Bose–Einstein condensation in an electro-pneumatically transformed quadrupole-Ioffe magnetic trap

Sunil Kumar¹, Sumit Sarkar¹, Gunjan Verma¹, Chetan Vishwakarma¹, Md Noaman¹ ² and Umakant Rapol¹

¹ Department of Physics, Indian Institute of Science Education and Research, Pune 411008, Maharashtra, India
² Present address: Institut für Physik, Johannes Gutenberg–Universität, D 55099 Mainz — Germany
E-mail: umakant.rapol@iiserpune.ac.in

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Abstract
We report a novel approach for preparing a Bose–Einstein condensate (BEC) of ⁸⁷Rb atoms using an electro-pneumatically driven transfer of atoms into a quadrupole-Ioffe magnetic trap (QUIC trap). More than 5 × 10⁸ atoms from a magneto-optical trap are loaded into a spherical quadrupole trap and then transferred into an Ioffe trap by moving the Ioffe coil towards the center of the quadrupole coil thereby changing the distance between the quadrupole trap center and the Ioffe coil. The transfer efficiency is more than 80%. This approach is different from the conventional approach of loading the atoms into a QUIC trap wherein the spherical quadrupole trap is transformed into a QUIC trap by changing the currents in the quadrupole and the Ioffe coils. The phase space density is then increased by forced rf evaporative cooling to achieve Bose–Einstein condensation of more than 10⁵ atoms.

1. Introduction
The first experimental demonstration of Bose–Einstein condensation in alkali atoms [1–3] led to a rapid growth of research in the area of ultracold quantum gases. It has given a completely new insight into the study of quantum matter at ultralow temperatures and opened up a new experimental test-bed for the study of condensed matter systems. It has provided the ability to emulate real-life condensed matter systems to gain new insights into superconductivity and superfluidity. Bose–Einstein condensates (BECs) subjected to periodic [4, 5] and disordered optical potentials [6–8] are some examples of quantum emulators. In addition, extreme control of these systems through light–matter interaction has enabled the creation and study of artificial gauge potentials [9, 10] and provided a path towards understanding new materials like topological insulators and the simulation of lattice gauge theories in high energy physics [11, 12].

Development of robust and yet simple experimental systems for routine production of BECs is always a challenge during the design phase. It often involves a trade-off between optical, mechanical and control systems complexities and modularity when attempting to achieve the desired scientific goals. The final challenge is the design of the trap. Driven again by the scientific goals, one chooses between a magnetic trap [13], all-optical trap [14] or a combined optical–magnetic trap [15]. Historically, different variants of the magnetic trap have been used.

The Ioffe–Pritchard (IP) trap [13, 16, 17] gives higher axial and radial trapping frequencies as compared to the time-averaged orbiting potential (TOP) trap [18] and has been widely used in the initial period after the demonstration of the BEC. IP traps have certain disadvantages such as the mode matching of spatially separated center of magneto-optical trap (MOT) with the center of magnetic trap, limited optical access to the trapping region and large power dissipation with relatively complex electronic control circuits for switching the magnetic trap. The advent of a modified quadrupole-Ioffe trap (QUIC) [16] solved the problem of mode matching and in addition had a simplified design consisting of only three coils (the two quadrupole coils and a third Ioffe coil having its axis perpendicular to the axis of the quadrupole coils). This scheme involves independent control of currents through the quadrupole and Ioffe coil. In addition, the geometrical design of the Ioffe coil in the QUIC...
trap has to be such that it does not obstruct the MOT laser beams in some cases. This poses some limitations in obtaining the desired trapping frequencies.

In this paper, we report a novel scheme of loading atoms into the QUIC trap, wherein atoms trapped in a spherical-quadrupole magnetic trap are transferred into a quadrupole-Ioffe (QUIC) trap by mechanically translating the Ioffe coil. The currents in the Ioffe and the quadrupole coils are left unchanged during this transfer process. The mechanical transfer of atoms by moving the magnetic trap center in space has been successfully achieved in the past for transferring atoms from a low vacuum region to an ultra-high vacuum region. The transfer of magnetically trapped atoms was first demonstrated by Greiner et al [19] by using a chain of quadrupole coils, in which the atoms were moved up to 330 mm from a low vacuum MOT loading region to an ultra-high vacuum region where the quadrupole magnetic field is converted to an Ioffe-type magnetic field using QUIC trap geometry. The center of the magnetic trap is moved in space by electronically changing the currents in a series of quadrupole coils in a synchronized manner. In another method, quadrupole coils were mounted on a linear actuator which is driven by a servo motor [20, 21]. The atoms are transported up to 550 mm to reach the ultra-high vacuum region in an IP type of trapping potential [20, 21].

In our trap, atoms are mechanically transferred from a purely quadrupole trap into a QUIC trap by moving the Ioffe coil towards the quadrupole trap center. In the original proposal of this trap [16], the quadrupole coils and the Ioffe coil are mechanically fixed around a glass cell and the atoms are transferred from the quadrupole trap into the QUIC trap by changing the current in the Ioffe coil. For the given geometrical constraints of the glass cell and to give clearance to the MOT beams, the Ioffe coil has to have a tapered design in many cases. This geometry tends to limit the achievable trapping frequencies for larger glass cells. In our case the cross section size of the quartz cell is 39 mm × 39 mm compared to a 30 mm × 30 mm glass cell in [16]. The geometrical constraints posed by the size of our quartz cell (39 mm × 39 mm) became critical in designing the Ioffe coil with desirable trap frequencies. Hence, we had to choose a non conical shaped Ioffe coil. If this non-conical Ioffe coil is mechanically fixed, it would obstruct the MOT laser beams during the loading of atoms in the MOT. We have solved the problem of the obstruction of the MOT beams by mechanically moving the coil out of the MOT beams during loading of the atoms into the MOT and moving the coil during loading into the magnetic trap. The transfer mechanism of the atoms is purely based on the distance between the center of the quadrupole coils and the Ioffe coil. This transfer does not depend on the control of currents in the Ioffe and quadrupole coils. In previous QUIC traps, when the atoms are transferred in the quadrupole trap, the current in the quadrupole coil is held fixed. Then, the current in the Ioffe coil is ramped up to transfer the atoms into the harmonic potential created by all three coils. After the atoms are transferred into the QUIC trap, the three coils are electrically connected in a series mode, so that there are no relative current fluctuations in the three coils. The mechanical movement demonstrated in this work achieves three goals: (a) it allows the use of larger glass cells while providing clearance for larger MOT beams, (b) it allows the use of a single power supply for driving the magnetic trap coils, thus simplifying the electronic control system for the magnetic trap and (c) it potentially allows the design of a QUIC trap with larger trap frequencies.

2. Experimental details

Our experimental setup consists of three sections: (a) a Rb effusion source, (b) a decreasing field Zeeman slower and (c) a rectangular quartz cell. The Rb effusion source and Zeeman slower designs are adapted from [15] with some modifications. A 75 s⁻¹ ion pump is used to pump the Rb effusion source region, two 150 s⁻¹ ion pumps are used before and after the Zeeman slower for pumping. In addition, there are two Ti sublimator pumps along with two 150 s⁻¹ pumps and a non-evaporable Getter (NEG) pump near the quartz cell. An atomic beam emanating from the Zeeman slower is used to load the MOT in the quartz cell. The MOT beams are orthogonal to each other and are incident at 45° to the cell. We load about 1 × 10⁸ ⁸⁷Rb atoms in about 35 s time. The magnetic field for the MOT and the quadrupole magnetic trap is generated by a pair of anti-Helmholtz coils. Each of the two anti-Helmholtz coils of the quadrupole trap is made of 15 layers with 19 turns in each layer wound with 1 AWG enameled magnet wire. Each layer is separated by 1 mm thick spacers. The anti-Helmholtz coils produce a magnetic field gradient of 13 G cm⁻¹ A⁻¹ in the axial direction. During the loading of the atoms in the MOT, the field gradient of the quadrupole coils is ~13 G cm⁻¹ and the detuning of the cooling beams is 2Γ from the ⁵⁴⁴S₁₂ (F = 2) → ⁵⁴⁴P₁₂ (F' = 3) state, where Γ = 6.1 MHz is the linewidth of the excited state. The laser beams have a 1/e² diameter of 22 mm with an intensity of about 3 times the saturation intensity of the ⁵⁴⁴S₁₂ (F = 2) → ⁵⁴⁴P₁₂ (F' = 3) transition. As mentioned earlier, during the entire loading sequence of the atoms, the quadrupole coils, Ioffe coils and the bias coils are connected in series. It has been seen that there is no appreciable effect on the nature of loading of the atoms in the MOT when the Ioffe and bias coils are disconnected. This is due to the fact that the shift in the center of the quadrupole field is less than 0.5 mm, which is negligible in comparison to the size of the cloud (~8 mm). Atoms are then compressed in the compressed-
MOT stage by increasing the detuning to $-4\Gamma$ while reducing the intensity to one tenth of the saturation intensity. Atoms are subjected to a polarization gradient cooling stage for 4 ms where the magnetic field is turned off while the detuning is ramped to $-8\Gamma$ and the intensity of the MOT beams is kept unchanged from the previous stage. At this stage we have about $8 \times 10^8$ atoms in the trap at a temperature of $\sim 30 \mu K$. Atoms are then optically pumped into the $5^2\!\!S_{1/2}, F = 2, m_f = 2$ state by applying a 250 $\mu$s pulse of circularly polarized laser driving the $5^2\!\!S_{1/2}(F = 2) \rightarrow 5^2\!\!P_{3/2}(F = 3)$ transition in the presence of a small bias magnetic field in the $z$-direction. By rapidly turning on the quadrupole magnetic field to 91 G cm$^{-1}$ in less than 2 ms we capture more than $5 \times 10^8$ in the purely spherical quadrupole magnetic trap. The temperature in the magnetic trap at this stage is a little over 500 $\mu K$. Atoms are then compressed adiabatically in 1500 ms from a 91 G cm$^{-1}$ to a 325 G cm$^{-1}$ magnetic field gradient and transferred into the modified QUIC trap.

Figure 1 shows the schematic diagram of our modified QUIC trap. This trap consists of two quadrupole coils in anti-Helmholtz configuration and a Ioffe coil mounted on a pneumatically actuated translator. We use a single DC power supply (Delta Elektronika Model SM60–100) for controlling the current and a single IGBT (Make EUPEC, model no BSM300GB120DLC) for switching the current through all the coils. The pneumatic translator is a commercially available product (Festo, model no. SLT-16–40-P-A) that provides a total translation of 40 mm. The translator is a two position translator that is guaranteed to give a positioning repeatability of $\pm 20 \mu m$. The position verses time profile of the translator is shown in the inset of figure 1. The applied air pressure is about 4 bar. The peak forward and reverse speed of the translator can be controlled by a pair of flow control valves. The Ioffe coil has 7 layers with 20 turns in each layer. Each of the two bias coils is made by winding 15 turns of insulated copper tubing of 3 mm OD and 2 mm ID. The bias coils generate a constant field of 0.84 G A$^{-1}$. The distance between the bias coils is 180 mm. All the coils except the bias field generating coils are enclosed in watertight Polyoxymethylene plastic assemblies and cold water is circulated to remove heat generated during the operation of the trap. In figure 2, we show the numerical simulation of the magnitude of the magnetic field along the axis of the Ioffe coil for different distances between the Ioffe coil and the center of the quadrupole coils for a current of 25 A passing through all the coils simultaneously, including the bias coils. When the Ioffe coil
is about 45 mm away from the axis of the quadrupole coils, the effect of the magnetic field created by the Ioffe coil is negligible. As the Ioffe coil moves closer to the quadrupole coil axis, a double minima in the magnetic potential starts appearing and the two minima merge at a distance of 23 mm.

After this stage, the pneumatic translator is triggered to initiate the translation of the Ioffe coil. Within less than 1 s the Ioffe coil reaches its final position where it almost touches the quartz cell. As shown in figure 2, as the coil keeps moving towards the center of the quadrupole trap, at a certain distance two minima appear in the magnetic trapping potential and then they finally merge when the coil reaches its end position. We have captured the transfer process of atoms in the QUIC trap by turning off the magnetic field at different stages of the position of the Ioffe coil. Figure 3 shows the absorption images of the atoms during the transfer process.

3. Results and discussion

In our experiment, we transfer more than 80% atoms from the spherical quadrupole trap into the Ioffe trap. A systematic study of the transfer efficiency of the atoms into the Ioffe trap as a function of the speed of translation of the Ioffe coil has been performed. Data in figure 4 show that there is a gradual increase in the transfer efficiency (up to 85%) of the atoms for peak speeds up to 80 mm s$^{-1}$ and then the efficiency drops a little. However, the range of efficiencies is limited to a narrow range between 75 and 85%. This experiment has been performed only in the available range of speeds that could be accessed by controlling the flow rate of the entrance valve of the pneumatic translator while keeping a constant pressure of 4 bar. We also observe that the rise in temperature does not change significantly (see figure 4) to affect the forced evaporative cooling process in the later stages. The QUIC trap used in our setup has a radial frequency of 2$\pi \times 140$ Hz and axial frequency of 2$\pi \times 21$ Hz which have been measured by perturbing the cloud of cold atoms. The bias field is $\sim 1$ G. The measured axial field gradient of the trap is 325 G cm$^{-1}$ and the estimated axial field curvature is 196 G cm$^{-2}$. Rf evaporation cooling is performed to further cool the atoms in the Ioffe trap by rf-induced spin flips. The rf frequency is swept
from 40 MHz to 1.919 MHz over a time period of 16.4 s in different linear stages. After evaporation, the thermalized cloud is probed by using an absorption imaging system which consists of single lens geometry and an EMCCD camera with a magnification factor of 1.0(1). Cooled atoms are released from the trap by switching off the magnetic trap. After the atoms expand ballistically, a near-resonant laser pulse of 40 μs is illuminated on the expanding cloud and the shadow is imaged onto the camera. The number density, temperature and the total number of atoms in the atomic cloud are calculated by analyzing these absorption images. When the rf frequency is lowered below 1.94 MHz, a sudden appearance of bimodal distribution is observed in the time of flight images shown in figure 5, which is the signature of a BEC phase transition. The estimated number of atoms in the BEC is $3.5(4) \times 10^5$. The instability of the bottom of the trap is below 3 mG measured over a period of couple of hours, proving the usability of this design.
4. Conclusions

In conclusion, we have demonstrated a novel method of loading atoms into a QUIC trap for the production of a Bose–Einstein condensate. Atoms are first loaded into a pure quadrupole trap after which they are transferred into an Ioffe trap by changing the position of the Ioffe coil. This transfer mechanism simplifies the electronics and delivers an added advantage of optimizing magnetic trap parameters while providing the freedom to choose larger MOT laser beams. This design allows for the use of only a single DC power supply and a single IGBT switch for all three magnetic field generating coils (anti-Helmholtz coils, bias coils and Ioffe coils) whereas, in previously used QUIC traps, there are at least two DC power supplies and more than three IGBT switches. The design of our trap geometry allows better optical access during loading in the MOT. This scheme enables the design of stiffer magnetic traps for faster production of BEC.

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