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Limitations of a multi-Raman-pulse atom interferometry acceleration sensor

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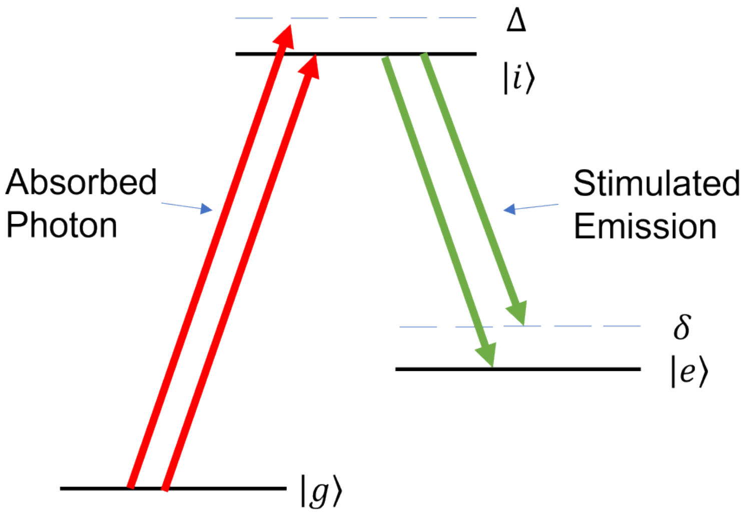
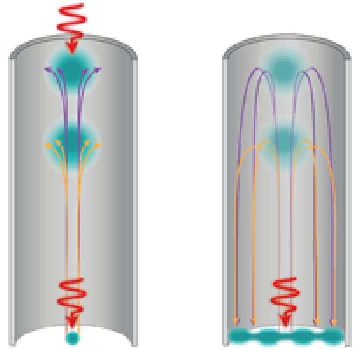
Outline

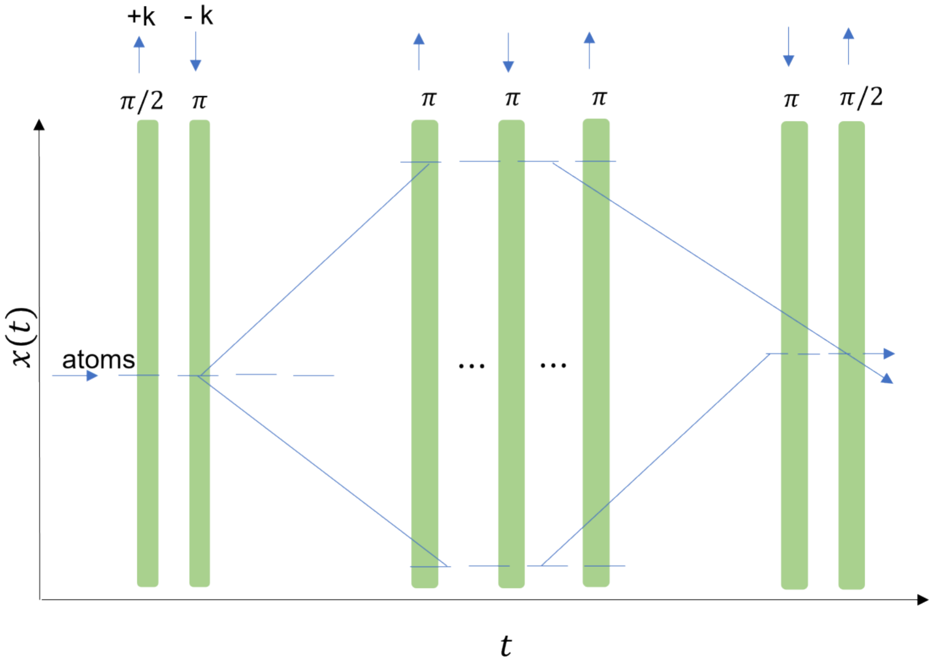
- Atom Interferometry Large Momentum Transfer
- Model
- Results
- Conclusions

Atom Interferometry Large Momentum Transfer

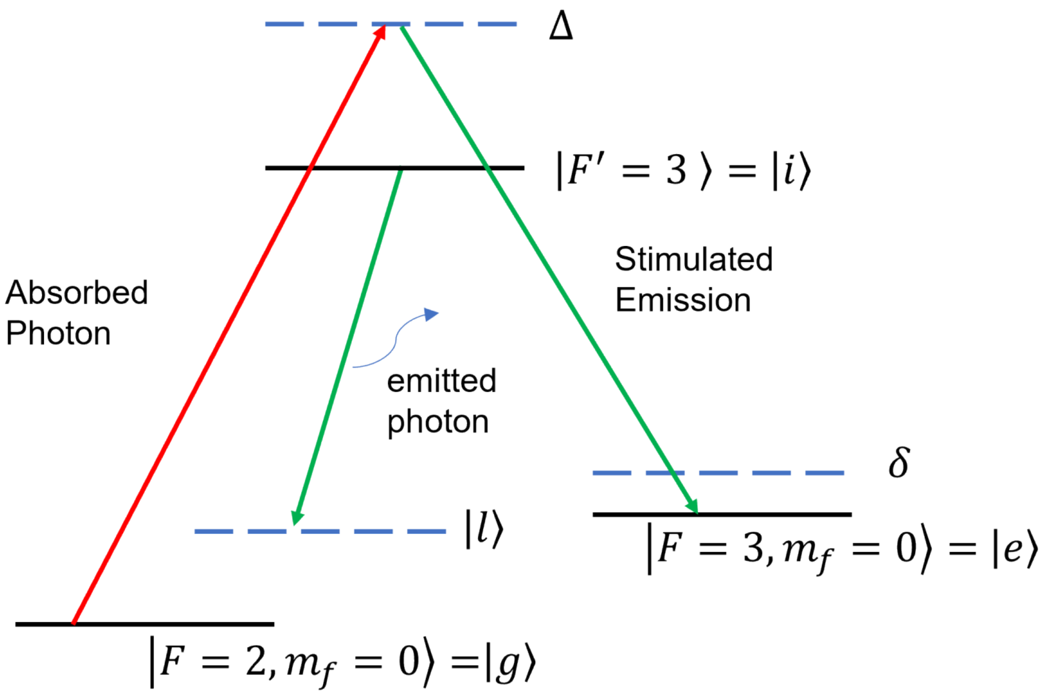
- Use counter propagating beams
  - Momentum kick of $+2\hbar k_{eff}$
  - Δ and δ are detuning offsets
  - Δ will be large to adiabatically eliminate the high energy state
- Want to increase sensitivity
  - Increase the integration time
    - $\Delta a \propto \frac{1}{T^2}$
  - Related to the amount of momentum transfer[1]
    - $\Delta a \propto \frac{1}{Nk_{eff}}$
- Increase in the Raman pulses is promising[2,3,4]
  - Setup can be compact
  - Short pulse time interactions
- $\Delta a = \frac{1}{2k_{eff}T^2} \tan\left(\frac{|c_e|}{|c_g|}\right)$







Model



- Unperturbed and interaction Hamiltonians described by

$$\widehat{H}_0 = \hbar\omega_{ge}\,|e\rangle\langle e| + \hbar\omega_{gi}\,|i\rangle\langle i|\,,$$

$$\widehat{H}_{\text{int}} = \hbar\Omega_1^* e^{i(\mathbf{k}_1\cdot\mathbf{x}_g-\omega_1 t)}\,|i\rangle\langle g| + \hbar\Omega_2^* e^{i(\mathbf{k}_2\cdot\mathbf{x}_e-\omega_2 t)}\,|i\rangle\langle e| + c.c.$$

- The loss will be into an indeterminate mode allowing us to use the Lindbladian

$$\dot{\rho} = -\frac{i}{\hbar}[H,\rho] + \sum_k \left(L_k\rho L_k^\dagger - \frac{1}{2}L_k^\dagger L_k\rho - \frac{1}{2}\rho L_k^\dagger L_k \right)$$

- Final state amplitude dynamics (in the rotating frame) for the atom

$$\dot{\tilde{c}}_g = \left[\frac{|\Omega_1|^2}{i\Delta - \frac{\gamma_3}{2}} e^{i\Delta t - \frac{\gamma_3}{2}t}\tilde{c}_g + \frac{\Omega_1\Omega_2^*}{i(\Delta+\delta) - \frac{\gamma_3}{2}} e^{i(\Delta_{kx}-\Delta t)-\frac{\gamma_3}{2}t}\tilde{c}_e\right] - \left[\frac{|\Omega_1|^2}{i\Delta - \frac{\gamma_3}{2}}\tilde{c}_g + \frac{\Omega_1\Omega_2^*}{i(\Delta+\delta) - \frac{\gamma_3}{2}} e^{i(\Delta_{kx}-\delta t)}\tilde{c}_e\right],$$

$$\dot{\tilde{c}}_e = \left[\frac{|\Omega_2|^2}{i(\Delta+\delta) - \frac{\gamma_3}{2}} e^{i(\Delta+\delta)t - \frac{\gamma_3}{2}t}\tilde{c}_e + \frac{\Omega_2\Omega_1^*}{i\Delta - \frac{\gamma_3}{2}} e^{i(\Delta'_{kx}-(\Delta+\delta)t)-\frac{\gamma_3}{2}t}\tilde{c}_g\right] - \left[\frac{|\Omega_2|^2}{i(\Delta+\delta) - \frac{\gamma_3}{2}}\tilde{c}_e + \frac{\Omega_2\Omega_1^*}{i\Delta - \frac{\gamma_3}{2}} e^{i(\Delta'_{kx}-\delta t)}\tilde{c}_g\right]$$

Model

- Now to consider the atom interferometer acceleration phase relation

$$\mathrm{dev}(a) = \left(\frac{2}{(2N_R T^2 |\mathbf{k}_{\mathrm{eff}}| - 2(N_R+1)|\mathbf{k}_{\mathrm{eff}}| T\tau_d)\cos\theta}\right)\mathrm{dev}(\phi)$$

$$= \alpha\left(\mathrm{dev}\left[\tan^{-1}\left(\sqrt{\left|\frac{c_e(t_f)}{c_g(t_f)}\right|^2}\right)\right]\right)$$

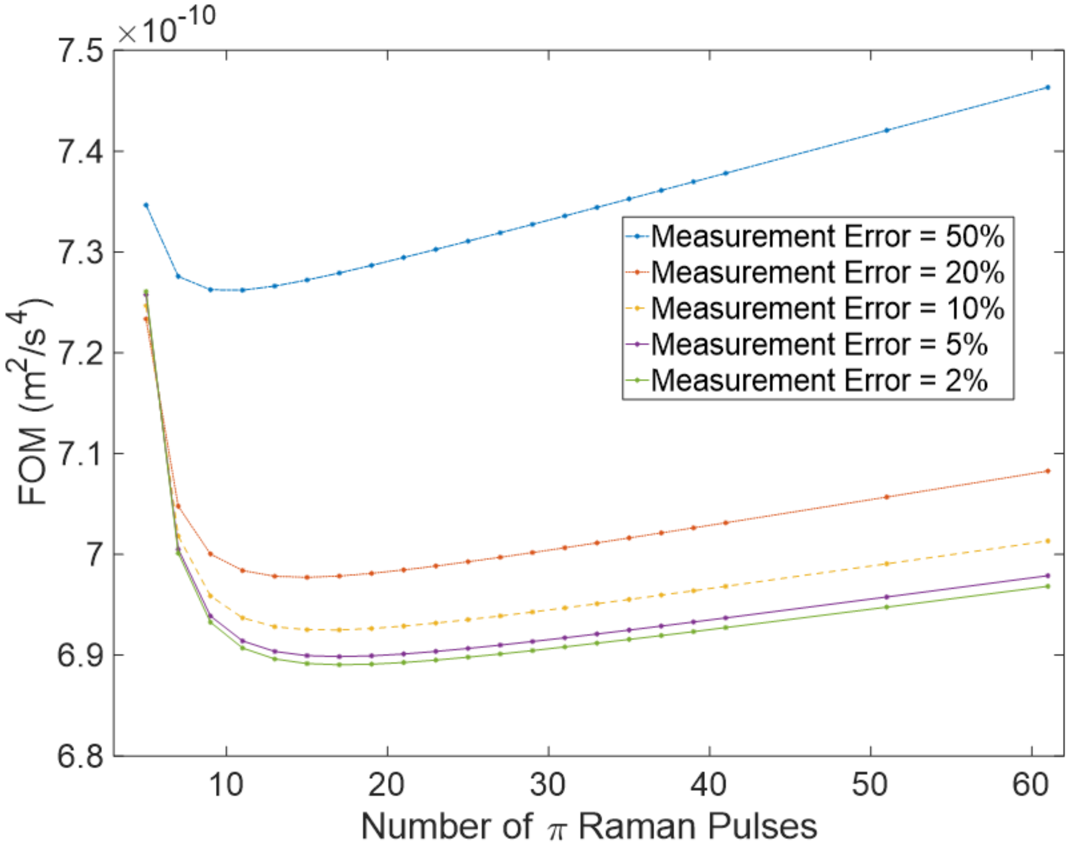
$$\left|\frac{c_e(t_f)}{c_g(t_f)}\right|^2 = \frac{|c_e(t_f)|^2}{1 - |c_e(t_f)|^2 - Q_{\mathrm{tot}}}$$

- Figure of merit of the error which incorporates both AC fluctuation and DC offset

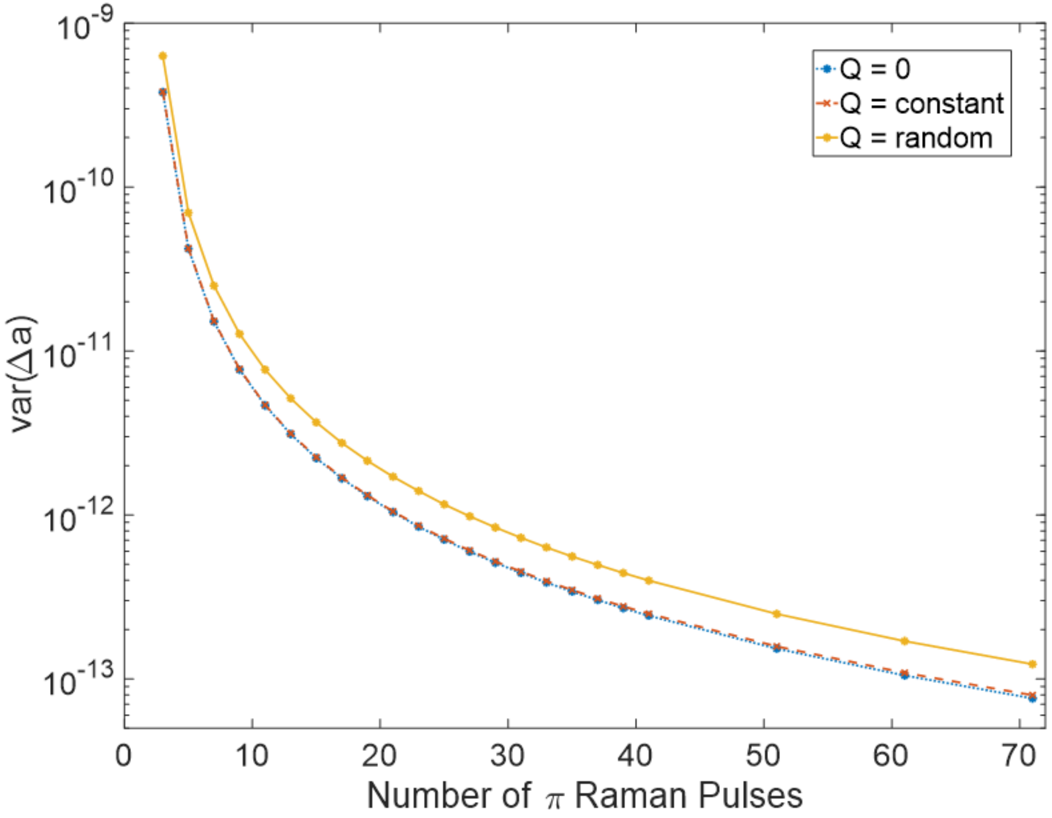
$$\mathrm{FOM} = \underbrace{(a_{\mathrm{tr}} - \langle \mathrm{dev}(a)\rangle)^2}_{\text{DC Offset}} + \underbrace{\mathrm{var}(\mathrm{dev}(a))}_{\text{Noise}}$$

Results

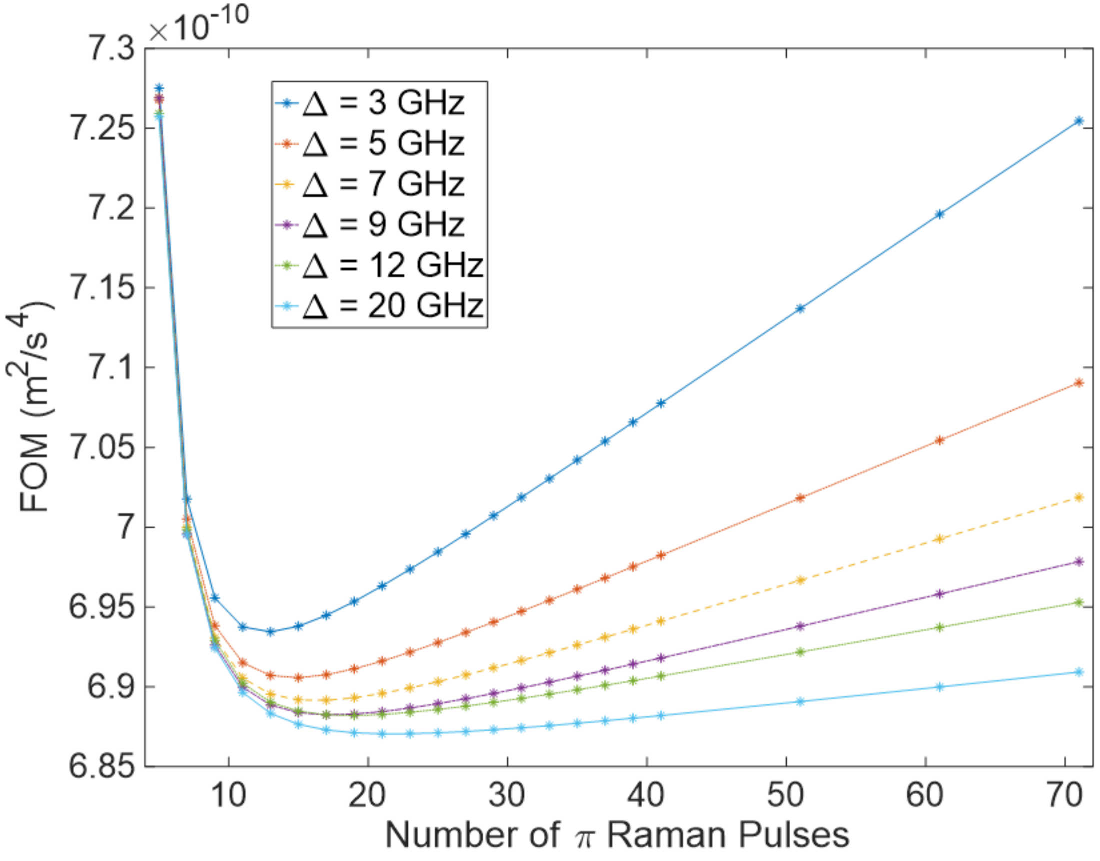
- FOM vs π Raman Pulses

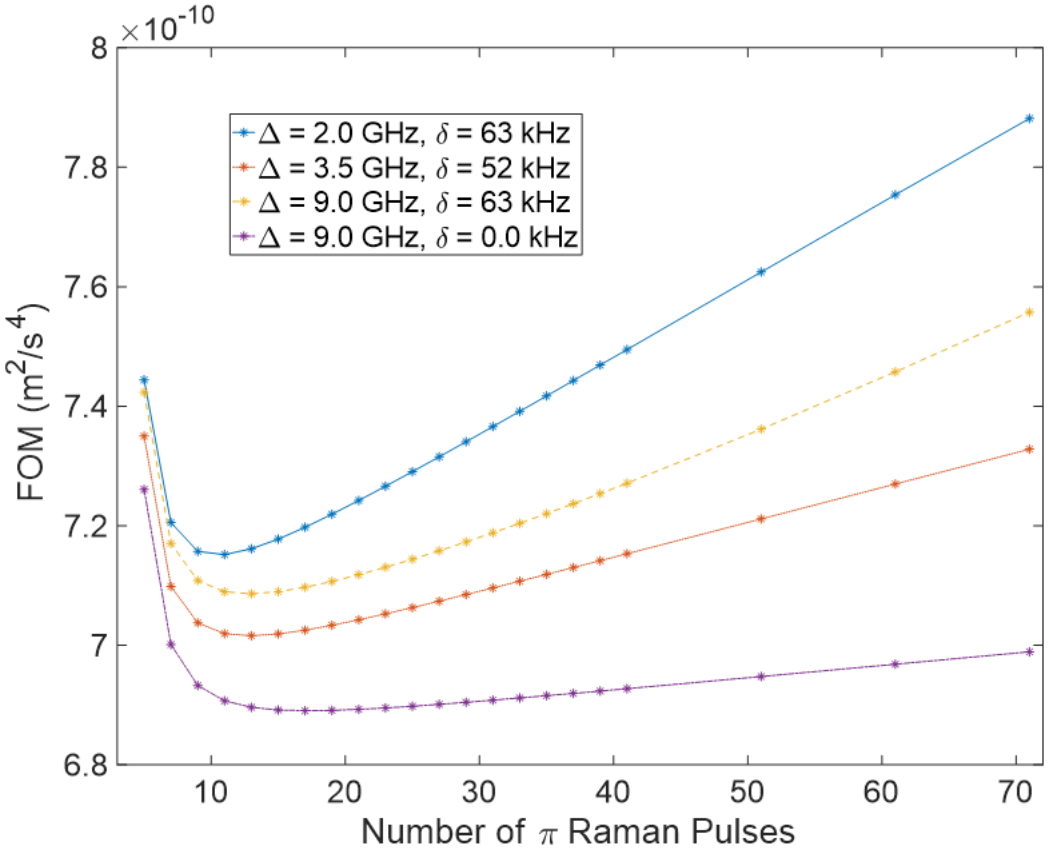


- Variance vs π Raman Pulses



Results





- *NOTE* – an increased detuning is better but requires more intensity which will effect contrast

Conclusions

- For low pulse numbers the quantum information loss is small and the FOM is dominated by N_R^{-2} dependent error reduction.
- When pulse numbers get high, the quantum information loss increases and the FOM becomes dominated by the DC offset.
- Increasing the single-photon detuning, Δ, will increase the number of pulses for minimum FOM (i.e. decrease the amount of spontaneous emission).
- Increasing the two-photon detuning, δ, will decrease the number of pulses for minimum FOM (i.e. the efficiency of the pulses decreases).
- For an idealized system, we see error on the order of $10^{-5}\ \mathrm{m}/s^2$.
- Combining with error compensating techniques could realize very precise atomic accelerometers[3,4].

THANK YOU!

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5. D. A. Steck, “Rubidium 85 D Line Data”, available online at http://steck.us/alkalidata (2021)

BACK UPS

Back Ups

- Determining the parameter Q

$$Q = \int_{t_0}^{t} \gamma_3 \widetilde{c}_i^* \widetilde{c}_i dt$$

$$\widetilde{c}_i = \left[\frac{i\Omega_1^*}{i\Delta - \frac{\gamma_3}{2}} e^{i(\mathbf{k}_1 \cdot \mathbf{x}_g)} \widetilde{c}_g + \frac{i\Omega_2^*}{i(\Delta+\delta) - \frac{\gamma_3}{2}} e^{i(\mathbf{k}_2 \cdot \mathbf{x}_e)} \widetilde{c}_e \right] e^{-\frac{\gamma_3}{2}t} - \left[\frac{i\Omega_1^*}{i\Delta - \frac{\gamma_3}{2}} e^{i(\mathbf{k}_1 \cdot \mathbf{x}_g + \Delta t)} \widetilde{c}_g + \frac{i\Omega_2^*}{i(\Delta+\delta) - \frac{\gamma_3}{2}} e^{i(\mathbf{k}_2 \cdot \mathbf{x}_e + (\Delta+\delta)t)} \widetilde{c}_e \right]$$

$$\overline{\widetilde{c}_i} = \left[\frac{-i\Omega_1^*}{-i\Delta + \frac{\gamma_3}{2}} e^{i(\mathbf{k}_1 \cdot \mathbf{x}_g + \Delta t)} \widetilde{c}_g + \frac{-i\Omega_2^*}{-i(\Delta+\delta) + \frac{\gamma_3}{2}} e^{i(\mathbf{k}_2 \cdot \mathbf{x}_e + (\Delta+\delta)t)} \widetilde{c}_e \right]$$

$$\overline{\widetilde{c}_i^*} = \left[\frac{i\Omega_1}{i\Delta + \frac{\gamma_3}{2}} e^{-i(\mathbf{k}_1 \cdot \mathbf{x}_g + \Delta t)} \widetilde{c}_g^* + \frac{i\Omega_2}{i(\Delta+\delta) + \frac{\gamma_3}{2}} e^{-i(\mathbf{k}_2 \cdot \mathbf{x}_e + (\Delta+\delta)t)} \widetilde{c}_e^* \right]$$

$$\overline{\widetilde{c}_i^*}\,\overline{\widetilde{c}_i} \simeq |\Omega_1|^2 \left[\frac{\widetilde{c}_g^2}{\left(\Delta^2 + \left(\frac{\gamma_3}{2}\right)^2\right)} + \frac{\widetilde{c}_e^2}{\left((\Delta+\delta)^2 + \left(\frac{\gamma_3}{2}\right)^2\right)} + \left(\frac{\widetilde{c}_g \widetilde{c}_e^*}{(-i\Delta + \frac{\gamma_3}{2})(i(\Delta+\delta) + \frac{\gamma_3}{2})} e^{i(\Delta_{kx} + \delta t)} + c.c. \right) \right]$$

$$Q = \gamma_3 |\Omega_1|^2 t_{\text{tot}} \left[\frac{\widetilde{c}_g^2}{\left(\Delta^2 + \left(\frac{\gamma_3}{2}\right)^2\right)} + \frac{\widetilde{c}_e^2}{\left((\Delta+\delta)^2 + \left(\frac{\gamma_3}{2}\right)^2\right)} + \left(\frac{\widetilde{c}_g \widetilde{c}_e^*}{(-i\Delta + \frac{\gamma_3}{2})(i(\Delta+\delta) + \frac{\gamma_3}{2})} e^{i\Delta_{kx}} + c.c. \right) \right]$$

Back Ups

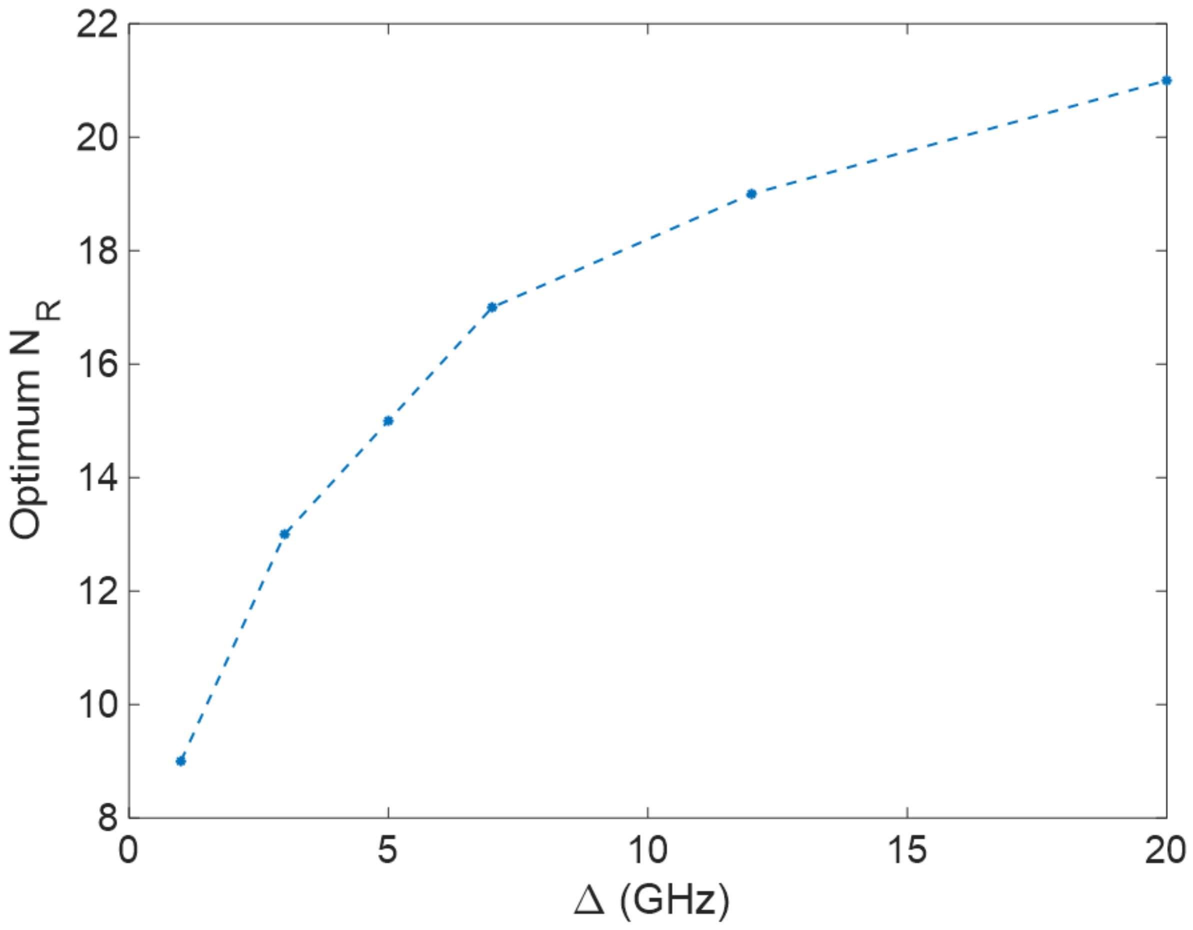
- Parameters used for a Rubidium-85 atom interferometer system

System Parameters

Free evolution time	100 ms
Time between successive pulses	150 μs
π-pulse length (t_π)	2.00 μs
$\pi/2$ pulse length ($t_{\pi/2}$)	1.00 μs
Single-photon detuning (Δ)	$2-20$ GHz
Two-photon detuning (δ)	$0-63$ kHz
Rabi frequency ($\Omega_1 = \Omega_2$)	212 MHz
Raman laser wavelength ($\lambda_1 = \lambda_2$)	780 nm
Spontaneous decay rate (Γ)	38.117 MHz
Mass of Rb^{85}	$1.419 \cdot 10^{-25}$ kg
MOT temperature	2 μK
a_{tr}	$1.85 \cdot 10^{-5}$ m/s^2

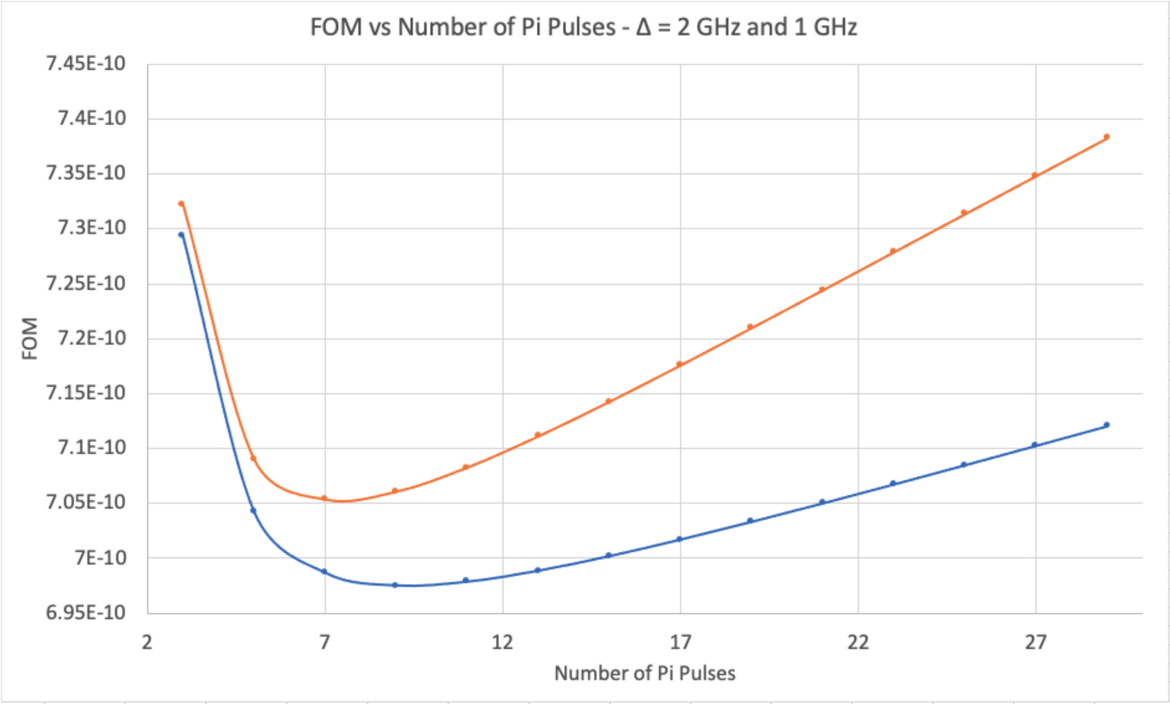
Back Ups

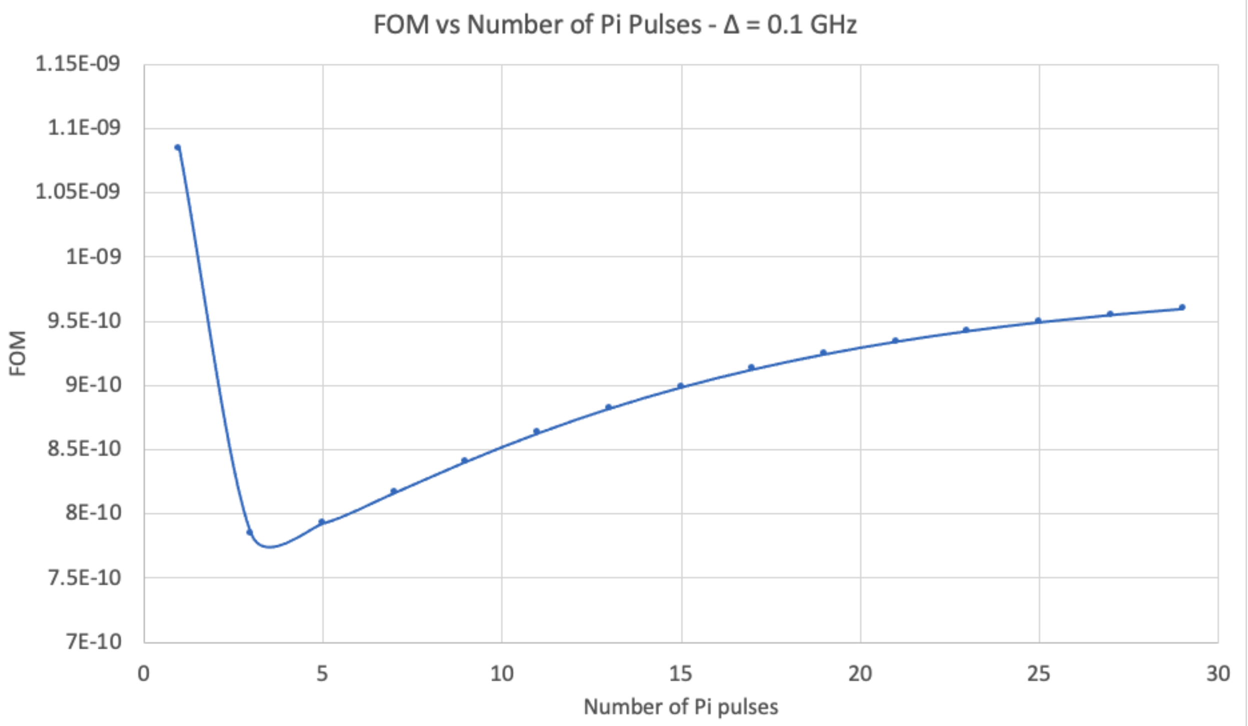
- An increasing single photon detuning gives an increasing optimum number of Raman pulses LMT



Back Ups

- System with 200 μs π pulse and lower single photon detuning





- Start to see larger ground state populations at the end of the pulsing sequence