Studies of the Plasma Puff Triggering Mechanism

of

Inverse Pinch Switch

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13. ABSTRACT (Maximum 200 words)

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_2. The optimal fill gas pressure for the azimuthally uniform plasma-puff was about 120 mTorr $< P_{opt} <$ 450 Torr for He and N_2. For Argon 120 mTorr $< P_{opt} <$ 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_2 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 the hypocycloidal pinch plasma-puff triggering. The main discharge of inverse pinch switch with plasma-focus driven plasma-puff trigger is found to be more azimuthally uniform than that with hypocycloidal pinch plasma-puff trigger in a gas pressure region between 80 mTorr and 1 Torr.

A comparative study of the INPIStron and a spark gap also reveals that the INPIStron with a low impedance $Z = 9$ ohms can transfer a high voltage pulse with a superior pulse-shape fidelity over that with a spark gap of $Z=100$ ohms.

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Table of Contents

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Studies of the Plasma Puff Triggering Mechanism of Inverse Pinch Switch

Abstract

The inverse-pinch plasma switch or INPIStron is a ultra high power switch and the commutating current path form an inverse pinch geometry. Therfroe, it requires production of a uniform annular plasma puff for proper initiation of the current path in the switch. In this study, 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_2. The optimal fill gas pressure for the azimuthally uniform plasma-puff was about 120 mTorr $< P_{opt} <$ 450 Torr for He and N_2. For Argon 120 mTorr $< P_{opt} <$ 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_2 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 the hypocycloidal pinch plasma-puff triggering. The main discharge of inverse pinch switch with plasma-focus driven plasma-puff trigger is found to be more azimuthally uniform than that with 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, emission from both an inverse-pinch plasma switch INPIStron) and a spark gap switch under test were studied with an optical multichannel analyzer (OMA). The color temperature of the argon plasma is approximately 4,000K which corresponds to the peak continuum emission near 750nm. There are the strong line emissions of argon in the 650 - 800 nm range and the lack of line emissions by 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. The result also indicates the considerable reduction of line emission with INPIStron switch over that of a spark-gap switch. However, the strong carbon line emission exists due to vaporization of the plastic insulator used. In order to reduce the vaporization of an insulator used, the present plexi glass 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 Z = 9 ohms can transfer a high voltage pulse with a superior pulse-shape fidelity over that with a spark gap of Z=100 ohms.

I. Introduction

New developments in high pulse power systems, such as lasers[1], intense relativistic electron beam accelerators[2], and fusion devices[3], 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 magneto plasma dynamic (MPD) thruster technology[4].

Spark gap switches, commonly used for high pulse-power commutation, have short lifetimes because of severe electrode heating from which surface erosion occurs even though this switch still covers the highest transfer range[5]. Also the important requirement of a fast recovery time has not been successfully realized in the spark gap.

One approach which has been taken to provide 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[6] (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 N_2 fill gas pressure was 10 mTorr[7]. An upgrading design for an inverse pinch switch is recently reported to meet the requirements for the output switch of an ultra-high-power (>30 GW) pulser[8]. The hold-off voltage of 1 MV is met by adopting multistage rim-fire electrodes and using SF_6 as the dielectric gas of the switch[8].

For the inverse pinch switch, an 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[9] or ring type third electrode[9], 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 rising time, a switching phase reproduction of less

than 20% at a pressure of 10 mTorr was observed. This indicates that a fast trigger pulse is required to increase the reproducibility. The wear of the trigger pins is eminent and the switch therefore has 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_2. A prototype of the plasma inverse pinch switch with plasma-puff trigger was tested[10] 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 are coaxially located under the main gap electrode pair and initiates gap breakdown by injecting annular plasma rings into the gap. The major advantages of the plasma-puff trigger is a circumferentially uniform current sheet formed by the initial surface discharge which in turn could initiate an uniform annular breakdown over the insulator in the main gap of the inverse pinch switch. The plasma-puff triggering device is in a hypocycloidal pinch[11] geometry and drives 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, produces electrons and ions for the main gap breakdown.

An another triggering concept was to utilize a plasma-focus driven plasma- puff and was designed and tested to determine the operating conditions and optimization of this method for the azimuthally uniform switching discharges for a wide range of fill gas pressures of Ar, He and N_2. The trigger electrode in this geometry are coaxially located above the main gap electrode pair and insulated by teflon from the main gap electrode. The plasma-puff triggering device is in a plasma-focus geometry and drives the current sheet axially downward and radially inward into the annular gap of the main electrode. The plasma-focus driven plasma produces electrons and ions for the main switch breakdown.

Details for characteristics of switching in an inverse-pinch switch will be found in appendix 2.

II. Summary

The plasma-puff triggering mechanism based on a hypocycloidal pinch geometry and plasma-focus Mather geometry were investigated to determine the optimal operating conditions for the azimuthally uniform surface flashover which initiates plasma-puff under wide ranges of fill gas pressure if Ar, He and N_2. The optimal fill gas pressure for the azimuthally uniform plasma-puff was about 120 mTorr $< P_{opt} <$ 450 Torr for He and N_2. For argon 120 mTorr $< P_{opt} <$ 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_2 was 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 inverse pinch switch with plasma-focus driven plasma-puff trigger is proved to be more azimuthally uniform than that with 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 the pulse transfer fidelity and efficiency revealed the INPIStron as the superior performer over that of 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 indicate the low current density and low material erosion in INPIStron. These findings again confirm the superiority of the INPIStron already found with respect to other parameters of high powers switching such as the voltage hold-off, the Coulomb transfer, the lifetime, material erosion, and the repetition rate.

Details for material erosion of electrodes and pulse transfer fidelity will be found in appendix 3.

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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 participated Scientific Personnel
Period : Sept 15, 1989 - Sept 14, 1993

K. S. Han	(Principal Investigator)	Sept 15, 1989 - Sept 14, 1993
J. H. Lee	(Faculty Associate)	Sept 15 1, 1989 - Sept 14,1993
Y. K. Kim	(Graduate Student)	Sept 15, 1989 - May 30, 1992
J. H. Kim	(Graduate Student)	June 1, 1990 - May 30, 1992
S. W. Lee	(Graduate Student)	Sept 1, 1992 - Sept 14, 1993

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

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

Sang W. Lee will complete his Master Science degree in Dec. 1993.
His M.S. thesis title will be "Submicrosecond Pulser with Blumlein Voltage Doubler"

V. List of Conference Papers
presented
period Sept 15, 1989-Sept 14, 1993

1. Eun H. Choi, Demetrius D. Venable, Kwang S. Han and Ja H. Lee, "Characteristics of Plasma-Puff Trigger for a Inverse-Pinch Plasma Switch", Bull. APS. Vol. 35, 1051 (1990)
2. 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 91CH3052-8, 904-907 (1991).
3. K.S. Han and J. H. Lee "Comparative Study of INPIStron and Spark Gap" 1992 20th Power Modulator Symposium, 92CH3180-7, 402-405 (1992).

Appendixes

1. "Characteristics of Plasma-Puff Trigger for a Inverse-Pinch Plasmas Switch" Eun H . Choi, Demetrius D. Venable, Kwang S. Han, and Ja. H. Lee Bull APS. <u>35.</u> 1051 (1990).

2. "Characteristics of Switching Plasma in an Inverse-Pinch Switch" Ja H. Lee, Sang H. Choi, Demetrius D. Venable, Kwang S. Han and Sang H. Nam, Technical Digest <u>91CH3052-8</u>, 904 (1991).

3. "Comparative Study of INPIStron and Spark Gap" Kwang S. Han and Ja H. Lee, 1992 20th Power Modulator Symposium, <u>92CH3180-7</u>, (1992).

Appendix 1

Sorting Category
<u>Plasma Physics</u>

<u>Characteristics of Plasma-Puff Trigger for a Inverse-Pinch Plasma Switch.</u>* EUN H. CHOI, DEMETRIUS D. VENABLE, KWANG S. HAN, and JA H. LEE, <u>Hampton University</u> --- 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_2. 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_2. 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_2 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.

(✓) Prefer Poster Session
( ) Prefer Standard Session
( ) No Preference

Signature of APS Member

<u>Kwang S. Han</u>
Same Name Tyepwritten

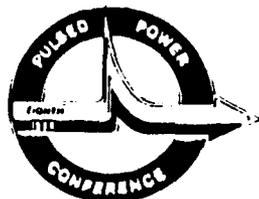**Bull. APS. Vol.35 No. 4, 1051(1990)**

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Appendix 2

DIGEST OF TECHNICAL PAPERS
Eighth IEEE International Pulsed Power Conference

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

Editors

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Sandia National Laboratories
Chairman, Technical Program Committee

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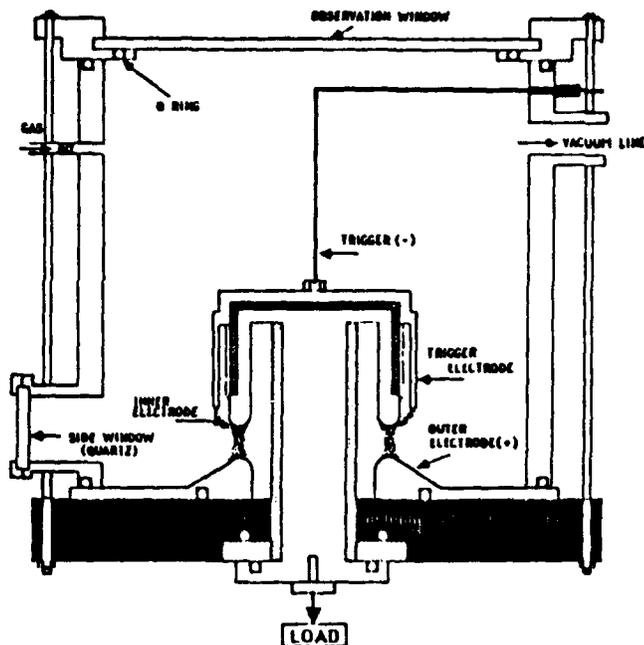
Fig. 1   Cross section of a high coulomb transfer INPIStron. The trigger electrode, shaped like a cap, is placed on the inner electrode and used for "plasma-puff" generation which in turn triggers the annular gap below.
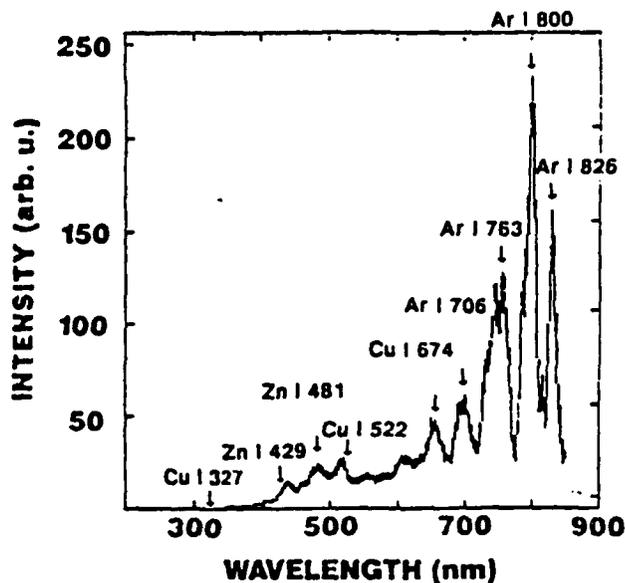

Fig. 2   A typical OMA spectrum of the plasma emission.

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-μs 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 ($\geq 10\,Hz$), average currents of $10 \sim 100\,amperes$ at voltages of $100 \sim 1000\,kV$, and pulse widths of $100 \sim 1000\,ns$ 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-kV hold-off voltage [6], the limit imposed by the pulse transformer used.

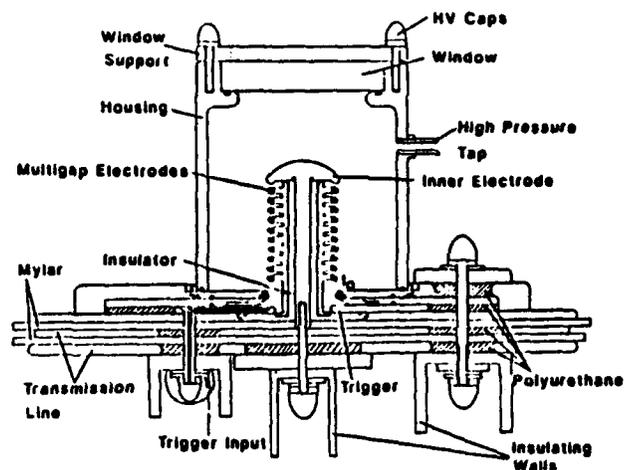Figure 3 shows the cross-section of the inpistron which was designed for 1-MV hold-off [7], and tested up to 250 kV.

Fig. 3   Cross-section view of the inpistron which is designed for 1-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 kV to find a new hold-off pressure at that voltage setting. Fig. 4 shows the results from the tests up to 250 kV. The pressure of N_2 gas to hold-off 250 kV was found to be 475 Torr. The overall mapping of voltage hold-off from 50 kV to 250 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 atm is sufficient for 1 MV hold-off. This result indicates that increases of the inpistron dimensions for higher voltage hold-off (i.e. 1 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 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
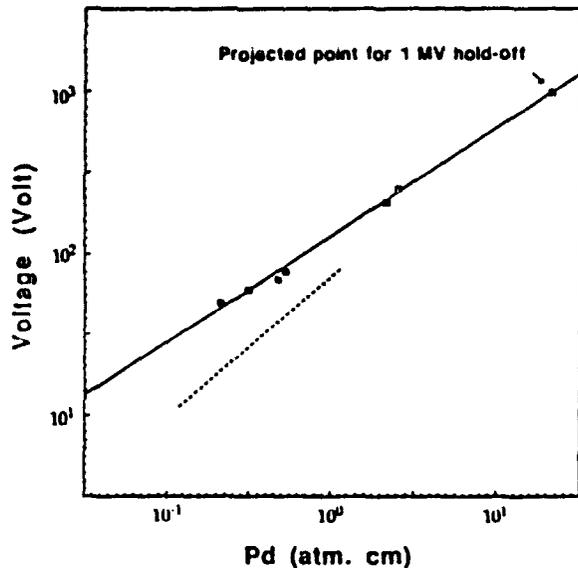
905

Fig. 4 Inpistron hold-off voltage (V_{h_0} 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.

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

and

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

where μ_o is the permeability, ϵ 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_o is the radius of inner electrodes.

The series characteristic impedance

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

is then

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

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

The titanate compound ceramic has a high dielectric constant (≥ 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. AlSiMag 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 break-down 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	μ_r	1	1
Relative Dielectric Const.	ϵ_r	1	50 (titanate)
Gap*	h [cm]	5	5
Inductance	L [nH/m]	1463	102
	L [nH]	73	5
Capacitance	C [nF/m]	7.61×10^{-3}	5.45
	C [nF]	0.38×10^{-3}	0.27
Characteristic Impedance	Z [Ω]	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 occurance 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 carefull 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].
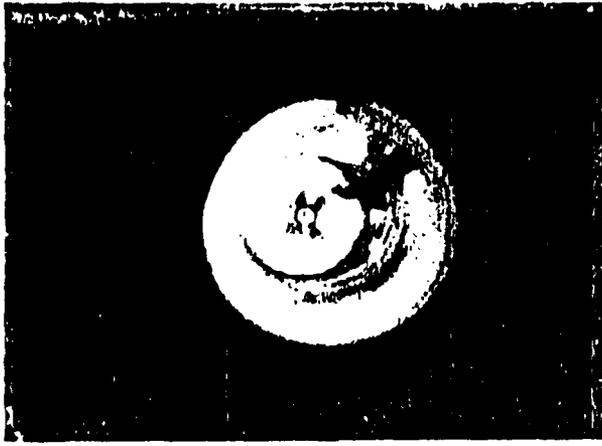
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Fig. 5 Picture of the inpistron plasma emission at 250-kV test. The uniform breakdown is appeared in the picture including the blurred image portion due to the blockage by a clip handle for a reflection mirror.

Energy Transfer: The inpistron demonstrated over 2 MA commutation at 25 kV with unmeasurable wear of switch components for cummulative 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-μs pulses.

Pulsewidth and Shape: The pulsewidth ($\leq 1 \mu s$) and shape are generally determined by the combination of risetime and falltime 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 Ω. 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.

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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 μs. 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 giga-volt•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-μs pulses with typically > 36kJ of energy at 1 megavolt and at the repetition rate of 10 Hz fed from a 4 - 6 Ω, fast pulse forming line (PFL). To date these requirements can be met only by a spark gap with a limited life.[1] 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 convnetional spark gap as shown in
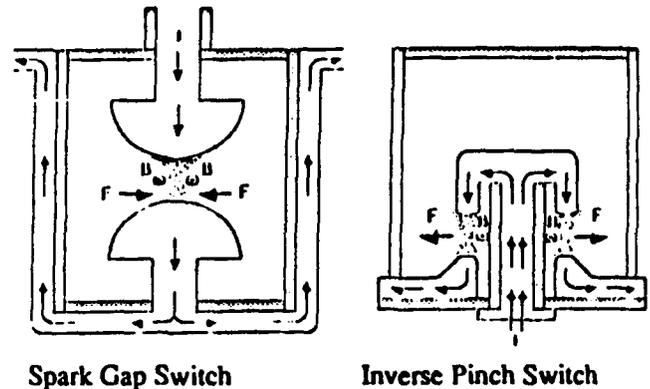

Spark Gap Switch   Inverse Pinch Switch

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 5×10^{10} V•A (i.e.25kV x 2MA) 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.[1-3] The detailed configuration and characteristics of the INPIStron were reported elsewhere.[1-3] 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
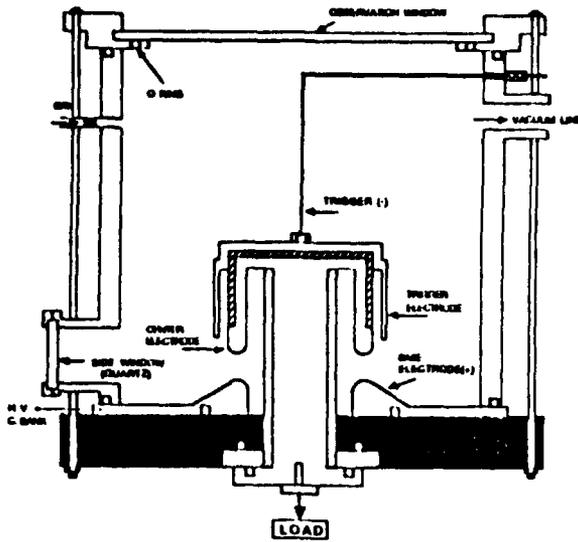
Fig.2 Detailed design of the inverse pinch switch

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 INPIStron 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 INPIStron 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 INPIStrons.

This presentation is the report of a recent study made with an INPIStron 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 INPIStron 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 INPIStron and the spark gap housed in the same chamber had impedances of Z=9 ohms and 100 ohms respectively. The low impedance of the INPIStron is the result of coaxial current path with a small (near unity) aspect ratio and having a large relative dielectric constant ϵ 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 Ω, the use of high-impedance switches such as spark gaps causes sacrifices in the pulse transfer fidelity

Table 1

Parameters	INPIStron	Spark-gap	Unit
Capacitance	8.21	8.21	μF
Capacitor energy	1.65	1.65	kJ
Operating voltage	20	20	kV
Cycle period	9.6	11.4	μs
Rise time	1.9	2.9	μs
Ringing frequency	104	88	kHz
Total circuit inductance	283	399	nH
Total resistance	25.35	27.01	mΩ
Switch inductance	17.6	147.8	nH
Switch Capacitance	219.9	14.7	pF
Switch impedance	8.94	100.27	Ω
Damping factor (R/2L)	4.47×10^4	3.38×10^4	Ω/H

initiation of the INPIStron have been tested and the range of working gas pressure that produce azimuthally uniform initiation of the switch were determined and reported elsewhere.[4] 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 μF 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 INPIStron.

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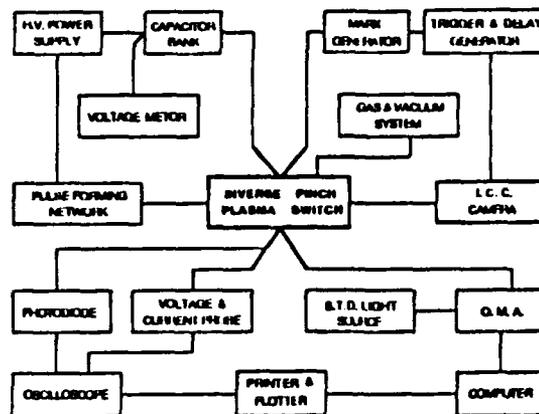

Fig. 3 Experimental set-up for INPIStron and Spark switch.

and the transfer efficiency.

The experiment was carried out to verify the above expectation with a train of real pulses with a 1-μs risetime from the pulse-forming Marx generator which had 13 stages of voltage multiplication. Because of large switching jitters ($\approx$ 1 μs) 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 INPIStron 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 INPIStron 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 INPIStron 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 INPIStron, 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 INPIStron and the spark gap were compared. Fig. 6 is representative spectra obtained with an identical spectrometer-optical-multichannel analyzer system. The spectra (time-intengrated) 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 INPIStron, indicating higher plasma temerpature 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.)
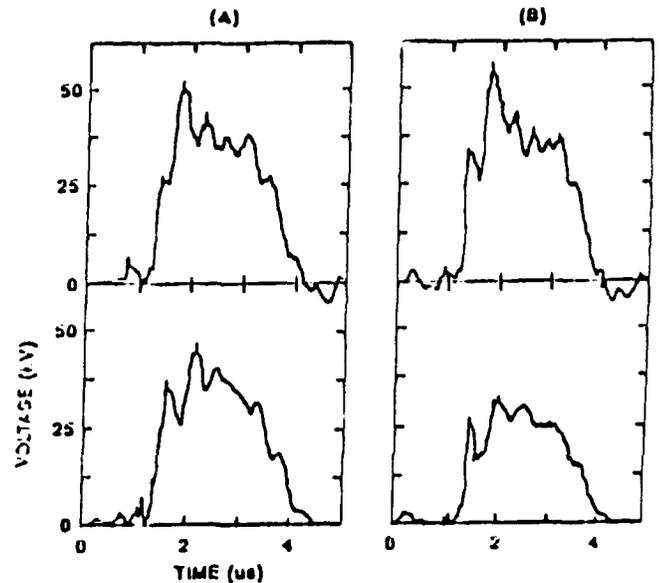

Fig. 4   Pulse transfer characteristics of (A) the INPIStron (B) the spark gap. The upper traces are the input pulses and the lower traces are switch outputs. This INPIStron performs with a better pulse shap fidelity and efficiency than that of the spark gap.
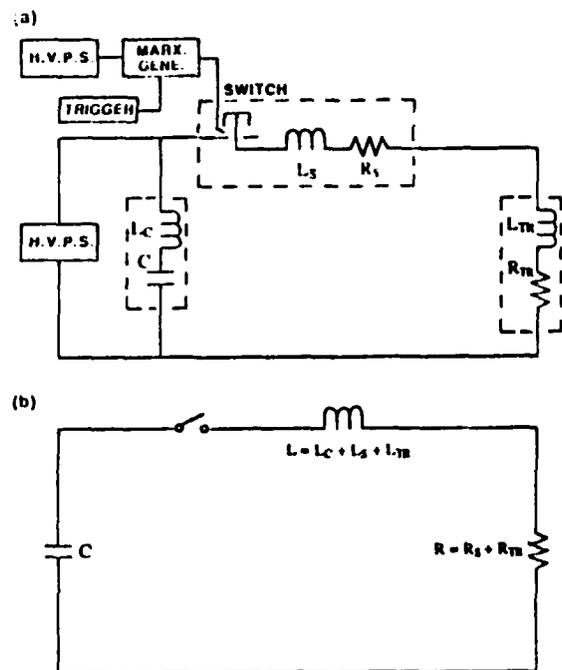

Fig. 5   Schematic (a) and equivalent (b) circuit of the system.

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

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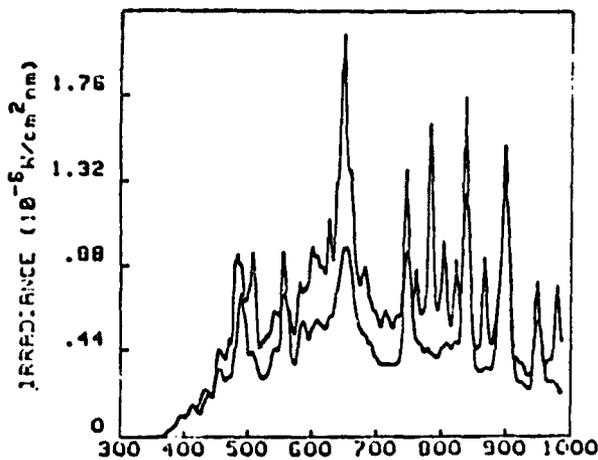
Summary and Conclusion

An extended study of the INPIStron for the pulse transfer fidelity and efficiency revealed the INPIStron as the superior performer over that of the reference spark gap. Also material errosion, 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 INPIStron. These findings again confirm the superiority of the INPIStron 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.

Acknowledgements