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.

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14. ABSTRACT
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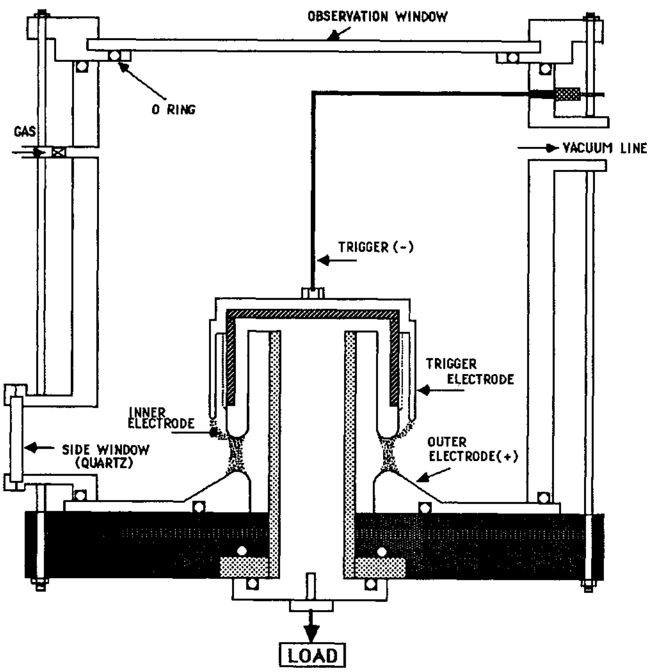

Fig. 1 Cross section of a high coulomb transfer INPIStron. The trigger electrode, shaped like a cap, is placed on the inner electrode and used for "plasma-puff" generation which in turn triggers the annular gap below.

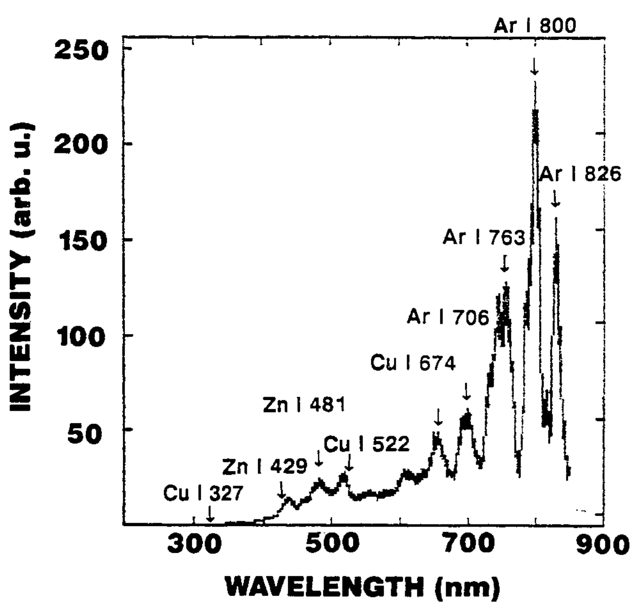

Fig. 2 A typical OMA spectrum of the plasma emission.

<u>High Voltage Inpistron</u>

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 $250\,kV$.

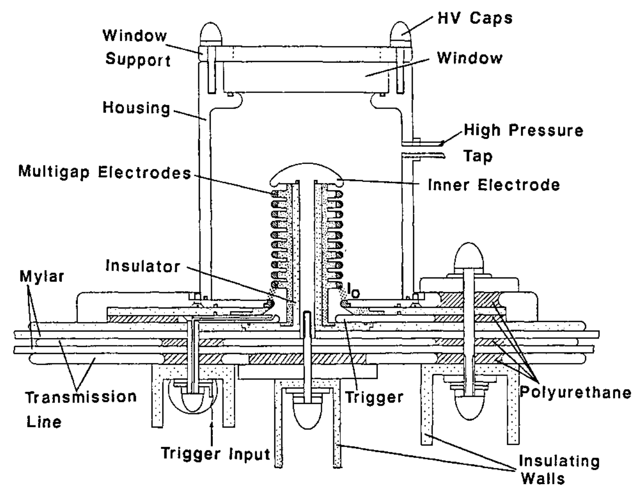

Fig. 3 Cross-section view of the inpistron which is designed for 1-MV hold-off test.

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

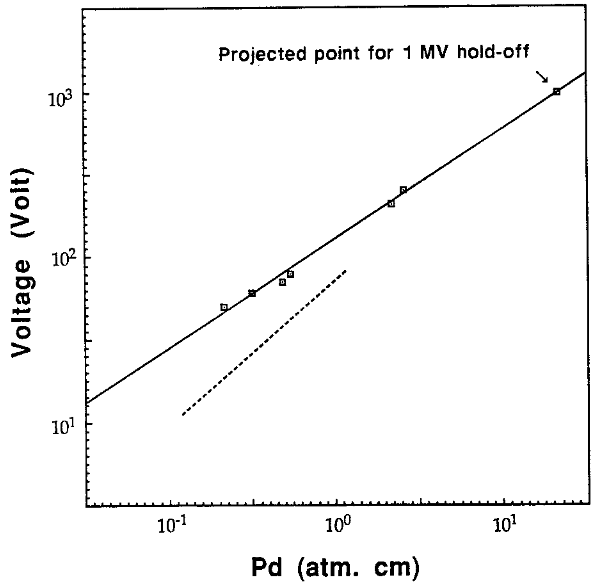

Fig. 4 Inpistron hold-off voltage (V_{ho} in kV) as a function of $p \cdot d$ in atm-cm where p is the chamber pressure and d the gap distance. N_2 gas is used for this test. Paschen curve for N_2 of a single gap in uniform electric field is also shown with the dashed line for comparison.

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

and

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

where 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_s is the radius of inner electrodes.

The series characteristic impedance

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

is then

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

A larger r_s and ϵ' (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 (≥ 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 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	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 useed 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].

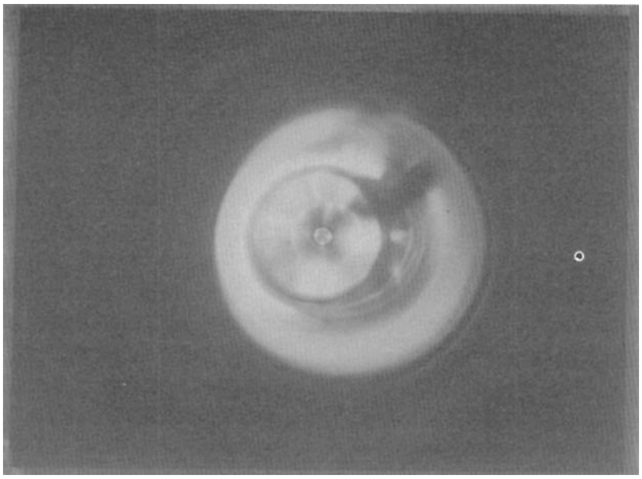

Fig. 5 Picture of the inpistron plasma emission at 250-kV test. The uniform breakdown is appeared in the picture including the blurred image portion due to the blockage by a clip handle for a reflection mirror.

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 $4 \sim 6\,\Omega$. 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.

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