Magnet Positioner

- Final Presentation

Dragos Ileana, Timmy Lin, Qu Tianchen & Badr Zouggari

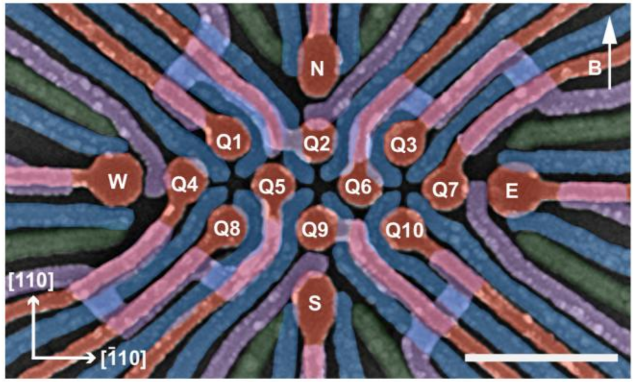
Overview

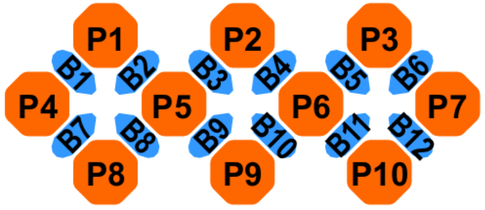
- **Problem context**: Theoretical background and motivation for the project
- **Problem statement**: Our exact problem statement and our planned solution approach
- **Design Process**: Steps taken from concept to realization
- **Technical analysis**: How the proposed design functions in detail
- **Discussion and reflection**: Results, challenges, and lessons learned
- **Summary and feedback**

Problem context: Germanium (Ge) hole spin qubits

- Suppressed hyperfine interactions (over GaAs) [3], due to:
  - low abundance of non-zero nuclear spins
  - p-type character of the valance band
  - isotopic enrichment to remove non-zero spins is possible

  ➔ Long T_2





10-qubit processor and layout [1]

- Strong natural spin-orbit coupling (SOC) [3] gives:

  ➔ all electric control of qubits via EDSR

  ➔ gate times << qubit coherence times

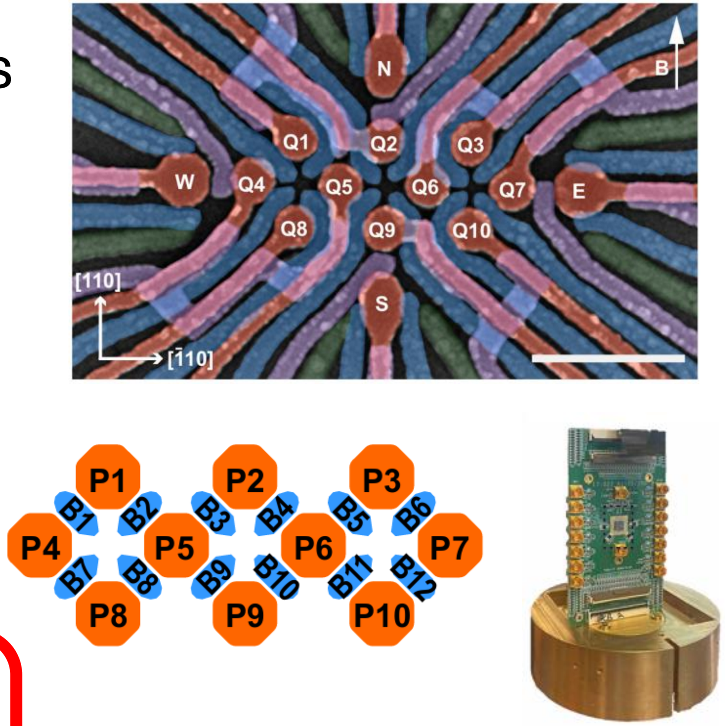
  ➔ but causes 1/f charge noise, affecting T_2^*

Problem context: Germanium (Ge) hole spin qubits

- Charge noise [3]:
  - g-tensor anisotropy ($|g_\perp/g_\parallel| \approx 10$) + angle deviations of magnetic field **B**
    ➔ quantization axis snaps to $\pm\hat{z}$ arbitrarily

- Hyperfine interactions [3]:
  - Ising-type with strong anisotropy
  - In-plane aligned **B** ➔ negligible noise

- “Sweet-spots” [3, 6]:
  - Optimal orientation of **B** field wrt. both the hyperfine plane AND the g-tensor plane
  - Hard to find optima + sensitivity to **B** field deviations



10-qubit processor and layout [1]

Problem context: magnet positioner

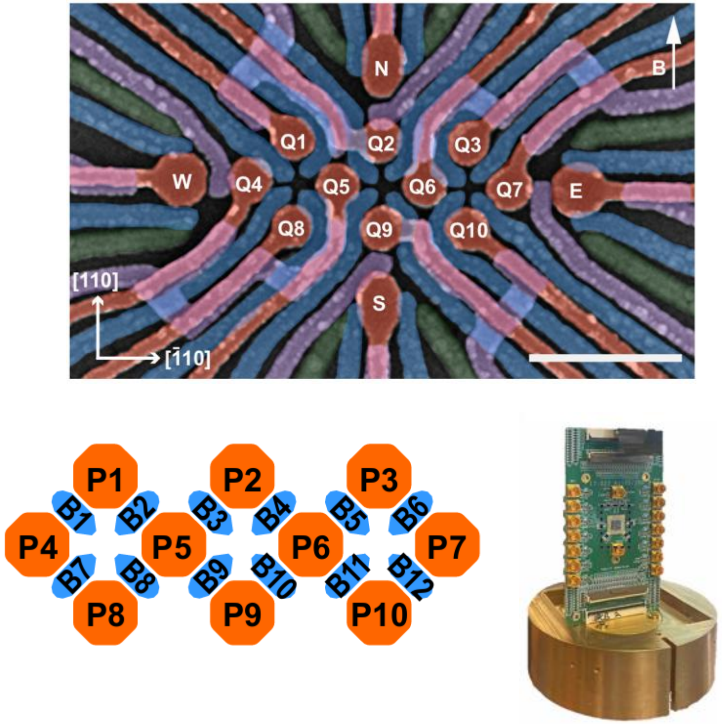
- Veldhorst group: 10 qubit QPU on Ge/SiGe heterostructure [4]

- Static uniaxial magnetic field **B** generated by superconducting coil inside refrigerator (sample inside coil bore) [1]

$$\mathbf{B} = \begin{bmatrix}0 & 0 & 3\end{bmatrix}\ \mathrm{T}$$

- Interior magnet occupies useful space for electronics

- Future 1000 qubit processor
  ➔ needs even more cryo-electronics



10-qubit processor and layout [1]

Problem context: magnet positioner

- Yu et al. (2025) [1]:
  - Test potential solution for saving more space inside refrigerator for electronics
  - **Solution:** Gantry system to position external permanent magnet below refrigerator.
  - Operation modes:
    1. Internal magnet only
    2. External magnet only
    3. Hybrid (internal + external magnets)

  ➔ Solution is promising

Magnet positioner [1]

	Internal magnet	Hybrid mode
T_2^*	$1.7\ \mu s$	$13\ \mu s$
T_2^H	$4.2\ \mu s$	$88\ \mu s$
Gate fidelity*	$-$	$> 99.9\%$

(Avg. single-qubit Clifford gate fidelity from Randomized Benchmarking)*

Problem Statement

1. **B** field not tunable with in-magnet
   ➔ **B** misalignment

2. 1000 quantum dots require more circuitry to cryogenic temperatures
   ➔ space becomes even more critical

3. Permanent magnets show control potential. Need precise, compact magnet positioning system.

➔ **Design and build an improved magnet positioner to free up space and allow tunability.**

Approach and Strategy

1. Adopt proven gantry-style external magnet positioner concept

2. A permanent magnet is positioned below the refrigerator on three axes

Succes Criteria

1. Positioning system must achieve at least 0.1 mm accuracy
2. Magnetic field must be continuously adjustable up to 25 mT
3. Qubit dephasing times must match superconducting solenoid performance
4. Achieve single-qubit gate fidelities above 99.9 percent
5. System must enable comprehensive magnetic field mapping capability
6. Mechanical design should minimize vibration-induced field fluctuations

Design Process

- Combining parts
- Test positioning accuracy
- Mapping magnetic field

Problem statement → Design → Manufacturing → Assembly

Design Process

Problem statement → Design → Manufacturing

- Combining parts
- Test positioning accuracy
- Mapping magnetic field

Prioritise x-plate!!

Technical analysis

- Motion limits → z: 60 cm, y: 30 cm, x: 60 cm

- Magnetic field:

  → $\geq 25\text{mT}$ at sample location when magnet is at highest z-coordinate (~7 cm between sample and magnet)

  → $\approx 0\text{mT}$ at sample location when magnet is at lowest z-coordinate.

Technical analysis

- Materials:
  - Aluminium alloy
    → resistant, light, non-magnetic
    → for large custom-made parts

  - Stainless steel
    → more resistant, heavier, non-magnetic
    → for metal brackets

  - Plastic
    → easy to fabricate with a 3D printer

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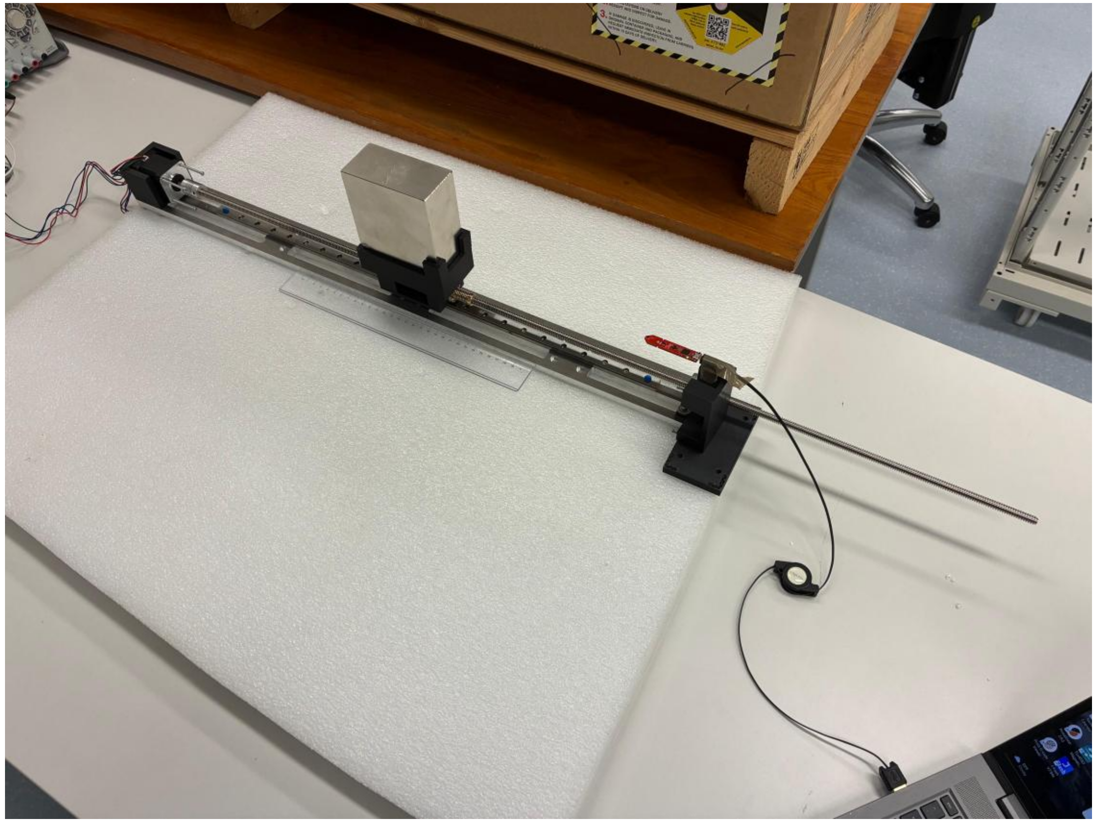
Technical analysis (movement)

- Improve positioning in x and y direction
- Backlash between lead screw and nut
- Solution: replace with anti-backlash nut

Technical analysis

- Magnet positioner (single direction)
- Test movement
- Comparing measurements with simulations



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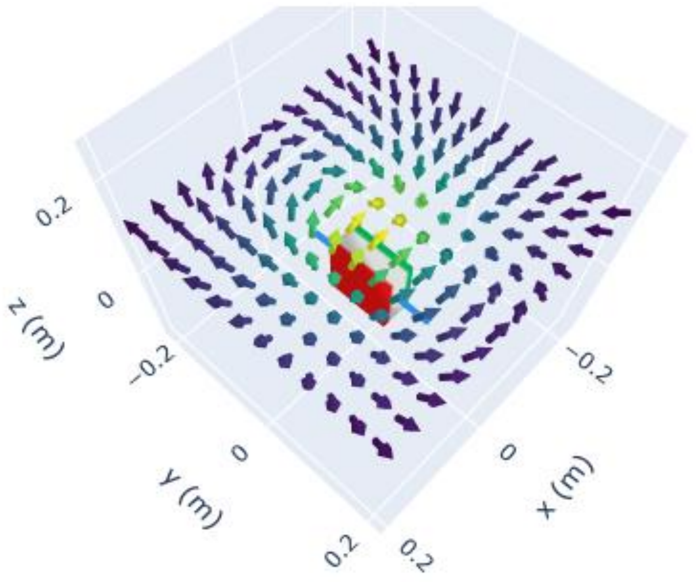
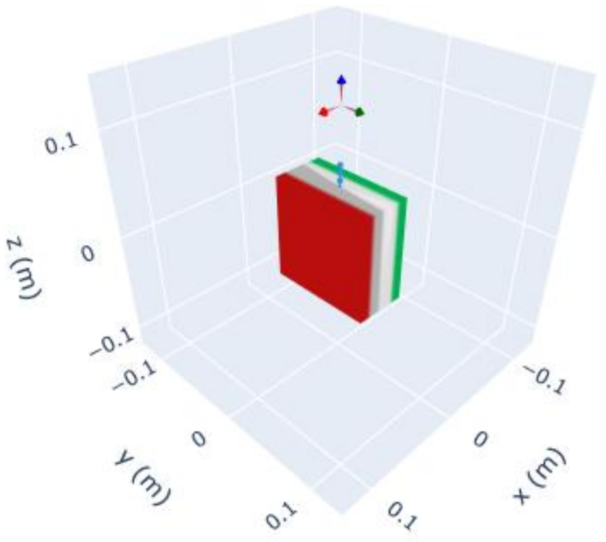
Technical analysis (simulations)

- Measurement on Z axis
- Simulation via Magpylib
- Theoretical estimation of magnetic gradient and noise

Magnetic field

- Assuming uniform magnetisation and permeability
- No need for exact magnetisation for the magnet
    - Calibrated by setting equal magnetic amplitude to the measurement at 7cm



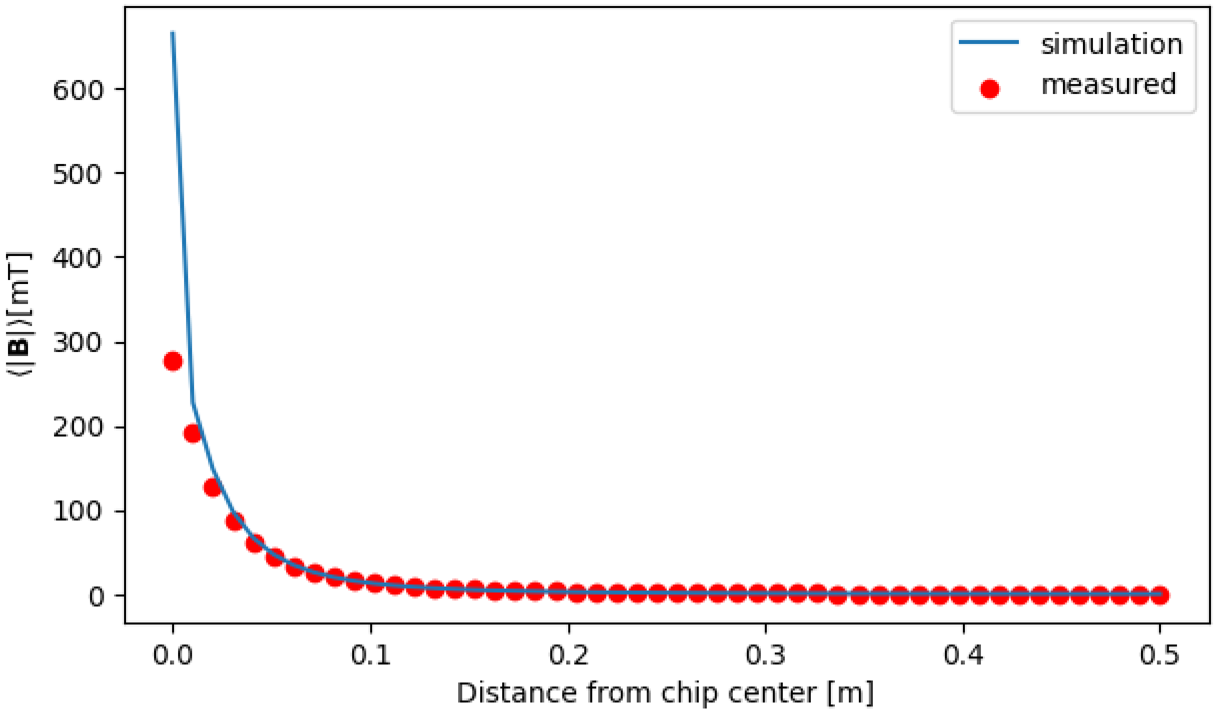


Magnetic field

Simulation results fit the measurement outcome except very close range

Possible causes:

- Hall sensor still take some room to measure
- Sensor placement inaccuracy



Inhomogeneity across the chip: Theoretical

What could be the magnetic field gradient across the chip? We characterize it by defining Deviation d:

$$d = \max_{\mathbf{r},\mathbf{r}' \text{ in chip}} \frac{||\mathbf{B}(\mathbf{r}) - \mathbf{B}(\mathbf{r}')||_2}{||\overline{\mathbf{B}_{\text{chip}}}||_2}$$

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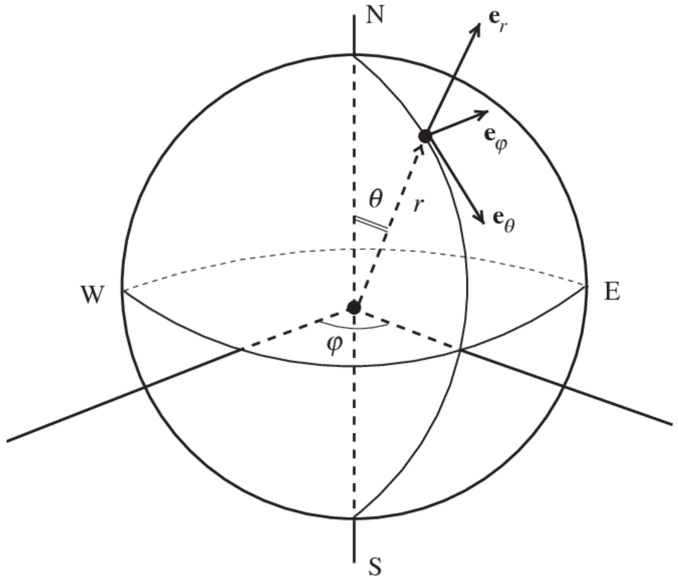
If we express using polar coordinates with the magnetisation direction being the zenith (z axis), the derivative tensor has a particularly nice form for points at the equator

$$\left.\frac{\nabla \mathbf{B}}{||\mathbf{B}||_2}\right|_{\theta=\frac{\pi}{2}} = \begin{bmatrix} \frac{3}{r}\hat{\theta} & -\frac{3}{r}\hat{r} & 0 \end{bmatrix}$$



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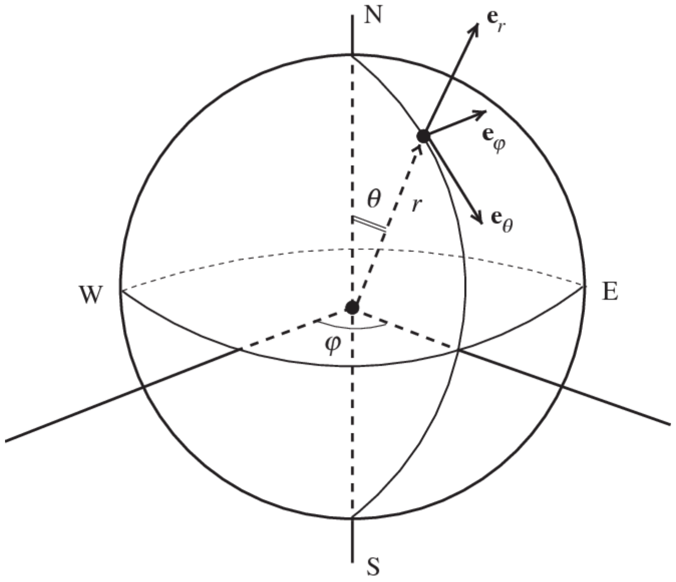


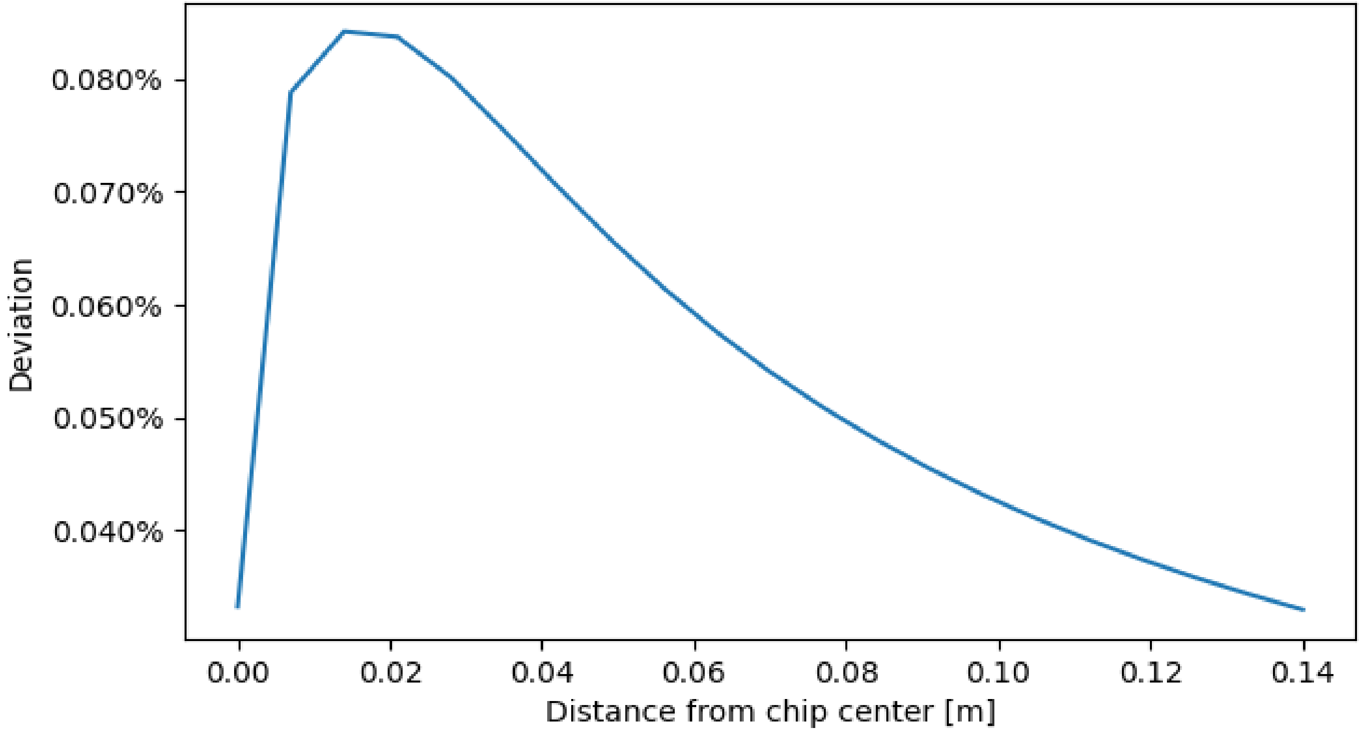
The chip is in $\hat{\theta} - \hat{\phi}$ plane, resulting deviation (first order)

$$d = \max_{\mathbf{a} \in \{0\} \times [0,a] \times [0,a]} \frac{||\mathbf{a} \cdot \nabla \mathbf{B}||_2}{||\mathbf{B}||_2} = \frac{3a}{r}$$

Inhomogeneity across the chip: Simulation

Simulation:

- Follows 1/r decay at long distance
- Breaks when distance is small: dipole approximation breaks, toward uniform at r=a

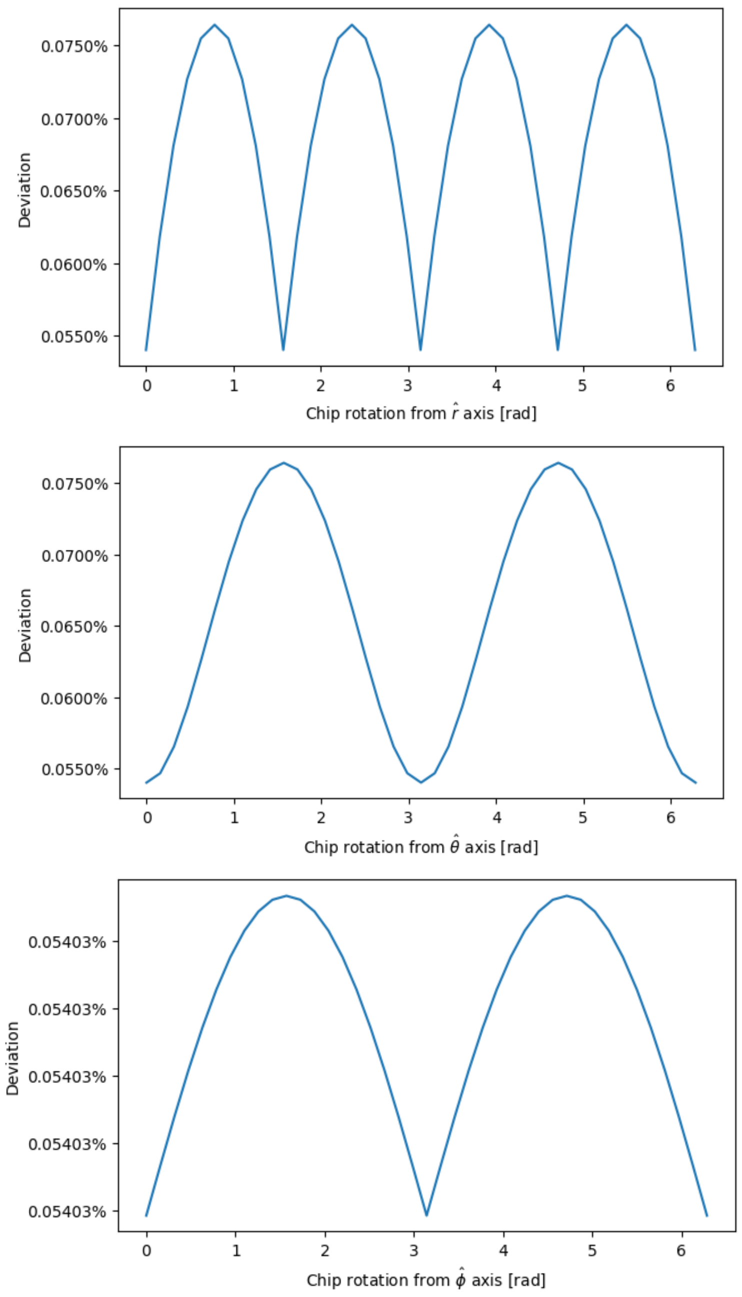


Inhomogenity across the chip

Deviation dependency on the orientation of the chip

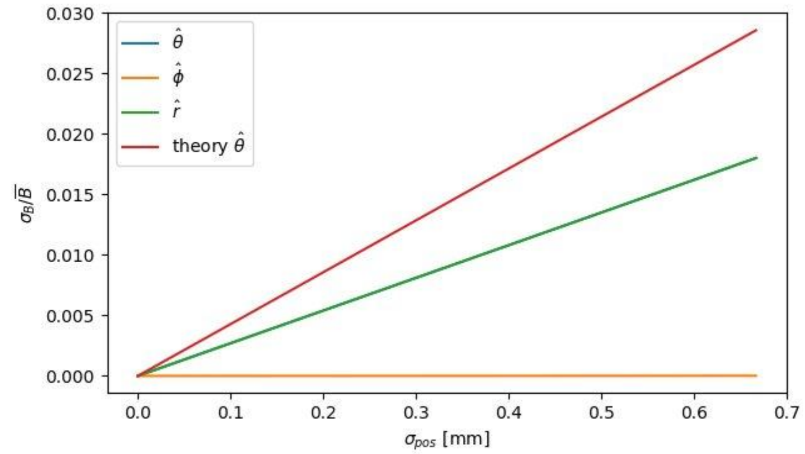
- Other "sweet spots" are also okay
- Simulation fits the theoretical prediction
  - A square-r $\hat{r}$ or $\hat{\theta}$ ifference for rotation at direction $\hat{\phi}$ rotation, hardly changes at direction rotation

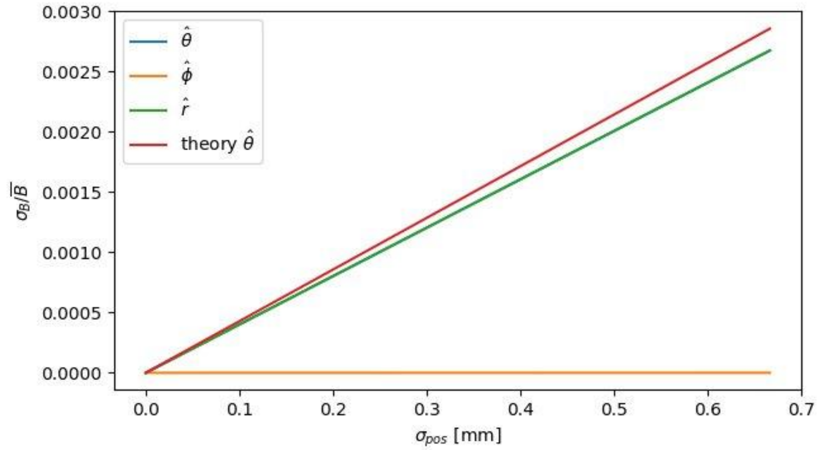
$$\left.\frac{\nabla \mathbf{B}}{||\mathbf{B}||_2}\right|_{\theta=\frac{\pi}{2}} = \begin{bmatrix} \frac{3}{r}\hat{\theta} & -\frac{3}{r}\hat{r} & 0 \end{bmatrix}$$



Noise analysis

- hysteresis effect
  - Only present when motor is working
  - Can be calibrated
- Mechanical vibration
  - Low frequency -> quasistatic noise
  - Assuming gaussian decay
  - Can be largely cancelled by dynamical decoupling





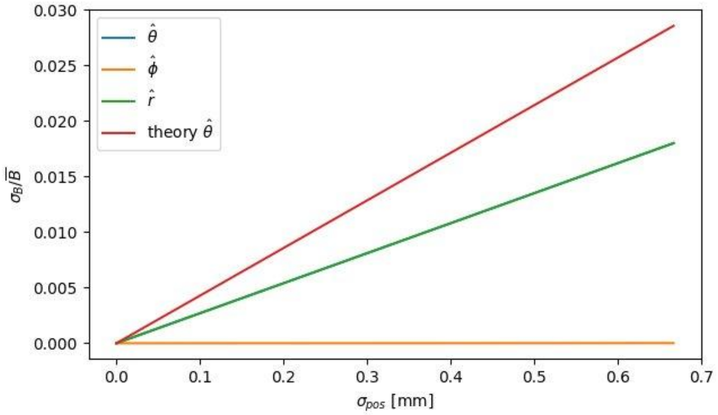
Noise analysis

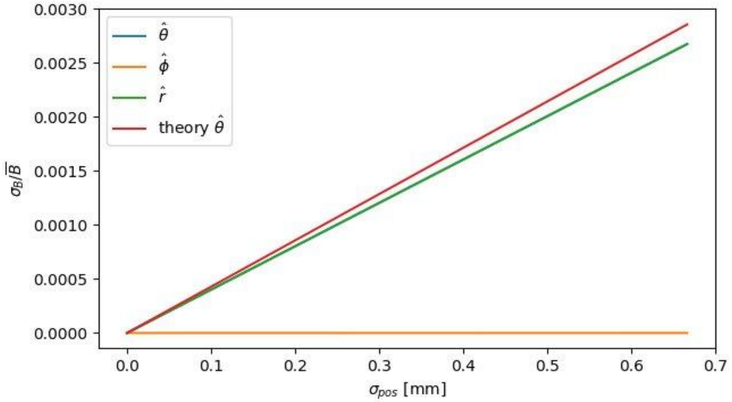
It does affect T2* time!

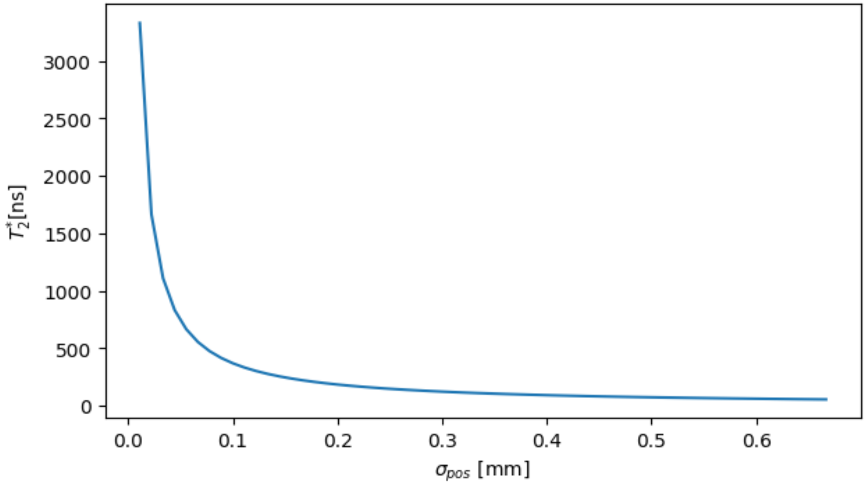
$$\sigma_\omega = \omega_L \frac{\sigma_B}{\overline{B}} = \omega_L \frac{3\sigma_{pos,r}}{r} \qquad T_2^* = \frac{1}{\sigma_\omega}$$

Only sensitive to vertical vibration

- Other directions either have vanishing gradient or have second-order effect on amplitude







Scale: maximum 2mm vibration -> $3\sigma_{pos} < 2mm$

Assuming Larmor frequency 1GHz

Discussion and Evaluation

- Project completion delayed by late parts delivery
- Assembly and final integration not reached within project period

Discussion and Evaluation

Per success criteria evaluate what we've achieved

1. **Positioning accuracy**

- Achieved experimental verification of 0.5* mm accuracy in the x-axis using an anti-backlash nut (*0.1 mm accuracy obtainable with more accurate measurement devices)

- Same mechanical principle is expected to apply for the y-axis once the assembly is complete.

Discussion and Evaluation

Per success criteria evaluate what we've achieved

2. Magnetic field range

- The system enables continuously adjustable magnetic fields up to 25 mT at the sample location

- Magnetic field generation and control is confirmed by measurements, simulations

Discussion and Evaluation

Per success criteria evaluate what we've achieved

3. Qubit coherence time

- Simulation estimates for qubit dephasing times (T_2^*) were conducted due to incomplete physical assembly

- Dephasing time is shown to depend strongly on vibration strength, particularly vertical vibrations relative to the magnet

Discussion and Evaluation

Per success criteria evaluate what we’ve achieved

4. **Gate fidelity**

- Verification pending project completion, since complete structure with magnet required

Discussion and Evaluation

Per success criteria evaluate what we've achieved

5. Magnetic field mapping

- Hall sensor evaluation allows logging and saving of field strength in a single direction

- Visualization efforts and postprocessing demonstrate that full 3D mapping is likely achievable after full mechanical assembly

Discussion and Evaluation

Per success criteria evaluate what we’ve achieved

6. Structural stability

- Material choices suggest mechanical robustness once manufacturing is finished

Conclusion

- Designed an external magnet positioner to free up valuable cryostat space for scalable quantum processors

- Used CAD modeling to create and refine the mechanical assembly, optimizing both for rigidity and compatibility with new fridge

- Achieved partial success in positioning accuracy and magnetic field mapping

- Project delayed by manufacturing lead times

- Described a plan of attack for completion of this project

Reflection:

- Reliance on external manufacturing increased risk of timeline slip
- Earlier orders and risk planning could have prevented delays

References

[1] C. X. Yu et al., "Optimising germanium hole spin qubits with a room-temperature magnet," 2025. arXiv: 2507.03390 [quant-ph]. [Online]. Available: https://arxiv.org/abs/2507.03390.

[2] G. Burkard, T. D. Ladd, A. Pan, J. M. Nichol, and J. R. Petta, "Semiconductor spin qubits," *Rev. Mod. Phys.*, vol. 95, p. 025 003, 2 Jun. 2023. DOI: 10.1103/RevModPhys.95.025003. [Online]. Available: https://link.aps.org/doi/10.1103/RevModPhys.95.025003.

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[4] V. John et al., "A two-dimensional 10-qubit array in germanium with robust and localised qubit control," 2025. arXiv: 2412.16044 [cond-mat.mes-hall]. [Online]. Available: https://arxiv.org/abs/2412.16044.

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Questions?

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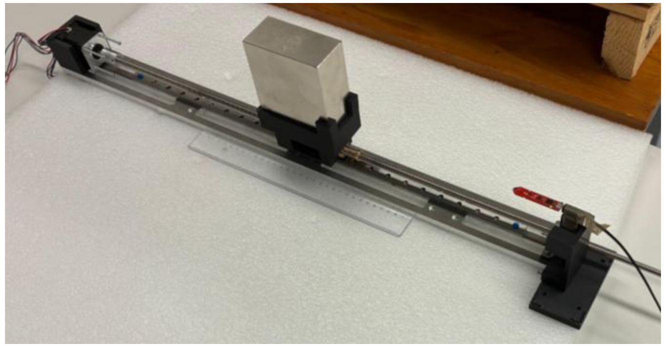
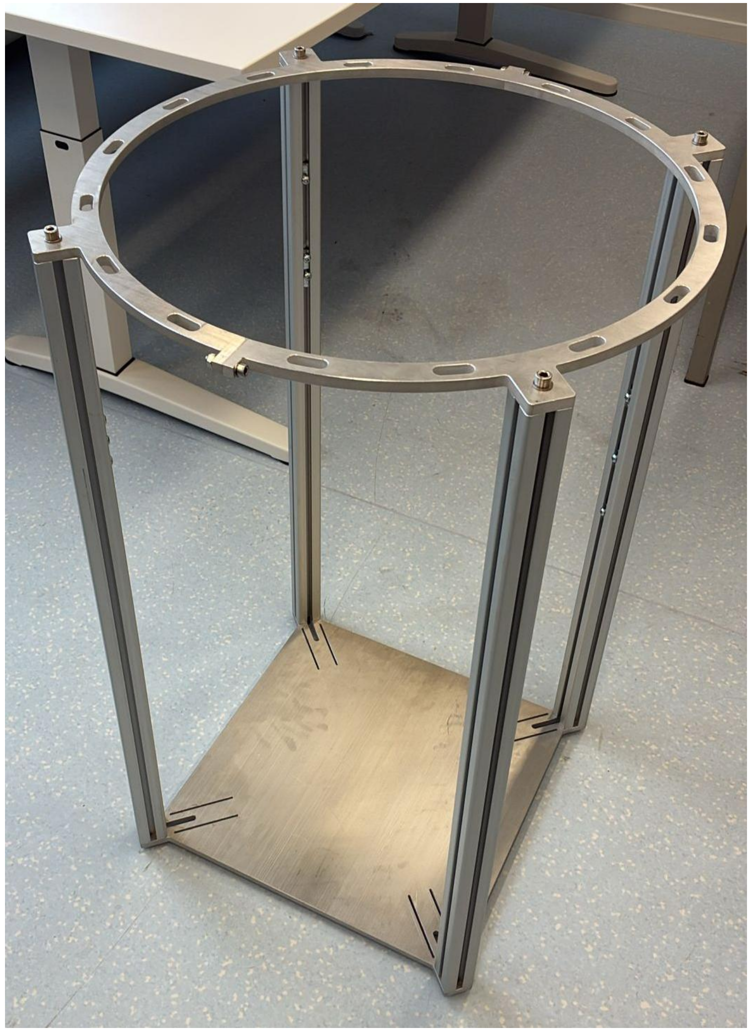
Bonus slides

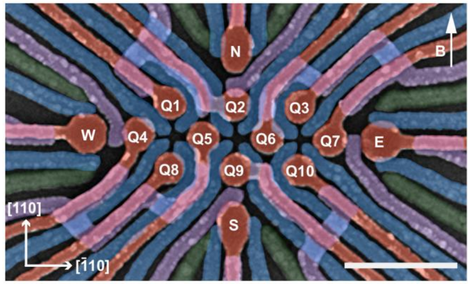
Figures

- X-plate setup (left)
- Gantry frame (right)





Figures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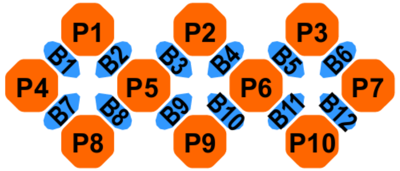
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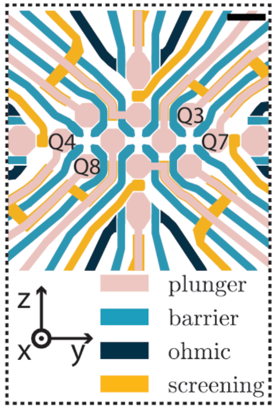
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Team
Magnet


Team
Magnet


Team
Magnet

Yu et al. (2025) – performance metrics

	T_2^*	T_2^H	Avg. single-qubit Clifford gate fidelity*
Internal magnet only	$1.7 \pm 0.12\ \mu s$	$4.23 \pm 0.11\ \mu s$	$-$
Hybrid mode	$13.41 \pm 0.53\ \mu s$	$88.77 \pm 9.99\ \mu s$	$> 99.9\%$

(*Randomized Benchmarking)