Theoretical study on sub-ns giant pulse laser induced air breakdown

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Laser ignition has been much attracted to various combustion fields because of its advantages: freedom of ignition point, multiple ignition points, wide acceptance of air/fuel ratio and pressure, etc. Giant pulse ceramic microchip laser can boost laser ignition field such as 'world first micro-laser ignited gasoline engine vehicle [1]'. We recently found out an optimum pulse width τ of ~600 ps for air breakdown by a minimum energy and the scaling law of air breakdown threshold intensity I_{th} using a pulse width tunable monolithic Nd:YAG/Cr:YAG ceramic microchip laser [2]. I_{th} was almost constant for longer pulses than ~600 ps, but had $\sim\tau^{-2}$ scaling for the shorter pulses. We here consider the mechanism of the scaling law theoretically. A generic rate equation of free electron density ρ can be given by

$$\frac{d\rho}{dt} = \eta_{casc}\rho - g\rho - \eta_{rec}\rho^3. \qquad (1)$$

The first term describes free electron gain through cascade ionization. The second term stands for diffusive electron loss out of focal volume and the third term accounts for three-body recombination loss. One can extend the classical microwave breakdown theories to optical frequencies. Considering an average electron undergoing a random translational motion by collision, the cascade ionization rate η_{casc} per electron can be given by [3]

$$\eta_{casc} = \frac{1}{\omega^2\tau_m^2+1}\left[\frac{e^2\tau_m}{cn\varepsilon_0 m\Delta E}I(t) - \frac{m\omega^2\tau_m}{M}\right], \qquad (2)$$

where τ_m is the mean free time between momentum transfer collisions, taken to be a half of 0.253 ps for 1 atm [4]; ω, laser frequency; ΔE, ionization energy; I, laser intensity; M, mass of air molecule.

The loss of diffusive electron out of the focal volume was estimated by cylindrical approximation of the volume (w_0, beam waist radius; Z_R, Rayleigh length), given by [3]

$$g = \frac{\tau\Delta E}{3m}\left[\left(\frac{2.4}{w_0}\right)^2 + \left(\frac{1}{z_R}\right)^2\right]. \qquad (3)$$

The recombination rate η_{rec} was taken to be $5\times10^{-28}\,cm^6/s$, an empirical value estimated by using temporal evolution of electron density of laser-induced plasma in air [5]. The threshold intensity was numerically calculated using Eq. (1) with assumptions that one free electron exists at a starting point of pulse and the critical free electron density for plasma is $2\times10^{19}\,cm^{-3}$. Figure 1 shows I_{th} as a function of τ for a laser with a wavelength of 1064 nm and w_0 of 20 μm. For a long pulse, the exponential growth of electron density is slowed down by recombination loss $(\propto\rho^3)$ when the density is close to the critical density. Then the growth follows the time evolution of the laser intensity, which results in the almost constant I_{th} and the breakdown timing around the center of pulse at threshold. When a pulse is shorter than the rise time of the exponential growth, a higher ionization rate due to a higher intensity is required to reach the critical density. In this region, I_{th} had $\sim\tau^{-1}$ for the current model. The deviation from the measurement and an alternative will be discussed at presentation. This work was supported by NEDO and authors thank NEDO members and machine shop engineers.

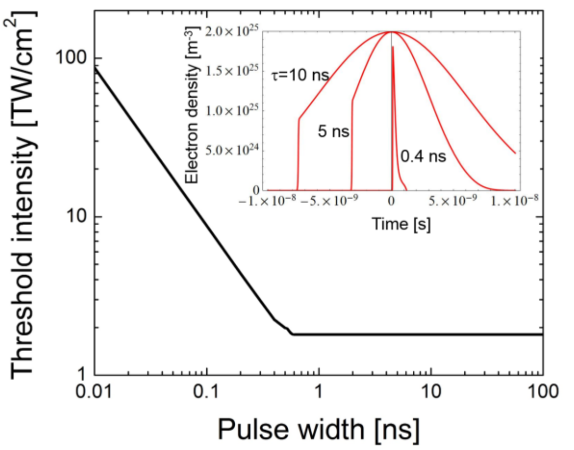

Fig. 1. Calculated breakdown threshold intensity as a function of pulse width. Inset: calculated electron density (m^{-3}) evolution in several pulses with I of 1.8 TW/cm^2.

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