Generating Robust Forces by Pulsed Adiabatic Rapid Passage on Metastable Helium

James Dragan, John Elgin, Harold Metcalf,
Stony Brook University, Stony Brook NY 11794-3800

Theory of Adiabatic Rapid Passage (ARP)

Optical Bloch Equations

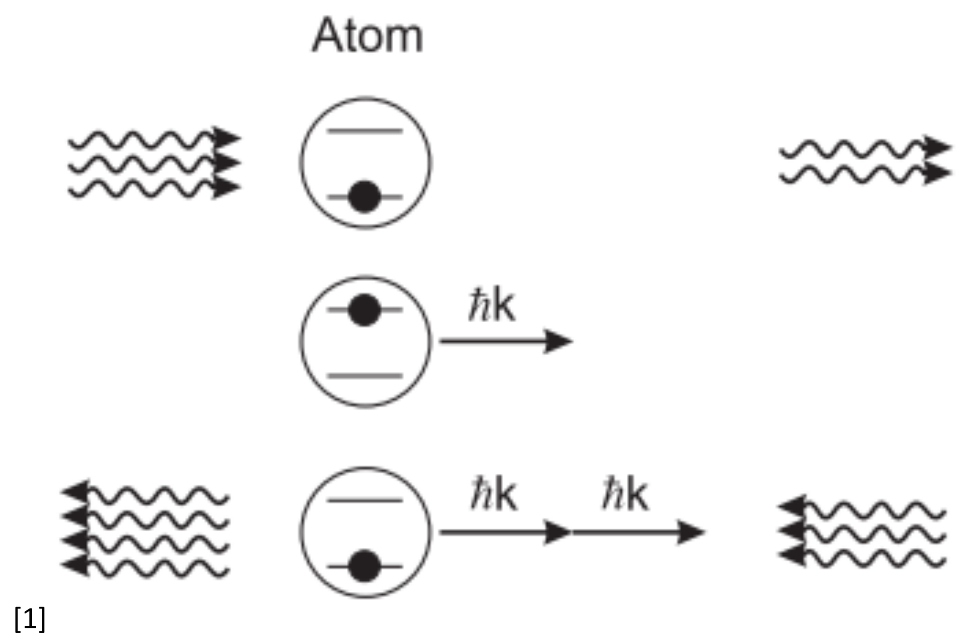
The Schrödinger equation leads to the optical Bloch equations for a near resonantly driven two-level system. These equations show the time evolution of the system as a set of coupled linear differential equations. The Bloch vector $\tilde{R}$ represents the state of the two-level system, is controlled by the laser, while the "torque" vector $\tilde{\Omega}$ contains the complex Rabi frequency and laser detu

$$\frac{d\tilde{R}(t)}{dt} = \tilde{\Omega}(t) \times \tilde{R}(t)$$

$$\tilde{\Omega}(t) = \begin{cases} \Omega_r(t) = \Omega_0|\sin(\omega_m t)| \\ \Omega_i(t) = 0 \\ \delta(t) = \delta_0\cos(\omega_m t) \end{cases} \qquad \dot{R}(t) = [\dot{u}, \dot{v}, \dot{w}] = \begin{cases} \dot{u} = \Omega_i w - \delta v - (\gamma/2)u \\ \dot{v} = \Omega_r w + \delta u - (\gamma/2)v \\ \dot{w} = \Omega_r v - \Omega_i u - \gamma(w+1) \end{cases}$$

$$\gamma = 1/\tau$$

ARP Force on a Stationary Two-Level Atom



Utilizing momentum transfer from the interaction between light and matter, two pulses from opposite directions impart two momentum kicks on an atom. In ARP, the force is more robust because it is controlled by experimental parameters oppose to being limited by atomic parameters.

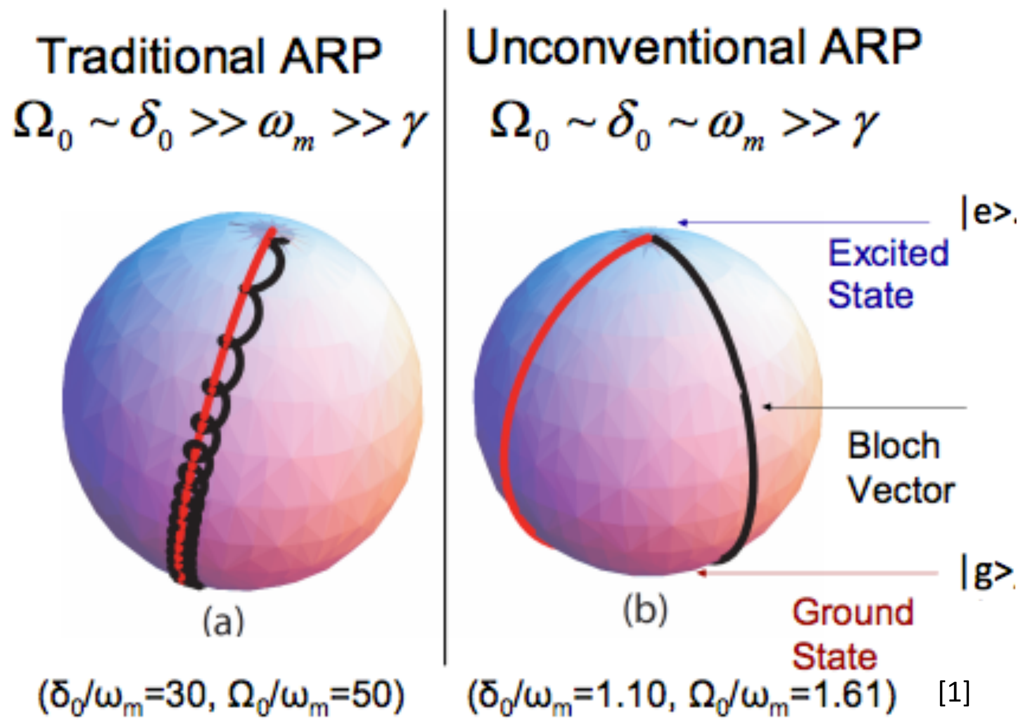
$$F_{ARP} \equiv \frac{\hbar k \omega_m}{\pi}$$ → Experimental parameter

$$F_{rad} \equiv \frac{\hbar k \gamma}{2}$$ → Atomic parameter

Adiabatic Rapid Passage

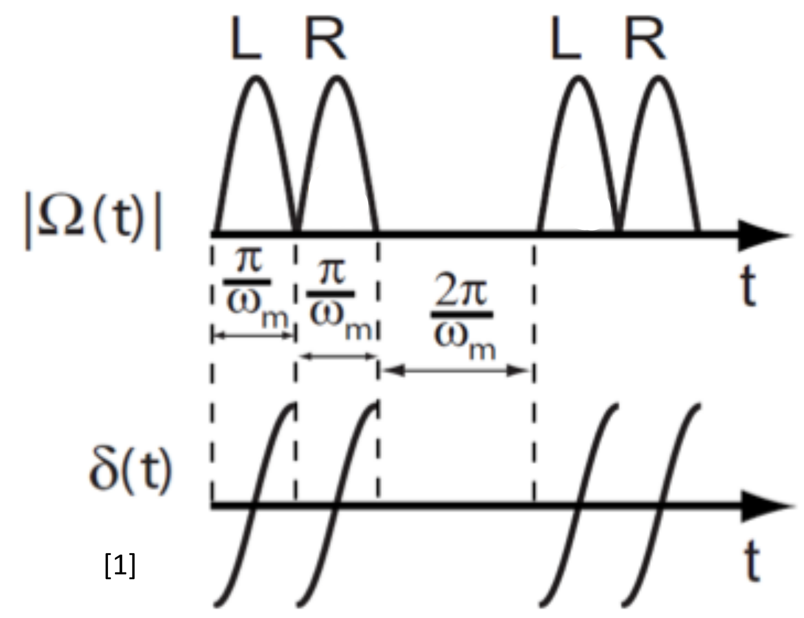
The evolution of the atomic state can be visualized on the surface of a sphere. The south pole $\tilde{R}$ = [0,0,-1] represents the ground state |g>, and the north pole $\tilde{R}$ = [0,0,1] represents the excited state |e>.

Adiabatic Rapid Passage is a technique used to invert the population of the two-level system by sweeping the frequency of the applied field through resonance. This is shown on the Bloch sphere as the adiabatic following of $\tilde{R}$ as it rotates around $\tilde{\Omega}$. The parameters used in this experiment fall under the Unconventional ARP condition because they are much more accessible experimentally.



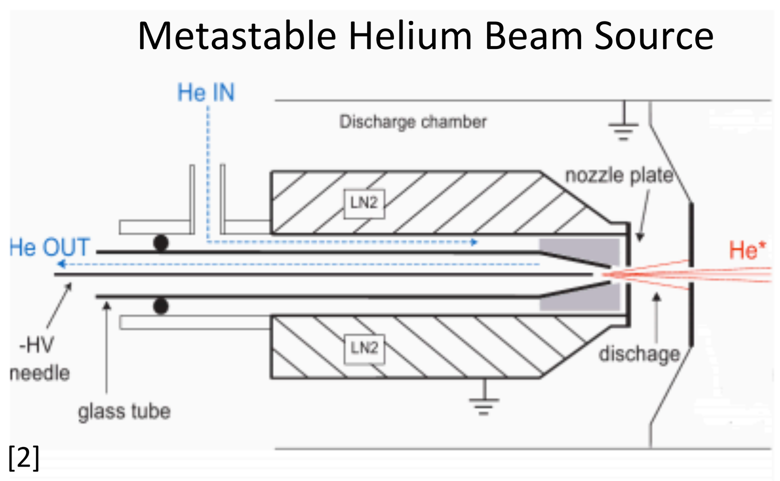
Pulse Parameters

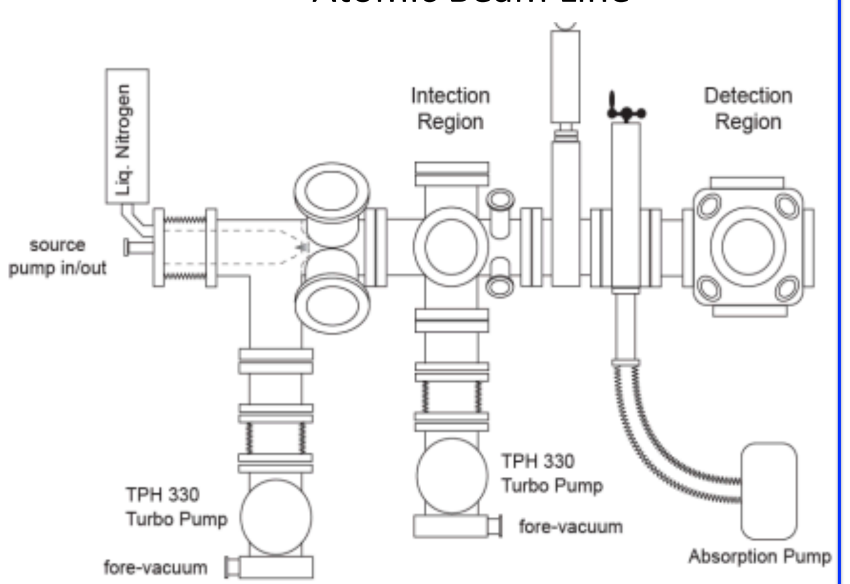
A depiction of our pulse scheme is shown. The half-period sine wave in the upper trace represents a pulse of duration $\frac{\pi}{\omega_m}$ = 3.125 ns. The upward frequency sweep of this pulse is shown in the lower trace. Immediately after the first pulse, a second pulse is incident from the opposite direction with an upward sweep as well. This is followed by a dead time of $\frac{2\pi}{\omega_m}$ = 6.25 ns.



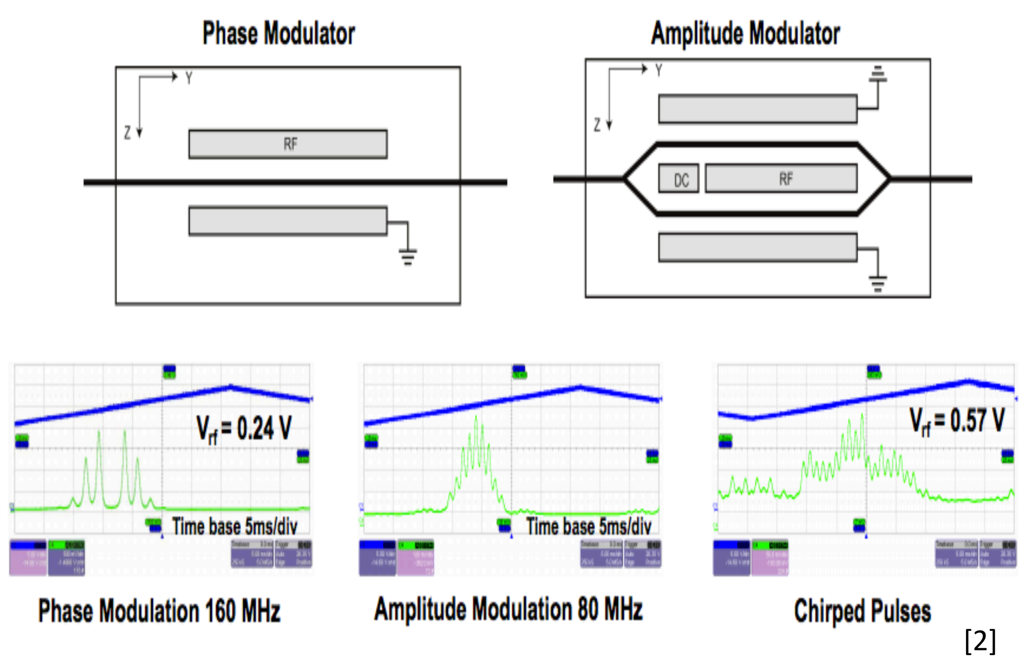
Experimental Setup

Vacuum System





Making Chirped Pulses



$$\bar{F}_{ARP} = \frac{\Delta p}{\Delta t} = \frac{2\hbar k}{4\pi/\omega_m} = \frac{\hbar k \omega_m}{2\pi} \approx 32 F_{rad}$$

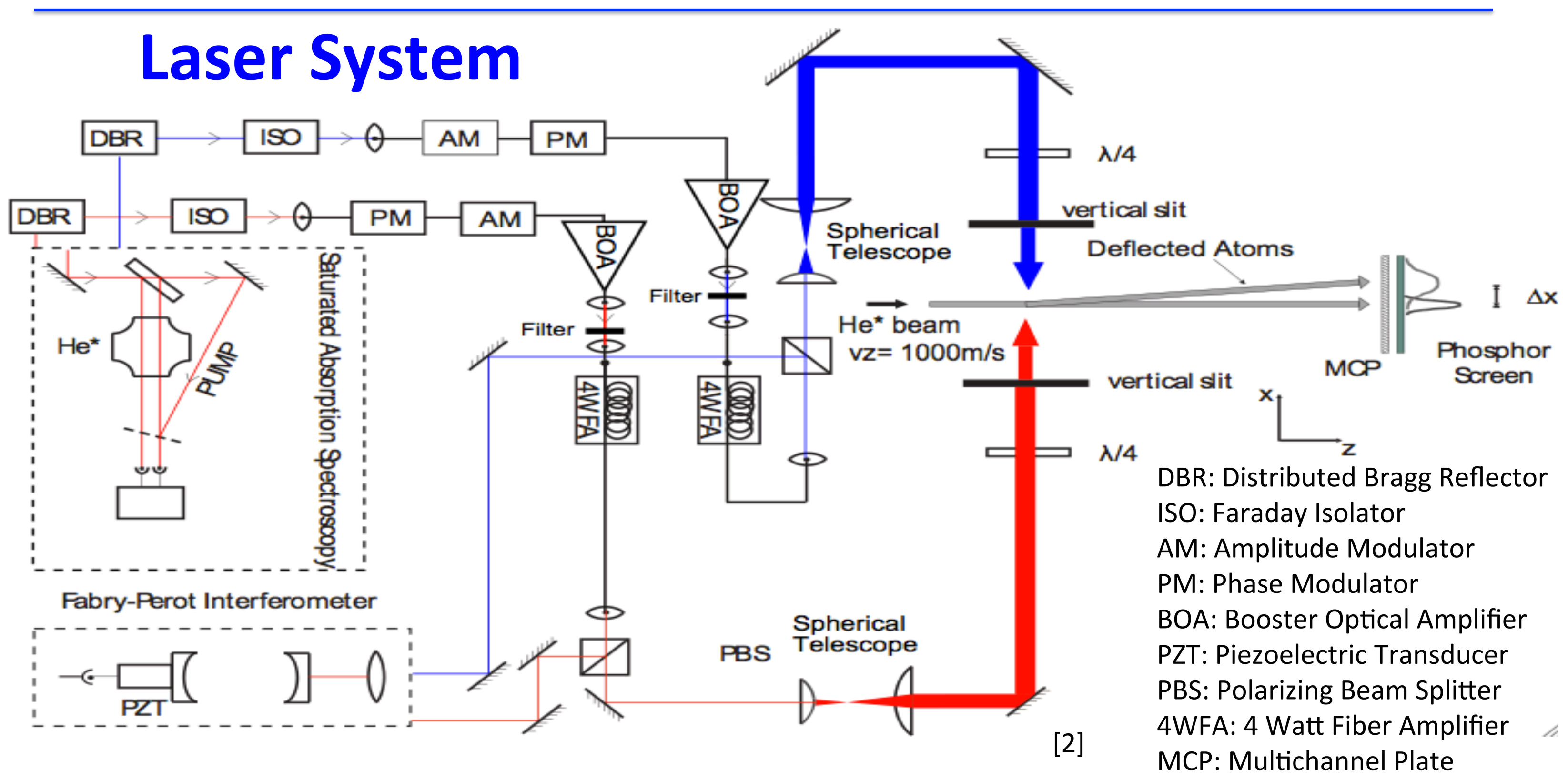
Chirping Frequency:

$$\omega_m = 100\gamma = 2\pi * 160\text{MHz}$$

Pulse Parameters: 80 MHz rep. rate with 25% duty cycle, resulting in a pulse length of 3.125 ns.

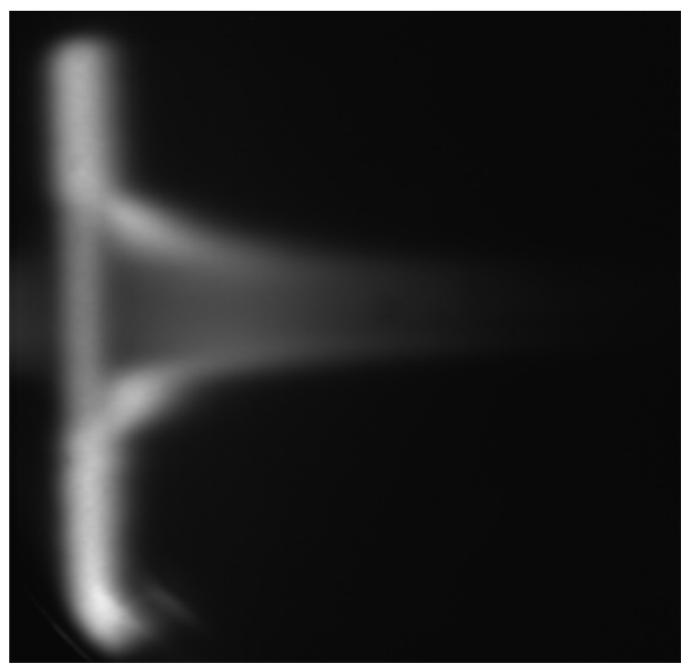
The dead time is introduced to ameliorate the detrimental effects of spontaneous emissions. Other limitations arise from experimental considerations. Note that laser cooling requires that the force be significant at some velocities but vanish at others. In the low intensity limit, the typical velocity capture range, $v_c \sim \frac{\gamma}{k}$, depends on atomic properties but for the ARP force, $v_c \sim \frac{\delta_0}{k}$, is much larger for for $\delta_0 >> \gamma$.

Laser System



DBR: Distributed Bragg Reflector
ISO: Faraday Isolator
AM: Amplitude Modulator
PM: Phase Modulator
BOA: Booster Optical Amplifier
PZT: Piezoelectric Transducer
PBS: Polarizing Beam Splitter
4WFA: 4 Watt Fiber Amplifier
MCP: Multichannel Plate

ARP Forces & Experimental Data



Here the ARP force is shown on a CCD camera that images light emitted by a phosphor screen. The bright vertical line is the atomic beam, collimated by a series of slits. The ARP force pushes atoms to the right beyond the strength of the radiative force (located around the dark spot just to the right of the atomic beam).

Conclusion and Outlook

It has been shown both numerically [1][4] and experimentally [2] [3] that the process of ARP can generate forces much greater than that of the radiative force. The experiment is ongoing to measure the velocity dependence of the ARP force for possible applications to laser cooling. Plans are to measure the capture range and the velocity dependence of the ARP force.

References

[1] Daniel Stack et al., Dynamic Effects in Optical Forces Produced by Adiabatic Rapid Passage, APS DAMOP 2011
[2] Daniel Stack et al., Velocity Dependence of the Optical Force Produced by Adiabatic Rapid Passage, APS DAMOP 2012
[3] Daniel Stack et al., Strong Optical Force Measurements Using Adiabatic Rapid Passage, APS DAMOP2011
[4] Daniel Stack et al., Bull. Am. Phys. Soc. **56**, No. 5, 152 (2011) Q1 17

Work is supported by the Office of Naval Research