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14. ABSTRACT
The creation of a continuous wave atom laser would greatly enhance the possibility of ultracold atom based, jam-proof, precision inertial navigation systems. This proposal is for instrumentation necessary to support the PI's current AFOSR grant. The proposal outlines the usage of equipment purchased through this DURIP grant to create the first continuous wave atom laser and for a novel single atom detector based on a carbon nanotube.

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DURIP Final Performance Report
Award #FA9550-05-1-0333
Instrumentation for Creation and Diagnostics of an Intense Cold Atom Beam: CW Atom Laser and Nanotube Single Atom Detector
Lene V. Hau, P.I.
14 February 2007

During the funding period we have created a novel low-power neutral-atom detector with single atom sensitivity, and unprecedented spatial and temporal resolution. We have made the first observations ever of trapping and detecting cold atoms with freely suspended nanotubes. These results open up a whole new regime for manipulation of cold atoms with nanostructures. The results are described below and will be submitted for publication. A scanning electron microscope (SEM), purchased with DURIP funding, for imaging and electrical characterization of the nanotube samples has been instrumental for these achievements. We have also outfitted the SEM with a controlled-flow gas inlet, which allows for removal of unwanted duplicate nanotubes or tube tips after the nanotube-growth step.

Furthermore, we have designed and built a setup for the production of an intense, cold atom beam. We have developed a beam source with the highest flux of cold atoms ever produced [1]. We have designed, manufactured, installed, and tested deflection, cooling, focusing, and magnetic waveguide sections for the beam line, as described below. Most recently, we reached a milestone and obtained highly efficient continuous wave (CW) loading of the magnetic waveguide. This has required significant machining, vacuum equipment, optics and optical detectors, and data acquisition equipment.

Finally, during the funding period we have significantly augmented our setup for slow and stopped light in Bose-Einstein condensates to create unique instrumentation for coherent optical information processing. This work was just published as the cover story of Nature, February 8, 2007 [2] and was widely reported in the press in this country as well as throughout the world (Europe, Australia, South America, Indonesia). As two examples of the press coverage, the work was reported in the New York Times on the day of publication, and the PI appeared on National Public Radio in the directly transmitted program 'Talk of the Nation: Science Friday' (on February 9).
For this setup, high-power DC Power supplies and high-laser-power acousto-optic modulator sections were purchased and constructed. This allowed for generation of a double-well atom trap and creation of a double-condensate system. Furthermore, light pulse generation and high-bandwidth light-pulse detection stages were constructed.

The instrumentation developed at Harvard during the DURIP funding period has created a unique infrastructure for coherent control of light and matter. Harvard strongly supports our efforts and has constructed a new laboratory for the PI and two collaborators. This laboratory, the Advanced Sensor Laboratory, has just been completed and will house some of the instrumentation developed and purchased under this DURIP grant. The laboratory will house equipment for fabrication, imaging, and testing of nanotube devices.

Coherent Processing of Optical Information: In these experiments, we stop and extinguish a light pulse in one Bose-Einstein condensate (BEC) and revive the light pulse in a totally separate condensate 160 microns away. The light pulse is converted to a traveling matter copy that is isolated in space, and hence can be trapped, manipulated and sent on to be revived as light in a second condensate. The work represents a new paradigm in quantum control, coherent optical information processing, and wavefunction sculpting.

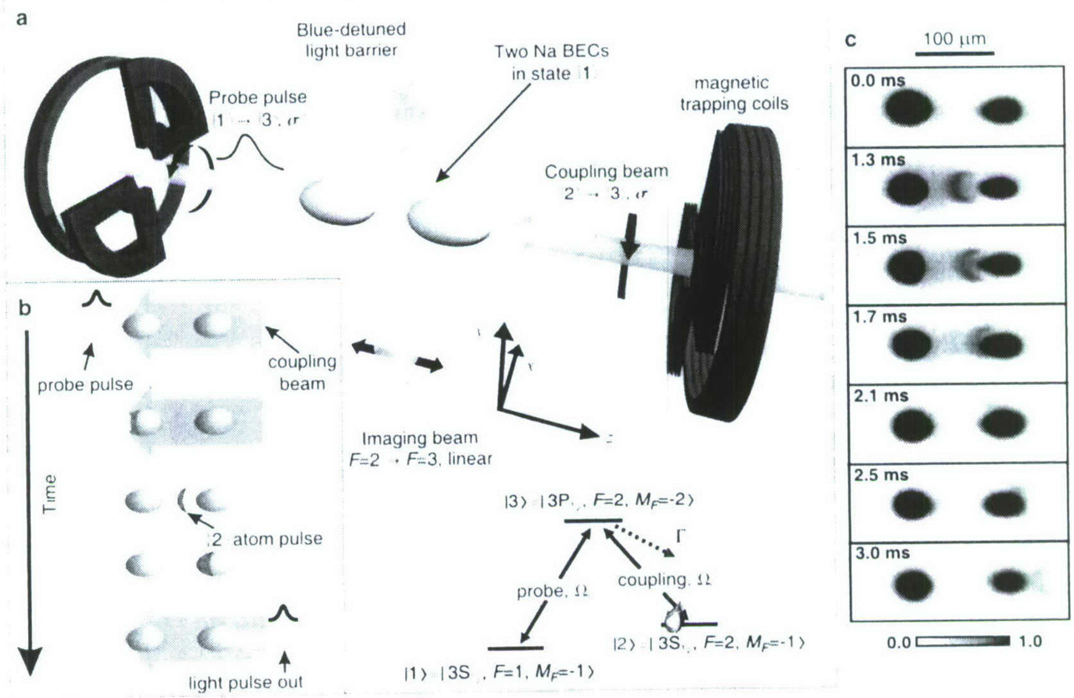
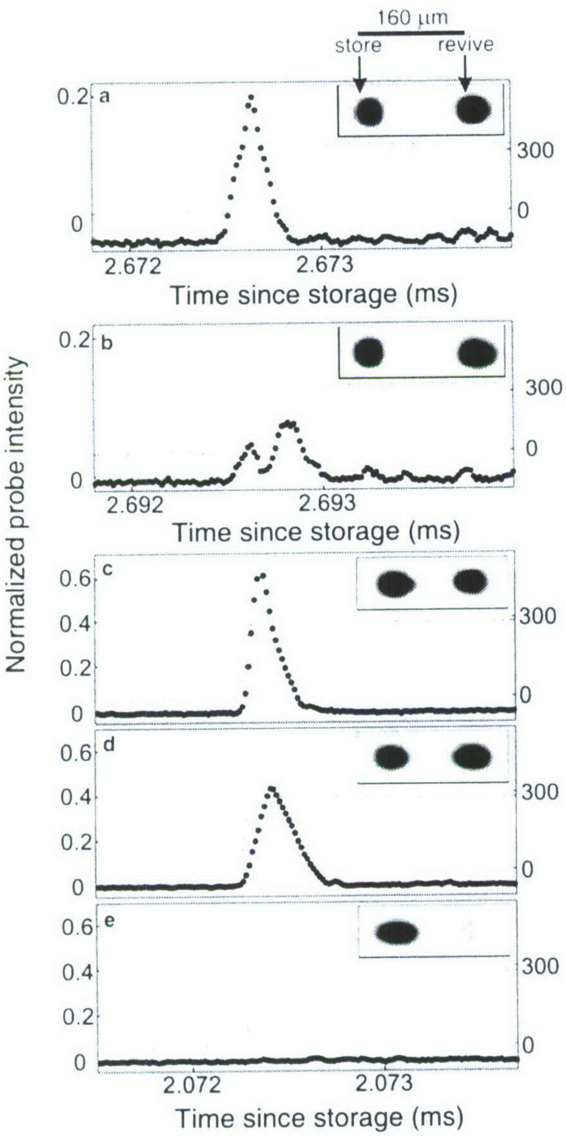


Figure 1: Diagram of the experiment. a, Two sodium BECs (pale blue) are prepared in state $|1\rangle$ in a double-well potential formed by combining a harmonic magnetic trap (dark blue) and a repulsive optical dipole barrier (focused 532 nm green laser beam with elliptical gaussian cross-section). The entire potential is turned off 1 ms before experiments begin, whereupon the probe (light orange) and coupling (orange) laser beams are introduced. Finally, the condensates are imaged with a laser beam (yellow), near resonance for the atoms' $F = 2 \rightarrow F = 3$ transition, after optical pumping to $F = 2$. **b,** Experiments begin with the injection of a probe laser pulse (light orange) into the first (left) BEC, while the cloud is illuminated by the counter-propagating coupling laser beam (orange). The pulse propagates into the condensate under ultraslow light conditions. After the probe pulse is spatially compressed within the cloud, the coupling beam is switched off, leaving an imprint of the probe pulse's phase and amplitude in the form of atomic population amplitude in state $|2\rangle$ (red). Each atom's $|2\rangle$ component has a momentum corresponding to two photon recoils (absorption from the probe beam and stimulated emission into the coupling beam) and is ejected towards the second (right) BEC. When this 'messenger' atom pulse in $|2\rangle$ arrives, the coupling beam is switched back on, and the probe light pulse is regenerated in the second condensate. Revived light pulses are imaged onto a 50 μm pinhole (to reject background light) and detected with a photomultiplier tube. **c,** Resonant absorption images of BECs and travelling messenger pulse, at indicated times since light pulse storage. No revival coupling beam is fired, and the messenger pulse is observed to travel through and beyond the second BEC.

Figure 2: Light pulse storage and revival in two separate condensates. Revived probe pulses, normalized to input pulse intensity, are plotted against time since pulse storage (dots, left-hand axis), and simultaneously recorded coupling intensity (dashed line, right-hand axis). Insets are resonant absorption images of the $|1\rangle$ condensates, 20 μs after revival. **a**, **b**, Light pulses revived in the second of a pair of independently condensed BECs. Atoms are evaporatively cooled in a 2.3-μK-deep double-well potential formed by a magnetic trap combined with a light barrier (the Bose-condensation temperature is 660 nK). After condensation, the magnetic potential is adiabatically softened to $\omega_z = 2\pi \times 20$ Hz and $\omega_r = 2\pi \times 40$ Hz. Subsequently, the light barrier is adiabatically lowered to 10μ, where μ is each well's resulting chemical potential. The trapping potential is then turned off in less than 200 μs. After 1 ms, the probe pulse is stored in the first BEC ($\Omega_p = 2\pi \times 2.6$ MHz, $\Omega_c = 2\pi \times 2.6$ MHz). In **a**, the light pulse is revived in the second BEC after 2.67 ms during which time the $|2\rangle$ atom pulse travels 157 μm. Note, $\Omega_{c,revival} = 2\pi \times 21.4$ MHz, resulting in a temporally narrowed output pulse[16]. In **b**, the messenger $|2\rangle$ pulse travels to a different location in the second BEC, where differences in density and phase patterns between the two lead to a bimodal structure. **c**, **d**, Revived light pulses from condensates formed by adiabatically splitting a single magnetically trapped BEC with a 1.5μ-tall light barrier, ramped up over 100 ms, and held constant for 1 s. A typical pulse (**c**) contains 6.9×10^3 photons, 2.2% of the input pulse energy. In **d,** a larger, denser second BEC yields a slower light propagation speed and a broader and less intense pulse, with similar energy to **c**. **e**, A control experiment in which experimental timing and conditions were exactly the same as in **c** and **d**, but with no second BEC.



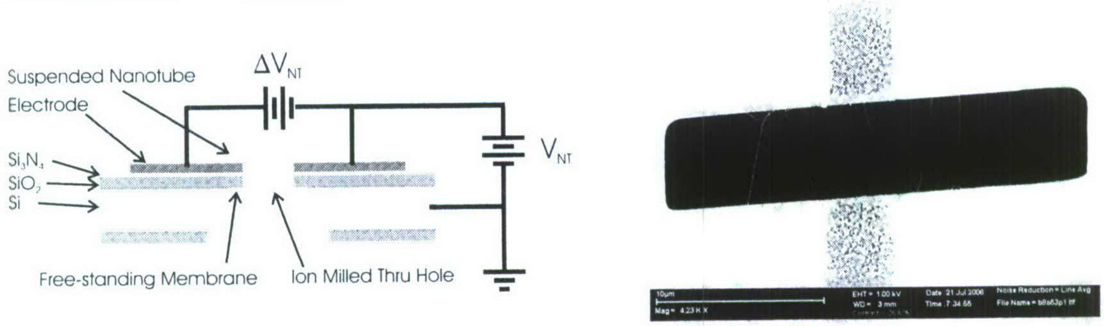


Figure 3: Schematic (left) of 3 mm chip with suspended nanotube and electrodes, and SEM image (right) of 5-micron-long nanotubes grown in our laboratory. We suspend the tubes between electrodes on either side of an FIB milled hole (dark region) in a thin free-standing silicon-nitride membrane.

Atom Detector: In this device, built with the current DURIP funding, a carbon nanotube is suspended across an ion-milled gap in a 3mm-wide silicon chip, with electrical contacts evaporated on the ends (see Fig. 3). The large, highly localized electromagnetic fields that are created by charging the nanotube polarize neutral atoms and pull them in toward the tube [3]. Near the surface, the electric field is large enough (1 to 10 V/nm) to field-ionize atoms [4]. For a positively biased nanotube, the stripped electron is pulled into the tube and the ion is ejected and detected by a channeltron electron-multiplier ion detector (Figure 4). With this system, we can identify ionization signals associated with individual atoms.

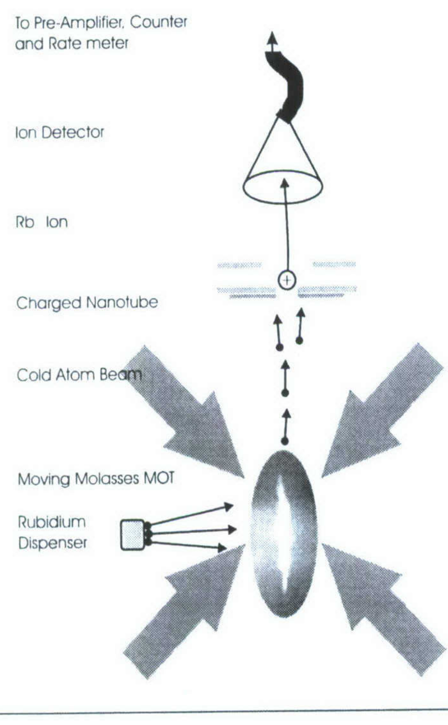


Figure 4: Schematic of experimental set-up showing getter dispenser to supply Rb atoms, laser beams to make the magneto-optical trap (MOT), recorded image of actual atoms forming a 1-cm long cloud in the MOT, atom beam path when cloud is launched, sample with suspended nanotube, path of ions to channeltron ion detector, and ion-detector.

The capture and ionization of cold atoms by charged, suspended nanotubes have recently been observed in our laboratory by detecting atom pulses of laser-cooled rubidium atoms (Fig. 5) (to be published). The rubidium atoms are trapped in a “moving-molasses” magneto-optical trap (MOT) formed by four laser beams which can be frequency tuned in pairs. The lasers create a damping force that cools the atoms, and a magnetic field gradient provides a transverse trapping force. Atoms are trapped, and then launched by shifting the frequency of the upper laser beams relative to the lower ones. The result is that a cloud of cold atoms is ejected towards the suspended nanotube, with a velocity controlled by the tuned frequency of the laser beams. A burst of ions is detected when the atoms reach the vicinity of the nanotube and are pulled in by its large electric field. We also measure the atoms independently with a probe laser beam. It is clear from the figure that the ionization signal closely follows the probe laser signal. The slight time shift between the two signals agrees with the delay due to the placement of the laser probe beam a few millimeters below the nanotube.

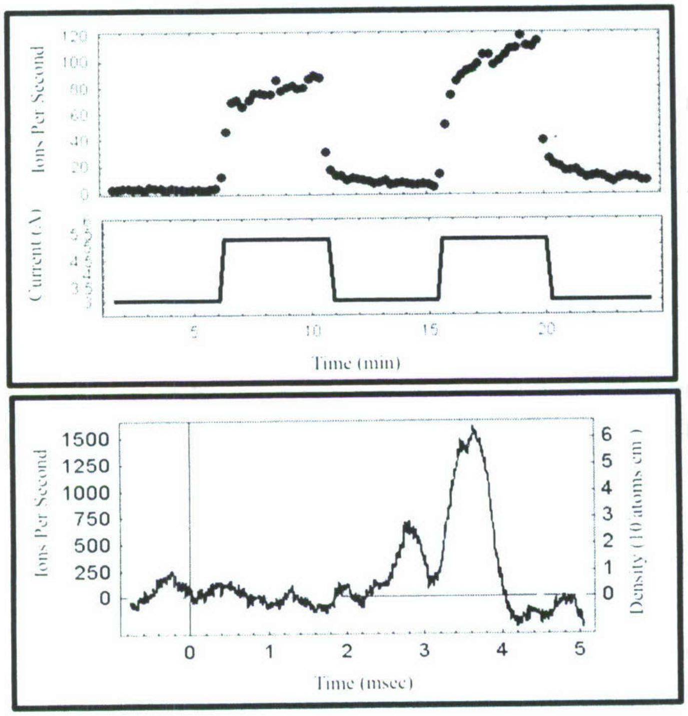


Figure 5: First experimental detection of Rb atoms with a nanotube. **TOP:** Detection of hot Rb atoms. When the getter current increases to 5.25 Amps, Rb is released, ionized, and detected. **BOTTOM:** Nanotube detection of launched, cold Rb atoms, velocity 4 m/s (black, left scale). Absorption measurement (gray, right scale) of the launched atom cloud as it passes through a laser probe beam in front of the nanotube.

Cold-Atom Beam Line: The input stage is a continuous beam of rubidium atoms with a flux of 3.2×10^{12} (1.0×10^{12}) atoms/sec at 116 (20) m/sec. This flux is one to two orders of magnitude larger than what had been obtained with the best previous cold atomic beam sources and it opens a new regime in the production of ultra-cold atomic samples. We plan to use this setup for creation of a continuous source of degenerate, Bose condensed atoms.

During the funding period, we have designed, built, and tested a system that we believe will attain this goal. A picture of the existing set-up is shown in Figure 6. A high flux atom beam is injected into a cold-atom beam line including atomic-beam deflector, transverse cooler, and atomic-beam focusing lens. Furthermore, one module containing an 18 inch section of magnetic waveguide has been constructed and installed with associated beam diagnostics. Extensive numerical calculations of evaporative cooling dynamics for atoms trapped and guided were performed, and we predict that a sufficiently high phase space density can be reached for the onset of Bose-Einstein condensation in a *continuous* atomic beam.

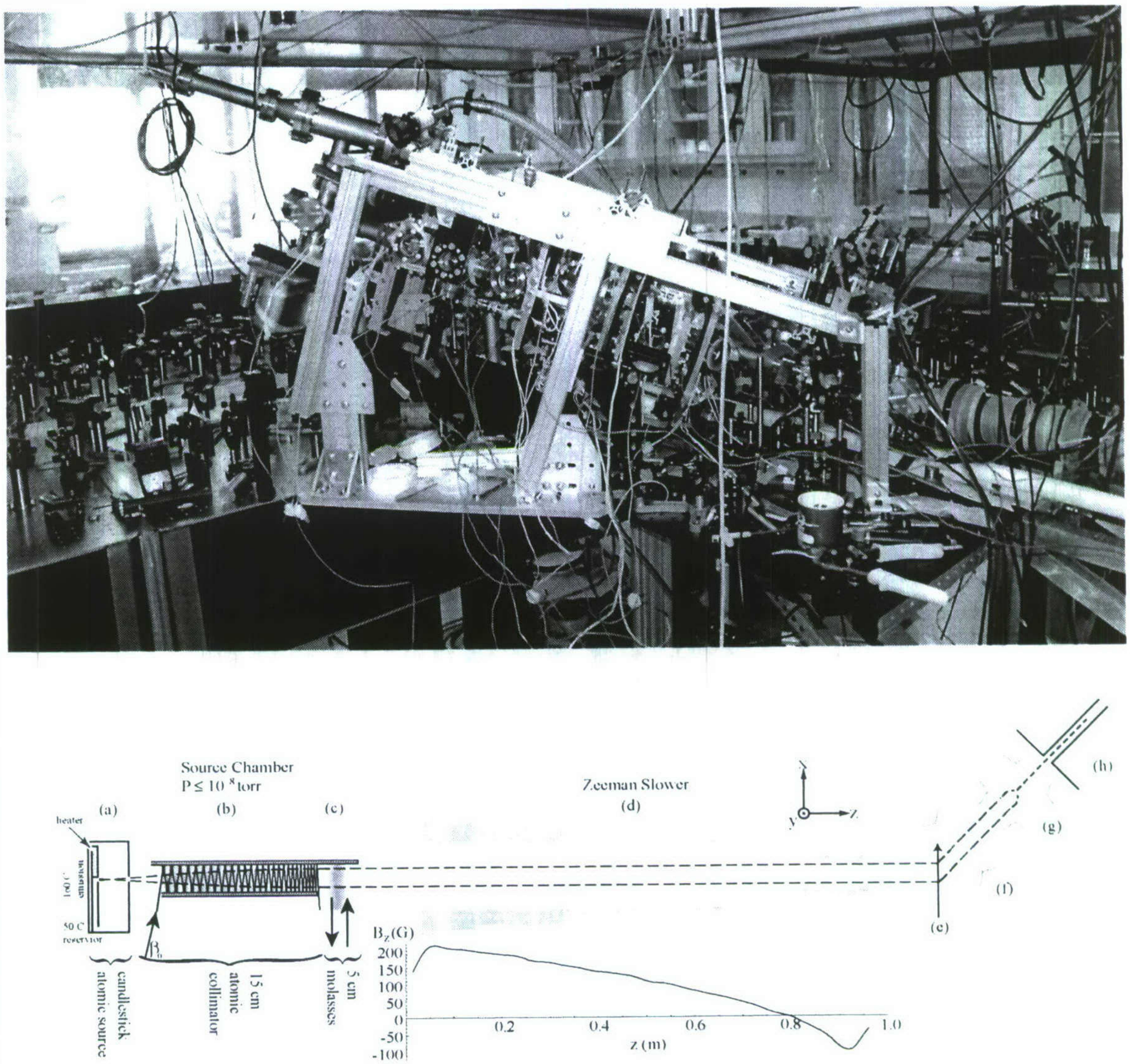


Figure 6: Photograph of the cold-atom beam line August 2006. An atomic beam is produced via a candlestick atomic beam source (a) with a divergence angle of 1/10 radian. The atoms in the beam then pass through a 20 cm long transverse collimation (b) and cooling (c) stage and are subsequently longitudinally decelerated and cooled by means of a 1 m long Zeeman slower (d), which is designed in the zero-crossing configuration shown. The beam is subsequently deflected (e), recollimated by a 2D molasses (f) and focused by at 2D Magneto Optical Trap (g) before being launched into a magnetic waveguide (h).

The installed magnetic guiding structure is shown in Figure 7. The guide consists of four current-carrying bars made from 3mm-square copper and with a current of 100 amperes per bar. Three biasing coils are wrapped around the entrance of the waveguide to aid in optical pumping of entering atoms. In addition, we have built an in-vacuum detector system (as shown), for detecting atoms in the guiding region.

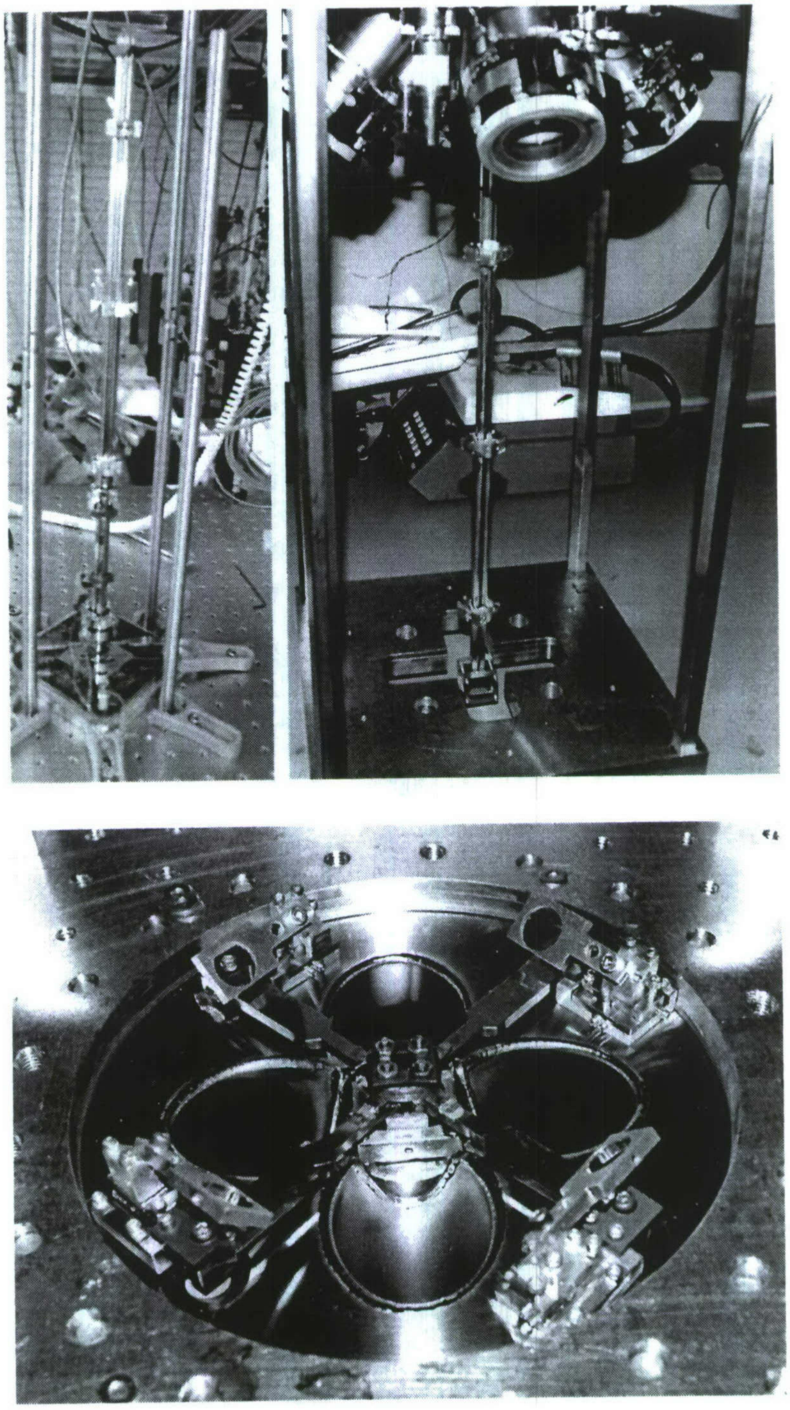


Figure 7: Constructed Magnetic Waveguide. Top left: waveguide is outfitted with in-vacuum mirrors for coupling of imaging laser beams. Top right: waveguide is being assembled in UHV chamber. Bottom: entrance section of waveguide with mirror mounts for injection diagnostics.

Once injected into the guide, the atomic beam will be evaporatively cooled into the Bose condensation regime by propagating the atoms along the guide in an appropriately tuned RF field in combination with a spatially varying bias magnetic field.

The evaporation scheme has been optimized with Monte Carlo simulations. We predict that a Bose condensed atom beam – an atom laser – will require only a 2 m length of guide. At the point of condensation, we predict a longitudinal mean velocity of 15 cm/s, a spatial transverse beam width of a few tens of microns, and an atom flux of a few times 10^{10}atoms/s. Most recently efficient CW loading of the magnetic wave guide was achieved, constituting a milestone towards the achievement of a continuous-wave degenerate atomic beam.

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Selected Publicity

During the funding period, two documentaries were made in our lab (one BBC/PBS special to be aired early in 2007 and a Swedish science program that was aired on the main Swedish TV channel on December 4, 2005; http://www.ur.se/vetenskap/443). The PI's pioneering work on Stopping Light was recently high-lighted as one of a select few milestones in the 160 year history of the Harvard Applied Sciences and Engineering (http://www.deas.harvard.edu/press/history.html).

Lene Hau was selected by the MacArthur Foundation as one of only 9 MacArthur Fellows to be featured in connection with the 25th anniversary of the MacArthur Fellows program. The 9 fellows were selected among all MacArthur fellows named over the history of the fellows program. See "MacArthur Fellows: the first 25 years, 1981-2005." (Published by the John D. and Catherine T. MacArthur Foundation, 2005).

The Library of Congress has recognized Lene Hau in its "Women Who Dare" 2007 desk calendar of accomplished women from around the world and throughout history. http://pomegranate.stores.yahoo.net/v252.html

Our work on coherent optical information processing was just published as the cover story of Nature, February 8, 2007 [2] and was widely reported in the press in this country as well as throughout the world (Europe, Australia, South America, Indonesia). As two examples of the press coverage, the work was reported in the New York Times on the day of publication, and the PI appeared on National Public Radio in the directly transmitted program 'Talk of the Nation: Science Friday' (on February 9).