Using laser-cooled atoms as a focused ion beam source

J. L. Hanssen, E. A. Dakin, and J. J. McClelland[a)]
Electron Physics Group, National Institute of Standards and Technology, Gaithersburg, Maryland 20899-8412

M. Jacka
Department of Physics, University of York, Heslington, York YO10 5DD, United Kingdom

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The authors describe a new method for creating a high quality focused ion beam using laser-cooled neutral atoms in a magneto-optical trap as an ion source. They show that this new technique can provide spot resolutions and brightness values that are better than the state of the art in focused ion beams. The source can be used with a range of different ionic species and can be combined with laser cooling techniques to exert unprecedented control over the ion emission, for example, producing single ions "on demand." The beam quality is a result of a high brightness and a narrow energy distribution, both of which stem from the cold temperature ($\approx 100\ \mu$K) of the atoms. The ions are produced by subjecting the cold neutral atoms to a photoionization laser, after which they become a compact source of nearly monoenergetic ions. With the application of a potential gradient, the ions form a beam that can be focused via standard ion optical techniques. They discuss estimations based on the initial size of the ion cloud and the energy distribution and show that the resulting beam has a low emittance. © *2006 American Vacuum Society.* [DOI: 10.1116/1.2363406]

I. INTRODUCTION

As the size of electronic and photonic devices decreases, the ability to precisely fabricate them becomes more challenging. For roughly 30 years, high-resolution focused ion beams (FIBs) have proven useful for a variety of tasks, such as microscopy, lithography, micromachining (i.e., ion milling and material deposition), and dopant implantation, necessary to create these nanoscale devices.[1] While FIBs are widely used and have seen great success, the current technology associated with FIB ion sources has reached a mature stage and further improvements are difficult to make. In order to open new possibilities for advancing FIB technology, we propose using a magneto-optical trap ion source (MOTIS) as a new high brightness source of ions.

The MOTIS attains very high brightness by concentrating on reducing the angular spread of the ions rather than the source size. The source is based on the ionization of magneto-optically trapped, laser-cooled neutral atoms. While other sources based on laser-cooled atomic beams have been proposed,[2] our source relies on the stationary, three-dimensionally confined cold atomic cloud of a magneto-optical trap (MOT). Magneto-optical trapping produces clouds of neutral atoms as small as 10 μm in diameter with temperatures in the range of 100 μK. Such a cloud of atoms, when ionized and accelerated, can result in an extremely bright ion beam. This brightness comes from a very narrow angular spread—as low as 10 μrad for a beam energy of 100 eV—which is a direct consequence of the very cold temperature of the atoms. Coupled with a source size on the order of tens of micrometers, this leads to an emittance on the order of $10^{-7}\pi$ mm mrad $\sqrt{\text{MeV}}$, a value that is significantly smaller than is possible with existing sources.

Over the years, a number of ion sources have been developed for FIB applications, including gas phase,[3] plasma,[4] and liquid metals.[5] Of all of the sources developed so far, the most widely used is the liquid-metal ion source (LMIS), in part due to the practicality of its implementation but fundamentally due to its very high brightness. This brightness, due mostly to its small source size (of order 50 nm), allows the production of focused ion beams with spot sizes on the order of 10 nm while maintaining currents in the range of 1–10 pA.

Despite their widespread use, existing ion sources possess limitations that impede progress toward broader applications and higher resolution. Because of the need to wet a tungsten tip with a liquid metal, the number of different ionic species that can be implemented in a LMIS is somewhat limited. Ga is by far the predominant element used, though other species, including Ag, Al, Be, and Cs, have been demonstrated.[1] These often require special conditions, such as a very hot tip or mass separation elements in the optics column, and tend to have less output current, so their applications are limited. The MOTIS can provide a broader choice of elements. To date, laser cooling has been demonstrated for the alkalis Li, Na, K, Rb, Cs, and Fr, the alkaline earths Mg, Ca, and Sr, the metastable noble gases He, Ne, Ar, Kr, and Xe, the metals Al, Ag, and Cr, and the rare earths Er and Yb. This range of elements opens new possibilities for doping and deposition, where the choice of element is crucial, and it is also advantageous for microscopy and micromachining where a choice of light or heavy element is desirable.

The LMIS also suffers from an extremely large energy spread, more than several eV, which is generally considered attributable to space charge effects occurring in the very

[a)]Electronic mail: jabez.mcclelland@nist.gov

small emission area on the surface of the emitter.[6] This energy broadening leads to chromatic aberration in the focusing optics that form the focused ion beam, limiting the achievable resolution and forcing a trade-off between beam current and resolution. While gas-phase and plasma sources have narrower energy spreads, on the order of 1 eV, the current is significantly less, restricting their usefulness. The MOTIS does not suffer from this problem. Because of the extremely low temperatures of MOTIS ions, the energy spread is dominated by the extraction potential gradient across the finite source size. With typical source sizes, widths of 100 meV or less are possible, greatly reducing the effects of chromatic aberrations and making design of focusing optics less demanding. Additionally, the low energy spread allows the beam to be focused to the nanometer scale at energies much lower than conventional ion sources. This opens possibilities for much better control over the implantation depth of ions and the size of the damage regions associated with ion milling.

In addition to improving upon the current capabilities of FIBs, the MOTIS will enable the development of new techniques that are not possible with any other source. The fact that a MOTIS begins with trapped neutral atoms allows for the simultaneous production of electrons and ions from the same source volume. Therefore, with a simple reversal of voltage polarity, the ion source can be changed into an electron source with an appropriate optical design.[7] This adds a degree of flexibility to the source and opens new possibilities for combining imaging with doping or machining using a single source. In addition, through advanced laser cooling techniques, the MOTIS can exert new degrees of control over the ion beam. For instance, the implementation of atom-on-demand techniques would allow the controllable production of a single ion at a time with greater than 99% probability.[8] The result would allow for deterministic doping of samples ranging from doses that are possible with current FIBs down to doses of single dopant ions. All of these characteristics of the MOTIS create a source with higher brightness and more flexibility, which can handle the demands of future nanofabrication.

II. SOURCE PERFORMANCE ESTIMATES

The cold neutral atoms in a magneto-optical trap[9] (MOT) are an appropriate place to begin our determination of the beam quality produced by a MOTIS. The geometry of a MOT consists of three orthogonal pairs of counterpropagating laser beams intersecting at the center of a quadrupole magnetic field. This type of trap can be created with any atom that has a closed (or nearly closed) strong optical transition in which the upper level has one unit of angular momentum more than the lower level. A velocity-dependent force which slows the atoms is created by tuning the wavelength of the laser light close to but just below the resonance of the atom in use. A trap center within the overlap of the laser beams is created by the magnetic field gradient, which contributes position dependence to the force. For present purposes, it is sufficient to work with typical characteristics commonly found in MOTs. The detailed behavior of a MOT is somewhat complex, and more in depth discussions can be found elsewhere.[10,11] The three-dimensional distribution of the atomic cloud depends on the magnetic field gradient, the light intensity, and the number of atoms in the trap but generally has a nearly Gaussian distribution in three dimensions with a size that can range from 10 μm to a few millimeters. The Doppler temperature associated with the laser cooling transition, given by $\hbar\Gamma/2k_B$, where Γ is the natural transition rate for the cooling transition and k_B is Boltzmann's constant, generally governs the temperature of the atoms, which is typically of order of 100 μK ($\approx$9 neV) for most MOTs. While the Doppler temperature is typically cold enough for generating a high quality beam of ions, we note that, if desired, significantly colder temperatures can be achieved by applying more sophisticated laser cooling techniques, such as polarization-gradient cooling.[12] The steady-state number of atoms in a MOT depends on the load rate and the loss rate and can vary greatly, with maximal values above 10^9 atoms. Maximum densities are of order 10^{11} at./cm^3, limited ultimately by losses due to collisions between the excited atoms in the trap. We will show that, with these conditions, it is possible to attain ion currents in the nanoampere range.

The neutral atoms in the MOT must be converted into ions in order to use them as a source. Photoionization, in which a high energy photon ejects an electron from an atom, leaving behind an ion, is the most efficient means of doing this.[13] This is accomplished by directing a laser beam at the atom cloud with photon energy equal to or greater than the difference between the excited state of the atom and the continuum. The photon must have only the minimum energy necessary to accomplish this task for the following reasons. First, this provides a means of selectively ionizing the atoms within the MOT because the photons only have enough energy to ionize excited state atoms, ensuring that background atoms that are not in the MOT do not become part of the ion beam. Secondly, any excess energy from the photon gets converted into kinetic energy of the ion-electron system. Compared to the extremely cold temperatures involved, the small amount of excess energy that the ion receives is considerable. For example, a gas of cold chromium atoms at 100 μK that is ionized by photons tuned 100 GHz ($\approx$400 μeV) above the ionization threshold will have its effective temperature increased by a factor of 2, which is enough to reduce the quality of the ion beam. It should also be noted that multiple photons with an energy sum equal to the ionization threshold can be used for the same purpose, and therefore it is not necessary to use only a single photon ionization process. This multiphoton process can be done nonresonantly or resonantly, where an intermediate excited state of the atom is used.

The normalized emittance ε and the normalized brightness β are two useful quantities that characterize the quality of an ion beam. It can be shown[14] that the normalized emittance is an invariant quantity along a focusing column (neglecting aberrations and space charge effects), allowing for the comparison of different systems. It is also possible to determine the final resolution of a system using this value.[14] For a source in a field free region with a Gaussian spatial distribution characterized by a standard deviation σ_x and a Maxwellian velocity distribution in the x direction characterized by a temperature T, the normalized emittance ε_x reduces to

$$\varepsilon_x = \sigma_x \sqrt{\frac{k_B T}{2}}. \tag{1}$$

Applying this expression to a typical chromium MOT with $\sigma_x = 5\ \mu\text{m}$ and $T = 100\ \mu\text{K}$, Eq. (1) yields a value of $\varepsilon_x \approx 3.3 \times 10^{-7} \pi$ mm mrad $\sqrt{\text{MeV}}$. This normalized emittance is three times smaller than the measured normalized emittance value for a gallium LMIS operated in high-resolution mode, $\varepsilon_x \approx 10.7 \times 10^{-7} \pi$ mm mrad $\sqrt{\text{MeV}}$.[15] It is important to note that for the LMIS to reach its lowest emittance, the beam must be apertured, a process that reduces the current output to the order of 10 pA. For the MOTIS, the emittance (and hence resolution) is independent of the current, provided space charge effects are negligible, because the emittance is not reduced through aperturing.

Assuming the MOTIS is coupled to a typical focusing column, we can calculate the expected attainable spot size using the emittance. Though the spot size is entirely dictated by the emittance of the ion beam for a perfect lens, for a realistic lens, the final resolution is limited by aberrations. The leading effects that limit the resolution of FIBs are spherical aberration and chromatic aberration. The final spot radius r_{total} is taken to be a root power sum of the various contributions including spherical aberration, chromatic aberration, and the emittance limited radius.[16] While chromatic aberration is a major component of the spot size in conventional FIBs, it is completely negligible in the MOTIS because of the very low energy spread. Therefore, neglecting the contributions from chromatic aberration, it can be shown that the minimum spot size for a given normalized emittance is

$$r_{\text{total}} \approx \gamma C_{\text{SA}}^{1/4} \varepsilon^{3/4} U^{-3/8}, \tag{2}$$

where γ is a numerical factor of order unity.[17] Using Eq. (2) with the above calculated emittance, a beam energy U of 1 keV, and assuming a realistic spherical aberration coefficient C_{SA} of 200 mm rad^{-3},[18] we calculate a spot radius of approximately 3.8 nm. For further verification, we have performed ray tracing simulations for a specific realization of the source, shown in Fig. 1, which give a spot size of $\approx$3.5 nm half-width at half maximum.[19]

While emittance highlights the quality of the beam, the useful current that can be focused into a spot is measured by the brightness, which depends on the amount of current I that is emitted from an area A into an solid angle Ω.[6] The normalized brightness, an invariant along the focusing column, is related to emittance by[20]

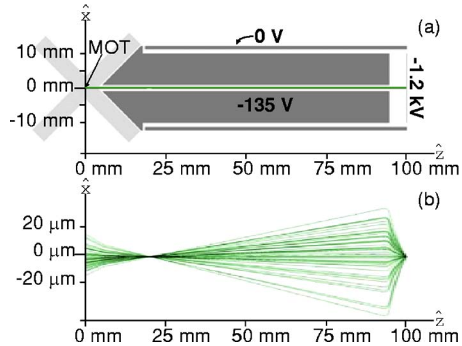

FIG. 1. Lens geometry used in ray tracing simulations (Ref. 19). (a) Scale drawing, showing electrostatic lens elements (dark gray) and MOT laser beams (light gray). The lens consists of three elements: a tapered cylinder held at −135 V, a grounded sheath surrounding the tapered cylinder, and a back plane held at −1.2 kV. At this scale, the atomic cloud is a small spot at the origin, and the ion trajectories lie along the horizontal axis ($x=0$ line). (b) Typical ion trajectories with vertical axis expanded by a factor of 365. These trajectories were calculated for a MOT having a spatial distribution with a standard deviation of $\sigma_x = \sigma_y = \sigma_z = 5\ \mu\text{m}$ and temperature of 100 μK. For clarity, only 50 of the 10 000 trajectories calculated are shown.

$$\beta = \frac{I}{\varepsilon_x \varepsilon_y}, \tag{3}$$

where ε_x and ε_y are the emittances in the two orthogonal directions transverse to the direction of propagation. Therefore, by knowing the brightness of a source, it is possible to calculate how much current can be focused into a spot.

In order to calculate the brightness of the MOTIS, the current that the MOTIS can supply must be determined. The current is generally dependent on the load rate of the MOT, the excited state population, and the photoionization rate. Generally, the source is operated in a pulsed mode, wherein the trap is first loaded with a cloud of atoms which is then exposed to the photoionization laser long enough to ionize the atoms. In this situation, the peak pulse current is simply the number of atoms ionized divided by the time it takes to ionize them. The number of excited state atoms in the trap can range from one atom to the order of 10^9 atoms, and the photoionization rate for typical atoms and modest lasers can be as high as $5 \times 10^4\ \text{s}^{-1}$.[21,22] Therefore, for a medium sized MOT of 10^6 atoms in a cloud with a standard deviation of 50 μm, an ionization rate of $2.5 \times 10^4\ \text{s}^{-1}$, and an ionization pulse of 40 μs (the inverse of the ionization rate), it is possible to attain a peak current of 2.5 nA in a pulse. The time averaged current is determined by the time it takes to replenish the MOT with atoms. Using the above example and a realistic reload time of 10 ms, an average current of 10 pA is attainable.

The calculated currents demonstrate that a MOTIS is indeed a high brightness source. With a conservative current estimate of 2.5 nA, the source has an instantaneous normalized brightness of 2.3×10^{10} A cm^{-2} sr^{-1} MeV^{-1} (or 9.2×10^7 A cm^{-2} sr^{-1} MeV^{-1} when time averaged). This value surpasses the measured brightness values of 5.8

$\times 10^7$ A cm^{-2} sr^{-1} MeV^{-1} for a gallium LMIS,[23] 2 $\times 10^{10}$ A cm^{-2} sr^{-1} MeV^{-1} for gas-phase ion sources,[14] and 10^5 A cm^{-2} sr^{-1} MeV^{-1} for plasma sources.[4]

So far, we have not taken into account the effects of space charge in the discussion of emittance and brightness of the MOTIS. Mutual repulsion of ions within the beam of any ion source causes some amount of beam expansion and results in a larger emittance and energy broadening. The current density in the beam determines whether or not these effects are negligible. Space charge effects increase with increasing current density.[24] In most situations the region of highest current density is usually located at the source and is the dominant source of space charge spreading and energy broadening.[14]

We can calculate that the MOTIS has a maximum current density at the source no larger than 10^{-3} A/cm^2 based on the current estimates described above. This is nine orders of magnitude smaller than the LMIS, which has a typical current density of 10^6 A/cm^2 or higher. This is a result of the fact that the MOTIS obtains its small emittance from a small angular spread instead of a small source area. This large disparity in current density suggests that space charge effects in the MOTIS will be much smaller than those in the LMIS and can be controlled sufficiently to yield 10 nm resolution. A more detailed analysis is beyond the scope of this article, but further analysis of space charge effects in the MOTIS can be found in Ref. 19.

III. CONCLUSION

In summary, magneto-optically trapped atoms can serve as a source for a high quality focused ion beam. Given the cold temperatures accessible through magneto-optic traps, it is possible to create a beam with extraordinarily low angular divergence and an emittance considerably smaller than conventional sources. Depending on the manner in which the source is controlled, the current can be varied from one ion at a time up to hundreds of picoamperes, leading to a high brightness that is better than the state of the art.

The MOTIS offers several advantages in addition to having the potential to produce a focused ion beam with better resolution and brightness than existing FIB sources. The source has a much narrower energy width than other ion sources, resulting in a much smaller chromatic aberration and the capability of nanoscale resolution at much lower energies. An ion beam can be created from a larger selection of atomic species than is available with liquid metal, gas-phase, or plasma sources, due of the range of atoms amenable to being trapped in a MOT. These attributes could increase the usefulness of FIBs in areas such as microscopy and micromachining. Also, novel laser cooling and trapping techniques will allow for exotic ion beams to be created. Through atom-on-demand technology, a single ion can be placed with 10 nm resolution deterministically. This opens the door for new technological advances as well as interesting new physics.

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