Trapping and manipulation of atoms for precision measurements

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Motivation : Cold Atoms Science and Technology

Fundamental Physics:

- *High resolution spectroscopy,*
- *Quantum degenerate gases (BEC),*
- *Condensed matter physics,*
- *Quantum physics,*
- *Quantum information, etc.*

Devices:

- *-frequency and time (atomic clocks),*
- *-sensors for magnetic and electric fields,*
- *-inertial sensors (rotation, acceleration)*
- *-atom trap trace analysis (dating, pollution, monitoring NPT)*
- *-UHV standards,*
- *- Cold atom electron source,*
- *-Cold atoms as Qubits*

Atom cooling activities at RRCAT:

1. **Bose-Einstein Condensation (BEC) Lab :** Double-MOT setup for ^{87}Rb atoms, QUIC trap, optical dipole trap, BEC, EIT, RF-dressing lab.
2. **Atom-chip lab:** Cooling and trapping of ^{87}Rb atoms atoms on Atom-chip.
3. **Cold atom gravimeter lab:** Setup for measurement of “g”.
4. **Cold atoms UHV sensor Lab:** preliminary results are there.

Dr. S. R. Mishra

Dr. S. P. Ram

Dr. V. B. Tiwari

Shri V. Singh

राष्ट्र की सेवा में परमाणु

रा रा प्र प्रौ के

RRCAT

ATOMS IN THE SERVICE OF THE NATION

Dr. S. Singh

Shri A. Chaudhary

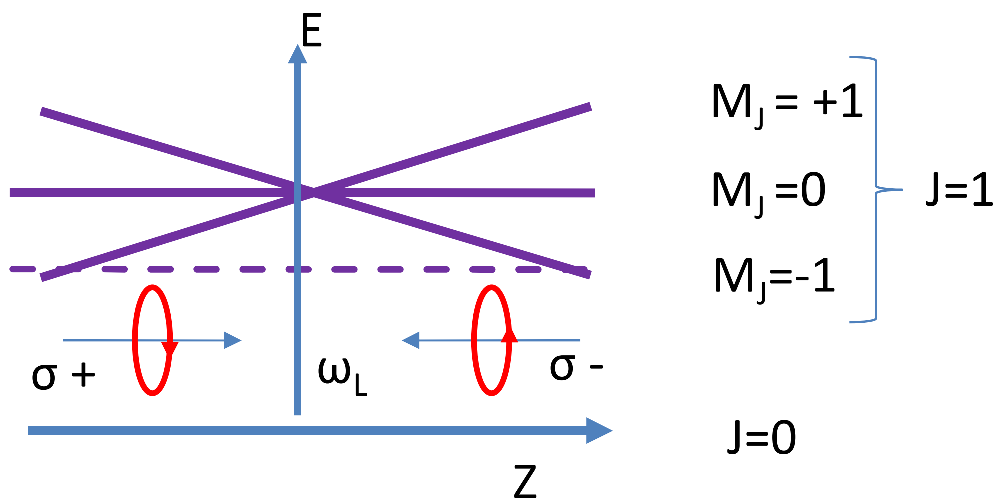
Shri K. Bhardwaj

Shri A. Chakraborty

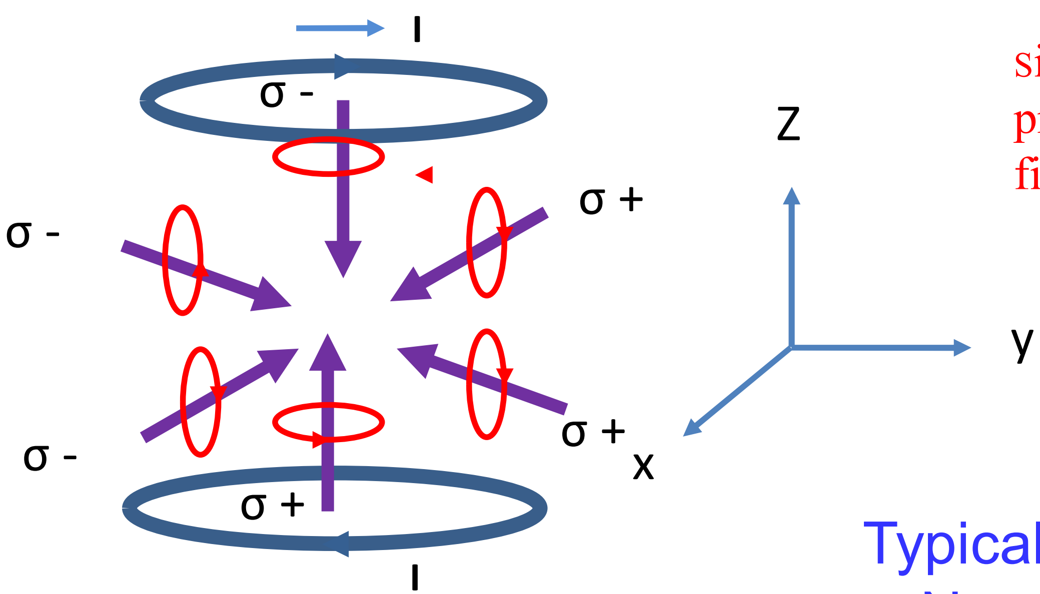
Kum. Charu Mishra

*Source of cold atoms : **Magneto-Optical Trap (MOT)***

Three dimensional cooling and trapping of atoms: from room temperature to micro-kelvin



$$F_{MOT} = -\beta v - kz$$



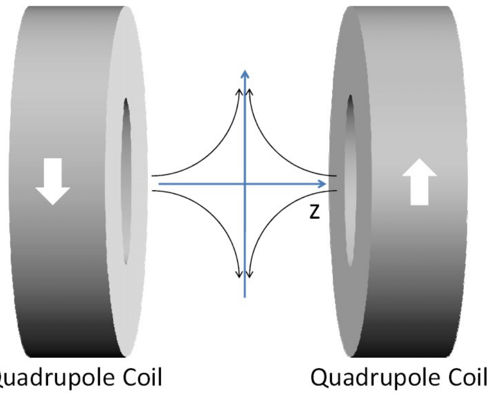
six beam configuration in presence of quadrupole magnetic field for MOT formaion.

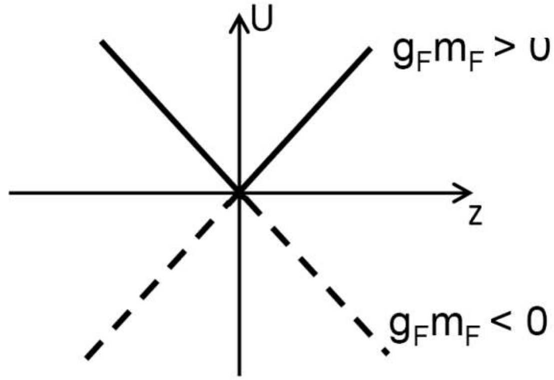
Typical Temperature ~ 20-500 μK
Number of atoms ~1-3 x 10^8

Magnetic Traps for cold atoms

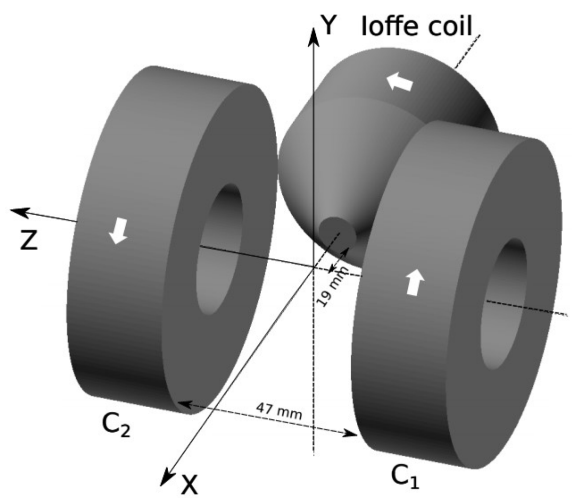
$$U = -\vec{\mu}.\vec{B} = \mu_B g_F m_F |\vec{B}|$$

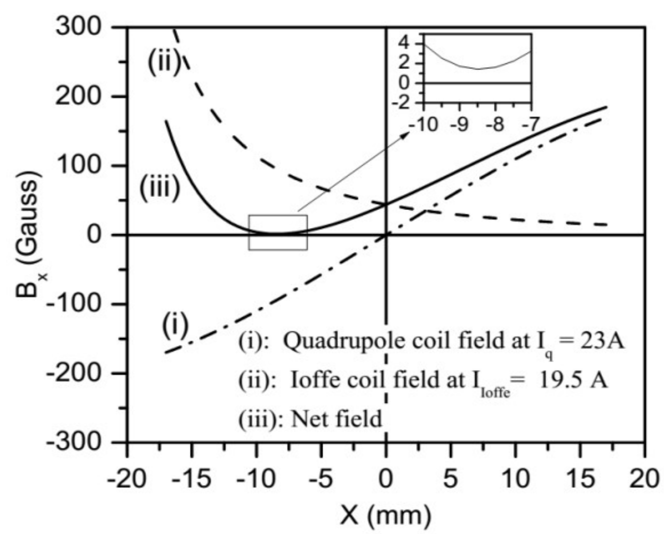
$$\mathbf{B^S}(\mathbf{r}) = B_q \begin{pmatrix} x \\ y \\ -2z \end{pmatrix}$$





(i) Quatrupole Trap

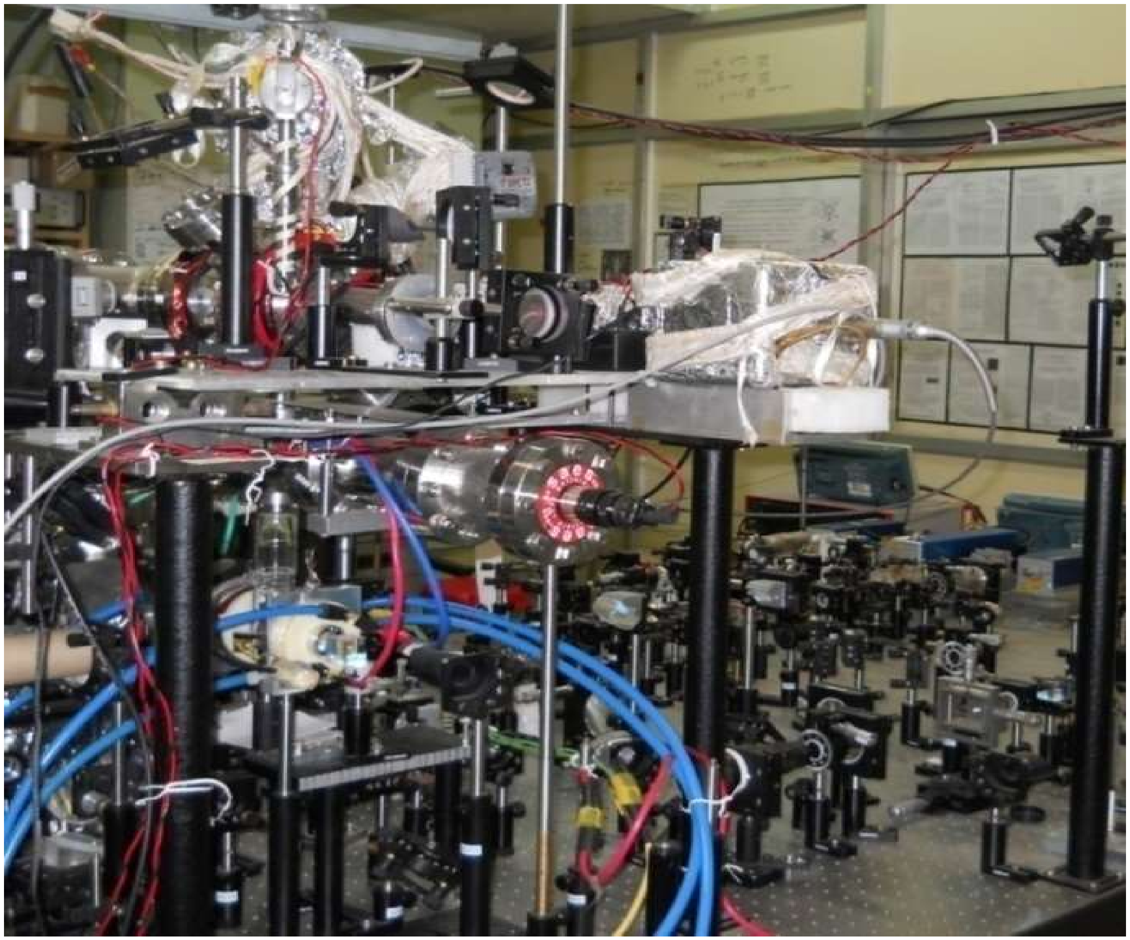


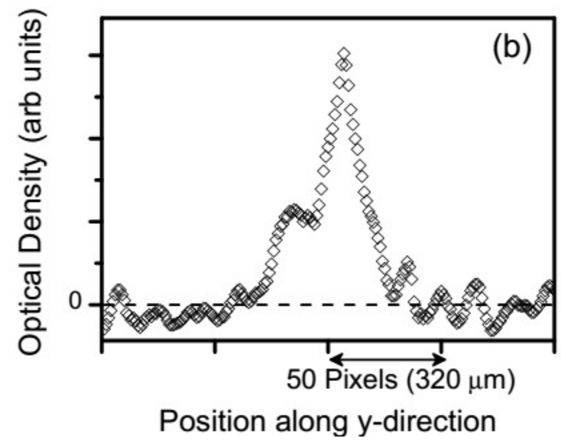


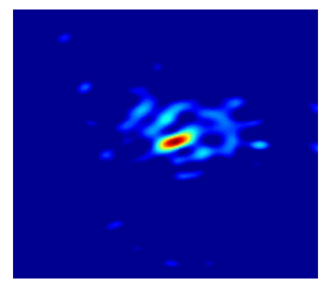
(ii) Quadrupole Ioffe Configuration (QUIC) Trap

Bose-Einstein Condensation of ^{87}Rb atoms at RRCAT :

Initially atoms are in vapor form at room temperature.
Laser cooling in Double-Magneto-optical Trap (MOT) followed by RF induced evaporative cooling in magnetic trap, leads to very low tempearture to reach Bose-Einstein condensation of atoms.





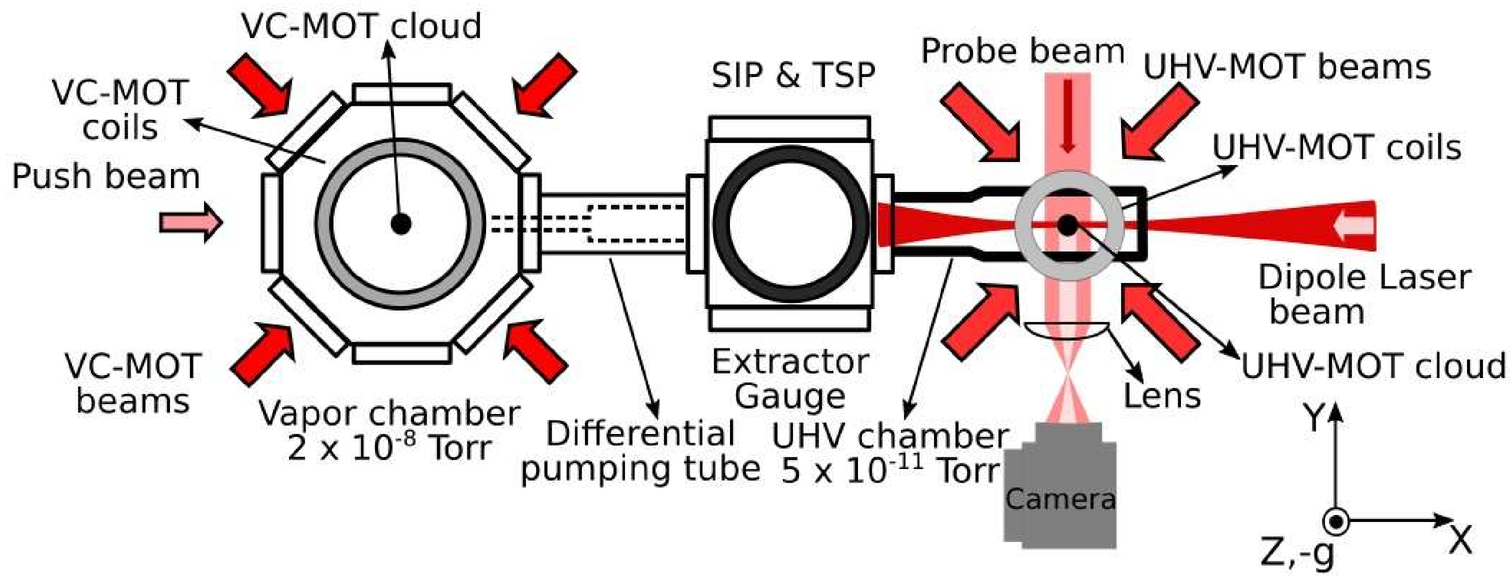


Atom cloud of BEC

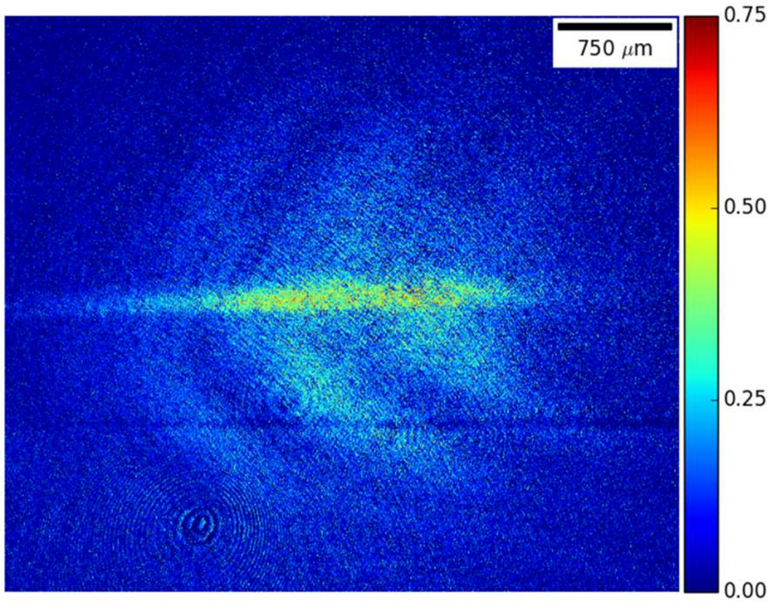
The final temperature of the cloud of the ^{87}Rb atoms: T~440 nK, N ~6x10^5 Bose Condensate.

Optical Dipole Trap

Dipole traps help in achieving larger density and faster evaporative cooling to reach quantum degeneracy. Atoms from UHV-MOT were trapped in dipole trap.



$$U = \frac{\Gamma^2}{8\Delta}(I / I_s)$$



Optical dipole trap beam parameters:

Wavelength: 1064 nm (Fiber laser)

Spot-size at UHV-MOT position: ~17 μm

Trap depth: ~ 0.15 mK/Watt

- Nearly 2×10^5 atoms were trapped in a single beam optical dipole trap of power 22 W.

Absorption imaging of trapped atoms in Dipole trap

AC-Stark shift in dipole trap modify the absorption cross-section at probe frequency. The correct estimation of number of atoms in the trap is done by taking taking AC-Stark shift into account. The estimated numbers were found to be in agreement with power law of trapping beam.

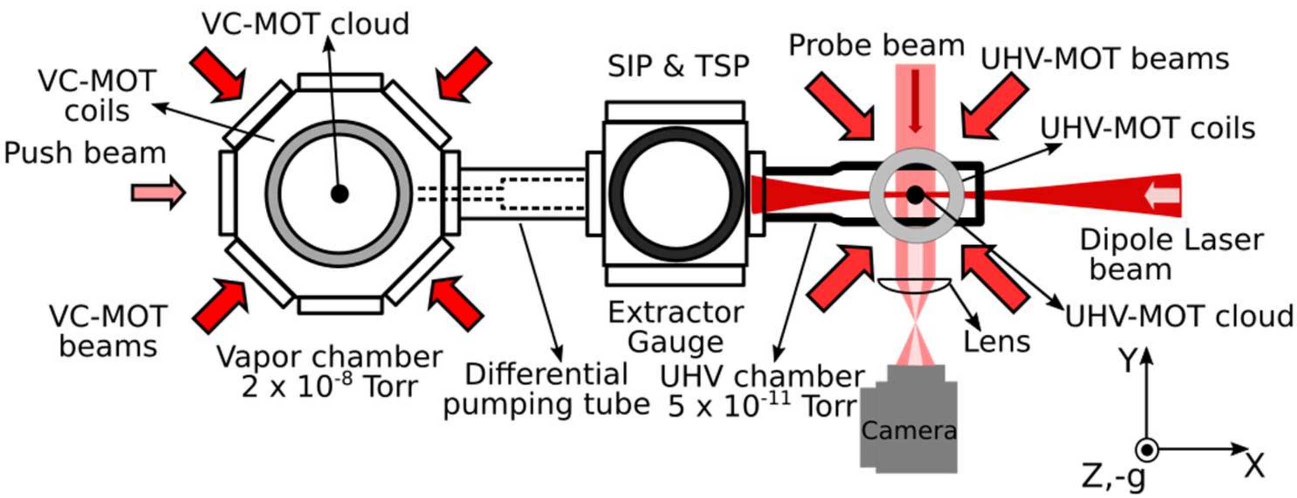


Fig: Schematic of the experimental setup

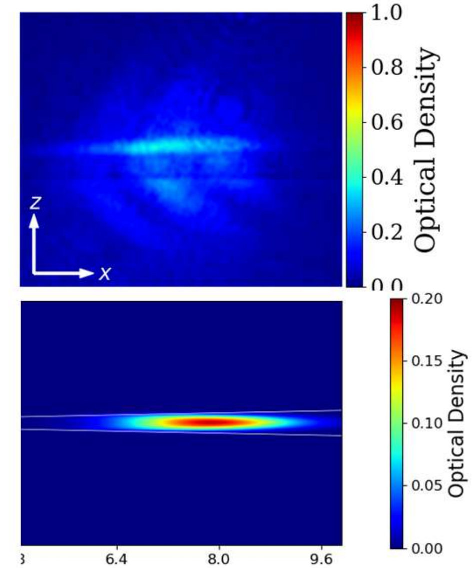
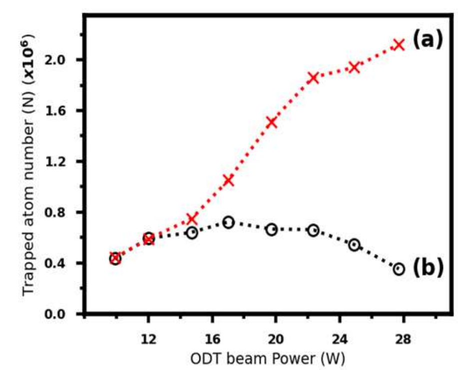


Fig: Experimental and simulated trapped cloud



Kavish Bhardwaj, et al , Phys. Scr. 96 (2021) 015405.

Fig: Variation in number of atoms with and without incorporating AC- Stark shi

Loading a MOT in UHV using a Rb atomic beam source

We have developed a simple Rubidium (Rb) atomic beam source to load a magneto-optical trap (MOT) setup in ultra-high vacuum (UHV) environment. The atomic beam source is generated from a pair of Rb dispensers joined in parallel configuration and placed inside a glass jacket having a narrow tube structure opening in the UHV chamber. A MOT has been loaded using this source with 2.3×10^{7} atoms of ^{87}Rb at a background pressure of ~3.5×10^{-10} Torr.

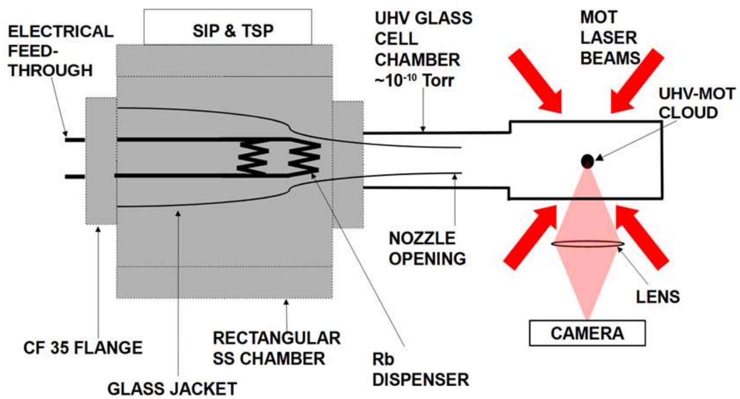


Fig: Schematic of the experimental setup

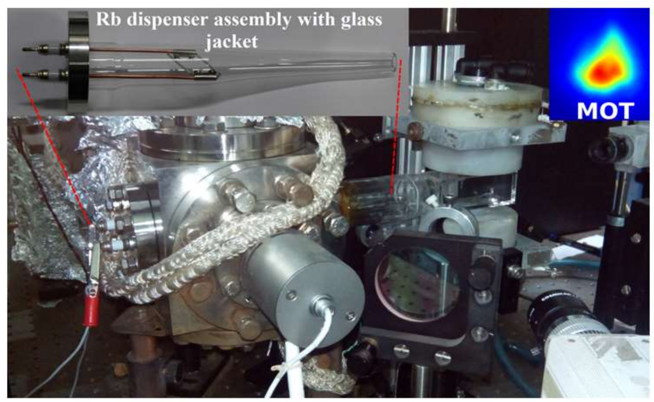


Fig: Photograph of the setup

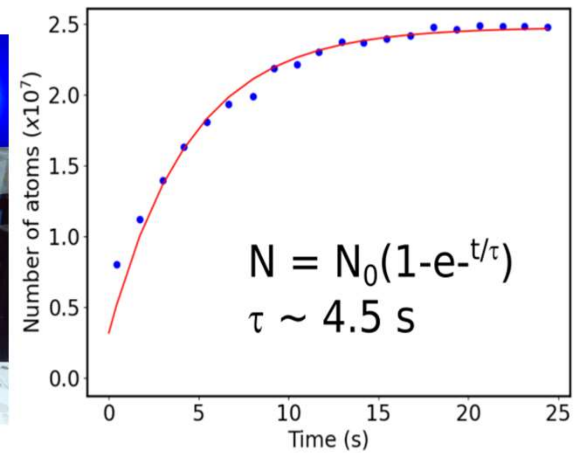


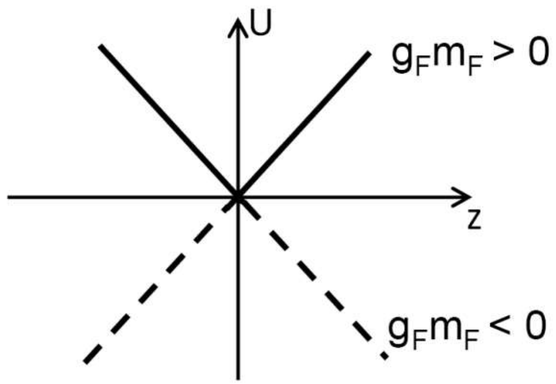
Fig: Loading curve of MOT for current of ~ 5 A through the Rb dispenser assembly.

Manipulation of atom trapping geometries using RF-dressed potentials

Magnetic trap + Strong rf-field → modified potential ("RF-dressed potential").

For example, consider static quadrupole magnetic field and an RF-field as given below.

$$\mathbf{B}^{\mathbf{S}}(\mathbf{r}) = B_q \begin{pmatrix} x \\ y \\ -2z \end{pmatrix}$$



$$\omega_0 = \frac{g_F \mu_B B_q}{\hbar} \sqrt{x^2 + y^2 + 4z^2}.$$

$$\mathbf{B}^{\mathbf{rf}}(t) = \{B_x \cos \omega t, B_y \cos(\omega t - \alpha), B_z \cos(\omega t - \beta)\}$$

RF-Dressed potentials

$$H(t) = -\mu \cdot \mathbf{B} = \frac{g_F \mu_B}{\hbar} \mathbf{F} \cdot \mathbf{B(r,t)}$$

B(r,t)=$B^s(r) + B^{rf}(t)$

V(r)=$\hbar m_F \sqrt{\delta^2 + \Omega^2}$ $\quad \delta = \omega - \omega_0.$

$$|\Omega|^2 = \left(\frac{g_F \mu_B}{2\hbar}\right)^2 \left[\frac{4z^2}{x^2+y^2+4z^2}\left(\frac{B_x^2 x^2 + B_y^2 y^2}{x^2+y^2}\right) + \left(\frac{B_x^2 y^2 + B_y^2 x^2}{x^2+y^2}\right) + B_z^2\left(\frac{x^2+y^2}{x^2+y^2+4z^2}\right) - \frac{2B_x B_y xy\cos\alpha}{x^2+y^2+4z^2} + \frac{4B_x B_y z\sin\alpha}{\sqrt{x^2+y^2+4z^2}} + \frac{4B_y B_z yz\cos(\alpha-\beta)}{x^2+y^2+4z^2} + \frac{2B_y B_z x\sin(\alpha-\beta)}{\sqrt{x^2+y^2+4z^2}} + \frac{4B_z B_x zx\cos\beta}{x^2+y^2+4z^2} + \frac{2B_z B_x y\sin\beta}{\sqrt{x^2+y^2+4z^2}}\right].$$

The potetial V(r) is inherently position dependent. Many new geometries can be made possible to trap cold atoms using the above potential.

Different RF-dressed trapping potentials for atoms

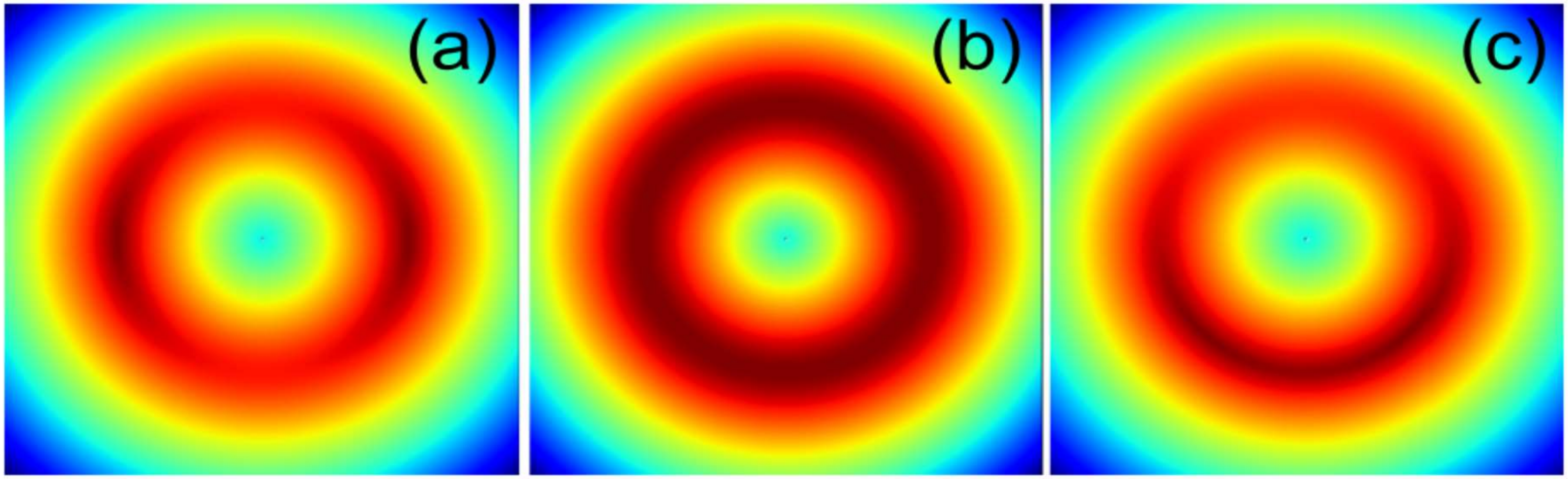
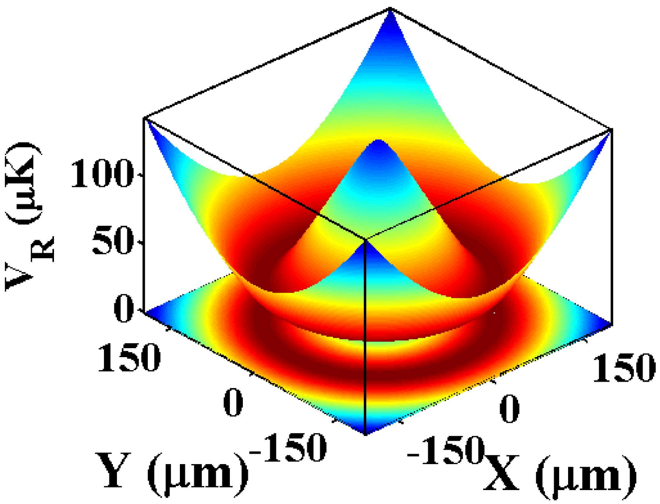


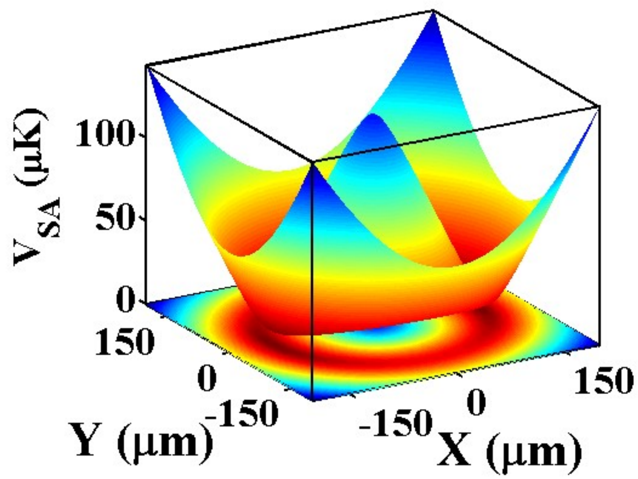
FIG. 2: (Color online) The calculated contours of rf-dressed potential $V(\mathbf{r})$ (Eq. (3), (4) and (5)) in the xy-plane for different values of parameters. Plot (a) shows a double-well potential with $B_x = 0.7$ G, $B_y = B_z = 0$, plot (b) shows the ring trap with $B_x = B_y = 0.7$ G, $B_z = 0$ and $\alpha = -\pi/2$, and plot (c) shows an asymmetric ring trap with $B_x = 0.7$ G, $B_y = 0$, $B_z = 0.2$ G and $\beta = 0$. The other parameters, $B_q = 100$ G cm^{-1}, $\omega = 2\pi\times1.5$ MHz etc., are common to all the plots. The colours from red to blue show the potential values in increasing order.

(A. Chakraborty and S R Mishra, J. Korean Phys. Soc. 65 (9), 1324-1335 (2014))

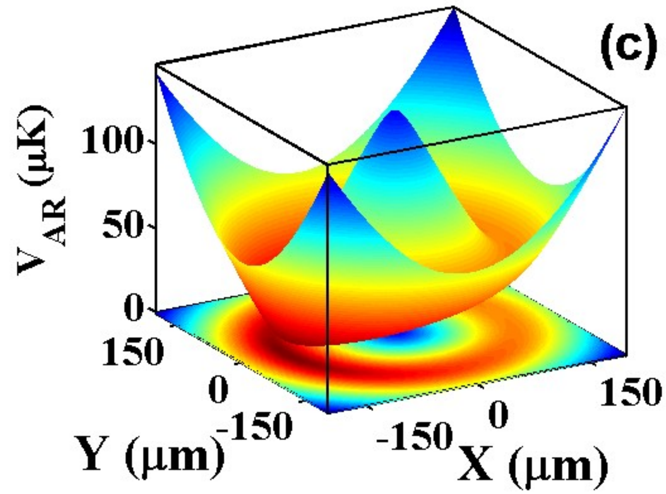
Ring trap



Split arc trap

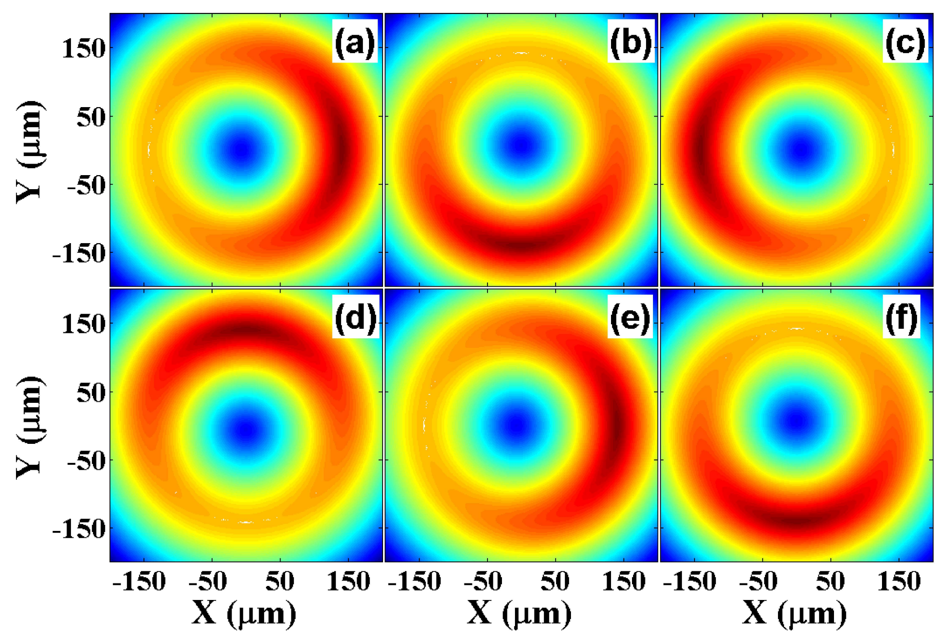


Tilted ring trap



The time-dependent potentials can also be realised with the rf-dressed potentials.

Modulation of phase of RF-field



Experimental realization of a ring trap for cold ^{87}Rb atoms

Quardrupole DC field and linearly/circularly polarized RF-field generates ring trap.
A ring has applications in the study of super-fluidity, Josephson oscillations, realization of atom gyroscope.

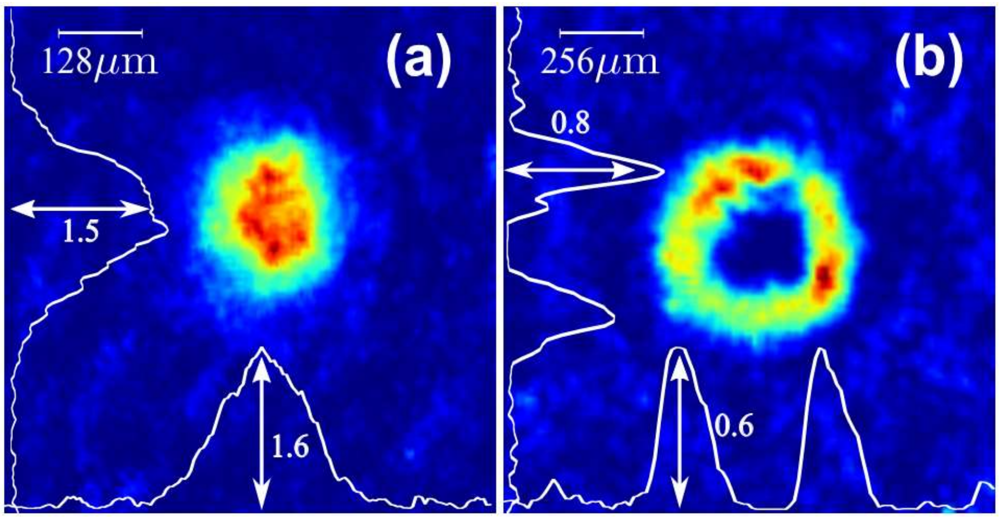


Fig.1.(a) atom cloud in qudrupole trap,
(b) atom cloud in the toroidal/ring trap.

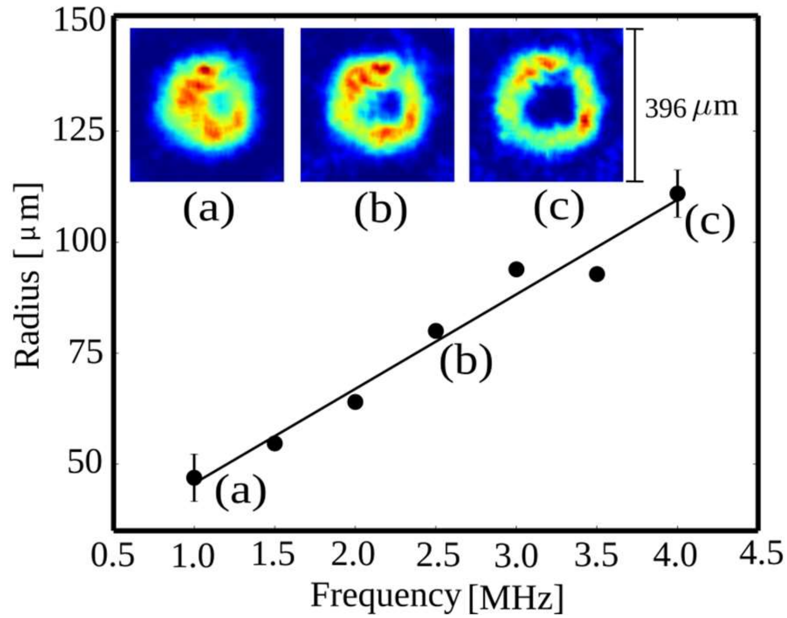


Fig.2. Vriation in radius of the trap with RF-frequency.

The RF evaporation of atoms in quarupole trap leads to temperature of ~20 μK with ~2.5×10^{5} number of atoms. Nearly 50% atoms are transferred to toroidal trap.

***Arijit et al, J. Phys. B*: At. Mol. and Opt. Phys., 49, 075304 (2016).**

Atom trapping with time averaged adiabatic potentials (TAAP)

TAAP) can be achieved by time averaging of the rf-dressed by applying the low frequency time orbiting potential (TOP) field in addition to dressing rf-field to perform the time averaging.

B(r,t)=$B^s(r) + B^{rf}(t)$ V(r)=$\hbar m_F\sqrt{\delta^2 + \Omega^2}$

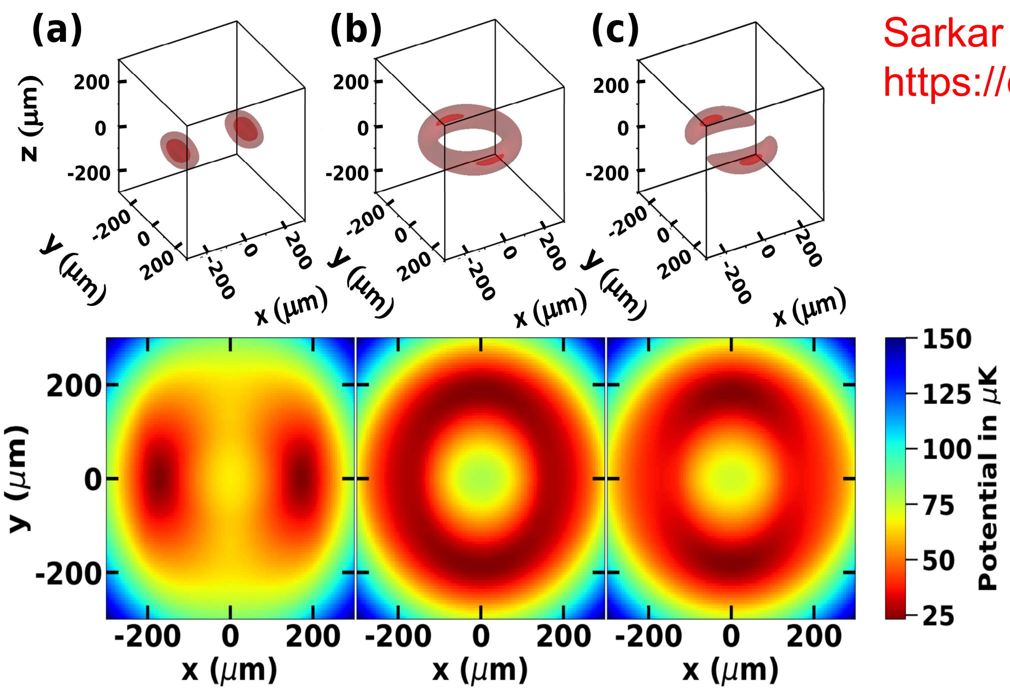
TOP Field :

$$B_T(t) = e_x B_T^x sin(\omega_T t) + e_y\, B_T^y sin(\omega_T t + \varphi_y) + e_z B_T^z sin(\omega_T t + \varphi_z)$$

(ωT) is kept larger than the frequency (ωr) of center of mass motion of the atom in quadrupole trap but smaller than the Larmor frequency.

$$V_{TAAP} = \frac{\omega_T}{2\pi}\int_0^{\omega_T} V dt$$

The versatility of TAAP scheme via time orbiting potential (TOP) fields and radio frequency (rf) fields. The conversion from one trapping geometry to another is also possible.



Sarkar et al, Eur. Phys. J. D (2021) 75:281
https://doi.org/10.1140/epjd/s10053-021-00290-6

Fig. The plots of potential (a) to (c) show the conversion of a x-direction double-well into a y-direction double-well due to change in TOP field. The upper plots in (a), (b) and (c) show the 3D view of iso-potential surfaces for different potential values 25 μK (intense red) and 35 μK (light red). The rf-field is linearly polarized in x-direction in all the plots. In plot (a), the TOP field is y-z circularly polarized (By = Bz= 1.3 G). In plots (b) and (c), the TOP field is x-z polarized with π /2 phase difference between x- and z- components. For plot (b), Bz = 1.3 G and Bx= 650 mG, and for plot (c), Bz= 1.3 G and Bx = 850 mG. The other common parameters in plots (a) to (c) are Bx rf = 700 mG, ωrf = 2π × 1.5 MHz, ωT = 2π × 7 kHz and B q = 100 G/cm.

Atom trapping on atom-chip.

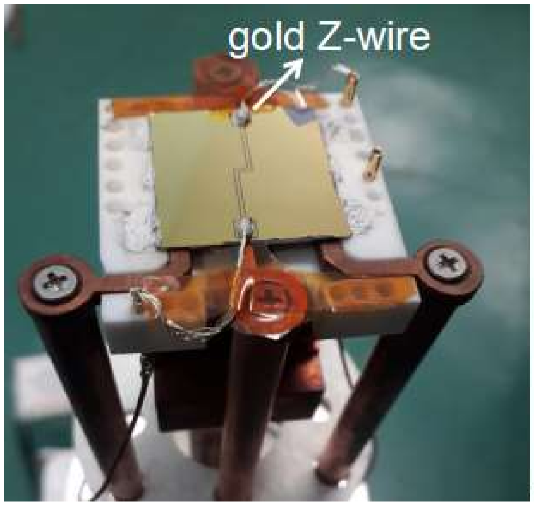
- Atom-chip trap: The trapping of laser cooled atoms in magnetic field of micro-fabricated current carrying wires on a chip.

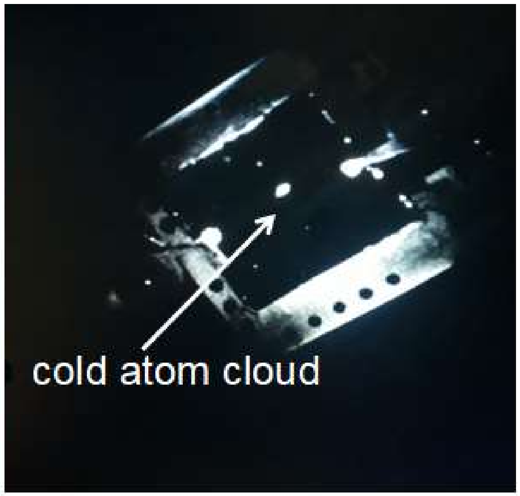
- Step towards miniaturization of atom-optic devices.

- Various sensor applications of atom-chip such magnetometer, atomic clock, gravimeter, etc are already demonstrated in other labs in the world.

Atom-chip at RRCAT.

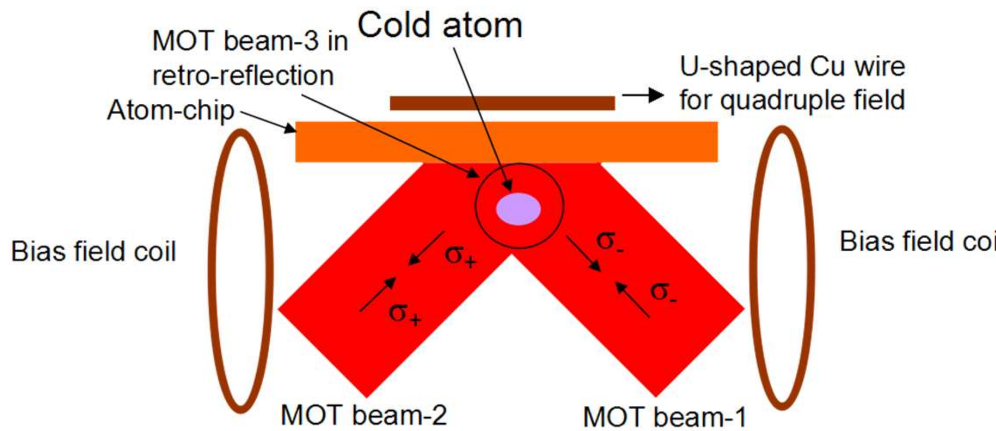
i. A magneto-optical trap (MOT) to cool Rb atoms near atom-chip.
ii. Trap these laser cooled atoms in a micro-trap of the micro-wire.



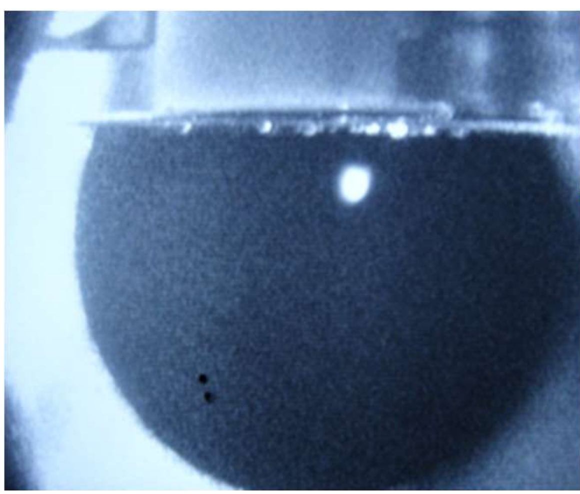


Atom-chip mounting system

Atom-chip 25 mm x 25 mm (wires in width of 200 um)



Cooling laser beam configuration for atom-chip MOT



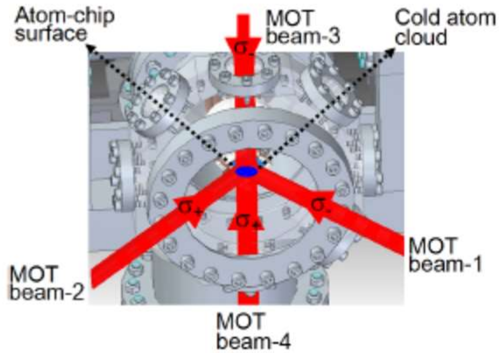
Atom chip surface

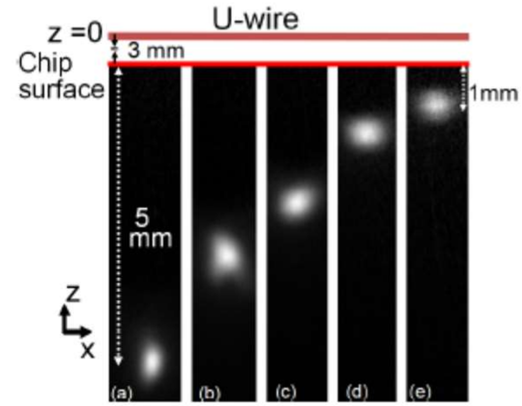
CCD image of cold atom cloud in atom-chip MOT

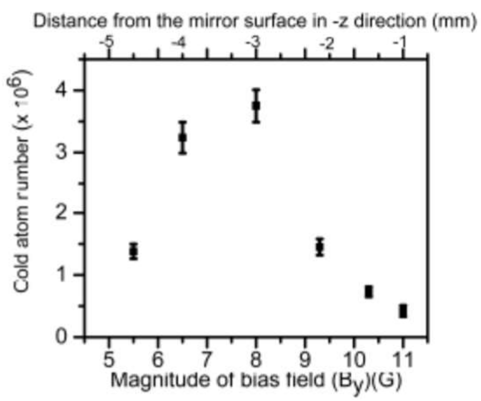
~5x10^7 ^{87}Rb atoms trapped in atom-chip MOT

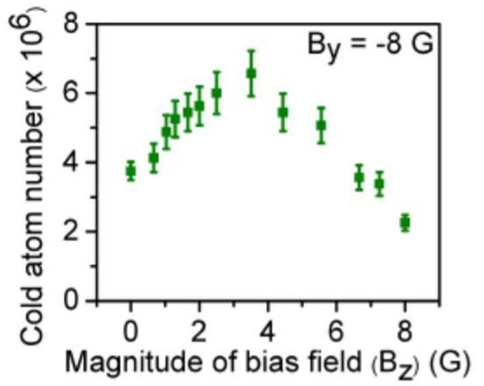
Optimization of U-MOT on atom-chip

1. Higher $B_y \Rightarrow$ Steeper gradient $\Rightarrow$ Smaller capture volume $\Rightarrow$ Tight trap $\Rightarrow$ Less number in U-MOT.
2. Lower $B_y \Rightarrow$ Smaller gradient $\Rightarrow$ Large capture volume $\Rightarrow$ Shallow trap $\Rightarrow$ Less number in U-MOT.





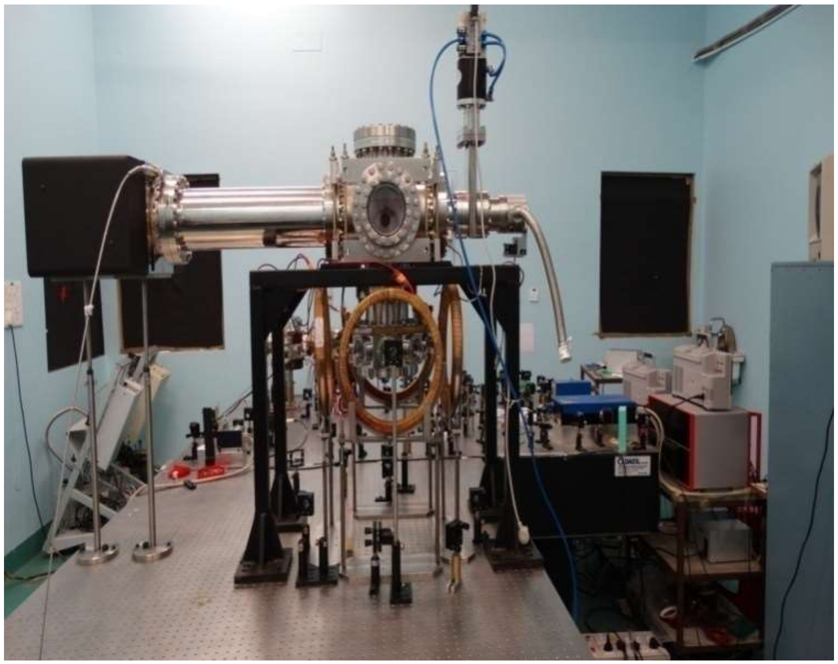




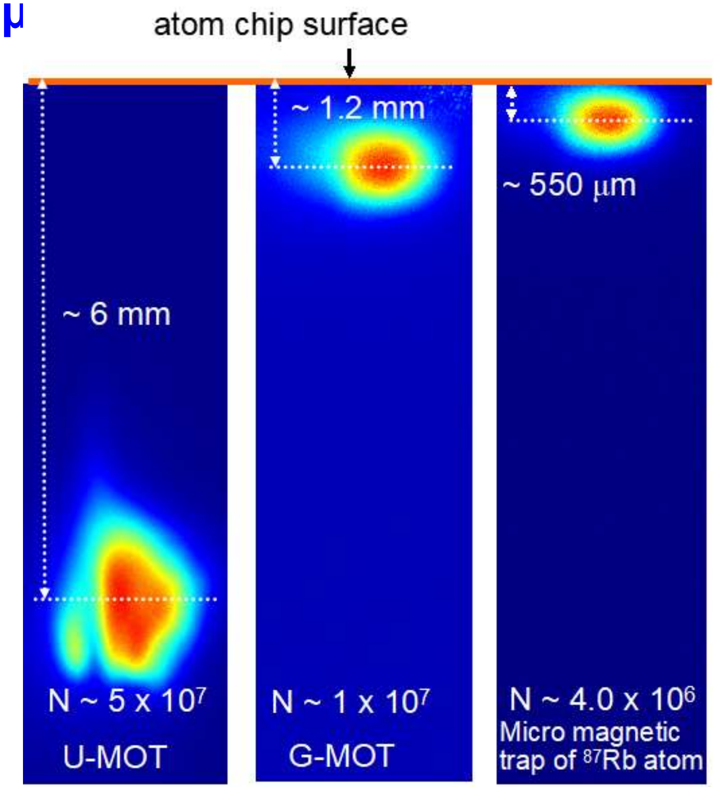
Vivek Singh et. al., J. Mod. Opt. (2018).

Atom-chip trap at RRCAT

Laser cooled Rb atoms have been trapped in micro magnetic trap of on atom-chip. The trap was formed by flowing a current (~2 A) in a Z-shaped gold micro-wire on atom-chip (cross-section : 200 μm x 2.5 μ



(a)



(b)

Fig: (a) Photograph of atom-chip setup, (b) CCD images of atom cloud on chip.

This atom-chip trap is first of its kind working in the country.

cold atoms Quantum Sensors work at RRCAT:

- *Cold atom gravimeter .*
- *Cold atoms vacuum Standards*

1.Cold atom gravimeter

Interest in sensitive measurement of position and time dependent Earth's gravity (g) is for getting information about :

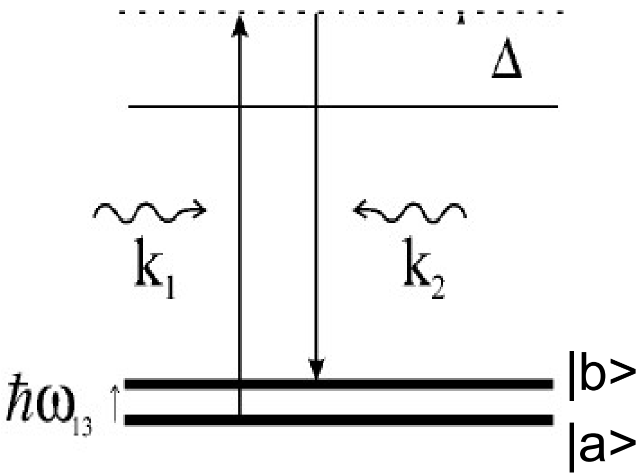
- **underground minerals, oil and gas fields.**
- **Underground structures, bunkers, etc.**
- **Seismic activities.**
- **Measurement of gravity tensor for general relativity.**

Cold atom gravimeters, based on atom interferometry, can provide measurement of "g" with accuracy 2 - 5 μ.gal.

(1 μ.gal= 10^{-8} m/s^2)

Presently, this is comparable or better than accuracy of state-of-art gravimeter available commercially (like falling mirror).

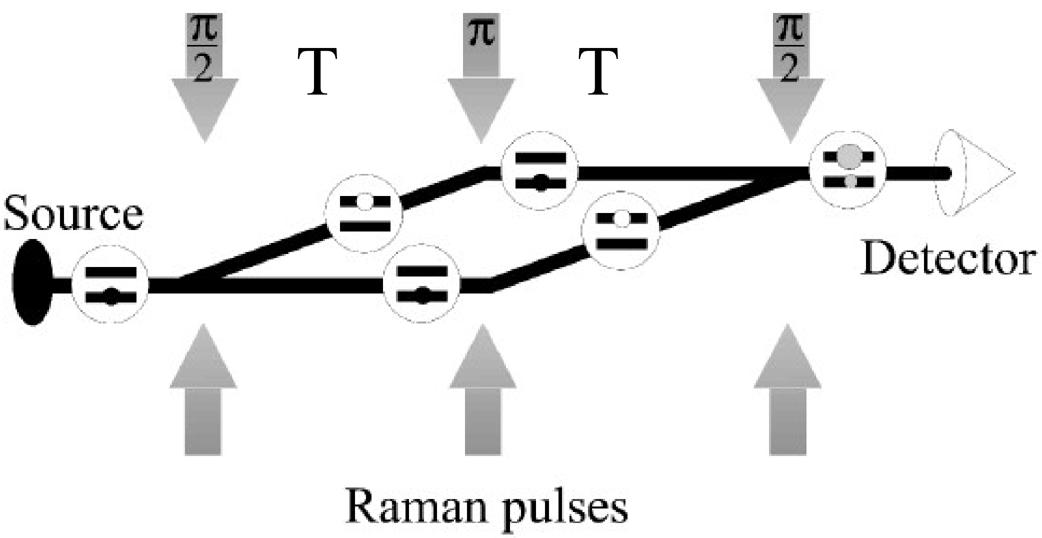
Working Principle : Raman pulse Mach-Zehnder atom interferometer



Stimulated Raman transition between |a> & |b> while atoms are moving under influence of g .

Atomic Fountain Geometry.

Time 2T is for evolution of atoms under gravitational acceleration.



"g" is measured by measuring number of atoms in state |b>.

Measurement of "g"

At the end of excitation pulses:

Population probability in $|a> = \frac{1}{2}(1+\cos(\Delta\phi))$

Population probability in $|b> = \frac{1}{2}(1-\cos(\Delta\phi))$

$$\Delta\phi = \Delta\phi_{light} = k_{eff}\, g T^2, k_{eff} = 2k$$

Gravimeter setup at RRCAT

Cold Rb atom based Gravimeter work is in progress.
MOT is working in [1,1,1] geometry.
Fountain is working . Raman beams are being set for measurement.

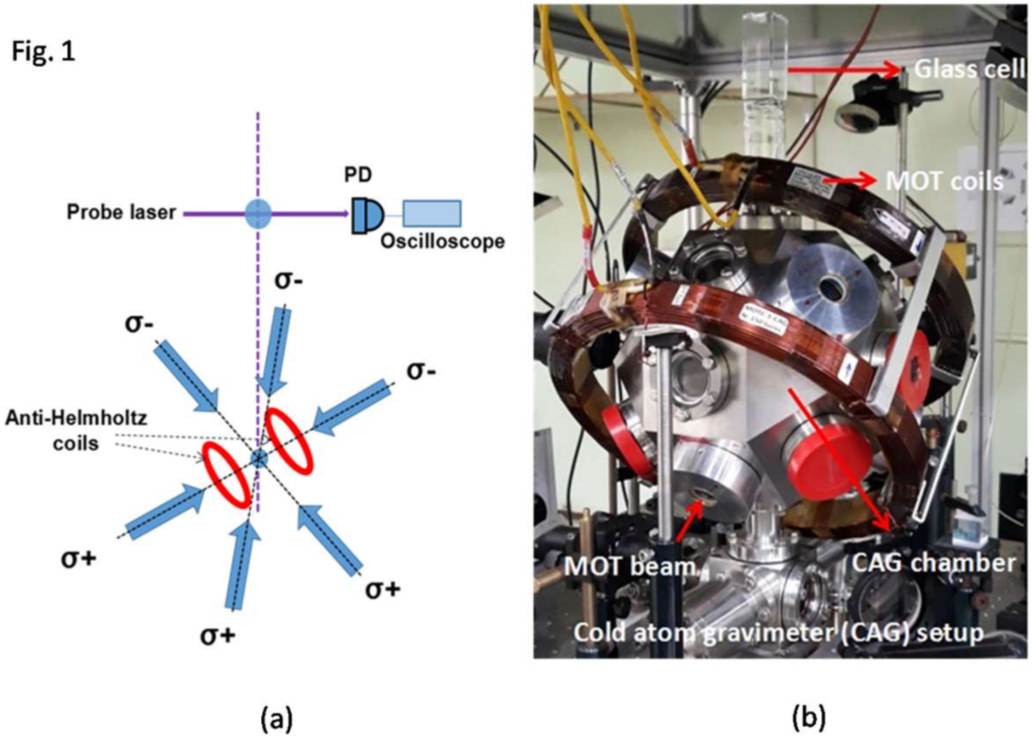


Fig.1: Schematic and photograph of setup

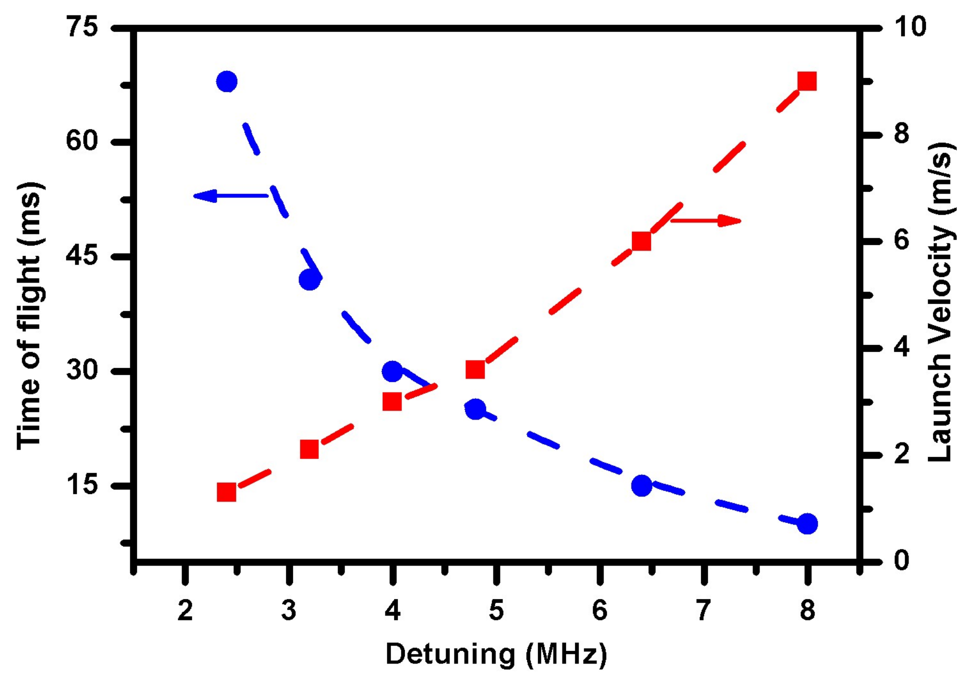


Fig.2:Launch velocity and TOF as function of detuning in molasses during launch of atoms.

2. Cold atom based UHV pressure Sensor

$$N(t) = N_s[1 - \exp(-t/\tau_L)]$$

$$N_s = R\tau_L = \alpha P_{Rb}\tau_L$$

$$\tau_L = \frac{1}{\beta P_{Rb} + \gamma_b}$$

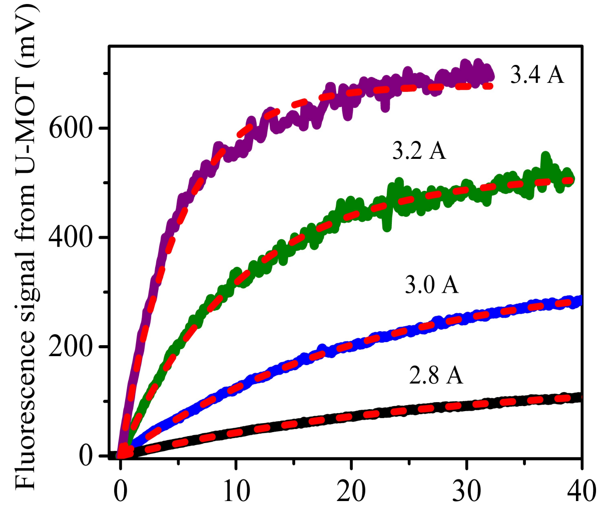
γ_b represents the collisional loss rate due to background non-Rb atoms/molecules

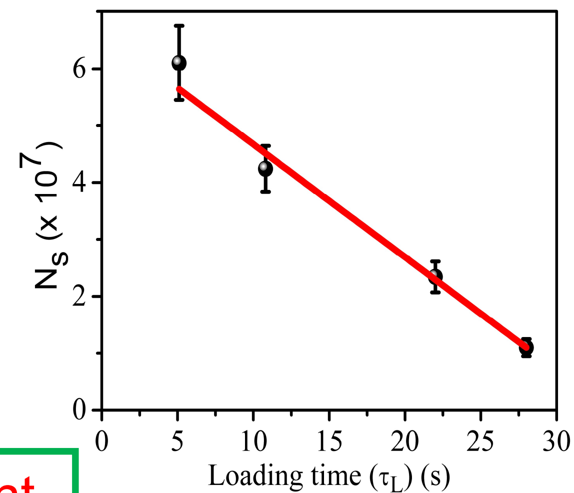
$$Ns = \frac{\alpha}{\beta}(1 - \gamma_b \tau_L)$$

$\alpha/\beta = (6.65 \pm 0.30) \times 10^7$ $\gamma_b = (2.90 \pm 0.06) \times 10^{-2}\ s^{-1}$

$\beta = 4.4 \times 10^7\ Torr^{-1}\ s^{-1}$ $P_{Rb} = N_s/\alpha\tau_L$

$P = \gamma_b / 4.9 \times 10^7$





$P = 5.9 \times 10^{-10}$ Torr

$P_{Rb} = 1.4 \times 10^{-10}$ Torr at 2.8 A getter current
$= 4 \times 10^{-9}$ Torr at 3.4 A getter current

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Work is in progress at RRCAT for compact and portable device.

Summary:

•Work is in progress for development of Cold Rb atom based high precision gravimeter for measurement of g with high accuracy (10-50 μGal, 1 μGal = 1×10^{-8} m/s^2). Applications exist in mineral exploration, study of seismic and tidal activity, other geo-sciences and space applications, etc.

•Cold Rb atoms based UHV pressure sensor is a quantum sensor (pressure range 10^{-8} to 10^{-10} Torr). Proof of principle demonstrated. Lower pressure range towards XHV side (10^{-12} Torr) can be covered with Li trapped in the magnetic trap. It can provide accuracy better than existing gauges. NIST at JILA, Colorado calls it quantum physics based “vacuum standard”.

Some Representative Publications related to activities

- "Enhanced atom transfer in a double magneto-optical trap set-up", S. R. Mishra, S. P. Ram, S. K. Twari, and S. C. Mehendale*, Phys. Rev. A 77 (6), 065402 (2008).*
- "A comparison of pulsed and continuous atom transfer between two magneto-optical traps", S. P. Ram, S. K. Tiwari, S. R. Mishra; *Journal of the Korean Physical Society, 57 (5), 1303 (2010).*
- "Investigation of atom transfer using a red-detuned push beam in a double magneto-optical trap setup", S. P. Ram, S. R. Mishra, S. K. Tiwari, and S. C. Mehendale, *Review of Scientific Instruments, 82, 126108 (2011).*
- "Detection of state-manipulated population in ^{87}Rb-MOT by absorption probe imaging", S K Tiwari, S P Ram and S R Mishra, Poster presented in *Topical Conference on Atomic Molecular and Optical Physics (TC-2010)*, 3-6 March 2010, RRCAT, Indore.
- "Magnetic trapping of laser cooled ^{87}Rb atoms in a Quadrupole-Ioffe configuration trap with a metal core Ioffe coil", S P Ram, S K Tiwari and S R Mishra, Proc. DAE-BRNS National Laser Symposium (NLS-20), Jan 9-12, 2012, Anna University, Chennai.
- S. Singh, et al, J. Phys. B : Atomic Molecular and Opt. Physics, 48, 175302 (2015).
- A Chakraborty et al, J. Phys. B : Atomic Molecular and Opt. Physics, 49, 075304 (2016).
- S R Mishra, et al, *Pramana* J. Physics, 88, April 2017.
- V Singh, V B Tiwari, S R Mishra, Laser Phys. Lett. 17, (2020), 035501.
- S. Sarkar et al , Eur. Phys. J. D (2021) 75:281, https://doi.org/10.1140/epjd/s10053-021-00290-6

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