controlled percolation. Limits of controllability are noted: geometric decay of gradients, saturation, heating in AC regimes, and hysteretic transitions. The target applications are microfluidic concentration, targeted delivery, and selective fixation of nanoparticles, where nonlinear effects are the primary tools for "drawing" internal fields. Two-component magnetic fluids with *radioactive* sources provide flexibility: separate optimization of magnetics and radiochemistry, use nonlinear assembly for internal gradient amplification, and rely on clinically established radioplatforms for dose verification.

1 Introduction

Magnetic nanofluids and ferrofluids have evolved from textbook examples of nonlinear continuous medium into engineering tools for the *programmable* reshaping of magnetic induction $\mathbf{B}$, gradients ∇B^2, and particle fluxes at micro- and millimeter scales. The fundamental reason for controllability is the nonlinear magnetization $M(H)$ of the dispersed phase and the resulting field-dependent effective permeability $\mu(H)$; near saturation this leads to self-focusing of induction, "magnetic pressure," and interface reconfiguration [1–3]. At the microstructural level, dipole–dipole interactions trigger robust chain formation, ribbon formation, and cluster percolation, which radically alter the magnetoviscous response and transport anisotropy [3–6]. As a result, the field governs *not only* the magnitudes of B and ∇B^2 but also the very architecture of the medium through which these quantities are distributed.

By "configuring fields" we mean a set of techniques that intentionally form, within a fluid volume: (i) local channels of elevated ∇B^2 for magnetophoresis, (ii) periodic or quasiperiodic "magnetic traps" for particle retention/sorting, and (iii) controllable anisotropy of the effective μ and rheology, which steers trajectories and fixes structures where needed. Three classes of nonlinear effects provide these levers.

First, geometric nonlinearities of the interface. The normal-field (Rosensweig) instability arises once a threshold H_c is exceeded and turns a flat surface into a ridge lattice, creating a spatially modulated map of ∇B^2 [1]. Modern experiments show that by varying layer thickness, viscosity, and field magnitude one can program the pattern's pitch and amplitude and thereby form arrays of traps and "microcollimators" inside thin films [16]. In thin Hele–Shaw gaps, weakly nonlinear analysis predicts controllable fronts and stationary structures that are convenient for channeling particle flow [17].

Second, nonlinearities of composition and structure. Polydispersity, mixtures of shapes (spheres + rods), and multicore particles create threshold self-organization scenarios: with increasing H and volume fraction the system undergoes a jump-like transition from a dilute "gas" to a network of chains with enhanced field conductance along $\mathbf{B}$ [3–6]. Anisotropic particles subject to the torque $\boldsymbol{\tau} = \mathbf{m} \times \mathbf{B}$ rapidly align and chain; the transition from slip to synchronous rotation is set by the Mason number, which provides a direct control knob for structural architecture [7, 11, 12]. This *structural register* allows even moderate fields to draw within the volume robust "field-conducting" pathways and local zones of high ∇B^2.

Third, dynamic nonlinearities. Harmonic and rotating fields excite odd harmonics in $M(t)$, phase shifts, and rectification regimes, in which combinations of frequencies yield a nonzero average drift of clusters at zero mean field. This opens the way to multi-frequency addressing of subensembles differing in Néel time and anisotropy [7, 13, 14]. In parallel, the same nonlinearities provide *feedback*: magnetic particle spectroscopy (MPS) and magnetic particle imaging (MPI) read out the $3f$, $5f$, and $7f$ harmonics and enable *in situ* mapping of saturation zones, clustering, and tracer distributions [20–23].

For applications, microfluidic concentrators, targeted delivery, and selective fixation of nanoparticles, the practical challenge is not to maximize H but to combine the above nonlinearities rationally: operate near presaturation (preserving $\mu(H)$ contrast), initiate self-organization only where it enhances retention, and control orientation/reconfiguration with nonstationary protocols. An important addition is inverse ferrofluids: dilute magnetic matrices enable label-free focusing and sorting of nonmagnetic objects via negative magnetophoresis and induced flows [8, 10, 26, 33]. These systems expand the toolbox for configuring fields in channels and thin layers where external gradients decay rapidly.

The limitations are known: geometric decay of gradients away from flux guides, saturation, heating in AC regimes, and hysteretic "gas–chains–network" transitions in polydisperse suspensions [3, 4, 6, 27]. Hence effective schemes use *combinations* of structural, geometric, and dynamic methods: local flux guides or ferromagnetic inserts for depth; mixtures of shapes or multicore particles for controllable percolation; and rotating/multi-frequency fields for targeted orientation and rectification. Such layered design moves magnetic fluids from being mere "carriers" into the class of active functional media, where field and medium are co-tuned.

The following sections systematize the tools for configuration. We begin with nonlinear magnetization and interfacial effects, including the Rosensweig instability and thin-cell geometries. We then cover self-organization and magnetorheology in mixtures, including anisotropic systems. After that come dynamic protocols (rotation, multi-frequency rectification) and feedback methods (MPS/MPI). We conclude with practical rules for choosing B, ∇B^2, and frequency regimes, and with a map of controllability limits for biomedical and microfluidic scenarios.

2 Nonlinear Effects for Configuring Fluid Surfaces and Internal Fields

The goal of considering nonlinear effects for configuring internal fields in magnetic fluids is to control the distribution of magnetic induction $\mathbf{B}$ and of gradients ∇B^2 inside a volume of ferrofluid (or inverse ferrofluid) so as to direct particle transport, concentrate labels, and form stable structures. The main levers are the nonlinear magnetization $M(H)$, dipole-induced self-assembly, field-dependent permeability $\mu(H)$, and nonstationary (harmonic/rotating) fields that generate multifrequency response and flow rectification [1–3, 6, 7].

For superparamagnetic dispersions $M(H)$ is often approximated by a Langevin function; as H increases the effective permeability $\mu(H)$ decreases (saturation), and the Maxwell stress tensor adds to the interfacial free energy. This produces an effective "magnetic pressure" and self-focusing of $\mathbf{B}$ in regions with larger μ [1, 2].

Practically, this is used to control the shape of droplets/films and to create local "magnetic nozzles" within microcells: increasing H enhances the B contrast between phases and strengthens directed transport. In Hele–Shaw configurations, weakly nonlinear analysis predicts a bifurcation with the formation of stable structures and fronts [18]. For highly viscous liquids, the dynamics can be slowed to widen the linear-growth regime of perturbations and simplify control [17].

The normal-field (Rosensweig) instability is a classical nonlinearity in which a flat surface becomes stably corrugated once a critical H_c is exceeded [1]. For field configuration this is useful because the ridges create a periodic modulation of ∇B^2, forming an array of "magnetic wells." They act as templates for capturing and sorting added particles or as distributed microcollimators of flows within a layer [16]. By tuning viscosity, surface tension, and layer thickness one can set the lattice pitch/amplitude and thus the gradient map.

In real ferrofluids the particles form chains, ribbons, and clusters; this self-assembly drastically changes the macroscopic response—magnetoviscosity, anisotropy, and effective permeability [3–6]. Chains align with $\mathbf{B}$ and act as high-μ field conductors at the microscale, concentrating induction in structural "threads." Hence two configuration routes: (i) *structural*—adjust concentration, polydispersity, and shape (spheres/rods) so that for a given H the desired cluster map appears; (ii) *dynamic*—design $H(t)$ to switch percolation on/off or to degenerate clusters along the flow. For sphere+rod mixtures, the torque $\boldsymbol{\tau} = \mathbf{m} \times \mathbf{B}$ drives rods into synchronous motion at low Mason number Mn; they chain faster than spheres and create anisotropic field-conducting pathways, raising local ∇B^2 [7, 11, 12].

An inverse ferrofluid moves nonmagnetic objects within a magnetic matrix down the *decrease* of B ("negative magnetophoresis"). The nonlinearity is twofold: (i) the matrix itself has $M(H)$; (ii) induced secondary flows alter trajectories [8, 10, 26, 33]. As a result, microchannels can provide precise focusing, separation, and "magnetic buffering" of flows label-free. For configuring internal fields this is convenient: a dilute ferrofluid and a permanent magnet suffice to generate an array of controllable "magnetic traps" along a channel.

Harmonic and rotating fields produce a nonlinear dynamic response: odd harmonics $3f, 5f, \ldots$ in $M(t)$, phase shifts, and for anisotropic particles a slip $\rightarrow$ synchronous transition governed by Mn [7, 13, 14]. This yields two engineering tools.

- **Rectification.** Multi-frequency protocols ($f_1 + f_2$) produce a nonzero average drift of clusters even at zero mean $\mathbf{B}$; field combinations create asymmetric trap potentials.

- **Programmable orientation.** Rotating fields ($10-50$ mT, $5-50$ Hz in viscous media) control the direction of chains/ribbons and hence the anisotropy of the effective μ within the volume [7].

The criteria are simple: retain the moment (Néel time τ_N) and ensure $Mn<1$ for rods so that structures follow the field and "draw" the desired ∇B^2 channels.

The same nonlinearities underpin magnetic particle spectroscopy (MPS) and magnetic particle imaging (MPI): they detect harmonics of the dynamic magnetization of tracers near a zero field point [20–24]. In field configuration, this enables *in situ* mapping of particle distributions and local saturation: *if* under a given $H(t)$ the composition/structure changes, the harmonic spectrum records where struc-

tures turned on, where saturation lowered $\mu(H)$, and how the internal B profile reconfigured.

Spatial gradients of H and T in magnetic nanofluids drive thermomagnetic convection, which can emerge *spontaneously* and alter the field and transport patterns [15, 19]. This is an undesired nonlinearity in configuration: frequency/amplitude of AC fields must be limited and dissipative regimes chosen to avoid uncontrolled vortices, especially in thin cells.

Practical configuration schemes

Structural modulation. Choose polydispersity and volume fraction so that at a given H chain percolation occurs only in the target zone. Sphere+rod mixtures help in the presence of a local gradient (flux guide, stent) or a rotating field: rods accelerate assembly and create directed "wires" of field [7, 11, 12].
Surface modulation. Drive the surface to the Rosensweig threshold to form a lattice of microtraps; the pitch is controlled by viscosity and H [**?**, 1, 16].
Inverse protocols. Use a dilute ferrofluid as a matrix to configure traps for nonmagnetic objects and flow channels via negative magnetophoresis and induced flows [8, 10, 33].
Multi-frequency addressing. Combine frequencies for rectification and selective excitation of subensembles with different τ_N; monitor via MPS [22, 23].

It is instructive to consider limits of controllability and regime estimation: **Depth.** External magnets yield large gradients only near the surface; deep targeting requires flux guides/inserts and catheter-based solutions.
Saturation. At large H the drop of $\mu(H)$ reduces useful contrast; it is better to operate near presaturation and control structure, not merely the magnitude of H [1, 3].
Heating. AC fields cause losses; high frequencies/large amplitudes of fast rotation can trigger hyperthermia and convection [**?**].
Stability. Strongly dipolar regimes are sensitive to polydispersity and shear; models and experiments show hysteretic transitions "gas–chains–network" [4, 6, 27].
Rod orientation. The requirement $Mn < 1$ at given viscosity η and frequency f yields a lower bound on B for synchronous mode. For plasma/extracellular media typical values are $B \sim 10-50$ mT at $f \sim 5-50$ Hz [7].
Drift. In the unsaturated case $F_{\text{mag}} \approx \frac{V\Delta\chi}{2\mu_0}\nabla B^2$; target values $\nabla B^2 \gtrsim 10^3 - 10^5$ T^2/m are achievable in microgaps and near flux guides.
Structural threshold. The chain-formation threshold is set by the dipolar coupling parameter λ and volume fraction; growth of large fractions sharply increases the magnetoviscous effect and anisotropy [3, 5, 25].
Feedback. The MPS spectrum $3f, 5f, 7f$ tracks the onset of saturation and cluster growth; MPI with FFP/FFL scanning yields 3D tracer maps [20, 21, 23].

3 Two-Component Magnetic Fluids with Radioactive Sources

By *two-component* magnetic fluids with radioactive sources we mean dispersions in which (i) one fraction provides magnetic response and controllability (e.g., multicore

SPIONs), and (ii) the second fraction carries radionuclides (radiolabels, $\alpha/\beta/\gamma$ emitters), and may itself be magnetic or nonmagnetic. This decoupling allows independent optimization of magnetophoresis/orientation and radiochemistry/dose, and it enables *cooperative* field-driven assembly.

Architecture classes.

1. *Magnetic spheres + radiolabeled spheres.* SPIONs (Fe_3O_4 core) as the "traction" phase and a separate radiolabeled fraction (^{177}Lu, ^{64}Cu, ^{198}Au, etc.) for dose; fractions can be of comparable size for matched microhydrodynamics [28, 29].
2. *Spheres + rods (or microcylinders).* Rods align and chain at low Mason number, creating anisotropic "flux guides" and zones of elevated ∇B^2; the radiolabel is placed mainly on the rods, while the SPION spheres boost the mixture's overall magnetic response [7].
3. *Core–shell hybrids and composites.* Fe_3O_4@Au with neutron activation of the gold shell to ^{198}Au combine magnetic control, CT/optical contrast, and β therapy; such particles can serve as one fraction in a binary fluid [30–32].
4. *Inverse ferrofluids.* A dilute magnetic matrix + nonmagnetic radiolabeled objects (e.g., Ho microspheres) with *negative* magnetophoresis for label-free focusing in microchannels and thin layers [8, 33].

Magnetophoresis is set by $F_{\mathrm{mag}} \approx \frac{V\Delta\chi}{2\mu_0}\nabla B^2$ (below saturation) or $F \approx m\nabla B$ at saturation. For *in vivo* at depth, **gradients** dominate: large ∇B^2 values are achievable near flux guides/stents and in microgaps; a single external magnet loses efficiency rapidly with depth [34,35]. Practically this yields two regimes: Locoregional delivery (intra-arterial) + retention by a *local* gradient (ferromagnetic stent, soft inserts) [35, 36]. and surface/intratumoral scenarios with short drift paths and additional structural orientation by a rotating field ($10-50$ mT, $5-50$ Hz) [7].

For radiochemistry and radionuclide selection we can use **^{177}Lu** (classic DOTA complexes), which provides β^- therapy and γ for SPECT. It labels SPIONs stably via DOTA/NOTA and shows long retention after intratumoral administration [28,37]. **^{64}Cu** offers PET diagnostics with a therapeutic component and serves as a "matched pair"; mature chelation protocols (NOTA/DOTA) exist [38, 39]. **^{198}Au** can be generated *in situ* by neutron activation of an Au shell on Fe_3O_4, combining magnetic control and β emission [30]. For **BNCT** (^{10}B), magnetic boron carriers (e.g., Fe_3O_4@Au@carborane) improve accumulation; neutron activation yields high-LET α and ^{7}Li locally [40–42].

Two-component design as a control lever includes a) Function separation: the SPION fraction is optimized for M_s, $\Delta\chi$, hydrodynamic size, and colloidal stability; the radiofraction is chosen by radiation physics, chelator stability, self-absorption, and half-life. This removes the "magnetism vs radiochemistry" trade-off [28, 29]; b) Nonlinear assembly: in "spheres+rods" mixtures, dipolar self-assembly creates *internal* channels of elevated ∇B^2. A radiofraction placed on rods concentrates in these channels without enormous external gradients [7]; c) Multiphysics: in core–shell hybrids one can couple hyperthermia and radiotherapy: heating can enhance perfusion/oxygenation and dose effectiveness, while the magnetic fraction assists retention [32, 47].

Key platforms and data are **SPION–DOTA–^{177}Lu** - stable labeling and long local retention with intratumoral dosing (mice, 4T1/CT-26), strong therapeutic effect without systemic toxicity [37], **Fe_3O_4@Au $\Rightarrow$ ^{198}Au** - synthesis and validation of multimodal nanoconstructs: magnetic control + CT/optics + β therapy; doses modeled for HCC [30, 31], **^{64}Cu/SPION** - PET tracking of distribution and PK of binary systems *in vivo*; established ^{64}Cu regulatory guidance [38, 39], **BNCT on magnetic carriers** - 2023–2025 reviews report improved boron delivery via nanocomposites and magnetic targeting [40–42] and **Holmium-166 microspheres** - not strictly "two-component," but an important reference: a clinically mature radioplatform with MRI visibility of distribution, combinable with a magnetic fraction in local regimes [43–45].

Field configuration and operating modes includes DC gradient + rotating field: DC provides drift and retention, low-frequency rotation (5 – 50 Hz) aligns rods, boosts anisotropy of effective μ, and increases local ∇B^2 [7]; Local flux guides: ferromagnetic stents/inserts create high ∇B^2 in the target zone, mitigating depth limits [35,36] and inverse modes (microchannels): dilute ferrofluids focus nonmagnetic radioparticles by negative magnetophoresis, useful for *ex vivo* concentrators and microdosers [8, 33].

Binary design permits targeted tuning of *self-absorption* in the radiofraction. For β emitters (^{177}Lu, ^{198}Au), shell/size control the energy fraction retained in the particle vs deposited in tissue; for γ it is important to minimize high-Z coating thicknesses to preserve imaging/efficacy. Ho-166 enables convenient dose control via SPECT/MRI [43, 44].

Regulatory and practical aspects include complex stability, in which chelators (DOTA/NOTA) and inert shells (Au, SiO_2) are critical to prevent radionuclide leakage [28,29], imaging and verification with PET/SPECT for ^{64}Cu/^{177}Lu; MRI/CT for Ho-166 and Fe_3O_4@Au [31, 38, 44] biocompatibility by PEG/albumin/chitosan reduce immune clearance and aggregation [31, 46] and field safety, which avoid hyperthermic windows in AC modes unless heating is intended [32].

Use cases and recommendations are **systemic/intra-arterial administration:** a single-component SPION fraction (60–100 nm, PEG) + a radiofraction (^{177}Lu–DOTA or Fe_3O_4@Au $\rightarrow$ ^{198}Au) with matched hydrodynamics; if a stent is present, add a minor rod fraction for anisotropy [7,35], **intratumoral/peritumoral delivery:** ^{177}Lu–SPION (stable labeling) + a SPION "traction" fraction for retention; use a rotating field to "pull" toward the rim zone [37] and **BNCT:** a boron-containing magnetic fraction + an auxiliary SPION fraction for targeting and MR control; follow current carborane/nanocomposite practice [40, 41].

4 Tandem magnetic nanoparticles linked by a nanotube: geometry, dynamics, frequency addressing, and prospects for nuclear medicine

We now consider "tandems" composed of two or more nanoparticles connected by a carbon or alternative nanotube (BNNT, halloysite, etc.). Tandem magnetic nanoparticles are two or more nanoparticles linked to each other by carbon nanotubes or alternative functional analogs, with at least one nanoparticle being magnetic. Even if only one node is magnetic (SPIONs, cobalt ferrite), the assembly behaves as

a single magnetoelastic object with controllable torque, orientation, and resonant modes. This enables scenarios for targeted delivery/retention of radionuclides and multimodal imaging (MRI/MPI + PET/SPECT).

Tandem geometry and a shifted center of mass

A "magnetic node + radio node" connected by a short nanotube of length $L \sim 0.1-0.4\,\mu$m exhibits torque anisotropy $\tau = mB\sin\theta$. For elongated geometry it is easy to achieve synchronous orientation in a rotating field at low Mason number Mn, as well as passive stabilization when the center of mass is shifted toward the denser (preferably radioactive) node ("bottom-heavy"): the gravitational moment reduces Brownian flipping and promotes near-wall margination in shear flow. In practice, the "traction" magnetic node is preferably multicore (nanoflower SPION, $d \sim 30-80$ nm) to ensure high M_s and MPI/MRI contrast, while the radio node is a sphere (Au, or SiO_2 with DOTA/NOTA for ^{177}Lu/^{64}Cu, or Au for ^{198}Au), which simplifies radiochemistry and reduces leakage.

Node shape variations: sphere, cylinder, disk

Shape determines orientational dynamics, near-wall margination, and "anchoring" in field gradients.

- **Sphere**: minimal hydrodynamic drag and isotropy; rational choice for the radio node (minimal γ/β self-absorption for a given shell).
- **Cylinder/rod**: high magnetic torque for $\mathbf{m} \parallel$ axis, rapid entry into synchronous regime at $Mn < 1$; optimal as the magnetic node and as an "anchor" in ∇B.
- **Disk/platelet**: strong resistance anisotropy; enhanced margination and "sliding" along endothelium in microcirculation.

For vascular delivery the pair *rod-as-magnet + sphere-as-radio* often wins: the rod sets orientation and retention, the sphere sets radiochemistry.

Orientation of the magnetic moment relative to the axis

The choice of $\mathbf{m}$ orientation in the magnetic node changes control modes:

- $\mathbf{m} \parallel$ the tandem "rod" axis: minimal "step-out" frequency and maximum thrust in a rotating field $(f \lesssim f_{\mathrm{so}})$.
- $\mathbf{m} \perp$ the axis: convenient for oscillatory protocols and excitation of bending modes of the linker; higher synchronization threshold.

In design we use the estimate $f_{\mathrm{so}} \approx \frac{mB}{2\pi\zeta_{\mathrm{rot}}}$, where ζ_{rot} is the rotational viscous drag of the tandem; increasing m and reducing hydrodynamic drag widen the useful frequency window.

Three-particle tandems and magnetoelastic addressing

A three-node chain (magnetic–radio–balancer) linked by a nanotube can be modeled as "beads connected by springs." Two engineeringly important modes arise:

$$f_{\parallel} \sim \frac{1}{2\pi}\sqrt{\frac{k_{\parallel}}{m_{\text{eff}}}}, \qquad f_{\text{bend}} \sim \frac{\beta^2}{2\pi L^2}\sqrt{\frac{\kappa}{\rho A}}$$

where $k_{\parallel}$ is the axial stiffness (tuned by the nanotube material/length), κ is the bending stiffness, β is the modal coefficient, and L is the linker length. Driving at $f_{\parallel}$ enables *coupling/decoupling* of nodes (bringing the radio node closer to a wall/stent), while driving at f_{bend} *anchors* orientation near substrates and brings the assembly into stable "poses." Different $k_{\parallel}$ and κ across particle batches provide *frequency multiplexing* for controlling several subensembles with a single coil system.

Frequency protocols and delivery/retention dynamics

DC + ∇B set drift and retention; a **rotating field** B_{AC} (10–50 mT, 5–50 Hz) orients tandems and forms *internal* paths of elevated ∇B^2 via chain formation of magnetic nodes. Above f_{so} a "step-out" occurs (loss of synchronization) with a drop in speed, which can be avoided by increasing mB or reducing ζ_{rot}. **Oscillatory modes** at $f_{\parallel}$ and f_{bend} can be used to: (i) "pull" the radio node toward a wall/ferromagnetic insert, (ii) adjust node spacing to tune β self-absorption and imaging, and (iii) enact selective adhesion-on/off with substrates. The nonlinear response of the magnetic node provides *feedback*: MPS/MPI read odd harmonics $3f, 5f, 7f$ and allow *in situ* tracking of orientation, saturation, and local concentration.

Linker materials and "light" analogs

CNTs provide high E and conductivity but require shortening, oxidative functionalization, and biocompatible shells to control toxicokinetics. **BNNTs** and **halloysite nanotubes** are alternatives with better biocompatibility and tunable stiffness; the BN family is simultaneously attractive for BNCT (carriers of ^{10}B). Choice of linker effectively sets the ranges of $k_{\parallel}, \kappa$ and the permissible frequencies without overheating.

Nuclear medicine: diagnostic and therapeutic applications

Diagnostics. A radiolabel on the radio node (^{64}Cu, ^{89}Zr, $^{99\text{m}}$Tc, ^{177}Lu) enables PET/SPECT, and the magnetic node provides MRI/MPI for quantitative tracking. The combination improves dosimetry accuracy and real-time distribution control.

Therapy.

- β emitters: ^{177}Lu on a SiO_2 sphere (DOTA/NOTA) or ^{198}Au via activation of an Au node (Fe_3O_4@Au $\rightarrow$ ^{198}Au). The magnetic node enhances retention near local ∇B sources (stents/inserts).
- α modes: ^{211}At@Au as an option for local high-LET dose under peritumoral/intratumoral administration and retention.

- *Combo*: radiotherapy + magnetic hyperthermia/photothermia on magnetoplasmonic heterodimers within the tandem.
- **BNCT**: BN linkers/nodes as ^{10}B carriers with magnetic targeting to raise $[B]_{\text{tumor}}$.

Risk and limit analysis

Depth of guidance. External magnets provide large ∇B only near the surface; deep targets require *local* flux guides (magnetizable stents, soft ferromagnetic inserts) and/or locoregional catheter delivery.

Linker toxicokinetics. CNTs are regulatorily sensitive; shortened and functionalized variants or BNNT/HNT analogs with better tolerance are preferable. Verification of RES retention and long-term biodegradation is required.

Heating and AC modes. Avoid unintended hyperthermia and thermomagnetic convection; choose frequencies/amplitudes below therapeutic windows if heating is not the goal.

Practical design guidelines

1. **Shape pair**: rod-as-magnet ($\mathbf{m} \parallel$ axis) + sphere-as-radio with added mass on the radio node (shifted COM) for passive stabilization and margination; match hydrodynamic sizes and surface charge (e.g., PEGylation) to suppress aggregation and ensure similar flow profiles.
2. **Frequencies**: keep $f < f_{\text{so}}$ in the orientational mode; use separate windows for $f_{\parallel}$ (tens of Hz) and f_{bend} (hundreds of Hz in physiological viscosity) for coupling/anchoring.
3. **Linker material**: tune $k_{\parallel}, \kappa$ by choosing CNT/BNNT/HNT and length L; balance fast response and biocompatibility.
4. **Verification**: PET/SPECT via the radio node + MPI/MPS via SPIONs; if hyperthermia is used, employ MPI multiharmonic thermometry.
5. **Infrastructure**: for deep targets, plan ferromagnetic stents/inserts with catheter delivery—this sharply increases local ∇B^2 and TRL.

5 Conclusion

Tandems on nanotube linkers combined with intelligent actuation are not merely "two materials in one carrier" but *magnetoelastic robots* at the nano-/microscale. The combination of (i) shape anisotropy, (ii) a shifted center of mass, (iii) controllable orientation of $\mathbf{m}$, and (iv) frequency-tunable axial and bending modes provides a rare set of levers for nanoplatforms: frequency-selective addressing, coupling/decoupling, retention at local ∇B, and multimodal imaging. For nuclear medicine, near-term application paths are **diagnostics** (PET/SPECT + MPI/MRI) and **local therapy** (^{177}Lu, ^{198}Au) under stent-guided or intratumoral administration. The main constraints—deep gradients and linker toxicokinetics—are addressed by *design* (rod-as-magnet + sphere-as-radio, shifted COM) and *infrastructure* (ferromagnetic inserts,

catheter routes). Thus, tandems are a realistic platform for combined radionanotherapy and high-precision imaging provided local sources of ∇B and standardized radiochemistry.

Nonlinearities of $M(H)$, dipolar self-assembly, and nonstationary response turn magnetic fluids into *programmable media*: one can *draw* channels of ∇B^2, create periodic traps, rectify transport, and obtain reproducible $\mathbf{B}$ profiles within the volume of interest. Effective strategies rest on three layers: (i) *microstructure* (polydispersity, shape), (ii) *field protocol* (DC+AC, rotating, multi-frequency), and (iii) *feedback* (MPS/MPI). Constraints—saturation, heating, and the geometry of gradient sources—require combining structural and field methods rather than relying solely on increasing H.

Two-component magnetic fluids with radio sources provide flexibility: separate optimization of magnetics and radiochemistry, use nonlinear assembly for *internal* gradient amplification, and lean on clinically verified references (Ho-166, ^{177}Lu) for dose verification. Depth limits persist and require *local* gradients (stents/inserts) and careful AC protocols. In the near term, practical pairs include SPION + ^{177}Lu (DOTA), $\mathrm{Fe_3O_4}$@Au $\rightarrow$ ^{198}Au, and for neutron activation—boron-containing magnetic composites for BNCT.

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