PULSE SLICED PICOSECOND BALLISTIC IMAGING AND TWO PLANAR ELASTIC SCATTERING: DEVELOPMENT OF THE TECHNIQUES AND THEIR APPLICATION TO DIESEL SPRAYS

by

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ABSTRACT

A line of sight imaging technique was developed which utilized pulse slicing of laser pulses to shorten the duration of the parent laser pulse, thereby making time gating more effective at removing multiple scattered light. This included the development of an optical train which utilized a Kerr cell to selectively pass the initial part of the laser pulse while rejecting photons contained later within the pulse. This line of sight ballistic imaging technique was applied to image high-pressure fuel sprays injected into conditions typically encountered in a diesel combustion chamber. Varying the environmental conditions into which the fuel was injected revealed trends in spray behavior which depend on both temperature and pressure. Different fuel types were also studied in this experiment which demonstrated remarkably different shedding structures from one another. Additional experiments were performed to characterize the imaging technique at ambient conditions. The technique was modified to use two wavelengths to allow further rejection of scattered light. The roles of spatial, temporal and polarization filtration were examined by imaging an USAF 1951 line-pair target through a highly scattering field of polystyrene micro-spheres. The optical density of the scattering field was varied by both the optical path length and number densities of the spheres. The equal optical density, but with variable path length results demonstrated the need for an aggressively shorter pulse length to effectively image the distance scales typical encountered in the primary breakup regions of diesel sprays. Results indicate that the system performance improved via the use of two wavelengths. A final investigation was undertaken to image coherent light which has elastically scattered orthogonal to the direction of the laser pulse. Two wavelengths were focused into ∼150µm sheets via a cylindrical lens and passed under the injector nozzle. The two sheets were adjustable spatially to allow probing of the sprays three dimensional structure. The test matrix included two nozzle diameters, 160 and 320 microns, and two fuels dodecane and methyl oleate. Results
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CHAPTER 1
OVERVIEW OF THE THESIS

This thesis contains a number of different experimental endeavors, so it is instructive to the reader to provide an overview of the contents of the chapters.

Chapter two provides the user with an overall introduction to the body of work contained in this thesis, this includes a motivation and a literature review.

Chapter three presents a description of the execution and characterization of the ballistic imaging technique developed in this study. Key findings include the measurement of the pulse duration as a function of beam overlap and gate beam power. Additionally, the results of experiments using scattering media of various path lengths and optical depths are presented as maximum resolution and contrast transfer functions. Results indicating the improved gate performance gained via the use of a two color imaging/switching system are also provided.

Chapter four presents trends observed during imaging of dodecane at elevated temperatures and pressures as well as dodecane and methyl oleate sprays at ambient conditions. Direct comparisons of ballistic imaging and shadowgraphy are shown and highlight the improved imaging which results from the application of ballistic imaging. A discussion of the varying spray cone angle observed with changing temperature and pressure is provided. Additionally, a presentation about the discovery of finger-like semi-periodic ligaments on the spray periphery which have been predicted by the modeling community is included.

Chapter five provides a discussion of the two-color orthogonal scattering technique. The methodology and the results of the experiment are provided for both methyl oleate and dodecane injected from 160µm and 320µm nozzles. A detailed description of the image processing and attempts to restore images whose focal plane was shifted are also included.
CHAPTER 2
INTRODUCTION

This thesis describes the development of an imaging technique utilizing an ultrafast laser to perform pulse-sliced ballistic imaging, spatial and polarization imaging, and elastic scattering of high-pressure fuel sprays. Work has focused on both the development of the technique and the acquisition of data that shows the breakup behavior in the near field for high-pressure sprays. Images acquired for this project reveal evidence of the breakup and shedding structures involved with the primary, near nozzle, atomization of various fuels. These complex structures represent the interface between liquid or high liquid volume fraction regions with the surrounding dominantly gaseous regions that are present in these optically dense sprays. The near-nozzle region of diesel sprays, because of high volume fractions of fluid present, is a high optical scattering environment for optical imaging. Line-of-sight spray measurements are an extinction map of the spray and rely on removal of energy from the beam; single elastic scattering measurements similarly create a map of liquid/gas interfaces based on redirection of laser energy into the image. Multiply scattered light is noise for either of these measurements; for extinction the multiply scattered light adds noise to the image by misrepresenting the actual location of the structures in the spray by conveying photons onto pixels which are not imaging that region of space. For scattering images, multiple scattered photons limit the ability to see structures deeper into the spray due the washing out of the image as the photons are sent out in seemingly random directions. Ballistic imaging techniques seek to remove a portion of scattered light to improve resolution revealing spray structures embedded in the droplet laden flow. The successful imaging of the structures requires the rejection of multiply scattered photons which act to blur image quality with irrelevant information. Rejection of these photons can be achieved by use of the following methods: Kerr cells, spatial filtering and polarization filtering. Rejection methods common
to Ballistic Imaging also apply to scattering images. Elimination of multiple scattering in single scattering images uses the same techniques: time gating may be used, spatial filtering limits the collection angle, and polarization may be used; in addition, for many cases, the multiple scattering signal may be much smaller than the single scattering for the edges of sprays.

Both of these signals rely on the scattering of light at liquid/gas interfaces. Extinction is energy removal from the beam via scattering and elastic scattering is the redirection of energy again due to a liquid/gas interface.

2.1 Motivation

Diesel engines are an important aspect of our transportation infrastructure, whose performance is greatly affected by the characteristics of the spray from their injectors. Characterization of the injector’s spray is therefore paramount to clean-running efficient diesel motors. Due to higher compression ratios, higher low-end torque, lean-burn combustion and higher volumetric energy density, diesel engines are more efficient than their gasoline counterparts. Compression ignition also allows the utilization of a wider number of fuel types such as biofuels, waste-vegetable oils and various surrogates due to the combustion process being less composition dependent than spark ignition based engines.

The ability to run diverse fuel types is advantageous, however each type of fuel will respond differently when injected out of the same injector geometry. This different spray behavior effects the emissions characteristics of each individual fuel because emissions are controlled by the fuel air mixing of the spray, the ignition properties of the fuel and the post ignition spray/combustion behavior. Thus the spray structure sets the initial conditions for the combustion process. This is true both from the perspective of the initial fuel-air mixture to the droplet formation and subsequent atomization of the fuel which controls the diffuse flame nature of compression ignition.

The primary emissions of concern from diesel engines are NOx and particulate matter. NOx emission is a particularly complicated result of compression ignition. Mainly the
byproduct of high combustion temperatures, NOx is formed via three primary sources; thermal, fuel and prompt. Thermal NOx formation occurs due to high temperature oxidation of diatomic nitrogen present in combustion air[1]. Three principle reaction mechanisms, dubbed the extended Zeldovich mechanism are the primary sources of thermal NOx production[2, 3]. Fuel NOx is the conversion of fuel bound nitrogen to NOx during combustion. The nitrogen contained in the fuel is converted to a free radical which reacts to form NO. Fuel NOx can contribute as much as 50% of total NOx due to combustion, this is a driving force behind the use of various surrogate fuels[1]. Finally, prompt NOx is formed when atmospheric nitrogen reacts, early in the combustion process, with radicals derived from the fuel such as C and CH, forming compounds of NH, HCH and CN which eventually oxidize to NO. Usually, considered a minor source of NOx, prompt NOx can become a major concern during low temperature combustion of oxygenated fuels like biodiesel[4].

In order to reduce tailpipe emissions of NOx, after-treatment of the engine exhaust is required. Since diesel engines operate at equivalence ratios of 0.075 under light loads and up to 0.6 under maximum power, three-way catalysts used in gasoline engines are of little use for NOx reduction. This is due to the fact that they are only effective in fuel rich conditions realizing only minimal NOx reduction in fuel lean operation. Diesel Oxidizing Catalysts (DOC) are designed to oxidize all compounds of a reducing nature, the goal of which is to create a fuel rich exhaust stream that can be more effectively after-treated via other means. The creation of fuel rich conditions results in lower overall efficiency. Additionally, when operated as the sole exhaust emissions treatment, the DOC can have undesired results. The oxidizing nature of the DOC actually promotes the creation of NOx by reducing N and NO into the more hazardous nitrogen dioxide[5]. Additionally, at temperatures above 400°C DOC oxidizes sulfur dioxide into sulfur trioxide which when combined with water forms sulfuric acid.

The adoption of ultra-low-sulfur diesel has opened the doors to more effective NOx reduction via lean NOx trap (LNT) technology. Previously, the higher sulfur contents of diesel
fuel caused poisoning of the LNT and the need to capture the hydrogen sulfide released during the desulfurization of the LNT[6]. LNT is a discontinuous operation consisting of two states of operation; NOx storage during lean operation and NOx reduction during rich operation. Since diesel engines don’t operate at fuel rich conditions inside the combustion chamber, the fuel rich conditions are achieved via tailpipe fuel addition. The optimization of the operational state the LNT is in at any given load and temperature has been the primary obstacle to effective NOx reduction. In newer vehicles, Selective Catalytic Reduction(SCR) is now operating in conjunction with LNT technology to meet ever more stringent emissions standards[7]. SCR is a developed technology which has been in use in stationary power plants for quite some time. SCR makes use of a urea/water mixture injected into the exhaust stream which via a zeolite catalyst reacts to convert NOx to diatomic nitrogen and water. In stationary applications where load is fairly constant SCR is effective at NOx reduction, however when operated under the transient load conditions associated with vehicle operation, the control of the urea injection becomes complex. Low exhaust temperatures pose a problem for conversion efficiency and can result in tailpipe emissions of nitrous oxide, formic acid, iso-cyanuric acid and most importantly ammonia[8]. So called ammonia slip is a public health concern and requires a NOx neutral SCR-catalyst heating strategy to minimize ammonia output[9].

Particulate matter or soot is the other main pollutant generated by incomplete combustion of fuel. Sub-micron particulate matter generated by unburnt fuel is especially harmful to respiratory health[10]. In order to ameliorate high soot levels emitted from diesel combustion, diesel particulate filtration technology (DPF) was created to aid in the complete combustion of fuel into ash. Many types of DPF’s exist in industry, though most are of the wall-flow variety with a honeycomb structure either made of cordierite or silicone carbide[11]. Unburnt fuel is trapped on the walls of the DPF until the accumulation level is enough to create a measurable amount of exhaust back pressure. At this point heat is added to the exhaust stream either directly by a fuel burner or by injecting fuel into the exhaust stroke
of the engine. By raising the temperature of the exhaust, the DPF is able to burn the fuel which is attached to the walls of the catalytic substrate.

Diesel combustion is a two stage event, the elevated temperature and pressure encountered at TDC in the compression stroke of the engine initiates an initial combustion event in which smaller fuel droplets which have become mixed into the surrounding air burn in a premixed flame. The heat from this combustion and the heat present in the compressed air in the cylinder act to evaporate the rest of the injected charge initiating the second diffuse flame combustion event. It is important to note that many times a diffusion flame is present during the injection event. This differs from other technologies which rely on compression ignition of homogeneous charges, such as homogeneous charge compression ignition (HCCI). By using gasoline to initiate a compression ignition event, a HCCI can make use of the greater thermal efficiency of a higher compression ratio, and the fuel efficiency of a lean burn condition. Fuel is injected into the cylinder during the intake stroke and the pressure and temperature is used to initiate the combustion process. The lean burn nature of the combustion event leads to a lower temperature in the cylinder which equates to lower NOx levels, however this also translates into higher levels of unburnt hydrocarbons and CO. Also, in some implementations, the lower combustion temperature warrants the need to somehow preheat the air, this lowers the power potential of the engine due to less dense in-cylinder air. The temperature inhomogeneity within the cylinder means that there is not well-defined combustion initiator which makes direct engine control problematic[12]. HCCI engines also have a limited range of operation, to improve this deficiency HCCI is being used at part load conditions in an engine which uses diesel or spark ignition at higher loadings [13].

During the course of this study, images have revealed high levels of inhomogeneity in diesel sprays. The inhomogeneity in the sprays make controlling emissions difficult as atomization of the fuel is unpredictable and although diesel engines run fuel lean, most of the excess air is 'floating' around the cylinder and not directly participating in the combustion of the fuel. This is problematic as diesel emission standards are increasingly stringent as time goes
A better understanding of the primary breakup mechanisms of diesel sprays would contribute to the reduction of NOx and soot emissions. That is, the ability to design injectors based on a better understanding of the physics involved with these high Weber and Reynolds number sprays would enhance the ability to reduce emissions. In a perfect world, diesel injectors would atomize fuel in an almost uniform way so as to have droplet distributions with small standard deviations and with droplets of the desired Sauter mean diameter. This may even entail tailoring the Sauter mean diameter of the droplets to match conditions within the combustion chamber[15]. This theoretically could be achieved by controlling the spray angle, as Sauter mean diameter has been shown to increase with a narrowing spray cone angle[16].

2.2 Background

Ballistic Imaging is not a new technique, Kerr gated picosecond imaging was developed in the early 1990s as a means to image biomedical samples[17]. However, this study is unique in that it uses the technique to probe structures in high-pressure fuel sprays. Challenges
unique to this environment include the need to have the imaging plane at a substantial stand-off distance while still maintaining spatial resolution on the order of 10 microns, the non-averaged single shot nature of the images and the locally very high spray velocities. Also, the use of high quality optics is required to maintain image quality in optically thick sprays and effective use of the Optical Kerr gate is necessary to produce appropriate pulse durations. This study has obtained the first images of fuel sprays at temperatures and pressures relevant to diesel engines. This was achieved via long range microscopy, where the image information is embedded in a laser pulse. Successful imaging of structures with scales on the order of tens of microns from meters away is a non-trivial exercise. The use of specialized optical components and optical design software (Zemax®) were necessary to achieve the desired resolution. The line of sight images captured with this technique have revealed trends in spray behavior as well as structures on the spray periphery not previously observed. Rejection of multiply scattered photons, via various methods, is the focus of Ballistic Imaging. As applied in this work, ballistic imaging is a line-of-sight image of the extinction of laser light that traverses the spray. The images captured in this study employed the use of temporal, spatial and polarization filtering to eliminate multiply scattered photons. Photons which pass through a spray with minimal interaction with the fuel form a spatial intensity distribution based primarily on local energy removal from the beam via elastic scattering. Traditional imaging methods which do not eliminate multiply scattered photons contain this energy distribution map based on the line-integrated spatial properties of the spray AND also include multiple scattered photons as noise in the image. Multiply scattered photons in an image are noise because they are photons that have been scattered out of the original beam (this process creates the image information) and then are scattered again into the detector plane (this is energy addition to the image in a way that does not correlate with spatial structure). When a large amount of multiple scattering is present for high extinction images, the multiple scattering dominates the image with the result being a map that shows the extent of the spray in a poorly quantifiable way but nothing that can directly relate
extinction at a location to spray properties.

2.3 Literature

In order to image the droplet field and liquid-gas interfaces with a diesel spray, measurements must be non-intrusive. This can be achieved with measurements based on the interaction of a laser with the droplet field. These interactions include scattering and absorption of photons. For line of sight measurements, this is energy removal from the beam and for most diesel like fuels, at mid visible wavelengths, absorption is relatively insignificant. Traditional line of sight images are simply an energy density map of the object plane onto an image plane where the variation of energy density is produced by the removal of photons by the spray across the spatial profile of the laser beam. For sprays, in a line of sight configuration, with no spray present one simply has a map of the energy distribution in the beam. With spray present, there is energy removal from the beam representing the presence of either droplets or liquid structures. In its simplest form, this is extinction across the profile of a laser beam which is governed by Beers law. Multiple scattering, scattering of previously scattered light, complicates images because it adds light back into an image in a way that does not represent the object plane. For instance, you might have a spot in an image that is naturally very dark. The intensity of the spot could be altered by light being added to it either from in-object plane scattering from light that is not from the parent beam, or from light that is added out of the object plane but that maps to that spot in the image. The same thing is true for scattering images, which are formed by the redirection of light. If there are single interactions of photons from the beam and the spray, a map is created of the spray structure. If multiple scattering is present in the images, it adds noise to the image as described above.

2.3.1 X-rays

The use of synchrotron generated x-rays has been used to image fuel sprays in the near-orifice of non-evaporating fuels. X-ray imaging has successfully measured fuel mass fraction
fuel velocity fields, and the effect of gas-density on penetration length. X-ray imaging has yielded information about fluid behavior inside the injector nozzle, and has produced time resolved radiography of Spray A diesel injectors. However, the use of x-ray radiation for imaging is not without significant challenges. X-ray techniques rely on energy absorption of the X-ray radiation; this in turn requires addition of an x-ray absorber to the fuel. As with all tracer additives, there is always the question of how well the tracer seeding material follows the fuel in the spray. Tracers must be added to create adequate absorption of x-ray radiation, and the limited potential for usage in wider studies of engines due to the need for a synchrotron are among these challenges. To date, no x-ray imaging results have been reported on fuel sprays in high temperature or combusting environments. Additionally, recent modeling results of phase-contrast x-ray imaging indicate significant problems in the use of the technique for imaging dense sprays.

2.3.2 Modeling and simulation

Modeling of high-pressure sprays has been an ongoing effort among the fluid dynamics community. Challenges associated with modeling primary atomization include the transient nature of the two-phase flow, the length and time scales of turbulent flow fields, discontinuous fluid properties at the phase interface, high density ratios, vaporization behavior in fuel rich environments, and complex injector geometries. Large eddy simulation and direct numerical solutions have been coupled in attempts to solve these problems and to generate solutions which mirror observed spray behavior. Other groups have utilized the vast amounts of available computational power to realize novel numerical approaches to simulate the turbulent nature of primary atomization.

Modeling studies of Rayleigh-Taylor and Kelvin-Helmholtz instabilities in high-pressure fuel sprays have predicted finger-like structures on the periphery of the spray. These predicted structures are close in size and wavenumber to structures imaged by us using ballistic imaging. Acceleration effects on high Weber and Reynolds number sprays were studied by the Sirignano group of UC Irvine. Their computational results indicate Kelvin-
Helmholtz waves on the order of 100\(\mu\)m which result in finer ligaments, 10-50\(\mu\)m, breaking off of the surface of these waves\[35\]. These ligaments are subjected to very-high accelerations normal to their interface, which is predicted to cause Rayleigh-Taylor instabilities at the tip of the ligaments. These instabilities are believed to be the start of droplet formation.

### 2.3.3 Spray Penetration

Another topic of interest to both the modeling and combustion community is spray penetration. Spray penetration is defined as the maximum length the liquid phase of an injected fuel jet reaches into the environment into which it is injected. The study of spray penetration has been a topic of concern for the last few decades\[36\]. Recent studies have compared results obtained from various facilities within the Engine Combustion Network\[37\]. These studies found that despite having widely varying operating conditions such as constant-pressure flow and constant-volume preburn chambers, results performed at the same environmental conditions were surprisingly similar\[38\]. However, one study determined that nominally identical injectors used in Spray A studies actually produce variable spray penetration and cone angles \[39\]. A comparison study of spray penetration of different bio-fuels has determined a correlation between spray penetration length and the boiling point of fuel\[40\].

### 2.3.4 Ballistic Imaging

Ballistic imaging (BI) is an ever-evolving field of study\[41\]. From its initial applications for biomedical imaging, the capture of ballistic and snake photons for imaging purposes has found many novel applications. In a broad sense, ballistic imaging is the exclusion of multiply scattered photons where this exclusion can be achieved in the following three ways. Spatial exclusion limits the collection angle of the optics, thereby limiting the photons that are not ballistic as they come through the beam. The use of polarizers removes multiply scattered photons which tend to be in a range of polarization states and not polarized identically to the beam. Finally, temporal exclusion uses the time gating effects of the Kerr cell to eliminate
late arriving photons, which also tend to be multiply scattered. Cutting edge research uses BI to image near-nozzle spray formation of diesel as it goes supercritical\[42\]. Subcritical diesel injection is characterized by a well-defined liquid/gas interface, surface waves, ligaments, and droplet formation. In contrast, at supercritical conditions, the gas/liquid interface is replaced by a thickened turbulent mixing layer with the cellular structure of a gas jet. Traditionally, BI has relied on an identical color switching beam which passes through the Kerr medium at an angle to the imaging beam. Recent work has demonstrated the effectiveness of using collinear two color arrangement, and we have demonstrated the two color system as well\[43\]. The use of collinear system removes elastic scattering between the gating beam and the Kerr medium as modeled and discussed in the work of Idlahcen et al\[44\]. Femtosecond BI systems gate time has been traditionally limited by the $\sim 2\text{ps}$ relaxation time of the $\text{CS}_2$. However, the novel application of a dual-gated arrangement has yielded a 200 fs gate time, this system actively switches the cell off rather than relying on molecular relaxation\[45\]. The development of a solid Kerr medium comprised of Bismuth based glass has demonstrated gate times shorter than 350ps and with 2.3 times the light transmission of a standard $\text{CS}_2$ Kerr medium\[46–48\]. There is emerging evidence that the very aggressive time gated imaging technique is difficult to execute in the variable density field associated with elevated temperature and pressure and also for evaporating sprays that are more optically thin\[49, 50\]. The gradients which are present in the background environment distort the images and present difficulties applying standard image processing techniques.

### 2.3.5 Other Imaging Methods

Other techniques under development that may enhance the understanding of the near nozzle break up region include digital particle field holography\[51, 52\] and 2f ballistic imaging\[53\]. Digital field holography has been proposed as a method of imaging the spray so as to create a 3D representation of the sprays structures. Imaging using a 2f setup has been shown to be less sensitive to alignment issues and to variations and fluctuations in the OKE-gate setup, and has yielded better contrast transfer functions when used to image smaller diame-
ter spheres. Additionally, analysis of the laser interaction with the Kerr medium may allow post-processing of images to enhance image quality[44, 54, 55].

Microscopic techniques have recently been employed to investigate the mixing and atomization processes of diesel sprays into high pressure and temperature environments[56]. Especially relevant to the refinement of current spray models, recent work by the University of Brighton employed ultra-high-speed microscopy to image the initial stages of diesel spray formation[57]. The results presented in their publication are of excellent quality and capture structures which have previously been seen in our studies. The use of a camera with 200 million frame/second imaging rate also allowed them to capture the development of a single spray event, and to deduce that the injector nozzles are not evacuated of fuel after an injection event.

The use of phosphorescent doping agents to study flow dynamics is a fairly new and versatile technique. Laser-induced phosphorescence using lanthanide-based molecular complexes, which possess long phosphorescence lifetimes of ∼1-2ms, have been used to image the liquid volumes within various fuel sprays[58]. Europium and terbium compounds can be effectively excited with third harmonic Nd:YAG pulses with emissions in the visible spectrum. The visible emissions, peak at 614 nm, coupled with the fact that the compounds only fluoresce in the liquid phase allow imaging of the core of sprays as they tear apart from both evaporation and shear stresses. To date, this technique has only been applied to lower-pressure (130 bar) continuous sprays due to the need to illuminate the fluid before being injected. These sprays indicate the presence of a core when injected out of a 200 µm single hole nozzle.

Phosphorescence imaging techniques have also been effectively used to map liquid and vapor concentrations, as well as to measure temperature profiles of both liquid agglomerations and single droplets in sprays[59–62]. The use of thermographic phosphors which, when excited by third harmonic ND:Yag radiation, emit two peaks at 633 and 659nm allows the liquid temperature to be calculated by examining the relative intensities of the two peaks.
CHAPTER 3
BALLISTIC IMAGING: EXECUTION AND CHARACTERISTICS OF THE METHOD

This chapter focuses on the careful characterization of the picosecond ballistic imaging technique. Key results of this characterization are:

- A two color OKE gate system provides superior image quality as compared to a single color system
- The two color system using a CS$_2$ OKE gate can achieve a 7ps imaging beam from a 15ps parent pulse
- A measurable improvement in imaging quality was observed in pathlengths of 20mm using 5µm polystyrene spheres
- A presentation of the effectiveness of the optical Kerr effect gate, spatial filtering of scattered light, and polarization filtering

3.1 Experimental Methods

The experimental setup for ballistic imaging includes a short-pulse laser, an optical train with well-controlled polarization, a telescopic imaging system, a delay line, an optical Kerr effect (OKE) gate, and a scattering medium (here a scattering cell or spray). Efforts at CSM have focused on the development of picosecond ballistic imaging, where a picosecond laser is used instead of the more expensive and complex femtosecond laser system. For example, the picosecond laser used in this research retails for $\sim$100,000 compared to over $350,000 for a typical femtosecond laser. The larger bandwidth of femtosecond pulses also leads to dispersion effects, which further complicate the optical train. The longer pulse length of the picosecond laser limits the maximum optical depth that can be successfully imaged, but as shown here, is capable of imaging diesel sprays.
3.1.1 Optical Train

A schematic of the optical setup is shown in Figure 3.1 with the 532nm output from a Coherent Leopard D-10 laser operating at 10 Hz repetition rate with 12±1mJ per pulse used to image the spray and the 1064 nm output (15±1mJ per pulse) used as the OKE gate beam. The OKE gate beam traveled across the table to a prism mounted on a translation stage and was then directed through a carbon disulfide (CS$_2$) cell. This part of the system is known as the delay line and is used to produce an overlap, in space and time, of the gate beam and the imaging beam [Figure 3.2]. The OKE gate was formed by a pair of crossed polarizers, P4 and P5, and the CS$_2$ cell. P4 was oriented to pass the non-scattered image beam, while the output linear polarizer (P5) of the OKE gate was set to be crossed with P4. The key to time gating is inducing temporary birefringence in the CS$_2$, which is a result of a nonlinear interaction of the gate beam with the carbon disulfide [17]. In the absence of the gate beam, the crossed calcite polarizers P4 and P5, which have extinction ratios greater than $10^{-5}$, block all laser light from reaching the camera, thus forming a high-speed optical shutter. Polarizers P1-P3 are used to adjust the image beam intensity and to create the correct polarization of the imaging beam. The two sets of iris-detector pairs placed near the laser in the path of each beam are used for timing and triggering of the camera. A series of four lenses are used in combination with the camera’s macro lens to create a highly magnified image of the spray. For the characterization experiments, an Air Force target was placed at the image plane of the camera followed by an optical cell filled with a polystyrene sphere suspension in water. The Air Force target has well characterized groupings of lines to measure the resolution of the images, while the scattering suspension simulates the droplet scattering experienced in a spray. An iris is placed in the optical path after the scattering cell to limit the solid angle of collection of the camera and reject a portion of the multiply scattered photons from reaching the camera.
Figure 3.1: Experimental schematic of ballistic imaging optical train for characterization experiments. A polystyrene sphere suspension and Air Force target provide a well-characterized scattering medium and image. P1-P5 are polarizers. Beams are shown cw for clarity.

Figure 3.2: Schematic diagram of the time overlap of the imaging beam and gate beam at the optical Kerr effect shutter. Changing this overlap in time effectively changes the on time for the shutter.
3.1.2 Image Capturing

Two cameras were used for this study: a Photometrics Cascade:650 imaging array (653x492, 7.4 m pixels) was used for the scattering cell measurements and shadowgraphy imaging, and a CoolSNAP Myo 20MHz 2.8Mpixel digital camera (1940x1460, 4.54 micron pixels) was used for the ballistic images of sprays. Both cameras are designed for low-light applications, and were used in conjunction with various neutral density filters and a 532nm narrow band pass filter to optimize signal levels and to filter stray light.

Image illumination was provided by a Continuum Leopard D-10 laser, which operates at 10Hz and is capable of 30mJ, 15 picosecond pulses at 1064nm. The Leopard laser system is capable of emitting pulses at 266, 355, 532 and 1064nm - a multi-wavelength capacity that lends more diagnostic capacity to the user (see Appendix A).

3.2 Method Characterization

The purpose of picosecond ballistic imaging technique is to reduce the number of multiply scattered photons reaching the camera. Ballistic imaging is the exclusion of non-ballistic photons via polarization filtration, temporal filtering and spatial filtering. Here we quantify the impact of each of these filtering methods on the image resolution and quantify the impact of the optical depth of the scattering medium.

3.2.1 Optical Kerr effect shutter

Picosecond ballistic imaging relies on precise timing of the optical Kerr effect shutter that excludes time delayed photons. The OKE gate beam can be delayed relative to the arrival of the imaging pulse as shown schematically in Figure 3.2. The imaging pulse arrives after the OKE gate is turned on by the OKE gate pulse. By varying the timing of the gate beam, the quality of the images can be adjusted as more or less scattered photons are transmitted onto the image plane during capture. Figure 3.2 depicts a stylized cartoon of the effect that gate and image beam overlap (shown in blue) has in picosecond ballistic imaging. If the gate beam arrives too early, the overlap area is reduced and too few photons reach the
camera resulting in an image with high noise and poor resolution. Alternatively, if the gate beam arrives too late, the overlap area is large but includes a larger percentage of scattered photons, blurring the image.

The best results achieved to date are with the Kerr cell transmission beginning to switch off just as the image pulse arrives at the Kerr cell (see Figure 3.2), resulting in transmitted imaging pulses of about 7ps (Figure 3.3). Pulse width was measured by autocorrelation, which revealed slightly asymmetric Gaussian transmitted pulses consistent with a parent Gaussian beam that has the asymmetry of the 2 ps relaxation time from CS$_2$ superimposed on the pulse transmitted by the gate. The full-width-half-maximum (FWHM) values of the transmitted pulse are shown in Figure 3 and were measured with varying delay between the image and gate pulses. The gate beam intensity was also varied to measure the impact of gate beam intensity on the intensity of the transmitted image beam. Although nonlinear, a more powerful gate beam resulted in more light transmission through the OKE gate. Subtle changes in the timing of the imaging and gating beams utilized to capture these images can result in observable differences in image quality.

As others have shown [43, 44], using different wavelengths for the gate and imaging beams prevents scattering of the gate beam from contaminating the transmitted image. To demonstrate this, an Air Force target was imaged through the OKE gate with a 532nm and 1064 nm gate beam, respectively (Figure 3.4). Scattering from the 1064nm gate beam was rejected by the 532nm filter on the camera and resulted in reduced image noise and increased resolution. The multi-wavelength capability of the picosecond laser allows for one laser to be used for both switching and imaging beams - a distinct advantage over other two-laser BI systems.

### 3.2.2 Pulse Slicing

In order to improve the quality of the ballistic images collected in this study, a technique known as pulse slicing was employed. Via pulse slicing, the portion of the pulse used for imaging is decreased. More specifically, the imaging pulse is shortened after traversing
Figure 3.3: Performance of the Kerr cell as measured by autocorrelation (See section 3.2.3). Image beam intensity decreases with increasing delay between the arrival of the gate and image beam at the Kerr cell (top). The ideal delay between gate and image beams yields the minimum gate width of 7 ps. The arrow indicates the timing used in these experiments.

Figure 3.4: Air Force target images using a 532nm switching beam (left) and a 1064 nm switching beam (right). Images collected without any scattering medium present.
the spray. The shorter pulse improves the quality of the images by increasing the ratio of ballistic photons collected versus scattered ones. Having a shorter pulse duration is important as scattered light arrives later compared to non-scattered light. That is, light from the beginning of the pulse could be scattered and arrive simultaneously with non-scattered light which occurs later in the pulse. This is especially important for objects of smaller size, because as the size of the object decreases the separation between the ballistic and scattered light decreases. With a longer pulse, larger numbers of photons which have undergone multiple scattering events will be contained in the resulting image. This blurs the image causing distinct features in the spray to become less discernible. The basic premise of pulse slicing is to utilize carbon disulfide as an ultra-fast chemical shutter. The birefringence of CS₂ allows control of the on time of the shutter via the polarization of the gate beam, that is the presence of the gate beam overlapped with the image beam. Ninety percent of the laser’s parent pulse, called the gating beam, is sent into the CS₂ Kerr cell to create a vertical polarization state in the cell. By mismatching the arrival time of the gating beam and the image beam, which transmits information, shorter imaging beam duration is achieved. That is, both by allowing the gating beam to arrive prior to the arrival of the imaging beam and having it leave the cell before the imaging beam completely transverses the cell, an effective gating time shorter than the duration of the native pulse is achieved. There is a physical limit to the ability to shorten the pulse which is governed by the interactions of Gaussian beams (the shape of the energy pulse in time is approximately Gaussian). The Gaussian multiplied by Gaussian interaction fundamentally limits our single pulse slicing technique to $\frac{1}{\sqrt{2}}$ of the original duration. The ability to shorten the pulse is further reduced by the 2ps relaxation time of the carbon disulfide, a time during which the polarization state is retained in the absence of the gating beam. Other groups have achieved improved reductions in pulse durations via the use of two gating cells, thereby removing the effect of the CS₂ relaxation time[45]. It is important to note the pulse slicing is not done to the pre-image or pre-gate pulse, but to the image beam that has traversed the spray and contains the multiply scattered
Energy levels in the 15 picosecond gating pulse affected the chemical stability of the CS$_2$. Initially, the carbon disulfide was contained in a 2mm layer between two windows. The need for quality, high resolution images required the use of high grade optical windows. It was observed that a layer was depositing on the window surfaces at the point of the gating pulses entry into the cell. Additionally, the energy levels of the imaging beam leaving the cell were found to fluctuate in a non-periodic manner. Even with periodic replacement of the CS$_2$, large shot-to-shot variations in transmitted image beam intensity were observed during autocorrelation. We believe this fluctuation was a thermally induced bleaching of the non-flowing CS$_2$. In order to mitigate both the deposition problem and the fluctuations, a pumped CS$_2$ cell was designed. The flowing cell consisted of a DC motor whose speed was controlled via a regulated power supply, this motor turned a gear pump through which CS$_2$ was pumped through 1/8” tubing to a flow cell. The flow cell was a custom machined housing with allowed optical grade windows to be mounted in a secure housing which allowed the fluid to be pumped between the windows. The windows formed a face seal with the housing via o-rings, additionally the space between the windows was also adjustable by inserting or removing viton rings.

Degradation was still present in this configuration, but the flowing nature of the cell prevented deposition on the windows. Fluctuations in the imaging beam were minimized and image quality was improved. Additionally, the use of in-line filtration allowed the removal of the byproducts of chemical disassociation.

### 3.2.3 Autocorrelation

Given that one of the major tasks of this project was to use Carbon Disulfide as the switching medium for the Kerr gate, a characterization of its effectiveness for limiting the image gate on time was needed. Autocorrelation was chosen as the only viable method to measure times of this length scale, as the direct measurement of pulse duration via electronics was not possible due to them not being fast enough to capture the pulse. To determine the
resulting pulse duration, a series of experiments were performed in an attempt to characterize
the pulse. The results of the initial few years of autocorrelation proved inconsistent due to
the non-linearities in the detectors and difficulties with alignment. Some measurements
were yielding 4ps; others were showing 15+ ps so no definitive conclusion could be drawn.
After the lab move, an entirely new autocorrelator was designed and built on a movable
platform. The task of building a functional, more compact device was a nontrivial endeavor.
In order to function correctly, the placement and alignment of the optical components had
to be as near to perfect as possible. A native beam is sent into the autocorrelator and is
split into two beams by a 50/50 beam splitter. One leg is stationary in space, while the
other is placed on a motorized translation stage powered by a Newport® CMA-25PP motor
controlled by a USP-300 driver. The idea being that the two beams are recombined inside a
BBO doubling crystal at a precise angle to produce a trace indicative of the original pulses
duration. This produced a third beam which traveled in a different direction than the two
original beams(see Figure 3.5). Significant adjustments finally provided a signal out of the
device. Measuring that signal was now the problem. Nonlinearities in the detectors used
to measure the output of the autocorrelator were discovered via separate testing. Reasons
for these non-linearities include a very high instantaneous energy flux, a very small signal
due to the short pulse and the requirement to integrate the pulse. Several commercially
available detectors, as well as detectors built in-house, were tested before a detector capable
of providing linear measurements of the ultra-short pulses was chosen. A Thorlabs® DET
210 was chosen due to its small, 1mm², silicon photodiode. The small photodiode has a much
lower capacitance, 6 pF, than the other detectors used previously. In order to accurately
measure the ultra-short pulse, high signal intensity of the beam, a detector must have a
low capacitance value to assure a small time constant. Measurements of the autocorrelator
traces were attempted using box-car integrators. However, the reaction time between the
triggering of the box-car and its data collection was too long to capture the signal. The initial
solution to this problem was to add more shielded cable to the output of the autocorrelators
detector. This required tens of meters of cable to achieve the needed $\sim 50$ns delay. The capacitive effect of that length of cable distorted the signal and was discontinued in favor of a laser delay line. The delay line required the beam to be passed across the lab four times to create the needed time offset. This was not possible at first, as the beam diverged too quickly to remain contained even on 2” mirrors. A set of optics were set in place to affect the Rayleigh range of the beam; it was a crude setup but it worked after some tuning. This method also proved problematic because the distances traveled by the laser required the use of two separate optical tables placed at opposite ends of the lab space. The vibrations and temperature variations inherent in the building caused the beam to wander around making autocorrelation difficult. An ultrafast (2gs/s) Gage® DAQ card was eventually acquired that would allow direct measurement without delay via the use of its pre-triggering capabilities combined with on-card pulse integration. The resulting data revealed a minimum pulse duration of 7ps [Figure 3.3].
3.2.4 Temporal Filtering

To test the effectiveness of the OKE gate, the imaging beam was passed through an Air Force target followed by a scattering cell filled with suspended polystyrene spheres. Three different path length cells were used: 2mm, 10mm, and 20mm. Images were collected using each cell with the OD varied between 0 and 9. The OD was measured by removing the Air Force target and placing an optical power meter at P4 in Figure 3.1. The power meter measured the imaging beam power with and without the scattering cell in place. The OD was calculated from Beers law as the negative natural log of the ratio of the two measured powers. It is important to note here that the Air Force target was placed before the scattering cell instead of in the middle of the cell as others have done[63, 64]. Although the total OD is unchanged, placing the target in the middle of the scattering cell reduces by a factor of two the level of image scattering. As a result, previous experiments with femtosecond ballistic imaging through scattering cells have achieved optical depths as high as 13, whereas our results show a maximum OD of 9. Thus care should be taken in directly comparing results between ballistic imaging scattering cell experiments.

Using path lengths of 2mm and 10mm, and for all values of OD, we found no measurable improvement in image quality when using the OKE gate. At short path lengths (e.g. 2 mm) with OD < 10, the delay between ballistic and multiply scattered photons is on the order of 1-3ps [20]. Thus, the 7 picosecond gate employed here has limited impact for short path lengths. A series of experiments were set up to explicitly produce the same optical depth with different path lengths through the cell. The intent was to show the effectiveness of the Kerr cell time gate with different size objects. Recall that greater lengths should produce greater separation in the ballistic photons and the scattered photons. Another potential reason for poor OKE gate performance may be imperfections in the polarizers used, as image degradation was observed with the OKE gate in place. There was however a measurable improvement for line pairs greater than 5 lp/mm at a path length of 20mm and high OD, as shown in Figure 3.6. The contrast transfer function, CTF, for a 20mm path length cell with
Figure 3.6: CTF calculated from an Air Force target imaged through a 20mm cell filled with 5 \( \mu \)m polystyrene spheres suspended in water (OD = 6.71). Spatial filtering was used with a solid angle of collection of \( \Omega = 0.002 \text{ sr} \). At 20mm, the OKE gate has a measurable effect on CTF. Data points represent the average of 3 line pairs with error bars equal to the standard deviation.

an OD of 6.7 was calculated using the Air Force target by monitoring the intensity through a three-line pattern. CTF was calculated using 

\[
\text{CTF} = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}},
\]

where \( I_{\text{max}} \) is the peak image intensity on a single line, and \( I_{\text{min}} \) is the minimum image intensity between adjacent lines. This was repeated for all lines in a three-line set and the average of the three was plotted as a single data point in Figure 3.6. The CTF revealed that the OKE gate improved image resolution for a 20 mm path length with high OD.

3.2.5 Spatial filtering

As others have shown [65, 66], limiting the solid angle of collection in ballistic imaging improves image resolution by preventing a portion of the single and multiply scattered light from being collected by the camera. As light travels through the scattering medium, photons passing through scattering objects (droplets, ligaments, etc), will undergo an elastic scattering event that changes the direction of the photon. This change in direction depends upon the scattering medium, the scattering particle size, and the wavelength of light. For a single
scattering event typical of micron-sized droplets, the majority of visible light is scattering in the forward direction at small angles relative to the initial direction of the photon. In dense scattering media, photons will experience more than one scattering event, or multiple scattering. As multiple scattering increases, the angular direction of the scattered light approaches a uniform distribution in $4\pi$ steradians (i.e. the light is scattered uniformly in all directions). Thus, greater levels of multiple scattering increase rejection of scattered photons by spatial filtering.

Our results show, with a $\sim7$ps gate, an improvement in resolution with a 20mm path length. If the system scales linearly, this implies a 2mm path, which is similar to the path in diesel sprays, would require a $\sim0.7$ps gate time. While this analysis is crude, it does show that very short gate times are required for the diesel spray and that the relaxation time for CS$_2$ will be a significant factor in gate performance.

![Figure 3.7: CTF of Air Force target images captured using 10mm scattering cell (OD = 8.35) with and without spatial filtering. Images were taken without OKE gate.](image)

The impact of spatial filtering on image resolution is shown in Figure 3.7. Spatial filtering was accomplished by placing an iris 200mm after the Air Force target with a diameter of 1cm, providing a solid angle of collection of 0.002 sr. A CTF of the Air Force target imaged at OD=8.35 shows a significant improvement when spatial filtering is used. In fact, we found
that spatial filtering had a more significant impact on image resolution than the OKE gate for all path lengths and optical depths studied.

### 3.2.6 Overall imaging performance

![Graph showing resolution vs. optical depth]

**Figure 3.8:** Highest resolution image achieved at increasing optical depth. Resolution decreases with increasing OD. Resolution was determined from the highest number of lines/mm discernable on the Air Force target.

Combining the effects of spatial and temporal filtering results in an imaging system that is able to collect images at very high optical depths. The maximum resolution using the 2mm cell at each OD is plotted in Figure 3.8. At low OD, the imaging system is able to resolve features as small as 10 µm. In sprays, low OD fine features along the periphery can be successfully imaged using this technique. As the OD increases, the resolution degrades, preventing fine features embedded in high OD regions of the spray from being successfully imaged. Thus, fine features in the core of the spray are not accessible with this imaging method and should be studied either with shorter pulse ballistic imaging or with x-ray imaging.

### 3.3 Conclusions

The characterization and demonstration of a 15 picosecond 532nm Nd:YAG laser-based ballistic imaging system is reported.

- A CS₂ OKE gate activated by a 1064nm switching beam was measured to have a 7ps gate width using autocorrelation.
- A two-color OKE gate system was also shown to have superior image quality due to removal of gate beam scattering.

- The 7ps OKE gate was observed to have little effect on image quality for scattering cell path lengths of 2mm and 10mm.

- A measurable improvement in image resolution was observed at a path length of 20mm at optical depths > 6. This indicates that for scattering environments sizes of greater than 20 mm, ballistic imaging with 7ps pulses is effective. Assuming a linear relation between gate width required and the 'scale' of the scattering field, diesel like sprays with a length scale of 1-2mm will require a gate width on the order of 1 ps in order to produce results superior to those that can be achieved with spatial filtering.

- Successful imaging through scattering cells with optical depths up to OD 9 are reported and show decreasing image resolution with increasing OD. A maximum resolution of 10 μm was achieved at OD’s less than three.
CHAPTER 4
BALLISTIC IMAGING SPRAY RESULTS

This effort is focused on a combination of developing the optical tools to probe the high-density region of a diesel spray and the use of these tools to improve our understanding of near-orifice spray behavior. Images taken near the injector orifice provide a valuable benchmark data set for development of advanced atomization and spray models. This work is based on a unique capability developed at the Colorado School of Mines (CSM) relevant to improvements in diesel engine technology. This experimental capability includes the ability to produce very controlled, diesel-like pre-injection conditions along with non-intrusive diagnostics specifically developed to monitor the near field of diesel sprays. The purpose of the facility and diagnostics is to investigate the controlling breakup modes of diesel sprays for operating ranges relevant to diesel engines.

4.1 Experimental Methods

Application of picosecond ballistic imaging to diesel sprays in pressure and temperature regimes relevant to actual diesel engine operating conditions has been the focus of this work at CSM. The experimental setup required includes the ballistic imaging optical train, image capture and post processing, a fuel injection system, the heated pressure vessel, and process control and data acquisition hardware. Each of these components is described below.

4.1.1 Ballistic imaging optical train

The 532nm output of a Coherent D-10 laser with pulse energy of 12±1 mJ and a 10 Hz repetition rate is directed as shown in Figure 4.1. Upon exiting the laser, the pulse is split into two legs by a 90/10 beam splitter. The higher energy pulse is used as the OKE (optical Kerr effect) switching beam, whereas the lower energy pulse is used for imaging purposes. The OKE beam traverses the table to a prism, which is attached to a translation
stage and subsequently directed through a CS$_2$ Kerr cell. Located at an intermediate plane in close proximity to the Fourier plane of the imaging beam, the OKE cell is activated by the switching beam, which enters at an angle of 11° from normal. A translation stage creates the delay line, which is used to control the overlap, in space and time, of the gate beam relative to the imaging beam in the Kerr cell (see Figure 3.2). Two crossed 20mm cube polarizers, P4 and P5 and the CS$_2$ cell make up the complete OKE gate. P4 is oriented to pass the image beam in its non-scattered state, whereas the output linear polarizer (P5) is set to be crossed with P4. Time gating produced via this setup is dependent on the rotation of the polarization state of the image beam, which is the result of induced birefringence in the carbon disulfide cell. The birefringence is produced by the interaction of the gate beam pulse with the CS$_2$.

Figure 4.1: Experimental schematic of ballistic imaging optical train. The HeNe laser and separate detectors are to measure the arrival of the imaging pulse and the spray injection timing. P1-P5 are polarizers. Beams are shown as cw for clarity.

The optical train for the image beam consists of two polarizers, P1 and P2, which are oriented to match the vertical polarization of the parent laser pulse and are used to assure clean polarization. After the polarizers is a 1/2 wave plate, which is used to control energy levels in the imaging beam. Following the wave plate is a polarizer, P3, which is set to be 45° with regards to P1 and P2, and in the same orientation as P4 of the OKE gate. Additionally, the image train contains four lenses, which are used to achieve two separate purposes. First
is to focus the image beam down so that it is completely contained within the radius of the switching beam while overlapping in the CS$_2$(gate beam is 6mm⊘ image beam is 1mm⊘), and secondly to form a telescopic effect at the imaging plane. Optimization of the image train was conducted using Zemax$^\text{®}$ software.

### 4.1.2 Image processing

In order to create an image that represents optical depth, a series of image processing steps were undertaken for each image (Figure 4.2). Prior to capturing spray images, a series of images were taken with the lens cap on the camera (background images). Additionally, images were captured of the laser with no spray, which constituted the baseline images. These series of images were then averaged and were labeled background ($B$) and baseline ($I_0$) respectively. Finally, the image of the spray was captured (labeled $I$ in Figure 4.2). A background subtracted optical depth image was created using Beers law. As can be seen from Figure 4.2, capturing a baseline is essential to achieving low noise images of sprays. The combination of laser speckle, refraction, and beam profile intensity variation in the image would otherwise interfere with spray features. All images were processed as outlined in Figure 4.2.

![Image processing steps](image.png)

Figure 4.2: A visual guide to the image processing steps used in capturing ballistic images of sprays. These images were collected with the Cascade camera.
4.1.3 Image capture

In order to capture images inside the pressure vessel, a timing scheme was designed to sync the laser pulse with the camera system and the injector firing (Figure 4.3). The timing of the trigger pulse was set by a photodiode that measured scattered light from an optic in the optical train. This photodiode signal was sent to a pulse generator, which in turn generated the triggering pulse for the image capture timing. The 10 Hz triggering pulse train was passed to a custom programmed PIC controller box, which also received an operator command to fire the injector. Upon receiving a request for an injection event, the injector controller fires the injector at a timing that coincides with the laser pulse passing through the spray. By adjusting the delay between the laser pulse sensed by the photodiode and the output pulse from the signal generator, the user can control the arrival time of the laser pulse to the spray with respect to the beginning of the injection event. In addition to communicating with the injector controller, the PIC also sent a TTL pulse to the camera, which effectively produced an image capture signal that enveloped the time period when the laser pulse is present. This pulse is delayed via a second pulse generator. By utilizing both pulse generators the user can adjust the timing of the image of the spray, relative to the beginning of the spray. Figure 4.3 shows the timing schematic. The TTL delay (~83ms) is carefully chosen to put the imaging pulse at the desired point in the spray, whereas the injection delay is set by the system dynamics. The image capture delay (~15ms) is set to capture the 12 ps imaging pulse as it passes through the spray. System timing jitter was experimentally determined by imaging the onset of the spray event to be 5μs. It is important to note that the TTL, imaging and injection delays are controlled at 100μs intervals. This makes the 5μs jitter negligible in the scheme of things.

In one study the camera was a Photometrics Cascade:650 imaging array (653x492 pixels, each 7.4 μm square), in another series of images a CoolSnap Myo camera was used (1940x1460 pixels, 4.45 μm square). These cameras are designed for low-light applications, and were used in conjunction with an ND 2.0 filter and a 532 nm band pass filter to optimize signal levels.
Figure 4.3: A schematic of the electronic timing used during imaging

and to filter stray light. Spray duration was tracked using a HeNe laser beam aligned to cross directly below the tip of the injector. The HeNe beam was directed to a detector and monitored on an oscilloscope. Spray duration, as determined by attenuation of the HeNe beam, was typically 3.0 to 3.5 ms. The imaging beam was monitored via a photo detector on the same oscilloscope. The arrival time of the imaging beam relative to the initiation of the spray was determined from the oscilloscope traces.

A Continuum® Leopard D-10 laser, operating at 10 Hz, was utilized to provide illumination for the images. This relatively inexpensive laser is capable of generating 15 picosecond pulses at 1064nm with energy levels up to 30mJ. In contrast to femtosecond lasers employed by other groups, the Leopard is capable of ballistic imaging as a stand-alone unit. The D-10 also provides the user with the capability to generate pulses at 266, 355, and 532nm, which enhances diagnostic capability.

4.1.4 Diesel injection system

The injection system used in all experiments is comprised of a Sturman® Industries HUEI type injector which was retrofitted with a custom machined single-hole on axis injector tip with an orifice diameter of 160 μm(L/D=4). This injection system is capable of multiple
pulse injections with pressures in excess of 200 MPa. The injector is controlled via a custom controller box and software which was provided by Sturman.

In order to provide the ability to synchronize the injection event and the arrival of both the laser pulse and the camera triggering window, a separate custom PIC based controller box was built in house. The PIC controller allows the digital word from the software to be delayed so as to match up the injection time with the following laser pulse. Initially, the box function was jittery, intermittent and would only fire one time before having to be reset. A PIC programmer was used to download the assembly code from the chip. It was determined, via oscilloscope traces, that the Sturman controller received a 28 bit word from the software. Examination of the code stored on the PIC revealed that the jitter was caused by an analog to digital voltage reading of a potentiometer designed to allow on board injection timing control. Removing this feature, and replacing the timing control with an external delay generator, cleared up the jitter from about 1 ms to around 5µs, but the injector still would only fire once and only on the second fire command. The code set the PIC to receive a 32 bit word, which explained the above mentioned problems. Setting the code to accept a 28 bit word restored functionality.

The injector was originally designed to reject the engine oil used to actuate injection back into the head of the engine via two ports on the top of the injector. This was a serious issue as the oil experienced a 3000 psi pressure drop as it left the injector. Several designs of oil control manifolds were designed and built in an attempt to seal the ports. The problem was that the amount of metal surrounding the ports was very small and rough. Epoxy with metal was added to the outside of the injector body to create a larger sealing surface for an O-ring to mount, eventually the epoxy broke off of the injector due to the shock forces involved with the injection. Finally the injector was disassembled and the top surface was lapped to a mirror finish, which allowed for an adequate seal to be formed. This was marginally successful in containing the oil, but was plagued by failing o-rings. Finally, the oil ejection ports were reamed out to 0.2205 inches and #6 hypodermic tubes were immersed in liquid
nitrogen and press-fit into the holes. This worked to contain the expelled hydraulic fluid, but the body of the injector continually leaked oil out of a weep hole built into the injector body.

An injector holder was designed to allow the injector to be used in the pressure vessel. The holder was necessary to both form a seal between the vessel and the injector, and to allow the fuel to circulate within the injector. The fuel was pumped through the injector, via the holder and external fuel lines, and was cooled by a liquid bath cooler to prevent coking of the fuel inside the injector tip.

During the course of this research, the injector failed several times. Twice small particles became lodged in our 160µm single hole tip. The injector tip was taken to Sturman and was blasted clean by a 30000psi hydraulic test stand. Several types of bio-fuel surrogates were used over time and some of those fuels reacted with the seals inside the injector causing the injector to need rebuilding. Dust from the lab getting into the oil storage resulted in the injector actuator become stuck open or closed due to bits of the dust getting caught in the tight tolerances between the actuator and its housing.

The hydraulic fluid used in this experiment was Mobil® DTE-24. DTE-24 is a fully synthetic hydraulic oil which was chosen due to it’s fluid properties at room temperature mimicking that of 15w-40 diesel engine oil at engine operating conditions (200°F). The fluid was pressurized with Baldor® electric motor which drove a Maraochhi® high-pressure pump. This pump filled a high pressure Schrupp® 2.5 gallon bladder type accumulator. The bladder accumulator was used to assure a high volume hydraulic fluid supply that would deliver a constant pressure flow of fluid which was isolated from the pump vibrations. Smooth delivery of high pressure oil was essential for consistent, reliable injector operation.

The time delay between release of the command to fire and the actual time of injection is dependent on the pressure of the hydraulic oil, the lower the pressure of the oil the longer the delay. This mandates careful monitoring of the pressure to assure that the timing reported in the images is correct. A digital pressure gauge was installed so as to be visible to the...
operator of the experiment. When operated at an oil pressure of 3000 psi, the jitter in the injection event is 5 $\mu$s. The jitter was measured by setting the electronics to capture images of the start of injection. All of the images captured showed that the leading edge of the injection event was contained within the field of view of the camera. Knowing that the field of view of the camera is 2.5 mm in the vertical direction and that the injection velocity is on the order of 500 m/s, 5$\mu$s of jitter was calculated.

To prevent fuel degradation and subsequent clogging of the injector, the injector body was encapsulated in an insulated housing. Modeling of the thermal conditions revealed that the injector tip assembly maintains a maximum temperature of approximately 150$^\circ$C. Cooling of the fuel is enhanced by recirculation of the fuel through the injector housing and into a cooling bath utilizing a coil-type heat exchanger. Examination of the disassembled injector revealed no signs of fuel coking (normally observed at 150 – 180$^\circ$C), even after operation for extended time at operating temperatures of 600$^\circ$C.

4.1.5 Pressure vessel

Experiments utilize a custom-manufactured combustion vessel capable of maintaining pre-injection conditions of 50 atm and 1000 K. As shown in Figure 4.4, the diesel engine simulator was split into an inner heated core surrounded by an exterior pressure vessel. The exterior pressure vessel has four orthogonal, purged optical ports for line-of-sight optical measurements and detection at 90$^\circ$. The inner heated core is the central air-bearing region and is 44.5 mm in diameter. The distance from the injector tip to the opposing wall is adjustable. Further details of the experimental system and gas extraction can be found in the literature [26] and are summarized in Table 4.1.

Due to the range of engine designs and operating conditions there is no standard diesel combustion event. Experiments conducted in the simulator described in this paper were designed to emulate a number of the important characteristics of diesel combustion. As shown in Table 4.1, the simulator effectively replicates most of the important characteristics of diesel combustion. The most striking difference between the simulator and engines, in
Figure 4.4: The Diesel Engine Simulator. Air or nitrogen is preheated by packed bed of steel ball bearings. Fuel is injected into the heated chamber toward a steel plate, which simulates the top surface of a piston.

terms of operating parameters, is pressure. The simulator was operated at 20 atm versus the 30 atm and greater typical of diesel engines; additionally, the simulator is isobaric.

Table 4.1: Comparison of typical diesel engine characteristics with the Diesel Engine Simulator.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Engine</th>
<th>Simulator (for most recent work)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Pressure</td>
<td>20-150 MPa [67], 20-80 MPa [67], 100-150 MPa [68], 20-170 MPa [69]</td>
<td>55-150 MPa</td>
</tr>
<tr>
<td>Nozzle orifice diameter</td>
<td>0.15-0.35 mm [67], 0.184 mm [68], 0.194 mm</td>
<td>0.160 mm</td>
</tr>
<tr>
<td>Nozzle orifice L/D</td>
<td>2-8 [67], 4</td>
<td>4</td>
</tr>
<tr>
<td>Number of nozzle orifices</td>
<td>3-8 holes</td>
<td>1 hole</td>
</tr>
<tr>
<td>Types of nozzles used</td>
<td>Pintle and hole-type nozzles</td>
<td>Hole-type nozzle</td>
</tr>
<tr>
<td>Mass injection</td>
<td>2-24 mm$^3$ per hole</td>
<td>4 mm$^3$ min.; 37 mm$^3$ max.</td>
</tr>
<tr>
<td>Chamber temperature</td>
<td>100-1200 K, 700-1300 K [70]</td>
<td>873 K</td>
</tr>
<tr>
<td>Chamber pressure</td>
<td>40-120 atm [67], 50-100 atm [69]</td>
<td>20 atm</td>
</tr>
<tr>
<td>Hard wall interaction length</td>
<td>50-60 mm [70]</td>
<td>100 mm</td>
</tr>
<tr>
<td>Liquid length</td>
<td>180 mm</td>
<td>30 mm</td>
</tr>
<tr>
<td>Change in chamber pressure</td>
<td>6 MPa [70]</td>
<td>25 kPa</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>16-22 [69]</td>
<td>None</td>
</tr>
<tr>
<td>Overall stoichiometry</td>
<td>Fuel lean [69]</td>
<td>Fuel lean</td>
</tr>
</tbody>
</table>

4.1.6 Orthogonal Imaging

The complexity of the ballistic imaging optical train may raise the question of whether this type of imaging is required to study the near-orifice region of diesel sprays. To quantify improvements in image resolution and clarity, sprays were imaged simultaneously using the
ballistic imaging technique, with spatial filtering (solid angle of collection of $\omega = 0.002$ sr), and with traditional shadowgraphy. To accomplish this, the imaging beam was passed through a 50/50 beam splitter and into orthogonal optical paths (Figure 4.5). The Myo camera was used for the ballistic imaging line (Camera 1), while the Cascade camera was used for the shadowgraphy experiments (Camera 2). Two identical cameras were not available at the time of these experiments, so the resolution of the two images has been matched via image post processing in Matlab (Figure 4.6).

Sample results from the simultaneous orthogonal imaging are shown in Figure 4.6. The 1450 atm injection pressure sprays were injected into ambient air. As can be seen, shadowgraphy captures the overall shape of the spray, but does not capture finer structures such as liquid ligaments and voids.\(^1\) Further, shadowgraphic images of the spray sometimes appear wider than the ballistic image due to scattering on the periphery of the spray where droplet loadings are significant. In contrast, the ballistic images show detailed structure on the or-

---

\(^1\)It is important to note that this statement is true for this particular physical setup. As discussed in chapter 3, the time gate produces a pulse of approximately 7ps which is not effective for imaging the length scales encountered in diesel sprays. In fact by limiting the collection angle within reason, better images are produced without the time gate.
4.2 Diesel Spray Imaging Results and Discussion

Two types of fuels have been investigated: dodecane and methyl oleate. Dodecane is a common diesel fuel surrogate and methyl oleate is a common bio-diesel surrogate. Several different test regimes were examined and will be presented individually and then compared in terms of observed trends. These include:

- Dodecane injected into ambient air at varying injection pressure (Table 4.2. Rows 1-2)
- Dodecane injected into room-temperature air at elevated air pressures (Table 4.2. Row 3)
- Dodecane injected into air at elevated temperature and pressure (Table 4.2. Rows 4-6)
• Methyl oleate injected into ambient air (Table 4.2. Row 7)

Table 4.2: Operating conditions tested, corresponding fuel properties [71–73], and non-dimensional groups.

<table>
<thead>
<tr>
<th></th>
<th>temp</th>
<th>temp</th>
<th>pressure</th>
<th>pressure</th>
<th>velocity</th>
<th>liquid</th>
<th>surface</th>
<th>liquid</th>
<th>Re</th>
<th>We</th>
<th>Oh</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(liq)</td>
<td>(charge)</td>
<td>(injection)</td>
<td>(charge)</td>
<td>(m/s)</td>
<td>density</td>
<td>tension</td>
<td>viscosity</td>
<td>(-)</td>
<td>(-)</td>
<td>(-)</td>
</tr>
<tr>
<td></td>
<td>(°C)</td>
<td></td>
<td>(atm)</td>
<td>(atm)</td>
<td></td>
<td>(kg/m³)</td>
<td>(N/m)</td>
<td>(Pa·s)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dodecane 1.</td>
<td>25</td>
<td>25</td>
<td>1</td>
<td>970</td>
<td>514</td>
<td>744.4</td>
<td>2.49E-02</td>
<td>1.32E-03</td>
<td>4.65E+04</td>
<td>1.26E+06</td>
<td>2.41E-02</td>
</tr>
<tr>
<td>2.</td>
<td>25</td>
<td>25</td>
<td>1</td>
<td>1450</td>
<td>639</td>
<td>744.4</td>
<td>2.49E-02</td>
<td>1.32E-03</td>
<td>5.79E+04</td>
<td>1.95E+06</td>
<td>2.41E-02</td>
</tr>
<tr>
<td>3.</td>
<td>25</td>
<td>25</td>
<td>20</td>
<td>1450</td>
<td>623</td>
<td>745.8</td>
<td>2.49E-02</td>
<td>1.35E-03</td>
<td>5.52E+04</td>
<td>1.86E+06</td>
<td>2.47E-02</td>
</tr>
<tr>
<td>4.</td>
<td>150</td>
<td>600</td>
<td>3</td>
<td>1450</td>
<td>672</td>
<td>650.0</td>
<td>1.39E-02</td>
<td>3.21E-04</td>
<td>2.14E+05</td>
<td>3.36E+06</td>
<td>8.57E-03</td>
</tr>
<tr>
<td>5.</td>
<td>150</td>
<td>600</td>
<td>12</td>
<td>1450</td>
<td>669</td>
<td>651.5</td>
<td>1.39E-02</td>
<td>3.26E-04</td>
<td>2.14E+05</td>
<td>3.36E+06</td>
<td>8.57E-03</td>
</tr>
<tr>
<td>6.</td>
<td>150</td>
<td>600</td>
<td>20</td>
<td>1450</td>
<td>666</td>
<td>652.7</td>
<td>1.39E-02</td>
<td>3.30E-04</td>
<td>2.11E+05</td>
<td>3.35E+06</td>
<td>8.67E-03</td>
</tr>
<tr>
<td>Methyl Oleate 7.</td>
<td>25</td>
<td>25</td>
<td>1</td>
<td>1450</td>
<td>581</td>
<td>868.8</td>
<td>2.90E-02</td>
<td>5.32E-03</td>
<td>1.52E+04</td>
<td>1.62E+06</td>
<td>8.38E-02</td>
</tr>
<tr>
<td>Methyl Butyrate 8.</td>
<td>25</td>
<td>25</td>
<td>1</td>
<td>1450</td>
<td>572</td>
<td>898.0</td>
<td>2.55E-02</td>
<td>5.58E-04</td>
<td>1.47E+04</td>
<td>1.84E+06</td>
<td>8.38E-02</td>
</tr>
</tbody>
</table>

For reference in comparing imaging results from different fuels and conditions, Table 4.2 has been compiled, which contains the majority of the experimental conditions with accompanying fuel properties and non-dimensional groups. Reynolds(4.1), Weber(4.2), and Ohnesorge(4.3) numbers were evaluated using the following equations from fuel properties and injection parameters [74].

\[
Re = \frac{\rho_l V}{\mu_l} \quad (4.1)
\]

\[
We = \frac{\rho_l V^2}{\sigma} \quad (4.2)
\]

\[
Oh = \frac{We^{1/4}}{Re} = \frac{\mu_l}{(\rho_l \sigma L)^{1/2}} \quad (4.3)
\]

where \(\rho_l, \mu_l, \sigma,\) and \(V,\) are the density, viscosity, surface tension, and velocity of the liquid fuel, and the characteristic length, \(L,\) was taken as the injector orifice diameter: 0.16 mm. The velocity was calculated from Bernoulli’s equation. The Reynolds number relates the ratio of inertial to viscous forces and the Weber number relates the ratio of momentum to surface tension forces and has been correlated with jet breakup regimes. The Ohnesorge number is given by the ratio of the fourth root of the Weber number and the Reynolds number and is an indicator of jet stability.
4.2.1 Direct comparison of ps ballistic imaging and shadowgraphy

Two cameras were used to simultaneously image a single injection: the Photometrics Cascade:650 was used for the shadowgraphy imaging, and a CoolSNAP Myo 20MHz 2.8Mpixel digital camera (1940x1460, 4.54 micron pixels) was used for the ballistic images of sprays. Shadowgraphic images were acquired by splitting the 532nm imaging beam with a 50/50 beam splitter and passing one leg through the spray without any temporal or spatial filtering. The other leg consisted of the ballistic imaging train described. Complete details of this experiment have been presented in section 3.1.1 [75].

Figure 4.7: Simultaneous orthogonal imaging of a methyl oleate spray injected at 1450 atm into ambient air. Image resolution for both images is 170 x 300.

Images of the same spray event captured simultaneously via the ballistic imaging technique and with traditional shadowgraphy show increased ability to identify small scale liquid structures on the periphery of the spray using ballistic imaging (Figure 4.7). There is also significant broadening of the spray with traditional shadowgraphy, which is likely due to the lack of scattering rejection in the shadowgraph. The long liquid ligaments, voids, and mass shedding evident in the ballistic image are also seen in the shadowgraph, but with much less detail.
4.2.2 Evolution of a spray

The ballistic imaging methods discussed above, combined with controlled injection timing, allows spray behavior to be studied over the life of the spray from start of injection to end of injection as well as ignition. For example, Figure 4.8 shows the evolution of a methyl butyrate spray from early injection to end of injection (images are from separate injections). Early after start of injection (images 1-3), the spray plume is clearly visible, in agreement with direct numerical simulation models [76]. Also seen is the typical widening of the spray seen at early injection times (image 4) followed by spray narrowing at intermediate times (images 5-6). Finally, near end of injection, the spray begins to become unstable (image 6), and finally shuts off leaving a low velocity stream of fluid without significant atomization (image 7).

Figure 4.8: Ballistic images of methyl butyrate sprays injected at 1450 atm into ambient air and captured at increasing times after start of injection. The total duration of a typical injection is 3 ms. The scale of optical depth, OD, is shown in the color bar on the right.

4.2.3 Effect of fuel type on spray behavior

Ballistic imaging studies of the effect of fuel type on the near-field region of the spray show non-trivial differences in spray breakup. Figure 4.9 compares ballistic images of methyl oleate (C_{19}H_{36}O_{2}, biodiesel surrogate) and methyl butyrate (C_{5}H_{10}O_{2}, no longer considered a suitable biodiesel surrogate due to non negative temperature coefficient (NTC) behavior) sprays in an ambient air background. The methyl butyrate, which has a lower molecular
weight and lower boiling point but similar surface tension and viscosity, shows significantly less spray shedding than the methyl oleate spray. The methyl oleate image also reveals very long ligaments running parallel with the spray.

Figure 4.9: Comparison of ballistic images of methyl oleate and methyl butyrate sprays at 1450 atm injection pressure in ambient air. The scale of optical depth, OD, is shown in the color bar on the right.

Ballistic imaging of the near-orifice region of biodiesel sprays is reported. Orthogonal, simultaneous images of a spray using ballistic imaging and shadowgraphy, respectively, demonstrate that ballistic imaging is superior in resolving fine features in the spray. Two biofuel surrogates are compared and show that at the conditions tested, fuel type impacts spray shedding in the near-orifice region.

4.2.4 Transient fluctuations in room temperature dodecane sprays

The bulk of the initial imaging undertaken in this study was of dodecane at standard temperature and pressure. This phase of testing was focused on validating the systems performance and provided proof of concept testing for pulse-sliced ballistic imaging. These

\(^2\)Again this is true only for this particular physical arrangement.
initial images revealed trends in the spray, which were present across the entire test matrix of fuels, temperatures and pressures. The most persistent trend observed in this phase of testing was the oscillation of the width of the spray in time (relative to start of injection) (Figure 4.10). Similar oscillations have been seen in all cases studied (Figure 4.17).

4.2.5 Injection pressure and double pulsed injection

In a separate experiment, the injection pressure of dodecane was varied from 970 to 1500 atm to examine the effect of injection pressure on the spray structure. This study revealed that at all three injection pressures, significant shedding was present on the sprays periphery (Figure 4.11). Other than a very slight narrowing of the spray cone angle with increasing injection pressure, there was little change in structure with increasing injection pressure.

In yet another experiment, the injector was double-pulsed at 1450 atm injection pressure into atmospheric conditions. This test was intended to examine the effects of multiple injections in rapid succession, a strategy used in modern diesel engines to reduce sooting.
Figure 4.11: Ballistic images of dodecane at various injection pressures revealed significant shedding in all cases.

[77]. The images show no significant differences in spray structure, but this may be due to the 3 ms time lapse between injection pulses (Figure 4.12).

4.2.6 Effect of charge pressure on dodecane sprays

The next series of images were captured of dodecane injected into air at room temperature and increasing pressure (Figure 4.13). Periphery shedding of the spray\(^3\) is seen at all pressures, with slightly more shedding at low pressure, but much less pronounced than what is seen at higher air temperatures (Figure 4.14, Figure 4.15). These images revealed that the near-nozzle spray angle increased with increasing air pressure at ambient temperature. There was also an increase in the fluctuation of the spray angle with increased air pressure, as seen from the error bars in the inset graph.

\(^3\)It is not apparent if the ‘core’ of the spray is a liquid or a high liquid volume fraction.
Figure 4.12: Images of a double-pulsed sequence of injections shows similar structure in each spray.

Figure 4.13: (left) Images of dodecane at room temperature and increasing pressures. Magnification with additional contrasting highlights shedding phenomena. (right) Spray cone angle increased with increasing charge pressure. Data points are averages over 30 images each. Error bars represent one standard deviation.
Figure 4.14: Example images which exhibit the trend of increasing cone angle with pressure.

Figure 4.15: Averaged cone angle for all sprays studied. Data points are averages over 30 images each. Error bars represent one standard deviation.
4.2.7 Effect of charge temperature and pressure on dodecane sprays

The most relevant testing regime to diesel engine studies was the imaging of dodecane injections at high air temperature and pressure. At these air temperatures, the liquid fuel is preheated in the injector to around 150°C due to conduction from the heated chamber. Dodecane was injected into air at 600°C and pressures from 3-20 atmospheres. At the higher-pressure levels, conditions are representative of the environment found in actual diesel engines (Table 4.1). The higher chamber pressure and temperature caused large density gradients in the pressure vessel making it impossible to acquire quality baseline images, \( I_0 \), due to significant shot to shot variation (Figure 4.2). The images shown here have been converted to optical depth by taking the negative natural logarithm of each image (pixel by pixel).

The captured images revealed many trends that varied with pressure and revealed breakup structures that to our knowledge have not previously been observed in the near-orifice region, but have been predicted by others [33, 78]. Initial images revealed large differences in the observed structures compared to those observed at the same pressures but lower temperature (Figure 4.13). Additionally, the observed spray cone angles increased with pressure (Figure 4.15), similar to the low temperature sprays (Figure 4.13). Further examination revealed that the observed shedding structures developed nearer to the injector with increasing pressure (Figure 4.16). The optical density of the spray is lower during the period of time when the shedding structures occur, which may be indicative of evaporation and mixing within the spray cone. Although a statistical analysis of the spray shedding structures has been unsuccessful due to the high background noise in the images at high pressure, spatial frequencies are observed to be approximately 10 mm\(^{-1}\), with ligament lengths between 50-200\(\mu\)m.

Some of the observed trends can be correlated to the data in Table 4.2 and some cannot. First, fuel properties are largely insensitive to the charge pressure (vessel pressure). On the contrary, fluid temperature has a more dramatic effect on density, surface tension, and viscosity. The Weber number nearly doubles as the fuel liquid temperature rises from
ambient to 150°C, while the Ohnesorge number is reduced by a factor of three for the same temperature change. The most significant change in fuel properties is the reduced viscosity at high temperature. This reduction in viscosity could in part explain the observed shedding structures seen in high temperature and pressure dodecane sprays.

A comparison of the spray cone angles of images taken at 20 atm and 25°C and those taken at 20 atm and 600°C reveal some interesting trends. Cone angle measurements were made of sprays over the entire injection event at the two aforementioned environmental conditions and plotted in Figure 4.17. The lower temperature spray reveals oscillation of the cones angle, whereas the higher temperature spray initially oscillates but then settles to an almost constant angle. Interestingly, this temporal region corresponds directly with the existence of the shedding structures caused by violent mass shedding. A similar trend is observed at 12 atm and 600°C.
Figure 4.17: Measured spray cone angles as a function of time. Sprays were injected into a 20 atm environment at 25°C and 600°C. The smooth region of the 600°C curve corresponds to the observation of spray shedding.
4.2.8 Spray structure in a biodiesel surrogate

To investigate the effect of fuel type on the near-nozzle region of diesel sprays, methyl oleate was substituted for dodecane for a series of images. Methyl oleate (C_{19}H_{36}O_2) is a common surrogate for biodiesel. The resulting spray images were very clearly different than those of the low air temperature and pressure dodecane tests. Foremost, the spray cone was markedly wider in the methyl oleate images (Figure 4.18). Additionally, the images reveal what appear to be large shedding structures along the periphery. This scale of shedding is not observed in the ambient dodecane images, but has been observed in high temperature and pressure dodecane sprays as discussed. The reason for these shedding structures in methyl oleate is not understood. In fact the increased viscosity of methyl oleate relative to dodecane should inhibit breakup (Table 4.2).

![Figure 4.18: Images of methyl oleate reveal a wider spray cone and peripheral shedding.](image)

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4.3 Conclusions

The following is a summary of the findings from this study. These findings are presented in an itemized list purely for brevity.

- First ballistic imaging of diesel spray injected into high temperature and pressure air
- This technique was applied to methyl oleate and dodecane sprays
- Trends in ambient spray behavior captured including oscillation in spray cone angle and fuel effects
- The environmental pressures into which the fuels were injected had an effect on spray cone angles. The higher the ambient pressure, the wider the spray cone angle.
- Injection of dodecane into high temperature and pressure environment revealed marked trends of cone angle fluctuation and significant mass shedding. Shedding structures were not observed at low temperature, even at elevated background pressures
- Shedding not observed at room temperature dodecane
- Shedding structures observed in dodecane sprays at 600°C have approximate spatial frequency of 10mm\(^{-1}\) with lengths of 50-200 microns
- Structures bear resemblance to those predicted by the Sirignano group, although direct comparison is difficult due to ballistic imaging being a line integrated measurement
- Methyl oleate sprays at ambient conditions shows a wider spray and "richer" shedding structures than dodecane at the same conditions
- It was observed later that spatial filtering can achieve the same results for the 1-2mm length scale and a 7-8ps pulse as the optical Kerr gate. For this spray, the results indicate that a shorter gate is needed to effectively remove the scattered light which cannot be eliminated by spatial filtering.
CHAPTER 5
SIMULTANEOUS PLANAR IMAGING USING TWO-COLOR ELASTIC SCATTERING

If a thin laser sheet is passed through the near nozzle region of a high pressure diesel spray, and the scattered light is captured orthogonally to the direction of the laser sheet’s direction of travel, structures within the spray can be identified. This technique provides spatially resolved information, with spatial resolution set by voxel size and image resolution. This is unique compared to line integrated imaging techniques like ballistic imaging. This is a diagnostic step forward and should provide complementary spray information.

The following is a list of diagnostic challenges to be aware of and possibly to overcome:

- The attenuation of the sheet as it traverses the spray could impact scattering signal strength and the ability to image spray structures
- Attenuation of the orthogonal scattered light may introduce difficulty in interpreting images and may obscure certain parts of the spray
- Attenuation of the laser sheet will likely be dominated by the scattering into a small forward angle. This likely will produce a certain amount of beam spreading.

5.1 Introduction

Ballistic images, while able to probe dense regions of the spray, present 2-D path-averaged maps of light attenuation that obscure much of the internal structure of the spray. Diesel sprays are highly transient with significant variation in internal structure that requires volumetric imaging (3-D) techniques to capture the spray breakup physics. Using a thin (∼100µm) sheet to slice through the spray provides a 2-D map, over the ∼100µm of the beam. Thus spatially resolved information is obtained which will provide superior spray breakup information compared to line-integrated techniques such as ballistic imaging. By
simultaneously imaging multiple sheets at different locations in the spray, one is able to observe an image pair that show structure within the spray. These image sets are a first step toward instantaneous fully three-dimensional imaging in diesel sprays.

Scattering images were collected at two injector orifice sizes (160µm and 320µm), with two fuels (methyl oleate and dodecane), at increasing times after start of injection (ASOI), at offset distances from the injector line of center, and over a range of injector pressures (400 atm to 1450 atm). Over 3000 images were collected.

5.2 Experimental Methods

Scattering measurements are based on the elastic interaction of a laser sheet with the liquid/gas spray field. As configured for this sequence of experiments, these measurements produce spatially-resolved measurements as opposed to the line-integrated measurements from ballistic imaging methods. Spatial resolution comes from the intersection of the laser sheet with the perpendicular oriented object field provided by the camera. The size of each voxel or volume based resolution element is therefore the area of each image of pixel with the depth of the measurement defined by the width of the laser sheet. Thus, the camera provides image based resolution from the size of the camera’s imaging chip and the laser slices a section of the spray for interrogation by the camera. Figure 5.1 illustrates the basics of the measurement and shows two laser sheets, parallel to each other, but offset by a controlled distance, that are used to acquire spatially resolved images of the spray. A critical aspect of these experiments is the dual color laser sheets. Each experiment allows acquisition of an image pair that are acquired at the same instant in time. By controlling the spatial offset in the sheets relative to one another, two simultaneous images of the spray are produced. This measurement is enabled by the distinct wavelengths of the two sheets (Nd:Yag second and third harmonic) which allows each camera to observe only the signal from the laser sheet assigned to the camera with the use of a band pass filter. Over a series of experiments, by varying the arrival time of the laser sheet in the spray, the offset of the sheets relative to one another, and the spray position relative to the laser sheets, a time series of volume images
can be created. Simultaneously acquired images can be correlated to identify 3-D structures in the spray field.

Figure 5.1: Two-sheet scattering measurement. 532nm and 355nm pulse sheets are simultaneously passed through the spray. Images of the scattering from these sheets is captured by two camera systems.

Figure 5.2 illustrates the overall experimental setup comprised of the Continuum Leopard, a series of beam shaping and delivery optics, the Sturman injector system which can be configured with spray nozzles with different hole sizes and orientations, scattering signal collection optics, and finally, the matched pair of CoolSnap Myo cameras.

The Continuum Leopard is one of the cornerstone pieces of equipment for this experimental program. This laser is intended to provide turn-key access to a 10-Hz series of 15 picosecond long pulses. The laser itself is one of the many lasers built around the properties of Nd:Yag and can be configured to provide multiple coincident beams that are fundamental in frequency (1.06 microns), second harmonic (532 nm), third harmonic (355 nm), or fourth harmonic (266 nm). Access to harmonics is provided by frequency doubling (or in the case of third harmonic, combined doubling and then frequency addition) crystals that are placed in the beam path after amplification. A critical element in using this laser feature is to note that the user must provide downstream color separation of the beams since frequency shift
Figure 5.2: Experimental setup for two-color scattering measurement. Green beam (532nm), blue beam (355nm), C: camera, L: lens, I: iris, PH: laser pinhole, P: polarizer, WP: wave plate, M: mirror, CL: cylindrical lens, DM: dichroic mirror, S: spray, BD: beam dump, BP: band pass filter.
crystals are not 100% efficient.

As shown in Figure 5.2 the beam pair exits the laser: one laser aperture for the 355 nm beam (this beam includes components of 532 nm and 1.06 microns as well) and the other aperture for 532 nm (this beam includes components of 1.06 microns as well). Use of dichroic reflectors for the 355 nm beam are used to direct the beam along on optical rail that includes focusing lenses, variable apertures, and laser pinholes. The dichroic reflector effectively removes the first and second harmonic from the beam. The 532 nm beam is similarly directed along an optical rail that includes focusing lenses, variable apertures, and a laser pinhole. Wavelength separation is both from the variable apertures (beam propagation direction and size for the fundamental wavelength beam is not exactly the same as for the second harmonic) and then dichroic reflectors at the end of the rail. Both beams are carefully managed with the use of a Keplerian telescope. This telescope combines two focusing lenses that are separated by the approximate sum of the two focal lengths. The size of the exiting beam is approximately equal to the entrance beam size times the ratio of the exiting focal length to the entrance focal length for the two lenses. These telescopes are critical to the experiment because: 1) they allow the beam diameter to be set as needed, 2) the telescopes can be arranged so that the Raleigh range for the beam extends through the measurement plane so that the sheets don’t diverge, and 3) a pinhole can be added at the focus plane for the telescope to remove non TEM\textsubscript{00} components of the beam.

Setting the beam diameter, allows us to fix the size of the beam to the approximate height of the spray field to be imaged. Setting the beam waist close to the exiting telescope lens is important as well. Each of the laser beams diverge dramatically, but within the so called Raleigh range the beam diameter\textsuperscript{4} is approximately constant. The length of the Raleigh range can be quite long with the length proportional to beam diameter (for instance, a 532nm beam with an 8mm diameter has a Raleigh range of 378 m). While the Raleigh range can be comfortably long for this series of experiments so that the beam does not diverge

\textsuperscript{4}The Rayleigh range is the propagation distance for the beam where the variation from the minimum waist size varies by the $\sqrt{2}$. 

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appreciably, the beam waist can be located nearly anywhere along the beam path. Control of the lens separation provides control of the beam waist position, which then provides a non-divergent beam for the distances used in this experiment.

Finally, the use of a diamond pinhole at the focus plane is critical to the overall success of the experiment. A critical aspect of the experiment is using beam shaping optics to set the width of the laser sheet that traverses the spray. This sheet needs to be relatively small (of the order of 100 microns) in order to slice the spray into multiple discrete elements. While an exact Gaussian beam is not a requirement for beam focusing, strongly non-Gaussian beams simply cannot be focused into aggressively small diameters. Initial measurements yielded M-factors of around $4^5$, far too large to produce a tight sheet thickness. A pinhole at the focus plane for the Keplerian telescope was used to reject the strongly non-Gaussian beam components with the results being a more Gaussian-like beam at the exit of the telescope. The pinhole size and location were chosen such that the beam was able to focus to a size similar to that predicted by theory. Because of the ultrafast nature of these measurements, instantaneous energy intensities at the focus plane are quite high and even diamond pinholes cannot withstand repeated impact from the laser fluence. Careful alignment of the beam at low power, along with out-of-focus larger pinholes used to provide some of the beam energy rejection required (not all of the apertures are shown in the diagram) allows the pinhole to reject energy along the edge of the beam while passing the very high intensity energy spot that represents the Gaussian components of the beam. Additionally, longer focal length lenses were employed to create a shallower beam focusing. That is, a longer focal length lens produces a larger focal spot size and lower energy densities at the focal point. This allowed more flexibility in the placement of the diamond pinholes, thus extending their useful lifecycles.

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5 The $M^2$ factor, known as the beam quality factor, represents the degree of variation of a beam from an ideal Gaussian beam. It is calculated from the ratio of the beam parameter product of the beam to that of a Gaussian beam with the same wavelength.
Following the exit from the Keplerian telescopes, the beams are directed back along the optical table and pass through waveplates (not required for 355nm) and polarizers to produce horizontal polarized light for both beams. Each beam is then directed through a cylindrical lens with the beams combined on green dichroic mirror (this mirror is fully transmissive to the 355 nm beam). The beams are carefully aligned to be parallel both by being exactly horizontal in terms of the sheet profile and parallel in their propagation both vertically and side-to-side horizontally. Relative beam position in the image plane can be controlled using a translation stage on the 355 nm beam reflector; thus the pair of beams can be overlapped exactly or separated in order to control the collection volume from each beam. Beam profiles were measured by sequentially traversing a razor blade across the beam and monitoring the beam energy after the razor blade with an energy meter. The so called 90-10 test yielded beam widths of 149 µm (fwhm) for 532 nm and 126 µm (fwhm) for 355 nm (See Figure 5.3).

![Figure 5.3: Results of razor blade probe of beam diameter and alignment.](image)

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5.3 Image Processing of Dual Colors

After verifying the position and sheet thickness for the 355 and 532 nm beams, as described earlier, resolution of the separate imaging trains was quantified. A USAF 1951 test target was placed in the plane corresponding to the centerline of the injector nozzle. A quartz-halogen bulb was placed behind the target to provide illumination, with a bandpass filter inserted to selectively transmit the wavelength being imaged. Images were captured separately, with the appropriate filter in place, and the smallest three-line pair on the target (Ronchi Rulings) which could be resolved was determined. In both cases, the resolution limits were sub ten microns; group 6 element 1 (7.81 um) for 355 nm and group 6 element 3 (6.2 um) for 532 nm. Next, the targets were moved on a translation stage to positions plus and minus 250 and 500 microns from the centerline to determine our depth of focus and resolution limits (Figure 5.4). Setting 10 µm as the required minimum resolution, the depth of focus was determined to be 500 um on either side of the centerline.

Figure 5.4: Images of the USAF test target

Given that the laser beam has a Gaussian profile, in both directions orthogonal to the propagation vector, it was necessary to measure the intensity of the beam as it appears in the object plane. The measurement of the beam’s spatial profile allows intensity corrections to be made in the images to enhance features in the spray. Lower fluence levels on the sheet edge mean lower intensities at camera for identical features, this requires image correction.
Intensity profile measurements were achieved by placing a cuvette filled with a solution of water and 5µm polystyrene spheres into the object plane such that the laser sheet passed through the solution. Images of the light scattered off of the spheres in the solution were captured for each wavelength and the intensities of the pixels in the rows of the image were summed to form a column of intensity values. This column was normalized and the resulting Gaussian profiles are shown in (Figure 5.5). It was also necessary to assure that the two cameras had the same field of view and magnification, this was achieved by imaging the USAF 1951 target for the same position using each camera. One of the MYO cameras had a sensor which was mounted at a slight angle, so corrections needed to be made to the images captured with this camera. The magnification of the two optical trains were slightly different, so corrections using this method were also achieved. Measurements of corresponding pixels were made and the final images were corrected using Matlab’s\textsuperscript{6} cpselect\textsuperscript{6}, cp2tform\textsuperscript{7} and

\textsuperscript{6}Control point selection tool, a graphical interface that enables selection of control points in two related images.

\textsuperscript{7}Creates a spatial transform from the control points selected via cpselect.

Figure 5.5: Intensity profiles of the laser beam sheets.
imtransform functions. Finally, having determined the depth of focus, intensity profiles and camera correction factors, it was time to capture spray images.

The pixel intensities in the images varied widely with the physical location and time of arrival of the laser sheets after start of injection (SOI). In order to capture images which did not saturate the ccd chip on the camera, ND filters of various density were placed into the imaging train of each wavelength according to the specific need of each leg. The cameras have a 14 bit dynamic range, so the ND filters were used to keep the maximum pixel intensities below 16838 counts (dark count was typically 102). The 355nm imaging train was less sensitive to light due to the lower quantum efficiency of the ccd to photons of 355nm, the attenuation of the bandpass filter used to reject other wavelengths; and the smaller energy level in the beams (155.4 µJ for 355nm and 1.094 mJ for 532 nm). This required the use of fewer ND filters compared to the 532 imaging train which used up to four separate filters for the brightest images.

The imaging results produced by the 355nm train were stunning and revealed intricate details of the spray’s structure. However, the images formed by the 532 beam did not show as many details of the spray structure. They appeared to be blurry and washed out compared to the 355 images. The larger spray structures were visible in both images, but the fine details were absent in the 532 results (Figure 5.6). It was determined that the addition of several ND filters to the 532nm optical train was effectively shifting the location of the object plane of the imaging system. This is due to the 1.5 relative index of refraction of the glass used to make the ND filters, that is each filter added 50 percent of its thickness to the imaging side of the thin lens equation, thus effecting the location of the object plane (5.1). The value of $s_i$ is set by the position of the camera and lens system. Changes in the effective value of $s_i$ due to pathlength increase from the ND filters shifts the 'in focus' object plane forward and out of the probe beam plane.

$$\frac{1}{f} = \frac{1}{s_0} + \frac{1}{s_i} \quad (5.1)$$

$^8$Applies 2-D transform to the image.
Knowing that the depth of focus of the system only allows an offset of 500µm from centerline, a series of images of the USAF target were taken from the focus to 5mm in 1mm steps to see the effects on image quality as the object plane was moved (Figure 5.7). It became readily apparent that the quality and resolution of the images degrades rapidly as the distance between the in focus position and the object plane increases. The knowledge that many of the images captured with the 532nm pulse were seriously affected by this shift in focus, demanded some type of post-processing recovery needed to be attempted. That is, the laser sheet remained stationary but the ‘in focus’ position of the object plane shifted forward. Initial attempts to bring the images into focus were undertaken using Adobe® Photoshop’s unsharpen mask and high-pass filter effects. The results were mediocre at best and too subjective for scientific publication.

The requirement for a more rigorous method for post-processing the images led to the application of a Wiener Filter. The Wiener filter is an effective way to restore images that have been degraded by a known degradation function, but the assumption must be made that the degradation process is linear and position invariant. This filter produces a result that has the minimum mean squared error between the restored image and the original image [79]. The full expression for the Wiener filter is contained in the bracketed expression on the right hand side of equation 5.2. When noise levels are small compared to the signal, as in the case of the images in this study, the expression reduces to equation 5.3, capital letters denote Fourier transforms. Where F is the restored image G is the degraded image and H is the degradation function. So using the focused image of the target to form F and the out of focus image to form G, H can be calculated.

\[
\hat{F}(u,v) = \frac{1}{H(u,v)} \frac{|H(u,v)|^2}{|H(u,v)|^2 + S_q(u,v) / S_f(u,v)} G(u,v)
\]

\[
\hat{F}(u,v) = \frac{G(u,v)}{H(u,v)}
\]

The calculated H(u,v) was used in Matlab’s® deconvwnr function in an attempt to bring the image which is 5mm out of plane back into focus (Figure 5.8). The results are very similar
Figure 5.6: Comparison of 355nm and 532nm Image Results, image pairs are of the same spray event
Figure 5.7: Image Degradation as Target is Moved Out of the Object Plane

to the original ‘in focus’ image as can be seen in the difference image (focus-restored), with the main numerical artifacts stemming from the differences in the field of view of the two images. However, attempts to focus the damaged 532nm spray images using the Wiener filter were unfortunately not very successful (Figure 5.9). This was a complex image reconstruction problem. The fact that photons in the image were potentially coming from multiple locations in the spray due to the highly scattering nature of the spray, rendered the effort difficult. Several attempts at focusing an image by both varying the focal plane correction and the estimated noise levels proved unsuccessful. This being said, the captured 532nm images still contain valuable information and are used in their degraded state. The images contain the same information as the 355nm images just with a noted decrease in resolution due to a shift in focus.

5.3.1 Image post processing

All of the image information which ends up on an individual pixel of the sensor array emanates from voxels contained within the measurement beam sheet. Take a voxel with a
Figure 5.8: Result of Wiener Filter Restoration of Out of Focus Image

Figure 5.9: Refocus results for the Wiener filter, focus depth and noise level examples
pixel height in the image plane of $\delta_h$, a pixel width in the image plane of $\delta_w$ and a depth of $dl$. At an individual pixel, each of these voxels contained within the laser sheet has the potential to affect the number of counts present on the pixel. Take equation 5.4 where $R_\lambda$ is the camera response, $e^*_\lambda$ is the local energy intensity, $(n\frac{d\sigma}{d\Omega})$ is the number density times the cross-section average, $\Omega_\lambda$ is the collection angle, $\tau_{net}$ is the net transmission of the entire optical train (lenses, filters etc.), and the last term is the differential volume of the voxel. The properties of the media are contained in the term $n\frac{d\sigma}{d\Omega}$ while all other terms are properties of the optical system.

$$\Delta s = R_\lambda e^*_\lambda (n\frac{d\sigma}{d\Omega}) \Omega_c \tau_{net} [\delta_h \delta_w dl]$$

For each pixel it is necessary to integrate along the voxel collection path length($l$), and evaluate $e^*_\lambda$ using the measured quantities of beam width and energy and the known geometry of the beam profile. This will move the equation to $E_h$, which is the total beam energy. By integrating along the laser sheet width (the 'l' in the collection path), the equation moves from $\Delta s_{\text{pixel}}$ to $S_{\text{pixel}}$.

$$S_{\text{pixel}} = \int \Delta S_{\text{pixel}} = \int (R_\lambda \Omega_c \tau_{net}) (n\frac{d\delta}{d\Omega}) (\delta_h \delta_w) e^*_\lambda dl$$

Model $e^*_\lambda$ as the product of two Gaussians.

$$e^*_\lambda = e'_\lambda \exp(-2h'^2/\delta_h^2) \exp(-2l'^2/\delta_l^2)$$

The term $\exp(-2h'^2/\delta_h^2)$ represents the variation along the sheet height, $\delta_h$ is 13.5-86.5% height of the beam. $h' = (h - \mu_h)$. The term $\exp(-2l'^2/\delta_l^2)$ represents the variation along the sheet height, $\delta_l$ is 13.5-86.5% height of the beam. $l' = (l - \mu_l)$.

We know that:

$$E_{b,\lambda} = \int \int e^*_\lambda dwdh$$

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Therefore:

\[ E_b = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e'^{\lambda} \exp(-2h'^2/\delta_h^2) \exp(-2l'^2/\delta_l^2) dh' dl' \]  

(5.8)

But:

\[ \int_{-\infty}^{\infty} \exp(-2h'^2/\delta_h^2) = \sqrt{\frac{\pi}{2}} \]  

(5.9)

Similarly:

\[ \int_{-\infty}^{\infty} \exp(-2l'^2/\delta_l^2) = \sqrt{\frac{\pi}{2}} \]  

(5.10)

So:

\[ E_b = e'^{\lambda} \left( \frac{\pi}{2} \right) \delta_h \delta_l \]  

(5.11)

Back to \( S_{\text{pixel}} \):

\[ S_{\text{pixel}} = \int_{-\infty}^{\infty} \left( R_\lambda \Omega_c \tau_{\text{net}} \right) \left( \frac{n \, d\delta}{d\Omega} \right) \left( \delta_h \delta_l \right) \frac{2E_b}{\pi \delta_h \delta_l} \exp(-2h'^2/\delta_h^2) \exp(-2l'^2/\delta_l^2) dl \]  

(5.12)

\[ S_{\text{pixel}} = R_\lambda \Omega_c \tau_{\text{net}} \left( \frac{n \, d\delta}{d\Omega} \right) \left( \delta_h \delta_l \right) \frac{2E_b}{\pi \delta_h \delta_l} \exp(-2h'^2/\delta_h^2) \sqrt{\frac{\pi}{2} \delta_l} \]  

(5.13)

\[ S_{\text{pixel}} = R_\lambda \Omega_c \tau_{\text{net}} \left( \frac{n \, d\delta}{d\Omega} \right) \left( \delta_h \delta_l \right) \sqrt{\frac{2}{\pi} \frac{E_b}{\delta_h^2}} \exp \left( \frac{-2h'^2}{\delta_h^2} \right) \]  

(5.14)

Where \( E_b \) is the total beam energy, \( \delta_w \) and \( \delta_h \) are the standard deviations in the width and height of the beam respectively, and \( e'^{\lambda} \) is the energy intensity of the center of part of the beam. The actual values from this experiment are show in Table 5.1.

<table>
<thead>
<tr>
<th>( R_\lambda ) (%)</th>
<th>( \delta_h ) (( \mu )m/pixel)</th>
<th>( \delta_l ) (( \mu )m/pixel)</th>
<th>( \Omega ) (sr)</th>
<th>( \tau_{\text{tens}} )</th>
<th>( \tau_{\text{optics}} )</th>
<th>( \frac{1}{e'_\lambda} ) (( \mu )m)</th>
<th>( \sigma_{\text{width}} ) (( \mu )m)</th>
<th>( \sigma_{\text{height}} ) (( \mu )m)</th>
<th>( e'_\lambda ) (mJ/( \mu )m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>355 nm</td>
<td>33</td>
<td>4.995</td>
<td>5.08</td>
<td>.00516</td>
<td>.70</td>
<td>.95</td>
<td>140</td>
<td>64.89</td>
<td>3573.3</td>
</tr>
<tr>
<td>532 nm</td>
<td>77</td>
<td>5</td>
<td>5.15</td>
<td>.00604</td>
<td>.818</td>
<td>.97</td>
<td>164</td>
<td>76.01</td>
<td>5278.8</td>
</tr>
</tbody>
</table>
All the images were processed to be $n \frac{dr}{d\Omega}$ with an arbitrary scale factor added to enhance visibility but $n \frac{dr}{d\Omega}$ can be recovered if necessary. The fitted Gaussian was used to represent the Gaussian beam profile based on Figure 5.5. A comparison between an image which has simply contrast adjusted and the corresponding image processed using the above methods is presented in Figure 5.10. Notice the increased levels of detail and the ability to see the spray in both the top and bottom regions of the image.

Figure 5.10: A comparison of an unprocessed image to the same image processed using the methods outlined above.

5.4 Imaging results

Given the aforementioned issues with the images captured with the 532nm laser sheets, this results section deals with the 355nm images. Several thousand images were taken of dodecane and methyl oleate sprays with an emphasis on examining the spatial and temporal
variations within the sprays.

5.4.1 Repeatability of the imaging of sprays

The repeatability of the images captures in this study is another way of validating this technique. For each spray condition (fuel, nozzle, timing and location in the spray), three images were captured to test the repeatability of the results. Figure 5.11 shows a sampling of these images. In each of the sets of three images, there are subtle differences in the individual sprays. However, the gross features, such as spray angle and the presence of structures on the spray periphery are virtually identical. The location of features are different but are similar in size and frequency. Examining the 1.5ms images, the dark streak that passes the length of the spray is present in all three images. Additionally, the illumination from the top to the bottom of the spray is very similar.

The sprays imaged at 3.5ms after the start of injection all possess similar pixel intensities and undulating structures on the spray edges. The narrow spray cone angle is also observable in each of the three images.

5.4.2 A time scale argument

As alluded to in chapter 3, there have been arguments whether the pulse durations of the beams (11ps for 355nm, 13 ps for 532nm) are sufficiently short enough to effectively capture the finer structures within the sprays. To demonstrate the efficacy of this timescale, a series of three spray images were captured with identical temporal and spatial locations. The three images were averaged to form a composite image which would simulate the result of taking an image with a longer duration pulse(Figure 5.12). The averaged image is shown on the far right of Figure 5.12. While capturing the gross features of the spray the image lacks the details seen in the other three images. An examination of the right side of the far left image reveals structures which protrude out of the cone of the spray. In the averaged image, these features are blurred out and not distinguishable. Additionally, the second image from the left has a brightly illuminated patch which runs two-thirds of the way down it’s left side in which
Figure 5.11: Images of methyl oleate imaged on the centerline of the spray demonstrating the repeatability of the spray results.
there appears to be globules of fuel. These features are not as pronounced in the averaged image. Finally, the second image from the right has a dark region running down the right side of the spray. This feature is not present in the composite image. The lack of prominent features in the washed out composite image lends credence to the ability of the picosecond imaging system used in this study to effectively capture intricate spray structures. It is important to note that the gross features of the average image are not substantially different than the instantaneous features. However, the variability in the spray signal is much higher in each individual image.

Figure 5.12: An examination of the imaging system’s ability to capture spray structures, the three images on the left form the averaged image on the right

### 5.4.3 Search for a spray core

There are several groups of thought about the nature of the core of high pressure diesel sprays. Ranging from liquid core lengths 100 times the orifice diameter to a complete lack thereof [80–82]. In this section, images are presented which seem to refute the presence of a liquid core. As an example of what an intact liquid core would look like, examine Figure 5.13. This image shows dodecane and methly oleate injections at the spray shutoff for both the 160µm and 320µm injector nozzles. The images on the far right contains a liquid core of
hydraulic fluid which was placed on the tip of the nozzle prior to injection. The filamentary core of hydraulic fluid both shows the distinct boundary indicative of a liquid core, and the ability of the imaging system to focus on this feature and resolve it.

Figure 5.13: Cores at shutoff, dodecane and methly oleate, 160 and 320µm nozzles. Image on far right has a liquid core of hydraulic fluid which demonstrates the distinct boundary.

A series of images of sprays were captured by traversing the laser sheet through the spray at several locations around and including the center of the spray (Figure 5.14). These images were captured using the 160µm injector nozzle using dodecane as the fuel. No distinct core was visible in these images.

A separate sequence of images were gathered lowering the injection pressure from 1450 atm to 410 atm in another attempt to find evidence of a liquid core. Again there was no conclusive evidence of a liquid core(Figure 5.15). It is worth noting that this may only be the case for this size nozzle, as the internal boundary layer effects in the 160µm nozzle are pronounced(Figure 5.16).
Figure 5.14: Images of dodecane, 160µm nozzle. Laser sheet is walked through the spray looking for evidence of a liquid core. Dimensions are relative to the centerline of the spray which was determined by examining intensity values. Imaged at 532nm.

Figure 5.15: Dodecane injected at decreasing pressures yields no evidence of a liquid core. Note the appearance of ligament and breakup structures at lower pressures. Imaged at 355nm.
Figure 5.16: Manufacturer supplied nozzle flow results, nozzle #2 is the 160µm #3 is the 320µm. Notice that twice the diameter is providing 7.2 times the flow, this indicates strong boundary layer effects.

5.4.4 Examination of signal levels

In the search for a liquid core in the spray, it became apparent that signal levels associated with a liquid core and those of a distribution of small scattering objects might be similar in magnitude. As the droplets in the spray trend towards smaller diameters, there ability to scatter light orthogonally increase. There is a limit to this trend, as droplets of diameters less than ∼0.5µm tend to produce very little signal (Figure 5.17).

It is postulated here that the scattering signal scales with surface area. This makes sense in the fact that, given the same volume fraction within a voxel, a collection of smaller spheres will have a larger overall sum of surface area (see Figure 5.18). There are a range of droplet sizes for which this postulation is correct. However, as mentioned above, very small particles have very low scattering signals. This lower scattering energy overwhelms the larger total surface area of the small particles. A maximum balance of scattering energy and surface area is achieved by particles of about 0.5µm (Figure 5.19, Figure 5.20).

Near the exit of the injector, it is likely that the droplets are not perfect spheres. Regardless using the scattering response of a sphere provides insight into signal strength and scaling. Scattering from a single sphere scales as diameter to the sixth power (Rayleigh scattering) and transitions through the regions sometimes termed Mie scattering to a crude proportionality to the droplet area (this occurs around 10 microns). The signal observed is from the sum of signals form each droplet or droplet fraction in a voxel. Figure 5.18

<table>
<thead>
<tr>
<th>Date</th>
<th>Injector S/N</th>
<th>Nozzle S/N</th>
<th>Nozzle Flow (mL/min)</th>
<th>Cam Speed (RPM)</th>
<th>Rail Pressure (psi)</th>
<th>Pulsewidth (mS)</th>
<th>QTY (mm³)</th>
<th>Standard Deviation (%)</th>
</tr>
</thead>
<tbody>
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<td>DA167824C01-12811461</td>
<td>002</td>
<td>162</td>
<td>1000</td>
<td>3000</td>
<td>3</td>
<td>13.84</td>
<td>1.02</td>
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<tr>
<td>12/8/2015</td>
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<td>003</td>
<td>540</td>
<td>1000</td>
<td>3000</td>
<td>3</td>
<td>99.68</td>
<td>0.49</td>
</tr>
</tbody>
</table>
shows the surface area in a voxel as a function of volume fraction and droplet size. What is apparent is that smaller droplet sizes produce much greater surface areas at fixed volume fraction.

![Scattering Signal vs. Droplet Radius](image)

Figure 5.17: Scattering energy versus droplet diameter.

Examine Figure 5.21, this image contains both a high number of scatterers in the upper portion of the image and a single 40 µm thick ligament of liquid fuel which is several millimeters in length. The pixel intensities on the edges of both the droplets and the ligament are of similar magnitude, however when taken as a region of the image the overall signal associated with the droplets is much higher. The high intensities located on the edges of the ligament are most likely due to the incident angle upon which the laser sheet interacts with it. The laser sheet hits the ligament at the critical angle and reflects off the the fluid towards the detector; this is also seen on the back side of the ligament due to internal reflection. This image then shows that both a single structure (the ligament) and a cloud of droplets can be resolved in the same image. The ligament is approximately 40 microns in size and can
Figure 5.18: Total surface area of spheres as related to volume fraction.

Figure 5.19: Scattering energy vs volume fraction for various droplet sizes.
Figure 5.20: Total scattering energy vs droplet size for various volume fractions.

be seen in terms of its boundaries. The bright droplet cloud area of the image is of similar scale but does not indicate object boundaries.

While it is difficult to set a boundary on the droplets in the cloud, it is clear that this portion of the image: 1) each voxel has signal from many scatterers, 2) the image clearly shows the ability to see features of a 40 micron feature, 3) note that the 40 microns is larger than the 5 microns square but smaller than the 140 micron depth, 4) if large objects were present (40 microns or bigger) they would be resolved. Hence, the droplet cloud represents liquid that is not contiguous but that is substantially smaller than 40 microns.

Several images captured in this study appear to have a shadow on the edge of the spray (see Figure 5.22). This shadow indicates the presence of large numbers of small objects which have low scattering energies. In order to examine the image in more detail, the image was divided into two regions and each region was contrasted independently (see Figure 5.23.) This image enhances features on the right (incident) side of the spray; however the pixel
Figure 5.21: An image of dodecane containing both a fluid ligament and a droplet cloud.
intensity levels in the spray still indicate a cloud of very small particles.

Figure 5.22: Image of dodecane injected from a 160µm tip showing a shadow effect in the spray. The laser sheet passes from right to left.

Another important question to ask is if one can distinguish several smaller ∼5µm droplets from a larger ∼30µm droplet. Refer once again to Figure 5.12, on the left periphery of the first three images there are several larger masses of liquid which are very distinct. As one looks further to the right in the spray, it is difficult to distinguish different masses from one another. The high signal levels indicated by the the bright areas on the left edge of the spray could be the result of many larger droplets scattering from several voxels, or from many smaller particles which tend to have higher scattering energies. It is clear that 40µm objects can be seen and resolved, but only a few of these objects can fit within a single voxel. This lends credence to the argument that bright parts of the imaged spray must be the result of the large total surface areas associated with smaller particles. Stemming from that conclusion, no individual particles can be resolved in these bright regions. Thus it appears it is difficult to determine larger masses from the combined effect of several smaller masses contained in a similar volume within the spray. However, it is obvious that the distinction can be made
when particles of fluid are distinct from the cloud of droplets (Figure 5.24).

5.4.5 Effects of fuel type

The effects of different fuels on structures within the sprays were studied by injecting dodecane and methyl oleate through both 160 and 320 µm nozzles. Sequences of images were taken varying the temporal and spatial locations within the sprays. These images clearly demonstrate striking differences in the structure, width and breakup characteristics of the two fuels. Take Figure 5.25 for example, the methyl oleate exhibits a narrower spray angle, more pronounced ligamentary structure and less vapor clouds on the periphery of the sprays. Additional images of dodecane reveal a hook-like structure on the edge of the spray, a sign of mass shedding (Figure 5.26). Methly oleate also exhibits hook like structures, however they are more complex in nature and seems to contain liquid ligaments Figure 5.27. Compare these spray structures to those emanating from the 320µm nozzle (Figure 5.28, Figure 5.29). Once again it is clear that the two fuels exhibit vastly different spray behaviors. Methyl oleate sprays again contain more ligaments on the spray periphery, this may be indicative of a more
Figure 5.24: An image of methyl oleate which highlights the ability to distinguish larger objects from the cloud of particles.
violent breakup. These ligaments appear to contain intact liquid regions emanating from the edge of the spray especially in the 0.2ms images of Figure 5.28. The dodecane sprays appear to have a wave-like phenomena on the outside of the spray, and the mass shedding of a high volume region into the surrounding somewhat quiescent low volume fraction region. The more uniform illumination of the dodecane images early in the spray event also indicate the presence of smaller droplets as compared to the methyl oleate, which has varied intensity levels.

![Figure 5.25](image)

Figure 5.25: A comparison of methyl oleate and dodecane sprays. A temporal(from start of injection) and spatial(off of spray centerline) mapping of the spray structures. 160µm nozzle.

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9As usual there are ligaments and intact fluid elements in the 0.5ms and later images, as this represents the injector shutoff.
Figure 5.26: Hook-like structures on the edge of the spray cone. Dodecane, 160µm nozzle.

Figure 5.27: Hook-like structures seen on the edge of methyl oleate spray. Notice the different structure present on the narrower spray.
Figure 5.28: A spray mapping of methyl oleate from a 320µm nozzle
Figure 5.29: A spray mapping of dodecane from a 320µm nozzle
5.4.6 Discussion of the limitations of the sheet scattering approach

The introduction of this chapter presented a hypothesis that a thin laser sheet could be used to image the spray, revealing internal structures present within the core of the spray. Questions regarding the ability to produce non-corrupted images of the spray were also poised. In this section the questions will be addressed and a discussion of the limitations of this method will be presented.

The first two questions regarding the attenuation of the laser sheet and the orthogonal signal have been answered by the images captured in this study; there is plenty of signal scattered orthogonally. As to the question about the intactness of the sheet, this is a difficult one to answer. Early in the study there was some confusion as to whether the laser sheet was propagating from the right to left or vise versa. In numerous images, there was little to no signal on the right edges of the spray periphery and an abundance on the left (Figure 5.26). This seemed to indicate that laser sheet entering the spray from left to right (see Figure 5.30 image a.). This however, is caused by the thin laser sheet scattering off of the droplets and ligaments within the spray and forming a cloud of photons which have been multiply scattered. The presence of objects which are on the left side of the image, not attached to the main body of the spray, which are clearly illuminated indicate that the sheet is still intact and coherent albeit with lower energy density. Now consider image b, this is a less optically dense spray than image a. The illumination of this spray is more uniform and there is evidence of the laser sheet impacting the tip of the injector on the right side. There are also clearly defined objects to the left of the spray, indicating an intact laser sheet. Finally examine image c, this is an image of the end of the spray where the liquid velocity is lower and the laser sheet experiences less scattering. This image clearly lends credence to the idea that the laser sheet does stay intact throughout the spray structure. This image also demonstrates the illumination of the injector on the right side.

The sheet appears to remain intact with varying levels of intensity as it interacts with the spray’s structure. However, the large amount of forward scattered and multiply scattered...
photons that are produced as the sheet traverses the spray makes it difficult to make a clear distinction as to the geometries of these structures, increasingly so as the sheet propagates farther into the spray. Laser sheets which are directed towards less optically dense portions of the spray, and those whose orthogonally scattered photons are not obscured by dense regions along their paths create tangible images of the spray structure. This is a limitation of this imaging method, in that the region of the spray that can yield quality images of structures is contained in the half of the spray closest to the gathering optics. Images captured when the laser sheet is farther away than the centerline of the spray are hindered by further photon interactions with the spray structures they must traverse to arrive at the image plane. This phenomena is quantitatively presented in Figure 5.31.\footnote{This figure was created by summing the total pixel counts in four of the raw images at different sheet positions in the spray and presenting the normalized averages.} As one walks outwards from the centerline of the spray, the images contain more photon counts until a maximum is reached as the result of a balance between scattering particles and attenuation from the spray itself.\footnote{The data for positions 0, 0.5, 1.0 and 2.0 mm are derived from the dodecane images contained in Figure 5.25.}

\subsection*{5.5 Future work}

The logical continuation of this work is to capture temporally spaced images of the same spray. With time separated images of spray structures, estimates of the Weber number of the structures in the spray can be generated. This would shed light on the stability of the
Figure 5.31: Summation of pixel counts versus location of laser sheet in the spray. Negative positions are past the centerline of the spray.

structures as well as the velocity and motion implied by the time delay. The difficulty with creating a time-delay in one of the wavelengths is that the delay requires the beam to pass across the lab for several meters. This is problematic as the laser beams are divergent. In order to control the divergence of the Gaussian beam profile, two pairs of lenses must be placed into the optical train of the beam being delayed. The first lens pair will act as a beam expander to expand the beam’s waist to allow the Rayleigh range of the beam to be sufficient to traverse the desired distance. A second lens pair is used in reverse to contract the beam size to half of the original waist diameter. This reversed expander allows the entire beam to fit within the field of view of the camera (3mm). This allows for better imaging, uses more of the light in the beam, and protects the tip of the injector from being ablated via the intensity of the beam sheet.
5.6 Conclusion

Presented here are a list of accomplishments and milestones from the elastic scattering study. This study was more successful than expected especially considering the optical depths of the sprays and the predominance of forward scattering light from droplets larger than 10 microns.

- As observed via Ballistic Imaging, Methyl oleate demonstrates a richer mixing structure than dodecane
- Images strongly suggest the near field region of the spray is comprised of particles of diameters smaller than 40µm
- Sprays emanating from the 320µm nozzle display markedly different spray behaviors than their 160µm counterparts, especially Methyl Oleate
- These sprays are inhomogeneous with regions which favor the production of NO\textsubscript{x} and regions of large fuel particles which will not fully combust producing soot particles
- The images give no indication of a intact liquid core
- The higher energy levels, quantum efficiency of the chip and transmission of the optics for 532nm introduced the need for the addition of neutral density filters. This resulted in the shifting of the narrow focal depth out of the intended region of the spray.
- The results are repeatable as demonstrated in Figure 5.11. This holds for both fuels and nozzle diameters.
This investigation was undertaken to probe spray behavior in the near nozzle region of diesel injectors. Two techniques were developed and employed to image this region of the spray; pulse-sliced ballistic imaging and two planar elastic scattering. It is important to note that many times diagnostic techniques are developed that do not yield tangible or important results. That is not the case with these two methods. On the contrary, the images captured by applying these diagnostics to sprays shed light on the physical breakup mechanisms of the fuels. In the next few paragraphs, highlights and results of this study will be presented for the interested reader.

6.1 Ballistic imaging

Pulse sliced ballistic imaging was developed at Colorado School of Mines for the purpose of imaging the near field region of fuel sprays. The method was characterized and applied to capture the first images of diesel fuel surrogates at temperatures and pressures encountered in a diesel engine. These images revealed trends in fuel breakup which varied with temperature and pressure. Additionally, ligamented structures were captured on the periphery of dodecane sprays at elevated temperature. These striking features were subsequently predicted by the modeling community; adding validity to both this work and the work of the Sirignano group.

Ballistic imaging is a line integrated technique that creates an 'map'of extinction. The ballistic part allows the formation of an image which shows the local transmission through the spray of light; this is a map of the removal of light by scattering and therefore shows regions of high and low fuel concentration. The move to scattering is to provide spatial resolution in an image instead of a line integrated image. In addition, the idea is that scattering will
allow more to be said about spray break up: are regions of high fuel concentration liquid structures or are they high volume fraction regions of smaller droplets.

Looking forward, picosecond ballistic imaging could be applied to sprays in even harsher environments. Modern diesel engines, which employ common-rail injectors, introduce fuel into the combustion chamber at pressures of 200 bar or more. This fuel is injected into an environment of up to 140 Bar and 1300K. It would be interesting and instructive to determine if the trends in fuel behavior seen in this study applied to these environmental conditions. Would the shedding features continue to occur closer to the injector tip as pressures are increased, or would altogether new behaviors be observed.

6.2 Two planar elastic scattering

The image results from the two planar elastic scattering study were better than expected. Images captured at 355nm display stunning features both on the spray periphery and within the spray itself. The ability to traverse the body of the spray by offsetting the injector’s position with regards to the laser sheet also allowed probing of the spray’s three dimensional structure. The results also reinforce the results from the ballistic imaging campaign, as they show similar features in the sprays.

Comparison of the images of dodecane and methyl oleate showed definitively that the fuels’ breakup behaviors are vastly different. Dodecane appears to atomize within the nozzle of the 160 \( \mu \)m tip, whereas methly oleate undergoes a violent mixing from areas of high volume fractions of fuel to low volume fractions located on the edges of the spray. For dodecane, the scattering results indicate that the features seen in both scattering and ballistic images are regions of high volume fraction with relatively small droplets mixing into low volume fraction regions. We know that sprays surrounding air near the spray base. The images show that along with this entrainment is a mixing of the high volume fraction, presumably high velocity regions with the surrounding low volume fraction, low velocity region. In short, this is mixing of a high speed jet of air and droplets with the nearly quiescent surroundings. For methyl oleate, the scattering images are consistent with at least some of the liquid still being intact.
and not in the form of small droplets. Regardless, we saw no evidence of a classic liquid core attached to the base of the injector. The methyl oleate show a spray that is breaking up very differently, with both break up to droplets and mixing occurring in the same region. The fuel property that drives this difference in fuel behavior has not been identified. However, from an engine design and control perspective, this will clearly provide challenges to in-cylinder emission control. Additionally, although the ability to image contiguous liquid elements with this technique was demonstrated, the study revealed no presence of a liquid core in either fuel and from either nozzle (160 and 320 µm).

All of the scattering results show a strong amount of non-uniformity in the spray interior. This non-uniformity is not an even gradient of fuel concentration that grows toward the spray centerline but rather shows regions of high concentration that move in time and space through the spray. It is clear that the spray will produce regions of high and low fuel concentration in an uneven fashion which further challenges in-cylinder combustion control.

Moving forward, temporally separating the beam sheets to capture the development of spray structures would provide data about the velocities and accelerations involved with the mixing structures. This would also yield estimations of Weber numbers and the lifetimes of the observed features. Adapting the hardware involved to work with the CSM pressure vessel would allow elastic scattering images to be captured at conditions previously studied during the ballistic imaging campaign. This would augment the data about the sprays and could potentially reveal structures which are not visible via line integrated methods.

As with ballistic imaging, this technique could be applied to the higher pressure and temperature environments typical of a modern diesel engine.
REFERENCES CITED


[52] Derek Dunn-Rankin, Ali Ziaee, John Garman, Wytze van der Veer, Jim Trolinger, Ben Buckner, and Ivan Tomov. Electronic Imaging & Signal Processing Time-gated holography to provide a glimpse into dense sprays.


APPENDIX A - LASER OPERATION AND THEORY OF OPERATION

The Continuum® Leopard D-10 used in this study is unique in the laser world as it uses several technologies to achieve picosecond pulses. This appendix is dedicated to giving a brief overview of the laser’s operating theory and an overview of the physical operation of the laser.

A.1 Theory of Operation

The Leopard D-10 is a saturable absorber based laser. The majority of lasers are based on the use of a resonant cavity. The leopard is no different, however it makes use of unique technologies to produce 15 picosecond native 1064nm pulses. The Leopard picosecond laser is a cavity dumped active/passive modelocked system. The oscillator is based on a resonator design using intra-cavity spatial filtering and large mode volume. The oscillator cavity employs the same mode locking used in standard TEM00 oscillators but with the addition of cavity dumping. Cavity dumping is an effective technique which results in high pulse energy. Cavity dumping is achieved via the use of a Marx board driven Pockels cell which is triggered by a photodiode.

When the lamps are fired, lasing begins in the cavity and the Acousto-optic modelocker forms a pulse. This pulse circulates in the cavity of the laser gaining in energy and being shorted by the saturable absorber(dye) with each pass. The dye absorbs the photons in the pulse as it traverses the oscillator and only the peak of the Gaussian pulse is able to bleach the dye and pass back into the oscillator cavity. This trims off the edges of the pulse, effectively shortening the pulse. The pulse is also shorted by the use of a GaAs wafer as a passive-negative feedback element. When the pulse train has achieved a high enough energy level, the GaAs wafer asserts its two photon absorption process and further trims off the end of the pulse. As the duration of the pulse lessens, the energy density of the pulse is able to trigger the GaAs wafer with less critical intensity. At this point, the pulse has dropped to
minimum width which is determined by gain bandwidth and dispersion. The energy level in the pulse is maximized and a single pulse in the stable region of the pulse train is picked off and cavity dumped out of the oscillator. The process of cavity dumping results in a lower pulse energy leaving the oscillator and requires the pulse to be passed twice through the amplifier rod to achieve high overall pulse energy.

The 1064nm pulse which exits the amplifier can be passed through a doubling crystal to form 532nm, or through two crystals to form 266 or 355nm outputs. This lends the user greater flexibility for optical diagnostics.

A.2 Operation and basic maintenance

This section will give insight on how to run the laser and do basic preventative maintenance.

A.2.1 Turning the laser on

Following the proper procedure for turning on the laser is essential for trouble free operation. Start by turning on the Thermo Fischer® chiller by flipping the switch to the on position and pressing the red button. Check that the temperature is set to 16°C. Let the chiller run for 20 minutes and then grab the lines which run to the wall chiller water supply. They should be cold to the touch, if not investigate why and make the necessary repairs before proceeding.

Now turn on the dye pump and make sure that the flow is laminar and that there are no bubble in the lines. Turn on the main power to the laser, followed by the power to the oscillator and amplifier. Wait five minute to allow the system to reach a thermal equilibrium, then turn the key to the run position and again wait for five more minutes. Locate the control box and press the auto/manual button so that auto is displayed on the controller. Press select until program 2 is displayed, now press activate. When you are wearing the appropriate safety equipment, press start to activate the flashlamps. Let the laser run for about 5 minutes and then press the shutter button to begin lasing. Leave the
shutters closed and let the laser run for twenty minutes before performing any experiments to allow the cavity to achieve thermal equilibrium.

A.2.2 Turning laser off

Press stop on the controller box. Then turn the key to off and turn off the dye pump. Shut off the power to the amplifier, oscillator and finally the main power. Wait for at least 10 minutes before turning off the chiller to allow the laser heads to cool down.

A.2.3 Changing the dye

You will need the following

- Patience, lots of it
- 1,2 dichloroethane (1,2 DICE) Sigma-Aldrich 284505 (This is really nasty stuff use maximum precautions when using it)
- Cole-Palmer syringe filter 02915-08 0.20 micron
- Q-switch 1 saturable absorber
- Aluminum oxide, basic, activated Sigma-Aldrich 199433
- Glass syringe
- Small beaker 100ml
- Stainless steel stirring stick
- Stainless steel small scooper
- Non reactive paper (shiny white paper tends to work well)
- Glass storage vessels with screw on lids. One for the dye mix and one for the 1,2 DICE
- Viton gloves
- Nitrile gloves to wear under the viton gloves
- Safety glasses
- Lab coat
- Fume hood
- Respirator (Very important)
- Accurate scale able to measure milligrams

Before beginning the process make sure that the appropriate safety equipment is being worn, and that the chemicals are in a functioning fume hood. Begin by filling a straight walled beaker 2/3 full with the aluminum oxide. Then pour the 1,2 DICE into the beaker until it is almost full. Using the stainless steel stirring stick stir the mixture making sure to expel the trapped bubbles of air. Then fill the beaker again and stir to mix thoroughly. Cover the beaker and let it sit for twenty minutes. Carefully pour the 1,2 DICE from the beaker into the ceramic bowl making sure to limit the amount of aluminum oxide that transfers to the bowl. Attach a syringe filter to the glass syringe and submerge the filter into the bowl.

Now using both hands, begin to draw the 1,2 DICE into the syringe. This is a tedious and time consuming task which is best accomplished by drawing a vacuum inside the syringe and letting the fluid to slowly pass through the filter. Pulling about 5ml of vacuum on the syringe seems to be the sweet spot for maximum transfer. Also don’t fill the syringe more than about 50 percent as the syringe will leak outside air past the seals. Remove the filter and transfer the 1,2 DICE into a clean container with a lid. Repeat the filtration process until all the 1,2 DICE is filtered. Repeat the aluminum oxide soak and filtration process until you have 150ml of 1,2 DICE. As mentioned before, this is a tedious task that is necessary for proper laser operation and no shortcuts should be taken. The aluminum oxide soaking is necessary to remove an impurity in the 1,2 DICE which absorbs photons at 1064nm, the first harmonic of the laser.
A.2.4 Mixing the dye

Using an accurate scale, measure 8-10 mg of Q-switch 1 onto the shiny white paper. Then transfer the dye to a container filled with 25 ml of filtered 1,2 DICE. Mix the solution well with a stainless steel stirring stick then cover and let sit for at least 20 minutes to assure the dye is completely dissolved into the 1,2 DICE.

A.2.5 Flushing out the old dye

This operation is going to be conducted outside of the fume hood so safety equipment should include at a minimum; Lab coat, glasses, viton gloves, a respirator, a near by fire extinguisher and another person present in the lab in case of mishap. Now, turn off the dye pump and disconnect the tubing where it enters the bottom of the optical dye cell. Use the 1/2 and 9/16 wrenches that have been ground down to fit in the laser cavity, making sure that the Swagelock® fitting attached to the cell does not rotate. This will prevent damage to the thread sealant and the cell. Carefully pull the tube out of the laser cavity and place the end into a glass container, you will have to hold it in your hand. Turn on the pump and let the used dye flow into the container. Let the pump run until the dye stops flowing out then turn it off.

Reattach the tubing to the dye cell and using the glass syringe fill the reservoir with 35 ml of filtered 1,2 DICE. Turn on the pump and let run for twenty minutes after the flow has been re-established in the tubing. This may take a couple of minutes for the pump to re-prime itself. Sometimes you must loosen the cap on the reservoir to initiate the prime. Repeat the draining procedure and refill run and drain again.

Periodically, it may be necessary to change the filter element in the in-line filter. This will be evident if the flow in the tubing is slow. Use a 9/16” and 3/4” wrenches to remove the filter housing and take the filter housing to the fume hood and using a second 3/4” wrench take the housing apart. Remove and replace the filter element with another 7 micron Swagelock® element(SS-4F-K4-7). A 15 micron filter may also be used if there is an immediate need(SS-
Make sure that the filter housing is reinstalled with the flow direction arrow pointed in the correct direction.

### A.2.6 New dye

After completing the two flushes of the dye system, using a clean glass syringe, fill the reservoir with 35 ml 1,2 DICE. Now add 7ml of the freshly mixed dye solution. Connect a BNC cable to the photodiode mounted by the prism in the laser cavity. If for some reason the detector is missing, use a DET 210 with a 1064nm bandpass filter. Turn on the laser see (A.2.1), open the shutter and disconnect the bnc going into the "trig out" of the high voltage detector mounted closest to the dye cell. Using the HP oscilloscope on the 50 ohm setting and with a 50 nanosecond horizontal scale, find the trace. Adjust the dye concentration a drop or two at a time, waiting 5 minutes between doses, until the flat section of the trace is about 200-250 nm long. There is a peak in the trace followed by a fairly flat section in the trace, only measure from the beginning of the flat section when determining the length of the train. The trace is made up of several little peaks that form an outline similar to the outline of a horse, the head being the initial peak followed by the "back" of the horse, the part to be measured.

Reconnect the BNC cable to the "trig out" and place a diffusing power meter at the 532nm exit port of the laser. If the dye concentration is right you should see at least 13 mJ per pulse with a standard deviation of about 5%. A properly tuned laser will output 16mJ or more per pulse. If the laser is dropping pulses add a couple of ml of filtered 1,2 DICE and re-examine the traces as explained above. Leaving the "trig out" connected, switch the oscilloscope to 1 megaohm and find the pulse train it should contain one sharp uptick, too much dye will cause there to be two sharp upticks and insufficient dye will exhibit none at all just a smooth trace.
A.2.7 Swapping the flashlamps

Every twenty million shots, it is imperative to replace the flashlamps. Failure to do so will result in catastrophic failure of the laser heads. Keep track of the shot count using the laser log book.

Turn off the laser and unplug the main power cord from the wall. Wait fifteen minutes before proceeding to allow the large capacitors which fire the flashlamps to fully discharge. Disconnect the leads from the temperature sensors on the top of the laser head to be serviced. Be careful as they are fragile and are expensive to replace. Now disconnect the white leads that attach to the ends of the flashlamp, making sure to note the orientation of the leads. Now find the large black thumb-wheel on the base of the laser head. Turn the wheel to disconnect the head from the body of the laser. Carefully remove the laser head being aware that water will now leak from the head as it is removed. Place the head on a clean surface and unscrew the allen head bolts which hold on the plastic retainers. Lay the parts out so it is easy to re-assemble the head later on, watch for small parts. Now in one motion, push the flashlamp out of the laser head. Keep tabs on the o-rings and plastic backing washers. Now in the same manner push the new flashlamp into the head, making sure that the protrusion on both sides are the same. Reinstall the o-rings and plastic backing washers, and then put the plastic covers back on and screw in the allen bolts.

Place the head back into the laser making sure the o-rings on the laser body are intact prior to screwing the head back in. Reconnect the leads to the lamp and the temperature sensor. Turn the laser back on check the water level on the bottom of the laser power supply, and fill with DI water if needed.

The amplifier uses two lamps, but the procedure id the same. Just make sure to note the orientation of the lamps and the layout of the connectors.

Oscillator uses part: 203-0019. Amplifier uses 2x part: 203-0032

There is always the option of calling Continuum® support at 1877.272.7783. Cliff is the resident Leopard laser expert, but others can help with simple maintenance.
APPENDIX B - PIC CODES

This is the code which operates the delay box which enables the synchronization of the injector, camera and laser pulse.

B.1 The code for the p16f873

; TYLER.ASM operates the timing control for a Sturman Injector.
; The injector control is a 32 byte command string, terminated with a ?
; The injector is to be synchronized with a laser flash. The laser
; sends a 10 Hz clock to this timer. The timer waits for a clock pulse
; and then re-transmits the command string, so that the command is
; synchronized with the clock. There is a variable delay between the
; laser clock and the re-transmission of the command string.
; After the command is delivered, there is a trigger pulse is output.
; The pulse is delayed by an external circuit and triggers a camera
; 16 MHz oscillator. Use timer 0, prescaled by 16 for timeouts.
; tmr0 rollover = 1.204mS, t0lo rollover = 0.262sec, t0hi rollover = 67sec
; Timer 1 is used for input capture on ccp2. Prescale timer 1 x8 = 2 uS/count
; Timer 1 is also used for output compare on ccp1.
; Timer 2 is not used.
; RS232 params: 19.2k Baud, 1 start, 2 stop bit.
; Operation sequence:
; 1 - wait for RX232 command with 30 second timeout (t0hi=0x72) for 32 chars
; and 4mSec timeout for one char.
; a. fill data table in RAM with 32 bytes
; b. check that last byte is a ?
; 2 - wait for input capture of 10 Hz clock on CCP2
; 3 - setup CCP1, output compare, to deliver the trigger pulse
; 3 - wait a variable length of time determined by oper setting on pot.
; 3 - deliver RX232 command to injector: 32 char @ 18.2kbaud
; 4 - output the camera pulse 100uS before the next laser pulse, using ccp1
; 5 - signal success

; Use the LED’s to signal improper operation

; 1 - Green led = waiting for RS232 command input
; a. timeout -> green led off, red led on for 0.1 sec (t0lo=0x64)
; Return to step 1.
; b. legal string received -> green led off, goto step 2.

; 2 - Tellow LED = waiting for 10 Hz sync pulse with 1 sec timeout.
; a. timeout -> yellow led off, red led on for 0.1 sec.
; Return to step 1.
; b. pulse recognized -> yellow led off, goto step 3.

; 3 - all three led’s on for one second

include <p16f873.inc> ; processor specific variable definitions
list p=16f873 ; list directive to define processor
CONFIG CP OFF WD TOFF BODEN ON PWRTE ON HS OSC
WRT ENABLE OFF LVP OFF CPD 0

; constants used in the program
define trighi 0xaf ; trigger delay time = 45,000 tmr1 counts = 900uS
define triglo 0xc8 ; time - low byte

; note: the camera trigger output compate time is the sum on the ccp2 input compare
; time + ttx + tpot. It will be within +/- 2mSec of the end of the transmit string
; This time should have a hitter of +/- 2 uS when compared to the laser clock.

; pin definitions
; port a is not used
; port b has bit 0 for a test pin output
; spare porta 0..5
define tstpin portb,0 ; test pin - output
; spare portb,1
define red portb,2 ; red led
define grn portb,3 ; green led
define yel portb,4
; spare portb,5..7
; spare portc,0
define clk portc,1 ; 10 Hz clock on CCP2
define pulse portc,2 ; output pulse on CCP1
; spare portc,3..5
define tx portc,6 ; command output to injector
define rx portc,7 ; command input
; RAM data area
cblock 0x0020
wtmp ; 0x20 context storage - working reg
stmp ; 0x21 - status reg
ftmp ; 0x22 - fsr reg
flg ; 0x23 gen’l purpose flag
lpcnt ; 0x24 gen’l purpose loop counter
temp ; 0x25 gen’l purpose temp var
t0lo ; 0x26 timer 0 rollover count lo byte
t0hi ; 0x27 hi byte
capflg ; 0x28 input capture flag for 1kHz
cmdflg ; 0x29 rs232 cmd flag
pulflg ; 0x2a output compare flag for output pulse
index ; 0x2b array index in cmd string
tclk ; 0x2c ccp2 capture time in 1mS units
volt ; 0x2d a/d result
tpot ; 0x2e oper delay time 0..64 mSec
rxflg ; 0x2f rx intr sets flag when char rec'd
rxch ; 0x30 rs inr saves char here
tend ; 0x31 end time for timeouts
tclkhi ; 0x32 ccp2 capture time using tmr 1 - hi byte
tclklo ; 0x33 ccp2 capture time using tmr 1 - lo byte
cmdstr:0x28 ; 0x34..0x43 40 char array of command characters
endc
; interrupt service
ORG 0x000 ; processor reset vector
clrf rp0 ; bank 0
clrf pclath ;
goto init ; go to initialization
ORG 0x004 ; interrupt vector location
movwf wtmp ; save w reg
movf status,w ; move status reg into w reg
movwf stmp ; save status register
movf fsr,w
movwf ftmp
poll bt&sc intcon,t0if ; check timer 0 intr
goto tmr0i
bt&sc pir2,ccp2if ; check input capture - 10 Hz clock
goto ccp2i
bt&sc pir1,ccp1if ; check output compare - trigger
goto ccp1i
btfsc pir1,rcif ; check rs232 rcvr
goto rxi
movf ftmp,w ; restore f reg
movwf fsr
movf stmp,w ; restore s reg
movwf status
swapf wtmp,f ; restore w reg
swapf wtmp,w
retfie ; return from interrupe
; hardware input/output initialization
init movlw trisa ; hsr->trisa
movwf fsr ;
movlw 0x3f
movwf indf ; porta digital all input
movlw adcon1 ; fsr->adcon1
movwf fsr
movlw 0x0e ; porta,0 analog input
movwf indf ; porta,1..5 digital output
movlw 0x81 ; a/d is on, use osc/32 clock
movwf adcon0 ; use chan 0 only
movlw trisb ; fsr->trisb
movwf fsr
clrf indf ; all output
movlw trisc ; fsr->trisc
movwf fsr
movlw 0xc2 ; portc 1,6,7 input, 0,2..5 output
movwf indf

; enable rs232 transmitter - not an interrupt
bsf rcsta, spen ; enable serial system
movlw spbrg ; fsr->baud rate gen
movwf fsr
movlw 0x0c ; setup baud rate for rx and tx
movwf indf ; @ 19.2kbaud movlw txsta ; fsr->tx status
movwf fsr
bsf indf, txen ; enable transmitter

; interrupt setup: timer 0 rollover
movlw option, eg ; fsroption
movwf fsr
movlw 0x03 ; prescape x16
movwf indf
bsf intcon, t0ie ; enable timer o intr

; interrupt setup: enable timer 1 for ccp1 and ccp2. prescale x8 = 2 uS
movlw 0x31 ; x8 prescale, timer 1 is on
movwf t1con

; interrupt setup: output compare in ccp1

; The time is set in sub = pulsout and the control is set to go high.
; CCP1 sets itself to go low on the next intr, within the service routine.
movlw 0x09 ; setup to go low on compare
movwf ccp1con
movlw pie1 ; fst->pir1
movwf fsr
bsf indf, ccp1ie ; enable ccp1 interrupt

; interrupt setup: input capture in ccp2
; intr enabled in clkwait sub
movlw 0x05 ; input capture on rising edge
movwf ccp2con ; enable input capture
; interrupt setup: rs232 receiver
bsf rcsta,cren ; enable receiver
movlw pie1 ; fsr->pie1
movwf fsr
bsf indf,rcie ; enable intr.
bsf rcsta,cren ; enable continuous rx
; enable interrupts
bsf intcon,peie ; enable peripheral interrupts
bsf intcon,gie ; gen’l enable
; program variable and port initialization
clrf porta
clrf portb
clrf portc
movlw 0x0a ; 10 mSec delay
movwf tpot
; DEBUG - put sub-routine calls here for testing
clrf tmr1l
clrf tmr1h
; main routine
main clrf cmdflg ; clear cmd flag
call getcmd ; get command
btfsb cmdflg,0 ; test command flag: 1=cmd rec’d
goto main0 ; skip if error, else goto 0
call err ; light red led
goto main ; loop back if no command

; got command
main0 clrf cmdflg ; clear cmd flag
call getv ; read pot
clr capflg ; clear ccp2 flag
call clkwait ; wait for 10 Hz clock
btfsc capflg,0 ; test input capture flag 1=succes
goto main1 ; skip if error, else goto 1
call err ; light red led
goto main ; loop back if no clock

; got clock
main1 clrf capflg ; clear 10 Hz flag
call pulsout ; setup the trigger pulse
call txdly
call txcmd ; transmit command
call demo ; demonstrate success with 3 led’s on
goto main

; subroutine reads the pot and calculates injector delay time
getv bsf adcon0,godone ; start conversion, ch 0
btfsc adcon0,godone ; wait for conversion
goto -1
movf adresh,w ; fetch 8 bits of result
movwf volt ; save to volt
bcf status,c ; clear carry
rrf volt,f ; divide volt by 4
bcf status,c ; clear carry
rrf volt,w ; move to w
movwf tpot ; save to tpot = 0..64 mSec

return

; subroutine waits for rs232 command with 10 second timeout for 32 char
; Exit with error for 10 sec timeout; return with cmdflg,0 = 1 if success
getcmd bsf grn ; green led is on
movf t0hi,w ; fetch t0hi - 10 sec timeout
addlw 0x26 ; w = t0hi + 10 sec
movwf tend ; save end time
clrf cmdflg ; clear the flag
; clear serial receiver
movf rcreg,w ; empty rx reg
movf rcreg,w ; and rx shift register
bcf pir1,rcif ; clear rx intr flag
; reset array and index

gtc0 movlw 0x21 ; 32 byte cmd string
movwf lpcnt ; use lpcnt to count chars
clrf index ; zero index
; check receiver

gtc1 btfsc rxflg,0 ; chk for rx intr flag
goto gtc3 ; goto 1 if flag
; check 30 sec timeout

gtc2 movf tend,w ; check 10 sec timeout
subwf t0hi,w ; w = t0hi - end time
btfss status,z ; check t0hi = end time
goto gtc1 ; goto 1 if no timeout

goto gtc4 ; exit if timeout
; char rec’d: save to cmdstr array, update index loop count
gtcm3 bcf rxflg,0 ; clear rcvr intr flag
movlw cmdstr ; w->array base
addwf index,w ; w->char address
movwf fsr ; fsr->char addr
movf rxch,w ; fetch rx char
movwf indf ; save to array
inwf index,f ; next addr
decfsz lpcnt,f ; count chars
goto gtcm1 ; repeat
; success - set flag, grn led off and exit
bsf cmdflg,0 ; set flag
; failure - grn led off and exit
gtcm4 bcf grn
return
; subroutine waits for 10 Hz clock with 1 second timeout
; success: returns with capflg set in the ccp3 intr service.
; yellow led on at entry and off at return
clkwait bsf yel ; turn on yellow led
movlw 0x04 ; 1 sec = 4 count
addwf t0hi,w ; w = t0hi + 1 sec
movwf tend ; load end time
clrf capflg ; clear capture int flag
bcf pir2,ccp2if ; clear intr flag
movlw pie2 ; fsr-> pie2
movwf fsr
bsf indf,ccp2ie ; enable input capture intr
cw0 btfsc capflg,0 ; check for input capture
goto cw1 ; goto 1 if flag

movf tend,w ; fetch timeout end time

subwf t0hi,w ; w = t0hi - end time

btfss status,z ; check t0hi = tend

goto cw0 ; loop back to 0 if no timeout

goto cw2 ; goto 2 if timeout

; success - save data and exit

cw1 movf t0lo,w ; fetch t0lo @ capture time

movwf tclk ; save to tclk

movf ccpr2h,w ; fetch capture time hi byte

movwf tclkhi ; save to tclkhi

movf ccpr2l,w ; fetch capture time lo byte

movwf tclklo ; save to tclklo

; exit yellow led off, ccp2 capture intr disabled

cw2 bcf yel ; yellow led off

movlw pie2 ; fsr-> pie2

movwf fsr

bcf indf,ccp2ie ; disable input capture intr

return

; subroutine sets up ccp1 output compare to go high 900us later

pulsout movf tclklo,w ; fetch low byte of capture time

addlw triglo ; add low byte of 900us delay

btfsc status,c ; check for carry

incf tclkhi,f ; incr high byte of capture time

movwf ccpr1l ; save w to low byte of compare time

movf tclkhi,w ; fetch high byte of capture time

addlw trighi ; add high byte of 900us delay
movwf ccpr1h ; save sum to high byte of compare time
movlw 0x08 ; setup CCP1 output compare
movwf CCP1CON ; to go high
return

; subroutine uses the pot voltage result to delay the transmit routine
txdly movf TCLK, w ; fetch capture time in T0LO units = 1ms/count
addwf TPOT, w ; w = laser pulse time + pot delay time
movwf TEND ; save sum to end time
movf T0LO, w ; fetch T0LO
subwf TEND, w ; w = T0LO - TEND
btfss STATUS, Z ; check T0LO = TEND
goto -3
return

; subroutine transmits the 32 characters in the command array
txcmd movlw 0x21 ; 32 chars in array
movwf LPCNT ; use LPCNT to end trans
clr index ; index starts at char 0 of array
txc1 movlw CMDSTR ; FSR->base of array
addwf INDEX, w ; w=address of char
movwf FSR ; FSR->CMD char
movf INDF, w ; fetch char
movwf TXREG ; start transmit
nop ; TXIF set when char->TSR
btfss PIR1, TXIF ; CLR when TXREG loaded
goto -2 incf INDEX, f ; next char
decfsz LPCNT, f ; check end of string
goto TXC1
return

; subroutine demonstrates success with all 3 led’s on for 0.1 sec
demo movlw 0x1c ; red, grn, yel are on
movwf portb

clrft0lo ; clear timer 0 lo byte
movlw 0x64 ; 0.1sec
subwf t0lo,w ; w = t0hi - 100ms
btfss status,c ; check for borrow
goto -3

clrftportb ; led’s are off
return

; subroutine lights red led for 0.1 second. Yel Grn are turned off.
err bcf yel ; yel grn off
bcf grn
bsf red ; red led on
movf t0lo,w ; fetch t0lo
addlw 0x64 ; w = t0lo + 100ms
movwf tend ; save to end time
movf t0lo,w ; fetch t0lo
subwf tend,w ; w = t0lo - end time
btfss status,z ; check t0lo = tend
goto −3
bcf red ; red led off
return

; stpbit sub-routine waits for 52uS to generate a stop bit
stpbit movf tmr0,w ; fetch start time - 4uS/count
addlw 0x0d ; add 52uS
movwf tend ; save to end time
movf tmr0,w ; fetch timer 0
subwf tend,w ; w = tmr0 - end time
btfss status,z ; check tmr0 = end time
goto -3 return
; interrupe service routines
; timer 0 intr maintains t0hi, t0lo, trx
tmr0i bcf intcon,t0if ; clear interrupt flag
movlw 0x01 ; incf t0lo - need to chk carry
addwf t0lo,f
btfsc status,c ; check for carry
incf t0hi,f ; incr hi byte
goto poll
; CCP2 is input capture for the 10 Hz clock on c1
ccp2i bcf pir2,ccp2if ; clear intr flag
bsf capflg,0 ; set capture flag
goto poll
; CCP1 is output compare to generate the camera trigger
; Within the interrupt service routine:
; 1- the control byte is set to go low on the next execution
; 2- THe time is set 100uS in the future.
ccp1i bcf pir1,ccp1if ; clear intr flag
movf ccpr1l,w ; fetch current time, low byte
addlw 0x64 ; add 200uS @ 2uS per timer 1 count
btfsc status,c ; check for carry
incf ccpr1h,f ; if carry, incr compare time hi byte
movwf ccpr1l ; save w to compare time lo byte
movlw 0x09 ; go low on compare
movwf CCP1CON

goto poll

; rs232 receiver service sets rxflg and saves current char to rxch
rxi movf RCREG,w ; fetch rec’d char
movwf RXCH ; save to RX CH
bsf RXFLG,0 ; set flag
bcf PIR1,RCIF ; clear intr flag

goto poll

END ; directive ‘end of program’