# Force Sensing

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## Abstract

## INTRODUCTION

## EXPERIMENTAL SETUP

Our experimental system consists of between 20 and 300 9Be+ ions confined to a single-plane Coulomb crystal in a Penning trap, described in Fig. 1 and (ref). The trap is characterized by an axial magnetic field $B = 4.45$ T and an axial trap frequency $\omega_z = 2\pi x 1.57$ MHz. A stack of cylindrical electrodes generates a harmonic confining potential along their axis. Radial confinement is provided by the Lorentz force from $\vec{E} \times \vec{B}$-induced rotation in the axial magnetic field. Time varying potentials applied to eight azimuthally segmented electrodes generate a rotating wall potential that controls the crystal rotation frequency $\omega_r$, typically between $2\pi \times 172$ kHz and $2\pi \times 190$ kHz. The spin-1/2 system is the ${}^2S_{1/2}$ ground state of the valence electron spin $|\uparrow\rangle$ ($|\downarrow\rangle$) $\equiv |m_s = +1/2\rangle$ ($|m_s = -1/2\rangle$). In the magnetic field of the Penning trap, the ground state is split by 124 GHz. A resonant microwave source provides an effective transverse field, which we use to perform global rotations of the spin ensemble with a Rabi frequency of 8.3 kHz. The T2 spin echo coherence time is 15 ms. Optical transitions to the ${}^2P_{3/2}$ states are used for state preparation, Doppler cooling, and projective measurement.

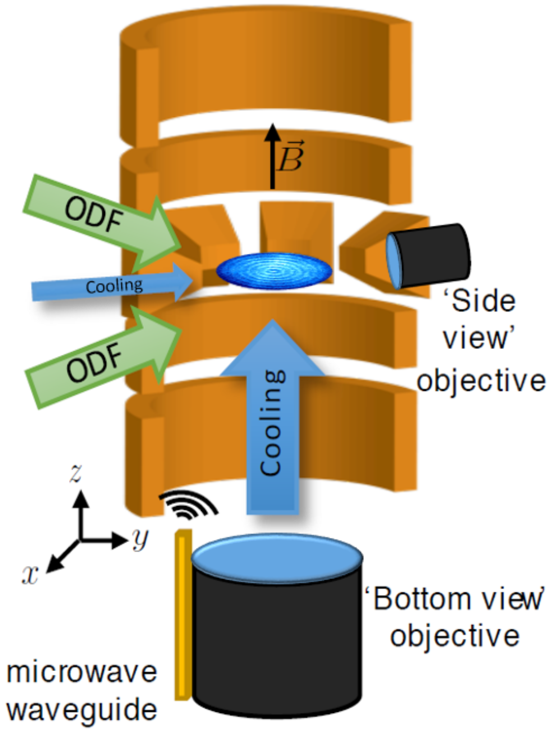
By measuring the decrease in the composite Bloch vector length produced by the application of a homogenous spin-dependent force, detailed information about the motional state of the ions is revealed. This spin dephasing is directly measured. The spin-dependent optical dipole force (ODF) is generated from the interference of a pair of detuned lasers, shown in Fig. 1a. The ODF couples the spin and motional degrees of freedom through the interaction

$$H_{ODF} = U \sum_i \sin(\delta k \cdot z_i - \mu t + \phi)\sigma_i^z \tag{1}$$

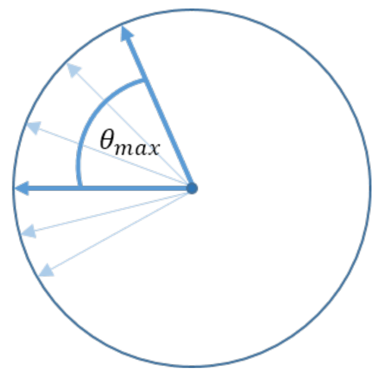
where $z_i$ is the position operator for ion $i$ and $\mu/2\pi$ is the ODF laser beatnote frequency. This can be approximated as

$$H_{ODF} = U \sum_i \sin(\delta k \cdot z_i) \cos(\mu t + \phi)\sigma_i^z$$

.




(a)




(b)

FIG. 1

To find the precession due to an axial oscillation, consider a classical driven motion of constant amplitude and phase, $z_i \to z_i + z_0 \cos(\omega t + \delta)$.

Then,

$$H_{ODF} = DWF \cdot U \cdot \delta k \cdot z_0 \cos((\omega - \mu)t + \delta + \phi) \sum_i \frac{\sigma_i^z}{2}$$

,

where $DWF = \exp(-\delta k^2 \langle z_i^2 \rangle /2)$.

For $\omega = \mu$,

$$\theta = \Delta\tau = DWF \cdot U \cdot \delta k \cdot z_0 \tau \cos(\delta - \phi) = \theta_{max} \cos(\delta - \phi)$$

where $\Delta$ is the energy difference between spin-up and spin-down for each ion.

We do our experiments phase incoherently (provide some motivation, ala Ozeri paper? or just explain that this is a limitation? probably both), but can extract the maximum precession angle, $\theta_{max}$. In a Ramsey sequence where the Bloch vector with no precession is rotated down to the dark state, the component along $-\hat{z}$ has length $\cos(\theta)$. Thus the probability for measuring spin-up is $P_\uparrow = \frac{1}{2}[1 - e^{-\Gamma\tau}\cos(\theta)]$, where $\tau$ is the total ODF interaction time and $\Gamma = \frac{1}{2}(\Gamma_{el} + \Gamma_{ram})$ is the spontaneous decay rate where $\Gamma_{el}$ ($\Gamma_{ram}$) is the elastic (Raman) scattering decoherence rate (Uys PRL ref). To model the phase incoherent experiment, one must average over this length, $\langle\cos(\theta)\rangle$. It can be shown that $\langle\cos(\theta)\rangle = J_0(\theta_{max})$, where $J_0$ is the zeroth order Bessel function of the first kind. Thus,

$$\langle P_\uparrow\rangle = \frac{1}{2}[1 - e^{-\Gamma\tau}J_0(\theta_{max}). \tag{2}$$

To create an axial oscillation, we apply an AC voltage (RF potential?) to the endcap of the Penning trap. This can be done either on-resonance or off-resonance with the center of mass mode of the ion crystal at $2\pi \times 1.57$ MHz. To calibrate the displacement of the ions as a result of this applied drive, we apply a static voltage to the endcap and measure the deflection of the ion crystal. From this calibration, we find 1 mV results in 1 nm of displacement.

## OFF-RESONANCE AMPLITUDE SENSING

Scanning the power of the ODF laser varies the strength of the measurement. By comparing the peak of the curve to the background, the signal and the signal-to-noise can be extracted. From this, the sensitivity of the sequence is found.

## ON-RESONANCE AMPLITUDE SENSING

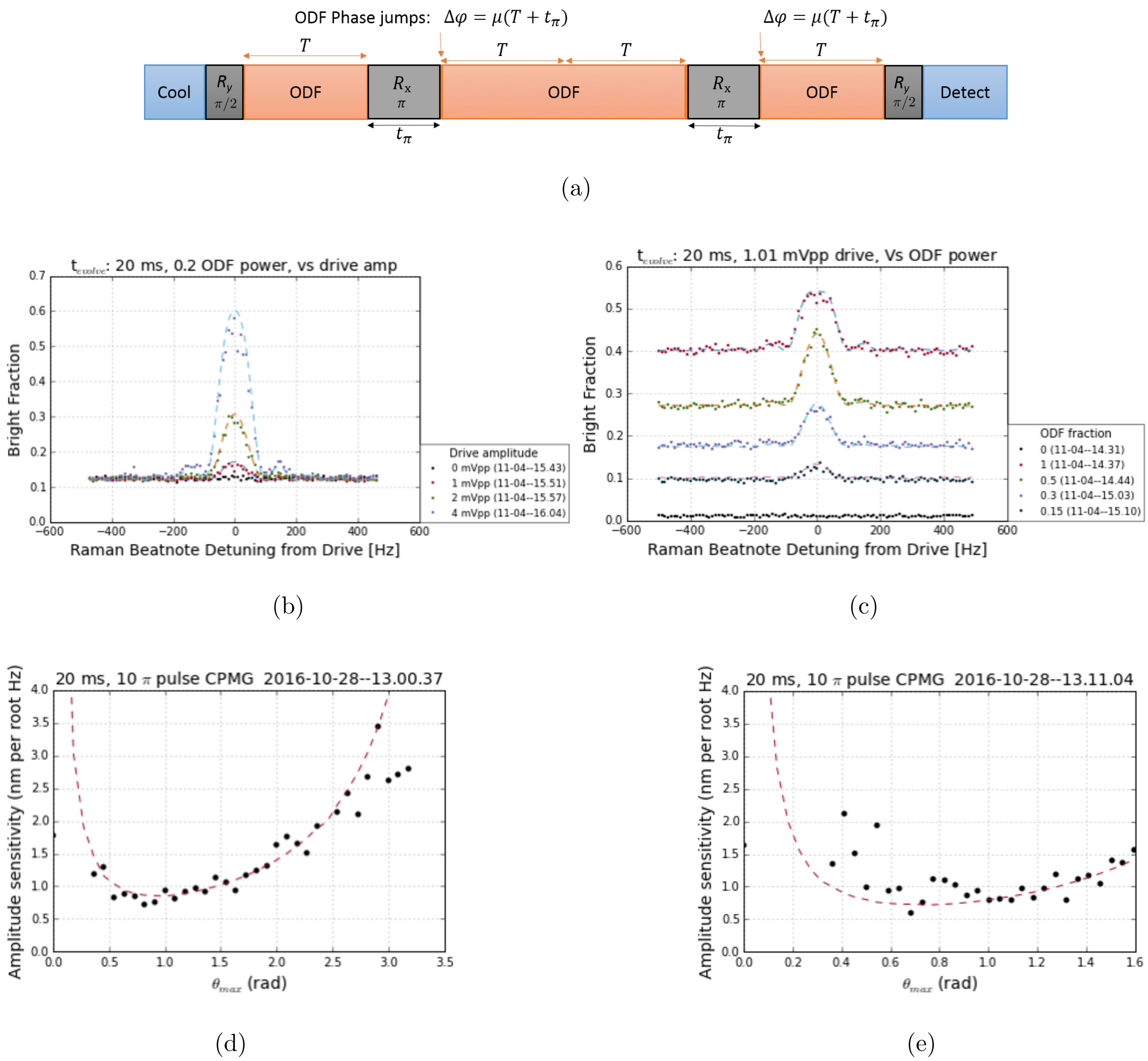

ODF Phase jumps: $\Delta\varphi = \mu(T + t_\pi)$
$\Delta\varphi = \mu(T + t_\pi)$
Cool
$R_y$ $\pi/2$
ODF
$R_x$ $\pi$
ODF
$R_x$ $\pi$
ODF
$R_y$ $\pi/2$
Detect
$T$
$t_\pi$
(a)
$t_{evolve}$: 20 ms, 0.2 ODF power, vs drive amp
Bright Fraction
Raman Beatnote Detuning from Drive [Hz]
Drive amplitude
0 mVpp (11-04--15.43)
1 mVpp (11-04--15.51)
2 mVpp (11-04--15.57)
4 mVpp (11-04--16.04)
(b)
$t_{evolve}$: 20 ms, 1.01 mVpp drive, Vs ODF power
Bright Fraction
Raman Beatnote Detuning from Drive [Hz]
ODF fraction
0 (11-04--14.31)
1 (11-04--14.37)
0.5 (11-04--14.44)
0.3 (11-04--15.03)
0.15 (11-04--15.10)
(c)
20 ms, 10 $\pi$ pulse CPMG 2016-10-28--13.00.37
Amplitude sensitivity (nm per root Hz)
$\theta_{max}$ (rad)
(d)
20 ms, 10 $\pi$ pulse CPMG 2016-10-28--13.11.04
Amplitude sensitivity (nm per root Hz)
$\theta_{max}$ (rad)
(e)

FIG. 2