

Soviet Free-Electron Laser Research

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Rand

The research described in this report was sponsored by the Defense Advanced Research Projects Agency under Contract No. MDA903-85-C-0030.

Library of Congress Cataloging in Publication Data

Kassel, Simon.

Soviet free-electron laser research.

"Prepared for the Defense Advanced Research Projects Agency."

"May 1985."

"R-3259-ARPA."

Bibliography: p.

1. Free electron lasers—Research—Soviet Union.

I. United States. Defense Advanced Research Projects Agency. II. Title.

QC689.5.L37K37 1985

535.5'8

85-6362

ISBN 0-8330-0643-6

The Rand Publication Series: The Report is the principal publication documenting and transmitting Rand's major research findings and final research results. The Rand Note reports other outputs of sponsored research for general distribution. Publications of The Rand Corporation do not necessarily reflect the opinions or policies of the sponsors of Rand research.

Published by The Rand Corporation

R-3259-ARPA

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Projects Agency



PREFACE

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

The report evaluates the development of free-electron lasers in the Soviet Union and includes a detailed comparison of Soviet and U.S. experimental efforts in this area. Soviet work on channeling radiation, considered by the Soviets to be a variant of the free-electron laser mechanism, is analyzed in another report under this study to be published under the title "Soviet Research in Charged Particle Beams Channeling in Crystals," R-3224-ARPA. The present document does not include devices based on the Smith-Purcell effect—a subject of considerable Soviet research activity and one that the Soviets also consider a form of free-electron lasers—on the grounds that it does not conform to the basic free-electron laser concept of potentially high output power and frequency.

This study is intended for specialists in free-electron laser research, U.S. government decisionmakers concerned with advanced technology problems, and students of Soviet science and technology.

SUMMARY

Soviet and U.S. research in the free-electron laser (FEL) area commenced at about the same time in the mid-1970s, at about the same level of effort. Now, in the mid-1980s, the Soviets appear at least equal to the U.S. in terms of the number of active writers and the depth and breadth of theoretical research, but they lag substantially behind in their experimental results. Experiments are most important for verifying the technical feasibility of the FEL concept and eventually converting it into a useful technology. The U.S. holds an advantage of more than two-to-one in the number of individual experiments performed that are directly pertinent to FEL development. More important, during the maturing period of FEL research, most U.S. experiments yielded significantly higher radiation frequencies, output peak powers, and efficiencies than those attained by the Soviets. In 1984, however, the Soviets reported a high-current FEL experiment that yielded 50 MW in output power at a wavelength of 3 mm, surpassing U.S. results.

The causes of the Soviet lag prior to 1984 are traceable to a more limited range of accelerator equipment available for the experiments, and relatively poor-quality electron beams characterized by high energy spread and divergence. The ultimate cause, however, could be the apparent scarcity, if not absence, of computer support for Soviet FEL research. Computer-aided design of electron guns and other accelerator systems has been a major factor in the enhancement of beam quality and the achievement of U.S. results. No evidence of significant computer support was found in Soviet FEL research. Another factor is the spinoff from research in other accelerator applications that stimulated much of U.S. research in FEL but does not appear to have played a large role in Soviet FEL research.

In terms of research institutions and accelerator facilities that are active in FEL experimentation, the U.S. maintains a broader research base than does the Soviet Union. In the latter, four major research institutes have been performing FEL experiments so far: the Lebedev Physics Institute, the Applied Physics Institute in Gor'kiy, the Nuclear Physics Institute in Tomsk, and, to a limited extent, the Khar'kov Physico-Technical Institute. FEL experiments of these organizations involved three high-current pulse line accelerators, one high-current induction linac, and two synchrotrons. A storage-ring facility is expected to be used for FEL experiments at the Nuclear Physics Institute in Novosibirsk. About 15 Soviet organizations, including the

above institutes, have been active to a varying degree in theoretical FEL research.

Although a roughly similar number of organizations were performing theoretical FEL research in the U.S., more of them were active in the experimental programs, which also involved a greater variety of equipment. U.S. research organizations performing FEL experiments include Stanford and Columbia Universities, the University of California at Santa Barbara, MIT, the Naval Research Laboratory, Los Alamos and Livermore national laboratories, and industrial corporations such as the Bell Laboratories, TRW, Boeing, Hughes, and EG&G. Stanford pioneered FEL research with its superconducting RF linac facility. The U.S. accelerators used in the experiments include several types of RF linacs, at least four types of high-current pulse lines, two types of high-current induction linacs, including the ETA at LLNL, a microtron, and a Van de Graff accelerator.

The Soviets stress high-current FEL experiments, which they began at the time of the initial Stanford SLAC experiments and in which they reached megawatt output at relatively high efficiency. These early experiments were characterized in both countries by a large contribution from cyclotron interaction due to poor quality of the electron beams used at the time. However, in the 1980s, a number of U.S. high-current experiments indicated a transition to true FEL regime. Only two Soviet experiments, one performed in 1982, featuring a Bragg mirror resonator, and the 1984 experiment, show similar progress.

The Soviets maintain an extensive, broad-based, and systematic effort in the development of FEL theory, primarily at the Lebedev Physics Institute. Here, they have initiated classical analysis of the FEL mechanism ahead of the U.S. and developed quantum-mechanical analysis of collective FEL regimes. Their detailed and wide-ranging treatment of FEL theory is in sharp contrast to their experimental activity which, in terms of publications, declined considerably in the 1980s.

Two conjectures can be advanced to explain this decline: One is that it was due to a number of deficiencies affecting Soviet FEL research, such as lack of adequate experimental equipment and computer facilities. While not so serious during the early exploratory phase, these deficiencies became critical during the maturing phase of the research. An alternative, and more plausible, conjecture is that the 1984 experiment is an outward indication of a more extensive unpublished experimental program launched in the wake of the earlier open exploratory FEL research.

ACKNOWLEDGMENTS

The author is deeply grateful to Dr. John A. Pasour of the Naval Research Laboratory for his expertise and for many helpful discussions that significantly improved this report. Careful reviews and valuable suggestions were contributed by Professor Victor L. Granatstein of the University of Maryland, Drs. N. H. Krikorian, Edward Knapp, and John Rink of Los Alamos National Laboratory, and Dr. Robert M. Salter of The Rand Corporation. Sincere thanks are due to Joan Allen for her able and unstinting help with the manuscript and to Will Harris for editing the report.

LIST OF SOVIET RESEARCH INSTITUTIONS

Acronym	Name of Institution
FIAN	Lebedev Physics Institute, Moscow
IAE	Kurchatov Institute of Atomic Energy, Moscow
IED	Institute of Electrodynamics, Kiyev
IFP	Institute of Physics Problems, Moscow
IMF-SGU	Institute of Mechanics and Physics, Saratov State University
IPF	Applied Physics Institute, Gor'kiy
IRE	Radiotechnical and Electronics Institute, Moscow
ISE	Institute of High-Current Electronics, Tomsk
IYaF-MGU	Institute of Nuclear Physics, Moscow State University
IYaF-SOAN	Institute of Nuclear Physics, Siberian Department, Academy of Sciences, USSR, Novosibirsk
IYaF-TPI	Institute of Nuclear Physics, Tomsk Polytechnic Institute
IVTAN	Institute of High Temperatures, Moscow
IZMIR	Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation, Irkutsk
KhFTI	Khar'kov Physico-technical Institute
MEI	Moscow Power Engineering Institute
MGU	Moscow State University
RFI	Institute of Radiophysics, Gor'kiy
TRTI	Radio-technical Institute, Taganrog
YeGU	Yerevan State University

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I. INTRODUCTION

BACKGROUND

The purpose of this report is to evaluate free-electron laser (FEL) research and development in the Soviet Union and to compare it with the corresponding activity in the U.S. In presenting this material, the intention is to acquaint U.S. researchers with the objectives, techniques, and results of their Soviet counterparts, as well as to provide the broad context of this area of Soviet R&D that consists of the organization, facilities, personalities, and leadership involved. The U.S.-Soviet comparison has focused on the experimental programs, the most important area of this new technology. Such a comparison provides a fairly good indication of the relative standing of the two countries in this specialized area of R&D, and also illustrates the strengths and weaknesses of Soviet R&D performance in general.

The FEL concept is based on the interaction of highly energetic electron beam pulses with periodic structures represented either by varying static magnetic or electric fields or by dynamic electromagnetic fields. The interaction can generate a narrow band electromagnetic radiation over a wide frequency range that can potentially extend from microwaves through the visible and into the ultraviolet regions. The attraction of the FEL resides first of all in its continuous tunability and in its potential to become a highly efficient and powerful laser system.

FEL research commenced in the early 1970s in both the U.S. and the Soviet Union, expanding slowly at first, and then rapidly in both countries. At this time, much is known about the theory of the FEL mechanism and its feasibility has been demonstrated experimentally.

The material for this report has been drawn from the open-source Soviet and U.S. technical literature for the period from 1972 to April 1984. U.S. sources have been used primarily for experimental data and overviews. The bulk of the material thus consists of Soviet theoretical and experimental research reports, overviews, and contextual information. Some Soviet reports have been published in U.S. technical periodicals, but most of the reports reviewed herein were taken directly from Soviet journals. The coverage is not intended to be exhaustive. While care has been taken to present a comprehensive picture of the Soviet FEL effort, the report omits some theoretical material,

particularly that emanating from institutes with minor involvement in this research. An exception is the area of experiments, where much effort has been expended to include all the available Soviet experimental reports directly pertinent to FEL.

OUTLINE OF THE REPORT

Section II compares individual experiments conducted by the USSR and the United States. The experiments are shown side by side in Table 2, each expressed in terms of the basic parameters necessary for comparison of performance. Table 2 represents a fairly long stretch of nontextual material, mainly because of the abundant information available. It merits presentation at the outset because it offers the best visual means of judging the relative standing of the two national technologies. The comparison is extended in Sec. III to the history of the theoretical development of FEL, providing an insight into the conceptual issues that shaped FEL research in both countries.

The remainder of the report is devoted primarily to the Soviet side of FEL research. Section IV describes the organizational features of this research in terms of the performer institutes and leadership, focusing on the role of the Academy of Sciences, USSR. Section V analyzes the scientific objectives of Soviet FEL research, for the most part as discussed by Soviet reviewers of their research program. Section VI presents conclusions. Readers interested in the technical detail of Soviet FEL theory and experiment will find it in App. A, arranged according to the key research teams engaged in this work. Appendix B contains a Soviet classification of FEL types.

II. COMPARISON OF U.S. AND SOVIET FEL EXPERIMENTAL EFFORTS

MAIN FEL EXPERIMENTAL TRENDS

Experiments to explore the FEL mechanism and its potential began in both countries at about the same time, in the mid-1970s, and produced significant results in the following years. Table 1 shows the chronology of FEL experimentation in the two countries. It also illustrates a considerable difference between the two in developmental trends and objectives.

The U.S. effort began at Stanford University with the superconducting RF linac experiment and low-current RF linac experimentation that has continued until the present day. High-current U.S. experiments were an outgrowth of high-power microwave research begun around 1972, when Friedman propagated a beam through a rippled magnetic field to produce tens of megawatts of cm-wavelength radiation, referred to at the time as stimulated magneto-resonant scattering.

Soviet FEL experiments began with high-current beams interacting with magnetostatic periodic structures (wigglers), employing pulse line accelerators from the start of the FEL effort. The Soviets were also the first to use the induction linac in an FEL experiment, reported in 1981. However, it appears to have been the only such effort on the Soviet side. In the low-current area, no Soviet FEL experiments with RF linacs have been reported in the press. Instead, the Soviets have maintained a continuous series of experiments with GeV synchrotrons in which wigglers are used to generate undulator radiation in the visible region of the spectrum.

The Stanford work provided an impetus for the continued development and understanding of the high-current FEL regime; in particular, it led to the realization that the undulator FEL and the electromagnetically pumped stimulated scattering are physically identical. However, the early high-current FEL output in both countries was somewhat obscured by other forms of emission, such as cyclotron radiation, due to relatively crude beam generation techniques. The subsequent experimental effort demonstrates steady progress toward the achievement of clear FEL radiation output.

In the area of high-current FEL, the outstanding difference between the experimental trends pursued by the two countries is apparent in their attitude towards output wavelength and power as research

Table 1
TIMETABLE OF U.S. AND SOVIET FEL EXPERIMENTS

Year	High Current			Low Current	
	Pulse Line Accelerators			RF Linacs	Synchrotrons and Other Accelerators
	Magnetostatic Pumps	Electromag. Pumps	Induction Lincas		
1975	*KhFTI [1] 3 cm 10 MW 1.5%			Stanford [22] 10.6 μ 4 kW	
1976	*FIAN [3] 3 cm 30 MW 5%	NRL [19] 0.4 mm 1 MW NRL [18] 8 mm 340 kW			
1977	Columbia [9] 1.4 cm 5 MW			Stanford [23] 3.4 μ 6 kW	*FIAN [25] Pakhra synchrotron 0.45 μ
1978	Columbia [8] 1.1 mm 0.03% NRL/Columb.[13] 0.4 mm 1 MW	*FIAN [15] 1.3 cm 160 kW			*IYaF-TPI [27] Sirius synchrotron 0.5 μ
1980	*IYaF-TPI [4] 11 mm 20 MW 0.4% Columbia [14] 0.6 mm 1 MW				

Table 1—continued

Year	High Current			Low Current	
	Pulse Line Accelerators			RF Linacs	Synchrotrons and Other Accelerators
	Magnetostatic Pumps	Electromag. Pumps	Induction Lincas		
1981	NRL [5] 4 mm 35 MW 2.5%	*IYaF-TPI [17] 3 cm 6 MW 0.3%	*IYaF-TPI [20] 9 mm 150 kW		*FIAN [33] Pakhra synchrotron 0.5 μ
1982	*IPF [7] 4.3 mm 2 MW 1%			EG&G/TRW [126] 10.6 μ	
	Columbia [12] 1.7 mm MW			10.6 μ 900 MW 3.7%	LANL [127]
1983	NRL [11] 8.57 mm 17 MW 3%	NRL [16] 2.1 mm 0.3 MW	NRL [133] 8 mm 4.2 MW 3%	TRW/Stanf.[128] 1.6 μ 1.2 MW 1%	Bell Lab. [21] microtron 100-400 μ
	NRL [134] 4 mm 75 MW 6%			MSNW/Boeing [129, 130] 10.6 μ	UCSB [35] Van de Graff 4%0.1-1 mm
1984	MIT [10] 1.7 cm 100 kW 12%	*IPF-ISE [135] 3 mm 50 MW			
			LLNL [131] 8 mm 80 MW 4%		

NOTES: The entries indicate the organization performing the experiment, bibliographic reference, and the FEL output frequency, power, and efficiency, if available. Soviet experiments are preceded by *.

objectives. U.S. researchers have from the outset considered the high-current FEL as a source of millimeter and submillimeter radiation and attempted to optimize output power within the constraints of short wavelengths. The Soviets seem to have stressed sheer power and to have been content with operating at centimeter wavelength at least until 1980.

The difference between the two countries is also evident in the apparent level of effort, measured by the number and frequency of published FEL experiments. In terms of the total number of FEL experiments reported since 1975, the U.S. is leading by at least a factor of two. From 1975 to 1981, both countries were even in terms of published experiments; after 1981, the U.S. took the lead, experiencing a steep rise in the number of successful experiments, while the Soviets showed a pronounced decline.

COMPARATIVE EXPERIMENTAL RESULTS: HIGH-CURRENT ELECTRON-BEAM FEL

It is possible to compare experimental results only within analogous areas of FEL technology. As shown in Table 1, the area of significant overlap between U.S. and Soviet experiments is represented by FEL based on high-current electron beams generated by pulse line and induction linac devices. Table 2 provides summaries of the operating parameters of high-current experiments in the area of the overlap.

Table 2 is a side-by-side display of the experiments of the two countries that are roughly contemporary and comparable in parametric terms. The first line of each experiment provides the institutional designation of the performer, the earliest submission date of the published report, and the bibliographic reference.

Many of the experiments listed in Table 2 demonstrate, in addition to FEL emission, the results of other interaction mechanisms, such as cyclotron radiation due to poor quality of the electron beam. They were included in the table because they appear to have been undertaken in the course of FEL development. Earlier precursor experiments, such as those by Nation in 1970, Friedman and Herndon in 1972, and Granatstein in 1974,^[131] were not included in Table 2 because they were performed in contexts other than that of FEL.

The first high-current pulse line experiment performed in the context of FEL development was the Soviet superradiant oscillator reported in 1975 by Faynberg, Tkach, and others at KhFTI (exp. 1).¹

¹Experiment numbers in this section refer to experiments listed in Table 2.

Table 2

COMPARISON OF SOVIET-U.S. HIGH-CURRENT FEL EXPERIMENTS

SOVIET	U.S.
<i>Pulse line accelerators, magnetostatic pumps, millimeter and centimeter wavelengths</i>	
1. KhFTI, 11 June 1975 [1, 2]	2. Columbia, 2 February 1977 [9]
Hollow electron beam	Hollow electron beam
Energy 230 keV	Energy 750 keV
Current 3 kA	Current 10 kA
Pulselength 1.2 μ sec	Pulselength 10-15 nsec
Magnetic rippled field pump, alternating iron and aluminum rings	Magnetic rippled field pump, alternating iron and brass rings
Field intensity 6 KG	Field intensity 5-7 Kg
Length 24 cm	Length 70 cm
Period 3 cm	Period 1.4-1.6-2 cm
Modulation degree 5-6%	Modulation degree 5%
Output emission	Output emission
Wavelength 3 cm	Wavelength 7 mm
Power 10 MW	Power 5 MW
Pulselength 0.7 μ sec	
Efficiency 1.5 %	Efficiency 0.1%

Table 2—continued

3. FIAN-RFI, 16 January 1976 [3]

Terek-1 accelerator

Electron beam

Energy 700 keV
 Current 0.8 kA
 Pulselength 20 nsec

Magnetic guide field 5 kG

Magnetic wiggler

Wiggler field 2.5 kG

Output emission

Wavelength 3 cm
 Bandwidth 5%
 Power 30 MW
 Efficiency 5%

4. Columbia, 6 July 1978 [8]

Pulserad 105

Electron beam

Energy 600 keV
 Current 3-10 kA
 Pulselength 15 nsec

Magnetic guide field 12 kG

Magnetic wiggler

Rippled wiggler field 30-55 cm long: (1) alternating
 iron and brass rings with period of 8 mm;
 (2) ferromagnetic helix, 6 mm pitch;
 (3) electromagn., ripple period 8 mm

Output emission

Wavelength 1.1-1.7 mm

Table 2—continued

5. IYaf-TPI, 27 June 1980 [4]

Electron beam	
Energy	1 MeV
Current	6 kA
Pulselength	60 nsec
Energy spread	10%
Magnetic guide field	
	12 kG
Wiggler—bifilar, helical	
Period	4 cm and 2.8 cm
Optimum length	60 cm
Output emission	
Pulselength	50 nsec
Efficiency	0.4%
Solid beam	
Wavelength	7.5 mm
Power	2.5 MW
Hollow beam	
Wavelength	11 mm
Power	20 MW

6. NRL, 16 November 1981 [5]
7 July, 1982 [6]

Electron beam	
Energy	1.35 MeV
Current	1.5 kA
Pulselength	60 nsec
Energy spread	1%
Magnetic guide field	
	20 kG
Wiggler—bifilar, helical, adiabatic transitions	
Period	3 cm
Length	63 cm
Field intensity	0.1-4 kG
Output emission	
Efficiency	2.5%
Wavelength	
	4 mm
Power	35 MW
Low energy spread of electron beam is considered a novel feature	

Table 2—continued

7. IPF, 20 April 1982 [7]

Hollow electron beam

Energy	350-600 keV
Current	0.4-1.0 kA
Pulselength	100 nsec
Diameter	6 mm

Magnetic rippled field pump, copper rings with radial cutouts

Field period	2 cm
No. of copper rings	12

Bragg mirror reflectivity 0.9

Output emission

Wavelength	4.3 mm
Peak power	2 MW
Efficiency	1%

8. NRL, 27 December 1983 [11]

Electron beam

Energy	1 MeV
Current	600 A
Pulselength	60 nsec
Velocity spread	<<1%

Axial guide field 20 kG

Wiggler—helical, adiabatic transitions

Period	3 cm
Length	63 cm
Variable field	up to 4 kG

Output emission

Wavelength	8.57 mm
Peak power	17 MW
Efficiency	3%
Total gain	50 dB

Table 2—continued

9. Columbia, 27 June 1982 [12]	
Hollow electron beam	
Energy	750 keV
Current	20 kA
Magnetic guide field	11 kG
Wiggler pulsed, bifilar, helical, adiabatic transitions	
No. of periods	60
Period length	12.5 mm
Output emission	
Wavelength	1.7 mm
Power	MW level
<i>U.S.</i>	
10. NRL, 26 August, 1983 [134]	11. MIT, 14 March 1984 [10].
Electron beam	
Energy	1.25 MV
Current	1 kA
Pulselength	50 nsec
Energy spread	0.1%
Axial guide field	20 kG
Electron beam	
Energy	164 kV
Current	5.1 A
Pulselength	15 μ sec
Energy spread	<1%
Axial guide field	0.7-7 kG

Table 2—continued

SOVIET		U.S.	
Wiggler—adiabatic input and output transitions		Wiggler—circularly polarized bifilar helix with adiabatic entrance	
Interaction region	63 cm	No. of periods	50
Period length	3 cm	Period length	3.3 cm
Peak field	3 kG	Peak field	1.5 kG
Output emission		Output emission	
Wavelength	4 mm	Wavelength	1.7-4.3 cm
Power	75 MW	Power	100 kW
Efficiency	6%	Efficiency	12%
		Low energy spread, high gain and efficiency. First detailed study of frequency vs voltage tuning of both high and low output frequency branches under high- current operation	

Table 2—continued

<i>Pulse line accelerators, magnetostatic pumps, submillimeter wavelengths</i>	
U.S.	
12. NRL/Columbia, 6 September 1978 [13]	13. Columbia, 20 December 1980 [14]
Electron beam	Electron beam
Energy 1.2 MeV	Energy 0.5-1 MeV
Current 25 kA	Current 20 kA
Pulselength 40 nsec	Pulselength 150 nsec
Magnetic wiggler	Magnetic guide field 10 kG
Period 8 mm	Wiggler bifilar helix
Length 40 cm	Period 8 mm
Field intensity 400 G	Field intensity 250 G
Output emission	Output emission
Wavelength 0.4 mm	Wavelength 1.0 and 0.6 mm
Power 0.5-1 MW	Power 1 MW
Efficiency 0.03%	

Table 2—continued

<i>Pulse line accelerators, electromagnetic pumps</i>			
SOVIET		U.S.	
14. FIAN, 6 December, 1978 [15]		15. NRL, 17 November, 1976 [19]	
Terek-1 accelerator		Electron beam	
Beam energy	600-740 keV	Energy	2 MV
Energy spread	0.1		
Beam current	4.2 kA	Current	30 kA
Pulselength	20 nsec	Pulselength	60 nsec
Beam diameter			
Internal	17 mm		
External	21 mm		
Backward wave oscillator		Microwave pump output	
Wavelength	3.2 cm	counterstreaming 2 cm pump wave generated by rippled field	
Pulselength	15 nsec		
Power output	10-300 MW		
Output emission		Output emission	
Wavelength	Power	Wavelength	Power
13.4 mm	160 kW	0.4 mm	1 MW
7.8 mm	70 kW		
4.75 mm	7 kW		
Conditions are defined for which high energy spread does not affect generation. Observed stimulated emission			

Table 2—continued

16. IYaf-TPI, 12 January, 1981 [17]

Tonus-1 accelerator	
Beam energy	0.8-0.9 MeV
Beam current	13 kA
Beam pulselength	80 nsec
Beam diameter	54 and 74 mm
Thickness	1-2 mm
Guide field	5.5 -13 kG
Magnetron output	
Wavelength	10.2 cm
Power	5 GW
Pulselength	30 nsec
H ₁₁ mode peak power	1 GW
Output emission	
Wavelength	3 cm
Peak power	6 MW
Overall efficiency	0.003

Electron accelerator operated with two loads in parallel: a magnetron across the pulse forming line and the accelerator diode

17. NRL, 29 March, 1976 [18]

IREB accelerator	
Beam energy	0.9 MeV
Beam current	2 kA
Pulselength	50 nsec
Guide field	5 kG
Magnetron output	
Wavelength	3.2 cm
Power	170 kW
Pulselength	500 nsec
Output emission	
Wavelength	8 mm
Power	340 kW

Table 2—continued

18. IPF-ISE, September 11, 1984 [135]

Sinus accelerator

Beam energy 650 keV

Beam current 5 kA

Pulselength 20 nsec

Backward wave oscillator

Wavelength 3.2 cm

Power output 500 MW

Output emission

Wavelength 3 mm

Power 50 MW

19. NRL, 18 April 1983 [16]

IREB accelerator

Beam energy 900 keV

Energy spread <0.01

Beam current 1 kA

Backward wave oscillator

Wavelength 2.4 cm

Power output 500 MW

Ouput emission

Wavelength 2.1 mm

Power <350 kW

Table 2—continued

<i>Induction linacs, magnetostatic pumps</i>	
20. IYaf-TPI, 10 December, 1981 [20]	21. NRL, 29 October, 1984 [133]
Electron beam	Electron beam
Energy 0.55-0.8 MeV	Energy 0.7 MeV
Current 500 A	Current 200 A
Rep. rate 1 Hz	
Drift tube	
Diameter 35 mm	
Guide field 9 kG	
Wiggler helical	Wiggler electromagnetic helical
Intensity 80-250 G	Intensity 625 G
Period 4 cm	Period 4 cm
Length 50 cm	
Output emission	Output emission
Wavelength 8-9 mm	Wavelength 8 mm
Peak power 150 kW	Power 4.0 MW
	Pulselength 2 μ sec
	Efficiency 3%
High energy spread and low beam current density account for very low efficiency.	Uniquely long pulse, no guide field. High gain.

Table 2—continued

22. LLNL ETA [21]	
Electron beam	
Energy	4 MeV
Current	400 A
Wiggler pulsed, linear	
Period	9.8 cm
Output emission	
Wavelength	3-8 mm
Power	80 MW
Pulselength	50 nsec
Efficiency	4%

The purpose was to produce a long (microsecond) high-power microwave pulse without breakdown. The beam was formed by a magnetron-type field emission electron gun in a magnetically insulated diode driven by a Marx generator. Shortly afterwards, M. D. Rayzer and others of FIAN reported on another megawatt-output superradiant oscillator (exp. 3). These experiments, like all Soviet high-current magnetostatic FEL experiments published before 1980, produced output radiation in the cm wavelength range. All U.S. high-current FEL experiments, with one exception (exp. 10), were in the mm and sub-mm range. One of the first two U.S. high-current FEL experiments (exps. 18 and 19), performed at NRL by Granatstein, Pasour, and others one year after the publication of Faynberg's effort, produced an output power of 1 MW at a wavelength of 0.4 mm. Other U.S. sub-mm FEL experiments were performed with magnetostatic structures by NRL/Columbia in 1978 (exp. 13) and Columbia in 1980 (exp. 14). No Soviet high-current FEL experiments appear to have been performed in the submillimeter region.

Most of the Soviet high-current experiments performed in the period from 1975 to 1982 were also characterized by low efficiency relative to the corresponding U.S. efforts. Soviet authors have attributed this to the high emittance and energy spread of the electron beam.^[3,4,20,7] At least until 1984, Soviet experiments showed little effort to improve the energy spread and none to improve the performance of FEL by such means as adiabatic transitions in wigglers, which began to appear in U.S. devices in 1981.^[5,6,12,11,10] An important method of improving beam quality, used in the U.S., has been computer-assisted diode design which, in some cases, reduced the axial energy spread to less than 1 percent^[5] For example, a modified version of the SLAC Electron Optics Code was used to derive electrode contours, providing a radial force balance for near-axis electron trajectories.^[6] There is no evidence that computer simulation has been used in any of the Soviet FEL experimental programs.

An example of U.S.-Soviet differences is afforded by two fairly similar experiments, one by Didenko of IYaF-TPI in 1980 (exp. 5), and the other by Granatstein of NRL in 1981 (exp. 6). Both experiments featured electron beams of the same order of magnitude, and similar wiggler lengths and periods. They operated at the same order of output wavelength: 4 mm for the U.S. FEL and 7.5 mm for the solid-beam Soviet FEL. However, the low-emittance beam and adiabatic-entry wiggler of the NRL machine yielded peak output power of 35 MW at 2.5 percent efficiency, while the IYaF-TPI machine produced 2.5 MW with an efficiency of 0.4 percent. The difference is significant

in view of the fact that the experiments were reported within one year of each other.

Another example, also involving IYaF-TPI on the Soviet side and NRL on the U.S. side, is found in the experiments with induction linacs. For similar electron beam energies, currents, and wiggler parameters, and for the same FEL operating wavelength of 8 mm, NRL reached an output power of 4.0 MW (exp. 21) compared with 150 kW obtained by IYaF-TPI (exp. 20). The NRL experiment was also distinguished by a long pulse of 2 μ sec. On the other hand, however, the Soviet experiment was performed roughly two years earlier (1981). Furthermore, the microsecond pulse technology was pioneered by the early Soviet KhFTI experiment (exp. 1), in which a pulselength of 0.7 μ sec was observed in 1975.

Ginzburg, Petelin, and others of IPF, performers of the 1982 FEL experiment with rippled field pump (exp. 7), have commented on NRL's 4 mm 35 MW device (exp. 6), saying that it was limited by low efficiency and coherence due to the lack (in superradiant regime) or inadequacy of the feedback system. They claimed that their experiment has been designed to solve this problem by using a high-Q resonator in the form of a metal waveguide section with a rippled wall that satisfied the Bragg condition for resonance wave scattering. The rippling was formed by copper rings with radial cutouts claimed to be preferable to solid rings because cutout rings avoid decreasing the axial field. On the basis of output parameters, this experiment appears to be a significant achievement in FEL development.

Didenko of IYaF-TPI, reporting on his 1981 experiment with counterstreaming magnetron pump (exp. 16), interpreted his use of gigawatt-level pump power as an attempt to advance FEL development beyond the point established by Granatstein in 1976 (exp. 17) and Rabinovich of FIAN in 1978 (exp. 14).

The Soviet attempt to overtake the U.S. in output emission power succeeded in 1984, when a joint team from the Institute of High-Current Electronics in Tomsk and the Institute of Applied Physics in Gor'kiy reported an output emission power of 50 MW at a wavelength of 3 mm (exp. 18). A similar experiment reported by NRL a year previously (exp. 19) produced an output power of less than 350 kW at a wavelength of 2.1 mm. The same pump power of 500 MW was used in both experiments. The Soviet experiment used a relatively new electron accelerator of the Sinus series, probably the Sinus-6 machine. It was reported in 1983 by the Gor'kiy institute as the electron beam source for a Cherenkov oscillator, which delivered up to 10 MW at a wavelength of 2 mm.^[136] According to Ref. 136, the Sinus-6 was first described in a 1981 publication.

LOW-CURRENT EXPERIMENTS

Although the Soviet literature indicates no FEL-related experimentation with RF linacs, it does show a systematic low-current effort based on the use of synchrotrons with magnetostatic periodic fields installed in their straight sections and thus generating what the Soviets call undulator radiation. It therefore appears that, in the low-current FEL development effort, the U.S. research has concentrated on the infrared region of the spectrum, while the Soviets have been interested in the visible and near ultraviolet regions. Undulator radiation observed in the Soviet experiments performed by FIAN with the Pakhra synchrotron and by IYaF-TPI with the Sirius synchrotron has, so far, been of a spontaneous nature.

According to Soviet authors,^[24] the earliest research on undulator radiation in the visible region of the spectrum has been performed by Alferov at FIAN in 1977. Alferov found the intensity of undulator radiation to be several times higher than the intensity of synchrotron radiation near the wiggler axis.^[25,26] A year later, a similar observation was reported by Nikitin of IYaF-TPI.^[27] Commenting on the pioneering work of Madey with the RF linac at Stanford University,^[22,23] the Soviet FEL theoretician M. V. Fedorov noted that Alferov's and Nikitin's experiments represent a parallel and independent investigation of spontaneous emission from electron beams scattered by spatially periodic fields.^[28]

Nikitin embarked on a systematic investigation of the angular distribution and linear polarization of undulator radiation in the visible region of the spectrum, as well as a study of its utilization potential in the vacuum UV region. The first experiment^[27] verified the basic theory of undulator radiation and showed that the electron beam angular divergence affects polarization and angular spectral distribution characteristics of both undulator and synchrotron radiations. The radial divergence of the beam was 0.5479×10^{-3} rad. Nikitin concluded that these characteristics determined the specific modes of the optical cavity in experiments with stimulated emission by IREB.^[27,29,30]

In subsequent experiments Nikitin observed that undulator radiation had high tunability, polarization, monochromaticity, and low angular divergence. The fundamental harmonic of the emission, at 0.5μ , exceeded the spectral density of synchrotron radiation by a factor of 200.^[24,31,32]

Alferov performed an experiment using a low-intensity wiggler field with sharply defined boundaries. He showed that in such a system the electron radiation has a high intensity and directivity. He has also observed a sharp dependence of radiation intensity on electron energy

and concluded that this dependence renders the system in principle suitable for the generation of stimulated emission.^[33]

Table 3 summarizes Soviet experiments with low-current devices.

PLANNED EXPERIMENTS

Storage Ring FEL

N. A. Vinokurov of IYaF-SOAN proposed an FEL modification in the form of an optical klystron whose gain would be higher than that of a conventional FEL by a factor of 100 to 1000. This would make it possible to install the optical klystron in an electron storage ring. The Institute has analyzed the problem of an optical klystron adapted to the VEPP-3 storage ring, designed the magnetic system, and measured the spontaneous emission spectrum and gain of the optical klystron. Experiments were performed at VEPP-3 injection energy of 350 MeV. In 1980, the optical cavity of the optical klystron was installed in the VEPP-3 storage ring and preparations were under way to generate coherent emission.^[34] According to the 1984 FEL review by Sprangle and Coffey,^[35] the VEPP-3 storage ring FEL experiment had a beam energy of 340 MeV, peak beam current of 20 A, and a measured gain per pass of 0.4 percent at a wavelength of 6 μ . This compares favorably with the gain per pass of 0.07 percent observed in the ACO storage ring of LURE in Orsay, although the latter operated in the visible, rather than infrared, region of the spectrum.^[36]

Colliding-beam Accelerator

In 1981, IYaF-SOAN was designing a 300 GeV linear colliding electron-positron beam accelerator system (VLEPP), similar to the 50 GeV SLAC linear collider being designed in the U.S. In the Soviet project, a neodymium glass laser beam was planned to collide with the VLEPP beams to produce photons by Compton scattering, with energy and brightness of the order of those obtainable from electron-positron collisions.^[37]

In connection with this project, A. M. Kondratenko and Ye. L. Saldin of IYaF-SOAN proposed to substitute an FEL for the glass laser and thus to dispense with an external source of coherent light, so that accelerator technology alone would serve the project. The high-density light beam would be obtained from coherent emission of a relativistic electron beam in a single-pass undulator. The same electron beam

Table 3

SOVIET SYNCHROTRON-BASED EXPERIMENTS WITH UNDULATOR RADIATION

1. FIAN, 25 July 1977 [25,26]. Alferov, Pakhra synchrotron

Electron beam energy	150 MeV
Magnetic wiggler	
Field intensity	360 G
Current	3 kA
Length	80 cm
Period	4 cm
Output emission wavelength	0.25-0.45 μ

Multiple passes through undulator. Undulator radiation intensity several times higher than synchrotron radiation intensity near wiggler axis.

2. IYaf-TPI, 4 April 1978 [27,29,30]. Nikitin, Sirius synchrotron

Electron beam	
Energy	170-240 MeV
Radial divergence	0.547×10^{-3} rad.
Magnetic wiggler	
Period	70 mm
Total length	700 mm
Field intensity	0.15-3 kG
Output emission wavelength	0.51

Table 3—continued

3. IYaf-TPI, 1 November 1978 [24,31,32]. Nikitin, Sirius synchrotron
Electron beam

Energy 50-900 MeV
 Energy spread 0.5%

The fundamental harmonic of undulator radiation at 0.5 exceeded the spectral density of synchrotron radiation by a factor of 200.

Magnetic wiggler, planar

Length 70 cm
 Period 14 cm
 Field intensity 0.25-1.5 kG

Output emission wavelength 0.5 μ

4. FIAN 1981, 15 May 1981 [33]. Alferov, Pakhra synchrotron

Electron beam peak energy 850 MeV

Magnetic wiggler

Length 100 cm
 Field intensity 27 G

Sharply defined wiggler field.

Output emission wavelength 0.5 μ

would be used at various acceleration stages to generate coherent emission and to convert it into high-energy photons.

The problems of phase matching, optimal length of the light pulse, and the required repetition frequency would all be solved automatically by the system. The electron beam, accelerated to an intermediate energy value, would pass through the undulator, generating a light beam of the same length and direction. To obtain the necessary phase lead of the light pulse, the electron trajectory would be curved at a certain point and the electrons would then be accelerated to peak energy. The light pulse would travel either in the vacuum chamber of the linear accelerator or in a parallel channel, and would be optimally focused on the electron beam traveling in the opposite direction. The high-energy photons produced by Compton scattering, traveling down the electron trajectories, would collide with analogously produced opposed electrons. To avoid collision with electrons after conversion, a deflecting magnetic field would be provided at the photon-electron meeting point.^[38] Table 4 shows a numerical example illustrating the proposed system.

Other Accelerators

In 1981, D. F. Alferov, leading performer of the undulator radiation experiments with the Pakhra synchrotron described above, evaluated the parameters of proposed FEL devices driven by the accelerators of the Photomeson Process Laboratory of FIAN. According to Alferov,

Table 4

PROPOSED FEL BASED ON THE VLEPP ACCELERATOR^[38]

Electron beam	pulse
Energy	10 GeV
Current	1 kA
Energy Spread	10-4
Cross-Section	0.01 cm radius
Angular divergence	10-5
Wiggler	
Magnetic field	20 kGauss
Period	20 cm
Total length	40 m
Coherent emission	
Wavelength	0.4 μ
Power	0.25 TW
Efficiency	0.5%

the Laboratory was then operating a linear induction accelerator and a standard microtron, in addition to the Pakhra synchrotron. A racetrack microtron was under construction.^[39]

Alferov postulated a 3.5 kG helical wiggler magnet with a period of 3 cm and internal diameter of 1 cm, noting that the design is not expected to present engineering problems. The number of periods of the magnet would be determined from case to case by a trade-off between the necessary generation threshold and acceptable efficiency. The optical cavity was 2 m long and the beam pulselength was 10 μ . Table 5 shows the accelerator and output emission data for the Laboratory equipment.

Alferov notes that the operating parameters of the linear induction accelerator and the standard microtron, both in service at the time, could provide efficient coherent undulator radiation in the submillimeter wavelength range. The introduction of the 40 MeV racetrack

Table 5

FEL PARAMETERS BASED ON ELECTRON ACCELERATORS OF THE
PHOTOMESON PROCESS LABORATORY OF FIAN^[39]

Item	Electron Accelerators			
	Linear	Microtron	Racetrack Microtron (Under Construction)	Pakhra Synchrotron
Electron beam				
Energy, MeV	5	11	40	150
Energy spread	0.05	0.003	0.001	0.001
Peak current, A	30	0.4	4	2
Average current, mA	1.3	0.01	0.18	300
Periodic magnet field				
Intensity, kG	3.5	3.5	3.5	3.5
Period, cm	3	3	3	2
No. of periods	10	30	50	80
Laser beam				
Wavelength, μ	300	60	5	0.2
Gain per pass	0.6	0.05	0.006	0.005
Efficiency	0.015	0.008	0.005	
Pulselength, microsec.	0.02	0.26	0.2	
Peak power	2.4 MW	35 kW	0.8 MW	7 mW
Average power	160 W	0.9 W	35 W	1 mW

microtron will make it possible to extend the wavelength range to infrared (up to $5\ \mu$), with an average stimulated emission power of 35 W. Further improvements could include the use of short beam bunches and wiggler taper.

III. COMPARATIVE HISTORY OF THEORETICAL FEL RESEARCH

The FEL experimental efforts presented in Sec. II were, of course, embedded in extensive theoretical research carried on in both countries. At this time, FEL research has also proceeded long enough to generate several overviews of past work. On the U.S. side, such reviews, published in 1983 and 1984, include general summaries by Prosnitz^[21] and Sprangle and Coffey,^[35] a brief but useful history of FEL research included in a paper by Coffey, Lax, and Elliott,^[40] and a more specialized review by Granatstein, Parker, and Sprangle.^[41] An account of recent Western FEL experiments is given by Roberson et al.^[131] It must be noted that the U.S. overviews covered very little of the Soviet work.

Soviet overviews of FEL research began appearing in 1979 and are comprehensive in their coverage of both Soviet and U.S. work. A relatively brief early summary was published in 1979 by V. L. Kuznetsov,^[42] followed by an assessment of FEL potential by Bratman, Ginzburg, and Petelin of IPF.^[43] In 1981, M. V. Fedorov of FIAN published a brief technical summary^[44] and an extensive review of FEL research.^[45] Finally, Didenko and Kozhevnikov of IYaf-TPI published a comprehensive FEL overview in 1983.^[2] The following historical account of FEL theory is based primarily on these sources.

Soviet writers note that the Soviet scientist V. L. Ginzburg first showed theoretically in 1947 that generation of millimeter and submillimeter wavelengths can be obtained by passing charged particles through a channel in a dielectric which, under certain conditions, does not attenuate the generated radiation. A closer approach to the principles of FEL was accomplished four years later by Motz in his analysis of the ubitron. The Soviets credit Pantell with the first theoretical paper on relativistic FEL, and Madey and his associates with the development of the equivalent photon method and its application to the magnetic wiggler field.^[45,2]

However, Petelin and Smorgonskiy of FIAN were the first to present (in 1973) an analysis of stimulated emission of a relativistic electron in a magnetic wiggler based on classical equations of motion,^[46] followed in the same year by FIAN's Kolomenskiy and Lebedev.^[47]

According to Coffey, Lax, and Elliott,^[40] classical analyses in the U.S. were initiated by Hopf et al.^[48,49] and Colson,^[50] and extended by Louisell et al.^[51] leading to the well-known pendulum equation.

Among Soviet theoreticians, the classical approach was later pursued by Bratman, Ginzburg, and Petelin,^[52] McIver and Fedorov,^[28] Alferov and Bessonov,^[53] and others. In their view, the classical equations for electrons moving in magnetic fields could be reduced to Landau's equation of the mathematical pendulum, in analogy to traveling-wave tube (TWT) theory. In 1977, Andreyev, Davydovskiy, and Sapogin of TRTI provided expressions for gain, saturation, and coherent modulation of the electron beam.^[54] In 1978, FIAN's Alferov published a year ahead of Louisell the classical analysis of FEL in a single-particle approximation reduced to the mathematical pendulum model.^[55] In the same year, Bratman published numerical solutions of pendulum equations applied to FEL theory found to be in very good agreement with analytical solutions.^[56]

The above analyses, performed in the single-particle approximation, were valid only for relatively low-density beams in which collective effects could be neglected. Analysis of conversion of electron energy into radiation energy, taking collective effects into account, was performed by Miroshnichenko in 1975,^[57] Kwan, Dawson, and Lin in 1977,^[58] Kroll and McMullin,^[59] and others.^[2]

In 1978, Bratman, Ginzburg, and Petelin generalized the results of the linear theory of FEL to cover the case of high gain per pass, providing numerical solutions of classical equations of motion of electrons in a strong wiggler field.^[56] In 1979, Alferov provided a qualitative analysis of nonlinear effects in FEL.^[53]

In the U.S.,^[40] nonlinear scattering theory was considered in 1980 by Sprangle et al., who analyzed efficiency and interaction length and presented numerical solutions to nonlinear equations describing the temporal steady-state of the free-electron laser; they showed that efficiencies could be increased to greater than 20 percent by appropriately decreasing the pump magnetic field.^[60]

An extensive analysis of FEL theory in terms of quantum mechanics was performed by M. V. Fedorov of FIAN. His direct quantum-mechanical computation of gain in FEL (small-signal approximation) was claimed to be much simpler than Madey's procedure. Fedorov obtained stimulated emission and absorption cross-sections directly from quantum electrodynamic analysis using second-order perturbations.^[61]

Fedorov criticized Hopf's 1976 paper,^[49] dealing with nonlinear effects in strong fields, for an unjustified break in mathematical derivation, invalidating its conclusions.^[45]

In 1979, Fedorov used quantum theory for analytical treatment of multiphoton processes and gain saturation in FEL. Fedorov showed that there was no equivalence between the single-photon transition

approximation in quantum mechanics and the small-signal approximation in classical mechanics, since FEL amplification was always of a multiquantum nature. To describe multiphoton transitions, one must proceed with quantum theory. To find gain in FEL, one must use either quantum or classical equations of electron motion in strong field, each approach being supplementary to the other.^[28] In 1980, Fedorov obtained equivalent expressions on the basis of classical theory.^[62]

The theory of efficiency and gain enhancement in FEL appears to have been mainly developed in the U.S.^[2,40] The effects of wiggler tapering were discussed in 1981 by Kroll, Morton, and Rosenbluth, who clearly delineated three operational modes of the laser amplifier.^[63] Brau discussed small-signal gain in tapered wigglers,^[64] and Georges and Louisell have recently presented the results of self-consistent numerical calculations for high-gain FEL amplifiers with exponentially decreasing wiggler periods.^[65]

IV. ORGANIZATION OF SOVIET FEL RESEARCH

The following institutes have published theoretical and experimental reports on FEL research:

Moscow-Gor'kiy Group

Lebedev Physics Institute, Moscow (FIAN)

Scientific Research Institute of Radiophysics, Gor'kiy (RFI)—up to 1976

Applied Physics Institute, Gor'kiy (IPF)—from 1977

Tomsk Group

Institute of Nuclear Physics of the Tomsk Polytechnic Institute (IYaF-TPI)

Institute of High-Current Electronics, Tomsk (ISE)

Novosibirsk Group

Institute of Nuclear Physics, Siberian Department, Academy of Sciences, USSR, Novosibirsk (IYaF-SOAN)

Khar'kov Group

Physico-technical Institute, Khar'kov (KhFTI)

Yerevan Group

Yerevan State University (YeGU)

Saratov Group

Institute of Mechanics and Physics, Saratov State University (IMF-SGU)

Other Institutes

Moscow State University (MGU)

Moscow Power Engineering Institute (MEI)

Radio-technical Institute, Taganrog (TRTI)

Kurchatov Institute of Atomic Energy, Moscow (IAE)

Institute of Physics Problems, Moscow (IFP)

Institute of Electrodynamics, Kiyev (IED)

Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation, Irkutsk (IZMIR)

The following institutes and organizations also appear involved in the FEL research effort by participation in the FEL meetings of the Academy of Sciences Problem Councils:¹

¹Science Councils for Major Complex and Inter-Branch Scientific and Technical Problems have been established by decrees of 1961 and 1963 and joint regulation of the State Committee for Science and Technology and the Academy of Sciences, USSR. In general, the science Councils are designed to coordinate scientific activities in all

Radiotechnical and Electronics Institute (IRE), Moscow

Institute of Nuclear Physics, Moscow State University (IYaF-MGU), Moscow

Institute of High Temperatures (IVTAN), Moscow

Energiya Scientific Production Association

The administrative jurisdiction under which these organizations operate is evenly divided between the Academy of Sciences and the Ministry of Specialized Secondary and Higher Education (the VUZ system). The sole exception is the Energiya Scientific Production Association, which probably operates within the industrial ministry system. Since, in the case of major research projects, VUZ research institutes often work under technical supervision of the Academy of Sciences, the latter appears to be in total control of Soviet FEL research.

The Soviet FEL research effort is reviewed and coordinated by the following Scientific Problem Councils of the Academy of Sciences, USSR:

Council on Coherent and Nonlinear Optics

Council on Plasma Physics

Council on Physical Electronics

Information on the activity of the Councils in the FEL area has been published in connection with a December 1980 session of the Bureau of the Coherent and Nonlinear Optics Problem Council hosted by FIAN. The session included members of the Problem Councils on Plasma Physics and Physical Electronics, Relativistic Electronics Section. The topic of the session was the future development of free-electron lasers and channeled particle emission under the chairmanship of A. V. Gaponov-Grekhov. The research institutions represented at the session were FIAN, IPF, IFP, IAE, IVTAN, MGU, IYaF-SOAN, ISE, IYaF-TPI, IYaI, Energiya, MRTI, and YePI.^[34]

Gaponov, the director of IPF, is an outstanding authority on high-power microwave oscillators and amplifiers and has been responsible for the development of the gyrotron and other relativistic microwave

research establishments participating in the solution of particular projects, and to provide solutions for those problems the government considers most important at the moment.^[66] The Councils play a significant role in planning, organizing, and coordinating research throughout the Academy and ministry systems. Since they are composed of working scientists and engineers from all sectors of the science system, the Councils provide horizontal linkages among institutions. They are of great importance in involving scientists and engineers in the decisionmaking process, since the Councils not only render technical advice but also provide scientists the opportunity to participate in policymaking.^[67]

devices. He is probably in charge of the Soviet R&D program in the area of high-power microwaves. The involvement of the Councils and Gaponov's chairmanship of their FEL session are strong indications that FEL development has attained the status of a major R&D project, at least on the Academy level, if not on a national level. The attendance of the Energiya Scientific Production Association at the session of scientific Councils also implies that at least some aspects of FEL development may be approaching a stage in which industrial support becomes relevant.

The focus of Soviet FEL activity resides in two groups of researchers. One represents a combined effort of FIAN in Moscow and IPF in Gor'kiy (until 1976, the Gor'kiy work on FEL had been carried on in RFI; it was moved to IPF in 1977). The FIAN-IPF research is probably headed by Gaponov himself with several other leading specialists, such as M. I. Petelin, V. L. Bratman, and N. S. Ginzburg of IPF, and A. N. Prokhorov, M. S. Rabinovich, and A. A. Rukhadze of FIAN. The other group works at IYaF-TPI in Tomsk under the leadership of A. N. Didenko, director of that institute. The two groups perform almost all the Soviet experimental work on FEL, and together account for over one-half of all Soviet theoretical FEL work in terms of the number of authors publishing on the subject. Table 6 illustrates the relative contributions of the main research groups to the Soviet FEL research effort.

The experimental equipment currently used in FEL research or expected in the near future for such use is shown in Table 7. It should be noted that the machines listed in the table—particularly the pulse line accelerators—are part of a larger number of pulse line machines available in Soviet research institutes that may be at some point drawn into FEL research.

Table 6

SHARES OF SOVIET INSTITUTES IN FEL RESEARCH
Percent of Publishing Authors up to 1983

Institute	Theory (%)	Experiment (%)
FIAN-RFI-IPF	28	54
IYaF-TPI	17	34
KhFTI	3	12
IYaF-SOAN	10	0
YeGU	18	0
Others	24	0

Table 7

MAJOR EXPERIMENTAL FACILITIES ENGAGED IN FEL DEVELOPMENT

Institute	Facility	FEL type
FIAN	TEREK-1 high-current accelerator, 1 MeV 20 kA	Relativistic ubitron, electromagnetic-wave pump
FIAN Photomeson Process Lab.	Linear accelerator, 5 MeV Microtron, 11 MeV PAKHRA synchrotron, 150 MeV	Undulator radiation
IPF	Sinus-6 high-current accelerator, 650 keV 5 kA	Electromagnetic-wave pump
IYaF-TPI	TONUS high-current accelerator, 1 MeV 15 kA	Relativistic ubitron, electromagnetic-wave pump
IYaF-SOAN	LIU rep-rated linear accelerator, 1 MeV 0.5 kA 1 Hz SIRIUS synchrotron, 1.5 GeV	Relativistic ubitron
		Undulator radiation
	VLEPP linear beam collider, 300 GeV (in design stage) VEPP-3 storage ring, 350 MeV (under construction)	Undulator radiation Optical klystron
KhFTI	Microsecond high-current accelerator, 230 keV 3 kA	Relativistic ubitron

V. OBJECTIVES OF SOVIET FEL RESEARCH

According to Soviet authors, the design of an efficient FEL in the millimeter and submillimeter ranges represents an as yet unsolved problem, largely because of the complexity of the electrodynamic system capable of selecting the desired output mode and, at the same time, transporting the high-current electron beam.^[68]

The major problems facing the developers of FEL are the production of electron beams with sufficient current density and beam quality characterized by low energy spread and low divergence. The main aims are to increase the generation frequency, increase output power, and study new systems and amplification principles.^[45]

In the ultrarelativistic limit, the optimum efficiency requirement imposed on the intensity of the RF field interacting with the electron beam is inversely proportional to beam energy, while the requirement for the length of the device increases as energy squared, the optimum efficiency and output wavelength remaining constant. The decreasing field intensity with increasing beam energy should make it possible to develop stimulated emission devices using ultrarelativistic electron beams for ever-shorter wavelengths, an objective otherwise limited by RF breakdown. The trend favoring shorter wavelengths is the opposite to that found in the case of weakly relativistic beam oscillators and amplifiers.

On the other hand, the increase in the length of the device with increasing beam energy imposes increasingly rigorous requirements on the precision with which the electromagnetic system is fabricated and on the monoenergetic quality of the electron beam.

These considerations apply to such types of stimulated electron emission devices as the TWT and orotron based on the Cherenkov effect, the monotron based on the transient effect, and the ubitron and the synchrotron oscillator based on the bremsstrahlung effect.^[69]

FEL power should be very high with the use of high-current electron accelerators. For an electron energy of tens of MeV, it may be possible to develop infrared FEL, of interest to physics of radiation-molecular interaction. FEL can also be pumped by high-power microwave sources, such as a magnetron. To achieve acceptable gain, microwave pump sources should have output power of 10 to 100 MW/cm², currently achievable in pulse mode.^[45]

According to theory and analytic data, the output emission wavelength is about $4E^2$ times shorter than the period of an

electromagnetic pump wave, and about $2E^2$ times shorter than the period of the spatially periodic magnetic field structure, where E is beam energy expressed in terms of the relativistic factor. This relativistic compression of the emission wavelength is a principal feature of FEL, responsible for the generation of short-wave oscillations in large-size structures. This feature is also present to a lesser extent in cyclotron resonance masers capable of generating powerful millimeter and submillimeter radiation, but it is not realizable in such devices as the backward-wave tube, the traveling-wave tube, the klystron, and the magnetron.^[2] However, in the ultraviolet range, for a 10 MeV FEL, it is hardly possible to design a magnetic wiggler with small enough period (10^{-3} to 10^{-4} cm). Instead, an electromagnetic-wave pump FEL pumped by a CO_2 picosecond laser can be used for this purpose.^[45] However, the high requirements imposed on such a FEL in terms of electron beam density and quality, and laser pump intensity, would render these devices very cumbersome. Therefore, current interest is focused on simpler scaled-down experiments with stimulated scattering in the millimeter and submillimeter ranges, such as FIAN's electromagnetic-wave pump FEL experiment^[15] and NRL's experiment.^[19]

It should be noted further that even in these relatively long wavelength ranges, the design of an efficient scattron adequate for a proof of feasibility represents an as yet unsolved problem that is much more complex than the design of relativistic oscillators based on other mechanisms, such as the ubitron, the gyrotron, and the Cherenkov oscillators. The reason is that stimulated scattering requires a powerful pump generator synchronized with the electron beam injector. The above experiments found a simple solution by using the same electron beam to generate the pump wave and to scatter it, and the most natural way to achieve this was to use the backward-wave oscillator as the pump.

However, this configuration requires the resonator to maintain not only the high-frequency waves scattered at small angles to the electron motion, but also the longer wavelength pump energy. To meet this requirement, special resonators must be developed, such as sections of rippled waveguides.^[70] Resonators with shallowly rippled walls represent distributed feedback systems analogous to optical resonators that do not utilize the conventional cavity mirrors, but provide feedback via backward Bragg scattering from the periodic ripple structure. Along with regular period ripples, these systems may also have variable phase ripples, or two rippled sections (Bragg mirrors) separated by a smooth waveguide.^[68]

A high-gain FEL can be obtained with intense electron beams having beam current exceeding 1 kA. However, in the Soviet Union the energy of such beams does not exceed a few MeV and, at this time, such beams cannot yield high efficiency. Higher efficiency should be obtained from electron beams with an energy of tens of MeV, although the achievable currents in such accelerators are at the level of single amperes.^[2] Efficient FEL operation requires that beam current density be 10^4 A/cm², beam energy be 1 to 5 MeV, and the energy spread be less than 1 to 5 percent for a 10 percent efficiency in the millimeter and submillimeter range. Recently, proposals were made to decrease FEL sensitivity to energy spread, making it possible to use the available inexpensive electron accelerators.

It was assumed that in most FEL systems the magnet period is constant over its length. This is the reason for the low efficiency of energy conversion, because, as electron energy is converted to electromagnetic emission energy, electrons are decelerated, disrupting the resonance conditions of generation and slowing the growth of wave amplitude. N. M. Kroll et al. (1981) showed that variation of the period and/or the magnetic field intensity of the magnet structure along the electron trajectory according to a suitable law, could increase efficiency up to 25 percent.^[2]

According to Soviet authors, in all FEL experiments performed through 1982 it was found that, for electron beam energy above 100 MeV, the gain in the optical region was so low as to cast doubt on the probability of generating coherent emission in magnetic undulators. They have therefore expressed interest in other methods of generating coherent emission in the optical and soft ultraviolet regions by FEL without undulators. One proposed method was based on stationary electric and magnetic fields that are homogeneous along the direction of motion of ultrarelativistic electron beams and inhomogeneous in the transverse direction. The electrons could then undergo transverse harmonic oscillations if the potential of such fields increased perpendicularly to the beam from the center outwards. Analysis indicates that in such a case it should be possible to obtain gains higher by the factor of gamma than those observed in conventional magnetic undulators.^[71]

Very-short-wave undulator emission might be obtained from the channeling effect of relativistic particles in crystal.^[52] It is also possible to consider solid-state systems for this purpose in which the periodic nature of the crystalline field is not significant; their closest vacuum analog is the strophotron.^[72,73]

VI. CONCLUSIONS

The technological implementation of new concepts in physics ultimately depends on the success of experimental programs, rather than on the maturity and sophistication of theory. In most comparative assessments of U.S. and Soviet R&D, this fact of life does not favor the Soviets, whose R&D has been marked by a preponderance of theoretical research and, in many areas, a relatively weak experimental base. The case of free-electron lasers is no exception, in spite of the apparently high level of Soviet experimental effort. Soviet FEL theory shows a vigorous development stimulated by a large community of outstanding scientists potentially capable of significant advances in this field. FEL appears to be a major R&D objective in the Soviet Union, is sponsored by the Academy of Sciences, and is being developed by key Academy institutes, with the institute directors taking an active role in this work. However, the corresponding experimental programs, at least as far as they are reflected in Soviet technical literature, do not seem to be commensurate either with the breadth and depth of Soviet theoretical effort, or with the U.S. experimental results.

To gain a clearer insight into this situation, it is useful to divide the period of experimental FEL research into two phases: phase one, covering the years from 1975 to 1980, and phase two, extending from 1981 to 1984, the last year covered by this report. During the first phase, the Soviets had kept pace with the U.S. in terms of the number and frequency of FEL experiments. During that time, the U.S. high-current experiments were dedicated to the millimeter and submillimeter wavelength range, while the Soviets stressed high-power output at centimeter wavelengths. Their high-current effort remained within the centimeter range throughout the first phase despite the Soviet aim of increasing generation frequency and developing efficient millimeter and submillimeter FEL systems.

During the second phase, the number of U.S. FEL experiments increased considerably. At the same time, U.S. research has been improving electron beam quality and, therefore, the efficiency of FEL devices. In contrast, the number of Soviet high-current FEL experiments has dropped sharply and, with the exception of the last experiment reported in 1984, there was little Soviet qualitative improvement. The Soviets reported millimeter output, but there were no Soviet high-current experiments in the submillimeter wavelength range.

In the 1984 report, after a year's silence on FEL experimentation, the Soviets announced the successful operation of an electromagnetically pumped FEL delivering 50 MW at a wavelength of 3 mm. This implies significant changes in the pattern of Soviet high-current FEL experimentation. Specifically, a marked improvement must have taken place in Soviet capability to produce quality electron beams. One should also assume some upgrading of Soviet FEL research in general.

The relatively conservative experimental results obtained by the Soviets during the first phase of FEL research can be ascribed to a number of reasons. First, one sees the scarcity and indifferent quality of Soviet experimental equipment. Since its inception, experimental FEL research in both countries made use of the already available electron accelerator facilities. In the U.S., in the area of high-current pulse line machines, low-megavolt, kiloampere units, such as the Pulserad accelerators, have become fairly commonplace in addition to such specialized machines as the VEBA at NRL. Soviet researchers have had to rely mainly on two workhorses of Soviet pulsed-power development: the Terek accelerator at the Lebedev Physics Institute and the Tonus at the Tomsk facility.

Second, there is the shortage of computing facilities. The generation and conditioning of high-quality, high-current electron beams is a difficult art requiring extensive trial-and-error experimentation. Computer simulation can provide a significant shortcut in this process, saving time, labor, and equipment. This has been readily apparent in the expanding U.S. application of computer codes to the design of electron guns and other aspects of accelerators and electron beam systems, which was instrumental to the improvement of beam quality and efficiency of conversion. Therefore, in the U.S., computers tend to augment an experimental base that has been richer in the first place. In the USSR, computer deficiency tends to compound further the limited quantity of accelerator equipment that seems to be available for FEL experiments. It is probable, therefore, that the most important single cause of Soviet lag in FEL experimentation was the chronic Soviet scarcity of computers and the corresponding lack of computer-aided design practice.

Third, Soviet FEL experimentation during the first phase was affected by lack of inter-institutional cooperation and insufficient spin-off from other accelerator developments. In spite of the weaknesses typical of Soviet R&D, the Soviets have an exceptionally well-developed pulsed-power technology, which is the base of FEL experimentation. Soviet research in the broad area of pulsed power, involving particle accelerators, beam conditioning, switches, energy storage systems, and beam dynamics studies, has been proceeding at a high

level of effort for the past two decades. The Soviets have also achieved significant results in the development of relativistic microwave devices. The apparently high status of the FEL research program should have made these resources available to its further progress. However, it is clear that the existing range of Soviet accelerator and beam conditioning facilities has not been fully utilized for FEL research at least during the first phase.

The 1984 experiment shows that some of these shortcomings have been alleviated. A relatively new electron accelerator facility, the Sinus-6, was brought into play, and effective beam conditioning techniques, perhaps including computer codes, must have been instituted to produce the announced results. Most important, however, the research has drawn the Tomsk Institute of High-Current Electronics (ISE) into cooperation with Gor'kiy's Institute of Applied Physics. The Tomsk Institute is the only research organization of the Academy of Sciences entirely dedicated to the development of pulsed power. Under the leadership of G. A. Mesyats, it has become a major source of expertise in this area over the years, representing precisely the capability needed to advance FEL research. Thus, the upgrading of beam quality implied in the results of the 1984 experiment was probably ISE's contribution.

However, the progress in Soviet high-current FEL research manifested by these results is not consistent with the otherwise barren Soviet experimental FEL literature of phase two. The early exploratory research in the U.S. and USSR during phase one had been accompanied by experimental reports published in the same quantity by both countries. The maturing research and advanced experiments of phase two have, in the U.S., been attested to by a relative profusion of publications. The Soviet results of this time, while surpassing the comparable U.S. work, have no such publication background. Two possible conjectures can be drawn from the Soviet pattern.

One is that the deficiency in computer facilities and pulsed-power expertise has proved critical in phase two of the FEL program and has led to a decline in Soviet FEL experimental activity. The 1984 experiment, according to this conjecture, was an isolated case brought about by the exceptional cooperation between IPF and ISE.

A more plausible conjecture is that the transition to a maturing phase of Soviet FEL research has largely removed experimental material from publication. One can assume that phase two is characterized by an intensive experimental program, cooperation among the institutions involved, spinoff from pulsed-power technology, and participation of classified facilities more advanced than those known from the literature.

Since low-current, high-energy FEL experiments are less encumbered by the beam quality problem, they are more compatible with Soviet experimental capabilities. This may be one reason for the large Soviet program to study undulator radiation in synchrotrons, which appears to be of the same order of magnitude as their FEL programs for high-current accelerators. Another reason may be the availability of the two large synchrotron installations in Moscow and Tomsk. That availability may also account for the Soviet interest in the visible and shorter wavelength regions.

Appendix A

RESEARCH ACTIVITY OF SOVIET INSTITUTES

THE MOSCOW-GOR'KIY GROUP

This group, consisting of the Lebedev Physics Institute (FIAN) in Moscow and the Applied Physics Institute (IPF) in Khar'kov, represents the largest experimental and theoretical FEL research effort in the USSR. Over 50 authors associated with these institutes have been active in work relevant to FEL, some of them publishing on the subject since the late 1960s. Two of FIAN's major accelerator systems, the Terek-1 pulse line accelerator and the Pakhra synchrotron, have been used for FEL experiments. FIAN's Photomeson Process Laboratory operates the Pakhra synchrotron and may also include a linear induction accelerator and a microtron in FEL experiments.

The importance of the combined FEL research effort of FIAN and IPF transcends purely quantitative considerations. FIAN is the largest and most prestigious physics research institute in the USSR and has contributed some of its leading physicists to FEL research: A. A. Kolomenskiy, M. S. Rabinovich, A. A. Rukhadze, V. L. Ginzburg, and A. N. Prokhorov. IPF, under the leadership of A. V. Gaponov-Grekhov, has been the center of Soviet high-power relativistic microwave development and has been outstanding among Soviet R&D institutions in bringing advanced technology projects to successful conclusion.

The joint research in high-power coherent emission generators based on high-current accelerators is headed by Kolomenskiy and Rukhadze on behalf of FIAN, while M. I. Petelin represents IPF. Current objectives of this research include production of high-density, high electron oscillation frequency, and low-energy-spread electron beams and highly selective quasi-optical resonant cavities necessary to push the pulsed microwave oscillators towards shorter wavelengths.^[34]

The FEL research of this group appears to break down into six distinct subgroups, or teams, each having its own area of FEL specialization. One of these teams, called Team 1 for the purpose of this report, represents the FIAN-IPF collaboration. Of the remaining teams, one represents IPF and four are associated with FIAN.

TEAM 1. Petelin, Smorgonskiy, and Rayzer, FIAN-RFI-IPF

This team has been active in the theoretical work on stimulated emission of electromagnetic energy from high-current relativistic electron beams since the 1960s. This work has been performed by Gor'kiy scientists supervised by Gaponov and led by M. I. Petelin, S. V. Smorgonskiy, and M. D. Rayzer. Until 1976, these authors published under the byline of the Radio-Physics Institute of Gor'kiy; since then they appear to have been transferred to IPF. The collaboration with FIAN involves experimental work, begun in 1973, that utilized FIAN's Terek-1 pulse line accelerator designed for 0.7 MeV, 20 kA, and 20 nsec.

In 1973, Petelin and Smorgonskiy published what was claimed to be the first analysis of stimulated emission in a magnetic wiggler field based on classical equations of motion.^[46] At the same time, they began the series of experiments with the Terek-1 electron accelerator^[74] under M. S. Rabinovich. In the first experiment, the accelerator was used to drive a high-efficiency backward-wave oscillator.^[75] In 1976, the Terek-1 was the basis of a relativistic ubitron with a magnetic wiggler structure,^[3] and in 1978, the Terek-1 with the backward-wave oscillator were used to drive the prototype of an electromagnetic-wave pumped FEL.^[15]

The early theoretical research of this team concerned the relativistic monotron, which can be regarded as a single-wiggler-period ubitron. It differs from other linear-beam devices, such as the orotron and the resonant O-type traveling-wave tube, by the absence of slow-wave structures. In the monotron, the relativistic linear electron beam is synchronous with an electromagnetic wave (one of the TM modes propagating in a metal waveguide) that propagates near the velocity of light. The length and cross-section of the monotron are significantly greater than the wavelength of emission, which makes it possible to operate at high frequency and output power. The maximum efficiency of the relativistic monotron is determined from linear theory for a moderate microwave field intensity.^[76] The research on the linear theory of the relativistic monotron, published in 1970, has been later (1973) extended to the nonlinear theory to estimate monotron efficiency within a broader range of field intensities and to determine its theoretical limit.^[77]

The theory of the ubitron was developed by Gaponov and Petelin in the early 1960s using a linear approximation for low field intensity. The nonlinear theory was introduced in 1973 to analyze stationary oscillation of an O-type ubitron with magnetostatic focusing of the electron beam in which the RF energy was obtained from axial motion

of electrons. A maximum efficiency of 55 percent at low beam energy was found to be theoretically possible. However, the energy spread in a real beam was expected to decrease the efficiency of the device. The conclusions derived from the nonlinear theory were that (1) ubitrons could be effective with both weakly relativistic and ultrarelativistic electron beams, (2) wavelengths shorter than the cm and mm range involved difficulties with short-period magnetic field structures and mode competition in the electrodynamic systems, and (3) in ubitrons, as in microwave devices with circular electron beams, the electrons could effectively interact with electromagnetic waves in waveguides and resonators having smooth walls.^[46]

The first experiment of this team used the Terek-1 accelerator to power a backward-wave oscillator. Table 8 shows the experimental parameters.

Soviet writers claim that the above experiment, reported in 1973, yielded the highest experimental efficiency (15 percent) so far observed in attempts to convert the energy of linear relativistic electron beams to electromagnetic field energy. At the same time, the efficiency of bremsstrahlung emission generated by undulating beams, as observed by Carmel, Nation, and Friedman (1972), did not exceed a fraction of 1 percent. According to Smorgonskiy, the efficiency in the latter case could theoretically be improved to high enough levels, especially in ubitron oscillators and amplifiers using curvilinear beams focused by periodic static fields.^[46] The transverse oscillations of beam particles

Table 8

BACKWARD WAVE OSCILLATOR EXPERIMENT^[75]

Terek-1 accelerator	
Beam energy range	600-740 keV
Starting beam current	3 kA
Beam current range	4-5 kA
Pulselength	20 nsec
Interaction region	
Peak magnetic field,	5 kGauss
Vacuum,	2×10^{-5} Torr
Output emission	
Wavelength	3.1 cm
Bandwidth	5 %
Pulselength	10 nsec
Power	400-500 MW
Efficiency	12-15 %

ensure beam interaction with fast waves, and the emission energy is supplied from the axial motion of the particles. According to Smorgonskiy, ubitrons are among the most powerful sources of electromagnetic radiation in the region of weakly relativistic energies.^[3]

The first relativistic ubitron experiment by the FIAN team is represented in Table 9.

The electrodynamic system in this experiment consisted of a circular cross-section waveguide whose parameters were calculated theoretically in ultrarelativistic approximation.^[46] The excited electromagnetic wave propagated upstream of the beam and was reflected from a grid near the anode of the accelerator that was transparent to the electron beam. The reflected wave did not interact with beam particles and emerged through a smooth stub at the collector end of the resonant cavity into a large-diameter waveguide and thence through a horn antenna into space.

The authors concluded that the experiment demonstrated the operation of the ubitron mechanism of interaction and that the efficiency of beam-to-electromagnetic energy conversion was higher than that observed at Cornell in the stimulated bremsstrahlung devices, but lower than that predicted theoretically in Ref. 46. This was attributed to the considerable axial energy spread of the beam electrons, the suppression of transverse electron oscillations by the focusing field, and the difference in the interaction mode of electrons located at different distances from the beam axis.^[3]

Table 9

RELATIVISTIC UBITRON EXPERIMENT^[3]

Terek-1 accelerator	
Beam energy	700 keV
Beam current	0.8 kA
Pulselength	200 microseconds
Magnetic wiggler	
Wiggler field	2.5 kGauss
Focusing field	5 kGauss
Vacuum	3×10^{-5} Torr
Output emission	
Wavelength	3 cm
Bandwidth	5%
Power	30 MW
Efficiency	5%

Nonlinear FEL theory has been generally considered for a relatively low undulator field and, consequently, a low electron oscillation amplitude, so that the dipole approximation could be used in the analysis of output emission. The case of high undulator field for which the dipole approximation was no longer valid has become the subject of the team's research because FEL emission frequency could thus be controlled by varying the undulator field. With high undulator field intensity, electron emission frequencies contain higher harmonics of the electron oscillation frequency. Furthermore, increasing pump intensity increases the amplitude of transverse electron oscillations and thus decreases the average axial velocity of the electrons. As a result, for any given harmonic, the emission frequency turns out to depend on the undulator field intensity. Thus the pump field can be used to control FEL output frequency as long as the former is high enough to affect significantly the average axial velocity of the electrons.^[78]

The focusing axial magnetic field also exerts an effect on the oscillation of the beam electrons, increasing their oscillation velocity. For a given pump field, this should reduce the excitation threshold of stimulated emission.^[79]

In 1982, Smorgonskiy published an evaluation of the practical effect of the electron beam energy spread on the starting current and efficiency of FEL.^[80] According to his analysis, the starting current of a monoenergetic beam was inversely proportional to the cube of the length of the interaction region. However, in a real beam with an appreciable energy spread, the inverse cube dependence of the starting current holds only for interaction regions whose length is below a certain limit. Beyond that limit, the starting current decreases linearly with increasing length of the interaction region. Smorgonskiy used these relationships to specify the maximum length of the interaction region and the minimum current density necessary to assure acceptable efficiency and output power of FEL. He postulated three types of FEL: the ubitron, the scattron, or electromagnetic-wave pump laser, and the crystal channeling FEL using a silicon single crystal. Table 10 shows Smorgonskiy's FEL specifications, which he compared with data of the 1977 Stanford experiment.^[23]

According to Smorgonskiy, the first row of the table represents relatively long-wavelength FEL based on standard accelerators whose beam quality ensures a fairly high efficiency. However, the beam quality in shorter-wavelength FEL can be obtained only with unique injectors, such as the Stanford accelerator shown in the table. The probability of realizing the crystal channeling FEL is considered low, at least for the above ranges of beam energies and with single crystal thickness of $1\ \mu$.

Table 10
FEL OPERATING PARAMETERS^[80]

FEL Type	Pump System	Beam Injector	Energy spread	Wavelength	Inter-action Length ^a	Theor. Efficiency (%)	Required Current Density (A/cm ²)
Ubitron	Magneto-static field 3 kGauss, 1 cm period, beam-wave coupling 0.3	High-current accelerator, 2 MV	0.1	0.4 mm	10	10	104
		Linear accelerator, 10 MV	0.01	25 μ 300	0.1	30	
Stanford ubitron	Magneto-static field 2.4 kGauss, 3.2 cm per. beam-wave coupling 0.8	Linear accelerator, 43 MV	0.0005	3.4 μ 650	0.1 ^b	2 ^b	
Scattron	10.6 μ CO ₂ laser, 100 TW/cm ² , beam-wave coupling 0.06	High-current accelerator, 2 MV	0.01	0.1 μ 3000	0.001	10	
Crystal channeling	Electrons oscillating in averaged potential well, beam-wave coupling 0.05	High-current accelerator, 2 MV	0.01	Downstream 100 A,	150	1	3×10^{12}
				upstream, 1 μ 1	10	1015	

^aDimensionless units;

^bActual efficiency was 0.01% and the current density computed for the cross-section of the interaction region was about 3.5 A/cm².

Parallel with its research on ubitron devices using magnetostatic periodic structures, the team was also working on counterstreaming electromagnetic-wave pump FEL. According to a 1978 Soviet report,^[56] the theory of the latter has reached the point at which the design of optimal parameters became feasible. The averaged motion of the electron was described by the same equations as those used in the TWT, where only the TWT electric field was replaced by the effective combined wave field of the electromagnetic-wave pump FEL. In the cw mode, the output power of such an oscillator could exceed considerably the expended pump power (the number of scattered pump quanta equals the number of emitted signal quanta, although the energy of the latter is higher by approximately γ^2). The relativistic electromagnetic pump FEL was considered suitable for the frequency range that was inaccessible to either conventional classical devices or lasers. Thus, given electron beam parameters not much beyond the state of the art, such as γ of 5 to 20, energy spread of 1 to 0.1 percent, current density of 10^5 to 10^7 A/cm², and a 10.6μ CO₂ laser pump of 10^{10} to 10^{11} W power (considerably below the state of the art), one could expect to obtain laser action within the tunable range from 2000 to 100 A at about 10^8 W.^[56]

Table 11 presents the specifications of the counterstreaming electromagnetic-wave pump FEL as reported in 1979.

TEAM 2. Petelin, Bratman, and Ginzburg, IPF

The work of Team 1 has been paralleled since the mid-1970s by a subgroup working entirely within IPF and led by Petelin, V. L. Bratman, and N. S. Ginzburg. It has focused on the electromagnetic-wave pump FEL and the rippled wiggler FEL, which it considered together with the cyclotron resonance maser.

The Team 2 authors analyzed the energy balance of the relativistic laser operating with a counterstreaming electromagnetic wave undergoing stimulated Compton scattering by a relativistic electron beam. Their analysis yielded starting and operating currents, oscillator efficiency, the permissible electron velocity spread, and the degree of pump coherence. The energy resources of available radiation sources and IREB were found to be sufficient in principle to obtain high efficiency and high frequency enhancement.^[56] However, they also noted that the existing resources (as of 1979) made it possible to reach only the classical Thomson, rather than the Compton, limit of stimulated scattering of electromagnetic waves by relativistic electrons. They use the term "scattrons" for all devices based on such a mechanism, and

Table 11

ELECTROMAGNETIC-WAVE PUMP FEL EXPERIMENT^[15]

Terek-1 accelerator		
Beam energy range	.....	600-740 keV
Energy spread	.....	0.1
Beam current	.....	4.2 kA
Pulselength	.....	20 nsec
Hollow beam diameter		
Internal	.....	17 mm
External	.....	21 mm
Interaction region		
Vacuum	.....	2×10^{-5} Torr
Backward-wave oscillator		
Wavelength	.....	3.2 cm
Pulselength	.....	15 nsec
Power output range	.....	10-300 MW
Output emission		
Wavelength, mm	Power, kW	
13.4	160	
7.8	70	
4.75	7	

consider the ubitron as a special case of the scattron in which a static periodic field plays the role of the pump wave.^[52]

These authors noted that practical realization of scattrons depends on the feasibility of obtaining sufficiently dense and monoenergetic electron and photon beams. High photon density is facilitated by high-Q cavities, while pump coherence requirements can be met even when summing the powers of independent generators. The energy spread of electrons in high-density beams needed for the highest frequency emission can be optimized by ion neutralization of the space charge.

High-power relativistic microwave oscillators for the pump function and high-current accelerators for injection of relativistic electrons could, in principle, by means of stimulated scattering, produce powerful coherent radiation in the millimeter and submillimeter wavelength ranges. However, in these ranges, the relativistic ubitron is much easier to realize since the pump function merely requires a moderate magnetostatic periodic field intensity of a few kGauss. The present state of the art can cover the frequency range of the vacuum relativis-

tic ubitron all the way to the visible spectrum. In the ultraviolet range, a laser-pumped scattron is more feasible.^[52]

In 1982, Bratman and Ginzburg published a linear theory of the scattron in which shallow lateral wall rippling provided the distributed feedback.^[70] In this configuration, the resonant cavity could maintain the high-frequency scattered mode as well as the longer-wavelength pump wave. The theory was based on an idealized model, neglecting such factors as homogeneity of the magnetic field, the effect of high-frequency space charge, and velocity dispersion. Given a sufficiently stable and long 1 MeV electron beam pulse, the proposed resonator could ensure the conversion of a cm pump wave into a high-power, single-mode, millimeter emission output. The authors claimed that their methodology, and particularly their conclusion that a single-mode generation can be obtained under conditions of a large Doppler frequency shift, are applicable also to the ubitron.^[68]

The last published Soviet FEL experiment was reported by this team in 1982.^[7] It was an advanced system employing rippled field and Bragg mirrors to ensure single-mode operation. The high-Q cavity was capable of transporting an intense electron beam and of ensuring selective excitation of a mode propagating at a small angle to the axial velocity of the electrons. The Bragg resonator consisted of a section of circular metal waveguide with two rippled areas at the ends, separated by a smooth area. The reflection coefficient of the Bragg mirrors was 0.9.

The electron beam was collimated by a double cathode in a magnetic field that maintained the 6 mm hollow beam at $\Phi r < 0.5$ mm and the transverse velocity spread below 0.05. The pump consisted of a spatially modulated magnetic field with a 2 cm period. Modulation was obtained by a set of copper rings with radial cutouts displacing the field of the pulsed solenoid. This was considered superior to solid rings since it did not decrease the axial field.

The resulting experimental system could be switched from FEL to cyclotron resonance maser regime by changing the parameters of the accelerator and the electron-optics system.

The experiment yielded a well-reproducible single 4.3 mm mode. Table 12 shows the observed parameters.

In a recent paper, Ginzburg developed a theoretical analysis indicating that the FEL magnetic pump field can be used to focus the electron beam.^[81]

Table 12

BRAGG CAVITY FEL AND CYCLOTRON RESONANCE MASER^[7]

Hollow electron beam		
Energy	350-600 keV	
Current	0.4-1.0 kA	
Pulselength	100 nsec	
Energy spread	0.05	
Output wavelength	4.3 mm	
Output pulselength	5-30 nsec	
	FEL	Cyclotron resonance maser
Number of pump copper rings	12	3
Output power	2 MW	6 MW
Efficiency	1%	4%
Frequency conversion	5	3-4

TEAM 3. Alferov, Bessonov, and Bashmakov, FIAN

This team, led by D. F. Alferov, Ye. G. Bessonov, and Yu. A. Bashmakov, has been specializing in theoretical and experimental studies of low-current, high-frequency FEL extending up to soft X-rays. The experimental work has been based on several high-energy accelerator systems of FIAN's Photomeson Process Laboratory, such as a 5 MeV linear accelerator, an 11 MeV microtron, and the 150 MeV Pakhra synchrotron.

The team's publications on the FEL concept go back to at least 1972, when its authors suggested the use of relativistic charged-particle beams in spatially periodic fields to generate electromagnetic radiation for vacuum ultraviolet and X-ray spectroscopy, and noted that there should be an optimal value of the periodic field that maximizes the emitted energy.^[82] These authors reflected a demand of the time for high-power sources of polarized, monochromatic, collimated, coherent radiation in a broad region of the spectrum, ranging from millimeter to hard vacuum ultraviolet wavelengths and applicable to research in high-energy physics, solid-state spectroscopy, molecular physics, biology, and photochemistry.^[83] The sources consisting of spatially periodic structures (undulators) and accelerators or storage rings were expected to be more efficient than Cherenkov oscillators and cyclotron resonance masers.^[53,55]

In 1973, the team published a general theory of undulator radiation, determining its spectrum and polarization for any periodicity of the

undulator structure, and the value of the optimal field maximizing the radiation energy and providing a high degree of monochromaticity of the radiation.^[83]

The team authors claim to be the first to note the possibility of generating coherent spontaneous undulator radiation in the hard vacuum ultraviolet, and the first to show the high directivity of stimulated undulator radiation in classical terms. They also show that the efficiency and gain of stimulated undulator radiation sources with a pre-bunched electron beam can be significantly higher than those of sources with a homogeneous beam.^[53] In their view, the principal difficulty in developing coherent radiation devices using relativistic particles in periodic electromagnetic undulator fields lies in the production of relativistic electron bunches whose length is of the order of the radiated wavelength.^[55] They have published a number of proposals based mainly on the collective accelerator concepts to solve this problem. One proposal concerned an electron accelerator capable of generating picosecond electron beams based on a double transmission line driven by a high-voltage pulse generator.^[84] A passive linear induction accelerator, designated the "Pilus" and first proposed in 1971, would provide a voltage gradient as high as 50 MeV/m that may be necessary for the psec accelerator.^[85] The psec electron bunches could then undergo further relativistic compression in a linear accelerator based on the impact acceleration principle developed in Ref. 86. This would make it possible to create high-power submillimeter undulator FEL oscillators delivering 100 kW.^[55]

Undulators installed in the straight sections of synchrotrons and storage rings produce intense spontaneous undulator radiation. According to recent experiments,^[25,27] the density of such radiation is considerably higher than that of synchrotron radiation. Alferov provides an example of an undulator in a 2 GeV storage ring generating several 100 W power at 10 A within a bandwidth of 1 percent. The potential capability of these sources of undulator radiation includes high directivity, spectral intensity, and a high degree of controllable polarization. They could be successfully used in a range of wavelengths including X-ray radiation, where contemporary lasers lose their efficiency. The expected high spatial coherence of undulator radiation would make it suitable for micro holography.^[39]

In 1977, the team reported observing undulator radiation in the Pakhra synchrotron. In this experiment (see Table 3), the spatially periodic magnetic field was installed directly in the straight-line section of the accelerating track so that repetitive passes of electron bunches through the field structure would increase the undulator radiation intensity.^[25] For an electron beam energy of 150 MeV, undulator

radiation was observed in the wavelength range from 2500 to 4500 Å.^[26]

The team has also been investigating electron beams with a short period of density modulation that are useful in generating coherent spontaneous undulator radiation with a higher frequency than that obtainable from stimulated radiation. The intensity and efficiency of undulator radiation sources could be increased and generation threshold current lowered if the external pump wave were replaced by a spontaneous radiation wave separated out by an optical cavity and amplified by the beam. This idea was being developed also by N. A. Vinokurov and A. N. Skrinskiy.^[53]

In its theoretical work, the team authors developed a classical analysis of FEL in a single-particle approximation reduced to the mathematical pendulum model. They thus obtained the conditions required for a total coherence of beam radiation when the radiation power in a given direction is proportional to the squared number of particles in the beam.^[55] The coherence conditions were then expanded to a number of special cases of practical interest in which coherent radiation had a higher intensity, directivity, monochromaticity, and degree of polarization than noncoherent radiation. Bunching of electron beams allowed for radiation in a broad range of wavelengths up to hard vacuum ultraviolet.

The team continued undulator radiation experiments (see Table 3) using the straight-line section of the Pakhra synchrotron. In 1981, intense monochromatic radiation was observed in the visible range of the spectrum from the interaction of the synchrotron electron beam and a magnetic field structure characterized by weak magnetic field of the same polarity with sharply defined boundaries. The electron beam energy was 850 MeV, while the magnetic field was 1 m long with an intensity of 26.6 Gauss. The nature of the dependence of the radiation intensity on the electron beam energy indicated, according to the authors, generation by stimulated emission. They conclude that electron radiation in a weak magnetic field with sharply defined boundaries is characterized in the long-wave range by high intensity and directionality, as well as other properties of practical interest.^[33]

Alferov attributes the recent rise of interest in sources of stimulated undulator radiation to the 1976 Stanford experiments with relativistic electron beams.^[39] The undulator with the transverse helical magnet used in these experiments was proposed by Alferov in 1973.^[83]

In 1982, Bessonov and A. V. Serov stated that the development of sources of monochromatic radiation in the X-ray and shorter wavelength region was a timely problem confronting modern science.^[132] One of the promising methods of solving this problem was

based on sources of spontaneous coherent undulator radiation operating on higher harmonics of relativistic electron beams. The basic components of such sources consisted of an electron accelerator, buncher, and undulator. The buncher modulated the beam density at visible and shorter wavelengths and could accomplish this task within the undulator structure as described in Ref. 53. Low energy-spread beams could be obtained by energy modulation in a short undulator and density modulation in free space. A maximum beam density modulation could be achieved over a shorter length if a sequence of bunching magnets followed the undulator. The degree of beam modulation could be significantly increased by variable-parameter bunchers (VPB). Their principle of operation is based on decreasing the amplitude of particle phase oscillation with slow variation of the undulator and wave parameters. Thus, adiabatic variation of the undulator parameters causes the amplitude of particle oscillation to vary as the inverse square of the phase oscillation frequency. Depending on the relationship between the phase oscillation frequency and undulator parameters, three types of VPB are possible: (1) wave VPB, in which the field intensity and relative phase velocity of the electromagnetic wave vary; (2) magnetic VPB, in which the magnetic field intensity and period of the undulator vary; and (3) combined VPB, in which the parameters of both the undulator and the electromagnetic wave vary. The wave VPB is simpler to build: A focused laser beam along the axis of the undulator provides the electromagnetic wave with increasing field intensity. However, this type of VPB has more rigid requirements imposed on the injected electron beam whose diameter should be about 1.5 mm, while the magnetic VPB requires an electron beam diameter of about 5 mm. The disadvantage of the latter is the need for a precise matching of the magnetic field and period variation. Both problems could presumably be eliminated by the combined VPB.^[132]

Recently, A. V. Serov, a member of this team, published a theoretical paper^[88] taking into account the gradient force arising in the motion of charged particles in high-frequency inhomogeneous fields. This force was heretofore neglected in FEL analyses that assumed that the electromagnetic field was independent of transverse coordinates.^[53] However, the effect of field inhomogeneities in the transverse direction on particle dynamics could be significant and could impose additional requirements on the parameters of the electron beam, the periodic structure, and the electromagnetic field. Serov provided equations describing the motion of charged particles in a helical structure traversed axially by a circularly polarized wave with Gaussian dependence on the transverse coordinates. His results indicate that there is a limiting electromagnetic field intensity that, when exceeded, causes a

disruption of the electron beam passing through the periodic structure. This, in turn, limits the theoretical FEL power.^[88]

TEAM 4. Fedorov, FIAN

This small team has been active since the late 1970s. It consists of M. V. Fedorov, J. K. McIver, D. F. Zaretskiy, and E. A. Nersisov. It specializes in FEL theory based on the quantum mechanical approach applied to strong fields.

Western and Soviet workers have initially developed expressions for FEL gain based on the small-signal approximation, and considered saturation effects only qualitatively or by numerical solution of simplified equations of the classical model. Fedorov claims to be the first to provide analytic solutions in the strong-field range. The energy emitted by the electron per pass in a strong helical magnetic field and gain were determined under saturation conditions. The analysis was based on a quantum mechanical approach in terms of stimulated bremsstrahlung emission and absorption.^[28] Fedorov, using the quantum theory for analytical treatment of multiphoton processes and gain saturation in FEL, showed that there is no equivalence between the single-photon transition approximation in quantum mechanics and the small-signal approximation in classical mechanics, since FEL amplification is always of a multiquantum nature. To describe multiphoton transitions, one must proceed with quantum theory, while to find gain in FEL, one must use either quantum or classical equations of electron motion in strong field, each approach being supplementary to the other.^[45]

According to Fedorov, his quantum mechanical approach makes it possible not only to reproduce all the results obtained in the small-signal approximation, but also to provide analytical solutions of gain in strong fields, i.e., to determine the saturation effects. The numerical solutions of classical equations obtained beyond the limits of small-signal approximation are inadequate to the task of understanding strong-field FEL processes.^[61] In a subsequent work, however, Fedorov did investigate the classical equations of motion of electrons in an FEL for the case when the electromagnetic field did not meet the conditions required by the small-signal approximation.^[62] There, he has found asymptotic expressions for output energy and gain in strong fields. Comparing classical and quantum mechanical analyses, Fedorov showed that identical results can be obtained from both approaches by averaging the measured parameters over the phase of the classical electron motion.^[62]

In a narrow sense of the word, FEL is a laser whose generation is based on the interaction of a relativistic electron beam with a spatially periodic magnetic field of the undulator. However, there are many other proposals for the amplification and generation of radiation from the interaction of relativistic electron beams with other systems. The Compton laser¹ is closest to the undulator-based FEL. In the Compton laser, the electron beam interacts with the field of two external electromagnetic waves: the pump wave and the amplified wave. The Compton laser has not been realized experimentally so far (FIAN's 1978 experiment,^[15] while cited, is apparently not considered here as experimental realization of the Compton laser), while theoretical analysis of gain in the Compton laser has been published in the small-signal approximation in the U.S. literature and under saturation conditions by Fedorov.^[89]

A significant issue in high-frequency FEL is gain improvement. Fedorov sought an increase in the gain of a Compton laser in terms of departure from collinearity between the electron and photon beams. When the electron and photon momentum vectors are collinear, linear gain is a decreasing function of the frequency of the amplified wave. As the direction of propagation of the amplified wave departs from that of electron motion, the wave frequency decreases, all other factors being constant, but remains high enough for the process to be of interest. As long as the gain structure remains the same for collinear and noncollinear configurations, the drop in frequency of the amplified wave may lead to an increase of gain.

Fedorov found an expression for gain in the noncollinear configuration and showed that such configuration was desirable when the energy spread of the beam electrons was relatively large. The optimal geometry obtains when the pump wave propagates upstream of the electron beam and the amplified wave propagates at a small angle to the direction of the electron motion.

The following example illustrates these relationships: For an electron beam current of 1 kA, energy 20 γ , diameter 0.5 cm, energy spread of 10^{-3} , length of interaction region of 5 cm, and pump wave electric field intensity of 5×10^7 V/cm, the gain is 1 percent and the angle of amplified wave propagation is 0.2. According to Fedorov, this indicates the feasibility of significant gain in the ultraviolet range when a CO₂ laser is used as a pump.^[89]

The quantum mechanical definition of gain was continued in Ref. 90, considering multiphoton processes in undulators with plane

¹Fedorov and some other Soviet writers use the term "Compton laser" for an electromagnetic-wave pump FEL.

polarization of the magnetic field. It was shown that strong magnetic undulator fields and relatively low energy beams (5 to 15 MeV) make it possible to increase the FEL output frequency significantly without an appreciable drop in gain.

Fedorov's investigation of strong-field and saturation effects in FEL was next extended to the case of long periodic structures (long interaction regions) and relatively large electron beam energy spread.^[91] He has found two nonlinear regimes: weak and strong saturation. In the weak saturation case, FEL gain increased monotonically and could be considerably higher than that in a short-undulator FEL. The concept of short or long undulator is relative. For example, in the 1977 Stanford experiment,^[23] the undulator was 5 m long with a period of 3.2 cm and an energy spread of 0.003, making it a short undulator. The long undulator regime can be achieved for the same length and period of the periodic structure with a larger energy spread of the electron beam typical of many accelerators. Since the gain in the long undulator tends to drop by some factor in relation to its short-undulator value, the latter can be recovered by increasing the beam current by the same factor.

The analysis of saturation in a FEL with long undulator is also applicable to the nonlinear theory of Compton laser gain with noncollinear geometry,^[89] since gain optimization in the linear regime is in this case determined by the relationship between the length of the interaction region and the electron energy spread.^[91]

In 1983, Zaretskiy and Nersesov published, under the byline of IAE, an FEL proposal with electric and magnetic periodic structures representing an alternative to the conventional magnetic undulator.^[71] According to these authors, all FEL experiments performed so far in the electron beam energy range above 100 MeV showed an unacceptably low gain. They proposed to replace the usual magnetic wiggler with strong electrostatic or magnetostatic field structures that would be homogeneous in the direction of the electron beam and have a high gradient in the transverse direction, imposing transverse harmonic oscillations on the electrons. In their preliminary analysis of this proposal, they assumed that the potential energy of electron-field interaction is a quadratic function of the transverse coordinate and noted that the necessary field configuration can be realized by electric and magnetic quadrupole lenses. The main conclusion of their analysis was that the theoretical gain of such a system was higher than the gain in a conventional magnetic undulator by a factor of γ . The numerical example for a storage ring in Table 13 illustrates their results.

The indicated magnetostatic field characteristics can be obtained, according to the authors, with a set of quadruple (or multipole)

Table 13
STORAGE RING FEL^[71]

Electron beam	
Energy, MeV	150
Energy spread	0.005
Electron density	$2 \times 10^{11} \text{ cm}^{-3}$
Diameter	0.2 cm
Interaction region	
Length	1 m
Field potential	
Electrostatic	1 MeV
Magnetostatic	60 kGauss/cm
Output radiation	
Transition (frequency)	1.8 eV
Gain	0.7

magnetic lenses made of samarium-cobalt alloy, for example. An electrostatic field can be set up by a system of negatively charged parallel plates in vacuum.

TEAM 5. Kolomenskiy, FIAN

The team of FIAN's leading physicist, A. A. Kolomenskiy, active in FEL theory, includes A. N. Lebedev, G. V. Martirosyan, and I. I. Pakhomov; their papers were published in the period from 1978 to 1983. The objective of this work is the study of the stimulated bremsstrahlung mechanism in the optical and shorter wavelengths.^[47] Besides the obvious theoretical advantages of this process, such as broad tunability and high absolute power, Kolomenskiy was interested in the possibilities to be derived from a circulating electron beam that gives up a part of its energy to radiation in discrete sectors of its orbit and makes up for these losses in other sectors, as is the case with cyclic accelerators and storage rings. The main problem was the effect of stimulated emission reaction on the beam, degrading its performance and limiting its theoretical gain and efficiency. Kolomenskiy considered the problem from quantum mechanical and classical viewpoints.

According to Kolomenskiy, a characteristic that is specific to high-current beams with high self-magnetic field is the generation of intense spontaneous bremsstrahlung directed mainly along the beam axis. The sharp spectral line of spontaneous radiation that depends on particle

energy suggests a laser amplifier or oscillator that would not require external fields, otherwise difficult to realize in practice.^[92]

Another practically useful concept pursued by Kolomenskiy was based on the case when phase velocity of the amplified wave is less than the velocity of light, and the refraction coefficient does not equal unity. Kolomenskiy attempts to show that these departures from vacuum conditions lead to substantial changes in the characteristics of excitation of undulator radiation.^[93] These conditions obtain when the electron beam interacting with the undulator propagates in a waveguide. Kolomenskiy notes that the waveguide makes it possible to increase FEL efficiency by varying the index of refraction to reduce the phase velocity along the waveguide. This would represent an efficiency enhancement additional to that obtained by a tapered wiggler.^[94]

TEAM 6. Rukhadze, FIAN

A leading FIAN scientist, A. A. Rukhadze, has published several papers with N. I. Karbushev, A. D. Shatkus, and S. N. Belov on an FEL problem related to that considered by Kolomenskiy above. While, according to Rukhadze, most theoretical FEL papers have considered unbounded systems, real FEL contain the interacting electron beams propagating inside finite waveguides. The transverse and axial bounds on the system may cause new effects, such as the inhomogeneity of the pump and scattered waves and excitation thresholds. Rukhadze therefore developed a theory of stimulated scattering of electromagnetic waves under more realistic conditions. The theory considered coherent scattering of E-waves in a circular waveguide of finite length by a hollow IREB, assuming a strong axial magnetic field.

The theoretical conclusions were illustrated by a numerical example of a 3 cm wave scattered by a 700 keV, 5 kA electron beam with 0.5 cm radius in a waveguide with 1.5 cm radius. For a pump wave power of 1 GW, the gain of the 1.7 mm output wave was 1.05 for a 70 cm long system, 1.25 for a 140 cm long system, and 2.5 for 360 cm. The theoretical efficiency could reach 2.5 percent for an output power of 180 MW.^[95]

This approach was applied to the development of linear theory of FEL with a cylindrical interaction region.^[96]

THE TOMSK GROUP

The second largest group of Soviet theoreticians and experimenters active in FEL research is located at the Nuclear Physics Institute of

the Tomsk Polytechnic Institute (IYaF-TPI) and is led by A. N. Didenko, director of IYaF. The FEL research of the Tomsk Group parallels that of the Moscow-Gor'kiy Group in that it consists of both theoretical and experimental work, and includes low-current synchrotron and high-current pulse line experiments. In addition, however, the Tomsk Group has performed FEL experiments with an induction linac. Similarly to the Moscow-Gor'kiy Group, the Tomsk Group consists of distinct teams, albeit under the same leadership of Didenko, assigned to the low-current and high-current FEL development. The low-current team has been active since at least the early 1970s, using the 1.5 GeV Sirius synchrotron facility operated by TPI as its experimental base. It has also been responsible for most of the theoretical work of the Group. High-current experiments commenced about 1980 with IYaF's workhorse pulse line accelerator, the 1 MeV Tonus. The high-current team has been cooperating with the Moscow-Gor'kiy Group and, particularly, with A. N. Prokhorov of FIAN.

Low-current Team: Didenko, Nikitin, Medvedev

Undulator radiation is observed when a spatially periodic magnetic structure is inserted into a straight-line section of a synchrotron. The group of authors under the supervision of Didenko and led by M. M. Nikitin and A. F. Medvedev considers undulator radiation as a potentially powerful form of electromagnetic energy in the vacuum ultraviolet and X-ray regions of the spectrum.^[97] It is expected to be brighter than synchrotron radiation by a factor ranging from 20 to 1000, although the efficiency of the undulator strongly depends on the emittance of the electron beam. The energy conversion efficiency at useful output power levels of the order of 100 kW is expected to become a dominant research objective when "technological applications" of undulator radiation, as these authors put it, are determined.^[27]

Nikitin and Medvedev noted that the properties of undulator radiation differed considerably from those of synchrotron radiation.^[27] They also noted the dependence of the angular spectral and polarization distribution of the radiation on the period and magnitude of the undulator magnetic field. However, the early theory was valid only for beams whose electrons had only axial velocity vectors, while electrons accelerated in synchrotrons underwent betatron and synchrotron

oscillations about an equilibrium. The directional distribution of electrons due to such oscillations affected significantly the properties of undulator radiation.^[98] In a series of experiments begun in 1975,^[97] undulator radiation was observed in the 1.5 GeV Sirius synchrotron equipped with a spatially periodic structure. The properties of undulator radiation were studied as functions of the parameters of the electron beam and undulator magnetic field. Computer facilities were used to optimize the undulator, resulting in a low resistance (10^{-3} ohm) and inductance (10^{-5} H), and reducing the magnetic field inhomogeneity to 0.5 percent in the radial direction and 5 percent in the axial direction for a peak intensity of 3.2 kGauss. The undulator current was 30 kA in 1 μ sec pulses. In the early experiments, the total undulator radiation power was studied as a function of the distance between undulator magnet poles, the length of its period, and the undulator current.^[97] IYaF authors claimed that the early work of Alferov at FIAN's Pakhra synchrotron was largely limited to the observation of undulator radiation and that comprehensive study of its properties was attempted in the series of experiments with the Sirius machine at IYaF. That study was primarily concerned with the angular spectrum and polarization distributions of undulator radiation. A report published in 1978 specified an undulator magnet of 10 periods, each 140 mm long, with a magnetic field variable from 0.15 to 3 kGauss, and an electron beam ranging from 170 to 240 MeV. The undulator radiation wavelength was 0.51 μ .^[27] The next experiment in the series was performed to study the reverse problem: using the measured parameters of undulator radiation to determine the parameters of the electron beam, such as angular dispersion and beam energy. These experiments showed that beam angular dispersion distorted significantly the angular energy distribution of undulator radiation. The radial dispersion of the beam was 0.5479×10^{-3} rad.^[29]

The 1978 experiments^[27] made it possible to achieve significant progress in the analysis of real properties of undulator radiation. It was found that the spectral density of undulator radiation generated by the electron beam was considerably lower than what could be expected from the radiation density of a single electron; if the latter was proportional to N^2 , where N is the number of undulator periods, the spectral density emitted by the entire beam was proportional to N .^[99]

Another finding of these experiments was the inadequacy of the early theory. Consequently, the IYaF team had attempted in 1979 to bring the theory into a closer conformity with experimental data and to extend the experimental methodology to the second harmonic of undulator radiation.^[24] For this experiment, the undulator was 700 mm long and consisted of 9 main sections with two correcting sections, the latter

introduced to eliminate the effect of the undulator on the electron motion in the synchrotron orbit. The correction was effected by varying the width of the single-turn rectangular solenoids and the distance between the poles of the undulator magnet.^[97] There were 5 periods, each 140 mm long. The experiment was performed in an electron energy range from 70 to 800 MeV and with the undulator field varying up to 3 kGauss. At some wavelengths, the spectral density of undulator radiation was observed to exceed the synchrotron radiation density by more than two orders of magnitude. The output radiation was found to have low angular dispersion, high degree of polarization, tunability, and quasi-monochromatic spectral characteristic.^[24,30] Subsequent theoretical research considered the effect of the correcting sections in undulators with any number of periods, including nonintegral numbers. When the number of periods was small, the correcting sections affected the undulator radiation significantly; thus the radiation generated in the correcting sections should be taken into account in the analysis.^[100]

The theoretical research published in 1981 involved the problem of off-axis velocity vectors of the electron beam. Two limiting criteria were considered: the $\alpha\gamma$ product much less than one and much more than one, where α is the angle subtending the range of variation of the particle velocity vector and γ is the relativistic correction factor. The first case is the so-called undulator regime, while the second is the synchrotron regime of radiation, which is much less well understood. The theory covered undulator radiation of ultrarelativistic electrons for any flat undulator of the second case.^[101]

The experimental reports published in 1981 concluded that the experimental results concerning the spectral properties of undulator radiation have verified both the numerical computation and analytical treatment of undulator radiation spectrum of the first three harmonics. The energy spread of the 500 MeV electron beam used in these experiments was 2.5 MeV.^[31,32]

High-current Team: Didenko, Fomenko, Shteyn

In 1980, Didenko, G. P. Fomenko, Yu. G. Shteyn, and others began experimental studies of high-current FEL using IYAF's 1 MeV, 15 kA Tonus accelerator and a 0.8 MeV, 500 A, 1 Hz LIU linear induction accelerator. One objective of these experiments was the achievement of sufficiently dense electron beams. Both solid and hollow beams were used, reaching densities of 10^{12} electrons per cubic cm, which corresponds to the Raman scattering mode. Hollow beams were preferable, because they had higher critical currents and thus could produce

higher output power. So far, three experiments have been reported: an undulator FEL based on the Tonus accelerator, an electromagnetic-wave pump FEL based on the Tonus and a magnetron providing the pump wave, and an undulator FEL based on the repetitive linear induction accelerator (see Table 2).

A recent theoretical paper by V. I. Grigor'yev considered the effect of a large energy spread in high-density electron beams. The main problem was the development of kinetic instability of the beam, which arises when the beam energy spread is as low as 5 percent. Under such conditions, for a focusing field of 8 kGauss and undulator magnetic field of 170 Gauss, the theoretical efficiency was 0.1 percent.^[102]

THE NOVOSIBIRSK GROUP

A team has been active in FEL research since 1979 at the Nuclear Physics Institute, Siberian Department of the Academy of Sciences (IYaF-SOAN) in Novosibirsk. In this work, the team has been under the continuous supervision of A. N. Skrinskiy, director of IYaF-SOAN, and is led by A. M. Kondratenko and Ye. P. Saldin. The publications of this team are primarily theoretical, while experimental FEL systems are considered in conjunction with storage rings and colliding particle beams. A number of experiments involving these facilities appear to be in the planning stage (see Sec. II, "Planned Experiments"). It is not clear at this time whether an experimental program involving any of these experiments has actually commenced at IYaF-SOAN.

Kondratenko and Saldin have been publishing theoretical papers on FEL since 1979, pursuing two aims: One was the development of a general theory of FEL, taking into account a finite cross-section of the electron beam and a high gain per pass of the undulator. The other was the application of FEL systems to electron accelerators of the type represented by the VLEPP linear colliding electron-positron beam machine being designed at IYaF. In each case, they attempted to relate the theory to projected engineering specifications involving parameters that appear well beyond the present state of the art.

FEL gain, as interpreted by classical theory, was considered the result of spatially periodic bunching of the beam in the wiggler and the subsequent coherent radiation of the modulated beam that was homogeneous (over a radiation wavelength of 1 micron) before entering the wiggler.^[103]

In a 1979 report, the team investigated the radiative instability of the electron beam in the undulator. When the beam parameters were held within certain constraints, the harmonics of beam density

fluctuations became unstable, their frequency resonating with the undulator period. When the undulator was long enough, the resonant harmonics grew in each pass until the electron beam became 100 percent modulated. This process was ascribed exclusively to the internal interaction between the beam particles and the emitted field. The effect of self-modulation of a relativistic electron beam in a single pass was also studied by others^[59,52] who, however, assumed an infinitely broad beam. The team's authors stressed the importance of allowing for the finite cross-sectional area of the beam and derived an expression for gain of a thin beam.

Another objective of Kondratenko and Saldin was the control of the axial motion of beam electrons in the undulator by means of an auxiliary axial magnetic field. The latter made it possible to increase the fraction of the beam energy converted into coherent electromagnetic radiation and to reduce the length of the undulator. The practical realization of this approach was envisaged as a coherent radiation source or an amplifier in the submillimeter wavelength range, with an electron storage ring as the electron beam source.^[103,104]

According to these authors, in past theoretical work gain per pass was computed assuming the electromagnetic field volume to be an independent parameter. This assumption does not hold in the general theory of FEL, which introduces the concept of transition beam current. When beam current is much higher than the transition current, gain is proportional to current density and electromagnetic field volume in the resonator coincides with the beam volume. Below the transition current, field volume is a function of gain and in the single-pass resonator gain is an exponential function of current.^[105]

THE KHAR'KOV GROUP

In 1975, a team led by Ya. B. Faynberg and Yu. V. Tkach at the Khar'kov Physico-technical Institute (KhFTI) performed the first high-current pulse line experiment with a superradiant oscillator (see Table 2). A puzzling circumstance is that no follow-up experiments by this team could be located in the literature, although other KhFTI authors continued to publish theoretical papers on the subject of FEL. The objective of this experiment was the development of a GW microwave oscillator capable of generating a microsecond output pulse. The problems encountered in such a task included a high-frequency breakdown caused by the MV/cm field intensities typical of the required MW power levels. To avoid this problem, Faynberg and Tkach resorted to an oscillator based on the interaction of a high-

current, spatially modulated, long-pulse IREB with a fast wave in a circular waveguide. A magnetron-type field emission electron gun driven by a Marx generator provided a 230 keV, 3 kA hollow beam, which was injected into a waveguide in a spatially periodic magnetic field. The field was modulated by alternating iron and aluminum rings. A MW level output was observed.^[1]

Contributions to FEL theory were made by V. A. Buts, V. I. Miroshnichenko, and V. V. Ognivenko of KhFTI. In 1979, Miroshnichenko analyzed the saturation of stimulated scattering of electromagnetic waves by an IREB in a magnetic field.^[106] In 1980, as an aspect of FEL theory, the team attempted to show that collective generation is possible in the interaction of an IREB with a slow wave propagating parallel to the electron beam, with the generated radiation having the frequency higher by a factor of gamma squared than the initial wave frequency.^[107] The most recent paper, published in 1983, showed that optimal FEL regimes are susceptible to stochastic instability of beam particle motion, leading to energy spread in a beam and a corresponding drop of conversion efficiency, as well as a loss of coherence. While in amplifiers this effect may not be significant, in oscillators it may lead to output field intensities considerably lower than predicted theoretically.^[108]

THE YEREVAN GROUP

A relatively large number of authors, led by G. K. Avetisyan, has been publishing papers under the byline of the Yerevan State University and the Yerevan Physics Institute since the early 1970s on the interaction of fast charged particles with magnetostatic structures and electromagnetic waves. The early papers suggested the use of the interaction as a means of detecting charged particles,^[109] and dealt with trapping of particles^[110] and radiation emitted by charged particles in the field of an electromagnetic wave.^[111] Later, the interest of this group expanded to the study of stimulated emission by charged particles moving in inhomogeneous media,^[112] problems of coherence of radiation by particles moving in homogeneous media,^[113] stimulated emission of particles interacting with laser fields in time-varying media,^[114] and quantum modulation of an electron beam passing through apertures in the presence of a laser field, called the stimulated diffraction process.^[115] The most recent paper, published in 1981, dealt with an FEL problem of emission line narrowing by the stimulated interaction of a charged particle beam with laser radiation in a wiggler.^[116]

THE SARATOV GROUP

This group, apparently under the leadership of B. G. Tsikin, has been publishing papers on FEL theory since 1972; it is associated with the Saratov State University (SGU). The early work of the group dealt with Compton scattering of electron beams. Since the laser beam energy scattered by the electrons is very small, Tsikin attempted to develop a method of storing the stimulated emission in an optical resonator, primarily to measure the time variation of electron velocities.^[117]

In 1977, Tsikin published a proposal to increase the gain of the electromagnetic-wave pump FEL based on auxiliary slow-wave stimulated scattering. According to Tsikin, the practical realization of this type of FEL is difficult because of the low gain due, in turn, to the low probability of stimulated scattering by a free electron, the strong effect of absorption transitions, and the low number of electrons participating in the amplification process. His preceding effort^[118] was aimed at increasing gain by a more complete utilization of the electron beam and a reduction in the role of absorption transitions. However, Tsikin felt that a significant solution of this problem was possible only by an additional interaction of a field with the electron beam. Such a field is the electromagnetic slow wave. Tsikin claimed that this enhanced the electron/laser-beam interaction by increasing the probability of stimulated Compton scattering. The slow wave is produced at a difference frequency between signal and pump wave frequency.^[119,120] Such three-wave interactions are efficient if the stimulating wave power density is 1 mW/cm^2 . However, the practical realization of such a UV and X-ray laser is hardly possible because the difference-frequency, slow-wave structure would be prohibitively small.

Appendix B

SOVIET CONCEPTS OF FREE-ELECTRON LASERS

DEFINITION

Free-electron lasers (FEL) are sources of coherent radiation that are tunable within a broad range up to ultraviolet and soft X-rays and have the potential for achieving very high peak and average power at high efficiency of conversion from electron beam to electromagnetic energy. FEL represents a conjunction of electron accelerator and laser technologies. FEL theory is being developed according to classical or quantum-mechanical approaches using numerical or analytic methods of solution, weak or strong field approximations, and single-particle or collective methods of describing electron behavior. A common property of all types of FEL is the Doppler conversion of electron oscillation frequency.

CLASSIFICATION

FEL devices can be classified according to two main principles: the method of synchronized interaction between the electron beam and electromagnetic fields and the relationship between the current density of the electron beam and the output radiation frequency.

ELECTRON-BEAM INTERACTION SYSTEMS

Bremsstrahlung Process

- Spatially periodic magnetic or electrostatic field (wiggler)
Example: The ubitron

The basic property of the wiggler is that the spatial periodicity of the magnetic field ensures conservation of momentum as well as conservation of energy.

Nonrelativistic ubitrons are some of the most powerful sources of cm and mm radiation. The transition to relativistic electron energies involves qualitatively new properties of stimulated emission in the wiggler field and offers the opportunity of a considerable increase in frequency. The electrodynamic system of the ubitron consists of a number of resonant cavities. In the simplest case of a single cavity, the device is called the monotron.

The O-type ubitron features electron-wave synchronization in which the wave frequency is close to the fast electron oscillations, taking the Doppler effect into account. Under other conditions of electron-wave synchronization, an M-type interaction is possible.^[46]

The advantage of ubitrons is their relatively high efficiency and low sensitivity to electron energy spread. Ubitrons are most suitable for the cm and mm wavelength range.

- Homogeneous magnetic field, spatially periodic electron trajectory

Example: The cyclotron resonance maser (CRM) or gyrotron

A smooth metal waveguide in a strong axial magnetic field contains a stationary monochromatic electron ring with nonzero velocity components that are transverse and parallel to the magnetic field. The rotational frequency of the electron ring is its cyclotron frequency. The gyrotron permits the excitation of an electromagnetic wave with phase velocity greater than the velocity of light.^[121] Cyclotron resonance masers are most suitable for generating high powers in the frequency range of 0.1 to 10 mm, practically inaccessible to other types of generators. The gyrotron is the most efficient variety of CRM. It has an electron gun with a highly compressed beam and a high-Q quasi-optical cavity with diffraction type emission extraction.^[122]

- Transversely inhomogeneous electric field (potential trough)

Example: The strophotron or crystal channeling of electrons

This is potentially suitable for X-ray lasers.^[122]

Parametric process (Thomson scattering)

- Intense electromagnetic field

Example: The scattron or Compton laser

The main attraction of scattrons is the potential for generating ultraviolet and X-ray wavelength radiation. These devices are based on stimulated Thomson scattering of an intense pump wave by a

relativistic electron beam. They require high density and quality electron beams and intense laser pump.^[70]

The electrons and the amplified wave interact with a pump wave that propagates in the opposite direction. In some configurations, the scattering process is stimulated by an auxiliary electromagnetic wave at a difference frequency between the signal and pump wave frequency. Such three-wave interaction is efficient if the stimulating wave power density is 1 mW/cm^2 . Stimulated Compton scattering by an electron beam represents a decay of the incident electromagnetic wave into a scattered wave and the density oscillation of beam electrons producing a longitudinal wave in the beam.

The scattron (synchrotron radiation generator) depends on the feasibility of using the most powerful available laser and an electron beam with the highest possible energy density and lowest emittance to develop UV and soft X-ray laser.^[122] The ubitron can be regarded as a special case of the scattron in which the periodic magnetostatic field plays the role of the pump.^[43]

Smith-Purcell Radiation (Variant of Cherenkov Radiation)

The difference between the Smith-Purcell laser and other FEL is that in the former the electrons are bunched by a longitudinal RF electric field, but in the latter they are bunched by a transverse magnetic field. This laser type has been realized as a practical device in the millimeter and submillimeter regions.^[123,124,125]

- Rippled or dielectric-filled waveguide; the flimatron
Example: Diffraction grating laser

Emission is obtained from electrons moving over the surface of a diffraction grating.

DENSITY-ENERGY (FREQUENCY) RELATIONSHIP

High current, low frequency. Because the number of electrons is large, collective effects play a major role and the Boltzman and Navier-Stokes equations apply. The amplification mechanism is stimulated Raman scattering of photons.

Large gain and high output power can be expected, while generation frequency is low, being proportional to gamma squared. The frequency is in the centimeter and millimeter range and the electrons are not completely free because of the collective effects.

Low current, high frequency. Because the number of electrons is low, the electron-field interaction is essentially of a single-particle type and utilizes single-particle motion equations. The amplification mechanism is single-particle scattering of free electrons. Low gain and output power but high frequency can be expected.

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Appl. Phys. Lett.	<i>Applied Physics Letters</i>
DAN SSSR	<i>Doklady Akademii nauk SSSR</i>
FP	<i>Fizika plazmy</i>
IEEE J. Quantum Electron.	<i>IEEE Journal of Quantum Electronics</i>
IVUZ—Fizika	<i>Izvestiya vysshikh uchebnykh zavedeniy.</i> <i>Fizika</i>
IVUZ—Radiofizika	<i>Izvestiya vysshikh uchebnykh zavedeniy</i> <i>Radiofizika</i>
Izv AN SSSR	<i>Izvestiya Akademii nauk SSSR. Seriya</i> <i>Fizicheskaya</i>
KSF	<i>Kratkiye soobshcheniya po fizike</i>
KE	<i>Kvantovaya elektronika</i>
Opt. Commun.	<i>Optics Communications</i>
Phys. Fluids	<i>Physics of Fluids</i>
Phys. Rev. A	<i>Physical Review A</i>
Phys. Rev. Lett.	<i>Physical Review Letters</i>
RiE	<i>Radiotekhnika i elektronika</i>
UFN	<i>Uspekhi fizicheskikh nauk</i>
VAN SSSR	<i>Vestnik Akademii nauk SSSR</i>
ZhETF	<i>Zhurnal eksperimental'noy i</i> <i>teoreticheskoy fiziki</i>
ZhETF, Pis'ma	<i>Pis'ma v Zhurnal eksperimental'noy i</i> <i>teoreticheskoy fiziki</i>
ZhTF	<i>Zhurnal tekhnicheskoy fiziki</i>
ZhTF, Pis'ma	<i>Pis'ma v Zhurnal tekhnicheskoy fiziki</i>

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RAND/R-3259-ARPA

