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Soviet Research on Crystal Channeling of Charged Particle Beams

Simon Kassel

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This report presents an overview of Soviet research in charged particle beam channeling in crystals from 1972 to the present, and the resulting electromagnetic emission, including Soviet proposals for channeling emission lasers in the x-ray region of the spectrum. It analyzes Soviet attitudes toward crystal channeling of charged particles as a subject of research, describes performers of the research, and indicates the level of effort involved. It presents a brief history of crystal channling research, the differences between channeling and other kinds of electromagnetic radiation, the definition of the main research issues, and estimates of the potential capabilities of channeling radiation, all based on the Soviet viewpoint. It then describes Soviet proposals for laser systems utilizing the channeling radiation mechanism, and analyzes Soviet experimental work involving the observation and measurement of channeling radiation. The author concludes that the outstanding feature of Soviet research in this area is the optimistic belief of Soviet specialists in the technological potential of this research, but finds that the role of the laser proposals in Soviet planning is ambiguous. Keywords:

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Soviet Research on Crystal Channeling of Charged Particle Beams

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PREFACE

This report was prepared in the course of a continuing study of Soviet research and development on high-current, high-energy, charged particle beams and their scientific and technological applications. It is part of a program, sponsored by the Defense Advanced Research Projects Agency, which provides systematic coverage of selected areas of science and technology in the USSR as reflected in the Soviet technical literature.

The report presents an overview of Soviet research in charged particle beam channeling in crystals and the resulting electromagnetic emission, including Soviet proposals for channeling emission lasers in the x-ray region of the spectrum. The particle species discussed are primarily electrons and positrons. The materials covered in the report were published in the period from 1972 to the present.

The report is intended for specialists in the fields of high- and low-current particle beams and free electron lasers, and for R&D planners concerned with the development of new research areas.

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SUMMARY

Electromagnetic radiation emitted by electron or positron beams channeling in crystals, a phenomenon discovered only a few years ago, has been of considerable interest to a group of Soviet researchers led by M. A. Kumakhov. The latter has proposed a channeling radiation x-ray laser to be tunable within a broad frequency range by simple rotation of the crystal. Following Kumakhov's initial work, the channeling radiation concept and its potential application to the x-ray and gamma laser have become the subject of a relatively large Soviet research effort.

The Soviet perception of the feasibility of stimulated radiation based on the channeling mechanism differs from the dubious view of some Western specialists who point to the many uncertainties inherent in the interaction of high power with the fragile crystal structure. This difference in approach also extends to the channeling radiation concept itself, which in the West tends to be regarded as basic physics research, while in the USSR it is included in the category of free electron lasers (FEL). Soviet FEL specialists comment routinely on channeling radiation in their assessments of FEL development, and the Academy of Sciences links channeling radiation with FEL research in its plans and seminars.

Soviet publications on channeling radiation began appearing in the early 1970s, led by Kumakhov at the Nuclear Physics Institute of Moscow State University; in a few years this research has expanded to at least seven institutes involving nearly 90 authors. Reports on the first experimental attempts to observe channeling radiation appeared in 1977 with inconclusive results. The same year marked the publication of Kumakhov's proposal for a channeling radiation laser. The proposal estimated a current density threshold for crystal damage of 1 MA/cm^2 for a 10 MeV electron beam, and postulated a current density requirement for amplification at 10 Angstroms that was two orders of magnitude higher. Kumakhov proposed to protect the crystal from damage by rapid scanning of the electron beam. Other Soviet researchers proposed methods of bringing the generation threshold density down to as low as 1 A/cm^2.

The Soviet research effort rose steadily from 1972 to 1978 but slowly in terms of published papers and the number of active authors. The turning point came late in 1978, when a joint U.S.-Soviet experiment was performed at the Stanford Linear Accelerator Center (SLAC) facility of Stanford University. Experimental observation of spontaneous

channeling emission at SLAC was accepted as conclusive by Soviet researchers, who then significantly expanded their effort.

The expansion was qualitative as well as quantitative. While the number of authors writing on channeling radiation grew from 6 percent to 20 percent per year, experimentalists began a systematic program of measurement of the characteristic parameters of channeling radiation, and the entire community of research institutes active in this field displayed an unusually strong pattern of institutional cooperation. Perhaps the most significant change was the appearance of major Academy of Sciences leaders as supporters of the research.

Foremost among these leaders is Ye. P. Velikhov, who is acknowledged regularly in the channeling radiation reports of several institutes published since 1978. Velikhov is vice-president of the Academy of Sciences for science and technology, board member of the State Committee for Science and Technology, and a leading proponent of advanced technology development in the USSR. Another supporter of the Soviet channeling radiation effort is A. N. Skrinskiy, director of the Nuclear Physics Institute in Novosibirsk, member of the Academy of Sciences, and a prominent specialist in high-current accelerator technology. Velikhov and Skrinskiy appear to have divided their supervision and support of this research along geographic lines, Velikhov attending to the institutes located in Moscow and Khar'kov, and Skrinskiy to those in Novosibirsk and Tomsk.

The changed pattern of Soviet crystal channeling research, with a new emphasis on experimentation, inter-institutional cooperation, and participation of the top leaders of the Academy of Sciences, clearly mark it as an important project, at least from the viewpoint of the Academy itself. It is also clear that the SLAC experiment was a major event in Soviet research on crystal channeling.

The SLAC facility was important to Soviet channeling radiation research in 1978, because the domestic accelerators available for this work appear to have been inadequate for a conclusive observation of the effect.

Two such machines have been used in the Soviet experiments: the Sirius synchrotron in Tomsk and the LU linear electron-positron accelerator in Khar'kov, both rated at 1 GeV. The energy spread and divergence of either accelerator were at that time not better than 0.5 percent and 0.4 mrad, respectively, while those of the SLAC were 0.1 percent and 0.01 mrad. Thus, SLAC was at the time much more capable of establishing the reality of channeling radiation than were the facilities available to the Soviets. After 1978, the quality of the Soviet charged particle beams has been gradually improved.

It is not possible to tell if the SLAC experiment was the cause or the result of the perception on the part of Soviet scientific leadership that crystal channeling warrants an expanded research level. Equally ambiguous is the role of the laser proposals in Soviet planning: Are the Soviets serious about the practical feasibility of channeling radiation lasers, or are these proposals advanced merely to stimulate interest in crystal channeling research?

Since the proposals for channeling radiation lasers predate the SLAC experiment, one possible conjecture is that the joint experiment was deliberately undertaken, on the Soviet side, as a first step in the verification of the feasibility of the laser concept. On the other hand, the SLAC experiment could have been performed without any practical application in view and its results, enhanced by the international setting, provided the stimulus for the expanded Soviet effort.

SOVIET INSTITUTES ACTIVE IN CRYSTAL CHANNELING RESEARCH

Abbreviation	Institute
IAE	Kurchatov Institute of Atomic Energy, Moscow
IPF	Applied Physics Institute, Gor'kiy
IYaF-MGU	Nuclear Physics Institute of Moscow State University
IYaF-SOAN	Nuclear Physics Institute, Novosibirsk
IYaF-TPI	Nuclear Physics Institute of Tomsk Polytechnic Institute
KhFTI	Khar'kov Physico-technical Institute
MGU	Moscow State University
YeFI	Yerevan Physics Institute

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I. INTRODUCTION

During the past decade, the Soviets have steadily expanded their theoretical and experimental research on electromagnetic radiation generated by relativistic electrons or positrons channeling in crystals. Soviet interest in this field is attributed to the many desirable properties of this radiation, such as high spectral and angular density, broad-range tunability of radiation energy in the x-ray and gamma-ray regions, and sharp directivity. According to Soviet authors, this mechanism for generating electromagnetic radiation also offers a theoretical promise of tunable x-ray and gamma-ray lasers, although most observers currently see little probability of practical realization of such devices. Nevertheless, Soviet researchers have analyzed the possibility of producing stimulated radiation by relativistic channeled electron beams and the use of such beams in a laser that is tunable within a broad range of frequencies, including ultraviolet and soft x-ray radiation.

This report provides a broad overview of Soviet research in this area, from 1972 up to the present, emphasizing the evident Soviet tendency to direct what is essentially fundamental scientific research toward practical applications. The report is primarily intended for U.S. specialists in the fields of crystal channeling and free-electron lasers. The level of technical detail presented in the report is thought to be sufficient to alert the specialist reader to new or promising approaches, techniques, or findings of the Soviet crystal channeling research. The report does not aspire, however, to a detailed coverage of these developments that would be necessary for a close technical analysis; for that purpose, interested readers are encouraged to request the referenced original documents. While the Soviet experimental findings and theoretical predictions presented here may differ considerably from Western experience in this field, this report does not attempt to evaluate the Soviet results. Instead, the intent is to stimulate discussion that, it is hoped, will lead to a comparative assessment of the Soviet and Western approaches.

Another prospective audience of this report consists of U.S. government decisionmakers concerned with the development of new fields of applied science research. For the benefit of that audience, the report includes, whenever available, the context of Soviet crystal channeling research involving the relevant Soviet organizations, leadership, motivation, objectives, and level of effort.

The report begins with an analysis of Soviet attitudes toward crystal channeling of charged particles as a subject of research, a description of performers of this research, and an indication of the effort level involved (Sec. II). A survey of Soviet interpretation of the nature of channeling radiation in Sec. III presents a brief history of crystal channeling research, the differences between channeling and other kinds of electromagentic radiation, the definition of the main research issues, and estimates of the potential capabilities of channeling radiation, all based on the Soviet viewpoint. This is followed in Sec. IV by a detailed description of Soviet proposals for laser systems utilizing the channeling radiation mechanism. Section V analyzes Soviet experimental work involving the observation and measurement of channeling radiation. For readers interested in the theoretical background of Soviet crystal channeling research, App. A provides a somewhat more detailed account of each of the main institutional groups engaged in this research. Appendix B lists the personnel of the Soviet research teams as reflected in the published literature.

II. THE SCOPE AND STRUCTURE OF SOVIET CRYSTAL CHANNELING RESEARCH

Soviet scientists who are engaged in channeling radiation research consider it related to research on free electron lasers (FEL), the crystal lattice representing a variant of the periodic structure interacting with the charged particle beam present in all FEL concepts. Thus, in a general classification of FEL types based on the shape of the field interacting with the electron trajectory, channeling radiation is regarded as a type of FEL mechanism based on a transversely inhomogeneous field [1].

In accordance with this approach, the Academy of Sciences appears to link FEL and channeling radiation in its organizational planning. For example, the Coherent and Nonlinear Optics Problem Council of the Academy of Sciences, USSR, holds periodic sessions on the subject of the future development of research designated as "free electron lasers and channeled particle radiation." The subject of "FEL and radiation by channeled particles" was also included in the agendas of the forthcoming XI All-Union Conference on Coherent and Nonlinear Optics and the III All-Union Seminar on "High-frequency Relativistic Electronics" [2].

The Soviet view that channeling radiation represents an integral part of the array of FEL mechanisms available for development is also reflected in the research plans and opinions of leading specialists.

A. V. Gaponov of the Applied Physics Institute in Gor'kiy, principal Soviet developer of relativistic high-power microwave devices, has stated that the near-term aims of FEL research are to determine the main FEL parameters, such as power, efficiency, and coherence, for the millimeter, submillimeter, infrared, optical, ultraviolet, and x-ray wavelength regions. Gaponov divided the electromagnetic spectrum in the following way: The submillimeter region can probably be covered by high-current accelerators and magnetic systems (cyclotron resonance maser, ubitron, etc.). The optical region has a promising candidate in the mode-locking FEL. The x-ray region is appropriate for channeling of charged particles, although the feasibility of stimulated radiation by this mechanism is not clear [2].

M. V. Fedorov, leading FEL specialist of the Lebedev Physics Institute, has stated that the feasibility assessment of crystal channeling of particles as a radiation source is a unique problem area and a subject of growing interest. However, according to Fedorov, the physics of particle channeling is significantly different from electron interaction with wigglers or from stimulated Compton scattering, even though it is related to FEL [3].

V. N. Bayer, theoretician of the Nuclear Physics Institute in Novosibirsk, views the study of relativistic channeling particles, radiation in periodic structures carried out in connection with FEL development, and the developing laser technology, as parts of a research effort concerned with the possibility of obtaining high electromagnetic field intensities [4].

M. A. Kumakhov of the Nuclear Physics Institute, Moscow State University, one of the authors of the basic theory of channeling radiation, considers the latter significantly superior, in terms of the most important parameters, to other known kinds of radiation, in the region from hard x-rays to hard gamma-rays [2].

I. I. Miroshnichenko of the Nuclear Physics Institute in Tomsk, principal Soviet experimentalist in channeling radiation, believes that the promising characteristics of the radiation, and particularly the spectral peak density and the high degree of monochromaticity, may lead to unexpected practical applications [5].

Table 1 lists Soviet institutes and team leaders in the crystal channeling field.

In addition to the above, V. L. Bratman and G. M. Genkin of the Applied Physics Institute in Gor'kiy, while primarily engaged in FEL research, have contributed some overview and theoretical papers on the subject of crystal channeling.

Soviet research in this area began with the theoretical work of M. A. Kumakhov of IYaF-MGU, also associated with IAE. While the basic theory of charged particle channeling in crystals was formulated by the Danish physicist J. Lindhard in 1965, Kumakhov claims to have predicted and formulated the theory of spontaneous radiation by relativistic channeling particles in x-ray and gamma-ray regions [6]. He has also performed a detailed analysis of angular, spectral, and polarization properties of dipole radiation from channeling particles and analyzed the stimulated radiation effect [7–12].

Kumakhov's pioneering work has been taken up by specialized teams in the various listed institutes. The publications of these institutes were mainly theoretical until the mid-1970s, when KhFTI and IYaF-TPI began the experimental search for observable evidence of channeling radiation. Their early observations were not conclusively accepted as evidence, however, until a joint U.S.-Soviet experiment was performed with the participation of KhFTI at the Stanford Linear Accelerator Center (SLAC) facility of Stanford University in November-December 1978. The SLAC experiment appears to be a

Table 1

STRUCTURE OF SOVIET CRYSTAL CHANNELING RESEARCH

Institute	Research Orientation	Team Leadership
Nuclear Physics Institute of Moscow State University (IYaF-MGU)	theoretical	M. A. Kumakhov
Kurchatov Institute of Atomic Energy (IAE), Moscow	theoretical	V. A. Bazylyev and N. K. Zhevago
Moscow State University (MGU)	theoretical	A. V. Andreyev and S. A. Akhmanov
Khar'kov Physico-technical Institute (KhFTI)	theoretical experimental experimental	A. I. Akhiyezer I. A. Grishayev I. I. Miroshnichenko
Yerevan Physics Institute (YeFI)	experimental	R. O. Avakyan
Nuclear Physics Institute (IYaF-SOAN), Novosibirsk	theoretical	V. N. Bayer
Nuclear Physics Institute, Tomsk Polytechnic Institute (IYaF-T[illegible])	experimental	S. A. Vorob'yev and A. P. Potylitsyn

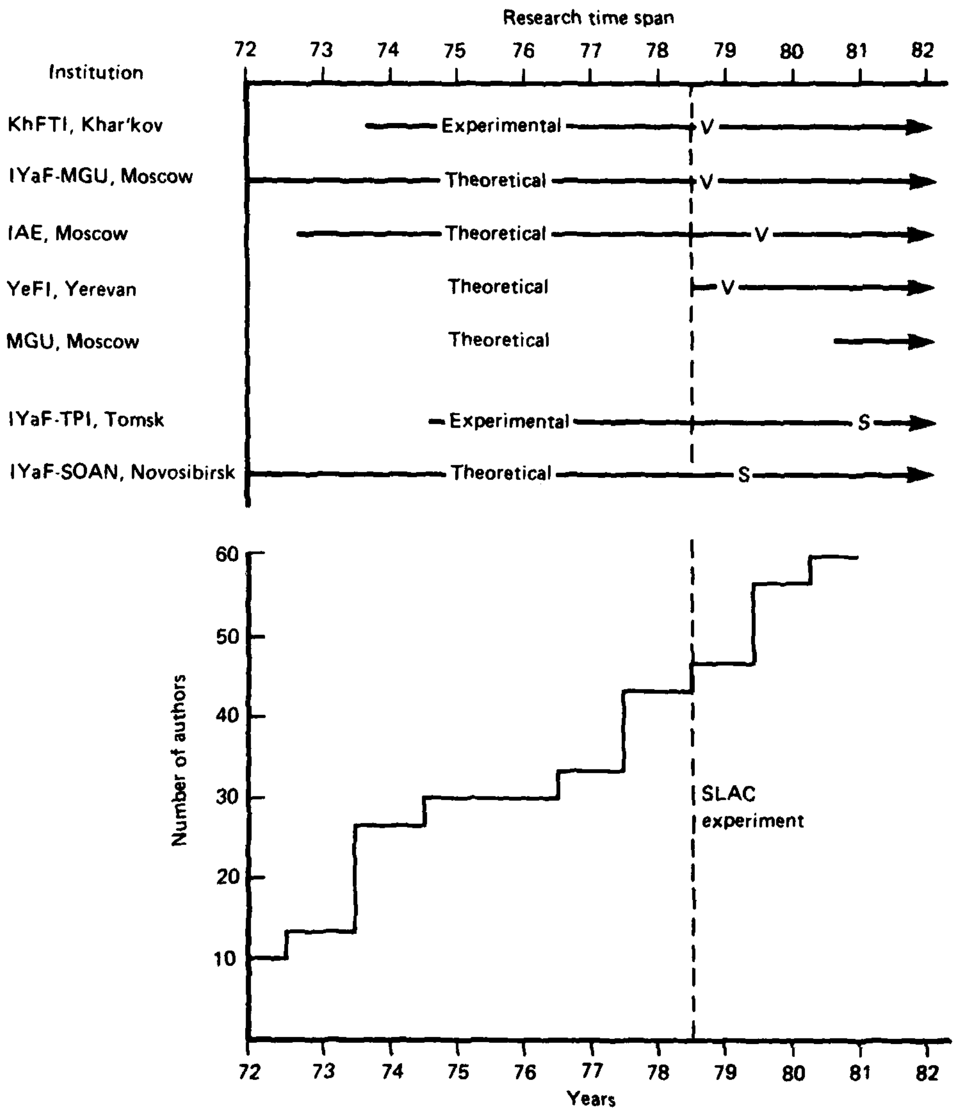
turning point in Soviet research on channeling radiation. Since that experiment, three important changes became clearly apparent in that activity:

1. Major Soviet figures prominent in pulsed power and particle accelerator development began supporting the research. The papers on channeling radiation published by the western institutes comprising IYaF-MGU, IAE, KhFTI, and MGU began to include acknowledgments of supervision by Ye. P. Velikhov, vice-president of Academy of Sciences, USSR. Similarly, the two Siberian institutes, IYaF-TPI and IYaF-SOAN began referring to A. N. Skrinskiy, director of the latter, as supporter of the work.
2. Intensive experimental work was begun by KhFTI and IYaF-TPI using their own facilities to provide a quantitative analysis of the observed radiation. At the same time, the growth rate of authors publishing in this field rose from 6 to 20 percent per year.
3. Prior to 1978, channeling particle research manifested relatively little inter-institutional cooperation, a condition typical

of Soviet practice; after 1978, however, there has been an intensive cooperation linking all of the above institutes with joint co-authorship, consultations, and technical assistance.

Figure 1 illustrates these developments; it shows graphically the years of relevant activity of each of the seven institutes involved, the beginning of sponsorship of this research by Velikhov in the Western USSR and by Skrinskiy in Siberia, the date of the joint U.S.-Soviet channeling radiation experiment performed at SLAC, and the rise in the Soviet level of effort expended on this research in terms of the number of publishing authors.

There is no conclusive evidence that the SLAC experiment was the direct or even the main cause of the expansion of Soviet channeling radiation research. Other research results obtained in the West and in the Soviet Union could have influenced Soviet decisionmakers to step up the research, and thus the joint international venture could be interpreted as a result, rather than a cause, of enhanced Soviet interest in the problems of channeling radiation. Nevertheless, the remarkable conjunction of events that took place in Soviet channeling radiation research is strongly suggestive of the pivotal role played by the SLAC experiment.



NOTE: V - first appearance of Velikhov
S - first appearance of Skrinskiy
as sponsors of research

Fig. 1—History of soviet channeling emission research institutions, leadership, and effort level

III. SOVIET VIEWS ON THE NATURE OF CHANNELING RADIATION

Among Soviet specialists in crystal channeling research, M. A. Kumakhov clearly emerges as the leading Soviet theoretician, exponent, and advocate of this fairly narrow field. Consequently, many of the views on the history, nature, and utility of the crystal channeling effect to be found in Soviet literature are Kumakhov's own. Kumakhov claims a share of the pioneering work in this field for himself and for Soviet scientists.

Thus, according to Kumakhov [6,89], in 1954, Soviet physicist M. M. Bredov and others observed anomalously long paths of keV ions in crystal targets and determined that they were a function of the initial ion energy and were not due to diffusion. The same effect was reported in 1960 by J. A. Davies et al. In 1963, M. T. Robinson and O. S. Oen performed computer simulation of the passage of ions in a copper crystal and concluded that ions moving at a small angle to the crystal lattice had a much longer mean free path than ions moving chaotically. They named the effect "channeling" [89]. In 1964, J. Lindhard formulated the classical theory of the *channeling effect*, introduced the concept of atomic strings and planes, and determined the critical angle within which the channeling effect was possible. In 1976, Kumakhov postulated a new effect: spontaneous radiation from relativistic channeling particles in the x-ray and gamma-ray ranges. The theory of this effect was published in 1977 by Soviet authors Kumakhov, Beloshitskiy, Bazylev, Zhevago, Akhiyezer, Boldyshev, Shul'ga, and Podgoretskiy, and by U.S. authors Terhune and Pantell. The first indication that the effect existed for electrons was given in 1978 by Agan'yants. The joint U.S.-Soviet experiment at Stanford University in the same year led to the discovery of spontaneous gamma radiation from 1–14 GeV positrons in planar channeling through a diamond single crystal. In 1979, the effect was measured by Datz et al., for low-energy (28–56 MeV) electrons and positrons [6].

According to Soviet authors, channeling radiation in crystals represents a new type of electromagnetic radiation. Kumakhov claimed to have shown that relativistic electrons and positrons channeling in single crystals should emit spontaneous electromagnetic radiation from transitions between states formed in the channel potential [7]. According to Miroshnichenko, the peak spectral density of this radiation considerably exceeds bremsstrahlung density which, together with the high degree of monochromaticity and polarization, opens up unexpected opportunities for practical applications. Kumakhov's analytic expression for the spectral distribution of channeling radiation, based on the harmonic potential approximation, also indicated that channeling radiation has a high degree of monochromaticity [14].

The characteristic depth of the channel potential is from 100 to 1000 eV for axial channels, and approximately an order of magnitude less *for planar channels (the potential increases with increasing charge of* the target nucleus). The number of energy levels in the potential well is small, increasing with the relativistic mass of the particle. The distance between these levels amounts to several eV, so that the transition frequencies lie within the optical region. The Doppler shift occurring at small angles to the beam direction, and the relativistic motion effect, displace the radiation frequency toward the x-ray and gamma-ray region.

The physical nature of channeling radiation differs markedly from other types of electromagnetic radiation generated by charged particle interactions. Kumakhov illustrates some of the basic differences among these types of radiation in Table 2.

Channeling radiation by ultrarelativistic electrons and positrons occurs mainly in the x-ray and gamma-ray regions. According to Bazylev, its intensity is so high that it can considerably exceed that of

Table 2

CHANNELING RADIATION COMPARED WITH OTHER TYPES OF RADIATION [13]

	Radiation type				
Property	*Channeling*	*Cherenkov*	*Bremsstrahlung*	*Synchrotron*	*Undulator*
Mass dependence of intensity	M^2	none	M^{-2}	M^{-2}	none
Energy dependence of intensity	E^2	none for relativist	E	E^2	E^2
Energy dependence of max.frequency	$E^{3/2}$	—	E	E	E^2
Mass dependence of max. frequency	$M^{1/2}$	—	—	M^{-1}	none
Emission threshold	present	present	none	none	none

synchrotron, bremsstrahlung, and transition radiation [16]. Kumakhov explains the high value of channeling radiation intensity as follows:

The intensity of radiation from a relativistic particle is inversely proportional to the radius of curvature of the particle in the crystal lattice field. Since the field gradients of atomic strings and planes are about 10^{11-12} eV/cm, the radius of curvature is very small. Therefore the radiation intensity is very high, about 6 to 9 orders of magnitude higher than that achieved in modern synchrotrons [14].

Another parameter used in comparisons of channeling radiation with other types of radiation was the effective absorption cross-section. Kumakhov defined it as resonance cross-section averaged over the spectral distribution of the given radiation type [13]. Thus the ratio of the effective photo-absorption cross-section in channeling to that in bremsstrahlung is more than 1000 for a 100 MeV beam. The channeling effective cross-section is also much higher than the synchrotron radiation cross-section [14].

The large effective absorption cross-sections of channeling radiation, and the possibility of exciting practically all nuclear transitions for particle beam energies from 1 to 10 GeV, led Kumakhov to conclude that channeling radiation opens up possibilities in nuclear physics that are new in principle [13].

Kumakhov was very optimistic about the potential of channeling radiation, particularly with regard to the feasibility of increasing its frequency and intensity. Thus, according to his theoretical predictions, for the same beam energy, one can change the maximum radiation frequency by a factor of 3 to 4 by changing the crystal orientation. By changing the crystal itself, frequency can be varied by an order, and radiation intensity by four orders of magnitude. At the maximum radiation frequency, the radiation intensity is approximately two orders of magnitude above the bremsstrahlung background for 1 GeV beams [13,14].

In comparison with planar, axial channeling has a lower monochromaticity, but much higher radiation intensity [14]. The radiation from electrons is at higher frequency and is more intense than that of positrons. However, the linewidth of electron radiation is broader, and the probability of capture by the channeling mode is lower [12].

At ultrarelativistic energies of the particle beam, spontaneous radiation power exceeds that of bremsstrahlung of well-channeled particles and focuses the beam, since the radiation damps out the amplitude of transverse oscillations. In planar channeling of positrons in silicon and tungsten, the focusing effect is stronger than multiple scattering by valence electrons for energies above 10 GeV (silicon) and 1 GeV (tungsten). This results in superfocused beams. The effect may in principle make it possible to accelerate channeled positrons by external fields, such as laser beams [38,14].

Kumakhov also considered stimulated transitions in crystal channeling, suggesting that it is possible to obtain coherent amplification of various frequencies within the region of crystal transparency, depending on the selected direction of amplification in relation to the direction of motion [7].

IV. CRYSTAL CHANNELING X-RAY LASERS

The FEL emission wavelength can be shortened by decreasing the period of the magnetic undulator field. However, it is fairly difficult to make it shorter than 1 cm. A much shorter periodic structure is available in crystals; therefore the channeling of electrons in crystal structures can produce a significantly shorter radiation wavelength than that obtained in magnetic undulators for the same electron energy. However, according to Didenko, stimulated radiation requires much higher beam current densities in such a case, leading to crystal damage [17].

The attractive property of lasers based on the crystal channeling mechanism is continuous tunability of the generated frequencies achieved by simple rotation of the single crystal about the direction of the incident beam. The frequency can also be varied by changing the crystallographic direction of channeling, or by changing the target crystal: Higher Z targets correspond to higher frequencies. Kumakhov has stated that the high gain per pass at high beam currents makes operation without mirrors feasible [7].

These lasers proposed by various Soviet researchers are claimed to have an advantage over free electron lasers with magnetic undulators in that the same gain can be obtained in the channeling radiation laser for particle beam energy two or three orders of magnitude lower than that required in the undulator. Furthermore, such an x-ray laser may be possible at reasonable energies [12].

Specific proposals for x-ray lasers based on this principle have been published by G. V. Kovalev, of unknown affiliation, by members of Moscow State University, and by Kumakhov. The basic problem considered in all these proposals is the current density requirement and its compatibility with the current state of the art in particle beam generation and with the stability of the crystal.

According to Kovalev, for the deep ultraviolet and the x-ray regions, the required channeled electron beam current density is feasible to achieve and should amount to 1.6 MA/cm^2 [18]. Kumakhov gives the required density in the x-ray region as 1 MA/cm^2 [12]. Elsewhere he claims that amplification at 10 Angstroms can be achieved with 100 MA/cm^2, provided the beam energy spread can be kept within 0.01 percent. According to Kumakhov, such current density can be reached at this time for a particle energy of 10 MeV. However, he says that for this energy the crystal can withstand beams only up to 1 MA/cm^2.

Storage rings can be used to reach 100 MA/cm^2 densities in the energy region of the order of 1 GeV [8,7].

In submitting these proposals, their authors also suggest ways to relax the beam density requirement. Together with increasing beam monochromaticity, Kovalev proposes the use of layered structures at high beam energies when the dipole approximation is not valid. In such a case, the threshold beam density would be 1.6 A/cm^2 [18]. Kumakhov would prevent crystal damage by fast scanning of the particle beam over the crystal [12]. To amplify only the forward radiation and to reduce the beam effect on the crystal, the beam should be scanned along the crystallographic planes [8].

Kovalev's proposal was based on the work of Kumakhov [13], Bazylev [19], and Vorob'yev [20]. He considered stimulated radiation of 10 eV photons in a laser without a mirror, where the direction of stimulated radiation is determined by minimum damping or by the geometry of the active medium. By increasing the electron beam energy, Kovalev expected in principle to achieve stimulated radiation in the deep ultraviolet or even in the x-ray region [18].

According to Kumakhov, there are no sufficiently powerful sources of hard gamma quanta (0.1 to 100 MeV) at this time. Synchrotron radiation falls off exponentially in this range and the bremsstrahlung spectral distribution is washed out. Spontaneous radiation is free of these problems. Above electron energies of 1 GeV, not only the differential, but also the integral radiation intensity are higher than bremsstrahlung density by an order of magnitude. The difference is two orders of magnitude above 10 GeV. Thus at high energies there is a very fast transfer of energy from electrons to photons; i.e., a superpowerful radiation takes place [12].

Channeling radiation of heavier particles, such as protons or mesons, would have a considerably lower frequency and intensity. If such a radiation were to be detected, it could be used to set up population inversion, establishing conditions for a coherent gamma cascade (a gamma laser). A three-level system with a metastable upper level (10^{-10} to 10^{-13} sec) and a sufficiently long relaxation time at the middle level (1 sec) could be used. Kumakhov provides the following expression for the pumping requirement of such a system:

$$t \, \sigma_{eff} \, N / S > 1 \, ,$$

where σ_{eff} is effective absorption cross-section, t is pumping time, N is the number of photons per second generated by the beam in crystal, and S is beam cross-section. For a beam current of 100 mA and crystal thickness of 1 mm, 10^{18} photons can be generated. Therefore, given

$\sigma_{eff} = 10^{-26}\ cm^{-2}$, $S = 10\mu^2$, and t = 100 sec, the pumping requirement can be met for the 100 keV transitions.

For 100 keV transitions, the pumping efficiency of channeling radiation is by four orders of magnitude higher than in the most powerful pulsed reactors, and six orders higher than that possible with synchrotron radiation [14].

The most systematic theoretical treatment of the problem of stimulated channeling radiation as a possible x-ray laser mechanism has been presented by A. V. Andreyev and others of Moscow State University (MGU). At the December 1980 meeting of the Scientific Problem Council of the Academy of Sciences, Andreyev's results were presented as a specific method of establishing a population inversion between the transverse-energy levels of a channeled electron and a mechanism of creating distributed feedback for x-ray radiation generation [2].

The inversion mechanism proposed by the MGU researchers was based on the difference in the dechanneling lengths of particles at different transverse-energy levels. They computed the partial electron dechanneling lengths at different levels, determined the threshold conditions of optical and x-ray radiation generation, and showed that a gain of unity per cm can be reached for electron current density of the order of kA/cm^2. This they considered proof of feasibility of a channeled electron laser. The objective of their research was to decrease the x-ray generation threshold, to avoid the mirror problem, and to reduce sharply the absorption coefficient [25].

According to Andreyev's theory, a channeled beam could generate x-ray radiation with a wavelength of a few Angstroms with the absorption coefficient reaching values of the order of 10–100 per cm and requiring a higher electron current density. However, this problem could be alleviated by two factors that significantly affect the propagation of x-ray radiation in perfect crystals: a sharp drop in absorption due to the Borrmann effect [21] and a distributed feedback due to dynamic scattering [22–24].

The diamond-like crystal lattice has strongly reflecting (220) planes. The Bragg diffraction conditions can always be satisfied by a suitable orientation of the beam channeled in the (010) plane. A longer mean free path can be achieved by multiple wave diffraction, or the anomalous Borrmann effect. When the Borrmann effect is taken into account, Andreyev expects the critical electron current density to be 10 kA/cm^2 [25].

Andreyev obtained the above current threshold value on the assumption of a single-mode potential well. In a later paper [26], Andreyev concluded that to obtain laser action, the most effective are the energy levels of the multimode (multipeaked) interplanar potential, since the resulting increased partial dechanneling length and narrowed energy level width decrease the generation threshold. The even-numbered levels in single-mode symmetric interplanar potentials have this property, so that it is possible to obtain population inversion between even and odd levels by appropriate selection of the crystal thickness. The disadvantage of such a scheme is the relatively short dechanneling length at the two selected levels. This is due to the fact that in a single-mode potential well, the wave function peaks for the first few levels with the most effective inversion mechanism are reached over a distance between levels comparable with the thermal oscillation energy of the atoms.

This method of achieving population inversion can be improved by using channeling planes with multimode potentials, such as the (111) plane in the diamond-like lattice. To obtain population inversion, the crystal thickness should lie between the partial electron dechanneling lengths of the upper and lower working levels.

Andreyev claims that the above considerations significantly reduce the threshold electron current density necessary for the stimulated emission gain to exceed losses. Thus, for the multimode potential, as compared with the single-mode potential, the threshold current requirement is lower by at least an order of magnitude. In the optical region, the threshold current density is a fully realizable 100 A/cm^2.

Andreyev concluded that realistic possibilities exist to achieve stimulated radiation, particularly in the optical range, by virtue of the difference in partial dechanneling lengths of the specified energy levels. Of particular interest are multimode interplanar potentials [26].

L. V. Rodygin and A. V. Smorgonskiy of the Applied Physics Institute at Gor'kiy have provided a general evaluation of the excitation conditions for free electron lasers on the basis of currently available electron accelerators. In line with Soviet practice, they have included channeling radiation as a possible variant of a free electron laser. Within the limitation of a relatively low energy electron beam, their evaluation turned out to be more negative than that of Soviet researchers directly engaged in channeling radiation work. They have assumed a 2 MeV accelerator with beam energy spread of 1 percent, a silicon single crystal 10☐ thick, and two possible directions of output radiation, downstream and upstream of the electron beam. For a downstream radiation at a wavelength of 100 Å, the efficiency was 1 percent and the required current density was 3×10^{12} A/cm^2. For the upstream radiation, the efficiency was 10 percent and the current density was as high as 10^{15} A/cm^2. Their conclusion was that, as far as a simple model is considered, stimulated channeling radiation is not a likely candidate for a free electron laser [27].

Bratman and Genkin of IPF, in discussing radiation by electrons moving above or through crystals with domain structure (see App. A), have also considered a free electron laser based on this structure.

Theoretically, an FEL with a beam moving above the domain structure is possible only with low-energy electron beams (0.5 to 1 MeV) generated by high-current pulse line injectors. For wavelengths from 100 to 5 μ, such an FEL would generate an output power from 1 to 10 MW with a 1 percent electronic efficiency. The electron beam necessary for this purpose, however, must simultaneously meet the requirements of high current density of 10^5 to 10^6 A/cm^2 and low energy spread of 0.01 [28]. For a beam moving through a crystal with domain structure, the generation of stimulated radiation requires an electron beam with similar parameters [17].

V. EXPERIMENTAL OBSERVATION AND MEASUREMENT OF CHANNELING RADIATION

Systematic experimental work aimed at the observation and measurement of channeling radiation has been carried on continuously, at least since 1976, by two Soviet institutes: the Nuclear Physics Institute of the Tomsk Polytechnic Institute (IYaF-TPI) and the Khar'kov Physico-technical Institue (KhFTI). IYaF-TPI used its 1 GeV Sirius synchrotron machine for this purpose, while KhFTI used a 2 GeV linear electron-positron accelerator. During the years 1977 and 1978, both institutes claimed successful observation of channeling radiation in their experiments [29,30]. However, both claims were challenged in later publications [31,5]. It is of considerable interest to note that conclusive acceptance of experimental observation of channeling radiation was forthcoming in Soviet reports only after the joint U.S.-Soviet experiment was performed using the SLAC facility at Stanford University in November and December 1978. The SLAC experiment was performed by SLAC scientists together with *channeling radiation* experimentalists of KhFTI and the Yerevan Physics Institute (YeFI). The work had the direct support of Soviet scientific leaders Ye. P. Velikhov and M. A. Markov, and of a number of U.S. leaders, such as W. Panofsky, R. Taylor, and others [5,32].

If the SLAC experiment was a turning point in Soviet research on channeling radiation, it was particularly so in the work of the KhFTI team, which dedicated a large portion of its subsequent activities to the analysis and interpretation of its results. It is possible that the evidence provided there was more credible because of superior quality of the SLAC beam. The two characteristic parameters cited in Soviet reports throughout the channeling radiation research were angular divergence and energy spread of the charged particle beams used in the channeling experiments. The electron beam of the Sirius synchrotron was used by IYaF-TPI at the energy level of 800 to 900 MeV; its energy spread was consistently reported at 0.5 percent, and its divergence was gradually reduced from 0.5 mrad in 1978 to 0.1 mrad in 1981. The electron and positron beams of the LUE accelerator of KhFTI had a 1 percent energy spread and from 0.1 to 0.4 mrad divergence at 1 GeV in 1977-1979. In 1980, they were reported as having 0.2 percent energy spread and 0.07 mrad divergence [33]. The SLAC positron beam had 0.1 percent energy spread and 0.01 mrad divergence [32].

The SLAC experiment was reported as being essentially limited to the first step of the research process: the first actual observation of channeling radiation. This was to be followed by detailed investigation of the observed phenomenon, primarily the measurements of the basic characteristics of channeling radiation. Both main Soviet teams have launched this phase of the research. The work of each team will now be briefly described.

THE KhFTI TEAM

Two phases of research on channeling radiation are discernible at KhFTI. The first phase, from 1972 to 1979, was led by G. D. Kovalenko and I. A. Grishayev. In their early papers they have investigated coherent bremsstrahlung of electrons and positrons impinging on silicon and niobium crystals, and the effect of rotation of crystal axis within a mrad angle giving rise to channeling of the charged particles. The high divergence of the particle beams, of the order of a mrad, adversely affected the validity of their results [34]. An improved beam of the LU 2 GeV linear accelerator with a divergence of 0.2 mrad permitted them to measure bremsstrahlung spectra of 1 GeV electrons and positrons in silicon, germanium, and niobium crystals, indicating that there is a significant difference in the bremsstrahlung cross-sections for electrons and positrons in axial channeling [35].

In 1978, the team announced experimental observation of channeling radiation predicted by Kumakhov [14,13], Bazylev [19], and Akhiyezer [36], and suggested the possible feasibility of intense x-ray and gamma-ray sources from ultrarelativistic charged particles channeled in single crystals. Their theoretical computations indicated that channeling radiation can be expected in the gamma-ray region below 2 MeV. The experiments consisted of measuring the radiation spectrum of 1 GeV positrons channeling in a silicon single crystal with a thickness of 50 μ along the <111> axis. The radiation energy was observed to be three times higher when the angle between the beam and the <111> axis was zero than when it was 0.006 rad [30]. The result of this experiment was later considered by KhFTI as ambiguous [5].

The investigation of the positron spectrum was followed by an experiment with electrons channeling in silicon. The effect of axial and planar channeling on gamma radiation of electrons was measured in the radiation energy region below 40 MeV. In the experiment, 1.2 GeV electrons with a 1 percent energy spread and 0.1 mrad divergence impinged on a 250 μ thick silicon single crystal. The electrons moved in the crystal parallel to the <111> axis (axial channeling) and to the (112) plane (planar channeling), as well as in a totally disoriented crystal (2 degrees vertically and horizontally from the aligned position). The results showed that the radiation of electrons moving in oriented crystal had much higher intensity than in disoriented crystal: by a factor of 20 for electrons moving parallel to the <111> axis and by a factor of 10 for electrons moving parallel to the (112) plane. However, even if the angular divergence of the electron beam was less than critical, the contribution of coherent bremsstrahlung to the measured spectrum could still be significant. The team's authors called for additional research to determine conclusively the nature of the observed radiation [37].

The above results were again criticized, this time by IYaF-TPI, on the ground that the experimental data were inadequate for a quantitative comparison with theory [31].

In the same year, it appears that further experimental work in this area was taken over by another KhFTI team under I. I. Miroshnichenko. The new team represented the Soviet side in the joint U.S.-Soviet experiment at Stanford, and the first results were published by KhFTI in 1979 [5]. Miroshnichenko's team was also responsible for the subsequent reports on channeling radiation experiments of KhFTI.

According to the authors of the Soviet report [5], the experiment provided the first measurements of the energy spectra of electromagnetic radiation from planar and axial channeling by high-energy positrons in crystals. The same report also announced the observation of a new effect: the radiation of relativistic channeled positrons, as predicted by M. A. Kumakhov, capable of "unexpected practical applications." The report added, as noted above, that previous experiments [30,29] attempting to observe spontaneous radiation failed to yield unambiguous results.

The experimental equipment consisted of the SLAC linear accelerator generating a positron beam at 4, 6, 10, and 14 GeV, and diamond crystals with a thickness of 0.7×10^{-3} and 5.2×10^{-3} of a radiation length. The positron beam had an angular divergence of 10^{-5} rad. The peak radiation energy ranged from 23 MeV for the 4 GeV beam to 120 MeV for the 14 GeV beam. These values were in good agreement with Kumakhov's theory and satisfied the $E^{3/2}$ dependence. It was therefore concluded that the observed radiation was radiation from channeling positrons.

A formal analysis of the SLAC experimental results was published in 1982 by KhFTI [32]. In the same year, Miroshnichenko also published a follow-up report of a systematic experimental and theoretical study of the radiation by positrons with the same energies as in the SLAC experiment propagating near the crystallographic planes of a diamond single crystal 80 μu thick [38]. One objective of the study was the verification of a hypothesis by the theoretical team of KhFTI which attributed the observed radiation to particles moving above the potential barrier as well as to channeling [39]. Miroshnichenko repeated the statement that the considerable interest in this topic was generated by the possibility of practical applications due to the "exceptional properties [of the observed radiation] of high intensity, monochromaticity, and polarization."

The following factors were analyzed: non-dipole radiation, radiation as a function of beam angle of incidence, the role of dechanneling and multiple scattering, dependence on the potential between crystal planes, and dependence of radiation on the angular distribution of the particle beam in the crystal. The data for the experimental part of this study were taken from the SLAC experiment.

In 1980, Miroshnichenko performed an independent experiment with the KhFTI linear accelerator to study the dynamics and radiation of ultrarelativistic particles in crystals as a step towards the "practical utilization of channeling radiation."

The experiment involved the propagation of 1.2 GeV electrons in diamond (0.3 mm) and silicon (0.24 mm) single crystals near the <110> axis and (100) plane, measuring the emitted gamma radiation. The divergence of the beam was 7×10^{-5} rad and the energy spread was 0.2 percent.

The results of the measurements indicated a number of characteristic properties of the radiation spectra: The spectral distribution of radiation intensity had a maximum near photon energy of 20 MeV for diamond and 30 MeV for silicon. At peak intensity, the ratio of channeling radiation in crystal to bremsstrahlung in amorphous material was 16 to 17 for silicon and 20 to 25 for diamond. There were narrow peaks at photon energies in the region from several MeV to several tens of MeV. When the beam incidence angle was greater than critical, the observed radiation was interpreted as being mainly due to motion above the potential barrier [33].

THE IYaF-TPI TEAM

IYaF-TPI of Tomsk is part of a large complex of research institutes heavily involved in pulsed power development. For several decades, it has been pursuing both high-current and low-current, high-energy charged-particle acceleration studies and the development of related equipment. The Tomsk team's work on channeling radiation has been carried on roughly parallel to that of KhFTI, over the same period of time, but independently of the U.S. SLAC experiments. On the other hand, the Tomsk team has been cooperating in this work with theoretical teams from IAE, MGU, and YeFI, including the principal theoretician of the channeling radiation concept, M. A. Kumakhov. The most recent experiments of this team have been performed with direct participation of the director of IYaF-TPI, A. N. Didenko.

The Tomsk team has been exclusively concerned with electrons as the particle species used in the channeling experiments. The earliest available experimental research reports of the Tomsk team indicate direct concern with channeling radiation by electrons propagating in crystals. The team's authors claim to be the first to report experimental observation of channeling radiation in 1975, calling it a new type of electron radiation in a crystal due to transitions between discrete levels of transverse coupled motion in channeling [29].

A report published in 1976 notes that the study of propagation of fast electrons in single crystals revealed a number of phenomena associated with the relative orientation between charged particles and the crystal lattice. It was shown that, together with the focusing effect, a part of the electron beam becomes, under certain conditions, coupled to the atom strings of the lattice and undergoes an anomalously deep penetration into the crystal. The reported experiment has explored the possibility of planar channeling of 0.8 to 2.0 MeV electrons, produced by a 2.5 MeV ESG electrostatic generator, in a single crystal. The angular distribution of electrons beyond the crystal was studied, using a silicon single crystal 7 μ thick. The distribution was measured for the angle of rotation about the <100> axis and the angle of inclination to the (011) plane relative to the beam direction [40].

In another early experiment, the Tomsk team obtained spectra and orientation dependencies of the photon yield indicating the existence of channeling radiation in the 800 MeV electron beam energy range. In the experiment, the internal 800 MeV electron beam of the Tomsk synchrotron, with divergence of 0.5 mrad and energy spread of 0.5 percent, was used with a diamond single crystal 0.016 radiation lengths (2 mm) thick. The electron momentum was in the (001) plane and coincided with the <110> axis. The spectral density of photon radiation was higher by a factor of 7 than that of coherent bremsstrahlung, and its dependence on the orientation angle indicated that channeling radiation dominated coherent bremsstrahlung [29]. However, as in the case of the early KhFTI data, these results were considered ambiguous by the SLAC team [5].

In a later series of experiments, published in 1978, the preliminary results of amplifying spectral density of low-energy gamma quanta indicated the possibility of gamma radiation by channeled electrons [41].

According to the theory of coherent bremsstrahlung, the yield of gamma quanta in any spectral region is minimum when the direction of the electron beam coincides with the crystal axis. However, such an orientation of beam and crystal axis gives rise to the channeling radiation effect, whereby the electrons moving in the crystal are coupled to individual atom strings [41].

The experiments were performed to study gamma quantum yield in the low-energy bremsstrahlung spectrum for 800 MeV electron beams. The objectives were to determine the region of applicability of the coherent bremsstrahlung theory and to search for features in this region that may be due to the electron channeling effect. The internal electron beam of the Tomsk Sirius synchrotron was used with a $10 \times 6 \times 2$ mm diamond single crystal. The measurements were performed for the electron beam momentum lying in the (001) plane at an angle θ to the <110> crystal axis.

Gamma spectrum was measured for $\theta = 0$ and $\theta = 1.18°$. A sharp peak of gamma radiation was observed at $h\omega < 60$ MeV for the zero angle, as compared with $\theta = 1.18°$. This result could not be explained by multiple scattering. Thus the anomalous yield of low-energy gamma quanta was attributed to channeling radiation of electrons. Theory shows that for electron beam energy of 800 MeV, the radiation frequency is 1.5×10^{22} Hz, corresponding to radiation energy of 60 MeV, which coincides with the upper boundary of the anomalous yield spectrum [42].

The first experimental observation of axial channeling by 900 MeV electrons in diamond single crystal and the resulting intense electromagnetic radiation was reported in 1979 [41]. The experiment involved the spectral composition and gamma radiation yield as a function of crystal orientation. The divergence of the Tomsk synchrotron electron beam was somewhat improved by that time, being held within 0.1 to 0.3 mrad, which was within the critical angle for axial channeling of 0.3 mrad. The diamond single crystal was 0.35 mm thick.

Electrons channeled along the <110> axis yielded a maximum for both the total energy and the number of 20 MeV quanta, contradicting the predictions of coherent bremsstrahlung theory. The channeled electron yield of 16 MeV radiation exceeded by a factor of 50 the yield from unoriented diamond or graphite crystals. The anomalous yield of low-energy gamma quanta was interpreted as channeling radiation by electrons moving coupled to individual atom strings in the crystal along helical trajectories. These results were reviewed and evidently approved by Kumakhov [41].

The observed radiation was finally acknowledged as the theoretically predicted electromagnetic radiation capable of occurring in a broad band of the spectrum from optical ι ,amma quanta generated by radiative transitions between energy levels of transverse motion of channeled electrons and positrons. The next step was to launch an experimental study of its energy, angular, and polarization characteristics. According to the Tomsk authors, such experiments were important because the channeling effect could be used to develop an intense hard gamma radiation for applications in nuclear spectroscopy, radiation physics, and technology.

In the same year, the Tomsk team performed an experiment to obtain the first measurements of gamma radiation spectra for the case of axial channeling of 600, 750, and 900 MeV electrons in a diamond single crystal 0.35 mm thick along the <110> axis [43].

At the same time, the team claimed the discovery and measurement of linear polarization of gamma-radiation emitted in planar channeling of a 900 MeV electron beam in diamond [88].

This inquiry was continued by an experiment with planar channeling in diamond. The team's authors noted, in this connection, the total lack of comparative experimental data for various atomic planes. The 900 MeV electron beam of the Sirius synchrotron was channeled in a 0.35 × 6 × 10 mm diamond single crystal whose large face was perpendicular to the <110> axis.

The authors offered a proof that the observed radiation was due to planar channeling of electrons based on the following considerations: The gamma radiation spectrum showed a peak in the low-energy region; the spectrum was obtained with the diamond oriented on axis and off axis in the (110) plane. In the radiation energy below 60 MeV, the spectral shape and photon yield remained the same in both cases, while according to the coherent bremsstrahlung theory, the spectrum peak should move almost linearly toward higher energies as the off-axis angle is increased [31].

In the course of this research, the team's authors claimed the discovery of an orientation effect consisting of ultrasonic oscillations of the diamond single crystal, the site of axially-channeled 900 MeV electrons.

In the experiment, the Sirius electron beam with a 0.5 percent energy spread and 0.3 mrad divergence impinged on a 10 × 6 × 0.35 mm diamond single crystal oriented with the <110> axis normal to the large face. The beam pulselength was 40 μ sec per each acceleration cycle. A piezoceramic ultrasonic detector was mounted parallel to the electron beam axis to record elastic waves generated by the charged particles passing through the crystal.

The total energy of gamma radiation and the ultrasonic detector signal were plotted as functions of the angle between the <110> axis of the diamond crystal and the electron beam axis. The plot showed that the maximum of total gamma radiation energy was correlated to the minimum of the acoustic signal; the latter first increased and then sharply fell with the approach to the crystal axis. The acoustic signal therefore indicated the capture of electrons by the channeling mode [44].

The first experimental observation of channeling radiation as a function of crystal orientation angle was claimed by the team's authors in 1980. The comparison of coherent bremsstrahlung and channeling radiation spectra helped specify those regions of photon energy and crystal orientation angle that determined which electromagnetic radiation was predominant [45].

The team's authors claimed to have performed the first absolute measurements of planar channeling radiation intensity in 1982. An electron beam with energies of 600 and 900 MeV impinged on a diamond single crystal 0.35 mm thick along the (001) plane. The beam divergence was 0.1 mrad. The measured intensity of planar channeling radiation, expressed as $\omega dN/d\omega$, where N was the number of emitted photons and ω photon energy in MeV, was 1.8×10^4 per cm.steradian at peak emitted energy of 6 MeV (900 MeV beam), and 7×10^4 per cm.steradian at peak emitted energy of 4 MeV (600 MeV beam) [46].

OTHER EXPERIMENTAL TEAMS

The team dedicated primarily to theoretical development of the crystal channeling concept headed by M. A. Kumakhov at the Institute of Nuclear Physics of the Moscow State University (IYaF-MGU) has reported on an experiment performed jointly with YeFI, using the Yerevan synchrotron with a 4.7 GeV electron beam having a 0.2 mrad divergence. The object of the experiment was spontaneous gamma radiation emitted by fast electrons channeling in a diamond crystal 100 μ thick. Axial <100> and planar (110) channeling modes were used. In comparison with bremsstrahlung and unoriented target, axial channeling radiation in diamond resulted in a two orders of magnitude higher yield of gamma quanta [47].

Another joint experiment with YeFI, this time by IYaF-TPI and IAE, was performed to study the energy dependence of angular distribution of electrons in planar channeling. The equipment consisted of a

Van-de-Graaf accelerator and a microtron. The beam energy was within the range from 0.85 to 5.4 MeV. The angular divergence of the incident electron beam was within 0.03 to 0.1°, which was less than the critical angle for planar channeling in silicon. The silicon crystal was 5 μ thick.

The experiment revealed the existence of an alternate two-peak and three-peak structure of angular distribution of relativistic electrons, as beam energy increased from 0.85 to 5.4 MeV in (110) planar channeling in silicon. This effect was interpreted as due to the motion of energy bands and the accompanying shift of wave functions of the states lying above the potential barrier [48].

By varying the relativistic mass of the channeled particles, one could control the position of energy bands above the potential barrier and thus significantly affect the channeling process. The experiment showed a sharply pronounced dependence of the angular distribution of planar channeled electrons leaving the crystal upon the incident beam energy.

A comprehensive evaluation of the results of the 1978 SLAC experiments in the light of theoretical predictions was published jointly by Kumakhov's and Bazylyev's teams in 1980–1981 [49,50]. The Soviet authors concluded that intense radiation from high-energy positrons channeling in a continuous planar potential had been observed experimentally at SLAC and that "The results of the experiment verified not only the relatively high radiation intensity predicted theoretically [by Kumakhov, Bazylev, and Zhevago], but also [provided] many fine details of the radiation spectrum" [49,50].

VI. CONCLUSIONS

The outstanding feature of Soviet research in crystal channeling of particle beams and the resulting channeling radiation is the optimistic belief of Soviet specialists in the technological potential of this research. While a degree of specialists' enthusiasm for their own work is to be expected, it also apears to be shared by the leadership of the Academy of Sciences. The latter views crystal channeling as part of free electron laser development, a relatively new and promising area of R&D that has been pursued in the Soviet Union at a high level of effort. It is significant that A. V. Gaponov, the leading Academician and developer of relativistic high-powei microwave devices, in formulating a general plan for the development of oscillator and amplifier devices by regions of the electromagnetic spectrum, noted that the x-ray region could be assigned to channeling radiation.

The optimism of Soviet specialists is evident in their prediction of high spectral and angular density, broad-range tunability of radiation energy in the x-ray and gamma-ray regions, and sharp directivity of channeling radiation. In particular, this includes Kumakhov's expectation that it should be possible, for the same beam energy, to change the maximum radiation frequency by a factor of 3 to 4 by changing the crystal orientation, and to change the frequency by an order, and radiation intensity by four orders of magnitude, by changing the crystal itself.

The Soviet optimism in this area of research extends to the practical realization of tunable x-ray and gamma-ray lasers based on channeling radiation. While no experiments with channeling radiation lasers have been reported, theoretical estimates of the current density generation threshold were set as low as 1 A/cm^2.

Soviet specialists invoke the attractive properties of crystal channeling lasers, such as a continuous tunability of the generated frequencies achieved by various means, from simple rotation of the single crystal about the direction of the incident beam to changing the target crystal. They also expect that high gain per pass at high beam currents would make operation without mirrors feasible. Finally, they claim that crystal channeling lasers have an advantage over free electron lasers with magnetic undulators in that the same gain can be obtained for particle beam energy two or three orders of magnitude lower than that required in the undulator.

These claims and expectations appear to be based on Soviet theoretical research. In some areas, such as the sensitivity of channeling radiation to the type and orientation of the target crystal, Soviet predictions may be excessive. However, an assessment of their validity, if any, requires a thorough technical analysis of the collection of theoretical papers generated by Kumakhov, Bazylev, Zhevago, Bayer, Vorob'yev, Shul'ga, and others, a task beyond the scope of this report.

Another aspect of Soviet research in this field that falls outside the limitations of this report concerns the timing of Soviet research milestones relative to that of the corresponding Western research. Soviet writers have made a number of claims of priority in the discovery of various aspects of the crystal channeling phenomenon and in the development of theory, as reported in the foregoing text. Some of these claims can be disputed by Western scientists in view of their own prior work. However, an objective history of crystal channeling research must await a comprehensive study of world literature in this field.

If the Soviets might have been remiss in acknowledging some Western priority claims, they nevertheless gave full credit to the work done at SLAC, mainly because of the joint U.S.-Soviet experiment performed there in 1978. The results of that experiment were regarded as a major milestone in the channeling radiation research not only by its Soviet participant, I. I. Miroshnichenko of KhFTI, but also by the other key figures of Soviet research in this field, Kumakhov of IYaF-MGU and Bazylev and Zhevago of IAE. The latter concluded two years after the SLAC experiment that its results verified the theoretical predictions of Kumakhov, Bazylev, and Zhevago.

The SLAC experiment was accompanied by a remarkable conjunction of events in Soviet crystal channeling research, including the rise in total effort level, greater cooperation among Soviet research institutes, and a new interest in this work on the part of Academy of Sciences leadership. The frequent acknowledgments of Ye. P. Velikhov, vice-president of the Academy, for the support of the work, appearing in the reports published after 1978, are particularly suggestive of the enhanced stature of this research.

It is, therefore, highly likely that the SLAC experiment was a turning point in the entire Soviet research effort involving crystal channeling by high-energy electron and positron beams. If that is the case, it provides an interesting illustration of the role of international cooperation in Soviet R&D. However, it also raises the question of whether the SLAC experiment was the result, rather than the cause, of the perception on the part of Soviet scientific leadership that crystal channeling warranted an expanded research level. Thus, research results obtained elsewhere in the West and in the Soviet Union could have influenced Soviet decisionmakers to step up the research, and the joint experiment was deliberately undertaken, on the Soviet side, as a first step in the verification of the feasibility of the laser concept. On the other hand, the SLAC experiment could have been performed without any practical application in view and its results, enhanced by the international setting, provided the stimulus for the expanded Soviet effort.

Equally ambiguous is the role of the laser proposals in Soviet planning: Are the Soviets serious about the practical feasibility of channeling radiation lasers, or are these proposals advanced merely to stimulate interest in crystal channeling research? Is the high optimism of the leading Soviet specialists concerning the potential of channeling radiation supported by convincing theory? The answers to these questions may reside in the details of the extensive theoretical framework developed by Kumakhov and his fellow scientists.

Appendix A

THEORETICAL RESEARCH BY INSTITUTIONS

INSTITUTE OF NUCLEAR PHYSICS, MOSCOW STATE UNIVERSITY (IYAF-MGU)

M. A. Kumakhov claimed to be the first to advance the idea of an intense x-ray and gamma-ray radiation emitted by channeled relativistic electrons and positrons [13,14]. He has also been promoting its development by stressing its high spectral and angular density, broad-range tunability of radiation energy in the x-ray and gamma regions, and sharp directivity. It is significantly superior, he said, in terms of the most important parameters, to other known kinds of radiation, from hard x-rays to hard gamma-rays [2]. Kumakhov and his associates performed a detailed analysis of the angular, spectral, and polarization characteristics of dipole radiation by channeled particles and also studied the stimulated radiation effect [7,8,13].

According to Kumakhov's own account, he has been working on the problem of producing stimulated radiation by relativistic channeled electron beams and using it to create a laser that is tunable within a broad range of frequenies, including ultraviolet and soft x-ray radiation [2].

Kumakhov provides the theoretical data in Table A.1 illustrating the differences between channeling radiation and bremsstrahlung.

Table A.1

EMISSION PARAMETERS AS FUNCTION OF ENERGY: CHANNELING RADIATION (I) OF POSITRONS IN SILOCON (110) CHANNEL COMPARED WITH BREMSSTRAHLUNG RADIATION (II)

Energy, GeV	Emission Power, W		Maximum Radiation Frequency, 10^{22} Hz		Number of Quanta, cm^{-1}	
	II	I	II	I	II	I
0.2	0.121	0.001	30	0.036	0.418	1.54
1	0.605	0.0257	150	0.358	0.418	3.88
5	3.02	0.64	750	4	0.418	8.45

SOURCE: Kumakhov, Ref. 14.

Table A.1 shows that, although the total intensity of bremsstrahlung is much higher than that of channeling radiation, the higher spectral density of the latter renders the number of quanta more than an order of magnitude higher than in bremsstrahlung.

Table A.2 provides a comparison of spontaneous channeling radiation with synchrotron radiation from the Pakhra synchrotron under construction in the USSR and from the DESY synchrotron in West Germany.

It is noted here that channeling may also yield radiation at shorter wavelengths than 1 Å at even higher efficiency, which is impossible for synchrotrons.

When particle beam energies from 1 to 10 GeV are used, channeling radiation can reach several tens of MeV. This means that practically all nuclear transitions can be studied and, since the effective cross-sections are large, it is clear that channeled radiation opens up possibilities in nuclear physics that are new in principle. When the particle beam divergence is less than $1/\gamma$, for a given angle, a single harmonic is emitted with a linewidth of ω/N, where ω is the frequency and N is the number of waves that can be fitted in the trajectory of the channeled particle. The wavelength is 1 μ for a 0.1 – 1 GeV particle, and the value of N can be brought up to 1000. Therefore, for a radiation energy of 100 keV, the linewidth is 100 eV, and a high degree of monochromaticity can be obtained for the given angle [13].

Table A.2

NUMBER OF PHOTONS, N, AT 1 Å WAVELENGTH

Particle Energy	$N.10^{-10}$ photon/Å.sec.mA.mrad	Remarks
	Pakhra Synchrotron	
1.3 GeV	0.05	Projected regime
	2100	Storage regime
	DESY Synchrotron	
7.5 GeV	5300	
	Channeling	
150 MeV	10^9	Electrons channeling in <110> direction in silicon crystal

SOURCE: Beloshitskiy and Kumakhov, Ref. 8.

Kumakhov claimed that his theory of planar channeling of positrons offers the most quantitatively reliable results obtained so far, since for positrons [13,52] the potential of the harmonic oscillator, generally used to compute radiation spectra, is sufficiently close to the real potential of the channel. However, this was not the case with electron channeling. Therefore, the results of electron channeling theory [7,8,13] were considered by Kumakhov to be only qualitative, even though electron radiation offered the greatest practical interest.

The theory of dipole radiation by channeled particles was further developed by Kumakhov in a series of papers in which he has also considered the theory of stimulated radiation and the design of a tunable laser [7,8]. However, he was criticized by Andreyev for this attempt on the ground that his results were limited to the computation of gain in transitions between transverse motion levels and that he gave insufficient attention to the design of real generation schemes [25].

The reverse effect of channeling radiation on the positron beam channeling in crystal may result in cooling (collimation) of the beam. Kumakhov found that spontaneous radiation stabilizes the motion of positrons in the channel so that the typical dechanneling length can be very large. However, if the initial divergence of the beam is close to the capture angle, beam collimation is not possible [10].

A particle moving at a small angle to the crystal axis and plane may be in a transition channeling mode in which channeling radiation and coherent bremsstrahlung appear at the same time [53].

Kumakhov has also considered various diagnostic applications of channeling radiation. In the measurement of the energy of ultrarelativistic particles in transparent media, the use of Cherenkov counters is not feasible when the channeled particles approach the speed of light, while channeling radiation may be effective [9].

The anomalous drop in bremsstrahlung in positron channeling (by a factor of 1000) can be used to determine the concentration of impurity atoms and radiation defects in crystals [11].

Crystal channeling can be used for focusing, collimating, and bending charged particle beams [54].

KURCHATOV INSTITUTE OF ATOMIC ENERGY (IAE)

The team headed by V. A. Bazylyev and N. K. Zhevago at IAE has published a considerable body of theoretical work on the subject of charged particle channeling in crystals and channeling radiation. The theory of the channeling effect was developed in the early 1970s at IAE by Yu. Kagan and Yu. V. Kononets using the density matrix formalism [55]. From 1974 to 1976, Bazylyev and Zhevago published a series of studies on emission by ultrarelativistic electrons, considering the effect of virtual quantum absorption and scattering on bremsstrahlung spectrum of ultrarelativistic electrons [56], the spectral-angular distribution of bremsstrahlung in absorbing media [57], and Cherenkov radiation as an intense x-ray source [58]. Their publications on channeling radiation began appearing in 1977 [59]. They have used the quantum mechanics approach for the case of radiation by channeled particles with relatively high energies precluding the use of the dipole approximation [15,16,52,60]. In [60], Bazylyev investigated the reverse effect of radiation on the motion of channeled particles.

Bazylyev and Zhevago considered particle motion in crystal channeling as similar in nature to particle interaction with special periodic electromagnetic fields that are set up in undulator devices.

Their studies involved the effect of frequency and spatial dispersion of the electromagnetic field in crystal on the radiation process and the radiation as a function of the channeling particle energy and type of the effective potential of the crystal [15,19,52]. In [15] Zhevago analyzed the effect of parametric coupling of the transverse and axial motions, and quantum recoil and the interaction of particle spin with the effective radiation field that becomes significant when the emitted energy is high. He also showed that there is an optimal energy of the channeled particle for which the spectral density of radiation reaches a maximum.

As in the case of Kumakhov, the most quantitatively reliable results were initially obtained by Bazylyev only for the case of planar channeling of positrons [15,19], and his channeling theory of electrons [19] was at that time only qualitative.

In [16] Bazylyev and Zhevago provided a more realistic theory of radiation in planar and axial channeling of high-energy electrons. The results of analyzing radiation spectra with different polarization were given for models of effective potentials of crystal planes and axes that closely approached the real potential. These results were compared with those of other authors, incidentally showing that the theory of planar channeling radiation developed by A. A. Vorob'yev and V. G. Baryshevskiy was based on erroneous results which led them to predict that x-ray and gamma-ray intensities will be negligible or comparable with those of transition radiation. This more rigorous approach has confirmed Kumakhov's preliminary conclusion about the high intensity of channeling radiation.

More recently, Bazylyev has developed a quantum theory of electron and positron scattering in the process of axial and planar channeling in thin crystals [61] and analyzed the problem of dechanneling in terms of the probability of transitions between transverse motion energy levels [62].

Zhevago has analyzed the so-called axial quasi-channeling effect, similar to super-barrier particle motion in crystals discussed by Akhiyezer. In quasi-channeling, the axial field strongly distorts the particle trajectory in the plane normal to the axis. As a result, the initially parallel particle beam diverges, forming a cone and a characteristic ring at the exit (the doughnut scattering observed by Uggerhoj). The relatively strong scattering of quasi-channeled particles should lead to an intense electromagnetic radiation. However, the properties of this radiation are quite different from those observed in axial channeling [63].

Finally, Bazylyev published several papers in 1982 dealing with the theory of ionization of atomic particles channeled by the interplanar potential of the crystal [64–66].

KHAR'KOV PHYSICO-TECHNICAL INSTITUTE (KHFTI)

As in the case of Bazylyev at IAE, A. I. Akhiyezer's work on channeling theory was preceded by the analysis of bremsstrahlung by fast particles moving along the atom string [67,68]. His publications on channeling began in 1977 with a basic theoretical discussion [36] and continued with the generalization of Kumakhov's classical analysis of planar channeling, involving a parabolic potential, to any potential [39].

Akhiyezer's team extended the area of interest beyond the channeling effect to new phenomena related to channeling. Thus, the team considered the super-barrier mode of particle motion postulated for the case when the energy of particle motion transverse to the crystal axis is higher than the potential barrier. Since it moves in a strong lattice field, the super-barrier particle, just as does the channeled particle, should generate intense radiation.

Thus, near the crystal plane there are channeled and super-barrier particles. Both emit intense radiation, but in different frequency regions. The greatest enhancement of radiation occurs in particles moving near the crystal axis. The share of super-barrier particles in the axial channeling mode is always high, while in the planar channeling mode it may be high or low, depending on the angle between the plane and the incident particle momentum vector [69]. The team predicted a considerable enhancement of the radiation of super-barrier particles in a crystal in comparison to the radiation by particles moving in an amorphous medium, and suggested an experimental method to observe the predicted effect [70].

Another predicted comparative enhancement of crystal effects relative to amorphous effects is that in the absence of channeling, the mean square scattering angle for relativistic particles in the crystal may considerably exceed the mean square scattering angle in amorphous media. This effect is due to the correlation between the successive collisions of the particle with lattice atoms and it strongly depends on the orientation of the crystal axes relative to the particle momentum, on the particle energy, and on the crystal thickness [71].

Akhiyezer also considers the theory of electromagnetic showers in crystals, showing that in a crystal the shower can develop over a much shorter path than in an amorphous material [72].

An apparently independent team at KhFTI, headed by V. V. Rozhkov and N. N. Nasonov, predicted a new variant of coherent bremsstrahlung consisting of the radiation from relativistic positrons that were reflected at small angles from a solid surface. The authors showed that coherent interaction of particles with atom strings on the surface of a single crystal qualitatively changes the spectral and polarization properties of the resulting radiation at high frequencies. This makes it possible to enhance the intensity of such radiation by various means. The authors mention several enhancement methods: the use of multiple reflection from parallel surfaces; multiple reflection of particles from a single surface in an external magnetic field parallel to the surface and perpendicular to the particle velocity vector; a wiggler structure; and increasing incident beam current, since the target surface is not much affected by the reflected beam [73].

Rozhkov and Nasonov also suggested a new type of oriented quasi-coupled motion of charged particles in external electromagnetic fields near a solid surface. An external electromagnetic field above a solid surface and a nonrelativistic particle (ion) incident on the field region and moving parallel to the surface were assumed. The field was configured so as to force the particle toward the surface. If the angle of incidence of the particle onto the surface were of the order of the channeling capture angle, the ion should experience a near specular reflection. The field would then again force the ion toward the surface, so that the latter would undergo quasi-periodic motion near the surface. The authors call this motion "supersurface channeling." It can also occur with relativistic particles, including high-energy electrons and positrons [74].

INSTITUTE OF NUCLEAR PHYSICS, TOMSK POLYTECHNIC INSTITUTE (IYAF-TPI)

Most of the theoretical output of the predominantly experimental team headed by S. A. Vorob'yev and A. P. Potylitsyn was published before 1979, presumably as a basis for the subsequent experimental work. Systematic theoretical treatment has been applied to evaluating the role of critical angle between crystal axes and electron beams in channeling radiation [75] and developing a theoretical model of bound states in fast electron channeling in single crystals [20]. In particular, the quantum-mechanical theory of bound states was applied to the motion of fast electrons along the atomic axes of silicon and gold single crystals. The authors claim to be the first to consider the role of strongly interacting bound states in Rutherford scattering and electron channeling [76].

They also claim to be the first to provide a theoretical analysis of bound molecular states in axial and planar channeling of electrons applied to the silicon single crystal [77]. This theoretical effort involved studies of the spectrum of electron channeling radiation for electrons channeled along those planar directions, such as (111) in diamond and silicon single crystals, whose potential cannot be described by the current model of isolated atomic plane and for which the channeling mode may turn out to be quasi-molecular [31].

The team performed theoretical investigation of the frequency spectra of channeling radiation as functions of energy and temperature, intended for the subsequent experimental studies of this radiation as a source of x-ray and gamma radiation [78].

To increase the monochromaticity and intensity of the gamma radiation source based on electron channeling, the use of a laser amplifier is now being considered. Another method of increasing the yield of gamma quanta from the crystal is the imposition of an external electric field normal to the channeling direction. As a result, the energy levels of the channeled electrons will be tilted and electron tunneling to neighboring atom strings will produce radiation. For an external electric field intensity of 1 MeV/cm and electron beam energy of 1 GeV, the photon energy will be 16 keV [43]

In 1981, the team developed the methodology whereby the principal characteristics of channeling radiation, such as angular spectral distribution, and total power of linear polarization components, can be obtained from the field distribution along the particle trajectory and the dielectric permittivity of the medium [79].

INSTITUTE OF NUCLEAR PHYSICS, NOVOSIBIRSK (IYAF-SOAN)

V. N. Bayer and his team approached the problem of crystal channeling from a generalized viewpoint of high-energy particle interaction with external electromagnetic fields. They brought to this study a quasi-classical operator methodology which they call the diagram operator method for analyzing processes in a homogeneous (constant in space and time) external electromagnetic field. The method was based on an operator representation of Green's function for a charged particle in a field [80,81].

While their interest in the field appears to have been focused on basic physics problems and astrophysical applications (high magnetic field intensities in pulsars), it has been extended to the study of intense laser beams which make it possible to achieve high intensities of the electromagnetic field of up to GV/cm [82,83].

Their interest in x-ray lasers and their possible applications has led to the study of relativistic particles moving in periodic structures, such as undulators, and in the field of a plane electromagnetic wave which can be regarded as a kind of undulator. They have applied their operator method to the development of a generalized concept of a free electron laser undulator [84].

The team's later work was directed towards further development of the theory of channeling radiation in crystals. According to Bayer, the theoretical treatment of channeling radiation by Kumakhov [13] and Zhevago [15] was based on simplified assumptions about the form of the potential well that were too far removed from the real world. Bayer has thus defined the planar channeling potential in a form qualitatively close to reality and found radiation characteristics that could be directly measured by experiment [85].

The team's authors consider this work as part of the development of free electron lasers driven by ultrarelativistic electrons and positrons. They have postulated a general theory of radiation in quasi-periodic motion of charged particles applicable to non-dipole radiation.

The angular distribution and polarization characteristics of radiation by particles moving in undulators and channeled in crystals have been obtained in quasi-classical approximation. The theory has been provided in a form convenient for practical applications such as radiation in undulators and channeling radiation in crystals [4].

The non-dipole radiation theory has next been applied to planar channeling of positrons. The data of the SLAC experiment were used as the basis for comparison with their theoretical results and for interpretation of the discrepancies found in the SLAC data. Bayer concluded that one possible cause of the discrepancies was that the diamond crystal used in the SLAC experiment had structural imperfections [86].

APPLIED PHYSICS INSTITUTE (IPF), GOR'KIY

According to V. L. Bratman and G. M. Genkin, undulator radiation has been finding a steadily increasing use as a source of electromagnetic radiation from microwaves to x-rays. The usual undulators are macroscopic magnet systems with periods ranging from tens of cm to mm. Beyond these are microscopic systems represented by the internal atomic field of crystals. Intermediate between the macroscopic and microscopic systems are the periodic domain structures that may also be considered as sources of undulator radiation.

Theoretically, a domain FEL would require electron beams from 0.5 to 1 MeV generated by high-current direct-diode injectors. For a wavelength of 100 to 5 μ, such an FEL would generate an output power from 1 to 10 MW with a 1 percent electronic efficiency.

Bratman has shown that undulator radiation can be observed in electrons moving above the domain structure. The periods of these structures are several orders of magnitude shorter than those of macroscopic systems, while the magnetic fields are high enough to impart to the particles oscillating velocities not only in motion within the crystal but also in motion above the surface. For example, in orthoferrites d = 150 μ, B = 100 Gauss, and in Co d = 100 μ, B = 3 kGauss. Since the field falls off rapidly away from the domain structure, the electrons must be within a period's distance from the surface [28].

Genkin analyzed the radiation from electrons propagating within a single crystal with a domain structure. He showed that in the domain structure, the power of this radiation can be considerably higher than that of channeling radiation [17]. Genkin proposed to propagate an electron beam through ferromagnetic material in a multi-domain state. The periodic magnetic field of the domain structure would generate undulator radiation. The period of the domain structure varies from 100 to 1 μ. In thin Ni-Fe single crystals, for example, the period is 2 μ.

In comparison with the channeling mechanism of generation, the multi-domain ferromagnetic crystal method has a number of advantages: high radiation frequency and power, good monochromaticity, insensitivity to crystal orientation, and tunability [87].

Appendix B

PERSONNEL OF SOVIET RESEARCH TEAMS ACTIVE IN CRYSTAL CHANNELING

(Taken from bibliographic references and published materials)

Authors	Technicians	Leadership Support	Reviewers	Professional Support
		YaF-MGU		
Kumakhov, MA	Telegin, VA	Velikhov, YeP	Vavilov, VS	Avakyan, RO
Beloshitskiy, VV	Khokonov, MKh	Khokhlov, RV	Romanovskiy, YeA	Miroshnichenko, II
Trikalinos, KhG			Teplov, IB	Kononets, YuV
Agan'yants, AO			Firsov, OB	Kadomtsev, BB
Vartanov, YuA			Bazylev, BA	Martynenko, YuV
Vartapetyan, GA			Zhevago, NK	Rukhadze, AA
Yaralov, VYa			Smirnov, BM	
Glebov, VI			Il'inskiy, YuA	
		BIAE		
Bazylyev, VA	Avakyan, AR	Velikhov, YeP	Afanas'yev, AN	Gurevich, II
Zhevago, NK		Kadomtsev, BB		Alferov, DF
Gevorgyan, LA				Bashmakov, YuA
Korkhmazyan, NA				Bessonov, YeG
Denisov, EI				Galitskiy, VM
Varfolomeyev, AA				Firsov, OB
Khlebnikov, AS				Avakyan, RO
Glebov, VI				Miroshnichenko, II
Kagan, Yu				
Kononets, YuV				
Babakhanyan, EA				
Vorob'yev, SA				
Beloshitskiy, VV				
Trikalinos, Kh				
Mikheyev, SA				
Tulupov, AV				
Ivanov, VV				
Goloviznin, VV				
Popov, DYe				
Avakyan, AL				
Yan Shi				
Demura, AV				
Kumakhov, MA				
		IYaF-SOAN		
Bayer, VN		Skrinskiy, AN	Fadin, VS	Miroshnichenko, II
Katkov, VM				Tsyganov, EN
Strakhovenko, VM				
Mil'shteyn, AI				

Authors	Technicians	Leadership Support	Reviewers	Professional Support
		MGU		
Andreyev, AV				
Akhmanov, SA				
Kuznetsov, VI				
Vysloukh, VA				
		YaF-TPI		
Potylitsyn, AP	Tsekhanovskiy, IA	Skrinskiy, AN	Ginzburg, VL	
Vorob'yev, SA			Tulinov, AF	
Vorob'yev, AA	Tatarin, A		Letokhov, VS	
Kalinin, BN			Kumakhov, MA	
Kaplin, VV			Kalashnikov, NP	
Babudayev, AYa			Bayer, VN	
Plotnikov, SV			Katkov, VM	
Popov, DYe			Strakhovenko, VM	
Vnukov, IYe				
Zabayev, VN				
Didenko, AN				
Adishev, YuN				
Moiseyev, MB				
Kurkov, AA				
Tomchakov, VK				
Nikitin, MM				
Lasukov, VV				
Yeponeshnikov, VN				
Denisov, FP				
Il'in, SI				
Kuznetsov, VM				
		KhFTI		
Akhiyezer, AI	Kobezskiy, VM	Velikhov,YeP	Fomin, PI	Tulinov, AF
Akhiyezer, IA	Popenko, VI	Markov, MA	Ter-Mikaelyan, ML	Letokhov, VS
Boldyshev, VF	Vishnyakov, VA	Feynberg, YeL		Kumakhov, MA
Shul'ga, NF	Shevchenko, SF	Chuvilo, IV	Kulibaba, VI	Kalashnikov, NP
Fomin, SP	Storizhko, VYe	Amatuni, ATs		Bayer, VN
Truten', VI	Golovna, AYa	Iponin, YeV		Katkov, VM
Rozhkov, VV	Nemashkalo, BA	Sorokin, PV		Strakhovenko, VM
Nasonov, NN	Kolesnikov, LYa			
Dyul'da, SV				
Voytsenya, AV				
Bochek, GL				
Grishayev, IA				
Kovalenko, GD				
Shramenko, BI				
Kalashnikov, NP				
Fisun, AN				
Morokhovskiy, VL				
Vit'ko, VI				
Miroshnichenko, II				
Avakyan, RO, YeFI				
Ganenko, VB				
Gendenshteyn, LE				
Pegushin, YeV				
Sanin, VM				
Shalatskiy, SV				

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KEY TO JOURNAL ABBREVIATIONS

Appl. Phys. Lett.	*Applied Physics Letters*
DAN SSSR	*Doklady Akademii nauk SSSR*
FP	*Fizika plazmy*
FTT	*Fizika tverdogo tela*
IVUZ—Fizika	*Izvestiya vysshikh uchebnykh zavedeniy-Fizika*
Izv AN SSSR	*Izvestiya Akademii nauk SSSR, Seriya fizicheskaya*
UFN	*Uspekhi fizicheskikh nauk*
VAN SSSR	*Vestnik Akademii nauk SSSR*
Z. Phys.	*Zeitschrift der Physik*
ZhETF	*Zhurnal eksperimental'noy i teoreticheskoy fiziki*
ZhETF, Pis'ma	*Pis'ma v Zhurnal eksperimental'noy i teoreticheskoy fiziki*
ZhTF	*Zhurnal tekhnicheskoy fiziki*
ZhTF, Pis'ma	*Pis'ma v Zhurnal tekhnicheskoy fiziki*

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