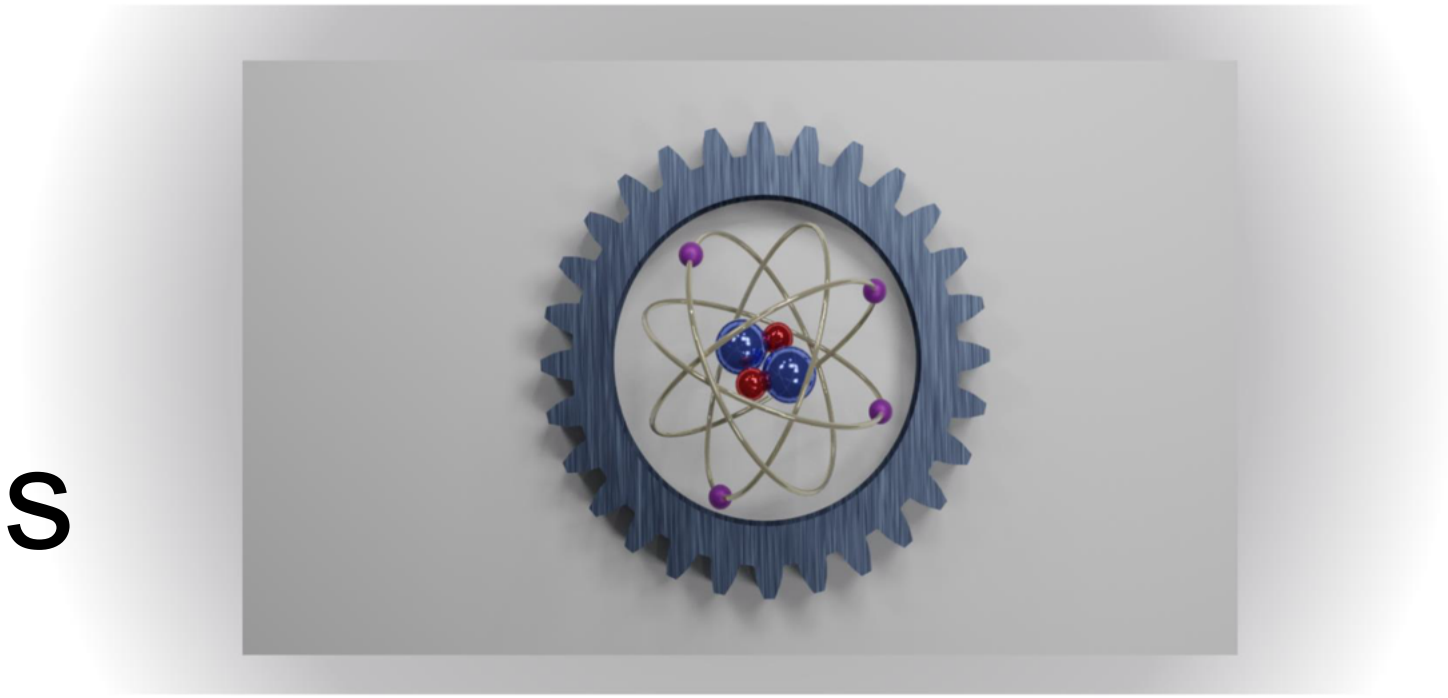
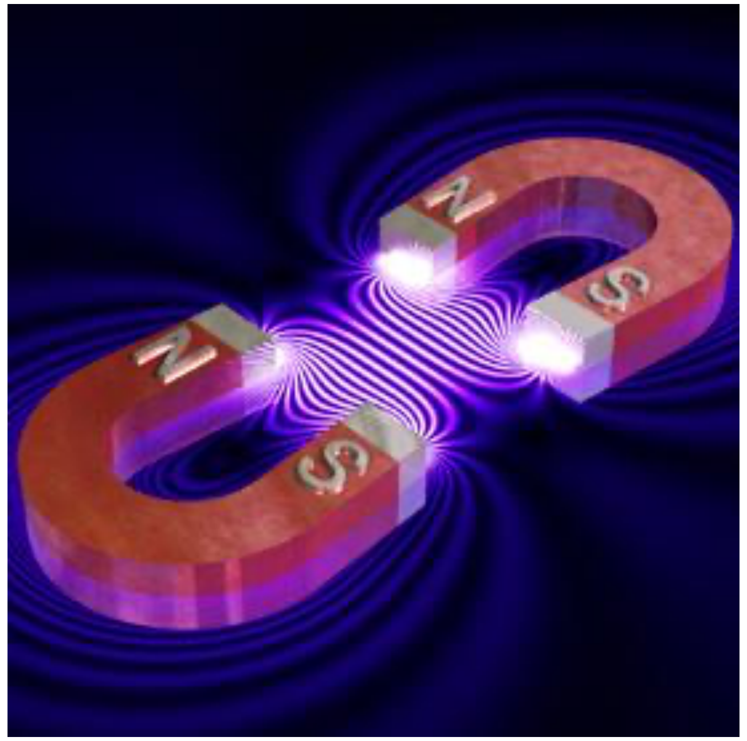
Magneto-quantum-mechanics: engineering of macroscopic quantum states using magnetic forces



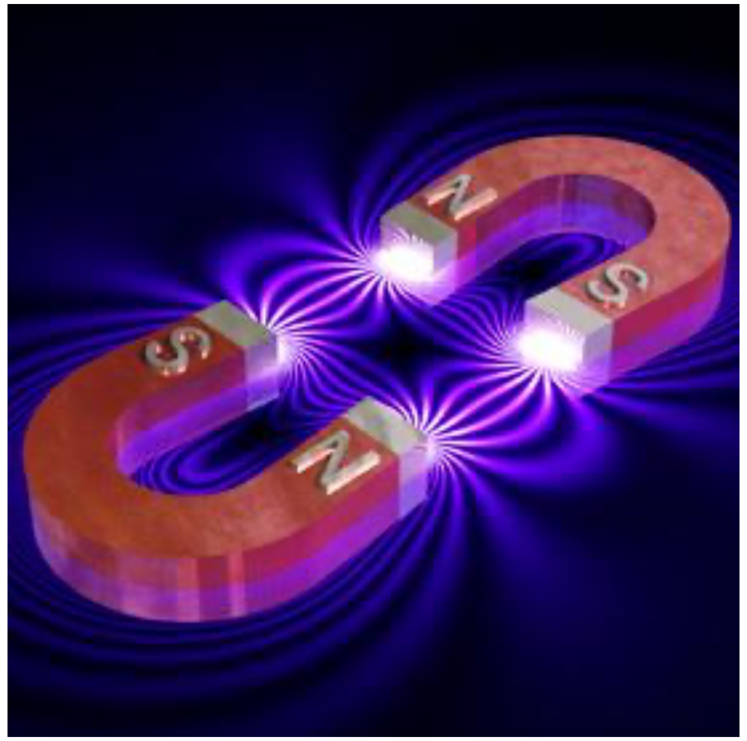
Jason Twamley

OIST

OKINAWA INSTITUTE OF SCIENCE AND TECHNOLOGY GRADUATE UNIVERSITY
沖縄科学技術大学院大学



http://www.bugman123.com/Physics/index.html

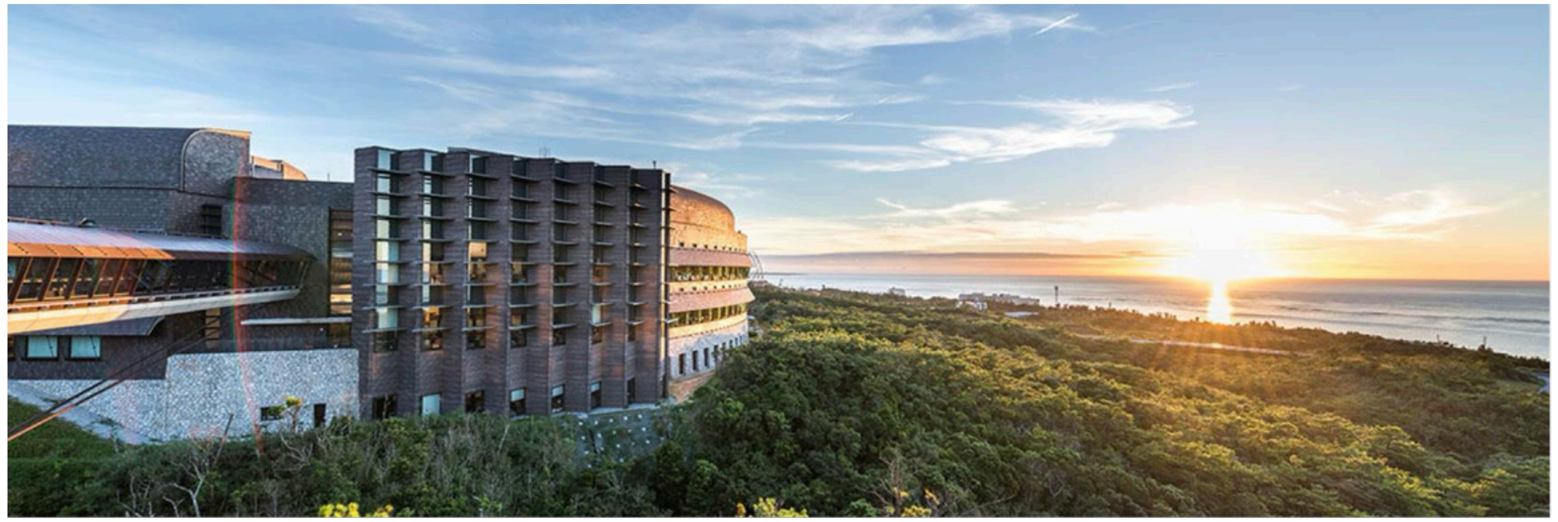


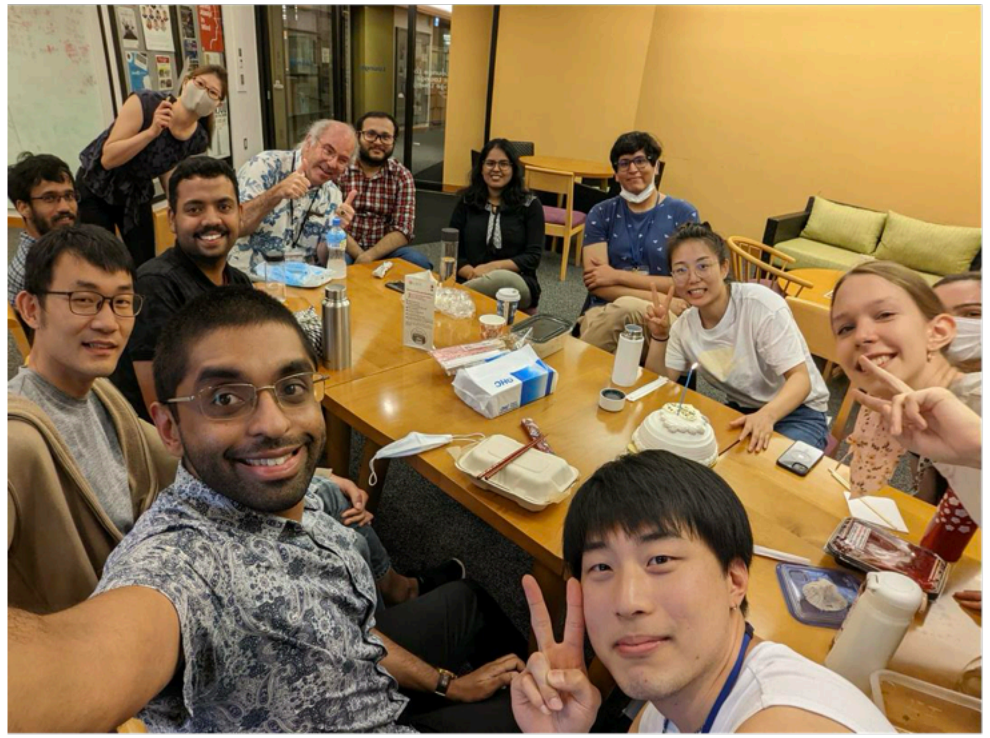
OIST Where is it?

OIST

Okinawa and the Quantum Machines Unit

CORAL REEFS/JUNGLE/BEACHES/FOOD/FOOD/FOOD



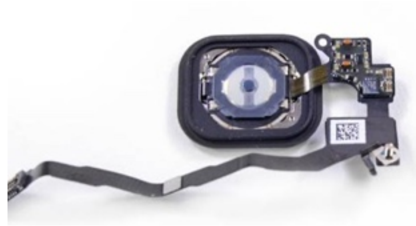


Hybrid Quantum Machines

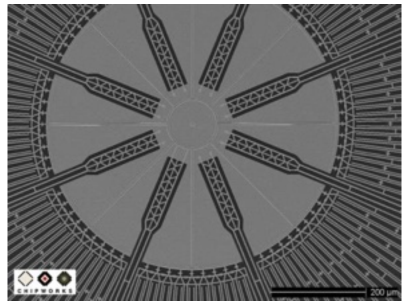
WILL ALL QUANTUM MACHINES BE HYBRID

All modern technology brings together a enormous range of different sub-technologies and by making them work together one can produce amazing functionality

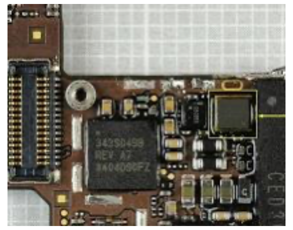
Tomorrow's quantum devices may also bring together different types of sub-systems in order to achieve an overall functionality not possible with a single sub-system alone.



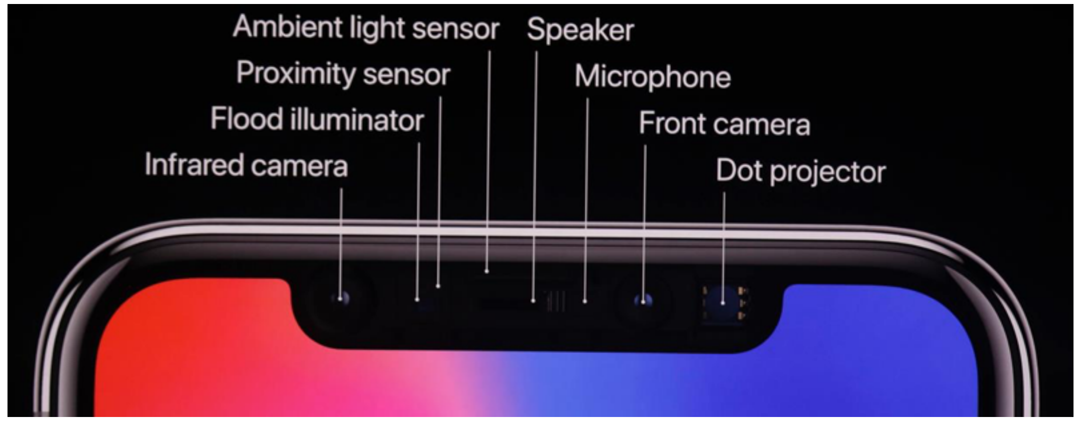
Fingerprint Sensor



MEMS Gyro



Magnetometer



Array of cameras and optical sensors and mics

What is a Quantum Machine

WE EXPECT ALL QUANTUM TECHNOLOGIES TO DEVELOP Q MACHINES

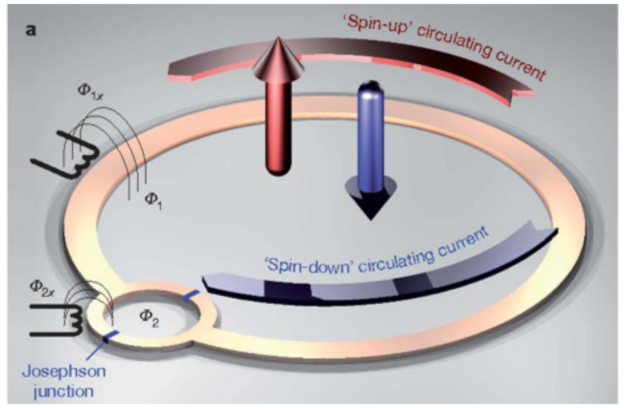
Motivation

- **Ultra-precise sensors:** gravimeters, gyroscopes, inertial sensors, sensors for dark matter, magnetometers, gravity waves…
- **Fundamental Science:** explore the fundamentals of quantum mechanics and explore the limits of the quantum world
- **Gravity & Quantum:** explore quantum science of massive systems – can explore the interaction of gravity with quantum!
- **Quantum Control and Computation:** use ideas from atomic/optical physics into quantum computing

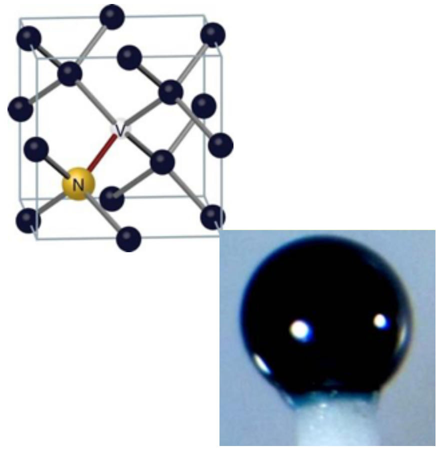
Quantum Building Blocks

COMPONENTS OF A QUANTUM MACHINE

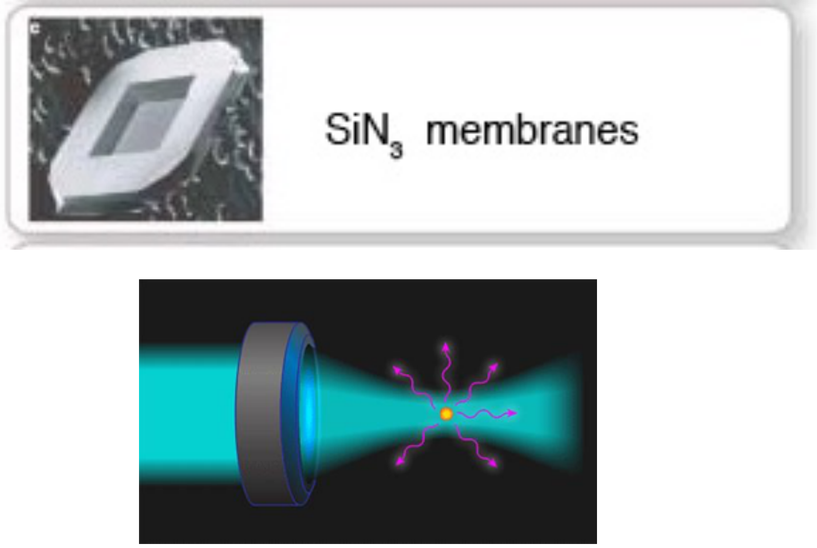
Quantum Machine – brings disparate types of physical quantum sub-systems together to provide an overall function not possible in any individual sub-system alone



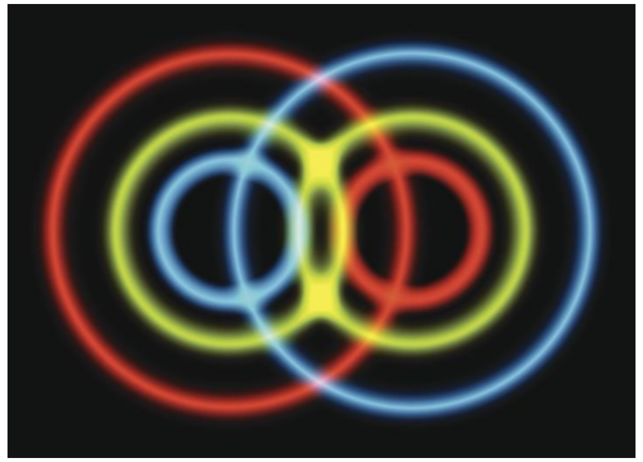
Superconducting Flux Qubit



Spin systems: NV in diamond, magnons in YIG



Mechanical systems: 2D moving membrane, motion of particle in optical tweezers



Photons: frequency/polarization/spatial modes – visible and MW

Four stories

SUMMARY

What's so interesting about levitated systems?

Improving the motional Quality factor in maglev systems

Magnetic levitated rotor with ultra-low loss

ENORMOUS Schrodinger Cats of massive objects?

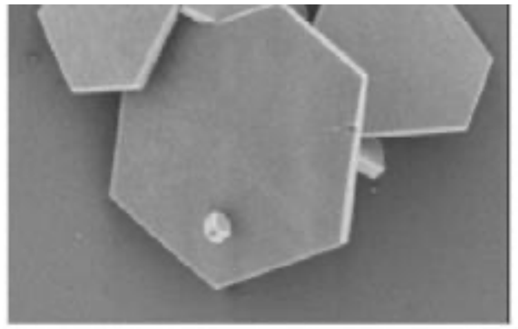
Spin-mechanical forces – moving object by spin states

What’s so interesting about levitated systems?

WHY IS IT INTERESTING AND USEFUL?

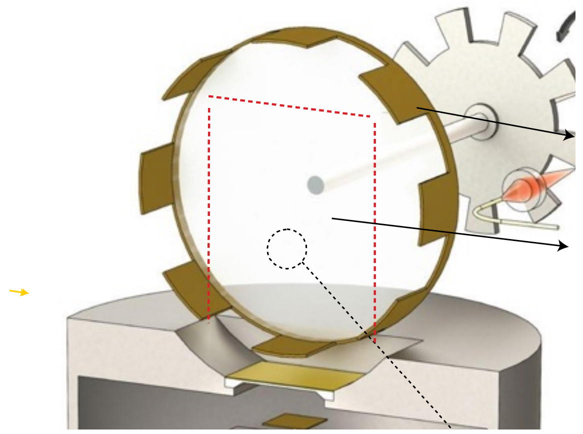
Mechanical systems which are levitated in vacuum can have ultra-low damping and can be useful for:

- **Ultra-precise sensors**: gravimeters, gyroscopes, inertial sensors, sensors for dark matter, magnetometers, gravity waves…
- **Fundamental Science**: generate really interesting mechanical quantum states – squeezed, Schrodinger Cats
- **Gravity&Quantum** : Massive systems – can explore the interaction of gravity with quantum!



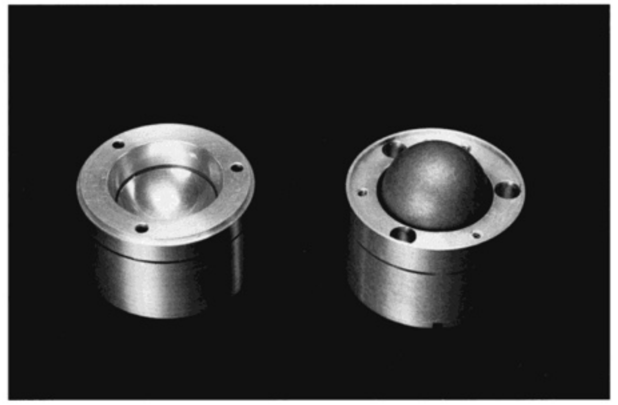
Optical Trapping of High-Aspect-Ratio NaYF Hexagonal Prisms for kHz-MHz Gravitational Wave Detectors

Geraci, et al, Phys. Rev. Lett. (2022)



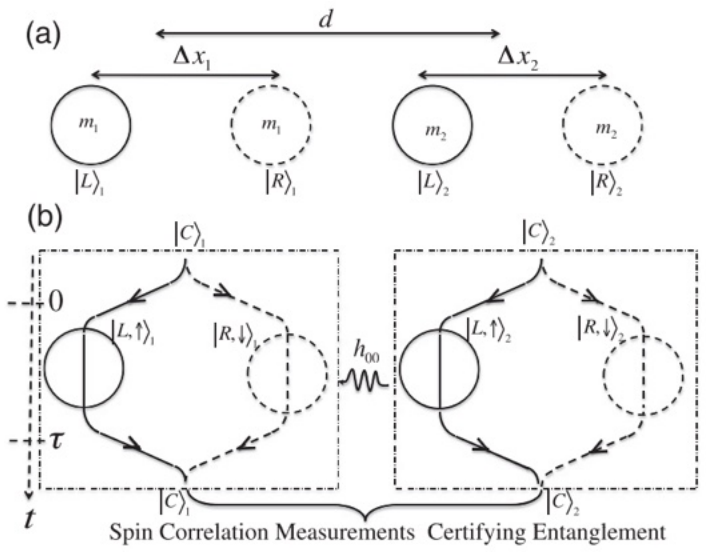
Experiments with levitated force sensor challenge theories of dark energy

Du, et al, Nat Phys (2022)



The superconducting gravimeter

J.M. Goodkind: Rev Sci Inst (1999)



Spin entanglement witness of quantum gravity

Bose, et al, Phys. Rev. Lett. (2017)

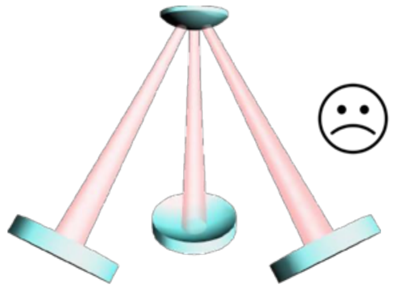
What's so interesting about levitated systems?

WHY IS IT INTERESTING AND USEFUL?

How can we levitate nano-micro sized objects?

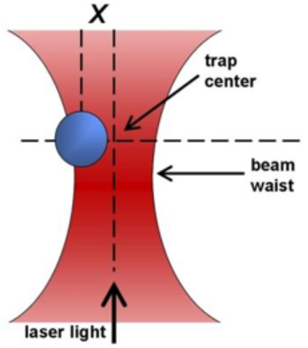
Many forms of trapping/levitation are active – they use active power/controls to trap the object

Optomechanical Levitation



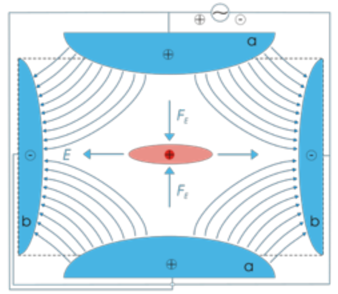
Large laser powers! PRL (2013)

Optomechanical Optical Tweezers



Large laser powers! APL (1976)

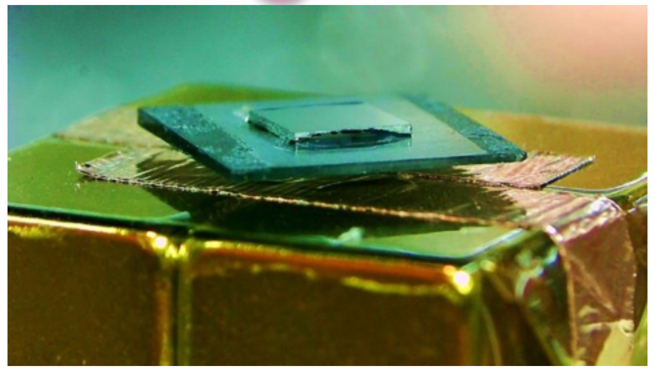
Electrodynamic Trap



Micromotion, ZNA (1953)

Magnetic levitation is passive – can levitate a diamagnetic object forever with no power! Possibly ultra-quiet?

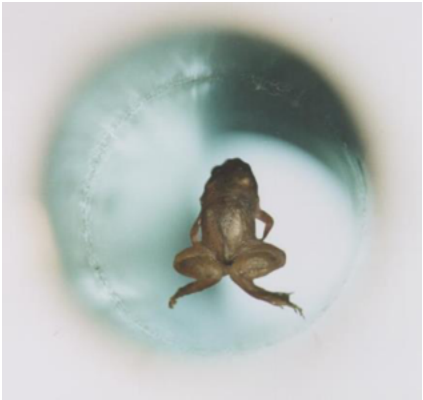
Diamagnetism!



$$F \propto -\nabla|\boldsymbol{B} \cdot \boldsymbol{B}|$$

Magnetic Levitation

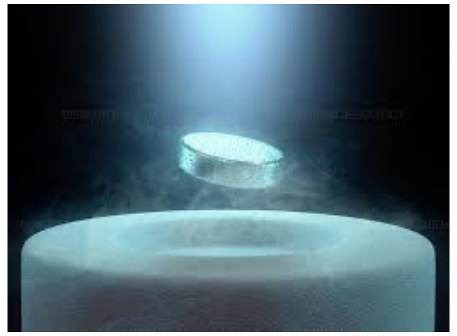
Diamagnetic Levitation



A flying frog!

Berry & Geim, Eur. J. Phys. (1997)

Meissner Repulsion



Four stories

SUMMARY

Improving the motional Quality factor in maglev systems

Priscila Romagnoli, OIST
Japan

Ruvi Lecamwasam, OIST
Japan

Shilu Tian, OIST,
Japan

James Downes, MQ,
Australia

JT, OIST

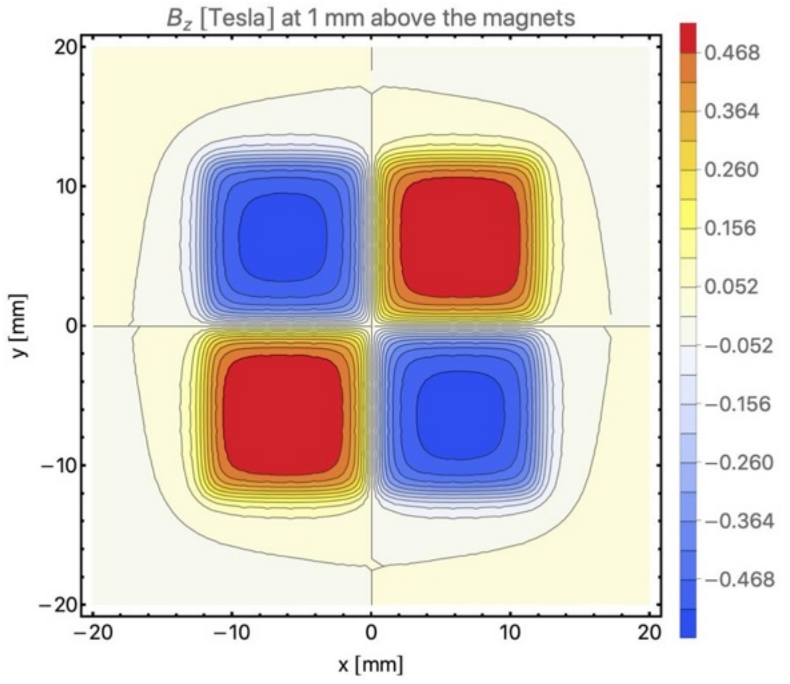
Appl. Phys. Lett. **122**, 094102 (2023)

Diamagnetic levitation

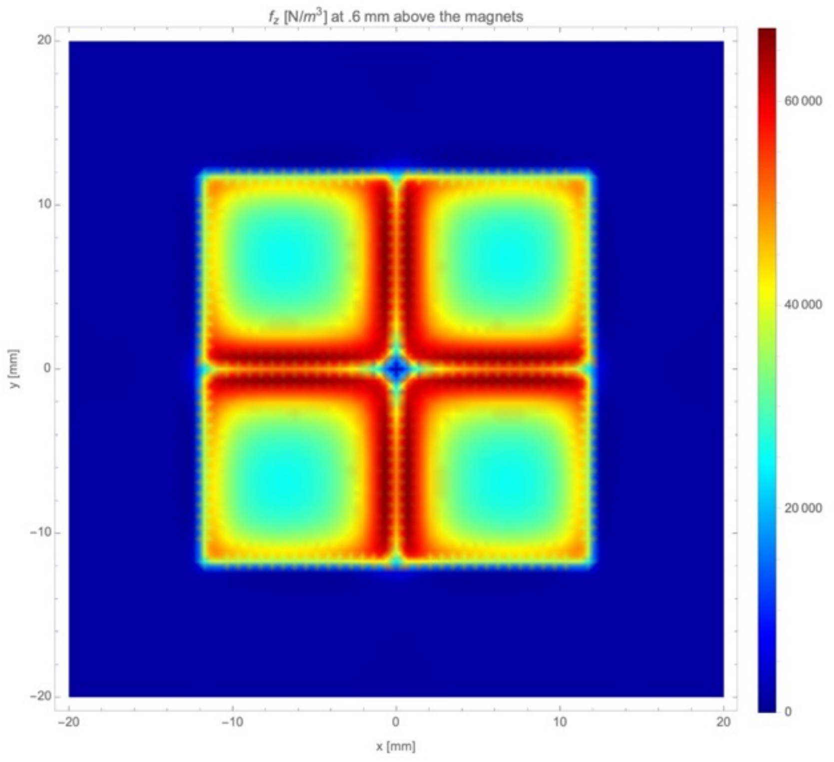
WHAT CAN WE LEVITATE AND HOW DOES IT VIBRATE?

- Highly Oriented Pyrolytic Graphite has largest diamagnetic response at room temp [anisotropic]
- No Cryogenics required
- Can levitate stably over checkerboard magnet array
- Can model vibrational and torsional oscillation frequencies

Material	Magnetic Susceptibility χ_v [× 10^{-5} (SI units)]
Superconductor	−105
Pyrolytic carbon	−40.9
Bismuth	−16.6
Mercury	−2.9
Silver	−2.6
Carbon (diamond)	−2.1
Lead	−1.8



Bz magnetic field above the magnets



Vertical Force Density above the magnets

$$\mathbf{f} = (\mathbf{M}\cdot\nabla)\mathbf{B} = \frac{1}{2\mu_0}\nabla(\chi_x B_x^2 + \chi_y B_y^2 + \chi_z B_z^2),$$

$$\mathbf{M} = \frac{1}{\mu_0}\boldsymbol{\chi}\cdot\mathbf{B}.$$

$$\mathbf{F} = \int_V \mathbf{f}\,d\mathbf{V}$$

$$\boldsymbol{\tau} = \int_V \mathbf{M}\times\mathbf{B}dV + \int_V \mathbf{r}\times\mathbf{f}dV,$$

Translational Mode	$\omega/2\pi$ [Hz]
ν_x	3.70551
ν_y	3.70552
ν_z	17.1166
ν_{xy}	3.7992
ν_{yx}	3.79916

Tilting Modes	$\omega/2\pi$ [Hz]
$\nu\tau_x$	16.8842
$\nu\tau_y$	16.894
$\nu\tau_{xy}$	16.8056

Low freq vibrations

Q-factor??

OIST

X. Chen *et al*, APL 116,(2020)

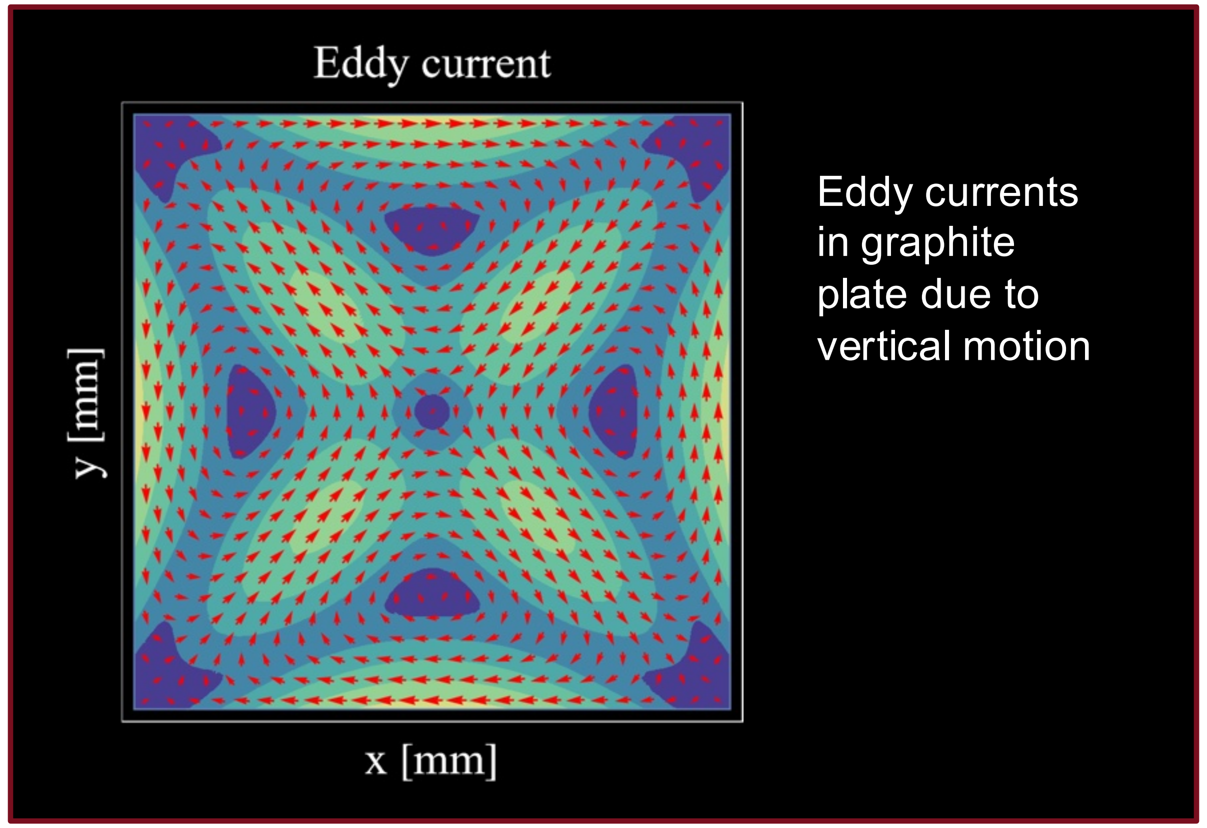
Eddy damping – low Q

EDDY DAMPING IS A DRAG!

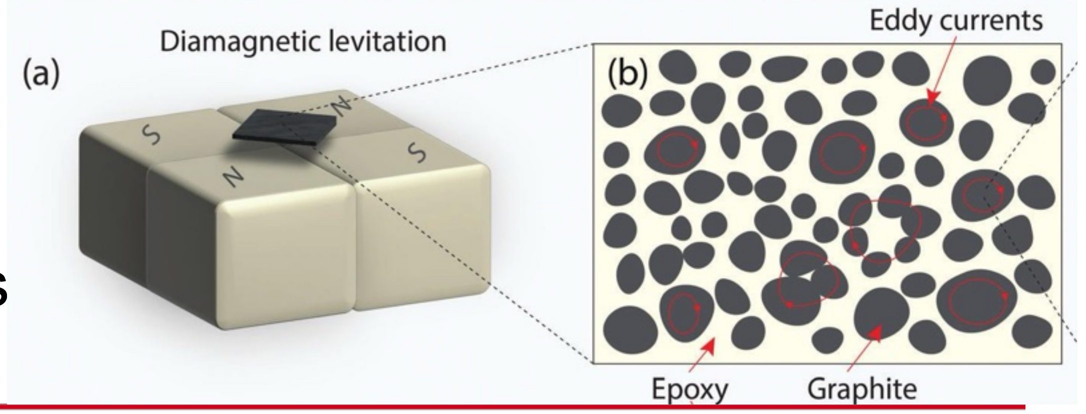
- Many highly diamagnetic materials are electrical conductors. Motion of a conductor in a magnetic field induces **eddy currents and loss** – graphite oscillation even in vacuum has low motional-Quality-factor.

- How to control this **– engineer the eddy currents in the graphite and control the motional Q without loosing too much diamagnetic lift?**

Material	Magnetic Susceptibility χ_v [× 10^{-5} (SI units)]	
Superconductor	−105	
Pyrolytic carbon	−40.9	Electrical Conductors
Bismuth	−16.6	Electrical Conductors
Mercury	−2.9	Electrical Conductors
Silver	−2.6	Electrical Conductors
Carbon (diamond)	−2.1	
Lead	−1.8	Electrical Conductors
Carbon (graphite)	−1.6	Electrical Conductors
Copper	−1.0	Electrical Conductors
Water	−0.91	



- One suggestion: composite- resin with micron sized graphite powder – reduces eddy currents but also reduces lift – does give high-Q !



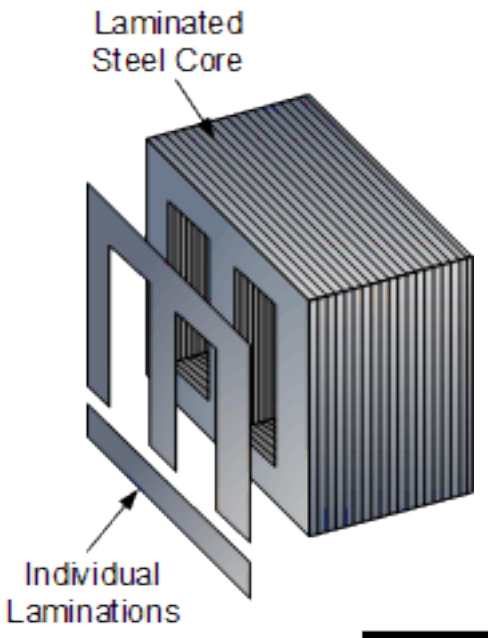
X. Chen *et al*, Adv Sci (2022)

OIST

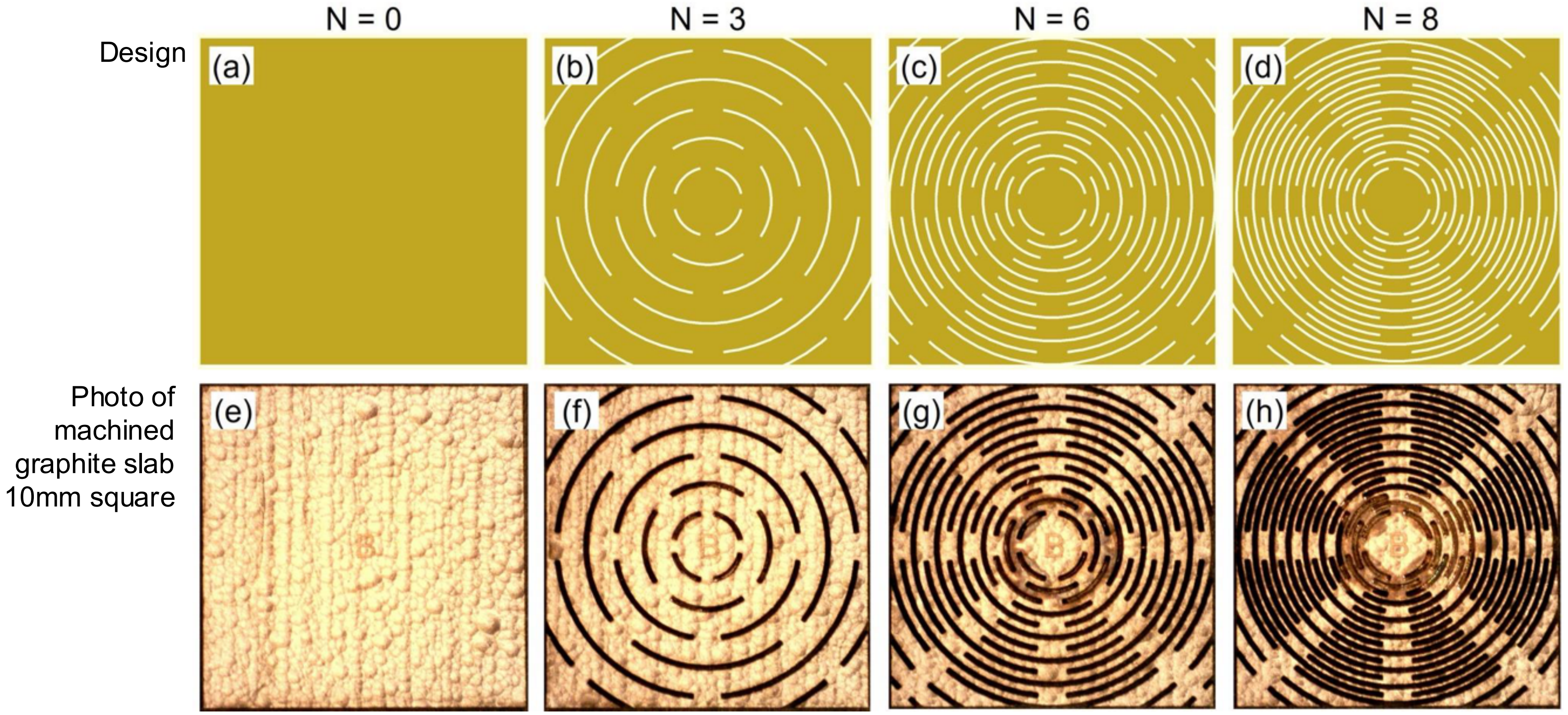
Eddy damping – low Q

HOW TO ENGINEER THE EDDY DAMPING!

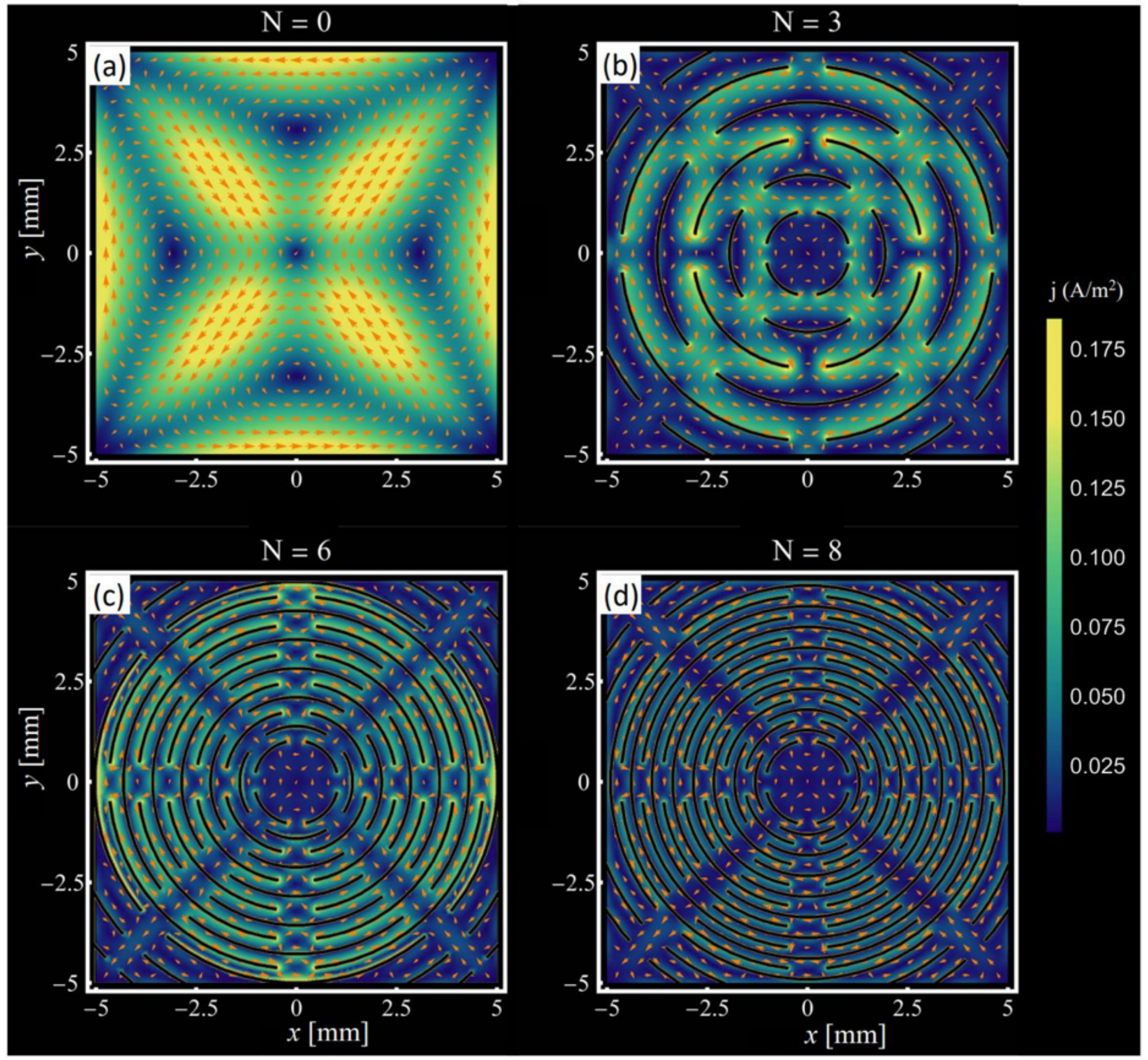
- Instead we follow route similar to how eddy currents are reduced in electrical transformers – physically interrupting the eddy currents.
- Interrupt the eddy currents by physically making tiny slots in the graphite slab



Laser Machining at OptoFab MQ Node



Eddy currents in slotted slabs greatly reduced

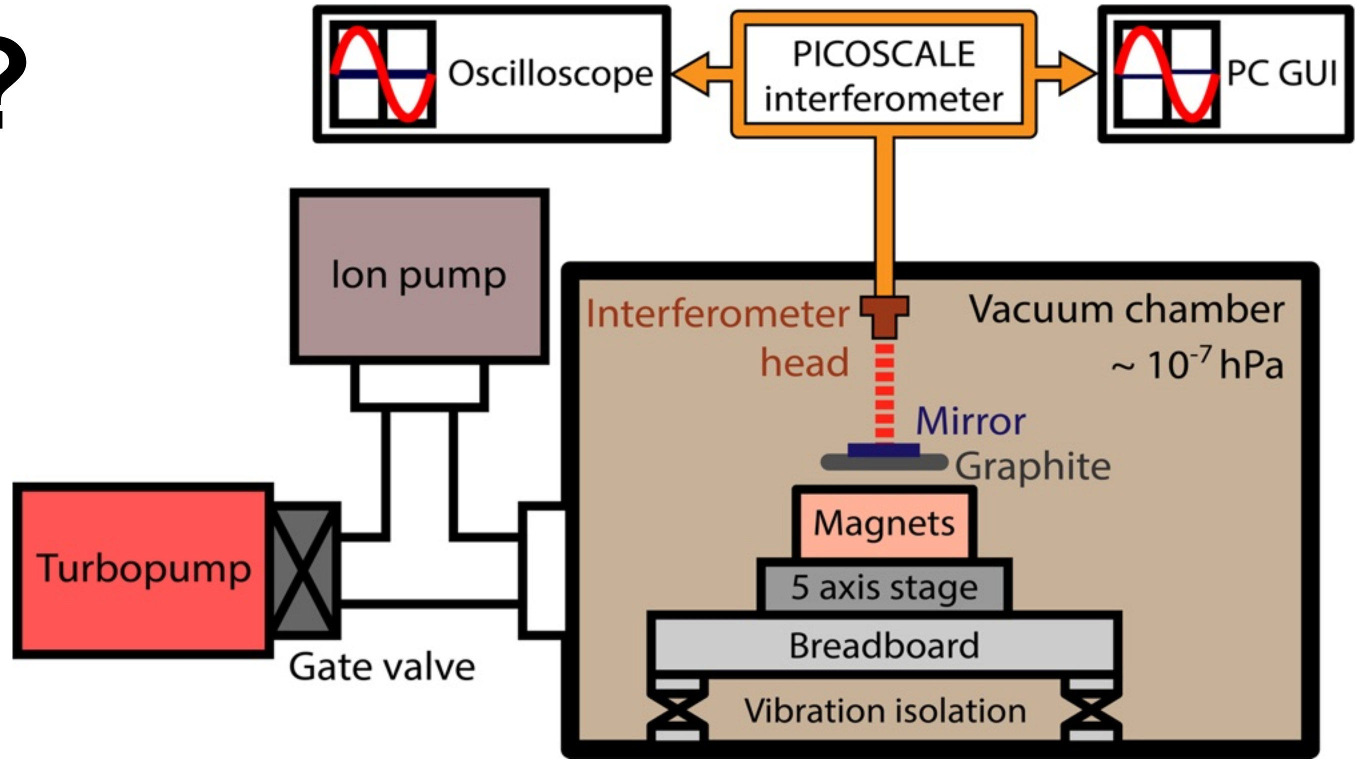


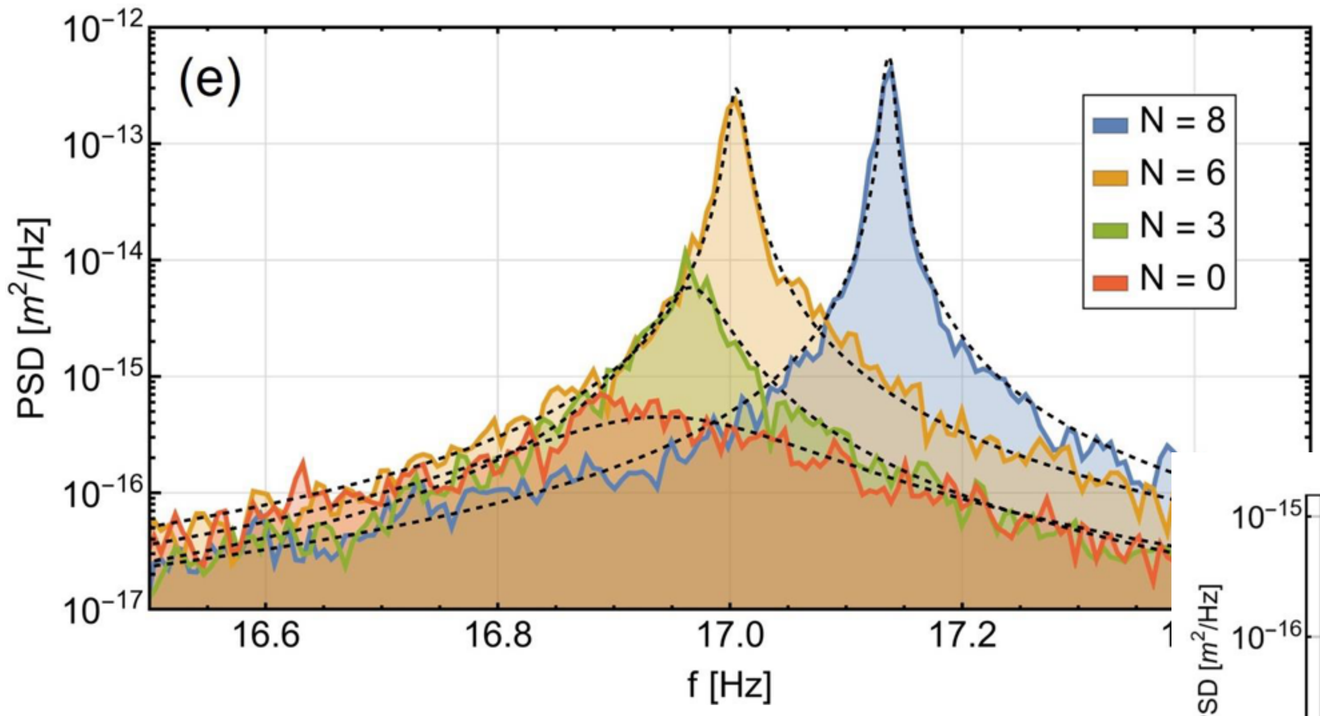
Eddy current simulations [Comsol/Mathematica]

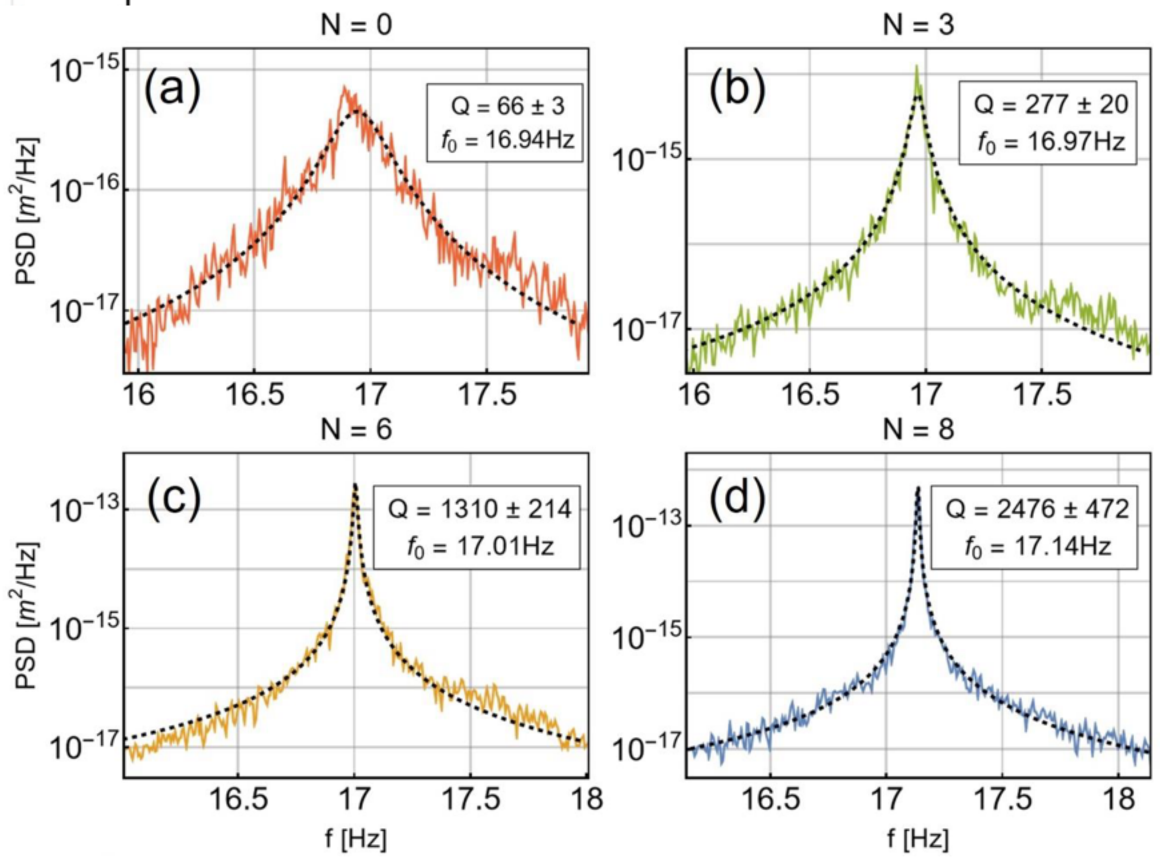
Measure Q of the levitated plate?

HOW TO CONFIRM THE IMPROVED DAMPING?

- Measure motion of plate (small mirror attached), using laser displacement interferometer – high vacuum – no pump vibrations using ion pump.

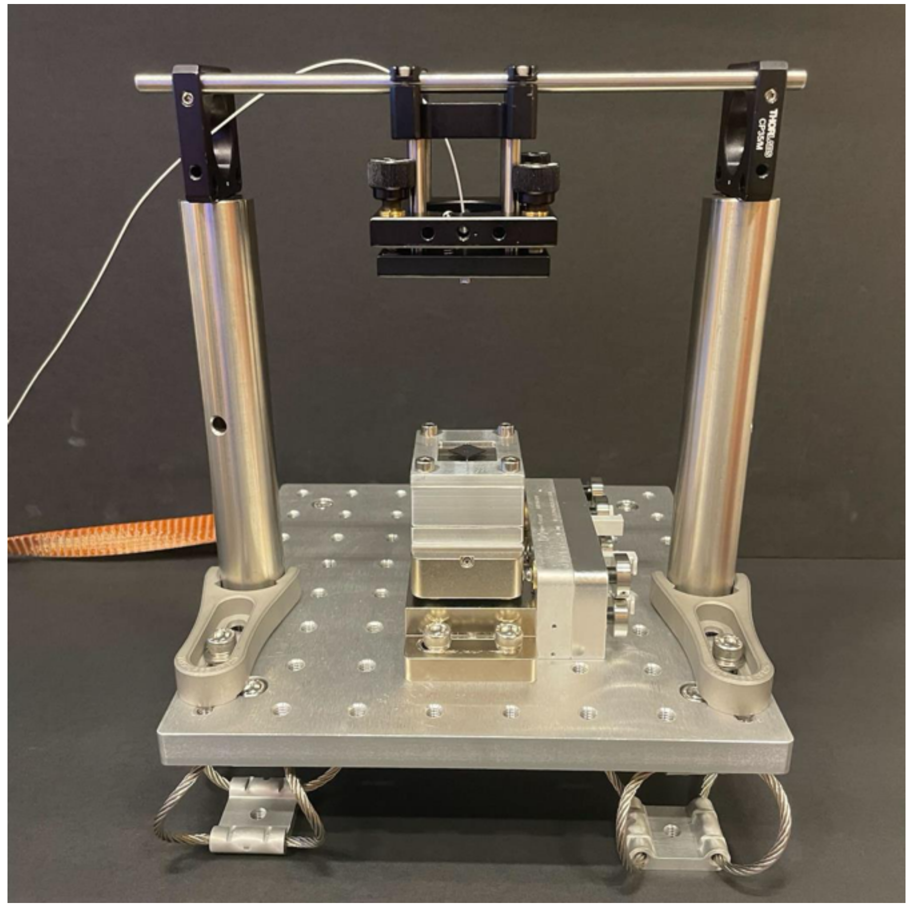






$$S(f) = \frac{8k_B T\gamma/m}{\left((2\pi f_0)^2 - (2\pi f)^2\right)^2 + (2\pi f\gamma/m)^2}$$

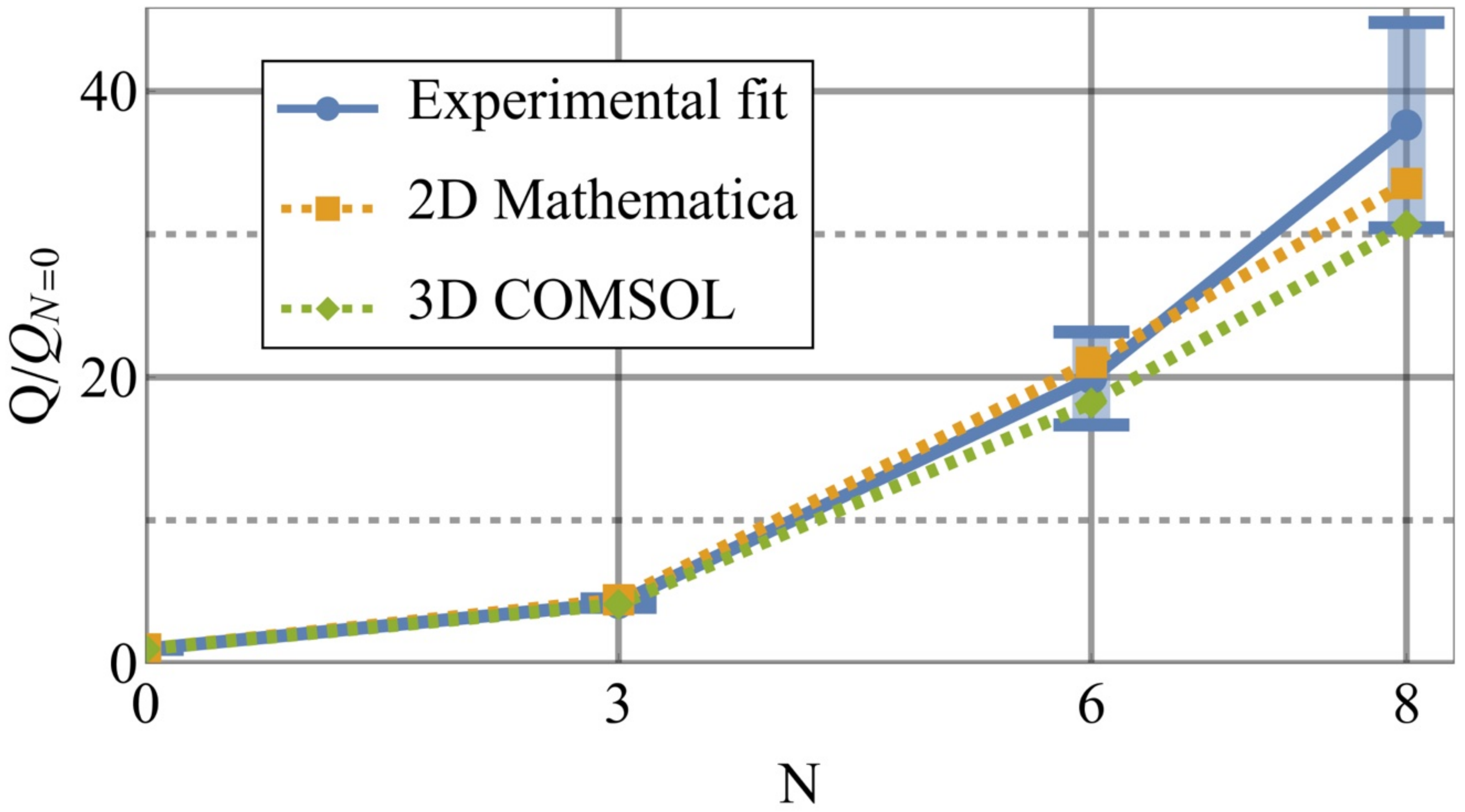
Q-factor increases



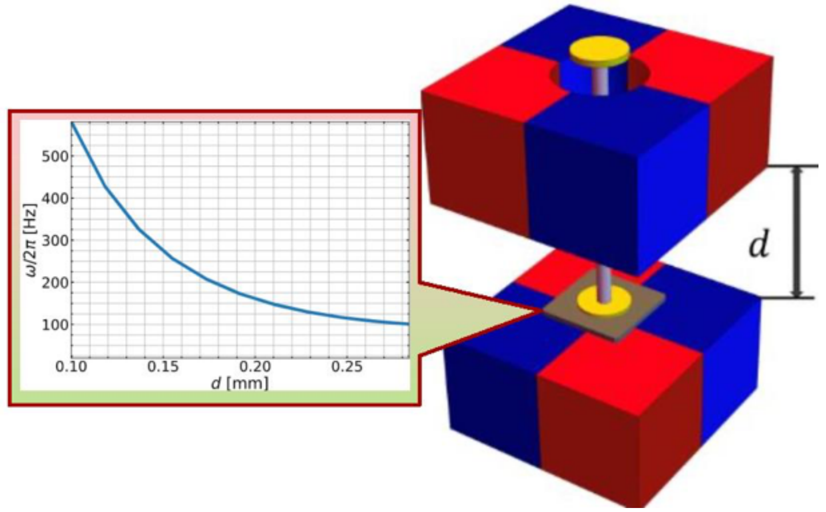
Measure Q of the levitated plate?

HOW TO CONFIRM THE IMPROVED DAMPING?

- Compare the Q-factor of the slotted plates with the solid plate with simulations done in Mathematica and COMSOL – very good agreement!
- Motional damping primarily due to eddy!
- Next – can we try some other diamagnetic materials to increase Q-factor and try feedback cooling?



Poster: Tatania Iakovleva



Use magnetically levitated cavity optomechanics to measure displacement to a resolution of

$$\Delta d \sim 10^{-21}\ \mathrm{m}$$

T. Iakovleva

B. Sarma

OIST

Appl. Phys. Lett. **122**, 094102 (2023)

arxiv.org/2302.06795

Improved Q factor

HOW TO IMPROVE THE MOTIONAL Q FACTOR

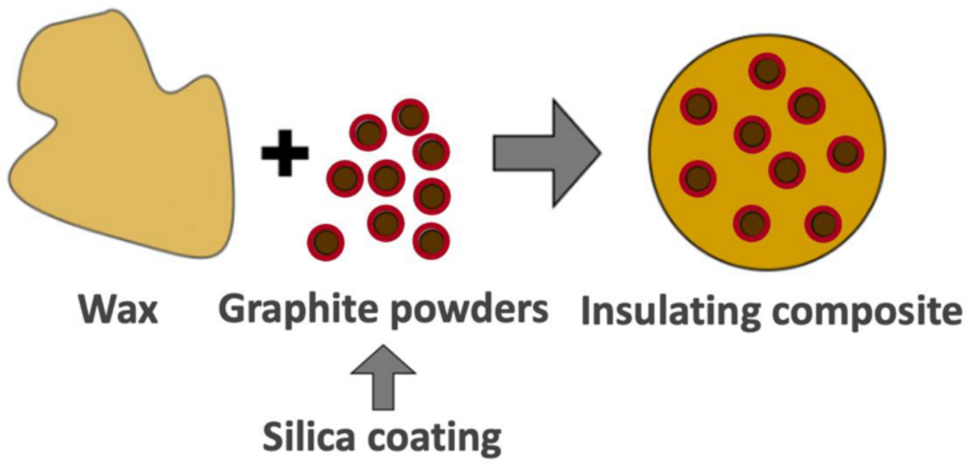
- To reduce eddy damping have to reduce eddy currents.

- To reduce eddy currents we make the plate out of micron size graphite particles which we coat to make each electrically insulating.

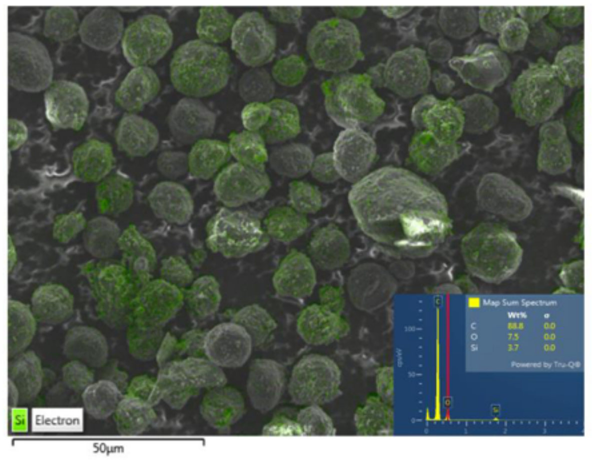
- The particles have random orientation and so the magnetic susceptibility becomes isotropic

- This changes the orientation of the plate when levitated

- Making graphite composite

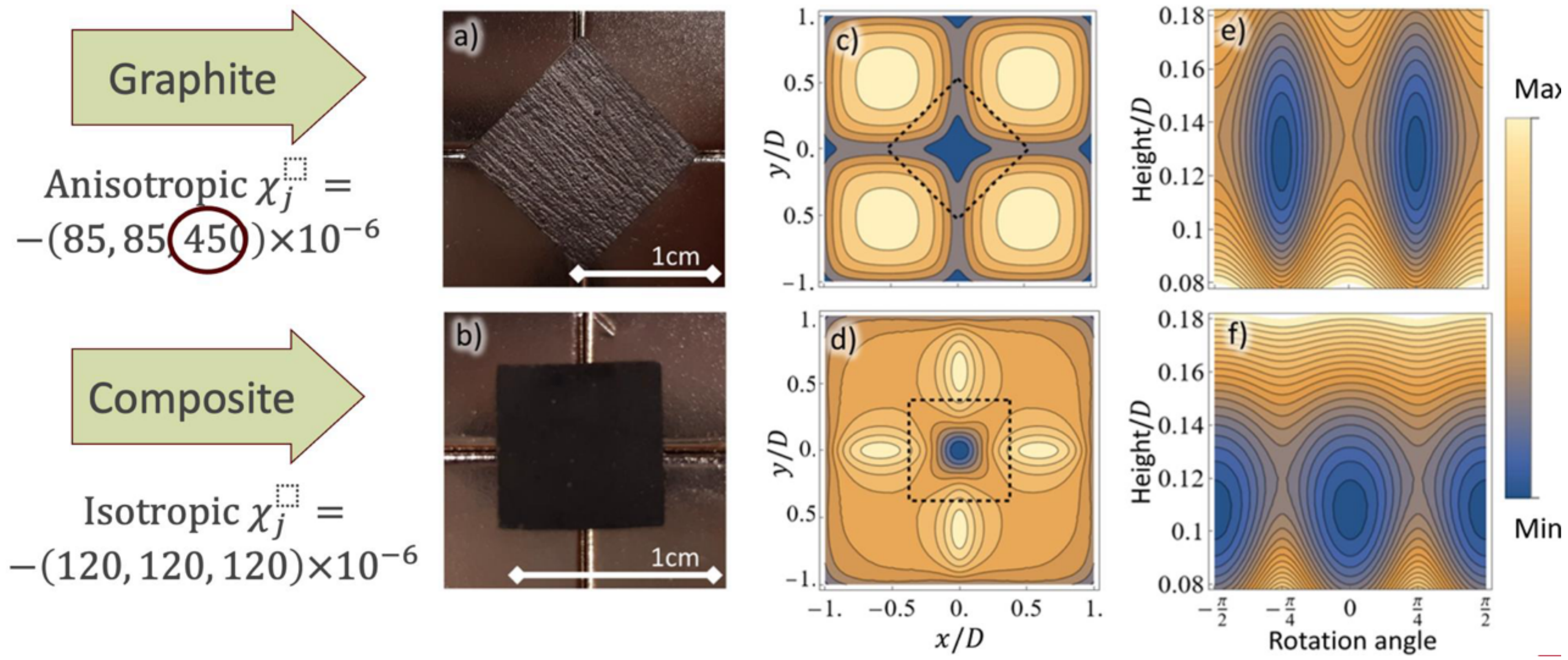


Green indicates the Si element, showing the complete coating



SEM and Si EDX

- Different orientations



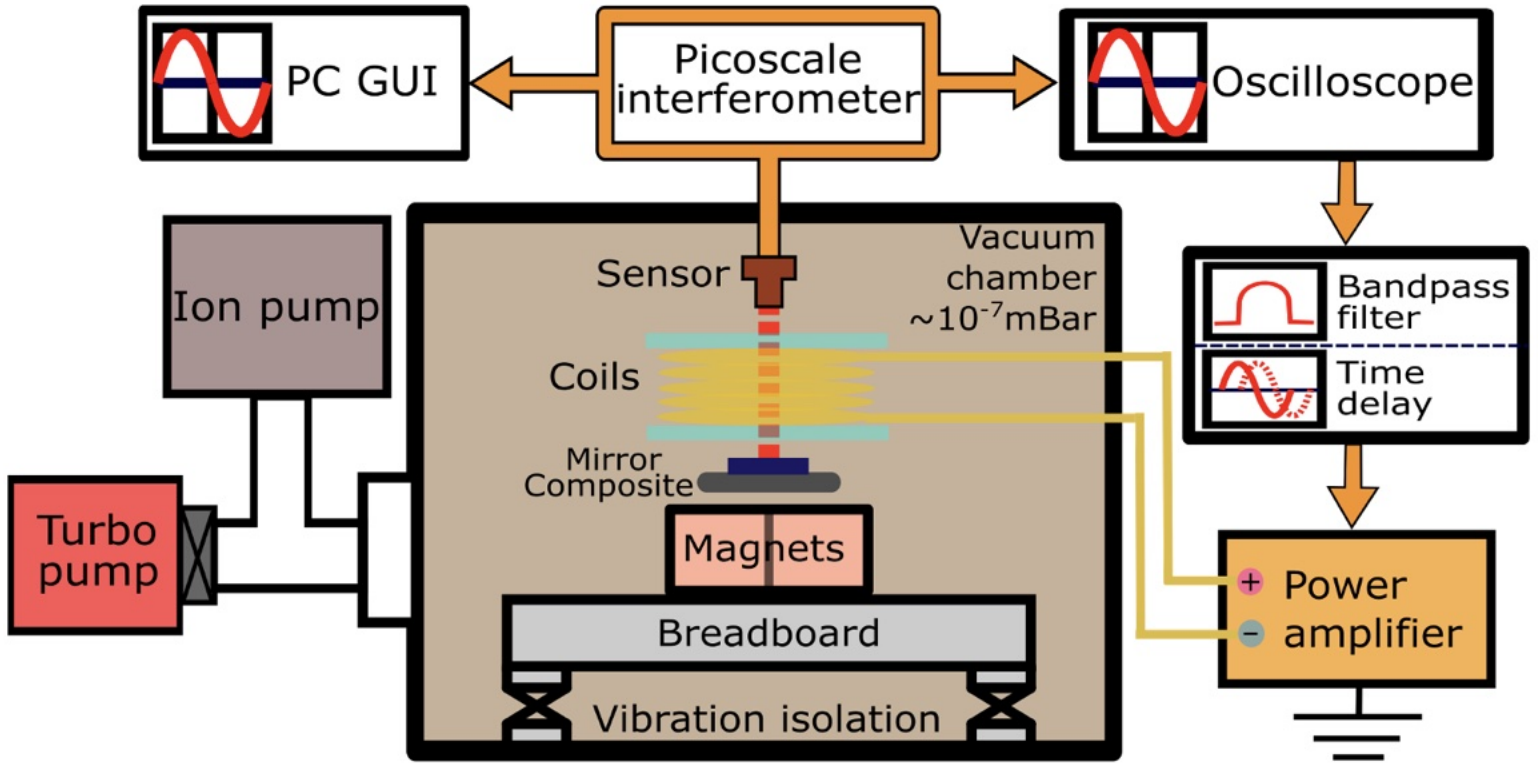
OIST

APL 124, 124002 (2024)

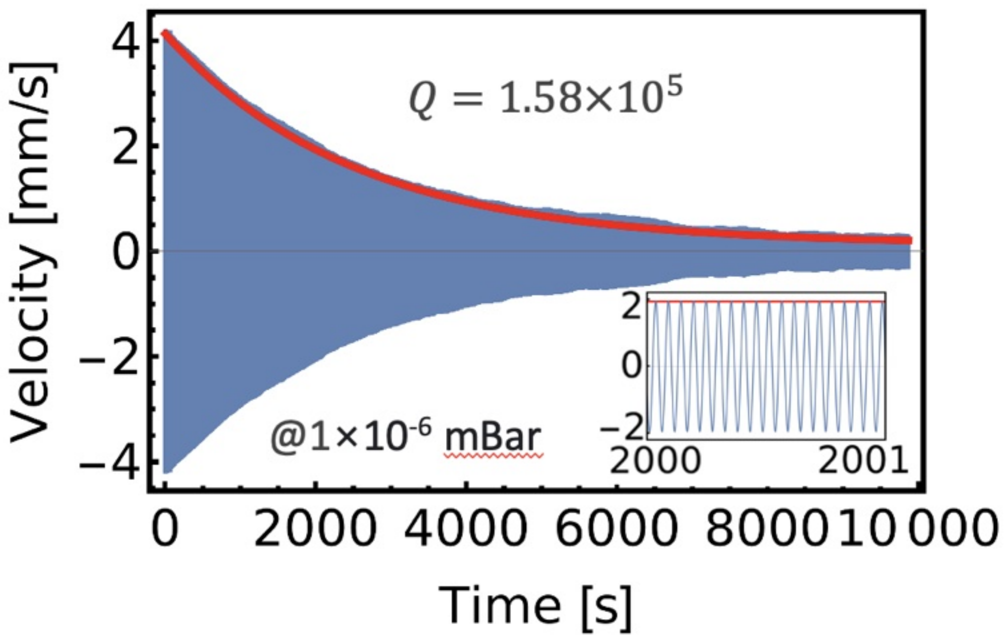
Improved Q factor

HOW TO IMPROVE THE MOTIONAL Q FACTOR

- Ringdown measurements yield a motional Q which is very high
- We build a setup where we can in-real-time apply a force using an electromagnet to the plate.
- We can then try to apply feedback cooling



- Achieve Q factors of 10^5



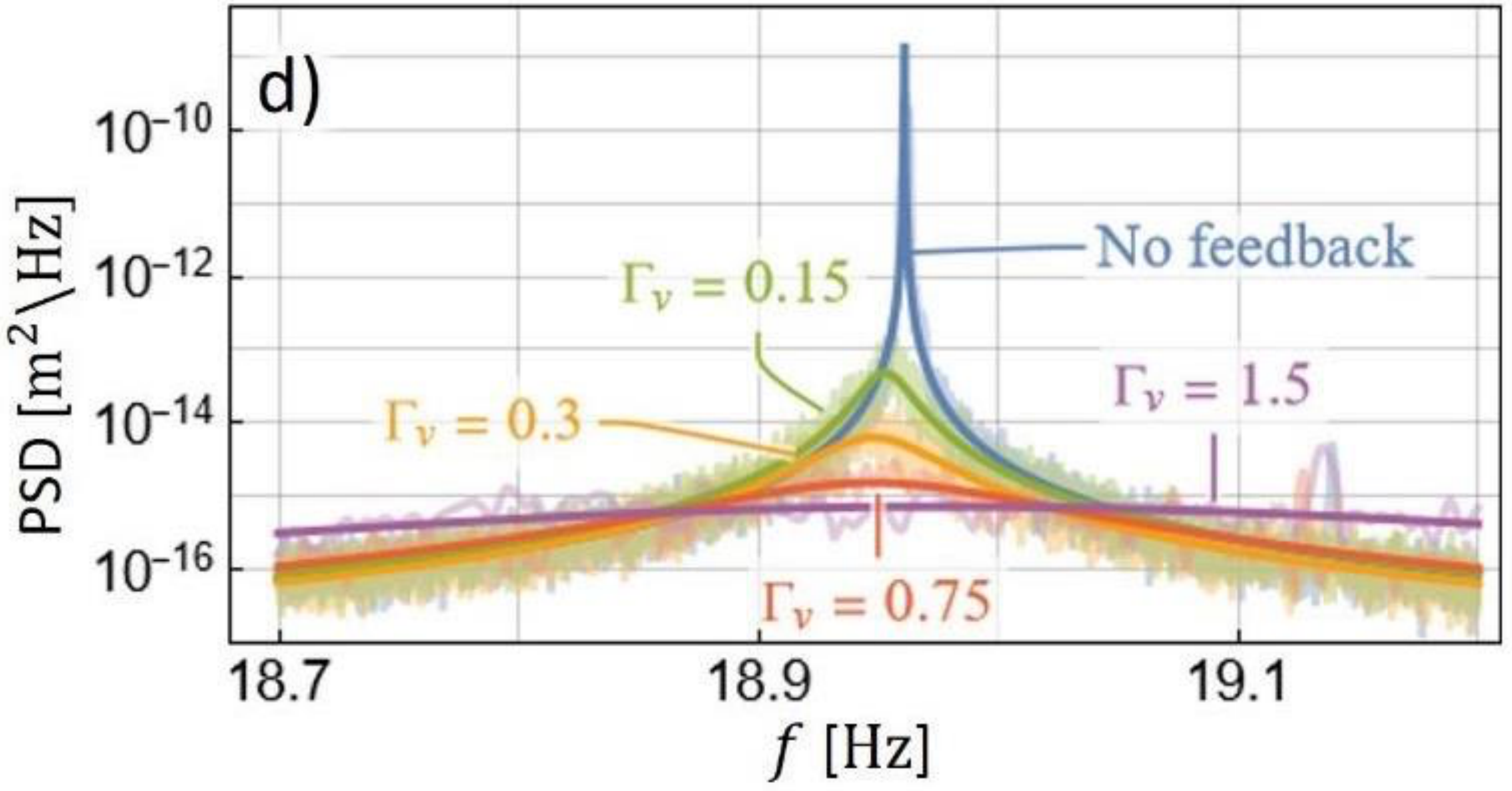
Ringdown measurement

Improved Q factor

HOW TO IMPROVE THE MOTIONAL Q FACTOR

- Delayed velocity feedback cooling using the coil for actuation
- The suppression of the vertical translational mode can be seen below, and increases with increasing feedback strength, Γ_v.
- The measured PSD fits the theory descriptions:
- CoM temperature is cooled by 3 orders of magnitude.
- Assume we start at room temp then the **massive, high-Q, cooled resonator** would reach acceleration sensitivity of $1.7 \times 10^{-12} g/\sqrt{\mathrm{Hz}}$, which is much better than the research scale atomic gravimeters.
- How to improve this further? Smaller graphite beads?

$$S_{xx}(\omega) = \frac{2k_B T\gamma/m}{\left[\omega_0^2 - \omega^2 + \omega\Gamma_v \sin(\omega\tau)\right]^2 + \left[\omega\gamma + \omega\Gamma_\nu \cos(\omega\tau)\right]^2}$$



APL 124, 124002 (2024)

Four stories

SUMMARY

Daehee Jim,
OIST, Japan

Shilu Tian, OIST,
Japan

Breno Calderoni,
OIST, Japan

Cristina Sastre Jachimska,
OIST, Japan

James Downes, MQ,
Australia

JT, OIST

Magnetic levitated rotor with ultra-low loss

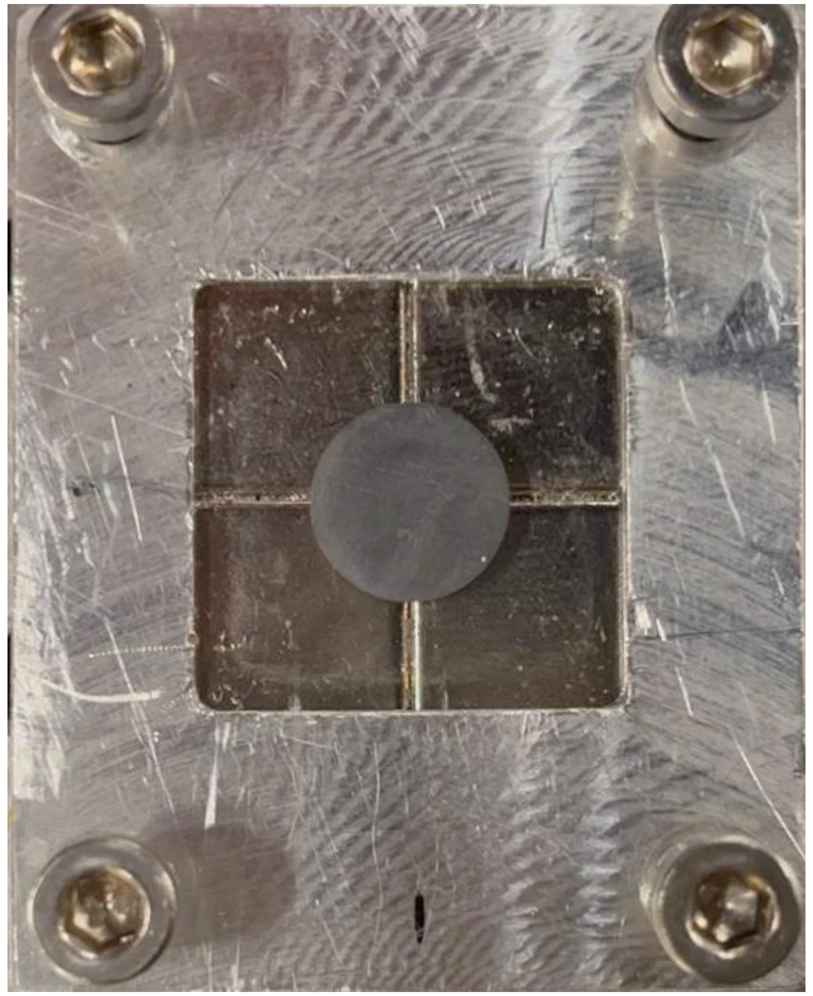
OIST

Commun Phys 8, 381 (2025)

Rotations

CAN WE AVOID EDDY CURRENTS ALTOGETHER?

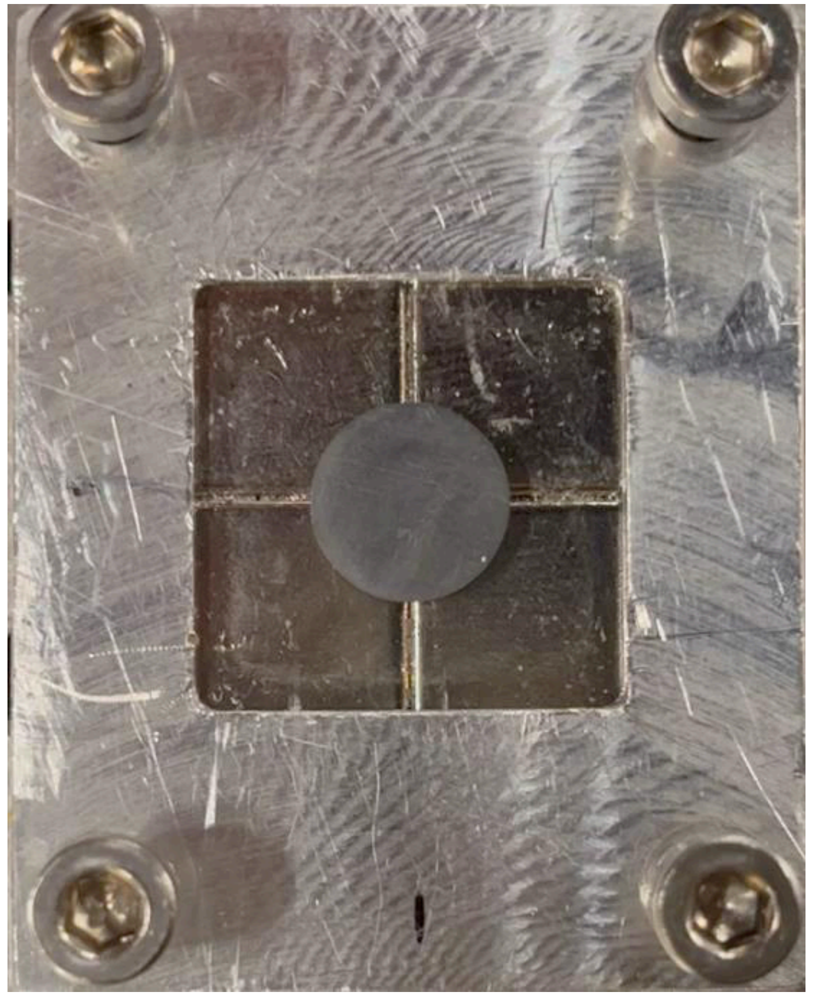
- Previously we worked to reduce the eddy current generated in the levitator
- Are there levitation setups which – in principle – no eddy currents are even generated?
- Look at rotations of the levitated plate? Square shape is fully trapped – ok -- make it a disk? Does it rotate freely?
- It stops quickly! Why?



Rotations

CAN WE AVOID EDDY CURRENTS ALTOGETHER?

- Previously we worked to reduce the eddy current generated in the levitator
- Are there levitation setups which – in principle – no eddy currents are even generated?
- Look at rotations of the levitated plate? Square shape is fully trapped – ok make it a disk? Does it rotate freely?
- It stops quickly! Why?
- Graphite is now axially symmetric but magnetic flux generated by magnets is not! Small elements in the graphite see changing flux and eddy damping happens!

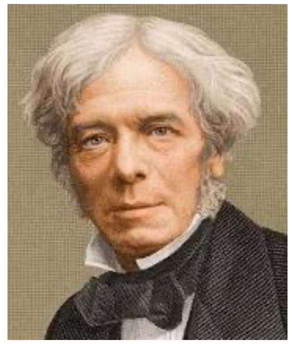


Can we have stable levitation of a graphite disk in an axially symmetric magnetic field? Mayne no eddy currents generated?

Rotations

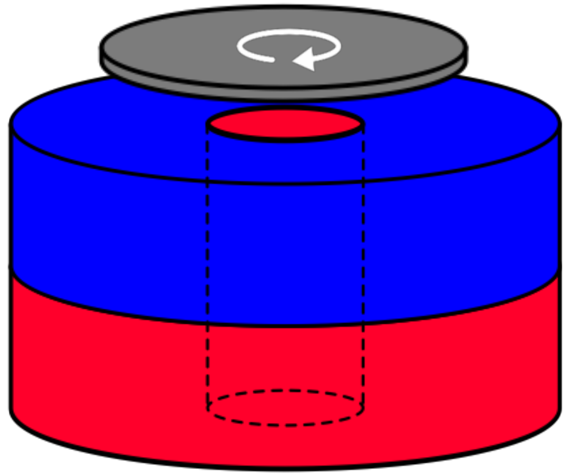
CAN WE AVOID EDDY CURRENTS ALTOGETHER?

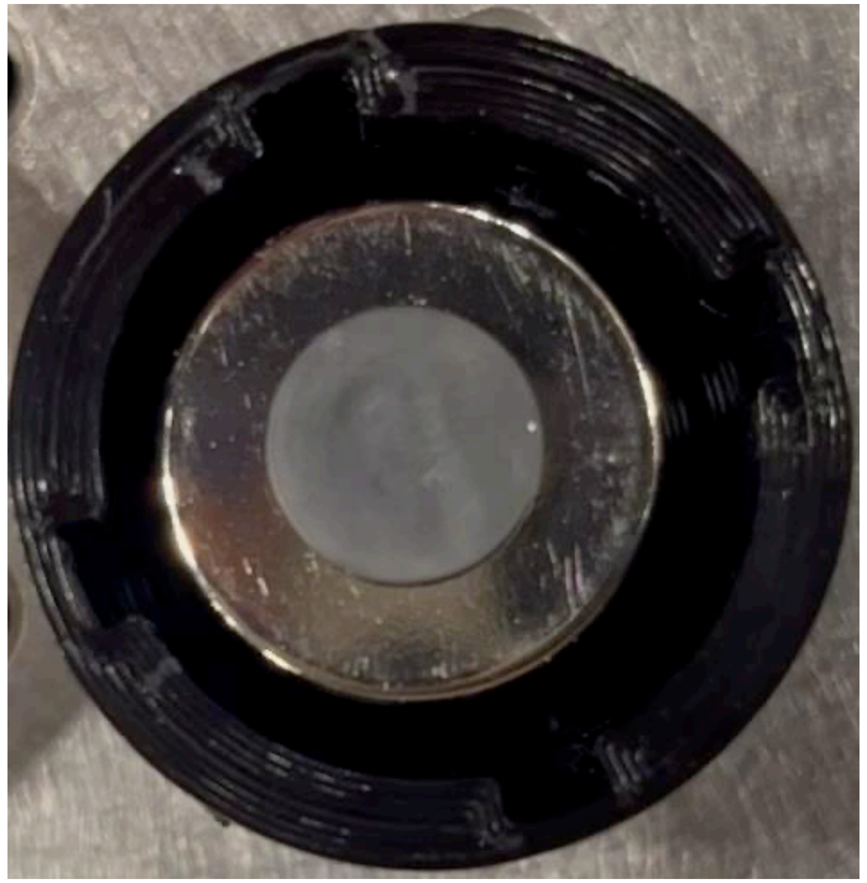
- Can have axially magnetized magnet array and this can levitate a graphite disk – v high! (previously known).
- So does a rotating conductor in an axial magnetic field experience eddy damping?
- Literature seems to have some votes for (no) and some votes for (yes)? Both theory and experiments!
- First Experiment by Faraday



- Let us try it!
- Spin it up in air….and it goes and goes….
- Lets look at it sideways…

Axially symmetric system

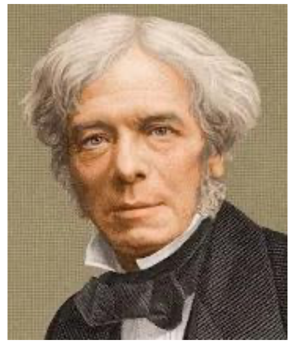




Rotations

CAN WE AVOID EDDY CURRENTS ALTOGETHER?

- Can have axially magnetized magnet array and this can levitate a graphite disk – v high! (previously known).
- So does a rotating conductor in an axial magnetic field experience eddy damping?
- Literature seems to have some votes for (no) and some votes for (yes)? Both theory and experiments!
- First Experiment by Faraday

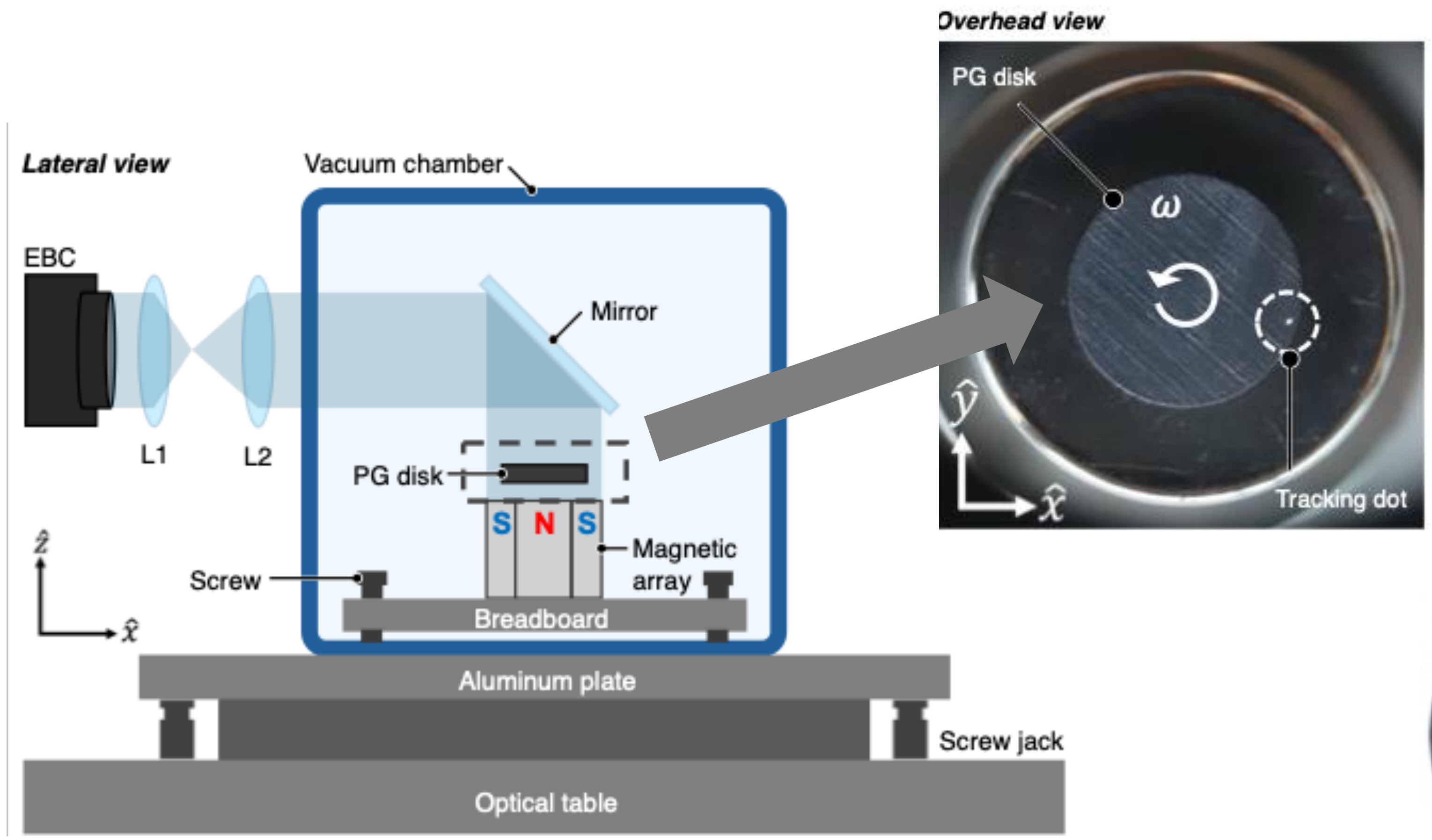


- Let us try it!
- Spin it up in air….and it goes and goes….
- Now let us vary the pressure….

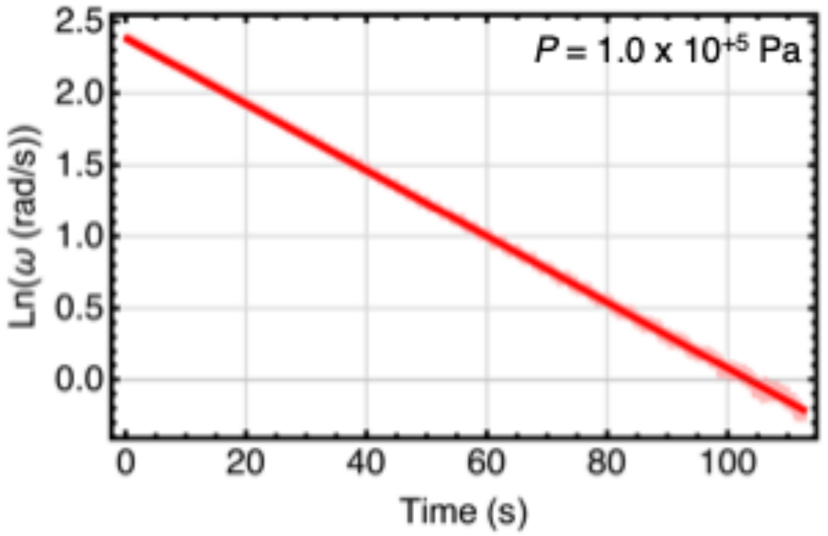
Rotations

CAN WE AVOID EDDY CURRENTS ALTOGETHER?

- Put setup in vacuum chamber – change pressure from atmosphere (continuum) to high vacuum (free molecular flow)
- Jiggle the optical table to get the disk rotating…watch the spin down
- Use event camera to track the motion of a small dot on the disk - very high frame rate.

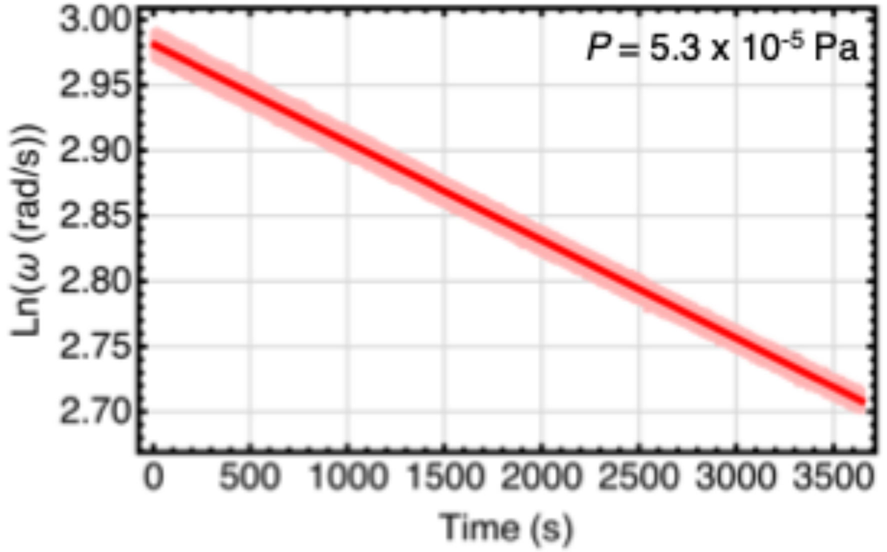


Event-base detection



High Pressure

$$\omega(t) = \omega_0 e^{-\gamma t}$$



V low Pressure

$$\gamma(P)\ ?$$

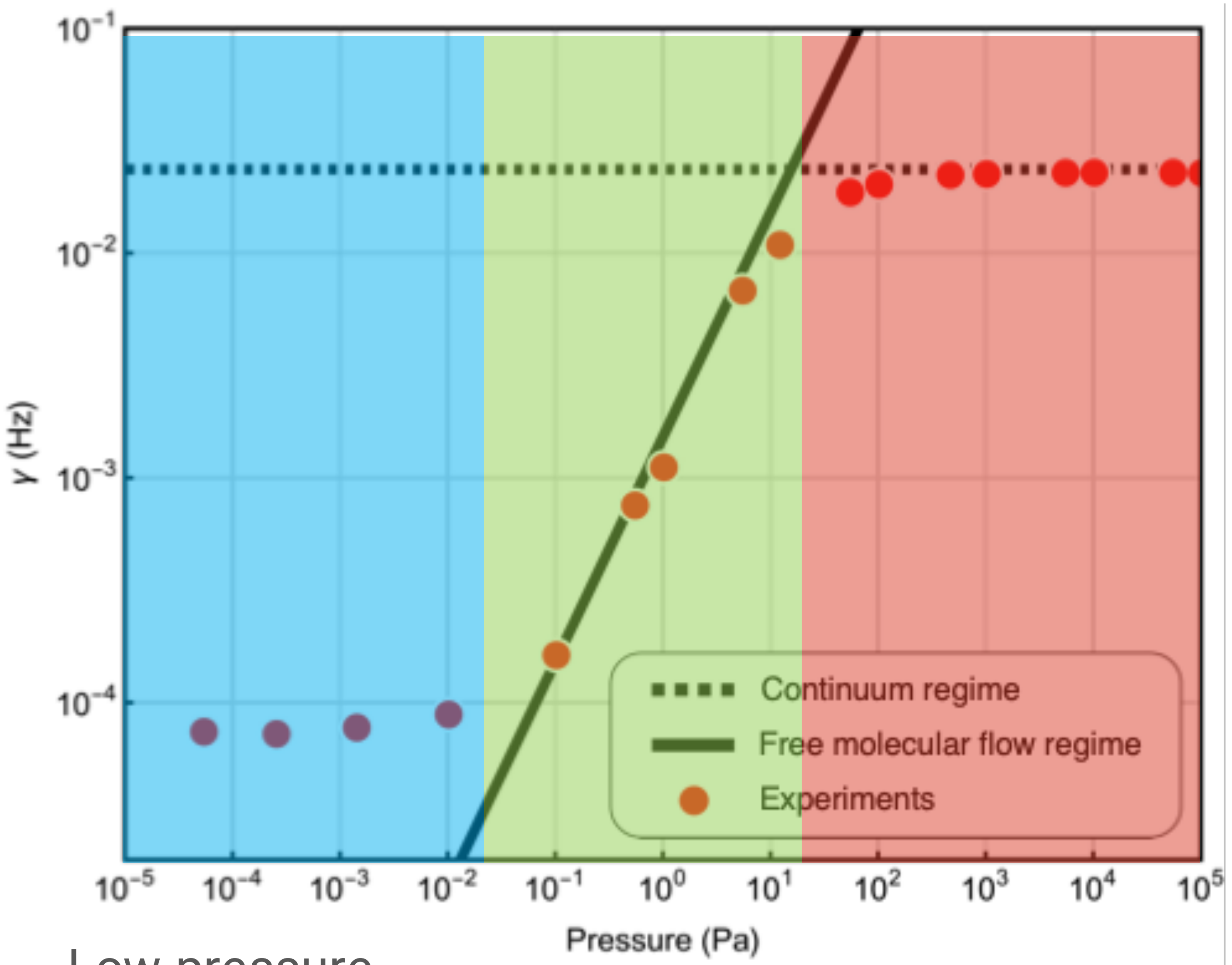
OIST

Gas friction damping

CAN WE AVOID EDDY CURRENTS ALTOGETHER?

Free molecular flow

Continuum

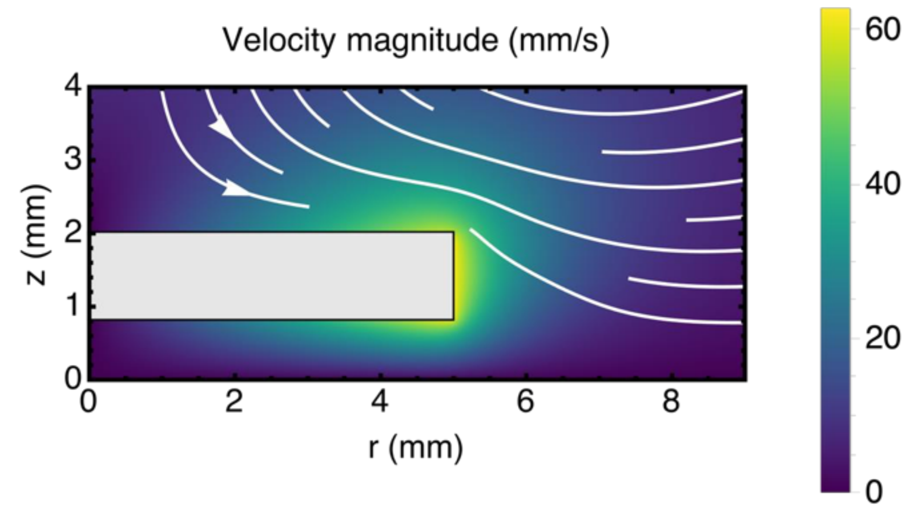


Low pressure

High pressure

Continuum regime (High pressure)

- Navier-Stokes solved using FEM (COMSOL).



Free molecular flow regime (Low pressure)

$$\gamma_{\mathrm{fm}}(P) = \underbrace{\sigma \frac{R^4}{I}\left(1 + \frac{2H}{R}\right)}_{\text{Disk geometry \& mass}} \underbrace{\sqrt{\frac{\pi m_0}{2 k_{\mathrm{B}} T}}P}_{\text{Gas properties}}$$

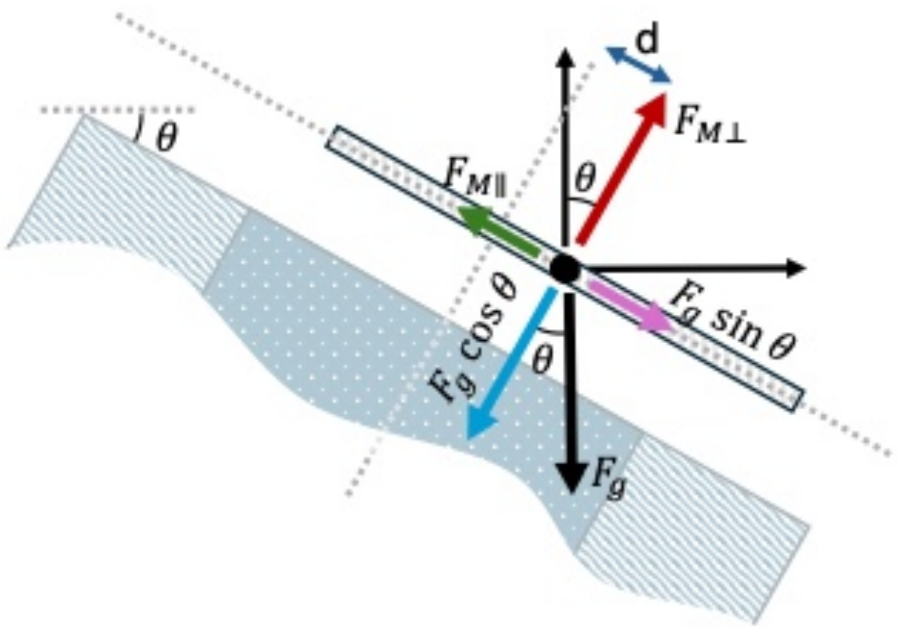
A plateau is observed at low pressure.

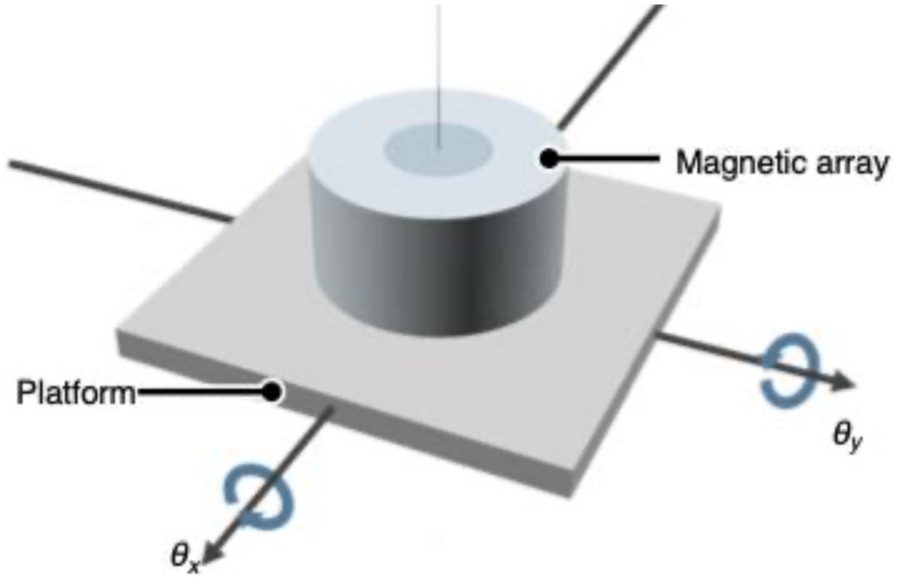
-> Other damping is dominating!

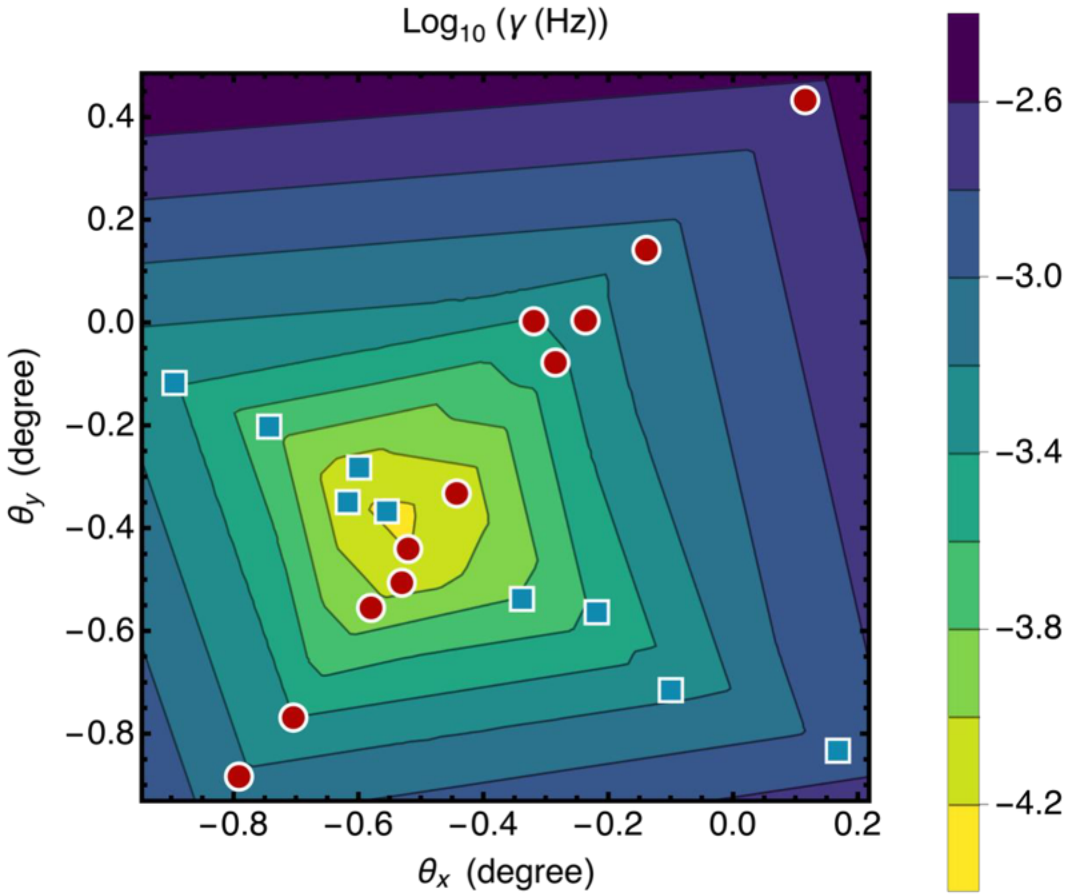
Tilting ruining axial symmetry

IF THE SETUP IS SLIGHTLY TILTED NO LONGER AXIALLY SYMMETRIC

- Tilt the entire vacuum chamber by tiny angles





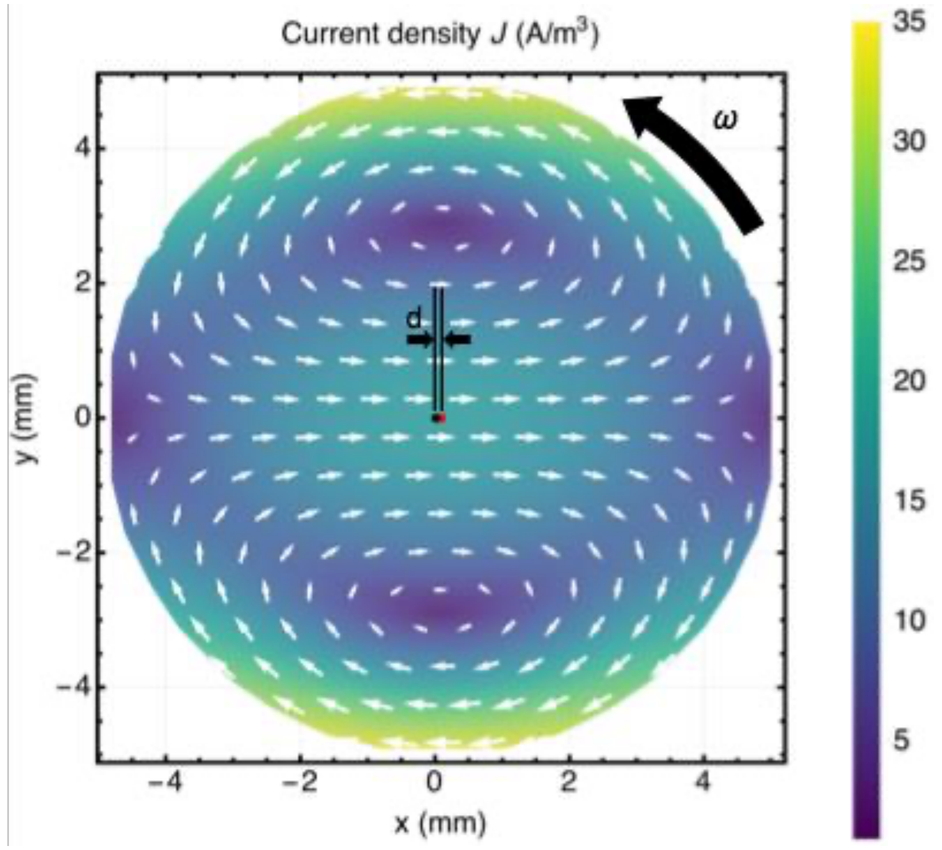


- The lowest damping is NOT ZERO
- Material imperfections in graphite and magnets?

Simulations and Analytics and Conclusion

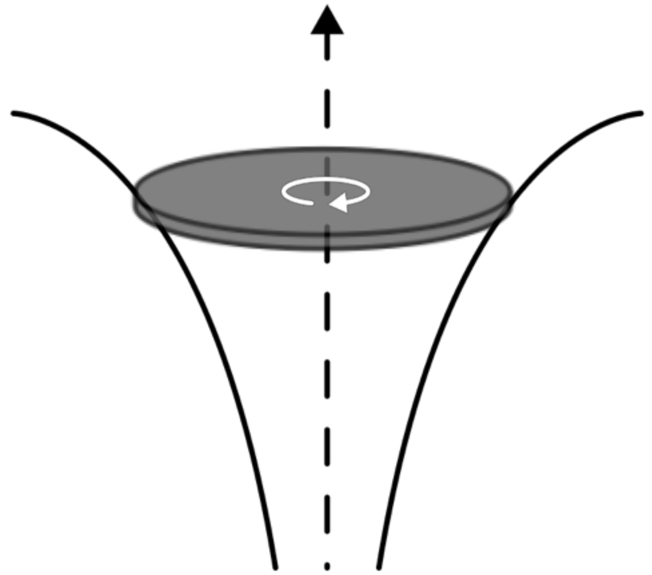
NUMERICAL SIMULATIONS AND ANALYTICS

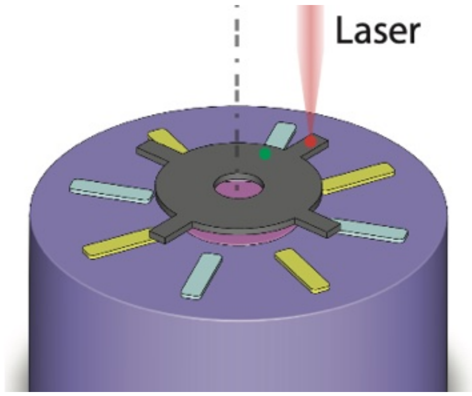
- Can try COMSOL – but no mesh ever axially symmetric – never zero damping - even when co-axial



Comsol off-axis eddy simulation

- Found nice simple **analytic proof** that a rotating conductor in any form of co-axial B field induces NO eddy current





- Can we use this for torque sensing/pressure sensing
- Very massive – can hold more than it's own mass
- How to actuate torques in vacuum?

arXiv:2506.03803v2

Four stories

SUMMARY

Sarath-Raman
Nair, Australia

Shilu Tian, OIST,
Japan

Gavin Brennen,
Australia

Sougato Bose,
UK

JT, OIST

How to engineer massive Schrodinger Katz?

OIST

Phys Rev Appl 24, 024061 (2025)

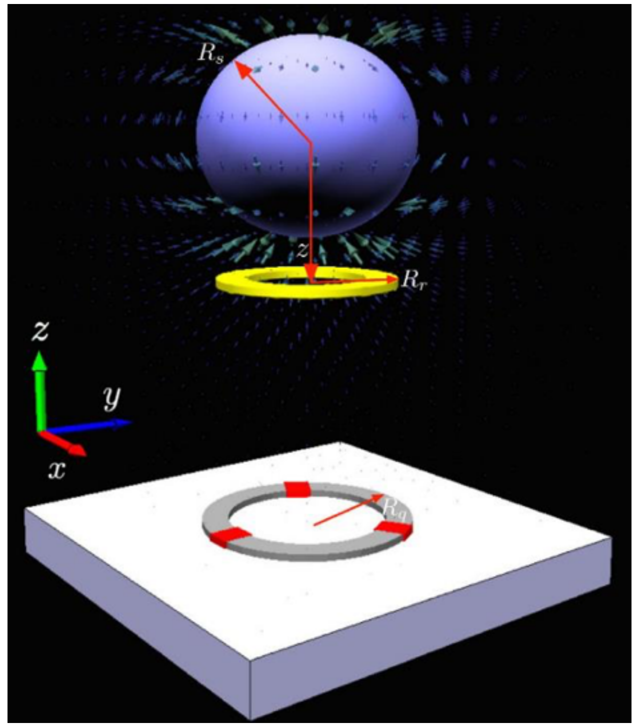
Schrodinger Cats with massive objects

MOTIVATION

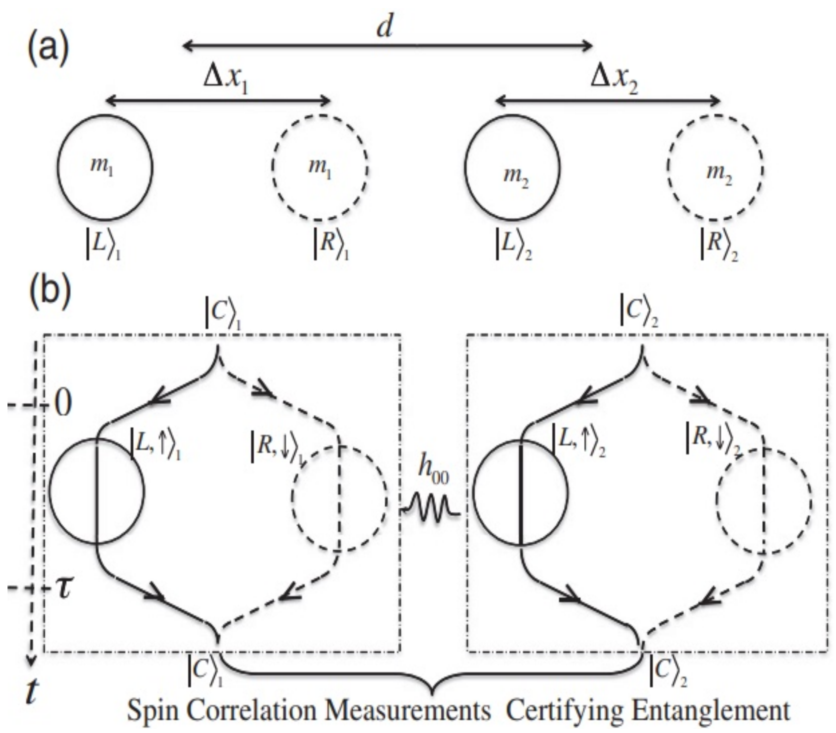
- Long time interest – what is the boundary between quantum and classical worlds
- Generation of macroscopic quantum states of massive objects in two spatial positions
- Can be useful for ultra-sensitive sensors
- Can also be useful to probe the links between the quantum world and gravity!

WITH MACROSCOPIC SUPERPOSITIONS OF MASSIVE OBJECTS

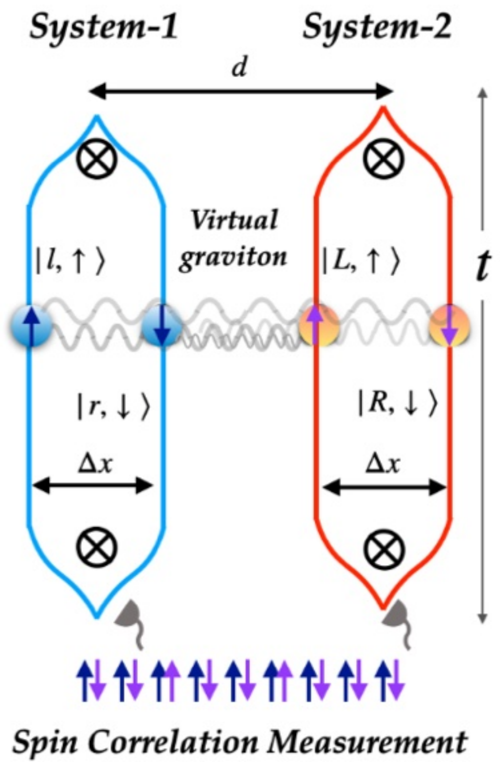
- Absolute gravimetry



- Link between Quantum & gravity



- Test quantum equivalence principle



M. Johnsson et al., Sci. Rep. 6, 37495 (2016)

S. Bose et al., Phys. Rev. Lett. 119, 2402401 (2017)

S. Bose et al., arXiv:2203.11628 (2022)

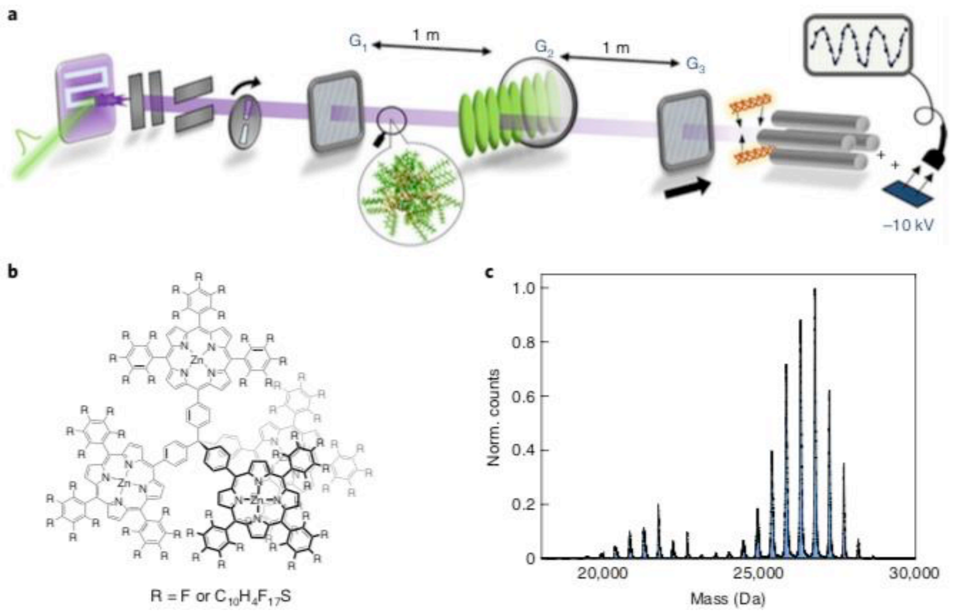
Quantum superpositions – what has been achieved?

REALIZED SUPERPOSITION

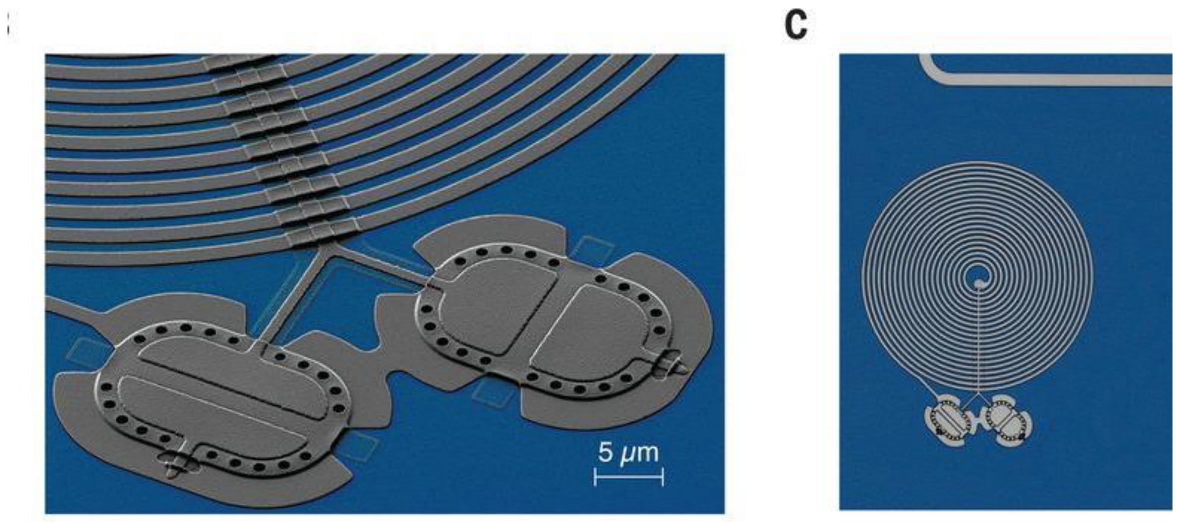
- Schrodinger's cat

https://en.wikipedia.org/wiki/Schr%C3%B6dinger%27s_cat#/

- Superposition realization using matter-wave interferometer in electrons, neutrons, ions, molecules…



Superposition of particles with masses exceeding 25,000 Da



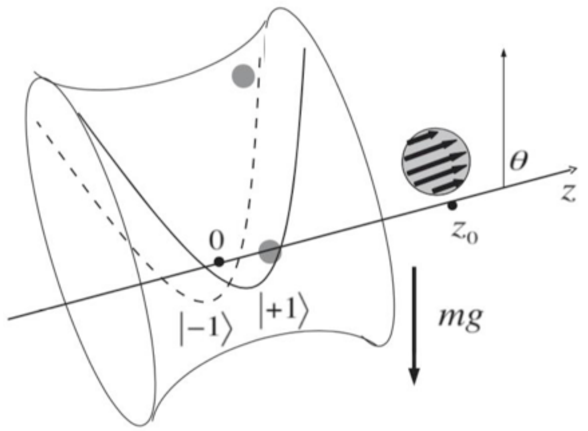
Entanglement of electromechanical drum modes, mass~70 pg

M. Arndt & K. Hornberger, *Nature Physics*, *10*(4), 271 (2014)
M. Zawisky et al, Nucl. Instrum. Methods Phys. Res. 481(1-3), 406 (2002)
C. Monroe et al., Science 272, 1131 (1996)
M. Arndt et al., Nature 401, 480 (1999)
S. Eibenberger et al., Phys. Chem. Chem. Phys 15, 14696 (2013)
Y. Y. Fein et al. Nat. Phys. 15, 1242 (2019)
T. Kovachy et al. Nature 528, 530 (2015)
S. Kotler et al, Science 372, 622 (2021)

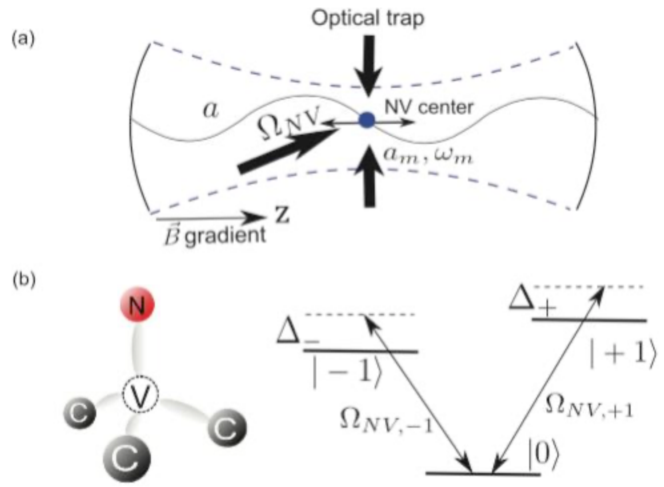
Macroscopic superposition

SOME PROPOSALS TO GENERATE MASSIVE SUPERPOSITIONS

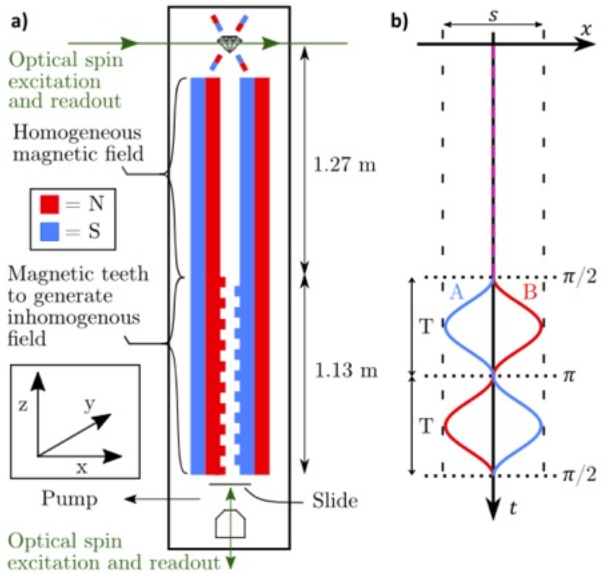
- Using NV-center diamond



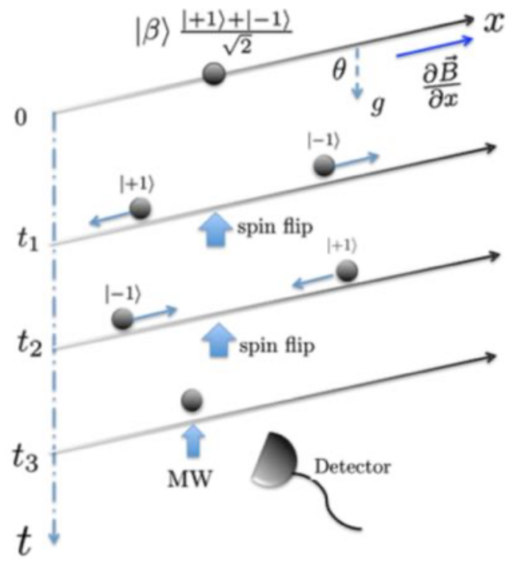
M. Scala et al., Phys. Rev. Lett. 111, 180403 (2013)



Z. Yin et al., Phys. Rev. A 88, 033614 (2013)

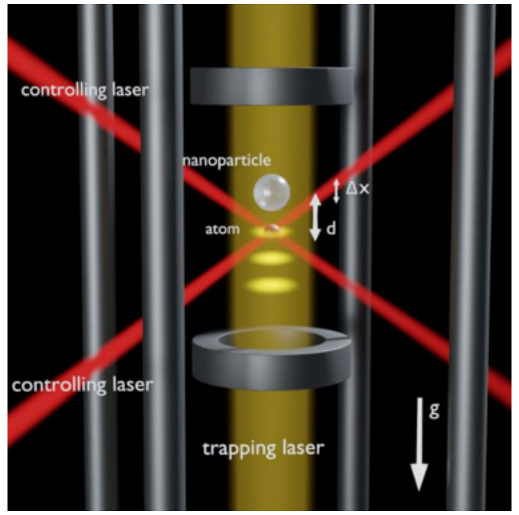


B. D. Wood et al., Phys. Rev. A 105, 012824 (2022)
S. Bose & G. W. Morley, arXiv:1810.07045 (2018)



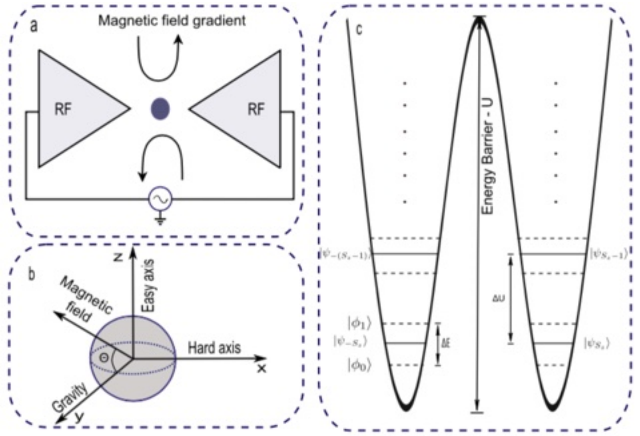
C. Wan et al., Phys. Rev. Lett. 117, 143003 (2016)
R. J. Marshman et al., arXiv:2105.01094 (2021)

- Atom-particle coupling



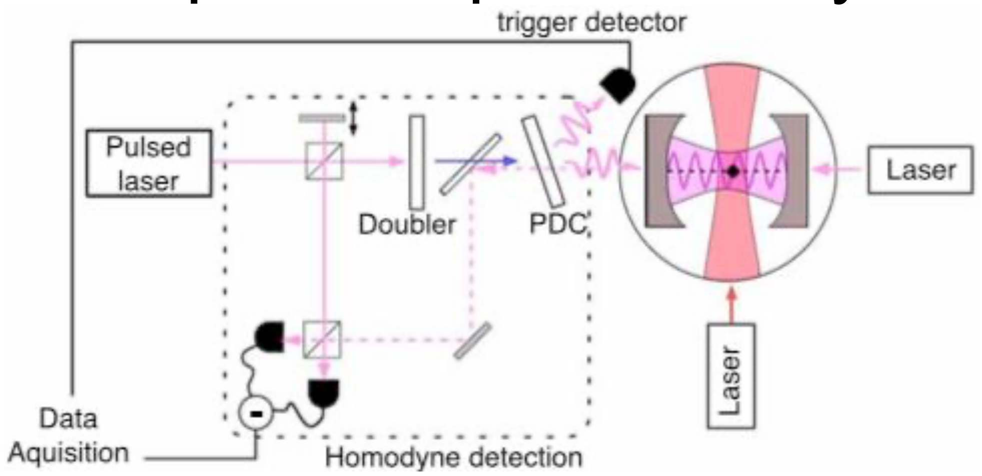
M. Toroš et al., Phys. Rev. Research 3, 033218 (2021)

- Ion trap and magnetic field



A T M A. Rahman, New J. Phys. 21, 113011 (2019)

- Optical trap and cavity

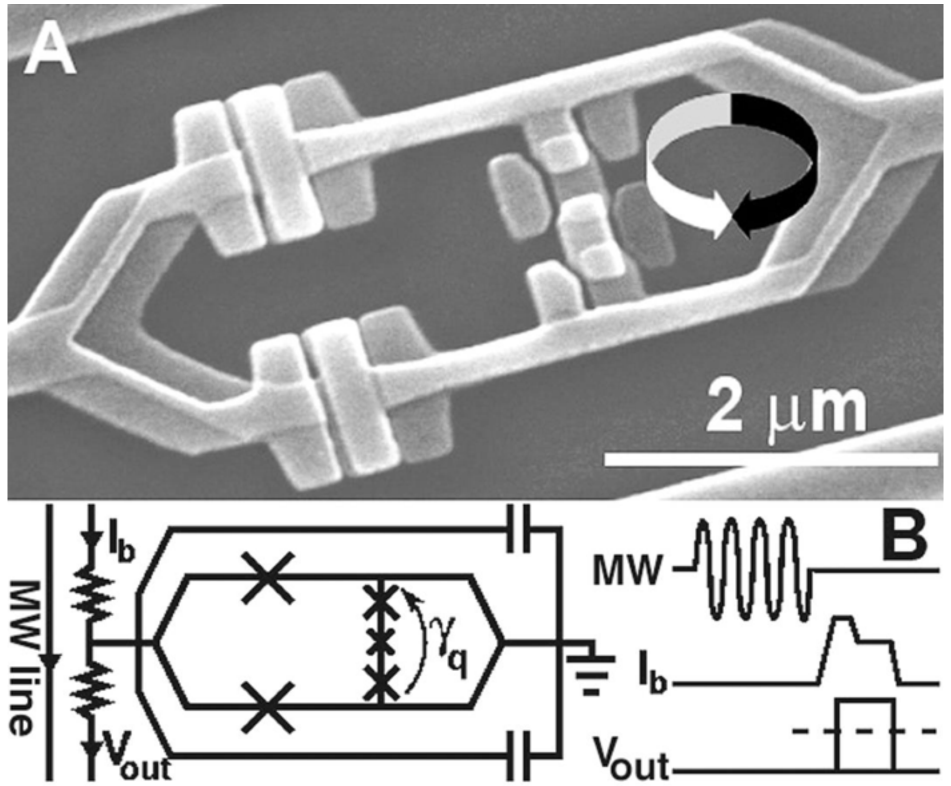


O. Romero-Isart et al., New J. Phys. 12, 033015 (2010)

Macroscopic superposition

OUR PLANS

- Using Quantum flux qubit



Large circulating current in quantum superpositions make quantum magnetic fields in superposition

We propose two schemes:

1. Superposition of Levitated Magnet

2. Superposition of Levitated Superconducting Flux Qubit

I. Chiorescu et al., Science, 299(5614), 1869 (2003)

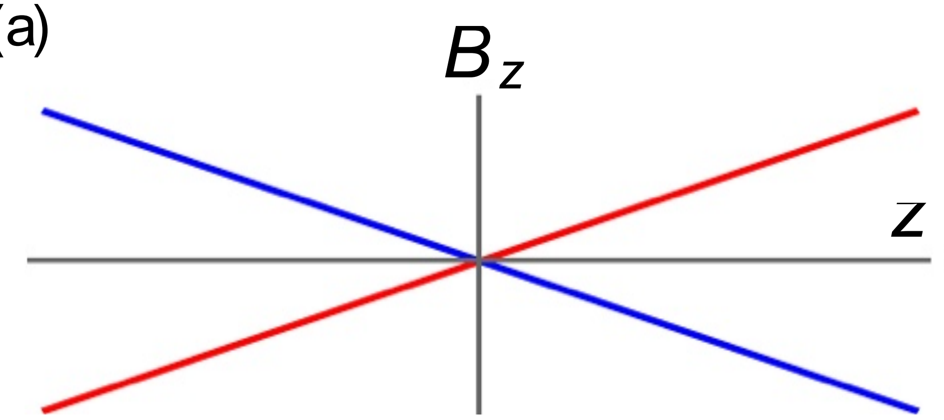
J. R. Friedman et al., Nature, 406(6791), 43 (2000)

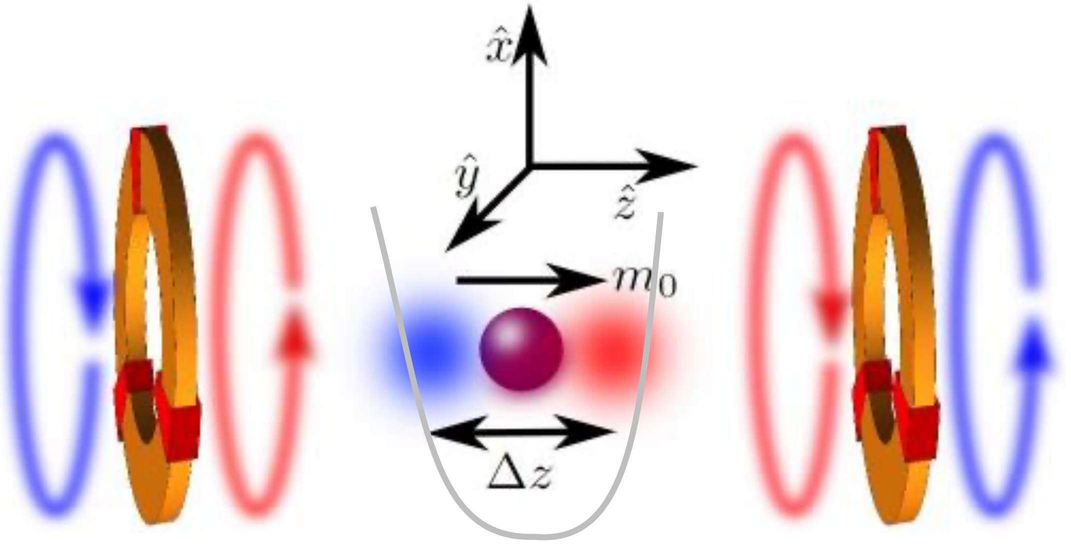
1. Superposition of Levitated Magnet

TRAPPED YIG SPHERE DISPLACED BY MAGNETIC FIELDS

- Consider Yttrium Iron Garnett (YIG), sphere trapped in 3D in a harmonic trap – can be MAGNETIC or OPTICAL trap
- YIG is a magnetic insulator – small remnant magnetization
- Position two ring flux qubits with oppositely circulating currents
- Magnetic field generated by Flux qubits form an anti-Helmholtz B field is zero midway and is linear
- Magnetic Interaction between YIG and B field causes the YIG to shift it's equilibrium to right by small distance
- Switch circulation of currents in Qubits and YIG shifts to the left
- Currents in Qubits can be in a superposition and thus YIG will be shifted into a superposition of two positions.

(a)





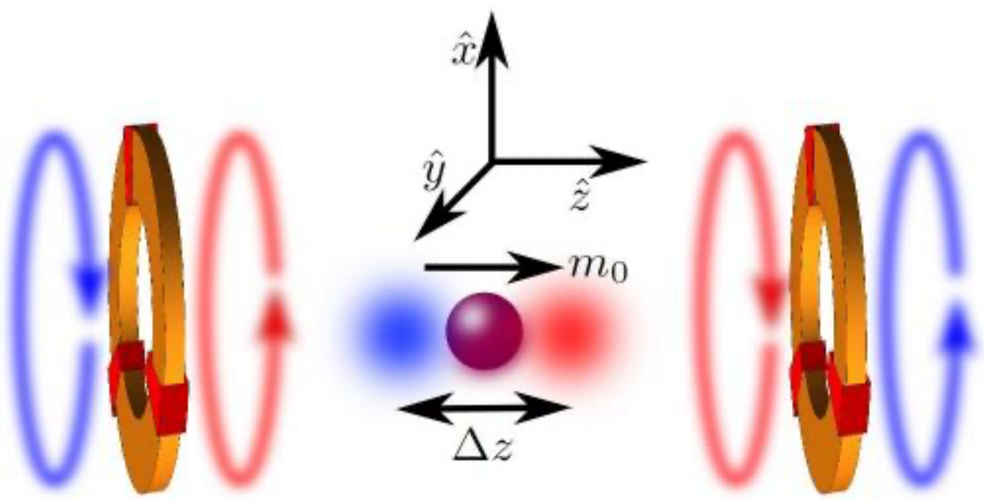
Superposition of Levitated Magnet

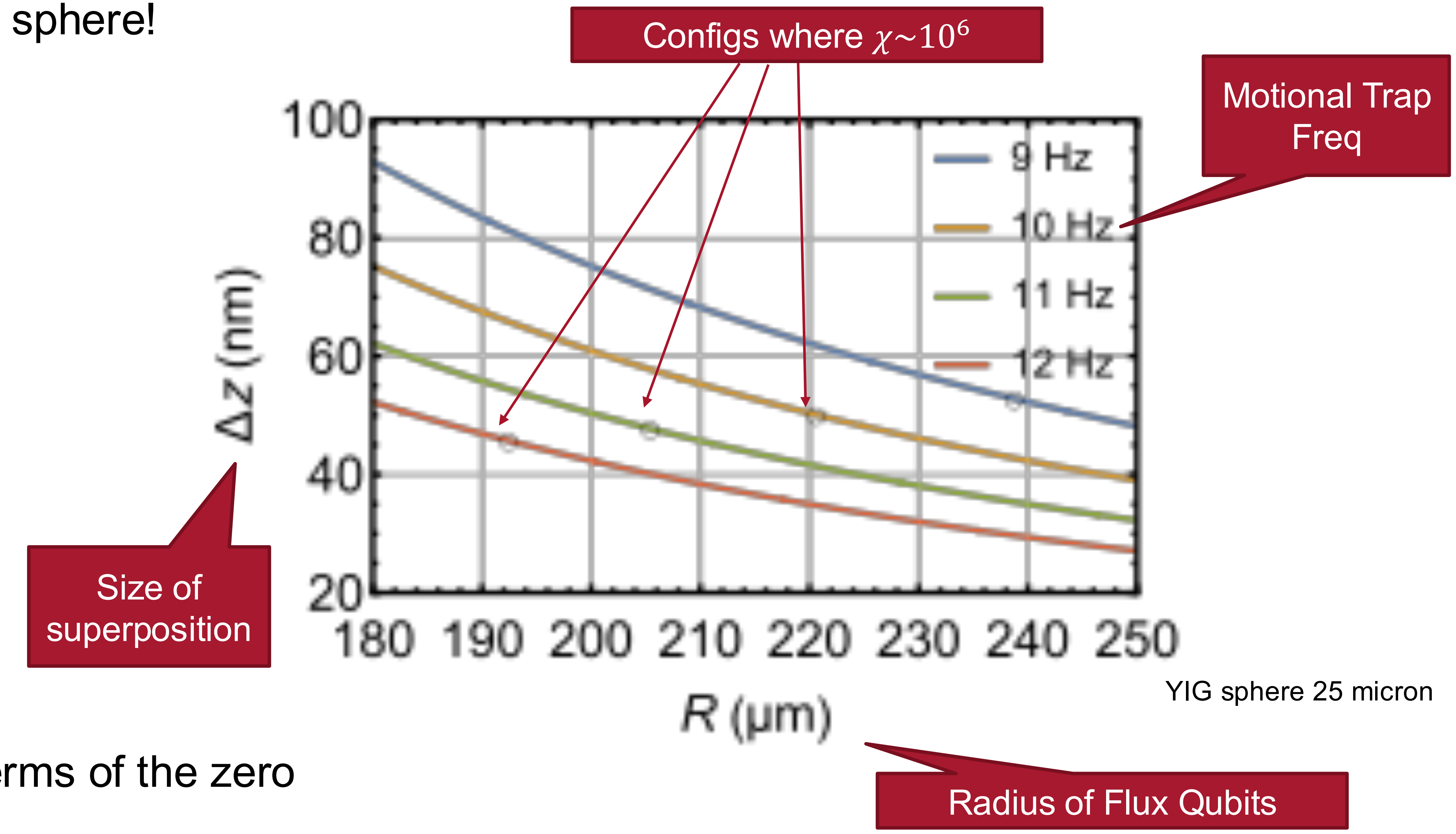
$$\chi \equiv \Delta z / z_{\mathrm{zpm}}$$

$$z_{\mathrm{zpm}} = \sqrt{\hbar/(2m\omega_z)}$$

HOW LARGE A SPATIAL SUPERPOSITION CAN WE GENERATE?

The spatial size of the superposition is INDEPENDENT of the size of the YIG sphere!





YIG sphere 25 micron

Can evaluate the displacement in terms of the zero point motional width δ. Can reach

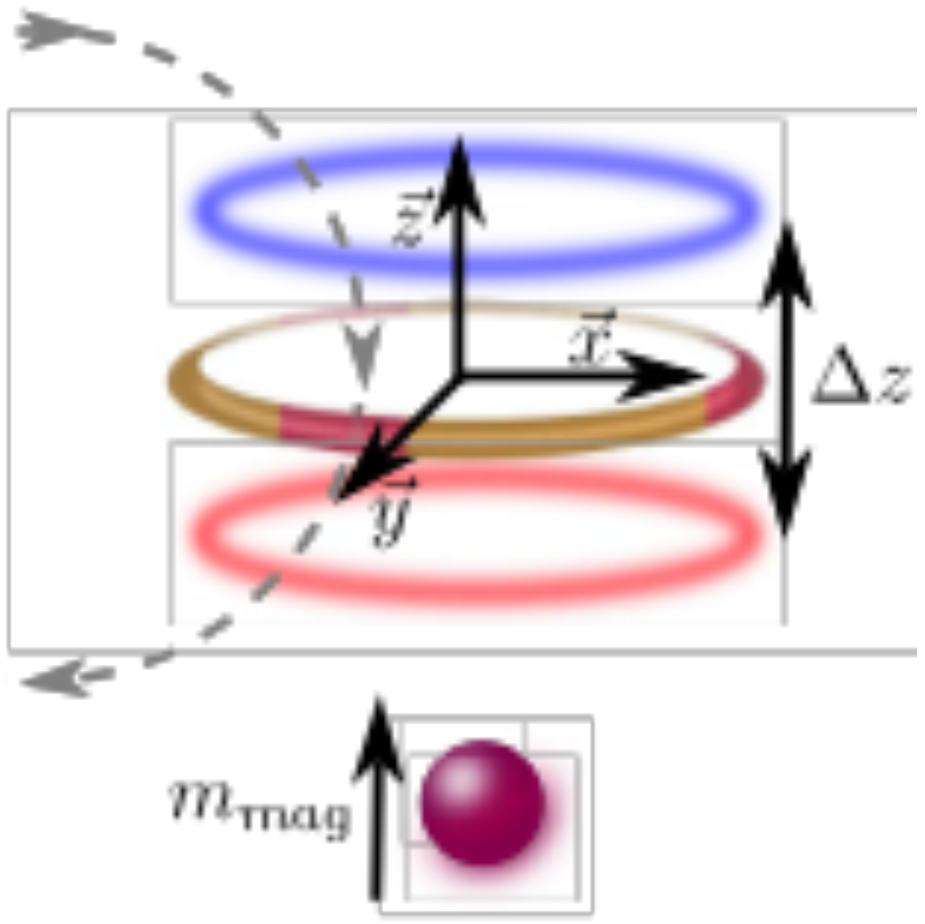
$$\Delta z / z_{\mathrm{zpm}} \sim 10^6$$

OIST

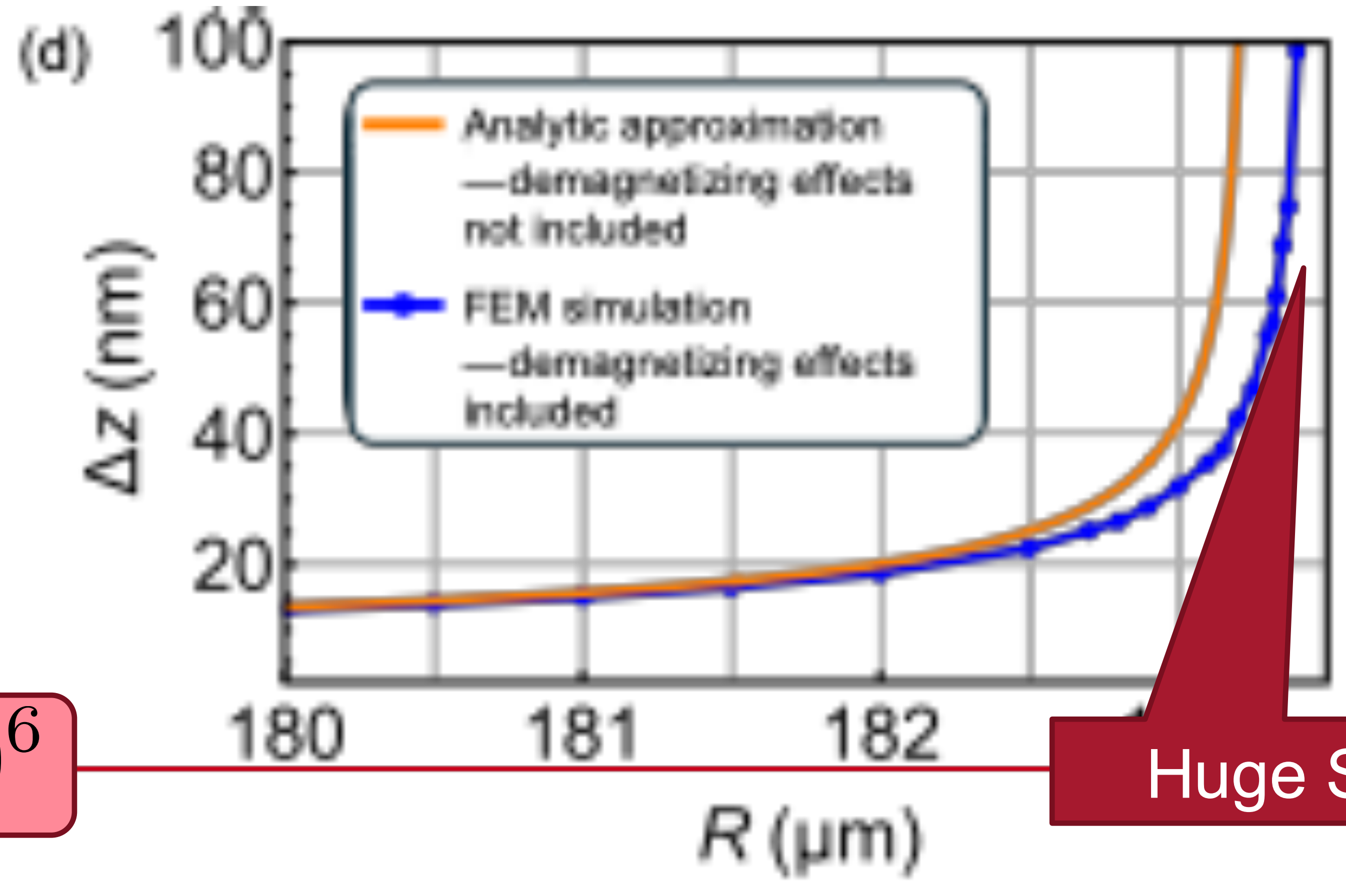
Floating an entire Flux Qubit

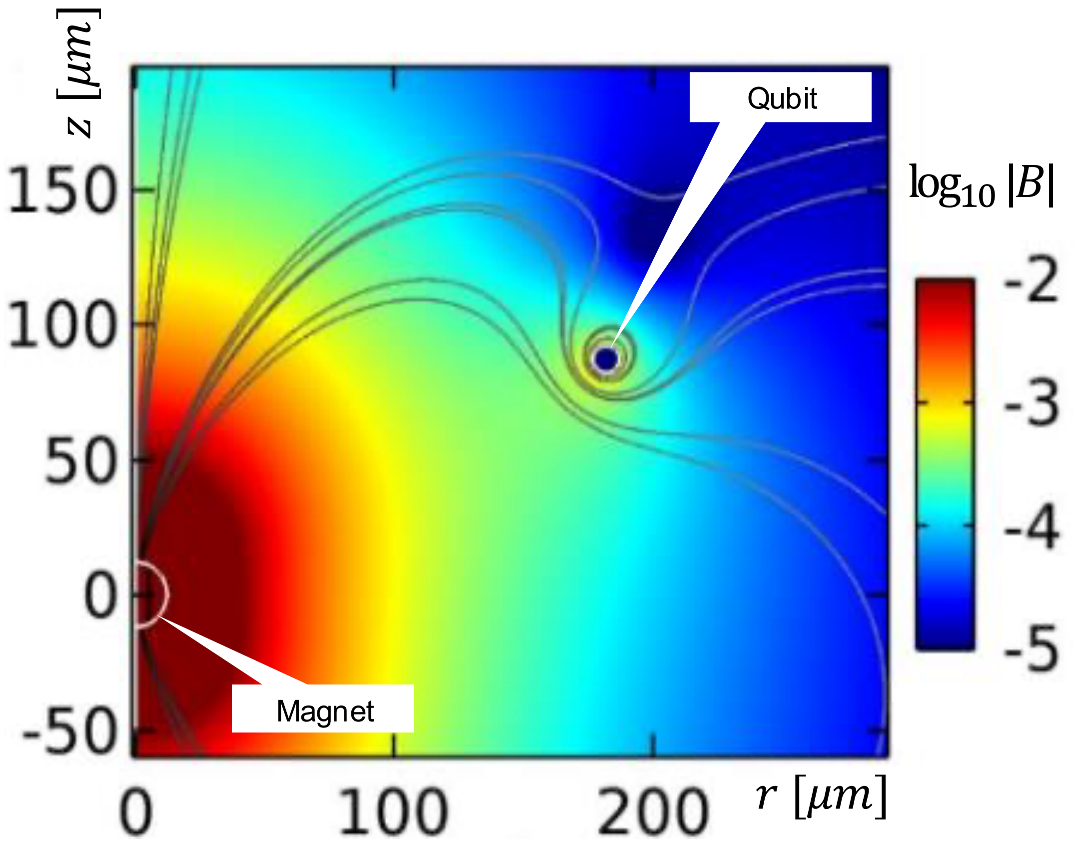
MASSIVE SUPERPOSITIONS

- Use single magnet to levitate AN ENTIRE SUPERCONDUCTING FLUX QUBIT – Meissner levitation of the superconducting ring
- FQ can be driven inductively – no contact needed –Take care of backaction onto magnetic field
- Depending on currents flowing in FQ massive shifts in equilibrium height.
- Levitated ring is also stable in horizontal direction and to tilts
- Both setups could have very high motional Q factors!



Paper goes into great details on decoherence etc..





Huge Shifts!

$$\Delta z / z_{\rm zpm} \sim 10^6$$

Phys Rev Appl 24, 024061 (2025)

Final Word

QUANTUM MACHINES ARE FUN!

- **Diamagnetic levitation** has great potential
- **Can we levitate entire superconducting qubits** to generate large superpositions?
- **Can we explore spin-forces** to execute more detailed control over the levitated motion?

.

Jason.Twamley@oist.jp

PhD students Internships!