Dipolar magnetostirring protocol for three-well atomtronic circuits

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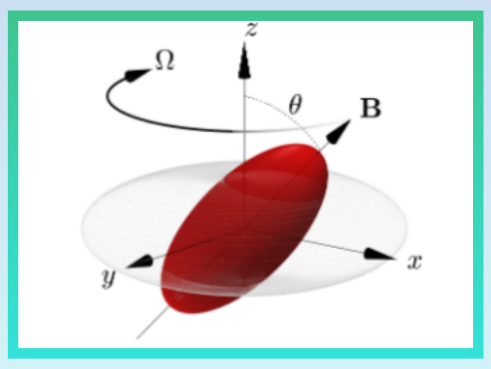
We propose a **magnetostirring** protocol to create **persistent currents** on an annular system, which are a fundamental part of the design of **atomtronic** devices. Under this protocol, **polar bosons** confined in a **three-well ring circuit** reach a state with high average circulation. We model the system with an **extended Bose-Hubbard Hamiltonian** and show that the protocol can create circulation in an atomtronic circuit for a range of tunable parameters. The performance and robustness of this scheme are examined. We also present a method for **predicting the optimal protocol parameters**, which improves the protocol's scalability and enables its application to systems with large numbers of bosons. This overcomes computational limitations and paves the way for exploring macroscopic quantum phenomena.

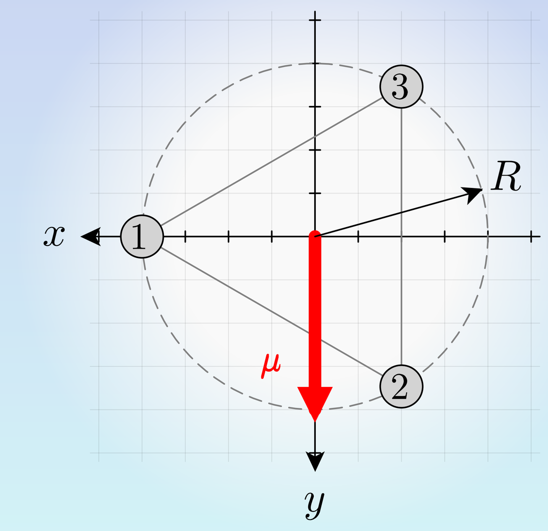
1. Motivation

- **Atomtronics** [1] is an emerging field that aims to build matter-wave circuits with **ultracold atoms**, such as with a BEC.
- One fundamental problem is the generation of **persistent circulation** in closed circuits.
- Current methods for generating circulation include barrier stirring [2] and phase imprinting [3].
- Here we use **magnetostirring** [4,5] as a new method for creating circulation by **rotating the polarisation** of **polar bosons**.



2. Model

- **3-well** triangular system.
- *N* **dipolar** polarised **bosons**.
- **Orientable polarisation**.



Circulation unit: $L_0 = \frac{2\pi}{\sqrt{3}} \frac{JmR^2}{\hbar}$

Extended Bose-Hubbard Hamiltonian:

$$\hat{H} = -J\sum_{j=1}^{3}(\hat{a}^\dagger_{j+1}\hat{a}_j + \hat{a}^\dagger_j\hat{a}_{j+1}) + \frac{U}{2}\sum_{j=1}^{3}\hat{n}_j(\hat{n}_j-1) + \sum_{j=1}^{3}\sum_{k\neq j}^{3}\frac{V_{jk}}{2}\hat{n}_j\hat{n}_k$$

The **long-range** dipolar interaction term is

$$V_{jk} = \frac{U_d}{|\mathbf{r}_j-\mathbf{r}_k|^3}\left\{1-3\left[\frac{\boldsymbol{\mu}\cdot(\mathbf{r}_j-\mathbf{r}_k)}{|\mathbf{r}_j-\mathbf{r}_k|}\right]^2\right\}$$

where $\boldsymbol{\mu}$ is the **polarisation** direction of the dipoles.

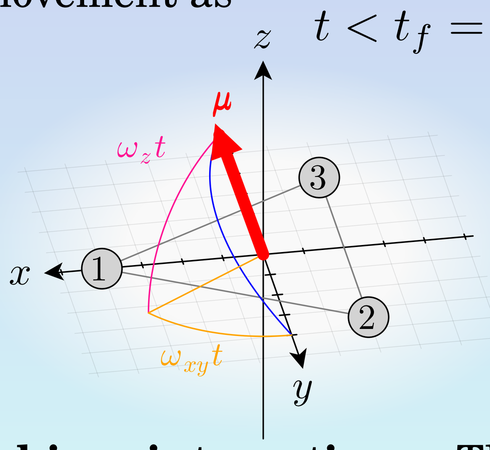
Circulation operator on a circular ring of radius *R*

$$\hat{L}_z = i\,\frac{2\pi}{3}\frac{JmR^2}{\hbar}\sum_{j=1}^{3}\left(\hat{a}^\dagger_{j+1}\hat{a}_j - \hat{a}^\dagger_j\hat{a}_{j+1}\right)$$

3. Protocol definition

- The interaction strengths are equal $U_d = U$.
- The **initial state** is the **ground state** of the initial Hamiltonian
- The polarisation follows a **spiral** movement as $t < t_f = \frac{\pi}{2\omega_z}$

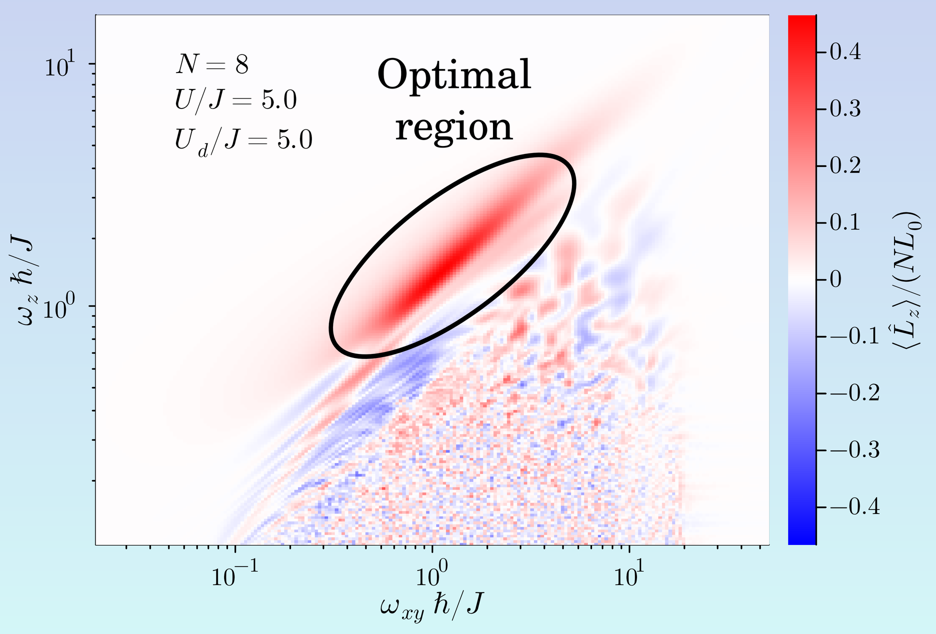
$$\boldsymbol{\mu}\cdot\mathbf{e}_x = \sin(\omega_{xy}\,t)\cos(\omega_z\,t)\,,$$
$$\boldsymbol{\mu}\cdot\mathbf{e}_y = \cos(\omega_{xy}\,t)\cos(\omega_z\,t)\,,$$
$$\boldsymbol{\mu}\cdot\mathbf{e}_z = \sin(\omega_z\,t)\,,$$



The final Hamiltonian has **vanishing interactions**. This ensures that the **generated circulation is preserved**.

4. Parameter optimisation

The two **free parameters** of the protocol should be **optimised** for each interaction strength $Ud = U$ and for each number of bosons N.



In plane projection parameter:

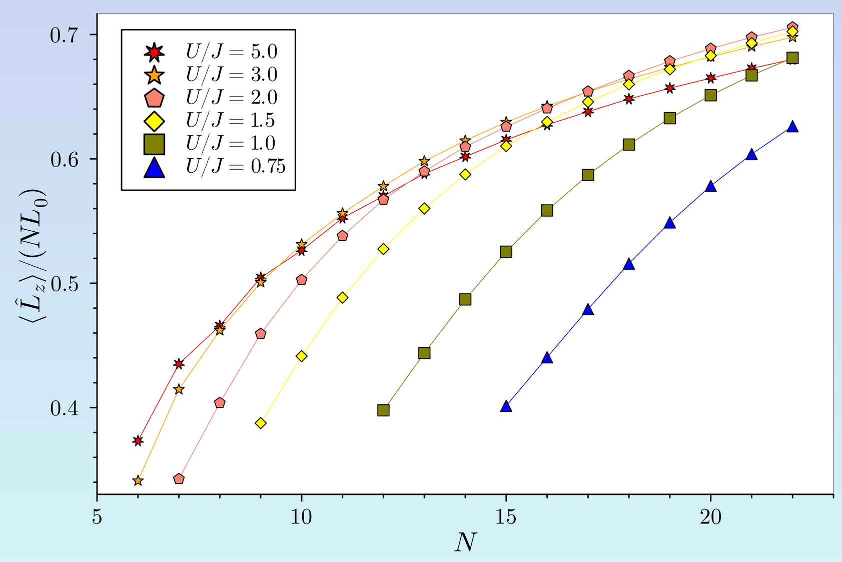
- $\omega_{xy}\,\hbar/J < 0.1$ adiabatic stirring (slow)
- $\omega_{xy}\,\hbar/J > 11$ antidipolar stirring (fast)

Azimuthal projection parameter:

- $\omega_z\,\hbar/J > 10$ quench protocol (short)
- $\omega_z\,\hbar/J < 0.5$ unresolved pattern (long)

5. Dependence on the number of bosons

The generated **circulation increases with the number of bosons**, increasing the performance of the protocol.

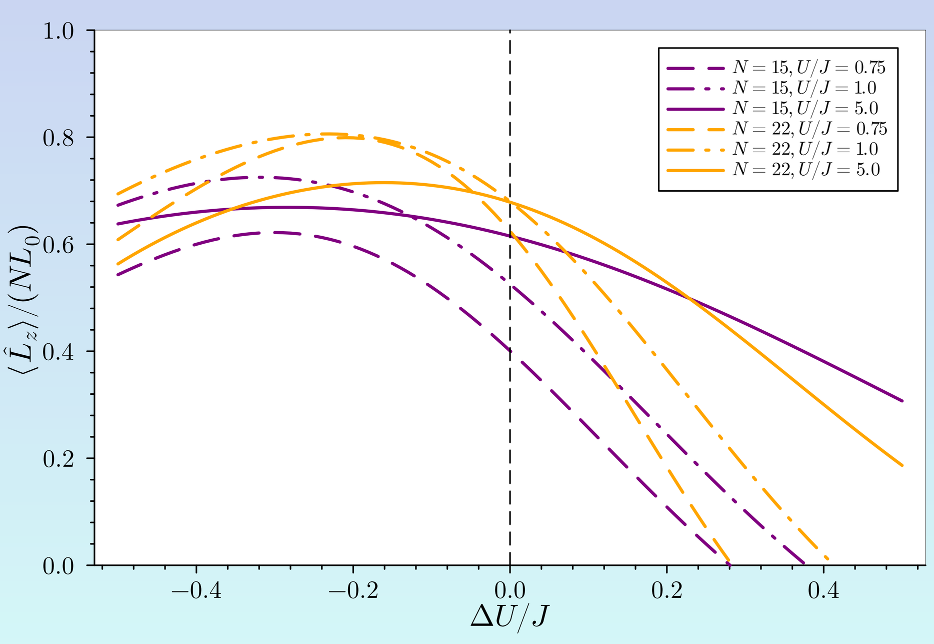


Many particles limit:

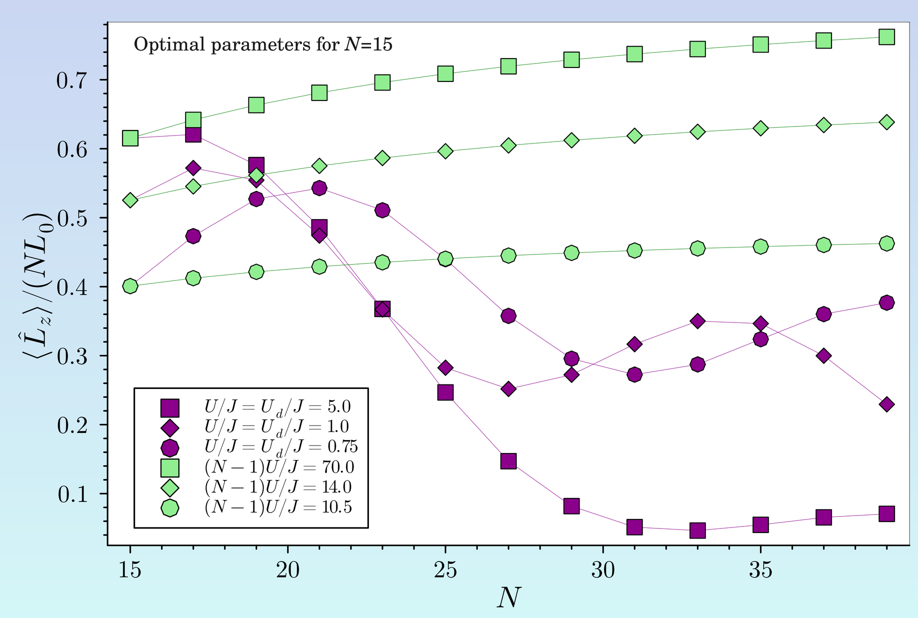
$$\langle \hat{L}_z \rangle/(NL_0) \underset{N>>1}{\longrightarrow} 1$$

6. Robustness

The generated circulation changes if $U_d \neq U$.



The circulation also depends on N. However, it becomes approximately constant for fixed. $(N\text{-}1)U/J$



7. Outlook

- **Magnetostirring** is a feasible **alternative** to the already existing techniques for **generating persistent currents**.
- Future work:
  - Consideration of continuos **toroidal condensates**.
  - Use of **quantum control theory** to find optimal polarisation trajectories (see Ref. [6]).

References

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