Laser Ignition For Combustion Engines – Part I

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With the advent of lasers in the 1960s, researcher and engineers found a new and powerful tool to learn and investigate natural phenomena and improve technologically critical processes. Nowadays, applications of different lasers span quite widely from diagnostics tools in science and engineering to biological and medical uses. In this series of tutorial articles basic principles and applications of lasers for ignition of fuels are briefly reviewed.

In order to ignite a mixture of gaseous fuel and air and initiate a flame, a localized input energy in a form of heat or active chemical species (radicals) must be added. The magnitude of this energy must be higher than a critical value called minimum ignition energy (Emin). The physics of combustion initiation guides us to a requirement of a minimum flame embryo (flame kernel) size or radius, say L_k . The L_k can be approximated by the thickness of a flame front (L_f) consuming the charge in a homogeneous fuel-air mixture. Hence, the simplest physical picture of the ignition can be thought of as injection of a certain minimum amount of energy (Emin) to raise the temperature of a spherical zone of fuel-air mixture with size of L_f to a distinct temperature referred to as "adiabatic flame temperature". The term "adiabatic flame temperature" defines a terminal temperature of a fuel-air mixture when combustion occurs under adiabatic condition (i.e., no heat losses from the combustion chamber). For example, experimentally speaking, the Emin of about 0.02 mJ energy is needed to ignite a stoichiometric mixture of hydrogen in air, whereas 0.4 mJ is required for methane and air mixture.

Fundamentally, there are four different methods in which laser light can interact with a combustible mixture to initiate ignition. They are referred to as thermal initiation, nonresonant breakdown, resonant breakdown, and photochemical ignition. In the following, a concise description of each is given. In thermal initiation of ignition, there is no electrical breakdown of the gas and a laser beam is used to raise the kinetic energy of target molecules in either translational, rotational, or vibrational form. Consequently, molecular bonds are broken and chemical reaction occurs leading to ignition with typically long ignition delay times. This method is suitable for charge mixtures with strong absorption at the laser wavelength. However, if localized ignition in a gaseous or liquid mixtures is an objective, thermal ignition is unlikely a preferred choice due to energy absorption along the laser propagation direction. Conversely, this is an ideal method for homogeneous or distributed ignition of combustible gases or liquids. Thermal ignition method has been used successfully for solid fuels due to their absorption ability at infrared wavelengths.

In nonresonant breakdown ignition method, because typically the light photon energy is in visible or UV range of spectrum, multiphoton processes are required for molecular ionization. This is due to the lower photon energy in this range of wavelengths in

comparison to the molecular ionization energy. The electrons thus freed will absorb more energy to boost their kinetic energy (KE) facilitating further molecular ionization through collision with other molecules. This process shortly leads to an electron avalanche and ends with gas breakdown and ignition. The multiphoton absorption occurs in presence of losses (electron diffusion outside the focused volume, radiation, collisional quenching of excited states, etc.), thus demanding very high input beam intensities (through tightly-focused high-energy short-duration laser beam pulses) for a successful ignition process. To assist the breakdown process, in some studies a metal needle is inserted just behind the beam focused volume as additional source of electrons. By far, the most commonly used technique is the nonresonant initiation of ignition primarily because of the freedom in selection of the laser wavelength and ease of implementation.

The resonant breakdown laser ignition process involves, first, a nonresonant multiphoton dissociation of molecules resulting to freed atoms, followed by a resonant photoionization of these atoms. This process generates sufficient elecctrons needed for gas breakdown. Theoretically, less input energy is required due to the resonant nature of this method.

In photochemical ignition approach, very little direct heating takes place and the laser bean brings about molecular dissociation leading to formation of radicals (i.e., highly reactive chemical species). If the production rate of the radicals produced by this approach is higher than the recombination rate (i.e., neutralizing the radicals), then the number of these highly active species will reach a threshold value, leading to an ignition event. This (radical) number augmentation scenario is named as chain-branching in chemical terms.

One of the potential advantages of the lasers lies in its flexibility to change the ignition location. Also, multiple ignition points can be achieved rather comfortably as compared to conventional electric ignition systems using spark plugs. Although the cost of the lasers has dramatically reduced to an affordable level for many applications, it is still prohibitive for technologically important applications such as automotive engines. However, their penetration in some niche markets, for example large stationary powerplants and military, are imminent. In the second part of the tutorial some applications of laser ignition in combustion engines are discussed.

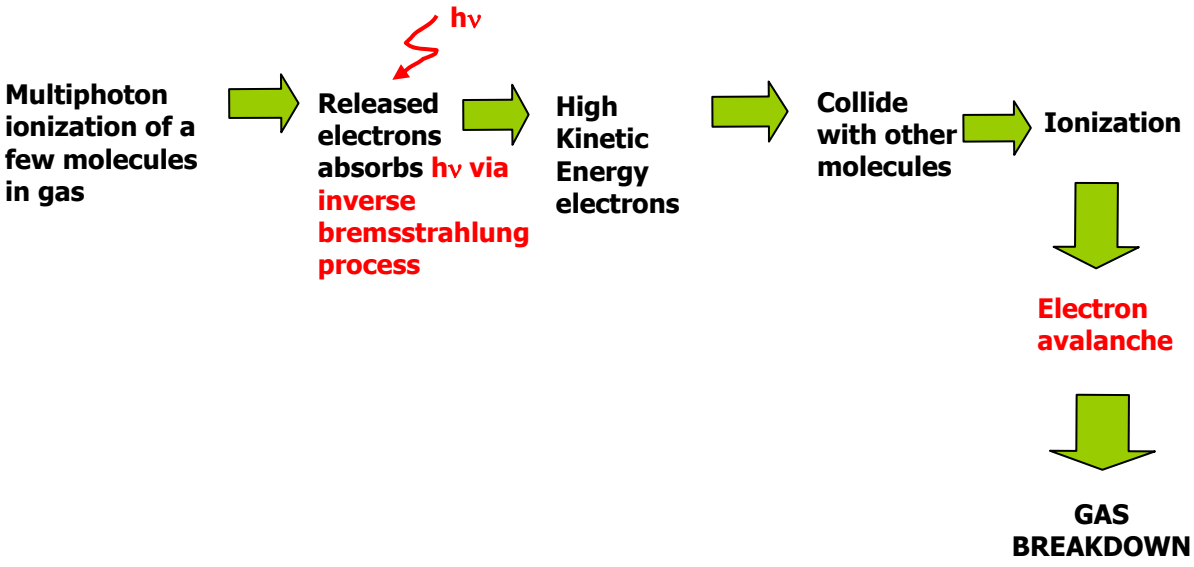

Figure 1. Nonresonant laser-induced ignition

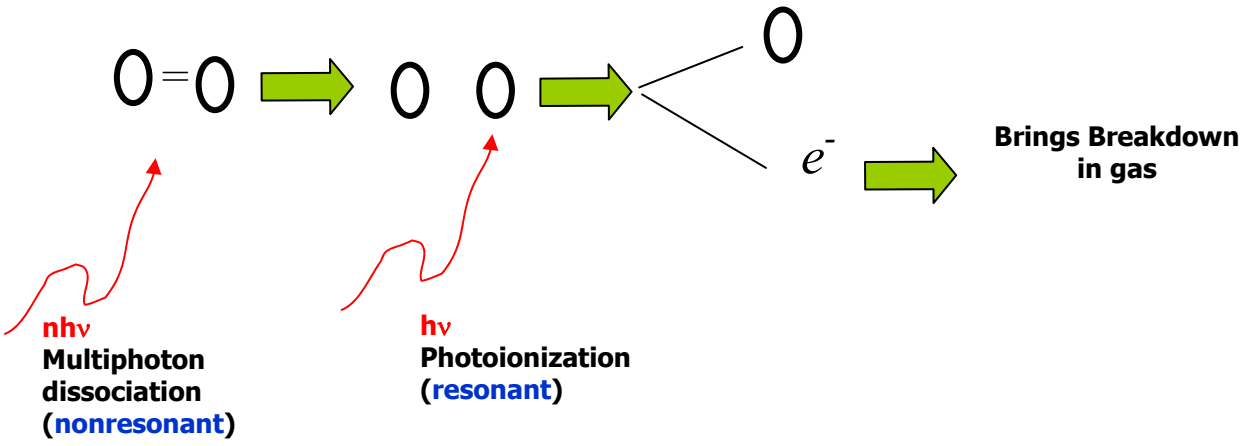

Figure 2. Resonant laser-induced ignition

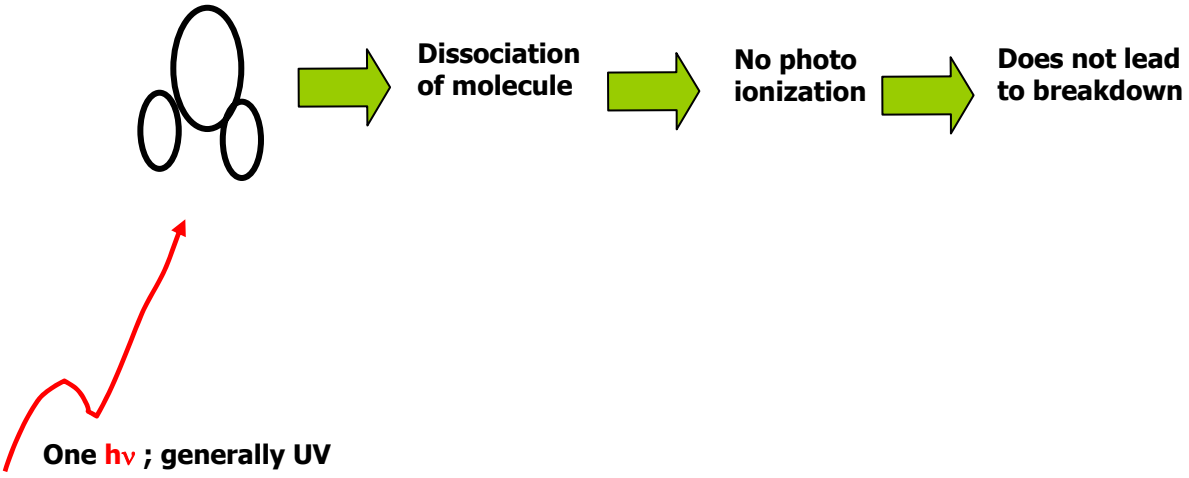

Figure 3. Photochemical laser-induced ignition