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LASER IGNITION OF LIQUID OXYGEN/ETHANOL PROPELLANTS

*Gajdeczko, B. F., Angioletti, M., Dryer, F. L.**
fldryer@phoenix.princeton.edu
http://www.princeton.edu/~combust/

Abstract

A prototype Laser Induced Plasma (LIP) igniter for a small rocket thruster was developed to demonstrate feasibility of laser ignition for ethanol/oxygen mixtures. Experiments were conducted with the oxidizer injected into the combustion chamber of the igniter either in gaseous or in liquid phase. The source of ignition was a single pulse of a Q-switched Nd:YAG laser. Pressure in the combustion chamber and laser pulse energy were varied to evaluate the igniter at different operating conditions. All tests were performed at pseudo-vacuum conditions and very low temperature regimes in order to simulate the thruster's operating conditions. Both qualitative visualizations and quantitative measurements were provided to fully characterize combustion events. It was concluded that LIP can produce reliable ignition for space propulsion systems. However, practical applications would require considerable additional engineering development of suitable optical energy delivery systems.

Objective

One of the promising propellant combinations considered for auxiliary space propulsion is liquid oxygen (LOx) and ethanol (LEt). Because oxygen/ethanol propellants are not hypergolic, they require suitable ignition systems. Electric spark devices, similar to automotive spark plug systems, can be considered. However, prototype electric spark devices typically are operated at relatively high firing rates causing considerable electrode wear after a relatively short period of operation.
Alternatively, optical ignition systems [**1**] have potential to:

- ***eliminate some of these difficulties.***
- ***simplify pulse controls of multiple thruster locations on Orbital Maneuvering System (OMS).***

The research summarized here investigates the ignition of gaseous oxygen and liquid ethanol spray mixtures at reduced temperature (-50°C) as well as the ignition of liquid oxygen and ethanol sprays and further extends previous characterizations **[2]**. Results presented here demonstrate and characterize the Laser Induced Plasma (**LIP**) ignition process in an environment that would closely resemble the ignition of oxygen/ethanol mixture in a prototype igniter of the NASA OMS thruster under space condition (vacuum and low temperature).

Experimental Set-Up

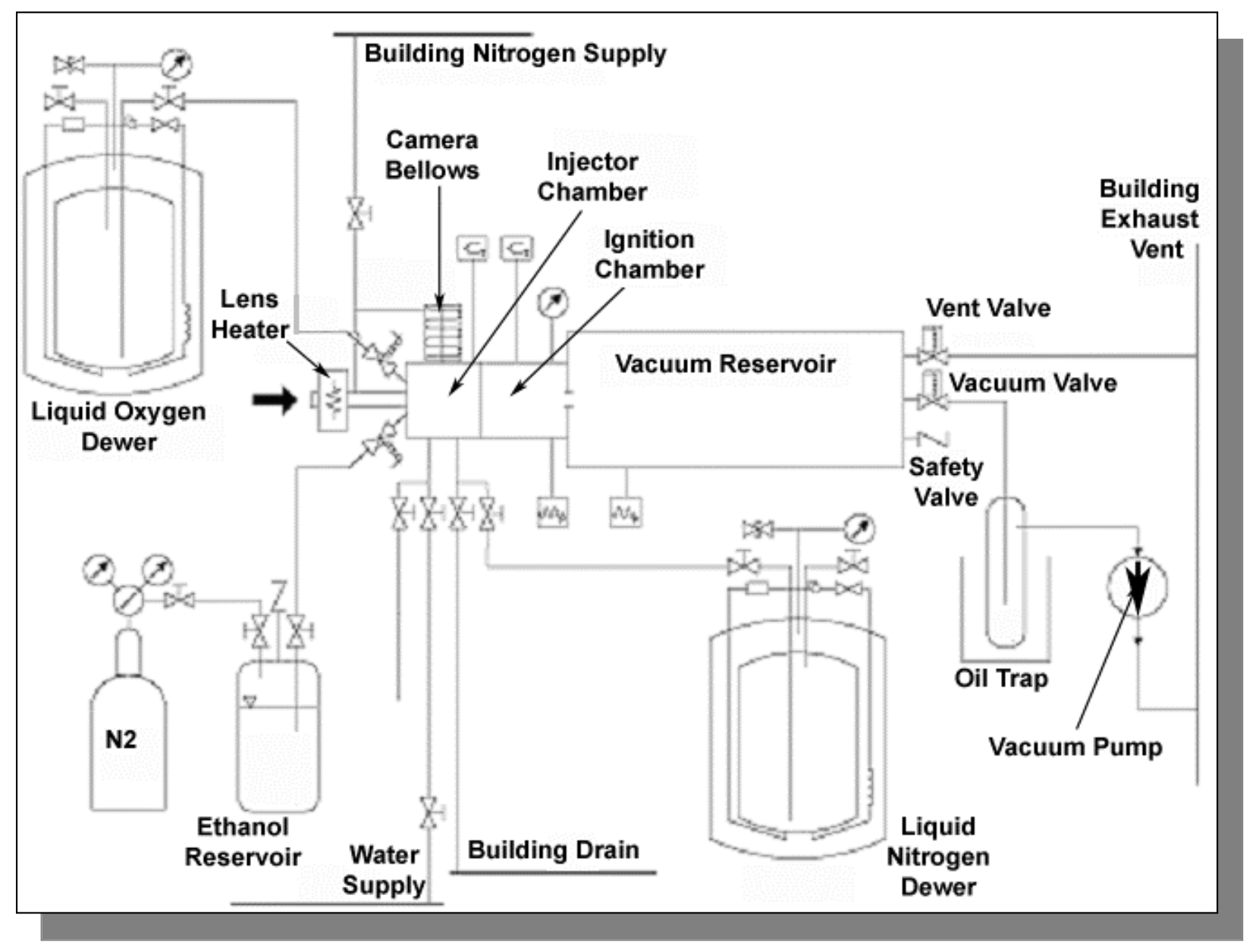

Figure 1. Schematics of the experimental apparatus

A lay-out of the experimental apparatus is displayed in **Figure 1**. The arrangement directed the laser beam into either the combustion chamber (for a single laser pulse) or diverted the pulse train to an optical beam dump (**Figure 2**). A computer-based system was developed to synchronize the actuations of the fuel and oxygen solenoid valves, discharge vacuum chamber valve, data acquisition equipment and camera with the selected laser pulse. Control hardware included electric relays used to activate the individual propellant solenoid control valves.

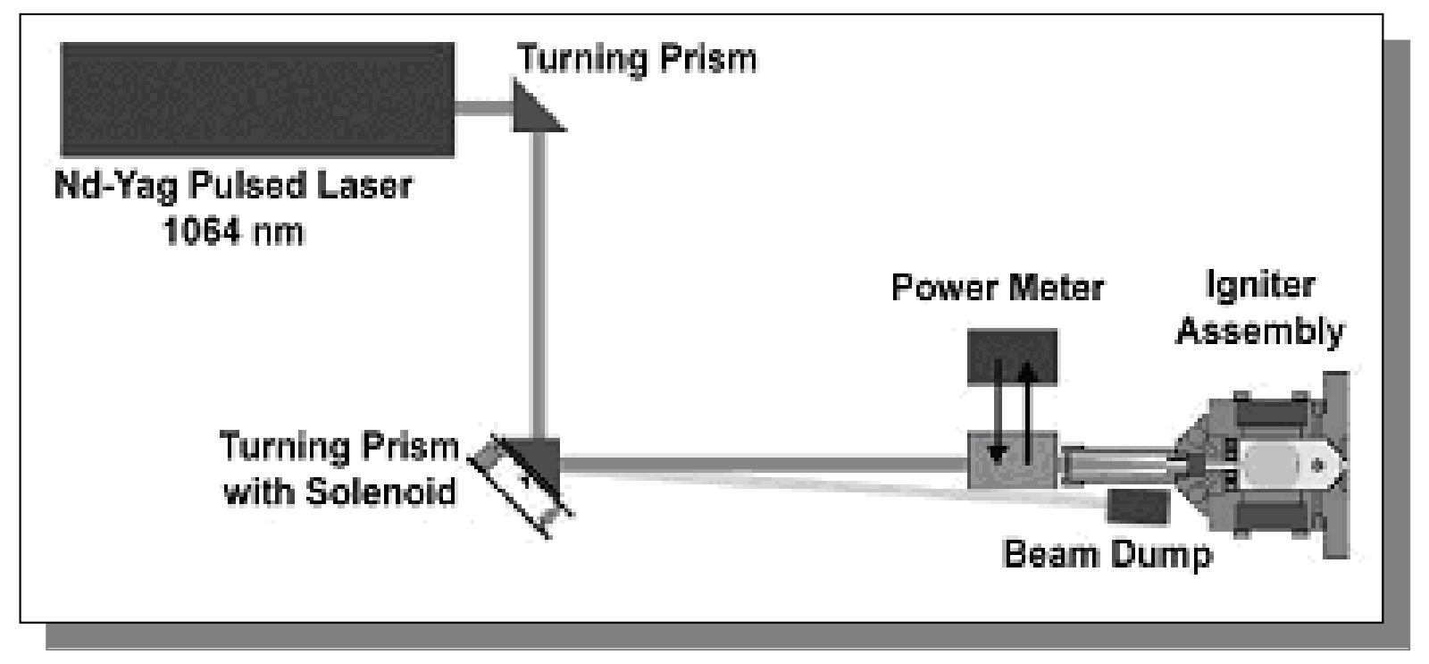

Figure 2. Laser beam path arrangement.

An optically accessible prototype igniter (**Figure 3**) was developed earlier to investigate optical ignition of ethanol/oxygen propellants for RCS thruster applications. In principle, the igniter can be retrofitted into a new propulsion system (RCS) originally developed at NASA for electric spark ignition studies.

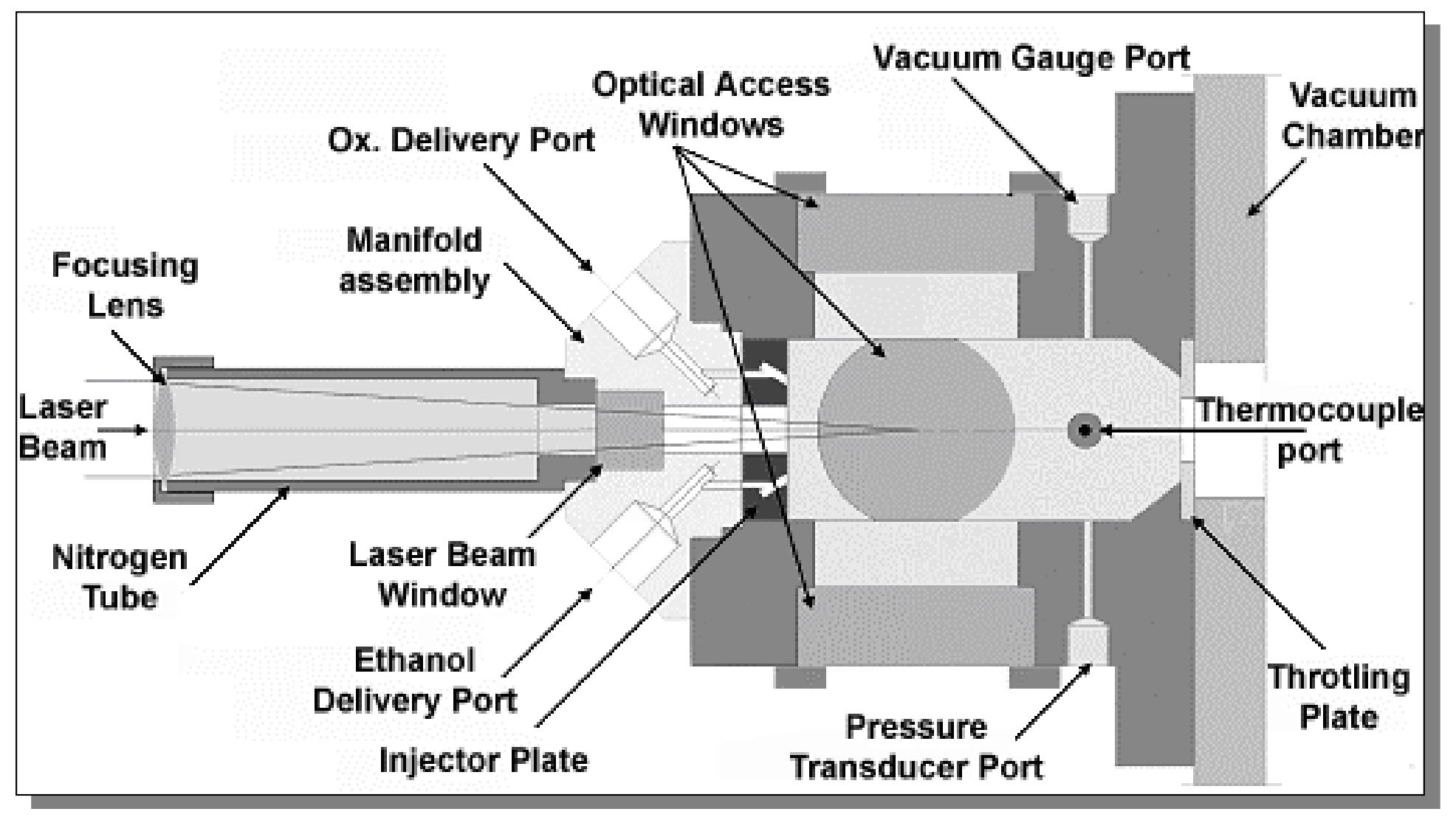

Figure 3. Close-Up view of the Igniter.

Qualitative investigation of propellant jets and plasma formation

Backlit photographs (frame 1 and 2) were taken with the Nd:YAG laser with an harmonic generator (532 nm) used as an illumination source. The laser and the valves were timed identically as they would be for igniting the sprays, so the images correspond to the actual configuration of the sprays just before the ignition. The images show the oxygen sprays at the top of the combustion chamber while the ethanol sprays are visible at the bottom.
The laser-induced plasma is visible as a small elongated bright region in the center of the window for all the cases, regardless of whether ignition occurs. However occasionally the plasma can become fragmented [**3**], which typically occurs when higher values of the laser pulse energy are used, in Figure 5 a close up view is provided.

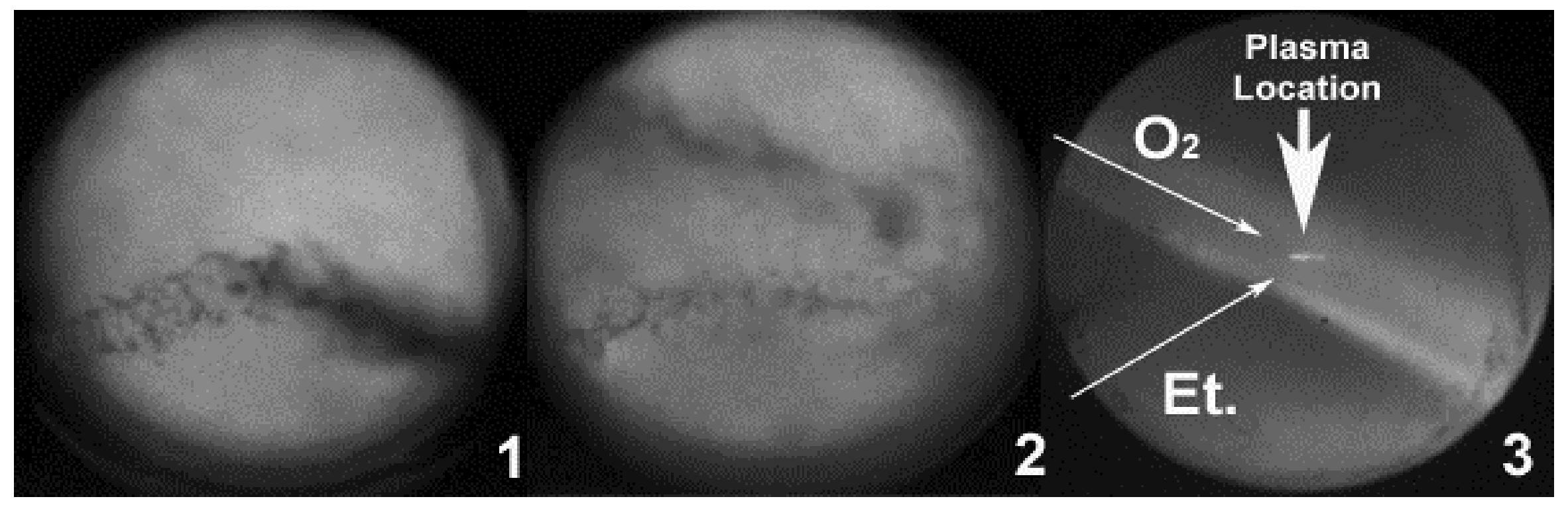

Figure 4. Backlit photographs of GOx/LEt injection (**1**), LOx/LEt injection (**2**) and propellants trajectories and plasma location (**3**).

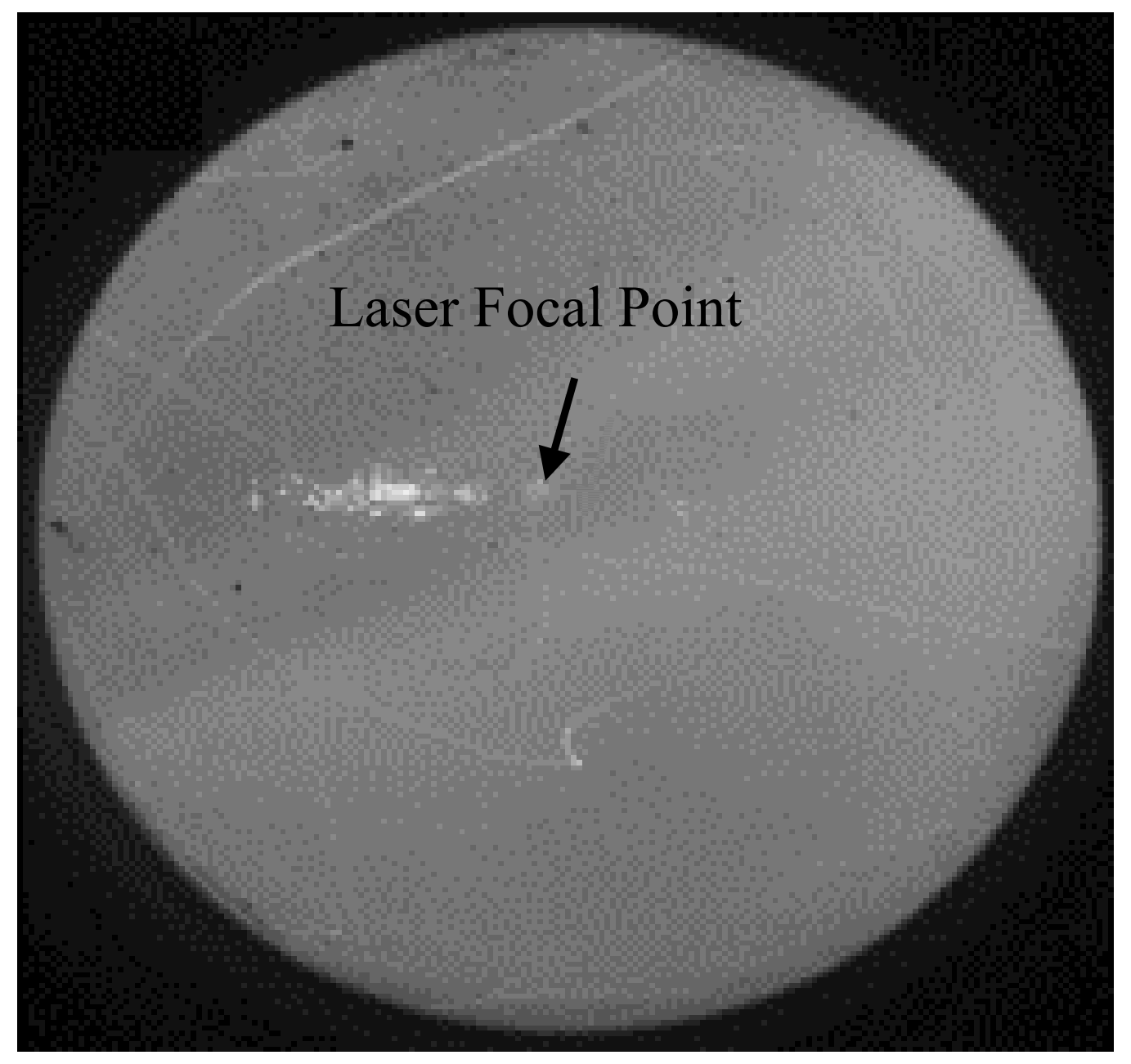

Figure 5. Close up view during a firing event. The plasma appears fragmented and elongated toward the laser source.

Pressure Traces and Photographic Images

Each ignition experiment was documented by both a combustion chamber pressure trace and a photographic image of the ignition event acquired through the ignition chamber window. Photographic images were taken with relatively long exposure time, extending over the entire duration of a single firing event.
For the experimental conditions tested, a success or failure of the ignition attempt could be unambiguously determined by the peak pressure values, the overall shape of the pressure traces, and the presence (or lack) of combustion luminosity. (In addition, successful ignition also resulted in a relatively strong acoustic effect.) Representative pressure traces and simultaneous photographic results for the highest value of the laser pulse energy, for each experimental condition, are shown in Figures 6, 7 and 8.

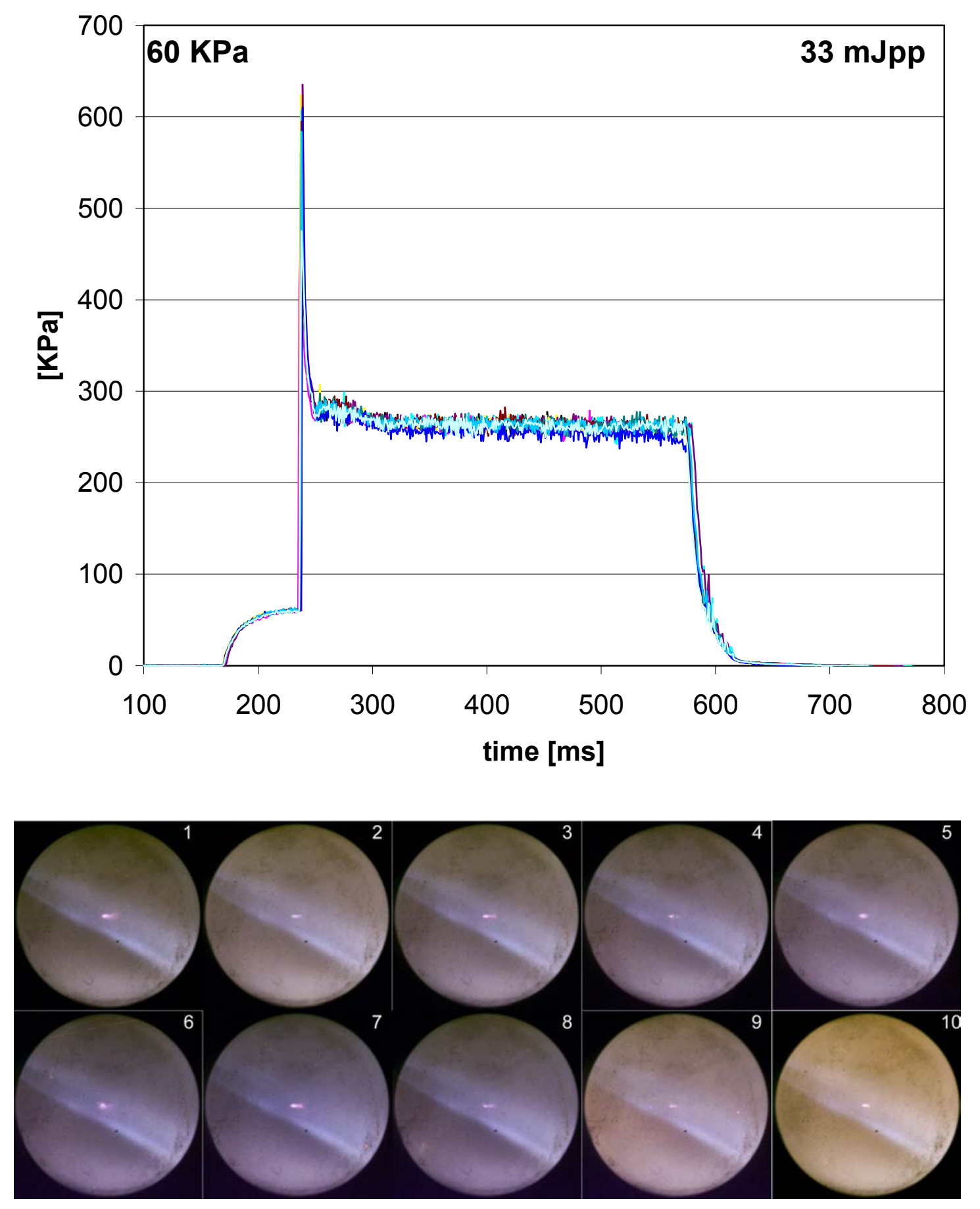

Figure 6. Simultaneous pressure traces and photographic visualizations for the mixture (LEt/GOx) at initial temperature of 293 K and initial pressure of 60 Kpa.

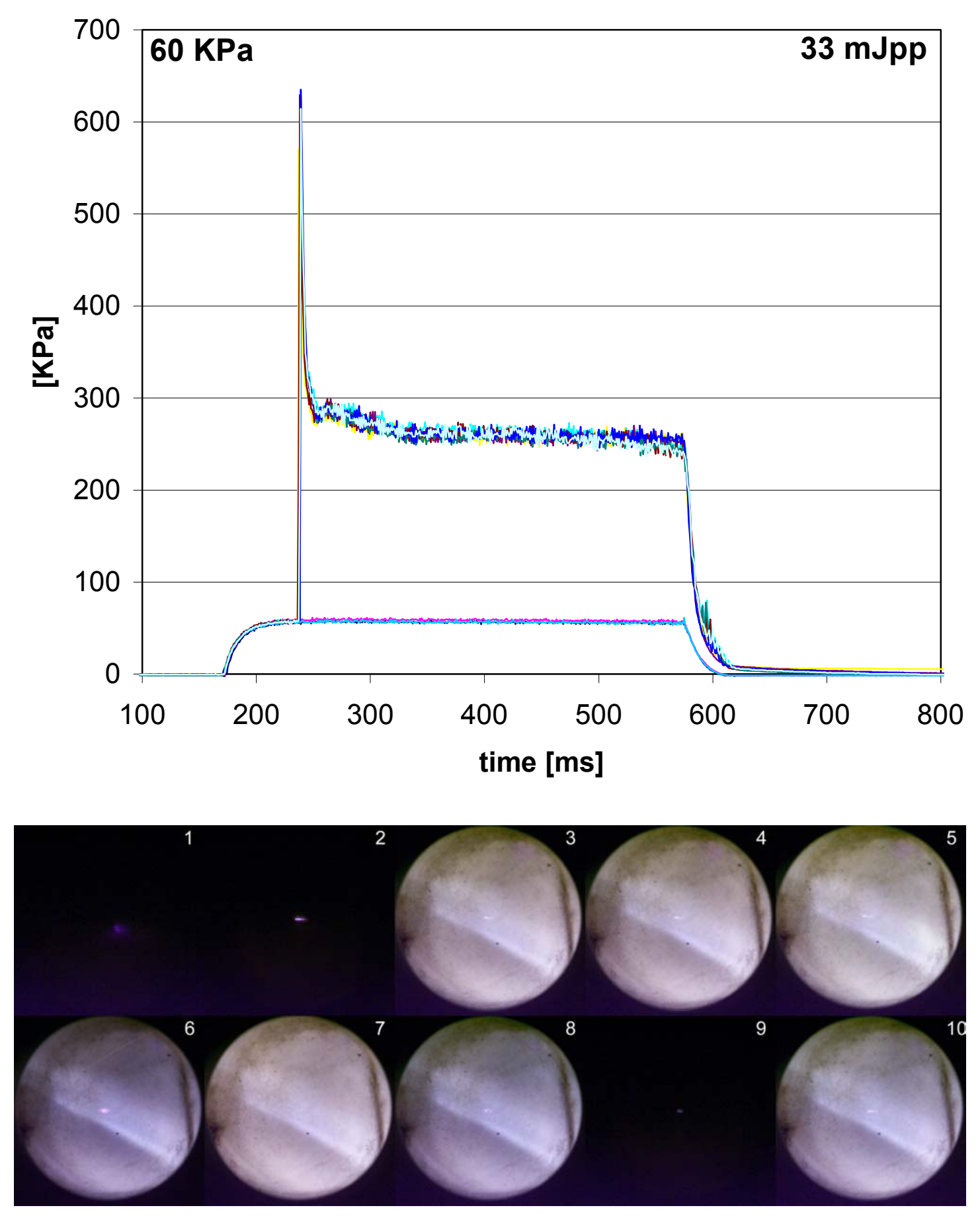

Figure 7. Simultaneous pressure traces and photographic visualizations for the mixture (LEt/GOx) at initial temperature of 223 K and initial pressure of 60 Kpa.

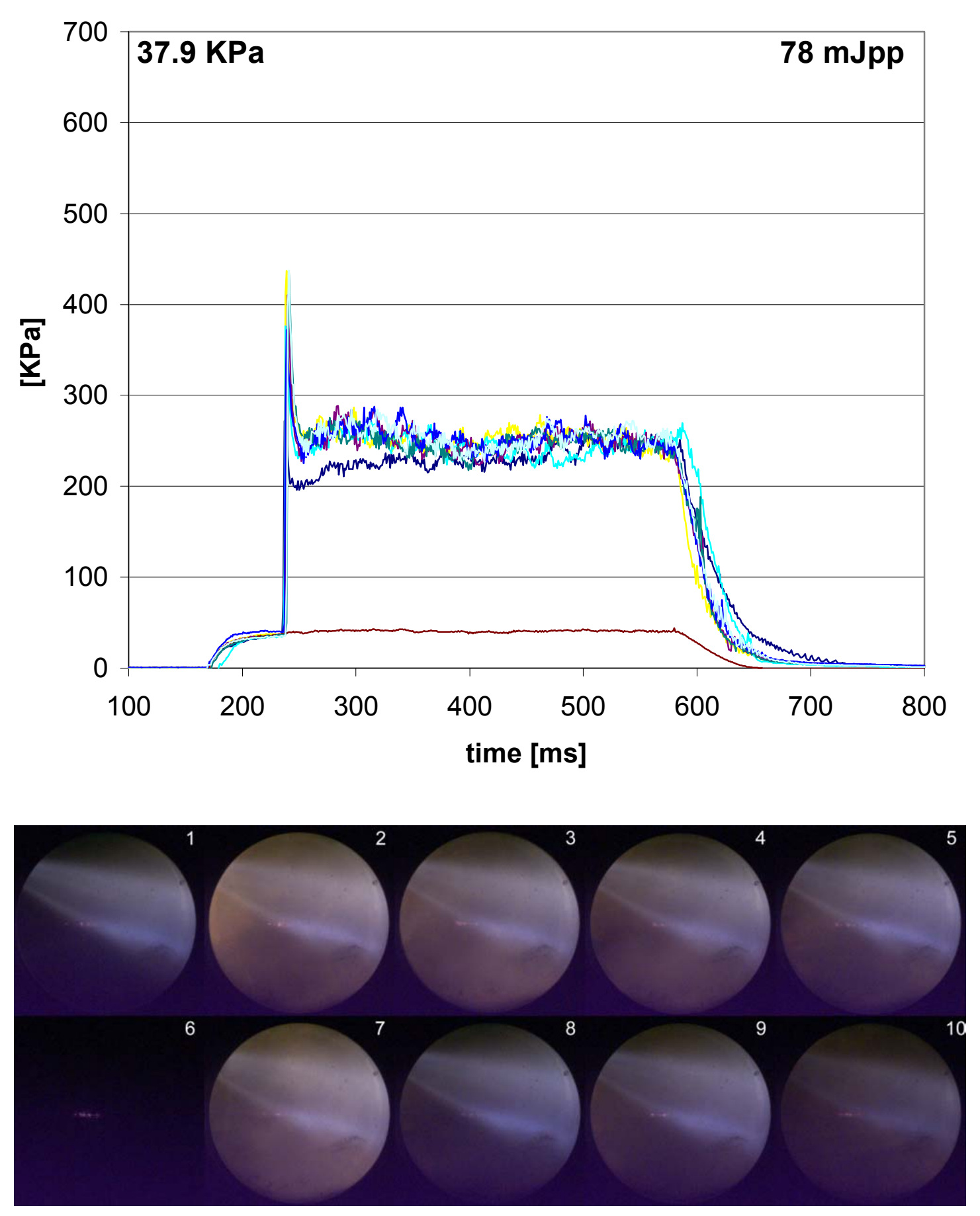

Figure 8. Simultaneous pressure traces and photographic visualizations for the mixture (LEt/LOx) at initial temperature of 223 K and initial pressure of 37.9 Kpa.

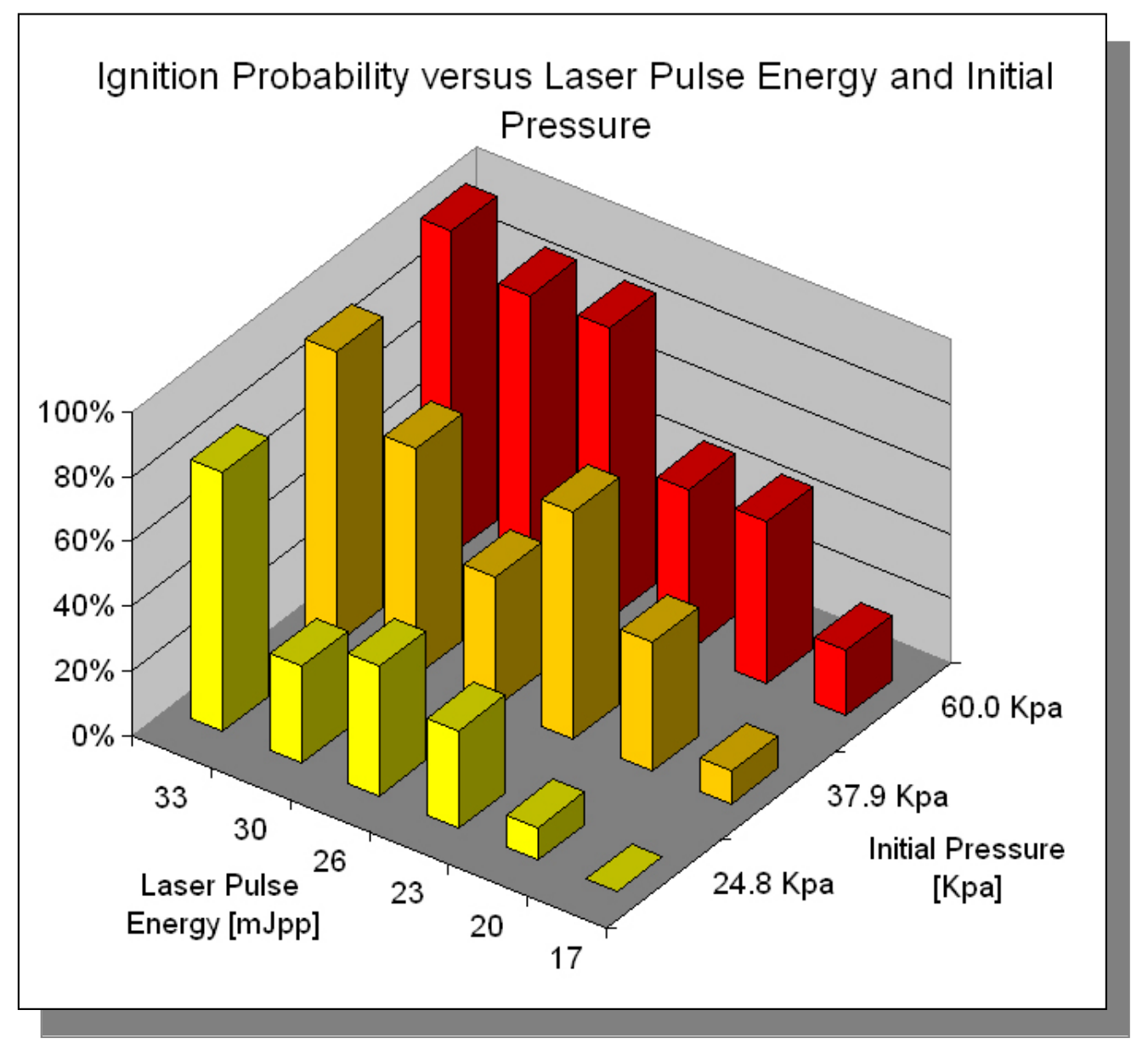

Figure 9. Comparison of ignition probability of gaseous oxygen / ethanol for different values of the initial pressure [2].

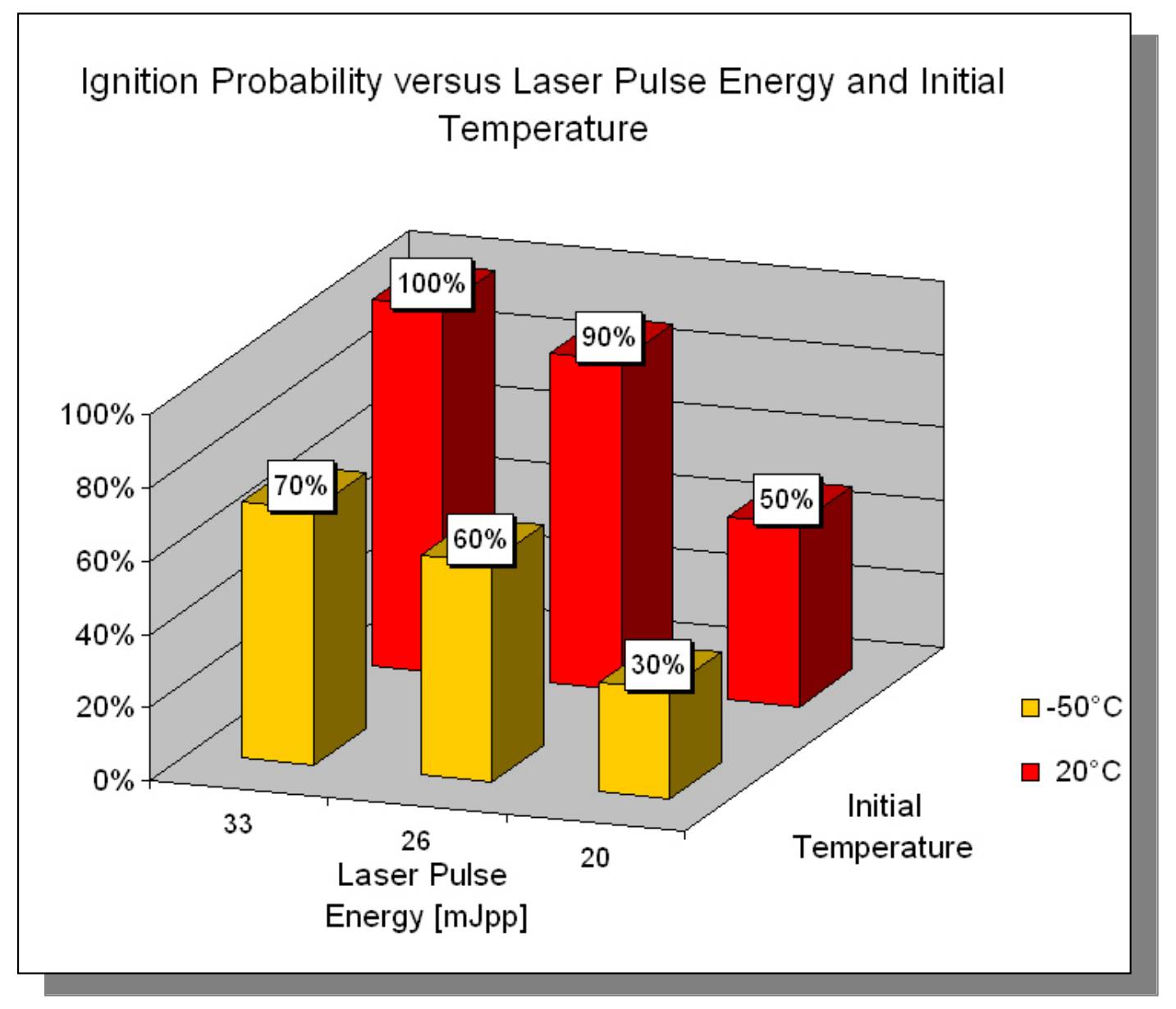

Figure 10. Comparison of ignition probability of gaseous oxygen / ethanol for 293 K and 223 K at constant pressure [2].

Some Statistical Data

The stochastic nature of the event implies a statistical probability of ignition for each set of independent test parameters and, therefore, necessitates a statistical data analysis approach. For the data presented here, ten ignition experiments were conducted for each set of independent variables to provide a statistical basis for assessing ignitibility. **Figures 9** and **10** show a comparison of ignition probability and correlate it with either the temperature or the pressure values detected at the time when the plasma breakdown occurs. The statistical stability of data (ten samples) is rather modest, but adequate to conclude that there is a significant increase in ignition probability at higher chamber temperatures (at the same pressure), or at higher chamber pressure (at the same temperature). When successful ignition becomes more difficult to achieve with these changes, an increase in the laser pulse energy is needed to increase the ignition probability.

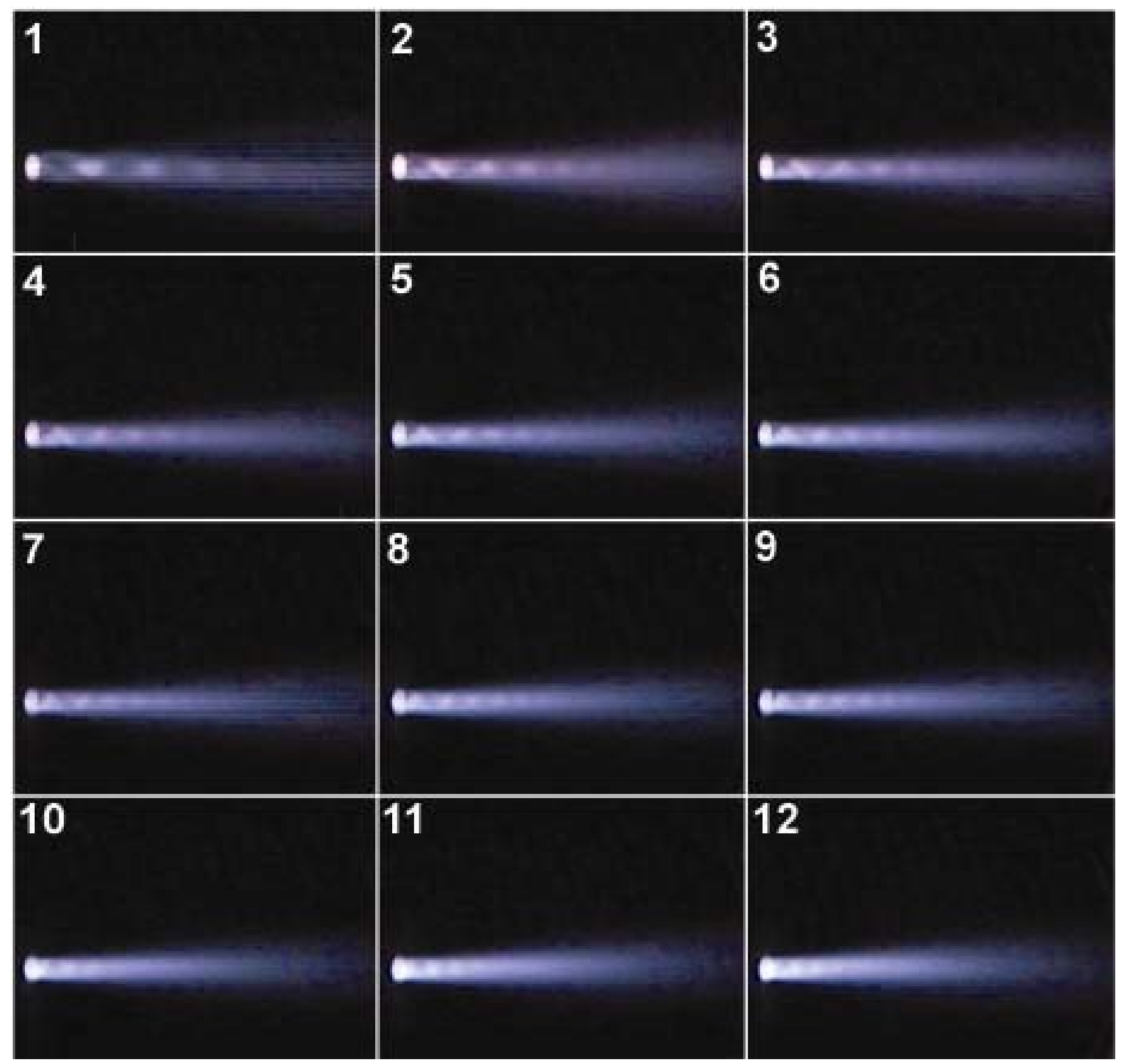

Figure 11. A sequential direct light photographic time history (total firing time of one second) of the thruster plume developed after a successful ignition event for liquid phase injection of both ethanol and oxygen.

Conclusions

A prototype laser igniter for a small rocket thruster with a combustion chamber volume of approximately 41 ml (2.75 in3) was constructed and used in tests to define the probability of laser ignition of gaseous oxygen/liquid ethanol and liquid oxygen/liquid ethanol sprays as a function of laser energy and chamber pressure. . The ignition energy was delivered from a pulsed Q-switched Nd:YAG laser beam focused through a small quartz window in the igniter. Experiments demonstrated that LIP is a reliable ignition source with gaseous and liquid oxygen and ethanol sprays with an overall stoichiometric equivalence ratio. In a series of experiments, where the temperature of the manifold was maintained at 223 K, it was shown that lowering the temperature of sprays results in a higher energy requirement to achieve ignition. On the other hand, at 293 K, the nominal chamber pressure (Different values were obtained at the same propellant flow rates by using interchangeable exit nozzle orifices.) significantly influences plasma generation at laser pulse energies near the breakdown threshold limit. With the current design of the igniter, the laser pulse energy needed for reliable ignition of liquid oxygen and ethanol mixtures was measured at ~80 mJpp for a 1064 nm Q-switched Nd:YAG laser beam focused with a 100 mm focal length lens. It was observed that under the conditions described above, laser-induced plasma generation is a necessary but insufficient criteria for achieving a successful ignition.

References

[1] P.D. Ronney, *Laser versus conventional ignition of flames,* Optical Engineering 33 (2), 510-521, 1994.
[2] B.F. Gajdeczko, M. Angioletti, F.L. Dryer, M. Lavid, *Laser ignition of oxygen/ethanol propellants under simulated space conditions*, 38th JANNAF, Destin, FL, 2002.
[3] N.G. Basov, V.A. Boiko, O.N. Krokhin, G.V. Sklizkov, *Formation of a Long Spark in Air by Weakly Focused Laser Radiation*, Sov. Phys. – Doklady, 12, 248, 1967.

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