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SOVIET RESEARCH AND DEVELOPMENT OF
HIGH-POWER GAP SWITCHES

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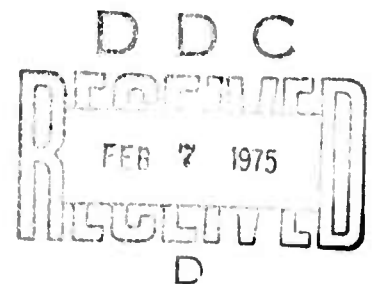
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Simon Kassel and Charles D. Hendricks



A Report prepared for
DEFENSE ADVANCED RESEARCH PROJECTS AGENCY



PREFACE

This Report has been prepared in the course of a continuing study of Soviet research and development of high-current relativistic charged-particle beams. The study is part of a program, sponsored by the Defense Advanced Research Projects Agency, which provides for a comparative analysis of selected areas of Soviet R&D as reflected in technical reports published in the USSR.

The material in the present Report deals with Soviet work on the triggered pressurized gap switch, considered by Soviet specialists to be the most critical element of the high-current electron-accelerator design. Specialized Soviet technical journals have been publishing information on the subject during the last ten years; the majority of reports appeared from 1969 to 1971. Other switching devices, primarily based on vacuum or low-pressure configurations, are not considered suitable to ultrahigh-current work and are not treated in this Report.

It is hoped that this analysis will be useful to American researchers active in government-sponsored programs involving high-current particle beams.

SUMMARY

The Tomsk Polytechnical Institute and the Institute of Atmospheric Optics of the Siberian Department of the Academy of Sciences, USSR, have been engaged in the comprehensive research and development of high-pressure gap switches for high-current electron accelerators. The work involves the establishment of broad theoretical foundations for the understanding of the physical phenomena associated with the structure and operation of gap switches, specification of the optimum operating characteristics, such as current rise time of a fraction of a nanosecond, and construction of prototypes.

The theory based on the avalanche-breakdown principle specifies alternate modes of discharge behavior depending on the quantity of initiating electrons, applied field, gap width, and gap pressure. Discharges with a large number of initiating electrons produce the same effect as multiple parallel gaps in minimizing gap inductance, which is further reduced by the application of ceramic dielectric to the electrodes. In this manner, it is possible to produce pulses as short as 0.2 nanosecond at 3 kA. The pulse-triggering technique involving discharge initiation by a fast-electron beam with a 3-nanosecond pulse front and a large cross-sectional area also minimizes inductance.

Triggered gap structures incorporating BaTiO_3 ceramics were built; these are capable of delivering pulses ranging in length down to 0.6 nanosecond and of maintaining pulse repetition frequencies of the order of kHz for peak currents in the kA range.

Multielectrode air-spark gaps for accelerator power sources have also been developed for 100-kA currents with a jitter of less than 5 nanoseconds and without the necessity to adjust gap length.

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I. INTRODUCTION

Research and development of high-current electron accelerators in the Soviet Union during the past decade has been a subject of major interest among a number of organizations under the direction of the Academy of Sciences, USSR. In general, this activity can be regarded as part of the current worldwide interest in the physics of high energy densities as manifested in the intensive evolution of, for example, the laser. High-current electron beams, as an alternative to laser beams to achieve high energy density, have not yet received the same degree of attention. One reason for this is the fact that the development of laser devices has been stimulated mainly by the broad range of possible technological and defense applications, while particle accelerators generally have been thought of as limited, for the most part, to research in the nature of matter. Only relatively recently has the technology of producing high-current electron beams begun to be developed on a modest scale in the United States and a few other countries.

Soviet technical literature indicates that the parallel effort in this direction for some time has been more intensive in the USSR than in the West. Characteristically, as has been the case with lasers, the Soviet development of high-current particle beams is motivated by the expected rewards of direct technological applications in a number of key areas that have been spelled out explicitly on several occasions in the Soviet press. Two specific targets of particle-beam development stand out as problems of principal concern to nearly all the participants in the Soviet effort.

The first is the application of electron beams to achieve controlled thermonuclear fusion. In this role, the electron beam is viewed as a direct alternative to laser beams in delivering a large amount of energy concentrated in a small volume within a short time interval. The inferior focus of the electron beam, as compared to the laser, is thought to be compensated for by the higher deliverable energy flow.

The second main target of the Soviet effort is the possibility of collective acceleration of intense beams of ions or protons produced by the interaction between the electron beam and plasmas. Collective acceleration, as a target of research, thus does not represent a direct technological application of high-current electron beams. However, the high specific energy gain achieved by the electron-beam-to-proton-beam conversion, as well as the different propagation characteristics expected of proton beams as the principal energy carriers, lead Soviet scientists to believe that a virtual technological revolution may be brought about by their successful development.

One of the principal prerequisites to the attainment of both of the above R&D objectives is the capability of a fast turn-on of the beam. This depends directly on a minimized inductance of the entire accelerator system and, particularly, of the triggered gap switch in the energy storage line. The development of an advanced low-inductance nanosecond gap switch, along with comprehensive research of the underlying physical phenomena based on the electron avalanche breakdown theory, has been concentrated in Tomsk, where the Tomsk Polytechnical Institute and the Institute of Atmospheric Optics of the Siberian Department of the Academy of Sciences, USSR, have assembled a team of scientists devoted specifically to this purpose.

The Tomsk research complex is part of a larger national effort to develop and study high-current electron beams, an effort involving several leading institutes in Moscow, Novosibirsk, and elsewhere. A general overview describing the aims of and organizations involved in this effort was given by one of the authors of this Report in a recent briefing on high-current beam-plasma interactions. The present Report on gap switches, part of the Rand follow-on program designed to study in detail the key phases of the Soviet effort, deals specifically with triggered gap research at the Tomsk complex and its applications in actual accelerators developed by the same research teams.

An analysis of the Soviet literature describing research on high-current short-pulse electron beams indicates that the overall Soviet work in the field is well-organized and comprehensive. Furthermore,

in terms of quantity, the literature itself appears to have shown a true exponential growth rate (see Fig. 1) since 1961. At that time

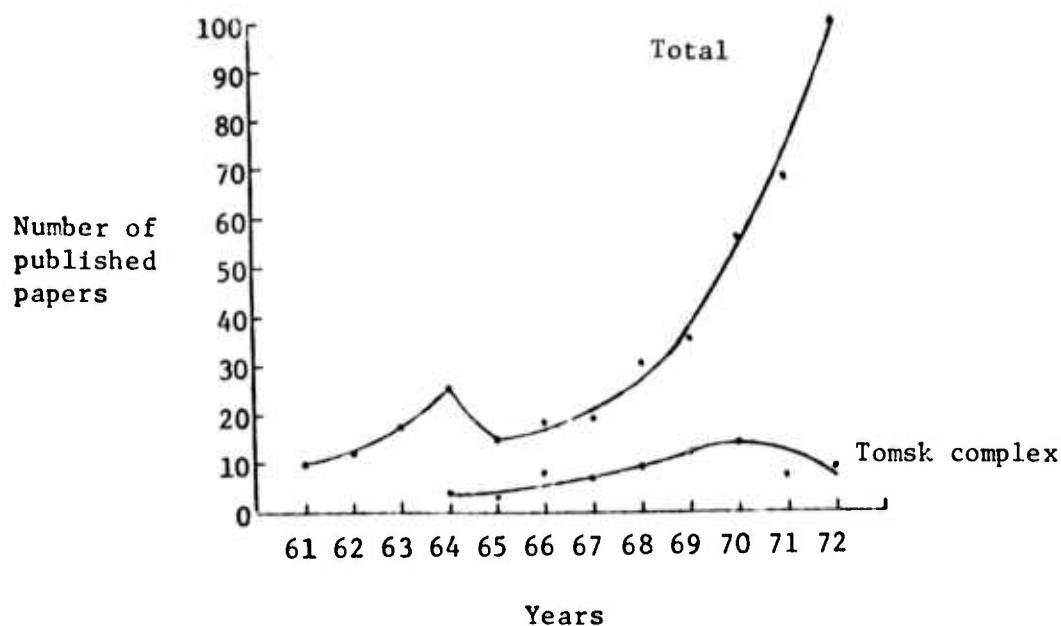


Fig. 1 -- Growth of Soviet publications on high-current particle beam research

about ten research papers were published annually; in 1972 the number approached one hundred. This growth rate becomes significant when it is compared with the overall growth rate of Soviet publications in science and technology, which is much lower and is probably slowing down.

The Tomsk effort, judging from the publication growth rate, initially paralleled the growth rate for all high-current particle beam research. It appears, however, to have peaked around 1970, when a large portion of the Tomsk research, according to the institutional by-lines of the published papers, was transferred to the Institute of Atmospheric Optics (discussed in the next section). The period after 1970 was marked by the publication of general reviews of past research. One possible inference to be drawn from these circumstances is that the research phase has been completed at the Tomsk complex and is being followed by the next stage of the RDT&E cycle, that of development.

II. THE NATURE AND APPLICATIONS OF HIGH-PRESSURE GAP SWITCHES

The research and development work on high-pressure gap switches at the Tomsk complex is under the direction of G. A. Mesyats, Deputy Director of the Institute of Atmospheric Optics, Siberian Department, Academy of Sciences, USSR, and head of its Department of Electronics. Mesyats, who holds the degree of Doctor of Technical Sciences, is a specialist in pulse technology, emission electronics, and electrical discharges in gas and vacuum; his general interests include the entire complex of problems relating to both the design and applications of linear pulse accelerators in the MeV, kA-MA range.

Working closely with Mesyats is a group of associates at his institute and at the Tomsk Polytechnical Institute, long known for its interest in high-current electron accelerators. The work of the Mesyats group has been remarkable in several aspects: The steady level of concentrated effort on high-voltage, high-current gap switches maintained for at least the past seven years, its systematic inquiry into all the known phenomenological and theoretical aspects of the problem, and the uniqueness of its research purpose have made this group one of the foremost research teams in the world currently active in this area.

The group has published research reports on most of the major elements of high-current electron-beam accelerators, including the design and construction of entire accelerators. Two areas of investigation emerge as the focal point of its activity: the high-pressure gap work described here and the research on plasma-emission and multiple-needle explosive-emission cathodes for high-current accelerators presented in an earlier paper.* The group thus appears to have developed a specific specialization in the area of nanosecond electrical discharges in pressurized and vacuum environments. *Mesyats believes that the pressurized triggered nanosecond gap switch represents the most*

* Simon Kassel and Charles D. Hendricks, *Soviet Development of Needle-Tip Field-Emission Cathodes for High-Current Electron Beams*, The Rand Corporation, R-1311-ARPA, August 1973.

important research problem in the design of high-current electron accelerators [1]. Indeed, the majority of research reports published by Mesyats and his group during the past several years were devoted to a wide-ranging and comprehensive study of this problem.

Triggered nanosecond gaps for many high-power applications, such as charged-particle accelerators, must meet a number of technical requirements. Mesyats specifies the most important of these as follows:

1. Rise time of 10^{-9} seconds or less (rise time is usually defined as the time of pulse rise from 10 percent to 90 percent of its peak current or voltage values)
2. Wide usable range of operating voltages (i.e., applied gap voltages)
3. Good stability (low jitter) of formative time lag (interval between the trigger and the gap operation)
4. Ability to operate with low amplitude of trigger pulse
5. Ability to handle high power

The standard switching devices normally used in high-current accelerators fail to satisfy all of these requirements. The Soviet authors give as one of the reasons for the development of gap switches their opinion that hydrogen thyratrons are not capable of providing pulse rise times shorter than tens of nanoseconds. U.S. experience indicates that hydrogen thyratrons are capable of producing current rise times of a few nanoseconds, but cannot carry large currents and have limited pulse repetition rates. While conventional pressurized spark gaps can yield a pulse rise as short as 10^{-10} seconds, their operating pressure (10 atmospheres or over of nitrogen, hydrogen, argon, etc.) makes their construction difficult and increases the required trigger pulse amplitude, which sometimes comes close to that of the main gap voltage. These switches also have a poor formative time lag stability (jitter), which can be improved by exposing the cathode to ultraviolet light; this further compounds the design difficulty by requiring a special illumination source. Pressurized spark gaps, moreover, have a narrow range of operating voltages. For example, in three-electrode

gaps, $U_{\max}/U_{\min} < 2$, a condition that requires a series connection of many gaps to increase the voltage range. Finally, high-voltage triggered switches may produce an undesirable direct electrical contact between the trigger circuit and the storage line [2].

Since high currents are passed through the switch in the "closed" state, the switch resistance, together with the resistance of the beam-forming diode, determines to a large extent the fraction of the energy of the main supply that is not available to accelerate the electron beam. That is, the switch is a lossy element in series with the main current circuit and gives rise to losses of the order of $I^2 R_s$ where R_s is the switch resistance and I is the current through the switch. The $I^2 R$ losses are essentially a waste and represent a loss of energy from the electron beam.

Switch inductance is another major property of the switch that affects the electron beam. The rise time of the voltage pulse at the beam-forming diode is directly proportional to the dynamic (i.e., in operation) inductance of the switch. To achieve short rise times, the effective switch inductance must be made as small as possible. This may be accomplished by using multichannel spark gaps or by placing many gaps in parallel and synchronously switching a number of energy sources to the load through the several gaps. In the multigap system, the gaps must be switched with as little jitter as possible for maximum effectiveness in reducing inductive effects and to obtain the best rise time possible. It is, of course, obvious that the impedance of other elements in the system will be as important as the gap impedance in determining pulse power levels and rise times. Thorough understanding of the discharge processes that take place in the gap switch is therefore essential to the successful design of high-performance machines to provide levels of beam energy and power that have not yet been reached.

No U.S. program of research and development of these devices appears to be as coordinated in the treatment of theory and experiment as the work of the Mesyats group. U.S. research is being done in various laboratories, including Sandia, the Air Force Weapons Research Laboratory (AWFL) at Kirtland, Ion Physics Corporation, AFCRL at Bedford,

Maxwell Laboratories, Physics International, and Field Emission Corporation. Moriarty et al. described research on laser-triggered gaps operating in the 1-3 MV range with jitter times of about 1.5 nanoseconds and rise or delay times (formative times) of 2-5 nanoseconds [3]. Pressures in the spark gaps were 10 or 20 atmospheres of various mixtures of nitrogen, argon, and sulfur hexafluoride.

Guenther, at AFWL, has been studying laser-triggered switches designed to control megavolt multikiloampere powers. He has obtained rise times as short as 2-5 nsec and jitter as low as 0.1 nsec and has indicated that rise times could be shortened even further by the use of parallel gaps or parallel channels initiated in the same gap [4]. This is possible (1) because of the low jitter provided by the laser-triggered switches and (2) because optical synchronization of more than one gap or channel can be accomplished comparatively easily.

III. THE MESYATS THEORY OF OVERVOLTED GAPS

The distinguishing characteristics of overvolted gaps are the pulse length and pulse rise times in the nanosecond or subnanosecond range. These pulses are associated with high field intensities of the order of 10^5 V/cm and higher in the gap. Under these conditions, the formative time is commensurate with the duration of such elementary processes as avalanche growth to critical size and relaxation of excited molecules. These factors impose a special characteristic upon the breakdown in terms of the spatial structure of the discharge, formative time lag, its statistics, etc. Under gas pressures of an atmosphere or higher, such a breakdown may proceed without a spark channel (i.e., a pinched discharge channel), even if the current reaches 10^5 A. Thus, it may be possible to avoid the formation of spark channels in the discharge plasma, or to promote many simultaneous parallel channels, either solution tending to minimize the dynamic inductance of the gap. The model of the discharge developed here is based on the concept of electron avalanches started by initiating electrons or an electron beam injected into the gap.

The multiplication of electrons and ions in an avalanche follows an exponential law until the number of electrons in the head of the avalanche reaches a critical value. That value is reached when the space charge field of the particles equals the applied electric field. The nature of the discharge thus depends on the ability of the avalanche to accumulate the critical number of electrons before it reaches the anode. If it is unable to do so, secondary avalanches are required to complete the discharge, which is then called a Townsend discharge. If the primary avalanche becomes critical before reaching the anode, it is transferred into a streamer and then into a discharge channel, and is called a streamer discharge.

To complete the streamer discharge the avalanche also must emit a sufficient quantity of photons capable of ionizing gas molecules near the avalanche head. The photons are emitted by the avalanche as a result of the relaxation of excited gas molecules, whose average

lifetime is between 10^{-9} and 10^{-8} sec. Therefore, the time required for the avalanche to become critical must be shorter than its time of flight to the anode, but longer than the lifetime of the excited molecules. For applied fields larger than 60 kV/cm, however, the critical time is shorter, and consequently, the discharge deviates from the streamer model. This deviation was observed repeatedly by Mesyat's group [5-10], which developed its own model of the behavior of nanosecond discharges in air at atmospheric and higher pressure and $E > 10^5$ V/cm, when the critical time is much shorter than the time of flight across the gap width and shorter than the lifetime of excited molecules.

The development of the pulsed discharge depends also on the current of electrons initiating the discharge and its uniformity over the surface of the cathode. In this case, the parameters to be compared are the critical time and the average time between the appearance of two successive initiating electrons from the cathode. If the latter is longer than the critical time, we have a single-electron initiation. If the critical time is much longer than the interval between two initiating electrons, a case of multiple-electron initiation obtains; then secondary processes play a smaller role in the rising current stage and the initiating electron current tends to be uniformly distributed over the cathode. Multiple-electron initiation avoids the problem of jitter, long rise times, and excessive inductance effects resulting from non-simultaneous development of multiple channels for the gap closure.

A further element affecting the pulsed discharge is the applied electric field intensity. If the average applied field is higher than 10^5 V/cm, the effects of microscopic projections on the surface of the cathode, which can increase the field by a factor of one hundred and more, become significant. Field enhancement at the microtips results in the emission of electrons from local spots on the cathode and sometimes an explosion of the projections. The applied electric field also affects photon emission from the avalanche of critical size by means of the following mechanism: The critical number of electrons in an avalanche is proportional to the electron temperature and inversely proportional to the Townsend ionization coefficient [10]. Since the

coefficient rises faster than the temperature as the field increases, the critical number of electrons in an avalanche decreases with the increasing field. This effect, in conjunction with the effect of the short critical time on the production of photons, causes a sharp drop in the photon yield from an avalanche at high applied fields.

Each of these dependencies was studied in considerable detail by the Mesyats group. Specifically, for the condition of $E \geq 10^5$ V/cm, the discharge mechanism was studied as a function of the number N_0 of initiating electrons, gap width d , applied field E , or the ratio of E/p , where p is gas pressure in the gap, and other factors.

IV. THE NUMBER OF INITIATING ELECTRONS

The effect of the initiating electrons is considered for two cases of the Mesyats model: low N_0 , which is usually taken as $N_0 \sim 1$ and designated as the single-electron initiation case, and high N_0 , where $N_0 \sim 10^4$, representing the case of multiple-electron initiation.

An early model of the nanosecond discharge by R. C. Fletcher [11] postulated a single-electron-initiated-avalanche-breakdown mechanism, equivalent to the streamer model, for the breakdown of 1-mm air gaps by 10^5 V/cm nanosecond pulses. Fletcher based the validity of his model on the fact that the formative time τ computed from the streamer theory agreed with his experimental data. Soviet evaluation of Fletcher's data, however, showed that his results were obtained with at least 10^4 initiating electrons [5, 12].

Mesyats's evaluation [6] showed furthermore that, if the breakdown is indeed initiated by a single electron, τ is one or two orders longer than Fletcher's figure. Other factors arguing against the single-avalanche streamer model are derived (1) from the behavior of gaps with a dielectric barrier (see below) where a streamer does not form and (2) from direct detailed observation of the discharge structure. In a series of comprehensive experiments [6, 7], the Mesyats group showed that the formative time of a discharge significantly depends on the number of initiating electrons. Their self-consistent model of the discharge is based on the development of avalanches initiated by free electrons in the gap.

The assumption about the large number of developing avalanches leads to the correct computation of the current rise time according to Fletcher's formula. The difference between single-electron and multiple-electron initiation is based on a comparison of the formative time of an avalanche with the average time interval separating two successive initiating electrons. If i_0 is the current of electrons from the cathode,

$$i_0 \gg \frac{eav_-}{\ln N_{cr}} \quad \text{for multiple-electron initiation}$$

and

$$i_0 < \frac{e\alpha v_-}{\ln N_{cr}} \quad \text{for single-electron initiation}$$

where e is the charge of an electron, α is the Townsend ionization coefficient, v_- is the drift velocity of electrons, and N_{cr} is the number of electrons in an avalanche reached in time t_{cr} , or over path length x_{cr} .

The formative time lag consists of

$$t_g = \sigma(i_0) + \tau,$$

where σ is the statistical component determined by the time required for the effective initiating electron to appear and τ is the time required for the formation of the discharge and does not depend on the electron current from the cathode.

A. THE CASE OF SINGLE-ELECTRON INITIATION

Mesyats and his group were the first to introduce the concept of single- and multiple-electron initiation of the discharge [12] and to show that the stage of the fast current rise, just as the stage of discharge formation, can be attributed to the development of electron avalanches and to the change in voltage due to the presence of resistance in the discharge circuit [13].

A number of different source mechanisms produce the initiating electrons. According to Mesyats's theory, in pure field emission a current of 10^{-10} A, for which σ is of the order of 10^{-9} sec, requires an electric field intensity of about 2×10^7 V/cm for 1 cm^2 of tungsten cathode surface. However, experimental data show that in vacuum gaps there are initial electron currents of 10^{-5} to 10^{-3} A for field intensities of 10^5 to 10^6 V/cm. This is attributed to microprojections on the surface of the electrode whose field intensity considerably exceeds the average microscopic field determined by theory for flat electrodes.

There is direct proof that the surface of the cathode affects the formative lag time and the electric strength of the gap in nanosecond

pulse breakdown [5]. It was found that thorough mechanical polishing of the cathode can bring the electric strength of a one millimeter gap to 1.4×10^6 V/cm for a formative lag of the order of one nanosecond. For 40 nanosecond pulses and air gaps .2 mm wide using single-crystal cathodes, the breakdown field intensity reached 3×10^6 V/cm, while in polycrystalline cathodes it did not exceed 1.3×10^6 V/cm.

As it was pointed out above, t_d was found to be longer by a few orders of magnitude in single-electron than in multiple-electron initiation. This is logically explained by the longer process of accumulating electrons in the gap [12, 13]. Mesyats suggested that the current rise in the gap in the initial stage of the discharge is due to avalanche chains [10]. Such a chain can be formed by the expulsion of some electrons from the preceding avalanche and the formation of the next avalanche, or by photoionization of gas ahead of the avalanche. Thus, the inhibition of the avalanche development due to the ionic space charge occurs when the ionic field becomes equal to the applied field; at that point the electron head separates from the avalanche and forms a new avalanche ahead of the preceding one. The new avalanche expels a new head of electrons, etc. Only electrons with a velocity greater than v_* are expelled. The chains of avalanches formed in this manner appear as fine, weakly luminescent channels just before the voltage drop across the gap [8, 10].

An attempt was made to compute the growth rate of the number of electrons in the avalanche [14]. Since it is impossible to do this for air at the given E and p because the avalanche develops in less than 10^{-9} sec, experimental data for avalanches in ether vapor were used and calculated by M-20 computer. The authors claimed that this approach was unprecedented in the literature. The ether vapor model was then recalculated for the case of a single avalanche in air, with $p = 760$ torr and $E = 10^5$ V/cm.

It was found that the avalanche developed to 10^8 electrons in 0.6 nsec. The avalanche front velocity was 1.5 times the drift velocity. It was found also that the average formative discharge time rose sharply with the number of preliminary discharges in the case of copper and tungsten electrodes. It appeared to Mesyats that this was due to deterioration

of the photoemissive properties of the cathode. This testifies to the significant role played by the photoelectric effect in the secondary process.

In single-electron initiation the steep portion of the current slope is similar to that obtained in multiple-electron initiation (discussed in Section B below). The slope, however, flattens out at a much higher level. Thus, while the formative lag in single-electron initiation is longer, the switching time, i.e., the time required for the gap to change from a nonconducting to a conducting state, is a fraction of the formative time lag. The conductivity in such a case is attributed to the formation of narrow diffuse channels 0.2 cm in diameter, observed 1-2 nsec after the fast voltage drop across the gap. The channels have a high electron density that reaches 10^{17} cm^{-3} . At that point, most of the energy acquired by the electrons from the field is lost to collisional excitation. The origin of the channels is attributed to the special features of the single-electron initiation process in which there is weak or no ultraviolet irradiation of the cathode and initiating electrons are more intensively emitted from a few points on the cathode. The channels are due to the development of avalanches, and their diameter, two orders larger than that of the streamer discharge channels, is due to the fact that in strong applied fields the initial avalanches reach larger sizes at short distances from the cathode, causing intense photoemission from the cathode regions directly beneath the avalanches [15].

B. THE CASE OF MULTIPLE-ELECTRON INITIATION

The multiple-electron-initiation case assumes that the main process of the discharge is collisional ionization from the ground state. For the condition of $E = 10^5 \text{ V/cm}$ and $p = 760 \text{ torr}$, 10^4 initial avalanches are sufficient for the formative lag to equal t_{cr} , and σ plays no role in the process. The formation of the avalanches is not inhibited by the ionic space charge. The steep current slope flattens out because of a drop due to circuit resistance, in the electric field across the gap, and this drop sharply reduces the Townsend ionization coefficient α . The initial voltage drop occurs across a plasma channel 0.9 cm in

diameter without individual internal conducting channels being formed. At the end of the fast voltage drop, the electron density is 10^{14} to 10^{15} cm^{-3} and the electron temperature $T_e = 2$ to 2.5 eV [15].

The characteristic feature of the multiple-electron-initiated discharge is the diffuse glow that appears in the first nanosecond after the application of the voltage pulse. The glow increases sharply in the fast-voltage-drop stage and remains uniformly distributed in the gap volume even after the current reaches hundreds of amperes.

The multiple-electron-initiated-avalanche-switching theory is applicable not only to overvolted gaps, but also to the case of discharge due to static breakdown voltage and below. The main condition is to provide a current of initiating electrons such that, when electron multiplication reaches 10^8 , the discharge current in the circuit is sufficient to begin the voltage drop across the gap. If the initiating electrons are distributed over the surface of the cathode, the switching stage is due to gas ionization without the formation of localized spark channels. For example, if the initiating electron current is 10^{-7} A , i.e., for $N_0 = 10^5$ and electron multiplication of 10^8 , the current in the circuit reaches 10 A . If we consider that, during the time the avalanche takes to reach 10^8 electrons the photoelectric effect causes additional electrons to arrive from the cathode, it becomes obvious that the total discharge current will considerably exceed 10 A .

Such a discharge results when an intense ultraviolet flash used for initiation produces a large number of electrons due to the photoeffect. It was shown that as voltage across the gap approached the static breakdown value, the time between the uv flash and the breakdown approached the flight time of the avalanche across the gap.

To minimize the inductance in the gap for the purpose of generating nanosecond and subnanosecond pulses, Mesyats proposed to coat the electrodes with high-permittivity dielectric [16]. The formation of a fine channel in the gap during discharge is the reason that circuit inductance cannot be brought down much below 10^{-9} to 10^{-8} henry, even if a large number of parallel-connected gaps is used. Under these conditions, it is difficult to achieve pulses shorter than 10^{-8} sec . The proposed solution that, according to Mesyats, would

permit the generation of pulses as short as 10^{-10} sec in currents above 10^2 A consists in simultaneously starting a large number of electron avalanches in one gas-filled gap, instead of using a large number of gaps in parallel.

If the circuit inductance is neglected, the theoretical lower limit for pulse length is 10^{-10} sec and the upper current limit is 4×10^3 A for $U_0 = 4$ kV and $C = 1.5 \times 10^{-10}$ f (gap capacitance). To test this theory, a triggered gap was built with a BaTiO_3 ceramic dielectric placed on the surface of the electrodes. The parameters of the gap were as follows: capacitance -- 1.5×10^{-10} f, gap width -- 0.3 mm, air pressure -- 1 atm, relative dielectric permittivity -- 80, voltage pulse -- 4 kV, and gap diameter -- 34 mm. The test results gave a peak current of 3 kA and a pulse length of 2×10^{-10} sec, values that are close to the theoretical limit [16].

The initiating electrons are produced by an ultraviolet flash from the discharge on the dielectric surface in the anode region. Because of the high permittivity of BaTiO_3 , the entire starting voltage falls on the microgaps between the ceramic and electrode surfaces and causes their breakdown. These microgaps are always present because of the imperfect contact between the dielectric and metal. The breakdown is formed over a large area of the ceramic in a time interval not exceeding 0.5 nsec [17].

The use of the dielectric thus produces the necessary number of initiating electrons at the cathode at the time voltage is applied to the gap, avoids the localization of spark channels so that the current flow channel has cross-sectional area equal to that occupied by the initiating electrons at the cathode, prevents strong electrode erosion, and allows for high pulse-repetition rates.

V THE EFFECT OF THE GAP WIDTH

Another major factor -- in addition to the number of initiating electrons -- controlling the behavior of high-energy nanosecond discharge in air is the gap width, d . A series of experiments indicated that for $E \approx 10^5$ V/cm and $p = 760$ torr the formative lag t_l , defined as the time from the application of voltage to the onset of fast current rise, showed a complex dependence on d [18]. Three distinct regions of this dependence were revealed on the basis of up to 1000 oscillograms taken from each region:

1. Slow variation of t_l for $2.9 < d < 11$ mm
2. Region of inflection for $2.6 < d < 2.9$ mm
3. Region of very fast increase in t_l for $d < 2.6$ mm

Thus, the formative lag strongly depends on d below 2.5 mm and is practically independent of it above 3 mm, provided $x_{cr} \ll d$. Higher electric fields push the d -dependence region toward narrower gaps.

Based on these results, luminosity observation experiments were used to study the d -dependence in greater detail for two cases of regions 1 and 3 [9]. For $E = 80$ kV/cm and $p = 760$ torr, a weak dependence gap of 4 mm and a strong dependence gap of 2 mm were used. For the given E/p , $x_{cr} \approx 0.4$ mm, so that the condition $x_{cr} \ll d$ was satisfied. It was found that $t_l \approx 0.5$ nsec for $d = 4$ mm and that $t_l \approx 100$ nsec for $d = 2$ mm.

These results are interpreted by introducing the concept of a critical gap width d_{cr} for the case of single-electron initiation. This is the gap length for which the number of developing avalanches reaches 10^4 by the time the first avalanche reaches the anode. If $d > d_{cr}$, the formative lag time should be sufficient to form 10^4 avalanches. Therefore, the formative lag time should be independent of d for $d > d_{cr}$; this was observed experimentally in [18]. If $d < d_{cr}$, the early avalanches close the gap before 10^4 avalanches are formed; this should increase t_l as a result of the redistribution of E in the

gap after it is filled with plasma. E becomes higher near the electrodes and lower in the middle, decreasing the growth rate of photons and charged particles and thus increasing t_λ .

Within this model, for $d > d_{cr}$, and considering that the main secondary process is the photoelectric effect at the cathode, the formation of a large number of avalanches occurs in a time comparable to the lifetime of excited molecules. For nitrogen molecules this is 4 nsec, which is close to minimum t_λ of a few nsec as determined in [12].

VI. THE EFFECT OF VERY HIGH ELECTRIC FIELDS

A number of new phenomena appear when the applied voltage across the gap exceeds 10^5 V/cm. At high E/p the energy lost by an electron in collisions is less than the energy acquired by it from the field. This results in a progressive acceleration of electrons, which become runaway electrons from the avalanche and generate X-rays at the anode. This process is particularly important in atmospheric breakdown at $E > 10^6$ V/cm.

Applied electric fields above 10^5 V/cm in gaps filled with atmospheric gases can cause the explosion of the cathode microtips and the explosive emission of electrons characteristic of vacuum breakdown. This type of discharge has not yet been studied in detail. Experiments performed in this range of applied field dealt with single-electron initiation [6] in narrow air gaps of 0.2 to 0.7 mm, pulse front of 2.5×10^{-10} sec, and $E = 1.4 \times 10^6$ V/cm. Extended formative lag was noted due to the statistical lag σ .

VII. THE INITIATION OF DISCHARGES BY A FAST-ELECTRON BEAM

Discharge initiation in high-pressure gas by a beam of fast electrons injected into the gap to prevent the formation of a spark channel is of particular importance. The main purpose of this method is the achievement of a large number of initiating electrons, uniformly distributed over the cathode surface or within the volume of the gap. In this case, breakdown can be obtained at gas pressures reaching tens of atmospheres, even when the gap voltage is significantly lower than the static breakdown voltage [16].

Discharges free of channels were obtained in gaps pressurized with nitrogen at 16 atm for $E > 10^5$ V/cm [19]. In the experiments, the cathode of the accelerator producing the initiating electron beam was positioned directly in front of the high-pressure gap. The parameters of the initiating electron beams were:

maximum energy	350 keV
current	2000 A
pulse length	10^{-8} sec
pulse front.	3×10^{-9} sec
beam aperture	20 cm^2

Experiments were performed to study the feasibility of various practical applications of the gap switch. In one series of experiments, the initiating electron beam was used to operate the gap in the 1-MV range. For a nitrogen pressure of 7 atm, the maximum current in a discharge free of channels was 40 kA at 700 kV. The energy dissipated in the gap was 10 J/cm^3 .

In another series of experiments, to maximize the plasma-filled volume of the gap, its electrode dimensions were made $40 \times 1 \text{ cm}^2$. The gap was discharged from a stripline. The initiating beam was injected through a thin foil anode that formed the cathode of the main gap, and the initiating accelerator cathode needle tips were arrayed along the entire 40-cm length of the gap cathode. The injected beam current was

1000 A at 400 keV. For a gap width of 1 cm, gas pressure up to 6 atm (CO_2 or O_2), and stripline voltage of 70 kV, the discharge extended over the entire gas volume without the formation of channels [19].

A channel discharge is also possible with electron beam initiation. Thus a spark channel can be made to appear in 10^{-9} sec by suitable adjustment of E/r . Several channels in parallel can be achieved in the same gap, significantly decreasing the gap inductance.

VIII. STRUCTURAL DETAILS

A. TRIGGERED-GAP DESIGN

The operation of triggered gaps with dielectric-coated electrodes is illustrated in the case of a nanosecond-pulse current generator built by the Mesyats group in 1967 as a power supply for semiconductor lasers [17]. The generator produces 1-kA pulses, with a 0.4-nsec rise time, for a charging voltage of 2 to 8 kV. The triggered gap is shown in Fig. 2, where 3 and 5 are the operating electrodes of the gap.

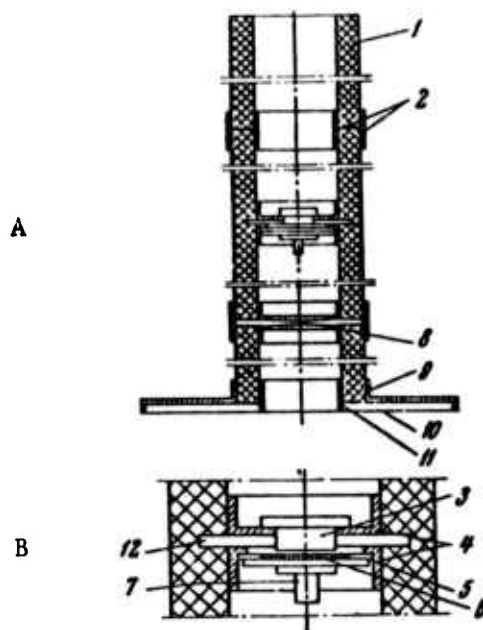


Fig. 2 -- Nanosecond-pulse current generator

A. Generator structure

B. Triggered gap

1 -- line section; 2 -- coupling; 3 and 5 -- electrodes; 4, 9, and 11 -- contacts; 6 -- barium titanate disc; 7 -- trigger electrode; 8 -- diode; 10 -- resistor; 12 -- insulating gap

Electrode 3 is made of molybdenum, and electrode 5 is molybdenum foil 150 μ thick with 0.4- to 0.5-mm holes distributed over the entire area under electrode 3. Disc 6, which is BaTiO_3 , is mounted between 5 and trigger electrode 7. The BaTiO_3 disc face on the side of electrode 7 is coated with silver, the coating extending over the entire surface area occupied by electrode 7. A constant gap of 100 to 150 μ is maintained between electrodes 5 and 3. Parts 3, 5, 6, and 7 are pressed by springs, coaxial with the cylinder body of the gap, against contacts 4, which are soldered to the silver coating of the cylinder representing a section of the storage line. Gap 12 provides insulation between contacts 4. The triggered gap is airtight and allows for a smooth variation of gas pressure from 1 to 5 atm.

Due to the high dielectric permittivity of the BaTiO_3 disc, the entire trigger voltage falls on the microgaps between the nonmetallized face of the disc and electrode 5, causing a breakdown. The discharge is found to extend over a large area of the disc in a time interval not exceeding 0.5 nsec. The initiation of microdischarges depends on the amplitude of the trigger voltage and, even with 1 kV, becomes time-stabilized with a jitter not exceeding 0.5 nsec. In this design there is no dielectric surface discharge. The trigger current is merely the displacement current in the system consisting of electrode 7, disc 6, and electrode 5. The behavior, low jitter, and short rise time of this system depends on the number of active microdischarges whose ultraviolet radiation enters the main gap through the holes in electrode 5 and initiates its breakdown. The formative time lag of the main gap current relative to the onset of the microdischarges depends on the overvoltage across the gap and has a minimum value of 1 nsec. The instability (jitter) of the lag (or pulse delay), even for 15- to 20-nsec lags, remains at the level of 0.5 nsec.

The minimum recorded current pulse front was 0.4 nsec. The generator was stable with a pulse repetition frequency of 7 kHz for currents of 500 to 600 A and pulse lengths of 7.5 nsec and less, and with a pulse repetition frequency of 3 kHz for currents of 1 kA and maximum pulse length. The generator can operate for 40 hours without disassembly of

the gap; beyond that electrodes 3 and 5 must be replaced. The total weight of the generator is 30 kg, and its power consumption is 200 W [17].

A further development of the pulse generator based on the BaTiO_3 dielectric is the subnanosecond-current-pulse generator built to produce pulse lengths of 0.6 nsec with smoothly variable current from 50 to 1000 A [20]. The principal feature of the gap is the air space between the BaTiO_3 disc and one of the electrodes. The air space (see Fig. 3) is formed by microprojections on the surfaces of the ceramic and the metal and, with suitable surface treatment, is maintained within 10 to 30 μ . In this design, the discharge develops over the ceramic surface, starting from the microprojections, and its light initiates an avalanche breakdown of the air space.

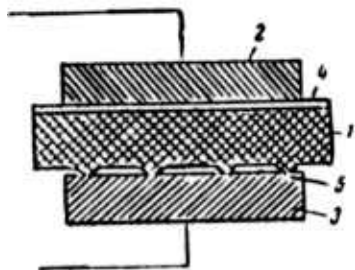


Fig. 3 -- Gap switch

- 1 -- BaTiO_3 disc
- 2 and 3 -- electrodes
- 4 -- silver coating
- 5 -- air space

The pulse repetition frequency is 3×10^4 Hz up to 500 A and 10^4 Hz up to 1 kA. The service life of the gap may reach 200 hours [20].

B. INITIATING-ELECTRON-BEAM ACCELERATOR

The electron beam initiating the discharge in the gap switch discussed in Section VII above was produced by a compact, high-current accelerator also built by the Mesyats group [21]. According to Mesyats, the design was intended for experimentation with electron beams of

10^5 to 10^7 eV, 10^4 to 10^5 A, and 10^{-8} to 10^{-7} sec to be used in such applications as collective acceleration of positive ions, production of high-temperature dense plasma, pulse radiolysis, radiography, etc.

The present accelerator operates at 500 keV, 10^4 A, and a 25-nsec pulse (Fig. 4). It features an open-core pulse transformer and a glycerine-filled coaxial line. The line impedance is $8\ \Omega$; its electrical length is 25 nsec; and the storage line charging time is 0.5 μ sec. A pressurized gas gap is used as the switching element; a plasma cathode (described in detail below) is used to emit electrons for higher currents, about 10^4 A, with a distance of 10 mm between

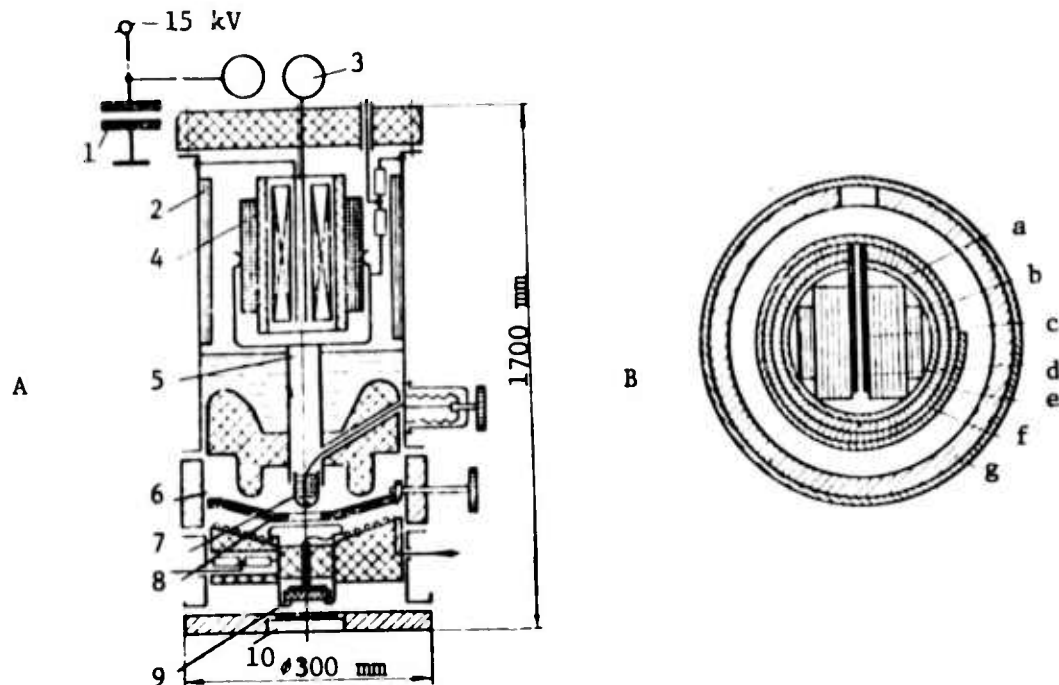


Fig. 4 -- 500-keV, 10^4 -A, 25-nsec accelerator

A. Accelerator structure

1 -- charging capacitor; 2 -- tube; 3 -- spark;
4 -- pulse transformer; 5 -- storage line;
6 -- gap chamber; 7 -- shaping gap; 8 -- cut-off
gap; 9 -- cathode; 10 -- anode

B. Transformer cross-section

a -- body; b, g -- core; c, d -- stripline;
e -- winding; f -- winding insulation

cathode and anode and an operating cathode diameter of 40 mm. For current up to 10^3 A, a needle cathode having 1600 needle tips, with the initial tip radius of 10^{-5} cm, is used. For $E \approx 10^8$ V/cm at the tip, the time delay before tip explosion is ≤ 1 nsec, so that explosion is almost simultaneous in all tips, ensuring uniform emission from a large number of needles.

The simplicity and compactness of this accelerator are primarily the result of using the open-core transformer in conjunction with a glycerine line and a plasma cathode. The matched-load transformer efficiency is 0.8, and the transformer coupling coefficient is 0.9. The stability of current-pulse amplitude at pulse-repetition frequency of 1 Hz is 10 percent. After 10^5 pulses no significant change in electron beam parameters was observed [21].

The plasma cathode developed for this accelerator is a source of pulsed electron current with pulse length of 10 to 100 nsec and amplitude of up to 2000 A [22]. The source is based on the principle of high-field-extraction electrons from discharge plasma in a vacuum. The unique design of the plasma cathode provides a current density of 200 A/cm². The usual plasma sources use either a high-vacuum discharge (vacuum arc) between metal electrodes, or discharges along the surface of a dielectric. The latter method was developed by Mesyats and Bugayev and reported in 1967 [23]. In both methods, electron emission is localized because of the formation of a spark channel.

The properties of electron sources can be drastically improved by a uniform formation of plasma over a large surface area of the cathode, as shown in Fig. 5. The equivalent circuit of this system consists of capacitance C_1 of the surface elements relative to the lower plate, capacitance C_2 of the surface elements relative to the mesh, and capacitance C_3 of the surface elements relative to each other. By varying ϵ of the material, substrate thickness, and pitch of the mesh, one can make C_3 and C_2 much smaller than C_1 . Then practically the entire pulse voltage across electrodes 1 and 3 falls on C_2 and C_3 , causing vacuum breakdown between the surface elements and the mesh and discharges along the surface of the substrate. Since the substrate on the mesh side is not metallized and has a high surface resistivity, discharge channels

IX. MULTIELECTRODE AIR-SPARK GAP

Another development of the Mesyats group of significance to the design of advanced high-current accelerators is the multielectrode triggered air-spark gap [24] for power sources capable of switching 100-kA currents at 50 kV, with jitter time of less than 5 nsec and without adjustment of gap length. The switch assembly (Fig. 6) consists of eight 2-mm gaps formed by an array of parallel cylindrical

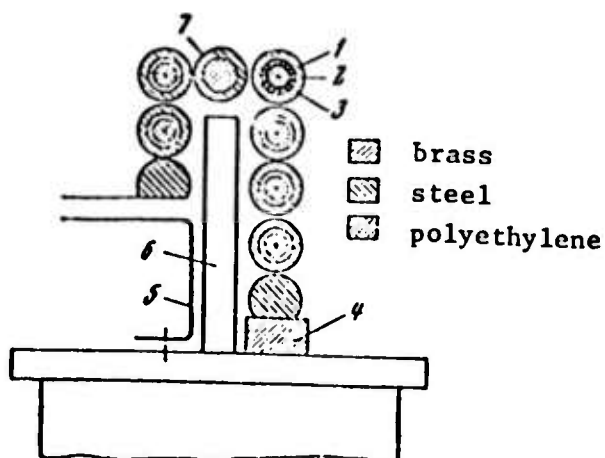


Fig. 6 -- Cross-section of switch in the plane of the discharge path

1 -- brass tube; 2 -- steel electrode; 3 -- coaxial cable without shielding; 4 -- capacitor; 5 -- load; 6 -- insulating mounting stud; 7 -- trigger electrode

electrodes. The steel outer electrode sleeves are 30 mm long and 17 mm in outer diameter. These are slipped over brass tubes 280 mm long and 10 mm in outer diameter. The long brass tubes are used to separate the insulators from the electrode surfaces and to provide the desired capacitance to ground by a polyethylene cable running through the tubes. The tubes are mounted in an inverted-U pattern to minimize inductance. The starting pulse is applied to the trigger electrode situated five gaps away from the capacitor and three gaps away from the load. Nearly

the entire starting voltage appears in the gaps next to the trigger electrode, ensuring a high overvoltage and stable operation. The asymmetry of the tube arrangement with respect to the trigger electrode equalizes breakdown times in the gaps on both sides of the trigger. The end electrodes of the assembly are mounted directly on the capacitor terminals.

The switches demonstrated stable operation with a load of 10^{-9} to 10^{-6} h within a starting voltage range of 8 to 50 kV. The time delay was 80 ± 5 nsec at 8 kV and 15 ± 1 nsec at 50 kV. In service time tests, 1000 discharges raised the minimum voltage to 9 kV. The switch was used in a 500-kV, 1-kA, nanosecond-current-pulse generator with a Tesla transformer as a charging-voltage source; the switch showed a jitter stability of 1 nsec for 10- to 20-nsec pulses with a pulse repetition frequency of 50 Hz. In a later model of the gap switch, the pulse-repetition frequency was improved to 200 Hz by rotating the cylindrical electrodes and cooling them with water [25].

The switch made it possible to design a 40-kJ capacitor bank without isolation elements between the load and the power supply [26]. The capacitor bank was developed by Mesyats in collaboration with the Institute of Automation and Electrometry, Siberian Department, Academy of Sciences, USSR. The low-inductance bank has a wide range of voltages and a short-circuit current of 2.5 MA. Several capacitor banks of this type can be connected in parallel to provide an energy storage of 1 MJ.

X. CONCLUSION

Mesyats and his coworkers have contributed a number of significant advances to the field of megavolt spark-gap switches. Perhaps one of the most important aspects of their efforts is the development of a well-thought-out, coherent research program to study gap switches. This program has led to an understanding of the electron-initiation processes occurring in the gap and to the development of the theory of overvolted gap-switch closure that goes beyond the Townsend and the streamer models, thus making it possible to develop gap switches by other than the standard procedure. Of course, much theoretical and experimental work preceded Mesyats, and he was able to utilize the earlier work as a basis of his research.

In addition to providing understanding in the high-voltage spark-gap field, Mesyats has developed and tested spark-gap switches capable of controlling and switching multimegavolt potentials and currents in the megampere range. While no data are as yet available on the actual application of these devices to any large, high-power machines, the specifications that he does provide indicate the achievement of jitter and rise times of the order of 10^{-10} sec.

His primary aim of achieving gap-switch closure without the formation of channels throughout the conducting volume appears to have been reached either through the use of e-beams with large cross-sectional area to initiate the discharge, or through the development of switches with the gap partially filled with BaTiO_3 . These switches in moderate-power machines provide for pulse repetition frequencies measured in kHz and service life up to 200 hours without switch disassembly.

The avowed application of Mesyats's gap switches is in electron accelerators for the study of collective acceleration principles. However, much of his work also appears to be directed towards laser research and development. Thus the $1 \times 40 \text{ cm}^2$ gap initiated by the electron beam, described above, can be interpreted as an e-beam pumped laser.

Mesyats's statement about the importance of the pressurized gap switches in the design of high-performance electron accelerators for work on fusion, collective acceleration, etc., finds a responsive

echo among the U.S. specialists. The latter, however, point out that, while the gap characteristics may indeed be a limiting factor in the e-beam devices, so are the diode characteristics. In particular, the most severe limitation of the diode is the electrical breakdown along its wall (i.e., the insulator structure separating the cathode from the anode). Mesyats's insistence on the ultimate limitation of the gap switch might possibly be taken as an indication that he has reduced the diode problem to the point where it is less critical than the gap switch.

The achievements of the Mesyats group are a positive indication of an ongoing intensive development of a high technology suitable for application to collective acceleration, fusion, laser pumping, high-intensity-microwave generation, materials research, and other areas. While Mesyats's work, as reported here, represents primarily advances in the science of gap switches, his total effort makes sense only on the assumption that it is stimulated by and contributes to the current needs of a highly developed accelerator technology. However, a complete evaluation of his work is not possible without considering other problems of accelerator development and its objectives.

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Describes triggered gap R&D at Tomsk, Siberia, a world leader in high-current particle accelerators. Soviet specialists consider the triggered pressurized spark gap switch the most critical element of such accelerators. This report describes the broad theoretical foundation based on the avalanche-breakdown principle; specification of operating characteristics, including fraction of a nanosecond current rise time; and prototype construction. Either a large quantity of initiating electrons or multiple parallel gaps minimize gap inductance, further reduced by ceramic dielectric at the electrodes. Pulses down to 0.2 nanosecond at a 3 kA are possible using a fast electron beam with 3 ns pulse front and large cross section. Structures incorporating BaTiO₃ ceramics can deliver pulses as short as 0.6 ns at kilohertz frequencies for kA peak currents, with up to 200 hours service before disassembly. Multielectrode air-spark gaps developed for kA currents have jitter under 5 ns without gap length adjustment. 44 pp. Ref. (MW)

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