Neutral gas dynamics in fireballs

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Fireballs are local discharge phenomena on positively biased electrodes in partially ionized plasmas. Electrons, energized at a double layer, heat neutral gas which expands. The gas pressure exceeds the plasma pressure, hence becomes important to the stability and transport in fireballs. The flow of gas moves the electrode and sensors similar to a mica pendulum. Flow speed and directions are measured. A fireball gun has been developed to partially collimate the flow of hot gas and heat objects in its path. New applications of fireballs are suggested. © 2011 American Institute of Physics. [doi:10.1063/1.3594744]

I. INTRODUCTION

The coupling between charged particles and neutral gas is of general interest in partially ionized gases. This topic applies to many fields of plasma physics such as space plasmas (ionosphere,1 photosphere,2 comets,3 star formation4), fusion plasmas (pellet injections,5 divertors6), laser-produced plasmas,7 processing plasmas (helicons,8,9 capillary discharges10), and even dusty plasmas.11 In high temperature plasmas, burnout of neutrals is of primary interest. In low temperature plasmas, the coupling of ion and neutral flows is of main interest. Localized plasmas, which produce temperature gradients, lead to pressure gradients and gas flows. One example of a localized plasma is a fireball or anode discharge.12–18 Little has been reported about neutral gas properties in and surrounding fireballs. Nevertheless, the transfer of momentum and energy from the charged particles to the neutrals is an important topic in the physics of fireballs.

The present paper describes measurements of gas flows created by pulsed fireballs. The paper describes first the experimental setup and diagnostics. The section on experimental results describes various properties of gas flows. A conclusion summarizes the new findings and suggests possible applications and further investigations.

II. EXPERIMENT AND PARAMETERS

The experiments were started in the Innsbruck single-plasma machine19 and followed up in a similar device at UCLA. These are simple dc discharge plasmas between a filamentary cathode and a grounded chamber wall as anode, as schematically shown in Fig. 1(a). The plasma of density and temperature indicated in Fig. 1(a) may be immersed into a uniform axial field $B_0 < 40G$. Plasma diagnostics are performed with Langmuir probes.

Gas flows are measured with mechanical sensors as shown in Figs. 1(a)–1(c). The sensor consists of a thin transparent mica sheet (1.5 cm $\times$ 1.5 cm $\times$ 0.05 mm) suspended with two wires to form a pendulum. Gas flows cause small angular deflections which are magnified and detected by reflecting a laser beam from the mica surface. If the mica sheet rotates an angle $\delta$, the laser beam is deflected by a distance $2R\delta$, where $R = 45$ cm is the distance from the mica sensor to the point of projection. The magnification is $2R/r_0 \approx 60$, where $r_0 = 1.5$ cm is the radius from the axis of rotation to the laser reflection point. The laser beam is detected with two identical photodiodes spaced by $\Delta x = 6$ mm apart in the direction of deflection. The light spot usually swings over both diodes. By recording the two diode signals on a dual channel oscilloscope one obtains both the direction and speed of motion of the laser light spot at the diodes and thereby the speed of the mica sensor. The diode pair is also movable so as to obtain a time-of-flight diagram of the laser spot. Two similar mica sensors were employed, one for measuring the flow in axial direction, a second one for measuring flows in radial direction. An actual picture of a mica sensor is shown in Fig. 1(c). The mica sheet has two holes through which a horizontal fiber glass string passes which in turn is supported by a forklike probe. The laser spot hits the bottom of the mica sheet. The actually used mica sheets were of rectangular shape. Further improvements included a thin wire for support which had less friction than a fiber glass thread. Further properties of the sensors will be discussed below.

Fireballs are created by biasing a electrodes positively in argon at pressures $0.13 < p < 1.3$Pa (1–10 mTorr). A new fireball electrode has been developed, consisting of a circular electrode (1.8 cm diam), recessed up to 4 cm in a glass cylinder closed at one end, so as to form a plasma gun with directional gas flow properties, as shown in Fig. 2. A spherical fireball may form at the open end of the gun with diameter controlled by electrode voltage and gas pressure. Gas flows are created by switching stable fireballs on and off with an externally pulsed voltage. The electrode voltage/current (typically $150V, 1A$, $t_{on} > 10ms, t_{off} > 1s$) is switched with a pnp transistor in the presence of dc discharge (typically $100V, 0.5A$) with electron density $n_e \approx 10^4cm^{-3}$, temperature $kT_e \approx 2eV \approx 10kT_i$. A digital camera is also used to take time-averaged images of fireballs.

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It is useful to review some basic parameters. In the mid-range of gas pressures ($p \approx 0.4\text{Pa}$) the neutral gas density is $n_0 \approx 10^{14}\text{cm}^{-3}$, the thermal velocity of neutrals at room temperature $[kT_0 \approx (1/40)\text{eV}]$ is $v_0 \approx 3.5 \times 10^4\text{cm/s}$, the argon neutral collision cross section is $\sigma_0 \approx 3.5 \times 10^{-18}\text{m}^2$, which yields a mean free path $\lambda_0 = 1/(n_0\sigma_0) \approx 3\text{ mm}$. The ion-neutral total collision cross section is $\sigma_i \approx 1.57 \times 10^{-16}\text{m}^2$, which yields a mean free path $\lambda_i \approx 6\text{ mm}$ and a collision frequency $\nu_i = v_i/\lambda_i \approx (7 \times 10^6\text{cm/s})/0.6\text{ cm} \approx 12 \times 10^9\text{Hz}$. Inside the fireball, energetic electrons ($kT_e > 10\text{eV}$) with electron-argon total collision cross section is $\sigma_e \approx 10 \times 10^{-28}\text{m}^2$, have a mean free path $\lambda_e \approx 10\text{ cm}$ and collision frequency $\nu_e = v_e/\lambda_e \approx (1.9 \times 10^6\text{cm/s})/10\text{ cm} \approx 1.9 \times 10^7\text{Hz}$ for $p = 0.4\text{Pa}$. The electrons outside the fireball are colder, which decreases the collisionality in a Ramsauer gas and yields $\lambda_e \approx 50\text{ cm}$ and $\nu_e \approx 1.7 \times 10^6\text{Hz}$.

### III. EXPERIMENTAL RESULTS

#### A. Motion of fireball electrodes

Fireballs are created when ionization occurs in an electron-rich sheath of a positively biased electrode. Ions in an electron-rich sheath cause sheath expansion and production of a double layer at the boundary of the fireball. The potential drop is of order of the ionization potential ($\approx 15\text{eV}$), resulting in plasma production by hot electrons inside the fireball. Steady-state double layers/fireballs are produced when electrons are collected and ions ejected at their respective saturation currents which establishes momentum balance. The latter also explains why 3D fireballs have a symmetric structure.

In most experiments on fireballs the electrodes are supported rigidly. When the electrode is movable it has been observed that it recoils when a fireball is formed. In order to investigate the cause of this effect the electrode has been suspended from a thin wire so as to form a gravitational pendulum. In order to minimize the mass, the electrode is made of a grid (four lines per mm, 2 cm $\times$ 2 cm a square), backed by a thin mica sheet so as to allow fireball formation only on one side. Whenever a fireball is formed the electrode strongly recoils in the direction opposite to the fireball. The pendulum makes large excursions when driven resonantly by pulsed fireballs as is shown in a short video clip. No motion is observed when the electrode is biased negatively to collect ions. The motion is only created during fireball formation and decay but not for steady state fireballs. The motion occurs with or without magnetic fields. If a fireball is created on a second electrode the unbiased pendulum is pushed away from the fireball. Nonconducting objects are also repelled radially away from a pulsed fireball.

From these observations one must conclude that the motion is not caused by electromagnetic forces or by electron and ion pressure but by neutral gas flow created during fireball formation. Localized heating produces gas expansion which can accelerate objects, a well-known example of which is the Crookes “radiometer.” The following experiments are designed to measure the gas flow in direction and strength.
B. Mica pendulum response

Time and space-resolved measurement of neutral gas flows at pressures of 0.13 Pa are not trivial. In the present work we use a small pendulum as a sensor for gas pressures. It is made of a thin mica sheet, which is deflected by gas flows. Small deflections are measured optically by reflecting a laser beam from the mica surface which greatly enhances the measurement sensitivity. The light-weight mica sheet (\(30 \text{ mg}\)) is supported vertically by two thin W wires (0.1 mm diameter) inserted through thin holes near the upper edges of the mica sheet. Two wires are needed to restrict the pendulum motion to one direction. The resonance frequency of the mica sheet is measured to be 0.13 Hz, which agrees well with the experimental result.

The measured oscillation is shown in Fig. 3 in both the time domain (a) and the frequency domain (b). Two light pulses are generated per period as the laser beam oscillates between the pivot point and the center of mass, \(m\) is the mass, and \(g\) the gravitational acceleration. For a constant mass density and thickness, and rotation axis along the upper edge one finds an oscillation period \(T = 2\pi/(3/3)^{1/2}\) of 5 Hz, which agrees well with the experimental result.

The measured oscillation is shown in Fig. 3 in both the time domain (a) and the frequency domain (b). Two light pulses are generated per period as the laser beam oscillates over the photodiode. Harmonics arise since the light pulses are not sinusoidal. The weak damping is mainly due to friction at the support points and less due to the low pressure gas.

C. Force on pendulum

In response to the turn-on of a fireball the sensor is deflected backwards and begins to oscillate. Of particular interest is the initial angular motion of the light beams from which the force on the sensor can be derived. Figure 4(a) shows the light signals from the two identical photodiodes and the fireball current waveform. The time lag between the two signals yields the velocity of the laser beam spot between the two diodes \(\nu = \Delta \xi/\Delta \tau\), with \(\Delta \xi\) being the distance between the two diodes. The time lag between equal intensity values is observed to decrease in time. Figure 4(b) shows the velocity \(\nu\) versus time \(t\) when the laser beam spot is between the two diodes. During the start of the oscillation the velocity rises linearly in time, implying a constant acceleration of the laser beam spot \(d\nu/dt = 2R\nu^2\delta/dt^2 = 22\text{ m/s}^2\). The mica plate is a rigid rotor whose angular acceleration is produced by a torque \(\tau = I_{\text{rot}}d\theta/dt^2\), where \(I_{\text{rot}} = \int r^2 dm = mr_0^2/3\) is the moment of inertia and \(\tau = \int d\tau = (pr_0^2)/2\) is a torque on the mica plate due to the gas pressure \(p\). The latter can be evaluated from the measured acceleration as \(p = (2/3)(m/r_0)\delta/dt^2 = (2/3) \times 30 \times 10^{-6}\text{kg} \times 23\text{ (m/s}^2\) \((1.5 \times 50 \times 10^{-3}\text{m}^2) \approx 3.1 \times 10^{-1}\text{Pa}.

As noted before the charged particle pressure is too small to account for this observation, \(nkT_e < nkT_e \approx 196\text{.}

FIG. 3. Oscillations of the radial mica pendulum. (a) Light detected by one photodiode from a reflected laser beam showing a weakly damped oscillation with two light pulses per pendulum period. (b) Fourier transform of the light pulses showing a pendulum resonance frequency of \(f_{\text{res}} = 5.1\text{ Hz.}

FIG. 4. (Color online) Measurement of the gas pressure at 3 cm distance from a pulsed fireball. (a) Light from two adjacent photodiodes whose time delay yields the instantaneous velocity of the mica sensor. Fireball current waveform at bottom. (b) Velocity of the laser spot increases linearly with time \(t\) relative to turn-on of the fireball. Slope yields acceleration from which the gas pressure on the mica sensor is calculated.
$10^9 \text{cm}^{-3} \times 2 \text{ eV} = 3.2 \times 10^{-4} \text{Pa}$. However, the neutral gas pressure is very significant, $n_0 kT_0 \approx 10^{14} \text{cm}^{-3} \times (1/40)$ eV $\approx 0.4 \text{Pa}$ at room temperature. Thus, when the gas inside the fireball is heated a transient pressure gradient develops which causes the gas to expand. Neutrals may also be accelerated by charge exchange from ions, but only outside the fireball where ions are radially accelerated at the double layer. In electron-neutral collisions only a small fraction ($m_e/2m_i$) $\approx 6 \times 10^{-6}$ of $kT_e$ is transferred to the neutrons. Thus, for a collision time $\nu_{z}^{-1} \approx 50\text{ns}$ the electron-neutral thermalization would take 8 ms without heat losses. However, neutrals traverse the fireball in $\approx 0.1 \text{ms}$ and transport the heat to the large bath of cold gas and the chamber wall. Radial flows will be established which last until a steady-state temperature profile has been established. Next we measure the flow velocity.

### D. Flow velocity

A fireball has been produced on an axially movable electrode. By increasing the distance between the fireball and the mica sensor a delay in the light peaks is observed. Thus the gas pressure on the mica pendulum exhibits a propagation delay from which the gas flow velocity can be obtained.

Figure 5 shows a time-of-flight diagram of the gas flow, i.e., the distance between the fireball and the mica sensor versus the time delay of the light pulses. The insert shows the light signal from one photodiode at two different positions $z$, depicting clearly a time delay $\Delta t$ which is determined at the half-intensity point of the light signal during the fireball pulse. The lower rectangular pulse is due to the light of the fireball pulse which exhibits no delay. The time delay of the laser spot only reflects the delayed motion of the sensor with distance from the fireball and has no relation to the speed of light. After the sensor has been accelerated the laser spot swings back over the photodiodes and produces the second shorter light pulse after the end of the fireball. The pulse width gradually increases with distance implying a decrease in the pendulum velocity with distance $z$.

![Figure 5](image.jpg)

**Figure 5.** (Color online) Time-of-flight measurement of the flow velocity of neutrals. Inset shows light pulses for two different distances $z$ between fireball and mica plate. The delayed onset of pendulum oscillations is due to the gas travel time from the fireball to the mica plate. Fireball parameters: $V_{\text{electrode}} = 150\text{V}$, $I_{\text{electrode}} = 0.2\text{A}$, $t_{\text{pulse}} = 25\text{ms}$, $t_{\text{rep}} = 5\text{s}$ in Ar at 0.4 Pa. The observed flow velocity $v \approx 37 \text{m/s}$ is well below the sound speed $v_s \approx 320 \text{m/s}$. Thus, the deflection of the mica sheet is not due to transient sound or shock waves. Those would be excited if the gas was heated abruptly. Here the gas heating is relatively slow which produces an expanding gas puff.

The flow of gas against the mica plate exerts a pressure, $p_0 = n_0 kT_0 V_{\text{flow}}^2$, where $n_0$ is the argon mass, $n_0 \approx 2 \times 10^{20} \text{m}^{-3}$ is the neutral density at 0.8 Pa, and $V_{\text{flow}} \approx 37 \text{m/s}$ is the flow velocity. The resultant pressure $p_0 \approx 1.9 \times 10^{-3} \text{Pa}$ is close to that inferred from the acceleration of the mica sheet in Fig. 4 ($3 \times 10^{-2} \text{Pa}$).

It is also interesting to consider the energy transport from the fireball to the neutral gas and the mica sensor. The latter is directly measured in the form of the kinetic energy $K = I_{\text{flow}} \omega^2/2 = (1/3) m_{\text{mica}} V_{\text{mica}}^2/2 \approx 1.8 \times 10^{-3} \text{J}$, where $V_{\text{mica}} = r_0 \omega \approx 0.06 \text{m/s}$. The energy density of the neutral gas flow was found to be $p_0 \approx 1.9 \times 10^{-2} \text{J/m}^3$. The volume of gas streaming toward the mica sheet is given by a cone with spherical angle given by the sensor surface and its distance $r_0 \approx 10 \text{cm}$ from the fireball center, $\Omega \approx 3 \times 10^{-3} \text{sr}$, hence $V_{\text{cone}} = (4/3) \pi r_0^3 \Omega \approx 13 \text{cm}^3$. Assuming constant energy density the kinetic energy in the gas flow is $K_{\text{gas}} = p_0 V_{\text{cone}} \approx 2.5 \times 10^{-7} \text{J}$. Thus, only a fraction 1.8/295% of the gas energy is transferred to the sensor.

Finally, one can also estimate the thermal energy in a fireball of radius $r_{\text{fb}} = 1.5 \text{cm}$ with density $\rho_{\text{fb}} = 10^8 \text{cm}^{-3}$ and temperature $kT_e = 10 \text{eV}$ and finds $U = n_e kT_e (4/3) \pi r_{\text{fb}}^3 / 2 \approx 2.3 \times 10^{-7} \text{J}$. In comparison, the total gas energy is $K_{\text{gas}} = p_0 (4/3) \pi r_0^3 \approx 8 \times 10^{-3} \text{J}$ or larger since the stream extends beyond $r_0$. Since the electron energy is small compared to the kinetic energy of the neutrons the electrons are not the energy source but only the means of transferring the externally applied electrical energy to heat the gas. The external power supply delivers $U = V_{\text{pulse}} \approx 150 \text{V} \times 0.1 \text{A}$ and $\Delta t \approx 1.5 \text{ms}$ to the fireball, most of which is dissipated by electrons at the fireball electrode, but some of it goes into kinetic energy of the gas via heating by elastic electron-neutral collisions. Ions have a better heat transfer to neutrals but have less energy to transfer. At a low degree of ionization neutrals cool ions and create ion flows. Thus, the neutrals can affect heat and charged particle transport.

### E. Pendulum time-of-flight measurement

In order to further interpret the waveform of the diode signals it is useful to perform a time-of-flight measurement of the laser beam spot, hence mica pendulum. For this purpose the pair of photodiodes has been placed at different positions along the direction of the laser beam spot deflection and at each location both diode signals have been recorded simultaneously from repeated experiments. A raw trace is shown in Fig. 6(a), which depicts both the light of the fireball pulse and that of the dc laser beam spot. The motion of the laser beam spot across the diodes produces light pulses whose delay or half width are a measure of the beam velocity. Since two discrete lines are resolved the laser beam spot is narrower than the diode separation and the beam excursion well exceeds the diode spacing. The first pair of diode pulses...
indicates that the mica sensor has been deflected away from the fireball. The second and subsequent pulses are due to the pendulum motion. As the diode pair is moved over a range \( 0 < x < 15 \text{cm} \) the time lag between the pulse pairs changes, which is displayed in the time-of-flight diagram of Fig. 6(b). The dashed lines indicate the pendulum oscillation, which is not sinusoidal during the fireball since the pendulum is accelerated. No data are obtained for \( x < 0 \) due to an access problem. The velocity and excursion of the mica pendulum is reduced by a factor \( 2R/r_0 \simeq 60 \) over that of the laser beam spot. During the fireball the laser spot moves at an average velocity of \( \Delta x/\Delta t \simeq 2.3 \text{ m/s} \), which increases to 3.3 m/s after the end of the pulse due to gas reflux in the direction of the pendulum swing. Well after the end of the fireball pulse the velocity gradually decreases and the pendulum oscillates sinusoidally.

At the start of the fireball the velocity increases which is best resolved by evaluating the time delay between the two diode signals which is shown in Fig. 6(c). The acceleration \( dv/dt \) decreases in time since with increasing deflection angle the gravitational restoring force decelerates the pendulum.

**F. Fireball pulse width dependence**

With the knowledge of the pendulum properties one can now interpret the observed dependence of the pendulum velocity on the pulse width of the fireball, which is shown in Fig. 7. The time dependence of the light detected by the two photodiodes [Fig. 7(a)] shows that prior to the fireball pulse the pendulum swings slowly toward the fireball. This motion is the remnant oscillation from the previous fireball applied 2 s earlier. The gas expansion created by the fireball decelerates the pendulum, reverses its motion, and produces the second pair of light pulses whose narrower spacing indicates an increased velocity. The gas expansion continues to accelerate the mica sensor until it reaches the maximum pendulum swing at \( t \simeq 120 \text{ms} \). Thereafter the mica sheet swings back toward the fireball and is decelerated by the gas expansion until the fireball is switched off. After the end of the fireball pulse the pendulum swings undisturbed with velocity \( v_{\text{max}} \). Thus, both the initial phase of the pendulum oscillation and the forces during the fireball determine its motion.
The peak velocity after the fireball pulse varies with pulse width as shown in Fig. 7(b). For very short pulses ($t < 10 \text{ ms}$) the gas heating, hence the force on the pendulum, are negligible. The largest velocity is observed when the pulse width is approximately one quarter of the pendulum period, provided the pendulum starts from at rest. When the pulse length equals approximately half the pendulum period the acceleration during the motion away from the fireball is canceled during the back swing toward the fireball when it moves against the gas flow.

G. Multiple fireball pulses

Successively repeated fireball pulses can influence the pendulum motion constructively or destructively. An example for a double pulse is shown in Fig. 8. For comparison, Fig. 8(a) starts with a single pulse which simply sets the pendulum into motion, indicated by repeated light pulses as the laser beam spot swings back and forth over the two photodiodes. When a second identical fireball pulse is added with a delay equal to half a pendulum period its force stops the return motion of the pendulum since there are no subsequent oscillations [Fig. 8(b)]. The effect is similar to that of a long pulse of width equal to a half period of the pendulum oscillation except that two discrete puffs of gas have been produced.

When the repetition time of the two pulses is increased to one pendulum period the oscillation is constructively enhanced. When a continuous train of pulses with $T_{\text{rep}} = T_{\text{period}}$ is applied the pendulum is driven resonantly to large amplitudes. This amplification permits sensitive measurements of small gas flows. When the pulse frequency is tuned through the pendulum resonance the pendulum reverses phase.

H. Gas expansion and contraction

The above results have clearly demonstrated that neutral gas expands when a fireball is turned on. When now show that a reverse gas flow is created when the fireball is turned off and the gas streams back into the volume occupied by the earlier fireball. Depending on the direction of motion the pendulum may be accelerated or decelerated by the return flow.

Figure 9 demonstrates in detail the acceleration and deceleration of the axial pendulum by a pulsed fireball. At the turn-on of the fireball the outflow of gas repels the mica sheet from the fireball (see sketch at top). This causes the laser beam spot to move from photodiode 2 to 1. The laser beam spot passes over the diode 1, reaches its maximum excursion, and crosses again diode 1 as the pendulum swings back. The large excursion is caused by the acceleration due to the gas outflow. As the pendulum returns it moves against the flow and is decelerated. It reaches diode 2 but does not swing beyond it since there is no second pulse from diode 2. Continued outflow accelerates the pendulum away from the fireball such that the beam passes again over diode 1 producing its third pulse.

Near the maximum excursion ($t \approx 150 \text{ ms}$) the fireball is switched off. As the pendulum swings back toward the fireball its velocity increases as indicated by the narrow pulse width for the fourth pulse on diode 1. The beam also

![FIG. 8](image-url)

**FIG. 8.** (Color online) Light from two adjacent photodiodes due to multiple short fireball pulses (large peaks) and due to the oscillating laser beam (adjacent double pulses). (a) A single fireball pulse causes the mica pendulum to oscillate repeatedly. (b) When a second fireball, delayed by one half period of the pendulum oscillation, is applied the resultant gas pressure stops the return swing of the pendulum and no further oscillations are observed.

![FIG. 9](image-url)

**FIG. 9.** (Color online) Acceleration and deceleration of the mica pendulum during a long fireball pulse. Acceleration occurs when the pendulum swings in the direction of the gas flow. The highest velocity is observed after the end of the fireball due to the added acceleration from the gas flowing back to the fireball after switch-off.
passes diode 2, overshoots it and returns to produce another signal on diode 2. The close spacing between the two diode signals also confirms the high speed of the laser spot ($v_{\text{max}} \approx 0.43 \text{ m/s}$).

The observation of a strong acceleration after the end of the fireball confirms that gas streams back toward the fireball. Gas heating during the fireball had created a density depression. After the fireball pulse the gas cools which creates a pressure minimum that is equilibrated by a return flow of ambient gas.

A fireball is a localized discharge around an electrode. The ambient plasma is also created by a finite discharge, although of much larger size. Thus, gas flows should also be produced by a pulsed discharge plasma without fireballs.

Indeed, the sensitive pendulum detector indicates gas flows as shown schematically on the top. The rest position of the laser beam spot is between both diodes.

The discharge current has a square waveform of low repetition rate since the pendulum is weakly damped. At the turn-off of the discharge the laser beam spot is deflected first toward diode 1, then toward diode 2. Since there are no repeated pulses on either diode the light beam does not overshoot beyond each diode. The laser beam was initially between the diodes. Its deflection toward diode 1 implies a gas return flow toward the decaying plasma source. The subsequent pendulum oscillations decay very slowly indicating little friction and no steady state gas flows. At the turn-on of the discharge ($t \approx 6 \text{ s}$) the laser beam spot happens to be on diode 2 such that the pendulum begins to move toward the discharge. The expanding gas from the discharge decelerates this motion since the laser beam barely deflects toward diode 1 which results in a small diode signal. The subsequent small diode signals show that the gas flow at turn-on has reduced the pendulum oscillations produced at the turn-off. The transient gas flows are in opposite directions, away from the discharge at turn-on, toward the discharge at turn-off, just like in fireballs.

The mica sensor has a remarkable sensitivity which can also detect pressure fluctuations in the background gas without a discharge. It is evident that the ratio of the peak signals from diode 1 and diode 2 varies, implying that the center position of the beam shifts in time or the pendulum rest position is randomly deflected due to gas flows. Small gas fluctuations can be caused by the vacuum pumps and/or leak valve.

I. Diverging and collimated flows

In order to map the flow field it would be desirable to have a movable sensor. However, a mica pendulum is not easily movable due to the laser beam alignment and port access. Thus, it was easier to move the electrode which produces the fireball. A double-sided 2 cm diameter disk without a constricting tube, movable in axial and radial directions, was first used to produce nearly spherical fireballs. Figure 11 shows that the mica sheet is deflected away from the fireball on either side of the fireball. The delay between the two diode signals is almost identical for both cases, but the direction of deflection is reversed. Because of the spherical symmetry of fireballs the gas flow is therefore radially outward, except for a shadow behind the electrode. The radially diverging flow must be transient to satisfy particle conservation without sources $\nabla \cdot (\rho \mathbf{v}) + \partial n/\partial t = 0$.

For some applications it would be desirable to produce a collimated gas flow. This can be partly accomplished by producing a fireball in a container, which prevents radially flowing gas. For this purpose the disk electrode has been inserted into a glass cylinder as shown in Fig. 2. For a small recession depth a spherical fireball still forms at the end of the cylinder. But when the electrode is recessed by about two tube diameters ($\approx 4 \text{ cm}$ for a 1.8 cm diameter tube) a long

![FIG. 10. (Color online) Gas flows in a pulsed discharge without fireballs. At turn-off of the discharge current $I_{\text{dis}}$, the pendulum is accelerated toward the discharge due to gas cooling. At turn-on the beam deflection and geometry (see sketch on top) indicates a gas flow away from the plasma caused by gas heating.](image-url)

![FIG. 11. (Color online) Radial flow from a spherical fireball is demonstrated by placing the fireball on opposite sides of the mica pendulum. The laser light pulses show opposite directions of pendulum motion with similar speeds. Distance between fireball and axial mica sensor $\Delta z = 5 \text{ cm}$.](image-url)
cylindrical fireball is formed. No magnetic field is applied. For a fireball current $I = 1\text{A}$, electrode area $A = 2.5 \text{ cm}^2$ and $kT_e \approx 10\text{eV}$ the density inside the gun is $n_e \approx 4.6 \times 10^{19}\text{cm}^{-3}$. By varying the electrode voltage the fireball can be terminated at the opening of the tube. In such a “fireball gun” the heated gas can only escape axially in one direction. With a gas feed into the tube a steady-state flow can possibly be achieved.

In order to measure the gas flow as a function of angle the gun is rotated horizontally while the radial mica sensor remains fixed. Figure 12(a) shows a polar plot of the velocity of the mica sensor due to gas flow from the fireball. The gas flow peaks along the gun axis with a half width of $\approx 30^\circ$. Such a directional gas flow is far more intense than that from a spherical fireball. Figure 12(b) shows that a wire crossing the fireball is heated and glows red ($T_{\text{wire}} \approx 500^\circ\text{C}$).

Assuming that the heating is caused by hot neutrals from the fireball their temperature must well exceed that of the wire since the pulsed heating occurs at a low duty cycle ($t_{\text{on}}/t_{\text{off}} = 0.1s/2s = 5\%$). Further work on heat transport is needed for new fireball applications.

**IV. CONCLUSIONS**

Neutral gas flows in pulsed fireballs and discharges have been investigated experimentally. The main diagnostic tool is a mica sensor, which is deflected by gas flows. The pulsed gun properties have been demonstrated so as to interpret the gas dynamics in fireballs. Heating and cooling of gas causes gas flows which have been measured for various pulse conditions. The flows from a spherical fireball are radially diverging but can be partially collimated by a cylindrical fireball outflow regions. High neutral gas temperatures are observed in the gun outflow regions.

These initial observations may open up a variety of further studies and applications. For example, the role of neutrals in the transfer of momentum and energy in fireball plasmas has not received much attention. Neutral burn-out in high current fireballs and resulting instabilities should be investigated. Since fireballs produce measurable pressure pulses low frequency sound waves can be excited with fireballs in plasmas whose dimensions exceed the sound wavelength.

Applications of gas flows include simple mechanical devices like the present pendulum, rotations like the Crooke’s radiometer, convection of dust particles, possible nanometer structures, drag of ions, etc. Flows can be used to pump gas, separate different gases, deposit gas on surfaces, perform plasma chemistry at high temperatures. The present sensor could be miniaturized for improved flow measurements at pressures $<0.1\text{Pa}$.

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AQ1: Please check the use of roman versus italic in mathematical expressions and in the text throughout for consistency.