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Rotation sensing with a compact Penning trapped calcium ion crystal system

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Outlines

Motivation of the study

The design of a quantum vibrational gyroscope

The experimental setup

1 Motivation of the study and the basic principle of Penning trapped ions

Motivation: Rotation sensing with Quantum sensors.

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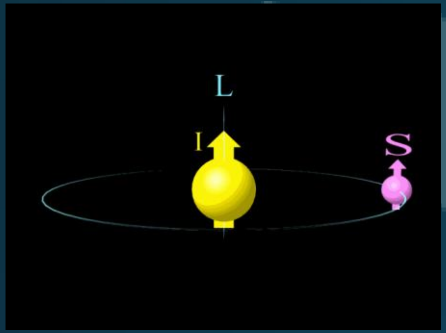
Atomic Spins as a Gyroscope

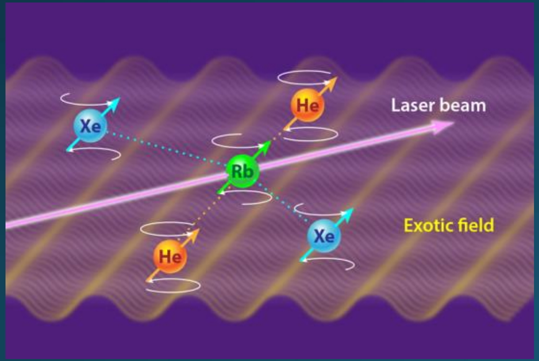


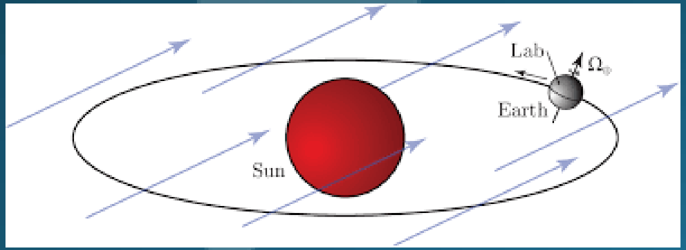
1. Spin owns angular moment. The quantity of the moment is integer or half integer of the Planck constant h.
2. The spins are a kind of quantum rotors.
3. Nuclear spins could be utilized for rotation sensing. This is the atomic spin gyroscope.

VS

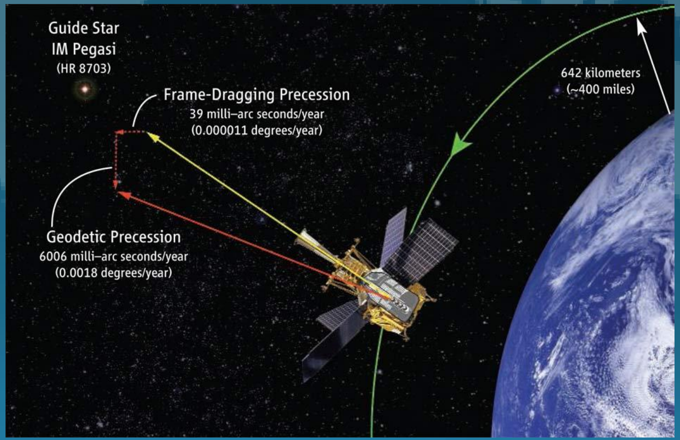
The traditional mechanical Rotor.

1. In the inertial space, the angular momentum of the mechanical rotor point to a certain direction.
2. The rotor will precess in the earth's gravity field.
3. Gyroscope could be made for rotation sensing.
4. The Gravity Probe B project. Testing Einstein's theory of relativity.





An atomic spin gyroscope could be utilized for testing new physics such as: CPT symmetry.



A mechanical Rotor in Space with a perfect ball.

Motivation: Rotation sensing with Quantum sensors.

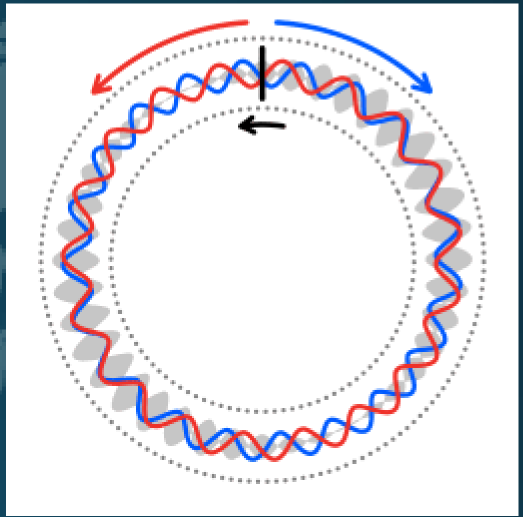
An atomic interference gyroscope
The Sagnac Effect in cold atoms

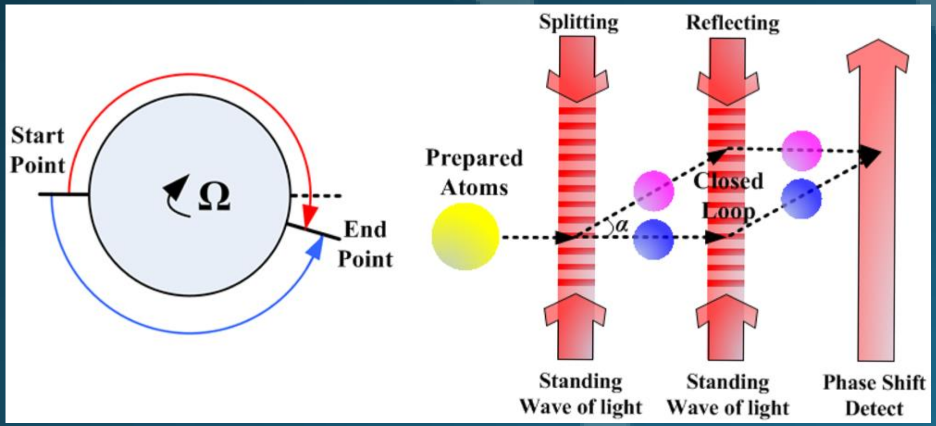
1. The cold atomic beam -- the matter wave.
2. Matter wave just like light could be utilized for interference.
3. Rotation induced Sagnac phase shift could be measured.

VS

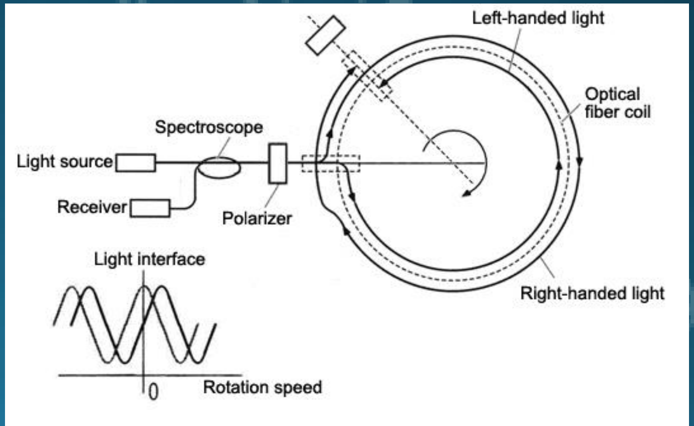
The Sagnac Effect Gyroscope.

1. A fiber optics gyroscope based on the Sagnac Effect.
2. Rotation causes the difference of the light's travelling distance.





An atomic interferometer gyroscope.



The fiber optics gyroscope.

Motivation: Rotation sensing with Quantum sensors.

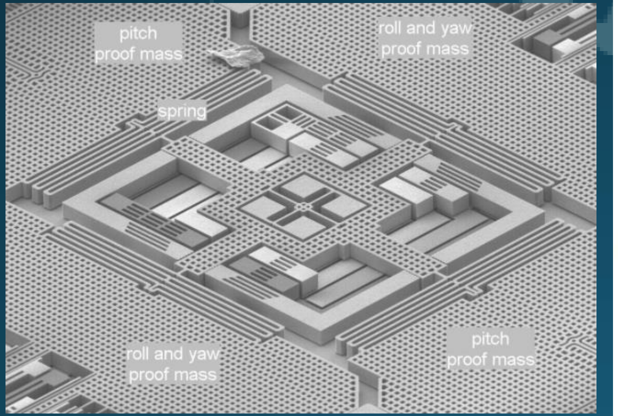
What about the vibration gyroscope(MEMS Gyroscope)

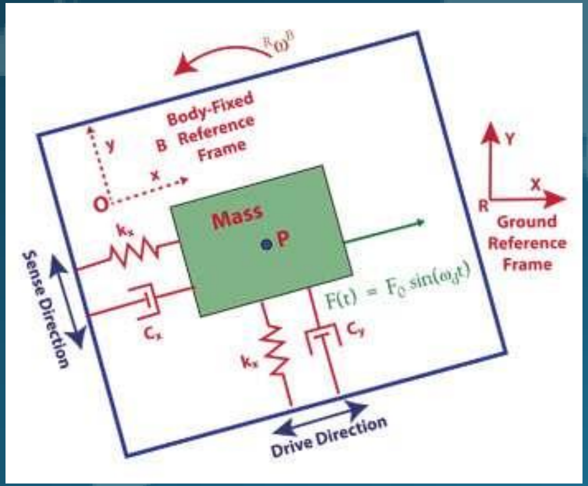
1. A Mass proof vibrate in one direction. The vibrations are always harmonic oscillators.
2. The rotation velocity will cause the Coriolis force.
3. Coriolis force induce the vibration in the orthogonal direction.

VS

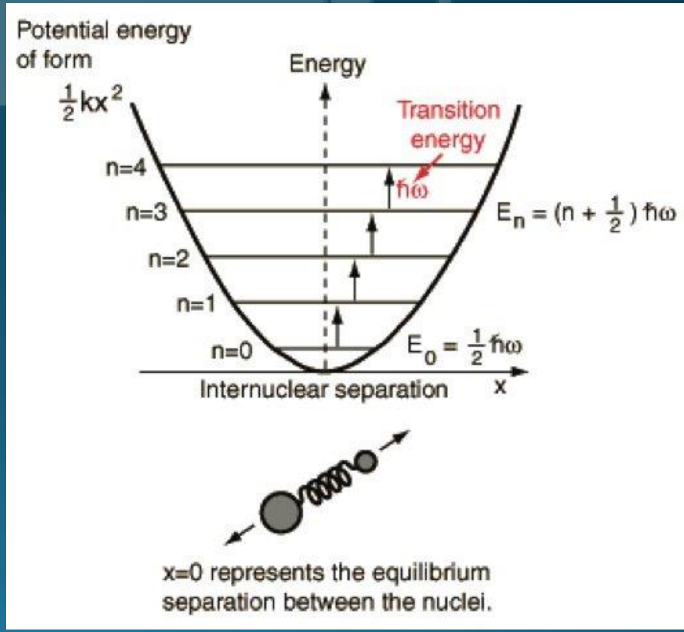
Is there a quantum sensor which is similar to the vibration gyroscope?

1. Quantum harmonic oscillators could be used to form a gyroscope.
2. Two oscillators should be coupled together to form the gyroscope.





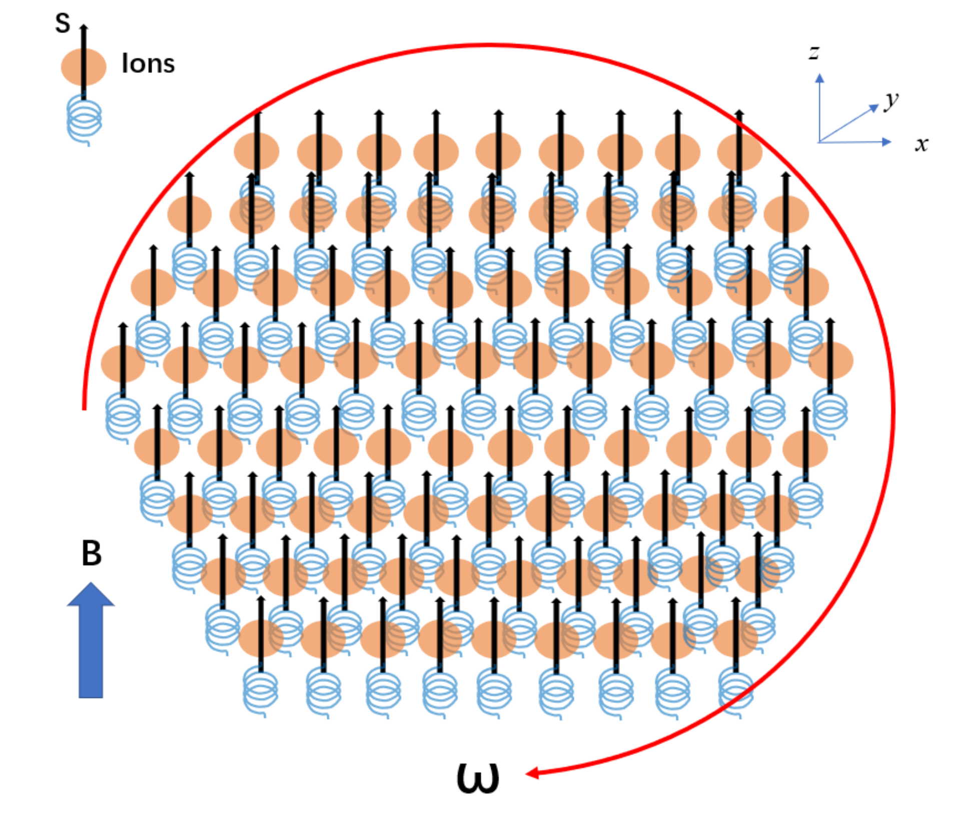
Traditional MEMS gyroscope.



The quantum harmonic model.

Motivation: New sensor development

Penning trapped ion crystals may form three dimension quantum harmonic oscillators.



1. The ions crystal is trapped by a constant magnetic field B and a quadrupole electric field. The magnetic field traps the ions in the x and y plane.
2. The quadrupole electric field traps the ions in the z direction.
3. Due to the E×B effect, the ions will rotate about B with rotation velocity ω.
4. The Calcium ions utilized in our experiment owns an electron spin S which could be utilized the detect the Coriolis force.

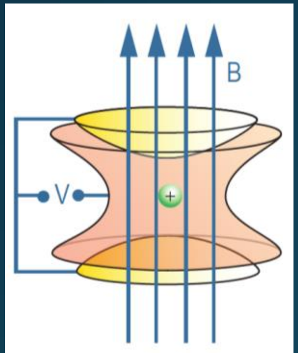
1. Driving oscillators: the x and y direction oscillators(This direction forms spherical oscillator).
2.The sensing oscillator: the z direction, this direction could also form a drum mode.

We can change the traditional harmonical mass into 2D ion crystal. New kind of sensors such as acceleration and rotation measurement could be measured.

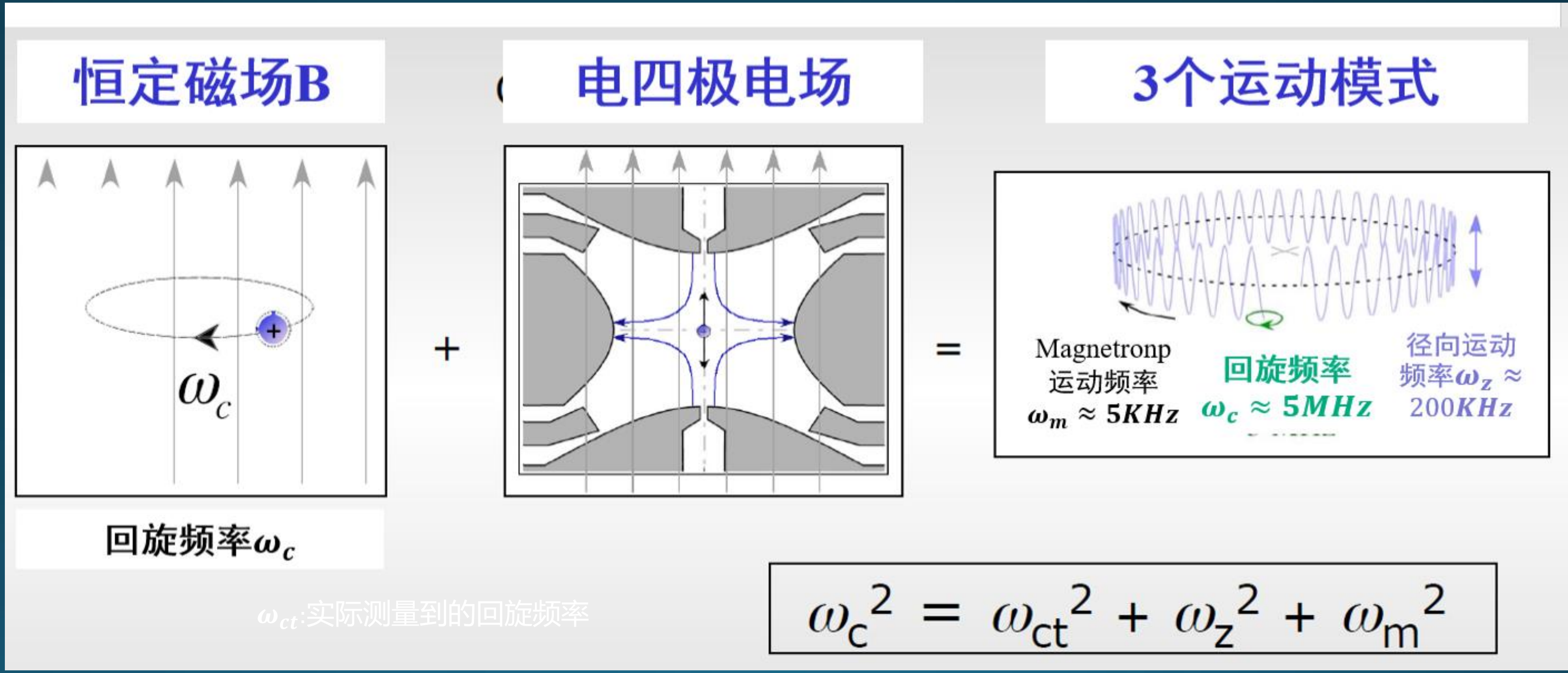
The principle of penning trapped ions

The configuration of the Penning Trap: Constant magnetic field B+Quadrupolar Electric field=3D confinement of the ion.

B confines the ions in the plane vertical to B. Quadrupolar Electric field confines the ions in the direction parallel to B.



Penning Trap



Three motion of the ions：

$$\omega_c = \frac{B}{(m/q)} \Longrightarrow m = \frac{B}{(\omega_c/q)}$$

m： ion mass；
q ： charge.

Ion crystal could be formed in the Penning Trap.

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2 The design of a quantum vibrational gyroscope

The design of a quantum vibrational gyroscope

Try to start with a single particles

1. **The motion of the particle can be described**

$$m\frac{d^2[x(t),y(t),z(t)]}{dt^2} = eV\frac{\nabla[2z(t)^2-y(t)^2-x(t)^2]}{4{z_0}^2} - e[\dot{x(t)},\dot{y(t)},\dot{z(t)}]\times\vec{B} - 2m\vec{\Omega}\times[\dot{x(t)},\dot{y(t)},\dot{z(t)}]$$

The acceleration of the ions.

The force from the electric field

The Lorentz Force

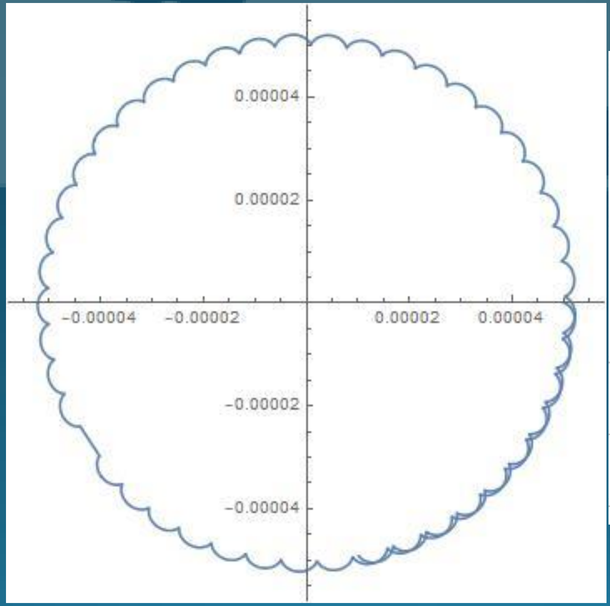
The Coriolis Force

The Numerical solution of the equation:

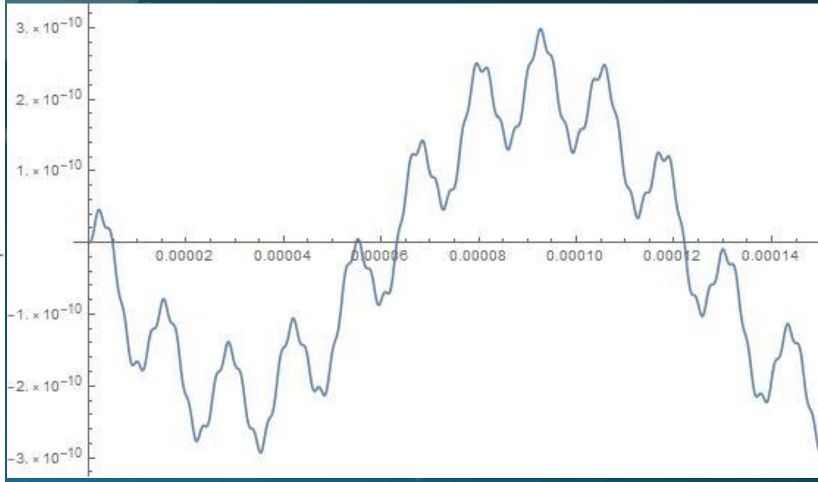
For Calcium ions, m=40, V=10V, B=1T, z_0=0.01m, r_0=2^0.5 z_0

Cyclotron frequency : f_c=383KHz
Axial frequency : f_z=78KHz
Magnetron frequency : f_m= 8KHz

If the rotation is in the x direction and the rotation angular rate is 10 rad/s. The motion of the single ion could be calculated.



The motion in the x and y plane

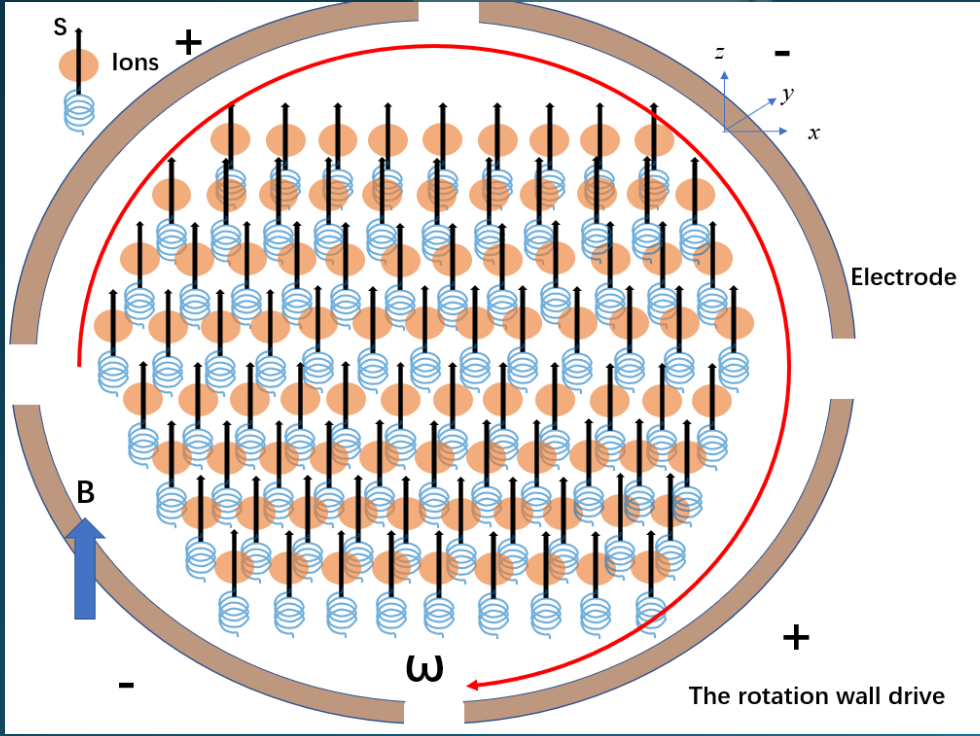


The motion in the z direction

The design of a quantum vibrational gyroscope

1.The single particle has a problem: The amplitude in the z direction is very small(On the order of 10^{-10} m with a typical angular velocity input).
2. The resonance frequency in the z direction is f_z=78KHz which is much larger than the magnetron motion frequency f_m=8KHz.
3. If $f_z=f_m$, the motion amplitude in the z direction will be much larger.

How we can achieve this?



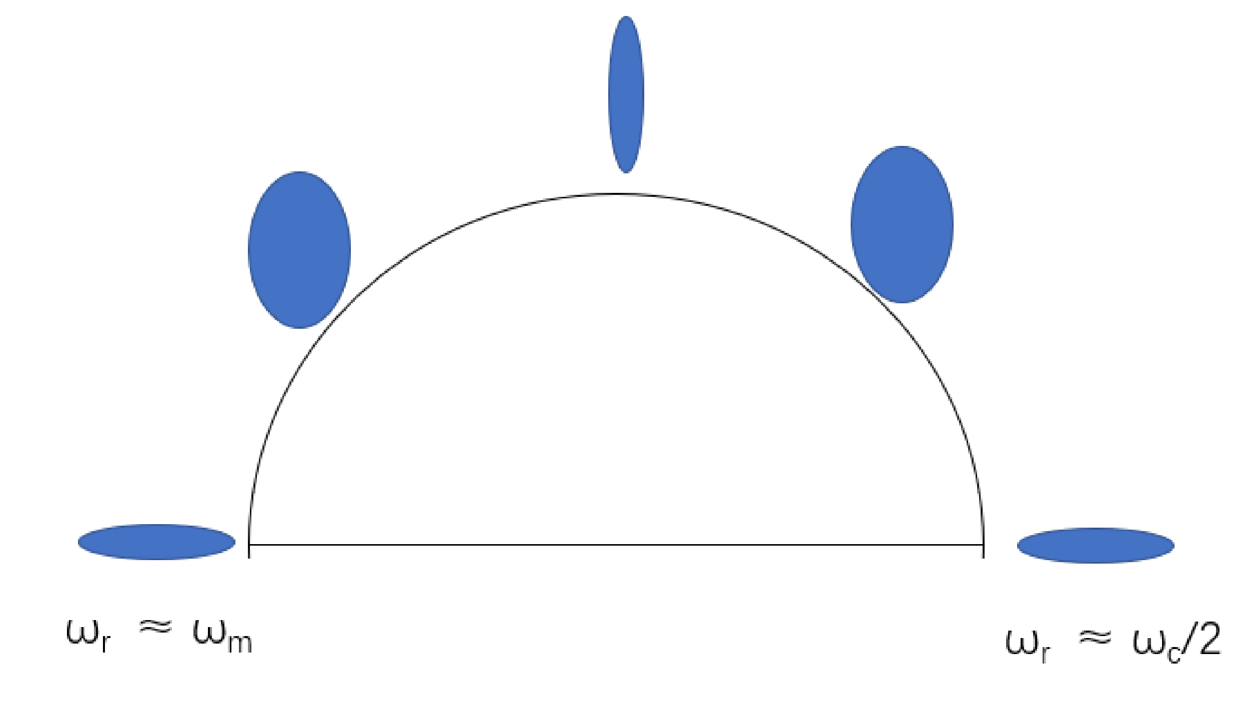
Ion crystal+Rotation Wall driving(the driving frequency is ω_r) of the crystal.

1. The ion crystal frequency could be controlled by the quadrupole rotating wall drive. The ion rotation frequency should be the same as the driving frequency.
2. The driving frequency could be the same as the axial frequency.
3. The axial quantum oscillator owns a high Q wich is on the order of 10^6.

Spheroid shape control of the ion cloud.

1. We assume that the ion cloud looks like a disk and thus the axial z motion could be looks like a drum mode.

2. The ion cloud shape need to be controlled through the rotation wall drive.



The spheroid shape of the cloud could be controlled by the rotation wall driving.

The number density of the ion cloud:

$$N_0 = 2\omega_r(\omega_c - \omega_r)\varepsilon_0 m/e^2$$

For Calcium ions, m=40, V=100V, B=1T, z_0=0.01m,r_0=2^0.5 z_0

Number density: $6*10^7/cm^3$.

Spheroid shape:

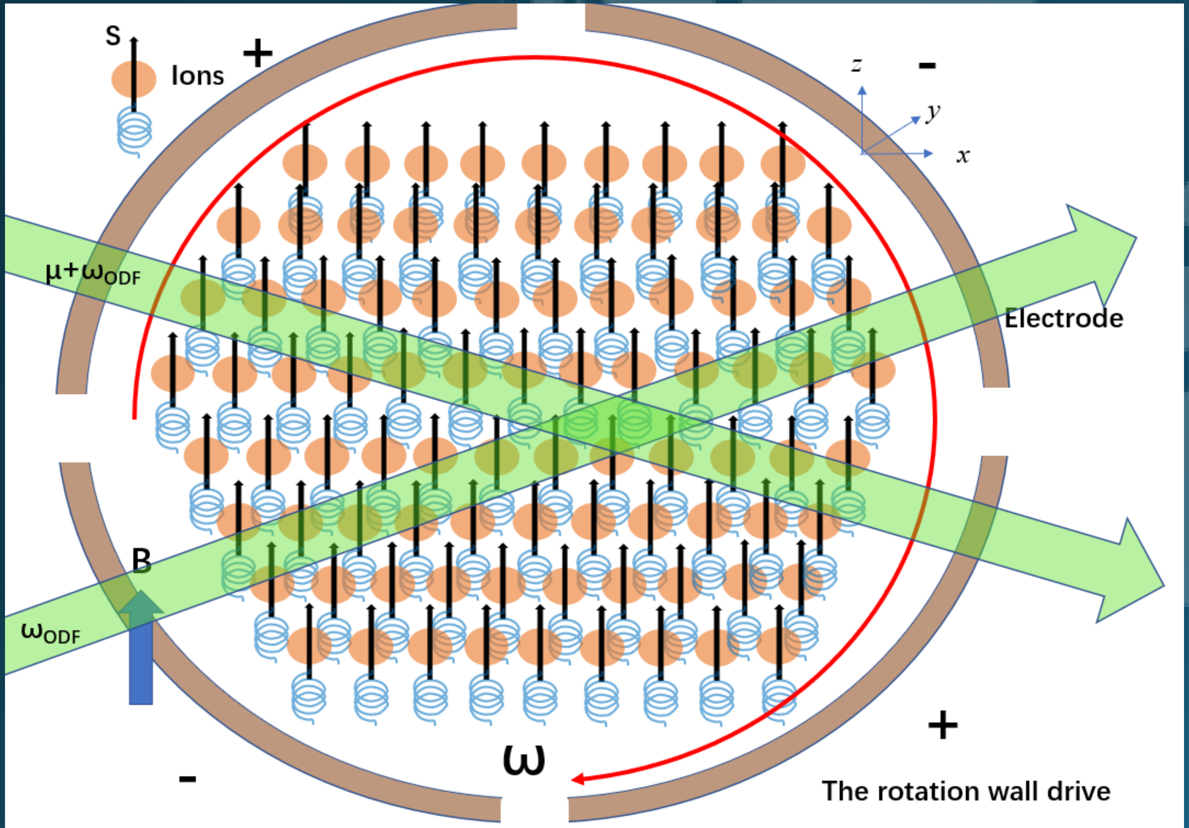
The shape parameter:

$$\beta = \frac{\omega_r(\omega_c - \omega_r)}{\omega_z{}^2 m} - 0.5$$

If $\omega_r = \omega_z$ β=0.05

Much smaller than 1, thus the shape could be more looks like a disk.

The design of a quantum vibrational gyroscope



The coupling of the axial motion with the spin state through Optical Dipole Force.

1.Optical Dipole Force(ODF) is utilized to couple the z direction motional state with the spin state.

$$\hat{H}_{ODF} = F_0 \cos(\mu t) \sum_i \hat{z}_i \hat{\sigma}_i$$

2. The change of the spin state can represent the change of the axial position.

3. Each ion could sense for the force smaller than 10^{-5}yN(K.A.Gilmore,et al, PRL 118, 263602,2017).
4. This force sensitivity could be utilized for the Coriolis Force Detecting.
5.The Drum mode vibration caused by the Coriolis force could be sensitively detected.

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3

The experimental setup

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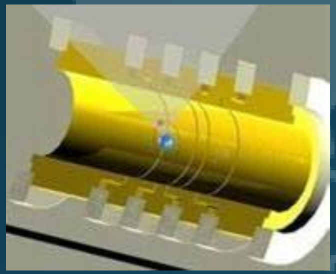
1. The electrodes

Harmonic Electric field is need.

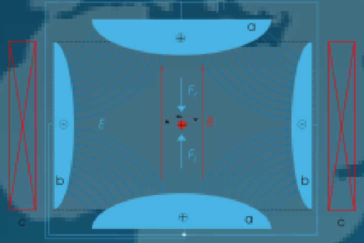
Electric field is need for the ions confinement

The 5 electrodes system



High harmonic

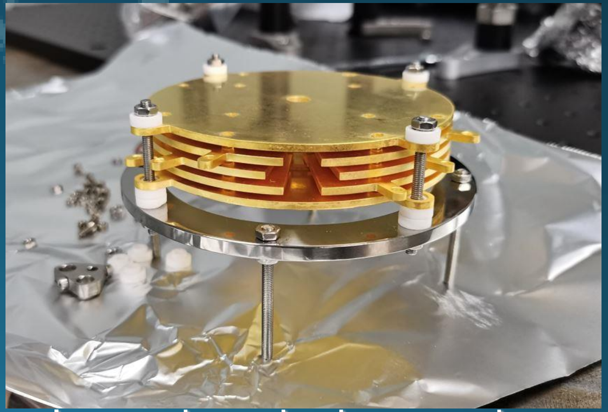
Inner surface is coated with gold.



Precision electric field

Precision machining and low roughness.

Titanium metal and inner surface is polished.



The electrodes which is used in our compact Penning trap.

Precision machining of the trap:

- 5 electrode design with sapphire isolation.
- The compensation electrode design for harmonic electric field. Coated with gold.
- Polished surface with roughness of 1um. Machining tolerance is 0.05mm.

The design of the compact Penning Trap

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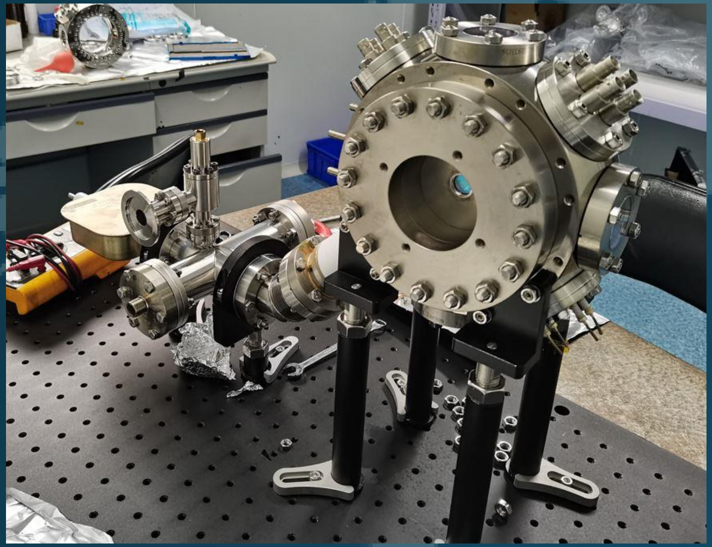
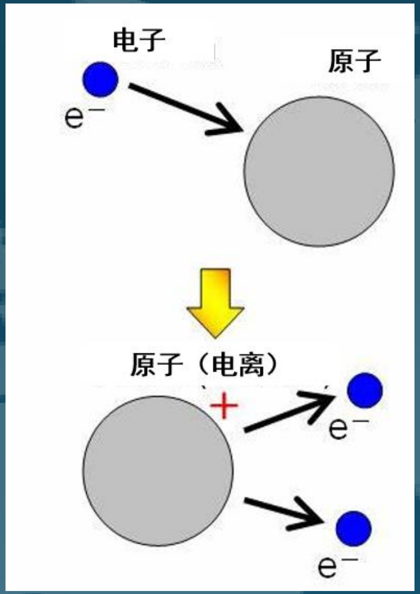
2. The vacuum system and ion loading

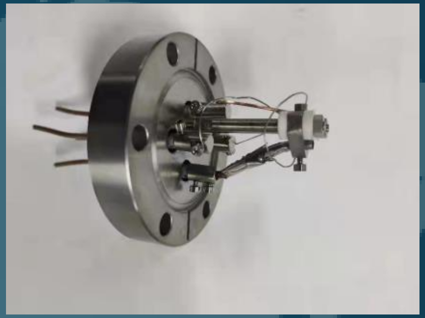


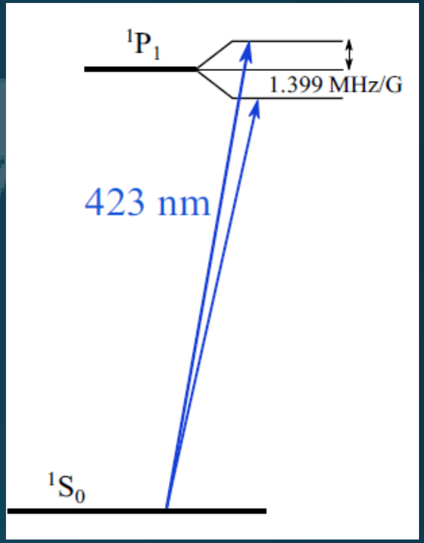
1.Ion pumping and getter pumping to below 10^{-7}Pa.
2. Vacuum cavity is made of Titanium.
3. Feedthroughs are utilized for electrical connectivity.
4. Future low temperature could be integrated for experiment simplification.

How to create the ions cloud. Ion loading:



Pulsed laser ionization





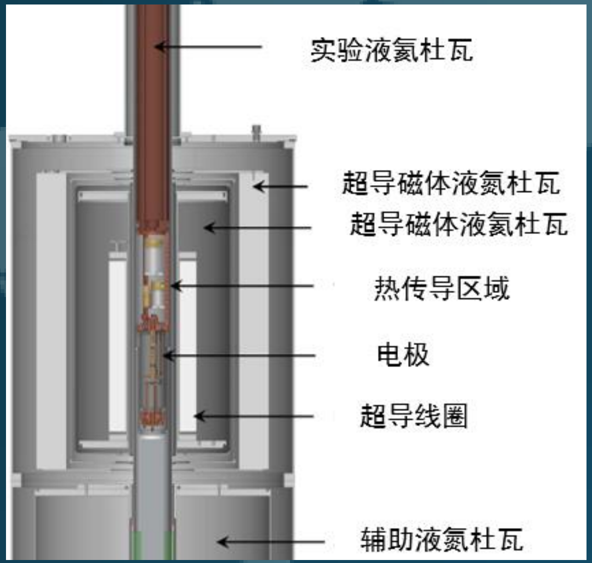
Optical pumping + pulsed laser ionization.

1. The source of Calcium is through heating.
2. 423nm laser is utilized to let the atoms jump to the higher level.
3. Pulsed 632nm laser ionized the atoms.

The design of the compact Penning Trap

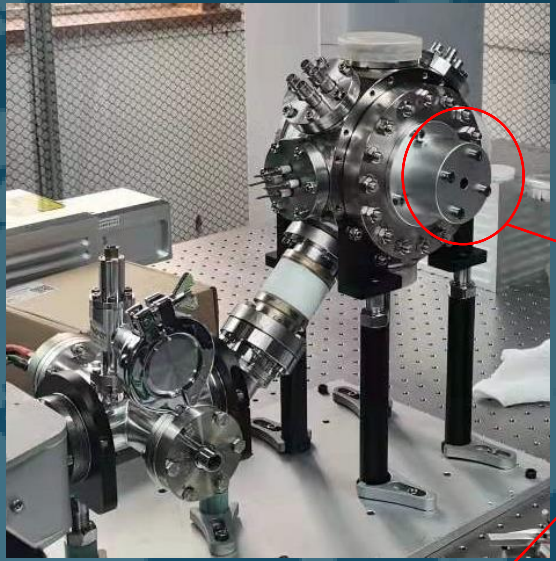
3. The magnet

From



Super conducting magnet. $2m^3$.

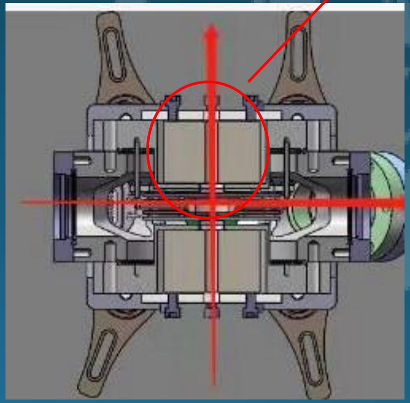
to

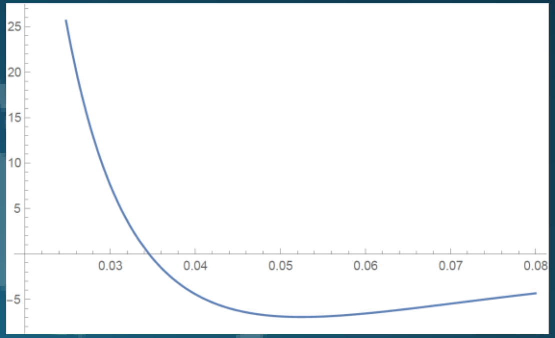


Compact permanent Magnet.

$0.001m^3$.

1. The cylinder magnet is 80mm in diameter and 80mm in length.
2. Two magnets are utilized to produce uniform magnetic field.
3. The magnet distance is 35mm and 0.7Tesla could be produced.





Control the distance of the magnet to get uniform magnetic field.

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Thanks for your attention！