Ultrashort Pulse Induced Micro-explosion Time Resolved Dynamics in Bulk UV Fused Silica

Md Mohsinur Rahman Adnan[1*], Abdallah A. AlShafey[2], Justin Twardowski[3], Noah Talisa[2], Michael Tripepi[2], Enam Chowdhury[3,1,2,**]

[1] Department of Electrical and Electronic Engineering, The Ohio State University, 2015 Neil Ave, Columbus, OH 43210
[2]Department of Physics, The Ohio State University, 191 W. Woodruff Ave, Columbus, OH 43210
[3]Department of Materials Science and Engineering, The Ohio State University 2041 N. College Rd, Columbus, OH 43210
Corresponding Author: adnan.14@osu.edu, chowdhury.24@osu.edu***

Abstract: *Ultrafast dynamics of ultrafast single pulse induced micro-explosions in bulk fused silica was captured using.time resolved shadowgraphy. Experimental and theoretical considerations identify such micro-explosions creating warm dense matter (WDM) states.*

Warm dense matter (WDM) is a phase of matter which is in too high a pressure-temperature state to be modeled as a condensed matter system yet too dense for plasma treatment. As such, matter existing in this state or phase cannot be thermodynamically described by a standard equation of state. WDM is of interest to the astrophysical community as it is hypothesized that it exists in the cores of giant planets and brown dwarfs [1]. It is also of interest to the laser community where WDM is created in processes such as inertial confinement fusion (ICF) , and ultrafast heating as an intermediate transition between the initial solid state and the final ideal plasma state [2].

In the experiment, the dynamics in bulk UV fused silica (UVFS) micro-explosions had been studied with individual pulses from a homebuilt Ti:Sapphire femtosecond laser with a pump wavelength, $\lambda = 780\,nm$, pulse duration, $t_p = 50fs$ and frequency doubled probe wavelength $390\,nm$ with orthogonal polarization with respect to that of the pump. and. The experimental setup can be seen in figure 1. The single pump pulses causing explosion were focused in a fresh site within a $\sim 2\mu m$ radius focal spot, $3.5\mu J$ energy/pulse and ~50 μm deep in the bulk, as the probe optical delay was varied. The intensity achieved was $\sim 6X10^{14}\ W/cm^2$. Special attention was given in measuring the group delay dispersion (GDD) caused by the focusing microscope objective (Mitutoyo Plan APO NIR 10x NA 0.26), and correcting them with a pair of chirped mirrors on the pump line. An identical objective was used to collect the time resolved shadowgraphs of the explosions. The power supplied ($70\ MW$) exceeds the critical power for self-focusing ($\sim 1.76\ MW$) [3], but the tight focusing setup (the energy absorption volume is within 10% [4] of tight focusing volume ~$0.475\mu m^3$[3]) to overcome this effect.

The laser frequency, $\omega = 2.42X10^{15}/s$ results in a critical electron density, $n_c = 1.84X10^{21}/cm^3$, which in turn yields an initial plasma frequency, $\omega_p = 5.36X10^{14}/s$, in proximity to the fused silica (UVFS) effective collision frequency estimate $\upsilon_{ei} \sim 5X10^{14}/s$ [5]. The threshold fluence for $780\,nm, 50\,fs$ laser pulse of UVFS is $F_{th} = 3.3J/cm^2$[6], which gives the energy absorption corresponding to the breakdown threshold of Silica to be $0.28\ MJ/cm^3$. Both adibabaticity parameter [4] and Keldysh parameter [3] calculations suggest tunneling ionization is controlling the operation regime. The impact avalanche ionization rate had been found to be $W_{imp} = 3.34X10^{15}/s$, close to the estimate of ~$10^{15}/s$, as found in [3].

After plasma breakdown, the plasma frequency rises to $\omega_p = 4.26X10^{16}/s$ with an electron density of $n_e = 5.71X10^{23}/cm^3$ and a plasma temperature $T_e = 49.65\ eV$. All these estimates are comparable to the estimates ($\omega_p \sim 10^{16}/s$, $n_e \sim 10^{23}/cm^3$, and $T_e \sim 50\ eV$) made in previous studies [3,4]. Moreover, the absorbed energy in the plasma ~6.43 MJ/cm^3 and the plasma pressure $\sim 3.44\ TPa$ is consistent with “WDM state of Silica” expectations [3,4]. Electron ion momentum exchange rate is calculated to be $\upsilon_{ei}^{mom} \sim 1.84X10^{16}/s$, which gives an energy exchange time of ~ 0.993 picoseconds. These values are comparable to estimates of previous studies $\upsilon_{ei}^{mom} \sim 2X10^{16}/s$ and an exchange time of few picoseconds [3,4]. Within this time, the electronic heat wave can move up to ~37.7 nm with respect to the Oxygen ions (the lighter ions). This gives a velocity of the electronic heat wave conduction as $\sim 37.96\ Km/s$.

This phenomenon had been captured with the help of a cooled 16-bit CMOS camera. The Signal to Noise Ratio (SNR) had been high enough to allow for capturing the expanding dense plasma cloud using time resolved shadowgraphy. As shown in figure 2, this phenomenon happens within ~ 35 to 70 picoseconds, which is comparable to the timescales for ions (Silicon and Oxygen) to start moving after the energy is transferred from electrons to ions reportedly estimated in [2]. The velocity of the "wavefront" (diffraction rings caused by the central dark plasma cloud) from captured images are calculated to be within ~$39 - 45\ km/s$, comparable to the estimated electronic heat wave conduction velocity.

Moreover, a novel ultrafast movement of a wavefront just beyond 700 picoseconds timestamp is observed. The phenomenon happens within 700 and 701 picoseconds, as depicted in figure 2. The front appears to be moving at a speed of $\sim 10^4\ km/s$, i.e. several orders of magnitude above the speed of sound in solids, and it is thought to be a phase transformation wave rather than a shock wave. Future work will include determining whether this process follows the thermodynamic shock Hugoniot curve or not.

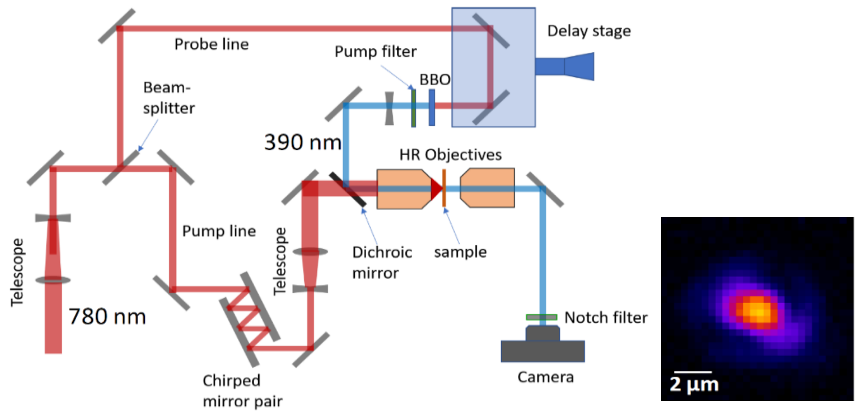

Figure 1: Pump probe setup – Energy/Pulse = 3.5uJ, Pulse duration = 50 fs, Projected intensity = 6×10^{14} Wcm^{-2}. Pump focal spot is shown to the right.

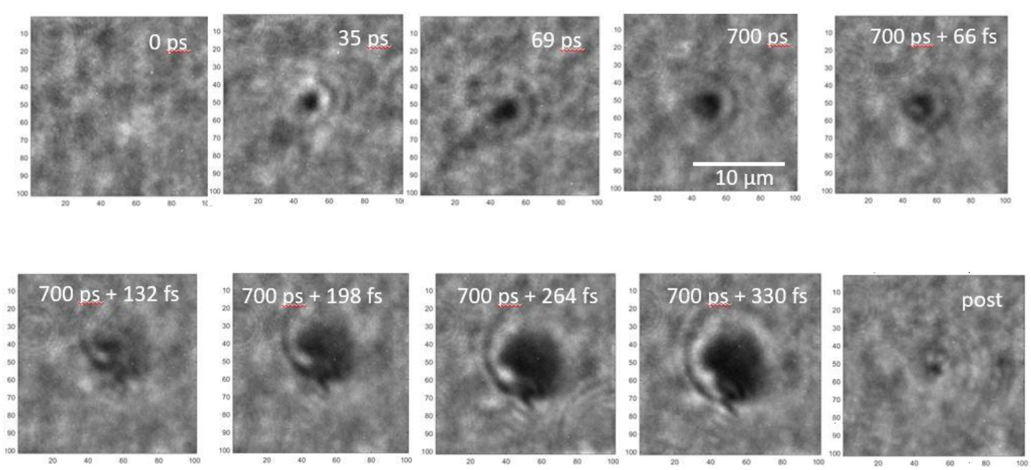

Figure 2: Micro explosion dynamics in UVFS.

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