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Effect of electrode temperature on the evolution of photoplasma under electric field

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Abstract. A photoplasma is produced by two-step resonant photoionization scheme by shining pulsed lasers on an atomic beam of barium (Ba). There is an interest in ion collection from photoplasma by electrostatic field when ion collection assembly is maintained at high temperature. A double furnace system consisting of two resistively heated furnaces has been developed. One furnace is placed on the top of the other in high vacuum chamber. The lower furnace is used to generate a wedge shaped barium atomic beam while the upper one heats the ion collection assembly. The photoplasma evolves in an external electric field produced by two parallel plate electrodes. The motion of electrons and ions in electric field generates currents that are recorded across series resistors connected to the electrodes. It is observed that a large dc current flows in the circuit when electrodes are kept at high temperature (~800 K). The large current is probably due to thermionic emission from Ba coated electrodes, electron impact ionization of vapor between electrodes, thermal ionization of vapor and leakage through insulator that holds the electrodes etc. When electrodes are at room temperature, the photoplasma is embedded in the atomic beam, where as it is produced in a vapor cell when electrodes are at high temperature. The photo-ion pulse is superimposed on the dc background current and its amplitude as well as time duration increase compared to that when electrodes are at room temperature.

1. Introduction
Plasma produced by photo-ionization of atoms with stepwise absorption of different frequencies photons is known as photoplasma. Its evolution and decay under electrostatic field with heated electrodes is a topic of interest from academic as well as technological view point [1-2]. When the electrodes are heated at temperature near the melting point of metal element, the metal ions from photoplasma reaching the electrodes are neutralized and collected in the form of liquid [3]. The occurrence of heated electrodes in laser-ionized experiments is also observed in resonance ionization laser ion source [4] which is a device used for producing wide variety of radioactive ion beams [5]. It is an important aspect to understand the mechanism of ion evolution and the factors influencing it in such type of laser-ionized plasmas. In order to investigate the effects of different parameters on ion collection at high temperature, a resistively heated furnace has been designed that heats a pair of parallel electrodes. In this paper we discuss the design of a high temperature furnace, its performance,
some problems faced at high temperature and their solutions together with the effect of temperature on photoplasma evolution.

2. Experimental set-up

The experimental system is made up with a double furnace assembly housed in a vacuum chamber and a laser system. The double furnace assembly consists of two resistively heated furnaces; one is placed on top of the other as shown in Figure 1. The lower furnace (LF) is the vapor generating furnace while the upper furnace (UF) is used to heat the ion collection assembly (ICA).

![Figure 1. Schematic of double furnace assembly consists of (a) Vapor-generating furnace (LF) and (b) Electrode-heating furnace (UF).](image)

Ba pieces are placed in a rectangular tungsten crucible surrounded on its vertical sides by a tantalum filament [6]. Ba is chosen because of its low melting point (1002 K), good vapor pressure (0.05 mbar at 1000 K), large oscillator strength (1.59) and medium ionization potential (5.2 eV) etc. The crucible is covered with a 5 mm thick tungsten lid, which has a series of collinear holes drilled along its length. The filament is heated directly by passing current through it and radiation from it heats the crucible. The effusive vapor is collimated by a set of slits. It forms a vertically moving strip-type rectangular beam of barium which is 100 mm long and 20 mm wide at a height of 70 mm from the top of the crucible lid [7]. The volume of heated zone for LF is ~ 850 c.c.

The UF houses a pair of parallel plate electrodes surrounded by its heating unit. Figure 2 shows the schematic of the heater assembly for heating the electrodes. It is a rectangular cage-shaped frame made up of molybdenum (Mo) rods open at top and bottom for the passage of atoms. Horizontal rods with insulating alumina tubes placed over them are arranged on each of the four sides to support the filament. The filament is made of Mo wire of 1mm diameter. It is wound over the insulators and is designed so as to provide open space for laser entry/exit and thermocouples. Electrodes of length 130 mm, height 110 mm and thickness 3 mm also made of Mo are placed vertically and symmetrically inside the heater cage with inter-
electrode separation of 35 mm. To contain the heat, the assembly is housed in a rectangular box with four thermal shields having appropriate openings for the entry and exit of laser beam, atomic beam and electrical connections [8]. The volume of heated zone for UF is ~ 5600 c.c. Two thick rectangular macor insulators on both sides hold the electrodes and they are placed outside the thermal shield. The UF is assembled on an inconel plate which is supported on the LF through six aluminum rods that are isolated with respect to ground with Teflon insulators.

![Figure 2. Schematic of the heater assembly for heating the electrodes.](image)

Both the furnaces are housed inside a cylindrical SS chamber with top and bottom flange. There are several openings on the flanges required for external electrical connections. A water cooling arrangements is there to cool the temperature of lower flange and lower part of the chamber. Step down transformers (20V, 100A for LF and 60 V, 100A for UF) are used for supplying electrical power. Power fed to the two furnaces is manually and independently varied. The operating pressure in chamber during the experiment was ~ 2.5x10^5 mbar.

Ba photoplasma is generated between two electrodes by two-wavelength, two-step resonant photoionization [9] using pulsed lasers. The excitation step (λ1 = 553.5 nm) is realized by pumping Rhodamine 6G dye in a dye laser with the second harmonic of a Q-switched Nd-YAG laser at 532 nm radiation. The third harmonic of the Nd-YAG laser provides the ionization step (λ2 = 355 nm). The two beam of radiation are combined using a beam combiner. They copropagate and overlap with the atomic beam to produce a cylindrical shaped barium photoplasma with circular diameter of ~ 8 mm and length ~100 mm. Since the pulse duration of the exciting pulse and ionizing pulse are ~ 7 ns and 9 ns respectively, the photoplasma is generated within ns time scale. The pulse repetition rate of the laser is 10 Hz.

The schematic circuit diagram for recording photoplasma signal is shown in figure 3. Electrode 1 (EL1) is connected to the negative terminal of high voltage power supply (M/s Aplab make, 1000V/0.3A) through a series resistor (1kΩ). Electrode 2 (EL2) and base plate
(BP) are grounded through series resistors separately. The photoionization signals developed in the electrodes are individually recorded by measuring the voltage drop across series resistors using a digital storage oscilloscope of 100 MHz bandwidth. The synchronous signal from the Q switch of Nd:YAG laser is used to externally trigger the oscilloscope. This ensures that the phenomena recorded are synchronous with the photoplasma generation.

![Figure 3. Schematic circuit diagram for recording photoplasma signal.](image)

The total current in the circuit is recorded by measuring the voltage drop across the series resistor connected to EL1 electrode. Two Chromel–Alumel thermocouples, one kept near the crucible and the other placed behind an electrode, measure temperature at two locations. The filament temperature is measured by a two-color pyrometer. The currents flowing through the series resistors have two parts, one is dc and other is ac part. The corresponding dc voltage drops across several series resistors are measured by digital multimeters.

### 3. Results and discussions

The temperature rise of filament and electrode with time at a fixed input power fed to UF is shown in figure 4. It shows that the filament attains steady state temperature almost instantaneously while the temperatures of the electrodes take longer time to attain the same because they are heated radiatively by the filament. The thermal inertia of the system is such that to perform any steady state experiment it must be allowed at least 60 minutes from the start of the heating. Since filament is the heat source and electrodes are heated indirectly, there is a temperature difference between them. It was observed ~ 550 K temperature difference between the two at 1.5 KW input power. The figure 4(b) shows that the temperature of electrode first increases and slowly decreases with time. Initially it increases because of heating the hot junction point and decrease due to heating of the cold junction of thermocouple which is connected through Teflon feed-through of the top flange. It indicates that the temperature of the top flange and the upper part of chamber increase. Several Teflon feed through in top flange are also heated and it’s out gassing rate increases. As a result vacuum inside the chamber decreases by an order of magnitude. To reduce the out gassing load i.e temperature of Teflon feed through, a copper limpet coil is brazed on the top flange as well as on the upper part of chamber. It reduces the temperature of the feed through and improves the vacuum inside chamber. The absolute magnitudes of electrode temperatures in
steady state depend on the input power and net radiation loss. Figure 5 shows the dependence of electrode temperature on input power fed to the UF filament.

Figure 4. Time dependent temperature measurement of (a) heating filament and of (b) the electrode with 1.5 kW power fed to UF.

Figure 5. Calibration of electrode temperature vs input power fed to UF.
When the input power \( \sim 1420 \text{ W} \) (45.7 A, 31.1 V) is fed to the UF, the ICA attains a temperature of \( 785 \text{ K} \) while the LF acquires 455 K without any power fed into it. Nearly 0.4 mA flows in the circuit with –1 kV on EL 1. With increasing the power of UF to 2325 W (55.9 A, 41.6 V), the ICA temperature gets raised to \( \sim 845 \text{ K} \). At the same time, the LF attains 490 K and the macor insulators supporting the ICA get heated to 400 K. The current flowing in the same circuit increases to 1.6 mA with the same voltage. The change in current is probably due to (a) leakage current through macor insulator and (b) thermionic emission from heated Mo filament. It is estimated that there is reduction of bulk resistivity of macor with the rise in temperature by a factor of \( \sim 1000 \) as compared to that at room temperature. It is estimated that the contribution of thermionic emission from Mo filament is very small. Though no power was fed to the LF, the temperature of the crucible was \( \sim 500 \text{ K} \). The vapor pressure of Ba is \( \sim 2 \times 10^{-10} \text{ mbar} \) inside the crucible at this temperature and the crucible contributes negligible Ba vapor between two electrodes.

Next both the furnaces are heated with powers of 530 W (40.7 A, 13 V) in LF and 750 W (33 A, 22.6 V) in UF. The crucible attains a steady state temperature of 820 K while the ICA attains 680 K. It is observed that the current flowing through 1 kΩ resistor connected to EL1 is \( \sim 0.8 \text{ mA} \) with –700 V applied on EL1. During this time the sides of ICA facing Ba vapor get coated and also vapor migrates to various locations. When the power fed into the heating filament of UF is increased to 1650 W (45 A, 36.6 V), while that of the LF is kept unchanged, it is observed that the temperature of ICA increases to \( \sim 775 \text{ K} \) and that of the LF remains almost unchanged. The current in the circuit starts to increase and large current flows in the circuit. It was observed that the large current burns the low wattage series resistor (2W) connected to electrodes and shorts the high voltage power supply. The components resistors and power supply were replaced with higher rating 750 W and 1KV/1A respectively. The deposited vapor on the electrode re-evaporates [8] and forms a vapor cell between two plates. Vapor also effuses through holes in ICA and deposits on the electrode holding macor insulators. A metallic thin film of Ba is formed on the macor that reduces its insulation and it behaves a short connection between electrodes at high voltage. To reduce the leakage path, the macor insulators cut in to two pieces and kept separately from each other. They are also placed in relatively lower temperature resign from the previous position. A thin aluminum sheet is placed in front of the insulator to prevent the direct deposition of Ba vapor on the insulators. This modification largely reduces the leakage path between electrodes. The Fig. 6 shows the temperature of (a) crucible, (b) electrode and (c) total current in circuit at -300 V applied on EL1 as a function of time. Under two different conditions, the UF power was 750 W (region I) and 1650 W (region II) while the LF power was kept fixed at 530 W. It is seen that a very large dc current flows in the circuit. Processes contributing to the large current can be thermionic emission from Ba coated electrodes, thermal ionization of barium vapor and electron induced ionization by thermionic electrons etc. A white coating has been observed on the faces of electrodes facing the atomic beam and it indicates the deposition of Ba and BaO on electrodes. Due to large current flowing in circuit, large voltage drops across the series resistor and the effective voltage between two plates reduces from the actual potential applied by external power supply.

When electrodes are kept at room temperature the photoplasma is produced inside the atomic beam. It is surrounded by a vacuum boundary between two plates and evolves under electric field. Where as at high temperature a vapor cell formed between two electrodes because of re-evaporation of Ba deposited on electrodes and photoplasma is formed within the vapor cell. So the photo ion pulses recorded with high temperature electrodes are superimposed on the dc background current flowing through vapor cell. The amplitude as well as time duration of photo-ion pulses produced in vapor cell increase as compared to that formed inside the atomic beam at room temperature.
Figure 6. Time dependent variation of (a) crucible temperature, (b) electrode temperature and (c) total current in circuit with -300V applied on EL1. LF power: 530 W, UF power: 750 W (I) and 1650 W (II).

As insulation of macor is largely reduced with it temperature rise, all macor make insulators are replaced by high purity (99.7%) alumina insulators to minimize the leakage. To identify the contribution of different physical processes to large current at high temperature, further experiments are in progress.

4. Conclusion
A high temperature furnace is used to study the temperature effect on photoplasma evolution. Experimental set up is modified to improve the performance of UF. An additional cooling arrangement is made to reduce the out gassing load of Teflon insulators. The electrode holding macor insulators are cut into two pieces shifted to relatively lower temperature region and shielded from direct deposition of Ba vapor to improve the insulation of macor. The Ba vapors deposit on the electrodes and various parts of UF while crucible is kept at high temperature. When sufficient vapor deposits and electrodes are kept at high temperature (~800 K), the deposited atoms are re-evaporated from them thereby producing a vapor cell. A large dc current flows in the circuit. It is due to thermionic emission from Ba coated electrodes and electron impact ionization of Ba vapor by thermionic electrons, thermal ionization etc. When electrodes are at room temperature, the photoplasma is embedded in the atomic beam bounded by vacuum boundary between electrodes, whereas it is produced in a vapor cell with electrodes at high temperature. The photo-ion pulse is superimposed on the dc background current and its amplitude as well as time duration increases with compared to that at room temperature. This is due to enhancement of vapor density as well as reduction in potential drop between the electrodes.
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