Working Towards an Active Stabilization System for a Low-loss, Free-space Optical Quantum Memory

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MOTIVATION

Error-free and long-lived quantum memories are a useful resource for quantum information science and technology because of their ability to synchronize independent and probabilistic quantum processes.

Various Quantum Memory Architectures that Currently Exist

	ORCA	EIT	AFC	Hybrid	Delay Line
Fidelity	N/A	> 0.99	N/A	N/A	> 0.99
Efficiency	0.25	0.85, 0.65	0.035, 0.001	0.06, 0.003	0.97, 0.82
Storage Time	86 ns	1 µs, 7 µs	2 ms, 50 ms	30 ns, 1.59 µs	12.5 ns, 1.25 µs
Bandwidth	250 MHz	3 MHz	160 kHz	500 MHz	1.52 THz
Time-Bandwidth	21.5	9	3200	20.2	6×10^6

ORCA: two-photon off-resonant cascaded absorption. EIT: electromagnetically induced transparency, AFC: atomic frequency comb. Hybrid: atomic ensemble memory and an optical delay line. For memories that had varying storage times, two storage times are their respective efficiencies are displayed. [1]

Our group is interested in the delay line quantum memory because of its ability to offer a high efficiency with excellent fidelity, bandwidth, and time-bandwidth product. In our design, a multi-pass modified Herriott cell (MHC) creates an optical loop that stores and releases a photon at programmable intervals.

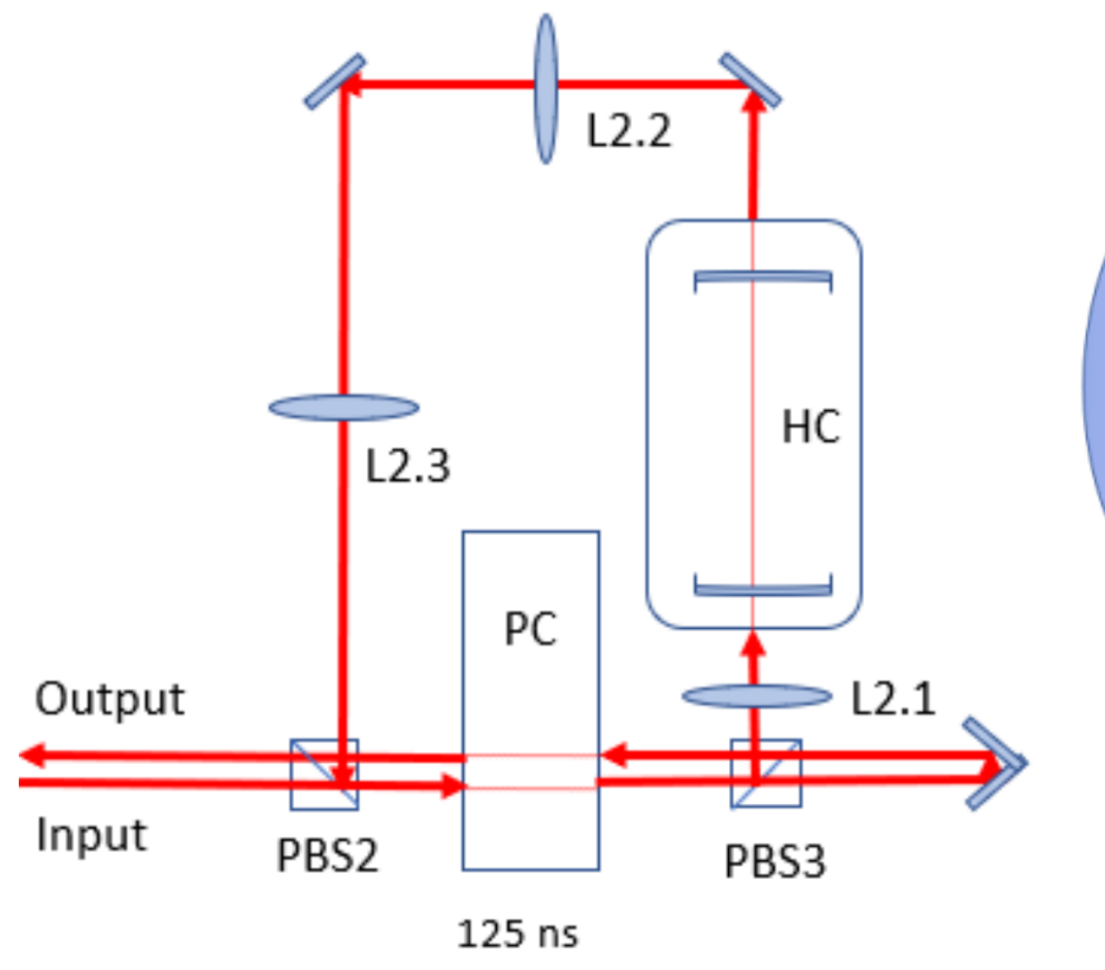
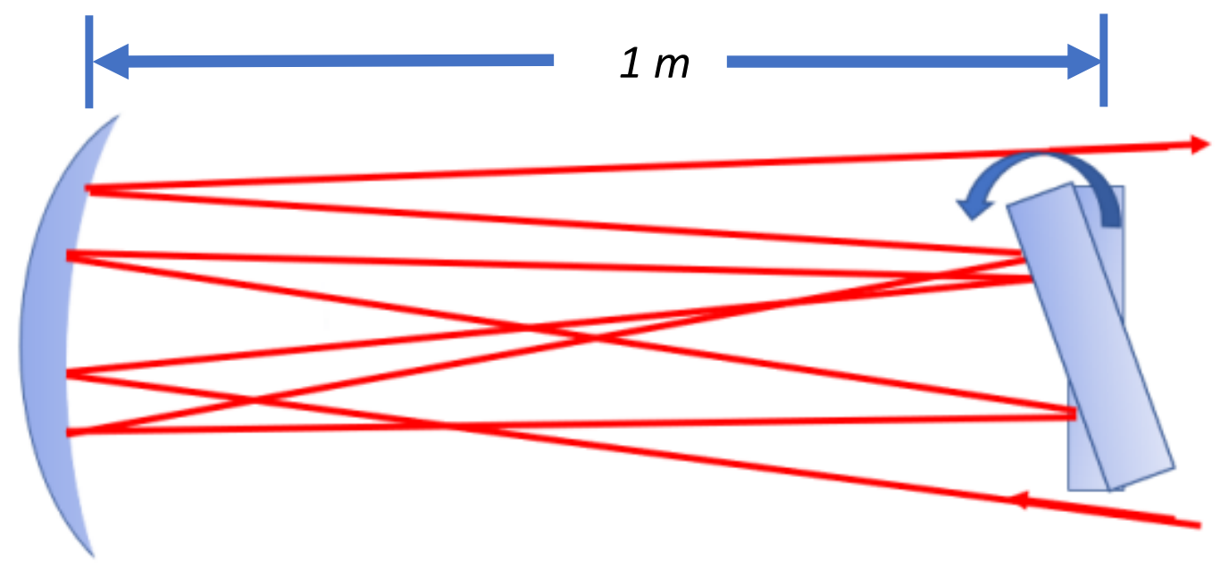


Diagram of a loop in an optical delay line. [1]

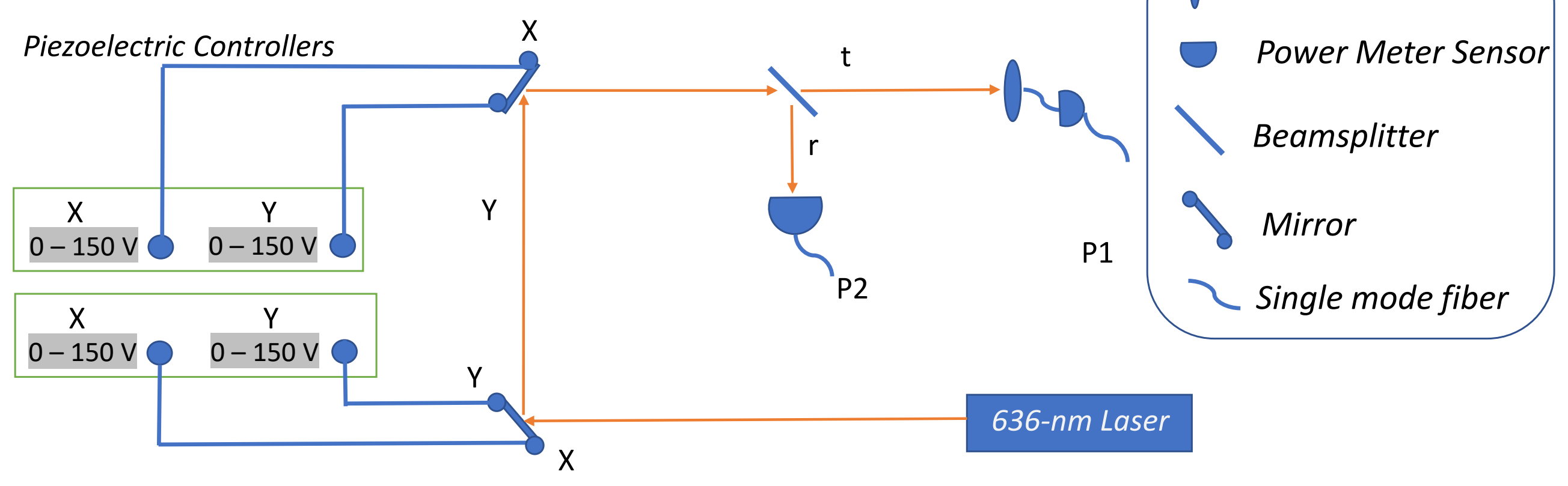
PC: Pockels cell, HC: Herriott Cell, PBS: Polarizing beamsplitter, L: Lenses



Simplified side view of modified Herriott cell, formed by creating a cavity with a spherical mirror opposite two adjacent square mirrors. [1]

Since our MHC has an effective optical path length of hundreds of meters, a robust active feedback system is required to maintain optical alignment.

EXPERIMENTAL STABILIZATION SYSTEM

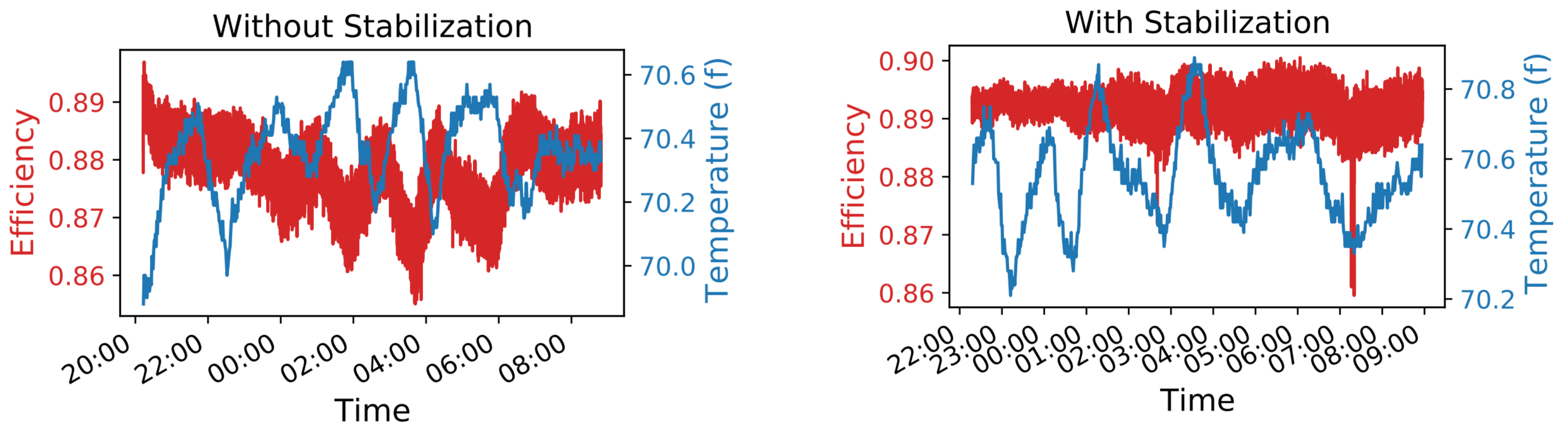


*Coupling efficiency is calculated as (P1/P2) * (r/t).*

- To develop the stabilization system, we first reduced the MHC setup to a simplified version, where we aim to stabilize optical coupling into a single-mode fiber with two motorized mirrors.
- Motors adjust the mirror angle in the tilt and tip directions, with a beam splitter inserted to normalize the optical power collected in the fiber.

PRIOR WORK

- Our research group has developed a stabilization system for fiber coupling with mirrors on DC servo mounts.
- Our existing system uses the Levenberg-Marquardt algorithm, which is a combination of the Gauss-Newton Algorithm (GNA) and gradient descent.
- If the coupling efficiency measured falls below a certain threshold, the stabilization algorithm is activated, which adjusts the mirror angles until the optimal coupling efficiency is obtained.

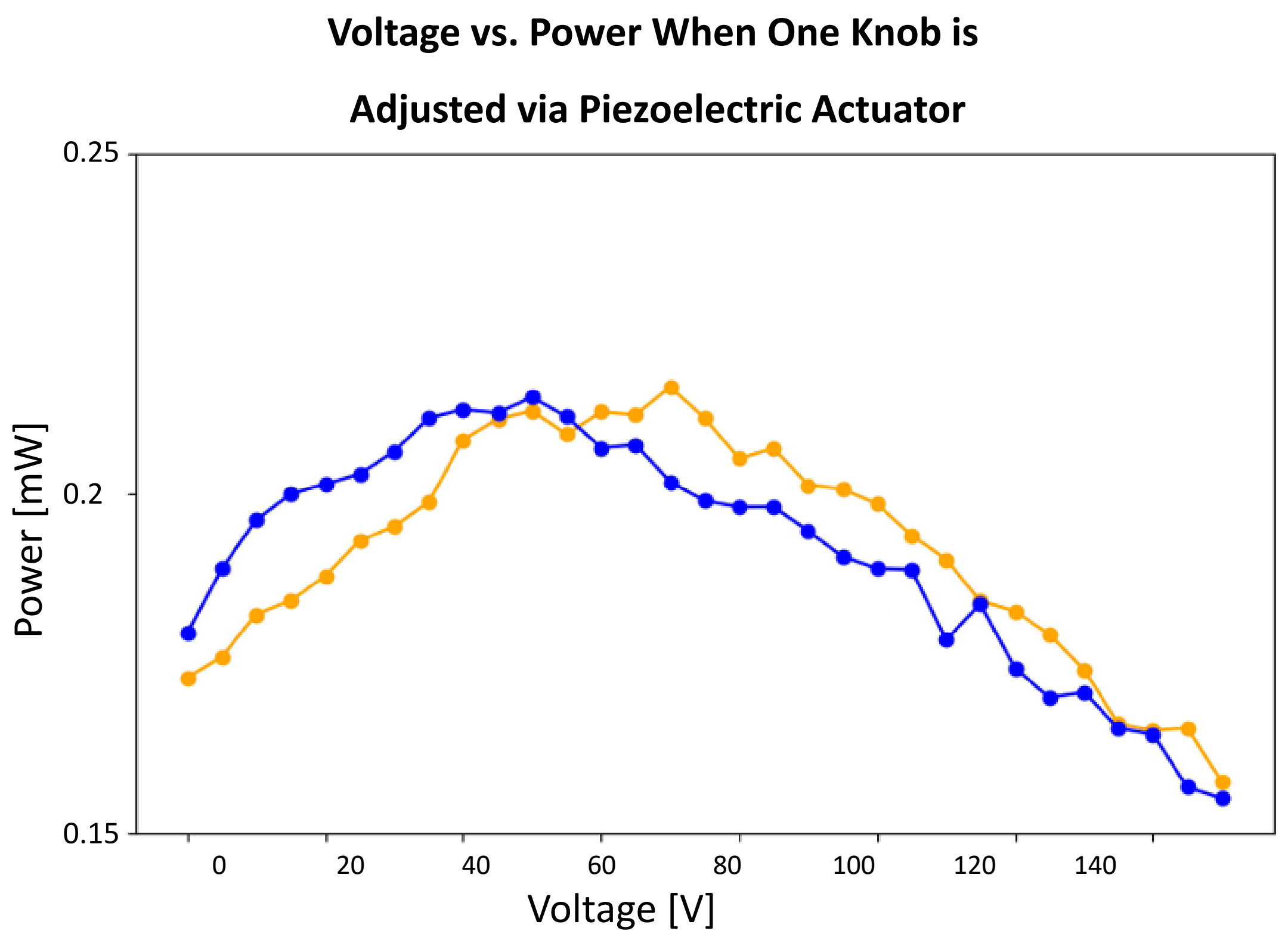


Fiber-coupling efficiency (red) for DC servo mirrors with and without stabilization for a single-mode fiber. The standard deviation for coupling efficiency without stabilization is 0.0058, whereas the standard deviation for coupling efficiency with stabilization is 0.0023.

Figures generated by Michael Vayninger.

- However, one drawback of the DC servo mirror is its large size, which prompted us to investigate the viability of replacing them with more compact piezoelectrically driven mirrors.
- Because of the nonlinearity associated with hysteresis in piezoelectric materials, we wanted to explore if the algorithm used for the DC servo mirrors would work for the piezoelectric mirrors despite the hysteresis.

Size comparison of DC Servo Mirrors Thorlabs Kinematic Mounts – KS1T (top) and Piezoelectric Mirrors Thorlabs Polaris Mounts – K1S3P (bottom).



Left: Illustration of hysteresis in piezoelectric mirror mounts. One knob was adjusted while the other three knobs were kept at a constant 40 V. Orange line displays the power readings when increasing the voltage from 0 V- 150 V (5 V steps). Blue line displays the power readings when decreasing the voltage from 150 V – 0 V (5 V steps).

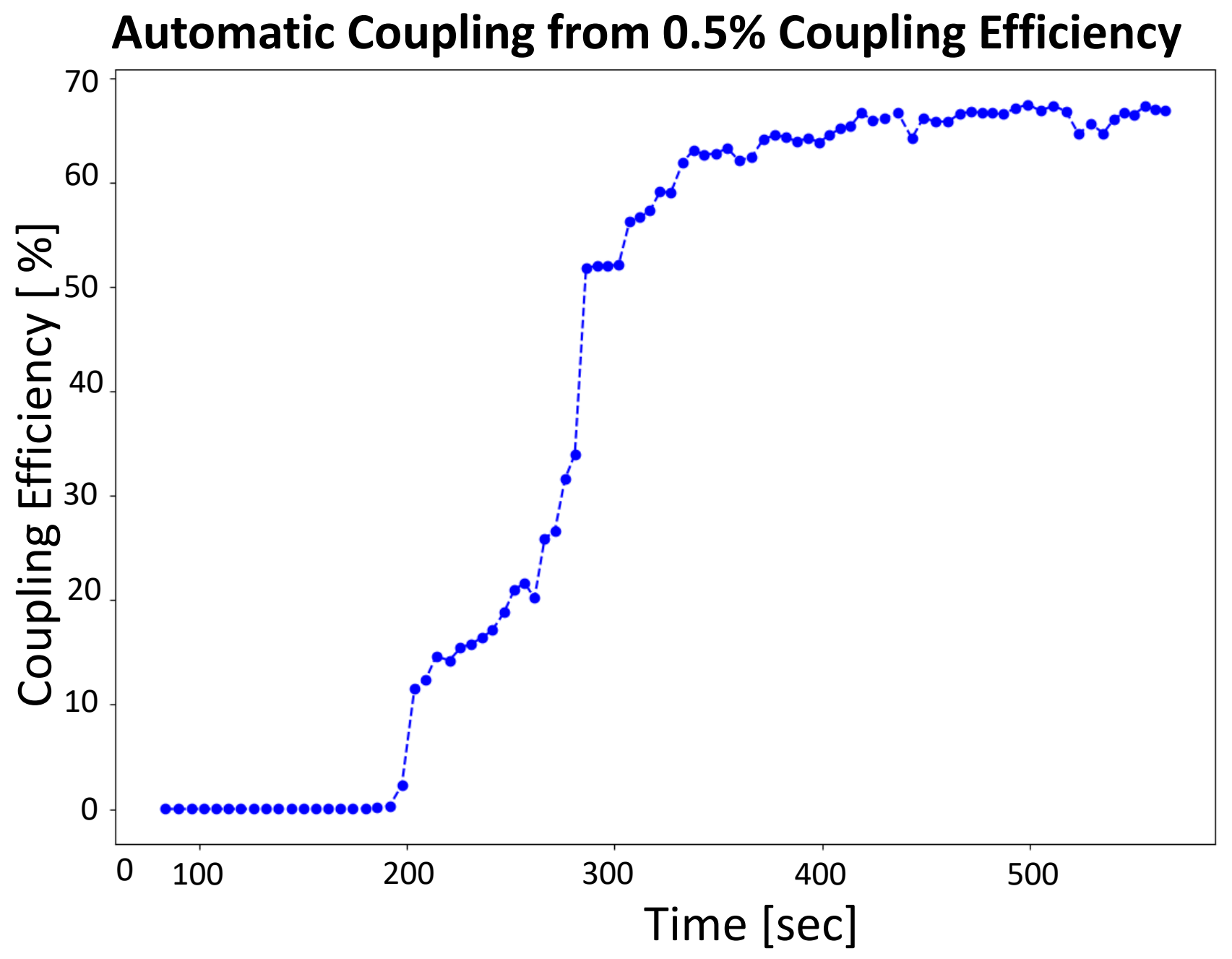
ALGORITHM

- Rather than utilizing Levenberg-Marquardt, we opted for a pure GNA implementation. This is because gradient descent has its advantages when the optimal value requires a bigger movement from the starting value. However, gradient descent has a slower convergence rate and the limited range of our piezoelectric knobs meant that we would rarely utilize the advantages offered by gradient descent.
- The piezoelectric mirrors are specified for > $5\text{x}10^{-4}$ radians movement of the beam. In comparison, DC servo mirrors are specified for $1.4\text{x}10^{-1}$ radians of movement.
- First derivatives were calculated using forward and backward sampling of the power readings (P1, P2), and second derivatives were calculated using central sampling.

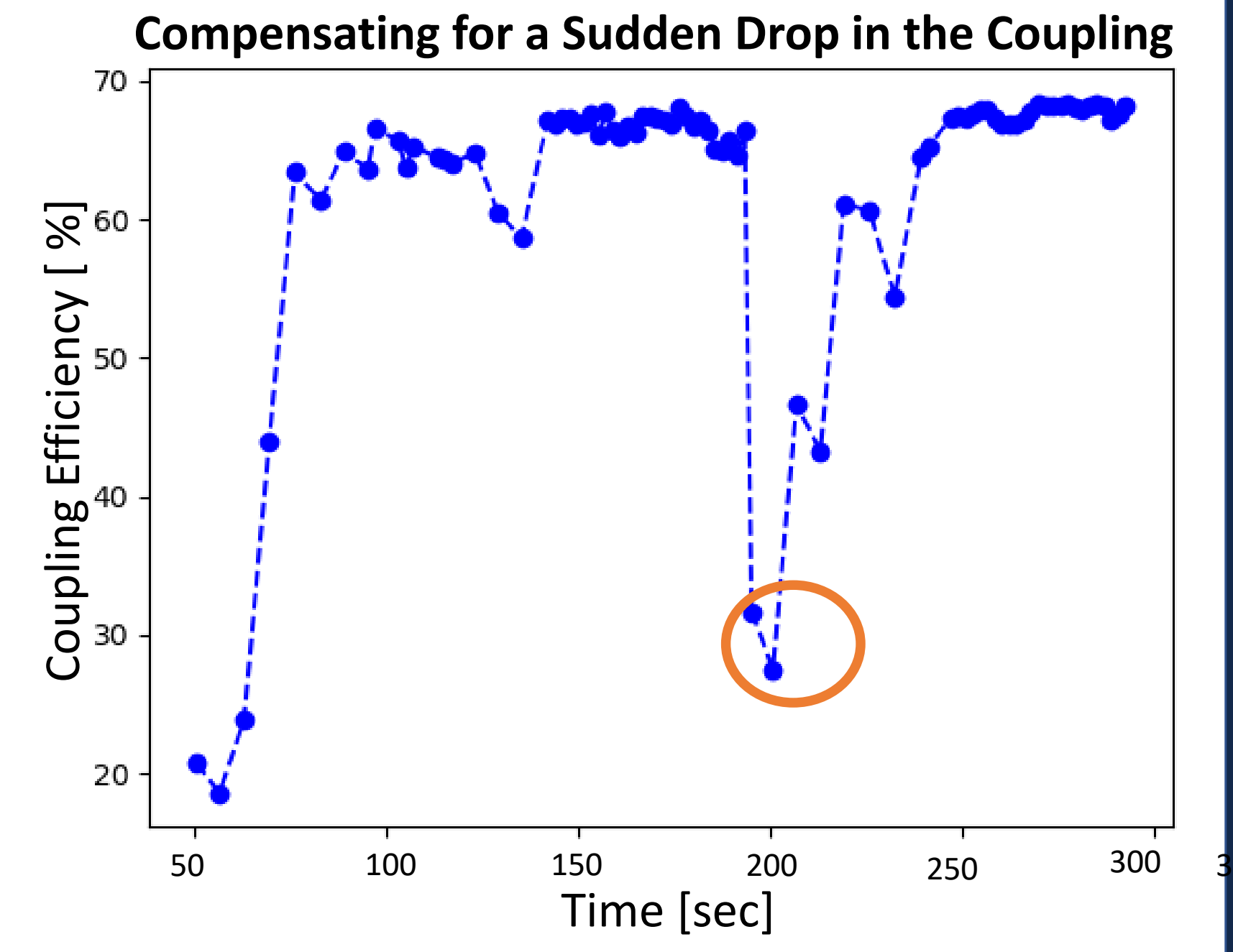
$$x_{k+1} = x_k - \left(\nabla^2 f(x_k)\right)^{-1} \nabla f(x_k)$$

RESULTS

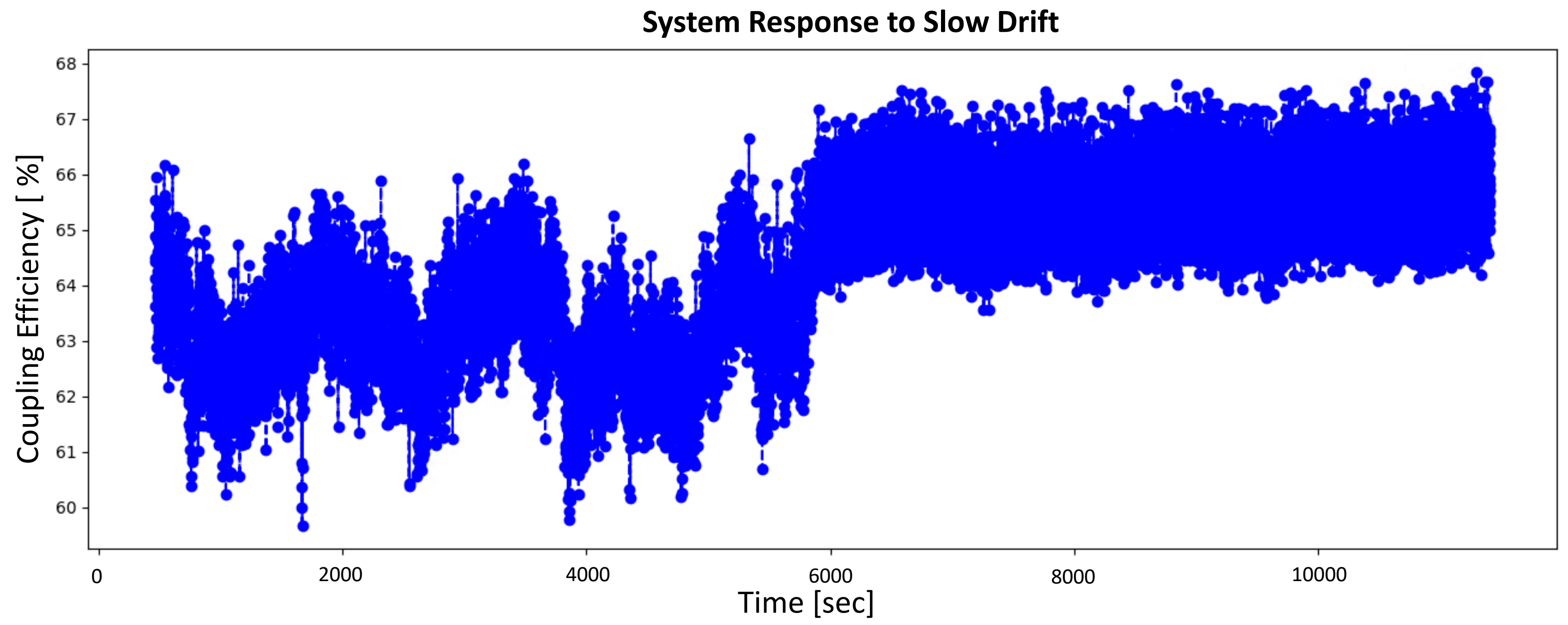
- To demonstrate the algorithm works as intended, three tests were devised:
  - Can the system increase coupling from an almost completely uncoupled system?
  - How does the system react to a sudden drop in the coupling caused by an external factor?
  - Can the system compensate for a slow drift in the coupling over a timescale of many hours?



Above: Demonstration of automatic coupling process for a single-mode fiber using the piezoelectric mirrors. No user modifications were needed. The protocol completed in approximately 3 minutes.



Above: Coupling efficiency when user manually decouples setup while the program is running (region circled). Program can detect drops in coupling efficiency and restore coupling.



Program ran for 4 hours without stabilization, then 4 hours with stabilization. Without stabilization, the mean coupling efficiency is 63.258% and the standard deviation is 1.053%. With stabilization, the mean coupling efficiency is 66.031% and the standard deviation is 0.723%

- We observed a factor of 1.457 reduction in the standard deviation with the piezoelectric mirrors, compared to a factor of 2.525 for the DC servo mirrors

CONCLUSION/FUTURE DIRECTIONS:

- Based on our results, we believe that piezoelectric mirrors are a viable replacement for the DC servo mirrors
- Currently, the algorithm is written in Python and runs on a PC that is connected to the power meters and piezo controllers via USB cables. To increase portability and simplify the stabilization hardware, we hope to instead use a microcontroller board.
- We wish to investigate if using a microcontroller and the analog inputs of the piezoelectric controllers will result in reduced system latency compared to using a PC and digital control via Python.
- To apply this system to our MHC, we would need to modify the external feedback mechanism of our simplified stabilization system. Currently, we are using the fiber coupling efficiency as feedback; however, when the inputs are single photons carrying quantum information, measuring the photons with a single-photon detector at the end of the collection fiber would destroy them. Some options that are to be explored include co-propagating classical light at a different wavelength with dichroic mirrors and using quad cells or separate optical fibers for feedback.

REFERENCES:

[1] Victoria (2020). New Opportunities for Photon Storage and Detection: An Exploration of a High-Efficiency Optical Quantum Memory and the Quantum Capabilities of the Human Eye [Unpublished PhD Dissertation]. University of Illinois Urbana-Champaign