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### ► To cite this version:

Harsh Purwar, Hongjie Wang, Mincheng Tang, Saïd Idlahcen, Ammar Hideur, et al.. Development of picosecond fiber laser for high repetition diesel spray imaging. 13th International Conference on Liquid Atomization and Spray Systems, National Cheng Kung University, Aug 2015, Tainan, Taiwan. hal-01259344

**HAL Id: hal-01259344**

**<https://hal.science/hal-01259344>**

Submitted on 20 Jan 2016

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## Development of Picosecond Fiber Laser for High Repetition Diesel Spray Imaging

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### Abstract

Today's diesel injectors operate at very high injection pressures of about 2000 bar resulting in injection velocities as high as 700 m/s in the near nozzle region. To better predict the behavior of the atomization process at such high pressures, we must record high-resolution spray images, and compare them to the numerical simulations. Now due to extremely high speed of the jet in this region even the fastest ultrafast camera fails to avoid the streaks in the spray images due to exposure times that are shorter than a microsecond but still remain too large in such conditions. Ultrafast imaging featuring ultra-short laser pulses to freeze the motion of the spray on the detector is a good solution to overcome this limitation. However, commercial high-energy ultrafast laser sources based on titanium-sapphire crystals are limited to a few KHz repetition rates.

Here, we propose a method for obtaining shadowgraphs of high-pressure diesel sprays using a high-repetition rate picosecond fiber laser source for illumination and an ultrafast camera for detection. The picosecond laser consists of a homemade passively mode-locked ytterbium-doped fiber laser operating in the all-normal dispersion regime. A fiber-Bragg grating-based filter centered at 1040 nm is included inside the cavity to limit the spectral bandwidth to less than 140 pm. The laser generates nearly transform-limited pulses with 30 ps duration and less than 1 nJ energy, at a repetition rate of 8 MHz. A two-stage fiber master-oscillator power-amplifier is used to boost pulse energy to more than 300 nJ. This corresponds to more than 2.5 W of average power. Using an electro-optic modulator placed after the laser output we could easily modify the system repetition rate.

Keywords: Spray, atomization, imaging diagnostics, ultrafast fiber lasers

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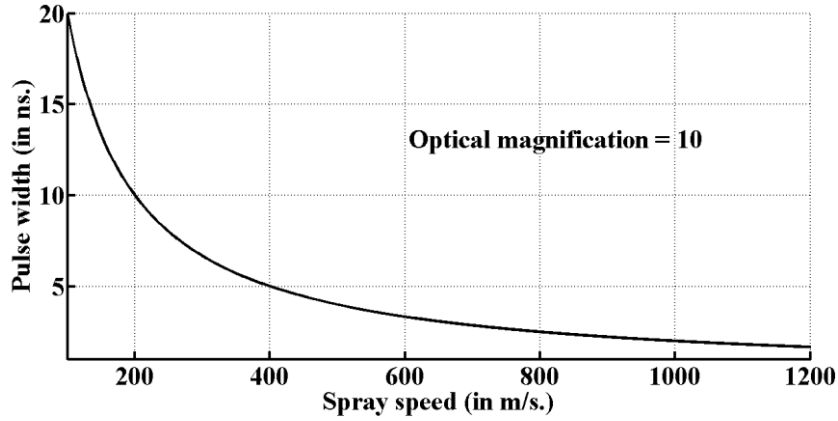
### Introduction

Fast moving objects at all length scales are difficult to observe and this has intrigued researchers for several years. It is one of the main reasons for the development of ultrafast light sources and detection systems. A straightforward way to see or capture a fast moving object is to use a continuous light source for illumination, with a camera fast enough to record the dynamics of the moving object with appropriate resolution. Another commonly used technique to achieve this requires a short flash or a pulsed illumination source, fast enough to freeze the motion of the high-speed moving object at the detector.

Our primary goal is to capture the formation of the high-pressure fuel sprays near the nozzle outlet in order to understand the complex process of atomization. We are mainly focused in the near nozzle region because most of the instabilities in the liquid jet, leading to its atomization arise in this region [1]. To understand how these instabilities originate and propagate it is crucial to record high-resolution images with high-repetition rate and compare them quantitatively with the images obtained through direct numerical simulations [2]. Another reason to concentrate in the near nozzle region is that most high-fidelity numerical calculations, for example calculations based on the level-set method, at present are limited to the near nozzle region as they require heavy computational resources for the far-field of the nozzle [3].

A common trend followed by the automobile industries to increase the efficiency of their fuel engines is to increase the injection pressure while decreasing the nozzle orifice diameter [4]. Today's diesel injectors thus operate at very high injection pressures resulting in very high injection velocities in the near nozzle region [5]. As a result, even the fastest ultrafast camera fails to avoid the streaks in the spray images when illuminated with continuous white light, due to its long exposure time (about 300 ns for customized Phantom ultrafast cameras), which is very short but still remains too large for this application. So as of today the only other option left to capture fast moving sprays is to use an ultrafast light source to freeze its motion at the detector. Figure 1 shows the maximum required pulse width of an ultrafast illumination source to freeze the motion of an object, moving with the high-speed (on the x-axis), on a camera with pixel size of 20  $\mu\text{m}$  for an optical magnification of 10.

It is clear from Fig. 1 that we need at least a nanosecond illumination source to capture the dynamics of the spray moving with high velocities. One could think of using the commercial nanosecond or picosecond laser sources for this purpose. However, these commercial ultrafast laser sources have very low repetition rates, for example, for most titanium-sapphire crystal based ultrafast lasers the repetition rates are limited to a few kHz. Hence such illumination sources cannot be used for high-repetition imaging of the fast moving sprays.

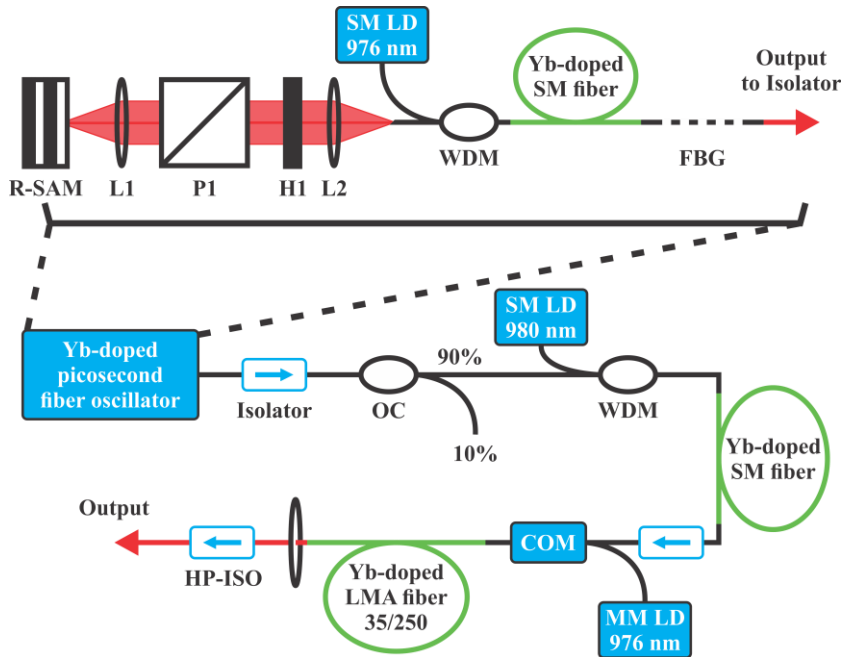


**Figure 1: Maximum required pulse width to freeze the motion of the spray at the detector of 20  $\mu\text{m}$  pixel size with optical magnification of 10.**

Here, we propose a method for obtaining shadowgraphs of high-pressure fuel sprays using a high-repetition rate picosecond fiber laser source for illumination and an ultrafast camera for detection.

### Design of the picosecond fiber laser

The picosecond laser system consists of a fiber master-oscillator power-amplifier (FMOPA) as shown in Fig. 2. It is based on a passively mode-locked ytterbium-doped fiber laser oscillator operating in the all-normal dispersion regime [6].



**Figure 2: Experimental setup of the fiber master-oscillator power-amplifier (FMOPA).**

**Nomenclature - R-SAM: resonant saturable absorbed mirror; {L1, L2}: biconvex lenses; P1: polarizer; H1: half wave-plate; WDM: wavelength division multiplexer; SM: single mode; LD: Laser diode; FBG: fiber Bragg grating; MM: multi-mode; OC: output coupler; COM: pump and signal combiner; LMA: large mode area; HP-ISO: High power isolator.**

The oscillator consists of a Fabry-Perot cavity comprising 15 cm of heavily ytterbium-doped single mode fiber (YDF) with a core mode field diameter of 6  $\mu\text{m}$  and a numerical aperture of 0.15 at 1080 nm. The YDF presents peak absorption of 1200 dB/m at 975 nm and its group velocity dispersion (GVD) has been estimated around +24 ps<sup>2</sup>/km at 1060 nm. It is pumped through a 980/1040 wavelength division multiplexer (WDM) using a single-mode laser diode. A fiber-Bragg grating-based filter (FBG) centered at 1040 nm is included in the cavity to limit the spectral bandwidth to less 140 pm [7]. The laser output is taken through the FBG, which presents a low reflectivity of 20%. Mode-locking is achieved by using a resonant saturable absorber mirror (R-SAM) which constitutes the end mirror of the cavity. It exhibits a high modulation depth of ~50% and a relaxation time of 9

ps. By adjusting the focusing conditions on the R-SAM to meet the saturation criteria, a sustained single-pulse mode-locking regime is achieved at a relatively low pump power level of about 150 mW. The core pumped single mode laser generates nearly transform-limited pulses with 30 ps duration and less than 1 nJ energy, at a repetition rate of 8.2 MHz.

A two-stage fiber power-amplifier is then used to boost pulse energy to some hundreds of nano-joules. The first stage is based on a core-pumped single-mode YDF and delivers more than 8 nJ energy. The final stage includes a double clad step-index YDF with a core diameter of 35  $\mu\text{m}$  from INO Inc. The fiber is based on the selective gain amplification concept to discriminate high-order modes and thus promote quasi-single mode operation. The measured M2 value of less than 1.15 confirms the very good quality of the guided beam. The fiber is cladding-pumped through a signal-pump combiner by two fiber-coupled multimode diodes emitting at 976 nm. Pulse energy as high as 300 nJ is achieved after the power amplifier without any temporal distortion. This corresponds to more than 2.5 W of average power. The corresponding auto-correlation trace measured at the FMOPA output is shown in Fig. 3.

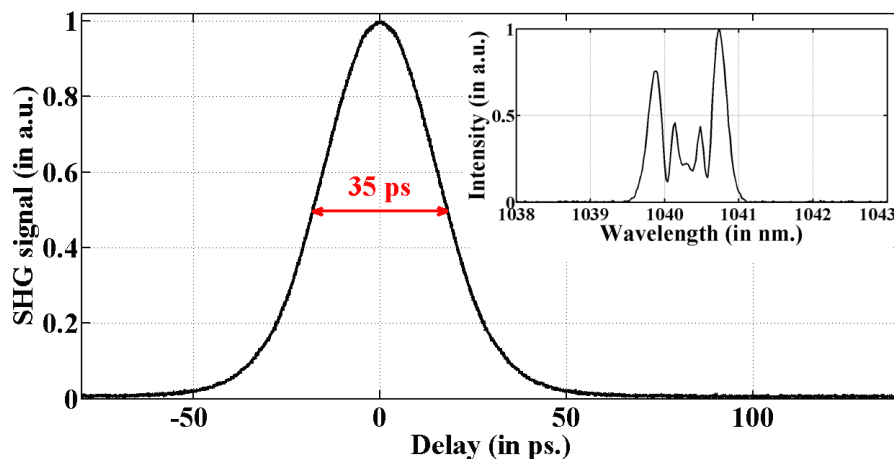


Figure 3: Autocorrelation trace measured at the FMOPA output. Inset: Optical spectrum measured after the amplifier.

It is worth noting that at this energy level the output pulses endure some spectral broadening due to self-phase modulation as shown in the inset of Fig. 3. For energies higher than 400 nJ, non-linear effects can cause severe temporal distortions on the output pulse. The fiber end is angle cleaved to avoid any parasitic reflection into the power amplifier. Moreover, a high-power isolator is added to protect the laser system from any parasitic feedback.

The amplitude stability of the mode-locked pulse train was evaluated by radio frequency (RF) measurements using the power spectra obtained with a microwave spectrum analyzer via a high-speed photo detector (8 GHz bandwidth). It exhibits very satisfying stability with a contrast of more than 50 dBm between the fundamental harmonic and the background as depicted on Fig. 4. This indicates that laser operation is very stable and free from any Q-switching instability.

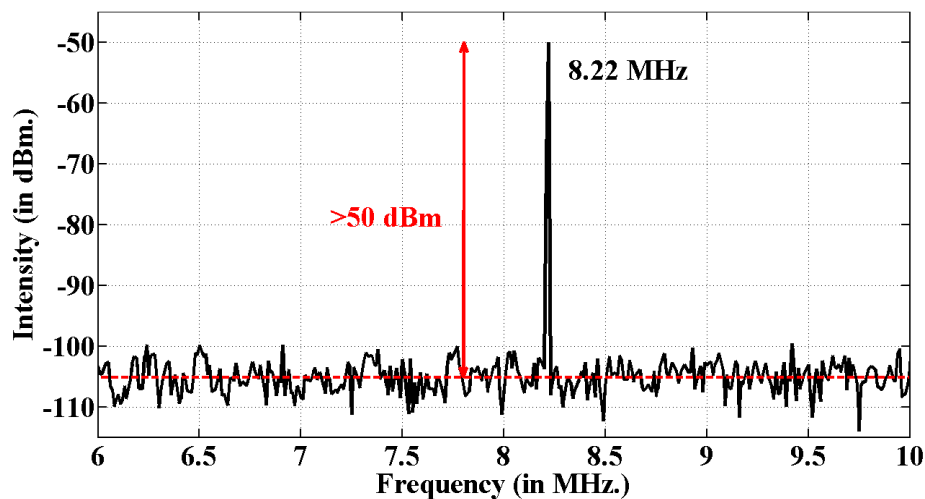
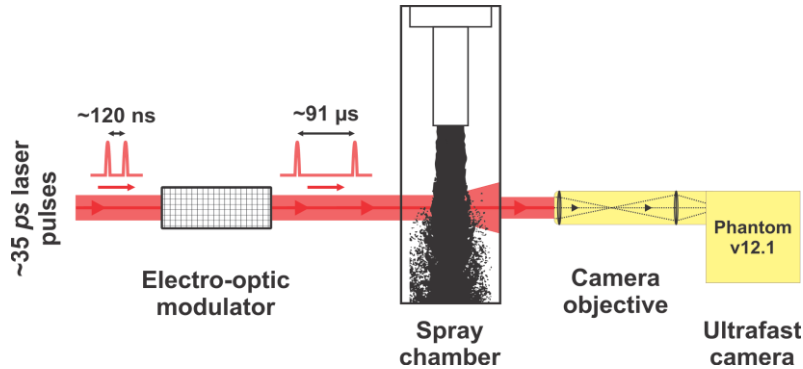


Figure 4: Radio-frequency spectrum.

### Spray imaging

The fiber laser ( $\lambda=1040$  nm, pulse width  $\sim 35$  ps, average power  $\sim 2.5$  W) was used for recording spray shadowgraphs using the ultrafast camera Phantom v12.1 with 300 ns of exposure time. The experimental setup is as shown in Fig 5. An electro-optic modulator was used to reduce the repetition rate of the fiber laser from 8.2 MHz (one laser pulse every 120 ns) to about 11 kHz (one laser pulse every 91  $\mu$ s) to have only one laser pulse in each frame of the ultrafast camera. Note that the repetition rate used in the experiment is limited by the ultrafast camera and not by the laser. The Phantom v12.1 was being operated at a resolution of 800x600 px with a maximum frame rate of 11001 fps. The synchronization between the laser, fuel injection and camera was adjusted using an electronic delay generator DG-645 from Stanford Research Systems.



**Figure 5: Schematic of the experimental setup for obtaining high-resolution spray shadowgraphs.**

The high-repetition fuel spray images illuminated using the ultrafast fiber laser are shown in the bottom half of the Fig. 6 and are compared qualitatively with the images obtained using continuous white-light from a Xenon lamp as the illumination source. The experimental setup in Fig 5 was modified accordingly - the electro-optic modulator was removed and the illumination source was changed to a Xenon lamp without disturbing rest of the setup including camera. To avoid pollution of the optical devices the fuel spray was injected into a closed chamber maintained at standard pressure and temperature with an injection pressure of about 200 bar using a single orifice nozzle with the orifice diameter  $\phi = 185$   $\mu$ m. Figure 6 contains the very first few frames captured using the ultrafast camera showing the formation of the spray. The time for each frame with respect to the start of the injection is indicated below the frame. The last frame, recorded after 1.7 ms from the start of the injection, in both cases show the spray after it has been formed and stabilized.

The spray images obtained with the developed picosecond fiber laser are sharper than the images obtained with white-light illumination. There are no streaks in the images obtained with the laser and the structures of the liquid jet are visible very clearly as if the spray was frozen while taking the snapshots.

### Summary and Conclusions

A homemade fiber laser capable of generating  $\sim 35$  ps laser pulses with an average power of 2.5 W at a repetition rate of about 8 MHz, centered at  $\lambda=1040$  nm was tested for high-pressure fuel spray imaging. The fuel spray images obtained at 200 bar of injection pressure using the developed picosecond fiber laser were qualitatively compared with the images obtained using continuous white-light illumination and were found much better in clarity. The liquid structures and ligaments are visible clearly in the images obtained with fiber laser. And now since the repetition rate of the laser is much faster than that of the commercial titanium-sapphire based ultrafast lasers, it has been demonstrated that it is possible to obtain clear images of the high-pressure fuel spray with a much higher repetition rate for a single injection. The only limitation is now the frame rate of the ultrafast camera.

Note that the fuel spray images demonstrated in this article were obtained at low injection pressure (200 bar). Nevertheless, as shown in Fig. 1, a laser pulse with pulse width of  $\sim 35$  ps would be sufficient to freeze the motion of the spray at the detector with sensor size of 20  $\mu$ m (as is in most ultrafast cameras) even if the injection pressure was as high as 2000 bar (with near field spray velocity close to 700 m/s). However, at such a high injection pressures there will be a lot of multiple scattering due to quick atomization of the fuel even for the targeted region ( $< 5$  mm from the nozzle outlet) shown in Fig. 6. As a result, the imaging spatial resolution will decrease and the spray characteristics will not be visible with the same clarity. Now, in order to get rid of multiple scattering more sophisticated imaging techniques such as ballistic imaging [8], structured laser illumination planar imaging (SLIPI) [9,10] or x-ray phase-contrast imaging [11,12] could be used instead of simple trans-illumination imaging.

The aim of this article was to introduce a simple, compact and cost-effective imaging setup for high-repetition fuel spray imaging in the near field of the nozzle at moderate injection pressures where the effects of

multiple scattering are not so prominent. Sophisticated imaging techniques could give us more reliable results at high injection pressures, however, to obtain high-repetition spray images using these techniques is still a challenge.

### Acknowledgements

We acknowledge support from the French Agence Nationale de la Recherche (ANR), through the program “Investissements d’Avenir (ANR-10-LABX-09-01), LabEx EMC3” and the Region Haute Normandie, through the project MIST.

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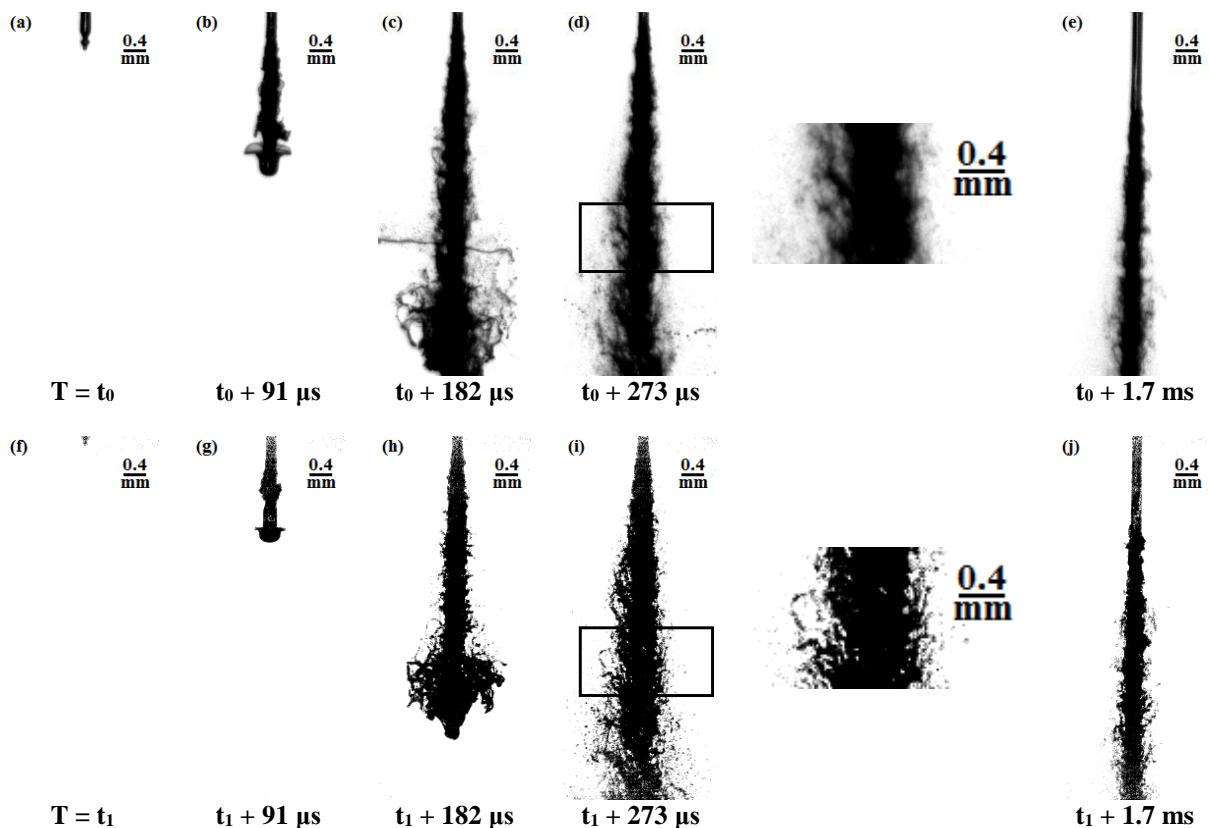


Figure 6: Spray shadowgraphs obtained using continuous white light (top, a to e) and picosecond fiber laser (middle, f to j) illuminations. A zoomed section from the (d)<sup>th</sup> and (i)<sup>th</sup> frames are shown at the bottom - left image corresponds to frame (d) (with continuous illumination) and the image on the right corresponds to (i) (with ps laser illumination).