



Control Conditions for Robust Atomic Interferometers

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Hamiltonian in momentum space:

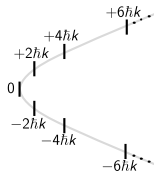
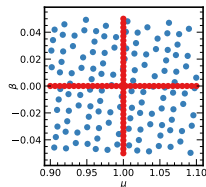
$$\hat{H} = \sum_n \left((E_n^{(0)}(t) + 2n\beta\hbar\omega_k) |n\rangle\langle n| - \mu S(t)(|n\rangle\langle n+1| + \text{H.c.}) \right)$$

with $E_n^{(0)}(t) = n^2\hbar\omega_k + n\hbar\dot{\phi}(t)$

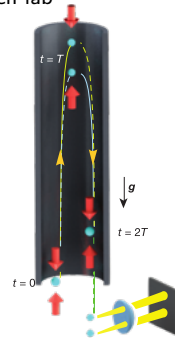
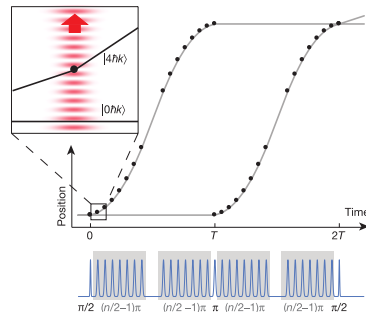
Robustness landscape: μ (pulse amplitude), β (initial velocity)

Ensemble optimization:

Optimize simultaneously for average of ensemble (μ, β) .



10 m atomic fountain at Stanford Kasevich lab



Kovachi et al. *Nature* **528**, 530 (2015)

① Splitting:

$$|0\rangle \rightarrow \frac{1}{\sqrt{2}} \left(|0\rangle + e^{i\Delta\phi} |N_S\rangle \right)$$

② ⑤ Amplification:

$$|0\rangle \rightarrow |0\rangle, |N_S\rangle \rightarrow e^{i\phi_+} |N_{\max}\rangle$$

After ②: kick

$$|N_{\max}\rangle \rightarrow e^{i\phi_{\text{kick}}} |N_{\max}\rangle$$

③ ⑥ De-amplification:

$$|0\rangle \rightarrow |0\rangle, |N_{\max}\rangle \rightarrow e^{i\phi_-} |N_S\rangle$$

④ SWAP:

$$|0\rangle \leftrightarrow |N_S\rangle$$

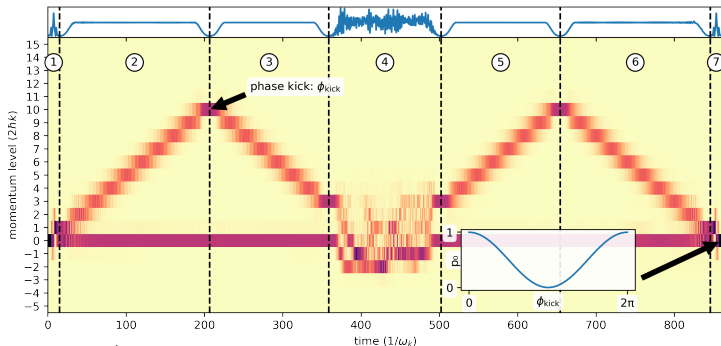
⑦ Recombination:

$$|0\rangle \rightarrow \frac{e^{i\phi_{00}}}{\sqrt{2}} \left(|0\rangle + e^{i\Delta\phi} |1\rangle \right), |N_S\rangle \rightarrow \frac{e^{i\phi_{10}}}{\sqrt{2}} \left(|0\rangle + e^{i(\Delta\phi+\pi)} |1\rangle \right)$$

Results in

$$p_0 = \frac{e^{i\Delta\phi} e^{-i\Delta\phi} e^{i\phi_{\text{kick}}}}{4} + \frac{1}{2} + \frac{e^{-i\Delta\phi} e^{i\Delta\phi} e^{-i\phi_{\text{kick}}}}{4}$$

- Phases ϕ_+ , ϕ_- cancel out!
- Final recombination only has to compensate $\Delta\phi$ of initial splitter!
- For $N_S = 1$, same pulse can split and recombine! – $\Delta\phi$ drops out!



Required kick response:

$$p_0 = \cos^2 \left(\frac{\phi_{\text{kick}}}{2} \right) = \frac{1}{2} + \frac{\cos(\phi_{\text{kick}})}{2}, p_1 = 1 - p_0$$

Population transfer functional:

$$J_{\text{pop}} = \frac{1}{2M} \sum_{(\mu, \beta)} \sum_k \sum_n \left(\left| \langle \phi_k^{(\mu, \beta)}(T) | n \rangle \right|^2 - \left| \langle \phi_k^{\text{tgt}} | n \rangle \right|^2 \right)^2$$