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Clamp System for the Pharos 2-MJ Capacitor Bank

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CONTENTS

ABSTRACT

A clamp system is now in operation on the Pharos magnetic-compression experiment's two-megajoule primary capacitor bank. Clamping the discharge circuit at the current maximum (about 17 megamperes with 16 microseconds risetime) converts the normal damped oscillatory waveform to an aperiodic current with an exponential decay time constant of more than 200 microseconds. This conversion permits study of the plasma in a region where the confinement time is no longer limited by the duration of the confining field. An important feature of the clamp-circuit design is the isolation of individual clamp switches by the starting switches during the capacitor charging period. Thus, only a small fraction of the total bank energy is dissipated in the clamp switch in the event of a prefire.

The 420 parallel clamp switches, developed at the Naval Research Laboratory, are a variation of the Pharos air trigatron starting switch, except that they are housed in a commercial Pyrex tee and evacuated to one millitorr.

The clamp-switch terminals, which are an integral part of the electrodes, allow direct mounting between the capacitor high-voltage stud and ground plates. No modification to the existing capacitor bank was required for installation, so the experimental program was not disrupted.

PROBLEM STATUS

This is a final report on one phase of the problem; work on other phases is continuing.

AUTHORIZATION

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CLAMP SYSTEM FOR THE PHAROS 2-MJ CAPACITOR BANK

INTRODUCTION

Large θ-pinch experiments are being used to study the production and heating of plasma by fast-rising magnetic fields. The high initial di/dt, required to give rapid acceleration to the plasma, dictates parameters for the energy-discharge circuit that result in an oscillating current in the load coil. The effective magnetic field for compression is therefore limited to the first half cycle of the oscillating current, and the need arises for longer compression times for plasma stability studies. To achieve an aperiodic current waveform and to maintain the high initial di/dt, the circuit is clamped at the time of the first current maximum. The subsequent coil current will decay exponentially with a time constant equal to the ratio of the inductance to the resistance of the clamped circuit.

The Pharos θ-pinch experiment (1) has a clamped two-megajoule compression bank operated in conjunction with a bias and a preheat bank. These three banks are discharged in parallel into a single-turn load coil, typically 180 cm long with a 10-cm bore, in the time sequence outlined in the following paragraphs.

First, the bias-field bank produces a slowly rising negative field which reaches a maximum of approximately 12 kG in 60 μsec. It provides a bias field to enhance the trapping of magnetic fields within the plasma during the preionization stage. When the bias field has risen to about one-third of its peak value, the preionization field is applied. This 40-kV, 9-kJ, low-inductance bank induces a 300-kHz oscillating current in the plasma. This oscillating field produces a fully ionized plasma after a few cycles.

The plasma is allowed to become quiescent after preionization, then the 20-kV, 2-MJ compression bank is applied. This bank delivers 17 MA, which rises in 16 μsec to its peak value and produces 100 kG in the coil. This field compresses the plasma and increases the temperature to 10^7 degrees and the electron density to 10^{17} cm^{-3}.

At the compression-current maximum, the clamp system is triggered and causes the coil current to decrease exponentially with a decay time constant in the order of 200 μsec. This time period permits study of the plasma in a region where the confinement time is no longer limited by the duration of the confining field.

DESCRIPTION OF PHAROS TWO-MJ DISCHARGE CIRCUIT

Energy-Storage Capacitor Bank

The two-megajoule capacitor bank consists of 1260 8.5-μF capacitors operating at 20 kV. The castor-oil-impregnated paper capacitors were made by British Insulated Callender's Cables, Ltd. The bank is assembled as 420 relatively high inductance (about 90 nanohenries) energy-storage modules isolated by their load cables, which are connected in parallel at the current collector, to form a low-inductance energy source. Each module consists of three capacitors, one starting switch (2), one charging resistor, and a mechanical shorting rod. Figure 1 shows one of these five-kilojoule modules as assembled in the rack. The total bank is subdivided into 12 sections (with 35 modules per section) which can be selected in any combination for experiments requiring less than the full two-megajoule energy.

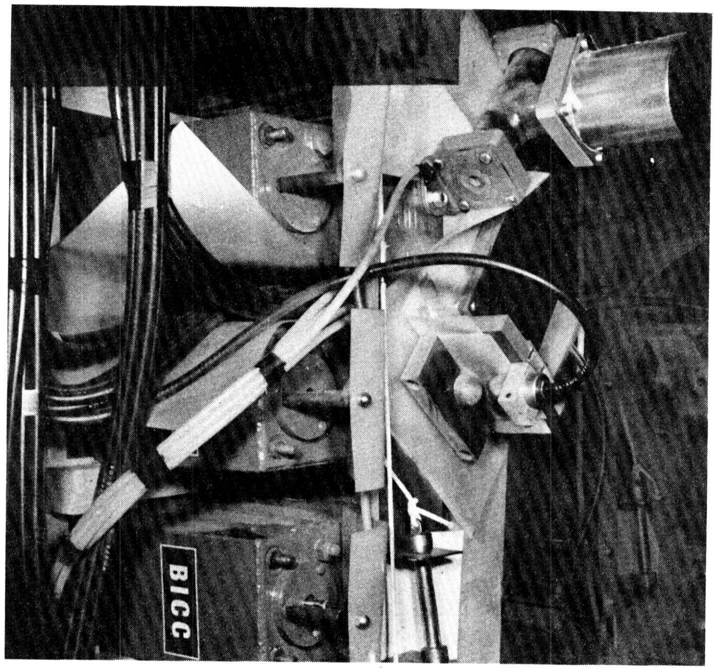

Fig. 1 - Five-kilojoule energy-storage module

Load Cables

The load cables are made from British Insulated Callender's Cables, Ltd. type 20 P-2 cable. This is a polyethylene-insulated, solid-inner-conductor cable with an inductance of 35 nanohenries per foot and a resistance of 1.9 milliohms per foot. The terminations are made by magnetically swaging copper ferrules to the conductors. The cable lengths range from 8 ft to 26 ft, with the average being 15 ft. Two load cables per module are used throughout the bank, except for a pair of sections (350 kJ) which are connected with three cables per module to obtain a lower inductance and better efficiency for low-energy experiments.

Current Collector and Terminals

The current-collector plate is made from two parallel copper sheets, 16 ft long and 5 ft wide, separated by four sheets of 0.0075-in. Mylar. The load cables are connected to 14 terminal blocks distributed along the back side of the collector plate. Load cables from each of the capacitor-bank sections connect to a separate terminal block, except for the two low-inductance sections, for which there are two terminal blocks each. A three-foot extension, on which the load coil is attached, is connected to the front side of the collector plate.

The collector plates are bolted together with 142, 1-1/2-in.-diameter insulated steel bolts and mass loaded with 50 tons of lead on the top and bottom in order to withstand the magnetic forces from the current pulses. Figure 2 shows the back side of the collector plate and the load-cable connections.

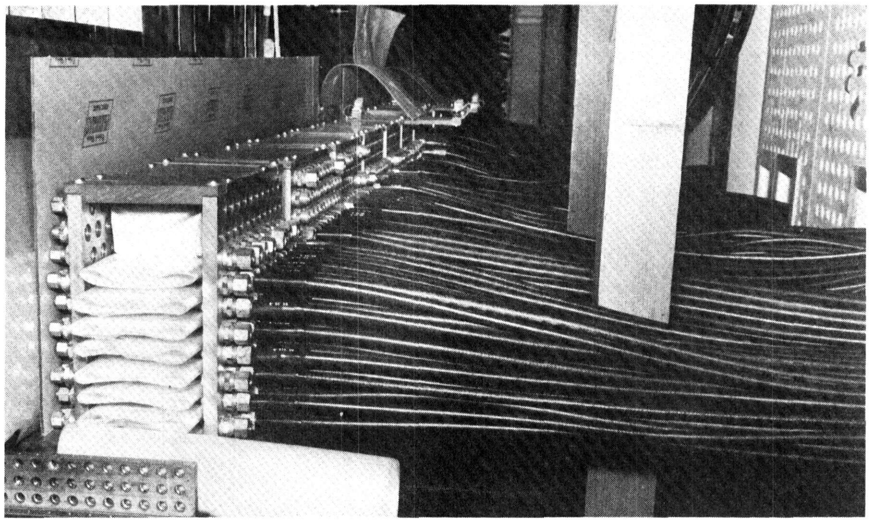

Fig. 2 - Collector plate and load-cable terminations

Load Coil

The load is a single-turn coil 180 cm long with a 10-cm bore. The total coil is constructed of nine parallel sections mounted in line, with spaces between them for optical diagnostics of the plasma. Each section was cast from copper-bronze and machined to close tolerances. The load-coil sections surrounding the plasma tube can be seen in Fig. 3.

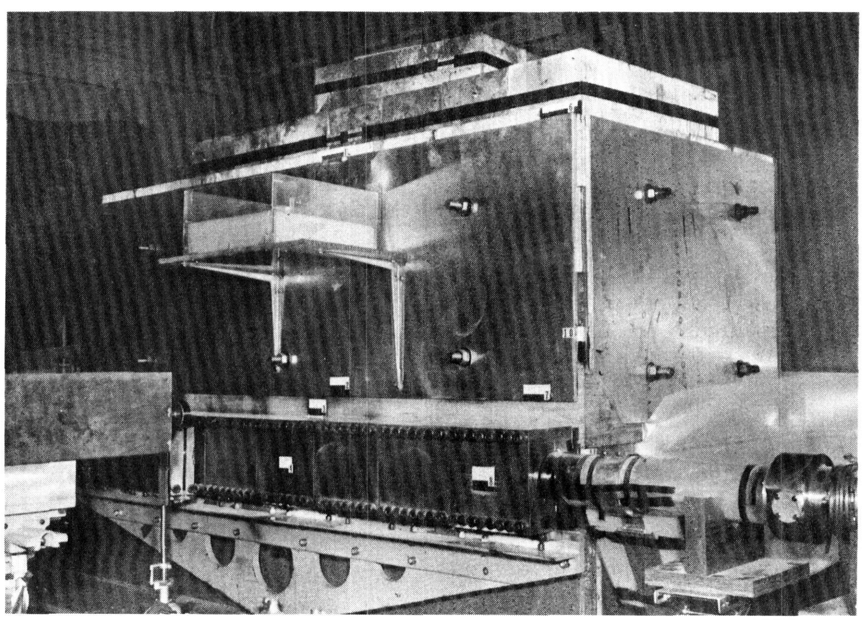

Fig. 3 - Load coil

DESCRIPTION OF CLAMP CIRCUIT

Circuit

The modular concept of energy storage is maintained by having a five-kilojoule clamp switch for each of the 420 modules of the Pharos main bank. The clamping-circuit arrangement is shown in Fig. 4.

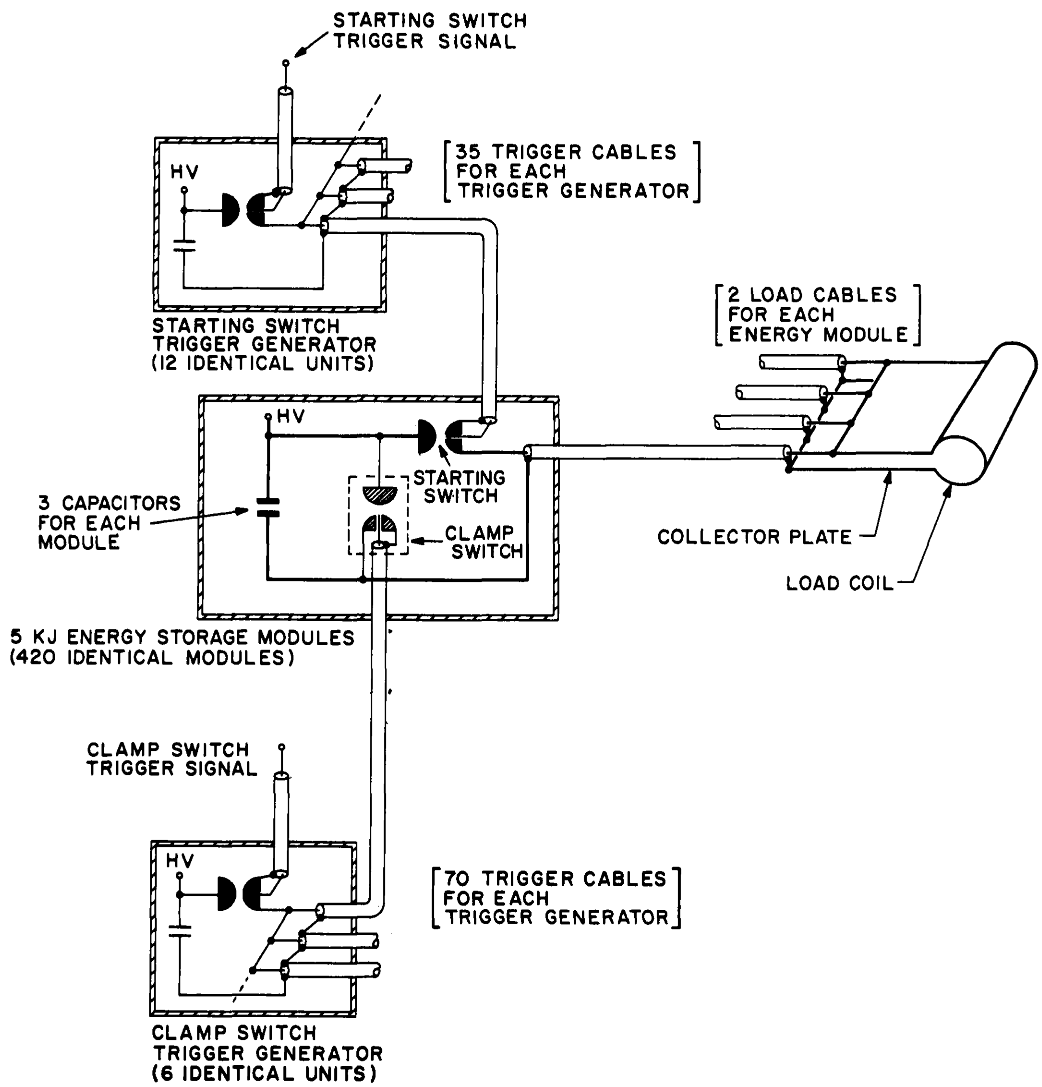

Fig. 4 - Clamp-circuit arrangement

It would be folly to presume that a large number of vacuum switches could be operated in parallel in a clamp circuit, with a complete guarantee that none would prefire. In a truly parallel-connected system, a prefire of a single clamp switch would lead to a catastrophic current for that switch and its connections. A very important system design feature is, therefore, a circuit and operational sequence that will withstand the currents resulting from switch prefires. By placing the clamp switches directly across the capacitors, they are checked for voltage holdoff during the capacitor charging. Isolation of the energy modules by the starting switches during the charging period will result in only the individual module being discharged if its clamp switch prefires. The ringing discharge current resulting from a prefire in this circuit is within the ratings of the clamp switch and the capacitors.

Clamp Switch

The clamp switches (3) are similar to the air trigatron starting switches used on Pharos, except that they are housed in a commercial Pyrex tee and evacuated to one millitorr. Tungsten-copper caps are brazed on the copper electrodes in the area of the gap. The copper trigger pin, located axially in the cathode, is insulated by an aluminum oxide bushing. The clamp switch, shown in Fig. 5, was developed at NRL particularly for the Pharos bank. The electrode assemblies were made by the Mallory Metallurgical Company from NRL specifications, and the assembly and tests were made at NRL.

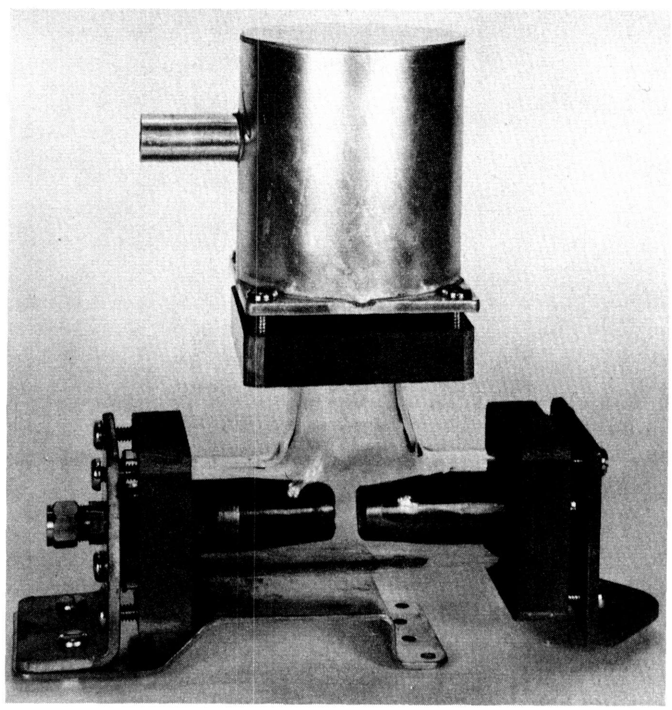

Fig. 5 - Clamp switch

Clamp-Switch Installation

The clamp-switch electrode terminals were designed specifically to fit on the existing energy-storage modules. The anode flange has a 5/8-in.-diameter hole that fits directly on a capacitor high-voltage stud. The cathode flange, by way of the short brass backstrap, attaches to the capacitor ground plate. Figure 6 shows a part (about 350 kJ) of the capacitor bank with the clamp switches mounted.

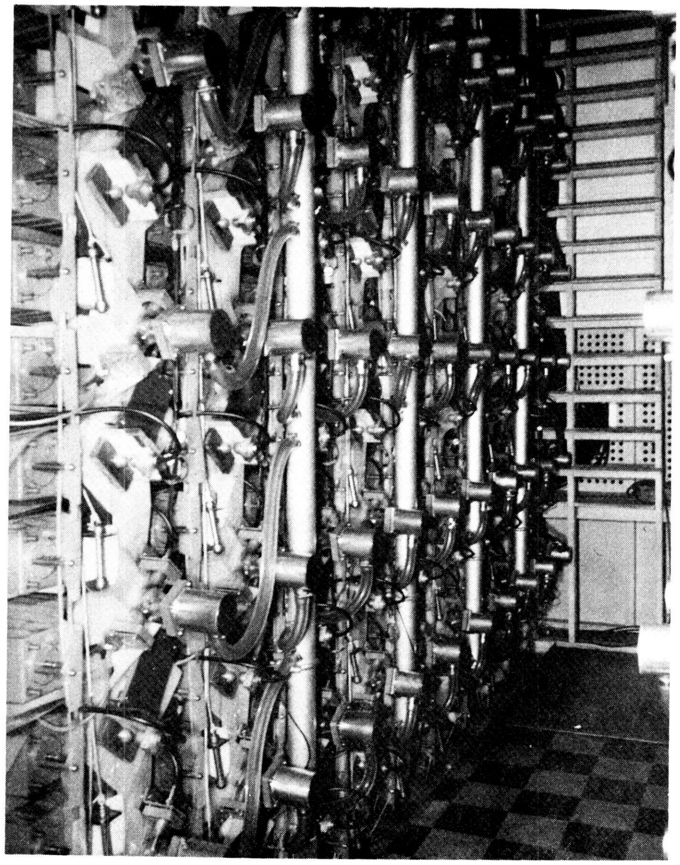

Fig. 6 - Section of energy-storage bank (350 kilojoules)

Vacuum System for the Clamp Switches

In the operation of many clamp switches in parallel on a common vacuum system, good vacuum techniques are certainly necessary. Particular features of note for this vacuum system are: (a) a dry-lobe, first-stage pump to eliminate backstreaming of pump oil vapors to the clamp switches, (b) a pump with no stalling pressure and hence suitable for large-impulse gas loads, (c) a pump with a high pumping speed, extending through the lower pressure range for recovery to one millitorr in less than one minute after a discharge (this approximately equals the sequence time required in the Pharos control system for bank charging, etc.), and (d) a quick disconnect for each clamp switch without shutting down the entire system.

Shown in the vacuum-pump assembly of Fig. 7 are: (a) two pumps, capable of single or parallel operation, (b) remotely controlled (from the operator's console) main manifold valves for each pump, (c) a dry air bleed system, and (d) a pressure monitor with recorder output on the operator's console.

Trigger System

The clamp-switch trigger system is a close duplication of the starting-switch trigger system. An adjustable-delay pulse generator for the clamp system is triggered by the

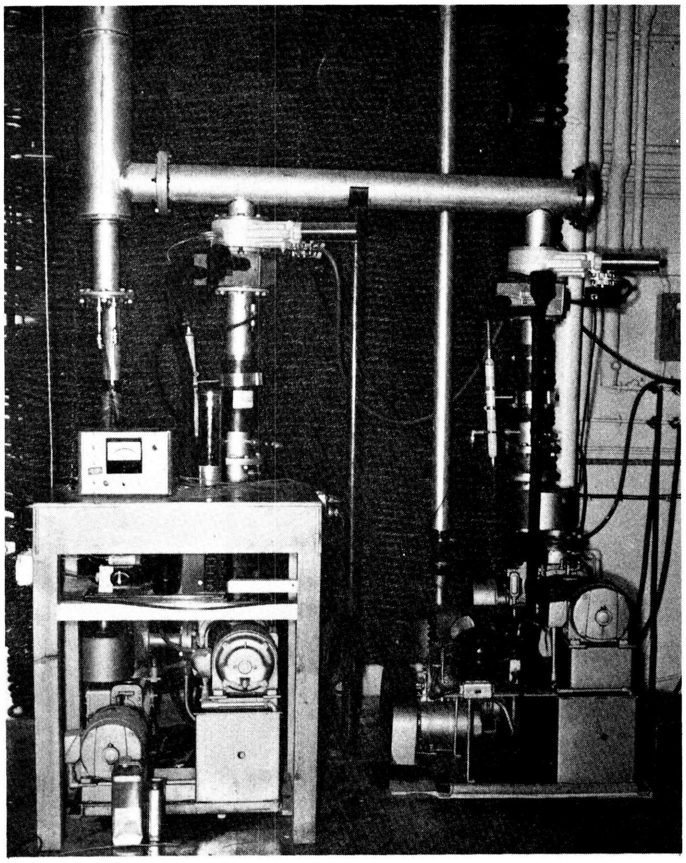

Fig. 7 - Vacuum-pump assembly

starting-switch pulse generator. This pulse triggers a thyratron, which fires a pressurized trigatron switch on a master trigger capacitor. The pulse from the master trigger capacitor is fed in turn to six trigger capacitors (one for each symmetrically selected pair of capacitor bank sections), each of which triggers 70 clamp switches. The less than 0.1 μsec jitter in the trigger system is well below that required for this clamping application.

ELECTRICAL PARAMETERS

The inductance and resistance values of the components in the two-megajoule circuit are shown in Fig. 8. Most of these values were arrived at by calculations based on values extracted from measured voltage and current waveforms. The variations of resistance between the ringing and clamped discharges are explained partly by skin penetration of the conductors, different starting-switch currents, etc. The position of the terminal block on the back of the collector plate greatly affects the inductance value of the collector plate for a particular section.

MEASURED WAVEFORMS

The voltage and current waveforms for both the ringing and clamped modes are seen for one megajoule in Fig. 9. The reverse field current and the preheat voltage can also

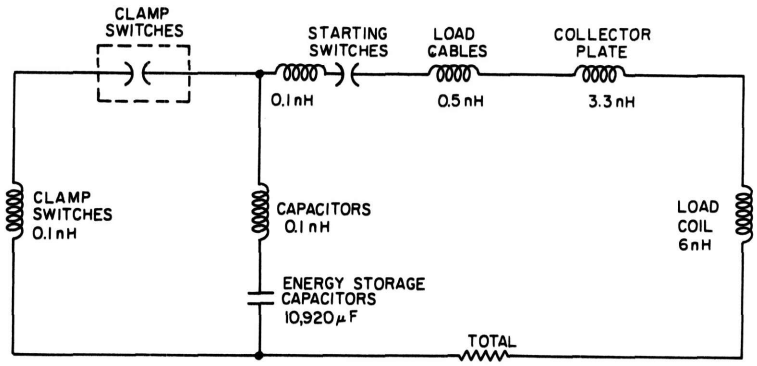

Fig. 8 - Circuit parameters for two-megajoule bank

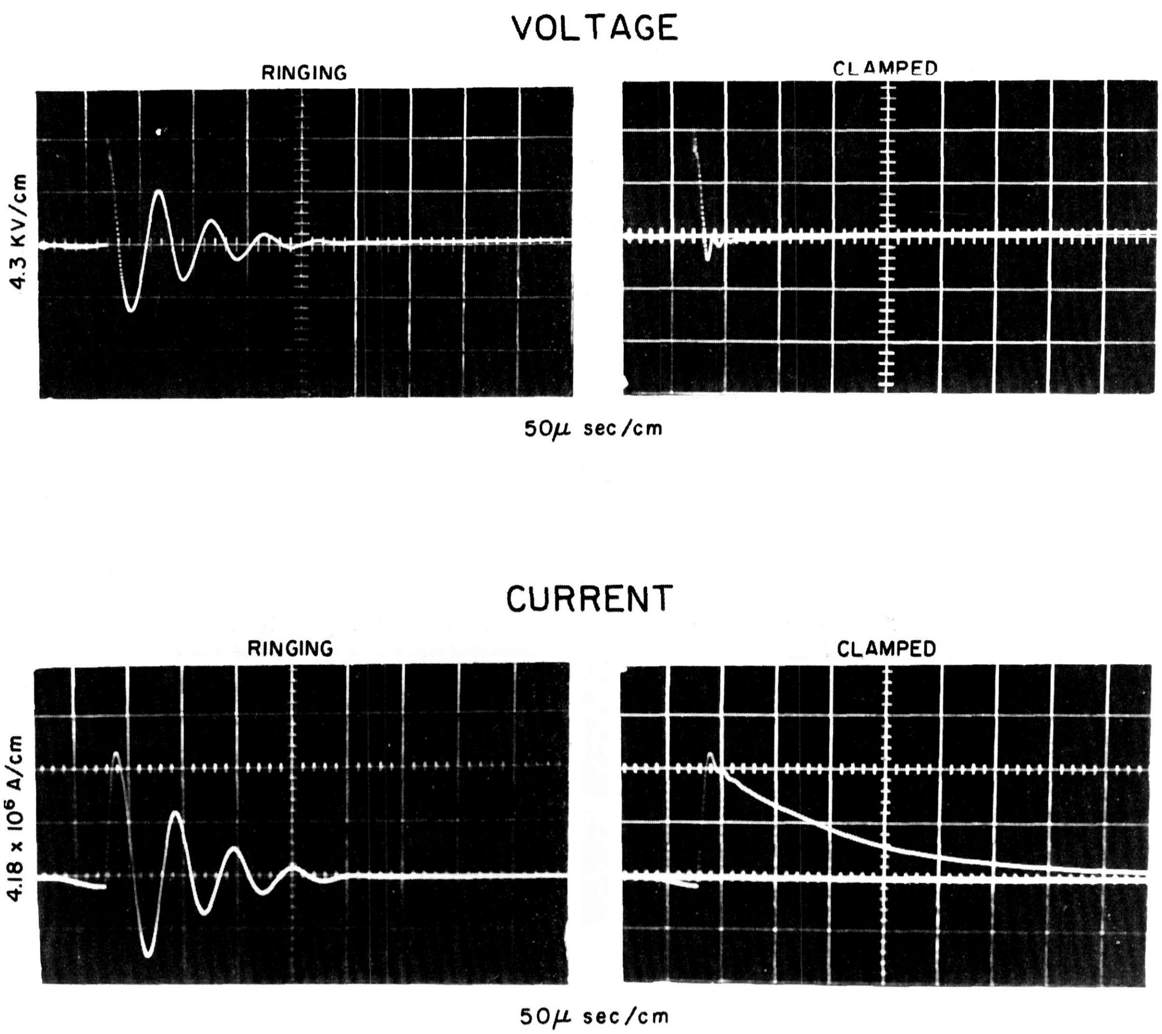

Fig. 9 - Voltage and current waveforms for one-megajoule discharge

be seen on the waveforms. After clamping, the exponentially decaying current has a time constant of 125 μsec for a 1-MJ discharge. For a full-bank discharge (2.0 MJ), the current maximum is 17 million amperes, and the decay time constant (L/R) after clamping is 200 microseconds. The amplitude of the oscillations occurring in the current waveforms just after clamping, due to the finite clamp inductance, are reduced from approximately 15 percent of maximum in a 350-kJ discharge to less than 8 percent in the 2.0-MJ discharge.

OPERATIONAL PROCEDURE

The clamp-switch vacuum pumps are not normally run overnight, and an initial 30-minute pumpdown is required to bring the system pressure to the operating range. In cases when the system has been let up to atmospheric pressure or has not been used for a number of days, the initial pumpdown may require as much as two to three hours. As the capacitor bank is charged, the voltage appears across the clamp switches. If a clamp switch prefires during this charging period, the pressure pulse on the common vacuum system will bring other switches into the pressure range of low-voltage breakdown, which causes them to prefire also. This avalanche of prefires will cause the overcurrent relay on the charging power supply to abort the shot automatically. The clamp-switch prefire is indicated to the operator by a pulse on the pressure-monitoring recorder on his console. After two to three minutes, the switch pressure will be in the operating range again. Since a prefire appears to clean the switch and increase its hold-off voltage, the condition which causes prefires tends to be a self-correcting one. Typically, there are one to four prefires at the beginning of a day and only isolated prefires thereafter. The clamp system can operate continuously at one discharge per two minutes, which is the normal rate for Pharos operation, and negligible temperature increase of the clamp switches has been observed after 25 successive discharges at this rate.

A switch on the console which energizes the clamp-switch trigger relay allows the operator to select either the ringing or clamped mode of operation. The clamp trigger delay is set to coincide with the time at which the current reaches maximum. This varies from eight microseconds for 350 kJ to 16 μsec for the full two megajoules. Figure 10 shows a section of a capacitor bank during discharge.

SUMMATION

The vacuum-switch clamp system for the Pharos main capacitor bank has operated for more than 6000 discharges, with negligible increase in complexity over the original circuit. By replacing parts occasionally, the clamp system should last for the life of the Pharos bank. No extensive changes were required in the existing capacitor bank, load cables, collector plate, and control system to add the clamp system. The effective magnetic-field duration was increased sevenfold at a relatively low cost and with only minor interruptions of the experimental program. Maintaining the modular concept of energy storage and using interchangeable and replaceable parts allows reliable operation with a minimum number of service shutdowns.

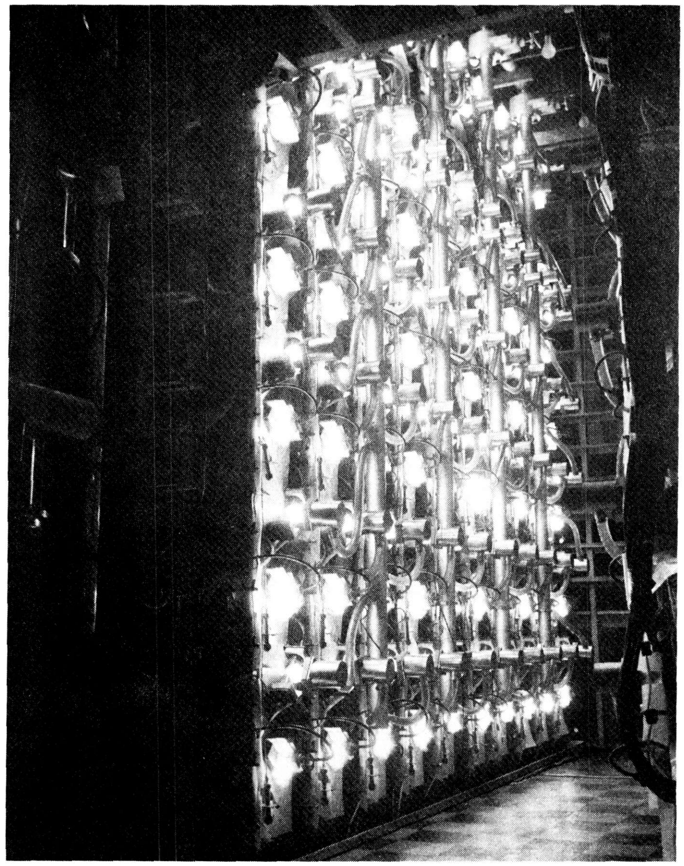

Fig. 10 - Section of capacitor bank during discharge

REFERENCES

1. Kolb, A.C., and Lupton, W.H., "A Pulsed-Field Plasma Experiment - PHAROS," in "High Magnetic Fields, Proceedings of the International Conference on High Magnetic Fields," Mass. Inst. of Technology, Cambridge, Mass., Nov. 1961; Cambridge: MIT Press, pp. 693-700, 1962

2. Lupton, W.H., "Fast Triggered Spark Switches for a Two Megajoule Capacitor Bank," Proc. Fifth International Conf. on Ionization Phenomena in Gases, Munich, Germany, 1961; Amsterdam:North-Holland Publishing Co., Vol. II, pp. 2059-2068, 1962

3. Young, M.P., "A 5-kJ Vacuum Clamp Switch for the Pharos 2-MJ Capacitor Bank," NRL Report 6418, Aug. 31, 1966

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Vacuum switch						
Low inductance						
Five-kilojoule switch						