Plume dynamics of laser produced air plasma

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Abstract: Dynamical evolution of air spark (plume) created using ns and ps laser pulses is investigated. Two dimensional temporal evolution images of the spark are recorded using intensified CCD orthogonal to the laser propagation direction. Optical emission spectroscopy is used to determine temperature and density of plasma. Assuming local thermodynamic equilibrium of plasma electron temperature ~ 1.1 eV and an electron density ~ 1.73 × 10^{18} cm^{-3} at the 210 mJ energy and vibrational temperature of \text{N}_2 ~ 0.45 eV is determined. The dependence of the electron density on the laser energy and delay time after the initiation of the spark is discussed. To study the plasma channel by hydrodynamic evolution of air spark in the laser focus, an experiment using pump probe configuration is done. An increase in the length by a factor of ~3 and increase in electron density by a factor of 1.5 was observed at 7 ns delay of the nanosecond pulse relative to the picoseconds laser pulse. An extensive investigation of channel formation will be discussed.

Introduction: Laser-produced plasma is transient in nature with characteristic parameters that evolve quickly and are strongly dependent on irradiation conditions such as incident laser intensity and pulse duration, laser wavelength, irradiation spot size, ambient gas composition, and ambient pressure. When a laser pulse focused in air, cascade breakdown via inverse bremsstrahlung is dominant when the product of the air pressure (P) and pulse width (\tau) P\tau > 10^{-7} torr-sec. For lower values of P\tau, multiphoton ionization is dominant mechanism for creating the spark. The spark plasma expands at the local sound speed, and collisions between the ions and ion-atom lead to the formation of the shock wave at the boundary between hot plasma and the weakly ionized gas on the periphery. Expansion of the shock wave in the plasma leaves the plasma density radially increasing thereby a waveguide is formed in to which a second pulse is injected.

The present investigation is designed to study the interaction of focused laser pulses ( nano-sec & pico-sec) of laboratory air at atmospheric pressure. Optical break down is created by focusing 8ns and 50 ps laser pulses of Nd:YAG laser at 1064 nm. Fast photography is undertaken to evaluate the evolution of plasma kernel. We report prolongation of the length of the plasma channel at atmospheric pressure in air at moderate laser intensity using two-pulse technique in a pump probe configuration. Spectroscopic methods are used for elucidating temperature and density of the plasma.

Experimental Setup: A schematic layout of the experimental setup is shown figure (1). In order to study the plasma formed in air we used the 1064nm, 8ns (full width at half maximum, FWHM, 8ns) pulses from Q-switched Nd:YAG laser ( Spectra Physics DCR-4G), which provides 900 mJ at 1064 nm at 10 Hz repetition rate and 1064 nm, 50 ps (FWHM, 50 ps) pulses from picosecond laser ( Quantel:YG901C) consists of an active passive mode locked oscillator and double pass amplifier which gives the maximum energy 80 mJ at the 1064 nm at 10 Hz repetition rate. Whereas nanosecond laser having active Q-switched oscillator (Quanta Ray INDI) gives an optical pulse 6ns (FWHM) and energy of 200 mJ at the second harmonic, 532 nm, with repetition rate of 10 Hz. To create a stable air breaks down, 8ns and 50 ps laser pulses were focused up to the maximum intensity ~ 8×10^{9} W/cm^{2} and ~ 6×10^{11} W/cm^{2} respectively. To investigate length of the plasma channel formed a 532 nm, 6 ns
laser pulse was injected into the channel at various delays relative to the picoseconds laser pulse. Variable delay between nanosecond and picosecond laser pulses was achieved using delay generator (SRS, DG535). This was also used to control the delay time between laser pulse and imaging system. Imaging of the plasma was accomplished using an intensified charge coupled device ICCD (DH720 Andor Technology) placed orthogonal to the laser propagation direction.

Results and discussion: In order to understand the evolution of electron density, temperature with time and expansion of the laser induced plasma kernel nano-second and pico-second laser pulses of 1064 nm is focused in air at atmospheric pressure. The information on the dynamics of the absorption of laser beam and propagation of the gas heating region is obtained by fast photography of the phenomenon. The laser beam is incident from the left hand side. It is been observed from the images (fig. 2) that plasma kernel is found to be advancing in the backward direction as the laser energy increases.

Figure 1 Schematic layout of the experimental setup

Velocity of the back front is found to be $1.4 \times 10^6$ cm/sec at 210 mJ. Plasma kernel becomes more asymmetrical and the backward moving plasma (opposite to the laser direction) grows much faster than the forward moving plasma (in the laser direction). This is because the radiation coming out from the hot plasma leaves the rarefied region in the focal volume. The layer of the gas present out side the plasma, although it is transparent to the laser beam, is heated by the plasma radiation. This outside gas close to the plasma will in turn be ionized to such an extent that it will strongly absorb the laser light. This layer will then be further heated very rapidly and the temperature increases. By this time a new layer of plasma nearer the laser will have become strongly absorbing, so the boundary of the plasma will move opposite to the direction of the laser beam.
The electron temperature of the spark is spectroscopically measured using ratio of intensity of spectral lines varies from 1.11 eV to 0.90 eV as delays is increased from 100 ns to 400 ns at 210 mJ energy. Transition probabilities ($A_{nm}$) and statistical weight are obtained from the literature.

The electron density measured using stark broadened profile of nitrogen NII transition at 649.2 nm shows variation of electron density from $1.73 \times 10^{18}$ cm$^{-3}$ to $0.86 \times 10^{18}$ cm$^{-3}$ on changing delay from 100 ns to 400 ns.

In order to compare the evolution of density, temperature and the expansion of plasma kernel with nanosecond pulse a 50 pico-second laser pulse is focused in air at the intensity of $6 \times 10^{13}$ W/cm$^2$. Figure 3 shows the sequence of the spark fluorescence images for various delays between the pump and probe pulses for air at atmospheric pressure where the picosecond intensity at the focus was $6 \times 10^{13}$ W/cm$^2$ and the probe pulse energy was kept just below than that required for air breakdown. As the delay is increased, the spark becomes longer in the direction away from the focusing lens. The length of the air spark at 7 ns delay between pumps and probe pulse increases by more than a factor of three times, than that of the without probe pulse shown in fig. 4. The length of the plasma channel first increases and then decreases with increase in delay is due to the fact that electron density takes some time to evolve for efficient guiding of the injected pulse.
In order to corroborate the prolongation in the length of the plasma channel we need to find out the electron density at various delays of nanosecond laser pulse relative to the picoseconds laser pulse. Assuming the plasma in local thermodynamic equilibrium the relative intensity of various NII transitions was used to find the plasma temperature. The slope of plot of $\ln(I/Ag)$ versus $E$ (excitation energy) for several spectral lines gives a temperature of $\sim 8.2$ eV of the plasma. In this experiment we measured the stark broadened line profile of 649.2 nm wavelength of NII charged ions at transition $3D^0 - 4p^3D$ at various delays and which has been used to calculate the electron density. The FWHM of the stark broadened line profile of NII transition at 649.2 nm without and with probe pulse at 7ns delay with broadenings of 0.36 and 0.54 nm respectively. The respective electron densities are $(0.98 \times 10^{17} \text{cm}^{-3})$ and $(1.47 \times 10^{17} \text{cm}^{-3})$, an increase in density by a factor of 1.5 with probe pulse.

**Conclusion:** We observe the maximum length as well as electron density of the channel is achieved at the injection delay of 7 ns thereafter length and electron density decreases due to the recombination of electrons to the parent ions. We observed the 10 times higher electron density due to nanosecond pulse as picoseconds pulse but electron density obtained due to nanosecond pulse have broad electron density profile that are unsuitable for guiding a small spot size. Due to the injection of probe pulse at controllable delay, the rate of recombination is reduces and enhances the ionization. This is why the electron density survives for longer time and hence increases the channel length.
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