Atom interferometer's potential application for the gravitational waves detection

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Outline of the talk

- Introduction
- Atom Interferometer principle
- Experiment setups
- Current status
- Atomic phase shift
- Sensitivity of atom interfrometry

- Pioneering experiments at Yale [1,2]and Stanford [3] displayed the fascinating potential of matter-wave interferometers for precision measurements.

[1] Gustavson, T.L., Landragin, A., and Kasevich, M.A., Class. Quant. Grav. **17**, 2385 (2000)

[2] Snadden, M.J., McGuirk, J.M., Bouyer, P., Haritos, K.G., and Kasevich, M.A., Phys. Rev. Lett. **81**, 971 (1998)

[3] Peters, A., Chung, K.Y., and Chu, S., Metrologia **38**, 25 (2001)

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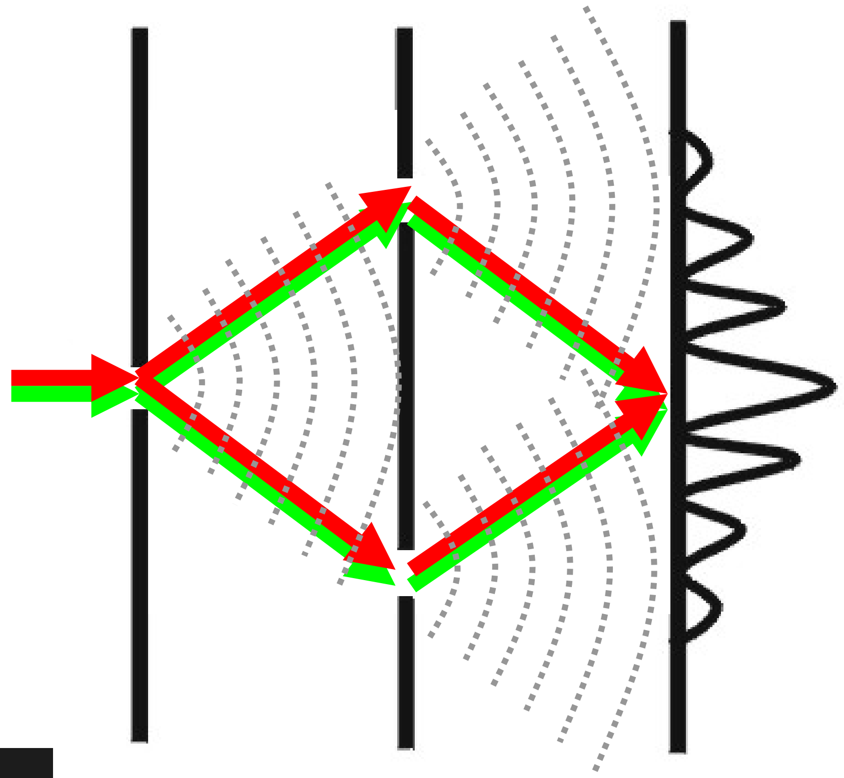
Wave Interference

interference

Photon

Atom



Young's double-slit Exp.

Sensitivity of Wave Gyroscopes

Atom Gyro

$$\delta_{gyro}(m>0) = \frac{4\pi m}{h}\Omega \cdot A$$

Light Gyro

$$\delta_{gyro}(light) = \frac{4\pi}{\lambda c}\Omega \cdot A$$

Ratio

$$R_{gyro} = \frac{mc^2}{\hbar\omega} = \frac{\lambda}{\lambda_{deB}}\frac{c}{\upsilon} \quad 10^{10}$$

Sensitivity of atom interferometer versus optical interferometer

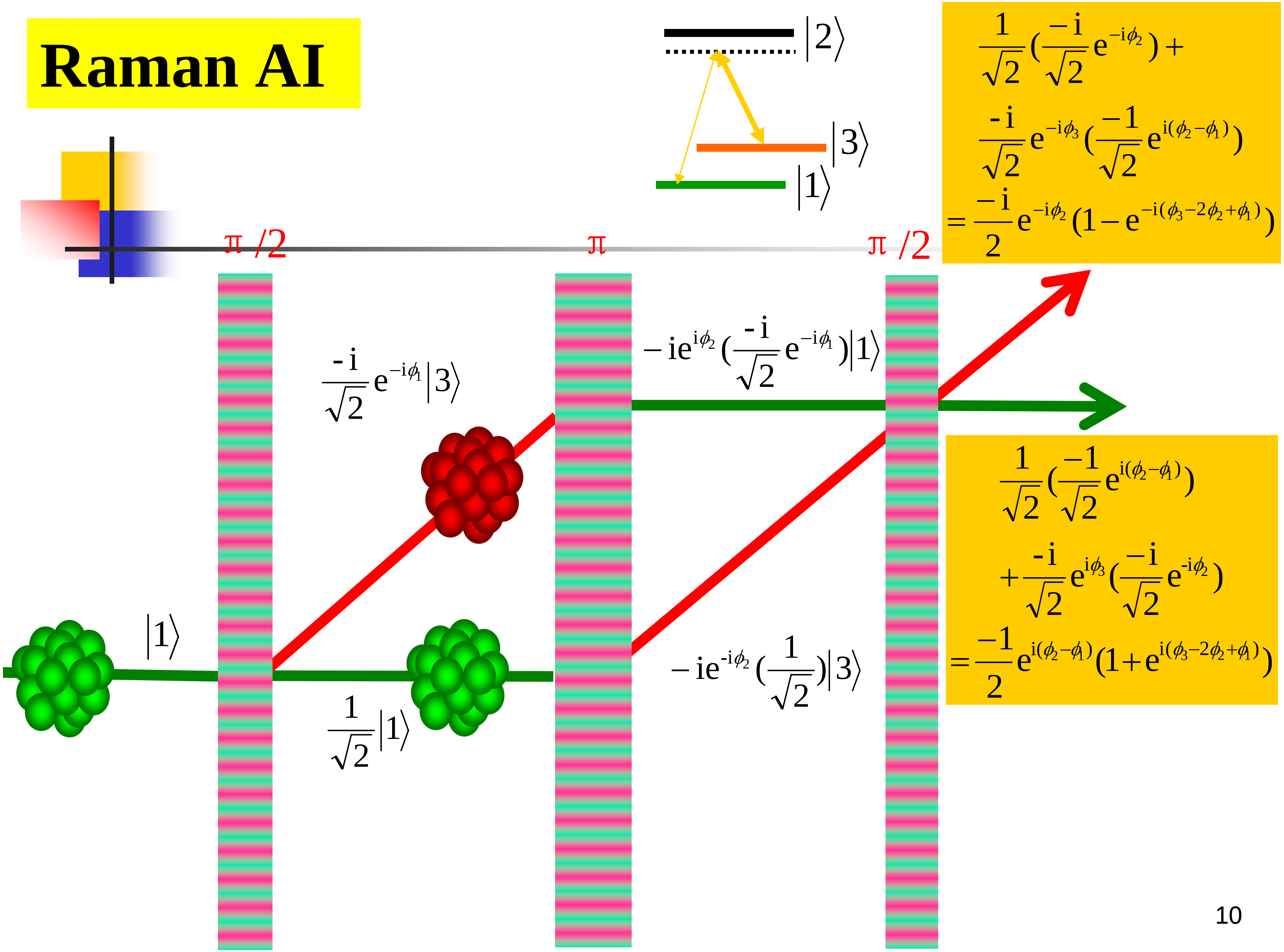
Atom Interferometer Principle

For the realization of atom optical elements like beam splitters or mirrors, one has to think of suitable methods for manipulating the atoms. In addition to former widely used massive ruled gratings, today the interaction between light and matter is used for this purpose. This can be understood as a coherent exchange of photons and, thus, photon momenta. This is depicted below side.

An atomic ensemble where the atoms have two energy levels |1> and |3> is split into two parts. The interaction acts on the internal as well as external degree of freedom. Therefore, a mechanical momentum can be transferred to the diffracted part. The fraction of the number of atoms that is diffracted depends on several parameters:

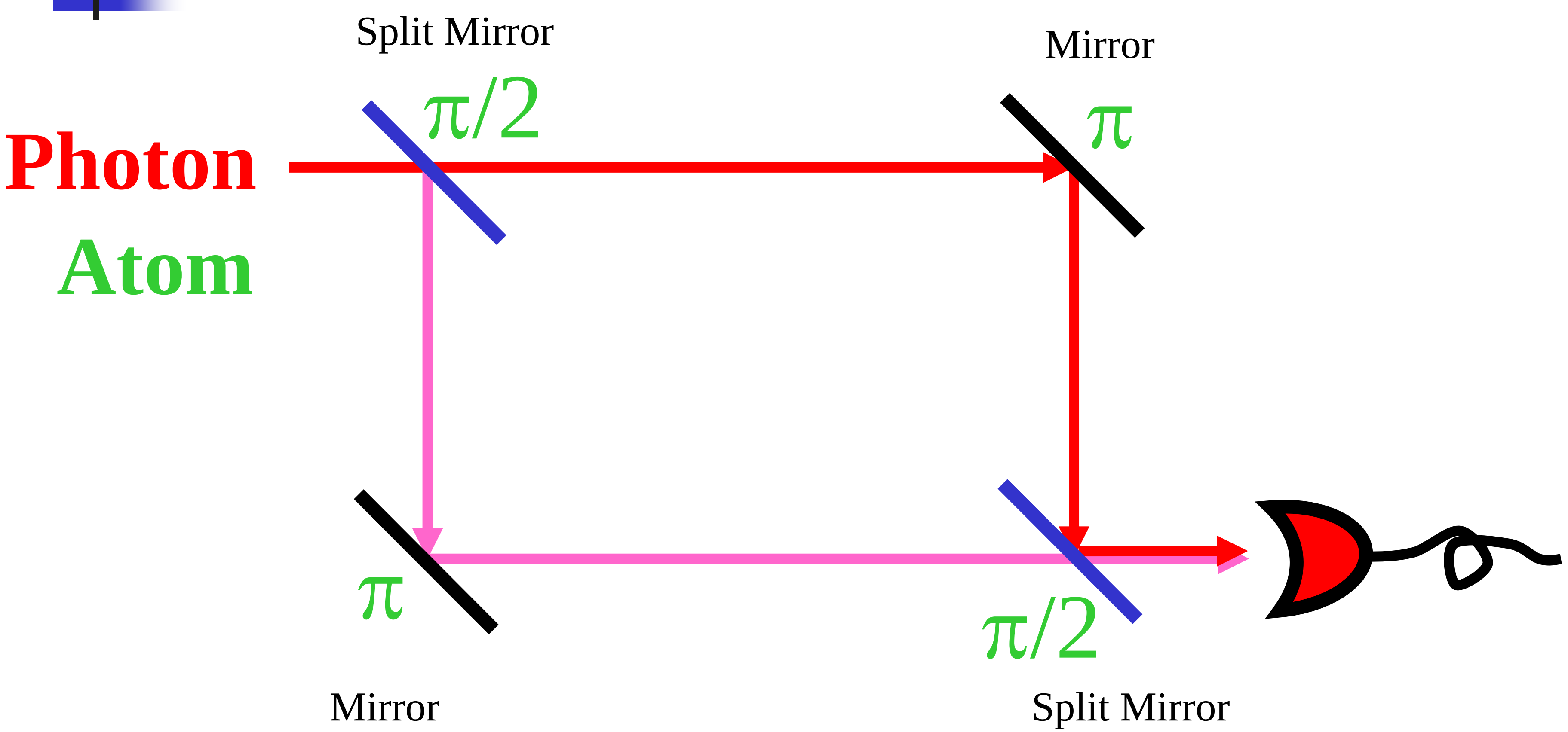
- laser power
- interaction time
- laser frequency

Raman AI

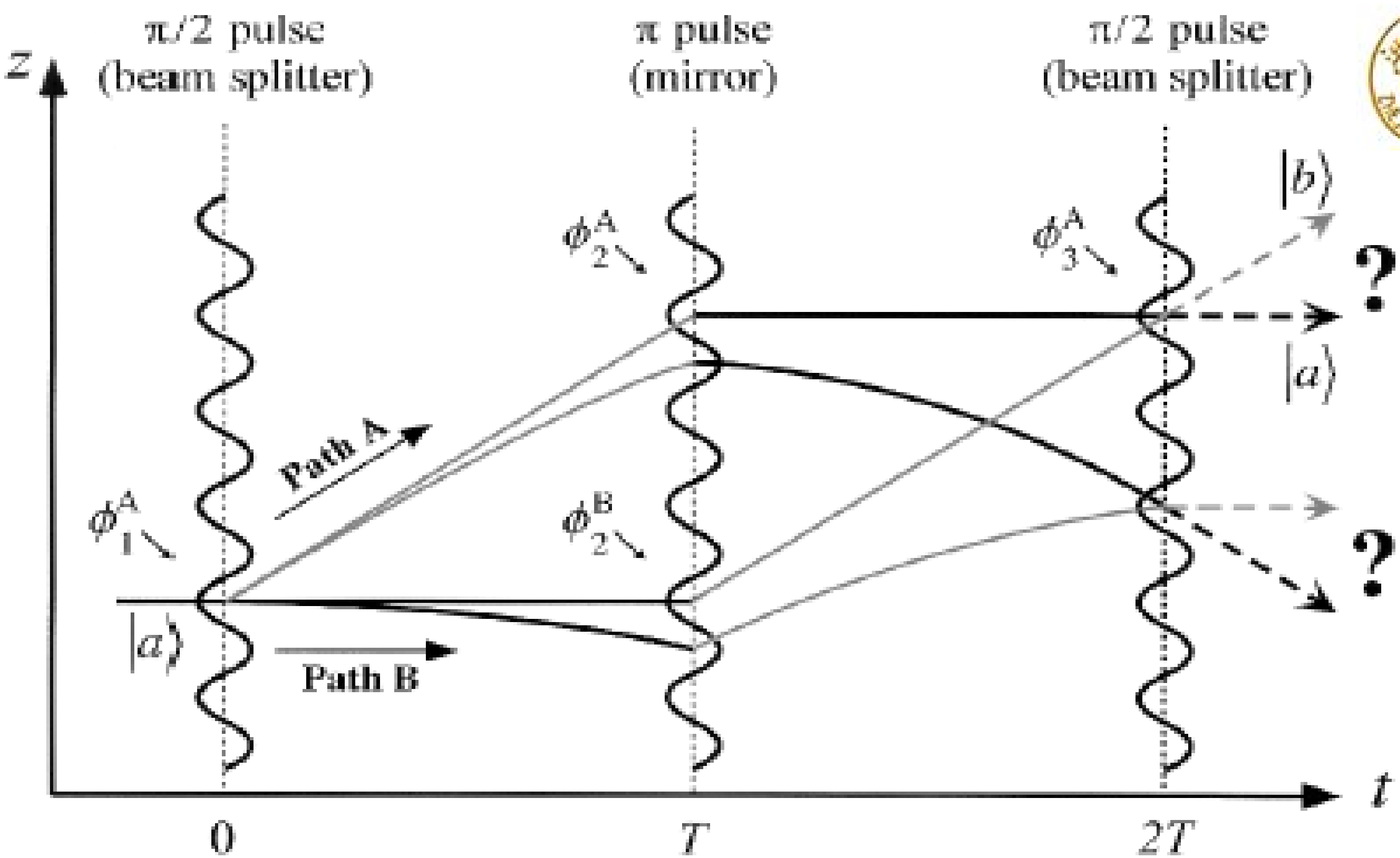


$|2\rangle$
$|3\rangle$
$|1\rangle$
$\pi/2$
π
$\pi/2$
$\frac{1}{\sqrt{2}}(\frac{-i}{\sqrt{2}}e^{-i\phi_2})+\frac{-i}{\sqrt{2}}e^{-i\phi_3}(\frac{-1}{\sqrt{2}}e^{i(\phi_2-\phi_1)})=\frac{-i}{2}e^{-i\phi_2}(1-e^{-i(\phi_3-2\phi_2+\phi_1)})$
$\frac{-i}{\sqrt{2}}e^{-i\phi_1}|3\rangle$
$-ie^{i\phi_2}(\frac{-i}{\sqrt{2}}e^{-i\phi_1})|1\rangle$
$\frac{1}{\sqrt{2}}(\frac{-1}{\sqrt{2}}e^{i(\phi_2-\phi_1)})+\frac{-i}{\sqrt{2}}e^{i\phi_3}(\frac{-i}{\sqrt{2}}e^{-i\phi_2})=\frac{-1}{2}e^{i(\phi_2-\phi_1)}(1+e^{i(\phi_3-2\phi_2+\phi_1)})$
$|1\rangle$
$-ie^{-i\phi_2}(\frac{1}{\sqrt{2}})|3\rangle$
$\frac{1}{\sqrt{2}}|1\rangle$

Wave Interference (Mach-Zehnder interferometer)



Kasevich and Chu (1991,1992)

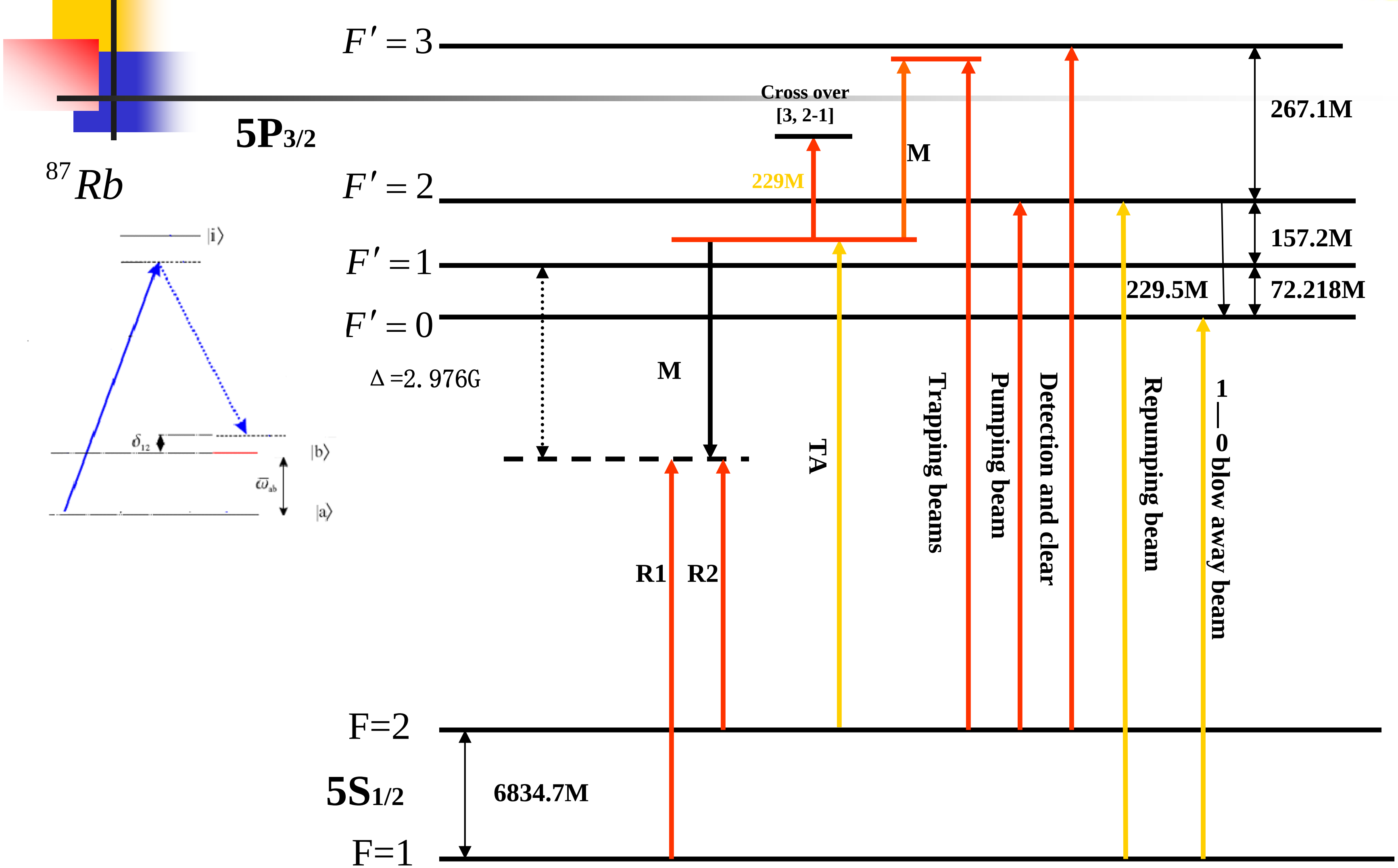


$$\Delta\Phi_{light} = (\Phi_1^A - \Phi_2^A) - (\Phi_2^B - \Phi_3^A)$$

$$\longrightarrow = [0 - (kvT - \frac{1}{2}kgT^2)] - [(-\frac{1}{2}kgT^2) - (kvT - 2kgT^2)]$$

$$\longrightarrow = -k_{eff}\, gT^2$$

^{87}*Rb* Atom Energy Level and laser frequencies



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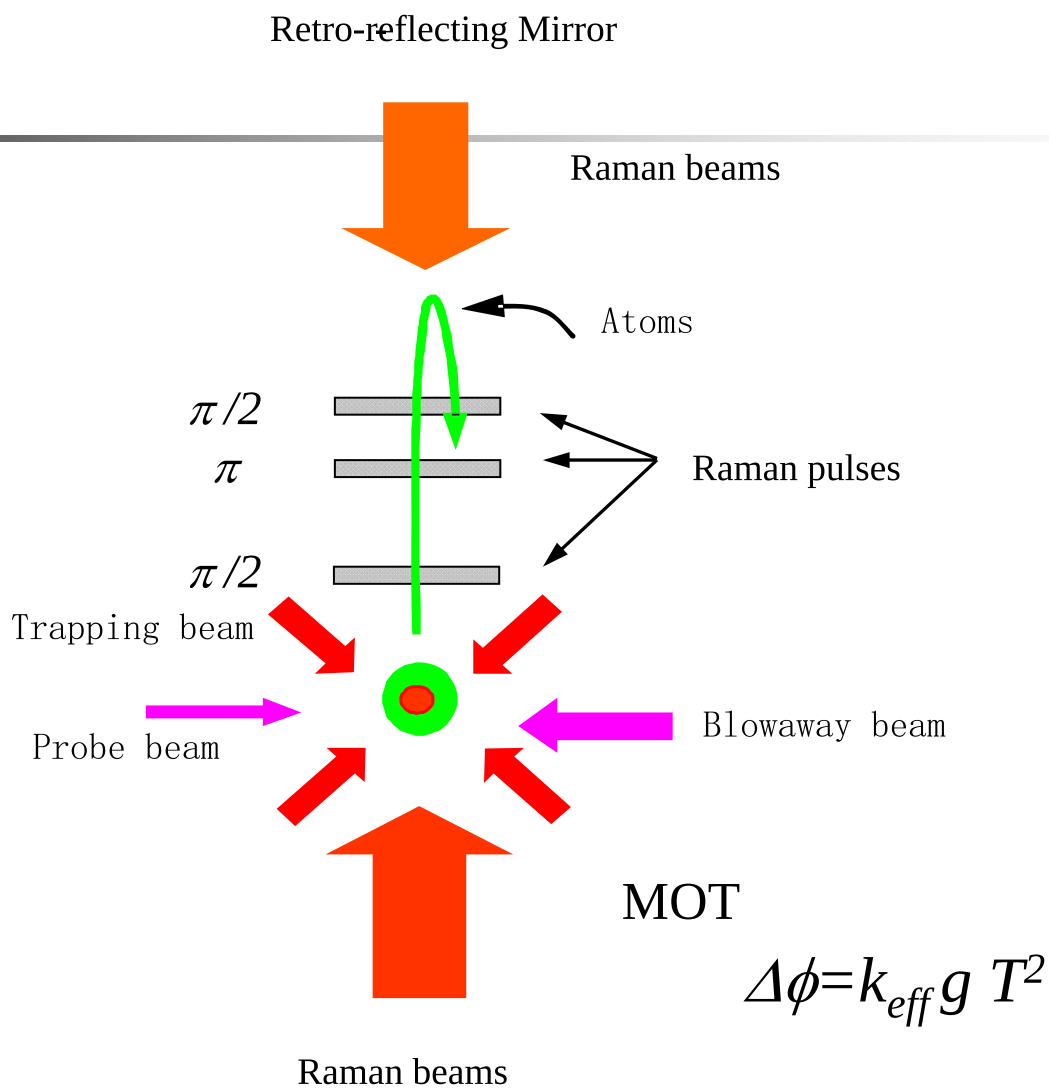
Experiment setups

- As a consequence, it seems favourable to combine consecutive interactions of this type to form different path topologies. In addition, after the final interaction the number of atoms in the different output ports depends on the laser phases at the times of interaction. When the number and types of interactions is chosen such that one or several of the possible paths overlap, an interference pattern of the atomic waves can be employed and an atom interferometer arises. In this aspect, atom interferometers have many similarities to the well known optical ones whereas here the parts of light and matter are interchanged. As an example this technique has been used for atomic clocks since many years whereas the 'optical' transition is realized by a microwave.

- In contrary to atomic clocks, where the interferometer is most sensitive to frequency changes because of the chosen topology, one can employ atom interferometers that are suitable for measuring inertial forces thanks to their sensitivity to phase shifts in the light field between the different atom-light interactions. These phase shifts arise from the fact, that under the influence of an external potential, e.g. the gravity field, the atoms experience different potentials for different interferometer paths. This results effectively in a temporal or spatial change of the times or points of the light-atom interaction, respectively.

Experimental setup scheme



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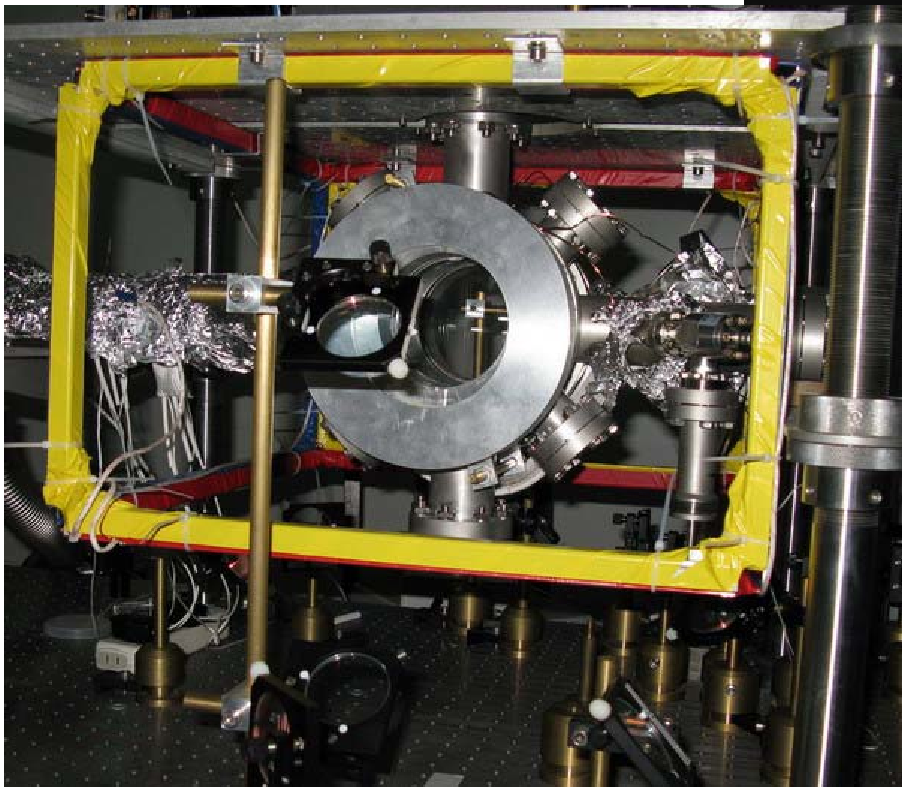
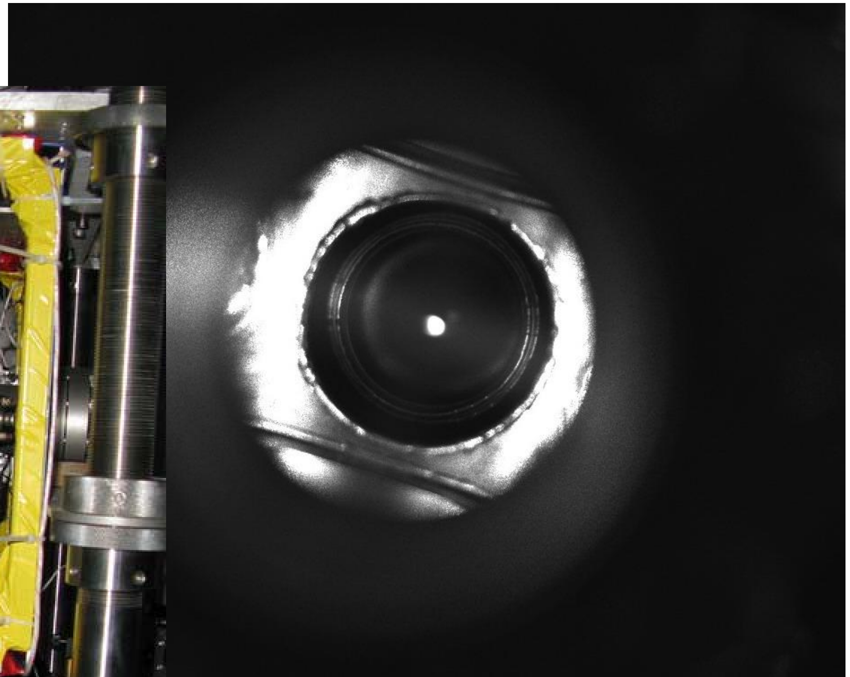
Current status in Zhejiang Univ.

- At the moment, the experiment is still under construction
- Several experimental steps will performed
- The crucial experimental parameters will be characterized
- The two key components of the experiment, sources has been completed and Raman Laser, are being set up.

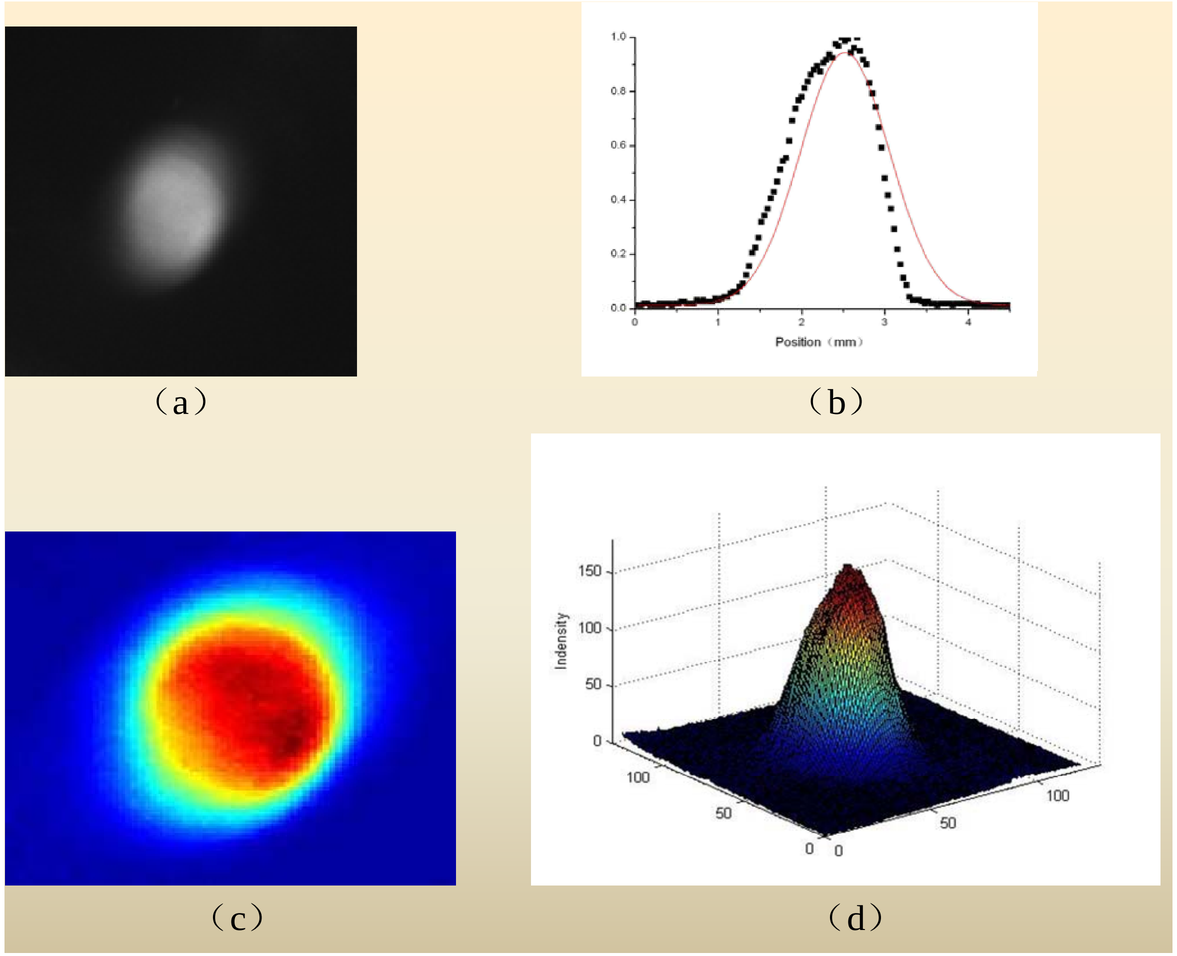
Laser frequency-stabilized system

Experiment setup and the cold atoms obtained in the lab. of Zhejiang Univ.



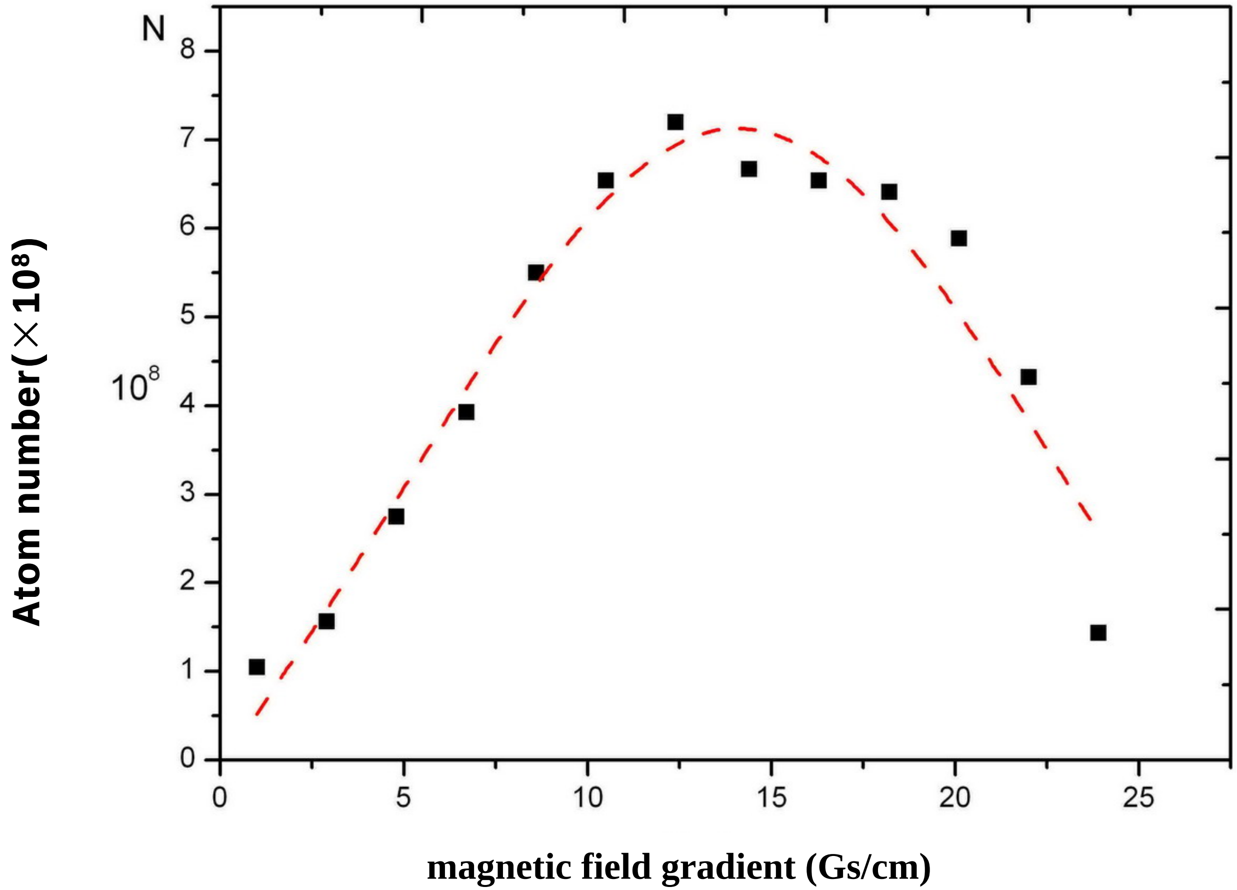


The cold atoms in MOT

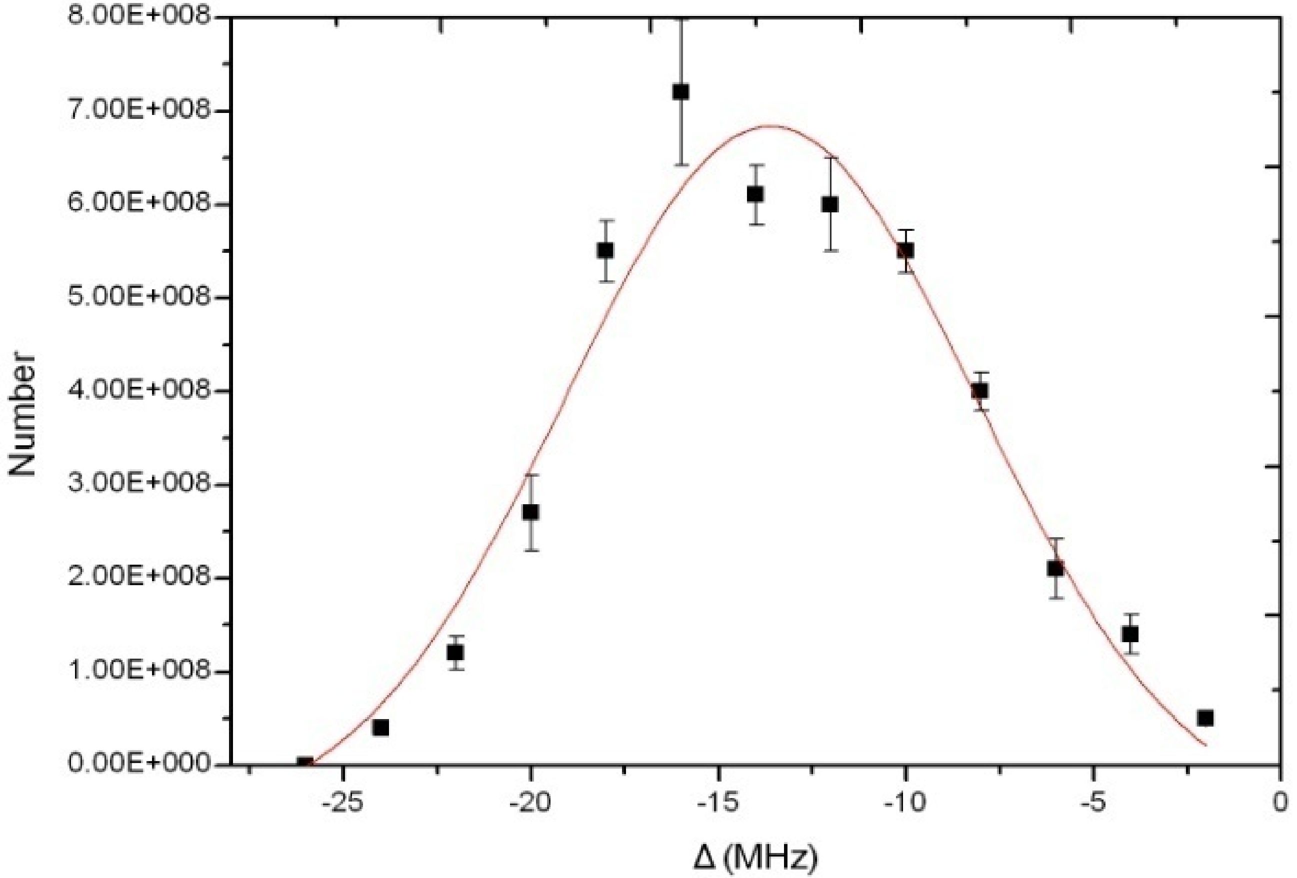


（a） （b） （c） （d）

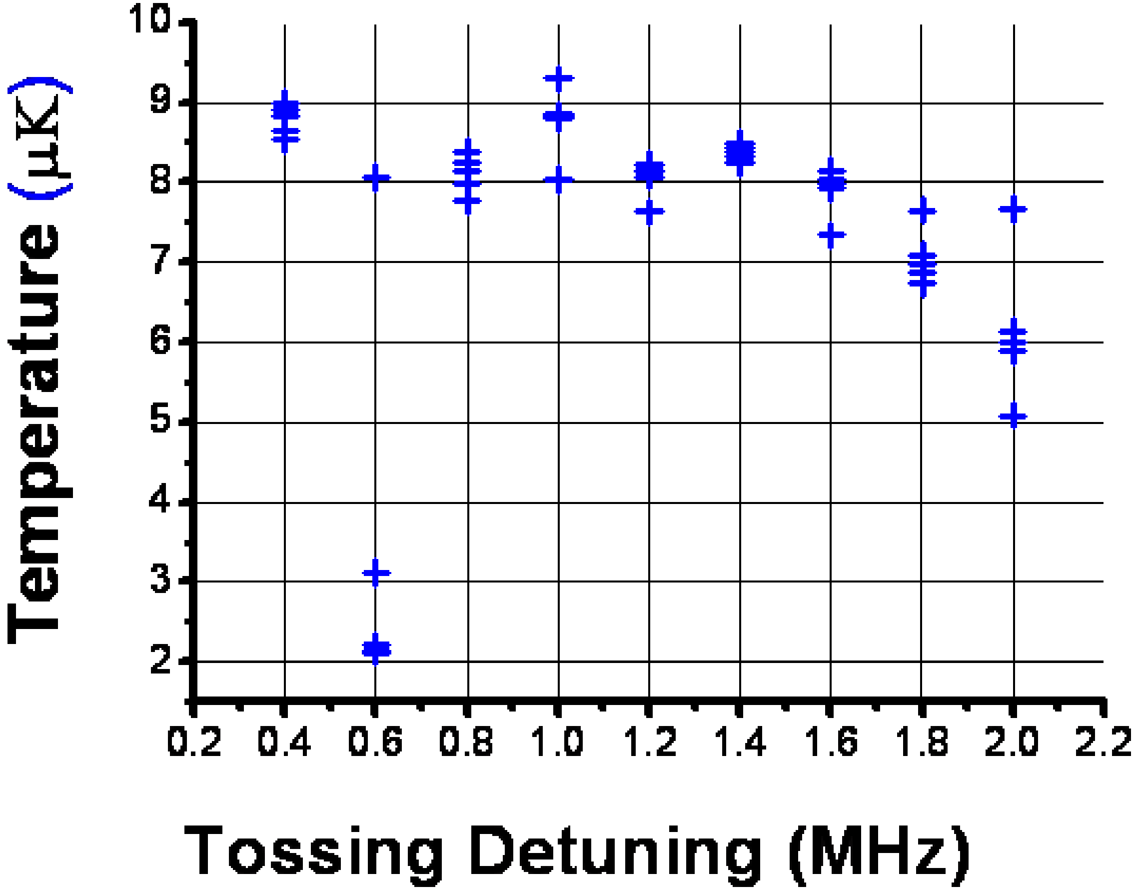
Relation to cold atoms number and magnetic field gradient



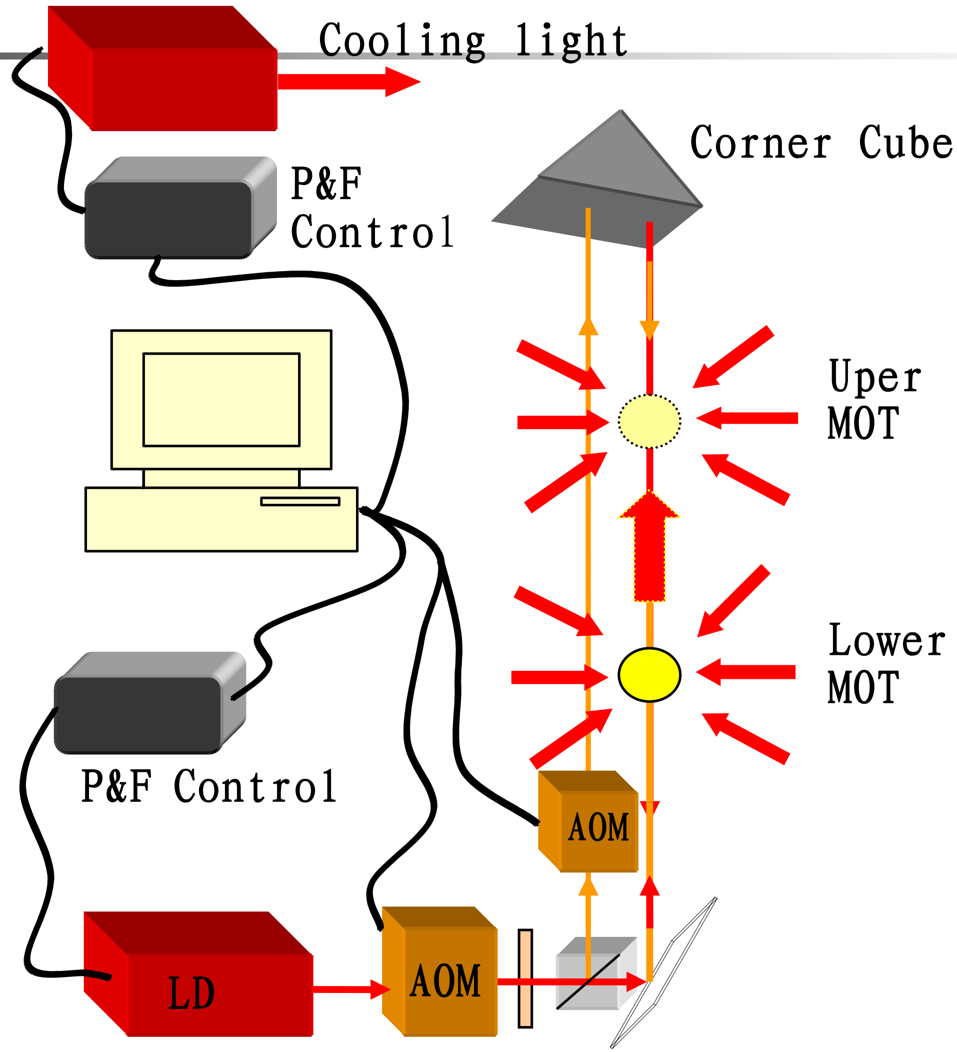
Laser frequency detuning relative to cold atoms number



Relation to cold atoms temperature and tossing detuning



Atom fountain configuration

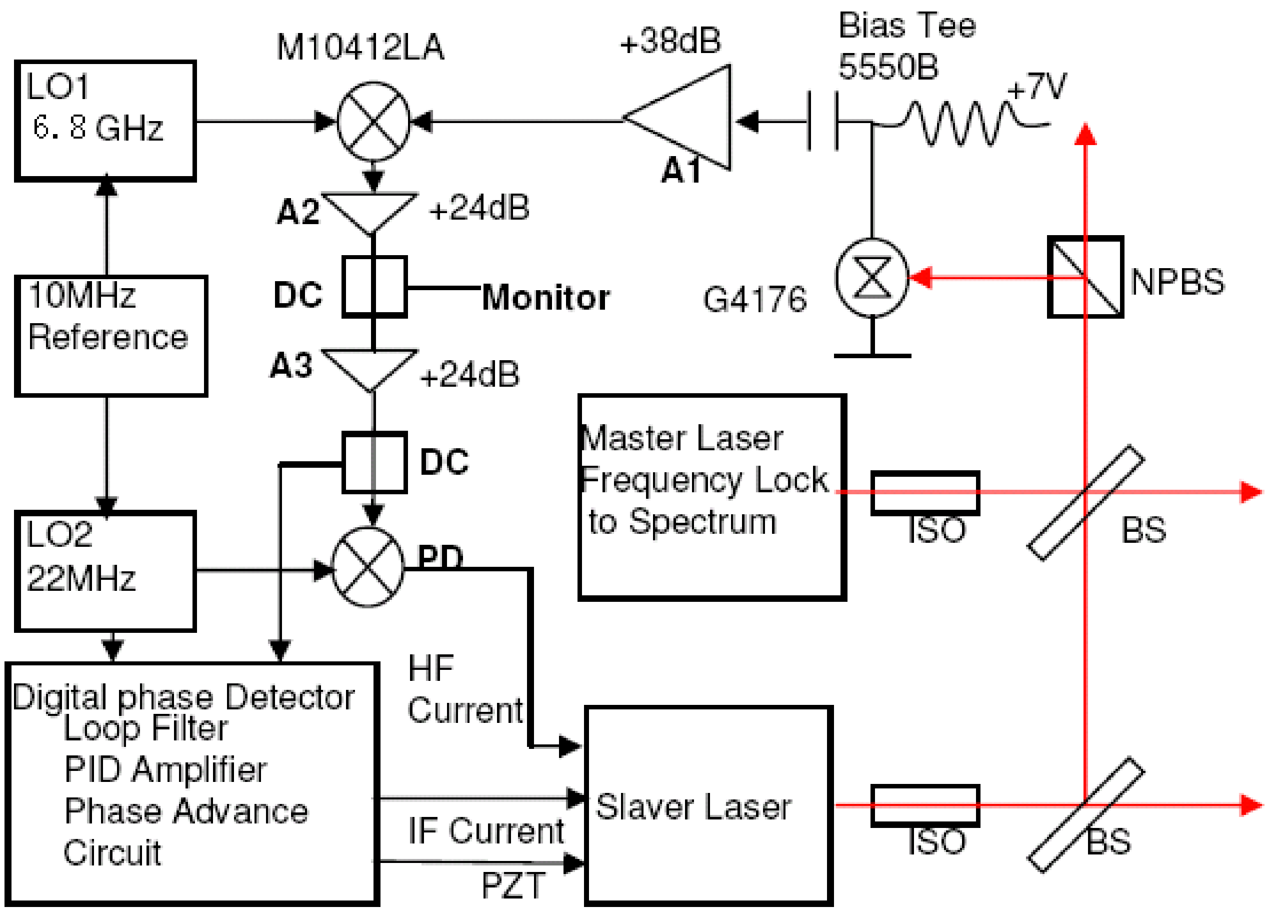


The experimental setup of atom interferometer for measurement gravity in Zhejiang University

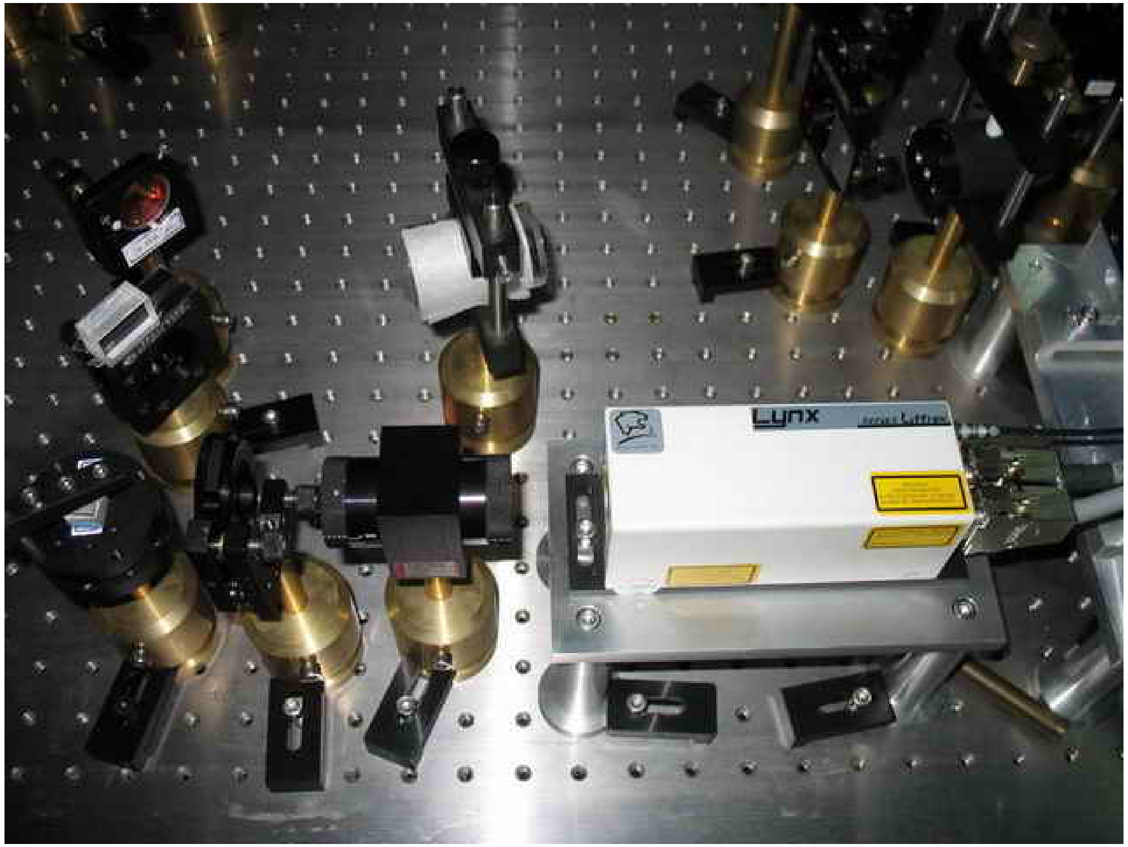
Interferometer laser

- As it is important to have a well controlled frequency and phase for the beam splitting lasers. We will use a Phase locked Raman Laser System for this purpose.
- The phase-lock is implemented at 6.834 GHz, the Rubidium-87 Hyperfine splitting between ground levels F=1 and F=2.

Raman laser system



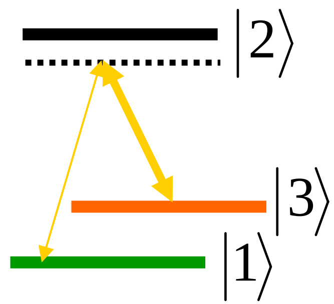
Laser system

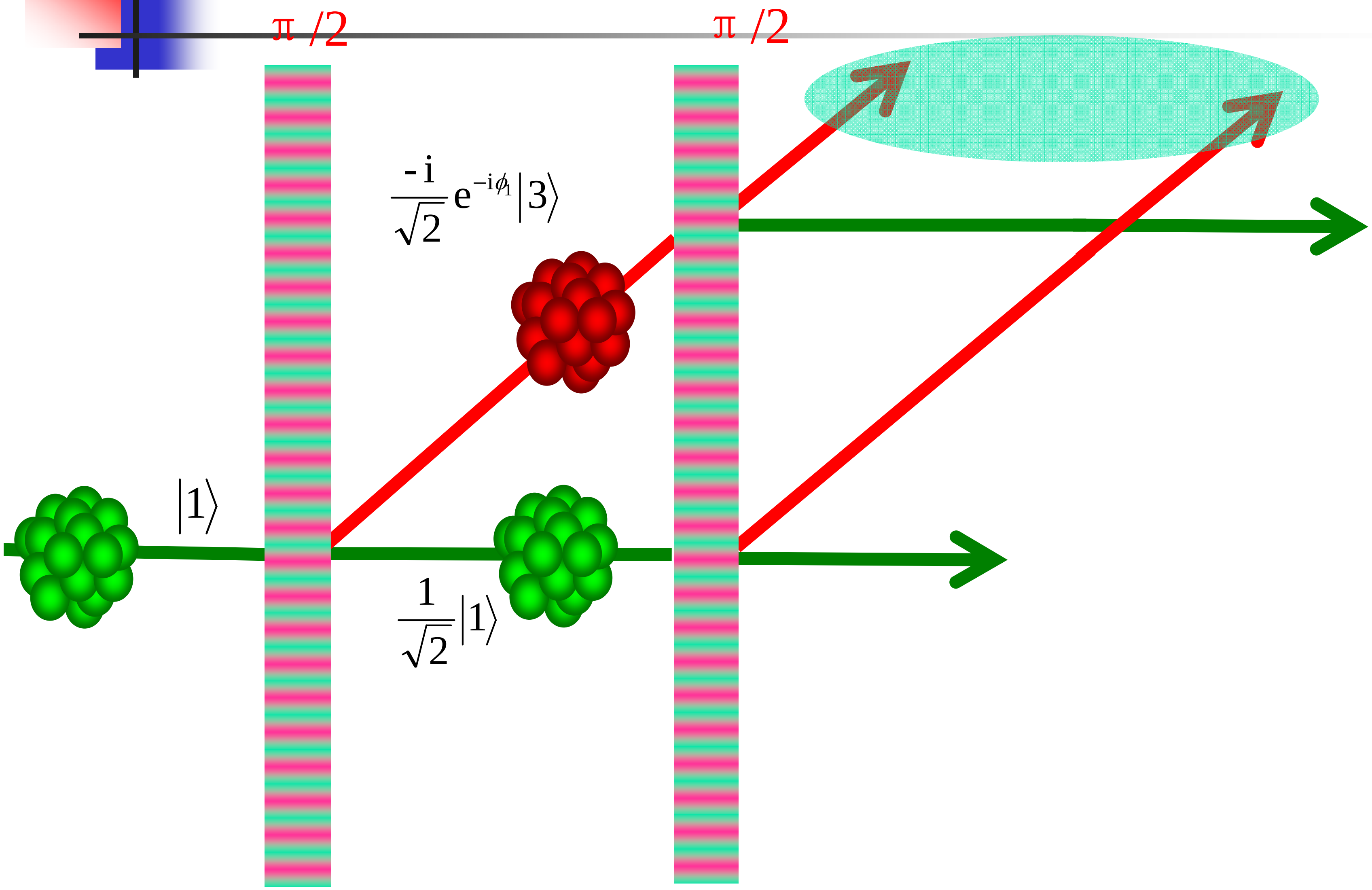


Detection

- For a good signal-to-noise ratio, the detection of both output ports is planned. A well controlled atomic number at the interferometer input is in principle not needed that way, but still favourable. The detection scheme, as well as the state preparation entering the interferometer, relies on optical pumping and fluorescence detection.

Ramsey–Borde AI





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Atomic phase shift induced by a gravitational wave

$$\delta\varphi = k\gamma q T_0^2[\sin^2(\xi T/2)/(\xi T/2)^2$$

$$-khV_0\xi T^2\sin(\xi T+\phi)[\sin^2(\xi T/2)/(\xi T/2)^2]$$

$$-khV_0T[\cos(2\xi T+\phi)-\cos(\xi T+\phi)]+\varphi_0-2\varphi_1+\varphi_2$$

with: $V_0=(p_0+\frac{\hbar k}{2})/M$ and $\gamma=(\xi^2/2)h\cos(\xi t+\phi)$

Ch.J. Bordé, J. Sharma, Ph. Tourrenc and Th. Damour, J. Physique Lettres 44 (1983) L983-990

Ch.J. Bordé, in Atom Interferometry, ed. by P. Berman, Academic Press (1997)

C.Antoine, C.Bordé, J.Opt. B: Quantum Semiclass.Opt., 5, 199-207 (2003)

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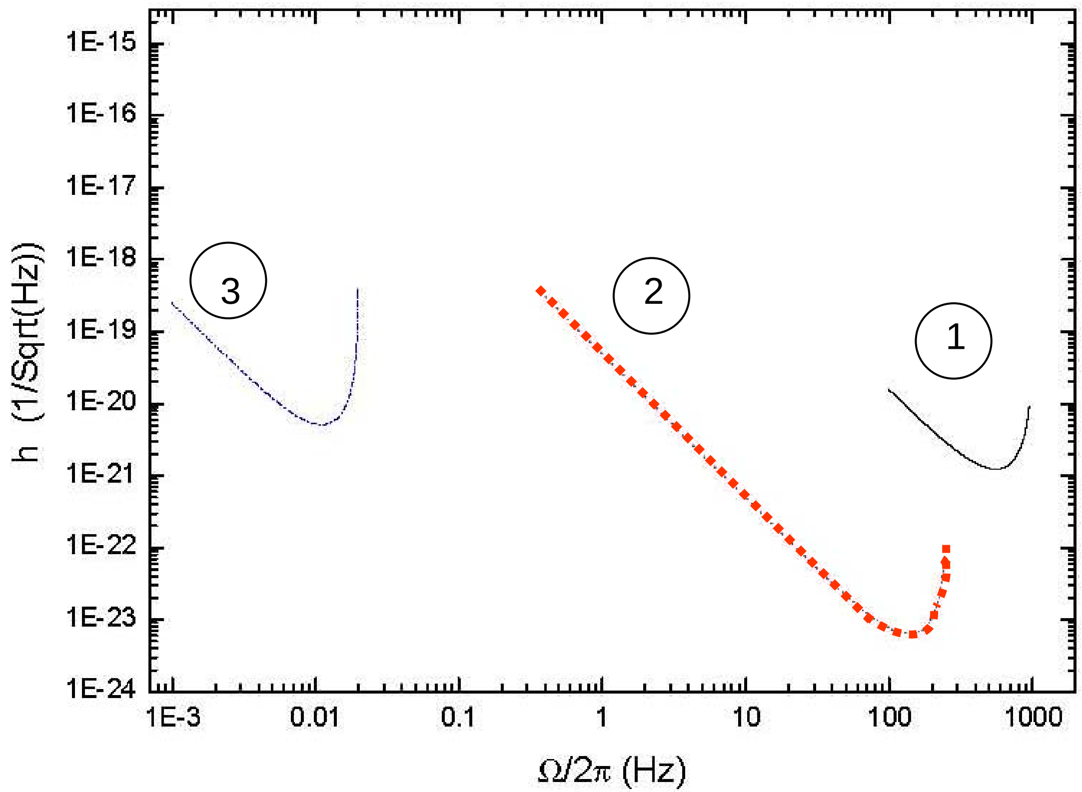
Some sensitivity curves for atom interfromet



$v_L = 10^6$ m/s; $\dot{N} = 10^{18}$ atoms/s; $T = 10^{-3}$ s; $L = 10^3$ m; $v_T = 10$ m/s (1)

$v_L = 10^7$ m/s; $L = 10^5$ m; $T = 10^{-2}$ s (2)

$v_L = 10$ m/s; $v_T = 5$ m/s; $L = 50$ m; (3)

Some factors for influence sensitivity of atom interfrometry

Systematic errors	$10^9\times$ Relative uncertainty
Instrumental	
RF phase shift	2.0
Coriolis effect	2.0
AC Stark shift	1.0
Synchronous noise	1.0
Dependence on pulse timing	1.0
Retro reflection	0.6
Laser-lock offset	0.4
Rb wavelength	0.3
Gravity gradient	0.2
Cold collision	0.2
Synchronous vibration	0.2
Synchronous fields	0.2
Changing $\boldsymbol{k}$ vector	0.1
Overall instrumental uncertainty	**3.4**
Environment	
Pressure correction	1.0
Ocean loading	1.0
Other environmental effects	2.0

A. Peters, K. Y. Chung and S. Chu， *Metrologia*, 2001, **38**, 25-61

Noise

- Vibration
  limit the resolution of ~ 10^{-6}g per launch. Using an active vibration isolation system one can get a resolution of ~10^{-8}g per launch.
- Rotation
- Measured noise
- Raman laser noise, including intensity noise and phase noise
- Shot and detection noise
- High frequency phase noise

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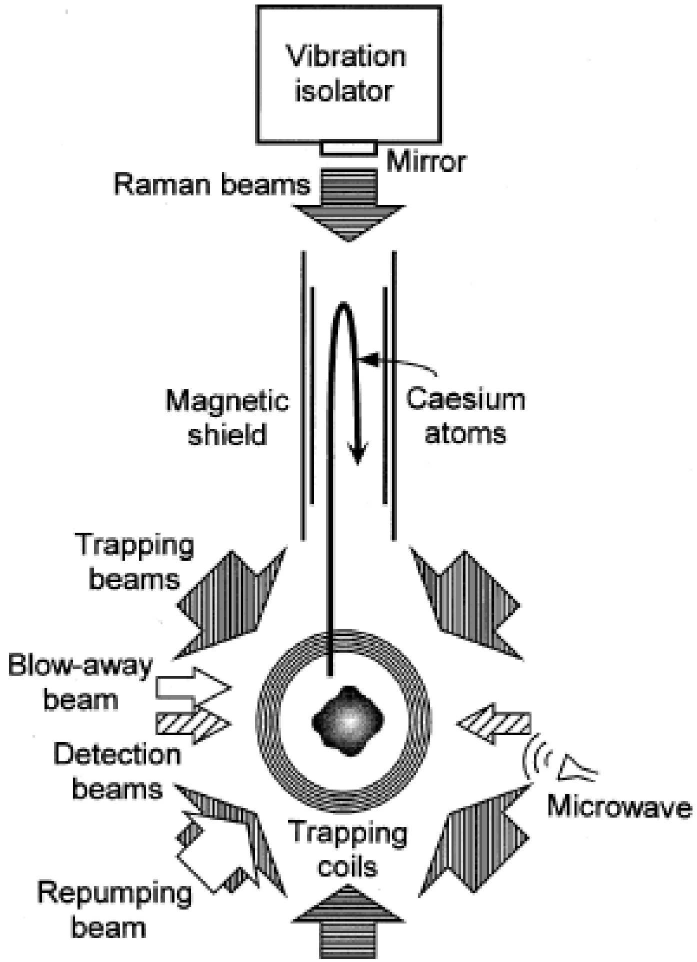
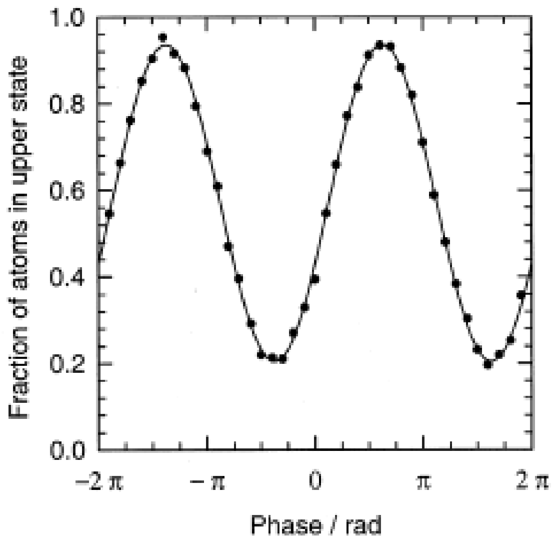
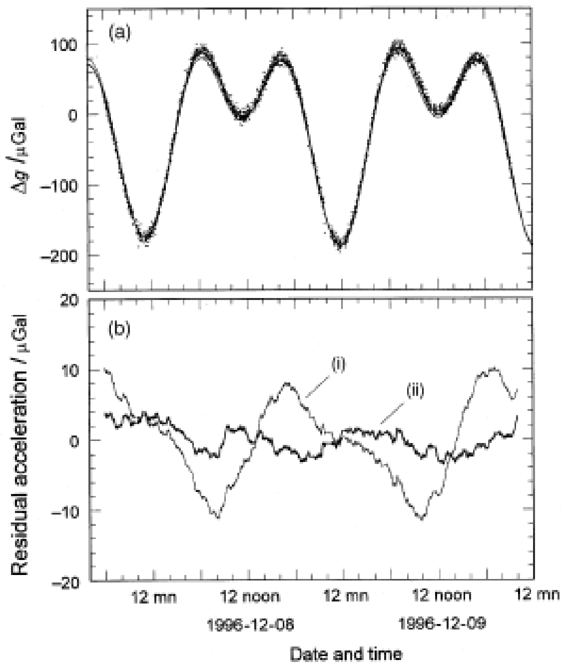






- **Performances:**

– **Resolution: $3\text{x}10^{-9}$ g after 1 minute**

– **Absolute accuracy: $\Delta g/g<3\text{x}10^{-9}$**

A. Peters, K. Y. Chung and S. Chu， *Metrologia*, 2001, **38**, 25-61

AI inertial sensors: performance summary

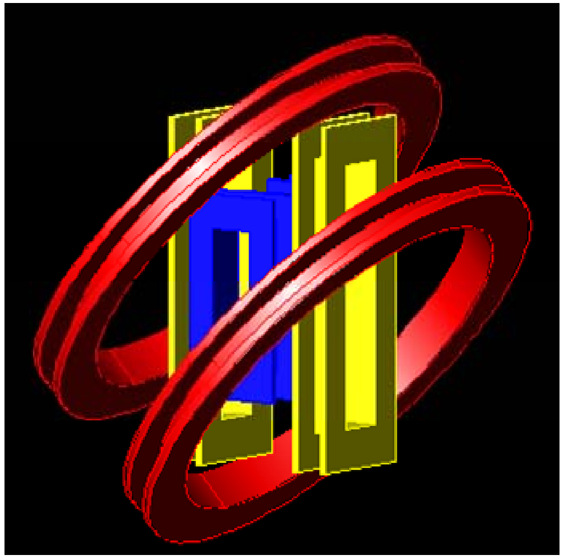
	Demonstrated ground	Anticipated ground	Projected space
Gyroscope ARW Bias stability Scale factor	 2×10^{-6} deg/hr$^{1/2}$ 6×10^{-5} deg/hr 5 ppm	 $<1\times10^{-6}$ deg/hr$^{1/2}$ $<10^{-5}$ deg/hr <1 ppm	 $<10^{-8}$ deg/hr$^{1/2}$ $<10^{-7}$ deg/hr <1 ppm
Accelerometer Sensitivity Bias stability Scale factor	 10^{-9} g/Hz$^{1/2}$ $<10^{-10}$ g $<10^{-10}$	 $<10^{-10}$ g/Hz$^{1/2}$ $<10^{-10}$ g $<10^{-10}$	 $<10^{-13}$ g/Hz$^{1/2}$ $<10^{-16}$ g ? $<10^{-12}$

How to improve sensitivity of atom interferometer

- In order to improve sensitivity of atom interferometer, we propose that atom interferometer should be set in a satellite in space. There are a lot of work to do in this aspect.

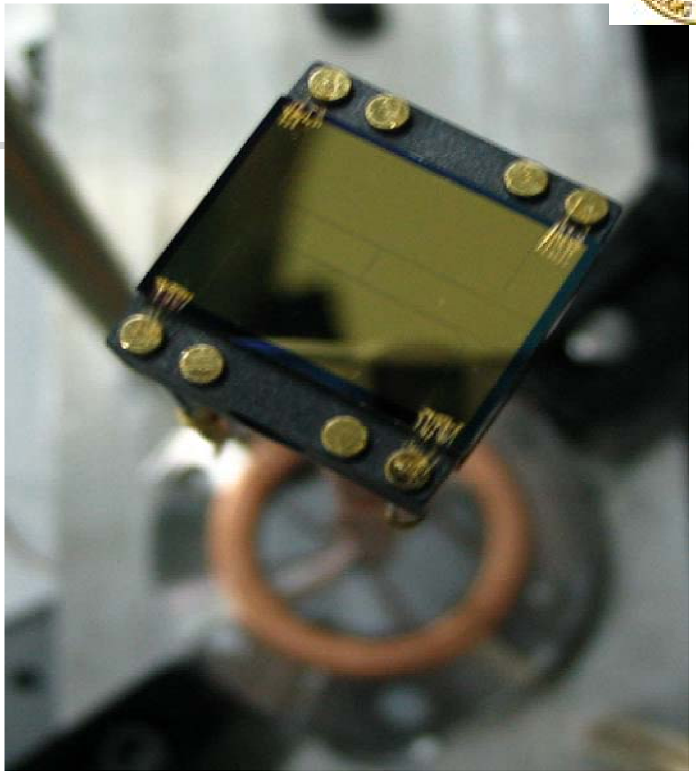
Laser cooling on chip

Magnetic Coils for the chip



Atomic chip

- BEC on chip (Shanghai Institute of Optics and Fine Mechanics (SIOM), and Zhejiang University) in Dec. 2008.



Group members

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- Prof. Dr. Xuanhui Lu
- Dr. Kaikai Huang
- PhD student He Chen
- PhD student Chengliang Zhao
- PhD student Xiang Zhang
- Ms. Students…

Thank you for your attention!