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Efficient wide-aperture neodymium glass rod amplifiers

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Abstract. **Amplifiers based on neodymium phosphate glass rods 60 – 100 mm in diameter are experimentally studied. The amplifiers are pumped by INP-16/250 tubular flash lamps placed in a universal pump cavity with a two-section mirror reflector. A compact high-voltage capacitive energy storage with a preionisation circuit was developed to supply the lamps.**

Keywords: *neodymium glass amplifier, mirror reflector, capacitive energy storage, preionisation circuit.*

1. Introduction

At present, there is a need for comparatively compact, inexpensive, and easy-to-use laser systems with neodymium-glass active elements (AEs) emitting ~1-ns pulses with an energy up to 500 J. First of all, such systems are required for pumping parametric amplifiers in petawatt chirped-pulse laser systems [1]. In addition, they can be used for pumping Ti : sapphire lasers [2], which requires pulses with a duration of about 30 ns.

At present, such laser systems are designed based on disk or rod amplifiers. Disk amplifiers can emit almost unlimited energy, while the maximum output energy of neodymium lasers with rod amplifiers does not exceed 300 – 500 J [3 – 5] in a pulse with a duration of the order of 1 ns. However, the use of rod amplifiers pumped by tubular pulsed xenon lamps is, as a rule, simpler and less expensive than the use of disk amplifiers. The cost of production and use of a laser system as a whole is to a great extent determined by the efficiency of the output cascades of its amplifiers.

In this work, we study and modernise wide-aperture neodymium-glass rod amplifiers described in [3, 5 – 7] in order to increase their efficiency. As a result of modernisation, we changed the amplifier reflector design, the type and number of pump lamps, and the electric circuit of the power supply of lamps.

Most constructions of rod amplifiers described in the literature use a special pump cavity for each AE size. This implies special reflectors and pump lumps. However, this is not always convenient because, to maintain continuous operation of a laser system, one has to have a reserve of different pump cavities for fast repair of amplifiers. Therefore, the creation of a universal pump cavity of output amplifier cascades is a topical problem.

The amplifiers described in this paper allow one to use any AEs with diameters from 60 to 100 mm and lengths of 300 – 330 mm in one and the same pump cavity. We also describe a capacitive energy storage (CES) for supplying the flash lamps of the amplifiers. The efficiency of the proposed amplifiers is estimated based on the performed tests.

2. Amplifier reflector

Reflectors can be divided into mirror and diffuse ones according to the type of their surfaces. Each type has its own advantages and disadvantages. As a rule, mirror reflectors are more efficient than diffuse ones since they more efficiently reflect light to active elements. However, improper choice of a mirror reflector shape may reduce all its advantages to zero [8]. Another drawback of mirror reflectors is that they not always allow one to obtain uniform gain distribution in the AE volume. In diffuse reflectors, it is easier to achieve a uniform gain but it is more difficult to obtain a high efficiency.

In amplifiers with a dense packing of lamps [5, 6] and with both mirror and diffuse reflectors, due to a large portion of pump radiation returned to the lamps, a high efficiency is achieved only at a low lamp load, when plasma in the lamps is sufficiently transparent. At high loads, i.e., when amplifiers must have both a high efficiency and a high gain, lamps efficiently absorb radiation that was not absorbed by the AE. As a result, the pump pulse duration decreases and the lamp radiation spectrum shifts to the blue [9 – 11]. This decreases the efficiency of amplifiers with closely packed lamps in the case of a high lamp load.

As was mentioned above, the surface and shape of reflectors strongly affect the laser amplifier efficiency. For example, in [3] we achieved a twofold increase in the efficiency of an amplifier with an AE 100 mm in diameter by replacing a diffuse reflector by a mirror one. Figure 1 shows the cross sections of amplifiers with these reflectors and 100-mm AEs. The amplifier shown in Fig. 1a is pumped by 18 INP-16/250 lamps [12]. This amplifier is equipped with a diffuse kersil reflector. The tight geometry of the pump cavity with the maximum possible number of lamps leads to a high homogeneity of the gain distribution over the AE cross section, but the power supply system for such a large number of lamps is very expensive and cumbersome.

The universal pump cavity developed by us (Fig. 1b), in contrast to the previous one, is equipped with only eight INP-16/250 lamps and a mirror reflector made of polished brass with galvanically deposited silver or of polished alumi-

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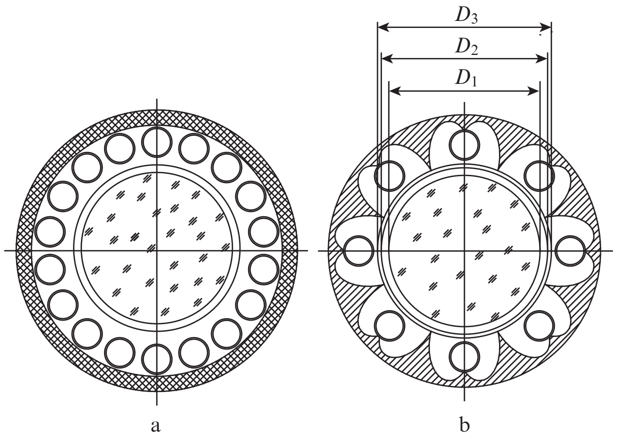

Figure 1. Cross sections of an amplifier with a diffuse reflector and dense packing of lamps (a) and of a universal amplifier (b). The AE diameter is 100 mm.

num foil with a protective coating [13]. The gains are approximately the same for both reflectors, but the reflector made of an aluminum foil much longer retains its efficiency, while the silver reflector requires regular polishing and cleaning. For example, the aluminum-foil amplifiers required no cleaning during active two-year use (~1000 pulses) in the setup described in [1, 3], while the reflectors with silver coating had to be cleaned from oxide two–three times per year to keep the gain unchanged.

The reflector has a two-section design. The shape of each section was close to the evolvent of a circle with a radius equal to the radius of the lamp (Winston shape) [14, 15]. This shape allows the reflector to efficiently transfer energy from the surface of lamps to the AE surface. In this case, the portion of energy returned to the lamps is minimal. We numerically simulated the energy transfer from lamps to the AE in the case of mirror and diffuse reflectors. Our estimates showed that the efficiency of a two-section mirror reflector with an evolvent or similar shape is significantly (by a factor of 1.5–2) higher than the efficiency of a diffuse reflector. The sizes of the cylindrical surfaces of the AE (diameter D_1), surrounding water (D_2), and the glass tube (D_3) affect focusing of the lamp radiation into the AE and, hence, the amplifier efficiency and the transverse gain distribution in the AE. Table 1 gives these diameters for amplifiers studied in this work.

Table 1. Dimensions of the AE cell.

D_1/mm	D_2/mm	D_3/mm
60	95	100
85	108	114
100	108	114

3. Capacitive energy storage of the amplifier

The flash lamps of the amplifier with a diffuse pump cavity of the standard design (Fig. 1a) are electrically supplied from a CES based on K75-28 foil capacitors with a capacitance of 100 μF and a nominal voltage of 3 kV [10]. In this pump cavity, we use a sequential lighting of all the 18 pump lamps. The CES consists of nine separate blocks. The total volume and mass of the electric power supply system are about 3 m^3 and 2000 kg, respectively, per one amplifier. The large number of connecting busses and power contacts carrying a high (up to 10 kA) CES discharge current determines a high cost of production and use of this storage.

To supply the eight pump lamps of the modernised mirror pump cavity of universal design (Fig. 1b), we developed a compact high-voltage capacitive energy storage ENE-60 based on four thin-film capacitors (Elkod, St. Petersburg) with a K75-100 self-healing dielectric, which have a capacitance of 100 μF and a nominal voltage of 17 kV [16]. The maximum energy stored in the ENE-60 is $E_{\max}$ = 58 kJ, and the allowable discharge current pulse amplitude is 20 kA. The overall dimensions of the ENE-60 are 600×800×1755 mm (smaller than 1 m^3) and the weight is about 400 kg, which are by more than threefold and by fivefold, respectively, smaller than the corresponding parameters of the low-voltage storage.

Figure 2 shows a simplified electric scheme of ENE-60. This storage is based on two identical discharge modules A1 and A2, each of them feeding four INP-16/250 pump lamps connected in series.

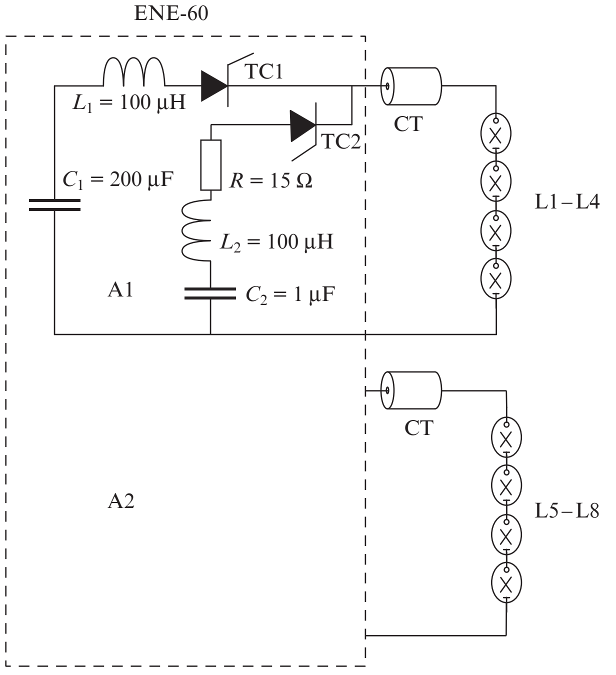

Figure 2. Electrical schematic of the ENE-60 discharge circuit: (TC1) main thyristor commutator; (TC2) thyristor commutator of the preionisation circuit; (CT) cable transmission line (PK50-11-13 cable); (C_1, C_2) storage capacitors; (L_1, L_2) current-forming inductors; (L1–L8) INP-16/250 flash lamps.

Capacitor C_1 stores half of the ENE-60 energy needed to supply lamps L1–L4 (L5–L8). Energy to the lamps is transmitted trough a specially developed thyristor commutator (TC1) based on four TI143-320-50 thyristors (OAO Elektrovypryamitel', Saransk) connected in series. The critical discharge regime, at which the energy from the ENE-60 is completely transferred to the lamps, is realised with the use of an air inductor L_1.

To increase the service life of pump lamps in the ENE-60, they were lighted using an additional low-energy preionisation circuit [17], consisting of a storage capacitor C_2 ($C_2 \ll C_1$), a thyristor commutator TC2, and a current-forming circuit $L_2 - R$.

Due to the cable transmission line capacitance and the reflector capacitance to the ground, switching of TC2 forms an overvoltage pulse, which has an oscillatory character (frequency ~0.5 MHz) and the first peak amplitude exceeding the ENE-60 charge voltage (U) by approximately 30%–35%, which is high enough for reliable breakdown of the four-lamp circuit. In this case, the amplitude of the current pulse through the lamps is ~500 A (Fig. 3a).

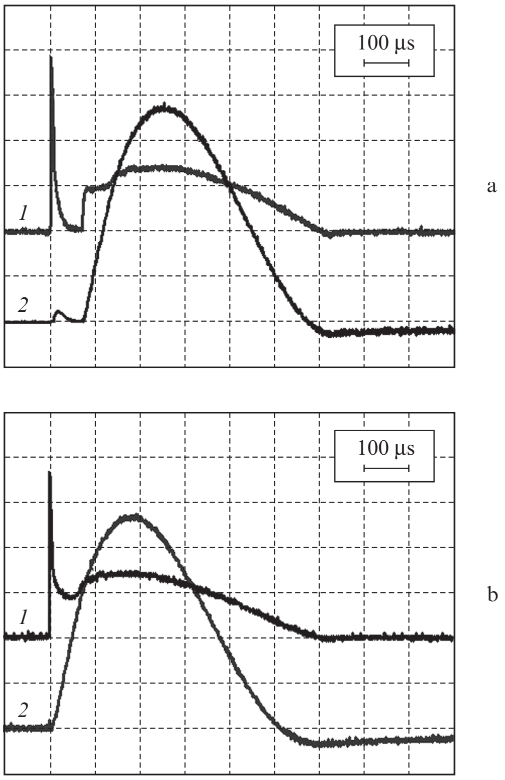

Figure 3. Oscillograms of voltage [beam (*1*), 5 kV div^{-1}] and current [beam (*2*), 2 kA div^{-1}] pulses at four lamps in the case with (a) and without (b) a preionisation circuit.

After a time interval Δt equal to ~80 µs (Fig. 3a), the main commutator TC1 switches working current through the lamps with an amplitude up to 10 kA. The value of Δt was chosen experimentally so that the voltage on the lamps at the instant of TC1 switching and the main current pulse appearance was minimal.

Our investigations showed that, when switched directly by the voltage from the main reservoir capacitor C_1 through TC1 without the preionisation circuit (Fig. 3b), the lamps fail sooner than after 10 pulses. The destruction of lamps occurred not only after a flash, but also at the instant close to the current peak (Fig. 4). This contradicts the well-known mechanism of lamp destruction in the case of conventional switching systems [10]. This phenomenon is obviously caused by the fact that the lamps in our case are discharged in a regime different from nominal, which does not allow them to operate with a lifetime claimed by manufacturers.

The reservoir capacitors C_1 and C_2 of both modules are charged to a required voltage of 10–14 kV from one and the same charger (not shown in Fig. 2). It is obvious that, to achieve a high laser amplifier efficiency, one must as much as possible increase the energy transferred from the storage to lamps and simultaneously retain their service life (number of flashes before destruction).

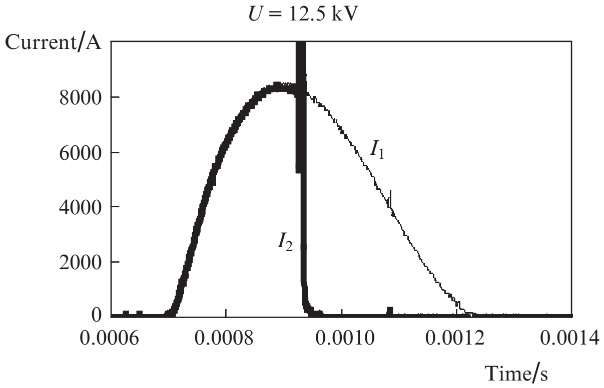

Figure 4. Oscillograms of current pulses for an ENE-60 without a preionisation circuit at the instant of lamp breakdown. In the case of curve I_1 lamps were not destroyed, while in the case of thick line I_2 they were destroyed during the flash at the load parameter $f_x = 0.376$.

As is known, the lifetime of pump lams is determined by the load parameter

$$f_x = E/E_x, \tag{1}$$

where E is the energy transferred to the lamp from the energy storage, $E_x = 22000ld(LC)^{1/4}$ is the lamp breakdown energy in joules [9], l and d are the discharge gap length and diameter in centimetres, L and C are the discharge circuit inductance and capacitance (in henries and farads). In particular, the breakdown energy for INP-16/250 lamps is $E_x = 10.5$ kJ.

The lamp lifetime (approximate number of flashes without breakdown) in the case of external lighting recommended by manufacturers is related to the load parameter by the empirical power dependence

$$N_x = f_x^{-8.5}. \tag{2}$$

In high-power laser systems, the maximum load parameters are usually chosen within the range 0.3–0.5. For the load parameter $f_x = 0.4$, which is achieved at an ENE-60 charge voltage of 13 kV, the lifetime of INP-16/250 lamps, according to (2), must exceed 2400. For a single-pulse regime typical for high-power laser amplifiers (one flash per 30 min), this number of pulses is quite satisfactory.

The ENE-60 capacitive storage with a preionisation circuit allowed us to obtain more than 50 pulses of the laser amplifier at an increased load of lamps ($f_x = 0.483$) without their destruction.

4. Measurement of the gain

To measure the gains of amplifiers based on the universal pump cavity, we used AEs made of GLS-22 neodymium phosphate glass. To prevent the luminescence drop, the laser rod faces were tilted at an angle of 7.5° and the lateral surface was etched. The concentration of neodymium ions in the glass rods of each diameter was chosen so that the transverse gain distribution was close to uniform. This concentration was 3×10^{19} cm^{-3} for amplifiers with AEs 100 and 85 mm in diameter and 6×10^{19} cm^{-3} for amplifiers with the AE diameter of 60 mm [7]. Figure 5 shows the simplified optical scheme of gain measurement. A master

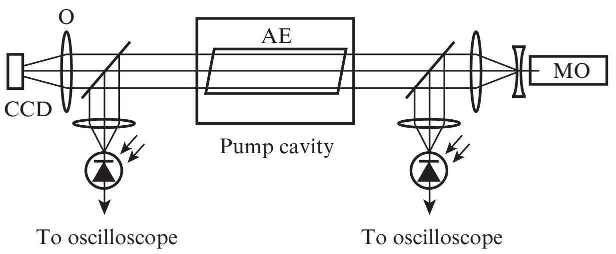

Figure 5. Optical scheme of the amplifier gain measurement.

oscillator (MO) with a Nd:YLF AE generated pulses with a duration of 15 ns, an energy of 1 mJ, and a pulse repetition rate of 2 Hz. The pump beam was broadened by a telescope, passed through the AE and objective O, and entered a CCD camera. The objective projected the output surface of the AE onto the CCD camera. Beamsplitters at the entrance and exit of the amplifier directed a part of radiation to photodetectors. Recording the beam intensity distribution at the exit of the cold amplifier (at the gain equal to unity), we can determine the transverse gain distribution. Using photodiodes at the entrance and exit of the amplifier, we measured the gain integrated over the AE cross section.

In the first column in Fig. 6, we present the transverse gain distribution for amplifiers with AEs of different diameters. In the process of measurements, the ENE-60 storage operated in the standard regime, i.e., with the preionisation circuit. As is seen from Fig. 6, gain variations are observed mainly in the radial direction, while gain variations in the azimuthal direction are noticeable only in large-diameter AEs. However, it should be noted that these gain variations do not prevent the use of such amplifiers. Radial variations, which are observed, as a rule, in amplifiers with diffuse reflectors [5], are usually compensated by appropriate laser beam profiles. Azimuthal variations can be reduced by using a pair of amplifiers. In this case, the amplifiers are rotated around the axis by an angle of $\pi/8$ with respect to each other. The second column in Fig. 6 lists the results on numerical multiplication of the transverse gain distributions given in the first column by the transverse gain distribution rotated by the angle $\pi/8$. One can see that the use of paired amplifiers considerably reduces the azimuthal gain variations. In particular, at a radial distance equal to 80% of the AE radius, the azimuthal gain variation for two unrotated amplifiers with AEs 100 mm in diameter is 12%–13%, while the corresponding variation for two rotated amplifiers does not exceed 6%–7%. Successively using this method for a multicascade amplifier in which the pairs of amplifiers rotated by the angle $\pi/8$ are rotated by $\pi/16$, it is possible to reduce the azimuthal gain variations to a negligibly low level.

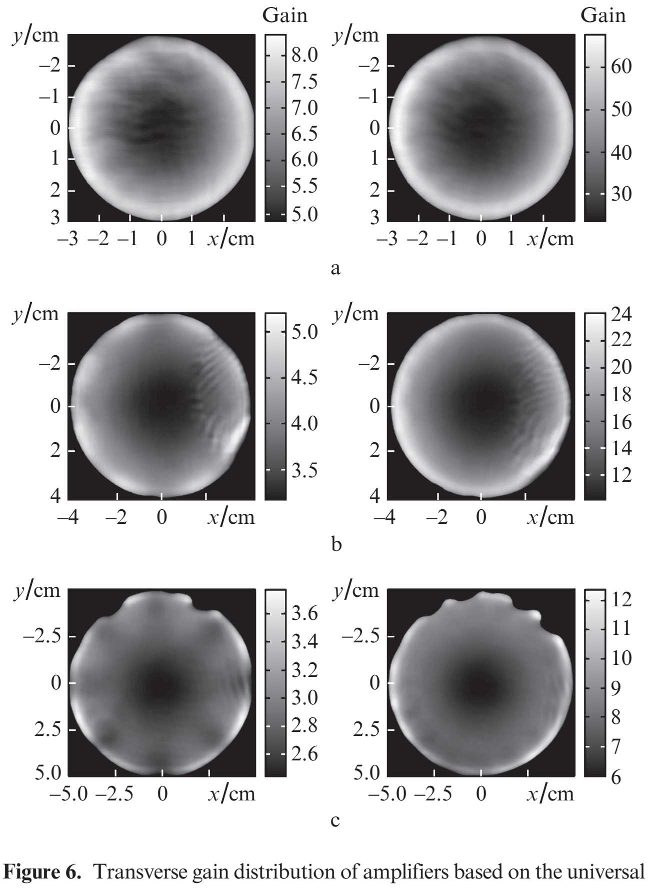

Figure 6. Transverse gain distribution of amplifiers based on the universal pump cavity for AEs 60 mm in diameter and 300 mm long at $E = 36$ kJ (a), 85 mm in diameter and 300 mm long at $E = 33$ kJ (b), and 100 mm in diameter and 300 mm long at $E = 36$ kJ (c). The left column contains experimental data, and the right column represents numerical simulation of the gain for two amplifiers rotated around the axis by an angle of $\pi/8$ with respect to each other.

The transverse gain distribution insignificantly changes with pump power. Therefore, below, to measure the dependences of the gain on the pump energy, we will use only gains averaged over the AE cross section.

For amplifiers with AEs 100 mm in diameter, we compared gains for different types of reflectors and ENE-60. The schematic cross section of amplifiers with a diffuse reflector and 18 pump lamps is shown in Fig. 1a; the storage for amplifiers of this type was designed according to the conventional scheme using low-voltage LNK-P4X-55-400 (ICAR, Italy) or K75-40 capacitors.

As follows from Fig. 7, in the case of a ENE-60 with a preionisation circuit, the gains of amplifiers with neodymium phosphate glass AEs 100 mm in diameter and 300 mm long are by 20%–25% higher than the gains of amplifiers without a preionisation circuit, which agrees with the results of [18]. The advantage of using preionisation systems becomes more evident if we take into account that, without these systems,

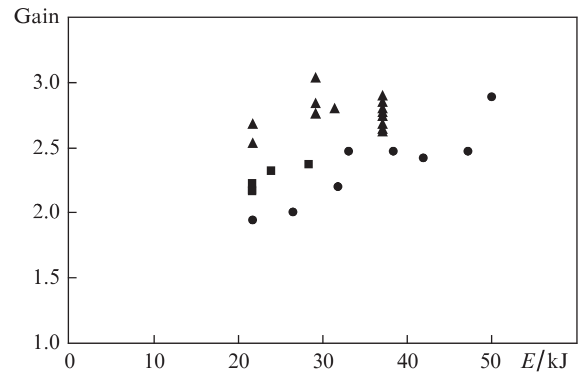

Figure 7. Dependence of the cross-section-averaged gain for an amplifier with a neodymium phosphate glass AE 100 mm in diameter and 300 mm long on the storage energy for the cases of a mirror reflector (Fig. 1a) and an ENE-60 storage without a preionisation circuit (■); a mirror reflector (Fig. 1a) and an ENE-60 storage with a preionisation circuit (▲); and a diffuse reflector (Fig. 1b) and a low-voltage storage (●).

breakdown of lamps occurs with a rather high probability (no later than after 10 pulses). Our analysis of different types of reflectors showed that the efficiency of pump cavities with mirror reflectors (Fig. 1b) is almost twofold higher than that of pump cavities with diffuse reflectors (Fig. 1a). Amplifiers with AEs of other dimensions were studied only in the case of using an ENE-60 with a preionisation circuit and mirror reflectors.

Figure 8 presents the dependences of the gain on the energy stored in the capacitors of the storage for AEs of different diameters. One can see that the gain for 100-mm AEs does not exceed 3 and is maximal at the energy $E = 30$ kJ. For amplifiers with AEs of smaller diameters, the gain is observed to increase even at $E > 30$ kJ.

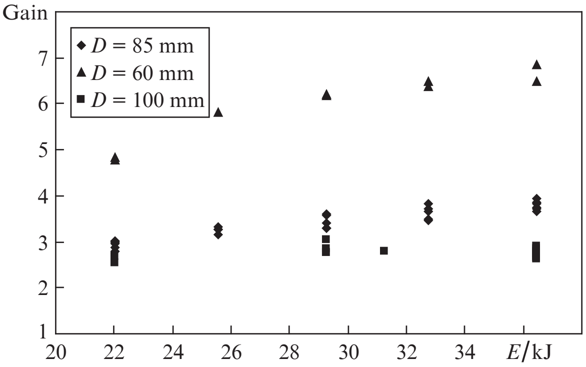

Figure 8. Dependence of the cross-section-averaged gain for amplifiers with AEs of different diameters, a universal pump cavity, and a ENE-60.

5. Conclusions

Based on our investigations, we can make the following conclusions.

The universal series of efficient amplifiers with large-aperture (60–100 mm in diameter) AEs and mirror two-section Winston reflectors exhibits insignificant azimuthal variations in the transverse gain distribution. These inhomogeneities can be easily compensated by rotating the amplifiers around their axes by different angles.

The use of our compact high-voltage capacitive energy storage ENE-60 with a preionisation circuit to supply the pump lamps of amplifiers allowed us to decrease the laser system size, increase the gain of amplifiers, and use load parameters above 0.4 without lamp breakdown. We achieved an output power of 330 GW in a pulse of a 1-ns duration. A high (70%) second-harmonic generation efficiency confirms a high beam quality in the laser systems with amplifiers [3].

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