HIGH-UNIFORMITY MAGNETIC FIELD OPTIMIZATION FOR TRAPPED-ION QUANTUM DEVICES

Nelson Ooi, advised by Professor Karan Mehta

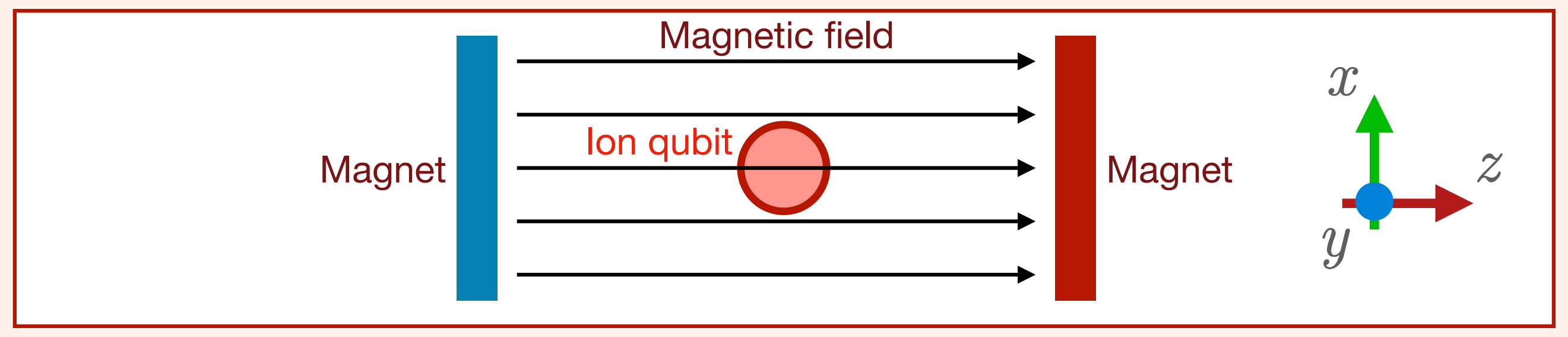
Cornell University
School of Electrical and Computer Engineering

Funded by Engineering Learning Initiatives

ABSTRACT

Trapped-ion quantum information processors require magnetic fields to define a quantization axis for qubit addressability [1]. However, spatial magnetic field gradients can cause undesirable ion qubit dephasing effects that distort encoded information [2], and introduce fluctuations in carrier frequencies that limit addressability [3]. Prior works on magnet geometries have achieved ~100ppm average nonuniformity over the ion trap [1, 4].

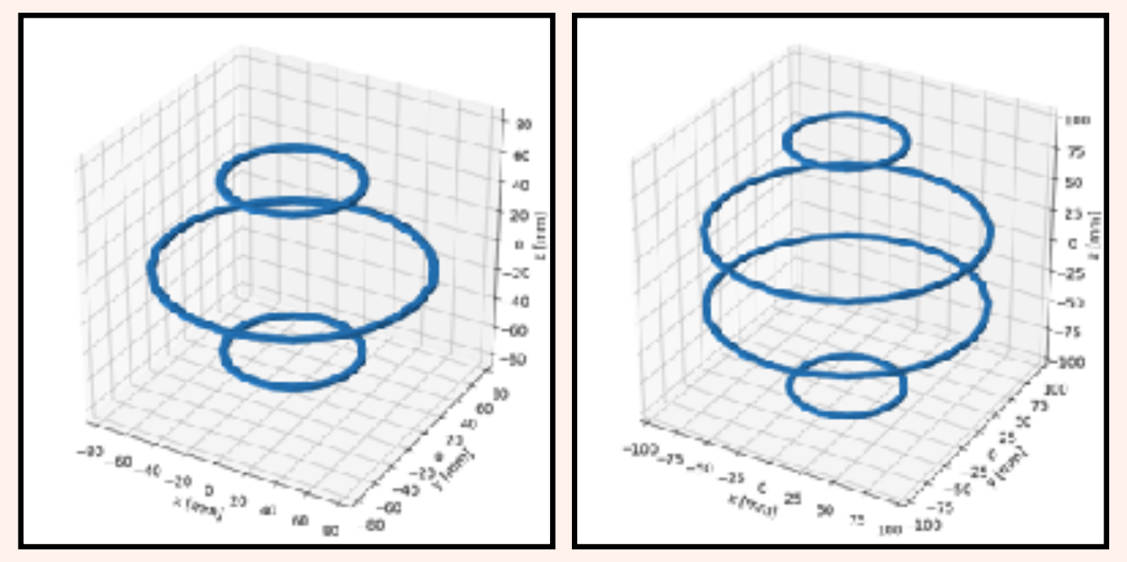
We present a novel multi-objective optimization scheme for permanent magnet geometries, and show that it can lead to **orders of magnitude improvements in magnetic field nonuniformity**, while potentially enabling **greater customization** of field strengths produced in the region of interest (ROI). We furthermore explore the **effect of permanent magnet manufacturing tolerances** on target metrics.



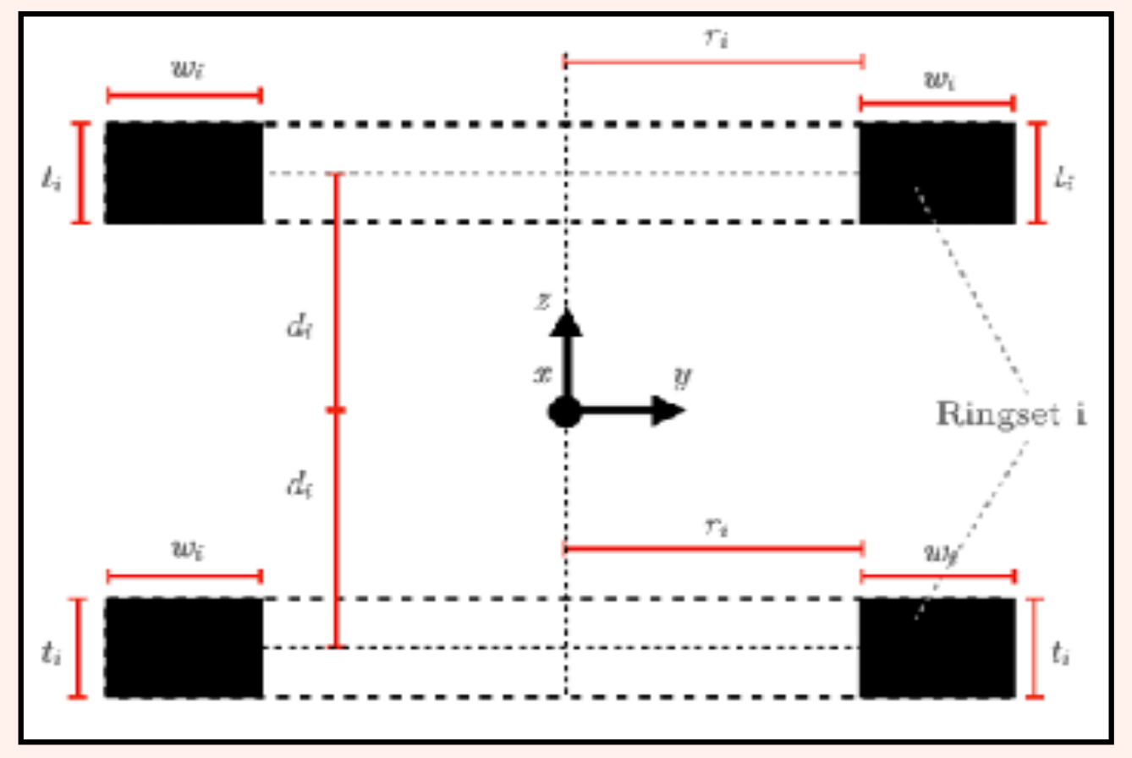
BACKGROUND

Nominal permanent magnet geometries chosen for optimization.

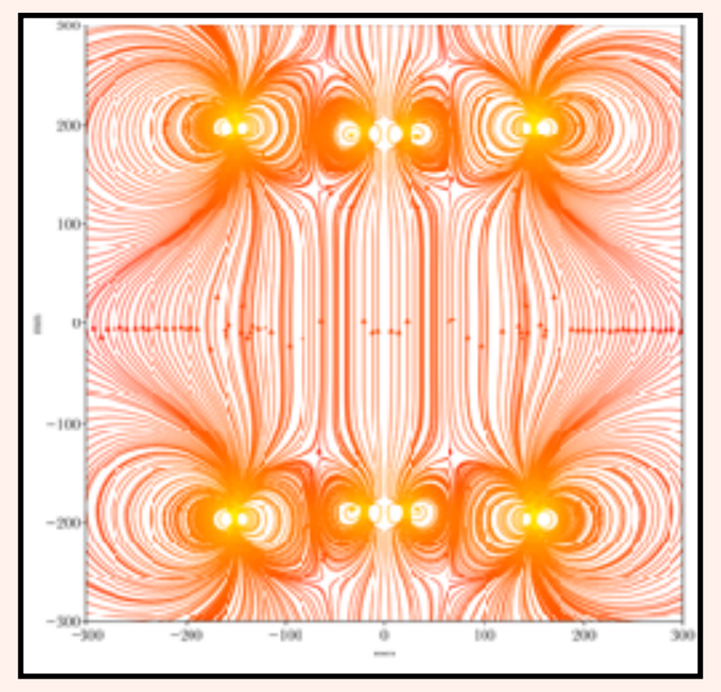
N-ring geometries



N = 3 and 4 ring geometries.



Ringset dimensions to be optimized.

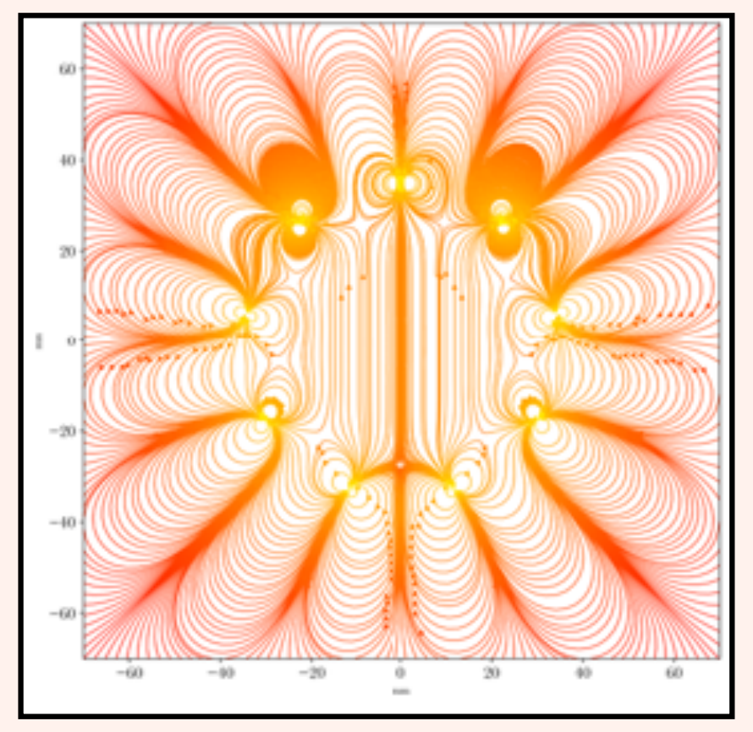


N-ring geometries are defined in terms of symmetric ringsets composed of 2 rings that each share the same dimensions and are equidistant from the origin. Each N-ring geometry has $\left\lceil \frac{N}{2} \right\rceil$ ringsets.

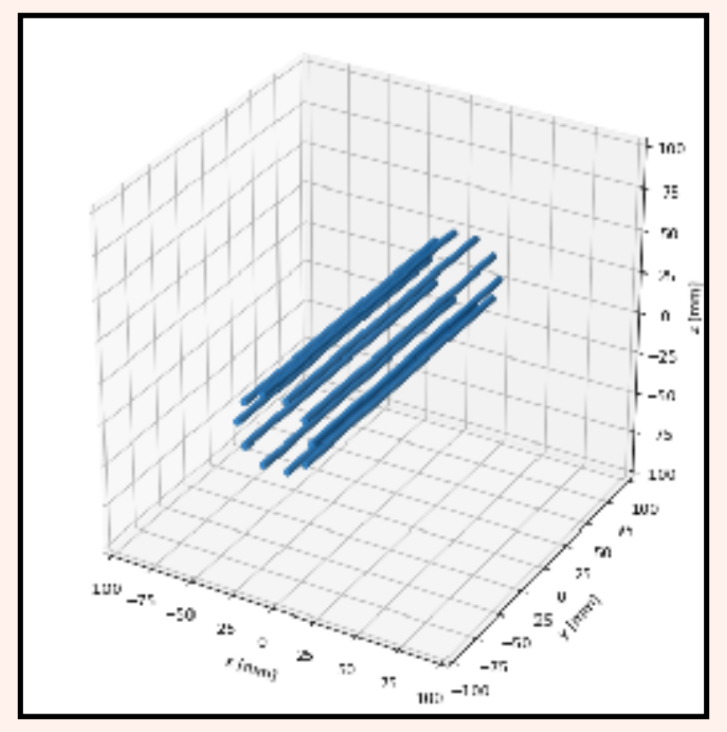
Magnetic field lines in xz-plane due to 4 ring geometry.

N-rod mangle (Halbach cylinder)

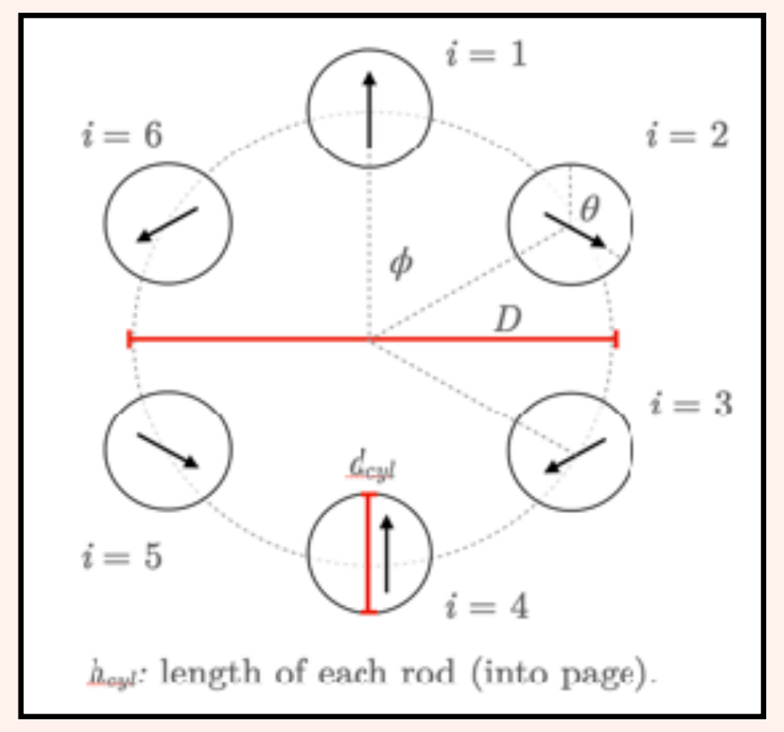
'Rod mangle' geometries are a type of Halbach cylinder, a geometry that generates high-strength uniform fields in its core [5]. The rod magnetization direction varies with angle along the circumference.



Magnetic field lines in xz-plane due to N = 9 rod mangle.



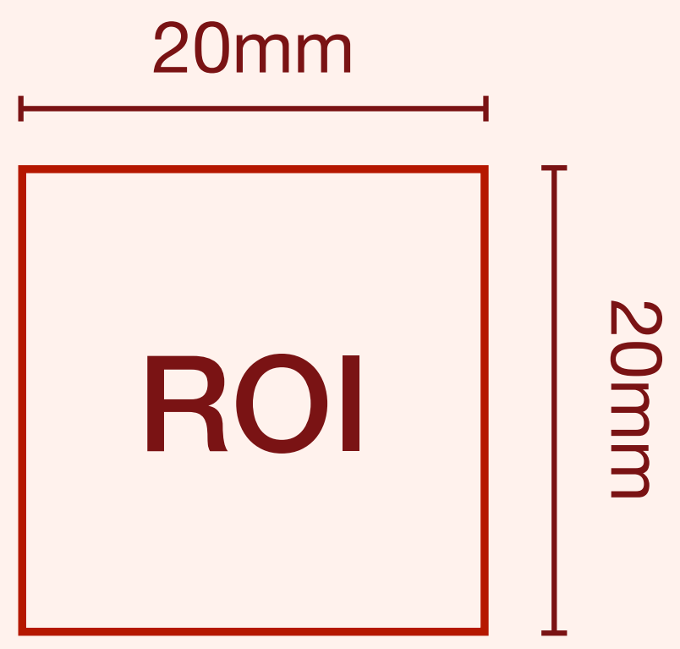
N = 10 rod mangle.



Rod mangle (N = 6) cutaway with magnetization direction and dimensions to optimize.

OPTIMIZATION PROBLEM DEFINITION

Optimization ROI & target central magnetic field strength



- Define the ROI in the xy-plane. The magnetic field intersects it perpendicularly, pointing parallel to the z-axis.
- Discretize the ROI into a grid of 101 by 101 points.

Point nonuniformity: $\eta_{ROI}(\mathbf{r}) = \left| \frac{B(\mathbf{r}) - B_0}{B_0} \right|$

Target magnetic field strength at origin B_0:

$B_{target} = 10G, \ \Delta_B = |B_0 - B_{target}|$

Δ_B defined as deviation from target.

Minimized xy-plane avg. field nonuniformity:

$$\bar{\eta}_{ROI} = \frac{1}{101^2} \sum_{x=1}^{101} \sum_{y=1}^{101} \left| \frac{B(x,y,0) - B_0}{B_0} \right|$$

(A) Samwise objective function

Single-stage optimization algorithm.

$$C(\mathbf{x}_0) \begin{cases} \frac{\Delta_B}{B_{target}} & \text{if } \Delta_B \geq \tau \\ \bar{\eta}_{ROI} & \text{if } \Delta_B < \tau \end{cases}$$

Our simulations use $\tau = 0.1$.

(B) Pippin cost function

Two-stage optimization algorithm.

Stage 1 cost function: $C_1(\mathbf{x}_0) = \bar{\eta}_{ROI}$
Use the optimized result from stage 1, $\mathbf{x}_1$, as the starting point for stage 2 optimizations.
Stage 2 cost function: $C_2(\mathbf{x}_1) = \Delta_B \cdot \bar{\eta}_{ROI}$

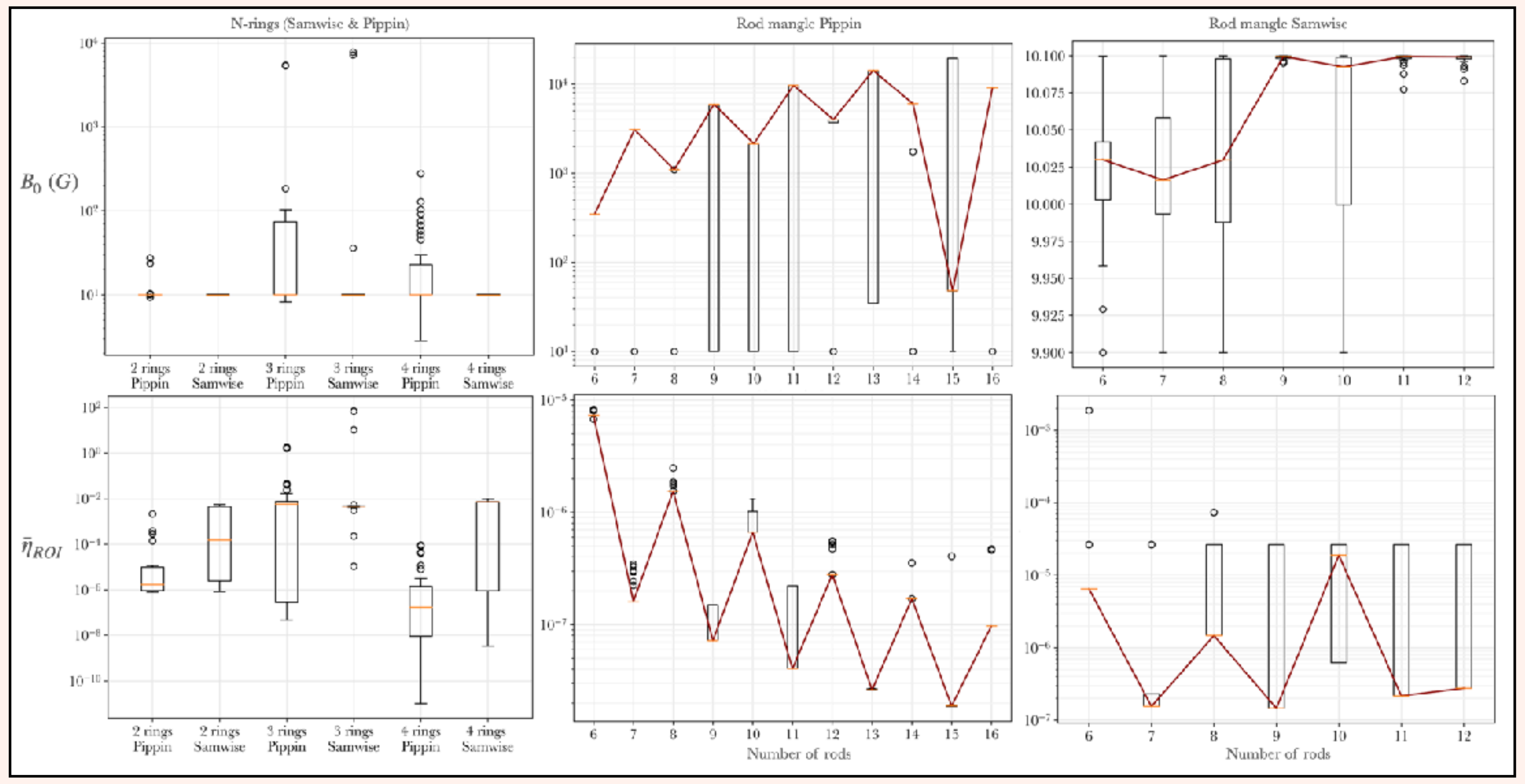
Optimization methodology

- Initialize with multiple random guesses $\mathbf{x_0}$ for each relevant geometry dimension to be optimized.
- Optimize under either the **Samwise or Pippin cost functions**, using the adaptive Nelder-Mead downhill simplex method [6].
- Repeat for other cost functions and geometries.

Parameters	N-rings	N-rod mangle (Samwise)	N-rod mangle (Pippin)
# randomized starting guesses (for each N)	50	25	25
N (ring or rods)	2 ≤ N ≤ 4	6 ≤ N ≤ 12	6 ≤ N ≤ 16

Volume constraint: all permanent magnet geometries are constrained during optimization to fit within a 340**mm** $\times$ 340**mm** $\times$ 620**mm cuboid.**

PERMANENT MAGNET MODELING & SIMULATION



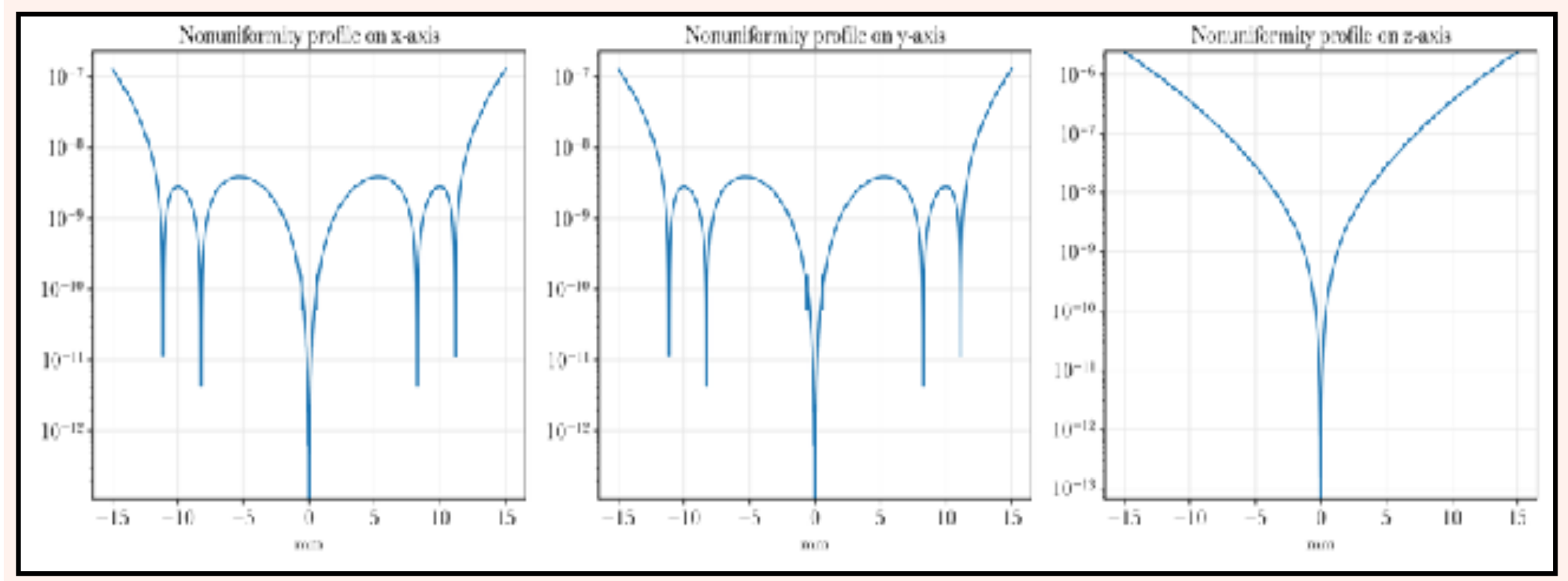
Python packages
Magpylib (magnets)
Numpy
Matplotlib
Scipy (optimization)

Magnetic parameters
Material: SmCo
Remanence: 1.09T [7]
μ_r: 1 (assumed)

SmCo is a suitable ferromagnetic material for cryogenic use-cases, with the lowest known magnetization temperature dependence of -0.03%/K [4].

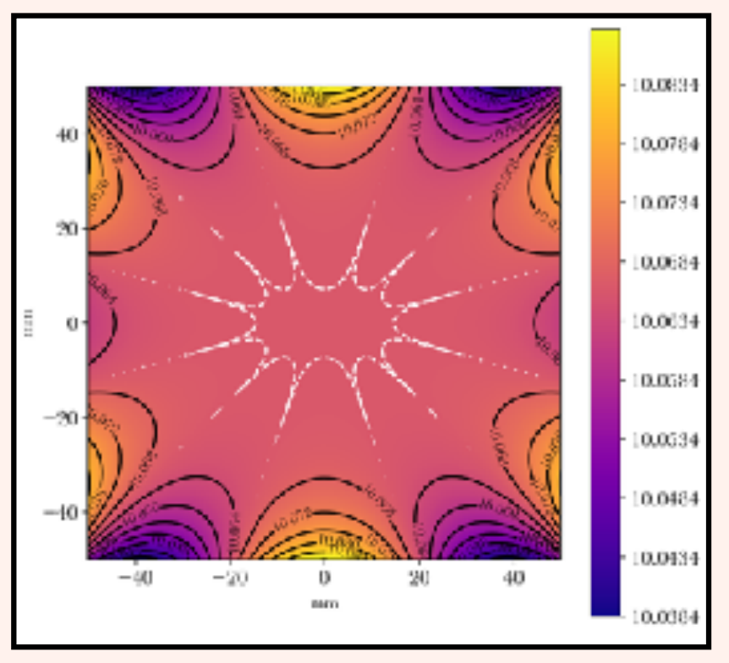
- Best-performing optimized permanent magnet geometries achieve on the order of <0.01ppm average nonuniformity over the ROI, lower than existing configurations by as much as **1000x.**
- **Samwise outperforms the Pippin** cost function by enabling convergence to both low average nonuniformity while simultaneously attaining the user-specified central field strength.

BEST N-RING & OVERALL GEOMETRY (4 RINGS, SAMWISE)



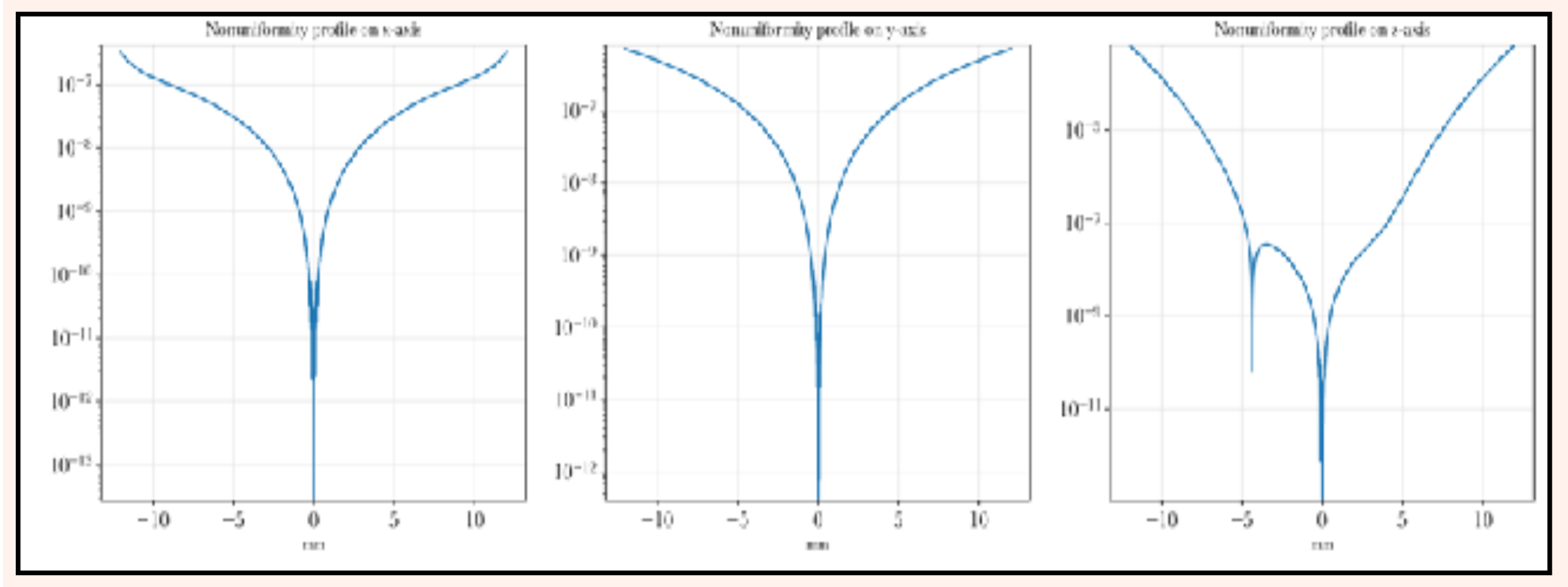
Nonuniformity profiles on coordinate axes.

$\bar{\eta}_{ROI} = 3.41 \times 10^{-9}, B_0 = 10.066G$



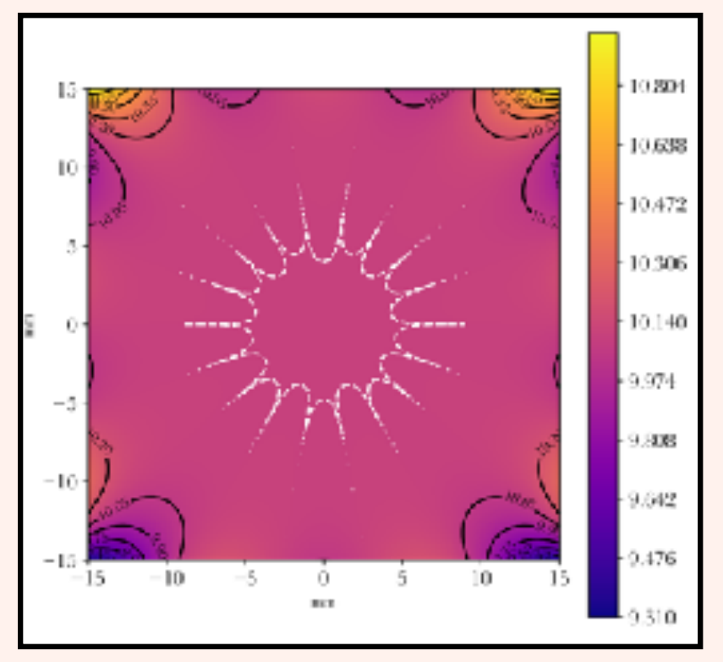
xz-plane magnetic field strength, with area of point nonuniformity $\eta_{ROI}(\mathbf{r}) < 10^{-7}$ outlined in white.

BEST N-ROD MANGLE GEOMETRY (N = 9, SAMWISE)



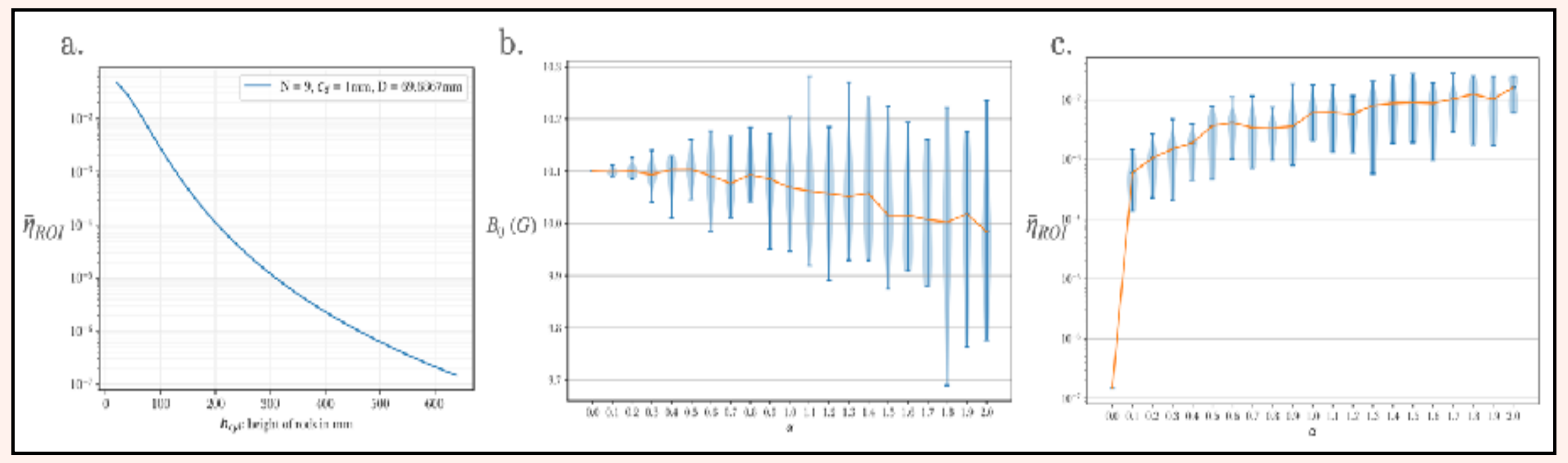
Nonuniformity profiles on coordinate axes.

$\bar{\eta}_{ROI} = 1.47 \times 10^{-7}, B_0 = 10.100G$



xz-plane magnetic field strength, with area of point nonuniformity $\eta_{ROI}(\mathbf{r}) < 10^{-7}$ outlined in white.

EFFECT OF TOLERANCES



We simulated effects of magnet dimension variations and tolerances on the performance of the optimal rod mangle geometry (N = 9, as above).
(a) **Lengthening rod height improves average nonuniformity**.
(b) and (c) **Increased tolerances result in greater deviations from target field strength and significantly higher average nonuniformity.**

Simulated normally-distributed rod mangle tolerances

- $\delta B_{rem} \sim N(0, (\alpha \cdot 0.02)^2)$ in T — Remanence variation [7].
- $\delta\phi \sim N(0, (\alpha \cdot 2)^2)$ in ° — Angular rod position variation.
- $\delta\theta \sim N(0, (\alpha \cdot 2)^2)$ in ° — Angular magnetization variation.

α is a tunable 'tolerance amplitude' parameter that varies between 0 and 2.

FUTURE WORK

Primary conclusions of our work

- Multiple order of magnitude improvement in magnetic field nonuniformity in trapped-ion devices is possible.
- Controlling manufacturing tolerances is crucial to curbing significant spikes in nonuniformity.

Our ongoing work

- Fabricating optimized permanent magnet geometries.
- Experimentally validating their efficacy in improving coherence.
- Utilizing ions to probe magnetic field gradient.

References

1. M. Malinowski, "Unitary and Dissipative Trapped-Ion Entanglement Using Integrated Optics," Doctoral thesis, ETH Zurich, 2021. doi: 10.3929/ethz-b-000516613.
2. D. Kielpinski, C. Monroe, and D. J. Wineland, "Architecture for a large-scale ion-trap quantum computer," *Nature*, vol. 417, no. 6890, Art. no. 6890, Jun. 2002, doi: 10.1038/nature00784.
3. F. Schmidt-Kaler *et al.*, "The coherence of qubits based on single Ca+ ions," *J. Phys. B: At. Mol. Opt. Phys.*, vol. 36, no. 3, p. 623, Jan. 2003, doi: 10.1088/0953-4075/36/3/319.
4. T. Ruster, C. T. Schmiegelow, H. Kaufmann, C. Warschburger, F. Schmidt-Kaler, and U. G. Poschinger, "A long-lived Zeeman trapped-ion qubit," *Appl. Phys. B*, vol. 122, no. 10, p. 254, Sep. 2016, doi: 10.1007/s00340-016-6527-4.
5. O. Cugat, P. Hansson, and J. M. D. Coey, "Permanent magnet variable flux sources," *IEEE Transactions on Magnetics*, vol. 30, no. 6, pp. 4602–4604, Nov. 1994, doi: 10.1109/20.334162.
6. F. Gao and L. Han, "Implementing the Nelder-Mead simplex algorithm with adaptive parameters," *Comput Optim Appl*, vol. 51, no. 1, pp. 259–277, Jan. 2012, doi: 10.1007/s10589-010-9329-3.
7. "Available Grades of Samarium Cobalt SmCo Magnet," *Stanford Magnets*. https://www.stanfordmagnets.com/smco-magnets-grade-info.html (accessed Aug. 09, 2023).