Time-of-flight measurement of the temperature of strontium magneto-optical trap

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Time-of-flight measurement

Time-of-flight measurement is a typical technique which is used to estimate the temperature of cold trapped atoms. Turning off the lasers which are used to trap the atoms results in free expansion of atomic cloud. The spatial width of the atomic cloud $\sigma(t)$ as a function of time depends on the temperature of the atomic temperature as [1, 2]

$$\sigma(t) = \sqrt{\sigma_0^2 + k_b T t^2/m}, \tag{1}$$

where σ_0 is the initial spatial width of the atomic cloud before turning of the trapping lasers, k_b is is a Boltzmann constant, T is a temperature of atomic cloud, t is a expasion time, and m is a atomic mass.

In this experiment, the atomic beam of strontium is produced by an effusive oven. The oven is heated to 400 C°, while the Zeeman slower (ZM) based on permanant magnet is used to slow down the atomic beam [3]. We use an atomic beam defelctor based on a 1D-optical molasses (OM) to deflect the atomic beam [4]. The atomic beam which is deflected from the Zeeman slower is delivered to a glass cell where the MOT magnetic coils are located.

Initially, the Zeeman slower and optical molassas. The atoms are loaded to the MOT by tuning the 461 nm laser for three second, after that the atomic cloud is appeared. The after turning on of MOT laser, the MOT laser is turned off to allow the atomic cloud to expand freely. At the same time, the laser Zeeman slower and the optical molassas are turn off to prevent the atomic beam from the oven goes to the MOT as shown in Figure 1. After expanding of the atomic cloud, the MOT beams are turn back on again to do the imaging of the expanded atomic cloud. At that point, the EMCCD camera camera is triggered and the image of the atomic clound is taken. By varying the expasion times, the evolution of the expanding atomic cloud is obtained as shown in Figure 2.

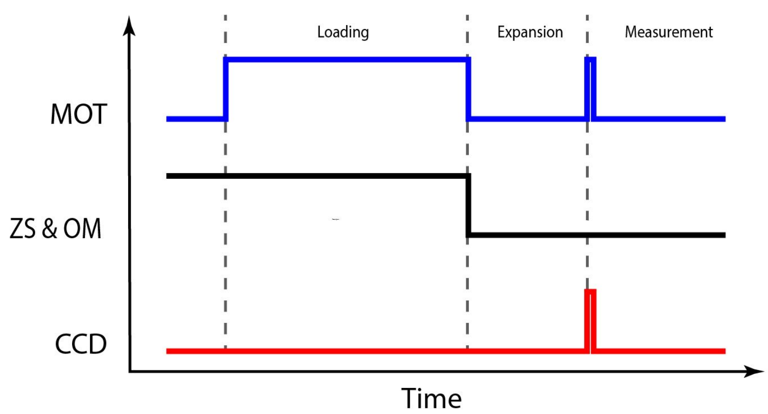

Figure 1. Time sequence for time-of-flight measurement of strontium magneto-optical trap.

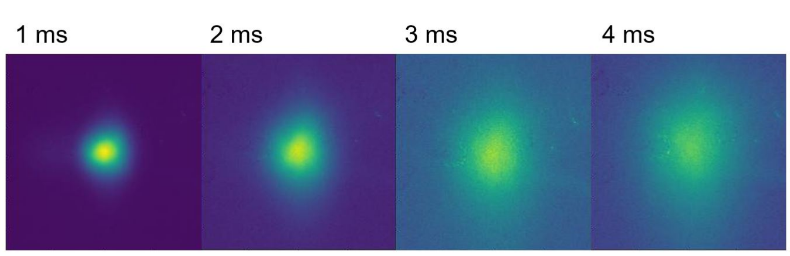

Figure 2. The images of atomic cloud at different time of flight

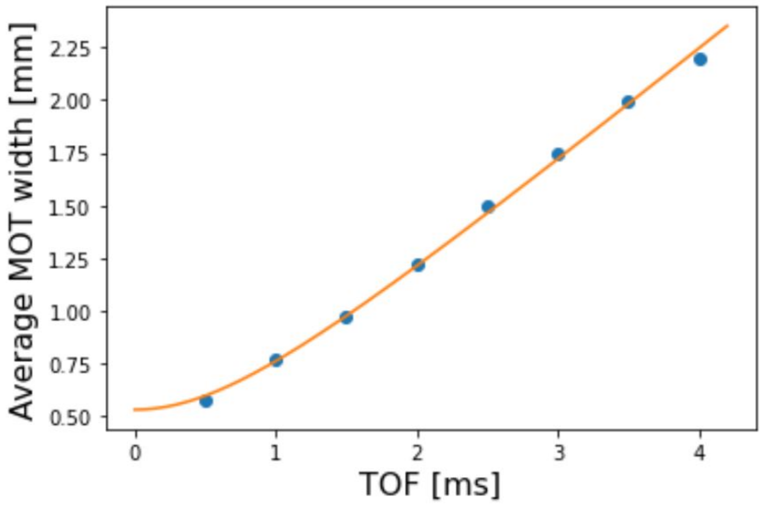

Figure 3. Average MOT width at different time of flight. The fitting shown that the temperature of the MOT is 3.14 mK

Python script

This is a Python script for estimating of temperature of MOT. The images of atomic cloud at different time of flight are fitted using a 2D Gaussian function. The average width of the atomic cloud at different time of flight are obtained and fitted with the model in equation (1) and the temperature of the MOT is obtained.

```
import matplotlib.pyplot as plt
import numpy as np
from astropy.io import fits
from scipy.optimize import curve_fit
from scipy.signal import savgol_filter

def load_file(dat_id):
    print('loading ',dat_id)
    # load camera data
    # cam_filename = data_folder + r'\{}.fits'.format(dat_id)
    cam_filename =r'{}.fits'.format(dat_id)
    hdul = fits.open(cam_filename, memmap=False)
    raw_data = hdul[0].data
    return raw_data

def twoD_Gaussian(x_tuple, amplitude, x0, y0, sigma_x, sigma_y, theta, offset):
    (x,y) = x_tuple
    a = (np.cos(theta)**2)/(2*sigma_x**2) + (np.sin(theta)**2)/(2*sigma_y**2)
    b = -(np.sin(2*theta))/(4*sigma_x**2) + (np.sin(2*theta))/(4*sigma_y**2)
    c = (np.sin(theta)**2)/(2*sigma_x**2) + (np.cos(theta)**2)/(2*sigma_y**2)
    g = offset + amplitude*np.exp( - (a*((x-x0)**2) + 2*b*(x-x0)*(y-y0) + c*((y-y0)**2)))
    return g.ravel()

def cloud_width(t, sigma_0, temp):
    return np.sqrt(abs(sigma_0**2 + 1.380649e-23*temp*t**2/(87.62*1.66054e-27)))
```

```
tof = [0.5,1.0,1.5,2.0,2.5,3.0,3.5,4.0] # Time-of-flight
fn = [50.02,51.11,52.46,53.29,54.25,56.49,57.54,58.52] # File's names
rd = [] # Raw data
photon_min = 0; photon_max = 30000;
bg = load_file("test1_Wed Jun  8 2022_14.59.37").astype(np.int16) #Background
bg = np.clip(bg[0],photon_min, photon_max)
crop_size = 450 # crop the picture
for i in range(len(tof)):
    image = load_file("test1_Wed Jun  8 2022_14."+'%.2f'%(fn[i])).astype(np.int16)
    image = np.clip(image[0],photon_min, photon_max)
    image = image - bg + np.max(bg) # Subtract the background
    image_filter = savgol_filter(image, 51, 3) # Filter the data to find the peak of the atomic cloud
    position_max = np.where(image_filter == np.amax(image_filter)) # The index of the peak
    # Crop the picture around the peak
    crop = np.transpose(image[position_max[0][0]-int(crop_size/2):position_max[0][0]+int(crop_size/2)])[position_max[1][0]-int(crop_size/2):position_max[1][0]+int(crop_size/2)]
    plt.imshow(crop); plt.savefig("Image" + str(i) + ".jpg"); plt.show()
    rd.append(crop);
```

```
X = np.array(range(crop_size))
Y = np.array(range(crop_size))
X, Y = np.meshgrid(X,Y)
X_Y = (X,Y)
sigma_r = [] # Average width of MOT cloud
for i in range(len(tof)):
    fig, (ax1, ax2) = plt.subplots(1,2)
    params, cov = curve_fit(twoD_Gaussian, X_Y, rd[i].ravel())
    ax1.set_title('Data'); ax2.set_title('Fitting')
    ax1.imshow(rd[i]); ax2.imshow(twoD_Gaussian(X_Y, *params).reshape(crop_size,crop_size))
    fig.suptitle("Time of flight = "+str(tof[i])+"ms")
    plt.tight_layout(); plt.show();
    sigma_r.append((np.abs(params[3]) + np.abs(params[4]))/2)
```

```
sigma_r_m = np.array(sigma_r)*26e-6 # The average spatial width of the atomic cloud in meter (2 pixel of camera is 26 micrometer)
tof_array = np.array(tof);
params_2, cov_2 = curve_fit(cloud_width,tof_array/1e3,sigma_r_m,p0=[0.5,0.002]);
t = np.linspace(0,4.2,1000);
print('Temperature of the MOT: %.2f mK' % (params_2[1]*1e3))
plt.plot(tof_array, sigma_r_m*1e3, 'o')
plt.plot(t, cloud_width(t/1e3,*params_2)*1e3)
plt.xlabel('TOF [ms]', fontsize=16)
plt.ylabel('Average MOT width [mm]', fontsize=16)
```

References

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[2] R. Hobson, W. Bowden, A. Vianello, I. R. Hill, and P. Gill, "Midinfrared magneto-optical trap of metastable strontium for an optical lattice clock," *Physical Review A*, vol. 101, no. 1, p. 013420, 2020.

[3] Y. B. Ovchinnikov, "A zeeman slower based on magnetic dipoles," *Optics communications*, vol. 276, no. 2, pp. 261–267, 2007.

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