

Artificial Vector Potentials

The “minimally-coupled” kinetic energy Hamiltonian, describing the dynamics of a charged particle q has the form

$$\hat{H} = \frac{1}{2m} (\hat{p} - q\vec{A}(\vec{x}, t)/c)^2, \quad (1)$$

where $\vec{A}(\vec{x}, t)$ is the classical vector potential. In the last decade, it has become possible to produce and observe the effects of so-called “artificial vector potentials” in ultracold quantum gases [1].

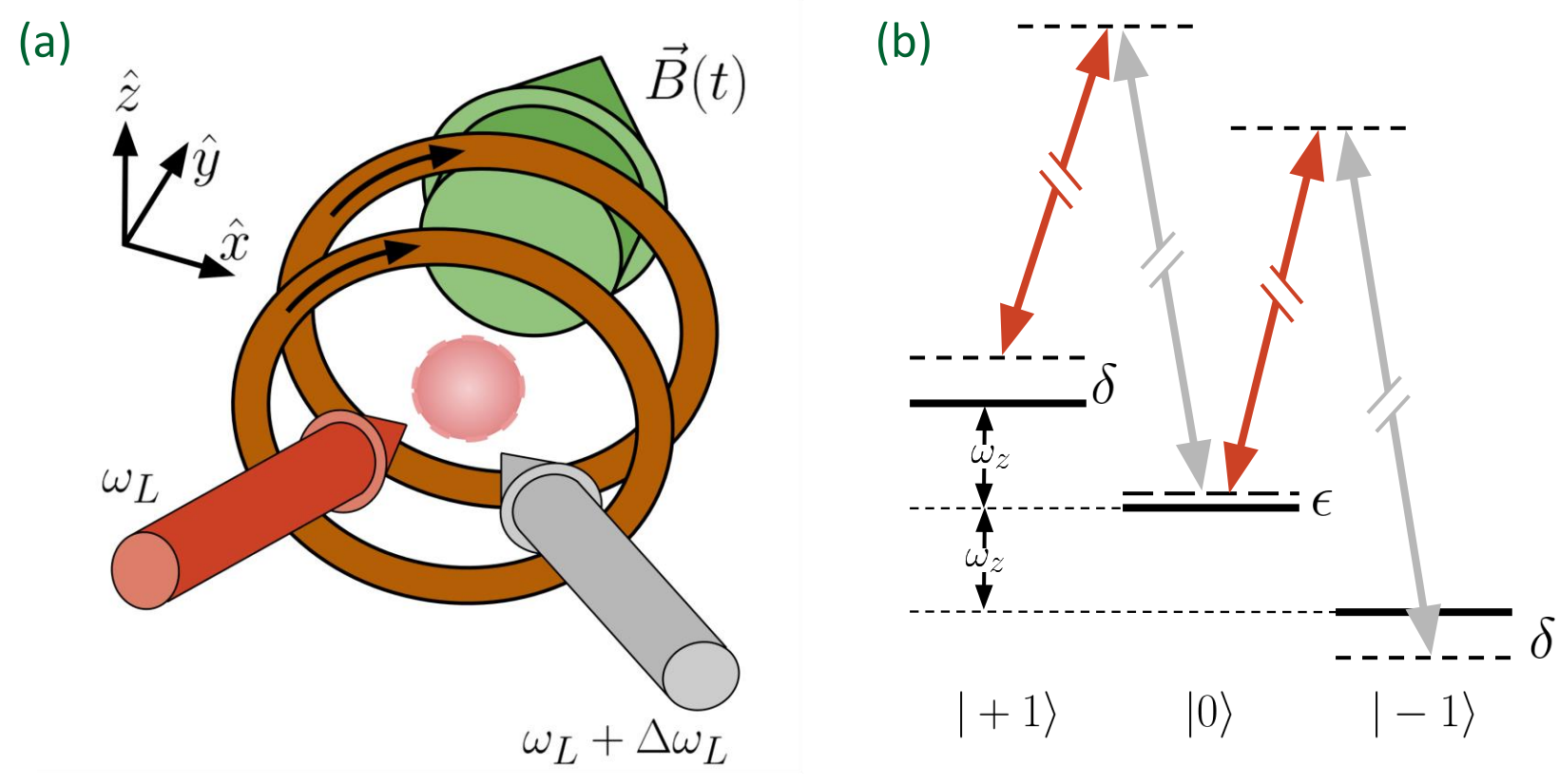


Fig. 1. (a) A bias magnetic field $B(t)$ providing a 2.4 mG field. Raman beams at 790 nm with 35 mW in each beam and $\Delta\omega_L = 1.5$ MHz. (b) Raman-coupled Zeeman-split levels of the ^{87}Rb $F=1$ ground state. ϵ is the quadractic Zeeman shift.

The Raman Coupling Scheme

In the Raman coupling scheme shown in Fig. 2a-b, a magnetic bias field $B(t)$ and two Raman laser beams provide the tools necessary to create an artificial vector potential. The bias field splits the Zeeman spin levels of an atom. Pairs of spin levels are coupled via two-photon, Λ -configuration Raman transitions. A Raman transition of this geometry supplies a recoil momentum kick of $2k_L$ to the atoms. Hence, the individual spin states become separated in momentum space from each other by $2k_L$; the three separated energy-momentum dispersions (dashed curves) in Fig. 2a illustrate this concept. A strong Raman coupling ($\Omega \geq 4.47 E_L/\hbar$) has the additional effect of mixing the spin states into one large parabolic ground state dispersion of effective mass m^* . A non-zero two-photon Raman detuning δ (see also Fig. 1b) shifts the minimum k_{min} of the parabolic dispersion to one side or the other in momentum space.

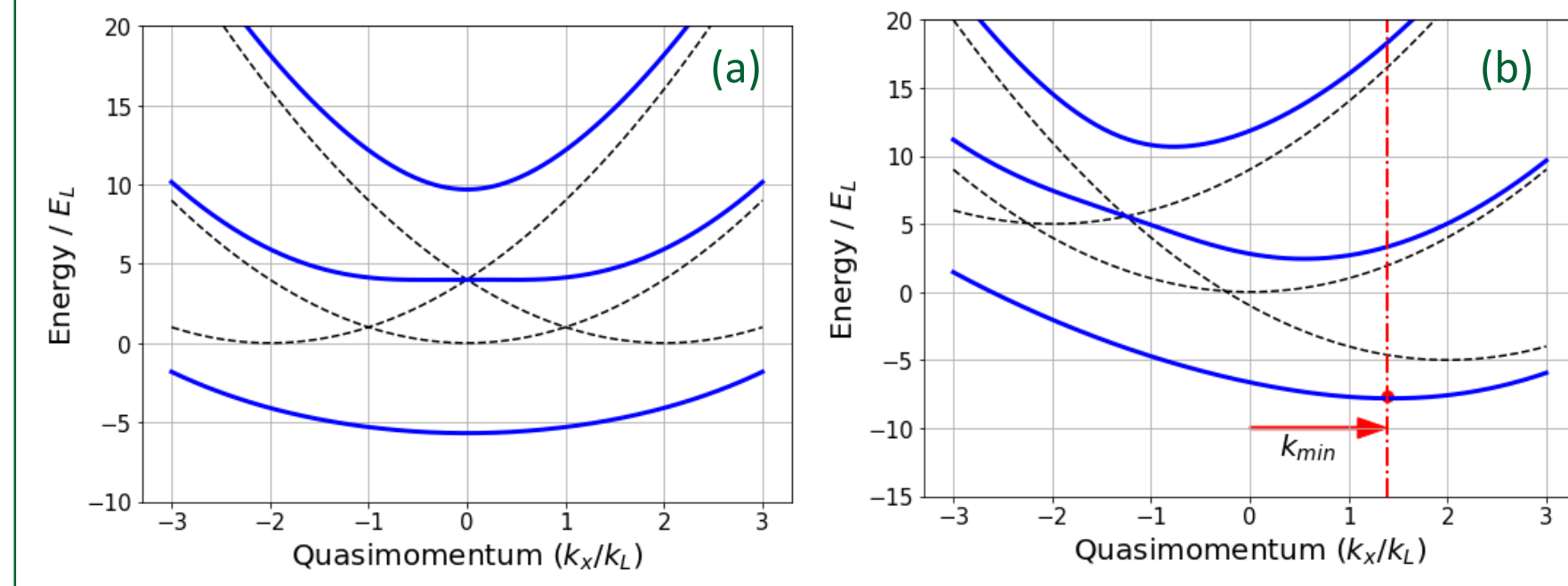


Fig. 2. (a) Raman-dressed spin-1 dispersions (solid) and individual undressed dispersions (dashed), strongly coupled at zero detuning. (b) Changing the detuning to a non-zero value (here, $\delta = -5E_L/\hbar$) shifts the minimum of the lowest dressed dispersion band.

A dispersion of this form, $\frac{\hbar^2}{2m^*} (\vec{k}_x - k_{min})^2$, is exactly analogous to the momentum representation of equation (1), where k_{min} is playing the role of the vector potential; in this sense, k_{min} is a synthetic – or artificial – gauge potential. With this Raman coupling scheme, we can make a Bose-Einstein condensate simulate dynamics of charged particles in a vector potential*.

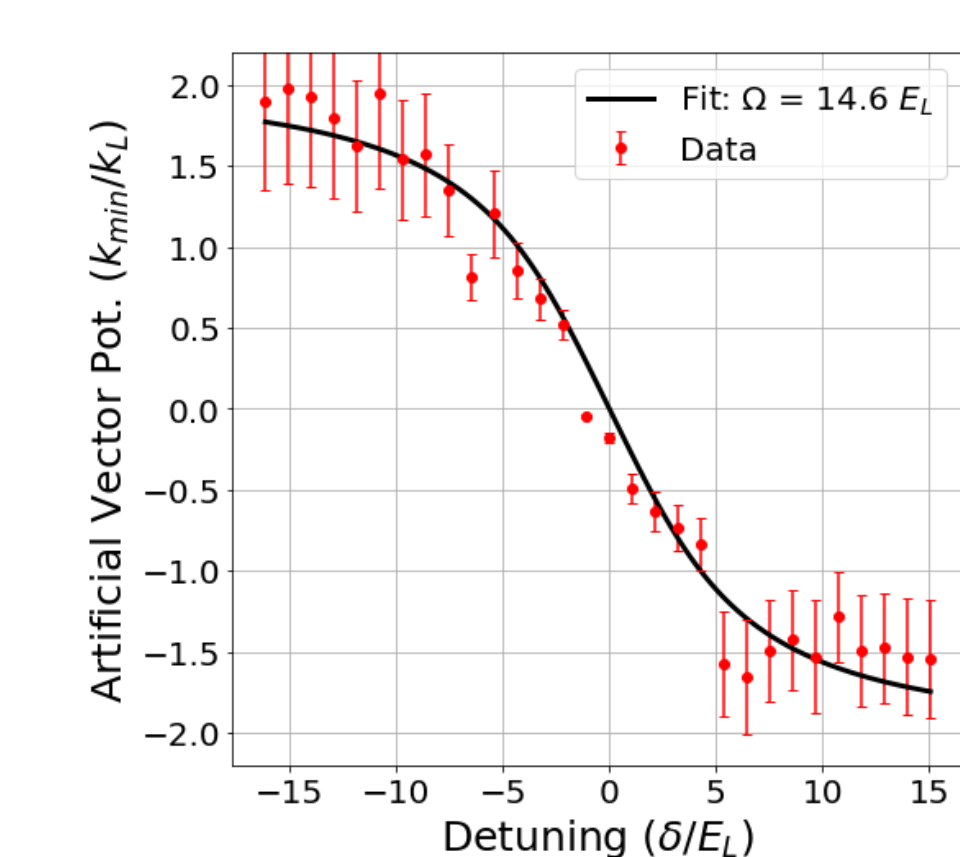


Fig. 3. The dependence of our measured artificial gauge potential k_{min} on the Raman detuning for an $\Omega = 14.6 E_L/\hbar$. Near zero detuning, the vector potential changes roughly linearly. (E_L is the natural energy scale of the system: $E_L = \hbar^2 k_L^2/2m$, where k_L is the single photon recoil momentum along the x-direction.)

*It's important to note that this specific Raman scheme cannot fully emulate so-called “dynamical gauge theories”, such as Maxwell’s equations. This is because the matter experiencing the synthetic field does not produce a back-action on the field itself [2].

Application: Artificial AC Electric Forces

Artificial vector potentials have been able to simulate phenomena such as charged particles in DC electric field pulses [3] (see Fig. 4) and magnetic fields [4], and even electromagnetic knots [5].

We want to extend upon these methods to simulate an oscillating electric field. A Raman detuning that varies sinusoidally can create an artificial AC vector potential (Fig. 5). The induced AC electric field $\vec{E}^*(x, t)$ will drive the motion of the atoms inside their harmonic confining potential. We expect the response of the atoms to depend upon the frequency of the trap potential, similar to a driven harmonic oscillator.

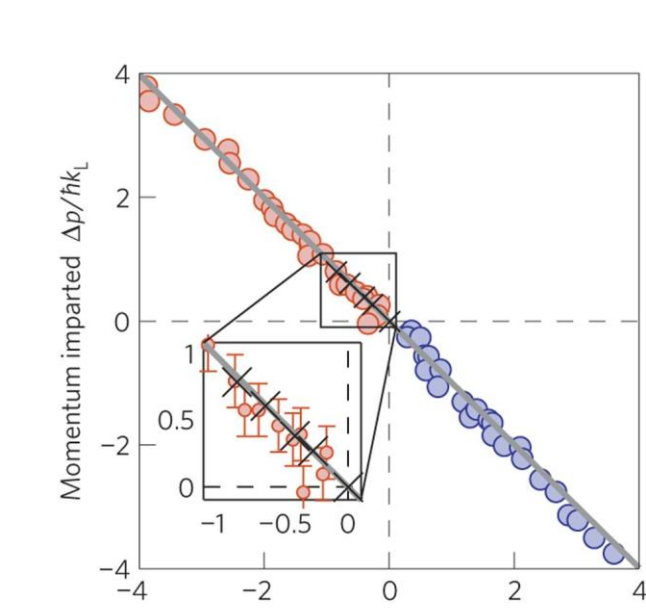


Fig. 4. Figure 3 from [3], demonstrating the change in momentum experienced by the atoms from rapid change in a synthetic vector potential (reproduced with permission).

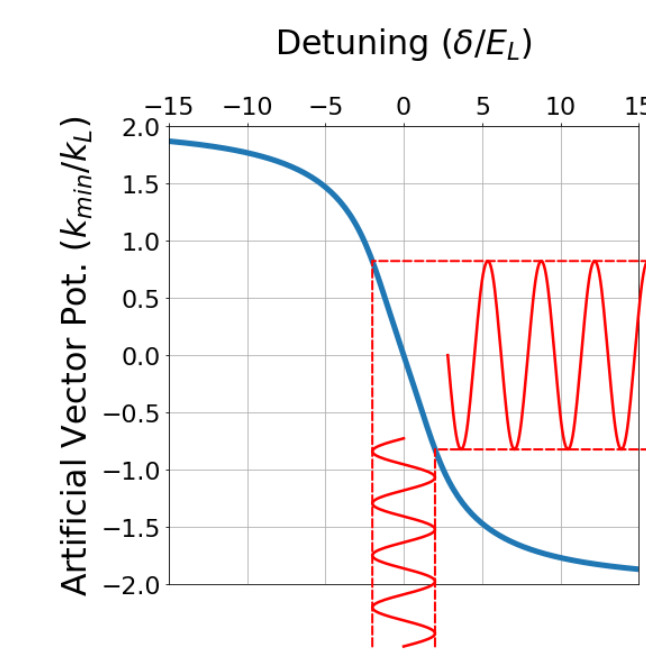


Fig. 5. Around small δ , a modulated Raman detuning produces a sinusoidal vector potential. This time-dependence would produce an artificial AC electric field.

Preliminary Results

From our TOF images (Fig. 7) we extract the atom number N_{mp} and position of each spin-component. These values allowed us to calculate the induced artificial vector potential k_{min} and the spin polarization $P = \frac{\sum m_F N_{m_F}}{\sum N_{m_F}}$ of the cloud for different values of T_{wig} (Fig. 8). We see that k_{min} and P oscillate at the same frequency. This is consistent with the experimental work and studies done on collective oscillatory motion in the presence of spin-orbit coupling [7] [8].

At low driving amplitudes we consistently saw that the atoms responded close to 60 Hz, which revealed an intrinsic 60 Hz ripple in the current supplying the bias magnetic field coils. The electrical current amplitude of that ripple corresponded to $\delta_0 \approx 10 E_L$. By feeding-forward a 60 Hz signal, we have initially been able to modify - but not yet completely cancel out - the effect of this ripple.

At larger driving amplitudes, we also observed density fringing taking place, mostly at the extrema of the clouds’ motion (Fig. 9). Further work is needed to understand this effect.

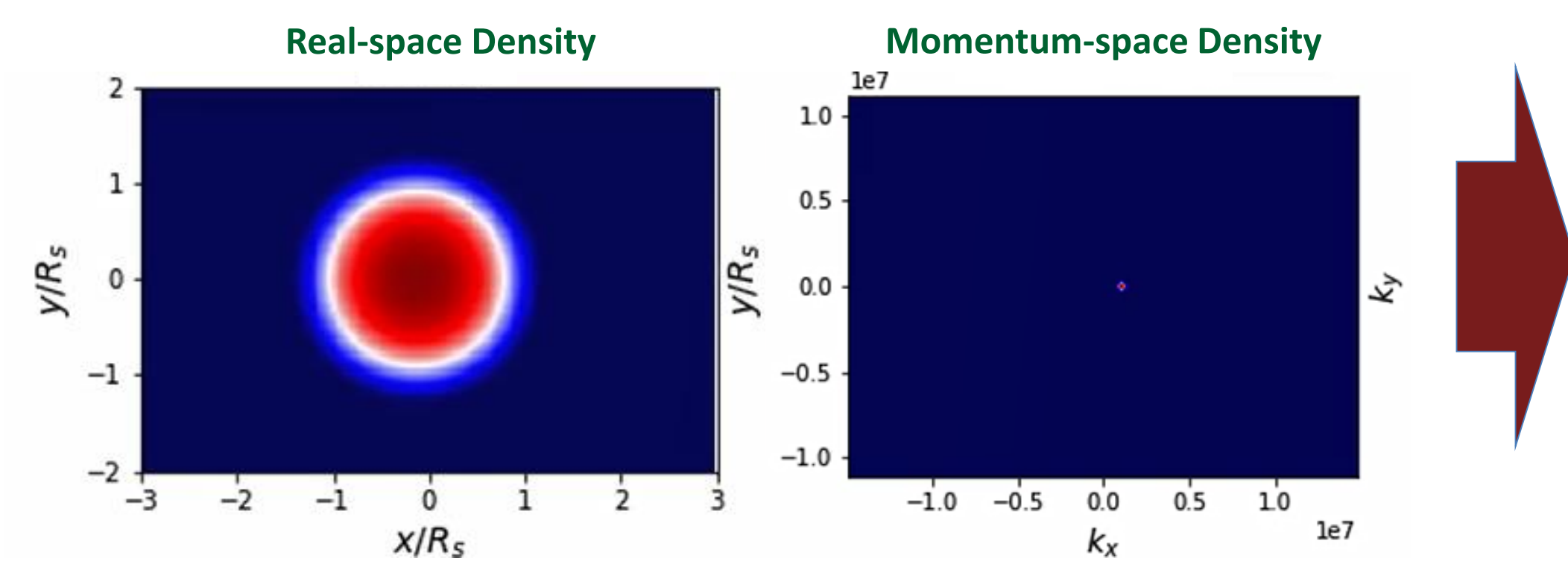


Fig. 10. A single-time snapshot of a BEC in a Gross-Pitaevskii equation simulation of an artificial vector potential subject to an oscillating detuning, where $\hbar\Omega = 10.5 E_L$, $\hbar\delta_0 = 0.25 E_L$, and the bare trap frequencies are $\omega = 2\pi (60, 60, 120) \text{ rad}^{-1}$. Notice that in this snapshot, the cloud position and momentum are both slightly displaced from zero.

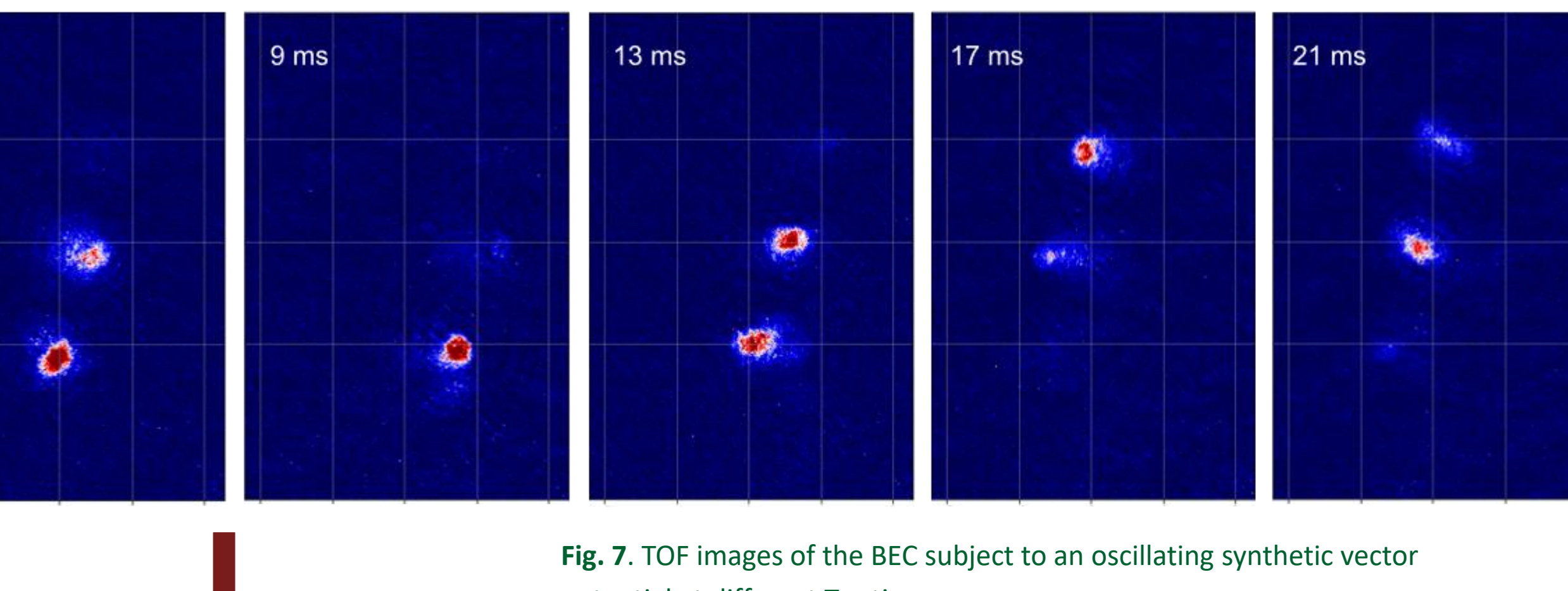


Fig. 7. TOF images of the BEC subject to an oscillating synthetic vector potential at different T_{wig} times.

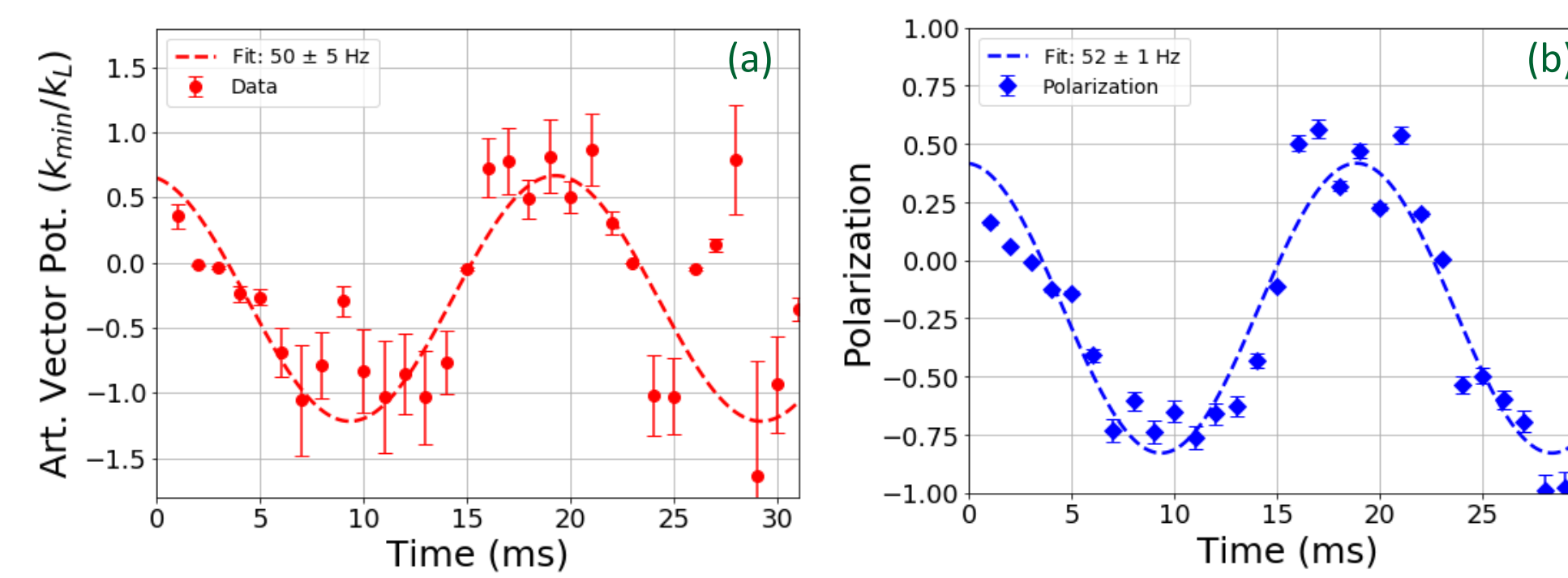


Fig. 8. The extracted vector potential (a) and the spin polarization (b) of the states as a function of T_{wig} . Both oscillated at about the same frequency.

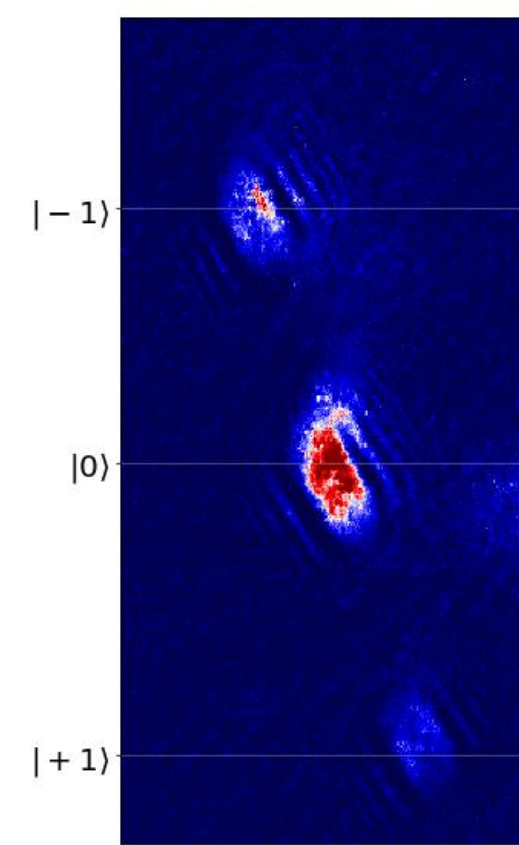


Fig. 9. Density fringing in TOF images of BEC subject to a larger amplitude AC artificial electric force ($\hbar\delta_0 = 12.5 E_L$). This image was taken near one of the peaks of oscillation.

We are also studying the dynamics of a trapped BEC in an artificial AC vector potential using GPU-accelerated, Python-based code that we have recently developed. The code propagates solutions to the mean-field Gross-Pitaevskii equation in real time [9]. From the simulations, we extract and analyze the position and momentum of the cloud as a function of time (Fig. 11).

While the experimental work is currently limited in the frequencies we can drive the artificial vector potential, these simulations provide a means to study the AC frequency-dependence of a driven condensate. Our initial results indicate that there is enhanced response when driven at close to half of the Raman-free trap frequency.

Fig. 11. Extracted positions and momenta from the simulated BEC for a drive frequency of 40 Hz. Fits to each quantity reveal a beating effect between the drive frequency and another at 31.5 Hz.

Experimental Sequence

- ❖ **RF, RF + Raman:** We initially prepare our BEC in the $|F, m_F\rangle = |1, -1\rangle$ ground state of ^{87}Rb . Using a RF-assisted loading technique developed by the Spielman lab [6], we move atoms in the lowest Raman-dressed energy band at zero momentum (Fig. 2a). We evaporate the ODT to a trap frequency of ~ 75 Hz (measured without Raman beams) along the x-direction.
- ❖ **Hold:** We have the option of ramping the detuning to a non-zero gauge potential. For now we keep it constant and the gauge potential zero.
- ❖ **T_{wig} :** For a variable amount of time, T_{wig} , we sinusoidally modulate the Raman detuning $\delta(t) = \delta_0 \sin(2\pi f t)$ via the bias current. Typical values of δ_0 are around 20 kHz.
- ❖ **Off, TOF:** We turn off the Raman beams and optical dipole trap (ODT) to project the Raman-dressed states back onto the bare spin-momentum states. We allow the atoms to fall in a vertical Stern-Gerlach gradient magnetic field, in time-of-flight for 25 ms. During TOF, the spin components with different momentum separate horizontally; the gradient field also separates the spin components vertically (see Fig. 7).

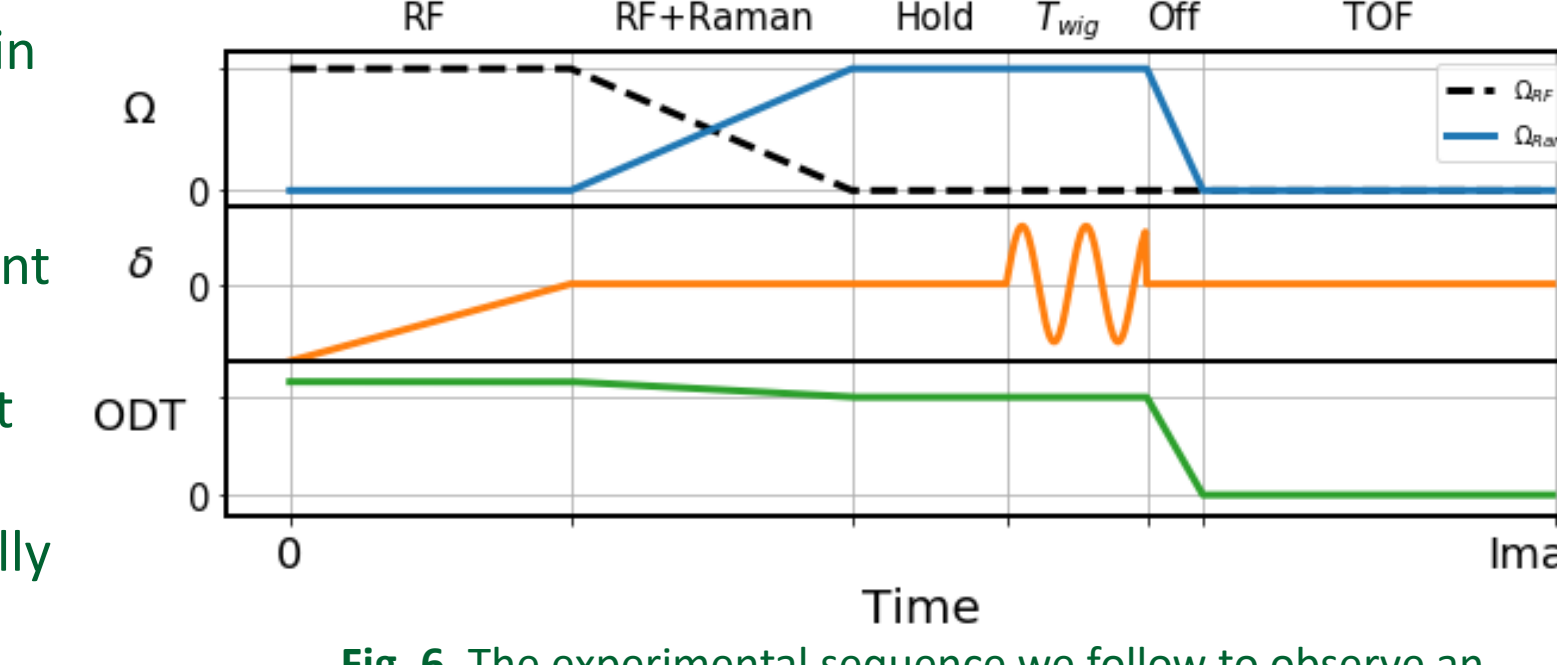


Fig. 6. The experimental sequence we follow to observe an artificial AC electric force.

Conclusion & Outlook

We have seen evidence of collective oscillations of a BEC driven by an AC artificial vector potential. Numerical Gross-Pitaevskii equation simulations of a BEC under like circumstances show similar results. We wish to refine and extend our work in the following areas:

- ❖ **Experiment** – To understand the BEC’s drive frequency-response, we will particularly need to reduce or control the 60 Hz ripple in the magnetic bias coil current. Improved feedback control on the current supply may provide the solution. We can also investigate the origin of the fringes sometimes seen in the TOF images. Furthermore, we wish to extend upon the artificial magnetic field techniques [4] and implement an oscillating detuning gradient. This will ideally emulate an oscillating uniform magnetic field, accompanied by oscillating, curling electric field (Fig. 12).

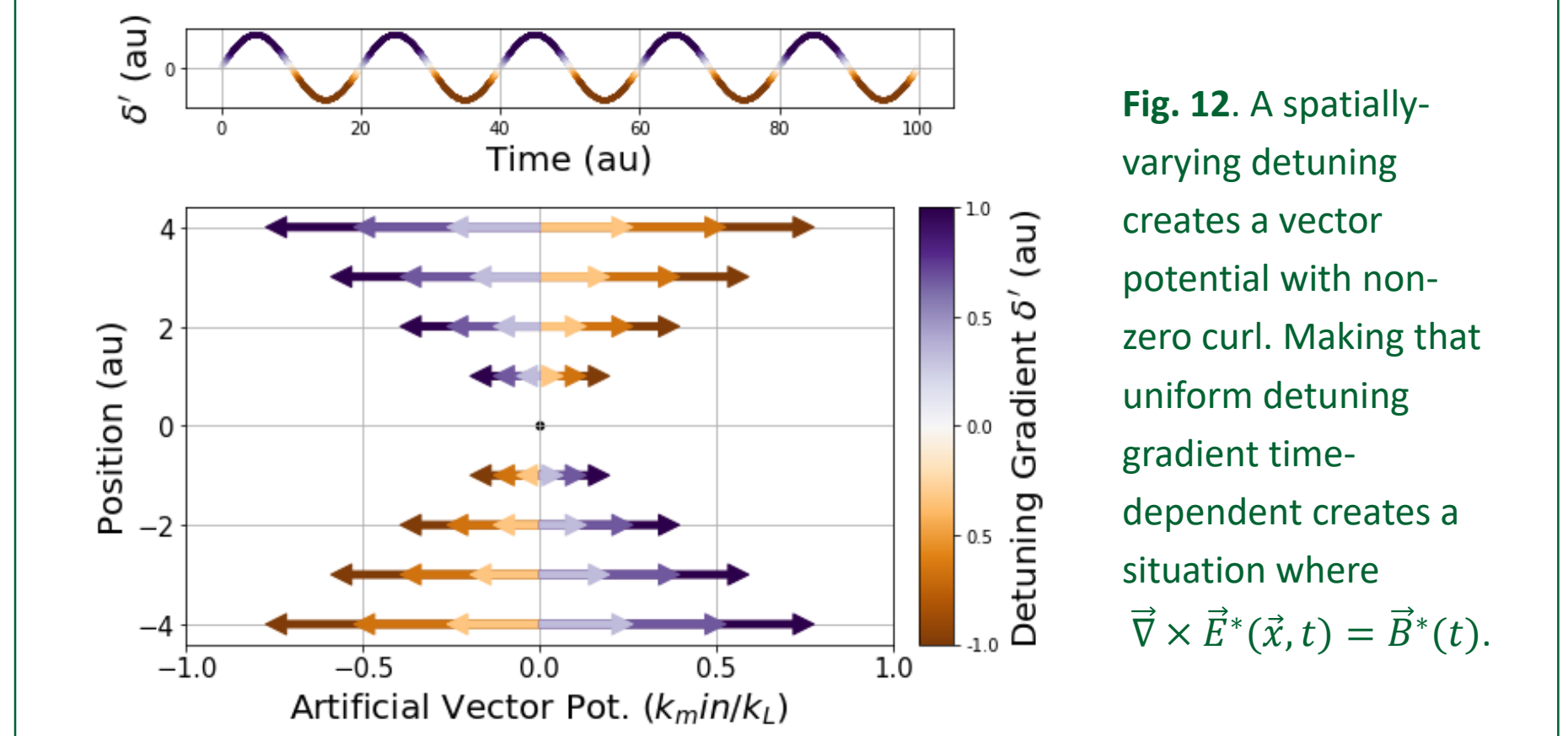


Fig. 12. A spatially-varying detuning creates a vector potential with non-zero curl. Making that uniform detuning gradient time-dependent creates a situation where $\vec{\nabla} \times \vec{E}^*(\vec{x}, t) = \vec{B}^*(t)$.

- ❖ **Simulation** – In our simulations, we want to investigate how interactions affect the way the BEC experiences and responds to an AC artificial electric force. Additionally, we will easily be able to simulate the time-dependent detuning gradient proposed above.

References

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