Divergence of an atom laser

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We will present experimental study of the divergence [1] of a quasi-continuous, rf-outcoupled, free-falling, ^{87}Rb atom laser [2]. Our data show that the laser beam is well-characterized by a divergence angle. We measure this angle versus radio-frequency (rf) outcoupler frequency, which chooses the vertical extraction point of the atom laser from the condensate. In choosing the extraction point, one chooses the thickness of the condensate to be crossed by the extracted atoms, as well as the width of the atom laser beam extraction plane. As a matter of facts, the gravitational sag shifts the entire condensate from the center of the magnetic trap to a region where iso-field surfaces are approximately planes of constant height z_0 across the condensate [2]. The relation between rf frequency $\omega_0 + \delta_{\rm rf}$ and coupling height z_0 is

$$\delta_{\rm rf} = -\Delta \frac{z_0}{R_z} - \frac{\mu}{\hbar}\left(1 - \frac{z_0^2}{R_z^2}\right) \tag{1}$$

where $\Delta = MgR_z/\hbar$ is the spectral half-width of the condensate, M is the mass of the atom, g is gravitational acceleration, and R_z is the Thomas-Fermi (TF) radius of the condensate along z. For our experimental parameters, $\mu/\hbar \ll \Delta$, so $\delta_{\rm rf}$ is roughly linearly dependant on z_0, with slope $-Mg/\hbar$. Therefore, in choosing the coupling frequency, we choose the height within the condensate at which the laser is sourced.

The experimental sequence is the following : we load a magnetic Ioffe-Pridchard trap by conventional laser cooling techniques. Thence, we rf-evaporate for 30 s the sample to get eventually a condensate of typically $4 \cdot 10^5$ atoms. At this point, we apply the weak rf-outcoupling field for as long as 10 ms to create our quasi-continuous atom laser. We turn off the magnetic trap and wait 6 ms before taking vertical absorption images. We analyse the images (such as Fig. 1) to measure the flux and divergence of the outcoupled laser.

There are several possible sources of divergence of the atom laser, including diffraction, magnetic lensing, and interactions both within the laser and between the laser and the condensate. In order to understand the divergence with a simple analytical model, we make several approximations: 1) that the interactions between atoms *within* the laser are not significant; 2)that the roughly parabolic density profile of the atom laser can be approximated by a Gaussian; and 3) that we can use stationary solutions of the Schrödinger equation with a paraxial-type of approximation, in which the fast degrees of freedom [3] are decoupled from the slow evolution of the transverse degrees of freedom, as in [4]. We follow a gaussian optics treatment

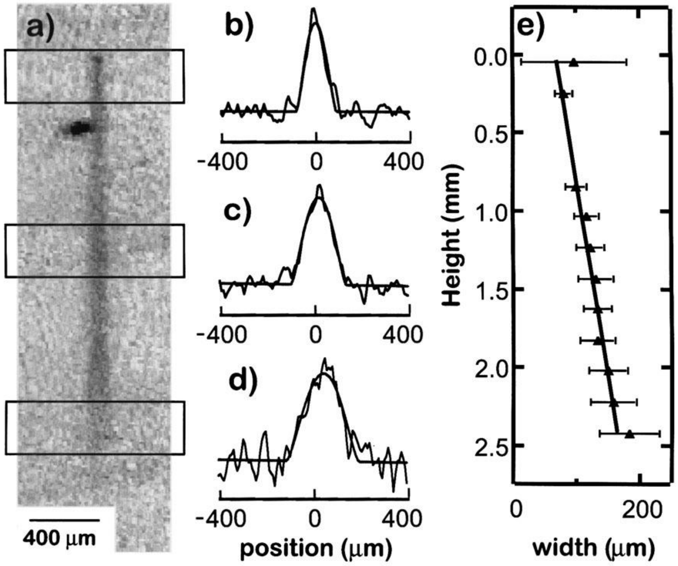

Figure 1: Typical continuous atom laser output. **(a)** Absorptive images. The condensate (the darkest area of image) is displaced from the beginning of the laser because of the magnetic kick separating atoms in the $m_F = -1$ and $m_F = 0$ states. **(b)-(d)** examples of absorption profiles taken from the three region boxed in (a). **(e)** The divergence angle of a single laser is found with a linear fit of measured widths.

similar to that of photonics laser [5] [6]. We treat the interactions between the atom laser and the condensate as a *thin lens* effect, while the following propagation in the magnetic potential created by the non-linearity of the Zeeman effect is considered as a *thick lens*. Finally, we treat the propagation of the laser between turning the trap off and absorption imaging as a free flight expansion. All these different steps of the propagation are individualy modelized using simple ABCD matrices. Finally, we combine the three different types of ABCD matrices to give the equivalent matrix for the complete propagative process. Thus, we are able to simply calculate the transverse size of the laser as a function of height, at the moment of imaging. The experimental results, as well as our ABCD treatment are shown on Fig. 2.

The primary feature of the experimental curve is its monotonous decrease with increasing δ_{rf} throughout the range of the data. This trend is due to the condensate lensing effect, as is demonstrated by comparison to the calculation without interaction effects (dashed curve). Out of the range of our data, there are two more salient features: (1) the divergence decreases for $\delta_{\mathrm{rf}} < -5\,\mathrm{kHz}$. This is due to a reduction in initial width of laser sourced from the very top of the condensate. (2) the divergence increases for $\delta_{\mathrm{rf}} > 5\,\mathrm{kHz}$ due to diffraction. A combination of diffraction and interactions imposes the minimum divergence possible on the atom laser, in our case approximately 6 mrad.

In conclusion, we have measured the divergence of an atom laser. We demonstrate that in our case, interactions are a critical contributor to the observed divergence. Finally, the strong

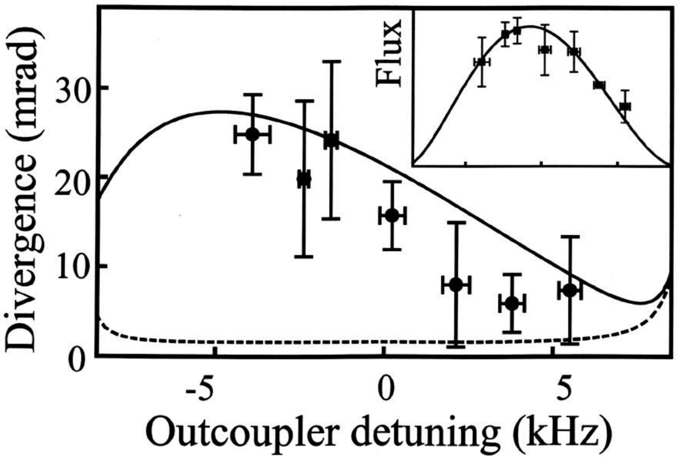

Figure 2: Divergence (half-angle) versus output coupler detuning from the condensate center. Experimental points are compared with the theoretical calculation (solid line). The dashed line represents the same calculation, but excluding the effects of the condensate-laser interactions. **Inset:** Output flux (arbitrary units) versus detuning, with the same frequency scale as the main figure.

parallel between atom and photon laser beams, both fully coherent, propagating waves, is emphasized by the success of a model obtained by generalization of the standard treatment of optical laser beams. The understanding of atom laser propagation provided by our measurements and model provides a basic tool for future experiments with atom lasers.

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