Lasers with Nuclear Pumping

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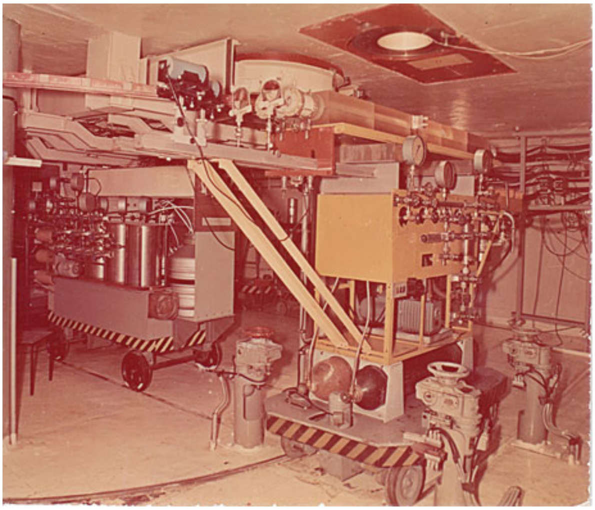
Preface

The majority of the credit for this book on nuclear-pumped lasers (NPLs) goes to its original Russian authors. I (George H. Miley) became the contributing American co-author when I learned of the Russian version of the book and proposed to develop a version in English. After correspondence with the Russian authors, I obtained permission from them to work on the English version. Subsequently, I managed to get a translation into English, which was not a simple task in view of the unique technical terminology and equations. While I made some minor changes and clarifications, these chapters generally follow the original Russian version. My additional contribution has been to add Chap. 13, a brief summary discussing work on this subject in the United States. Chapter 13 is somewhat similar to the Russian view of American work provided in the early chapters, but brings in some new perspectives.

The field of NPLs was born before the Cold War and the "Star Wars" program in the United States, when Karl Thom at NASA headquarters took an interest in NPLs for space power beaming. That led to research programs at NASA's Langley Research Center, and the University of Florida. About this time I obtained support from the DOE for research at the University of Illinois, and later received some additional support from NASA. Other laboratories with programs at the time included Sandia National Laboratory (where David McArthur achieved the first NPL in the United States, using a cooled CO lasing medium and the pulsed nuclear reactor located at Sandia), and also Los Alamos National Laboratory where the pulsed Godiva reactor was employed. These programs were relatively small, however, and focused on basic research about radiation-induced plasmas as well as NPLs. But NPLs became entangled in "Star Wars" and became a part of the cat and mouse game between Russia and the United States. This provided greatly expanded funding for classified programs in several of our National Laboratories (such as Lawrence Livermore National Laboratory, Sandia National Laboratory, and the Idaho National Engineering Laboratory), intended to compete with the classified work in the "secret science cities" in Russia. This competition led to great strides forward in both countries. However, the end of the Cold War era also abruptly ended the flow of money to NPL research in the United States. Thus very few American researchers work in this area at the present, and the national laboratory programs on NPLs have all stopped. In contrast, the Russian laboratories have managed to maintain a reasonably vigorous program, as is discussed in this book.

Because I had one of the few unclassified early programs on NPLs in the United States, I was one of the few American scientists free to discuss NPLs with Russian researchers. These conversations started in September of 1981 when I met several of their scientists during Tenth European Conference on Controlled Fusion and Plasma Physics in Moscow, where I spoke about radiation-induced plasmas. Alex Filyukov, a Russian scientist, approached me during the meeting and struck up a conversation about my NPL work. This was during the height of the Cold War, so these conversations were often vague and guarded on their part. I could speak more freely because I knew little of the classified work occurring within the United States. Alex's questions made it clear that he had studied all of my papers on the subject in great detail—he even knew some details that I had forgotten! It became obvious to me that he had been asked by their KGB or some official agency to interrogate me. After several discussions over the period of the conference, Alex stated that I was on "the right track" with my NPL research, but that he and Russian colleagues had some great concepts they could not yet disclose. This led to continued discussions and invitations for me to visit and give seminars at several places such as Moscow State University. Later after the fall of the Iron Curtain, I was able to visit the Russian "secret science cities" where the classified NPL research was going on. During those trips I met many more NPL researchers, including the co-authors of this book.

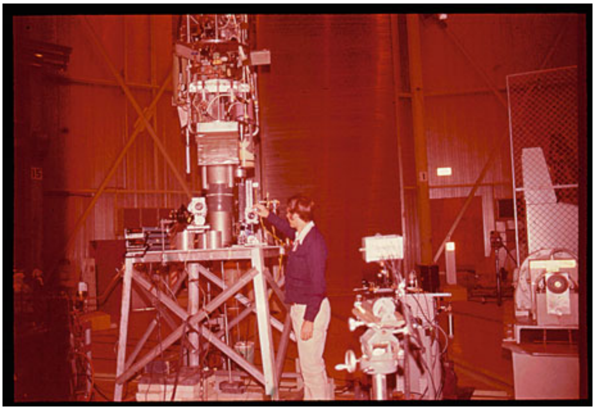
My work on NPLs led to memorable collaborations and visits to Russia even prior to the collapse of the Berlin Wall. My recollections from these remarkable times are recalled in the text. Some memories are shown here via photos. In my first trip to Russia after the end of the Cold War, the Russian NPL scientists disclosed that they had held "All Russian" NPL conferences each year, rotating among locations at Sarov (Arzamas-16) and Snezhinsk (Chelyabinsk-70) two main secret science cities in the USSR. I was presented with this photograph of attendees at the first such meeting. The senior scientists who attended were some of the top laser and nuclear scientists in Russia and included my co-authors of this book.



On those trips to Russia, I visited five specially built research reactors designed for NPL research in the “secret” laboratories. Shown above (reactor VIR-2M, Sarov) is a pulsed system with large laser pump regions located on top of the structure standing on posts in the foreground. The laboratory room containing the NPL and reactor incorporated special openings through a shielding wall with diagnostics behind. This allowed good detector sensitivity with minimum radiation interference. These facilities and NPL research on them are discussed in detail in this book.

I made four trips to the USSR prior to the fall of the Berlin Wall. These trips were for discussions of NPLs, at the invitation of the Russians, hosted by Alex Filyukov and scientists from the Lebedev Physics Institute in Moscow. At the time I learned that Alex Miskevich had been doing leading experiments at a laboratory somewhere north of Moscow, but I was not permitted to visit it. A few months after the fall of the Berlin Wall, I was invited to come again, and was hosted by Alex Miskevich (second from left—I am to his left, wearing glasses), and observed his NPL facilities at the Moscow Engineering and Physics Institute (MIFI). He is shown holding one of his laser cells. During this visit I learned that there were major programs in the Russian Laboratories in the “secret cities” of Obninsk, Chelyabinsk-70, and Arzamas-16. I was invited to visit them, and shortly after that I made trips to the laboratories in these secret cities (where my present co-authors are located).

This photo shows U.S. scientists from the NASA Langley Research Center preparing a NPL experiment for the Fast Burst Reactor at the Army Aberdeen Test Laboratory in Maryland. Jack Fryer (technician), Frank Hohl, Nelson Jalufka, and Russell De Young are shown with the experimental setup.



Russell De Young at the Aberdeen Fast Burst reactor where nuclear laser experiments were carried out. The reactor is shown between two test laser setups. One is the Box Laser and the other is polyethylene (neutron moderator) covered cylindrical gas tube laser.

Much of the early NPL work in the United States was done by scientists at NASA Langley Research Laboratory, who made use of the excellent pulsed reactor facilities at the Army Aberdeen Maryland Laboratory. Dr. Frank Hohl, who was in charge of this work, and Dr. Russell De Young, who did his thesis on NPLs with me at the University of Illinois, were major contributors to the research. The photo above shows Frank Hohl and Russ De Young along with another NPL scientist Nelson Jalufka. The pulsed reactor at Aberdeen is shown in the second photo.

Here Dr. Mark Prelas and Dr. Fred Boody are being greeted by the director of the Arzamas 16 Laboratory upon their arrival for a workshop in 1991.

Another University of Illinois graduate, Dr. Mark Prelas (a Professor at the University of Missouri Columbia), along with Dr. Fred Boody (MS at University of Illinois and PhD from University of Missouri) were heavily involved in early NPL work. In particular, they focused on the concept of using nuclear pumped "flash-lamps" to pump the laser medium. Following the fall of the Berlin Wall, they made several visits to the Russian NPL laboratories and participated in meetings there, much as I did.

These photographs are intended to provide the reader some feeling for the flavor of the early NPL research. They certainly do not provide nor are they intended to provide a full picture of all the people and facilities that have been utilized in this work.

The association of NPLs with "Star Wars" was unfortunate and deleterious to NPL research in the United States. As the reader will discover, there are many very important civilian applications for NPLs that have been overlooked due to the associate with military applications. An additional problem was that just as the technology began to emerge, nuclear reactors fell into disfavor due to fears initiated by the Chernobyl and Three Mile Island reactor accidents. Practical NPLs would require the design of special types of nuclear reactors (both for terrestrial and space applications) and as a result of public concerns such reactors were "not in the cards." However, the situation is now slowly changing, as many feel nuclear reactors should play an important role in the world's future energy economy. The most unfortunate recent accident is the Fukushima Daiichi nuclear disaster in Japan represents a new setback in acceptance. But many people believe this will pass as lessons learned improve reactor safety and the Fukushima event was an extreme example. Consequently, the vision of a reactor-based laser system for various applications cannot be ruled out. This is particularly true in view of the importance of potential applications such as power beaming, inertial confinement fusion, chemical and materials processing, and deflection of asteroids and other space debris. Hopefully this book, the first on the subject, will introduce a new generation of scientists and engineers to this exciting and very important field of science. The ultimate applications for NPLs may well be something not yet envisioned, and the basic science remains challenging and intriguing. My Russian co-authors have, in my view, provided a unique insight into the status of the field and the potential now open to move into important applications. Thus I am extremely pleased to have played a role in helping bring this information to a much wider scientific audience.

I want to thank Autumn West, Robyn Bachar, and Maria Lipson for their diligent work on the translation and proofreading. However, I must take ultimate responsibility for this version of the Russian book, including any mistakes or omissions that have crept in. I also wish to thank my many colleagues and students who contributed to the advancement of NPLs in the United States and whose work I discuss here.

The first 12 chapters in this book are derived from the original version in Russian. Rather than attempting to discuss them myself, I felt it best to use the Russians' description. Thus, the following introduction is adapted from the original Russian edition. In this section, "authors" refers to my Russian co-authors.

The use of nuclear radiation to pump active media and create nuclear-pumped lasers (NPL) on this basis is a comparatively new scientific–technical area. It is at the interface of two disciplines—quantum electronics and nuclear physics. This area has rapidly evolved over the last 40 years, from the first proposals on the use of nuclear energy sources for pumping lasers to the creation of diverse NPLs. Now NPL research has reached the point where engineering design development of continuous and pulsed nuclear laser units for various applications—integrated devices based on the achievements of nuclear physics and technology, quantum electronics, gas dynamics, optics, etc.—has become possible.

The authors of this book have participated in studies into NPL-related issues since the late 1960s. At that time, NPL research was in its incipient phase. In a number of laboratories (primarily in the United States), attempts were made to pump various active media with nuclear radiation and thus prove the fundamental possibility of direct conversion of nuclear energy into laser radiation. To search for NPL active media and study their characteristics, the All-Union Scientific Research Institute of Experimental Physics (VNIIEF) formed a science team consisting primarily of graduates of the Moscow Engineering and Physics Institute (L.Ye. Dovbysh, V.M. Karyuk, M.F. Kostenko, V.N. Krivonosov, S.P. Melnikov, A.N. Sizov, A.A. Sinyanskiy), which initially was directed by A.M. Voinov and A.T. Kazakevich, and later on by A.A. Sinyanskiy. Academicians Yu.B. Khariton and A.I. Pavlovskiy devoted great attention to the development of these studies. In the first phase of the exploratory research, significant assistance was provided by I.V. Podmoshenskiy (S.I. Vavilov State Optical Institute [GOI])—a virtual scientific consultant of the team of young researchers. The decision on organization of the work to study the problems of NPLs specifically at VNIIEF was a natural one, since in that period (and at present), VNIIEF was one of the few organizations with an inventory of diverse, powerful pulsed reactors. It was this circumstance that made it possible to implement the first successful experience in laser pumping with nuclear radiation in 1972, and then to continue research into various NPL problems.

The authors have striven to show the most important results and phases of NPL development not only at VNIIEF, but also at other Russian and foreign laboratories. The book may not be entirely free of subjectivity, because as a rule a scientific publication is the result of a compromise of an author (or authors) desiring to present the modern state of research in a given field with adequate completeness while displaying the achievements of his or her own laboratory.

The basic reason for writing this book was the lack of a scientific study that reflected in adequate detail the status of the work on NPL problems and prospects for their development. The authors worked to systematize information accumulated over decades, which had frequently been published in scientific publications or digests of conference materials that were available only in limited circulation.

This book may also be seen as a reference work, because it contains information about virtually all studies published in the last approximately 40 years related to NPLs.

This book consists of 13 chapters: Chaps. 1–6 (except for Sections 1 and 2 in Chap. 6), 11, and 12 were written by S.P. Melnikov; Chaps. 7–9 were written by A.N. Sizov; and Chap. 10 and Sections 1 and 2 in Chap. 6 were written by A.A. Sinyanskiy. Chapter 13 has been added by our American co-author, George H. Miley.

Chapter 1 provides the chronology of basic events associated with the advent and study of NPLs. The specifics of pumping lasers with nuclear radiation are also discussed.

Chapter 2 provides data on the characteristics of the pulsed reactors that were used to conduct the bulk of the studies of NPLs in Russia and abroad. It examines lasers and the experimental procedures, and discusses the specific features of experimentation with pulsed reactors associated with the problem of radiation resistance of optical materials and photodetectors.

Chapter 3 systematizes the extensive material on the results of experimental studies of spectral, energy, and threshold characteristics of various types of NPLs radiating at the transitions of Xe, Kr, Ar, Ne, C, N, O, Hg, Cd, and I atoms, the ions Cd+, Zn+, and Hg+, the CO molecule, and the molecular ion N_2+. The results of studies of a number of active media for which no generation was detected during nuclear radiation pumping are discussed. And finally, Chap. 3 looks at a method of laser pumping with fast neutrons, and cites the results of studies of NPLs based on a He-Xe mixture in experiments with the BR-1 pulsed reactor.

Chapter 4 is dedicated to a discussion of processes that occur in a low-temperature nuclear-excited plasma: from the initial processes of ionization and excitation of the medium by nuclear particles to subsequent plasma-chemical reactions leading to the populating of laser levels. Data are cited on the energies of formation of primary particles of plasma (ions and excited atoms). In addition, Chap. 4 provides a survey of experimental work studying the parameters of nuclear-excited plasma and spectral luminescence characteristics of gas media.

Chapter 5 discusses the kinetics of plasma-chemical processes and lasing mechanisms of all currently known gas NPLs, and looks at NPL kinetic models published in the literature and the results of computations of their characteristics.

Chapter 6 contains information on the results of investigations of the more complex nuclear laser devices, which are structural elements of multichannel reactor-lasers operating in fixed or pulsed modes. This chapter also gives the parameters of certain variations of designed pulsed reactor-lasers.

Chapter 7 briefly examines information about the methods of calculating the specific energy deposition of ionizing particles. The influence of non-uniformities of uranium-containing layers on the efficiency of the energy contribution of uranium nuclear fission fragments to the gas is studied. The dependence of the energy deposition and its effectiveness on the thickness of the layers and the density of the gas are considered. A dimensionless parameter of optimization of the energy deposition is introduced as a function of the reduced thickness of the uranium layers and the ratio of the transverse dimension of the excited volume to the length of the free path of the average fragment in the gas. It is demonstrated that the functional dependence of this parameter is in good accord with experimental data on the output power for lasers pumped by fission fragments. Experimental data to determine the energy deposition, the causes of their mutual discrepancy, and deviation from theoretical results are analyzed.

Chapter 8 is dedicated to studies of optical non-uniformities arising in hermetically sealed gas lasers excited by fission fragments. Formation and development of these non-uniformities are caused by the specifics of distribution of the specific energy deposition of fission fragments and relaxation thermal and gasdynamic processes. It is shown that owing to heat exchange of the excited gas with the walls and the substrates of laser cells, a wall zone is formed with large positive values of the refraction index gradient. These values are so great that lasing can be carried out only outside the zone limits. The size of the wall zone increases over time: for pumping pulse durations of ~ 0.1 s, it encompasses virtually the entire volume of the laser cell. Estimates are cited regarding the influence of optical non-uniformities on laser beam divergence, and results of calculations of the distribution of non-uniformities are compared with experimental results. The possibilities for improving optical characteristics of hermetic lasers by varying the initial parameters of the gas and the conditions of energy input are studied. The optical non-uniformities in the quasi-stationary and stationary (with external cooling of the cell) modes of irradiation are investigated.

Chapter 9 examines the specific features of flowing-gas lasers. The drawbacks of longitudinal circulation of gas mixtures are discussed. The influence of turbulent pulsations on laser optical characteristics, based on which the constraints on gas pumping speed are found, is evaluated. The advantages of transverse gas circulation, with subsequent release of excess heat downstream of each laser channel to radiators, are underscored. The derivation of equations describing the action of the radiator is provided, and their solution is cited. The structure of gas flow in the laser channel with transverse circulation is described. A model for forming optical non-uniformities in the flowing-gas channel, one that concurs with the experiment, is introduced. Methods are proposed for approximate calculation of gas density distribution in such a channel. Possibilities of combined heat removal are discussed, in which the heat is removed simultaneously both by flowing the laser-active gas itself, and by surrounding the channel with an external coolant.

Chapter 10 is dedicated to a discussion of problem issues associated with development of multichannel stationary reactor lasers and their possible applications.

Chapter 11 provides a survey of the works investigating the possibility of pumping solid-state and liquid laser media with nuclear radiation and creating different versions of pulsed reactor lasers based on them.

Chapter 12 is a review of articles about the results of investigations of nanosecond pulsed NPLs. These lasers are usually pumped by radiation of the most powerful source of energy, a nuclear explosion. Such lasers can be used to resolve one of the problems of inertial thermonuclear fusion determination of the levels of energy that laser drivers must have to obtain specific amplification gains of the target.

Chapter 13**,** as noted earlier, has been added to the English version by George Miley to provide some added insight into research in the United States.

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The authors would also like to express their gratitude to the associates of the scientific–technical library of the Institute of Nuclear and Radiation Physics at VNIIEF for assistance in finding information, and to S. Yu. Pikuleva for providing the figures in Chap. 4.

Updated to add: Finally, we are most grateful to our U.S. co-author, George H. Miley, who made this English version of the book possible.

Champaign, IL, USA George H. Miley

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