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DEPARTMENT OF ELECTRICAL ENGINEERING  
SCHOOL OF ENGINEERING  
OLD DOMINION UNIVERSITY  
NORFOLK, VIRGINIA

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RADIATION PRODUCTION BY CHARGED PARTICLE  
BEAMS EJECTED FROM A PLASMA FOCUS

By

G. Marshall Molen  
Principal Investigator

Final Technical Report  
For the period July 15, 1979 - October 31, 1980

Prepared for the  
Air Force Office of Scientific Research  
Bolling Air Force Base  
Washington, DC 20332

Under  
Contract No. F49620-79-C-0151

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*Submitted by the*  
Old Dominion University Research Foundation  
P.O. Box 6369  
Norfolk, Virginia 23508

February 1981

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| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number)<br><br><b>The scope of this investigation concerns the development of a pulsed radiation source using the charged particle beam ejected from a plasma focus device. The concept represents a rather simple method of producing intense bursts of relatively soft x rays for applications such as the testing of satellite components for radiation hardening and survivability. The plasma focus is operated in a modified geometry such that electron bursts which originate in the plasma column at the onset of the plasma pinch are transported from the focus region to a target chamber by means of a conductive drift</b> |                                            |                                                                                               |

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tube. X rays are produced at a converter by thick-target bremsstrahlung.

This report describes the progress that has been made in the construction of such a radiation facility. The plasma focus, identified as the Mark IV, is nominally rated at 34 kJ with a capacitance of 168  $\mu$ F at 20 kV. The current status of the investigation is such that the device after considerable modifications, is now operational and diagnostic hardware is being developed to measure the electron bursts from the dense plasma.

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## RADIATION PRODUCTION BY CHARGED PARTICLE BEAMS EJECTED FROM A PLASMA FOCUS

### A. PROJECT DESCRIPTION

During the contractual period from July 15, 1979 to October 31, 1980, an investigation into the production of charged particle beams from a plasma focus has been initiated. The scope of the investigation concerns the development of a pulsed radiation source using the charged particle beam ejected from a plasma focus. The concept represents a method of producing intense bursts of relatively "soft" x rays for applications such as the testing of satellite components for radiation hardening and survivability. With the plasma focus in a somewhat modified geometry, electron bursts which are produced at the onset of the anomalous resistance in the plasma column are transported from the focus region to a target chamber by means of a conductive drift tube. At the target, x rays are produced by thick-target bremsstrahlung. As will later be described, it is believed that this concept offers significant advantages as a radiation source because of the versatility in the selection of the target material as well as the minimization of the blast effects from the plasma focus discharge.

In this investigation, such a plasma focus device has been constructed on the campus of Old Dominion University in Norfolk, Virginia. The device, originally identified as the Mark IV plasma focus, was previously located at The Aerospace Corporation in Los Angeles, California, where the principal investigator for this investigation was a former employee. As will later be described in some detail, the principal accomplishments during this investigation are that the experimental apparatus has been completely assembled and many design improvements made so as to make the experiment operational. This has also included the design and construction of diagnostics to measure the relevant beam parameters.

### Accelerating Mechanisms in the Plasma Focus

X radiation produced at the termination of the collapse phase of the plasma focus has been studied by numerous researchers and is now understood to result from both thermal and nonthermal processes.<sup>1</sup> The co-existence of the non-thermal radiation together with the radiation from the hot, dense, thermal plasma can lead one to deduce higher electron temperatures than are actually present. The origin of the nonthermal x rays is large accelerating electric fields produced at the termination of the dense pinch phase which accelerate electrons and ions to energies corresponding to a potential that is many times the capacitor-bank charging voltage. Radiation with energy above 20 keV and extending oftentimes into the hundreds of kiloelectron-volts is produced by thick-target bremsstrahlung when the energetic electrons bombard the center electrode. The emission can be enhanced by placing a high-Z stud (e.g., tantalum or tungsten) on the axis of the center electrode. A third source of x-ray emission results from material that is ablated from the anode surface and which forms a dense cloud that rapidly moves away from the anode surface. The x-ray emission associated with this mechanism is generally in the intermediate range (4-20 keV).<sup>1</sup>

Several authors have speculated on the mechanism responsible for the rapid disruption in the current which induces these intense fields. Gary<sup>2</sup> calculated the electric and magnetic fields that would result if one assumed an area of anomalous resistivity caused by a microinstability. Bostick<sup>3</sup> has proposed that the explosive decay of the magnetic structure in localized filaments in the plasma focus could cause the observed acceleration. Other work by Bernstein and Comisar<sup>4</sup> has considered the electric fields generated by a rapidly constricting current discharge and has shown that the electric fields are sufficient to

accelerate ions to axial energies greater than 400 keV. The response of the electrons when subject to given electric and magnetic fields has also been computed using numerical integrations of the three-dimensional relativistic equations of motion.<sup>5</sup> Although the exact nature of the mechanism responsible for this disruption in current and ensuing electric fields is not well understood, the intense fields are known to accelerate ion bursts in one direction from the plasma pinch while accelerating electrons in the opposite direction. For a positive center electrode, electrons are accelerated from the plasma into the anode while ions are accelerated away from the anode surface.

When the plasma focus is operated with deuterium gas, it has also been concluded for both the Mather and Filippov geometries that beam-target reactions of the ejected deuterons with the stationary gas may account for much of the neutron yield.<sup>6-9</sup> The fractional contribution of this mechanism compared to the thermonuclear neutron production is primarily dependent upon the filling pressure. The accelerating mechanisms are most dominant for the low-pressure regime. This author has previously reported measurements of the ion beam current and has identified charge exchange processes as responsible for neutralizing much of the ion current.<sup>10</sup>

Since the initial investigation described here, several other researchers have conducted experiments on plasma focus devices in which they have observed the intense electron bursts. Nardi and Bostick have analyzed the internal structure of both the ion and electron beams ejected from the plasma focus.<sup>11</sup> While the major emphasis of their investigation has been the filamentary structure of the beams as recorded on targets, they have detected peaks in the ion and electron energy spectra at 300 to 400 keV. These investigators have recently reported 1-10 ns pulses where the composite internal structure of each filament is a sequence of concentric circles with a discontinuous pattern.<sup>12</sup> Another investiga-

tion by Gerdin, Stygar, and Venneri has attempted to determine the ratio of the electron to ion currents that are ejected from the focus.<sup>13</sup> Similar experimental results were obtained by Lee, Hohl, and McFarland in which they investigated the electron bursts from the plasma focus using x-ray measurements, thin-foil dosimetry, and beam current monitoring.<sup>14</sup> This latter group observed that the electron burst was highly collimated, and they measured beam currents of 10 kA with a Faraday cup at the beam port. The duration of the high-energy electron beam was also recently measured by another group by means of a Cerenkov detector, and they concluded the pulse was less than 0.4 ns.<sup>15</sup>

#### Research Tasks

The research tasks of this investigation are as follows:

- a. The Mark IV plasma focus device will be transferred from The Aerospace Corporation and assembled at Old Dominion University. The plasma focus will be configured so as to operate in the electron acceleration mode.
- b. The production of focused electron beams in the plasma focus device and the x rays that these electron beams produce will be investigated.
- c. The energy of the ejected electrons will be measured by observing the depth of penetration in dielectric films.
- d. The ejected electron beam current transported through the drift tube will be measured with a high frequency Faraday cup.
- e. The temporal current profile measured with the Faraday cup will be compared with the x-ray emission from the converter material.

#### Potential Applications of a Plasma Focus Accelerator

The research conducted in this investigation has important potential applications as a relatively simple device for producing intense electron bursts of a few nanosecond duration. Conceivably the beams may be useful as an accelerator

for pellet implosion in the fusion program. Of more direct interest to the Air Force are applications as a pulsed x-ray device for radiation simulation studies. As an example, the concept has already proven useful as a pulsed photon source for SGEMP and TREE testing of satellite components.<sup>16</sup> While conventional plasma focus devices have been used for such applications, their usefulness has been somewhat limited because of the debris produced by the plasma focus discharge.

The concept of extracting an electron burst from the focus region and delivering to a remote target where x rays are produced by thick-target bremsstrahlung has obvious advantages as a simulator because of the isolation from the hot plasma. It is possible to produce clean, single x-ray pulses of 10-30 ns pulsewidth which for the Mark IV plasma focus have an x-ray flux greater than  $10^{10}$  Rad(Si)/sec at 10 cm from the converter. It is also important for this application that there is a significant fluence in the soft x rays. The isolated target permits greater access and allows the sample to be placed arbitrarily close to the source. Another most important consideration is the target material that is used as the x-ray converter. Some selection in the desired spectrum can be obtained by choosing the target material so as to utilize the characteristic emission spectrum. This has previously been demonstrated using targets fabricated from tantalum and aluminum.<sup>16</sup>

## B. STATUS OF RESEARCH EFFORT

The investigation of charged particle beams from a plasma focus requires considerable experimental hardware and support equipment. With the assistance of AFOSR, a plasma focus device was acquired in September 1979 from The Aerospace Corporation in Los Angeles, California, where the principal investigator of this investigation was a former employee. The initial experiments on beams from plasma focus devices were first conducted on this device.<sup>17</sup> This plasma focus, identified as the Mark IV, is nominally rated at 34 kJ corresponding to a capacitance of 168  $\mu$ F at 20 kV.

The equipment transferred to Old Dominion University from The Aerospace Corporation consisted of the vacuum chamber, electrodes, capacitors, and some support equipment. However, many items of equipment necessary to the operation of the system were not included. It was also found that most items that were received required a significant effort to make them operational. Considerable work was also required to modify the equipment so as to adapt to the system being constructed at Old Dominion University.

Thus the most significant effort in this investigation has been the construction of the laboratory which has included the repair and adaptation of many items of support equipment. As will be described, the construction of the plasma focus system has been completed, and the device is currently operational. During the initial phases of the investigation, the laboratory operated on a minimal budget and monies were not available for the purchase of new capital equipment. A significant contribution was made by the Department of Electrical Engineering at Old Dominion University which was primarily used to pay undergraduate students to assist in the assembly of the experiment. More recently the laboratory has received additional support from other agencies such as the National Science Foundation and the Naval Surface Weapons Center which has enabled the laboratory

to improve their facilities.

#### The Plasma Focus Experiment

A drawing of the plasma focus experiment configured in a mode so as to couple electron bursts from the center electrode is shown in Fig. 1. The electron burst is coupled through a 1.5-cm diameter aperture in the center electrode (anode) to which is attached a 5-cm I.D. copper drift tube that extends 82 cm from the surface of the anode. As previously described, when the device is operated in the low-pressure regime, high axial electric fields occur at the termination of the dense pinch phase which accelerate electrons to relativistic velocities. Typical operating parameters are static fill pressures of 2.5 to 3.5 Torr deuterium and capacitor bank voltages of 12 to 16 kV. Although the device is nominally rated at 34 kJ, the machine is typically operated at a reduced voltage of 14 kV and a corresponding bank energy of 17 kJ so as to reduce the risk of insulator damage. As shown in the figure, the electron beam source is operated in the grounded-switch mode so that the center electrode and attached drift tube are at ground potential. This connection permits either electron beam diagnostics or an x-ray converter to be attached to the output flange that is located at the end of the drift tube. Also shown in the figure is a diagnostic tube which is connected to the x-ray converter. A thin x-ray window of 0.13 mm Kapton (for example) is used to isolate the diagnostic tube from the ambient gas in the plasma focus chamber.

A photograph of the plasma focus experiment is shown in Fig. 2. In this photograph the plasma focus vessel is surrounded by a lead cylinder which is used for x-ray shielding. The lead shield has removeable ports so as to facilitate diagnostics of the plasma focus discharge. Also shown are two of the four capacitor modules which are connected to the electrodes by strip lines. The vacuum

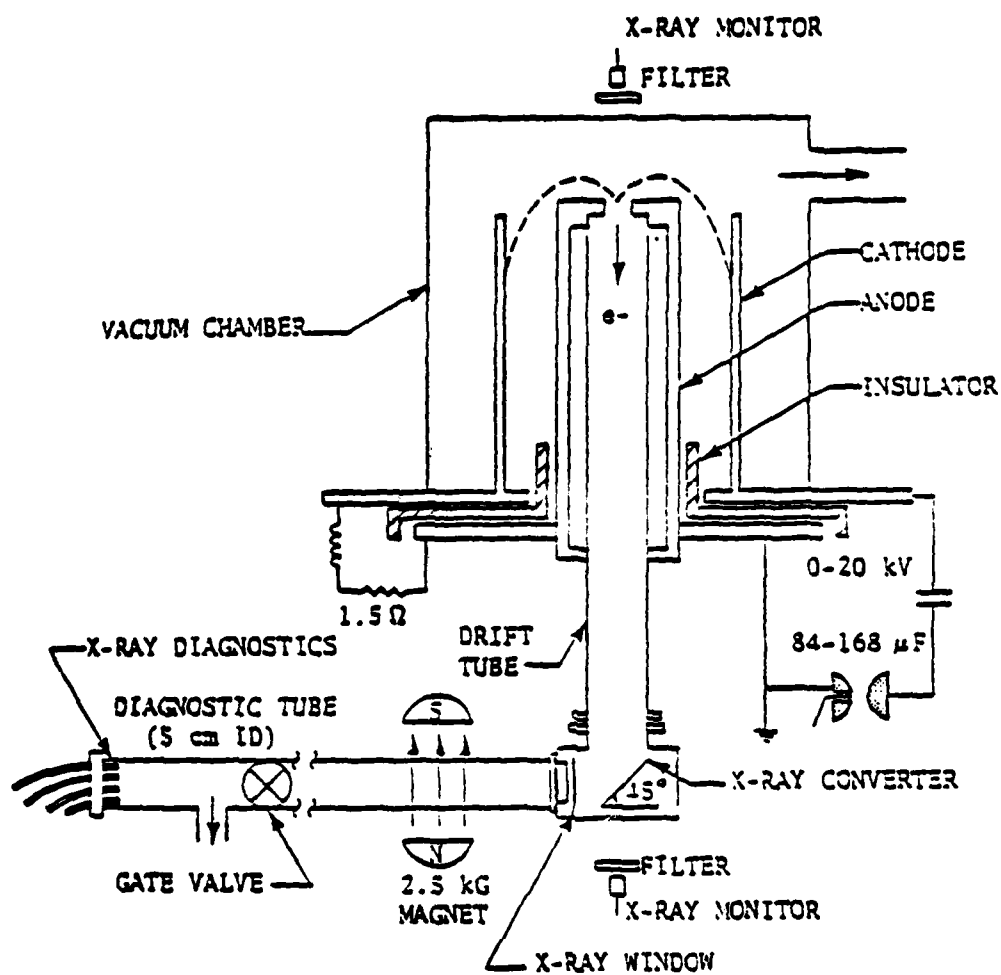


Fig. 1. Experimental arrangement of the Mark IV plasma focus simulator



Fig. 2. Photograph of the plasma focus experiment.

system and hydrogen gas feed system may be seen in the background. Also in the background and to the left are the high voltage power supply, trigger electronics, and a corner of the screen room. The screen room is interfaced to diagnostics used on the experiment by coax cables supported inside a copper pipe and terminating in a junction box as shown in the top of the photograph.

Presented in Fig. 3 is a view of the plasma focus vessel. The lead shield is shown in the photograph suspended by an overhead hoist. Also shown is the Pyrex tubing which connects the plasma focus chamber to the vacuum system. The diagnostic ports can be seen in the photograph by carefully examining the plasma focus vessel.

#### Development of Laboratory Facilities

The progress in the development of the laboratory facilities is best illustrated using the block diagram shown in Fig. 4. The figure includes the major components of the plasma focus system as well as several of the more important diagnostics. The experiment was assembled in an air-conditioned laboratory on the University campus that is entirely dedicated to pulse power experiments. The 27 ft x 37 ft laboratory is located on the ground floor with an outside loading dock and has three-phase electrical service as well as natural gas and compressed air. A 66 sq. ft. storage room and a photographic dark room are located adjacent to the laboratory.

Referring to Fig. 4, the progress of the current investigation is as follows:

- a. Screen room - a 10 ft x 16 ft copper screen room was provided by the University. The screen room was assembled in the laboratory and an appropriate isolation transformer and line filters were connected so as to provide electromagnetic shielding. Two terminal boxes are mounted adjacent to the experiment so that a maximum of nine coax connectors for diagnostic cables are available

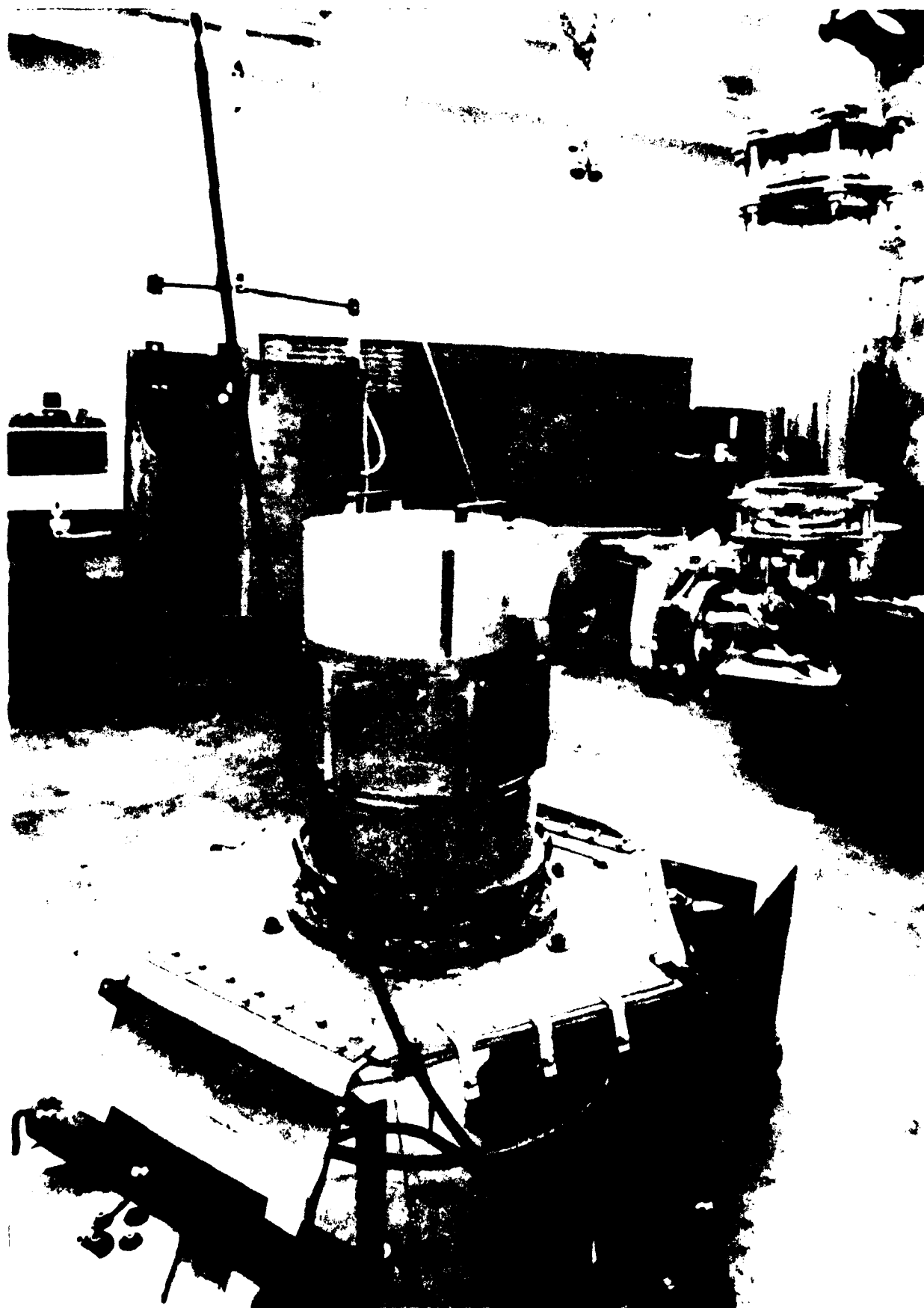


Fig. 3. Photograph of the plasma focus chamber.

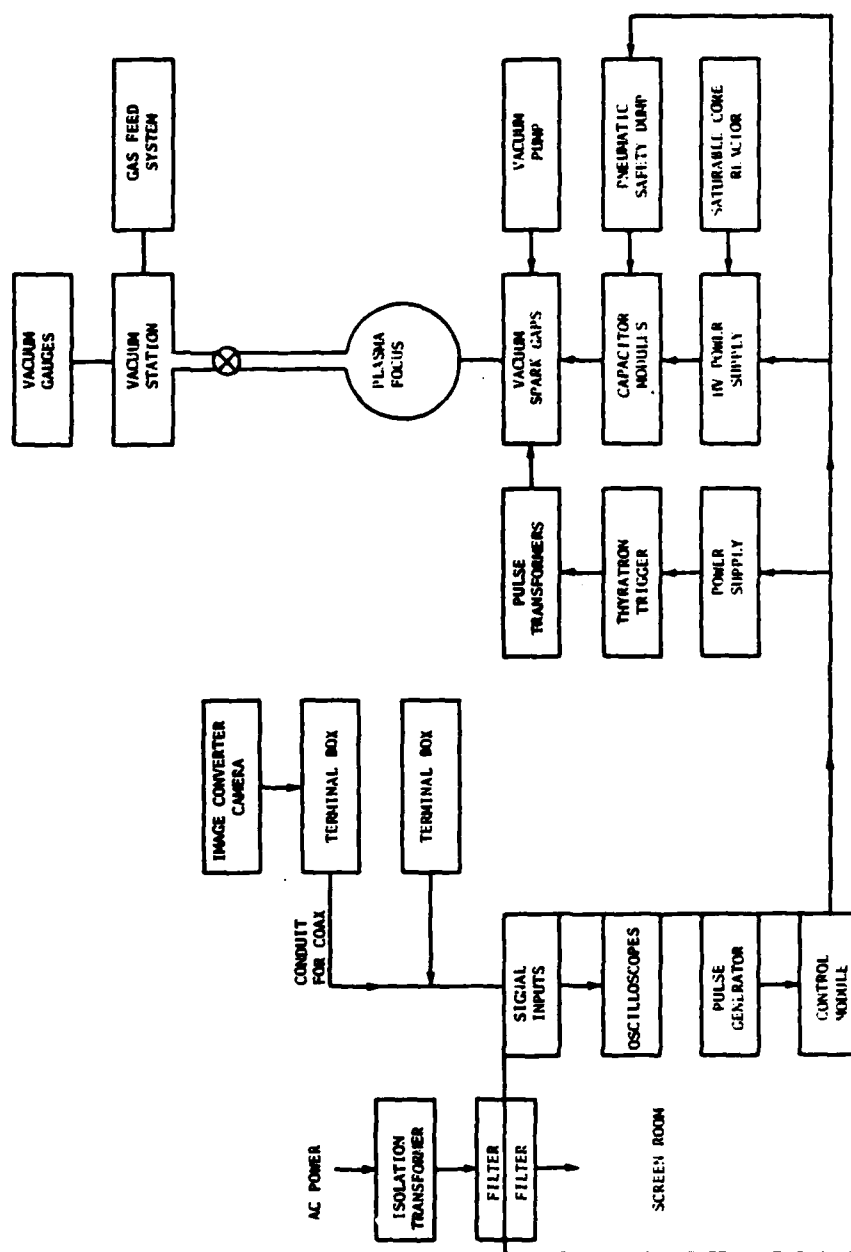


Fig. 4. Block diagram of the experimental arrangement.

at each box; the terminal boxes connect to the screen room by copper pipes. A control module is mounted inside the screen room so that the operator can control the experiment from a single panel. This module consists of relays and sequence circuits which operate a pneumatic safety dump, surge the high voltage power supply, and automatically actuate the plasma focus when the capacitors are fully charged. The circuit was designed to be both functional as well as an additional safety feature for laboratory personnel.

b. Plasma Focus Device - The major components of the Mark IV plasma device were obtained from The Aerospace Corporation. The chamber was rigidly mounted, and several blanking plates were machined for sealing the diagnostic ports of the chamber. The chamber walls, electrodes, and insulators were also thoroughly cleaned and inspected before installation. The device is currently operating and energetic electron bursts have been detected.

c. Vacuum System - The vacuum station to the Mark IV system was not available from The Aerospace Corporation; however, parts of the vacuum station to another experiment were obtained. This surplus equipment did not include a mechanical pump nor many other vital components. Fortunately a used system from NASA/Langley Research Center was obtained. The system includes a model 1397 Welch forepump, a 3.5 in. diffusion pump, electrically-actuated pneumatically-driven valves, and an ionization gauge. Using components from the surplus station, a considerable effort was devoted to rebuilding the system. Both the mechanical and diffusion pumps required an extensive overhaul. Base pressures of  $10^{-6}$  Torr have been obtained. A photograph of the vacuum controller and instrumentation is shown in Fig. 5. Also shown is a flexible bellows which adapts the vacuum station to the Pyrex tubing.

Associated with the vacuum station, a gas feed system for metering hydrogen or deuterium gas into the plasma focus chamber was constructed. Provisions

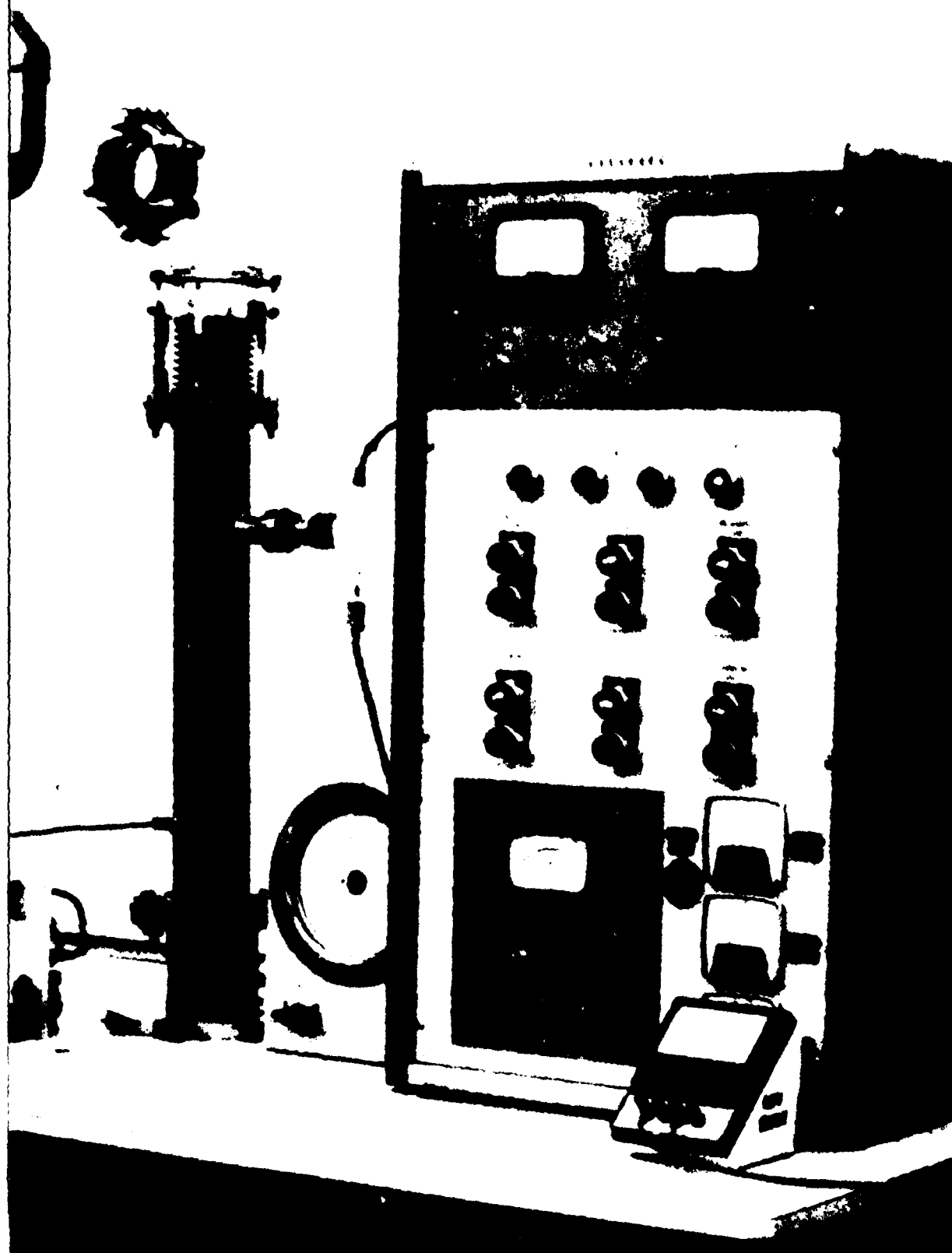


Fig. 5. Photograph of the vacuum station and controller.

were made for several gauges to be included so as to monitor both the base pressure and the chamber pressure when filled with gas. These instruments consist of a diaphragm vacuum gauge, ionization gauge, and several thermocouple gauge tubes distributed throughout the system.

d. Capacitor Modules and Vacuum Spark Gaps - The capacitors to the experiment were received in good condition from The Aerospace Corporation, and the units were connected to the plasma focus device by striplines. Vacuum spark gaps switch each of the four modules which consist of three 14  $\mu\text{F}$  capacitors. The switches, which were each refurbished, are evacuated by a mechanical vacuum pump, and nitrogen is slowly leaked into the system so as to achieve the desired threshold voltage. The mechanical vacuum pump was provided by the University.

e. High Voltage Power Supply - The original high voltage power supply to the Mark IV plasma focus was received from The Aerospace Corporation. The unit was not operational, and it was determined that considerable expense would be required to repair the supply. A 50 kV/20 mA supply was later obtained from surplus with the assistance of AFOSR. The power supply was intended for high-voltage, low-current applications that require good voltage regulation. Laboratory personnel have reconfigured the supply so as to produce a maximum output of 25 kV at 40 mA. Provisions were also made so that the supply could be operated in the surge mode. This was accomplished by adding a saturable core reactor in the primary circuit to limit the current during capacitor charging. The output voltage is monitored by a voltmeter located on the control panel inside the screen room. This supply was adequate for the initial phases of the investigation; however, charging times in excess of one minute are required. A larger power supply of considerably higher current capability was recently

obtained with funds provided by a NSF grant so that the charging time can be reduced. A safety dump consisting of a  $\text{CuSO}_4$  water resistor is connected to the output by means of an electrically actuated, pneumatic cylinder which is also controlled from inside the screen room.

f. Spark Gap Trigger Circuit - The vacuum spark gaps that switch the capacitor modules to the plasma focus load require a trigger voltage of 8 to 10 kV. The original unit was not available and laboratory personnel fabricated an appropriate thyatron circuit from miscellaneous components. The pulse generator is coupled to the vacuum switches by individual pulse transformers. The thyatron tube is similarly triggered from inside the screen room by a 600 V pulse generator which was constructed using Krytron tubes (product of EG & G). This latter generator has four outputs with a digital circuit for variable delay.<sup>18</sup>

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#### D. PROFESSIONAL STAFF

I. The professional staff member associated with this project and the extent of his reported effort is as follows:

1. Dr. G. Marshall Molen: Principal Investigator, Associate Professor in Electrical Engineering, SS No. 460-68-6501, Secret security clearance.

- a. Reported effort during duration of original contract (July 15, 1979 - July 14, 1980) was 1.9 man-months.
- b. Effort during extension of contract (July 15, 1980 - October 31, 1980) was approximately 0.3 man-months at no charge to the contract.

II. Other professional staff members associated with this project but not paid from this contract:

1. Dr. James L. Cox, Jr.: Associate Professor in Physics, SS No. 244-66-8765. Provided consultations on beam propagation in plasmas at no charge to the contract.
2. Mr. Hugh C. Kirbie: Instructor in Electrical Engineering, SS No. 458-94-5792. Provided assistance in establishing laboratory at no charge to the contract (August 15, 1980 - October 31, 1980). Mr. Kirbie is a coinvestigator on the grant that extends from this contract.

III. The graduate student support utilized on the project and the extent of his reported effort is as follows:

1. Mr. Gregory P. Robertson: Graduate Research Assistant in Electrical Engineering, SS No. 224-78-9922. Effort charged to this contract was 1.3 man-months (August 16, 1979 - October 31, 1979).

## E. PROFESSIONAL INTERACTIONS

### I. Technical presentations by professional staff member at scientific meetings:

1. G.M. Molen, "Measurement of Electron Bursts Produced by a Plasma Focus" presented at Amer. Phys Soc., Plasma Physics Division Meeting, Boston, MA, November 14, 1979. Abstract published in Bull. Amer. Phys. Soc., Vol. 24, p. 1080.
2. G.M. Molen, "Intense Charged Particle Beams Ejected from a Plasma Focus" presented at IEEE Intl. Conf. on Plasma Science, Madison, WI, May 19, 1980. Abstract published in Conf. Record of 1980 IEEE Intl. Conf. on Plasma Science, IEEE cat. no. 80CH1544-6NPS, p. 74.
3. G.M. Molen, "Electron Burst from Dense Plasma Focus", Plasma Physics Seminar presented to the Plasma Physics Division at the Naval Research Laboratory, Washington, D.C., Jan. 30, 1980.
4. G.M. Molen, "Electron Bursts from a Plasma Focus", Plasma Physics Seminar presented to the Physics Department at the College of William and Mary, Williamsburg, VA, March 21, 1980.

### II. Consultative and advisory functions to DoD agencies by professional staff member:

1. G.M. Molen, participant in DoD Workshop on Particle Beam Research sponsored by AFOSR and ARO, USAF Academy, CO, Jan. 9-10, 1980.
2. G.M. Molen, "Pulsed Power Systems Analysis", consulting services to Naval Surface Weapons Center, Dahlgren, VA, May 15, 1979 to November 30, 1980, under contract N60921-79-C-A188.

### III. Research activities with other sponsoring agencies

1. G.M. Molen, Principal investigator, "Charged Particle Beams from a Plasma Focus", National Science Foundation, May 15, 1980 to

May 14, 1981, grant no. CPE-7925563.

2. G. M. Molen, Principal investigator, "A Plasma Focus Opening Switch",  
Naval Surface Weapons Center, August 11, 1980 to August 10, 1982.

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