STATE OF THE ART WITH PLASMA CURRENT INTERRUPTORS

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The state of research is considered for high-power pulse generators based on inductive energy stores and plasma interruptors. The main attention is given to plasma interruptors in which the low-resistance state lasts about 10^{-6} sec. Basic features are indicated and characteristic components in the theory with an indication of problems in using the devices and particular examples of existing equipment.

A major line in high-current electronics concerns nanosecond high-voltage pulse generation with power $\geq 10^{12}$ W. Traditional methods are based on capacitor stores and shaping components, but there is ongoing interest in inductive stores, whose main advantage is their greater specific energy capacity. The main problem in developing a generator with an inductive store lies in the high-resistance current interruptor, which transfers the stored energy to the load in about 10^{-8} sec. Plasma current interruptors PCI have been extensively researched recently.

The PCI operating sequence is as follows (Fig. 1). A hydrocarbon plasma link ($n \simeq 10^{13}$-10^{15} cm^{-3}) is produced near the pulse generator between the grounded and high-potential electrodes. The plasma in the gap is injected with a plasma gun or surface spark source through holes in the outer or inner electrode in a few μsec (delay Δt) before the current starts to flow in the PCI. The current amplitude I_s^0 at which the trip operates is dependent on ΔT. The generator current initially flows through this gap and transfers energy from a capacitative store to the inductive one, with the pulse not passing to the load. Under certain conditions, the plasma goes from the low-resistance state to a high-resistance one, i.e., the resistance of the plasma link increases sharply, and an induced emf is generated, with the energy flow transferred to the load.

PCI have been tested with lifetimes for the low-resistance state (conduction times t_c) of 10^{-8}-10^{-6} sec. These PCI are used to input 10^4-10^6 J to the inductive store at currents of 10^5-10^7 A. Rates of resistance increase in the output stage have been obtained of up to 10^9 Ω/sec with resistances of up to 20 Ω [1, 2]. Voltage levels of 0.3-5 MV have been attained with initial ones of 0.05-0.5 MV [3, 4] in generators with intermediate inductive store and PCI. The characteristic energy output times are 10^{-8}-10^{-7} sec with output power levels of 0.3-3 TW [1, 3, 5]. PCI are used in the PBFA-2 equipment to double the output voltage to the design value of 30 MV with an output power of 150 TW [6].

Advances in the design of generators with intermediate inductive stores and PCI involve solving two basic problems. Firstly, there is increasing the conduction time. The longer that time, the greater the energy that can be input to the inductive store with a given initial voltage level. Secondly, there is raising the resistance R of the PCI in the high-resistance state. For a given I_s^0, the resistance and the rate of increase govern the voltage level and power in the output pulse.

This involves elucidating the current flow in the plasma in the low-resistance and high-resistance states. Appropriate experiments have been performed to identify the general regularities (dependence on electrode geometry and polarity, as well as effects from the composition, concentration, formation mode, and injection direction for the plasma, and effects from the parameters of the discharge circuit and initial voltage, as well as effects from external magnetic fields etc.), as well as for detailed study of the electron-ion flux distributions at the electrodes, the rates and directions in which the current penetrates the plasma, and the plasma displacement under electrodynamic forces.

The following effects have been identified for PCI: the polarity effect [7] (fall in R_s when the polarity of the internal electrode is switched from negative to positive); the rising dependence of t_c and the falling dependence of R_s on the central electrode diameter [3]; and the rising dependence of I_s^0 on the plasma concentration n ($I_s^0 \sim n$ [8], $I_s^0 \sim n^{0.5}$ [9], $I_s^0 \sim n^{0.25}$ [8]) in accordance with the concentration), which is accompanied by increased leakage in the PCI in the high-resistance stage [5].

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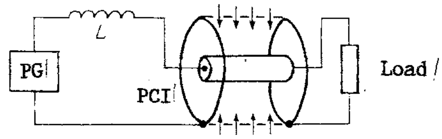

Fig. 1. Connection circuit for plasma current trip (plasma injection through holes in the outer electrode).

An external axial B_z adversely affects the interruption parameters for a PCI with internal cathode but can improve them if the internal electrode is the anode [11]. There is a positive effect from an external azimuthal B_φ field coinciding in direction, shape, and amplitude with the field produced by the trip current [11]. Magnetic-probe measurements have shown that a current layer about 3 cm wide is accelerated over the PCI zone, and the conduction stage continues until that layer has passed through the entire PCI zone previously filled with plasma [12]. Photographic recording has been used in the optical range from the end of the PCI with exposure times of 80 nsec, which showed that a dark area arises near the cathode in the initially completely luminous electrode gap, and this has a tendency to expand up to tile instant of current interruption [13]. Long before the high-resistance phase sets in, an ion current appears at the cathode surface with an amplitude much exceeding the Child–Langmuir value. In the conduction stage, the proportion of ion current is 20-30%, while in the high-resistance stage it is 50-80% [14].

Theoretical studies do not give a complete understanding of the operating mechanism, although the various mode, describe various characteristic features quite well. The mode of operation resembles that in a pulsed plasma accelerator, a plasma focus, or a Z pinch. The prototype for current PCI may be provided by the devices used by A. A. Plutto in examining the formation of high-power electron beams and collective ion acceleration. All these devices show an anomalous increase in resistance in the current-bearing plasma due to various instabilities [15].

The [16] model is the most popular of the analytic models for PCI, which explains the operation via the successive occurrence of four phases: conduction, erosion, accentuated erosion, and magnetic insulation. This is well confirmed for PCI with $n \approx 10^{13}$ cm^{-3}. For larger n, an idea due to Weber [8] and afterwards extended in [17] is more fruitful, on which the current interruption arises from plasma displacement by the hydrodynamic forces through a distance equal to the initial switch length. The experimental results agree well with the consequences of this [17]. For example, it implies $I_s^0 \sim n^{0.25}$, which in turn explains the increased leak in PCI as I_s^0 increases as due to increase in the number of ions ($\propto$n), which cannot be contained by the azimuthal magnetic field [17].

Developments in plasma interruptors have reached a state where they can be used in pulse generators providing terawatt levels. Further progress is largely held up by the lack of clear understanding of the operating mechanism.

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PROPERTIES OF A GAS DISCHARGE IN THE FIELD OF AN INTENSE SOUND WAVE

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The influence of a sound wave on the parameters of a gas discharge is investigated. The behavior of the electric field, the gas temperature in the discharge, and the electron temperature and density in the field of a sound wave is clarified. Modulation of the discharge current and electron density and temperature by a sound wave and the phase shift between oscillations of different plasma components are investigated, as well as modulation of the discharge current by a sound wave in a nitrogen discharge. The influence of sound on the contraction of a nitrogen discharge is also revealed.

In the propagation of acoustic waves in a plasma, changes can occur both in the plasma parameters and in the acoustic waves themselves. Two papers were published in 1965 that defined the beginning of the development of these two fields of research. The possibility of sound amplification in a plasma, associated with nonuniform volume heat release in the interaction of electrons with heavy particles in a stratified nonequilibrium plasma, was shown in [1]. In [2] it was established experimentally that stratification of the positive column occurs under the influence of an acoustic wave set up along a discharge.

The first experimental studies of sound amplification in a plasma were described in [3]. A traveling wave was excited in a discharge tube 4 cm in diameter in helium, neon, and argon at a pressure 4 torr and a sound frequency 7.1 kHz. It was found that the amplification ratio increases with increasing current. In [4] sound amplification ratios were measured on similar equipment in an argon discharge with the same parameters but in a somewhat different frequency range (1-2.3 kHz) and at pressures from 1 to 100 torr. The amplification ratios in the two series of measurements [3, 4] coincided, but there was one difference. In [3] a difference was observed between the sound amplification ratio α measured with sound propagating with and against the direction of electron drift. Measurements were made in the current range 10-100 mA. A difference in a developed at a current higher than 60 mA; α increased with increasing current, and at 100 mA the amplification ratio was 50% higher for sound propagation in the direction of electron drift than for the opposite direction. In [4] those graphic dependences coincided

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