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High-peak-power lasers at the IPPLM, Warsaw

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A short review of major achievements in research on high-peak-power lasers carried on for over twenty years at the Institute of Plasma Physics and Laser Microfusion (IPPLM) is done. The most important trends in the IPPLM's research on high-peak-power neodymium, CO_2 and excimer lasers are discussed. The largest laser systems built within the scope of this research, particularly four-beam nanosecond 100-GW and picosecond terawatt Nd:glass lasers and nanosecond 10-GW CO_2 laser are presented.

1. Introduction

In Poland, research on high-peak-power lasers (HPPLs) was initiated at the beginning of the 70's. At first it was conducted at the Military Academy of Technology, Warsaw. Since 1976 research in this field has been carried on mainly at the Institute of Plasma Physics and Laser Microfusion (IPPLM) in Warsaw. The main reason for undertaking the work on HPPLs in our country was the prospect of applying such lasers to studies of hot plasma as well as in research related to controlled nuclear fusion. Later the range of HPPLs' applications in studies conducted in Poland considerably expanded to include the various kinds of basic research in the field of high-intensity light interaction with matter, X-ray and high-energy particles generation and application, non-linear optics and others.

The research on HPPLs conducted for over two decades at the IPPLM has comprised a wide range of problems particularly related to:

– physics of HPPLs, including both theoretical and experimental research into generation and amplification of short- and ultrashort laser pulses, pumping of active media of lasers, propagation of laser radiation in optical systems,

– technology and design of elements and sub-assemblies of HPPLs,

– design, construction and exploitation of high-peak-power laser systems in experiments.

The above work has been concerned both with solid-state lasers (Nd:glass lasers, Nd:YAG lasers) and gas lasers (CO_2 lasers, excimer lasers, iodine photodissociation lasers) and has been carried on within wide domestic and international co-operation.

In this paper, a short review of major achievements in research on HPPLs carried on for over twenty years at the IPPLM – the main centre of Poland's research in this field, is done. At the beginning general principles of design and operation of HPPLs are characterized. Next, the most important trends in the research on HPPLs conducted at the IPPLM, such as the research concerning neodymium lasers, CO_2 lasers and excimer lasers, are discussed. The largest laser systems built within the scope of this research at the IPPLM, especially four-beam nanosecond 100-GW and picosecond terawatt Nd:glass lasers and nanosecond 10-GW CO_2 laser are presented.

2. General principles of high-peak-power laser design

The HPPLs are extremely complex optical systems usually containig a great number of various optical and optoelectronic subsystems. That is why, before discussing IPPLM's works on these lasers, the presentation of some general principles of HPPL design and operation will be useful.

The obtaining of high-peak-power radiation generated from the pulse laser is basically possible in two ways: through increasing the energy of the laser pulse or through shortening its duration. The second way is definitely more effective because it makes obtaining high power pulses in the systems of much smaller dimensions, lower degree of complexity and much lower construction and working cost possible. For generating giga- and terawatt powers pulses of duration between a few nanoseconds and several dozen femtoseconds are used. Such pulses are usually obtained in generating systems of low energy and power, and later they are amplified in the system of laser amplifiers. To make the pulse amplification effective at least three conditions should be fulfilled [1], [2]:

$$\tau > \frac{1}{\Delta\nu_a} \tag{1}$$

$$E \sim E_s, \tag{2}$$

$$B = \left(\frac{2\pi}{\lambda}\right)\int_0^L n_2 I(z)\mathrm{d}z < B_{cr} \approx 3-5 \tag{3}$$

where: τ – pulse duration, $\Delta\nu_a$ – spectral bandwidth of amplifying medium, E – energy density of radiation (in J/cm^2), E_s – saturation energy density of an amplifier, I – intensity of radiation, λ – wavelength, L – length of propagation path in the medium, and B is the measure of wave front deformations of the beam caused by nonlinearity of the medium refraction coefficient $n = n_0 + n_2 I$. The possibility of simultaneously fulfilling conditions (1)–(3) depends mainly on pulse duration τ and on the kind of the active medium ($\Delta\nu_a$, E_s, n_2). For nano- and subnanosecond pulses ($\tau \geqslant 10^{-10}$ s), which in this paper will be called short pulses (SPs), the three conditions (1)–(3) can be fulfilled both in the case of solid-state active media (*e.g.*, Nd:glass, Nd:YAG, Ti:sapphire) and in some gas media (excimer media, CO_2). Thus high-power SPs can be generated in laser systems designed according to a traditional scheme: generator–preamplifier–main amplifier. In the case of picosecond and femtosecond pulses which here will be called ultrashort pulses (USPs), the simultaneous fulfilment of the three conditions is possible for practically one group of gas lasers only (excimer lasers), whereas it is not possible for solid-state lasers. So, obtaining high-power USPs in solid-state laser systems designed according to the traditional scheme is not effective and requires the use of other solutions.

It is evident from the above that the principles of high-peak-power laser system design depend on whether it is a system generating SPs or USPs. For characterizing these principles we will divide HPPLs into two groups: short-pulse HPPLs and ultrashort-pulse HPPLs.

2.1. Short-pulse high-peak-power lasers

Short-pulse HPPLs are mostly designed according to the above mentioned traditional scheme. In agreement with this scheme, three basic subsystems can be distinguished: generator, preamplifier and main amplifier. The primary task of the generator is to generate a pulse of required length, temporal shape and contrast as well as spatial characteristics enabling the pulse to propagate in the remaining part of the system with minimal losses. The spectrum of the generated radiation should be adjusted to the band of amplification of amplifiers used in the system. The preamplifier is mainly supposed to raise the energy of the generated pulse to the level which enables effective extraction of energy from the main amplifier. The main amplifier is the essential reservoir of energy for the amplified pulse. Its basic function is to ensure the required increase in energy of the pulse formed in the generator and the preamplifier. The main amplifier also decides about the efficiency and the output energy of the laser. Therefore, the creation of conditions of effective accumulation of energy in the active medium and its extraction is a basic problem.

The preamplifier and the main amplifier consist of a number of amplifying stages of apertures rising in the direction of the system's output. This assures the growth of the pulse energy with limiting its intensity growth to the level defined by the condition $B < B_{cr}$. In large laser systems used in research on thermonuclear fusion, the main amplifier is often a multichannel system ensuring both simultaneous and symmetrical lightening of the target by a few laser beams.

Meeting the requirements imposed on the parameters of radiation in experiments, especially in plasma experiments, creates the necessity of supplying the laser system with many other subsystems, *e.g.*, systems of temporal pulse shaping. Thus, active systems are used making controlling the shape of the pulse possible as a result of external stmulation (for instance, by applying a voltage pulse of a suitable profile to Pockels cell) as well as passive systems which make use of the suitable properties of some non-linear elements (for example, saturable absorbers) or optical arrangements. Most often they belong to the generator or the preamplifier.

The systems of shaping spatial radiation distribution are further important subassemblies. Most often these include so-called spatial filters, relay systems and various kinds of apertures. They eliminate unfavourable effects of radiation diffraction and beam self-focusing in optical elements of the system, adjust the beam aperture to subsequent amplifiers and adequately profile the distribution of energy in the beam.

In high-power laser systems it is also indispensable to use optical isolators. One of their functions is to prevent the mutual coupling of individual amplifiers and thus prevent chaotic emission of the energy stored in these amplifiers. For this purpose both saturable absorbers and electrooptical systems are used. Another task of the isolators is to suppress the pulse reflected from the target. The isolators fulfilling this task are unidirectional systems which transmit the radiation propagating towards the target and suppress the radiation propagating in the opposite direction. Mostly, magnetooptical systems (so-called Faraday's isolators) and plasma isolators are used here.

In high-power lasers generating the infrared radiation converters of radiation frequency are often used. They allow the shortening of the wavelength of radiation by two, three or four times as a result of harmonic generation or frequency mixing in nonlinear crystals. This creates the possibility for the laser to work either in the visible or ultraviolet range.

The difficulties encountered when designing the most advantageous laser system and controlling its parameters are connected, among other things, with the fact that it is generally a strongly non-linear and non-stationary system. With high levels of radiation intensity appearing in these systems, part of optical sub-assemblies are becoming non-linear elements whose characteristics can depend on time. We may deal here with both non-linearity of refraction coefficient and medium gain coefficient as well as phenomena such as non-linear light scattering or non-linear absorption. Thus, according to the kind of laser, the level of radiation intensity, laser pulse duration, *etc.*, each laser system requires its own characteristic methods of optimization and controlling of radiation parameters.

So far, the largest short-pulse HPPL is a ten-beam laser NOVA, built in LLNL, the U.S.A., used for research on nuclear fusion. This laser generates nanosecond pulses of energy equal to 100 kJ [3]. A bit smaller, kilojoule lasers have also been built in Japan, France and Great Britain.

2.2. Ultrashort-pulse high-peak-power lasers

It has already been mentioned that in the case of pico- and femtosecond pulses actually only excimer lasers (*e.g.*, KrF, XeCl, ArF) ensure the fulfilment of conditions (1)–(3) and the effective amplification of a pulse to high energies. This results from a broad gain bandwidth of these lasers ($1/\Delta\nu_a \leqslant 10^{-13}$ s), low saturation energy density ($E_s \sim 1-2$ mJ/cm^2) and low density of the active medium (small n_2) [4]. Thus high-power USPs can be obtained in these lasers with the use of a traditional scheme of a laser system design. In so-called hybrid laser systems built according to this scheme, in which excimer media are used in a preamplifier and main amplifier, subpicosecond pulses of power exceeding 1 TW were obtained [5].

In the case of solid-state lasers things are basically different from those appearing in excimer. For generating high-power USPs both Nd:glass lasers and broadband crystal lasers such as Ti:Al$_2$O$_3$ and Cr:LiSAF are considered most useful among solid-state lasers. Gain bandwidth in Nd:glass allows us to amplify pulses of $\tau >$ 300 fs, whereas in the above mentioned crystals the pulses of $\tau > 10$ fs. One of the characteristic features of these media is relatively high density of active ions and the high value of saturation energy density ($E_s \geqslant 1$ J/cm^2) which ensures a high compactness of the laser arrangement. However, on the other hand, high E_s leads to the situation in which at $\tau \leqslant 10^{-12}$ s and $E \sim E_s$, the pulse intensity attains a very high value: $I \sim E_s/\tau \geqslant 1$ TW/cm^2. With such intensity and a relatively high n_2 value $B \gg B_{cr}$. This means that USP cannot be effectively amplified in solid-state lasers because with $E \sim E_s$ a strong self-focusing of the beam, damage to the medium and dissipation of the energy of the amplified radiation would take place. To overcome this physical limitation, Strickland and Mourou put forward a method called chirped pulse amplification (CPA) [6] which was a turning point in the technology of generating high-power USPs. The idea of the method is illustrated in Fig. 1.

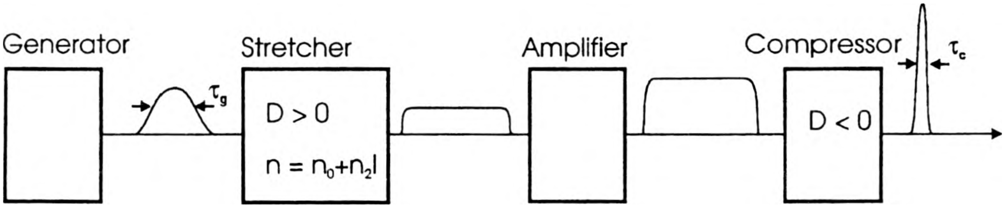

Fig. 1. Idea of generation of ultrashort high-power pulses by CPA method.

In the CPA method a short pulse produced in a generator of a laser system is first elongated in the dispersing system of positive dispersion ($D > 0$). This system (so-called stretcher) simultaneously introduces a "chirp" of the frequency in the pulse spectrum, that is, the dependence of frequency upon time (the frequencies on the front slope of the pulse are moved towards infrared and on the back slope – towards ultraviolet). The stretched pulse is amplified in the system of laser amplifiers to reach the energy density close to E_s. As the pulse is long (usually $\tau \sim$ 1 ns) the intensity of radiation is relatively low, which allows us to achieve a high pulse energy with the condition $B < B_{cr}$ being kept. The amplified pulse is then recompressed (shortened) in the compressor of negative dispersion ($D < 0$), owing to which the pulse power strongly increases (proportionally to the value of the pulse shortening).

The CPA method is usually realized in one of two variants differentiated by the function of the stretcher in the system. The choice of one of the variants is as a rule imposed by the duration of the pulse emitted from the generator.

Variant I – with the non-linear stretcher – is used when the pulse from the generator is relatively long: $\tau_g \approx 50-100$ ps. As the width of the spectrum of such a pulse is too small to make the pulse compression to pico- or subpicosecond range possible after the amplification, the stretcher's task is not only to elongate the pulse and introduce the frequency "chirp", but to widen the spectrum as well. The stretcher's function is fulfilled by either an optical waveguide or a system consisting of an optical waveguide and diffraction gratings of $D > 0$. The spectrum widening appears as a result of self-phase modulation caused by the non-linearity of waveguide refraction coefficient ($n = n_0 + n_2 I$). Owing to the stretcher's positive dispersion, the spectrum widening is accompanied by the pulse stretching and origination of frequency "chirp". After amplification, the pulse of an increased spectrum width $\Delta \nu_c$ is compressed in a system of diffraction gratings of a negative dispersion. Because usually $\Delta \nu_c \gg \Delta \nu_g$, the pulse after compression can be much shorter than the pulse from the generator ($\tau_c \sim 1/\Delta \nu_c \ll \tau_g \sim 1/\Delta \nu_g$). Variant I of the CPA method is mostly used in neodymium laser systems. The role of generators in these systems is usually played by Nd:YAG or Nd:YLF lasers with active mode locking. High-power picosecond lasers presented in [7], [8] are examples of such systems.

The impossibility of exactly adjusting the spectrum characteristics of a stretcher (a non-linear system) to the characteristics of a compressor (a linear system) is a major disadvantage of variant I. It results in lowering the efficiency of compression and the relatively low pulse contrast. For that reason, variant II, deprived of this disadvantage, has recently been more and more often used. In this variant, used both in Nd:glass lasers and crystal lasers the duration of the pulse produced in the generator is similar to the one required at the output of the laser system (usually $\tau \leqslant 10^{-12}$ s). In this case, there is no need to widen the pulse spectrum and it is possible to use a linear stretcher (a set of diffraction gratings of $D > 0$) causing only the stretching of the pulse and introducing the frequency "chirp". Like in variant I, the set of diffraction gratings of $D < 0$ is the compressor. Through an adequate choice of the stretcher's and the compressor's geometry it is possible in this case to adjust their spectrum characteristics in a considerably better way than in variant I, due to which the compression efficiency and the pulse contrast are high. Laser systems using variant II of the CPA method have been presented, *e.g.*, in papers [9]–[18]. An example of such a solution is, in particular, the Nd:glass laser system built at the IPPLM [12].

In terawatt CPA lasers Nd:glass [9]–[12], [18], Ti:Al_2O_3 [13]–[15] and Cr:LiSAF [16], [17] are used as active media. The highest powers and energies of USPs are obtained from the Nd:glass systems owing to the possibility of using amplifiers of high apertures in them. The duration of pulses generated from these systems ranges from 0.5 to 3 ps. Crystal lasers generate pulses of lower energy and power than glass lasers, but their duration is shorter by a number of times. Moreover, they ensure a more compact structure of the system.

The largest CPA laser has been set working at Lawrence Livermore National Laboratory, the USA [11]. In this laser, owing to making use of one of amplifying channels of NOVA laser system, built for the research on nuclear fusion, pulses of record-breaking power of ~ 1000 TW with the duration of ~ 1 ps and the energy of 1 kJ were obtained. Lasers of powers ranging from 10 to 100 TW have been put in motion in France, Great Britain and Japan [9], [10], [15]. In some other countries, including Poland, pico- or subpicosecond lasers of powers 1–10 TW have been built [12], [14], [18]. The launch of these unique devices started a fast development of new trends of physical research and paved the way for a lot of extraordinary uses of laser radiation.

3. Solid-state lasers

The subject matter of HPPLs comprises a range of problems concerning both the physics of phenomena occurring in these lasers and technical problems. Therefore, an optimally constructed and properly working HPPL is generally a result of a great number of various technological and designing projects as well as a great deal of basic research. In the first part of this section, we shall draw reader's attention to the main trends of basic research related to high-peak-power solid-state lasers which has been carried out at the IPPLM and afterwards we shall present the two largest neodymium lasers built at the Institute.

3.1. Basic research

The IPPLM's basic research related to solid-state HPPLs can be divided into three groups of issues:

- generation of short- and ultrashort pulses,
- interaction of laser pulses with non-linearly amplifying and absorbing media,
- propagation of laser beams through various optical elements and optical systems.

In these three groups both experimental and theoretical investigations have been carried out. In the experimental ones mainly Nd:YAG and Nd:glass lasers were used.

Basic research on short-pulse generation was focused on searching for new effective methods of controlling the process of SP production in a laser cavity and on shaping SPs outside a laser cavity. Within the scope of this research, novel methods of controlling the generation of nanosecond pulses with the use of multi-step Q-switching [19], [20], pulse Q-switching [21] and two-photon absorption [22] have been worked out. A few methods of shaping nano- and subnanosecond pulses outside a laser cavity have been put forward and realized. In particular, a new electrooptical method [23] and some non-linear methods making use of stimulated Brillouin scattering (SBS) [24], non-linear absorption [25] and harmonic generation [26], [27] are worth underlining. The possibility of controlling the process of generating picosecond pulses in a mode-locked laser by two-photon absorption [28] and four-wave mixing [29], [30] have been investigated. Various aspects of USP production by compression of "chirped" pulse have been examined [12], [31]. A number of theoretical models of SPs and USPs generation in solid-state lasers, making a comprehensive analysis of the investigated processes possible, have been worked out [19], [21], [22], [28].

The high intensity of the radiation propagating in HPPL causes that both gain coefficient of an ctive medium and absorption coefficient of some optical elements of the laser system are the function of radiation intensity. Thus HPPL can be treated as a non-linear absorbing-amplifying system. At the IPPLM, theoretical models and methods of analysis of such non-linear systems have been worked out, particularly including multi-photon interaction of radiation with a medium [32]–[36]. The influence of non-linear amplification and non-linear single- and multiphoton absorption on the time-spatial structure of the laser pulse [36], [37] as well as extraction of energy from the amplifying medium and limiting parameters of the pulse in the laser system [38], [39] have been investigated. The results of theoretical and numerical analysis were compared with the results of numerous experiments carried out with the use of Nd:glass and Nd:YAG laser systems [25], [32], [33], [36], [40].

The creation of optimal conditions for laser radiation propagation in HPPL and laser beam focusing on the target requires using many various elements and optical systems shaping the spatial distribution of the intensity of radiation in a laser beam. In solid-state HPPLs a substantial difficulty in controlling the spatial distribution of radiation intensity is nonlinearity of the refraction coefficient of optical elements of the laser system, particularly the active medium, which causes the laser beam self-focusing. At the IPPLM, methods of analysis have been worked out and numerous numerical and experimental investigations relating to laser radiation propagation through various optical elements and optical systems [41]–[48] (*eg.*, hard and soft apertures, lenses, spatial filters, relay systems), and real solid-state laser channel as a whole [41], [49], [50] have been carried out. The elaborated computer codes particularly took radiation diffraction, amplification with saturation, self-focusing and thermooptical effects into consideration [50]. A number of theoretical and experimental investigations, whose aim was to work out the ways of controlling the spatial distribution of radiation intensity inside a cavity of a solid-state laser and improve the quality of generated laser beams have been carried out [51]–[54].

The results of basic research, presented above in short, independently of their cognitive value, played an important role in elaborating and improving many subsystems of solid-state HPPLs built at the IPPLM and were helpful in optimizing the construction and operation of these lasers.

3.2. Laser systems

At the IPPLM, a few neodymium lasers generating multigigawatt nanosecond pulses (single-beam, two-beam and four-beam lasers) as well as a terawatt Nd:glass laser generating picosecond pulses have been built. The nanosecond lasers were designed according to the scheme: generator–preamplifier–main amplifier. As the active media Nd:YAG (in the generator) and Nd:glass (in the preamplifier and in the main amplifier) were used. In the picosecond laser, the chirped-pulse-amplification technique was applied. Both in the laser oscillator and the amplifiers Nd:glass was used as an active medium.

Figure 2 presents the optical scheme of the largest nanosecond lasers, put into operation at the IPPLM in the mid-1980's [41]. The Q-switched laser oscillator and amplifying laser heads of the generator of the laser system presented contain Nd:YAG rods of 6 mm in diameter. The short 1.5 ns pulse is cut off by electrooptic system from the 20 ns one emitted from the oscillator. Due to utilizing the SBS mirror in the generator, the prepulse is suppressed and 1 ns pulse with 10^6 contrast ratio is formed. The preamplifier and the main amplifier contain Nd:glass rod of

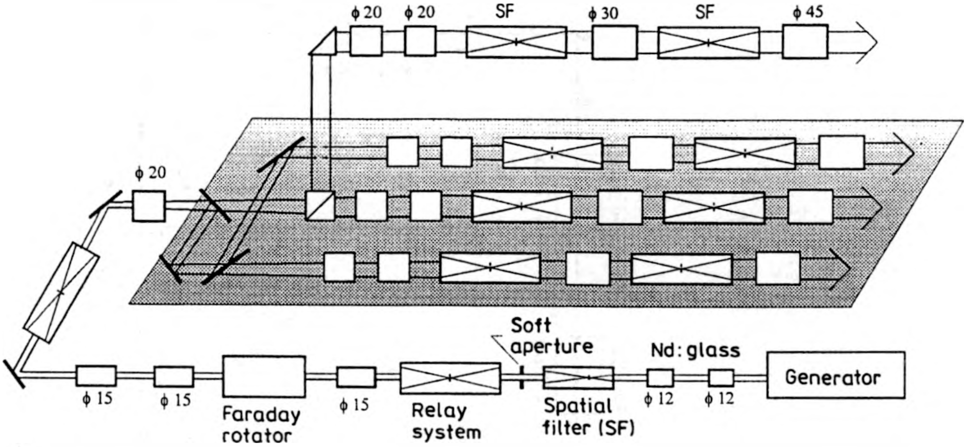

Fig. 2. Optical scheme of the nanosecond four-beam Nd:glass laser system.

diameters from 12 to 45 mm. The control system of the laser beam spatial parameters consists of the spatial vacuum filters, the soft dielectric aperture and the relay systems. The system forms required distribution of energy in the laser beam and a better focusing on a target is achieved. It provides high filling of the aperture of laser rods and decreasing of a small-scale self-focusing, which can cause damage to active medium. The Faraday's rotator protects the laser from the backscattered radiation with the isolation factor higher than 37 dB. The output (extreme) parameters of the laser system presented are as follows:

energy	4×30 J,
peak power	4×30 GW,
pulse duration	1 ns,
beam divergence	$\leqslant 10^{-3}$ rad,
wavelength	1.06 μm.

At the beginning of the 90's, the four-beam laser was reconstructed into a three-beam laser with two infrared ($\lambda = 1.06$ μm) channels and one so-called diagnostic channel operating in the green ($\lambda = 0.53$ μm) [55]. The system of the second harmonic (2ω) pulse generation with possibility of regulating its duration in the subnanosecond range was installed in the diagnostic channel. The system was based on generation of the second harmonic by means of two mutually delayed pulses of perpendicular polarization. The generation of 2ω (and similarly 3ω) occurred in the spatial and temporal overlap of pulses during their passing through the KDP crystal type II [26], [27].

The IPPLM's terawatt CPA picosecond laser [12] was put into operation in 1995. The optical diagram of the laser is presented in Fig. 3. The laser comprises:

– passively mode-locked, feedback-controlled and cavity-dumped Nd:glass oscillator,

– double-pass grating stretcher of a pulse,

– regenerative Nd:glass amplifier,

– contrast enhancing systems with Pockels cells and electrooptic deflectors,

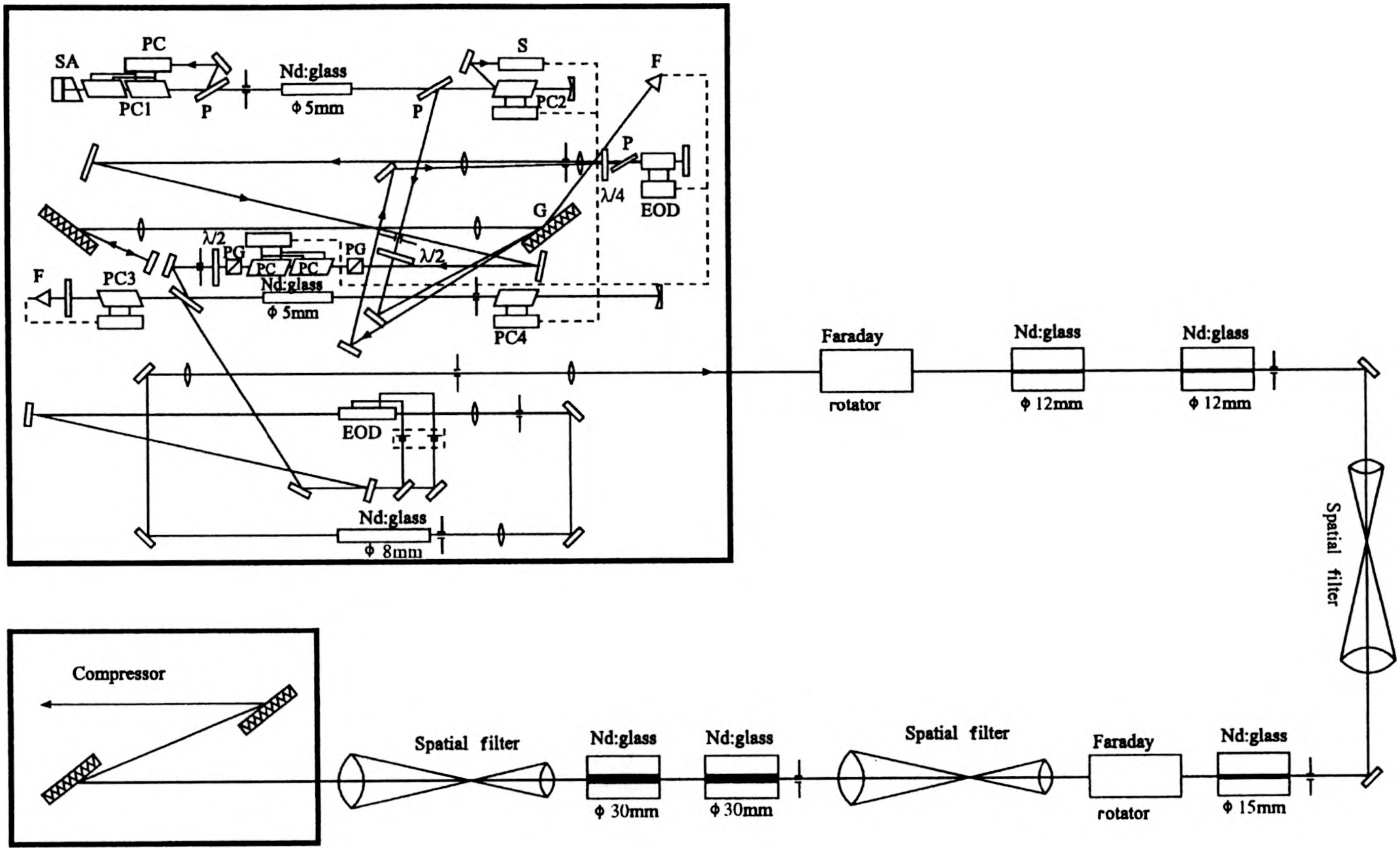

Fig. 3. Optical scheme of the picosecond terawatt Nd:glass CPA laser system.

- single-pass Nd:glass amplifiers with apertures of 8 mm, 12 mm, 15 mm, and 30 mm,
- relay system including a set of lenses, diaphragms, mirrors, and spatial filters,
- Faraday rotators,
- a large-aperture grating compressor of a pulse.

The Nd:glass oscillator produces a single pulse of duration $\tau \approx 1-1.5$ ps and energy $E \approx 0.5$ μJ. The double-pass grating stretcher (two holographic gratings, 1800 lines/mm), having positive dispersion, elongates the pulse to about 0.5 ns. After passing through the contrast enhancing system the elongated chirped pulse is injected to the regenerative amplifier which amplifies the pulse to the energy $E \approx 5$ mJ. Both the oscillator and the regenerative amplifier operate with repetition rate up to 1 Hz. The subnanosecond pulse from the regenerative amplifier is directed to the system composed of the electrooptic deflector based on an $LiTaO_3$ crystal, a lens, and a circular diaphragm, which enhances the long-time-scale ($\geqslant 1$ ns) intensity contrast ratio of the pulse by 10^6 times. Then, this pulse is being amplified in the system of single-pass Nd:glass amplifiers to the energy level of $3-4$ J. In the output of the amplifying system, the pulse compressor is placed comprising two holographic diffraction gratings of 110×110 mm^2 in dimensions (1700 lines/mm) which, due to its negative dispersion, compresses the subnanosecond joule-level pulse to the region of picoseconds. By now, the compressor operates in a single-pass version and it produces a rectangular beam of 85×60 mm^2 in dimensions. Thanks to the application of an optimized image relay system in the chain of amplifiers, the transverse distribution of the energy in the beam is quite uniform. The laser system is capable of producing picosecond pulses of parameters as follows:

energy	2 J,
peak power	>1 TW,
pulse duration	1.2 ps,
beam divergence	$<10^{-4}$ rad,
wavelength	1.05 μm.

The intensity of radiation in the focus of parabolic mirror ($f = 27$ cm, $D = 11$ cm) attains the value of nearly $5 \cdot 10^{16}$ W/cm^2 at the pulse peak power of about 0.5 TW [56], [57].

4. CO_2 lasers

4.1. Basic research

The basic research related to high-peak-power CO_2 lasers performed at the IPPLM was focused on the following subjects:

- TEA uv-preionized CO_2 laser oscillators and amplifiers,
- short-pulse CO_2 laser generators,
- electron-beam-controlled CO_2 laser amplifiers,
- theoretical modelling of CO_2 pulse lasers.

At the IPPLM a few kinds of TEA uv-preionized CO_2 lasers have been worked out. They differ particularly in solutions of supply systems, preionization systems, composition of an active mixture as well as in size and geometry of some elements. The biggest one of these lasers, built in 1978 and working as a free-running laser oscillator, has the active aperture of 15 cm and the volume of active medium of $\sim 100\ \mathrm{dcm}^3$ [58]. In the most technologically advanced TEA CO_2 laser consisting of 4 modules whose active medium's dimensions were $3 \times 4 \times 50\ \mathrm{cm}^3$, sliding discharge was used, which, together with innovatory constructional solutions, ensured high gain and homogeneity of the active medium [59], [60]. This laser was used as the preamplifier in the short-pulse high-power CO_2 laser system built at the IPPLM [60]. The TEA uv-preionized CO_2 lasers have been subject to many years' experimental and theoretical research [59]–[63] which has made it possible to understand their operation better and optimize their working conditions.

Free-running CO_2 pulse lasers generate pulses of the duration of several dozen of nanosecond or longer. That is why the achievement of the pulse of $\tau \sim 10^{-9}$ s requires the use of some special methods of a short pulse forming. At the IPPLM two kinds of short-pulse CO_2 laser generators have been worked out. In the first one, 2 ns pulse was produced in the laser system comprising hybrid free-running CO_2 laser oscillator (with TEA section and low-pressure section) and electrooptic forming system placed outside of the laser cavity [60], [64]. In the second type of the short-pulse CO_2 laser generator, originally developed at the IPPLM, a nanosecond laser pulse was formed directly in the CO_2 laser oscillator containing electrooptic Q-switch inside the laser cavity. The laser could operate in so-called PTM regime [65], [66] or self-injection regime [66]–[69] (depending on the course of voltage applied to the Q-switch) and could generate well controlled, single-mode pulses of 1–10 ns duration [66], [68], [69].

For short-pulse high-power CO_2 lasers it is necessary to use electron-beam -controlled amplifiers as only in such amplifiers homogeneous pumping of large volumes of an active medium and accumulating sufficiently high energy in it is possible. At the IPPLM, two types of e-beam-controlled CO_2 amplifiers have been built. The smaller one, with the active area of $7 \times 7 \times 100\ \mathrm{cm}^3$, has been designed according to the conventional scheme in which the electron beam from one e-gun excites one active area containing the amplifying medium [70]. The dual-beam amplifier is a second type of e-beam-controlled amplifier (Fig. 4) [71]. It consists of two basic parts: a two-sided electron gun and two amplifier chambers. The electron gun provided with a two-sided cold cathode, is supplied from two parallel operating five-stage Marx generators (5×50 kV). Amplifier chambers contain active media of dimensions $20 \times 20 \times 120\ \mathrm{cm}^3$ and pressure 1–3 bar. The distance between the main electrodes varies from 10 to 20 cm. Each active medium is pumped from a two-stage Marx generator (2×60 kV). A specially developed trigger pulse cable generator ensures proper synchronization of the electron gun and system supplying the active media. The comprehensive experimental studies of e-beam controlled CO_2 amplifiers were related to various aspects of the operation of e-guns and characteristics of the active medium of the amplifier. Particularly, the spot structure of the cathode plasma in the initial phase of the gun operation was revealed and the influence of the shape and amplitude of the supply voltage pulse on the spatial distribution of the e-beam

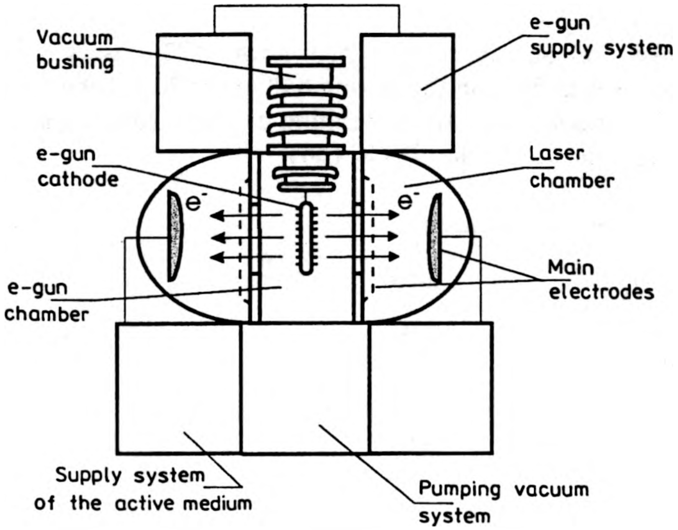

Fig. 4. Simplified diagram of the dual-beam electron-beam-controlled CO_2 laser amplifier.

current density was explained [72]. The influence of various electrical parameters of the amplifier as well as composition and pressure of the active medium on the process of electrical discharge in the medium and small-signal-gain coefficient was investigated [60], [70], [71]. The e-beam controlled CO_2 amplifiers were applied as the preamplifier and main amplifier in the short-pulse high-power CO_2 laser system [60].

The theoretical modelling of CO_2 lasers has comprised a wide range of issues concerning uv-preionized lasers, e-beam-controlled amplifiers as well as generation and amplification of short pulses. The theoretical models and computer codes developed at the IPPLM make particularly possible:

- modelling of characteristics of an electron gun [72], [73],
- calculation of transport coefficient and the rate of level pumping on the basis of the solutions of Boltzmann's equation [61], [63],
- calculation of current and voltage characteristics of a discharge as well as the dynamics of changes in electron concentration in the medium [60], [62], [63],
- modelling of the active medium kinetics on the basis of a five-temperature model [60], [62], [63],
- analysis of the pulse propagation in amplifiers with regard to all relevant relaxation processes and coherent effects for single- and multi-frequency radiation [66], [68], [74],
- modelling of short pulse generation in CO_2 laser with a Q-switch with regard to fast relaxation processes taking place in the active medium, heterogeneity of a photon flux in the cavity, variable-in-time cavity losses as well as the real placement of cavity elements in particular [66], [68].

The models developed made it possible to analyze various physical processes taking place in CO_2 lasers and optimize the laser devices being built as well as to accurately predict their parameters.

4.2. Laser systems

At the IPPLM, two long-pulse and one short-pulse high-power CO_2 lasers have been built. Long-pulse CO_2 lasers were built in the second half of the 70's. They were TEA uv-preionized lasers with a module structure operating as a free-running laser oscillator. Their parameters are shown in the Table [58].

Table. Parameters of long-pulse high-power CO_2 lasers.

Parameters	L-200	L-1000
Energy [J]	200	1000
Pulse duration (FWHM) [ns]	100	100
Peak power [GW]	1	5
Beam aperture [cm]	4	15
Intensity in a focus [W/cm^2]	$5 \cdot 10^{11}$	10^{12}

Short-pulse high-power CO_2 laser, set working in 1984, was built according to the scheme: generator – preamplifier – main amplifier [60]. Its optical scheme is shown in Fig. 5. The laser comprises: hybrid laser generator with electrooptic system of a short pulse formation, double-pass uv-preionized preamplifier, e-beam-controlled preamplifier and large aperture e-beam-controlled dual-beam amplifier.

The hybrid free-running laser oscillator, consisting of atmospheric and low-pressure sections, generates single-mode pulses of duration about 80 ns. A good coincidence between a longitudinal cavity mode and the maximum of the low-pressure section gain spectrum is achieved by changing the optical length of the cavity with the help of the NaCl etalon. A short 2 ns pulse is formed by a two-stage electrooptic cut-off system comprising two Pockels cells made of GaAs and two Ge polarizers. The polarization of both Pockels cells is ensured by a generator of high-voltage nanosecond pulses, triggered by a laser pulse.

The preamplifier with uv-preionization consists of four modules. Each module of active volume $4 \times 3 \times 50$ cm^3 is independent and includes: Rogowski profile electrodes (main electrodes), excitation circuit, gas-tight plexiglass box and a preionization system. One of the main electrodes is solid and the other one is mesh. An auxiliary multiple spark discharge on a third electrode is the source of preionization of the discharge volume. This electrode is situated beneath the mesh electrode. Each set of electrodes is individually supplied with its own discharge circuit. Each discharge circuit is separately triggered from a central control trigger generator. The amplifier operates with $CO_2{:}N_2{:}He = 1{:}1{:}4$ mixture and ensures a small-signal gain coefficient equal to 3.5 m^{-1}.

The e-beam-controlled preamplifier has the active volume $7 \times 7 \times 100$ cm^3 and operates with $CO_2{:}N_2{:}He = 1{:}1{:}3$ mixture at atmospheric pressure. Its electron gun is fed from the 5-stage Marx generator (5×50 kV). The system that supplies the active medium includes a condenser battery loaded up to 35 kV. A small-signal gain coefficient of the amplifier is equal to 3.5 m^{-1}.

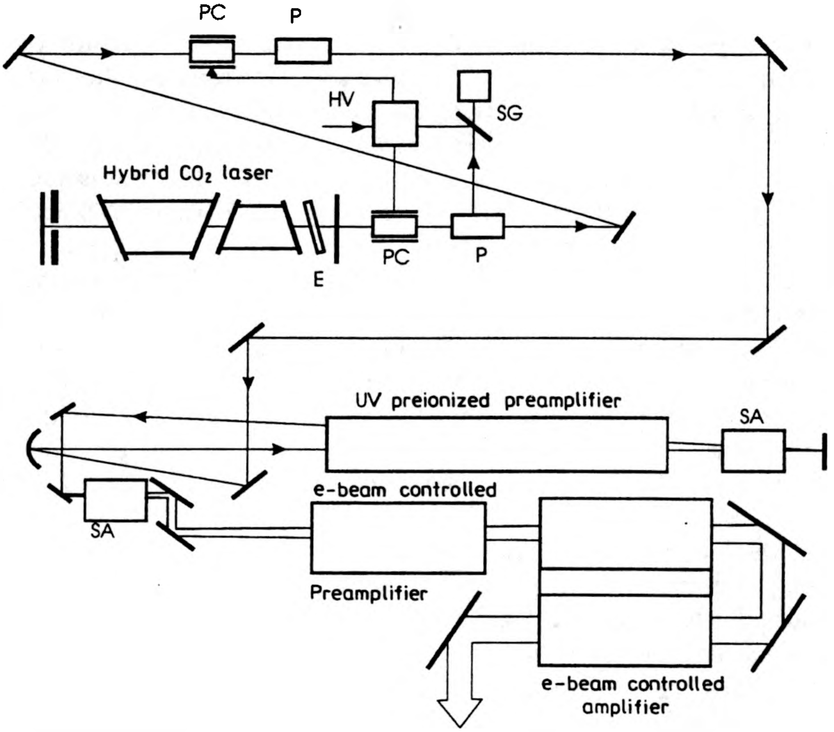

Fig. 5. Optical scheme of the nanosecond high-power CO_2 laser system. PC – Pockels cell, SA – saturable absorber, P – polarizer, SG – spark gap, E – etalon.

The dual-beam amplifier described in Subsec. 4.1 is the main amplifier of the laser system. It mostly operates with the active volume $10 \times 20 \times 120$ cm^3 with CO_2:N_2:He = 1:1:3 mixture at 1.5 bar pressure. A small-signal gain coefficient of the amplifier attains the value of 3.2 m^{-1}.

There are two broadband saturable absorbers in the laser system consisting of mixtures of SF_6, C_2H_5OH and Freon 502. They improve a contrast of the short laser pulse and prevent the laser from self-starting and parasitic oscillations [60], [75].

The output parameters of the laser system presented are as follows:

energy	20 J,
pulse duration	2 ns,
peak power	10 GW,
beam aperture	10 cm,
wavelength	10.6 μm.

After focusing, the intensity in laser beam achieves values of $10^{12}-10^{13}$ W/cm^2.

5. Excimer lasers

Excimer lasers are a kind of gas lasers in which the generation of coherent radiation occurs as a result of quantum transitions of molecules existing practically in an excited state only. These molecules are called excimer molecules and they can form as a result of collisional processes (collisions of excited atoms, recombinations of ions, *etc.*) taking place in the medium excited by means of electrons or photons. Unlike the earlier discussed neadymium lasers and CO_2 lasers generating the radiation in the near infrared range (neodymium lasers, $\lambda \approx 1.05$ μm) or the middle infrared (CO_2 laser, $\lambda \approx 10.6$ μm), excimer lasers emit mainly ultraviolet radiation. The most interesting group of excimer lasers are rare-gas halide excimer lasers, among which XeCl lasers ($\lambda = 0.308$ μm) and KrF lasers ($\lambda = 0.248$ μm) are the most popular ones. Rare-gas halide excimer lasers have got the highest efficiency among ultraviolet lasers and make obtaining both high average power and high pulse energies possible, which in combination with the broad gain bandwidth enables us to obtain short- and ultrashort pulses of high peak-power [4], [76].

The work on rare-gas halide excimer lasers was begun at the IPPLM in the first half of the 80's. At that time these lasers were still relatively poorly known, therefore the research on them was mainly of basic character. It particularly aimed at development of:

- uv-preionized discharge pumped lasers,
- lasers applying electron beams,
- novel methods of SPs and UPSs' generation,
- theoretical models and numerical research on rare-gas halide excimer lasers.

Excimer lasers pumped by uv-preionized discharge are the simplest excimer systems. Apart from a relatively simple structure, another advantage of theirs is the possibility of working with high repetition rate (up to several kHz). In HPPLs they can be both used as generators and amplifiers (in the systems of not too high energies) [76]. At the IPPLM, a few constructions of XeCl uv-preionized discharge lasers have been worked out. These lasers usually operated with the mixture He+Xe+HCl of the pressure $1-1.5$ bar and generated pulses of energy ~ 100 mJ, duration of $20-30$ ns and $\lambda = 308$ nm [77]–[80]. One of the interesting results of the research on these lasers was demonstration of the ability of XeCl laser to operate with a four-component mixture He+Xe:Kr+HCl (which is much cheaper than a three-component mixture with pure Xe) with the parameters close to the ones obtained from the laser with a three-component mixture [79], [80].

The development of excimer lasers using electron beams was connected with the necessity of developing electron guns suitable for these lasers. At the IPPLM, two types of such e-guns have been constructed and examined. The first one was a short-pulse high-current e-gun useful mainly for a direct e-beam pumping of excimer media [81]. That type of a gun, built in cooperation with the Institute of General Physics, Moscow, ensured the lateral pumping of the excimer by two counter-propagating electron beams of aperture 20×1 cm^2, electron energy $E_e \approx 200$ keV, current density $j_e \approx 100$ A/cm^2 and duration of current pulse $\tau_e \approx 50$ ns [81]. The second type of the gun constructed at the IPPLM was a long-pulse e-gun of relatively low current density, meant for e-beam sustained discharge (EBSD) lasers. The gun generated the sufficiently homogeneous e-beam of aperture 30×2 cm^2 and $E_e \approx 200-230$ keV, $j_e \approx 5-10$ A/cm^2, $\tau_e \approx 0.8-1$ μs [81], [82]. This gun was used in EBSD XeCl excimer laser, whose scheme is presented in Fig. 6 [82], [83]. The gun was supplied by a five-stage Marx generator. The electron beam was injected into the active medium through the window of 20 μm thick titanium foil. The active Ar + Xe + HCl mixture was located in the chamber of stainless steel sealed with MgF_2 windows. The electric discharge in the mixture of the volume $32\times2.5\times2\ \mathrm{cm}^3$ was realized between the screen electrode of brass covered by nickel, fastened to the electron gun window, and the bulk aluminium electrode. The active medium was supplied by the condenser battery of capacity 200 nF using the spark gap triggered by the voltage pulse of electron gun. The laser resonator of 70 cm in length was obtained by the use of spherical aluminium mirror having radius of curvature of 2 m and the plane dielectric mirror of transmission 15% for 308 nm.

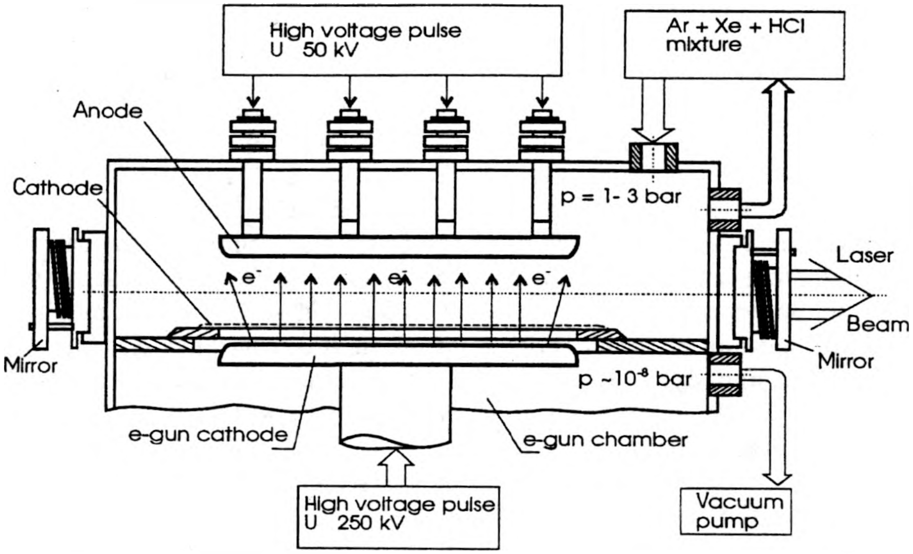

Fig. 6. Diagram of the e-beam-sustained discharge XeCl excimer laser.

The XeCl laser presented in Fig. 6 was capable of producing 0.5 – 1 J ultraviolet (308 nm) pulses of duration about 200 ns. An interesting feature of that laser was the ability of continuously changing the pulse duration in the range of 20 – 200 ns (without any relevant change in the pulse power) through the change of the active mixture's pressure [82], [83]. That laser was applied to detailed experimental investigations of the influence of the various input parameters of EBSD XeCl lasers (composition and pressure of the active mixture, the supply voltage of the active area, e-beam parameters) on the energy, power and duration of the generated laser pulses [82], [83]. The results of these investigations also proved very useful for the development of theoretical models EBSD excimer lasers [84], [85].

Although the experimental and design work on excimer lasers was undoubtedly of major importance for the development of such lasers in Poland, the most valuable scientific results were obtained in the research on methods of SPs and USPs generation in rare-gas halide excimer lasers and in the theoretical modelling of these lasers. At the IPPLM, a fast-pulse Q-switching method was put forward and its ability to obtain subnano- and picosecond pulses from KrF laser proved [86] – [88]. An idea of the general method (called fast mode locking – FML) of USPs generation in short-gain-duration lasers (including particularly excimer lasers) was formulated [89], [90]. The detailed numerical studies of the generation of ultrashort pulses in KrF and XeCl lasers by FML method in the variant with Pockels modulator [91] and in the variant with an electrooptic deflector [89], [92] were conducted. It was proved that in conditions typical of these lasers it is possible to achieve picosecond pulses in the Pockels modulator variant, whereas in the variant with electrooptic deflector pico- and femtosecond pulses are obtainable. A pulse compression method making it possible to obtain the compression of $\sim 10^2$ in an excimer system and thus achieve pico- or femtosecond pulses of high power and contrast was developed [93], [94].

At the IPPLM comprehensive theoretical and computer models of rare-gas halide excimer lasers concerning both long-pulse free-running lasers and short-pulse Q-switched or mode-locked lasers have been developed. In the case of long-pulse lasers these models related to e-beam pumped KrF laser [95] as well as EBSD KrF and XeCl lasers [84], [85]. The computer modelling of these lasers has covered in particular: calculations of the electron distribution function and rates of some collisional processes (*e.g.*, excitation, ionisation) with the use of numerical solutions of the Boltzmann equation; e-beam deposition in the active medium; kinetics of collisional molecular reactions (more than 100 reactions); dynamics of electrical discharge; and dynamics of laser light generation. Various aspects of e-beam pumped and EBSD excimer lasers operation were analysed by means of these models [84], [85], [95].

The theoretical model of a short-pulse excimer laser worked out at the IPPLM [96] – [98] includes the following partial models:

a) The model of interaction of a pulse with the excimer amplifying medium, taking into account excimer systems with the ground state both unbound (*e.g.*, KrF, ArF) and weakly bound (*e.g.*, XeCl, XeF).

b) The model of pulse interaction with non-linear saturable absorber considering, in particular, excited-state absorption.

c) The model of non-linear losses of the multiphoton type (in the absorber and in other elements of the system).

d) The model of radiation propagation in the laser cavity taking into account two coupled photon fluxes in the cavity, interaction with active and passive cavity elements, externally programmed variable-in-time cavity losses, as well as a realistic layout of the cavity elements.

Versatile verification of the model performed by comparing the results of computations and the results of numerous experiments described in the literature has shown their excellent agreement [96], [97] and has proved correctness and accuracy of the model. This model has become a theoretical basics for the development of a novel method for generation of SPs and USPs in rare-gas halide excimer lasers and a convenient tool for analysis of various physical processes in short-pulse KrF and XeCl lasers [89]–[92], [98], [99].

6. Conclusions

In the paper, the main IPPLM's achievements in high-peak-power laser physics and technology have been discussed in short. The results of the Institute's research work in this field, covering solid-state lasers, CO_2 lasers and excimer lasers was particularly the development of novel methods of short- and ultrashort pulses generation, development of comprehensive theoretical models of the above mentioned lasers, investigation and explanation of various physical phenomena occurring in HPPLs as well as construction of several large high-peak-power laser systems. The nanosecond 100-GW four-beam Nd:glass laser, nanosecond 10-GW CO_2 laser and picosecond terawatt Nd:glass laser are considered to be the largest of these systems. The HPPLs built at the IPPLM have been used in various kinds of experiments in the field of hot plasma and nuclear fusion, high-intensity laser-matter interaction, X-ray and high-energy particle generation, non-linear optics and others. The development of the various techniques and devices which are applied in other branches of science and in the development of modern industrial technologies has been a sort of a side effect of the research on HPPLs carried on at the Institute.

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