Abstract. The paper describes experimental and theoretical studies of shock propagation in weakly ionized plasmas and of plasma effects on supersonic aerodynamics. Laser Schlieren measurements of shock profiles and velocities in continuous and pulsed glow discharges in conjunction with CFD modeling show that “anomalies” are explained by conventional gas dynamics, with critical role of non-one-dimensionality due to transverse temperature gradients. Experiments with pulsed discharges directly prove the thermal mechanism of shock dispersion. For aerodynamic applications, localized and controllable energy addition to the flow through plasma could provide a tool of controlling shocks and heat fluxes, and of steering. Filamentary microwave plasma initiated and guided by low-power lasers and electron beams could be such a flexible and efficient tool. Successful development and testing of a small-scale wind tunnel with microwave-driven plasma is reported.

1. Introduction
Weakly ionized gases (plasmas) could find several types of applications in high-speed aerodynamics, such as shock wave control, drag reduction, vehicle steering, sonic boom attenuation, ignition of combustion in engines, and MHD power extraction and enthalpy by-pass. There are at least two groups of fundamental issues that have to be resolved prior to any practical applications:
1. What is the mechanism, or mechanisms, of plasma effects on supersonic flow, especially on shock waves? Are the mechanisms thermal, due mostly to Joule heating, or there exists a plasma-specific phenomenon (electric double layer, ion-acoustic or other waves, etc.) that affects shock waves?
2. How efficiently one can generate, sustain, and control plasmas in high-speed airflow?

Several research projects at Princeton University address these and other plasma-related issues. In this paper, we review some of the ideas and results of these projects. First, we describe theoretical and experimental studies of “anomalous” effects in shock propagation through glow-discharge plasmas [1–4,7,8]. We show that the experimentally observed effects can be explained by conventional gas dynamics that takes into account non-one-dimensionality of the problem. Since microwave streamer discharges can propagate supersonically and could be useful in aerodynamics as concentrated energy sources, we discuss triggering and guiding those discharges by lasers [3,5] and recent development of an experimental facility for studies of microwave plasmas in supersonic flow [6]. Electron beams are also discussed as an energy-efficient way of generating plasmas that can be sustained in high-speed flows [9].

2. Experiments on shock propagation in steady-state glow discharges [4,1]

2.1. Experimental facility and procedures [2–4]

Experimental studies of shock waves in weakly ionized plasmas were performed in longitudinal continuous or pulsed glow discharges. The discharge tube, 3.8cm i.d. and 120cm full length, was made of quartz. Shock waves were generated by a spark discharge at the one end of the tube. The shock wave entered the discharge through a narrow (2mm) ring electrode made of stainless steel foil mounted flush with the wall. The electrode nearest to the spark was always the anode, in order to prevent the incoming shock wave from passing by the hot cathode region.

Laser Schlieren method was used for detecting the shock front. A He-Ne laser beam crossed the discharge horizontally along the diameter and was then focused onto the plane of a knife by a lens (f=50cm). The beam 1/e diameter was about 0.3mm. A photodiode with a response time of 20ns measured the light intensity after the knife edge. The signal was recorded by a digital oscilloscope with 10Ω resistor at the input, and a time resolution 0.1μs.

After the laser beam crossed the discharge it was retro-reflected from a small 90° prism and passed through the discharge once more with the spatial offset and then focused onto the knife edge. This produced two closely separated Schlieren signals of opposite signs. Shock wave velocity was found by dividing the distance between the two
beam passages (12 to 21mm) by the time gap between Schlieren signals. This method provided an accuracy of absolute velocity near 3% (\(\pm 10\text{ m/s}\)) and that of relative velocity about 0.5% (2m/s).

Experiments were performed in an \(\text{Ar-N}_2\) mixture (1% of \(\text{N}_2\)). Addition of nitrogen substantially improved the radial uniformity of the discharge. A pure argon discharge contracted at currents \(i>30–40\text{mA}\) (for pressures \(p\geq 30\text{Torr}\)). With nitrogen the discharge was not contracted at all conditions studied \((p\leq 100\text{Torr}, i\leq 100\text{ mA})\). To prevent electrophoresis and accumulation of impurities, the gas mixture was pumped through the discharge with a rate of 300sccm, which corresponded to 5–10cm/s linear speed in the tube.

For \(p=30-50\text{Torr}, i=30-100\text{mA}\) the measured electric field was from 8 to 14 V/cm. Assuming a Bessel radial profile for gas temperature, we calculated the reduced electric field \(E/N\) (\(N\) is gas number density) and electron number density \(n_e\). Averaged over the tube cross section, these values are \(E/N=1.2–1.4\text{Td}, n_e=(1.2–4)\times 10^{10}\text{cm}^{-3}\).

We have used Ultraviolet Filtered Rayleigh Scattering (UV FRS) developed in our group \([10–12]\) to measure temperature profiles of the discharges. For the range of experimental conditions studied, \(p=30–50\text{Torr}, i=30–100\text{mA}\), the steady-state centerline temperature range was found to be from 440\(\pm 30\)K to 830\(\pm 70\)K. Fig.1 shows the experimental temperature profile of an argon plasma at pressure 50Torr and current 20mA. Similar measurements were done in argon +1% nitrogen mixture at 50Torr and different values of electric current. The experimental points are in good agreement with computation. On the plot, the experimental points are fitted with a Gaussian curve.

**Fig.1.** Radial temperature profile in Ar glow discharge tube measured by UV Filtered Rayleigh Scattering. Pressure and electric current are indicated on the plot. Fitting curve is Gaussian.

### 2.2. Results of shock studies in steady-state discharges and comparison with CFD modeling \([1, 4]\)

In our earlier work \([1]\), we performed a 2D inviscid modeling of shock propagation through a discharge-heated gas and concluded that transverse gradient and non-one-dimensionality play a crucial role in shock propagation in glow discharges, and that multi-peak laser Schlieren signals are simply due to the shock curvature. For better comparison with experiments, the code was made from 2D into axisymmetric.

The plasma region between the infinitesimally thin electrodes was considered uniform along the tube axis \((x)\), and to have a symmetric radial temperature profile described by the Gaussian fit to the experimentally measured profile. Both wall temperature and the gas temperature outside the discharge were put equal to room temperature. Mach number of the incident shock was selected so as to give the shock velocity in the uniform room-temperature gas at a given location close to that measured experimentally with the discharge off. For comparison with laser Schlieren measurements, the density gradient integrated in \(x\) direction across the “laser beam” and averaged in the radial direction across the tube was computed.

Fig.2 shows measured and computed Schlieren signals in pure argon. Similar comparison was done for \(\text{Ar}+1\%\text{N}_2\). Agreement between the computations and experiments, in both shock velocities and the two-peak signal shapes, is excellent. The two-peak structure of the laser Schlieren signals is due to the curvature of the shock front in a region with transverse temperature gradient. The first peak in the Schlieren signal comes from the portion of the shock that propagates through the hot centerline region. The high temperature and low density in this region result in both higher speed of the shock and lower intensity of the peak compared with those corresponding to colder near-wall regions. The portion of the shock moving through the cold near-wall region lags behind and produces a strong peak in the signal due to the high density near the wall.

For further quantitative comparison between computational and experimental results, Figures 3 and 4 show the width of Schlieren signals versus centerline temperature and the shock velocity versus average temperature in the discharge. Again, excellent agreement exists between computations and experimental data. This provides a strong evidence of conventional, thermal mechanism of shock propagation in weakly ionized plasmas.
Fig. 2. Experimentally measured and simulated laser Schlieren signals for shocks in glow discharge in Ar at 50 Torr. The discharge current is 20 mA. The first of the two laser beams is located 18 cm from the entrance to the discharge, and the spacing between the two beams is 3.6 cm. The measured and computed shock velocities are indicated on the figure.

Fig. 3. Width of the Schlieren signal in the discharge (Δ) minus the signal width with the discharge off (Δ₀) versus temperature difference between the axis and the wall. Gas mixture Ar+0.16% N₂, pressure 50 Torr. First laser beam is 24.8 cm inside the discharge; spacing between the two beams is 2.9 cm.

Fig. 4. Shock wave velocity versus average temperature in the discharge. Conditions are the same as in Fig. 3.

To distinguish between thermal and plasma-specific mechanisms of shock propagation, it would be desirable to eliminate temperature effects while maintaining plasma with the same density of charged particles, electric field, etc. Fortunately, in pulsed discharges, a relatively long time interval exists when electron, ion, and excited molecule densities are quite high while the temperature is low.

In our studies, the pulsed mode of the discharge was produced by using a transistor switch in series with the discharge. The rise time for the current pulse was 20\(\mu\)s, and the pulse duration was about 0.5ms. It was found that this time was insufficient to get a uniform discharge. In fact, when the discharge was turned on, undesirable transitional processes (for example, discharges on the wall of the tube) were observed. Therefore a weak pilot discharge with 1mA current was maintained between pulses, which resulted in a fairly uniform volume pulsed discharge. Fig.5 shows the discharge pulse shape and the time dependence of discharge integral emission (with no shock wave). Clearly, near the middle of the pulse the emission reaches its steady-state value, similar to that of the continuous discharge. The initial peak of intensity is a result of the higher electric field arising in the discharge immediately after the transistor switch is opened.

As shown in Fig.6, for the pilot discharge a small acceleration, accompanied by some widening and weakening of the signal can be noticed, but the changes are very small compared to the higher-current continuous discharge. This is no surprise since the electron number density in the pilot discharge is \(\sim 10^{8}\) cm\(^{-3}\) only and the measured axial gas temperature is less than 320K. Much more important is that Schlieren signal obtained from the pulsed discharge, as seen in Fig.6, closely matches both no-discharge and pilot-discharge curves, and is very unlike the signal from the continuous discharge. After the transistor switch is turned on, the discharge current reaches its new steady-state value in \(\sim 20\mu\)s. This value is almost the same as in continuous discharge. The electric field strength \(E\) in the pulse was found to be somewhat larger than in the continuous discharge, but the \(E/N\) values were almost identical. Thus, the electron number densities and mean electron energies should be very close to those in the continuous discharge. This is confirmed by the behavior of the discharge emission (Fig.5).

The increase in gas temperature during the pulse, calculated from the simple energy balance equation, is \(\Delta T=0.4K-0.6K\). Thus, the pulsed discharge has electron component parameters (\(E/N, n_e, T_e\)) the same as in the continuous discharge, but the gas temperature is the same as in the pilot discharge, that is, close to room temperature. Comparing the three Schlieren curves of Fig.6 shows that changing the electron density by two
orders of magnitude does not affect shock wave propagation, while changing gas temperature from $T_g \approx 320$ K to $T_g \approx 500$–600 K (from the pilot or pulsed discharge to the continuous discharge) affects the shock dramatically. This result is a strong evidence of thermal mechanism of shock wave–plasma interaction.

Further evidence of the thermal mechanism is provided by comparison of shock profiles in two different gases, $Ar$ and $Ar-N_2$, in Fig.7. For a meaningful comparison, one has to take into account that addition of nitrogen changes the electron drift velocity and also can affect ionization and recombination processes. As a result, plasma parameters such as $E/N$, electron number density, and gas temperature are different for $Ar$ and $Ar-N_2$ plasmas even if the gas pressure and discharge current are similar. Data presented in Fig.7 show that for the condition of equal gas temperatures similarity of the signals is the best. This supports unambiguously the thermal mechanism of shock dispersion.

4. Laser triggering and guiding of microwave discharges [3, 5]

Studies of microwave discharges in free air and other gases [13, 14, and references therein] have established that at pressures of hundreds of Torr, microwave plasmas sustained by traveling waves can exist in two principal forms. At low microwave intensity, the plasma is uniform and hot (several thousand degrees). When the microwave electric field is high enough, the plasma exist as a few dynamically evolving streamers, or filaments. On open-shutter photographs, the plasma looks like a “bird’s nest”, although only a few filaments exist at each moment of time. Each filament grows because of the polarizational amplification of electric field near its ends. In fact, due to the amplification effect, streamers can grow even in the so-called subcritical field, with the average electric field strength considerably below the critical breakdown threshold. This permits development of propagating filamentary microwave plasmas in subcritical fields by initiating the first streamer by a metallic pin or a sphere.

Microwave streamer plasmas are very interesting from both fundamental and practical standpoints. For aerodynamic applications, the ability of filamentary discharges to propagate supersonically in a quiescent gas, or to be stationary in a supersonic flow, is especially important. Microwave filaments can be successfully used for shock wave attenuation, because of concentrated energy addition. Sharply non-uniform temperature distribution in the “bird’s nest” would disperse and attenuate shocks similar to, but stronger than, glow discharge plasma with non-uniform temperature. To prevent appearance of undesirable discharges in wrong places and in the wrong time, the microwave field strength should be kept below the critical breakdown field, so that the plasma could be started only with a remote initiator: a laser or an electron beam. Additionally, lasers can potentially guide plasma filaments and could even create a regular grid of plasma filaments instead of the “bird’s nest”. It is important that the plasma would be sustained by a microwave power, and only triggered and guided by the laser.

In our laboratory, ArF laser was successfully used to initiate and guide microwave streamers [3, 5]. The microwave source used in the experiments had 50kW of power at a frequency of 2.45GHz, pulse length of 1ms, and pulse repetition rate of a few Hz (essentially, a single-pulse regime). The power level was not enough to study plasmas in free air, and streamers were initiated in a microwave waveguide-based resonant cavity filled with the room air. Without initiation, the electric field in the waveguide was below that needed for breakdown.

When ArF laser beam was directed through a narrow window and focused at a location inside the waveguide, a streamer would start. The streamer would continue to grow long after the 15-ns laser pulse, following the trace left by the laser beam, as shown in Fig.8. As seen in the figure, the streamer followed the trace of the laser beam rather than the electric field that was, of course, normal to
the walls of the waveguide, even though the laser beam was directed at an angle to the electric field. In fact, in the experiments, streamers still developed when the pulsed laser beam was directed at almost 45° to the field.

Fig. 8. Development of the microwave streamer initiated in the waveguide by a laser pulse. Parameters of the microwave source: frequency – 2.45GHz, pulse power – 50kW, pulse length – 1ms. Parameters of the ArF laser: wavelength – 193nm, pulse energy – 50mJ, pulse length – 15ns.
As seen in Fig.8, during the growth of the streamer its ends are brighter than the middle section. This could be expected, since the electric field is stronger at both tips. A few microseconds after initiation, the streamer became bright throughout its length. At the end of its development, the streamer would reach the wall of the waveguide and would keep there until the end of the microwave pulse. The average electron number density in the streamer, estimated from the Stark profile of Hβ line, was on the order of $10^{15}$ cm$^{-3}$.

The experimental results are encouraging, and further studies, including laser-initiated microwave streamers in deeply subcritical fields, initiation of more than one streamer at a time, and studies of laser initiation and guiding of microwave plasmas in both free air and resonant cavities could be very interesting.


The basic configuration of the wind tunnel is determined by the need to create a plasma in the region of supersonic flow. A schematic of the facility is shown in Fig.9, and Fig.10 shows the plenum and nozzle cutaway. A plasma is created with a 50kW, 1 ms pulse of microwave source at 2.45GHz, which induces electric breakdown of the air in the region of supersonic flow. Microwaves are introduced into the plenum through an EM window mounted over a port on one wall. The direction of propagation is then turned 90° by an aluminum reflector, so the microwaves travel coaxially with the flow through the plenum chamber and nozzle section. The aluminum reflector is made with a dense array of ¼ inch holes in it to allow passage of air while simultaneously reflecting the microwaves. The breakdown location is controlled by two factors: a reduced static pressure in the high-speed section and increased field intensity downstream of the throat. Microwave discharges occur more easily at low pressure due to the reduced collision frequency, and introducing microwaves through the plenum where the air is at high pressure avoids the risk of parasitic breakdown near the window housing and window surface.

As shown in Fig.9, the waveguide walls are tapered to create an enhancement of the electric field as the microwaves propagate downstream. The nozzle contours within the taper are made of dielectric material so as to transmit the microwave radiation. The taper continues down to and slightly beyond the cutoff dimensions for 2.45GHz. This generates a reflection, reversing the propagation direction as the microwaves reach the cutoff point. This taper is used as one end of a microwave resonator. The other end of the resonator is formed by a triple stub tuner on the generator side of the entrance window. This arrangement allows for the build-up of a standing wave in the wind tunnel. In order to provide a further field enhancement at the intended breakdown location, and to provide for spatial localization of the plasma, two 1 cm long metal pins are mounted opposite each other on the inside walls of the wind tunnel. In principle, plasma could be triggered and guided by a laser instead of pins (see the previous section), and the laser control will be explored in future work.

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Fig.9. Schematic of the microwave-driven plasma wind tunnel facility.

Fig.10. Plenum and nozzle cutaway view.

The flow of air proceeds from the plenum, through the nozzle, and into the 2"×2" test section. The air is then discharged into a vacuum tank. The nozzles are contoured to achieve Mach 3 flow in the test section. Flow conditions in the test section are 20Torr static pressure, 110K static temperature, and a Mach number of 3.

The microwave field distribution was measured along the centerline of the wind tunnel from the reflector plate to the wind tunnel exit plane. To complement the measurements described above, as well as to permit parametric studies of the effect of changes in the electrical properties of the wind tunnel, a commercial finite element code was used to simulate the electric field standing wave pattern.
Electric breakdown can occur in either of two locations, depending upon conditions. Under static conditions below about 30Torr, breakdown occurs upstream of the throat, slightly below the centerline of the wind tunnel. Above 30Torr under static conditions breakdown occurs downstream of the throat at the intended location. These two positions correspond to the two peaks in field intensity found in the simulation. Note that under flow conditions, with higher pressure upstream of the throat than downstream, the breakdown will also occur in the downstream location.

Breakdown in the wind tunnel was recorded with photodiodes and high-speed camera. Measurements of the plasma luminosity were made both with flow and under static conditions. In all cases the tests were performed in air with microwave pulse duration of 1ms. The results indicate the initiation of the plasma within 10μs after the start of the microwave pulse without flow, and within 20μs after the start of the pulse with flow. Brighter plasma was observed with flow than without flow, as shown in Fig.11.

Fig.11. Comparison of plasma with and without the flow
The photographs shown in Fig.11 were made with a gated, intensified CCD camera. The view is through the axial diagnostic port shown in Fig.9, looking upstream into the wind tunnel. Images of the plasma were taken both with the wind tunnel running and under static conditions at 60Torr and room temperature. The pressure was chosen for static conditions to match the density with the Mach 3 flow for comparison. In all cases the camera gate was maintained at 3\mu s. The images show the plasma generated while the wind tunnel was brighter and more contracted than the plasma generated under static conditions. The location of the plasma within the tunnel appears to be stable for the duration of the 1ms pulse. Note that each image represents a separate instance of plasma generation.

Thus, a Mach 3 wind tunnel with integrated microwave plasma generating capability has been designed and tested. Further work on plasma aerodynamics in this facility is currently under way.


Beams of high-energy electrons represent a very energy-efficient way of generating plasmas in both closed tubes and channels and open air. When the initial energy of beam electrons is high enough, the beam can penetrate the gas and generate plasma far from the injection point. E-beams can be guided by magnetic fields, minimizing lateral spread of the plasma. If ionization level or electrical conductivity has to be maximized, e-beams can create nonequilibrium ionization in cold gas with energy cost of only 35eV per ion-electron pair, which is 2-3 orders of magnitude better than electric field-sustained discharges. Plasmas created by e-beams are stable and reasonably uniform, and can be sustained in supersonic flow.

As an example, Fig.12 shows computed parameters of the plasma generated by e-beam with current density of 10mA/cm² in air at 1atm, 2000K. (The temperature is maintained at 2000K by convectively cooling the gas). At steady state, the current of low-energy plasma electrons back to the injection plane balances the beam current. The number density of plasma electrons reaches 10¹³ cm⁻³. The calculations were performed with the so-called “forward-back” approximation.

The efficient ionization of low-temperature air by e-beams makes them attractive as ionizers in hypersonic MHD channels such as those in the AJAX concept. Theoretical analysis of e-beam plasmas in MHD channels is reported in a separate paper at this conference and in other recent papers.

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References