Three-wire magnetic trap for direct forced evaporative cooling

Shengwang Du[1,*] and Eun Oh[2]
[1]*Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*
[2]*U.S. Naval Research Laboratory, Remote Sensing Division, Washington, D.C. 20375, USA*
(Received 24 September 2008; published 8 January 2009)

We propose a simple three-wire-based magnetic trap potential for direct forced evaporative cooling of neutral atoms without using induced spin-flip technologies. We have devised a method for controlling the trap depth without sacrificing its frequencies by only varying wire currents and external magnetic fields. By having multiples of these wires on different levels integrated into an atom chip, it is possible to attain Bose-Einstein condensation without the conventional forced evaporation technique.

DOI: 10.1103/PhysRevA.79.013407 PACS number(s): 37.10.Gh, 37.10.De, 03.75.Be, 85.85.+j

Traditionally, forced evaporative cooling has been the only way to achieve gaseous Bose-Einstein condensates (BECs). To maintain high cooling and collision rates, an efficient forced evaporation requires continuous rampdown of the trap depth without reducing the trap tightness. A main drawback in a conventional magnetic trap with external coils is that varying coil current also changes trap frequencies. Thus, spin flip induced by radio-frequency (rf) radiation has been a standard method for obtaining BECs in magnetic traps [1–3]. Recently, surface-induced evaporation by moving the magnetic trap toward a flat surface has been reported [4]. In an optical dipole trap, evaporative cooling is realized by reducing the laser power to lower the trap depth, which, however, often leads to a weaker confinement [5,6].

Motivation for this work comes from the rapidly developing field of atom chips, which integrate atom traps and waveguides using lithographically patterned wires (or magnets) on a substrate [7–18,22]. Atom chips provide an attractive way to manipulate ultracold atoms within a very small volume. Moreover, the magnetic fields generated from patterned wires on the chip overcome the limits (such as trap frequencies) of the conventional coil configuration with significantly less current. For a comprehensive review on chip microtrap design, several references can be found in [14–17]. However, even chip-based BEC production still utilizes rf- or surface-induced evaporation.

In this paper, we propose and design a simple wire-based magnetic trap for direct forced evaporative cooling without involving any spin-flip technology. In such a trap, the potential depth and frequencies can be controlled independently by adjusting wire currents and external bias fields. As a specific application to direct forced evaporative cooling, we show that the trap frequencies can stay nearly constant while the trap depth is decreased. The design is immediately suitable for incorporation into an atom chip.

The H-wire pattern of the proposed magnetic trap is shown in Fig. 1. It is an Ioffe-Pritchard- (IP-) type trap, similar to the widely used Z-wire trap [13,14]. The transverse (y-z) confinement is obtained by the x-directional wire with current I_0 and the y-directional external bias magnetic field B_{y0}. The two wires along the y direction with a separation of d carry the same current I_1 and contribute to the longitudinal weak confinement. The x-directional external magnetic bias field B_{x0}, which affects the transverse trap frequencies at the center, is also used to adjust the trap potential bottom to reduce spin-flip loss. The x-directional wire has length L_0, and the two y-directional wires have length L_1. All three wires have the same width (w) and height (h) for simplification.

Before proceeding with numerical simulation with real dimensions, it is instructive to study the ideal wires (without height and width) for insight into trap manipulations. The trap distance z_0 from the wire surface can be determined from the x-directional current I_0 and the y-bias field B_{y0}:

$$z_0 = \frac{\mu_0 I_0}{2\pi B_{y0}}, \tag{1}$$

where μ_0 is the vacuum magnetic constant. One can show that the transverse magnetic quadrupole field gradient in the y-z plane can be expressed simply as

$$B'_\perp \equiv \left|\frac{\partial B}{\partial z}\right|_{z_0} = \frac{B_{y0}}{z_0} = \frac{2\pi B_{y0}^2}{\mu_0 I_0}. \tag{2}$$

In the longitudinal direction along the x axis, the magnetic field forms a harmoniclike potential with a second-order derivative:

$$B''_\parallel \equiv \left|\frac{\partial^2 B}{\partial x^2}\right|_{x=0} = B_{y0}\frac{I_1}{I_0}\frac{4z_0^2[3(d/2)^2 - z_0^2]}{[(d/2)^2 + z_0^2]^3} \xrightarrow{z_0 \ll d} \frac{12 B_{y0} I_1 z_0^2}{I_0 (d/2)^4}. \tag{3}$$

At the trap center $(0,0,z_0)$, the magnetic field is along the x direction with a magnitude of

$$B_0 = B_{x0} + 2B_{y0}\frac{I_1}{I_0}\frac{z_0^2}{(d/2)^2 + z_0^2} \xrightarrow{z_0 \ll d} B_{x0} + 2B_{y0}\frac{I_1}{I_0}\frac{z_0^2}{(d/2)^2}. \tag{4}$$

Equations (1)–(4) characterize the IP potential near the trap center [19,20]. The trap depth is determined by the external bias field $(B_{x0}, B_{y0}, 0)$:

*dusw@ust.hk

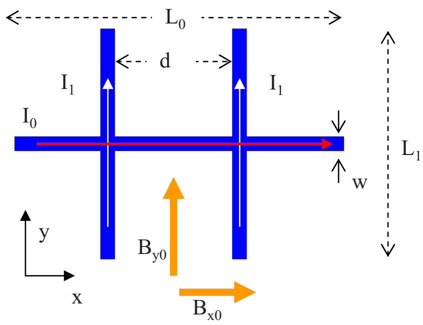

FIG. 1. (Color online) Schematic of a H-wire trap pattern design in a two-dimensional plane accompanied with external bias magnetic fields (B_{x0},B_{y0}). The x-directional wire with a length of L_0 carries the same current I_0. The two y-directional wires with a length of L_1 and separation of d carry the current I_1. All the wires have the same width of W and height of h (not shown).

$$U_m = M_F g_F \mu_B \sqrt{B_{x0}^2 + B_{y0}^2}. \quad (5)$$

where M_F is the magnetic momentum number of the trapped atoms. g_F and μ_B are the Lande g factor and Bohr magneton, respectively. When the atomic temperature is comparable to the trap depth, most atoms experience linear trap slope in the transverse plane and the field gradient in Eq. (2) dominates the tightness of the trap. When the atoms are very cold and only occupy the trap center locally—e.g., ultracold atoms at the end of an evaporative cooling—they see a three-dimensional cigar-shaped nonisotropic harmonic trap with longitudinal trap frequency determined by Eq. (3) and transverse trap frequency determined by

$$B''_{\perp} \equiv \left| \frac{\partial^2 B}{\partial z^2} \right|_{z_0} = \frac{B'^2_{\perp}}{B_0} - \frac{B''_{\parallel}}{2}. \quad (6)$$

Equations (1)–(6) show it is possible to fully control all the trap parameters with wire currents and external bias fields. To show how simply the trap can be implemented for a direct forced evaporative cooling, we consider a simple case under the limitation of $z_0 \ll d$ (i.e., the atoms are trapped very close to the wire surface) and $B_{x0} \ll B_{y0}$. Compared to the tight transverse confinement, the longitudinal confinement is much weaker ($B''_{\parallel} \ll B''_{\perp}$). With the above approximations, we can maintain constant B_0 and thus get

$$B'_{\perp} \sim \frac{B_{y0}^2}{I_0}, \quad B''_{\perp} \sim B'^2_{\perp} \sim \frac{B_{y0}^4}{I_0^2},$$

$$B''_{\parallel} \sim \frac{I_0 I_1}{B_{y0}}, \quad U_m \sim B_{y0}. \quad (7)$$

Equations (7) show that the trap depth can be changed by varying the y-bias field B_{y0}. By keeping the ratio of B_{y0}^2/I_0 and $I_0 I_1/B_{y0}$ fixed, the trap gradient and frequencies remain mostly unchanged. Moreover, while decreasing the trap depth during evaporation, the trap frequencies can even be increased or decreased simply by controlling the currents and bias fields. This manipulation of trap confinement provides a novel way to control the cooling, collision, and loss rate during the forced evaporation stage of BEC. For example, during the first stage of evaporation with relatively hot atoms, the trap frequencies can be increased while the trap depth is decreased to speed up the evaporative cooling to reach so-called "runaway" evaporation. In the last stage of the evaporative-cooling near-degenerate regime, the trap frequencies can be reduced during cooling to minimize the loss caused by three-body recombination [21]. Because an IP trap can be characterized by its trap depth, bottom potential, and longitudinal and transverse frequencies, full control requires at least four parameters which are met by the H-wire trap: I_0, I_1, B_{x0}, and B_{y0}.

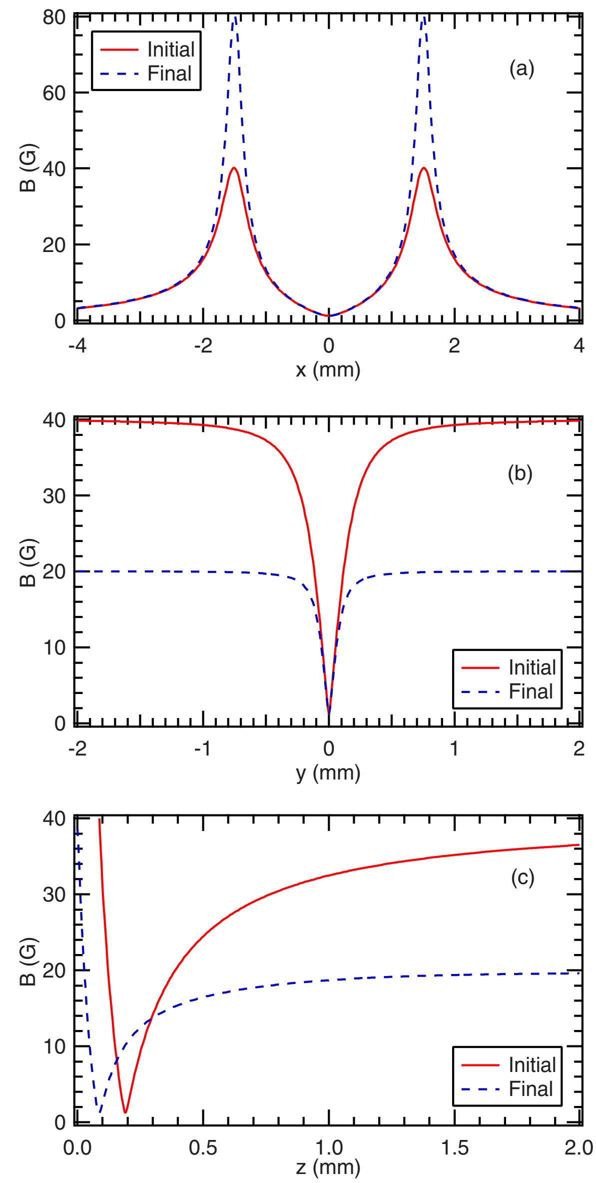

FIG. 2. (Color online) H-wire magnetic trap potential plots in all three (x, y, and z) dimensions are shown in (a), (b), and (c), respectively. The initial trap (solid, red) with trap frequencies of (24,2253,2253) Hz is obtained with the parameters $I_0=I_1=4$ A, $B_{x0}=0$, and $B_{y0}=40$ G. The final trap (dashed, blue) with trap frequencies of (17,2114,2114) Hz is obtained with the parameters $I_0=1$ A, $I_1=4$ A, $B_{x0}=0.64$ G, and $B_{y0}=20$ G.

To show, in reality, how the H-wire trap potential can be

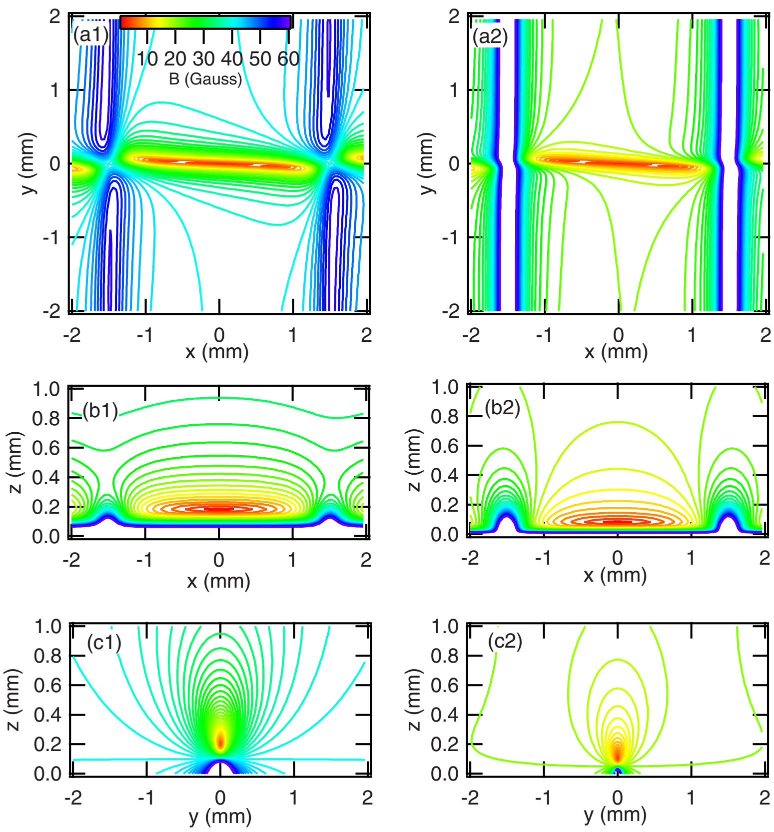

FIG. 3. (Color online) H-wire magnetic trap potential contour plots in *x*-*y*, *x*-*z*, and *y*-*z* planes with the same parameters in Fig. 2. The initial trap is shown in (a1), (b1), and (c1). The final trap is shown in (a2), (b2), and (c2).

implemented for direct forced evaporative-cooling, we perform a numerical simulation with real three-dimensional wires. All three wires have the same width $w=100$ μm and height $h=10$ μm. The *x*-directional wire (I_0) has length $L_0=10$ mm, and the two *y*-directional wires (I_1) have length $L_1=6$ mm and are separated by $d=3$ mm. To calculate trap frequencies, we consider ^{87}Rb atoms trapped at the Zeeman state $|5S_{1/2}, F=2, M_F=2\rangle$. The initial trap at $z_0=191$ μm before evaporation, obtained with currents $I_0=I_1=4$ A, and bias field $(B_{x0},B_{y0},0)=(0,40,0)$ G, has a trap depth of 40 G and trap frequencies of $(24,2253,2253)$ Hz. At the trap center, a net field of $(1.22,0,0)$ G is enough to avoid spin-flip loss. To lower down the trap depth by a factor of $1/2$, we ramp down the *y*-bias field B_{y0} from 40 to 20 G. To keep the transverse field gradient constant, the current I_0 is also ramped down from 4 to 1 A while holding the ratio B_{y0}^2/I_0 constant. The current I_1 remains at 4 A throughout. To keep the IP trap center net field B_0 constant to avoid spin-flip loss, the *x*-bias field B_{x0} increases from 0 to 0.64 G linearly respect to the *y*-bias field B_{y0}. The final trap at $z_0=87$ μm has a trap depth of 20 G and trap frequencies of $(17,2114,2114)$ Hz. Both the initial and final trap potentials along the *x*, *y*, and *z* axes are plotted in Fig. 2. Even though the potential barrier along the *x* axis increases when the atoms are moved much closer to the surface, the trap depth, determined by the lowest barrier in the trap, is indeed reduced by a factor of $1/2$. To prove that the reduction of trap depth is indeed three dimensional, we show the potential contour plots in Fig. 3. Comparing the initial trap [(a1), (b1),

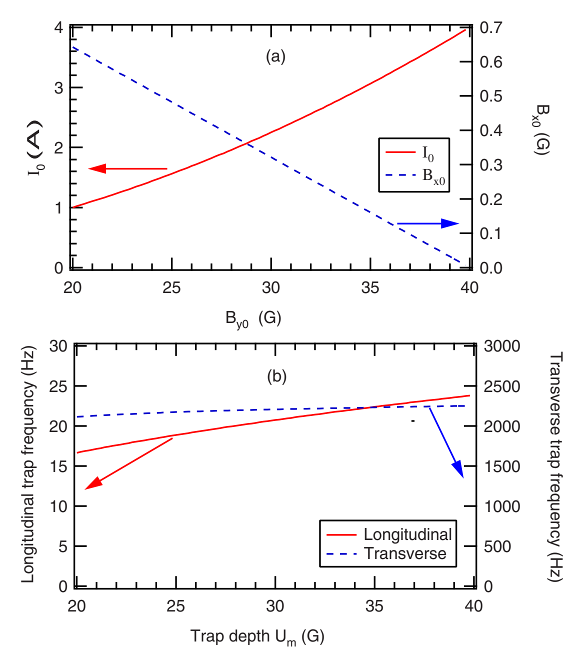

FIG. 4. (Color online) Control parameters and trap frequencies during a forced evaporation by ramping down the *y*-bias field B_{y0} from 40 to 10 G and holding $I_1=4$ A constant. (a) The current I_0 and *x*-bias field B_{x0} vs the *y*-bias field B_{y0} during evaporation. (b) The longitudinal and transverse trap frequencies vs the trap depth during evaporation.

and (c1)] with the final trap [(a2), (b2), and (c2)], in the trap center local volume, the final trap potential overlaps with the initial trap very well. It is clear that the trap depth is reduced three dimensionally and the hotter atoms can escape from the final trap efficiently. Ramping of the control parameters I_0 and B_{x0} relative to the y-bias field B_{y0} is shown in Fig. 4(a). As shown in Fig. 4(b), variation of the trap frequencies are very small while the trap depth is changed. In principle, those small variations can be further corrected by increasing the current I_1, which is held constant in the above case to avoid over heating. The H-wire trap parameters discussed here can be realized by a standard atom chip [12].

It is necessary to point out that the above-discussed design is practical with the contemporary atom chip technology. The limitation comes from the maximum current applied to the small thin microwires. In this paper, we use the same wire dimensions as the published experimental work [12] where the maximum current through a Z wire is 4 A. We have tested such an atom chip with continuously input 4 A to the same size of wire ($10\ \mathrm{mm} \times 100\ \mu\mathrm{m} \times 10\ \mu\mathrm{m}$) and find that it survived for 4 min before it was broken inside a vacuum. Due to much tight confinement (>kHz) achievable in an atom chip, evaporative cooling toward BEC can be done in a much shorter time (~ 1 s) [10–12] than conventional systems. In the discussed example, the current I_0 ramps down from 4 to 1 A, and $I_1 = 4$ A holds constant—this serves as the initial stage of the evaporation, which takes about several hundred ms. After the atoms reach their runaway evaporation stage, the currents I_1 can be decreased to <2 A to avoid overheating. Therefore, the proposed H-wire trap integrated with an atom chip for a direct forced evaporation without using rf radiation and surface-induced spin flip is practical.

We do point out that there is also a limitation of the above discussed single H-wire trap. For an initial trap, a larger trap volume and depth ($\sim$mK), which require larger currents and thus larger wire dimensions, are necessary for efficiently loading atoms from precooled sources, such as a magneto-optical trap (MOT). However, a final trap toward BEC production with smaller trap volume and depth ($<\mu$K), while keeping the same trap frequencies, requires a much smaller wire dimensions. Therefore, a full range of direct forced evaporative cooling is not practically achieved by a single H-wire trap. An improved direct forced evaporation should contain multilayer H-shaped wires with different wire sizes to match different requirements at MOT and BEC stages. Such a configuration is mainly an engineering feat which is feasible in multilayer chip technology today.

Another more attractive application of such a H-wire trap may be to combine it with the rf forced evaporation technique. In this case, direct forced evaporation serves as an initial cooling stage before applying rf radiation which can start from a much lower rf frequency. This dramatically simplifies the rf circuit and reduces rf power consumption—furthermore, a conventional function generator may be enough to satisfy the evaporation requirement at the final stages of attaining BEC. This in turn simplifies the experiment with less complexities in a BEC system.

In summary, we have proposed a H-wire magnetic trap configuration for direct forced evaporative cooling of neutral atoms without involving induced spin-flip technologies, such as rf radiation and external flat surfaces. We show it is possible to control the trap depth with only a very small variation of trap frequencies by varying wire currents and external bias fields in a very simple way. An improved cooling strategy involving several H wires with different dimensions is also discussed. Its application includes simplifying BEC on-atom-chip production and simplifying rf evaporation by serving as an initial cooling.

We would like to thank D. Z. Anderson and C. Sackett for helpful discussions. E.O. would like to thank G. Bartman for helpful comments on the manuscript. E.O. was supported by the Office of Naval Research. The work was supported by startup funds from the Department of Physics, The Hong Kong University of Science and Technology, Hong Kong, China.

[1] M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman, and E. A. Cornell, Science **269**, 198 (1995).
[2] K. B. Davis, M.-O. Mewes, M. R. Andrews, N. J. van Druten, D. S. Durfee, D. M. Kurn, and W. Ketterle, Phys. Rev. Lett. **75**, 3969 (1995).
[3] K. B. Davis, M. O. Mewes, M. A. Joffe, M. R. Andrews, and W. Ketterle, Phys. Rev. Lett. **74**, 5202 (1995).
[4] D. M. Harber, J. M. McGuirk, J. M. Obrecht, and E. A. Cornell, J. Low Temp. Phys. **133**, 229 (2003).
[5] C. S. Adams, H. J. Lee, N. Davidson, M. Kasevich, and S. Chu, Phys. Rev. Lett. **74**, 3577 (1995).
[6] M. D. Barrett, J. A. Sauer, and M. S. Chapman, Phys. Rev. Lett. **87**, 010404 (2001).
[7] D. Muller, D. Z. Anderson, R. J. Grow, P. D. D. Schwindt, and E. A. Cornell, Phys. Rev. Lett. **83**, 5194 (1999).
[8] D. Muller, E. A. Cornell, M. Prevedelli, P. D. D. Schwindt, A. Zozulya, and D. Z. Anderson, Opt. Lett. **25**, 1382 (2000).
[9] R. Folman, P. Kruger, D. Cassettari, B. Hessmo, T. Maier, and J. Schmiedmayer, Phys. Rev. Lett. **84**, 4749 (2000).
[10] W. Hansel, P. Hommelhoff, T. W. Hansch, and J. Reichel, Nature (London) **413**, 498 (2001).
[11] H. Ott, J. Fortágh, G. Schlotterbeck, A. Grossmann, and C. Zimmermann, Phys. Rev. Lett. **87**, 230401 (2001).
[12] S. Du, M. B. Squires, Y. Imai, L. Czaia, R. A. Saravanan, V. Bright, J. Reichel, T. W. Hansch, and D. Z. Anderson, Phys. Rev. A **70**, 053606 (2004).
[13] J. Reichel, W. Hansel, and T. W. Hansch, Phys. Rev. Lett. **83**, 3398 (1999).
[14] J. Reichel, W. Hansel, P. Hommelhoff, and T. W. Hansch, Appl. Phys. B: Lasers Opt. **72**, 81 (2001).
[15] R. Folman, P. Kruger, J. Schmiedmayer, J. Denschlag, and C. Henkel, Adv. At., Mol., Opt. Phys. **48**, 263 (2002).
[16] J. Reichel, Appl. Phys. B: Lasers Opt. **74**, 469 (2002).
[17] J. Fortágh, and C. Zimmermann, Rev. Mod. Phys. **79**, 235

(2007).
[18] Y.-J. Wang, D. Z. Anderson, V. M. Bright, E. A. Cornell, Q. Diot, T. Kishimoto, M. Prentiss, R. A. Saravanan, S. R. Segal, and S. Wu, Phys. Rev. Lett. **94**, 090405 (2005).
[19] D. E. Pritchard, Phys. Rev. Lett. **51**, 1336 (1983).
[20] W. Ketterle, D. S. Durfee, and D. M. Stamper-Kurn e-print arXiv:cond-mat/9904034.
[21] E. A. Burt, R. W. Ghrist, C. J. Myatt, M. J. Holland, E. A. Cornell, and C. E. Wieman, Phys. Rev. Lett. **79**, 337 (1997).
[22] X. Li, M. Ke, B. Yan, and Y. Wang, Chin. Phys. Lett. **24**, 1545 (2007).