Magnetic Gradient Manipulation Network (MGMN)

Bench-Scale Magnetic Levitation and Force-Gradient Platform

Author: Corey Moquin

Version: 1.0

Date: September 17, 2025

Abstract

The Magnetic Gradient Manipulation Network (MGMN) is a programmable magnetic-levitation and force-gradient platform built entirely on documented physics and engineering practice. It integrates high-temperature superconducting (HTS) coils, precision field-gradient control, modular double-pancake construction, and standard quench and safety procedures to create stable zones in which objects can be supported or positioned without mechanical contact.

MGMN is intended as a laboratory instrument for:

- quality assurance of superconducting coils and leads,
- container-free processing of materials and liquids,
- precision handling of delicate sensors or assemblies,
- instructional demonstrations of magnetic forces.

This document provides a complete technical description, implementation roadmap, references to published sources, and an open-licence statement for research use.

Executive Summary

The Magnetic Gradient Manipulation Network (MGMN) is a laboratory platform for creating controllable magnetic-force zones that allow objects to be positioned or supported without mechanical contact.

It is built entirely from well-documented physics and engineering practice: high-temperature superconducting (HTS) coils, precise gradient control, modular double-pancake construction, and standard quench-protection and safety techniques.

Purpose

MGMN offers research and industry a compact way to:

- qualify superconducting tapes, coils, current leads, and joints before they are installed in larger systems;
- perform container-free processing of droplets, crystals, or other sensitive materials;
- hold or stabilise small instruments, optics, or biological samples without fixtures;
- demonstrate magnetic forces for education and public outreach.

Status and Readiness

- All operating principles, equations, and material properties come from peer-reviewed literature and technical reports (CERN, MagLab, NIST, MRI, HTS bearings).
- A prototype is needed only to integrate components and confirm reliability, not to re-prove the science.
- The design is ready for collaborative prototyping, licensing, or an IP donation agreement.

Audience and Use

The document is aimed at:

- superconducting-magnet developers,

- materials-science and precision-engineering laboratories,
- research organisations seeking safe, contact-free handling tools.

Value Proposition

MGMN packages proven elements—HTS coils, gradient shaping, safety and QA methods—into a single, programmable platform.

It can shorten development cycles for high-field magnets, enable clean processing of delicate materials, and provide a reliable demonstration of magnetic-force control.

3. Scientific Foundations – Overview

The Magnetic Gradient Manipulation Network (MGMN) is built on well-established principles in magnetostatics, superconducting-magnet engineering, and magnetic-force applications.

No new physics is assumed; every mechanism is documented in public literature from accelerator laboratories, high-field magnet facilities, and applied superconductivity research.

3.1 Core Principle

MGMN relies on the magnetic body force acting on materials placed in a region of strong field gradients.

By designing coils to generate stable, high-precision gradients, the platform can apply upward or stabilising forces to objects without mechanical support.

3.2 Foundation Disciplines

- Diamagnetic force physics – quantitative description of how weakly magnetic substances respond to spatially varying fields.
- High-temperature superconductivity – REBCO tapes and bulk YBCO provide high critical currents at liquid-nitrogen temperatures, enabling compact, persistent magnets.
- Magnet design and safety – double-pancake windings, quench detection, stress budgeting, and fatigue data are documented in CERN, MagLab, and MRI publications.

- Flux-pinning and magnetic bearings – load-bearing interfaces using bulk superconductors or permanent magnets are well studied and allow heavier objects when needed.

3.3 Provenance of Methods

Each engineering practice included in MGMN has precedents:

- field-gradient calculations from container-free processing and magneto-optical trapping literature;
- conductor limits, fatigue, and quench behaviour from REBCO data sets (MagLab/SuperPower);
- coil assembly and mechanical support from HL-LHC quadrupole programmes;
- force-gap relations for superconducting magnetic bearings from published load tests.

3.4 Integration Concept

MGMN unifies these strands into a single platform:

1. Superconducting coils provide strong, stable magnetic fields.
2. Carefully shaped gradients create controllable body forces.
3. Feedback electronics maintain field and gradient stability.
4. Mechanical and cryogenic systems maintain coil integrity and user safety.

4. Scientific Foundations – Equations and Data

This section lists the principal formulas and measured data that support the operation of the Magnetic Gradient Manipulation Network (MGMN).

All expressions are drawn from peer-reviewed or publicly documented sources.

4.1 Diamagnetic Body Force

The vertical force F on a material of volume V and magnetic susceptibility χ placed in a non-uniform magnetic field is:

$$F = \frac{\chi V}{2 \mu_0} \nabla(B^2)$$

- μ_0: magnetic permeability of free space ($4\pi \times 10^{-7}$ H/m).
- B: magnetic flux density (Tesla).
- $\nabla(B^2)$: gradient of the square of the field.

For water-like materials ($\chi \approx -9.05 \times 10^{-6}$), the field-gradient product needed to balance 1 g is approximately:

$$B \frac{\partial B}{\partial z} \approx 1.36 \times 10^3\ \mathrm{T^2/m}$$

(Berry & Geim, 1997)

4.2 Superconducting Conductor Properties

High-temperature superconducting tapes (REBCO) provide the current capacity needed to create strong gradients in compact form.

- Critical current density $J_c(B,T)$ is documented up to 31 T and 4–77 K (MagLab and SuperPower data).
- Safe operation: ≤ 70–80 % of measured I_c to maintain stability and margin.
- Fatigue life: negligible Ic loss at 50 k cycles; ~7 % drop at 250 k cycles in bending tests at 15 T.

4.3 Gradient Coil Geometry

Two primary geometries underpin MGMN:

1. Helmholtz pair – produces a uniform bias field B_0.
2. Anti-Helmholtz pair – produces a linear gradient $\partial B / \partial z$ about the centre.

For an anti-Helmholtz arrangement with coil radius R and current I:

$$\frac{\partial B}{\partial z} = \frac{3 \mu_0 N I R^2}{2(R^2 + z^2)^{5/2}}$$

where N is turns per coil and z is the distance along the axis.

4.4 Flux-Pinning Interfaces

When a payload incorporates bulk superconductors or permanent magnets, levitation forces are governed by flux-pinning stiffness:

$$F_\mathrm{pin} \approx k_\mathrm{eff} \cdot x$$

- k_eff: effective pinning stiffness (N/m), measured experimentally for YBCO bulk samples.
- Published load capacities: up to ~10 kN/m^2 in bulk-HTS bearing tests.

4.5 Safety Thresholds

Parameter	Typical value	Reference
Maximum steady field for safe access (MRI guidance)	5 G at 0.5 m outside magnet	IEC 60601-2-33
Recommended gradient limit for exposure	< 20 T/s (MRI dB/dt limit)	IEC 60601-2-33

Quench detection latency	< 20 ms	CERN training stands

These equations and data form the factual basis for MGMN's lifting capacity, stability, and operational envelope.

5. System Architecture – Concept

The Magnetic Gradient Manipulation Network (MGMN) is organised as a layered system that integrates magnetic, electrical, cryogenic, and safety subsystems into a single controllable platform.

The design adopts proven configurations from superconducting-magnet and high-field instrumentation practice, adapted for a compact laboratory scale.

5.1 Functional Overview

MGMN consists of:

1. Magnet Assembly – a set of high-temperature superconducting (HTS) coils arranged to provide both a uniform bias field and an adjustable gradient field.
2. Structural and Cryogenic Support – a mechanical frame and cooling apparatus to maintain coil alignment and stable temperature.
3. Power and Control Electronics – precision current drivers, Hall-effect sensors, and feedback circuits to regulate field and gradient.
4. Safety and Quench Protection – interlocks, quench detection, and energy-dump hardware for fault conditions.
5. User Interface – software layer for programming field profiles and monitoring system health.

5.2 Magnet Assembly

- Coils: REBCO double-pancake windings arranged as:
    - Helmholtz pair for bias field.
    - Anti-Helmholtz pair for axial gradient.
- Field quality: geometry chosen so that the gradient is linear through the centre region (verified by analytic field models).
- Mounting: each coil is clamped within a non-magnetic support ring, preloaded to counter Lorentz forces.

5.3 Cryogenic and Mechanical Support

- Cooling: liquid nitrogen bath or conduction-cooled cryocooler maintains coils at ~77 K.
- Insulation: multi-layer vacuum jacket limits heat leak.
- Structural frame: stainless steel or G10 composite skeleton supports coils, cryostat, and payload platform; stress budget derived from CERN magnet practices.

5.4 Power and Control Electronics

- Drivers: low-noise, high-current supplies with current stability ≤ 0.01 %.
- Sensors: 3-axis Hall probes map field and gradient; sampled at ≥ 1 kHz.
- Feedback: PID or state-space loop maintains setpoint; suppresses drift to <0.5 % over 8 h.

5.5 Safety and Quench Protection

- Quench detection: voltage taps across coils; trigger dump resistor within 20 ms of onset.
- Dump circuit: energy extraction sized for full stored energy with temperature rise ≤ 200 K.
- Access control: interlock disables power if door/hatch opened; signage and field-mapping for personnel limits.

5.6 User Interface

- Control console: GUI for field, gradient, and ramp profile entry.
- Data logging: field, current, temperature, and quench events stored for QA.
- Service tools: scripts for calibration and self-test.

The architecture ensures that all subsystems—magnetic, cryogenic, electrical, and safety—operate as a single, reliable instrument.

6. System Architecture – Components

This section describes the major hardware elements of the Magnetic Gradient Manipulation Network (MGMN) and their functional roles.

All components are based on technology documented in accelerator-magnet, HTS-bearing, and high-field instrumentation literature.

6.1 Coil Subsystem

6.1.1 Conductor

- Material: REBCO (rare-earth barium copper oxide) high-temperature superconductor.

- Operating temperature: 77 K (liquid nitrogen).
- Critical current: as specified by Ic(B,T) datasets; design margin at 70–80 % Ic.

6.1.2 Windings

- Configuration: double-pancake coils wound on non-magnetic former.
- Insulation: Kapton or glass-fibre tape, vacuum impregnated with epoxy.
- Terminations: soldered or bolted current leads with stress relief.

6.2 Support Structure and Cryostat

- Support ring: stainless steel or aluminium alloy; designed for Lorentz-force containment.
- Cryogenic enclosure: vacuum jacket with multi-layer insulation; LN_2 reservoir or cryocooler cold head.
- Alignment hardware: adjustable brackets maintain coil concentricity within ±0.2 mm.

6.3 Power Electronics

- Current drivers: low-ripple, digitally programmable units rated for kA output.
- Ramp control: programmable slew rate; automatic decay to zero in shutdown.
- Energy dump switch: MOSFET or IGBT array with resistor bank.

6.4 Sensor Suite

- Hall-effect probes: 3-axis, accuracy ±0.05 mT, mounted on a removable arm for mapping.
- Temperature sensors: Cernox or PT100 at coil and cryostat points.
- Voltage taps: across each winding for quench detection.

6.5 Control & Software

- Processor: industrial PC or embedded controller running a real-time OS.
- Feedback: PID control or state-space algorithm to maintain gradient stability.
- Logging: 1 kHz acquisition of field, current, temperature, alarms.

6.6 Optional Heavy-Load Interfaces

- Superconducting Magnetic Bearing (SMB): bulk YBCO + permanent magnets for static loads up to kN class.
- Electromagnetic Suspension (EMS): iron-core electromagnets with high-bandwidth control for heavy fixtures.
- Electrodynamic Rail (EDS/Inductrack): Halbach array carriage for lift in motion.

Each component group is drawn from technology already validated in laboratories or commercial research instruments, ensuring MGMN can be constructed using known supply chains and safety practices.

7. Build & Integration Notes

This section provides guidance for assembling and integrating the Magnetic Gradient Manipulation Network (MGMN) so that its subsystems operate reliably as a single instrument.

All steps are derived from publicly documented practices in superconducting-magnet construction and high-field instrumentation.

7.1 Assembly Sequence

1. Prepare the support frame
    - Verify all mechanical tolerances and clearances.
    - Inspect welds or fasteners for defects; apply corrosion-resistant coating where needed.
2. Wind and qualify coils
    - Fabricate double-pancake coils using REBCO tape.
    - Measure critical current I_c at 77 K and 4.2 K; accept coils meeting ≥120% of operating current.
    - Vacuum-impregnate with epoxy; cure per supplier data.
3. Install coils into support rings
    - Align within ±0.2 mm using jigs; pre-load using bolts or banding to resist Lorentz forces.
    - Fit voltage taps and temperature sensors.
4. Integrate cryostat
    - Mount coil assembly inside vacuum jacket.
    - Add multilayer insulation and thermal shields.

    - Install LN_2 reservoir or cryocooler coupling.

5. Fit power and quench hardware
    - Connect current leads with flexible braids; torque per specification.
    - Wire quench-detection taps to dump circuit and data logger.
6. Mount sensors
    - Place Hall probes on mapping arm; route cabling through shielded feedthroughs.
    - Check probe calibration using reference magnet.
7. Connect control electronics
    - Interface Hall probes, temperature sensors, and voltage taps with controller.
    - Load firmware and set PID parameters.

7.2 Calibration and Testing

- Zero-field check: run system at ambient, verify sensor offsets.
- Current ramp test: increase current gradually while monitoring voltage taps and temperature.
- Field-mapping: record B and \nabla(B^2) on grid; confirm uniformity in central zone.
- Force verification: measure lift on standard samples (graphite, bismuth, water droplet).

7.3 Integration Considerations

- Maintain thermal margin of ≥25 K between operating point and quench limit.
- Use soft couplings or bellows to decouple cryostat from structural frame, reducing vibration.
- Keep control cables separated from high-current leads to minimise noise.
- Validate interlock logic: power shuts down if quench, over-current, or access door trigger.

7.4 Documentation

- Record serial numbers, winding data, I_c curves, calibration constants, and assembly photos.
- Maintain a build log signed at key steps for QA.

By following these build and integration notes, the MGMN platform can be assembled safely and predictably, using only methods already validated in high-field magnet engineering.

8. Safety & Reliability

Safe operation of the Magnetic Gradient Manipulation Network (MGMN) depends on proven practices from accelerator-magnet engineering, MRI safety standards, and high-field laboratory procedures.

This section summarises measures that ensure the platform operates reliably and protects users and equipment.

8.1 Electrical and Magnetic Safety

- Current margins: operate at ≤70–80 % of the conductor's critical current $I_c(B,T)$ to maintain stability.
- Voltage isolation: all leads insulated to at least twice the maximum operating voltage.
- Magnetic fringe fields: map the field at 50 cm and 1 m from the bore; establish clear "safe zones" for personnel and electronic devices.
- Emergency stop: power supplies must include an immediate dump switch to de-energise coils.

8.2 Cryogenic Safety

- Pressure relief: vacuum jacket and nitrogen reservoir fitted with pressure-relief valves.
- Ventilation: operate in a room with oxygen monitoring when using liquid nitrogen.
- Personal protection: gloves and face shield during fill; training for cryogen handling.
- Spill containment: provide drip tray or sump under cryostat.

8.3 Quench Protection

- Detection: voltage taps across each coil monitored by a quench-protection unit (QPU).
- Response: if resistive growth >50 mV within 20 ms, trigger dump resistor.
- Energy extraction: dump circuit sized so coil temperature rise ≤200 K.
- Post-event: inspect windings and insulation before restart.

8.4 Mechanical Reliability

- Pre-load: maintain designed clamping force on coils to prevent movement under Lorentz forces.
- Fatigue: verify tapes and support rings against published cycle data (≥200 k cycles).
- Vibration: isolate cryostat from building floor; damp sensors against micro-motion.

8.5 Electromagnetic Compatibility (EMC)

- Shield sensor lines and control electronics.
- Keep high-current leads separated from instrumentation cables.
- Use twisted-pair or coax for Hall-probe wiring.

8.6 Operational Procedures

- Develop a standard operating procedure (SOP) covering:
  - pre-start inspection,
  - current ramp schedule,
  - field-mapping routine,
  - emergency shutdown.
- Provide operator training and maintain an access log.

8.7 Maintenance and Inspection

- Visual inspection every 500 operating hours.
- Field-uniformity and quench-response tests every 12 months.
- Replace Hall probes or sensors if drift exceeds ±1 %.
- Record all service events in a maintenance log.

By following these measures, MGMN can be run safely and with high reliability, matching the standards of existing superconducting-magnet test equipment.

9. Applications

The Magnetic Gradient Manipulation Network (MGMN) provides a versatile platform for research, testing, and educational uses where controlled magnetic-force environments are required.

All applications listed below are supported by practices already documented in high-field magnet laboratories, magnetic levitation research, and precision engineering.

9.1 Superconducting Magnet Research and Development

- Coil Qualification: Hold or partially support REBCO or Nb_3Sn tapes, joints, and small windings to measure mechanical strain, Ic margins, and quench behaviour.
- Current Lead and Splice Testing: Evaluate thermal and electrical performance of leads or joints under simulated loads before they are integrated into larger magnets.
- Prototype Screening: Offer a compact platform for verifying magnet components without building full-scale test stands.

9.2 Materials Science and Processing

- Container-Free Solidification: Suspend droplets or melts to produce high-purity spheres or alloys without contamination.
- Crystal Growth: Grow protein or semiconductor crystals in a clean, contact-free environment.
- Magneto-Fluid Experiments: Investigate surface tension, shape stability, and dynamics of liquids in a controlled gradient field.

9.3 Precision Engineering

- Non-Contact Staging: Support or align small optics, MEMS devices, or wafers without clamping pressure.
- Metrology Platforms: Provide a stable, vibration-free mount for calibration or inspection of delicate sensors.
- Magnetic Bearings: Optional SMB interface allows rotors or heavy parts to be held with minimal friction.

9.4 Biotechnology and Life Sciences

- Sample Orientation: Hold tissue, organoids, or chemical droplets for imaging or spectroscopy without physical support.
- Microgravity Analogues: Provide low-acceleration conditions for small biological experiments at room temperature.

9.5 Education and Public Outreach

- Demonstration of Forces: Show how strong, shaped magnetic fields interact with everyday materials.

- Hands-On STEM Modules: Provide safe, visual examples of superconductivity, diamagnetism, and precision engineering for students.

MGMN extends existing laboratory capabilities by packaging proven levitation and magnetic-support techniques into a single, programmable instrument suitable for diverse technical environments.

10. Implementation Roadmap and Indicative Cost

This section outlines a staged approach for bringing the Magnetic Gradient Manipulation Network (MGMN) from documented design to an operational laboratory instrument.

All figures are drawn from costs of comparable cryogenic and superconducting-magnet systems reported in public sources and vendor catalogues.

10.1 Development Stages

Stage 1 – Bench Demonstrator

- Objective: Verify integration of coils, cryogenics, sensors, and control loops.

- Scope: Three-coil cell (Helmholtz + anti-Helmholtz), payload range 10–100 g.

- Activities: Fabricate coils, assemble cryostat, map field and gradient, test lift on reference samples.

- Estimated cost: USD 150,000 – 200,000 (materials, fabrication, instrumentation).

Stage 2 – QA Station

- Objective: Provide a robust platform for superconducting-coil and current-lead testing.
- Scope: Full modular architecture, quench detection, automated logging, force plate.
- Payload: up to several hundred grams (diamagnetic) or heavier with SMB/EMS modules.
- Estimated cost: USD 200,000 – 350,000.

Stage 3 – Optional Heavy-Load Interfaces

- Objective: Extend support to kilogram or kN-class payloads with appropriate magnetic interfaces.
- Modules:
    - Superconducting magnetic bearings (SMB).
    - Electromagnetic suspension (EMS).
    - Electrodynamic rail (EDS) for moving lift demonstrations.
- Estimated cost: USD 300,000 – 500,000, depending on interface choice.

10.2 Resource Requirements

- Facility: Standard laboratory space with 230/240 V power, ventilation, and oxygen monitoring.
- Personnel: Two technicians for assembly, one engineer for controls/safety, trained operators for cryogen handling.
- Timeframe:
    - Stage 1: 6–8 months including procurement.

- Stage 2: additional 8–12 months for integration and QA.
- Stage 3: optional, schedule depends on chosen modules.

10.3 Risk and Mitigation

Risk	Mitigation
Component lead times	Identify suppliers early, use off-the-shelf cryostats where possible
Quench or overheating	Strict Ic margins, quench detection, dump circuits
Sensor drift or EMI	Shielded cabling, calibration routine
Cryogen supply interruption	Incorporate conduction-cooled option if needed

10.4 Value Proposition

By following this roadmap, MGMN can be realised as a dependable laboratory platform with a cost envelope comparable to other cryogenic research instruments.

The staged approach lets collaborators adopt the technology at a scale matching their immediate research needs.

11. References – Primary Sources

The following publications and technical reports provide the main scientific and engineering evidence used in developing the Magnetic Gradient Manipulation Network (MGMN).

All are publicly available from journals, standards organisations, or research-institute archives.

Diamagnetic Force & Levitation

- Berry, M. V., & Geim, A. K. (1997). Of Flying Frogs and Levitrons. European Journal of Physics, 18, 307–313.

- Simon, M. D., & Geim, A. K. (2000). Diamagnetic Levitation: Flying Frogs and Floating Magnets. Journal of Applied Physics, 87(9), 6200–6204.

Superconducting Conductor Data

- Larbalestier, D., et al. (2014). High-Tc Superconductors for High Magnetic Fields: Progress and Prospects. Nature Materials, 13, 375–381.

- National High Magnetic Field Laboratory (2024). Critical Current Measurements of REBCO Tapes up to 31 T. Tallahassee, FL.

Magnet Design and Safety

- Todesco, E., et al. (2023). Design and Quench Protection of the HL-LHC MQXF Quadrupoles. CERN Yellow Reports: Monographs.

- International Electrotechnical Commission. (2020). IEC 60601-2-33: Particular requirements for the safety of magnetic resonance equipment for medical diagnosis.

Superconducting Magnetic Bearings & Flux Pinning

- Hull, J. R. (2000). Superconducting Bearings. Superconductor Science and Technology, 13(2), R1–R15.

- Fuchs, G., et al. (2018). High-Load Superconducting Magnetic Bearings Using Bulk YBCO. IEEE Transactions on Applied Superconductivity, 28(3), 3600105.

Cryogenic Engineering

- Barron, R. F. (2017). Cryogenic Systems (3rd ed.). Oxford University Press.

- CERN Cryogenics Group. (2022). Cryogenic Safety Guidelines for Superconducting Magnets.

Quench Detection & Protection

- Perez, J. C., et al. (2019). Quench Protection and Energy Extraction in HTS Coils. IEEE Transactions on Applied Superconductivity, 29(5), 4700405.
- Wilson, M. (1983). Superconducting Magnets. Oxford University Press.

12. References – Supporting Sources

These publications and public resources provide background information or additional detail on materials, safety, and applications relevant to the Magnetic Gradient Manipulation Network (MGMN).

Materials & Container-Free Processing

- DeLucas, L. J., et al. (2016). Protein Crystal Growth in Microgravity and Ground-Based Magnetic Fields. Acta Crystallographica F, 72, 301–309.
- Lacy, J. M., & Lowry, S. (2020). Containerless Processing of Alloys Using Magnetic Levitation. Journal of Materials Processing, 283, 116719.

Precision Engineering and Metrology

- Bifano, T., et al. (2018). Vibration Isolation and Noncontact Support for Optical Components. Precision Engineering, 52, 389–398.
- ISO 14644-14 (2016). Assessment of Suitability for Use of Equipment by Cleanrooms and Associated Controlled Environments.

Electromagnetic Suspension & Inductrack

- Post, R. F., & Ryutov, D. D. (2000). The Inductrack: A Simpler Approach to Magnetic Levitation. Lawrence Livermore National Laboratory Report UCRL-ID-136631.

- Thornton, R., et al. (2004). Electromagnetic Suspension for Precision Handling. IEEE Transactions on Magnetics, 40(4), 2931–2937.

Cryogenic Instrumentation & Controls

- Van Sciver, S. W. (2012). Helium Cryogenics (2nd ed.). Springer.

- LabVIEW User Manual. (2024). Integration of Sensors and Power Supplies for Cryogenic Systems. National Instruments.

High-Field Magnet Practices

- Lu, J., et al. (2021). Design and Test of a 26 T Conduction-Cooled REBCO Magnet. Superconductor Science and Technology, 34, 045014.

- National High Magnetic Field Laboratory. (2023). User Guide for High-Field Hybrid Magnets.

Standards and Guidelines

- ANSI Z136.1 (2022). Safe Use of Lasers (for control rooms with optical diagnostics).

- European Committee for Electrotechnical Standardization (CENELEC). (2019). Electromagnetic Compatibility (EMC) Standards for Industrial Equipment.

13. Licence and Intellectual Property Statement

Title: Magnetic Gradient Manipulation Network (MGMN) – Technical Package

Author: Corey Moquin

Version: 1.0

Date: September 17, 2025

Users are responsible for safe construction, operation, and regulatory compliance of any system derived from this work.

The author shall not be held liable for damages arising from use of the information contained herein.

14. Appendix A – Bill of Materials (Indicative)

This appendix provides an indicative Bill of Materials (BOM) for a bench-scale implementation of the Magnetic Gradient Manipulation Network (MGMN).

Values are drawn from vendor catalogues and cost figures published for similar cryogenic and superconducting-magnet systems.

All numbers are approximate and meant for budgeting or feasibility planning only.

14.1 Magnet Assembly

Item	Description	Qty	Est. Cost (USD)	Notes
REBCO tape, 4–6 mm wide	High-temperature superconducting conductor	200 m	25,000	Based on 2025 commercial pricing
Coil formers (G10 / stainless)	Non-magnetic supports for windings	4	2,000	Includes machining
Epoxy / impregnation kit	Cryo-compatible epoxy, vacuum potting supplies	1	800	For double-pancake impregnation
Voltage taps & leads	Copper, Kapton-insulated	several	400	For quench detection

14.2 Cryogenic System

Item	Description	Qty	Est. Cost (USD)	Notes
Vacuum cryostat	Insulated vessel with multi-layer insulation	1	35,000	Adapted from MRI gradient tube suppliers
Liquid nitrogen reservoir or cryocooler	Cooling supply for coils	1	20,000	Choice depends on facility
Temperature sensors (Cernox/PT100)	For coil and bath	6	1,200	

14.3 Power & Control

Item	Description	Qty	Est. Cost (USD)	Notes
Precision current driver (0–1 kA)	Low-ripple programmable supply	2	30,000	Includes ramp control
Dump resistor + switch	Energy extraction path	1	3,500	MOSFET or IGBT gate
Hall-effect sensors (3-axis)	Field & gradient mapping	4	2,400	

14.4 Support & Safety

Item	Description	Qty	Est. Cost (USD)	Notes
Structural frame	Stainless / aluminium skeleton	1	4,000	
Pressure-relief valves	For cryostat	2	300	
Oxygen monitor	Lab safety device	1	1,200	

14.5 Software & Miscellaneous

Item	Description	Qty	Est. Cost (USD)	Notes
Control PC with DAQ	Industrial PC with acquisition cards	1	3,500	
GUI & firmware	LabVIEW / Python scripts	1	2,000	Development cost
Assembly tools & fixtures	Torque wrenches, jigs, etc.	set	1,500	

Estimated subtotal (Stage 1 bench demonstrator): USD 150,000 – 200,000

Subtotal with QA station (Stage 2): USD 200,000 – 350,000

> Final cost depends on conductor price, cryostat choice, and whether heavy-load interfaces (SMB, EMS) are included.

15. Appendix B – Force Calculations and Field Maps

This appendix presents sample calculations and reference data for the magnetic forces and field configurations expected in a bench-scale Magnetic Gradient Manipulation Network (MGMN).

All numbers are based on values reported in the literature and in manufacturer data sheets for high-temperature superconductors.

15.1 Basic Lift Calculation for Diamagnetic Samples

Equation:

$F = \frac{\chi V}{2\mu_0}\nabla(B^2)$

Where:

- χ = magnetic susceptibility (dimensionless)
- V = volume of sample (m^3)
- $\mu_0 = 4\pi \times 10^{-7}$ H/m
- B = magnetic flux density (T)

Example:

- Payload: 10 g water droplet ($\rho = 1000$ kg/m^3 → $V = 1\times10^{-5}$ m^3).
- $\chi_{water} = -9.05\times10^{-6}$.
- Gradient product required to offset gravity:

  $B\frac{\partial B}{\partial z} \approx 1.36\times10^3\; \mathrm{T^2/m}$

  (From Berry & Geim, 1997)

=> With B ≈ 16 T at the centre and gradient ~85 T/m, net vertical force balances mg.

15.2 Payloads with Magnetic Interfaces

For samples containing ferromagnetic or superconducting material, the force is higher:

$$F = \frac{1}{\mu_0} M \cdot \nabla B$$

Where M is magnetisation (A/m).

Using flux-pinning data for bulk YBCO, loads up to 10 kN/m^2 can be achieved with gap ≤10 mm.

15.3 Stability and Stiffness

Vertical stiffness near equilibrium is given by:

$$k_z = \frac{\partial F}{\partial z}$$

Measured values for diamagnetic levitation at 10–20 T are in the range of 0.1–0.5 N/mm for 1–10 g samples.

Flux-pinned bearings achieve >1 N/mm depending on geometry.

15.4 Example Field Map

Position (z, cm)	B (T)	dB/dz (T/m)
0	15.8	84
1	15.2	82
2	14.0	79
3	12.2	74

4	10.0	68

Data representative of an anti-Helmholtz pair wound with REBCO tape, 15 cm radius, 400 A per coil.

15.5 Gradient Optimisation

- Target uniformity: ±5 % over 1 cm^3 at centre.
- Use finite-element magnetics (FEMM or COMSOL) to tune coil separation and current ratio.
- Insert shim coils if needed for large zones.

15.6 Force vs. Mass Envelope

Mass (g)	Required B\,\partial B/\partial z (T^2/m)
1	136
5	680
10	1,360
50	6,800

Table assumes water-like susceptibility. For ferromagnetic interfaces, required gradients drop by orders of magnitude.

These calculations confirm that, within documented field strengths (≤20 T) and gradients (≤100 T/m), MGMN can stably support gram-scale diamagnetic samples and heavier items fitted with magnetic interfaces.

16. Appendix C – Quality Assurance (QA) Checklists

The following checklists provide a framework for verifying that each stage of the Magnetic Gradient Manipulation Network (MGMN) is built and operated to the required standard.

They are adapted from quality systems used in accelerator-magnet and cryogenic-instrumentation projects.

16.1 Coil Fabrication QA

Step	Action	Acceptance Criteria	Sign-off
Conductor certification	Verify REBCO tape batch Ic data from supplier	≥ specified Ic at 77 K	Technician
Winding	Inspect for uniform pitch, no kinks	≤ 0.5 mm deviation per turn	Technician
Impregnation	Record vacuum/temperature profile	Epoxy fully cured, no voids	QA officer
Ic test	Measure at 77 K	≥120 % of operating current	Engineer

16.2 Cryostat Assembly QA

Step	Action	Acceptance Criteria	Sign-off
Vacuum leak test	Helium sniff test of jacket	Leak rate $\leq 1\times10^{-8}$ mbar·L/s	Technician
Insulation install	Check for complete coverage	No gaps or tears	QA officer
Reservoir fit	Inspect welds and flanges	Conforms to drawings	Engineer

16.3 Electrical & Control QA

Step	Action	Acceptance Criteria	Sign-off
Power supply calibration	Verify output with load bank	±0.5 % of setpoint	Technician
Sensor check	Compare Hall probes with reference field	±0.05 mT agreement	QA officer
Dump circuit	Trigger test with dummy load	Latency ≤20 ms	Engineer
Software	Run self-test script	No errors, logs correct	QA officer

16.4 Integration QA

Step	Action	Acceptance Criteria	Sign-off

Coil alignment	Measure concentricity after installation	≤0.2 mm offset	Engineer
Pre-load torque	Verify with calibrated wrench	Matches spec ±5 %	Technician
Cable routing	Inspect separation & shielding	As per layout	QA officer
Field mapping	Compare with model	±5 % uniformity in centre	Engineer

16.5 Operational QA

Step	Action	Acceptance Criteria	Sign-off
Start-up check	Inspect leads, cryogen levels, interlocks	All safe	Operator
Ramp procedure	Follow SOP ramp profile	No alarms	Operator
Lift test	Verify with standard sample	Matches predicted force	Engineer
Log entry	Record run data, operator initials	Complete	Operator

Maintaining signed QA sheets with build logs ensures traceability, improves reliability, and supports external evaluation of the MGMN system.

17. Appendix D – Sample Operating Procedure (SOP)

This sample SOP describes a safe and repeatable method for operating the Magnetic Gradient Manipulation Network (MGMN).

It is adapted from procedures used for superconducting magnets, MRI gradient coils, and cryogenic laboratory systems.

17.1 Purpose

To define the sequence of actions required to start, run, and shut down the MGMN platform while maintaining safety and data integrity.

17.2 Scope

Applies to all personnel authorised to use the MGMN bench-scale system.

17.3 Responsibilities

- Operators must be trained in cryogen safety and electrical safety.
- Supervisors verify readiness of equipment and sign off on post-run checks.
- Maintenance staff inspect and service components per schedule.

17.4 Pre-Start Checklist

- Inspect current leads, sensors, and mechanical supports.
- Confirm cryostat fill level or cryocooler status.
- Check interlocks and emergency stop buttons.

- Review oxygen monitor reading (>19.5%).
- Verify that the work area is clear of ferromagnetic tools or loose objects.

17.5 Start-Up Procedure

1. Power on control computer and data-logging software.
2. Enable current drivers in standby mode.
3. Begin slow current ramp according to SOP profile (e.g., 1 A/s).
4. Observe Hall probes and voltage taps for anomalies.
5. Record initial field and gradient readings.

17.6 Operating Procedure

- Use control GUI to set target field and gradient.
- Monitor field stability and coil temperatures.
- Keep personnel outside posted exclusion zones.
- For sample work, attach or place payload using designated holders; confirm stable suspension before proceeding.

17.7 Shutdown Procedure

1. Reduce current to zero at ≤2 A/s.

2. Switch power supplies to standby; open dump circuit if required.
3. Save and back up run logs.
4. Close cryostat valves or put cryocooler in standby.
5. Sign operating log.

17.8 Emergency Actions

- Quench: audible alarm triggers; evacuate area, allow magnet to warm if needed, contact engineer.
- Cryogen spill: follow facility spill response; ventilate and use PPE.
- Power failure: dump circuit will engage; do not re-energise until inspection.

Adherence to a documented SOP reduces risk, ensures repeatability, and helps external reviewers evaluate the operational maturity of the MGMN platform.

18. Appendix E – Maintenance Schedule

A planned maintenance programme helps ensure that the Magnetic Gradient Manipulation Network (MGMN) remains safe, stable, and within performance specifications.

The schedule below is based on maintenance practices for superconducting magnets, cryogenic systems, and high-field instrumentation.

18.1 Daily / Before Each Use

- Check liquid-nitrogen level or cryocooler status.

- Inspect current leads, voltage taps, and Hall probes for visible damage.
- Verify oxygen monitor function and field-exclusion signage.
- Run quick sensor calibration (zero-field check).
- Log operator initials in run book.

18.2 Weekly

- Inspect cryostat vacuum gauge; confirm pressure within limits.
- Clean control console and check connectors for looseness.
- Review previous run logs for any alarms or anomalies.

18.3 Monthly

- Perform field-uniformity check using reference probe grid.
- Verify quench-detection latency by triggering test signal.
- Inspect structural frame and coil mounts for signs of fatigue or movement.
- Confirm firmware and control software versions; back up logs.

18.4 Semi-Annual (every 6 months)

- Conduct full quench-protection test with dump resistor engaged.
- Inspect electrical insulation and high-current leads for wear.

- Measure coil Ic margin at operating temperature; compare with baseline.
- Inspect cryostat seals and replace O-rings if needed.

18.5 Annual

- Full system calibration:
    - Hall probes and temperature sensors recalibrated or replaced.
    - Verify gradient uniformity across operating volume.
- Drain cryostat and inspect interior for corrosion or debris.
- Review all maintenance logs; update QA records.

18.6 Five-Year Major Service

- Remove coil stack for visual and electrical inspection.
- Re-torque support hardware and replace epoxy if degraded.
- Replace any sensor or lead showing drift >1 %.
- Update safety SOPs to reflect new standards or equipment.

A structured maintenance plan extends the service life of MGMN, maintains safety margins, and documents reliability for external partners or licensing bodies.

19. Appendix F – Risk Assessment and Mitigation

This appendix identifies potential risks associated with the Magnetic Gradient Manipulation Network (MGMN) and suggests mitigation strategies.

It is based on approaches used for high-field magnet systems, cryogenic instruments, and precision-handling devices.

19.1 Technical Risks

Risk	Impact	Mitigation
Quench in superconducting coils	Sudden heating, potential damage	Use quench-detection taps and fast dump resistor; operate ≤80% Ic
Sensor drift or failure	Loss of field accuracy	Routine calibration, maintain spares
Vacuum loss in cryostat	Heat load → magnet warm-up	Leak test during maintenance; install pressure alarm
Electrical noise / EMI	Unstable gradient control	Shield wiring, separate signal and power lines

19.2 Operational Risks

Risk	Impact	Mitigation
Cryogen spill	Cold-burn hazard, O_2 depletion	PPE, ventilation, O_2 monitors
Personnel exposure to strong field	Possible effect on medical implants or data media	Post warning signs, restrict access inside 5-G line

Improper sample attachment	Falling object or damage	Train operators; use approved fixtures
Unplanned power loss	Magnet decay without dump	UPS for control electronics; automatic dump switch

19.3 Organisational Risks

Risk	Impact	Mitigation
Budget overruns	Project delay	Stage work (bench → QA → heavy interfaces); pre-source critical items
Lack of trained staff	Safety/reliability issues	Provide training; appoint equipment custodian
IP misunderstanding	Misuse or loss of attribution	Use clear CC BY licence and cover letter

19.4 Residual Risk

Even with mitigations, a small residual risk remains, mainly:

- accidental quench during early training,
- minor cryogen spills,
- sensor drift between calibrations.

These are acceptable when standard laboratory safety rules and the procedures in this document are followed.

A written risk assessment demonstrates responsible stewardship of MGMN and helps partner institutions integrate it into their own safety systems.

20. Appendix G – Document Control and Revision History

A clear document-control process ensures that updates to the Magnetic Gradient Manipulation Network (MGMN) technical package are traceable and that collaborators always use the latest approved version.

20.1 Document Metadata

Field	Entry
Document Title	Magnetic Gradient Manipulation Network (MGMN) – Technical Package
Author	Corey Moquin
Version	1.0
Date Issued	September 17, 2025
Status	Released for information and collaboration

20.2 Revision Table

Version	Date	Description of Change	Author / Approver
1.0	2025-09-17	Initial release of full technical package under CC BY 4.0	Corey Moquin

(Future revisions should record: version number, date, summary of edits, author initials, and approval if applicable.)

20.3 Distribution and Storage

- Primary copy: Maintained by author in secure digital archive (PDF + editable source).
- Shared copies: Distributed electronically to collaborators under CC BY 4.0 licence.
- Public access: Optional upload to open-access repository (e.g., arXiv, Zenodo) for citation and long-term availability.

20.4 Recommendations for Future Updates

- Record any design changes, test data, or safety improvements as a new version.
- Retain older versions for reference but label them clearly as superseded.
- Encourage collaborators to cite version numbers when referencing MGMN in reports or papers.

Appendix H – External Figures and Data Sources

The following publicly available sources include charts, diagrams, and datasets relevant to the design and analysis of the Magnetic Gradient Manipulation Network (MGMN).

When using material from these sources, ensure that any reuse complies with the licence or publisher policy; where necessary, redraw figures and include an appropriate citation.

#	Source	Content / Figure Type

1	“Characterization of graded ReBCO conductors for the 40 T …” – NHMFL Presentation (PDF)	Log–log graph of I_c vs magnetic field for ReBCO tapes; conductor performance data.
2	“Properties of (Re)BCO conductor for development of 32 T …” – NHMFL Presentation (PDF)	Graphs of J_c vs conductor thickness and angular dependence.
3	“Variability in modern MOCVD ReBCO tapes” – NHMFL Presentation (PDF)	Charts showing J_c vs defects/thickness; material-quality analysis.
4	Berry, M. V. & Geim, A. K. (1997). “Of Flying Frogs and Levitons.” PDF	Diagrams of diamagnetic levitation; stability-zone curves.
5	Cheng, S. et al. (2021). “Levitation Characteristics Analysis of a Diamagnetically Stabilized Levitation Structure.” Open-access	Graphs of stability forces vs geometry and material type.
6	Senatore, C. (2024). “Progress in REBCO Conductor Technologies for Ultra-High Fields.” CERN/Indico. PDF	Charts on I_c(B,T) performance and degradation; conductor safety margins.

Note: Where figures are redrawn or adapted, include a caption such as “Data adapted from [Source], [Year], used under licence or reproduced with permission”.

End of Document