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Progress Towards a High Data Rate Grating Magneto-Optical Trap

Roger Ding, Adrian S. Orozco, Peter D. D. Schwindt, Jongmin Lee
Sandia National Laboratories, Albuquerque, New Mexico, USA

Overview

Light-pulse atom interferometers (LPAIs) are important for advanced inertial sensing applications due to their exquisite sensitivity and long-term stability but operating in real-world environments remains challenging. Cold-atom LPAIs interrogate freefalling atoms with a sensitivity $\sigma_g \propto 1/T_{\text{AI}}^2$ for interrogation time T_{AI}, therefore the best sensitivity is achieved by maximizing T_{AI} but this causes the LPAI to be susceptible to dynamics occurring on timescales $\lesssim T_{\text{AI}}$.

High Data Rate Approach

Mitigate detrimental effects of relative motion between the atoms and interrogation lasers is to operate the LPAI at high cycle rates (R)

$$R \equiv \frac{1}{T_{\text{Cycle}}} = \frac{1}{T_{\text{Cooling}}} + \frac{1}{T_{\text{AI}}} + \frac{1}{T_{\text{Overhead}}}$$

necessitating a tradeoff between signal ($\sim T_{\text{Cooling}}$) and sensitivity ($\sim T_{\text{AI}}$).

Building on previous work that demonstrated a grating magneto-optical trap (GMOT) LPAI accelerometer [1], we present work towards achieving high cycle rate ($R \gtrsim 100$ Hz) GMOT operation. This is enabled by recapturing atoms from cycle-to-cycle [2,3], reducing T_{MOT} and maximizing T_{AI}. This result will enable development of fieldable LPAIs tolerant of dynamics.

Light-Pulse Atom Interferometry (LPAI)

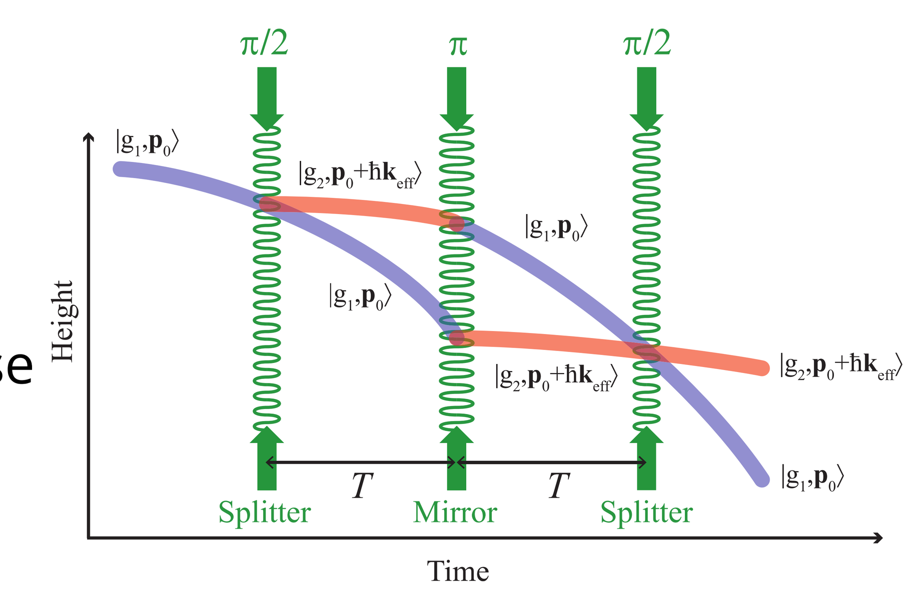
Drive Doppler-sensitive Raman transitions between ^{87}Rb ground states using $\frac{\pi}{2} \to T \to \pi \to T \to \frac{\pi}{2}$ pulse sequence (note $T_{\text{AI}} \approx 2T$).

- Atomic population coherently oscillates between

$$|g_1\rangle \equiv |5\ ^2S_{1/2}, F=1, m_F=0\rangle$$
$$|g_2\rangle \equiv |5\ ^2S_{1/2}, F=2, m_F=0\rangle$$

- Resulting interference fringe phase is sensitive to accelerations

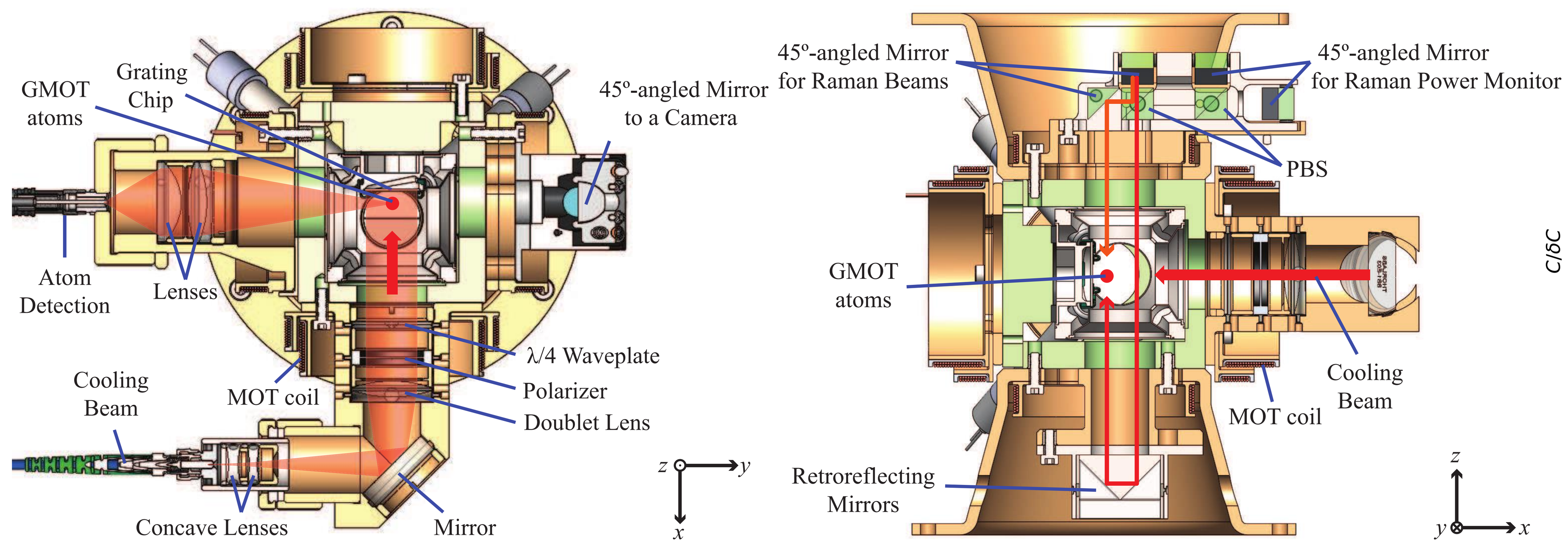
$$\Delta\phi = \boldsymbol{k}_{\text{eff}} \cdot (\boldsymbol{a} - 2\boldsymbol{v} \times \boldsymbol{\Omega})T^2$$



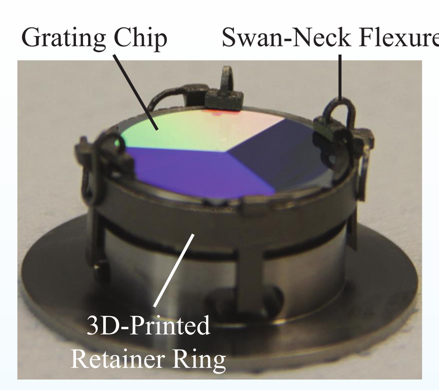
Prototype Compact LPAI System

Structure was primarily designed with the goals of minimizing mechanical degrees-of-freedom while maintaining a compact formfactor [1].

- "Alignment-free" optics system with all fiber delivery of 780 nm light
- Nonconductive materials (FR4, PEEK) to reduce eddy currents

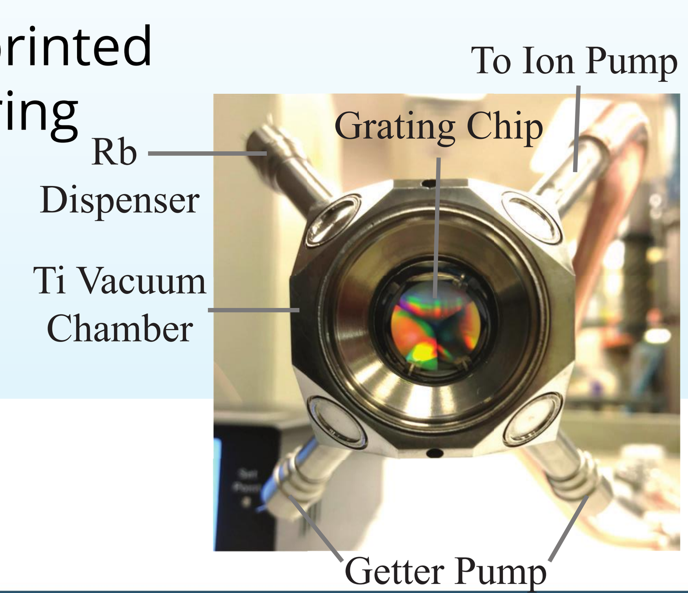


In-house-fabricated grating chip is composed of three binary gratings in a triangular orientation to form a tetrahedral GMOT [4-6].

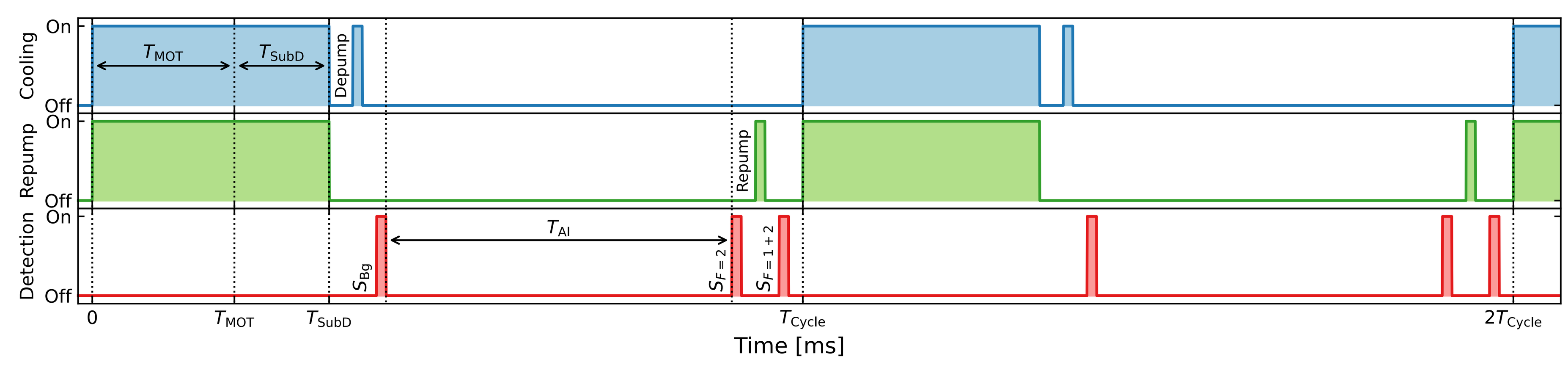


Vacuum package is similar to the passively-pumped system that has sustained a MOT for ≳2 years [7].

- Volume: $1.6 \times 1.6 \times 1.6$ in^3 ($4 \times 4 \times 4$ cm^3)
- Internally-mounted grating chip using 3D-printed Ti swan-neck flexure mount and retaining ring
- Includes Rb dispensers, NEGs, and AR-coated fused silica viewports
  - Sapphire viewports were used in [7] to reduce He permeation



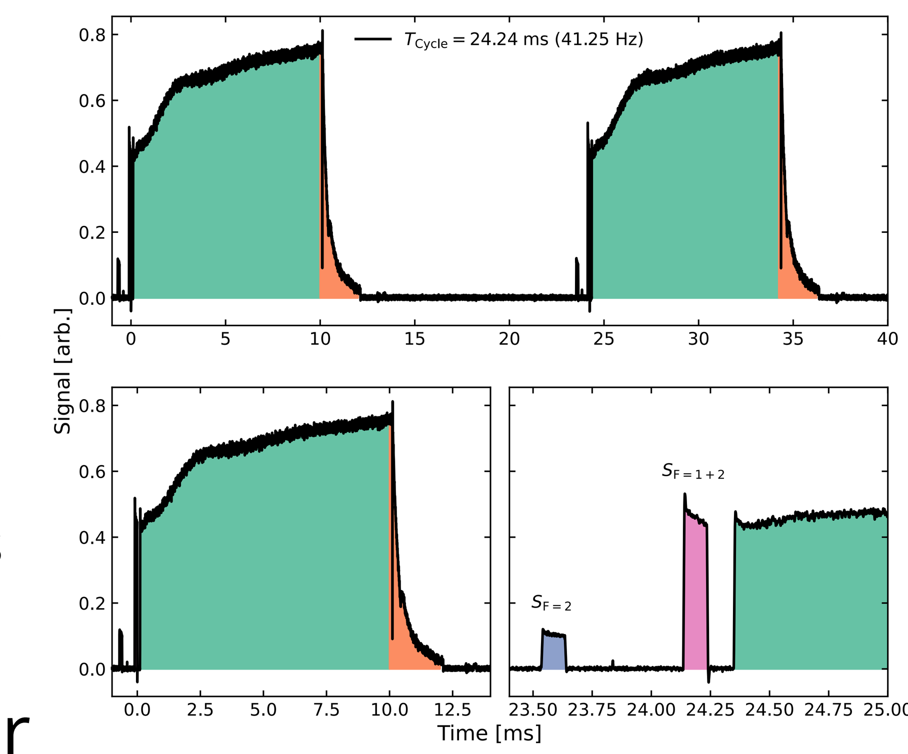
High Data Rate GMOT Experiment Cycle



Contrast (C) SNR as figure of merit

$$C = \frac{(S_{F=1+2} - S_{\text{Bg}}) - (S_{F=2} - S_{\text{Bg}})}{(S_{F=1+2} - S_{\text{Bg}}) + (S_{F=2} - S_{\text{Bg}})}$$

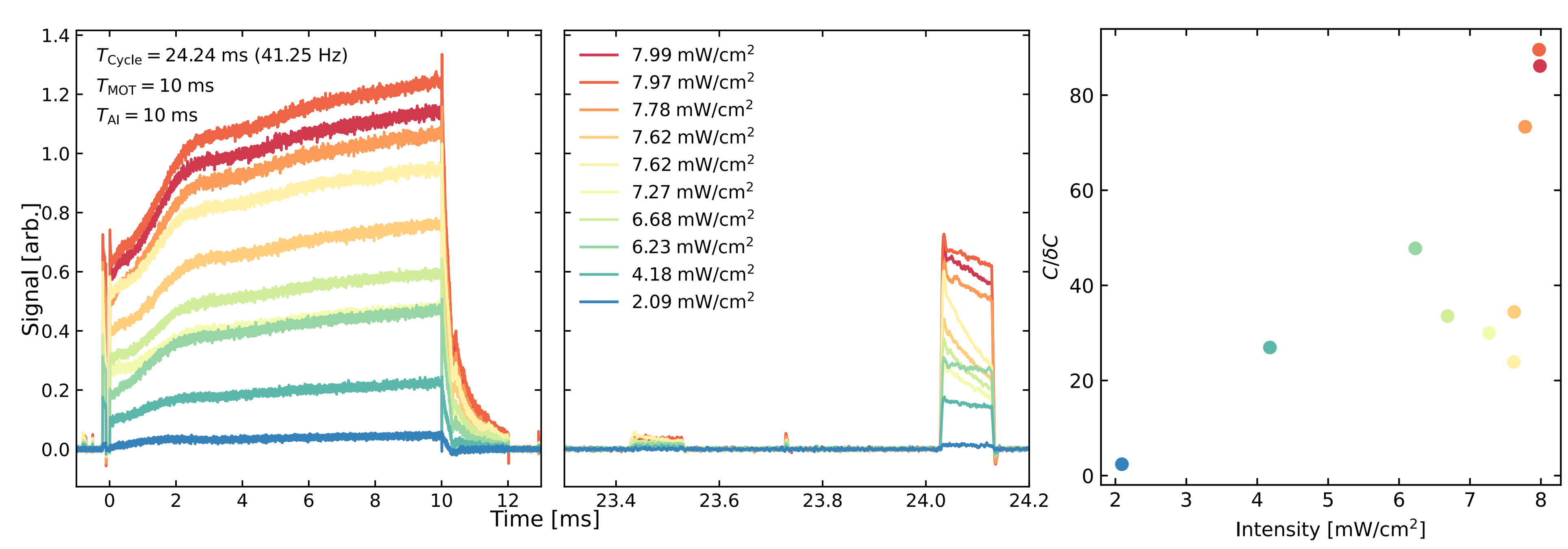
- $C/\delta C \sim 1/\sigma_g = gkT^2/\delta\phi$
- S_{Bg} : background fluorescence after depumping atoms to $F=1$
- $S_{F=2}$: atoms that would have transferred due to Raman AI pulses
- $S_{F=1+2}$: total atom signal



Varying GMOT Cooling Power

Maximum atom number is expected to occur with $\approx 10-30$ mW/cm^2 of cooling power [8,9].

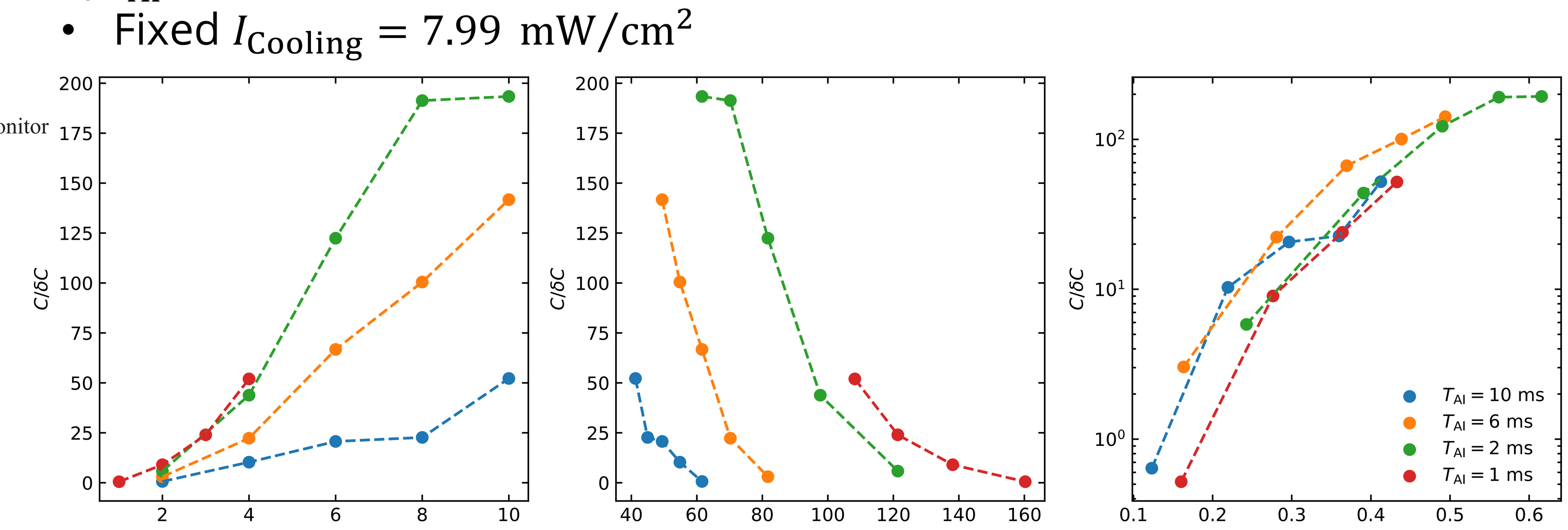
- Prototype system cooling power limited by inefficient truncated-Gaussian "flat-top" beam shaper (~ 16.4% delivered to grating)
- Fixed $R = 41.25$ Hz : $T_{\text{Cycle}} = 24.24$ ms, $T_{\text{MOT}} = 10$ ms, $T_{\text{AI}} = 10$ ms



Varying Cycle Rate (Varying T_{MOT} and T_{AI})

Explore tradeoff between signal ($C/\delta C$) and potential LPAI sensitivity ($\sigma_g \propto 1/T_{\text{AI}}^2$).

- Fixed $I_{\text{Cooling}} = 7.99$ mW/cm^2



Next Steps and Future Directions

- Increase GMOT cooling power $\gtrsim 10$ mW/cm^2 to reach predicted maximum GMOT atom number [8,9]
- Replace single-sideband (IQ) modulators [10-13] with acousto-optic modulators (AOMs) to improve system reliability
- Calibrate fluorescence to extract atom number
- Measure temperature after sub-Doppler cooling
- Implement D_2 Λ-enhanced grey molasses for GMOT [14,15]

References

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