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## Final Technical Report

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Plasma-Puff Initiation of High Coulomb Transfer Switches

K. S. Han, D. D. Venable, Ja H. Lee, E. H. Choi, Y. K. Kim

J. H. Kim and D. X. Nguyen

Abstract

The plasma-puff triggering mechanism based on a hypocycloidal pinch geometry was investigated to determine the optimal operating conditions for an azimuthally uniform surface flashover which initiates plasma-puff under wide ranges of fill gas pressures of Ar, He and N<sub>2</sub>. The optimal fill gas pressures for the azimuthally uniform plasma-puff were about 120 mTorr < P<sub>opt</sub> < 450 Torr for He and N<sub>2</sub>. For Argon 120 mTorr < P<sub>opt</sub> < 5 Torr for Argon. The inverse pinch switch was triggered with the plasma-puff and the switching capability under various electrical parameters and working gas pressures of Ar, He and N<sub>2</sub> was determined. It was also shown that the azimuthally uniform switching discharges were dependent on the type of fill gas and its fill pressure. A new concept of plasma-focus driven plasma-puff was also discussed in comparison with hypocycloidal pinch plasma-puff triggering. The main discharge of the inverse pinch switch with the plasma-focus driven plasma-puff trigger is found to be more azimuthally uniform than that with the hypocycloidal pinch plasma-puff trigger in a gas pressure region between 80 mTorr and 1 Torr.

In order to assess the effects of plasma current density on material erosion of electrodes, emissions from both an inverse-pinch plasma switch (INPIStron) and from a spark gap switch under test were studied with an optical multichannel analyzer (OMA). The color temperature of the argon plasma was approximately 4,000 K which corresponded with the peak continuum emission near 750 nm. There are the strong line emissions of argon in the 650 - 800 nm range and a lack of line emissions of copper and other solid material used in the switch. This indicates that the plasma current density during closing is low and the hot spot or hot filament in the switch is negligible. This result also indicates considerable reduction of line emission with the INPIStron switch over that of a spark-gap switch. However, a strong carbon line emission exists due to vaporization of the plastic insulator used. In order to reduce the vaporization of the insulator, the plexiglass insulating material of INPIStron was replaced with Z-9 material. A comparative study of the INPIStron and a spark gap also reveals that the INPIStron, with a low impedance of Z = 9 ohms, can transfer a high voltage pulse with a superior pulse-shape fidelity over that of a spark gap with Z = 100 ohms.

# Plasma-Puff Initiation of High Coulomb Transfer Switches

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## I. Introduction

New developments in high pulse power systems, such as lasers, intense relativistic electron beam accelerators, and fusion devices, often require electrical switching capabilities beyond what are currently available. The requirements for a high power switch are, in general, fast rise time, high current handling capability, fast recovery time (which affects the repetition rate), fast thermal energy dissipation, free from component damage, and high hold-off voltage. In addition, reproducibility of switching action and a long lifetime are particularly emphasized for space application of magnetoplasmadynamic (MPD) thruster technology.

Spark gap switches, commonly used for high pulse-power commutation, have short lifetimes because of severe electrode heating from which surface erosion occurs. Yet this switch still covers the highest transfer range. Also the important requirement of a fast recovery time has not been successfully realized in the spark gap.

One approach to providing a high coulomb transfer switch having a longer useful life, higher current capability and faster switching than those of existing high power switches has been developed by Lee ( U. S. Pat. No. 4475066). The inverse pinch structure is designed to carry high currents with significantly reduced erosion of electrodes and to reduce the inductance of the switch by using coaxial current paths. Preliminary results show that the peak current handling capability was larger than 350 kA at a hold-off voltage of 14 kV when fill gas pressure of N<sub>2</sub> was 10 mTorr. An upgraded design for an inverse pinch switch was recently reported to meet the requirements for the output switch of an ultra-high-power (>30 GW) pulser. The hold-off voltage of 1 MV is met by adopting multistage rim-fire electrodes and using SF<sub>6</sub> as the dielectric gas of the

switch.

For the inverse pinch switch, the initial uniform breakdown is a key factor for obtaining reproducibility and for long-life operation. Accordingly, the development of an inverse pinch current in the switch depends on the trigger mechanism. In the preliminary experiment, the triggering of the switch was provided by a pin-type or ring-type third electrode, and azimuthally uniform initiation was limited to a narrow range of working gas pressures. By using the trigger pins with a trigger pulse having 100 ns rise time, a switching phase reproduction of less than 20% at a pressure of 10 mTorr was observed. This indicated that a fast trigger pulse was required to increase the reproducibility. The wear of the trigger pins was eminent and the switch therefore had a short lifetime.

In this research, a new triggering mechanism called "plasma-puff" was designed and investigated to determine the operating conditions for a wide range of filling gas pressures of Ar, He and N<sub>2</sub>. A prototype of the plasma inverse pinch switch with plasma-puff trigger was tested<sup>10</sup> to characterize the hold-off voltage, the anode fall-time, the switch resistance, the energy dissipation, the recovery time, and the V-I phase relation with a high current load of 0.5 MA. The plasma-puff trigger electrode was coaxially located under the main gap electrode pair and initiated gap breakdown by injecting annular plasma rings into the gap. The major advantage of the plasma-puff trigger was a circumferentially uniform current sheet formed by the initial surface discharge which in turn could initiate a uniform annular breakdown over the insulator in the main gap of the inverse pinch switch. The plasma-puff triggering device was constructed in a hypocycloidal pinch geometry and drove the current sheet (plasma) radially inward into the annular gap of the main electrode. The plasma driven by the current sheet, i. e., the plasma-puff, produced electrons and ions for the main gap breakdown.

Another new triggering concept of a plasma-focus driven plasma-puff was designed and tested to determine the operating conditions and to optimize this system for azimuthally uniform switching discharges for a wide range of fill gas pressures of Ar, He and N<sub>2</sub>. The trigger electrode in this geometry was coaxially located above the main gap electrode pair and insulated by

teflon from the main gap electrode. The plasma-puff triggering device was in a plasma-focus geometry and drove the current sheet axially downward and radially inward into the annular gap of the main electrode. The plasma-focus driven plasma produced electrons and ions for the main switch breakdown.

Details for characteristics of switching in an inverse-pinch switch are found in Appendix 2 and Appendix 3.

## II. Summary

The plasma-puff triggering mechanism based on a hypocycloidal pinch geometry and a plasma-focus Mather geometry was investigated to determine the optimal operating conditions for an azimuthally uniform surface flashover which initiates plasma-puff under wide ranges of fill gas pressure of Ar, He and N<sub>2</sub>. The optimal fill gas pressures for the azimuthally uniform plasma-puff were about 120 mTorr < P<sub>opt</sub> < 450 Torr for He and N<sub>2</sub> and 120 mTorr < P<sub>opt</sub> < 5 Torr for Argon. The inverse pinch switch was triggered with the plasma-puff and the switching capability under various electrical parameters and working gas pressures of Ar, He and N<sub>2</sub> were determined. It was also shown that the azimuthally uniform switching discharges were dependent on the type of fill gas and its fill pressure. The main discharge of the inverse pinch switch with the plasma-focus driven plasma-puff trigger was proved to be more azimuthally uniform than that with the hypocycloidal pinch plasma-puff trigger in a gas pressure region between 80 mTorr and 1 Torr.

A hold-off voltage greater than the test voltage used here will be required for the inverse pinch switch for future applications. It might be necessary to adopt a multi-ring and multi-gap arrangement to obtain the optimal switching operating conditions for such high voltage applications.

An extended study of the INPIStron for pulse transfer fidelity and efficiency revealed the INPIStron as the superior performer over the reference spark gap. Also material erosion as compared with the emission spectra of the closing plasmas in the two switches, showed

considerable differences which indicated the low current density and low material erosion in the INPIStro. These findings again confirm the superiority of the INPIStro already found with respect to other parameters associated with high powers switches such as the voltage hold-off, Coulomb transfer, lifetime, material erosion, and repetition rate.



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Conference, San Diego, CA June 16-19, 1991 (Digest of Tech. Papers, IEEE Cat. No. 91CH3052-8, P.904)

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15. J. H. Lee, S. H. Choi and K. D. Song "Preliminary Test for Megavolt Inverse-Pinch Plasma Switch," Nineteenth Power Modulator Symposium, San Diego, CA June 1990, Paper 8-20.
16. E. H. Choi, K. S. Han, D. D. Venable, J. H. Lee, "Characteristics of Plasma-Puff Trigger for an Inverse-Pinch Plasma Switch," Spring Meeting of the American Physical Society, Wash. DC, April (Bull. APS 35, 1051 (1991)).

#### IV. List of all Participating Scientific Personnel

Period : March 1, 1989 - June 30, 1993

|               |                          |                              |
|---------------|--------------------------|------------------------------|
| D. D. Venable | (Principal Investigator) | March 1, 1989 - present      |
| K. S. Han     | (Principal Investigator) | March 1, 1989 - present      |
| E. H. Choi    | (Research Associate)     | March 1, 1989 - Feb 28, 1990 |
| Y. K. Kim     | (Graduate Student)       | Sept. 1, 1989 - May 30, 1990 |
| J. H. Kim     | (Graduate Student)       | June 1, 1990 - May 30, 1992  |
| D. X. Nguyen  | (Graduate Student)       | Sept. 1, 1991 - Present      |

Yong K. Kim completed his Master of Science degree in July of 1992. His M. S. thesis title was "Comparative Study of Closing Plasma in Inverse Pinch Switch".

Jong H. Kim completed his Master of Science degree in July of 1992. His M. S. thesis title was "Plasma Dynamics in a Hypocycloidal Pinch Device".

Dung X. Nguyen will complete his Master Science degree in the Fall of 1993.

## V. List of Progress Reports Submitted

1. Annual Progress Report: Period Feb 1, 1989 - Feb 28, 1990
- 2.. Annual Progress Report: Period April 1, 1990 - March 31, 1991
3. Annual Progress Report: Aug. 9, 1991- Aug. 6, 1992

## VI. List of Conference Papers

Presented

Period March 1, 1989-June 30, 1993

1. Eun H. Choi, Demetrius D. Venable, Change S. Han and Ja H. Lee, "Characteristics of Plasma-Puff Trigger for an Inverse-Pinch Plasma Switch", Bull. ASP Vol. 35, No. 4 1051 (1990)
2. Ja H. Lee, E. H. Choi, D. D. Venable and Change S. Han, "Ultra-High-Power Plasma Switch INPUTS for Pulse Power Systems", 25th Intersociety Energy Conversion Engineering Conference (IECEC) Proceeding. Vol. 1, 414-419 (1990).
3. Ja H. Lee, Sang Choi, D. D. Venable, K. S. Han, "Characteristics of Switching Plasma in an Inverse-Pinch Switch", 8th International Pulsed Power Conference - 1991, IEEE 91 CH3052-8, 904-907 (1991).
4. K. S. Han and J. H. Lee, "Comparative Study of INPIStron and Spark Gap", 1992 20th Power Modulator Symposium, 92 CH3180-7, 402-405 (1992).
5. Kwang S. Han, Ja H. Lee, "INPIStron Switched Pulsed Power for Dense Plasma Pinches", 9th International Pulsed Power Conference (June 21-23, 1993) Albuquerque, New Mexico, Paper PIII66.

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# Appendix

Appendix 1

Abstract Submitted  
for the 1990 Spring Meeting of the  
American Physical Society

16-19 April 1990  
Meeting Date

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Sorting Category  
Plasma Physics

Characteristics of Plasma-Puff Trigger for a Inverse-Pinch Plasma Switch.\* EUN H. CHOI, DEMETRIUS D. VENABLE, KWANG S. HAN, and JA H. LEE, Hampton University --- The plasma-puff triggering mechanism based on a hypocycloidal pinch geometry was investigated to determine the optimal operating conditions for the azimuthally uniform surface flashover which initiates plasma-puff under wide ranges of fill gas pressure of Ar, He and N<sub>2</sub>. The optimal fill-gas pressure range for the azimuthally uniform plasma-puff was about 120 mTorr  $\leq P_{op} \leq$  450 Torr for He and N<sub>2</sub>. For Argon 120 mTorr  $\leq P_{op} \leq$  5 Torr. The inverse-pinch switch was triggered with the plasma-puff and the switching capability under various electrical parameters and working gas pressures of Ar, He and N<sub>2</sub> was determined. The azimuthally uniform switching discharges were dependent on the type of fill gas and its fill pressure. A new concept of plasma-focus driven plasma-puff will be discussed in comparison with the current hypocycloidal-pinch plasma-puff triggering.

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- No Preference

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Reno, Nevada

Appendix 2

PROCEEDINGS OF THE  
25th INTERSOCIETY  
ENERGY CONVERSION  
ENGINEERING CONFERENCE

Participating  
Societies

VOLUME 1

**Aerospace Power Systems**

- Space Power Requirements and Issues
- Space Power Systems
- Space Nuclear Power
- Automation
- Power Electronics
- Burst and Pulse Power
- Power Management and Distribution
- Space Energy Conversion
- Space Solar Power

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# ULTRA-HIGH-POWER PLASMA SWITCH INPIS FOR PULSE POWER SYSTEMS

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## ABSTRACT

A new and novel plasma switch, inverse pinch switch (INPIS), having a commutation geometry based on an inverse-pinch mechanism, has been tested and shown to alleviate the shortcomings of conventional spark gaps. The INPIS switch or INPIStron is currently being upscaled for high-voltage (approximately 1 MV) operation with a multigap arrangement similar to Sandia's rimfire electrodes used for ultra-high-voltage hold off. Preliminary results of the multigap INPIS tests at 250 kV and plasma-puff initiation methods are presented, and an application to compact pulser systems is discussed.

triggering method. The INPIS is currently being upscaled for high-voltage (approximately 1 MV) operation with a multigap arrangement similar to Sandia's rimfire electrodes for ultra-high-voltage hold off. Preliminary results of the multigap INPIStron tests at 250 kV with different plasma-puff methods are presented. Also the application of the INPIStron as the output switch of a compact pulser is discussed.

## INTRODUCTION

Conventional switches used in pulse-power systems become inadequate for commutating power levels greater than  $10^{10}$  volts · amperes. The spark gap is often employed for high-pulse-power systems, but its useful life is very short (less than  $10^4$  shots) unless a bulky multigap arrangement is adopted. Therefore, upscaling the pulse power for electromagnetic launchers, magnetoplasmadynamic thrusters, high-energy lasers, and beam generators is severely hampered by the lack of capable switches.

A new and novel plasma switch, inverse pinch (INPIS) switch, having a commutation geometry based on an inverse-pinch mechanism, has been tested and shown to alleviate the shortcomings of conventional spark gaps [1]. Figure 1 illustrates the principle of the INPIStron (b) in comparison with a conventional spark gap (a). Note that the  $\mathbf{J} \times \mathbf{B}$  force acting on the plasma is directed inward in (a) but outward in (b). Therefore the annular current path in (b) is radially dispersed while the current column in (a) is "pinched" on the axis. The INPIStron geometry results in a low current density, running-arc mode and a low inductance. The results obtained for 36-kJ, 20-kV operation of the INPIStron showed that in comparison with the spark gaps, (1) switch inductance and current density are substantially reduced, (2) equally fast commutation time (less than 50 ns) is obtained, (3) the useful life is significantly increased by a factor of approximately  $10^4$ , and (4) plasma-puff initiation of the gap breakdown is found to be the best

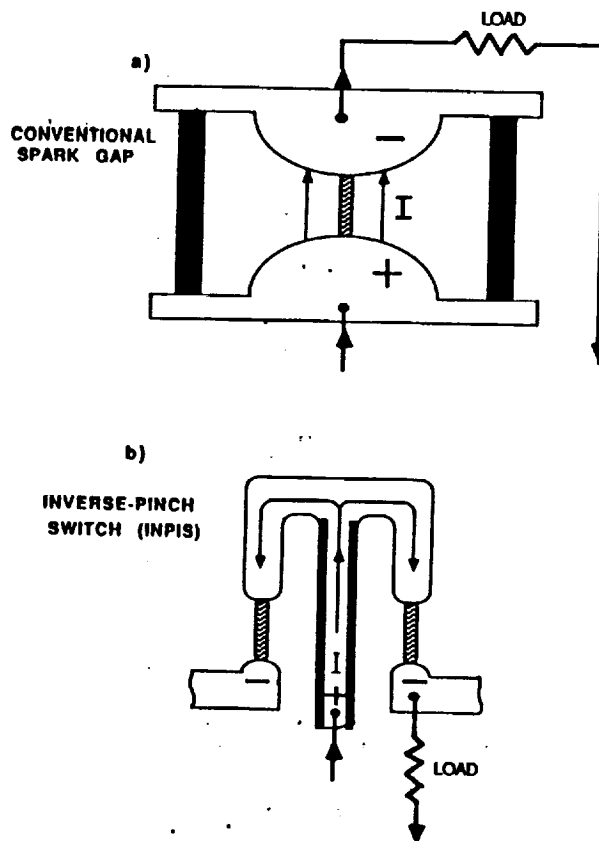


Figure 1. Principle of inverse-pinch switch (INPIStron) (b) in comparison with conventional spark gap (a).

## SWITCH GEOMETRIES

Figure 2 shows a cross section of the INPISTron tested up to 25-kV, 10-kJ commutation as reported in [1]. The arrows in the figure indicate current directions which form an inverse-pinch geometry. The  $I_o$  and  $I_p$  represent the initial and peak current position, respectively. The position of  $I_p$  depends on the  $\mathbf{J} \times \mathbf{B}$  force and the gas dynamic parameters used for the switch. Also shown is the trigger electrode in a disk shape located below the outer electrode. The prototype switch was successfully tested for more than 2000 shots without noticeable wear and has established a proof-of-principle and demonstrated its advantages over the existing switches.

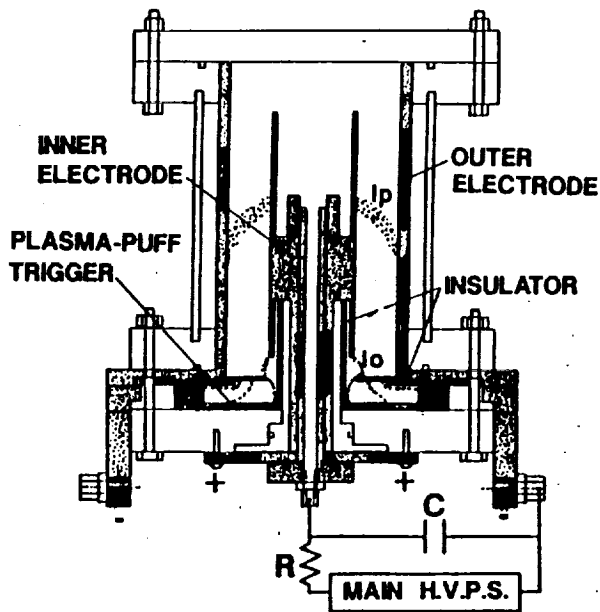


Figure 2. Cross section of an INPISTron with plasma-puff trigger.

In order to scale-up the hold-off voltage of the INPISTron, a multigap geometry is adopted and design concepts for a megavolt (MV) INPISTron were studied and reported [2]. Figure 3 shows a cross section of the MV INPISTron. The electrodes have a cylindrical configuration and are coaxially placed as for the 20-kV INPISTron in figure 2. The coaxial arrangement, i.e., inner electrode within the outer electrode, forms an annular gap between the electrodes where the initial switch breakdown occurs. However, the inner electrode for the MV INPISTron has a series of conducting rings on its "mushroom skirt" to form a series of gaps between them for ultra-high-voltage hold off. This arrangement is similar to the rim-fire spark gap of Sandia National Laboratory [3] except for the first annular gap that replaces the spark gap. The inner electrode has a conducting column on the

axis surrounded by a tubular insulator which is extended through the hollow center of the outer-electrode base and the plasma-puff trigger electrode below. The annular opening, which is formed between the insulator surrounding the inner electrode and the base of the outer electrode, is the exhaust channel of the plasma-puff originated in the chamber with the trigger electrode below. The trigger electrode and the base of the outer electrode form a planar chamber in which a plasma ring is generated and launched radially inward when the trigger pulse is applied. The details of the plasma production in this geometry, called hypocycloidal-pinch (HCP), can be found elsewhere [4]. The plasma ring is then accelerated (or puffed) upward along the cylindrical insulator surrounding the inner electrode to initiate the breakdown of the first annular gap of the INPISTron. The other annular gaps in series between the ring electrodes also break down simultaneously due to over-voltage caused by the lowest-gap closing.

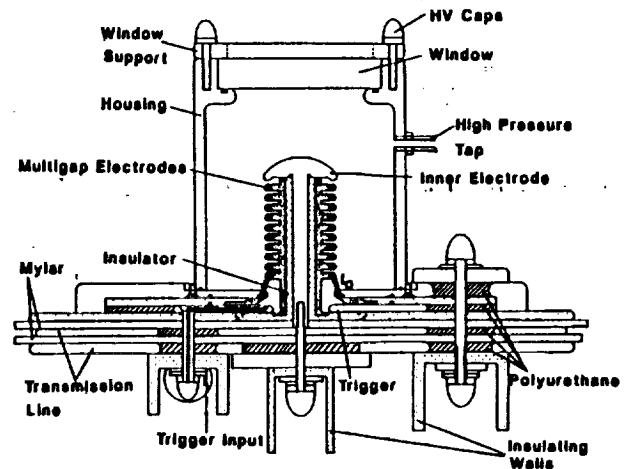


Figure 3. Cross section of a MV INPISTron with multiple gaps.

After breakdown, the current sheet  $I_p$  is immediately dispersed out in a radial direction and then axially sweeps over a wide area of the electrode surface until the current ceases to flow. The motion of the current sheet is the result of the inverse-pinch mechanism working on the plasma and the snow-plow model may be used for simulation of its dynamics. The current-sheet velocity is known to depend on the gas density and electrical input parameters [4].

The load coupling with the switch is made, for example, by a flat plate transmission line. A 20-ohm water resistor was used as the load for testing.

## TESTS AND RESULTS

### Preliminary Test

Figure 4 shows the pulsed power circuit used for the MV INPISTron tests with a 200-kV pulse-forming Marx

generator. The hold-off voltage of the switch was measured for various chamber pressures.

The Marx generator had 12 stages of L-R-C modules with triggerable spark gaps between them for high-voltage pulse erection. The total stored energy was 15 J which produced a flat-top pulse of 1- $\mu$ s duration. The flat-top voltage was varied up to 200 kV, 1- $\mu$ s by the charging voltage.

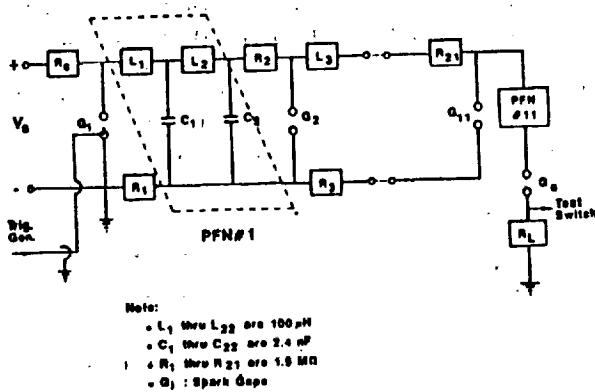


Figure 4. Schematics of pulse forming Marx generator.

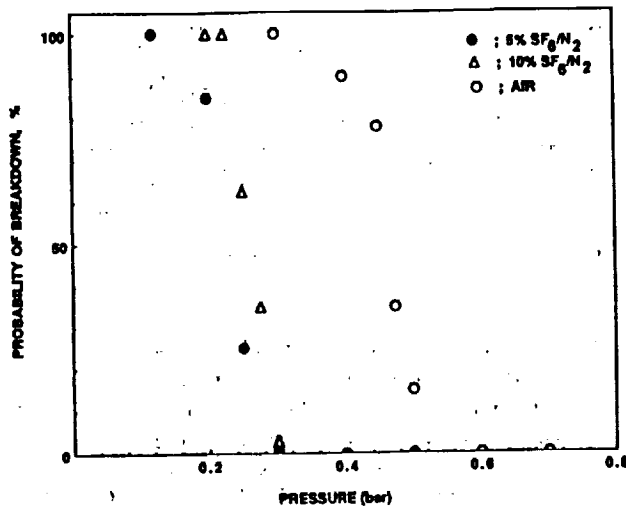


Figure 5. Probability of self-breakdown vs gas pressure for 200-kV, 1- $\mu$ s pulse.

For the tests the MV INPISTron was placed in ambient atmosphere with over-extended mylar sheets for prevention of external breakdown. The switch chamber was filled with a 10 percent SF<sub>6</sub>/N<sub>2</sub> gas mixture at various total pressures. The switch breakdown voltage was determined by observing the attendant light emission from the switch gaps through a closed-circuit TV camera system, and the electrical signal monitored on an oscilloscope. Figure 5 shows the probability (%) of self-breakdown vs fill-gas pressure for a 200-kV pulse.

These data indicate that 0.3 atm (or 230 torr) of 10 percent SF<sub>6</sub>/N<sub>2</sub> mixture is sufficient for holding of a 200-kV pulse significantly lower than the value for a single gap of 5 cm. A linear extrapolation gives 1.2 atm of the mixture for 1-MV hold off; this may be compared with >4 atm cited in [2].

#### Tests With Pulse Transformer

Since the preliminary test was aimed for determining the voltage hold off without causing severe damage to the switch structure, a small amount of the stored energy <15 J; therefore, a peak current of only <50 amps was used. After the successful preliminary test; high-energy, high-current testing was conducted with an oil-immersed high voltage pulse transformer. (A Stangenes model SI-6119 with 1:10 turns ratio.) The oil tank of the transformer is made large enough to place the INPIS switch inside; thus, the whole section of the high voltage (secondary) circuit could be immersed in oil. All high-voltage components were placed inside the oil tank and the switch had a set of water resistors in parallel as the load. The test circuit is shown schematically in figure 6. The testing procedure starts with the charging of the capacitor C through a resistor R<sub>C</sub>. When the capacitor is fully charged, the high-current INPIS is triggered by a 40-kV, 25-ns pulse from the trigger generator (not shown). The primary winding of the pulse transformer is thus energized by the capacitor discharge through the INPIS—primary—damping resistor R. Then the secondary winding of the pulse transformer produces a step-up ( $\times 10$ ) voltage to the MV INPIS connected with the load. The voltage and current of the secondary circuit are measured with a capacitor voltage divider and a current transformer (not shown) provided by the pulse transformer manufacturer. The INPIS emission accompanying the breakdown is visible through the window placed on the switch chamber. The breakdown voltage was determined for various chamber pressures. The highest test voltage of 250 kV required a N<sub>2</sub> pressure of 400 torr or more for hold off. The extrapolation of the results indicates that 2 atm of N<sub>2</sub> will suffice for 1-MV hold off, again considerably smaller than the expected value of 5 atms. in Ref. 2. Testing is underway to characterize the relevant parameters of the switch and results will be reported in the future.

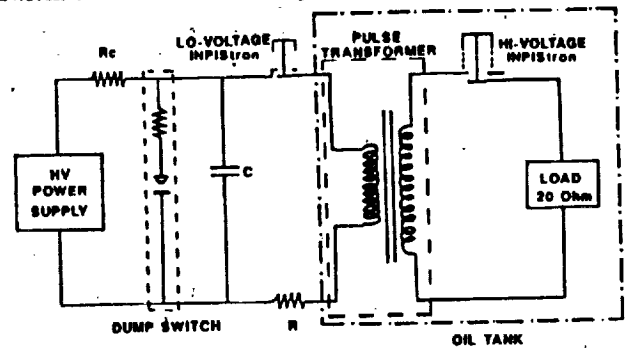


Figure 6. Schematic of test circuit with high-voltage pulse transformer.

## Plasma-Puff Triggering

The INPIStroon switch is designed to carry a high total current but with a significantly reduced current density on the electrodes by using a coaxial geometry. However the advantages of the new switch can be realized only after having azimuthally uniform breakdown of the annular gap. The conditions for homogeneous formation of pulse discharge in the gas have been discussed by various researchers. These conditions are concerned with the prevention of streamer formation which subsequently leads to arc discharge. It has been found that a minimum free-electron density in the discharge volume, which depends on the species of gas and its pressure, is required for a homogeneous discharge formation. The generally accepted minimum free-electron density to initiate homogeneous discharge is  $10^7$ - $10^8$  electrons/cm<sup>3</sup> in the pressure range 1-6 atm.

To achieve this minimum electron density, various triggering mechanisms such as UV-light generated by spark arrays, x-ray preionization, e-beam preionization and laser preionization have been employed in gas discharge switch research. In this research a new triggering method called "plasma-puff" is tested. Preliminary results of this method were reported in Ref. 4. Figure 7 shows the imploding plasma accelerator, called hypocycloidal pinch (HCP) device, used as the plasma-puff trigger for the INPIStroon. The HCP device was originally designed for production of a high-density, high-temperature plasma focus on the axis of the device [5]. The application of this device to "plasma-puff" triggering requires a significantly reduced energy input for production of required electron density of  $> 10^7$ /cm<sup>3</sup> in order to initiate a uniform discharge in the gap. The implosion velocity, the

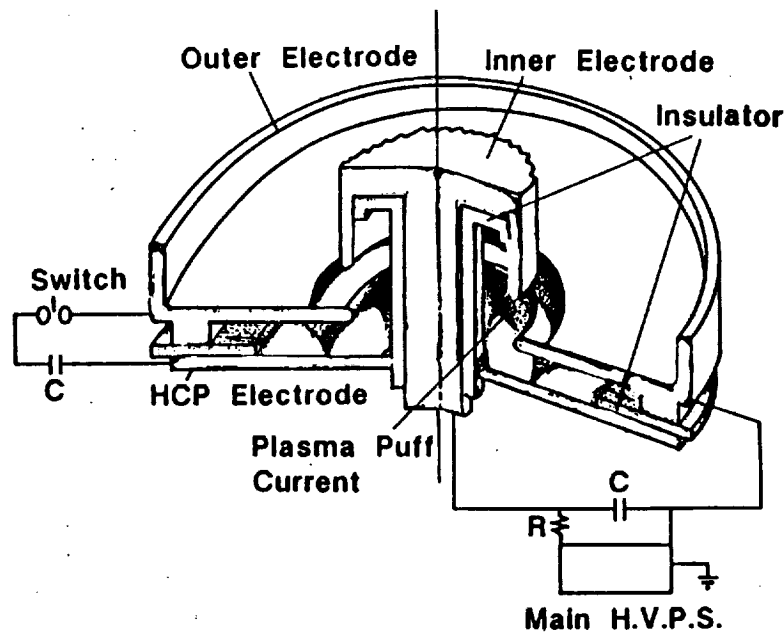


Figure 7. Imploding accelerator (HCP) produced plasma-puff trigger.

electron temperature, and the density can be estimated by a simple snow plow model coupled with the thermodynamics of a plasma. Figure 8 is a photograph showing the uniform discharge in the annular gap. The photograph is obtained with an image converter camera with 20-ns exposure times. The angle of plasma emission is used as the measure of the discharge uniformity and plotted as a function of gas pressures in figure 9. In the range from 0.2 to 4 torr, all three gases (N<sub>2</sub>, He, and Ar) produced an azimuthally uniform discharge, i.e., emission from 360 degrees, but in the higher pressure range, argon discharge was produced from only 180 degrees. In the lower pressure (<0.2 torr) range,

the uniformity is reduced for all three gases. When these results are reflected to Figure 10, self-breakdown voltage vs pressure, we find that the INPIStroon can be operated under the optimum condition for the hold-off voltage from 0.3 to 20 kV.

Other plasma-puff geometries are also under investigation to extend the operating ranges of the switch. Figure 11 shows an alternate geometry for plasma-puff triggering of the INPIStroon. This geometry again utilizes the surface discharge over the insulator placed between the center electrode and the trigger electrode as shown in figure 11. In fact the geometry is identical to the gun breech of a dense-plasma

focus device. This trigger geometry is advantageous especially for operating the switch in the left side of Paschen curve or the pseudo-spark range where a plasma velocity of  $>10^6$  cm/s could be easily obtained, thus minimizing the delay in switch commutation. The preliminary results with this geometry (or plasma-gun puff) are encouraging and will be reported in the future.

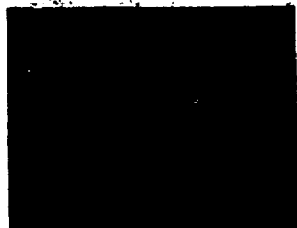


Figure 8. Photograph of light emission from annular gap. Operating conditions: Pressure, 20 m torr; Trigger voltage, 45 kV; pulse, 30-ns; Main gap voltage, 14 kV; Exposure time, 200 ns. Left  $2\mu$ s, Right  $5\mu$ s after trigger.

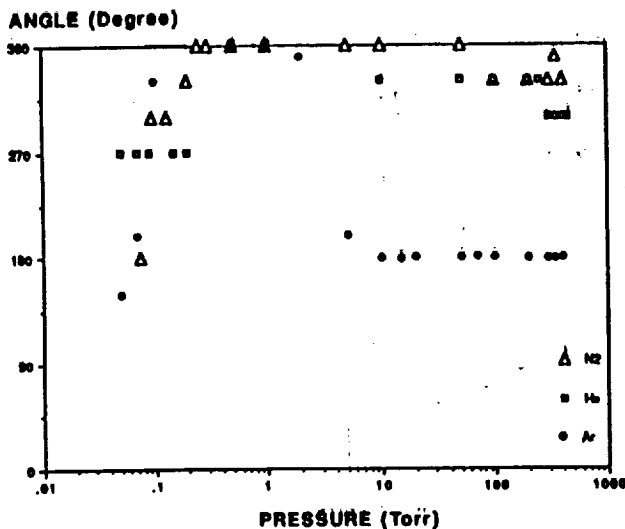


Figure 9. Discharge uniformity vs pressure.

#### APPLICATION TO COMPACT PULSER

The MV INPIStroon development is supported by Army EDTL/SDIO for possible adaptation of the INPIStroon as the output switch of a MV compact pulser. The requirements and performance goal of the pulser are as follows: Pulse energy-36 kJ, pulse-width-1  $\mu$ s flat top, pulse risetime  $\approx$  100 ns, flat top voltage-1 MV, 500 kV on load, load impedance-4 ohms, repetition rate-10 Hz for a few seconds, and useful life  $>10^4$ .

#### BREAKDOWN VOLTAGE (kV)

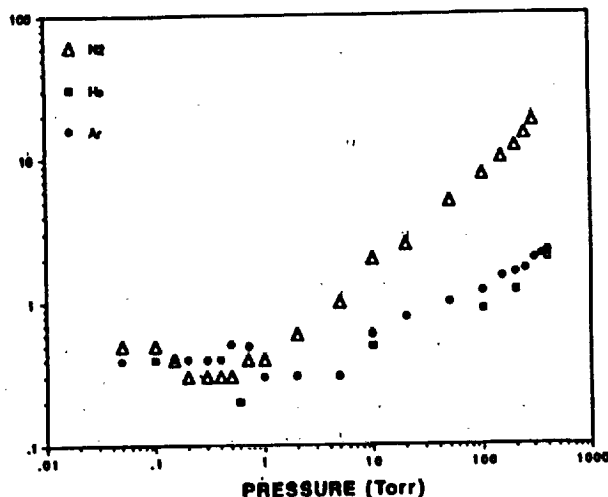


Figure 10. Self-breakdown voltage vs pressure.

Among these stringent requirements, the operating voltage of 1 MV, pulse energy of 36-kJ or 72-kA current commutation i.e., 0.072 C charge transfer in 1  $\mu$ s, repetition rate of 10 Hz in a burst mode, and 4-ohm load impedance are directly related to the output switch and need to be addressed.

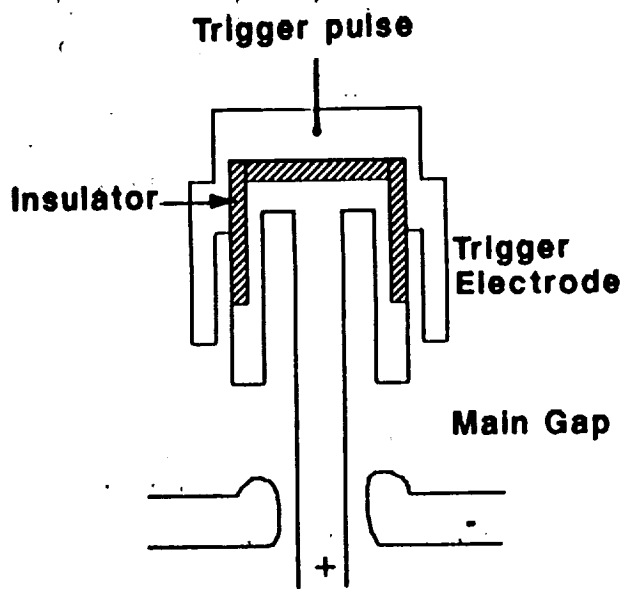


Figure 11. Coaxial-gun produced plasma-puff triggering method.

#### 1-MV Switch Operation

Since tests for up to 200 kV operation of the INPIStroon were successful, and there seem to be no fundamental

problems in voltage scaling with the multigap electrode (as evidenced by Sandia results), achievement of this requirement will be a straight forward effort.

### 36-kJ Energy Transfer

The 36-kJ energy transfer means 72-kA current commutation at 1 MV or 0.072 Coulomb charge transfer through the switch. Since the INPIS already demonstrated over 1-MA commutation at 25 kV with unmeasurable wear of switch materials for 2000 shots, this requirement could be easily met.

### 1- $\mu$ s Pulse Width With 100-MS Risetime

This requirement is to be fulfilled by the compact pulser itself, but it indirectly places requirements on the output switch for pulse shape preservation. The output switch should have a matching impedance to the load and a minimal dissipation. The INPIStron is based on a coaxial current path, and its impedance and capacitance  $C$  can be estimated by  $L = (\mu/2\pi) \ln(r_o/r_i)h$  and  $C = 2\pi\epsilon h / \ln \frac{r_o}{r_i}$  where  $\mu$ , and  $\epsilon$  are respectively the permeability and dielectric constant of the insulator,  $r_o$  and  $r_i$  are the radii of inner and outer current paths, respectively, and  $h$  is the height of the coaxial current path. For a typical geometry we have  $\epsilon = 4\epsilon_o$ ,  $r_o = 55$  mm,  $r_i = 15$  mm, and  $h = .2$  m, and we get  $L = 55$  nH and  $C = 36$  pF; thus, the series impedance  $s = (L/C)^{1/2}$  is 39 ohms. Although this value is significantly low compared with that ( $s > 250$  ohms) of a typical spark-gap switch, an effort to reduce this value is needed. Since  $s \propto \ln(r_o/r_i) \sqrt{\frac{\mu}{\epsilon}}$ , a larger  $r_i$  and  $\epsilon'$  (relative dielectric constant) will be helpful. For example  $r_i = 30$  mm,  $r_o = 50$  mm and  $\epsilon' = 50$  for titanate,  $s$  could be reduced to 4.2 ohms, the matching impedance. These values are still reasonable for the INPIStron adopted by the compact pulser system.

### The Repetition Rate of 10 Hz on a Burst Mode

This requirement calls for the recovery time of the switch to be 100 ms or less. The INPIStron is in essence a

modified spark gap, and recovery time will be similar. A high repetition rate up to 1 kHz is possible when blow-down flow is used for removing the used gas from the spark-gap switch chamber. Therefore, achieving 10 Hz on a burst-mode operation of the INPIStron will be an easy task when the high-repetition-rate pulser is available.

### CONCLUSIONS

Preliminary test results of the MV INPIStron for high-voltage hold-off and plasma-puff triggering indicate that the switch could meet all requirements placed on the output switch of the compact pulser under development by the U.S. Army Electronic Technology and Devices Laboratory/Strategic Defense Initiative Office.

### ACKNOWLEDGEMENTS

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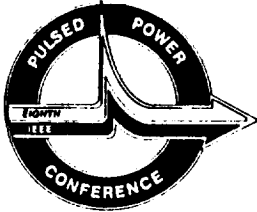
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# Appendix 3

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## DIGEST OF TECHNICAL PAPERS Eighth IEEE International Pulsed Power Conference

Sheraton Harbor Island East Hotel  
San Diego, California  
June 16-19, 1991



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# CHARACTERISTICS OF SWITCHING PLASMA IN AN INVERSE-PINCH SWITCH

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## Abstract

Characteristics of the plasma that switches on tens of giga volt-ampere in an inverse-pinch plasma switch (INPISTron) have been made. Through optical and spectroscopic diagnostics of the current carrying plasma, the current density, the motion of current paths, dominant ionic species have been determined in order to assess their effects on circuit parameters and material erosion. Also the optimum operational condition of the plasma-puff triggering method required for azimuthally uniform conduction in the INPISTron has been determined.

## Introduction

The INPISTron [1,2] is a plasma switch which operates in an inverse pinch mechanism. The inpistron consists of a center electrode which has the shape of a mushroom and a hollow base electrode separated by an annular gap. The switching of the inpistron is achieved by generating a tubular plasma. The behavior of tubular plasma in the inpistron is controlled to be in inverse-pinch mode by the induced field. This is a strong contrast to the single filament of plasma that is generated by electron avalanche in the conventional spark gaps. The unique geometry of inpistron and inversely pinched plasma render many features different from the conventional plasma switches. The coaxial current path with a large aspect ratio in the inpistron also results in a significantly reduced inductance, and it can be adopted to a very low-impedance (a few ohms) system.

The dispersion and motion of tubular plasma reduce not only current density, but also dwell-time on a specific location of electrode surface. Hence, the inpistron is able to bear very high currents [3] due to the dispersion of plasma current. And the wear of inpistron electrodes is much small compared to that of the spark-gaps and uniform everywhere in the electrodes due to the sweeping motion of plasma over the all area of electrode. The combination of these features makes a long life operation of the inpistron possible. Detailed analysis of the Coulomb density which is responsible for the wear of inpistron electrodes is found in Ref. [3].

However, these advantages of the inpistron can be only realized only after having azimuthally uniform breakdown of the annular gap. In the previous studies [3,4], various triggering mechanisms and switch operational conditions were used for obtaining an azimuthally uniform breakdown in the inpistron.

The characteristics of the tubular plasma in the inpistron are under study in order to understand their effects on circuit

parameters and material erosion. Fast photography with an image converter camera and uv-visible spectroscopy with an optical-multichannel analyzer (OMA) are performed, and the plasma dynamics and plasma property parameters are determined. The design and test of inpistron have been made for a megampere and a megavolt applications separately, even though the inpistron is capable of running at both high current and high voltage.

## High Coulomb Transfer Inpistron

The test of the inpistron for high Coulomb transfer was performed on a system which comprises of a capacitor bank, a power supply, a Marx generator for a high voltage trigger pulse and a vacuum pump unit. The 60-kJ capacitor bank is composed of 18 capacitors in parallel. The total capacitance of the bank is 48.6  $\mu F$ . This bank may be charged up to 50-kV. The trigger pulse with 30-ns risetime is generated by the Marx generator.

The hypocycloidal-pinch (HCP) plasma-puff trigger [4] was used for the initiation of breakdown for the inpistron. Measurements were made to test the characteristics of the HCP plasma-puff trigger, as well as the performance of the inpistron. These measurements were made with frame and streak photographs, and voltage and current signals at both low and high pressure sides of the Paschen curve. The peak forward currents were calculated by using the oscilloscope photograph of Rogowski coil voltage signals. The test results showed that the inpistron was capable of transferring 2-MA at 25-kV hold-off voltage [4]. The performances of inpistron in total power transfer capability reside in the region where the spark-gaps are located. The spark-gaps are able to maintain their power transfer capability beyond  $10^7$  kVA. However, the life of the spark-gaps is, on the contrary, very short while the inpistron is expected to have its life span equivalent to that of thyratrons.

Fig. 1 is the cross section of a high current inpistron coupled with a coaxial plasma-puff trigger unit. The trigger unit is placed as "a cap" on the inner electrode and generates "a plasma-puff" in the discharge chamber with a high voltage pulse.

Fig. 2 is a typical optical multichannel analyzer (OMA) spectrum of the plasma emission from the inpistron. The color temperature of the argon plasma for this run is approximately 4,000 K corresponding to the peak continuum emission near 750 nm. The strong line emission of argon in the 700 ~ 800 nm range and the lack of line emissions by copper and other solid materials used in the switch are indication of the low current density and the lack of hot spot or hot filament in the switch.



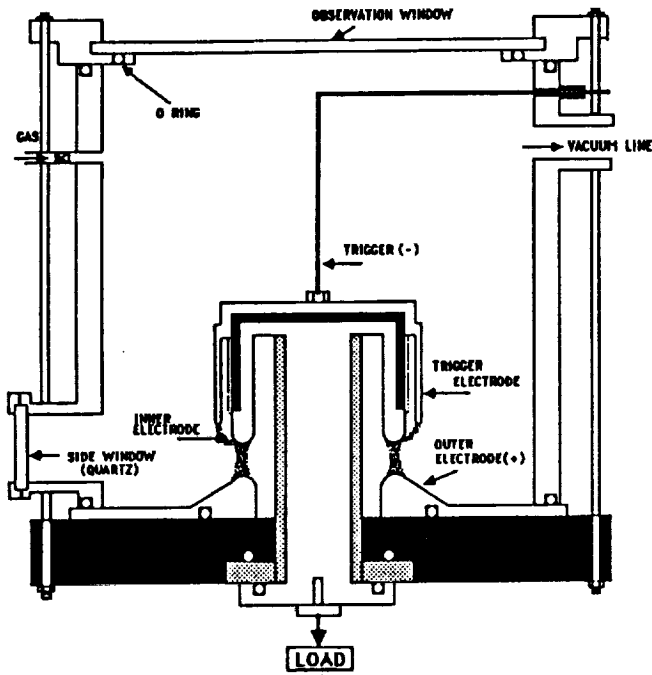


Fig. 1 Cross section of a high coulomb transfer INPISTron. The trigger electrode, shaped like a cap, is placed on the inner electrode and used for "plasma-puff" generation which in turn triggers the annular gap below.

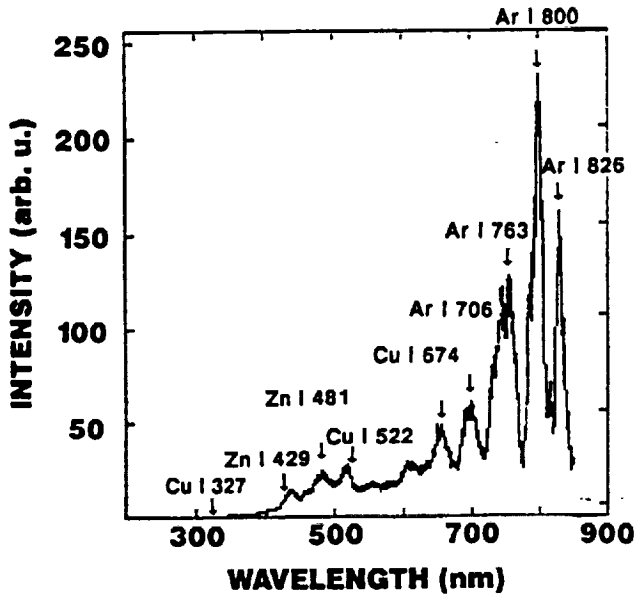


Fig. 2 A typical OMA spectrum of the plasma emission.

### High Voltage Inpistron

Most of the pulsers requires the abilities for its final stage output switch to transfer at least tens of kilojoule energy with a modest repetition rate, a mega-volt hold-off against the train of  $1\text{-}\mu\text{s}$  pulses with hundreds of nanosecond risetime from a fast pulse forming network (PFN). The pulser PFN might have  $4 \sim 6\ \Omega$  system impedance. Thus, the impedance matching

with the system's impedance becomes a critical issue for the switch. As analyzed by Burkes [5], these requirements can be met only by a spark gap at near the upper limit of its performance. Furthermore, the pulser requires drastic reductions in weight and volume. Therefore, the switch must be compact and light weight.

A compact, high voltage, low impedance, and high power switch is, therefore, essential for the development of the compact pulser system. The switching capabilities such as repetition rate ( $\geq 10\ \text{Hz}$ ), average currents of  $10 \sim 100$  amperes at voltages of  $100 \sim 1000\ \text{kV}$ , and pulse widths of  $100 \sim 1000\ \text{ns}$  flat-top must be available for the compact pulser system. In these respects, the inpistron, which out-performs the spark gap, is uniquely qualified for the compact pulser. The inpistron has successfully been tested for up to  $250\text{-kV}$  hold-off voltage [6], the limit imposed by the pulse transformer used.

Figure 3 shows the cross-section of the inpistron which was designed for  $1\text{-MV}$  hold-off [7], and tested up to  $250\ \text{kV}$ .

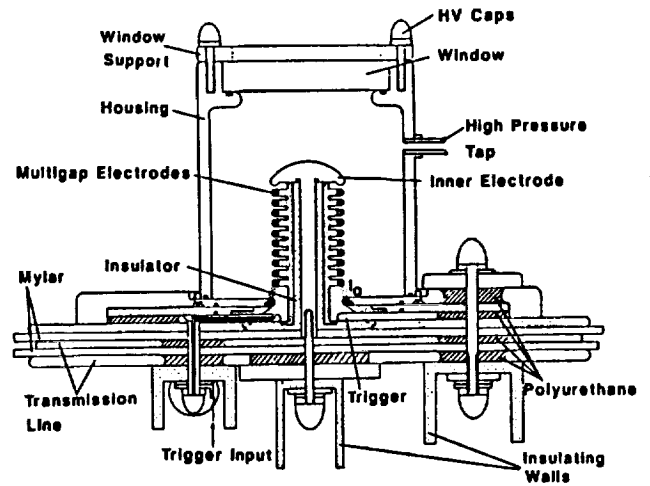


Fig. 3 Cross-section view of the inpistron which is designed for  $1\text{-MV}$  hold-off test.

The voltage hold-off test was started from low pressure ( $\sim 1$  Torr) and low applied voltage.  $N_2$  was used as the working gas. The test voltage was increased in a step of  $10\ \text{kV}$  to find a new hold-off pressure at that voltage setting. Fig. 4 shows the results from the tests up to  $250\ \text{kV}$ . The pressure of  $N_2$  gas to hold-off  $250\ \text{kV}$  was found to be  $475$  Torr. The overall mapping of voltage hold-off from  $50\ \text{kV}$  to  $250\ \text{kV}$  shows approximately a linear profile in the high pressure side as expected from the Paschen curve. The solid line in Figure 4 is the curve fitting of data points. By the extrapolation of the data, we find that the  $N_2$  pressure of  $2.76\ \text{atm}$  is sufficient for  $1\ \text{MV}$  hold-off. This result indicates that increases of the inpistron dimensions for higher voltage hold-off (i.e.  $1\ \text{MV}$ ) may not be necessary. The actual size of the inpistron tested is  $6$  inches in diameter and  $6.5$  inches high. And the weight is approximately  $20\ \text{lbs}$ . However, the weight may be reduced by a factor of  $2$  if the design is optimized.

The azimuthally uniform breakdown is an important and deterministic factor to realize the advantages of the inpistron. The uniform breakdown in a switching action of the inpistron warrants a low inductance and a longer useful life. The inductance of the inpistron which has a coaxial current path, can be determined by

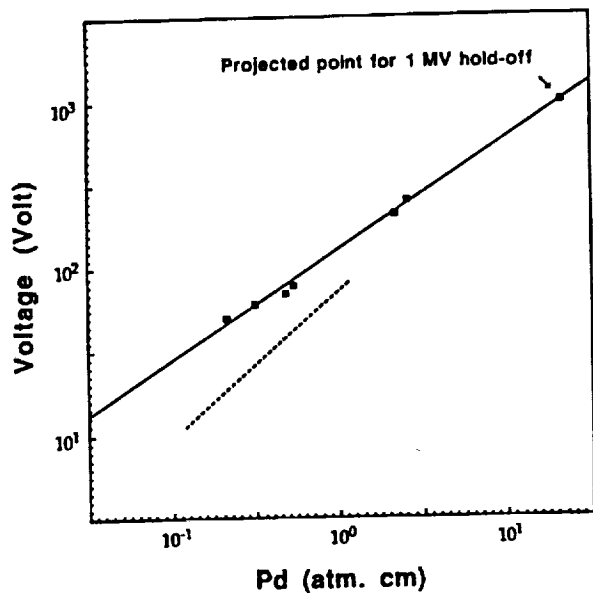


Fig. 4 Inpistron hold-off voltage ( $V_{ho}$  in kV) as a function of  $p \cdot d$  in atm-cm where  $p$  is the chamber pressure and  $d$  the gap distance.  $N_2$  gas is used for this test. Paschen curve for  $N_2$  of a single gap in uniform electric field is also shown with the dashed line for comparison.

$$L = \frac{\mu h}{2\pi} \ln \frac{r_p}{r_s}$$

and

$$C = 2\pi \epsilon h / \ln \frac{r_p}{r_s}$$

where  $\mu_s$  is the permeability,  $\epsilon$  the dielectric constant of insulator,  $h$  the length of a current column or a plasma ring,  $r_p$  the radius of a plasma ring, and  $r_s$  is the radius of inner electrodes.

The series characteristic impedance

$$Z = \sqrt{\frac{L}{C}}$$

is then

$$Z = \frac{1}{2\pi} \sqrt{\frac{\mu'}{\epsilon'}} \ln\left(\frac{r_p}{r_s}\right).$$

A larger  $r_s$  and  $\epsilon'$  (the relative dielectric constant) are helpful for reducing the impedance. For the inpistron tested,  $r_p = 50$  mm,  $r_s = 30$  mm, and  $\epsilon' = 50$  (for titanate ceramic). Hence  $Z$  is approximately  $4 \Omega$ .

The titanate compound ceramic has a high dielectric constant ( $\geq 400$ , i.e. titanate compound ceramic) and dielectric strength ( $\geq 260$  V/mil). The adoption of such a ceramic for insulator, even without changing the configuration of the inpistron, will easily reduce the impedance by an order of magnitude. Commercially, there is high dielectric constant ceramic (Ref. AISiMag Technical Ceramics, Inc., Laurens, SC) upto  $\epsilon' = 1800$  available. Therefore, a reduction of the inpistron impedance for an impedance matching with a given transmission line is a straight-forward effort. Table I lists the characteristics of an inpistron compared to those of conventional spark-gap. Also note that the current in the inpistron is dispersed over a wide area of the inner electrode surface when the uniform breakdown is sustained. Hence, the current density on the electrode is significantly low (an order of magnitude at least) and the wear of electrode surface is alleviated to lengthen the switch life.

TABLE I. HIGH VOLTAGE SWITCH CHARACTERISTICS

| Characteristics            | Symbols          | Rimfire [8]           | INPIS [6]        |
|----------------------------|------------------|-----------------------|------------------|
| Outer diameter             | $D_o$ [cm]       | 150                   | 10.              |
| Inner diameter             | $D_i$ [cm]       | 0.1                   | 6.               |
| Relative Permeability      | $\mu_r$          | 1                     | 1                |
| Relative Dielectric Const. | $\epsilon_r$     | 1                     | 50<br>(titanate) |
| Gap*                       | $h$ [cm]         | 5                     | 5                |
| Inductance                 | $L$ [nH/m]       | 1463                  | 102              |
|                            | $L$ [nH]         | 73                    | 5                |
| Capacitance                | $C$ [nF/m]       | $7.61 \times 10^{-3}$ | 5.45             |
|                            | $C$ [nF]         | $0.38 \times 10^{-3}$ | 0.27             |
| Characteristic Impedance   | $Z$ [ $\Omega$ ] | 439                   | 4.33             |
| Plasma Dynamics            |                  | z-pinch               | Inverse-pinch    |

\* The same length is used for comparison.

The switch breakdown tests were carried out by only employing over-voltage after removing the HCP trigger unit, because the HCP trigger unit added complexity for electrical insulation to the breech of the switch. The location where the HCP unit is interfaced with the flate-plate transmission lines was often the site of external breakdowns.

Observation of fairly uniform breakdown of the inpistron even without a trigger pulse indicates that further uniformity can be obtained when plasma-puff trigger is applied. Indeed the inpistron could be used for both modes, with or without trigger, preserving the advantages in the risetime and useful life.

The self-breakdowns of inpistron were witnessed visually for verification, and the current and voltage signals were obtained on an oscilloscope. The picture shown in Fig. 5 is plasma emission from the switch. In the picture a half of the circle around the inner electrode is bright, indicating occurrence of discharge while the other half was shadowed (see the gray area in the picture) due to one of the handles of the clips which were used to hold a mirror. Under the careful investigation of the picture, one can still see the images of three bright circles in the shadow. These bright circles show the state that the uniform breakdown is undergoing through each ring of the multistage inner electrode. We have observed such uniform breakdown phenomena for all of the tests with various pressures and applied voltages.

Such experimental results are very encouraging and firm signs for the inpistron to be the best-suited switch for the high voltage pulser applications. The feasibility study so far has proven that the inpistron is capable for high voltage hold-off and azimuthally uniform switching. However, the test was limited to a 250 kV hold-off by the pulse transformer used.

### Concluding Remarks

**Voltage Hold-Off:** Since tests for upto 250 kV operation of the inpistron were successful, there seems no fundamental problems in voltage scaling with the multigap electrode as evidenced in Ref. [8].

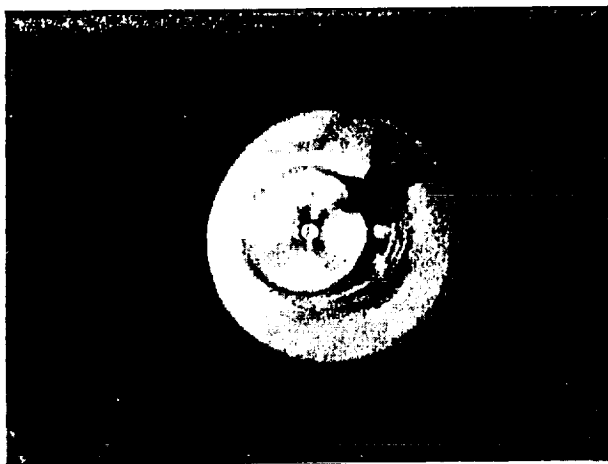


Fig. 5 Picture of the inpistron plasma emission at 250-kV test. The uniform breakdown is appeared in the picture including the blurred image portion due to the blockage by a clip handle for a reflection mirror.

**Energy Transfer:** The inpistron demonstrated over 2 MA commutation at 25 kV with unmeasurable wear of switch components for cumulative 2000 shots. The sweeping motion of current sheet over a wide area of the electrode, due to the inverse-pinch mechanism, reduced its current density significantly (see Table I). In other words, the inpistron is able to carry very high current beyond the damage threshold of conventional switches. A peak current above 2 MA was forwarded in the previous tests [4] with 5- $\mu$ s pulses.

**Pulsewidth and Shape:** The pulsewidth ( $\leq 1 \mu$ s) and shape are generally determined by the combination of risetime and fall-time of modulated current from a PFN. The distortion of a PFN pulse shape by the final-stage output switch is an undesirable and it becomes a major concern to the development of the pulser. The distortion of a PFN pulse shape is determined by the impedance of the final stage switch. The best performing switch should have an impedance matched to that of the pulser PFN. The stringent pulser impedance requirement ranges 4 ~ 6  $\Omega$ . Such impedance matching requirement narrows down the choice of the output switch for the pulser. Even for this parameter alone the inpistron is the unique candidate for the pulser applications because of the combination of its intrinsically low inductance and high capacitance of the coaxial geometry.

The contribution of a circuit element to the current risetime is roughly determined by its inductance and capacitance. With the inpistron, the risetime is inherently faster than that with a trigatron switch for the low switch inductance (see Table I).

**Repetition Rate:** The repetition rate test requires a very high power power supply (megawatt class) and is left for future effort. However, it is expected to render up to 1-kHz operation as demonstrated by the spark gap.

#### Acknowledgments

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# Conference Record of the 1992 Twentieth Power Modulator Symposium

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# COMPARATIVE STUDY OF INPISTron AND SPARK GAP

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## Abstract

An inverse pinch plasma switch, INPISTron, was studied in comparison to a conventional spark gap. The INPISTron is under development for high power switching applications. The INPISTron has an inverse pinch dynamics, opposed to Z-pinch dynamics in the spark gap. The electrical, plasma dynamics and radiative properties of the closing plasmas have been studied. Recently the high-voltage pulse transfer capabilities of both the INPISTron and the spark gap were also compared. The INPISTron with a low impedance  $Z = 9$  ohms transfers 87 % of an input pulse with a halfwidth of  $2 \mu\text{s}$ . For the same input pulse the spark gap of  $Z = 100$  ohms transfers 68 %. Fast framing and streak photography, taken with an TRW image converter camera, was used to observe the discharge uniformity and closing plasma speed in both switches. In order to assess the effects of closing plasmas on erosion of electrode material, emission spectra of two switches were studied with a spectrometer-optical multichannel analyzer (OMA) system. The typical emission spectra of the closing plasmas in the INPISTron and the spark gap showed that there were comparatively weak carbon line emission in 658.7 nm and copper (electrode material) line emissions in the INPISTron, indicating low erosion of materials in the INPISTron.

## Introduction

A compact and high power switch capable of gigavolt-ampere level operation is essential for the development of the compact pulser systems useful for beyond the-state-of-arts applications. For example a compact pulser requires that the final output stage switch should be able to transfer a train of  $1\text{-}\mu\text{s}$  pulses with typically  $> 36\text{kJ}$  of energy at 1 megavolt and at the repetition rate of 10 Hz fed from a  $4 - 6 \Omega$ , fast pulse forming line (PFL). To date these requirements can be met only by a spark gap with a limited life.<sup>1</sup> Furthermore, the compact pulser requires a six-fold reduction in weight and a two-fold reduction in volume of the conventional pulser system. Therefore, the switch must be compact and of light weight. We reported earlier an INPISTron, a coaxial plasma switch, out-performed the conventional spark gap meeting the above requirements and thus uniquely qualified for the pulser. This presentation includes a report of recent investigation on the INPISTron pulse power-transfer characteristics in comparison with that of a spark gap.

## Inverse-Pinch Plasma Switch, INPISTron

The INPISTron has a novel electrode geometry in contrast to the conventional spark gap as shown in

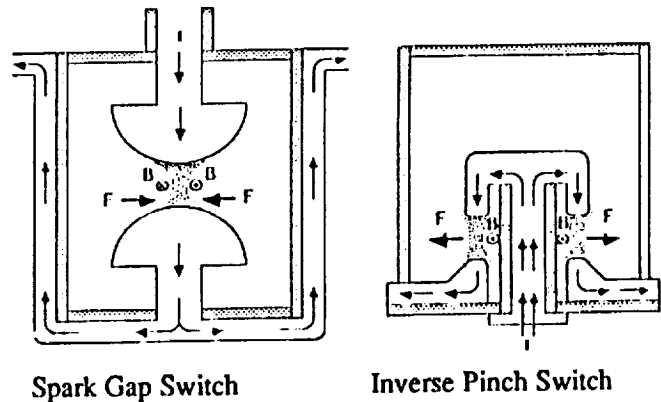


Fig. 1 Principal of inverse pinch switch and spark gap. (Trigger arrangement are not shown)

Fig. 1. The plasma dynamics employed in the INPISTron is an inverse-pinch, opposed to a z-pinch dynamics in the spark gap. Therefore the current sheet in the INPISTron is dispersed by the ponderomotive force  $F = J \times B$  which quadratically increases with the total current since the self-induced magnetic induction  $B$  is proportional to  $J$ . Hence the INPISTron is capable of commutating ultra-high current without severe erosion of the electrode material. In earlier work a pulse train of  $5 \times 10^{10} \text{ V}\cdot\text{A}$  (i.e.  $25\text{kV} \times 2\text{MA}$ ) at 1 Hz has been transferred to a low impedance load via a single unit of this switch. Also the switch was operated with hold-off voltages up 250 kV and a design for 1-MV has been made.<sup>1-3</sup> The detailed configuration and characteristics of the INPISTron were reported elsewhere.<sup>1-3</sup> Fig. 2 is the cross section of a high current INPISTron coupled with a coaxial plasma-puff trigger unit employed in this study. The trigger unit was placed as "a cap" on the inner electrode and generated "a plasma-puff" in the annular discharge chamber when a high voltage pulse was applied. The electrical parameter used for testing the INPISTron and the reference spark gap used are listed in Table 1. Various methods for plasma puff

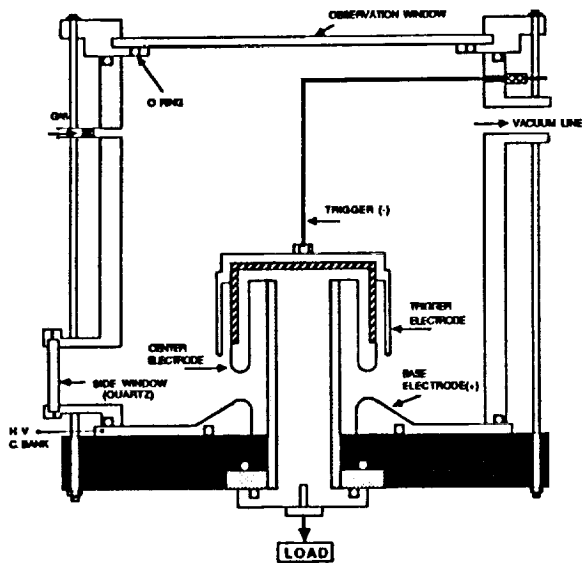


Fig.2 Detailed design of the inverse pinch switch

Table 1

| Parameters               | INPIStro           | Spark-gap          | Unit              |
|--------------------------|--------------------|--------------------|-------------------|
| Capacitance              | 8.21               | 8.21               | $\mu\text{F}$     |
| Capacitor energy         | 1.65               | 1.65               | $\text{kJ}$       |
| Operating voltage        | 20                 | 20                 | $\text{kV}$       |
| Cycle period             | 9.6                | 11.4               | $\mu\text{s}$     |
| Rise time                | 1.9                | 2.9                | $\mu\text{s}$     |
| Ringing frequency        | 104                | 88                 | $\text{kHz}$      |
| Total circuit inductance | 283                | 399                | $\text{nH}$       |
| Total resistance         | 25.35              | 27.01              | $\text{m}\Omega$  |
| Switch inductance        | 17.6               | 147.8              | $\text{nH}$       |
| Switch Capacitance       | 219.9              | 14.7               | $\text{pF}$       |
| Switch impedance         | 8.94               | 100.27             | $\Omega$          |
| Damping factor (R/2L)    | $4.47 \times 10^4$ | $3.38 \times 10^4$ | $\Omega/\text{H}$ |

initiation of the INPIStro have been tested and the range of working gas pressure that produce azimuthally uniform initiation of the switch were determined and reported elsewhere.<sup>4</sup> This experiment was performed on a system which comprised of a capacitor bank, a power supply, a Marx generator for a high voltage trigger pulse and a vacuum pump unit. The 3.6 kJ capacitor bank composed of 3 capacitors in parallel and a total capacitance of  $6 \mu\text{F}$  was charged up to 40 kV. The trigger pulse with 30 ns risetime generated by the Marx generator was used for the initiation of breakdown for the INPIStro.

Diagnostics used were frame and streak photographs, and voltage and current probing at both low and high

pressure side of the Paschen curve. The peak forward currents were obtained by using the oscilloscope trace of Rogowski coil voltage signals. The test results showed that the INPIStro was transferring the pulse power as expected from the circuit analysis when the "plasma-puff" initiation took place uniformly in the annular gap. At the Hampton University a single unit INPIStro is currently employed to replace multichannel spark-gap array used in past in a high energy capacitor bank and realized compactness, simplicity, reliability and cost effective operation. Compact high energy pulsers necessary for high power laser excitation, dense plasma production, weapons effect simulation, electromagnetic launchers and electric propulsion in space will similarly benefit from adoption of INPIStros.

This presentation is the report of a recent study made with an INPIStro and a spark gap in order to compare pulse transfer fidelities and material erosion in an identical pulsed power system.

### Comparative Study of Pulse Transfer Fidelity

Fig. 3 shows the experimental setup used for the study. The INPIStro and the spark gap were alternately inserted in the identical pulse circuit which consisted of a high voltage power supply, a pulse-forming Marx generator, a trigger pulse generator, and the two high-voltage probes connected to a fast-two-channel oscilloscope (TEK556).

The INPIStro and the spark gap housed in the same chamber had impedances of  $Z=9 \text{ ohms}$  and  $100 \text{ ohms}$  respectively. The low impedance of the INPIStro is the result of coaxial current path with a small (near unity) aspect ratio and having a large relative dielectric constant  $\epsilon$  of the insulator that surrounds the inner electrode. Since the transmission lines and the loads of ultra-high pulse power system are designed to have  $Z < 10 \Omega$ , the use of high-impedance switches such as spark gaps causes sacrifices in the pulse transfer fidelity

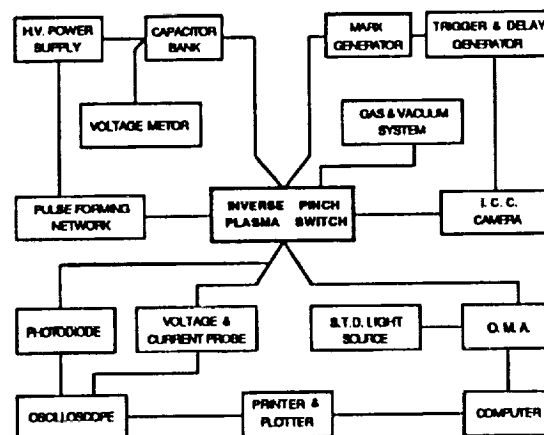


Fig. 3 Experimental set-up for INPIStro and Spark switch.

and the transfer efficiency.

The experiment was carried out to verify the above expectation with a train of real pulses with a 1- $\mu$ s risetime from the pulse-forming Marx generator which had 13 stages of voltage multiplication. Because of large switching jitters ( $\approx 1 \mu$ s) among the switches (mini spark gaps) placed between stages when the Marx was elected, the output pulses contain multiple spikes as shown on the traces in Fig. 4. As indicated, Fig 4(A) was obtained with the INPIStrom and Fig. 4(B) was with the spark gap reference. The upper traces represent the input pulse monitored at the input electrode (anode) and the lower traces represent the pulse at the output point on the switch electrodes (cathodes). The high-voltage probes used here were Tektronix model P6015 which had square-pulse shape and voltage calibrations. As shown, the peak power reduction through the switch for the INPIStrom is 11% while that for the spark gap is 42%. No significant changes in the half width of the pulse are observed for both switches. The ratio of the input-and output-pulse energy ( $E = \int P \cdot dt$ ) or the pulse-energy transfer efficiency for the INPIStrom is 87% while the ratio for the spark gap is 68%.

These findings are significant in that the choice of the output switch can influence the pulse-power system efficiency substantially. Replacing a spark gap with an INPIStrom, as has done here, will result in an increase of greater than 50% in the output peak power. The equivalent circuit for the setup are shown in Fig. 5 which were simulated by PSPICE program and found a good agreement with the results shown in Fig. 4 except the noise spikes resulted from the pulse forming Marx pulser.

### Spectra of Closing Plasmas

In order to assess the effects of plasma current density on the erosion of electrodes and insulators, emission spectra of INPIStrom and the spark gap were compared. Fig. 6 is representative spectra obtained with an identical spectrometer-optical-multichannel analyzer system. The spectra (time-integrated) indicate the color temperature of the argon plasma of approximately 4,000 K corresponding to the peak emission near 750 nm. The upper trace, which represents the emission spectrum of the spark gap, shows substantially higher irradiance of both continuum and line emissions in comparison to the lower trace for the emission from the INPIStrom, indicating higher plasma temperature and impurity content due to evaporation of materials in the spark-gap-plasma. (However the quantitative analysis of these spectra have not been done yet.)

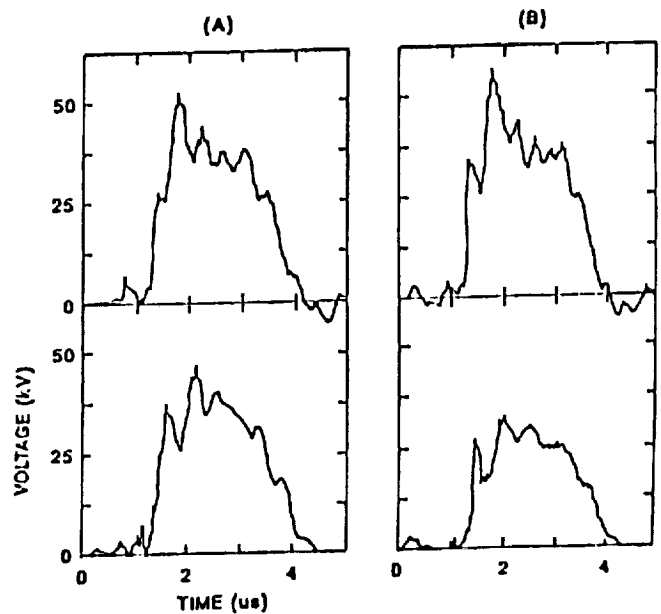


Fig. 4 Pulse transfer characteristics of (A) the INPIStrom (B) the spark gap. The upper traces are the input pulses and the lower traces are switch outputs. This INPIStrom performs with a better pulse shape fidelity and efficiency than that of the spark gap.

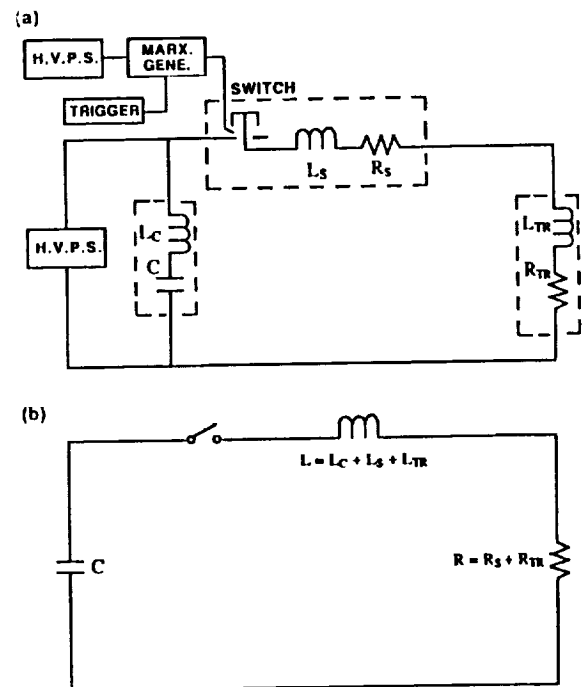


Fig. 5 Schematic (a) and equivalent (b) circuit of the system.

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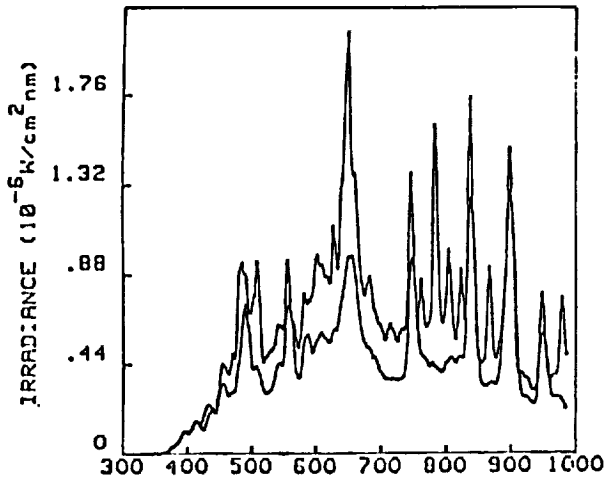


Fig. 6 Line emission from INPIStrotron and spark gap for comparison. Upper trace is for a spark gap trace for INPIStrotron.

## Summary and Conclusion

An extended study of the INPIStrotron for the pulse transfer fidelity and efficiency revealed the INPIStrotron as the superior performer over that of the reference spark gap. Also material erosion, compared with the emission spectra of the closing plasmas in the two switches showed considerable differences which indicate the low current density and low material erosion in the INPIStrotron. These findings again confirm the superiority of the INPIStrotron already found with respect to other parameters of high power switching such as the voltage hold-off, the Coulomb transfer, the lifetime, material erosion, and the repetition rate.

## Acknowledgments

The INPIStrotron was developed under research program sponsored by Army Research Office and monitored by Dr. David Skatrud and Dr. Bob Guenther at Physics Division. The original concept of the INPIStrotron was disclosed in the U.S. patent Number 4,475,066 issued to Ja H. Lee who is adjunct professor of physics and senior scientist of NASA Langley Research Center.



## Appendix 5

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### INPIStrotron SWITCHED PULSED POWER FOR DENSE PLASMA PINCHES†

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#### ABSTRACT

The inverse plasma switch INPIStrotron was employed for 10kJ/40kV capacitor bank discharge system to produce focused dense plasmas in hypocycloidal-pinch (HCP) devices. A single unit and an array of multiple HCPs were coupled as the load of the pulsed power circuit. The geometry and switching plasma dynamics were found advantageous and convenient for commutating the large current pulse from the low impedance transmission line to the low impedance plasma load.

The pulse power system with a single unit HCP, the system A, was used for production of high temperature plasma focus and its diagnostics. The radially running down plasmadynamics, revealed in image converter photographs, could be simulated by a simple snow-plow model with a correction for plasma resistivity.

The system B with an array of 8-HCP units which forms a long coaxial discharge chamber was used for pumping a Ti-sapphire laser. The intense uv emission from the plasma was frequency shifted with dye-resolution jacket to match the absorption band of the Ti crystal laser near 500 nm. An untuned laser pulse energy of 0.6 J/pulse was obtained for 6.4 kJ/40 kV discharge, or near  $10^3$  times of the explosion limit of conventional flashlamps.

For both systems the advantages of the INPIStrotron were well demonstrated: (a) a single unit is sufficient for a large current (greater than 50 kA) without increasing the system impedance, (b) highly reliable and long life operation and (c) implied scalability for the high power ranges above  $I_{\text{peak}} = 1 \text{ MA}$  and  $V_{\text{hold}} = 100 \text{ kV}$ .

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