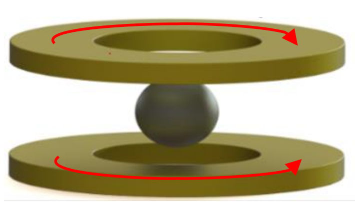
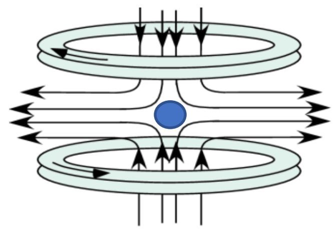
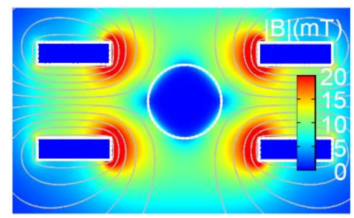
Levitation of Superconducting Microparticles

Background:

Magnetically levitated particles promise to reach ultra-low mechanical dissipation due to fewer loss mechanisms. Furthermore, the magnetically levitated particle can be coupled via flux to superconducting circuits, which allows for quantum manipulation of its centre-of-mass (com) motion. Thus, magnetically levitated particles are a promising novel platform for developing ultra-sensitive force and acceleration sensors, both in the classical and in the quantum regime.







Schematic of Anti-Helmholtz Coil with two coils vertically stacked and current flowing in opposite directions	Quadrupole magnetic field generated due to counter-current of the Anti-Helmholtz Coil (AHC) trap	COMSOL simulation of quadrupole magnetic field with strong gradient and zero field at the trap center

In this project, we demonstrate levitation of micrometre-sized superconducting particles by using a chip-based magnetic trap architecture. The chip-trap is based on an Anti- Helmholtz Coil (AHC) design that generates a quadrupole-like magnetic field of tuneable strength. An AHC design is simply two coils placed on top of each other and separated by a small distance, and a current running in opposite directions through the coils as shown below. The AHC based chip-trap is fabricated from multi-winding superconducting Niobium coils on two separate chips, which are stacked vertically. Using this chip-trap, a sub-100 mm lead spheres can be levitated at a temperature of 7K and a current that generates a strong magnetic lift force, which overcomes the van-der Waals force of the particle resting on the chip surface.

This platform can prepare a macroscopic system with about 10^{13} a.m.u. in a quantum superposition state, which can be used to investigate various decoherence mechanisms. This platform has applications in fields beyond fundamental physics: the fragility of the quantum system makes it extremely sensitive to external forces or accelerations. This extreme sensitivity can be used to develop highly sensitive quantum gyroscopes or gravimetry sensors that can be used for space or defence applications or in research.

Problem Statement:

1. **Calculate the supercurrent** needed in the Anti-Helmholtz Coils **to generate a magnetic field** strong enough **to levitate** and trap **a superconducting particle** by overcoming gravitational force and Van der Waal's attraction. Discuss the effect of this value on the design of the coils. Which parameters must be modified in order to increase the trap strength? Should we increase the number of turns in the coils? If so, by how many?

2. **Model the levitating particle as a harmonic oscillator** equivalent to a spring mass system that oscillates due to the kinetic energy gained from levitation and potential energy of the magnetic field. **Calculate the resonance frequency** of the magnetic trap at which the particle oscillates.

Materials:

- **Particle** - lead
- **Coils** - niobium
- **Surface** - silicon <100>

Parameters:

- Diameter of top and bottom coils (D) = 300 µm
- Separation between coils (l) = 150 µm
- Diameter of the particle (d) = 50 µm
- **Please make necessary assumptions for other parameters and give explanation**

Key Steps:

1. Calculate the gravitational force acting on the particle
2. Calculate the Van der Waal's force between the particle and surface
3. Calculate the magnetic force required to overcome these forces
4. Calculate the corresponding field strength and field gradient
5. Calculate the superconducting current needed to generate this field
6. Analyze the dependency of this current on different physical parameters.
7. Calculate the Kinetic Energy of the particle gained from levitation
8. Calculate the potential energy of the particle in the magnetic field
9. Write the corresponding 2nd order differential equation of the harmonic oscillator
10. Derive the formula for the resonance frequency of the trap harmonic oscillator

References:

1. Quick overview video of the project **(timestamp 33:37 onwards)**:
   https://www.youtube.com/watch?v=JrA_wqrSlCY

2. A detailed explanation of the chip-based trap and its simulation model
   Latorre, M. G., Hofer, J., Rudolph, M., & Wieczorek, W. (2020). Chip-based superconducting traps for levitation of micrometer-sized particles in the Meissner state. Superconductor Science and Technology, 33(10), 105002. https://doi.org/10.1088/1361-6668/aba6e1

3. A mathematical analysis of the AHC trap and its equations
   Hyun Youk (2005) Numerical study of quadrupole magnetic traps for neutral atoms: anti-Helmholtz coils and a U-chip. Canadian Undergraduate Physics Journal, Vol. III, Issue 2.
   https://www.youklab.org/papers/CUPC2005_Youk.pdf