Building a Lock-In Amplifier for an Ionization Experiment

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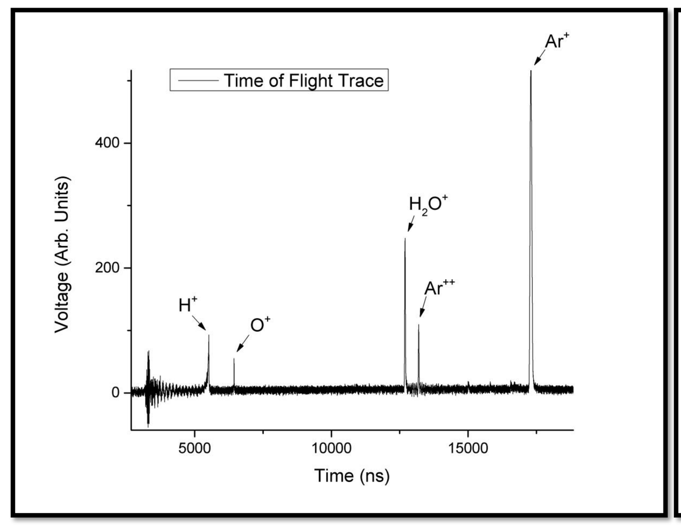
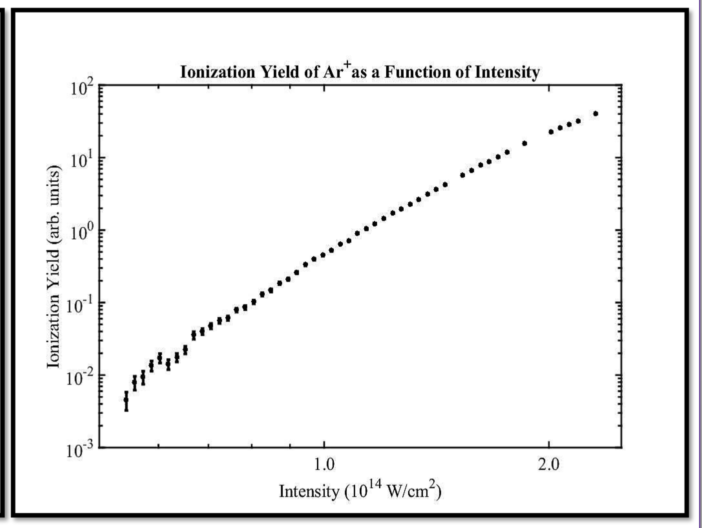
Objectives

- Develop a better understanding of molecular processes by precisely measuring ionization yields of different molecules using ***time-of-flight mass spectrometry***.
- In order to measure yields across a broad spectrum of intensity, we need a detection scheme with a ***large dynamic range***.
- The detection scheme must also have ***excellent temporal precision*** because we are interested in differentiating between signals that could be only hundreds of nanoseconds apart.

What is Time-of-flight Mass Spectrometry?

- Time-of-flight mass spectrometry involves measuring the time it takes atomic or molecular particles to travel toward a detector while undergoing an acceleration.
- Different types of ions have different masses and charges, so the acceleration each type experiences differs, causing the ions to ***spread out according to their charge to mass ratio***.
- We can use the signal from the ion detector to determine the yield of different ions. However, it can become very weak at low intensities, so we need a method for detecting it even if the signal-to-noise ratio is very small.





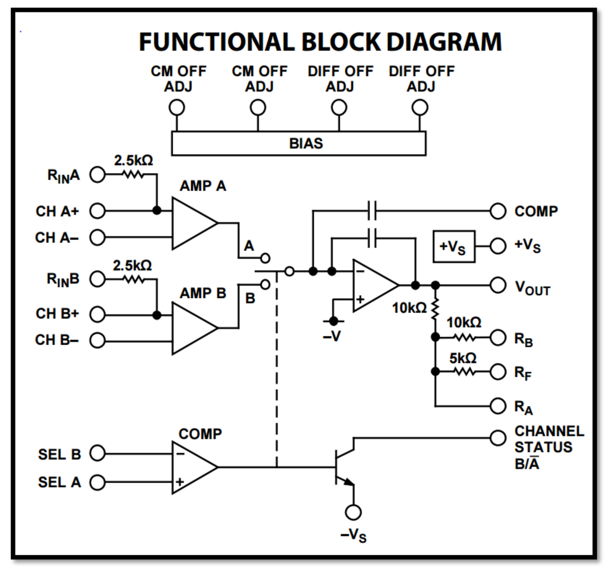
Plot of a signal generated by an ion detector from a time-of-flight mass spectrometry experiment (left). Plot of ionization yield of Ar^+ as a function of intensity (Right). Notice how quickly yield decreases with intensity and how much larger the relative error becomes. We wish to obtain reliable data at even weaker intensities.

What is a Lock-In Amplifier?

- A lock-in amplifier is an electronic device used to obtain information from a signal with a ***low signal-to-noise ratio***.
- The signal from the experiment is multiplied by a ***reference signal*** that has the ***same frequency***.
- The product is then integrated over many periods, resulting in a ***DC signal that is proportional to the amplitude of the original signal.***

Building a Lock-In Amplifier

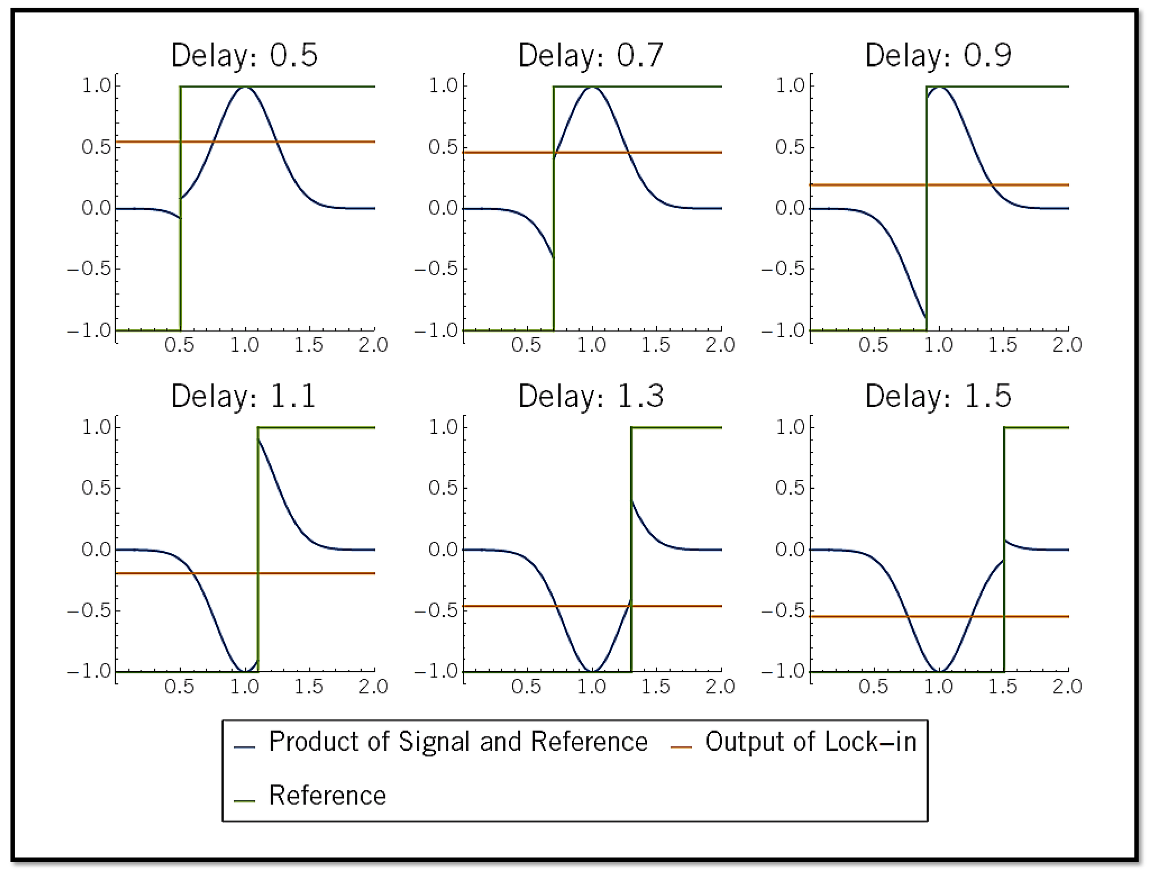
- A simple lock-in can be built using only a ***phase detector*** and an active ***RC integrator***.
- We chose to use the AD630 modulator/demodulator chip as a phase detector because it can accept analog signal inputs.



Functional diagram of the AD630 chip[1] used as a phase detector. In our wiring configuration, it behaves like an op amp with a gain that switches between plus one and minus one depending on the comparator input.

Method

- There is one major issue with using a lock-in for a time-of-flight mass spectrometer: ***multiple peaks need to be measured at the same time***.
- We developed a way to recover the original waveform of the signal via ***incrementally changing the phase*** of a square-wave reference signal by adding a delay.
- If the edge of the reference signal is sharp, the output of the lock-in will change as we shift it through the signal.
- ***The derivative of the change in output*** of the lock-in with respect to phase shift will return the ***original wave form***.
- The temporal resolution of this method depends on the ***sharpness of the reference signal*** and the ***number of delay steps taken***.



Visualization of reference scan method. Notice that the value of the integral changes most quickly as the reference crosses the signal's maximum.

Experiment

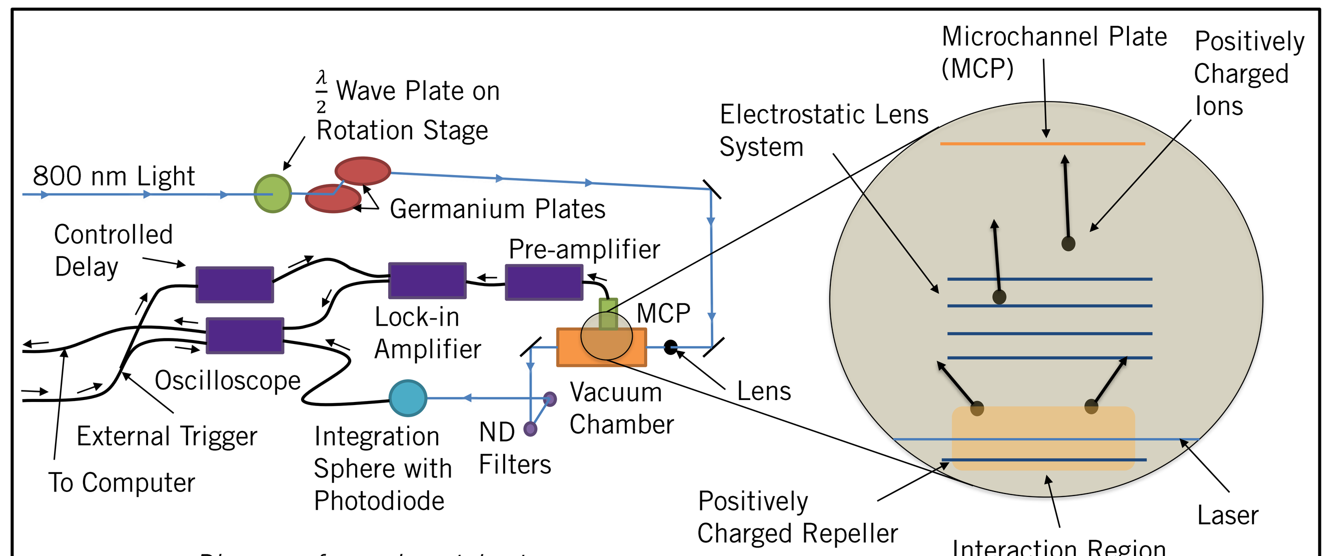
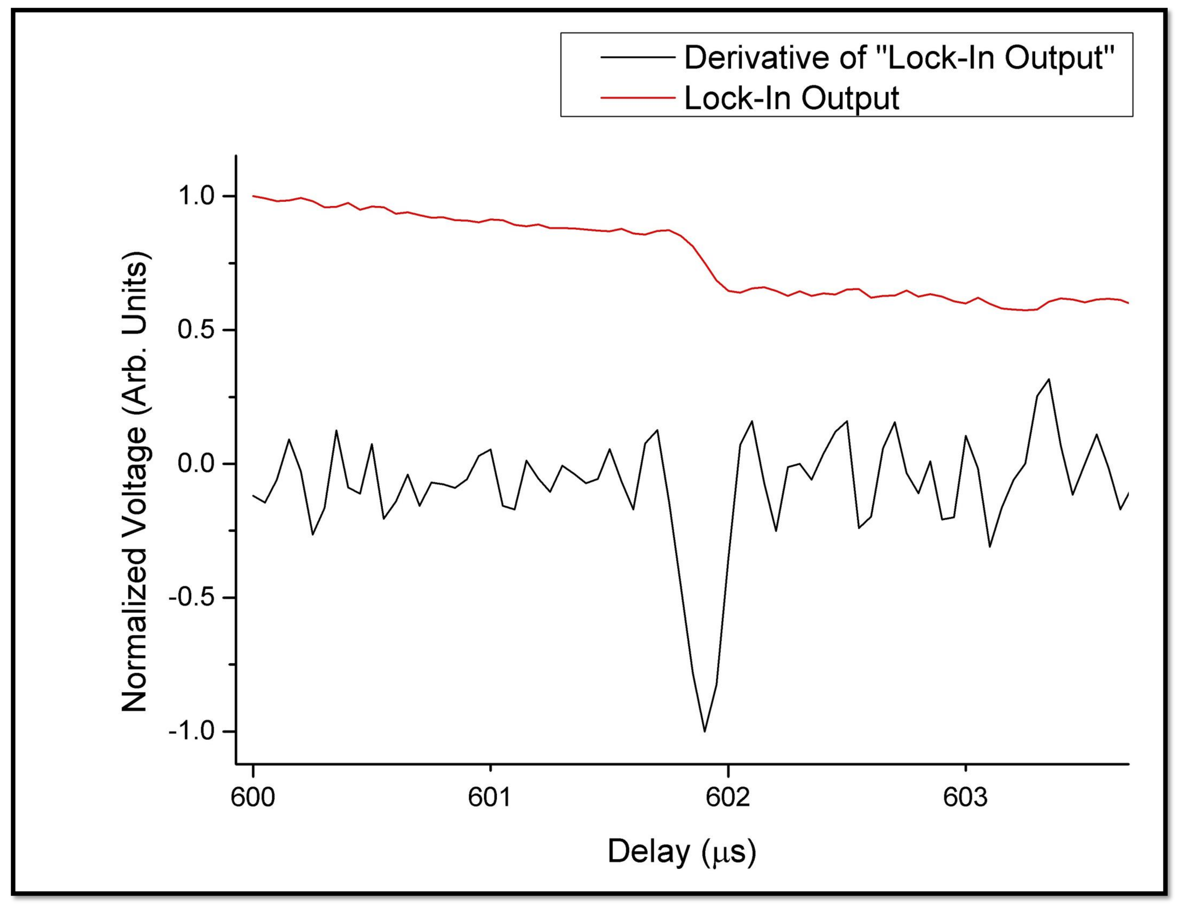


Diagram of experimental setup.

- Laser focuses on an effusive jet of argon inside the vacuum chamber.
- Ions are accelerated towards the microchannel plate detector, a device that generates a signal with ***picosecond precision***.
- The phase of the reference signal is changed using a delay generator controlled by a computer.
- The photodiode monitors the consistency of the laser output.
- λ / 2 wave plate and germanium plates provide a way to control the intensity of the laser using properties of polarization.

Preliminary Results

- We did not observe a change in the output of the lock-in as we scanned through the phase of the reference with the Ionization experiment.
- In order to get a proof-of-concept, we switched to measuring the output of a photodiode rather than the MCP detector.
- The post-analysis consisted of averaging all the recorded data points for each delay step and then taking the derivative with respect to delay.
- The following plot shows that it is possible to resolve a signal with a width on the order of ***hundreds of nanoseconds***.



Mean output of lock-in as a function of delay plotted alongside its derivative.

Discussion and Outlook

- We believe the main reason for the lock-in's inability to detect the mass spectrometer's signal is the ***sharp time resolution of the MCP***. It is possible that the slew rate of the AD630 chip was not large enough to detect such fast changes in voltage. ***Adding another integrator circuit before the AD630*** with a very short RC constant would group several peaks from individual ion hits into wider peaks corresponding to each type of ion. This could increase the sensitivity of the lock-in; however, it may also affect the temporal resolution.
- There was also considerable noise on the output of the lock-in. This could be a sign of a malfunctioning integrator, or it could be caused by the circuit having been built on a temporary prototype board. ***Placing the circuit inside a metal box*** could help shield it from electric noise caused from the environment.
- In conclusion, we have developed a novel way of detecting pulses on the order of hundreds of nanoseconds. While there are still more tests and modifications to be made before we see improvements to the dynamic range of the ion detector, it is clear that ***lock-in amplifiers are powerful tools that can be adapted to many different applications***.

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1 Analog Devices, "Balanced Modulator/Demodulator," AD630 datasheet, 2015.

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