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A RAND NOTE

INDICATIONS OF A SOVIET PARTICLE-BEAM WEAPON PROGRAM I. HIGH-CURRENT ELECTRON-BEAM PROPAGATION IN AIR (U)

Simon Kassel

August 1981

N-1737-ARPA

Prepared For The Defense Advanced Research Projects Agency

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Declassified on: January 26, 2015

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SANTA MONICA, CA 90406

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(U) PREFACE

(U) This Rand note was prepared in the course of a continuing study, sponsored by the Defense Advanced Research Projects Agency, of Soviet research and development of high-current, high-energy, charged-particle beams and their scientific and technological applications.

U [redacted] The note is the first in a series investigating, on the basis of evidence in Soviet open-source technical publications, the possible existence of a Soviet military program to develop charged-particle beam weapons and the probable history of such a program. The note explores work on the atmospheric propagation of such beams in the USSR. Other notes examine the development of pulsed-power closing switches* and indications of a new generation of charged-particle accelerators.**

(U) The note, prepared for the Director's Office, DARPA, may also be of interest to pulsed-power specialists.

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*(U) Simon Kassel, *Indications of a Soviet Particle-Beam Weapon Program: II. Pulsed-Power Closing Switches* (U), The Rand Corporation, N-1738-ARPA, August 1981 (Secret).

**(U) Simon Kassel, *Indications of a Soviet Particle-Beam Weapon Program: III. The Timing of Pavlovskiy's Accelerator Development* (U), The Rand Corporation, N-1739-ARPA, August 1981 (Secret).

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A RAND NOTE

INDICATIONS OF A SOVIET PARTICLE-BEAM WEAPON PROGRAM I. HIGH-CURRENT ELECTRON-BEAM PROPAGATION IN AIR (U)

Simon Kassel

August 1981

N-1737-ARPA

Prepared For

The Defense Advanced Research Projects Agency

Rand
SANTA MONICA, CA. 90406

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(U) The likelihood of a Soviet military program to develop charged-particle-beam weapons and the probable history of such a program are investigated on the basis of evidence in Soviet open-source technical publications. Individual notes examine three aspects of pulsed-power development: atmospheric propagation of high-current electron beams; repetitive pulsed-power switch technology; and probable history of Soviet accelerator developments. (EFP)

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(U) SUMMARY

U [redacted] The development of ground-based charged-particle beam weapons depends on the resolution of the problem of beam propagation through the atmosphere. The necessary research must provide a thorough knowledge of the laws of interaction between high-current beams and air, and of the behavior of low-pressure channels in air formed by such beams. While these issues could be resolved by direct experimentation with high-current electron accelerators of adequate beam energy, such accelerators are not known to exist at this time. In their absence, the required knowledge must be approached less directly, by laboratory experimentation with available equipment, or by computer simulation. Soviet researchers can be expected to stress the experimental methods.

U [redacted] Among the wide range of research topics pertinent to high-current charged-particle beam technology, air propagation experiments are the least ambiguous indicator of a beam-weapon application. The Soviet open-source literature contains evidence of two kinds of such research activity: studies of (1) electron-beam propagation in low-pressure air at beam energy levels of about 1 MeV and (2) low-pressure channels formed in air by electric discharges. The Soviet work exhibits several characteristics that can be interpreted in terms of a military beam-weapon program: the use of air as the medium of beam propagation, capability for channel tracking, lossless energy propagation along the channel, focus on hose instability, determination of pressure and temperature profiles and expansion rates of channels, etc.

U [redacted] Some of these characteristics are also significant to research on inertial confinement fusion, where the problems of beam transport from the generator to the target are quite similar to those of the beam-weapon application. The difference between fusion and weapon applications in this respect resides in the species of gas through which the beam propagates. For the endoatmospheric beam weapon, air is the unique medium of propagation. However, air is not a suitable medium for fusion research, and beam transport experiments in such research would tend to rely on a range of gases not necessarily including air.

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U [redacted] This note plots the progression of experimental research on a time axis starting with about 1961. The history of the air experiments is also considered in the context of Soviet pulsed-power development and of the work of A. I. Pavlovskiy, although the relevance of Pavlovskiy's high-current accelerators to the beam-weapon application has not been established.

U [redacted] The hypothetical Soviet program shows three distinct stages of development: The first stage could have started before and lasted through the 1960s. It marked a preliminary buildup of pulsed-power support and early Pavlovskiy accelerator design. The air experiments were mainly based on electric discharges.

U [redacted] The second stage of the program, which extended through the first half of the 1970s, saw the advent and experimental use of high-current diode accelerators of the order of 1 MeV and the design of Pavlovskiy's radial line accelerator. The air experiments consisted of both studies of electron-beam propagation in air and continued research on electric discharges. The first and second stages produced published literature.

U [redacted] The third stage, beginning in the mid-1970s, marked a severe curtailment of publications on air propagation. It may have ushered in a new, higher level of more realistic experimentation and new accelerator equipment, perhaps of the order of 50 MeV, warranting the imposition of secrecy.

U [redacted] The above hypothesis about a possible Soviet beam-weapon program is speculative. The underlying Soviet technical data do not prove the existence of such a program. However, the air propagation data show a prolonged, systematic research effort that must have provided the Soviet researchers with a considerable understanding of the problem. The experimental methods and results are of interest to the designers of charged-particle beam weapons. A striking example of a weapons-pertinent research is the series of experiments performed by Yu. P. Usov of the Institute of Nuclear Physics, Electronics, and Automation in Tomsk. Usov observed the channel-tracking ability of a high-current electron beam pulse in air by bending the beam in a magnetic field.

CONTENTS

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(U) AIR PROPAGATION OF HIGH-CURRENT ELECTRON BEAMS IN THE USSR

U [redacted] This note explores the military implications of Soviet research and development of high-current charged-particle beams technology. Based exclusively on Soviet open-source literature, the report seeks to shed some light on the question of the existence of a Soviet beam-weapon program by focusing on the technical publications that would probably result from such a program.

(U) Soviet technical literature on the subject of high-current charged-particle accelerators and particle beams has reached an impressive volume. The collected materials published in the last decade alone bear the names of over 1300 Soviet authors affiliated with approximately 40 research institutes. These materials for the most part consist of technical reports emanating from Soviet R&D projects aimed at a range of scientific and technological applications in this subject area. Military applications are not explicitly mentioned in the Soviet reports as goals of their projects

(U) Any experiment in the area of high-current particle-beam technology may have a variety of possible applications as a logical objective. Furthermore, much of the same equipment serves various technological applications. The diversity of applications and commonality of hardware make it especially difficult to associate particular Soviet R&D projects with a military purpose. On the other hand, these same characteristics increase the likelihood that at least the early stages of weapon-oriented research, if it exists, will be reflected to some extent in the published literature. The prestige and legitimacy of Soviet researchers, their vital contacts with Western science, the benefits to particle-beam technology (PBT) in general, and the educational considerations all depend on the publication of research results.

U [redacted] The nature of atmospheric propagation of high-current electron beams is the most important area of inquiry in the early stages of particle-beam weapon development. Among the various aspects of PBT, atmospheric propagation is unique to the weapons concept; at the same

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time, it represents a scientific, rather than an engineering problem and is thus more likely to leave a trace in the publications. For these reasons, it was selected as the subject of the present report.

U [redacted] The ability of high-current electron beams to propagate in the free atmosphere over distances significant to weapons applications is a matter of conjecture at the present time. The verification of such an ability is expected only after accelerators of sufficient energy, current, and operational repetition rate become available. Without these machines, a limited understanding of beam propagation can be pursued by either of two methods: (1) scaled-down experiments with single high-current beam pulses, electric discharges, and similar phenomena or (2) computer simulation of beam propagation conditions.

(U) Beam-propagation research in the United States has so far relied heavily on computer simulation. Corresponding work in the USSR, however, can be assumed to have followed a different approach: Inferior computer capability and the predilection for simple experimental procedures may well have driven Soviet researchers to rely to a greater extent on laboratory experimentation. Indeed, published Soviet papers on charged-particle beams and their applications deal overwhelmingly with analytic and experimental studies and show only a modest use of numerical modeling.

(U) The problem of charged-particle beam propagation in air is embedded in the larger area of beam interactions with neutral gas and plasmas. W. H. Bennett and J. D. Lawson's investigation of the properties of intense electron beams during the 1950s provided the impetus for the study of these interactions. The opportunity for beam-plasma interaction experimentation came in the late 1960s, when intense relativistic electron-beam (IREB) accelerators became available. The Soviet technical papers selected for analysis in Appendix A describe experiments involving IREB propagation in air, performed mainly at low pressures, with the use of drift tubes. The problems investigated in these papers include beam neutralization and stability, optimum propagation pressures, and the formation of channels in air by the beams.

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(U) High-current electrical discharges in air represent another experimental approach relevant to the study of atmospheric IREB propagation. The analysis of Soviet papers on this subject is given in Appendix B. Materials on high-current pulse discharges across long gaps in free air, with or without the aid of exploding wires and optical breakdown, have been published in the USSR since 1965. These Soviet studies deal with (1) the properties of discharge channels in air, including pressure, temperature, expansion rates, and heat transfer and (2) the hydrodynamics and chemistry of hot air. They can thus provide important benchmark data on the complex phenomenon of the heating of air by particle beams. The heating mechanisms involving charged-particle beams when chopped electron beams are used are in some ways similar to those of a discharge, since the ohmic heating contribution becomes dominant in a rarefied channel.*

U [redacted] There is significant degree of probability that at least some of the Soviet experimental research projects considered in Appendixes A and B of this report have been performed in association with the development of a charged-particle weapon. This conclusion is supported by several characteristics of the Soviet experiments involved:

- The Soviets' use of air as the medium for propagating high-current electron beams points to a weapon, rather than a science, program. Ground-based weapons would operate in air; air is not, however, the preferred medium for nonweapon applications of charged-particle beams.
- The Soviet tendency in these studies is to minimize interaction and, at the same time, to provide optimal stability to the propagating beam. Hose instability is emphasized as the most serious impediment to propagation.
- An experiment by Usov** demonstrating the tracking force of a low-pressure channel on a beam bent in a

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*(U) Richard Briggs, private communication.

**(U) See below, pp. 15-18.

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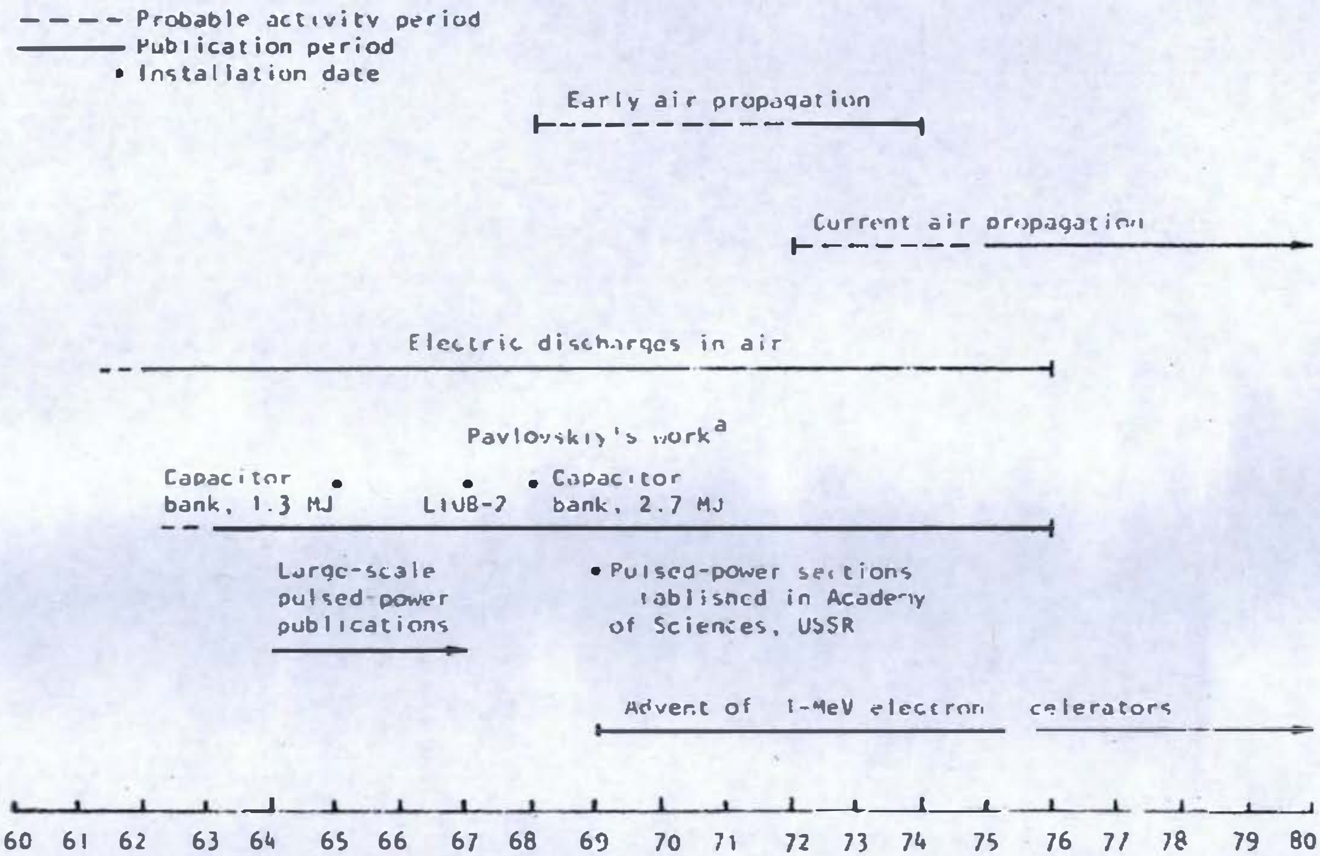
magnetic field represented an important contribution to the solution of a problem unique to beam weapons: the tracking of low-pressure channels in air by high-energy beam pulses.

[redacted] Soviet research has, furthermore, generated an impressive collection of data on the properties of air heated by electric discharges and electron beams. Knowledge of the heating mechanism applicable to the beam-air interaction is essential to the resolution of the basic uncertainty involved in the beam weapon design, namely, the feasibility of atmospheric propagation.

[redacted] These observations do not constitute a proof that the USSR has been pursuing a charged-particle weapons development program, or even that the Soviet work discussed in Appendixes A and B is weapon-oriented. For example, the research aimed at minimizing interaction and preserving the stability of the beam, mentioned above, is also applicable to inertial confinement fusion, although air is not a suitable medium of propagation for that application. One can seldom be certain of the motivation of Soviet papers on particle-beam research. The most that can be said with certainty is that this work has considerable utility to the development of charged-particle weapons. Beyond this statement, we must deal in probabilities.

[redacted] If the Soviet papers in question have indeed been associated with a weapons program, the timing of the research work reflected in them is significant. These papers suggest that Soviet research on electron-beam propagation breaks down into two parts: first, an early cycle of experiments, performed by three teams, and second, what may be called the current cycle, performed by two other teams. The electric discharge work, which began well before the propagation work, continued over a 15-year period (see Fig. 1).

(U) The timing of a research activity reflected in a published report involves three dates: the publication date of the report, the date of its submission to the editor, and the time of the actual activity. The first two are almost always given in the publication. For the purpose of this study, the most important is the third, or earliest date,



[a] See: Simon Kassel, *Development and Potential of Radial-Line Accelerators* (U), The Rand Corporation, R-2112-ARPA March 197, (Confidential).

Fig. 1--Timetable of Soviet charged-particle beam experiments and related projects

which may precede the other two by a considerable time lapse. In dating the Soviet research, it would be desirable to estimate the earliest possible period of activity so as to determine the origin of the research project involved. In the case of the air propagation experiments, this report based its estimates of the earliest activity periods on the publication dates of the most recent U.S. papers cited by the Soviet authors and actually used in the preparation of the citing papers. The dashed lines in Fig. 1 show the time periods that air propagation research could have taken place, beginning with the earliest possible date based on citations of U.S. works. The solid line shows the corresponding publication periods of the Soviet papers.[*]

(U) The meaning of the air propagation and electric discharge research periods is enhanced in the context of other pertinent Soviet activities. Figure 1 therefore shows the periods marking the appearance on a large scale of publications on pulsed-power development, as well as several other events that may be significant to the hypothesis of a Soviet beam-weapon development program. One such event was the establishment in 1969 of working sections on pulsed power and on high-current electron accelerators at the Scientific Council on Theoretical and Electrophysical Problems of Electric Power, Academy of Sciences, USSR. Pulsed-power research became at that time a major component of the national R&D effort in advanced electrical energy concepts.[**] The construction of the early Soviet high-current electron accelerators probably began in the same year.[***]

U [redacted] The consideration of Soviet research activities that may be pertinent to an assumed military program should include the work of A. I. Pavlovskiy. Pavlovskiy's electron accelerators, and especially his

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[*] (U) In the case of air propagation reports, the time lag between submission to the editor and publication did not exceed one year. The average lag for electric discharges was two years. The difference could be attributed to the greater importance of the institutes doing the propagation work.

[**] (U) Simon Kassel, *Pulsed-Power Research and Development in the USSR*, The Rand Corporation, R-2212-ARPA, May 1978.

[***] (U) Simon Kassel and Charles D. Hendricks, *High-Current Particle Beams. I. The Western USSR Research Groups*, The Rand Corporation, R-1552-ARPA, April 1975. See also: L. N. Kazanskiy, A. A. Kolomenskiy,

radial-line accelerator, perhaps more strongly than any other Soviet published accelerator designs, suggest a beam weapon.* Figure 1 also shows Pavlovskiy's publication period and the launching times of some of his major research facilities, including the two large capacitor banks and the LIUB-2 linear induction accelerator.

(U) The events represented in Fig. 1, taken together, may be interpreted as follows:

U [redacted] An extensive Soviet effort to develop pulsed-power and high-energy-density technology began shortly before, or at the beginning of, the 1960s. By the end of that decade, the effort had gained sufficient momentum to warrant the establishment of two pulsed-power sections in the Academy of Sciences to coordinate and direct the various activities involved. The national effort, aimed at a wide range of applications of pulsed-power technology, has since its inception included particle-beam weapons as a major component.

U [redacted] The hypothetical military program to develop a particle-beam weapon at the outset probably consisted of at least two parts:

- o The development of hardware, entrusted to Pavlovskiy (and perhaps other leading Soviet accelerator designers). Pavlovskiy built a succession of high-energy, high-current, intermediate storage systems and inductive accelerators.
- o The theoretical and experimental resolution of the problem of air propagation of high-current particle beams.**

(U) During the early and middle sixties, in the absence of high-current electron accelerators, air propagation was investigated with

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G. O. Meskhi, R. N. Yablokov, "*Impul's* Accelerator Operation at 800 keV, 30 kA, 50 nanoseconds," *Atomnaya energiya*, Vol. 42, 1977, p. 113.

*(U) Simon Kassel, *Development and Potential of Radial-Line Accelerators* (U), The Rand Corporation, R-2112-ARPA, March 1977 (Confidential).

**U [redacted] This problem was also one of the first to be considered in the U.S. beam-weapon projects.

the aid of electric discharges in air. As electron accelerators became available in the seventies, air propagation experiments were added to the program. The teams working on early air propagation, electric discharges in air, and the radial-line accelerator continued to publish accounts of their research activities until the middle seventies, at which time such publication apparently ceased.*

U [redacted] The lack of further publication on these subjects could be interpreted to mean either that the military program had been discontinued or that further work had been classified and barred from publication. The second alternative implies that a new phase of the military program began during the mid-1970s. The new phase would involve more realistic experimentation with particle-beam propagation and the availability of more powerful high-current accelerators, perhaps of the order of 50 MeV.

U [redacted] The above hypothesis postulating, first, the existence of a Soviet beam-weapon program and, second, the military orientation of Soviet experimental research is highly speculative. All of the conclusions were inferred from selected data, and all of the data taken separately could be interpreted to imply nonmilitary applications. A nonmilitary interpretation of these data, however, would be somewhat less consistent than a military interpretation.

U [redacted] In sum, assuming the existence of a Soviet military program, we can discern three stages of its development, as shown in Fig. 2. The first stage, originating perhaps before the 1960s and lasting until nearly the end of that decade, consisted of preliminary theoretical work and the buildup of pulsed-power equipment. The experimental research performed during that stage was based on a relatively primitive technology. The second stage, extending from the late 1960s to the mid-1970s, was ushered in by the advent of (1) high-current diode accelerators with energy of about 1 MeV and (2) Pavlovskiy's early induction accelerators, which permitted scaled-down propagation experiments. Both stages generated a relatively abundant literature on the

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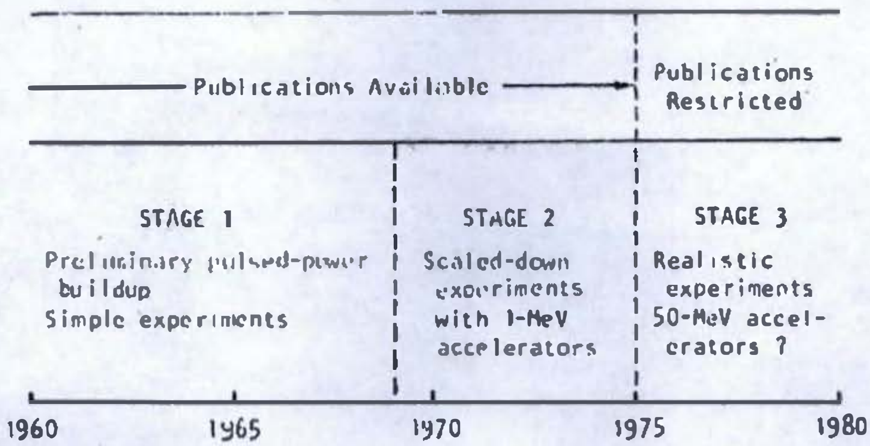
*(U) Searches of open-source literature cannot be exhaustive enough to guarantee that no subsequent publication has been overlooked. The search of the 1976-1979 period showed that most of the authors involved continued to publish, but on other subjects.



[redacted]

(U) Fig. 2--Hypothetical Soviet beam-weapon development program

research results. The third stage, which began in the mid-1970s, was marked by a severely restricted publication policy. It is possible that new, more powerful equipment has been introduced during the third stage, permitting more realistic experimentation.

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Appendix A

(U) BEAM PROPAGATION IN AIR

(U) THE NATURE OF SOVIET RESEARCH

(U) Experimental research reports from five Soviet institutes for the period from 1970 to the present were found to deal with IREB interaction with air at pressures ranging from 10^{-} to 10^{3} Torr. The principal parameters of the electron beams ranged from 0.8 to 2 MV, 30 to 80 kA, and 16 to 50 ns. None of the reports was explicitly associated with any single application; all were concerned with the problems of beam neutralization, self-focusing, and optimum propagation conditions.

(U) The five Soviet institutes dealing with beam-air interaction, their chief researchers in this field, their major machines, and their periods of publication are listed in Table A.1. Each researcher listed heads a research team. Research team members are listed in Appendix C.

Table A.1

SOVIET RESEARCH INSTITUTES REPORTING ON IREB PROPAGATION IN AIR

Institute	Principal Investigator	Accelerator	Publication Period
Kurchatov Institute of Atomic Energy, Moscow	L. I. Rudakov	*Neptun*	1970-1972
Institute of Nuclear Physics, Electronics and Automation, Tomsk	Yu. P. Usov	*Tonus*	1972-1978
Yefremov Institute of Electrophysical Equipment, Leningrad	L. V. Dubovoy	*REP-5*	1977-1978
Physico-Technical Institute, Khar'kov	Yu. V. Tkach	Waterline	1972
Lebedev Physics Institute, Moscow	A. A. Kolomenskiy	*Impul's*	1972-1973

U [redacted] The reports of the five research teams published within the time periods shown in Table A.1 indicate a definite Soviet interest in the propagation of intense relativistic electron beams through low-pressure channels in air. The probability that this interest derives from charged-particle weapon applications is suggested by the following characteristics of these reports:

U [redacted] 1. Focus on air as the medium of IREB propagation. Few IREB applications other than weapons utilize air as the principal medium of interaction with the beam. Certain industrial electron accelerators provide for the extraction of the beam into the atmosphere, but these feature low-current beams or cw beams with propagation characteristics different from those of the beams that would be used in a weapon.

U [redacted] 2. Attempts to determine optimum channel pressures for propagation and to minimize propagation loss. The principal applications of CPB technology other than for weapons--applications in which the beam interacts with a gaseous or plasma medium--are plasma heating for fusion research, certain types of microwave generators, and laser pumping. In these cases, the aim is to enhance the beam-medium interaction, to encourage suitable kinds of instabilities, and to maximize the energy transfer from the beam to the medium. Research aimed at preserving the beam and minimizing the interaction, other than that necessary to establish a propagation channel, can be assumed to have a limited range of applications other than for beam weapons.

U [redacted] 3. Study of the confining force of the propagation channel. The concept of pulse tracking through a channel in free air is unique to the weapon application.

U [redacted] 4. Attention paid to the problem of hose instability. This is known to be the most serious instability that affects long-distance propagation of high-current beams and is a major subject of study in beam weapon development.

U [redacted] 5. Stress on the determination of propagation distance.

(U) It must be noted that issues 2 to 5 are also pertinent to inertial confinement fusion research, and some of the work of the Soviet teams considered here may be oriented toward fusion.

✓ [redacted] The time periods during which the several teams were concerned with these issues and the particular accelerators used are significant to the hypothesis that a possible weapons program is involved.

(U) Let us first consider the three teams whose publications are limited to the period 1970–1973. These teams, headed by Rudakov, Tkach, and Kolomenskiy, continued to publish research reports after 1973, but only on subjects other than beam behavior in air. Furthermore, the accelerator facilities used in the propagation experiments are not mentioned again in connection with the subsequent work of these researchers.

(U) For example, Rudakov used the *Neptun* accelerator in his propagation experiments, which were reported on in 1970–1972. Work published after that period concerned his electron-beam pellet fusion research, which featured a series of accelerators from the *Triton* and *Tral* to the *Angara* and *Kal'mar*. A similar pattern occurred in Kolomenskiy's case. His work published in 1972–1973 was based on the *Impul's* accelerator. Kolomenskiy apparently did not use the *Impul's* in his later research, dealing with collective acceleration.

✓ [redacted] Tkach used a waterline accelerator in the work published in 1972. Since that time, his research has extended to other areas, most notably, microwave generation by electron beams. The waterline accelerator has no official designation and is therefore more difficult to trace through the publications.

U [redacted] This sequence of events may be interpreted to mean that the three air propagation projects and the accelerators were ordered and funded by the military. After 1973, the projects were either discontinued or classified. In either case, the accelerator facilities belonging to the military would no longer appear in the open sources.*

U [redacted] It should be emphasized that this hypothesis is highly speculative. The accelerators may have been phased out of active research or broken down and their components diverted to other facilities. They may even be still active, and their "absence" due solely to our limitations in covering the published sources.

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*(U) Soviet regulations for industrial R&D contracts specify that instruments, equipment, and test stands acquired by the Academy of Sciences institutes at the expense of the customer must be returned to the customer at the end of the research project [1].

Declassified [redacted] U

U [redacted] The remaining two teams of Usov and Dubovoy continued work in this area at least until 1978. Dubovoy's accelerator, the REP-5, has not been given sufficient exposure in the open sources to determine its specialization. Usov's [illegible] accelerator has been used for the propagation studies since its commissioning in 1972. However, since 1976 it has also been used for microwave generation research. The continuing work of the two teams does not invalidate the hypothesis of the military nature of the propagation studies. The arrangement of work of the Tomsk and Leningrad teams may have differed from that of the other teams.

U [redacted] The above hypothesis implies the existence of a military research and development program with charged-particle beam weapons as its objective. If the hypothesis is correct, the publications of the five teams between 1970 and 1973 would represent the theoretical and experimental results of an earlier, nonsensitive phase of the program.

[redacted] A factor tending to reinforce the military hypothesis is a 1972 paper by A. A. Rukhadze [2]. In this paper, Rukhadze, an associate of Kolomenskiy at the Lebedev Physics Institute, reviewed the development of high-current electron beams for the Academy of Sciences, USSR. According to Rukhadze, intensive and systematic studie of high-current electron beams began in 1968. Pointing out the need for fast pulsed-power sources that would be more powerful than the low-inductance capacitor banks used up to then, Rukhadze indicated that the MHD storage devices and generators developed by A. Ye. Sheyndlin and Ye. P. Velikhov were the most important for this purpose.

U [redacted] In 1972, when Rukhadze published these remarks, Soviet CPB technology, or at least its nonweapon applications, did not appear to be more advanced than the corresponding U.S. technology. At that time, any consideration of exotic pulsed-power sources, such as the explosive MHD devices, would have seemed premature in the United States, and Rukhadze's remarks would have been viewed as purely visionary. Nevertheless, Rukhadze could have been motivated by the existence of a Soviet long-range program requiring the development of new high-density, low-weight power sources.

Declassified

[redacted] U

SOVIET RESEARCH RESULTS

1. The Institute of Nuclear Physics, Electronics, and Automation, Tomsk

An experiment that clearly illustrates Soviet interest in electron-beam propagation through low-pressure channels in free air was reported in 1977 by Yu. P. Usov and his team, who investigated channel tracking by electron-beam pulses [3]. To ensure a free environment for the propagating beam so that it would not be affected by the walls of the drift tube, Usov provided a large-volume experimental chamber for the propagation medium.

The beam was injected into the chamber containing low pressure air. The beam trajectory was curved by an external constant magnetic field of 200 gauss transverse to the beam path.

The electron beam and equipment parameters were as follows:

Electron energy	1.0 MeV
Beam current	35 kA
Pulse length	60 ns
Pulse rise time	20 ns
Cathode diameter	4 cm
Drift tube length	60 cm
Drift tube diameter	8 cm
Experimental chamber height	80 cm
Experimental chamber diameter	80 cm
Magnetic field inhomogeneity	<5 %

The position of the electron beam and the distribution of charge density over the beam cross section were determined by an array of 50 collectors forming an arc 35 cm in radius and vacuum-insulated from the chamber. The accuracy of beam position measurement was 1 cm as determined by the collector spacing. The beam traversed a distance of 70 cm before reaching the collectors.

Although a 1-MV beam was used, the experimental results showed that the beam trajectory radius in a magnetic field of 2 to 200 gauss was shorter than the Larmor radius computed for 1-MeV electrons. The actual radius corresponded to electron energy of 0.4 MeV. The radius remained constant in the range of air pressures from 0.1 to 0.6 Torr. The shortening of the radius is interpreted as follows: While 0.5- to 1-MeV electrons constituted 90 percent of all electrons in the beam, the first 10 ns of the pulse contained electrons with an energy below 0.5 MeV. This energy distribution remained constant for any distance from 20 to 200 cm. The plasma channel was thus established by these low-energy pulse-front electrons. The succeeding higher energy electrons in the pulse tended to increase the radius, but the resulting electric field kept the entire pulse confined to the initial channel.

Other media of beam transport in this series of experiments included plasma in a uniform magnetic field and thin wires. In the former, a plasma channel was established by an rf discharge between 8 x 40-cm copper electrodes at a gas pressure below $10^{-[illegible]}$ Torr. The magnetic field was varied up to 130 gauss. Two cases were considered:

- Channel width was 2 to 3 times larger than the beam diameter. The beam was confined to the channel at all values of B. At high B (near 130 gauss), a part of the beam left the channel and moved close alongside the channel boundary. At weaker fields, the Larmor radius of the electrons was much larger than the width of the channel and the beam trajectory was therefore free to move with varying electron energy, without leaving the channel.
- A more interesting case (according to authors) was that of channel diameter being less than beam diameter. The channel was established by a thin-walled plastic (Lavsan) cylinder enclosing gas at a pressure of 0.1 to 1 Torr. The cylinder walls were thin enough (15 μ) to permit the beam to leave the channel without significant losses. The cylinders were 60 cm long and 1.2, 2.2, and 3.2 cm in diameter; the beam diameter

was 4 cm. The pressure in the experimental chamber was 3 x 10⁻⁴ Torr. The field varied from 0 to 200 gauss. It was found that the effectiveness of beam transport in B field increased with rising neutralization. In spite of the fact that most of the electron beam was in vacuum and the neutralizing positive ions were in the dielectric cylinder, this geometry permitted the self-focusing of the beam and assured effective beam transport. In the B field, the electrostatic field of the positive ions was able to hold the electron beam near the plasma channel [3].

In the case of beam transport along a thin wire, the wire was considered a narrow plasma channel. The effectiveness of this means of beam transport in a magnetic field of 200 gauss decreased with increasing wire diameter [3].

These experiments were preceded by the following studies:

1974 Reflection of a beam from a conducting surface [4].

1975 Capture of a beam in a closed orbit by electrostatic action of a reflecting surface [5].

1975 Beam propagation in plasma at low pressure (10^{10} cm^{-3}) due to strong preionization of residual gas [6].

1976 Beam propagation in air of 0.6 to 1 Torr over a distance of 2 m. Pulse shortened at 1 m above 20 Torr. Beam propagated 30 cm at up to 150 Torr [7].

In the most recent series of experiments with the large volume experimental chamber [8,9], the highest effectiveness was observed at pressures of 0.09 to 0.06 Torr. In this range, hose instability, which displaced the beam laterally one diameter, was observed. The hose did not disrupt the channel, and the lateral displacement of the electron beam was confined to the channel boundary which conducted the return current.

It was concluded that a high-current REB can propagate in large volumes of gas, forming a channel for the return current. The cylindrical plasma layer representing the channel boundary shorts the beam current in the accelerator and retains the self-focusing condition. The plasma layer also stabilizes the transverse displacements of the beam. Increasing the pressure to 100 Torr produces an instability that quickly blows up the beam. This disruption of the beam is considered to be due to the high pressure, rather than to the large volume [8,9].

2. The Kurchatov Institute of Atomic Energy, Moscow

The best known Soviet experiment in air propagation, published in 1972, was performed by Rudakov, who attempted to determine the distance of propagation of an electron beam in air at atmospheric pressure. Rudakov used the *Neptun* accelerator designed for 1 MV, 30 kA, 40 ns [10,11]. The beam parameters were 660 kV, 12 kA, 40 ns. In air at atmospheric pressure, the beam blew up at the distance of 12 cm. The propagation distance in air decreased from 20 cm at 0.4 atm to 10 cm at 1.6 atm. The distance rapidly increased as the pressure dropped below 0.4 atm [12].

This experimental procedure was not new: S. E. Graybill and S. V. Nablo had performed a similar experiment in 1966 [13]. The objective of the U.S. researchers was to verify the Bennett pinch theory, an exercise in basic research. Since it would have been pointless for Rudakov to repeat the verification six years later, it is reasonable to assume that his experiment had applied-research purpose associated, according to an explicit statement in his report, with propagation distance.

Rudakov's experiment was part of a study whose first results were published in 1970. An early paper [14] was a theoretical study of REB stability in plasma channels. The conditions for the occurrence of hose instability were investigated, the hose being considered the most dangerous instability for beam propagation. Gas ionization and return current were investigated for IREB propagating in air and helium at pressures between 10 Torr and 1.6 atm [15]. Theoretical analyses and experimental verification studies were performed to determine the principal mechanism of ionization of the neutral gas; the ionization was found to be based on secondary electrons driven by the electric field induced by the beam.

3. The Physico-Technical Institute, Khar'kov

Yu. V. Tkach's treatment of hose instability contributed significantly to the study of IREB propagation in air [16,17].

The waterline accelerator used in these propagation experiments had the following characteristics:

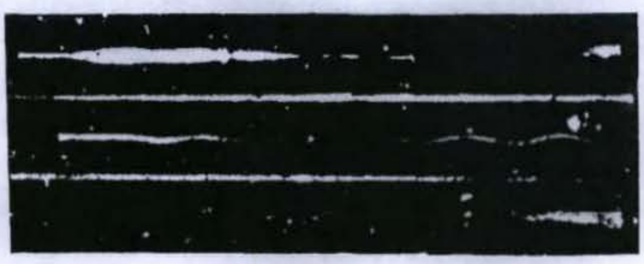
Electron energy	1 MeV
Beam current	60 kA
Pulse length	30 ns
Energy spread	20 %
Drift tube length	3 m
Drift tube diameter	11 cm
Gas pressure	0.01 to 20 Torr

The optimum propagation pressure range for nitrogen was from 0.05 to 0.8 Torr. Sausage instability was observed at 0.2 Torr and beam current of 30 kA (Fig. A.1,a). Hose instability was observed at higher currents, above 40 kA and 1 MV (Fig. A.1,b).

a

b

c



30 kA
$2\cdot10^{-1}$ torr

50 kA
$4\cdot10^{-1}$ torr

55 kA
1 torr

Fig. A.1--IREB propagation in gas (nitrogen) [16]

Hose growth rate was computed (after Rudakov) according to:

$$\sigma_{hose} \approx \left(\frac{n_1 m}{n_0 M}\right)^{1/2} \frac{v}{r_0} \langle\theta\rangle$$

where n_1 and n_0 are beam and plasma densities, respectively, m is electron mass, M is ion mass, r_0 is the initial beam radius, and v <θ> is the average spread of transverse velocities.

Under the experimental conditions, σ_{hose} varied from 3 x 10^8 to 10^6 s^{-1}, and the product of σ_{hose} and pulse length varied from 10 to 3. Therefore, hose instability could be observed only with the highest currents obtainable in the experiment.

The wavelength of hose instability is limited by the condition

$$\lambda > \frac{2\pi r_0}{\langle\theta\rangle} \approx 20\text{-}40 \text{ cm}$$

The values of hose instability λ measured in the experiment were about 40 to 50 cm.

Tkach performed experiments to determine the effectiveness of beam transport in air as a function of air pressure [17]. The range of pressures for a 0.6 to 0.7-MeV, 40-kA beam, corresponding to optimum propagation conditions in air, extended from 0.5 to 2 Torr.

In interpreting his results, Tkach referred to W. H. Bennett, whose paper was published in 1968. Bennett showed that when the current rise time is significantly shorter than the skin-effect time, a return current formed in the plasma neutralizes the magnetic self-field of the beam. Below 0.2 Torr, because of the low plasma density, the return current is insufficient for neutralization, the electron Larmor radius is shorter than the beam radius, and the beam is pinched off. At low pressures, the rise time of the return current becomes comparable to the pulse length, a condition that also contributes to the decrease of energy transferred by the beam. The experimental data shown in Table A.2 illustrate the systematic nature of Tkach's experiments [17].

Table A.2

RETURN CURRENT RISE TIME (ns) IN VARIOUS GASES
AS A FUNCTION OF PRESSURE (0.8 MV, 25 kA)

	Pressure, Torr				
Gas	0.1	0.3	0.6	1.0	2.0
Hydrogen	23.5	18.0	14.5	12.5	10.0
Helium	20.0	17.5	16.5	16.0	15.0
Neon	21.0	14.5	13.0	12.0	11.0
Argon	22.0	11.5	9.5	9.0	--
Air	20.0	13.0	8.5	7.0	--
Air(theoretical)	27.0	9.0	7.0	6.0	--

Above 4 Torr, one of the mechanisms degrading beam propagation is the scattering of return current electrons by the ions and atoms of the gas. Tkach also quotes similar results obtained by P. A. Miller and J. B. Gerardo (1972) and by D. W. Swain (1972). Tkach's experiments showed that between 0.5 and 2 Torr, the electron beam propagates 80 percent of its energy over a distance of 3 m.

Another parameter of propagation, the velocity of the ionization front, was also discussed by L. S. Levine, I. M. Vitkovitsky, and D. A. Hammer (1971). The front velocity measured by Tkach was in agreement with the theoretical formula derived by Rukhadze in 1971. The observed velocity did not exceed 1.6×10^{10} cm/s.

4. The Yefremov Institute of Electrophysical Equipment, Leningrad

In 1977-1978, L. V. Dubovoy and his team at the Yefremov Institute published a study involving the propagation of high-current relativistic electron beams with $\nu/\gamma < 1$ in air and nitrogen at pressures ranging from 10^{-} to 10 Torr. The study sought to (1) determine the conditions under which the return current in the conducting plasma channel markedly exceeded the beam current and (2) develop a theory of the anomalously high losses in beams propagating in gas at . < 1 Torr.

The experimental equipment consisted of the REP-5 accelerator [18] with the following characteristics:

Electron energy	1.5 MV
Beam current	60 kA
Pulse length	16 ns
Pulse rise time	3 ns
Angular velocity spread	0.1 rad
Metal drift tube length	60 and 120 cm
Drift tube diameter	12 cm
Beam diameter	0.6 cm

The beam established a conducting channel filled with weakly ionized plasma. Previous experiments showed a strong broadening of the energy spectrum of the beam and an anomalously high collision frequency of plasma electrons. These phenomena were considered indications of intense processes of beam-plasma turbulence in the system.

The peak return current observed at 0.03 Torr, larger than peak beam current, coincided with the maximum broadening of the beam energy spectrum. Dubovoy noted that up to that time, only Rukhadze (1974) had attempted to provide a theoretical foundation for the large return current. Dubovoy and his team found the computed peak value of the return current to be twice that of the beam current. For the corresponding peak pressure, the radial velocity of the plasma channel was 2×10^{8} cm/s. The increase in beam radius per pulse was 3 cm [19].

The case of anomalously high losses was illustrated by an experimental distribution of beam energy loss as a function of initial pressure. The distribution contradicts the behavior of a beam interacting with neutral and ionized gas predicted by the pair collision theory. As the density of particles in the path of the beam decreases, the beam energy should, according to theory, increase monotonically. Dubovoy maintained that attempts to explain the contradiction as beam loss from coulomb repulsion or magnetic pinching were not convincing, since the anomalous beam energy behavior was observed in neutralized beams as well. Dubovoy theorized that the beam energy behavior was caused by the turbulence of the high-current electron beams and verified the theory in an experiment using the REP-5 accelerator (1.5 MV, 50 kA, 20 ns).

The experimental results included a marked energy spread at the end of the drift tube, indicating turbulent beam scattering by the microfluctuations of plasma instability excited by the beam. The turbulent scattering of beam electrons increased the transverse pressure of the plasma channel electrons. These considerations led to an analytical expression for the beam energy which was in agreement with the experimental data [20].

5. The Lebedev Physics Institute, Moscow

A team of researchers of the Lebedev Physics Institute in Moscow, working under A. A. Kolomenskiy, has been pursuing theoretical and experimental studies of gas focusing at least since 1971. The team members claim that the phenomenon of electron beam neutralization and gas focusing has been discussed by Soviet physicists since 1932. At that time, Ya. I. Frenkel' and S. A. Bobrovskiy, and in 1930 D. . Davydov and S. I. Braginskiy, showed theoretically that the beam electrons should be pulled towards the beam axis as a result of space charge neutralization. They also acknowledged that the American physicist W. T. Link was one of the first observers of this phenomenon, using a high-current electron accelerator.

The early period of the Kolomenskiy team's work may be placed at around 1970 because of a reference made by two of its members to the publications of T. Martin (1969), F. M. Charbonnier et al. (1967), and S. E. Grayhill (1967) dealing with the uses of 10^4 to 10^6-A, 10-MV electron accelerators. These publications were called "recent" in a 1972 paper by A. V. Agafonov and A. N. Lebedev, who further stated:

> Electron beams with these parameters are of extraordinary interest to a number of applications which, however, require an effective mechanism of transverse focusing. The self-fields of the beam are strong enough to cast doubt on the utility of external magnetic fields to control particle dynamics. Therefore, it is necessary first to develop passive methods to control and focus the beam, using the self-field of the beam or the gas ions formed by the beam for this purpose [21].

In the same paper, Agafonov and Lebedev considered a nonstationary focusing process--including variation of beam radius and kinetics of ion accumulation--leading to conditions for beam stability (initial transverse electron velocity and gas pressure in the drift tube) [21].

Also in 1972, Kolomenskiy's group presented an analysis of the steady state of an unneutralized beam in vacuum, considering it an essential precursor of the transient analysis and, in particular, of the analysis of high-frequency beam instabilities. The analysis was performed in a two-dimensional geometry [22].

The principal experimental device has been the *Impul's* accelerator (800 kV, 30 kA, 50 ns). In 1972, researchers at the Lebedev Institute observed beam compression only in the range of gas pressures between 0.4 and 1 Torr. Below 0.05 Torr, the beam blew up because of coulomb repulsion; above 1 Torr, the beam bent into the wall of the drift tube, which was about 80 cm long [23]. A further report, published in 1973, described the drift tube as about 2 m long, made of glass, and lined with stainless steel mesh. This time a plasma channel 3.5 cm in diameter was observed throughout the length of the tube in the air pressure range between 0.1 and 0.4 Torr. Between 0.4 and 1 Torr the beam was focused down to 1 cm in diameter (for a 4-cm injection diameter). However, at 1 Torr, incipient hose instability was observed. The beam parameters at that time were 300 kV and 20 kA [24].

The subsequent work of the team, published from 1974 to 1978, deals with magnetic focusing of the beam propagating in vacuum. A 1977 paper, however, may be of interest; it reported an experiment with the *Impul's* beam in vacuum propagating in a dielectric drift tube. The beam pulse nose erosion created plasma which neutralized the beam and permitted focusing and propagation without external magnetic field [25].

Appendix B

(U) ELECTRON DISCHARGES IN AIR

THE NATURE OF SOVIET RESEARCH

High-current pulse discharge across long gaps in free air has been the subject of sustained research in the USSR since the late 1950s. The purposes of this work, as stated in some of the relevant Soviet research reports, include the study of the behavior and parameters of discharge channels in air, means of heating hot and cold plasmas, development of sources of intense light for pumping lasers, electron acceleration, and protection of high-voltage power lines from lightning.

Only Soviet research reports claiming the first of the above aims, the dynamics of discharge channels in air, are considered here. In this group of papers, the experimental studies focus on the development of methods for the precise measurement of (1) temperature, pressure, and density of the plasma in the discharge channel and (2) velocity of expansion of the channel boundary. Theoretical development is pursued to improve the understanding of the mechanisms of channel and shock-wave formation, with particular attention to the role of radiant flux in the energy transfer in the channel.

The experiments involved microsecond current pulses ranging from 20 to 400 kA and interelectrode gaps ranging from 1 mm to 50 cm. The background of this research appears to be predominantly Soviet; the relevant papers cite mainly Soviet work and only rarely Western sources. The theoretical approach is also typically Soviet; the principal analytic tool is the hydrodynamic theory based on the concept of self-similar flow developed by S. I. Braginskiy and other Soviet researchers. Soviet researchers appear to have accumulated a considerable body of knowledge about ionized channels in free air involving high energy densities.

Table B.1 shows several teams of researchers to be engaged in this work in widely scattered locations. Research team members are listed in Appendix C. A. A. Rukhadze of the Lebedev Physics Institute is one the Soviet reviewers of this research. Rukhadze has specialized in the theory of stability and propagation of high-current charged-particle beams.

Table B.1

SOVIET RESEARCH INSTITUTES REPORTING ON ELECTRIC DISCHARGES IN AIR

Institute	Principal Investigator	Publication Period
Unknown	S. I. Andreyev	1965-1976
Lebedev Physics Institute, Moscow	N. G. Basov	1970
Kiev Polytechnic Institute	Yu. K. Bobrov	1974
Tadzhik State University, Dushanbe	M. A. Sultanov	1974-1976
Chuvash State University, Cheboksary	G. M. Goncharenko	1970

SOVIET RESEARCH RESULTS

1. The Moscow-Kiev Group

The most sustained effort in the area of electric discharges in air has been made by a team headed by S. I. Andreyev. The team's reports, which have been appearing since 1965, carry no institutional affiliation [26-29]. The team's main interest is the effect of the self-field of very high currents (above 300 kA) on the discharge channel and the radiant flux as a means of energy transfer in the channel. Some of the basic experimental results used by this team were contributed by N. G. Basov, who performed a series of experiments at the Lebedev Physics Institute in Moscow in the late 1960s to test high-current discharges in air as a possible laser pump [30,31].

Another contribution to this work was an interesting paper on a 50-cm discharge channel published by Yu. K. Bobrov of the Kiev Polytechnic Institute [32].

The work of Andreyev's team started with the early hydrodynamic theory of expansion of the discharge channel developed by Braginskiy and later verified experimentally by the team. The initial conclusion was that the channel expansion velocity during the first half-period of the discharge current could be determined with adequate accuracy on the assumption of constant plasma conductivity [26]. Subsequent research developed a more complex picture of the high-current discharge phenomena. The studies were concerned with the resolution of two basic problems [29]:

- The effect of the radiant flux on the development of the discharge channel.
- The gas-dynamic motion of the resulting plasma in terms of self-similar solutions and the departure from self-similarity caused by magnetic pressure (pinch effect).

N. G. Basov's team took the approach that if the gas [illegible] followed the constraint of self-similarity, the radiant flux could be taken into account in the energy balance, using the radiative heat transfer approximation [30,31]. Basov, a Soviet laser systems developer, performed a series of experiments with high-current discharges in atmospheric air primarily to study such discharges as a possible pump source for lasers.

High-current discharges under atmospheric pressure form a dense plasma ($10^{1?}$ to $10^{1?}$ cm^{-3}) with a temperature of 2 to 5 eV. With high capacitor bank energy, the plasma volume is large enough for radiation to play a major role in the energy transfer. Basov described the mechanism of the high-current discharge as follows: A cylindrical shock wave travels at a few km/s through undisturbed gas. Directly behind the shock wave front, the gas is compressed and heated to several thousand degrees. Nearer to the center of the channel is a region of high temperature (a few eV) which appears as luminosity. Since plasma conductivity rises sharply with temperature, the electrical energy is deposited mainly in the hot region; adjoining gas is then heated by conduction.

In the energy balance, the electrical energy input, E_I equals the sum of thermal energy E_T, kinetic energy of gas motion E_K, and radiant energy E_R:

$$E_I = E_T + E_K + E_R .$$

Basov computed this balance for a 20-cm discharge initiated by exploding wire from a 50-kV capacitor bank with currents of 400 kA in air at atmospheric pressure, depositing up to 25 kJ in the channel in 20 μs. E_R was computed as black-body radiation at wavelengths of over 2400 Å, the temperature and radiating surface of which are functions of time. The temperature varied from 5 to 2 eV in the 20-μs period. The channel expansion velocity was 2 to 2.5 km/s. The experimental data showed that during the first 20 μs, 60 percent of the energy stored in the capacitor bank was deposited in the plasma and 20 percent of the deposited energy was converted to light, the frequency range of which corresponded to the transparency region of air.

On the basis of these experiments, Basov obtained an approximate self-similar solution for the case when the channel expansion front is preceded by a shock wave. The approximation was based on the assumption that the photon diffusion contribution to the channel expansion velocity was less than the gas-dynamic velocity [30,31].

According to Andreyev, however, the radiative heat transfer approximation is valid only for a steep channel expansion front with a uniform temperature distribution behind the front. It is not valid if a large part of the radiant flux is carried by photons with a mean free path that is long in comparison with the width of the front. Moreover, the self-field of high currents disrupts the temperature distribution in the region between the shock-wave front and the channel.

Yu. K. Bobrov observed significant effects of the radiant flux emitted from the discharge channel plasma on the gas parameters in the shock compression region and on the velocity of the shock wave [32]. He had performed a spectroscopic analysis of the temperature and density distribution of channel plasma created by a pulse discharge in atmospheric air. The current was 10 to 50 kA, with a rise time of 1 to 22 μs, discharging across a 50-cm gap.

The experimental results were interpreted with the aid of concepts about gas dynamics of the detonation and deflagration of combustible gas applied to the conditions at the boundary of the discharge channel. The channel was regarded as the front of a cylindrical ionized wave, the velocity of which is determined by radiant heating of cold gas.

Earlier studies of spark discharge in gas (S. I. Braginskiy, I. S. Marshak, and S. L. Mandel'shtam) established a basic theoretical model of the breakdown of the discharge gap and the flow of a high pulse current. For pulse discharges in free atmosphere, the experiments revealed the presence of shock waves initiated by the spark. This served as a basis for the development of Braginskiy's gas-dynamic theory of the spark. The mechanism of the expansion of the hot spark channel can be represented by a model of nonequilibrium and equilibrium thermal waves. Bobrov considered the pressure discontinuity at the channel boundary significant in the development of gas-dynamic models of the spark discharge. The spectroscopic studies of the temperature and density distribution in a pulse channel in air were used to develop space- and time-resolved characteristics of the channel.

The characteristic feature of the radial temperature function is the flat plateau in the center of the channel and the sharp drop of temperature at the channel boundary. As the current increases from zero to maximum and the temperature decreases, the electron density increases in time. The consideration of ionization equilibria in the channel makes it possible to use the obtained electron temperature and density data in calculating the density and kinetic pressure of gas in the discharge channel. Moreover, it is possible to determine the variation of these quantities with time and at the channel boundary. Bobrov thus found, in addition to the gas density jump at the channel boundary, a pressure jump with a lower pressure in the channel. The gas pressure in the channel increased with time.

The existence of pressure discontinuities and the time functions of gas and electron density were also derived from the general principles of gas dynamics. Thus, the theoretical value of the velocity of the ionization wave, under given experimental parameters, was 420 m/s. This is close to the experimental value of dr/dt = 474 m/s

The evaluation of the ionization wave velocity based on the assumed mechanism of radiative heat exchange and electron thermal conductivity confirmed the validity of the radial distribution of gas pressure and density in the channel derived from experimental data. The front of the slow ionization wave may be likened to the deflagration front, with a corresponding pressure drop. The ionization wave front (channel boundary) acts as a moving permeable piston. The channel boundary emits gas pressure waves which transfer energy from the channel to the shock-wave region. This explains why the shock-wave front accelerates when the channel expansion velocity increases. The gas at the channel boundary moves in a direction opposite to that of the shock-wave front. The front encounters gas of higher density, increasing in time the gas density in the discharge channel. The rise of gas density with time leads to increasing electron density in the channel, although the temperature and degree of plasma ionization continue to decrease [32].

The effect of a pronounced pinch effect on the distribution of temperature, density, and pressure in a discharge channel in atmospheric air was studied by Andreyev's group with a 24-kv, 400-kA discharge current with ≈ 2 x 10^{11} A/s rise rate. The shock wave generated in the breakdown of a 1.2-cm gap between flat electrodes reached a velocity of 2 to 3 km/s [27,28]. The measurements were obtained under conditions where the magnetic self-field pressure decreased the channel expansion rate and the shock wave was detached from the "plasma piston."

The shock wave absorbs radiant flux from the plasma channel. Flux absorption can change the temperature and pressure of the gas and the velocity of the shock-wave front. The energy balance in the shock compression region was computed to determine the principal mechanism responsible for the increase in the shock-wave temperature. The intensity of the radiant flux incident on the shock wave was evaluated, taking into account the length of the radiating plasma cylinder, spectroscopic data for air, and plasma temperature and pressure distribution along the radius of the discharge channel.

The results of the computation showed that at peak current (t = 4.5 μs), the power of the radiant flux in the region of spectral opacity for air, i.e., in the region of flux absorption by the shock wave, reached 14 MW, while the power of the heat flux due to electron thermal conductivity was 41 kW. The input of electric power to the shock wave, computed from current density distribution along the radius was 790 kW. These figures show that the main contribution to the increase in temperature in the shock wave is made by the radiant flux [27].

The radial distribution of temperature obtained in these experiments was strongly inhomogeneous. The time behavior of temperature during the first half-period of the discharge current indicated that the self-similar flow pattern was strongly distorted during the expansion of the channel [28]. The distortion occurred when the shock wave reached the 2- to 3-km/s velocity and the channel plasma temperature reached (40 to 70) x 10[illegible] K. At peak current, when the pinch was most pronounced, the channel axis temperature was 72,000 K. The highest temperature gradient was observed approximately in the middle of the radius [29].

2. The Tadzhik-Chuvash Group

M. A. Sultanov of the Tadzhik State University in Dushanbe also studied high-current discharges in atmospheric air. Like the authors discussed above, Sultanov was concerned with the development of the hydrodynamic theory of discharge channel expansion and the mechanism of channel heating. Sultanov, however, stressed the contamination of the channel with plasma flares ejected from the discharge gap electrodes.

Sultanov's experiments involved peak currents of 30 kA with a rise rate of 2 x 10[illegible] A/s and current pulse length of 350 μs. The electrodes were 10 mm in diameter; the gap 10 mm long. The study focused on the explosive and shock-wave phenomena occurring in the discharge channel and at the electrode surface [33-35].

Sultanov observed that electrode flares ejected at various velocities play a major role in the variation of structural and spectroscopic characteristics of the discharge channel. In particular, such flares affect the channel expansion velocity, propagation velocity of the shock wave, temperature and electron concentration in the channel, and properties of plasma around the channel. Sultanov suggested the following mechanism of high-current pulse discharge: The breakdown of the inter-electrode gap leads to the formation of a thin current-conducting channel which absorbs a large amount of energy in a relatively short period of time. The heating and subsequent expansion of the channel is due to Joule heat. The rapid expansion of the channel is followed by the arrival of electrode flares formed by heating, melting, and vaporization of electrode surfaces. The different velocities of the electrode flares cause density perturbations in the channel and plasma heating by hydrodynamic effects [35].

The theoretical analysis was based on several earlier Soviet studies in this area, the first of which was the work of B. V. Kolachev [36], who performed discharge experiments in supersonic (M = 4.5), subsonic, and zero air flows. Kolachev noted that fast air flow considerably affected the prebreakdown process in the discharge gap and changed the shape of the discharge channel. The electrical characteristics of the discharge, such as current and voltage pulse shapes, were affected little by the air flow.

G. M. Goncharenko and I. N. Romanenko of the Chuvash State University in Cheboksary provided another early study [37]. These authors employed the self-similar flow approach to compute the channel radius expansion, based on hydrodynamic theory. In their experiments, currents varied from 2 to 70 kA and gap lengths from 1 to 20 mm. Their purpose was to determine channel parameters at pressures up to 100 atm, when instabilities develop in long gaps.

Also of interest was N. I. Fal'kovskiy's spectroscopic study of a free discharge in air, using currents of 10 to 100 kA and voltages up to 50 kV [38]. Single current pulses of 20 μs with a rise time of 3.5 to 7.5 μs were passed across a 20-mm gap. For the 100-kA current, the temperature in the channel decreased from 65,000 K at 100 ns to 30,000 K at 15 μs.

Appendix C

SOVIET RESEARCH TEAMS

Members of the Soviet research teams discussed in Appendixes A and B are listed below by type of experiment performed and institute affiliation. The principal investigator of each team is listed first.

AIR PROPAGATION EXPERIMENTS

Institute of Nuclear Physics, Electronics, and Automation
Tomsk, 1974-1978

Yu. P. Usov

A. N. Didenko	Ye. T. Protasevich
G. I. Kotlyarevskiy	A. I. Ryabchikov
Ya. Ye. Krasik	V. V. Tikhomirov
A. V. Petrov	V. A. Tuzov

Kurchatov Institute of Atomic Energy, Moscow, 1972-1973

L. I. Rudakov

D. B. Fil'kin	I. V. Novobrantsev
S. S. Kingsep	Yu. L. Sidorov
G. P. Maksimov	V. P. Smirnov

A. M. Spektor

Physico-Technical Institute, Khar'kov, 1972-1974

Yu. V. Tkach

N. P. Gadetskiy	S. S. Pushkarev
Ye. A. Lemberg	V. D. Shapiro
I. I. Magda	V. I. Shevchenko
I. N. Mondrus	G. V. Skachek
I. P. Panchenko	A. I. Zykov

Yefremov Institute of Electrophysical Equipment
Leningrad, 1977-1978

L. V. Dubovoy

V. I. Chernobrovin | A. S. Perlin
T. S. Gosteva | V. A. Rodichkin
B. A. Ivanov | V. B. Shapiro
S. A. Kolyubakin | G. R. Zablotskaya

Lebedev Physics Institute, Moscow, 1972-1973

A. A. Kolomenskiy

A. V. Agafonov | V. M. Likhachev
Yu. N. Chekhonadskiy | I. V. Sinil'shchikova
L. N. Kazanskiy | O. A. Smit
A. N. Lebedev | V. S. Voronin

Yu. T. Zozulya

ELECTRIC DISCHARGES EXPERIMENTS

Unknown Affiliation, 1965-1976

S. I. Andreyev

S. N. Leonov | R. A. Liukonen

B. I. Orlov

Lebedev Physics Institute, Moscow, 1970

N. G. Basov

B. P. Borovich | V. B. Rozanov
Yu. Yu. Smoylov | V. S. Zuyev

Kiev Polytechnic Institute, 1974

Yu. K. Bobrov

N. I. Fal'kovskiy | I. K. Fedchenko

Tadzhik State University, Dushanbe, 1974-1976

M. A. Sultanov | L. D. Semkin

Chuvash State University, Cheboksary, 1970

G. M. Goncharenko | I. N. Romanenko

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AE--*Atomnaya energiya*
FP--*Fizika plazmy*
IVUZ FIZ--*Izvestiya vysshikh uchebnykh zavedeniy, seriya fizika*
KSF--*Kratkiye soobshcheniya po fizike*
PTE--*Pribory i tekhnika eksperimenta*
VAN SSSR--*Vestnik Akademii nauk SSSR*
ZhETF--*Zhurnal eksperimental'noy i teoreticheskoy fiziki*
ZhETF, Pis'ma--*Pis'ma v Zhurnal eksperimental'noy i teoreticheskoy fiziki*
ZhPS--*Zhurnal prikladnoy spektroskopii*
ZhTF--*Zhurnal teoreticheskoy fiziki*
ZhTF, Pis'ma--*Pis'ma v Zhurnal teoreticheskoy fiziki*