



# Efficient Ionization Investigation for Flow Control and Energy Extraction

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## **Abstract**

Nonequilibrium ionization of air by nonthermal means is explored for hypersonic vehicle applications. The method selected for evaluation generates a weakly ionized plasma using pulsed nanosecond, high-voltage discharges sustained by a lower dc voltage. These discharges promise to provide a means of energizing and sustaining electrons in the air while maintaining a nearly constant ion/neutral molecule temperature. This paper explores the use of short  $\sim 5$  nsec, high-voltage  $\sim 12$  to 22 kV, repetitive (40 to 100 kHz) discharges in generating a weakly ionized gas sustained by a 1 kV dc voltage in dry air at pressures from 10 to 80 torr. Demonstrated lifetimes of the sustainer discharge current  $\sim 10$  to 25  $\mu$ sec are over three orders of magnitude longer than the 5 nsec pulse that generates the electrons. This life is adequate for many high speed flows, enabling the possibility of exploiting weakly-ionized plasma phenomena in flow-fields such as those in hypersonic inlets, combustors, and nozzles. Results to date are obtained in a volume of plasma between electrodes in a bell jar. The buildup and decay of the visible emission from the pulser excited air is photographed on an ICCD camera with nanosecond resolution and the time constants for visible emission decay are observed to be between 10 to 15 nsec decreasing as pressure increases. The application of the sustainer voltage does not change the visible emission decay time constant. Energy consumption as indicated by power output from the power supplies is 194 to 669 W depending on pulse repetition rate.

## **Introduction**

NASA is currently engaged in research to develop low-cost alternatives for access-to-space and novel concepts for high Mach number propulsion. In recent years, plasma flows have rapidly become the basis of new technologies that find application to hypersonic propulsion. It is anticipated that combining technology developments in electromagnetics, aerodynamics, and chemical kinetics may lead to a breakthrough for improving aerospace vehicle performance. As an example, the Russian AJAX hypersonic vehicle concept has coupled magnetohydrodynamic (MHD) elements at the inlet and nozzle of a scramjet to increase performance (Ref. 1). AJAX relies on the possibility of extracting part of the inlet air kinetic energy for subsequent use at a downstream location of the engine. Analyses of the AJAX concept lead to the conclusion that energy bypass of a scramjet can result in subsonic ramjet propulsion being maintained in the Mach 10 to 16 speed range (Ref. 2). This paper explores an extension of these analyses to turbojets (Refs. 3 and 4) as shown in Figure 1. Our efforts are motivated by a need to develop a single flow-path solution to a Mach 7 air breathing engine, without mode transitions and/or "deadweights". The concept seeks to ultimately maintain Mach 3 at the inlet of an existing turbojet such as the Allison J-102 through a flight envelope up to Mach 7 by using MHD enthalpy extraction and inlet flow control. Current activities include establishing a model for a jet engine with energy bypass for determining the design and operating conditions in which the thrust-to-weight ratio, thrust per unit mass of fuel consumption and effectiveness of energy utilization are maximized; and evolving a testing scheme for a jet engine for demonstrating and quantitatively assessing the effectiveness of the energy bypass scheme.

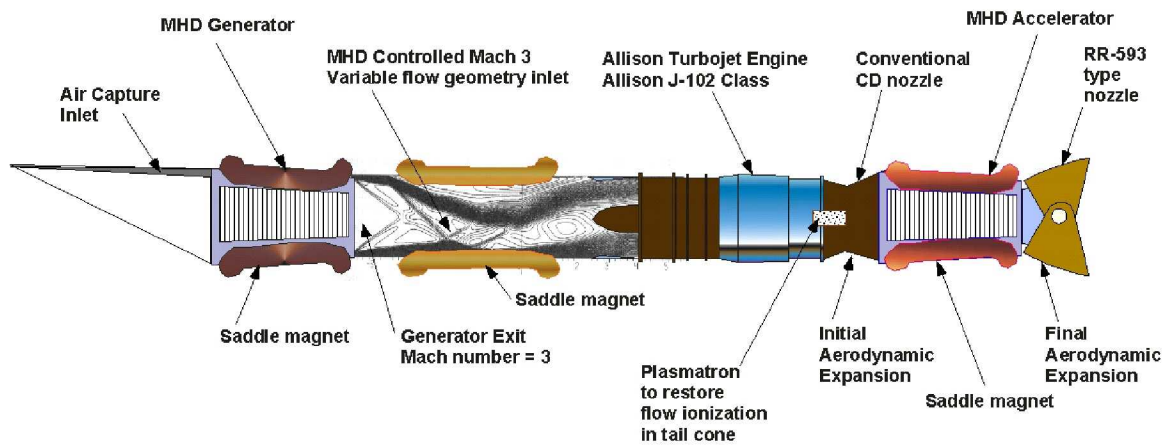


Figure 1.—MHD Energy Bypass System Incorporating Jet/Gas Turbine Engines.

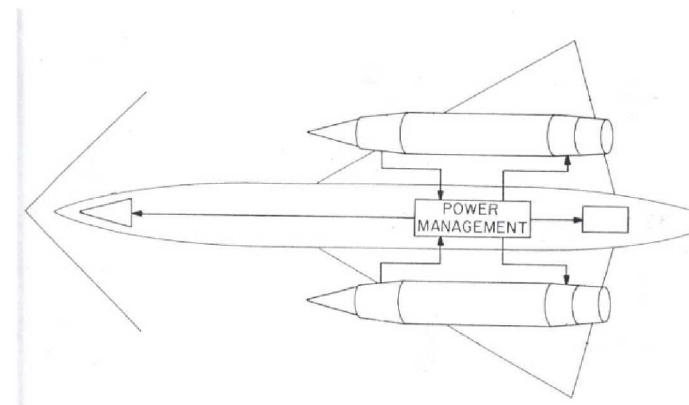


Figure 2.—Concept vehicle showing MHD energy bypass of a turbojet and potential energy management system.

As with the scramjet, three primary aeropropulsion purposes are served by the concept. First, the enthalpy into the combustor is reduced allowing more efficient addition of energy in the combustor without exceeding temperature limitations on the turbine materials. Second, the applied electromagnetic fields and their body forces can enhance off-design performance by manipulating the flow features in supersonic/hypersonic inlets thereby reducing total pressure losses, and entropy changes for the same level of flow compression by other means. Third, electrical power removed can be used for various on-board vehicle requirements including plasma flow control around the vehicle. In addition, the expanding flow in the high speed nozzle may also be augmented by the electromagnetic body forces to generate more thrust. A concept vehicle showing power generation and distribution is shown in Figure 2. There is a growing interest in power management on hypersonic vehicles as is evident in the work reported in plasma-based aerodynamics, including hypersonic flow control, power generation, heat transfer reduction, flow manipulation through MHD (magnetohydrodynamic) forces, drag reduction, and noise suppression (Refs. 5 to 7).

In order for these plasma applications to become practical, the development of efficient means of ionization is necessary. Specifically, we are pursuing nonthermal means of ionization. In recent years, it has been established in various experiments that a nonthermal plasma can be generated, such that in this plasma state, low electron number density seems to be able to give rise to significant electrical conductivity for air. The generation of nonthermal subatmospheric discharges such as the pulser-sustainer discharge (Ref. 8) provides a means of energizing electrons in the gas while maintaining a nearly constant ion/neutral molecule temperature. These nonthermal subatmospheric pressure discharges are reported to offer energy efficiency in the generation of plasmas in air in that a major fraction of the electrical discharge power at these conditions goes into the vibrational excitation of nitrogen (Ref. 8).



Thermalization and breakdown is avoided through the application of short  $\sim 20$  nsec, high-voltage  $\sim 20$  to  $40$  kV, repetitive ( $40$  kHz) pulses. The pulse duration is much shorter than the characteristic time for the ionization instability development,  $\sim 10^{-3}$ – $10^{-4}$  sec. At low dc voltage ( $1$  kV), a sustainer discharge is reported to continue to move the electrons in the flow with only vibrational excitation of the collision partners due to the orders of magnitude difference in their collision masses. The sustainer current is reported to have characteristic lifetimes of  $20$   $\mu$ sec thus providing steady state ionization between the repetitive ( $40$  kHz) pulses (Ref. 8). Thermalization of the flow due to the release of the vibrational energy does not have time to occur in high speed flows. For this reason, joule heating of the flow and its attendant entropy increase and total pressure loss are reported not to occur.

In order for inlet power extraction devices to be geometrically compatible with a turbojet, the authors are proposing an annular Hall type generator concept shown in Figure 3. This geometry was successfully developed into the Stationary Plasma Thruster for space propulsion by the Russians using very low pressure xenon plasmas and is flying on the Russian Express satellite (Ref. 9). The geometry was also previously explored briefly for stationary combustion driven MHD power generation in the 1950s (Ref. 10). The interaction experiments were conducted with combustion products seeded with potassium to enhance the conductivity. The proposed turbojet application uses high altitude dry air and nonthermal ionization in the core flow to alleviate known problems such as loss of conductivity due to electron-water molecule interactions and short circuiting through the higher conductivity thermal boundary layers. The proposed geometry can be visualized as having a “spiral curtain” of conductivity shaped like an auger in the annular passage. Nonequilibrium conductivity generated by the crossed pulser-sustainer discharge method is proposed to provide the conductivity in the flow (Refs. 8, 11, and 12). The generator has an externally applied radial magnetic field throughout the volume of the annulus. The axial flow of ionized gas through the annulus interacts with this applied radial magnetic field to produce an azimuthal Hall current, which further interacts with the magnetic field to set up an axial electric field known as the Hall voltage. There are only two electrodes at the entrance and exit of the annulus with insulator wall in between. The load or axial electric field applied across these electrodes determines the MHD interaction (energy extraction/addition) with the flow. Efficiency of the ionization process is critical to the viability of the thermodynamic process. The concept potentially offers variable inlet geometry performance without the complexity of moving parts simply by varying the generator loading parameter. Another critical technology necessary for the implementation of this concept is lightweight cryogenic magnet technology and recently, superconducting properties of carbon nanotubes have been measured offering the possibility of lightweight cryogenic magnets for aerospace applications (Ref. 13).

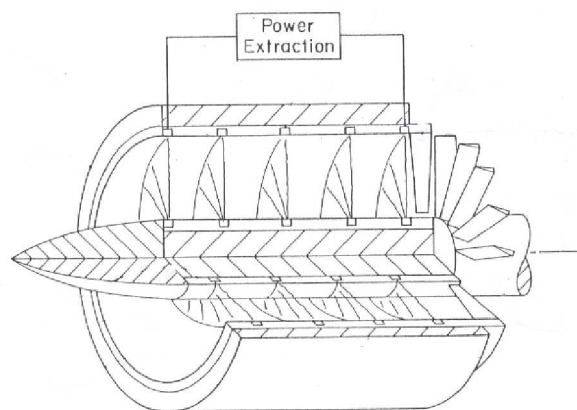


Figure 3.—Annular Hall type MHD power extraction concept for the inlet of a turbojet showing spiral path of conductivity generated by e-beam ionization.

The work presented in this paper explores plasma generation in air using the pulser-sustainer technique at various subatmospheric pressures corresponding to high altitude, high speed flight and in the process advocates incorporation of the technology into power management devices on hypersonic vehicles. This paper reports results to date in a bell jar analyzing plasma generation over a range of operating conditions (pressure, pulse repetition rate, pulse energy). The buildup and decay of the visible emission from the pulser-sustainer excited air is measured with nanosecond resolution and sustainer currents with up to 25  $\mu$ s lifetimes are demonstrated.

## Experimental Apparatus and Results

Specifications for this effort are set by reports of efficient coupling of electromagnetic energy into subatmospheric air by the use of pulsed nanosecond discharges (Ref. 14). The desired ionization is produced by the intense, localized, rapid heating of electrons by the nanosecond discharges. The subatmospheric conditions of interest are set by the pressures during Mach 7 flight at 30 km altitude where a static pressure of 8 torr ahead of the vehicle is compressed to 20 to 80 torr behind an oblique shock with a downstream Mach number of 4 to 6. The proposed MHD generator would be designed to reduce this Mach number to the desired compressor inlet Mach number of 3. A static experimental capability to study pulser-sustainer discharges called Vacuum Facility 69 (VF69) is shown in Figure 4. The high voltage power supply specifications include a maximum amplitude of 60 kV with a 2 nsec rise time, 5 nsec pulse width, and a 3 nsec fall time. The pulse repetition rate can be varied from 6 to 100 kHz. The dc power into the pulser is supplied by a 150 to 240 V, 12 A supply. The sustainer floating power supply used for these experiments is rated for 1 kV potential and 0.1 A. The cylindrical bell jar is also shown and is easily pumped down to the desired pressures by a mechanical pump. It has ports with electrical feedthrus and windows for optical access. The bell jar is evacuated below 0.1 torr and then filled to the desired pressure with dry air from a storage bottle. An ultra high repetition rate, gated, intensified CCD camera is shown at the window. Its capabilities include strobing successive pulses with a variable delay resolution down to 2.5 psec. The pulser-sustainer electrode setup with pulser electrodes 2.5 cm diameter and 2.5 cm apart and cylindrical sustainer electrodes 0.6 cm diameter is shown in Figure 5.

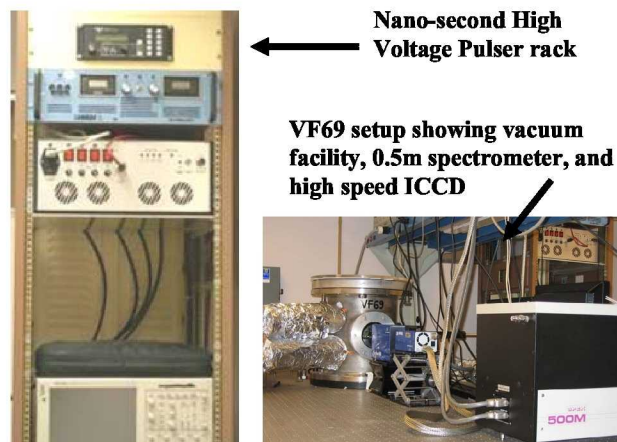


Figure 4.—New vacuum facility for air plasma studies.

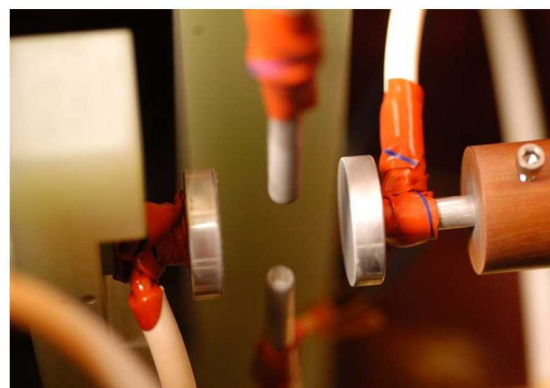


Figure 5.—Pulser-sustainer electrode configuration inside the bell jar.



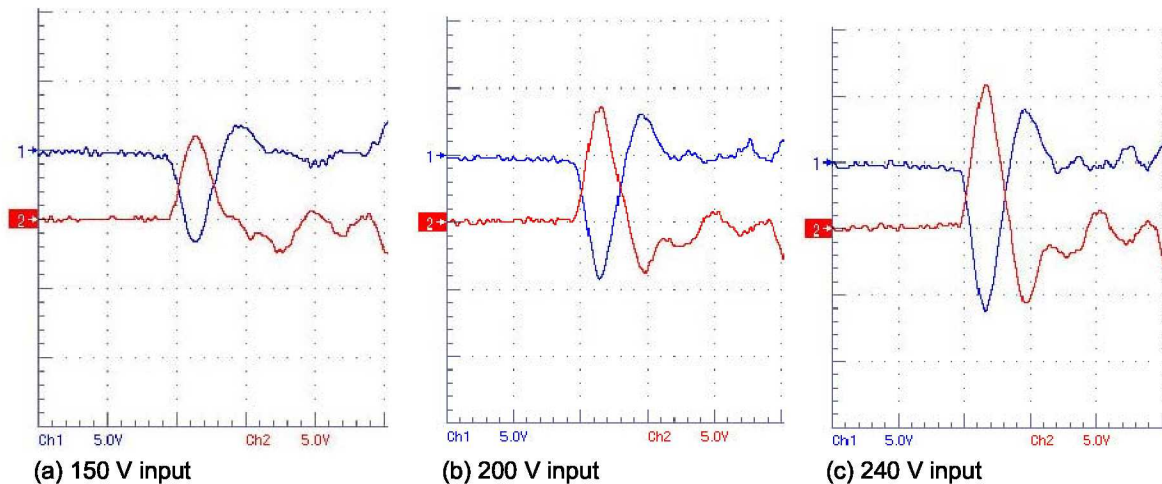


Figure 6.—Voltage probe measurements with 150, 200, and 240 V input to the Pulser showing 5 ns pulse width (scale: 10 ns/div) and output differential voltages of 12, 18, and 22 kV, respectively.

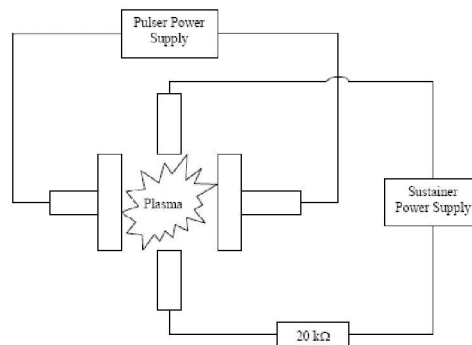


Figure 7.—Electrical circuit schematic.

Figure 6 shows the pulse amplitude and width generated by the pulser as observed on a digital phosphor oscilloscope (500 Mhz Bandwidth) with a high voltage probe with 1000:1 attenuation, 75 MHz bandwidth, and 4 nsec rise time. The pulses are approximately 5 nsec in width and vary in amplitude with input voltage to the pulser. For example, Figure 6(a) shows that with 150 V input to the pulser, one electrode floats 6 kV above ground and the other floats 6 kV below ground for a 12 kV differential voltage across the pulser electrodes. Similarly, Figure 6(b) shows 18 kV differential voltage with 200 V input and Figure 6(c) shows 22 kV differential voltage with 240 V input.

A series of tests were conducted with these pulser characteristics along with an applied sustainer voltage of 1 kV DC. A 20 k $\Omega$  resistor was placed in series with the sustainer to limit the sustainer current below 0.1 A. A schematic of the electrical circuit is shown in Figure 7. The dry air filled bell jar pressure was varied between 10 and 80 torr and the pulser frequency was varied from 6 to 100 kHz. A mismatch in the unknown load of the plasma and the required pulser's load impedance (0.4 to 1.0 k $\Omega$ ±50 percent) resulted in some unknown fraction of the power being reflected back into the pulser. Frames of the visible emission recorded by the ICCD camera on successive 40 kHz pulses delayed by nanosecond intervals are shown in Figure 8 at 50 torr pressure.

A nondimensional plot of this visible emission is shown plotted versus time in Figure 9. The visible emission from the 5 nsec discharge peaks at about 6 nsec and then decays with a time constant of about 12 nsec.

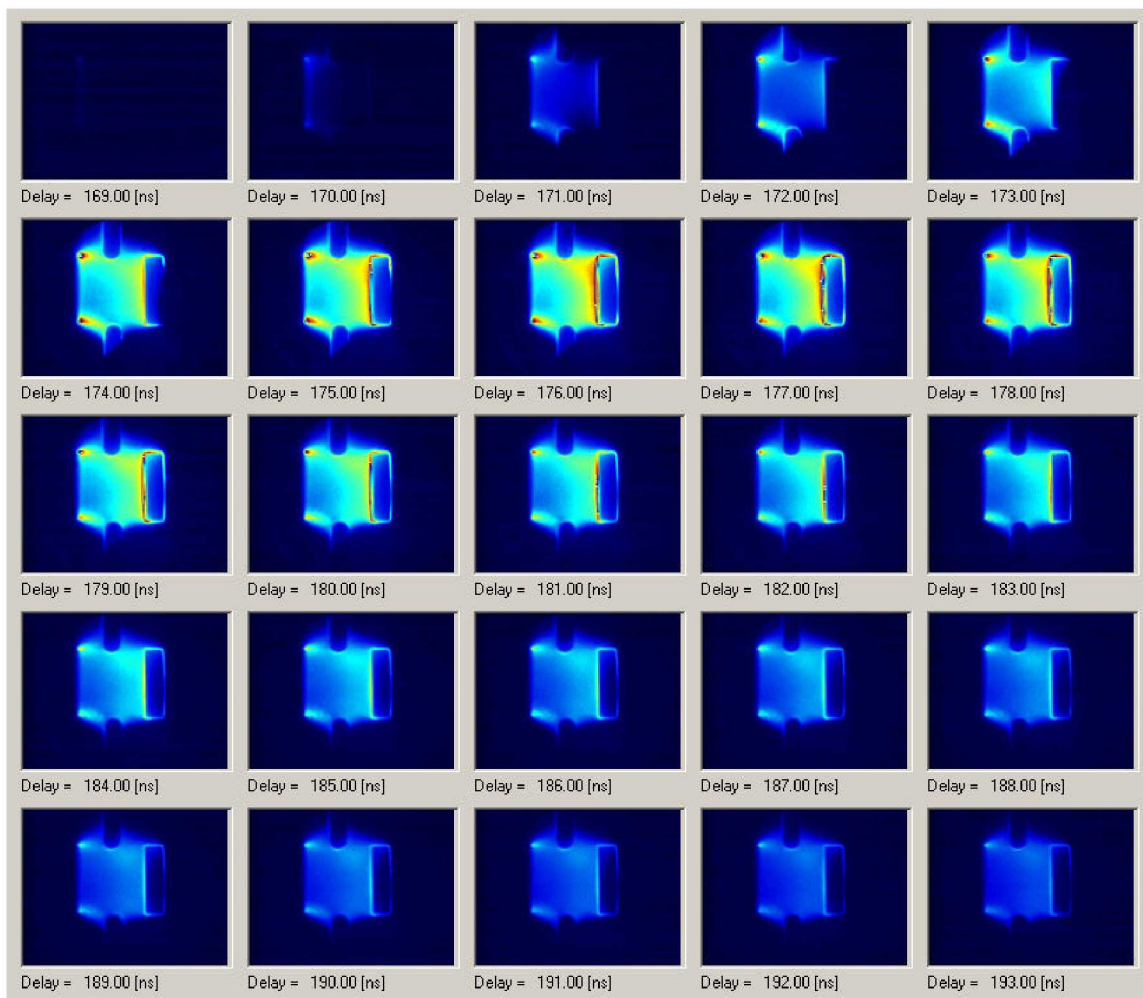


Figure 8.—Visible emission of pulser-sustainer discharge in 50 torr dry air at nanosecond increments.

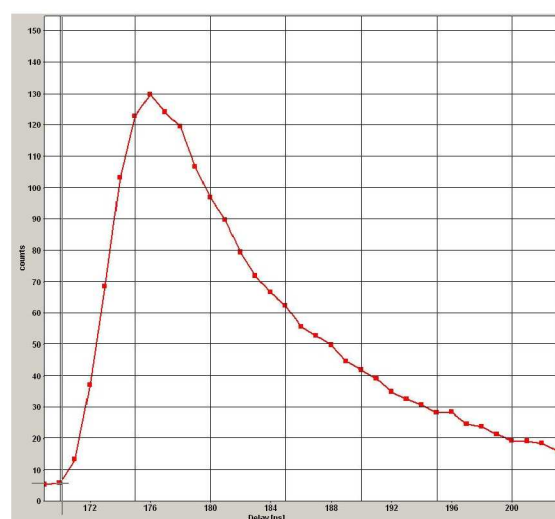


Figure 9.—Visible emission decay at 40 kHz repetition rate in 50 torr dry air showing time constant for decay of about 12 nsec.

The sustainer circuit power supply output terminal voltage and current trace when the pulser is pulsed at 6 kHz are shown in Figure 10. Voltage traces 1 and 2 are measured with the high voltage probe with 1000:1 attenuation, 75 MHz bandwidth, and 4 nsec rise time. Current trace 3 is measured with a current probe with a bandwidth of DC to 50 MHz and a rise time less than 7 nsec. Voltage measurements indicate that the sustainer electrodes are near ground potential with one pulser electrode floating 6 kV above ground and the other floating 6 kV below ground. Figure 10 shows that voltage trace 1 on the sustainer remains at ground and voltage trace 2 is driven to a relatively constant 1 kV below ground by the sustainer power supply in voltage control mode. At this relatively constant sustainer voltage, the current shown on trace 3 drops from approximately 35 to 25 mA between pulses indicating that the conductivity decreases between pulses.

A similar set of traces when the pulser is pulsed at 40 kHz is shown in Figure 11. The measured differential voltage at the output terminals of the sustainer power supply is a steady state 1400 V between pulses as indicated by traces 1 and 2. The current between pulses is a relatively constant 54 mA indicating a relatively constant conductivity between pulses. Note that the sustainer current is maintained for 25  $\mu$ sec which is three orders of magnitude longer than the visible emission.

At 54 mA the voltage drop across the 20 k $\Omega$  current limiting resistor is 1080 V. With 1400 V across the circuit, this leaves a voltage across the electrodes of 320 V. At 54 mA, the sustainer is then putting 17 W into the plasma to maintain the conductivity. The plasma resistance is estimated from this voltage-current characteristic to be a relatively constant 5.9 k $\Omega$ . Assuming a cube of plasma 2.54 cm on a side, an estimate of conductivity  $\sigma_e = 0.0067$  mho/m is obtained from this resistance. High voltage nanosecond pulses applied to the circular electrodes generate the high temperature electrons ( $T_e = 1$  ev) (Ref. 12) and

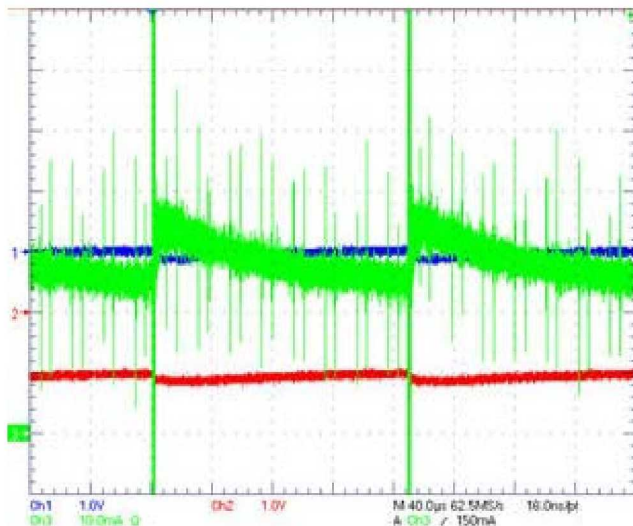


Figure 10.—Sustainer current at 6 kHz repetition rate in 50 torr dry air.

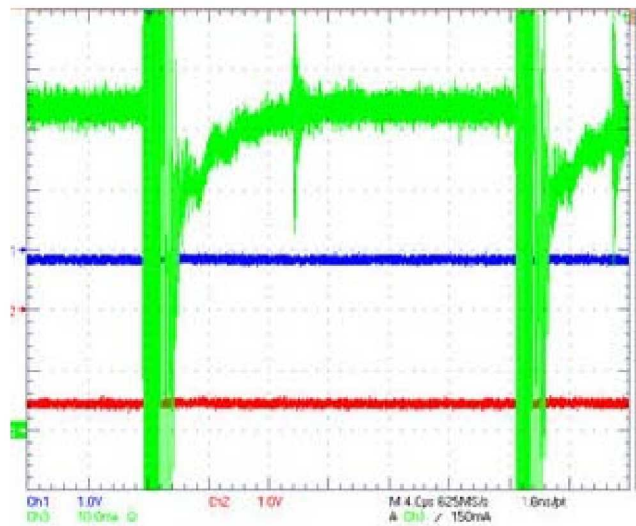


Figure 11.—Sustainer current at 40 kHz repetition rate in 50 torr dry air.

$$n_e = \frac{\sigma_e m_e n Q c_e}{e^2}$$

where  
 $e$  = electron charge  
 $m_e$  = electron mass  
 $n$  = number density of molecules  
 $Q$  = momentum transfer cross section ( $6.5 \times 10^{-16} \text{ cm}^2$  for  $\text{N}_2$ )  
 $c_e$  = mean random thermal velocity of electrons ( $6.7 \times 10^7 \text{ cm/sec}$  for 1 eV electrons)

Based on a number density of air of  $2.69 \times 10^{19} \text{ cm}^{-3}$  at standard temperature and pressure, this electron number density corresponds to an ionization fraction in the 50 torr air of  $1.1 \times 10^{-8}$ , which is a weakly ionized gas. Total power into the flow is estimated to be 345 W with the pulser inputting 328 W at the 40 kHz repetition rate and the sustainer depositing an additional 17 W into the flow. (Note that a 40 kHz pulse repetition rate was also used in Reference 8 to generate the nonequilibrium ionization in Mach 3 flow at a static pressure of 8.4 torr.)

These data along with similar data indicating a relatively constant conductivity between pulses are presented in Table I. Results over the pressure range of 10 to 80 torr are tabulated. In examining Table I, one notes that the pulse repetition rate needed to achieve steady state ionization between pulses increases from 40 to 100 kHz as the pressure is increased from 10 to 80 torr, i.e., the time between pulses decreases from 25 to 10  $\mu\text{s}$ . This time is over three orders of magnitude longer than the 5 nsec pulse that generated the electrons. The time constants for visible emission decay are calculated from data observed with the ICCD camera. They are observed to be between 10 to 15 nsec decreasing as pressure increases. These constants are relatively independent of pulse rate at a given pressure. When the sustainer voltage is applied, little change in the visible emission is noted up to 20 torr, but above 30 torr the sustainer voltage makes the visible emission much more uniform in the volume without any noticeable change to the decay

Pressure	Pulse Rate	Voltage to Pulsar	Pulsar Power	Time Constant	Current through Plasma	Voltage across Plasma	Sustainer Power	Total Power	Plasma Resistance	Plasma Conductivity	Electron Density	Ionization Fraction
Torr	kHz	V	W	nsec	mA	V	W	W	kg	mho/m	cm <sup>-3</sup> x10 <sup>10</sup>	x10 <sup>-8</sup>
10	40	150	183	15	61	180	11	154	3.0	0.0078	0.7	2.20
10	40	200	236	15	56	230	18	342	5.0	0.0078	1.43	1.20
10	40	240	470	13	56	280	16	486	5.0	0.0078	0.43	1.20
20	40	150	183	15	60	290	18	201	4.8	0.0082	0.90	1.30
20	40	200	326	13	56	280	16	342	5.0	0.0078	0.85	1.20
30	40	150	183	15	57	263	15	183	4.6	0.0086	1.30	
30	40	200	324	13	57	260	15	339	4.6	0.0086	1.40	1.30
30	60	150	272	14	52	260	14	286	5.0	0.0078	1.30	1.20
30	60	200	486	12	50	300	15	501	6.0	0.0066	1.10	1.00
40	40	150	186	15	56	280	16	201	5.0	0.0078	1.20	
40	40	200	328	13	56	280	16	344	5.0	0.0078	1.70	1.20
40	60	150	272	12	51	280	14	286	5.5	0.0072	1.60	1.10
60	40	200	328	12	54	320	17	345	5.9	0.0067	1.90	1.10
60	60	150	272	13	52	260	14	286	5.0	0.0078	2.10	1.20
60	60	200	486	12	49	280	10	450	7.0	0.0056	1.53	
60	60	150	272	12	49	420	20	292	8.6	0.0046	1.50	0.71
60	60	200	486	11	37	260	10	496	7.0	0.0056	1.90	0.89
70	60	200	488	12	50	400	20	508	8.0	0.0049	1.90	0.77
70	80	150	361	9	46	400	18	318	8.0	0.0044	1.60	
70	80	200	652	10	37	460	17	669	12.4	0.0032	1.30	0.52
80	100	150	459	10	33	440	15	474	13.3	0.0030	1.30	0.46

[illegible]



time constant. In other words, the visible emission does not continue during the time between pulses when the current is being driven by the sustainer voltage. Spectroscopy of this emission has not been conducted. The voltage-current characteristics of the sustainer are used to calculate a plasma resistance between 3 to 13 k $\Omega$  in the 16 cc plasma cube increasing with increasing pressure. The sustainer powers are small  $\sim$ 11 to 20 W due to the 0.1 A current limitation of the power supply. Energy consumption by the pulser depends on pulse repetition rate and input voltage and varies between 183 to 652 W. Due to the mismatch between the load and the power supply, the amount of this power that is actually put in the plasma is unknown. Total energy consumption as indicated by both power supplies is 194 to 669 W. Conductivities in the 16 cc cube of plasma are derived from the resistance. They are between 0.003 to 0.013 mho/m, decreasing with increasing pressure. Electron number densities between 0.4 to  $2.1 \times 10^{10}$  cm<sup>3</sup> are estimated from the conductivities using the above equation. The estimated ionization fraction is determined by dividing the electron number density by the total number density of molecules in the air. Ionization fractions are relatively constant at  $1.2 \times 10^{-8}$  from 10 to 50 torr and decrease to  $0.5 \times 10^{-8}$  at 80 torr. Some of the observations above are believed to be due to the current limitation on the sustainer power supply. It is believed that more sustainer power could stem the loss of conductivity as pressure is increased.

## Concluding Remarks and Future Plans

An efficient means of generating plasmas in air could open the door to practical, nonmechanical, aerodynamic devices for high speed flow energy management in inlets, combustors, and nozzles of hypersonic vehicles. An experimental capability to study the characteristics of pulser-sustainer discharges in generating weakly ionized plasmas is being developed at NASA Glenn. To date, we completed the setup of a new high altitude bell jar with both high voltage pulse generator and sustainer power supplies. The pulser specifications include: maximum amplitude of 60 kV with a 2 nsec rise time, 5 nsec pulse width, and a 3 nsec fall time. The pulse repetition rate can be varied from 6 to 100 kHz. The DC sustainer power supply used for these experiments had a capability of 1 kV floating and 0.1 A. Weakly ionized plasmas are generated over a range of operating conditions (pressure, pulse repetition rate, pulse amplitude). We photograph the buildup and decay of the visible emission with nanosecond resolution. Using the DC sustainer voltage-current characteristics, we estimate steady state plasma conductivity, electron number density, and ionization fraction. In future work, the volume of plasma will be increased and the sustainer current capability will be increased to 3.0 A. Spectroscopy of the emission and millimeter wave interferometry will be used to measure electron number density and temperature. Plans to generate plasmas in a wind tunnel to study their impact on high speed flows are being developed.

## References

1. Brichkin, D.I., Kuranov, A.L., and Sheikin, E.G., "Scramjet With MHD Control Under AJAX Concept. Physical Limitations," AIAA-2001-0381, 39th AIAA Aerospace Sciences Meeting, Reno, NV, January 8-11, 2001.
2. Bruno, C., Czysz, P.A., and Murthy, S.N.B., "Electro-magnetic Interactions in a Hypersonic Propulsion System," AIAA 97-3389, 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Seattle, WA, July 6-9, 1997.
3. Murthy, S.N.B. and Blankson, I.M., "MHD Energy Bypass for Turbojet-Based Engines," IAF-00-5-5-05, 51st International Astronautical Congress, Rio de Janeiro, Brazil, October 2-6, 2000.
4. Blankson, I.M. and Schneider, S.J., "Hypersonic Engine Using MHD Energy Bypass With a Conventional Turbojet: A Progress Report," AIAA-2003-6922, 12th AIAA International Space Planes and Hypersonic Systems Conference, Norfolk, VA, December 15-19, 2003.
5. Poggie, J. and Gaitonde, D.V., "Magnetic Control of Flow Past a Blunt Body: Numerical Validation and Exploration," *Physics of Fluids*, vol. 14, no. 5, May 2002, pp. 1720-1731.



6. Kimmel, R.L., Hayes, J.R., Menart, J.A., and Shang, J., "Effect of Magnetic Fields on Surface Plasma Discharges at Mach 5," AIAA Paper 2004-2661, 35th AIAA Plasmadynamics and Lasers Conference, Portland, OR, June 28-July 1, 2004.
7. Frieshtadt, V.L., Kuranov, A.L., and Sheikin, E.G., "Use of MHD Systems in Hypersonic Aircraft," Technical Physics, vol. 43, no. 11, November 1998, p. 1309.
8. Nishihara, M., Rich, J.W., Lempert, W.R., Adamovich, I.V., and Gogineni, S., "Low-Temperature  $M = 3$  Flow Deceleration by Lorentz Force," Physics of Fluids, vol. 18, no. 8, August 2006, pp. 086 101-086-111.
9. Shumlak, U., Jarboe, T. and Sprenger, R., "Physics of the Hall Thruster," AIAA Paper 97-3048, 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Seattle, WA, July 6-9, 1997.
10. Karlovitz, B. and Halasz, D., "History of the K and H Generator and Conclusions Drawn from Experimental Results," 3rd Symposium on Engineering Aspects of Magnetohydrodynamics, 1964, pp. 187-203.
11. Nishihara, M., Jiang, J., Rich, J.W., Lempert, W.R., Adamovich, I.V., and Gogineni, S., "Low-Temperature Supersonic Boundary Layer Control Using Repetitively Pulsed Magnetohydrodynamic Forcing," Physics of Fluids, vol. 17, no. 10, October, 2005, pp. 106 102-106 112.
12. Nishihara, M. and Adamovich, I.V., "Numerical Simulation of a Crossed Pulser-Sustainer Discharge in a Transverse Magnetic Field," IEEE Transactions on Plasma Science, vol. 35, no. 5, October 2007, pp. 1312-1324.
13. Chapman, J., Schmidt, H., Ruoff, R., Chandrasekhar, V., Dikin, D., and Litchford, R., "Flightweight Magnets for Space Application Using Carbon Nanotubes," AIAA 2003-0330, 41st AIAA Aerospace Sciences Meeting, Reno, NV, January 6-9, 2003.
14. Zhukov, V.P., Kindisheva, S.V., Kosarev, I.N., Starikovskaia, S.M., Starikovskii, A.Y., and Kelley, J.D., "Plasma Production for MHD Power Generation by Nanosecond Discharge," AIAA-2006-1370, 44th AIAA Aerospace Sciences Meeting, Reno, NV, January 9-12, 2006.

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14. ABSTRACT Nonequilibrium ionization of air by nonthermal means is explored for hypersonic vehicle applications. The method selected for evaluation generates a weakly ionized plasma using pulsed nanosecond, high-voltage discharges sustained by a lower dc voltage. These discharges promise to provide a means of energizing and sustaining electrons in the air while maintaining a nearly constant ion/neutral molecule temperature. This paper explores the use of short ~5 nsec, high-voltage ~12 to 22 kV, repetitive (40 to 100 kHz) discharges in generating a weakly ionized gas sustained by a 1 kV dc voltage in dry air at pressures from 10 to 80 torr. Demonstrated lifetimes of the sustainer discharge current ~10 to 25 msec are over three orders of magnitude longer than the 5 nsec pulse that generates the electrons. This life is adequate for many high speed flows, enabling the possibility of exploiting weakly ionized plasma phenomena in flow-fields such as those in hypersonic inlets, combustors, and nozzles. Results to date are obtained in a volume of plasma between electrodes in a bell jar. The buildup and decay of the visible emission from the pulser excited air is photographed on an ICCD camera with nanosecond resolution and the time constants for visible emission decay are observed to be between 10 to 15 nsec decreasing as pressure increases. The application of the sustainer voltage does not change the visible emission decay time constant. Energy consumption as indicated by power output from the power supplies is 194 to 669 W depending on pulse repetition rate.					
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