Control of Quantum Dynamics on an Atom Chip

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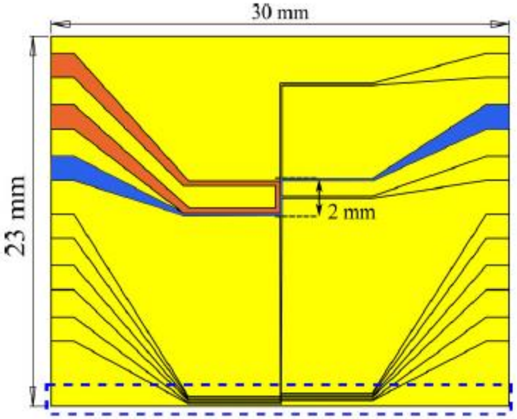
EGAS 46

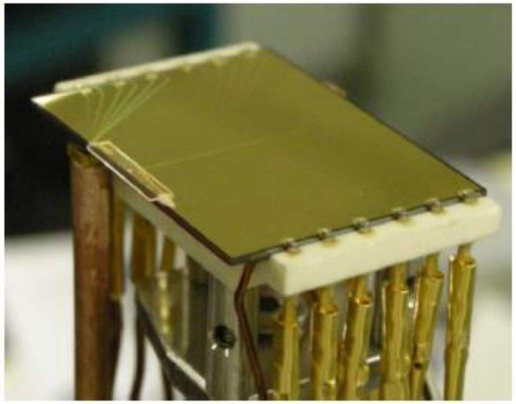
Control of Quantum Dynamics on an Atom Chip

- AtomChip Experiment
- Optimal Control of Quantum dynamics
- Inverting time evolution
- Creating subspaces via Quantum Zeno Dynamics
- Conclusions

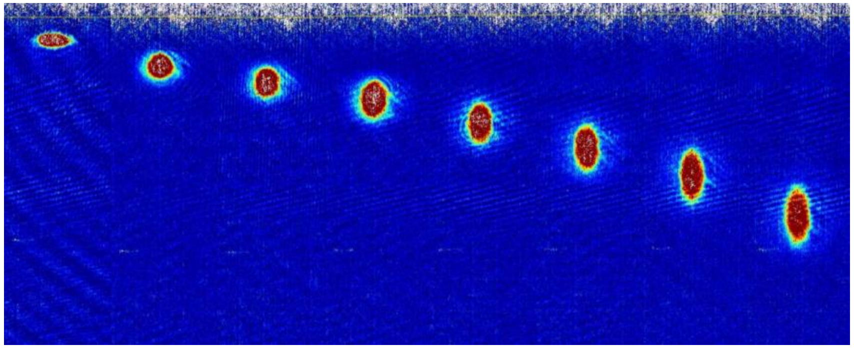
European Laboratory for Non-Linear Spectroscopy

Atom Chip Experiment

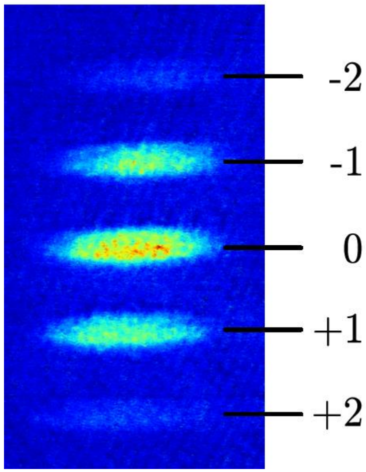




- Compact, easy-to-use and stable setup
- From zero to BEC in 8 seconds
- Integrated auxiliary conductors as RF antennae

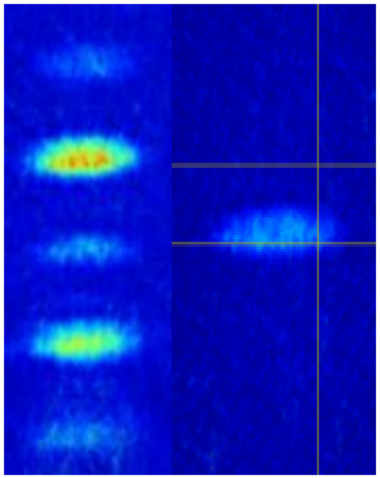


Stern-Gerlach discrimination



Hyperfine state discrimination

F=2 F=1



"Degenerate Quantum Gases Manipulation on Atom-chips"
I. Herrera, J. Petrovic, P.Lombardi, S. Bartalini and F.S. Cataliotti
Physica Scripta **T149**, 014002 (2012).

A multi-state interferometer on an atom chip
J. Petrovic, I. Herrera, P. Lombardi, F. Schaefer, F. S. Cataliotti
New Journal of Physics **15** (4), 043002 (2013)

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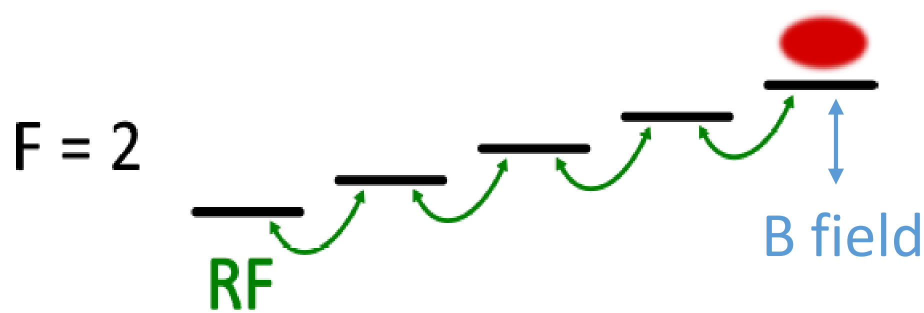
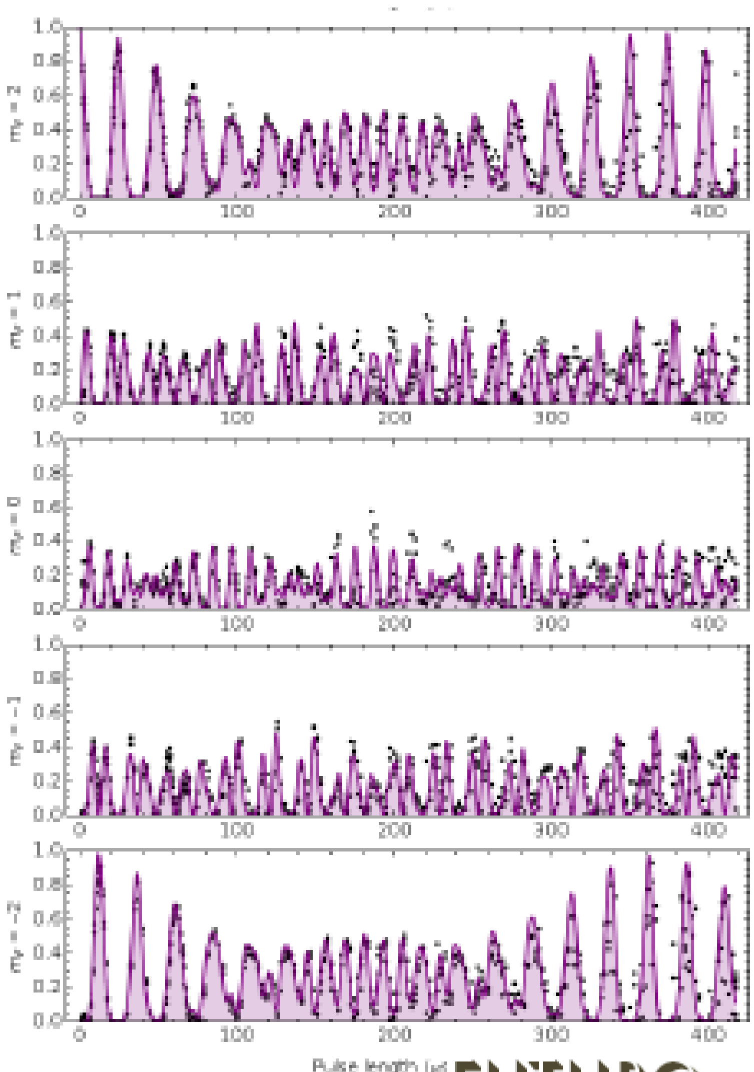
The system

$$H_{RWA}(\alpha) = \hbar \begin{pmatrix} \omega_2(B) - 2\omega & \Omega & 0 & 0 & 0 \\ \Omega & \omega_1(B) - \omega & \sqrt{3/2}\,\Omega & 0 & 0 \\ 0 & \sqrt{3/2}\,\Omega & \omega_0(B) & \sqrt{3/2}\,\Omega & 0 \\ 0 & 0 & \sqrt{3/2}\,\Omega & \omega_{-1}(B) + \omega & \Omega \\ 0 & 0 & 0 & \Omega & \omega_{-2}(B) + 2\omega \end{pmatrix}$$

$$\alpha = \{\Omega, B, \omega\}$$



Constant pulse evolution



Energies of the levels are given by the Breit-Rabi formula.

$$\Delta E_{F=I\pm 1/2} = -\frac{h\Delta W}{2(2I+1)} + \mu_B g_I m_F B \pm \frac{h\Delta W}{2}\sqrt{1+\frac{2m_F x}{I+1/2}+x^2}$$

$$x \equiv \frac{\mu_B B(g_J - g_I)}{h\Delta W} \qquad \Delta W = A\left(I+\frac{1}{2}\right),$$

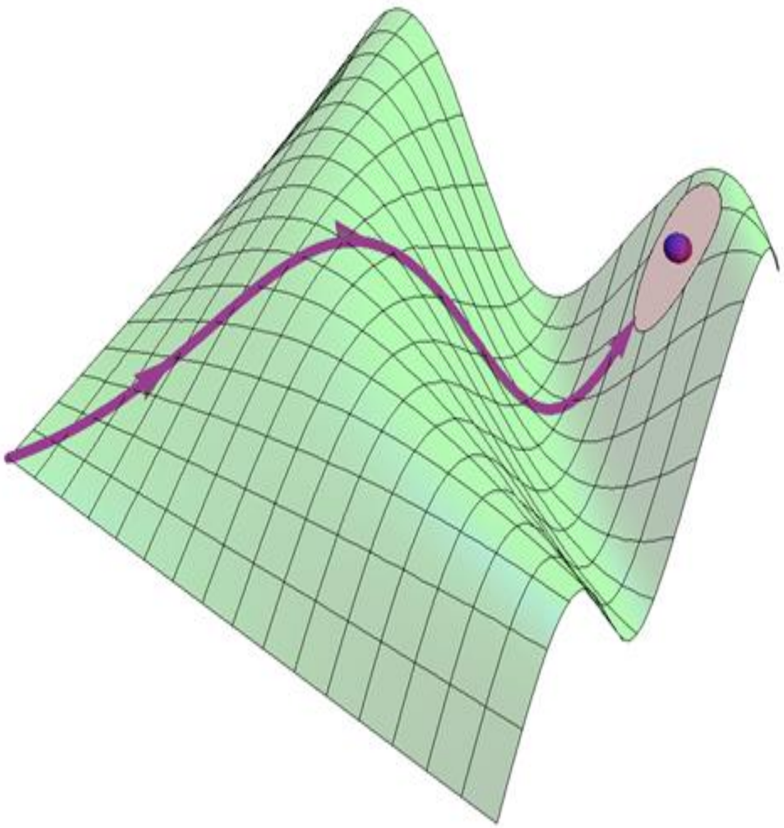
$$H_{RWA}(\alpha) = \hbar \begin{pmatrix} \omega_2(B)-2\omega & \Omega & 0 & 0 & 0 \\ \Omega & \omega_1(B)-\omega & \sqrt{3/2}\,\Omega & 0 & 0 \\ 0 & \sqrt{3/2}\,\Omega & \omega_0(B) & \sqrt{3/2}\,\Omega & 0 \\ 0 & 0 & \sqrt{3/2}\,\Omega & \omega_{-1}(B)+\omega & \Omega \\ 0 & 0 & 0 & \Omega & \omega_{-2}(B)+2\omega \end{pmatrix}$$

Optimal control of Quantum dynamics

C. Lo vecchio et al. arXiv:1405.6918

CRAB optimization

- $\varepsilon = \sum_i \frac{|p_i - b_i|}{2} \rightarrow \varepsilon_{T,}\ \varepsilon_E\ (\varepsilon \in [0,1])$
- $p_i = \rho_{ii}(T)$
- b_i target state population



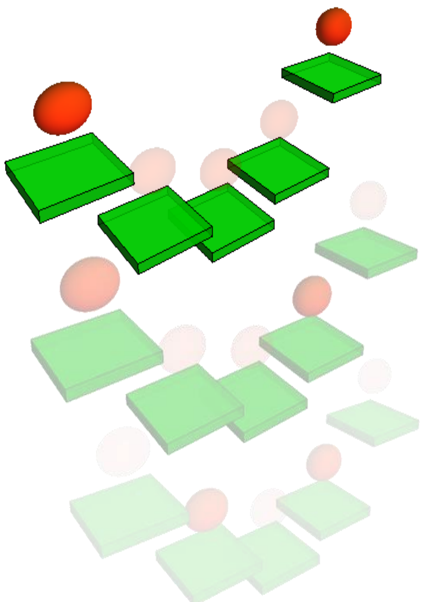
Experimental constraints

- $\omega\ (t) \in 2\pi\ [4150, 4600]$ kHz
- $B = 6.1794$ Gauss
- $\Omega = 2\ \pi\ 60$ kHz
- $T = 100\ \mu s$

Target states

C. Lo vecchio et al. arXiv:1405.6918

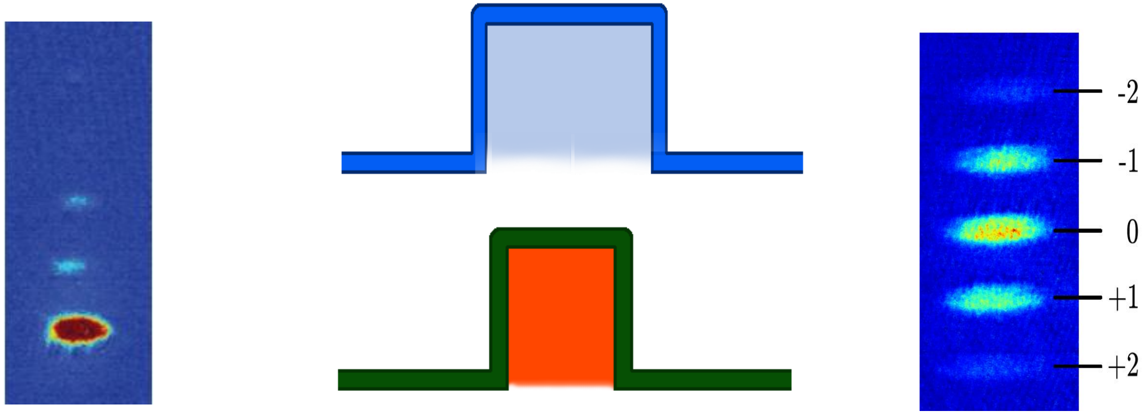
Target State	ρ_{11}	ρ_{22}	ρ_{33}	ρ_{44}	ρ_{55}
A	1/2	0	0	0	1/2
B	1/2	0	0	1/2	0
C	0	1/2	0	1/2	0
D	1/2	1/2	0	0	0
E	0	1/3	1/3	1/3	0
F	1/5	1/5	1/5	1/5	1/5
G	0	1	0	0	0
H	0	0	0	1	0
I	0	0	1	0	0



The Experiment

C. Lo vecchio et al. arXiv:1405.6918

Homogeneous magnetic field



FM modulated RF driving field

$|\psi_{in}> = |m_F = 2>$ $\quad$ $|\psi_{out}> \rightarrow \rho_{ii} \Rightarrow \varepsilon_E$

Time

Outcome

C. Lo vecchio et al. arXiv:1405.6918

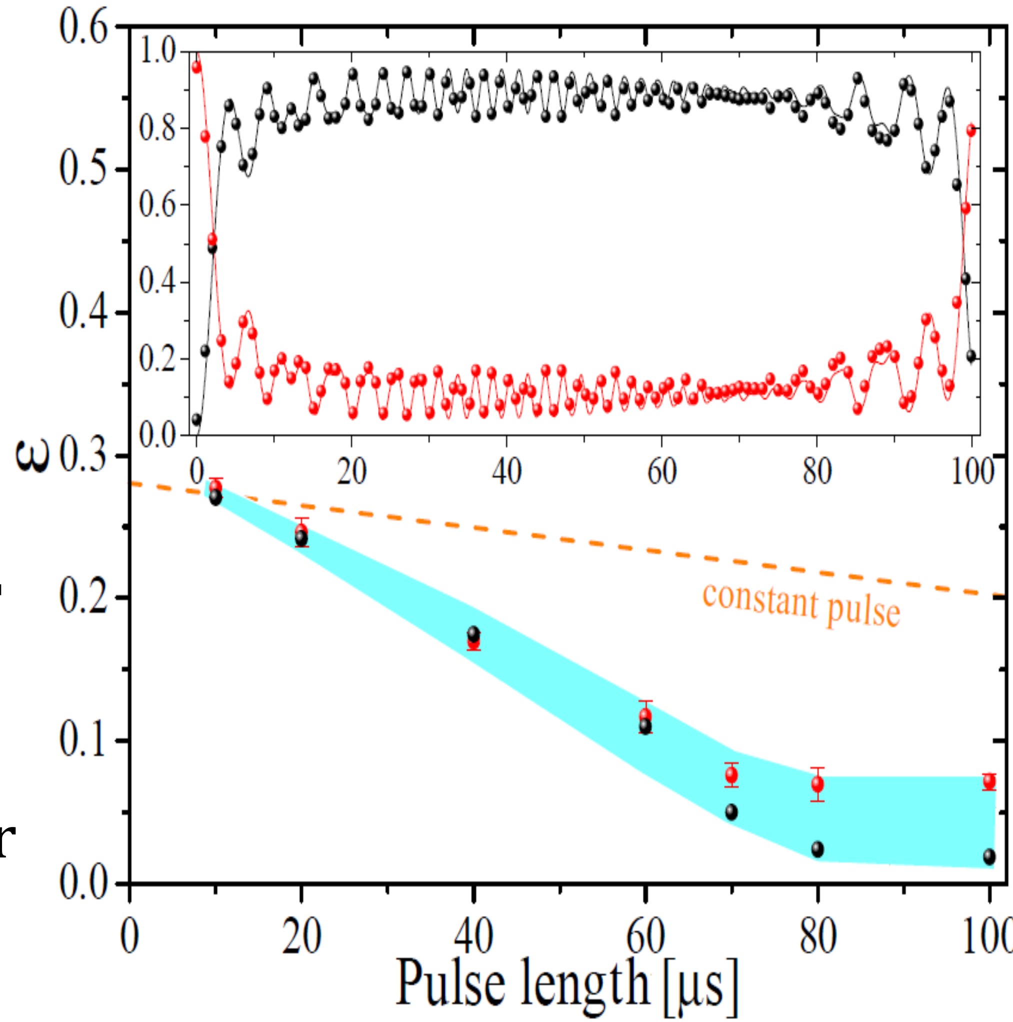
Target State	ε_T	ε_E	$\mathcal{F}$
A	0,04(3)	0,07(1)	0,71
B	0,04(2)	0,02(1)	0,67
C	0,04(3)	0,04(1)	0,11
D	0,03(2)	0,02(1)	0,71
E	0,04(2)	0,03(1)	0,02
F	0,02(1)	0,03(1)	0,45
G	0,05(4)	0,04(1)	0,15
H	0,04(3)	0,03(1)	0,07
I	0,07(3)	0,07(1)	0,15

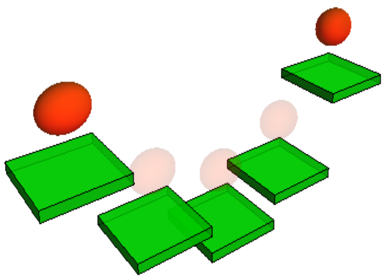
- $\mathcal{F}(\rho_0, \rho_T) = Tr\sqrt{\rho_0{}^{1/2}\rho_T\rho_0{}^{1/2}}$ Uhlman fidelity

Reducing the pulse length

C. Lo vecchio et al. arXiv:1405.6918

- State preparation A
- Different optimized pulse length T
- Same constraints for all pulses





Checking coherence

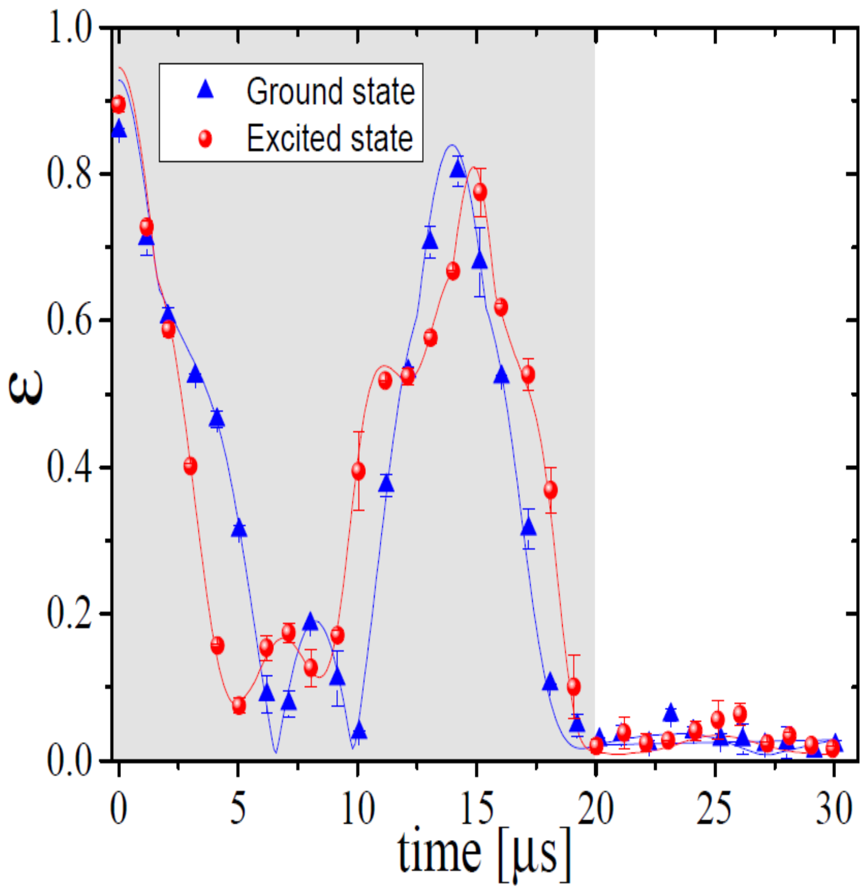
C. Lo vecchio et al. arXiv:1405.6918

Excited and ground state of the RF driven Hamiltonian

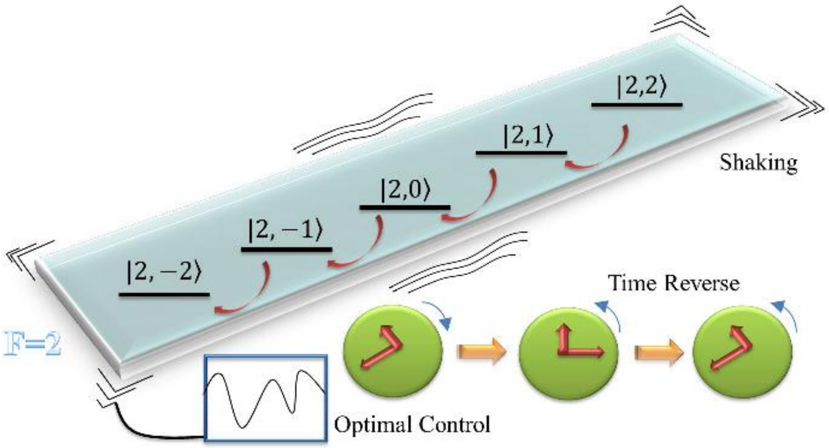
$$H(t,\alpha) = \hbar \begin{pmatrix} \omega_2 - 2\omega & \Omega & 0 & 0 & 0 \\ \Omega & \omega_1 - \omega & \sqrt{3/2}\,\Omega & 0 & 0 \\ 0 & \sqrt{3/2}\,\Omega & \omega_0 & \sqrt{3/2}\,\Omega & 0 \\ 0 & 0 & \sqrt{3/2}\,\Omega & \omega_{-1} + \omega & \Omega \\ 0 & 0 & 0 & \Omega & \omega_{-2} + 2\omega \end{pmatrix}$$

$\omega_n = \omega_n(B)$

- $B = 6{,}1794$ Gauss
- $\omega = 4{,}323$MHz

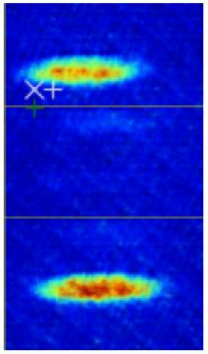


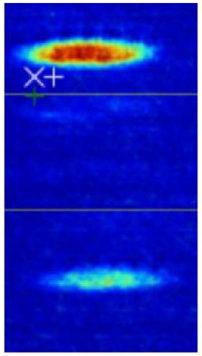
Inverting the time evolution

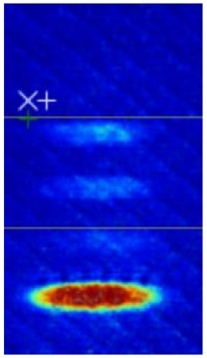


$$\frac{d}{dt}\rho(t) = -\frac{i}{\hbar}[H_0 + H_F(t), \rho(t)]$$

Starting state	After OC pulse	After OC pulse – OC pulse	After OC pulse + OR pulse







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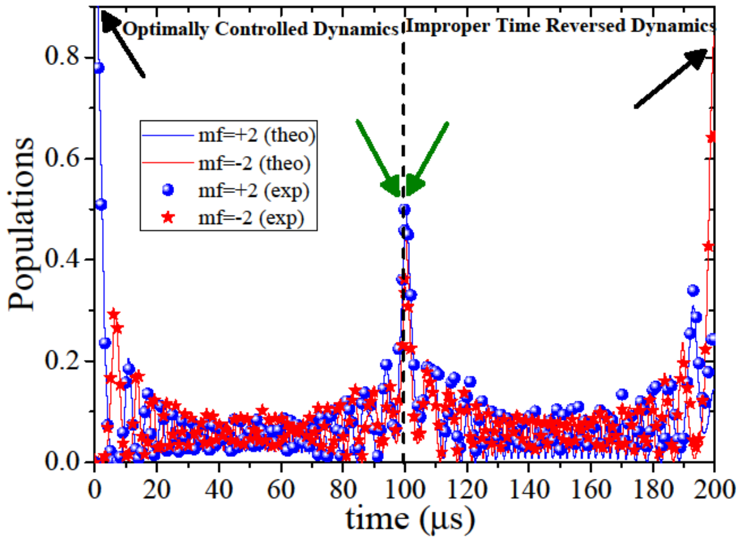
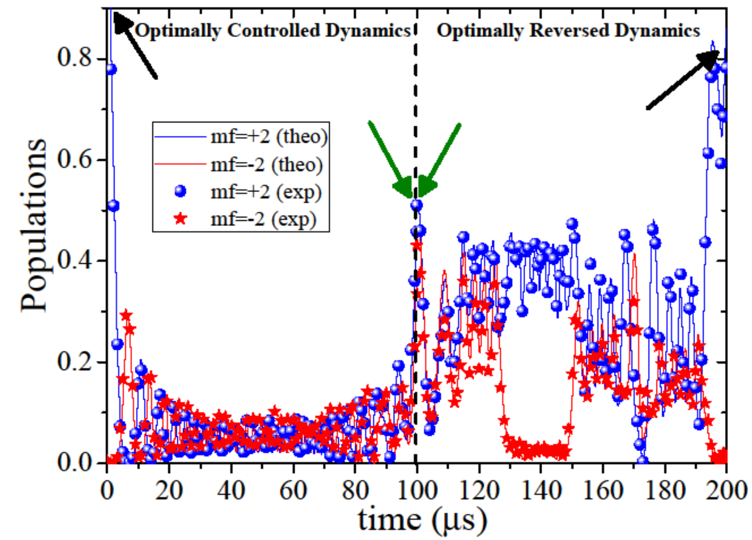
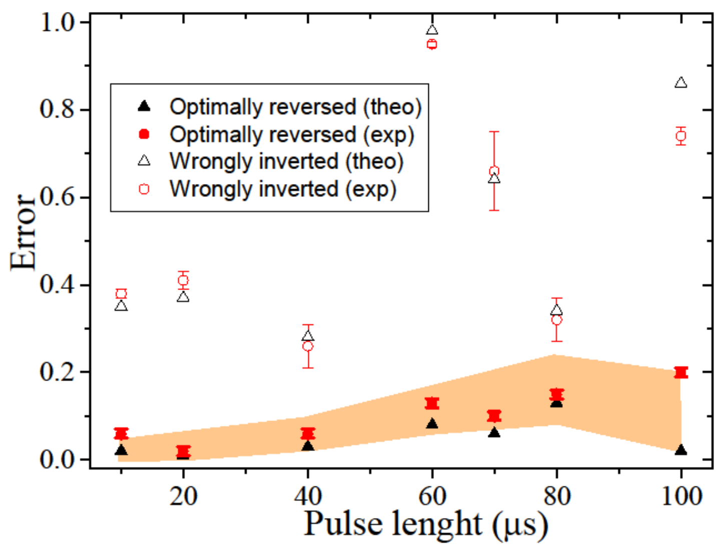
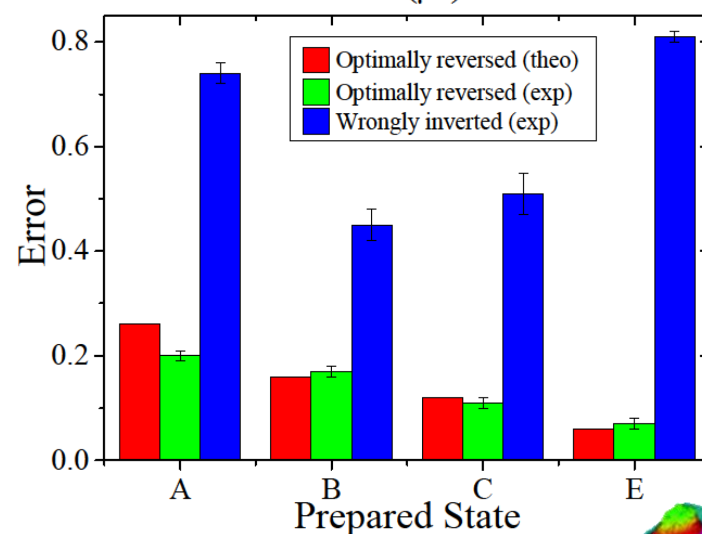
Inverting the time evolution



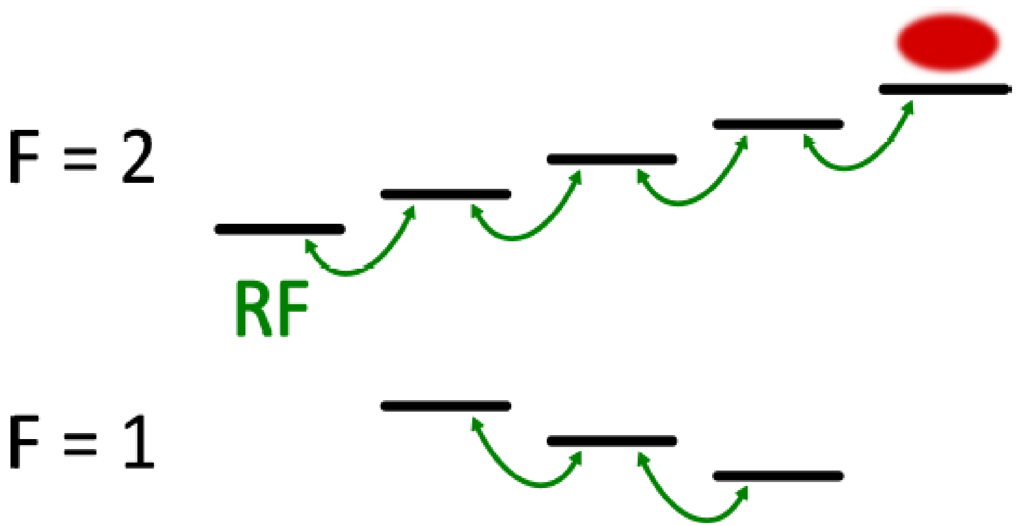






Separating subspaces via Quantum Zeno dynamics

F. Schaefer et al Nat. Comm. 5:3194 (2014)



$$H_{F=2} = \begin{pmatrix} 0 & \frac{\sqrt{4}}{2}\Omega & 0 & 0 & 0 \\ \frac{\sqrt{4}}{2}\Omega & 0 & \frac{\sqrt{6}}{2}\Omega & 0 & 0 \\ 0 & \frac{\sqrt{6}}{2}\Omega & 0 & \frac{\sqrt{6}}{2}\Omega & 0 \\ 0 & 0 & \frac{\sqrt{6}}{2}\Omega & 0 & \frac{\sqrt{4}}{2}\Omega \\ 0 & 0 & 0 & \frac{\sqrt{4}}{2}\Omega & 0 \end{pmatrix}$$

Separating subspaces via Quantum Zeno dynamics

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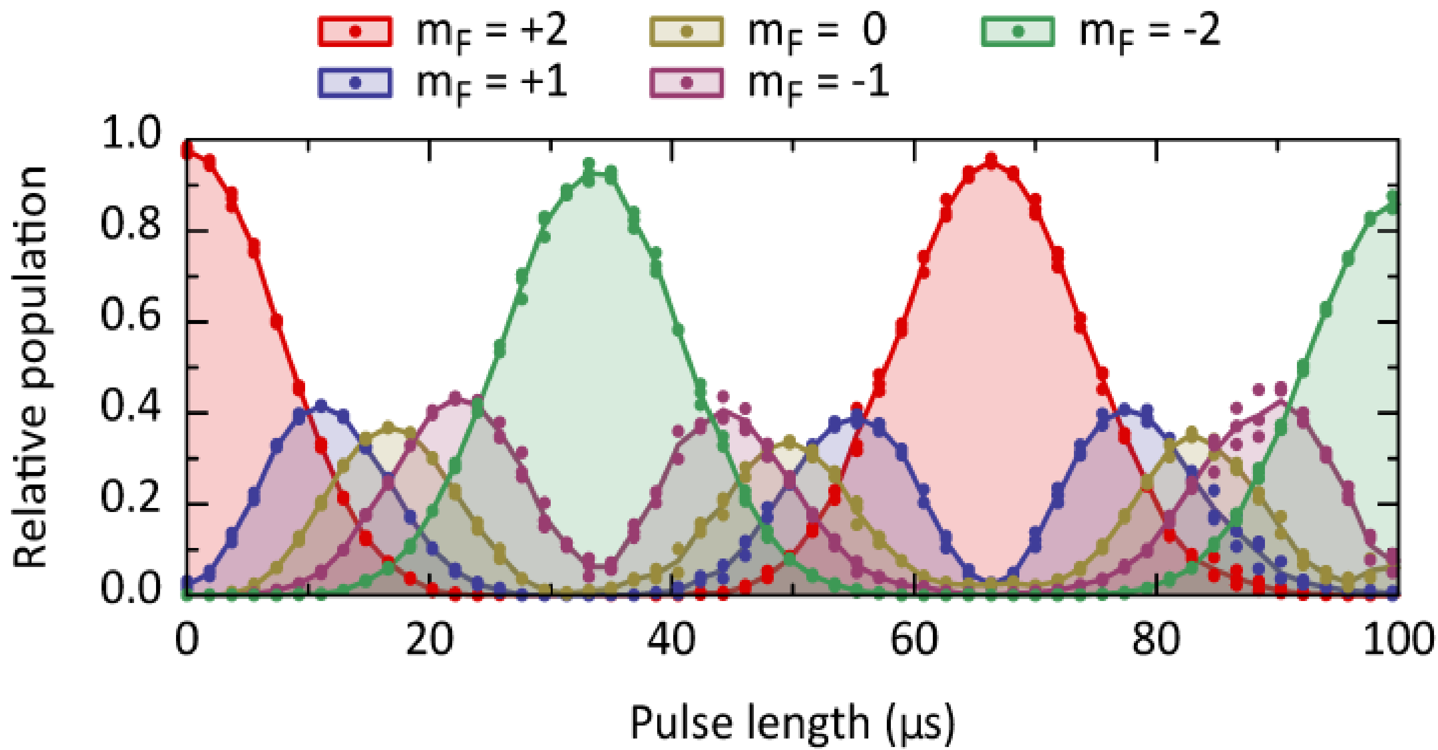

- RF pulse: $\Omega_{RF} = 2\pi\, 15$ kHz
- Raman beams: off

Separating subspaces via Quantum Zeno dynamics

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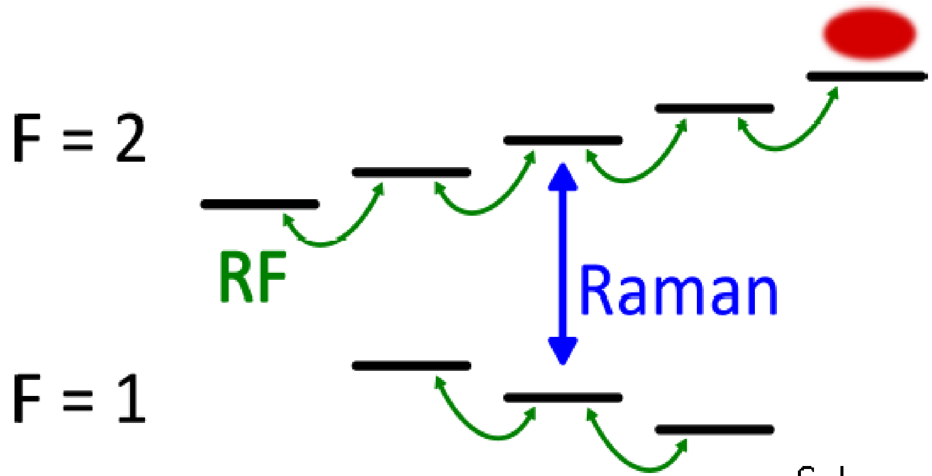

Subspace projections:

$$P = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \qquad \bar{P} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Separating subspaces via Quantum Zeno dynamics

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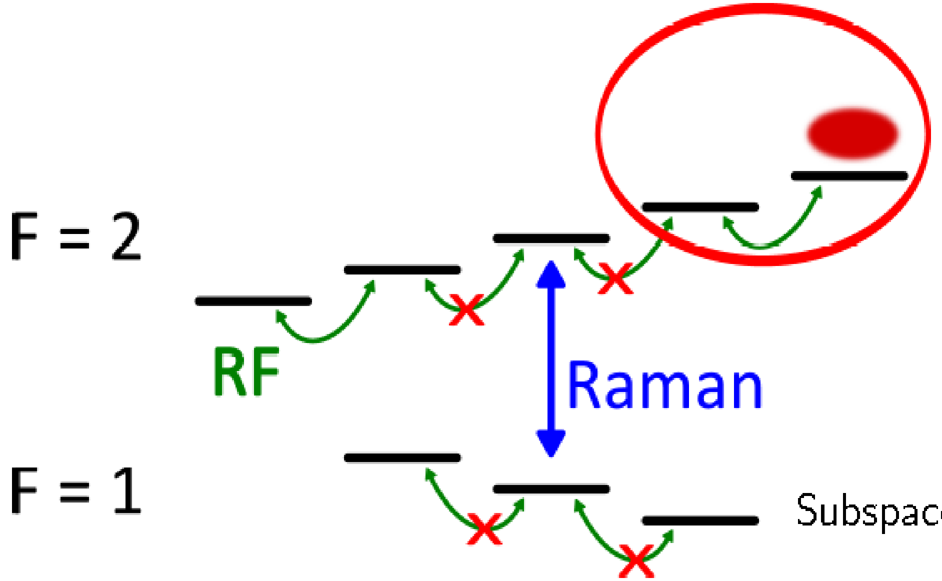

Subspace dynamics:

$$PH_{F=2}P = \begin{pmatrix} 0 & \frac{\sqrt{4}}{2}\Omega & 0 & 0 & 0 \\ \frac{\sqrt{4}}{2}\Omega & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{\sqrt{4}}{2}\Omega \\ 0 & 0 & 0 & \frac{\sqrt{4}}{2}\Omega & 0 \end{pmatrix}$$

Separating subspaces via Quantum Zeno dynamics

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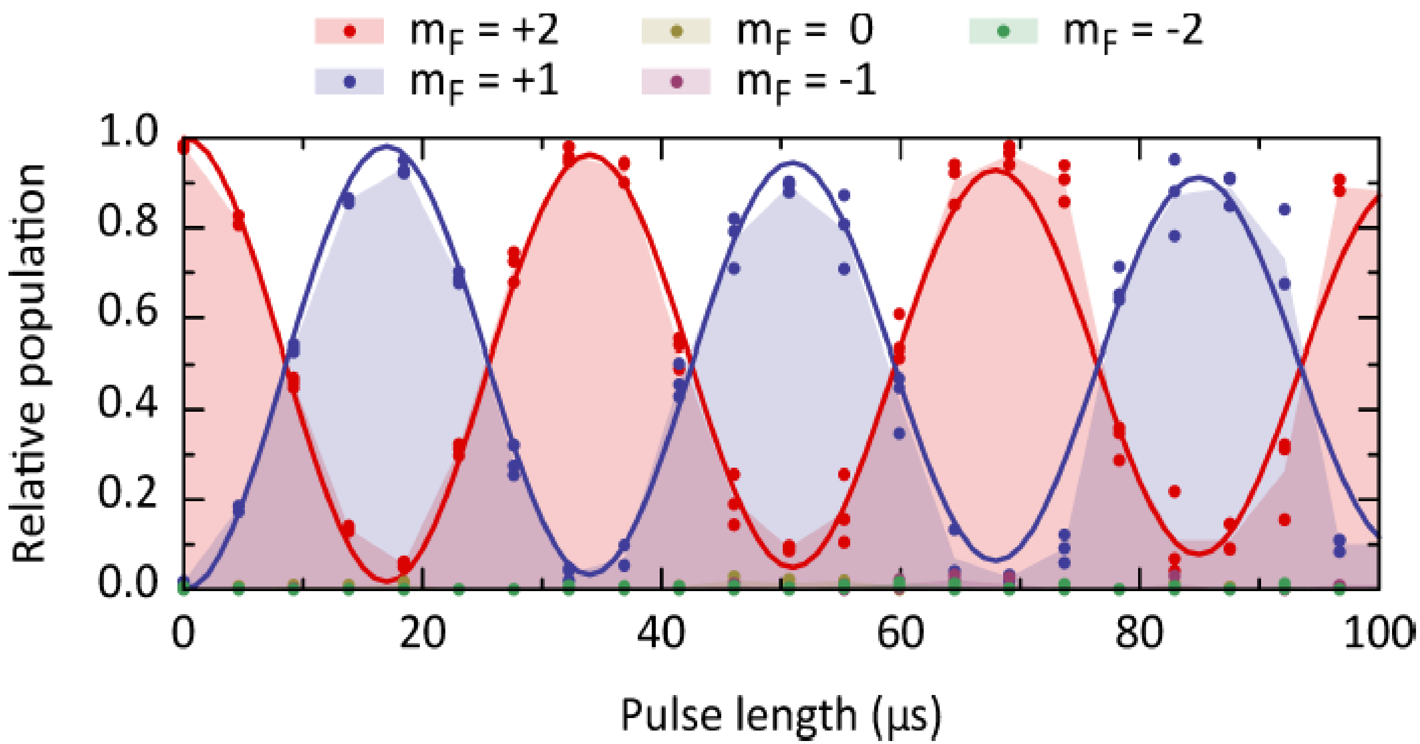

- $\Omega_{\mathrm{RF}} = 2\pi\,15$ kHz, $\Omega_{\mathrm{Raman}} = 2\pi\,200$ kHz
- $t_{\mathrm{lifetime}} = 50$ ms, $t_{\mathrm{deph}} = 3.1$ ms

Separating subspaces via Quantum Zeno dynamics

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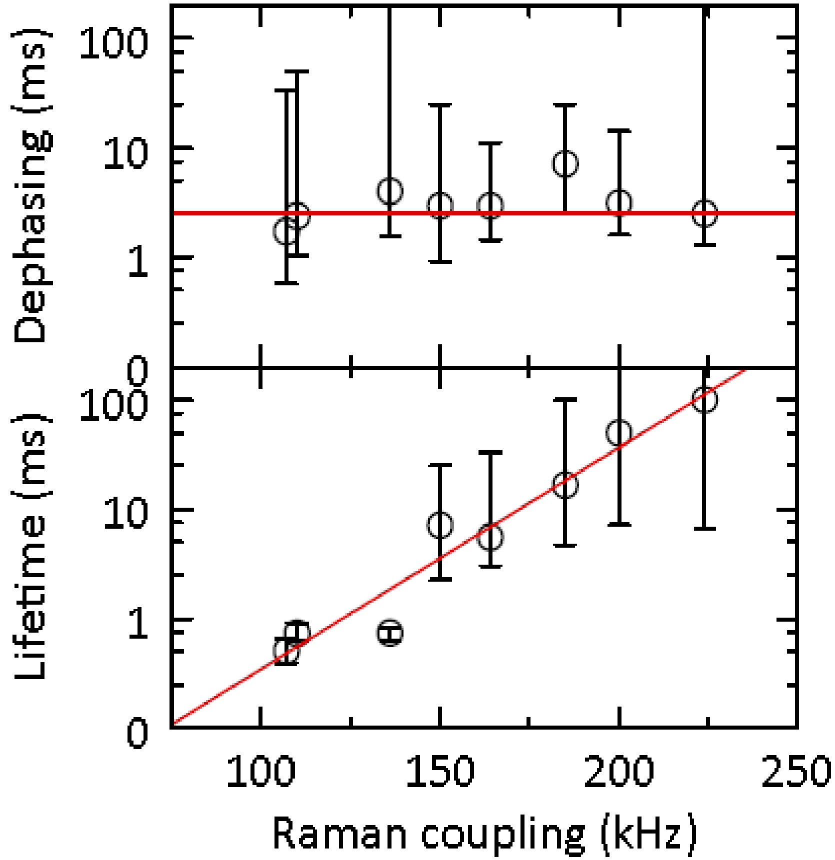

- Observe a strong transition from free to Zeno dynamics
- Lifetime increases by factor ≈ 100
- Dephasing time approx. constant

Conclusions

- Optimal control strategy allow to reach any point of the Hilbert space of interest.
- The error in the states preparation depends on the time length of the optimized evolution.
- Different states can improve an atomic interferometer sensitivity.
- Population evolves passing through all the levels
- Returning to the initial state requires control also of return dynamics

Conclusions

- Frequent observations with negative results can confine the dynamics to a subspace of the complete Hilbert space.
- The lifetime in the subspace depends strongly on the rate of observation.
- The coherence in the subspace decays only slowly.
- Resulting dynamics of different "measurement" schemes are observed to be similar.
- We created a dynamically protected Qubit.

The Team

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Theory Support

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