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14. ABSTRACT This document is the final report on the activities carried out under AFOSR Grant F49620-01-1-0096. It describes the instrumentation and equipment acquired, their use, and impact on our research program on atmospheric pressure, non-equilibrium plasmas. <div style="text-align: right; font-size: 2em; font-weight: bold; margin-top: 20px;">20011126 070</div>						
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Final Report

Atmospheric Plasma Research

AFOSR Grant F49620-01-1-0096

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Abstract

This document describes the various activities carried out in support of our experimental research program, under AFOSR grant F49620-01-1-0096. The main objective of this grant is to provide diagnostics instrumentation to be used to characterize non-thermal discharges at atmospheric pressure. Our research program on generation and application of cold plasmas has been mainly conducted under AFOSR sponsorship. Non-thermal plasmas at atmospheric pressure have direct applications in microwave communications, in shielding defense equipment against directed EM weapons, in biological and chemical decontamination, and in several industrial processes.

The discharges under investigation produce large volume, steady-state plasmas between electrodes which are energized either by DC, AC, or RF power sources. Only a relatively moderate amount of input power (few hundred Watts) is necessary to maintain plasmas at atmospheric pressure with a number density in the 10^{10} - 10^{12} cm^{-3} range.

The research is carried out at The Applied Plasma Technology Laboratory of Old Dominion University, which is located at the ODU Applied Research Center. Collaboration with ODU's Department of Ocean, Earth, and Atmospheric Sciences is established to conduct work on the biological applications of the discharge.

Research Activities

The research activities supported by this grant are either directly or indirectly related to the Air Plasma Ramparts Program (APRP), which is managed by Dr. Robert J. Barker. Our aim is to generate a large volume, non-thermal, atmospheric pressure plasma with an adequate amount of input power. We are also investigating the applications of this kind of plasma to biological decontamination, pollution abatement, and its interaction with electromagnetic waves. Several generation methods are being investigated. Figure 1 through Figure 3 show three different methods by which relatively large volume, non-thermal, atmospheric pressure plasmas have been routinely generated. Figure 4 and Figure 5 show photographs of plasmas generated by the Glow Discharge at Atmospheric Pressure (GDAP) and the Resistive Barrier Discharge, respectively.

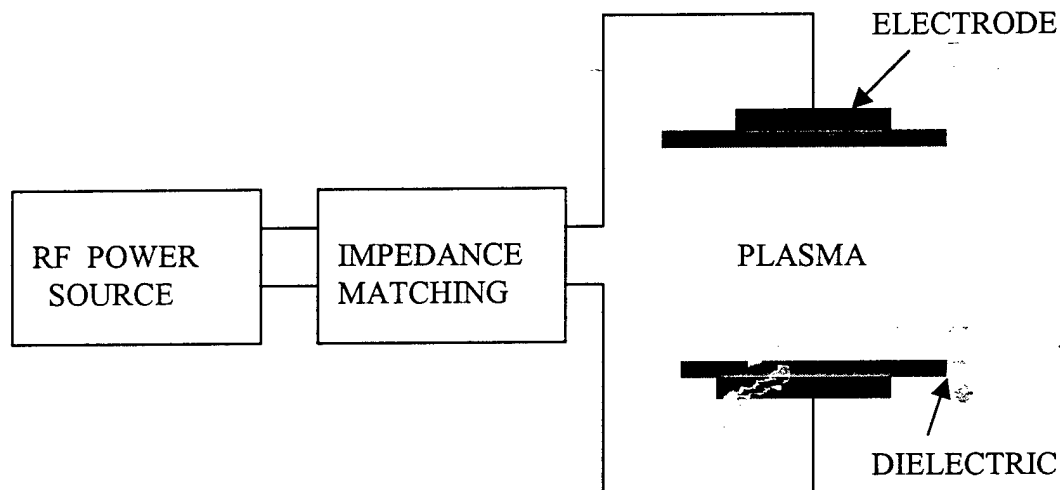


Fig. 1 Configuration of the Glow Discharge at Atmospheric Pressure

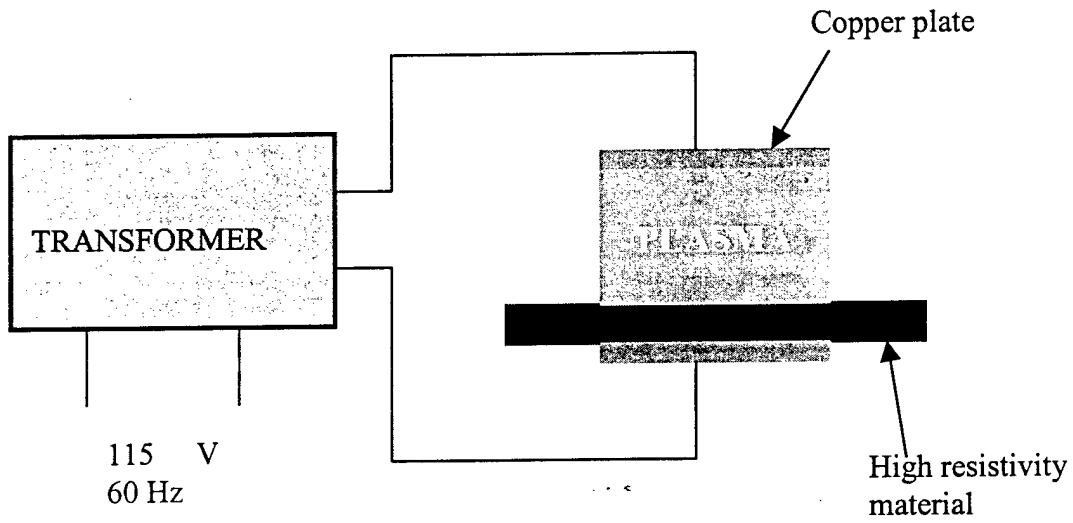


Fig. 2 Configuration of the Resistive Barrier Discharge

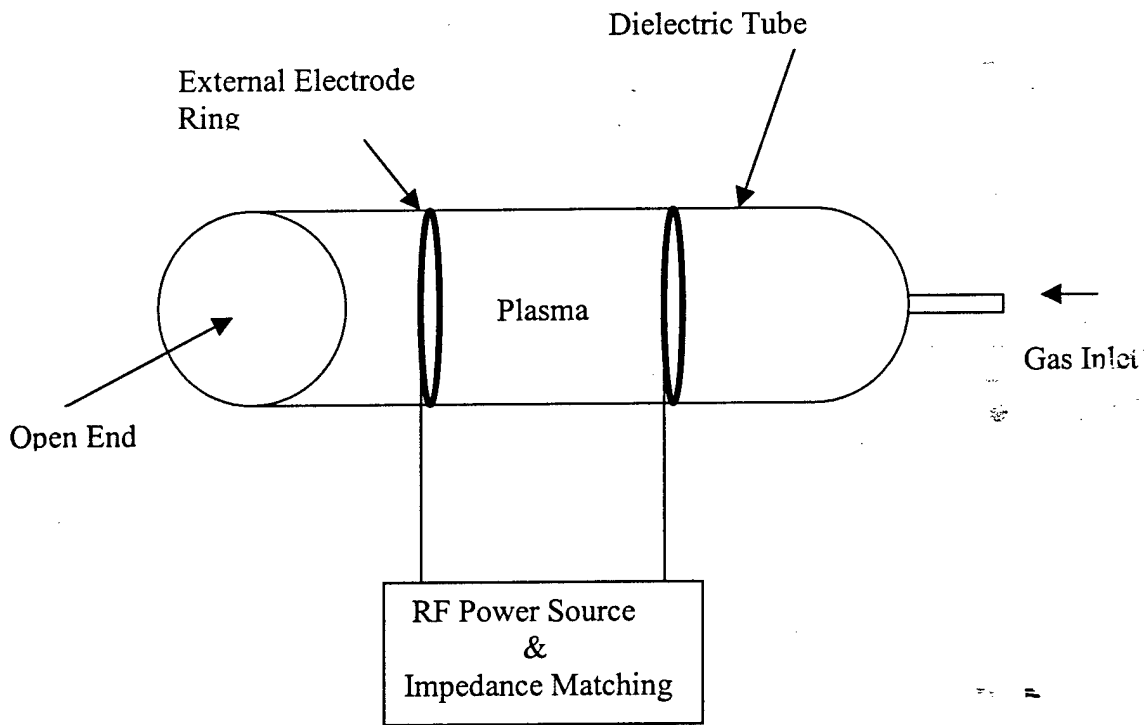


Fig. 3 Configuration of the Electrodeless Discharge at Atmospheric Pressure

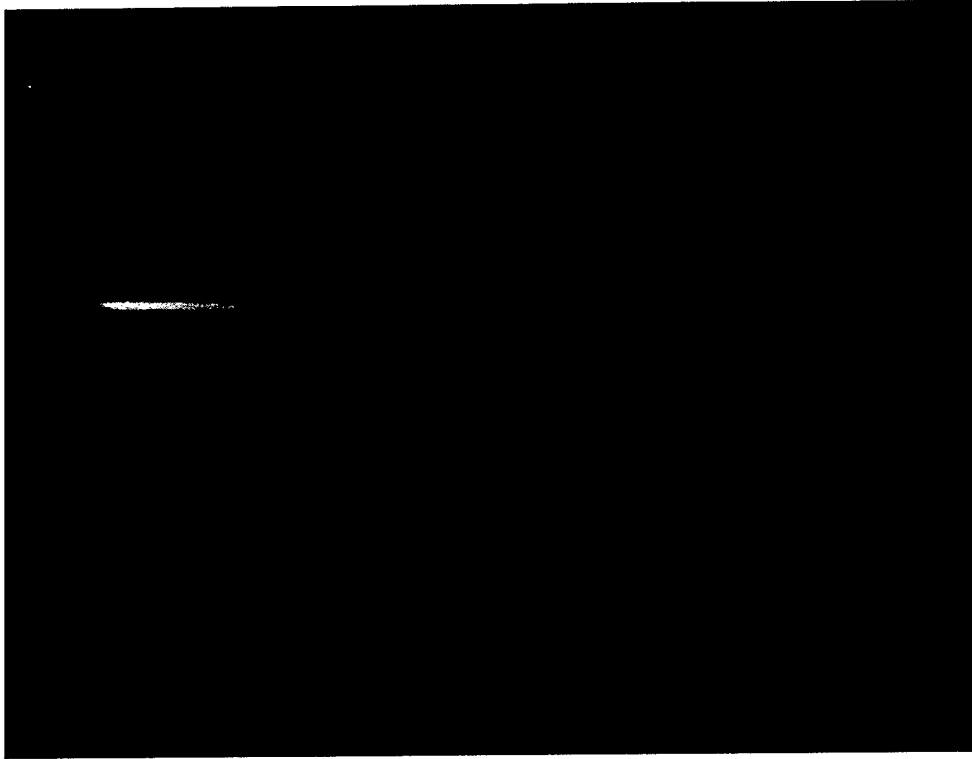


Fig. 4 Photo of the Glow Discharge at Atmospheric Pressure (GDAP)
 $V_{\text{rms}} = 5 \text{ kV}$; $f = 20 \text{ kHz}$; $10^9 \text{ cm}^{-3} < n < 10^{11} \text{ cm}^{-3}$; $T < 500 \text{ K}$ Gas mixture: helium + air.

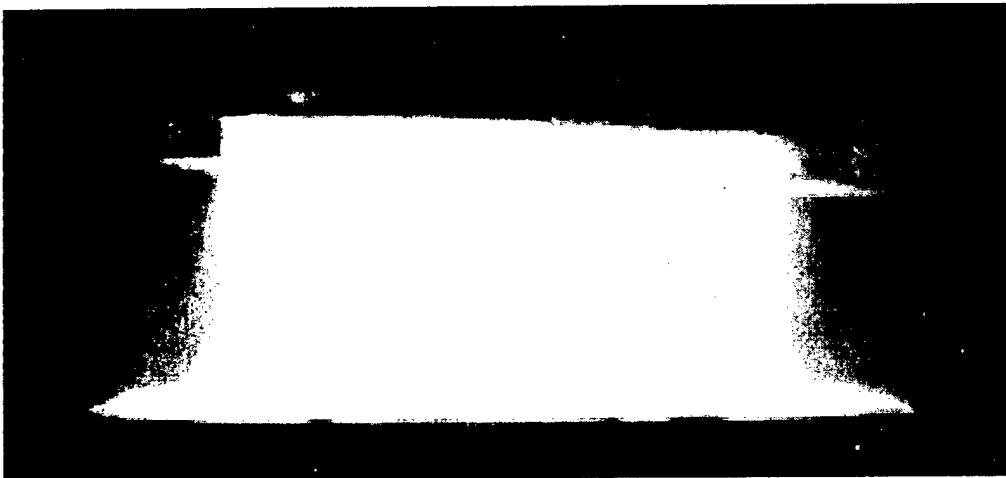


Fig.5 Photo of the Resistive Barrier Discharge (RBD)
 $V_{\text{rms}} = 13 \text{ kV}$; $f = 60 \text{ Hz}$; Helium

All the plasma discharges generated by the above mentioned methods can be used to treat the surfaces of materials, decontaminate various media, and breakdown polluting gases (such as VOC's , SO_x, and NO_x). Each of these applications requires an optimum set of plasma operating parameters, such as temperature, number density, and power density. Therefore plasma diagnostics is a very crucial task to understand thoroughly the physics and chemistry of the discharge. This understanding will allow us to find means to optimize the power consumption of these discharges, and to tailor the plasma for each specific application.

Impact of the purchased Instruments on our research activities

The acquired instrumentation allows us to build an experimental setup for each generation scheme discussed above, and to conduct both electrical and spectroscopic measurements. The electrical diagnostics are useful in the study of the stability of the discharges, and the onset of instabilities. The spectroscopic diagnostics allow us to carry out optical emission spectroscopy, which enables us to measure such key parameters such as the electron number density and gas temperature. Both the electron number density and gas temperature are important parameters in the Air Plasma Ramparts Program. Achieving a parameter range suitable to the APRP goal, with an acceptable level of applied power, is one of our research interests. Optical emission spectroscopy also allows us to analyze the light emitted by atoms, molecules, and radicals when they are excited by the field or by collisions with other particles. The wavelengths detected are characteristics of the excited species. Monitoring the discharge over a broad spectral range provides a detailed account of what active species are present in the plasma. This is important for such applications as pollution abatement, decontamination, and plasma-surface interactions, since it is the short-lived active species (such as O, OH, N, H, O₂^{*}) which react with the materials under test and induce the desired changes.

List of Purchased Instruments and Equipment

1. Imaging Spectrograph (Spectra Pro 558, with Photomultiplier and Spectrasense software): Used for optical emission spectroscopy
2. Digital Oscilloscope (Tektronix TDS 784D) and options: Used for measuring fast signals.
3. Residual Gas Analyzer (Stanford Research Systems, QMS 200): Used for gaseous by-products analysis.
4. Pumping System (Leybold Vacuum, PT 60): Used to evacuate discharge chamber
5. RF Power Supply (Huettinger PFG 2500/RF): Used to energize discharge electrodes
6. Stainless steel chamber and accessories: Used as discharge enclosure capable of holding low pressures.

Examples of Measurements

1. Electrical and light measurement

To characterize the RBD discharge we looked at its current and light emission. The current waveform revealed that even if the discharge is driven by a DC voltage, the current is rather pulsed. Our experiments showed that the current signal exhibited a pulsed form with

pulses few microseconds wide at a repetition rate of few tens of kHz. This suggests that when the discharge current reached a certain value, the voltage drop across the resistive layer became large to the point where the voltage across the gas became insufficient to ignite the discharge. Therefore, as the discharge extinguished, the current dropped rapidly and the voltage across the gas increased to a value capable of initiating the discharge again. To verify this we used a photomultiplier tube (PMT) to monitor the discharge light emission. Figure 6 shows both the discharge current and the PMT output signal. It is clear that there is correlation between the current pulses and the light pulses. In addition, it is interesting to note that the current pulses are not similar, especially in magnitude. This suggests that the discharge was not temporally uniform, and that both its number density and light emission fluctuated in time.

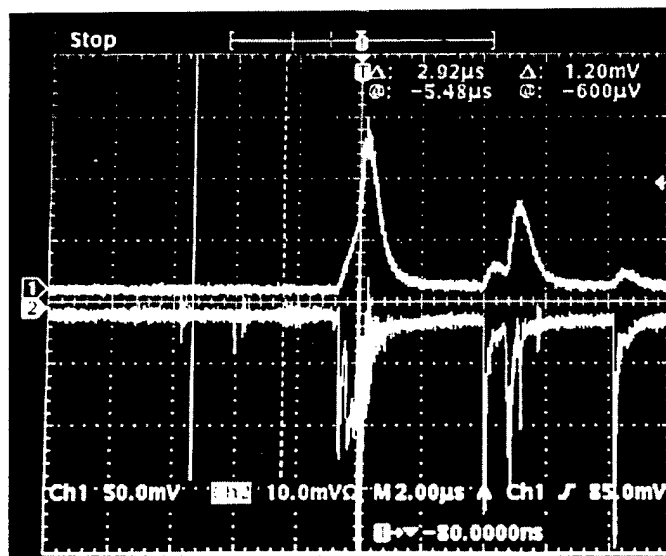


Fig. 6 Discharge current (yellow, top) and PMT signal

An archival paper describing the characteristics of the RBD has just been accepted for publication in the IEEE Transactions on Plasma Science Special Issue on Images in Plasma Science.

2. Spectral measurement of UV emission from a DBD-based discharge

Non-equilibrium high pressure discharges are good sources of excimers (excited dimers or trimers). Excimers are short lived and lose energy via emission of radiation (VUV, UV, and even visible). Figure 7 shows the emission spectrum of a DBD-based UV lamp. This spectrum was taken with the Spectrometer purchased under this grant.

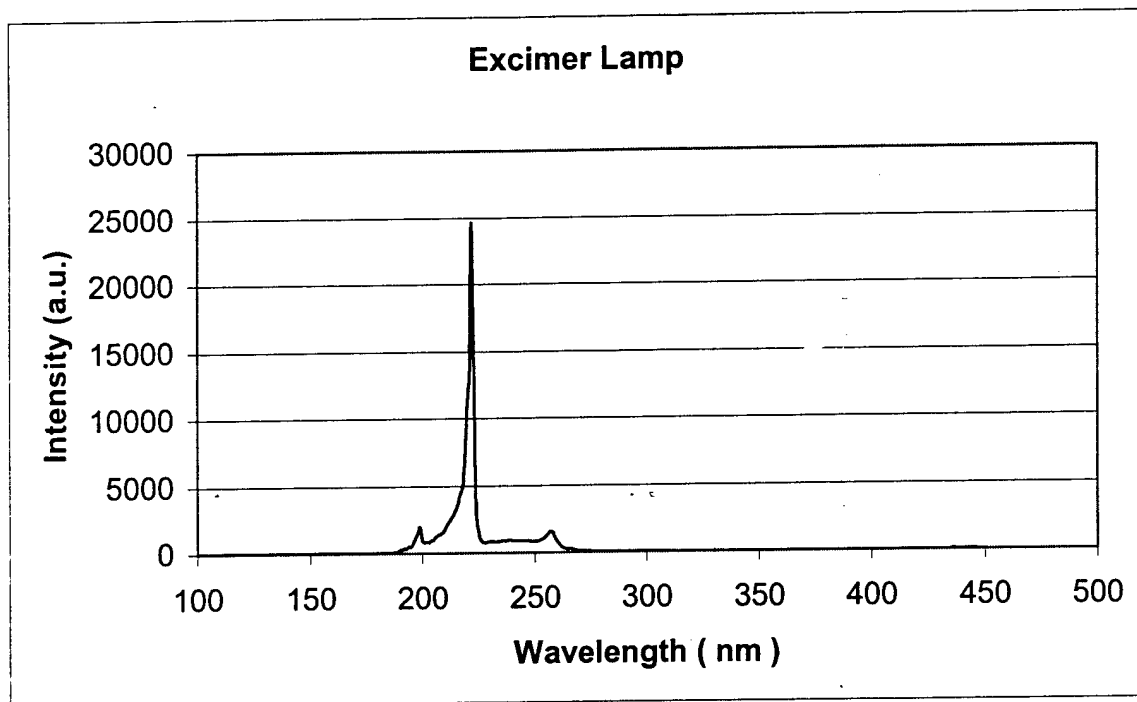


Fig. 7 Emission spectra of a DBD-based lamp obtained by the Spectra Pro 558 Spectrograph

Biological Applications

In collaboration with ODU's Department of Ocean Earth and Atmospheric Sciences we have been conducting experiments on the effects of the non-thermal plasma generated by the RBD on bacteria. These experiments were carried out by a Graduate Student (Mr. Paul Richardson). Mr. Richardson not only studied the germicidal effects of the plasma, but he also investigated the effects of the discharge on the biochemical pathways of bacteria and on their cell morphology. It was discovered that non-thermal plasmas exhibit sub-lethal effects which could induce changes in enzyme activity. These changes can have direct impact on the metabolism of plasma-treated bacteria. Also, using electron microscopy, it was discovered that the effects of plasma on cell morphology was dependent on the type of microorganism. Apparently, when exposed to a lethal plasma dose, Gram negative bacteria undergo substantial cell damage, while Gram positive bacteria show no visible morphological changes. This work was presented at the IEEE Pulsed Power Plasma Conference in Las Vegas, Nevada, and at the International Symposium on Plasma Chemistry in Orleans, France. Copies of these papers were attached to our progress report to AFOSR regarding grant F49620-00-1-0168. In addition, an archival paper was submitted for publication in the upcoming IEEE Transactions on Plasma Science Special Issue on the Non-Thermal Medical/Biological Applications of Ionized Gases and Electromagnetic Fields.

Collaborations with Other Groups

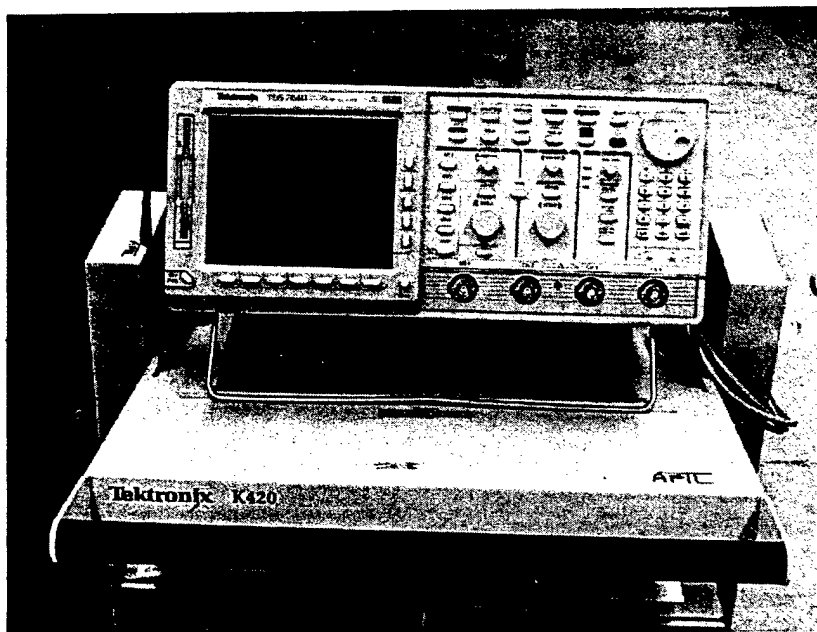
The P.I. is involved in the research activities of the Plasma Rampart MURI Program directed by AFOSR in cooperation with DDR&E. In this context, a collaborations with Prof. K. H. Schoenbach's group at ODU and Prof. Igor Alexeff (Univ. Tennessee) have been ongoing. These collaborations are mainly on diagnostics for gas temperature and electron number density measurement. In addition, the P.I. of this project is a member of the research team at ODU, working on the AFOSR-funded Compact Pulsed Power MURI. This effort is headed by Prof. Edl Schamiloglu of the University of New Mexico.

Other Activities of the P.I.

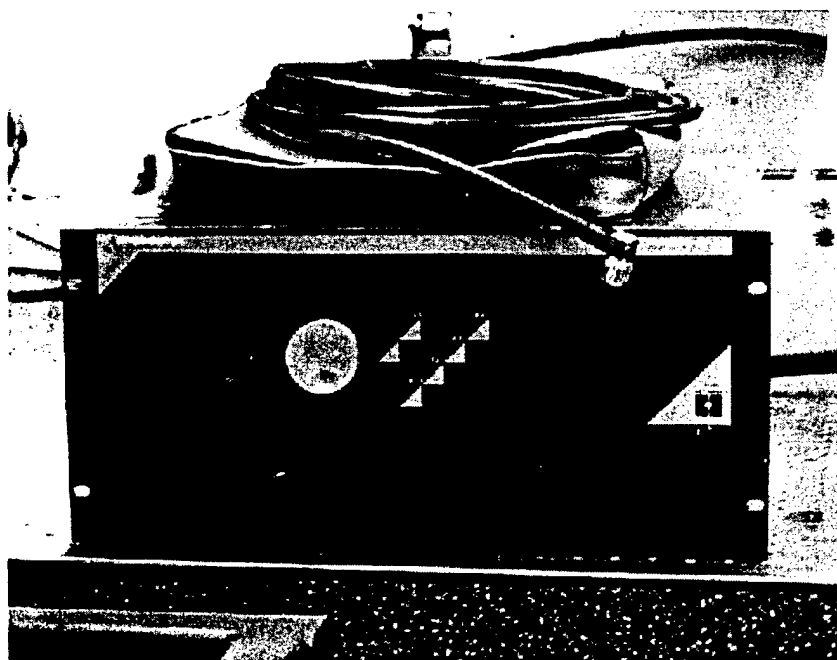
The P.I. served as a Session Chair at the Pulsed Power Plasma Conference, which was held at Las Vegas, NV, June 17-22, 2001. This session was on the Medical, Biological, and Environmental Applications of Plasmas. The P.I. will also serve as the organizer of the same session in the upcoming IEEE International Conference on Plasma Science, which will be held in Banff, Canada, May 2002. In addition, the P.I. is presently serving as Co-Guest Editor of the IEEE Transactions on Plasma Science Special Issue on the Non-Thermal Medical/ Biological Applications of Ionized Gases, and Electromagnetic Fields. This issue is scheduled to appear in August 2002.

Appendix

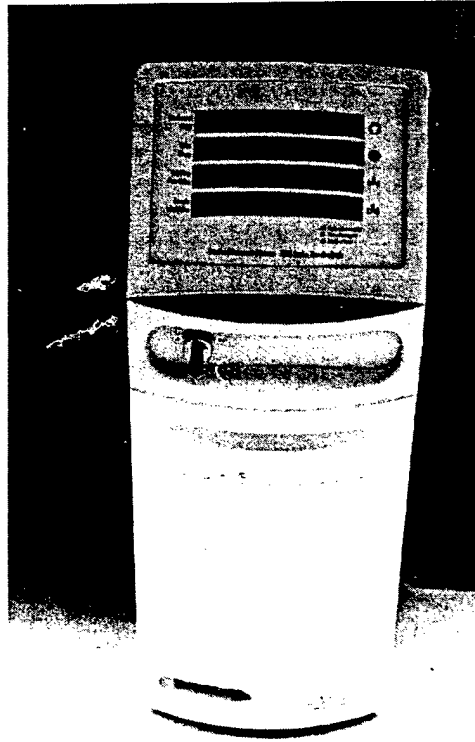
Photos of Main Instruments and Equipment



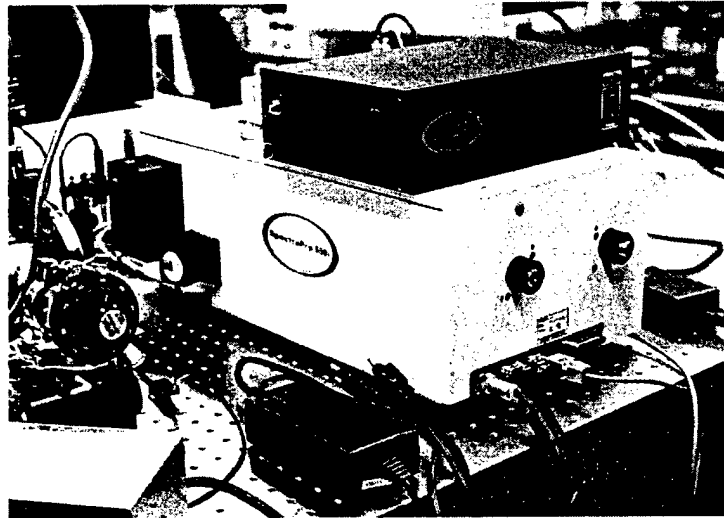
Wide band Oscilloscope



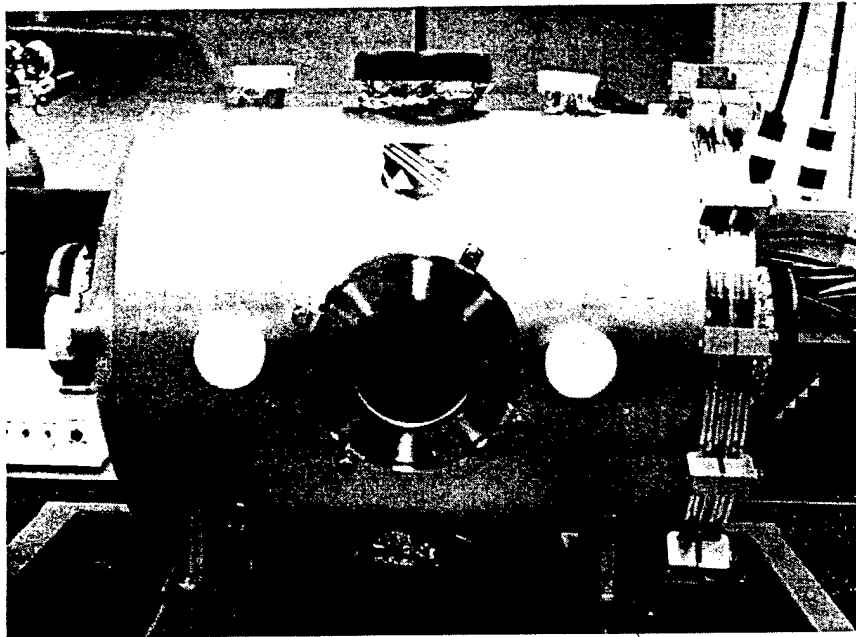
RF Source



Residual Gas Analyzer



Imaging Spectrograph



Chamber



Pumping System