Towards Pressure Measurements Via Incoherent and Coherent Rayleigh Scattering Diagnostics

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Abstract

Engineering systems and physical models where thermodynamic and fluid properties (such as pressure, temperature, and velocity) rapidly change over time require interrogation schemes that can instantaneously and quantitatively map out these changes. In combustion and fluid diagnostics, dynamic pressure measurements are often difficult to obtain, especially under highly volatile conditions where traditional physical probes cannot be sustained. Filtered Rayleigh scattering (FRS) is a nonintrusive, in situ laser diagnostic technique capable of making such measurements with high temporal resolution when used in conjunction with a pulse-burst laser. My research goal is to use FRS for pressure and simultaneous measurements, addressing design and calibration challenges along the way. In this report, I will discuss my research plan, current progress, and future work ahead for this project.

1 Research Goal

Traditional physical probes present some issues in making fluid and thermodynamic measurements. First, they are intrusive, meaning that their presence alters the environment, such as a fluid flow. Second, some of these devices, such as barometers and pressure gauges, cannot maintain structural integrity, especially if their materials are unsuitable or corrosive to the environment. Knowing pressure fluctuations is important under rapidly changing environments, where pressure can determine the performance of a system or shed insight into the dynamics of a process. Pressure equilibrates quickly, typically at time scales related to the size of the system divided by the speed of sound. Examples involving significant pressure gradients and time-varying pressure include ignition, sonic flows, and combustion engines. To this end, laser-based Rayleigh scattering incorporating atomic/molecular 'notch' filters, termed filtered Rayleigh scattering (FRS), offers simple yet incredibly powerful methods for studying complex environments and time-evolving physical phenomena. While I will primarily focus on developing and using filtered Rayleigh scattering (FRS) for dynamic pressure measurements, I will also spend some time at the Princeton Plasma Physics Laboratory (PPPL) developing another Rayleigh diagnostic capable of making fluid measurements among other things, coherent Rayleigh-Brillouin scattering (CRBS).

2 Experimental Apparatus

FRS is simply Rayleigh scattering that employs a 'notch' atomic/molecular vapor cell, tuned to an absorption feature, in front of the photodetector/camera in order to suppress background scattering from walls, windows, or other nearby surfaces. Typically, these background scatterings occur at the laser frequency. Since the Rayleigh-Brillouin scattering (RBS) lineshape is broadened by thermal and acoustic motion of the molecules, if the laser frequency is positioned within the absorption band of the filter, then the direct background scattering cannot reach the observer, but the tails due to the broadening will still pass through since they extend beyond the filter cutoff range. The filter used for my purposes is an iodine vapor cell, whose absorption spectrum has good overlap with a frequency-doubled Nd:YAG laser (wavelength centered about 532 nm).

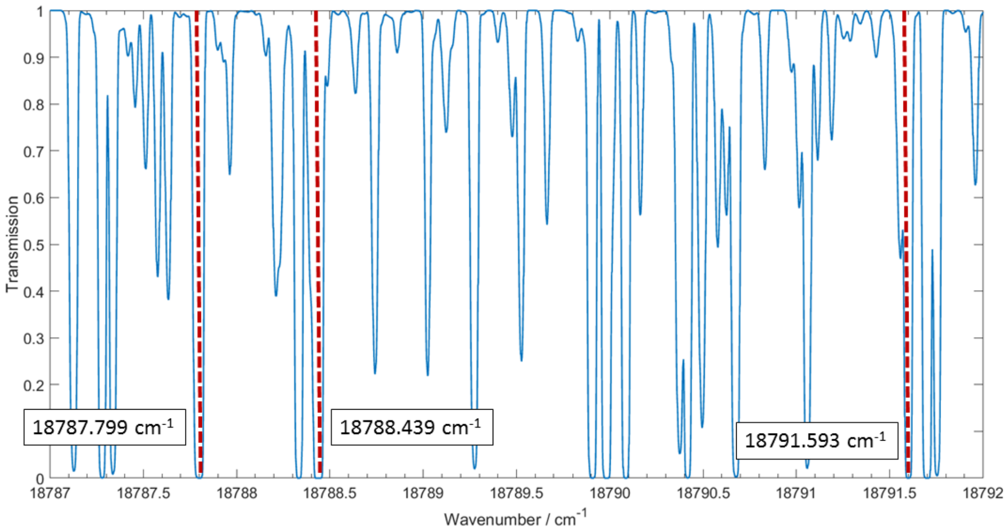

Figure 4: Model of the iodine absorption spectrum in the $\lambda = 532$ nm range. The dashed line indicates transition chosen.

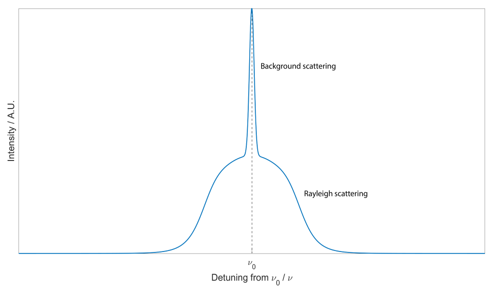

Figure 1: Rayleigh scattering lineshape with laser background scattering centered at ν_0.

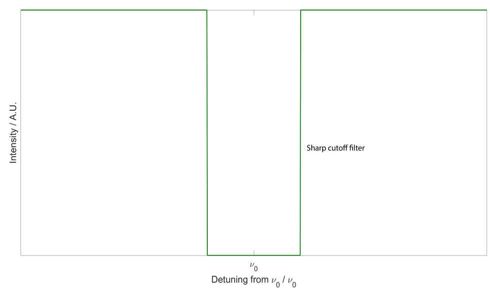

Figure 2: Ideal filter centered at ν_0.

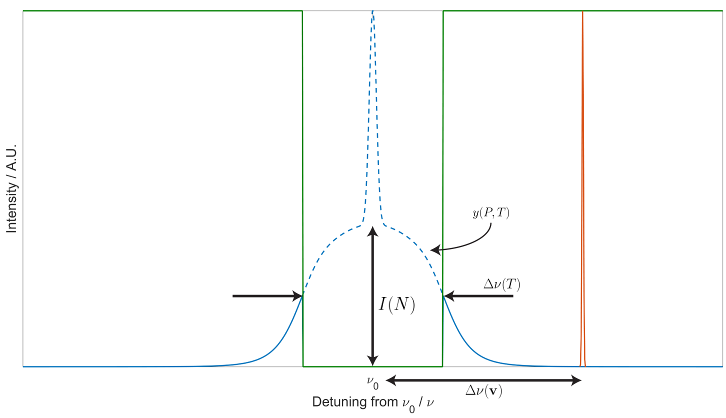

Figure 3: Observed scattering lineshape with ideal filter in place. N is the number density of the fluid and $\mathbf{v}$ is the velocity vector of the particle.

Furthermore, the width of this absorption band can be actively controlled via the atomic/molecular vapor pressure, enabling various degrees of linear sensitivity to the pressure (P), temperature (T), and velocity (v) of the gas or flow. The signal is then a convolution of the RBS lineshape, effectively described by the y-parameter, and the transmission profile of the filter, which blocks most of the scattering at the central laser wavelength. Past studies have demonstrated the use of different filters for high spectral resolution and background scattering suppression, and so my efforts will involve characterizing and calibrating vapor cells including iodine, mercury, and potassium. The filter transmission can be expressed as a function of the sensitivities corresponding to (P, T, v):

$$dI(P,T,v) = \partial_T\big|_{(P,v)}\, dT + \partial_P\big|_{(T,v)}\, dP + \partial_v\big|_{(P,T)}\, dv \tag{2.1}$$

Each partial term corresponds to the sensitivity to a specific parameter while keeping the other two fixed: temperature due to broadening, pressure due to change in density, and velocity due to the Doppler shift associated with particle motion. To further advance these filter models, I am developing algorithms to incorporate transmission as a function of laser parameters such as power and spectral purity, as well as external pressure broadening to better predict the cell's sensitivities to the fluid parameters. Validation of these filter/lineshape models will be experimentally facilitated via MHz pulse-burst FRS in the process of making pressure measurements.

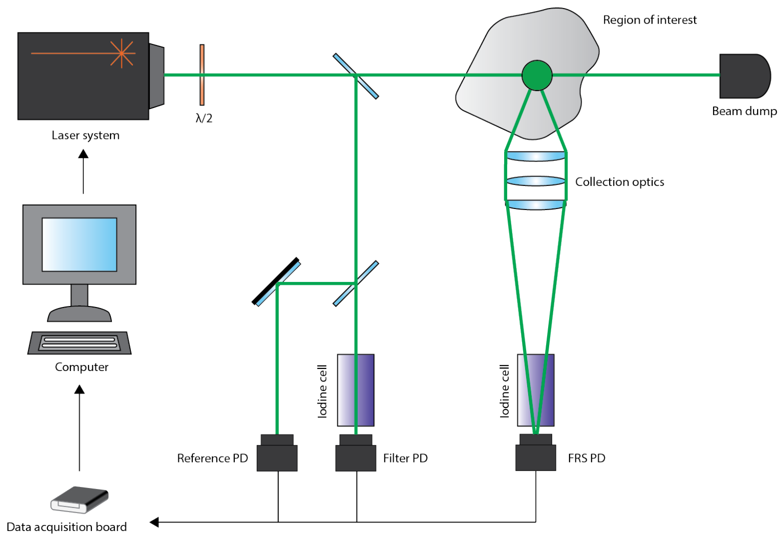

Figure 5: Schematic of a typical FRS experiment. The photodetectors can be replaced with an intensifier + camera (ICCD) configuration (with the iodine cell in front of the camera) for two-dimensional imaging measurements.

The preliminary task will focus on using laser and pulsed electric discharges in air and other gas mixtures to test methodologies and evaluate the measurements; such discharges create pressure wave expansions with a core high temperature region, and have rapid pressure variations. The long term target of pulse-burst FRS will be towards measurement of P-fields in a rotating detonation engine. Such engines show great potential for high specific propulsion and high efficiency by using the detonation cycle as opposed to the Brayton cycle, but reliable experimental data of their internal dynamics, complex reactions, and design are still needed. Pressure change is one of the important factors for determining detonation-based engines since these are examples of "pressure-gain" combustion systems. Nevertheless, other environments such as sonic flows and molecular gases will be explored as well for validation of the techniques.

On the part-time side, I have also been working on another project at PPPL. PPPL has a one-of-a-kind CRBS setup enhanced with chirped pulses that allows very fast acquisition of the RBS lineshape in a single shot (SS-CRBS). CRBS is a coherent four-wave mixing technique that measures gas density perturbations induced by two pump beams: a CRBS signal is produced by phase-matched Bragg scattering from this density 'grating' and its intensity is proportional to the square of the gas density. Remote pressure measurements has been demonstrated using SS-CRBS, and I plan on evaluating its potential as a diagnostic capable of making dynamic measurements of steady as well as time-varying pressure while evaluating its advantages and disadvantages in comparison to FRS.

3 Current Progress

During this summer, I have been mainly working on setting up the FRS experimental system, diagnosing the pulse-burst laser (PBL), and struggling to obtain sufficient attenuation from the filter at the output laser light power. At the heart of the first task is the iodine vapor cell, which I have constructed and evacuated down to the order of mTorr. Integration of active laser wavelength control and data acquisition via LabVIEW were also performed and successfully tested. We also have a fast ICCD camera to keep up with the MHz repetition rate of the PBL. The third task follows from the second task because in order to have sufficient attenuation at the absorption band of the molecular cell (the filter), good spectral purity and sufficient energy per pulse are required. The PBL doubles the fundamental light at 1064 nm to 532 nm; therefore, an iodine vapor cell is suitable because it has many active transitions near 532 nm. Spectroscopic computational models predict, at certain fixed cell temperature conditions, that the line at 18787.80 cm^{-1} (532.26 nm) has transmission values down to approximately 3×10^{-5}. This line is chosen for absorption because it has good optical depth over reasonable iodine vapor pressures ranges (around 1-2 Torr) and it is well isolated from neighboring transitions, so that the lineshape tails will not get suppressed either.

With the current PBL configuration, we were only able to achieve transmission of no more than on the order of 10^{-4}. All other transitions with greater attenuation also dipped down to no more than 10^{-4}, so this indicates to us that either laser 'noise,' such as amplified spontaneous emission (ASE), at unwanted wavelengths or insufficient laser power is limiting the proper attenuation of the cell. It turns out that it is a combination of both issues; we only measured a few μJ per pulse of SHG light out and found signal at the end of the photodiode even without the AOM on.

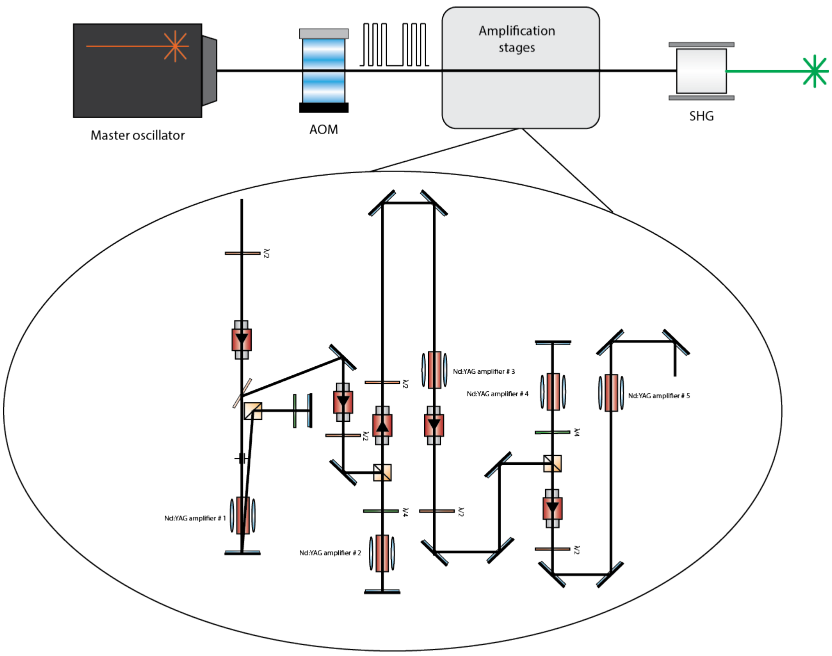

Figure 6: Schematic of current pulse-burst laser setup. Legend: AOM – acoustic optical modulator. PBS – polarizing beamsplitter. SHG – second harmonic generation.

I am currently working to resolve this issue by suppressing the ASE, which limits the gain achievable, at the first amplifier, where the laser experiences the highest gain. I will attempt to do this by trying out two ideas: first, I will switch the order of pulse generation (at the AOM) and amplification, so that the strong CW laser is amplified uniformly first, from which the pulses will be generated. Second, I will implement a phase conjugate mirror (PCM) to isolate the low intensity pedestal superimposed on the high intensity pulses which make up the desired output of the pulse burst train. The intensity of the ASE component before the PCM should be well below threshold, on the low intensity side, and as a result, it is not reflected by the PCM into the system. Either we will need to buy a PCM or construct one, the latter which requires more time and effort.

4 Future Work

After demonstrating that we have a working PBL with sufficient energy per pulse, at least on the order of mJ, and have eliminated most of the ASE, I will finish characterizing the iodine cell attenuation over several vapor pressures and calibrate the system to be used over a range of (P, T, v) sensitivities as described by 2.1. Next, I will implement FRS measurements using the single FRS setup, by making single-point measurements in laser discharges of air, nitrogen, and hydrocarbon/air mixtures using a short pulsed laser. Two-dimensional Rayleigh imaging will also be implemented by replacing the photodiodes with an ICCD camera; for these measurements, initial work will seek to image pressure fields. Both mercury and potassium vapor cell will also be considered and experiments will be developed using an available tunable Ti:Sapphire laser operating at 762 nm for mercury and 766 nm for potassium. Some additional apparatus that might need to be constructed or modified for testing include a chamber to house gases, flames, and/or plasmas, as well as a wind tunnel for flow measurements. Finally, I will set up a variant through which I can perform simultaneous, single-point measurements of (P, T, v) in the laser direction, which will lay the groundwork for later variants that will enable 2D measurements of these quantities in regions of interest. The advantage in using three separate iodine cells is that they provide a unique combination of signals for a given (P, T) combination.

It should be noted that the focus of this research is to mainly establish the capabilities of the FRS methodologies for measurement of pressure. We can also extend similar procedures for other fluid/thermodynamic quantities of interest.