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GARPUN-MTW: A Combined Subpicosecond/Nanosecond Ti:Sapphire/KrF Laser Facility

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1. Abstract

Multiterawatt hybrid GARPUN-MTW laser is described being developed under Petawatt Excimer Laser Project at P.N. Lebedev Physical Institute as a test bench facility for verification the challenge of KrF laser as a driver in the fast-ignition concept of Inertial Confinement Fusion. It implements direct amplification of ultra-high intensity subpicosecond UV laser pulses alone or on a par with nanosecond pulses in a multi-stage e-beam-pumped 100-J, 100-ns GARPUN KrF laser facility. Ti:Sapphire front-end "Start 248M" operates with a rep rate 0-10 Hz, pulse energy and duration at fundamental wavelength (744 nm) > 8 mJ and < 60 fs, at 3ω (248 nm) > 0.5 mJ and < 65 fs. It consists of Kerr lens mode-locked master oscillator (<30 fs, 80 MHz, 150 mW, wavelength centered at 740 nm) pumped by 2ω diode-pumped CW Finesse 4W Nd:YAG laser (3.5 W, 532 nm), all reflective-optics pulse stretcher up to 200 ps, regenerative amplifier (10 Hz, > 0.4 mJ, 740 nm) and multi-pass amplifier (10 Hz, > 15 mJ, 740 nm), both pumped by 2ω pulsed Lotis LS-2134 Nd:YAG laser (10 Hz, 10 ns, 532 nm), two-gratings compressor, and 3ω converter with two BBO crystals (8% efficiency). During the first phase at GARPUN-MTW output 1.6 J is expected in subpicosecond pulses combined with several tens of joules in nanosecond pulses. Further up-grading parameters are shortly discussed.

2. Petawatt KrF Lasers in the Inertial Confinement Fusion

Short femtosecond or picosecond pulses with ultra-high intensities (UHI) >10^{18} W/cm^2 in a focused beam of multi-TW lasers are of a great importance for many fundamental fields and practical applications. In the fast-ignition concept [1, 2], which is considered today as the most promising way for the Inertial Confinement Fusion (ICF), thermonuclear reaction is implemented in two steps: a conventional "long" nanosecond laser pulse (typically $\tau_{long} \sim 5$ ns) produces an implosion of a shell pellet and the following short UHI laser pulse ($\tau_{sh} \sim 1 \div 20$ ps) heats and ignites the collapsed fuel before it begins to expand. For a novel target design where 0.5-PW, 0.6-ps UHI pulse was delivered through a cone to the center of a spherical target preliminary compressed by 2.5-kJ, 1.2-ns pulse, 1000-fold increase in the neutron yield and 20÷30 % efficiency of UHI pulse coupling to the plasma energy were demonstrated by Kodama *et al.* [3]. If the efficiency would be the same for UHI pulse of 10÷20-ps duration, equal to expanding time of the compressed region, the total energy of the main ICF laser driver can be significantly reduced down to a few hundred kilojoules. For comparison, in the conventional ICF scheme 1.8 MJ is projected for the National Ignition Facility (NIF) at LLNL, USA [4] and Laser Mega Joule (LMJ) at CEA/CESTA Laboratory, France [5].

Non-linear processes in amplifiers restrict the maximum power of UHI pulses, the obstacle being overcome in solid-state facilities by chirped pulse amplification (CPA) [6, 7]. But additional laser beamlines are required for CPA and them to be equipped by very costly large-size diffractive gratings. Controversially, excimer laser systems using gaseous gain medium with essentially low non-linear refractive index are the only ones capable to produce UHI pulses in direct amplification scheme. Their obvious disadvantage is low saturation energy density, i.e. for KrF amplifier $Q_s = \frac{h\nu}{\sigma} \cong 2$ mJ/cm^2 ($h\nu$=5 eV, the energy of quantum, σ =2.5·10^{-16} cm^2, induced emission cross section), which is three orders of magnitude less than for solid-state lasers. As a result, large apertures are required for KrF amplifiers to obtain output power high enough. This is achievable with e-beam pumping technique. Another difference impacting architecture of KrF amplifiers is short lifetime of the upper laser level. For KrF (B→X) laser transition, radiative lifetime is τ_r= 6.5 ns; collisional quenching reduces it to $\tau_c \sim 2$ ns. As pumping time τ_p is significantly longer (for discharge-pumped excimer lasers minimum τ_p ~15-20 ns, whereas for e-beam-pumped ones, τ_p = 100÷500 ns), a multi-pass [8], multi-beam (or angular multiplexing) [9, 10] or Raman summation schemes [11-13] are required to extract the stored energy efficiently.

An important feature of KrF driver for the fast ignition application is very fast population inversion recovery time $\tau_c \sim 2$ ns of the gain medium. This means amplification of a short UHI laser pulse ($\tau_{sh} << \tau_c$) can be repeated each 2 ns and it hardly affects subsequent amplification of long pulses ($\tau_{long} \geq \tau_c$). Therefore it will be very attractive to amplify both long laser pulses for pellet compression and UHI short pulses for fuel ignition in the same large-scale e-beam-pumped amplifiers (Fig. 1) [14]. On the other hand, amplification of a quasi-continuous train of long pulses in angular multiplexing layout would deplete the population inversion and control amplified spontaneous emission (ASE), which is rather high due to a short radiation lifetime.

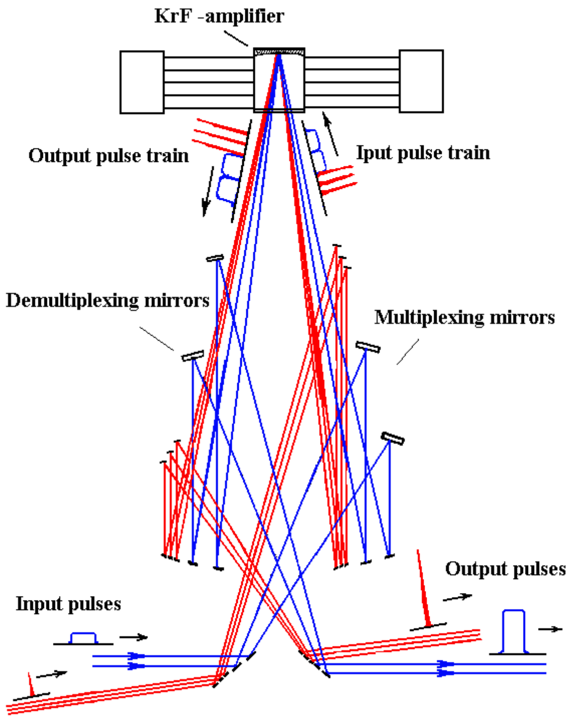

Fig. 1. *Principle of simultaneous angular multiplication of short & long pulses in KrF amplifiers.*

Several approaches for UHI excimer laser systems (mainly KrF) were realized to date (see [15, 16] and references cited therein). The most promising one utilizes Ti:Sapphire front-end to produce femtosecond pulses at 745-nm wavelength, which then are frequency-tripled into

KrF (B→X) transition. As it has limited 2.5-nm bandwidth, the seed pulses shorter than ~ 50 fs are not necessary. The shortest pulse amplified in a discharge-pumped KrF laser was 60-fs long [17]. The highest output power up to 10 TW was achieved at Super-SPRITE KrF facility equipped with e-beam-pumped TITANIA amplifier with 60-cm-aperture [18, 19]. The pulse with a peak power of 3–4 TW (>10 J, ~ 3 ps) was obtained with 60-cm-aperture final amplifier of Super-ASHURA facility being combined (Owadano *et al.*, 2001) in laser-plasma interaction studies with 100-J, 20-ns pulse [20]. CPA amplification was also successfully used in KrF amplifiers [21, 22], although it was not as efficient as in solid-state lasers. Nevertheless, short-wavelength KrF lasers provide better focusing of radiation and are capable in reaching intensities as high as 10^{20} W/cm^2 [18, 19, 23].

The goal of the present first phase of Petawatt Excimer Laser Project (PEL Project) started at P.N. Lebedev Physical Institute [24] is verification of the above-described fast-ignition ICF concept utilizing KrF drivers for simultaneous amplification of short & long laser pulses.

3. GARPUN Laser Facility

Layout of the hybrid Ti:Sapphire/KrF multiterawatt laser facility GARPUN-MTW for amplification of combined subpicosecond/nanosecond pulses is shown schematically in Fig. 2. A newly developed Ti: Sapphire front-end "START-248 M" is currently upgrading the GARPUN KrF laser facility [25, 26]. The final large-aperture GARPUN amplifier module operates since 1990 and has generated about 8,000 shots with output energy of up to 100 J [27]. It has an active volume dimensioned 16×18×100 cm pumped by two-side counter-propagating 350-keV, 60-kA (50 A/cm^2), 100-ns e-beams with magnetic field (~0.08 T) guiding. Another 10×10×110-cm BERDYSH module pumped by a single-side magnetic field-guided 350-keV, 50-kA (50 A/cm^2), 100-ns e-beam provides up to 25 J in free-running oscillation. A high-voltage power supply of electron guns consists of two separate 7-stage Marx generators with 14 kJ (GARPUN) and 3.0 kJ (BERDYSH) energy storage at 500-kV pulsed voltage and five water-filled Blumlein pulse forming lines (PFLs) of 7.6 Ω wave impedance, which supply pulses of ~350 kV voltage to four cathodes in GARPUN's vacuum diodes and one cathode in BERDYSH module. All PFLs are synchronized by means of laser-triggered switches.

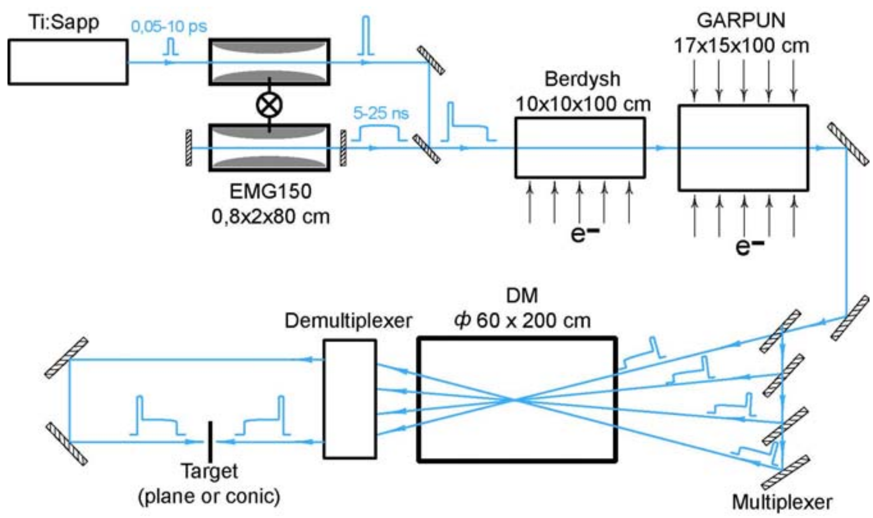

Fig. 2. *Layout of hybrid Ti:Sapphire/KrF laser facility GARPUN-MTW for amplification of combined subpicosecond/nanosecond pulses.*

Excimer master oscillator is a commercial Lambda Physik EMG TMSC 150 laser with two separate discharge chambers synchronized by a common thyratron. It can be configured in different ways, for instance, as two independent oscillators or amplifiers or, being combined together in an injection-locked configuration, to produce narrow-band (~0.2 cm^{-1}) radiation tunable over emission band. At the present, two performances are considered: (i) the excimer master oscillator arranged in the narrow-band mode produces 20 ns, 0.2 mJ pulses, whereas a short pulse from Ti:Sapphire front-end is going roundabout to be combined subsequently with a long pulse; (ii) one of discharge chambers of the master oscillator operates in a conventional broad-band (~ 50 cm^{-1}) mode with approximately the same pulse energy and duration as in (i), while the other chamber serves as an amplifier for the short pulses (Fig. 2). Being combined together, short & long pulses are to be amplified successively in BERDYSH and GARPUN amplifiers. Large-scale DM amplifier with optical diameter of 60 cm and active length of 200 cm will be implemented at the second phase of PEL Project. This amplifier was designed at High-Current Electronics Institute (Tomsk, Russia) based on the 2-kJ XeCl prototype pumped by radially convergent e-beams [28].

E-beam transport and pumping of GARPUN amplifier have been measured and compared with simulations using Monte Carlo code [29]. The code accounted for real geometry of vacuum diodes and laser chamber filled with a working gas and restricted by foil windows, sidewalls and optical windows. Avalanche electron motion was considered between their collisions with atoms until particles will either stop or exit from the current construction element to another. Motion of secondary electrons was tracked on a par with primary electrons. This allows us to take into account correctly reflection by the walls, as well as reflection from the vacuum diodes. For each layer energy deposition, the particle and energy fluxes through their borders, as well as energy and angular spectra of particles were calculated. Figures 3, 4 demonstrate energy deposition in dependence on Ar pressure filling the laser chamber and 2D distribution of specific pumping energy (or power) in the middle cross-section of GARPUN laser cavity at 1.75-atm Ar pressure.

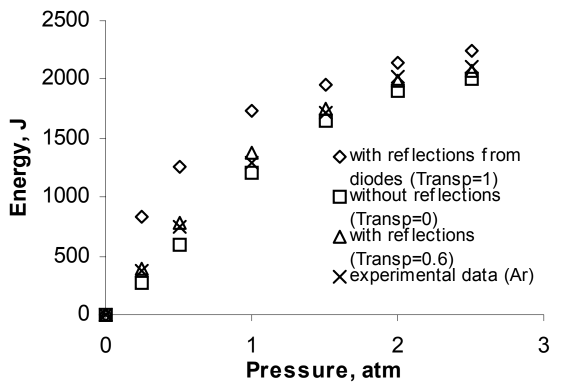

Fig. 3. *Comparison of experimental data and simulations of energy deposition in GARPUN laser cavity filled with Ar gas.*

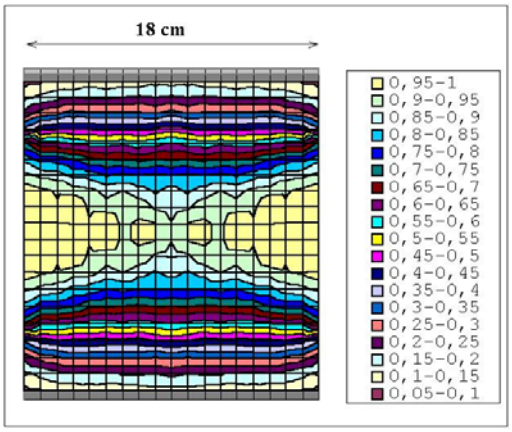

Fig. 4. *Relative distribution of specific pumping energy (or power) over cross-section of GARPUN laser cavity filled with Ar at 1.75-atm pressure. E-beams are injected from left and right sides.*

4. Ti:Sapphire Front-End "START-248 M"

Ti:Sapphire front-end "START-248 M" was designed and constructed by Avesta Project Ltd. A layout of the laser is shown in Fig. 5.

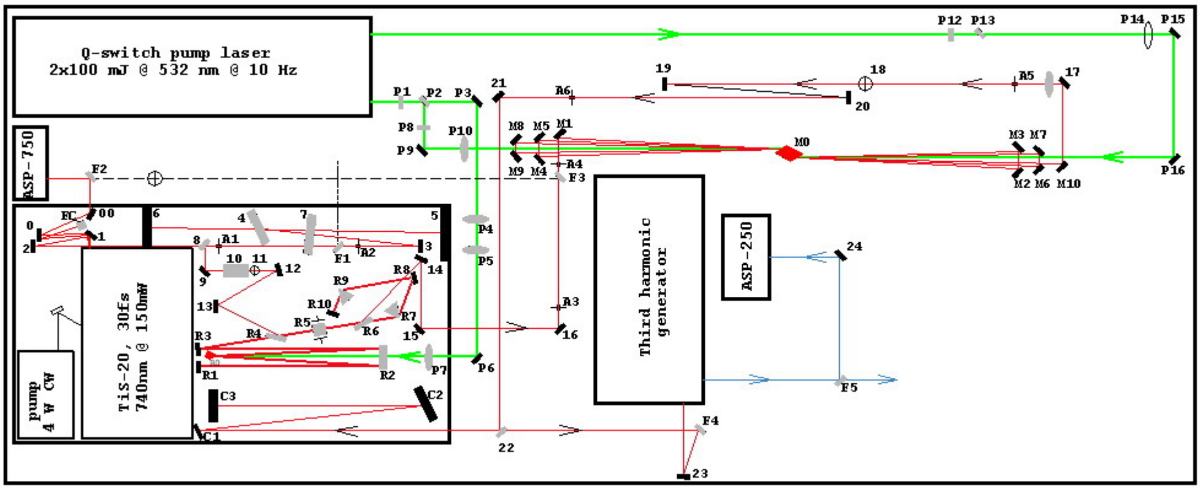

Fig. 5. Layout of Ti: Sapphire front-end.

Facility occupies a standard 120×300-cm^2 laboratory table. Ti:Sapphire oscillator TiS-20 with Laser Quantum 4-W CW Finesse 532 DPSS pumping laser (λ=532 nm), grating stretcher and compressor, and regenerative amplifier are enclosed in a common 60×110-cm^2 box. On the same table there are a multi-pass amplifier pumped by a pulsed two-channel Lotis-Tll Nd:YAG LS-2134 laser (2×100 mJ, 532 nm), 3-ω converter, ASP-750 and ASP-250 spectrometers for fundamental wavelength and the third harmonics, respectively. The Kerr lens mode-locked oscillator TiS-20 when being pumped by 4-W CW radiation produces a continuous 80-MHz train of 30-fs pulses with nJ-level of energy and average power of 0.2 – 0.3 W. By choosing appropriate mirror's reflection, it is optimized to oscillate in a broad band of 28 – 32 nm centered at 740 nm. Femtosecond pulses are stretched up to 200 ps in a double-pass all-reflected stretcher using a diffraction grating with 1200 grove/mm and 750-mm-length mirror telescope. Afterwards they are forwarded through a Faraday isolator into regenerative amplifier where a single pulse is cut off of the train by a Pockels cell and amplified by ~10^6 times. The regenerative amplifier has Z-folded resonator cavity, which is precisely tuned into required spectral range by a prism pare and they also compensate the second- and third-order dispersions. The crystal (one side is cut at Brewster angle, another is HR coated to reflect both pumping and laser radiation) is effectively pumped by a fraction of the pulsed radiation produced in the first channel of Nd:YAG LS-2134 laser. The rest radiation, being varied with the help of polarization rotator and thin-film polarizer, is used to pump a multi-pass amplifier.

Ejected from the regenerative amplifier ~1-mJ pulse is directed to the next amplifier stage, in which, after 5 succeeding passages accomplish output energy of up to 15 mJ. The pumping power in the Brewster angle crystal might be increased if necessary using the other channel of the pump laser with energy varied with the help of polarization rotator and polarizer. Pumping beams are focused into the crystal from opposite sides by lenses. After amplification, the pulse is compressed to ~50 fs in double-pass two-grating compressor. After compressor it contains ~ 8 mJ energy at ~744-nm wavelength. Next, the radiation is frequency tripled (λ=0.248 nm) in two successive non-linear processes – by means of second harmonic generation (λ=0.372 nm) in 150-μm-thick BBO (type I) crystal and collinear mixing of the fundamental and 2ω beams in another 100-μm-thick BBO (type I) crystal. The efficiency of 2 ω and 3ω conversion is >30% and 4-8%, respectively. The output laser beam is linearly-polarized and has a diameter of 8 mm. The summary parameters of "START-248 M" front-end are presented in Table 1.

TABLE 1: PARAMETERS OF TI:SAPPHIRE FRONT-END “START-248 M”

Repetition rate	0-10 Hz
Pulse width at λ=744 nm	< 50 fs
Pulse width at λ=248 nm	< 60 fs
Pulse energy (@ 10 Hz) at λ=744 nm	> 8 mJ
Pulse energy (@ 10 Hz) at λ=248 nm > 0.5 mJ	> 0.5 mJ
Beam diameter at λ=744 nm	10 mm
Beam diameter at λ=248 nm	8 mm
Stability of energy at λ=744 nm	< 3%
Stability of energy at λ=248 nm	< 5%

To date, Ti:Sapphire front-end has been synchronized with KrF master oscillator of GARPUN laser facility: short and long pulses can be gradually moved one with respect to the other (Fig. 6). Pilot experiments on amplification of a short pulse in double-pass configuration in the discharge-pumped amplifier were performed and a gain factor of 5 was measured with output energy of ~1.5 mJ. This corresponds to energy density of 6.5 J/cm^2, which is 3.25 times more than saturation density Q_s.

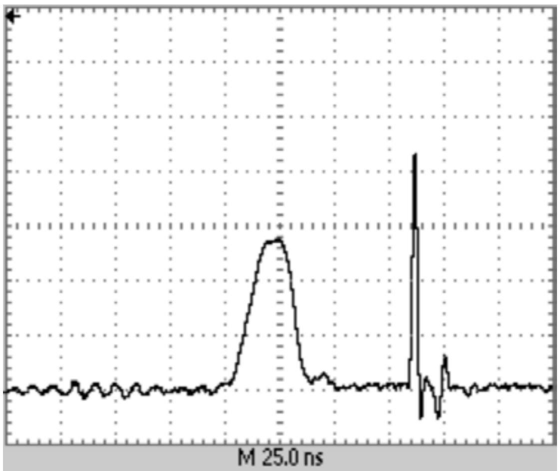

Fig. 6. *Synchronized laser pulses of KrF master oscillator (left) and Ti:Sapphire front-end (right).*

5. Effect of the Amplified Spontaneous Emission on the Contrast of Short Pulses

In large-aperture KrF amplifiers and oscillators, ASE can considerably reduce the output laser energy. In a short-pulse laser-target interaction, ASE produces a pre-pulse on a target before arrival of the main UHI pulse, which is unacceptable in many applications. A ratio of the UHI pulse intensity (or energy density) at the target to corresponding values for the pre-pulse, which is referred to as a contrast ratio, is an important characteristic of laser system. In this section we discuss numerical simulations and experiments being performed at GARPUN amplifier to estimate expected ASE intensity on the target.

A numerical quasi-stationary M-code was used for self-consistent calculations of the ASE and kinetic processes in large-aperture KrF lasers [30]. Within generalized “forward – back” multi-direction approximation, a set of 6 simultaneous radiation transfer equations for so-called ASE waves and 2 equations for axial signal waves were solved together with kinetic equations for about one hundred reactions between several tens components involved into KrF active medium kinetics. Vibrational relaxation processes and temperature dependence of rate constants were included in the kinetics. A diffusive reflection of the ASE by sidewall of laser chamber was taken into account.

For single-pass GARPUN amplifier filled with gas mixture $Ar/Kr/F_2$ = (89.65/10/0.35)% at p = 1.4 atm and specific pumping power W_b=0.62 MW/cm^3, a small-signal gain coefficient was calculated to be g_0 = 7.6·10^{-2} cm^{-1}, nonsaturable absorption coefficient α_{ns}= 4.4·10^{-3} cm^{-1}, saturable absorption coefficient α_s = 0.8·10^{-3} cm^{-1}, and saturation intensity I_s = 1.53 MW/cm^2. Numerical simulation of I_{out} (I_{in}) dependence performed neglecting ASE demonstrated in the unsaturated region somewhat higher output intensities than in experiments [29]. When the ASE was taken into account, I_{out} decreased 3−5 times. This gives for a depletion of the small-signal gain coefficient by the ASE g_{ASE} /g_0 = $(1+I_{ASE}/I_s)^{-1}$ = 0.79−0.84 and average ASE intensity I_{ASE} = 0.3−0.4 MW/cm^2. By applying the same saturation factor to the experimental results, we obtain the corrected small-signal net gain coefficient g_0^{net} = (7.7−9.0)·10^{-2} cm^{-1}. Note that numerical simulations with accounting for the ASE give 2-3 times less output intensities in the unsaturated region than experimental ones. As in this region I_{out} ~ exp(g_0L) strongly depends on g_0L product, the discrepancy might be explained by minor theoretical error in g_0 or by underestimated e-beam pumping power and some enlargement of axial gain length due to electron scattering.

Examples of ASE simulations for single-pass and double-pass configurations are demonstrated in Fig. 7. They are compared with near-field ASE experimental results (measurements were done nearby the laser window and recalculated to the boundary of the gain medium) in Table 2.

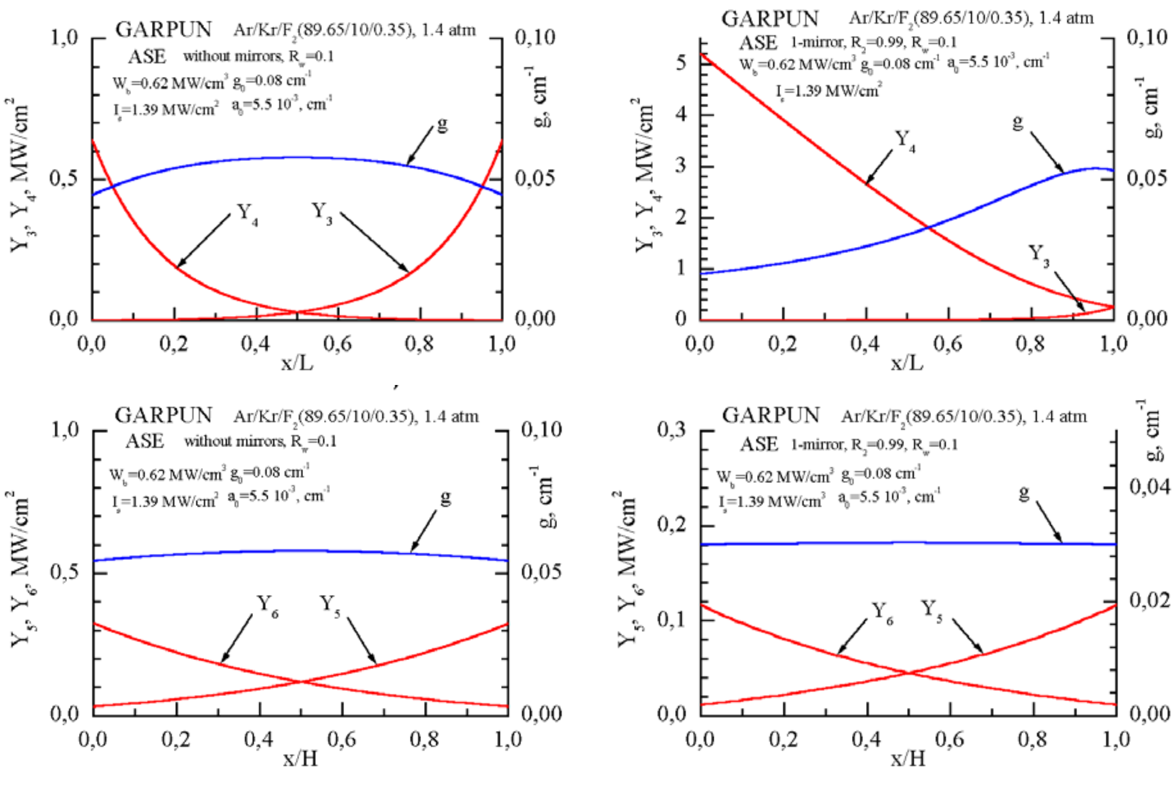

Fig. 7. *Calculated distributions of the ASE along the axis of GARPUN amplifier (top) and in transverse direction (bottom) in single-pass (left) and double-pass (right) schemes.*

TABLE 2. NEAR-FIELD ASE MEASUREMENTS COMPARED WITH NUMERICAL SIMULATIONS.

Pumping & amplification configuration	Experimental values		Simulated values
	Energy density, mJ/cm^2	Intensity, MW/cm^2	Intensity, MW/cm^2
Full pumping & single-pass	22.8	0.56	0.63
Full pumping & double-pass	188	4.64	5.2
Half pumping & single-pass	7.0	0.18	-
Half pumping & double-pass	9.9	0.24	-

The ASE waveforms had FWHM duration $\tau_{1/2}$ = 40 ns, which was significantly shorter than the duration of pumping pulse (~100 ns). Seemingly, this "sharpening" of the axial ASE waveform was caused by an exponential factor with the index of exponent being proportional to instantaneous value of pumping power. It is seen from Table 2 that experimental values of the peak ASE intensity are in a good agreement with simulated ones. The measured ratio of the ASE signal in the double-pass measurements to that in the single-pass ones is 8.25, which coincides with simulated data. Note that for a half pumping scheme, this ratio falls down to 1.4 because of lower amplification exponent.

Far-field zone ASE being measured in a single-pass configuration was proportional to the solid angle. These gave for the ASE power per solid angle, $\frac{dW_{ASE}}{d\Omega}$ = $3.5\cdot10^9$ W/sr. Then ASE intensity on a target can be written as $I_{ASE}^{t\arg} = \frac{1}{F^2}\frac{dW_{ASE}}{d\Omega}$, where F is a focal length of focusing optics. If, for instance, F = 30 cm in a single-pass amplifier configuration under usual pumping conditions, $I_{ASE}^{t\arg}$ = 4 MW/cm^2. For a double-pass GARPUN configuration this value would be 8.25 times more. Note that for long enough amplification length, when the ASE intensity inside amplifier $I_{ASE} \geq I_s$, I_{ASE} begins to grow linearly with the length (see Fig. 7). At still longer lengths, the ASE intensity tends to saturate at the level $I_{ASE} = (g_0/\alpha_{ns})I_s \approx 20$ MW/cm^2, which is 4 times more than the output value for double-pass GARPUN amplifier. In the limit, the ASE intensity on a target for a successive double-pass amplification of short pulses in both BERDYSH and GARPUN amplifiers will be about 100 MW/cm^2, which is near the threshold for plasma formation by 100-ns irradiation pulse [31].

6. Simulations of Long and Short Pulses Amplification in GARPUN-MTW

Non-coherent amplification of a short pulse successively in double-pass BERDYSH and GARPUN KrF-amplifiers was simulated using the equation [32]

$$\frac{df}{dx} = g(x)\left(1-e^{f}\right) - \alpha_{ns}(x) f, \qquad 0<x<L, \qquad (1)$$

where $f = Q/Q_s$, $g(x) = \sigma N^*_{KrF}(x)$, $Q = \int I(x,t')dt'$.

To reduce ASE in the amplifiers, it was assumed that a long pulse with duration equal to the pumping time ($\tau_{long} = \tau_p$ =100 ns) and intensity $I_{in} = 10^{-3} I_s$ was supplied to the entrance of the amplifiers chain. This quasi-steady radiation together with the ASE forms longitudinal profiles of gain $g(x)$ and absorption $\alpha_{ns}(x)$ coefficients, which are used afterwards in Eq. (1). The energy of a short pulse at the entrance of the first BERDYSH amplifier was assumed to be E_{in} = 0.1 mJ, which is easy achievable with Ti:Sapphire front-end (see Section 4).

Figures 8, 9 demonstrate the dependences of the output energy density on the input energy density, both reduced to the saturation energy density Q_s, and distributions of Q/Q_s along the relative length of double-pass amplifiers. The output energies of 80 mJ and 1.6 J are expected for BERDYSH and GARPUN amplifiers, respectively.

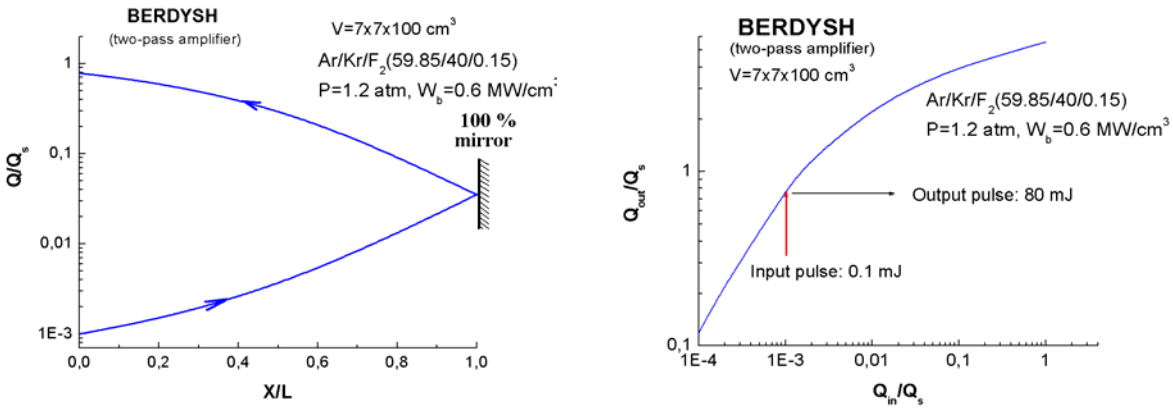

Fig. 8. *Simulation of a short pulse amplification in BERDYSH double-pass amplifier: distribution of relative energy density along the relative length (left) and dependence of relative output energy density on the input one (right).*

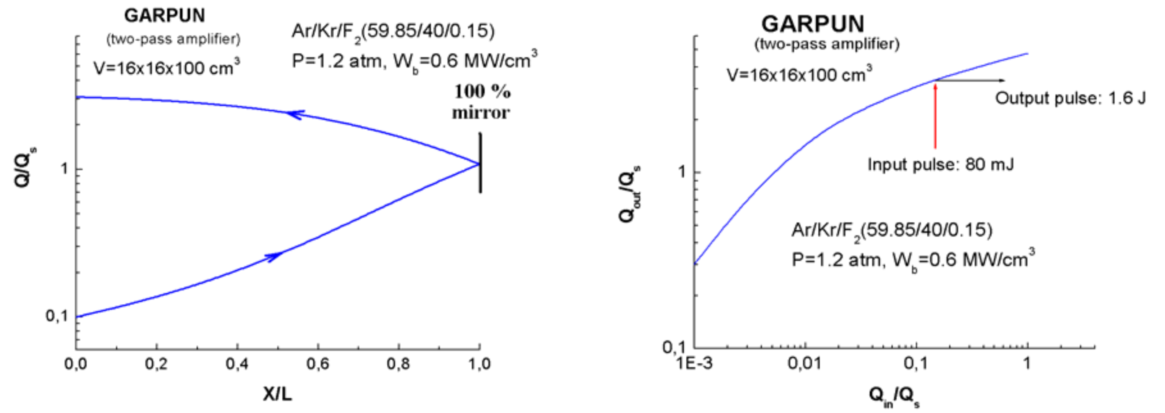

Fig. 9. *Simulation of a short pulse amplification in GARPUN double-pass amplifier: distribution of relative energy density along the relative length (left) and dependence of relative output energy density on the input one (right).*

Simulations were performed also for DM double-pass e-beam-pumped (τ_p=250 ns) amplifier of 60-cm diameter and 200-cm length to be installed at the second phase of PEL Project. The energy in a single short pulse will increase up to 18 J (Fig. 10) while up to 4 kJ is expected in a 250-ns-duration train of long pulses amplified with a stage gain $M\approx$ 20 and intrinsic efficiency $\eta_{eff}\approx$10% (Fig.11). Specific pumping power W_b=0.15, 0.30, and 1 MW/cm^3 was a variable parameter. In assumption of 150-fs short pulse and its radiation divergence $5\cdot10^{-4}$ the ratio of the short pulse intensity to the ASE background on a target was estimated to be in the range $2\cdot10^8\div3\cdot10^9$.

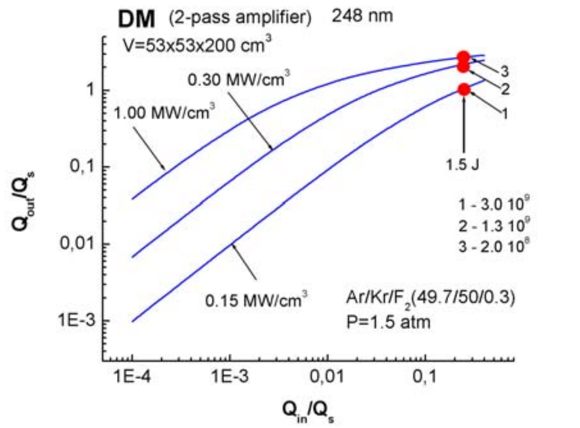

Fig. 10. Relative output energy density of a short pulse for DM double-pass amplifier in dependence on the input one for various specific pumping powers. The contrast ratios 1-3 correspond to the marked points.

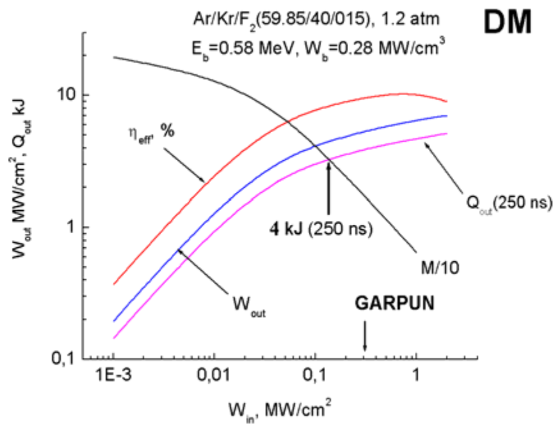

Fig. 11. Output parameters (intensity W_{out}, energy Q_{out}, intrinsic efficiency η_{eff}, and stage gain M) of DM amplifier for 250-ns train of long pulses in dependence on input intensity.

7. Conclusions

Petawatt Excimer Laser Project (PEL Project) has started at P.N. Lebedev Physical Institute with the goal to generate ultra-high intensity subpicosecond pulses and to verify the fast-ignition ICF concept utilizing e-beam-pumped KrF drivers for simultaneous amplification of short & long laser pulses. At the present first phase PEL Project implements up-grading of 100-J, 100-ns multi-stage GARPUN KrF laser facility by a femtosecond Ti:Sapphire front-end. Pilot experiments were performed to synchronize KrF and Ti:Sapphire master oscillators and to produce combined femtosecond/nanosecond pulses with variable time delay. Gain and absorption measurements in GARPUN amplifier being compared with numerical simulations based on quasi-stationary numerical code precede future experiments on amplification of both short and combined pulses in e-beam-pumped large-aperture amplifiers. Amplified spontaneous emission was also measured and simulated to evaluate the pre-pulse intensity on a target produced by the amplifiers chain. To control the ASE level it was proposed to amplify short pulses in the medium depleted by quasi-steady laser radiation. Numerical simulations predict that 1.6 J can be obtained in subpicosecond pulse at multi-terawatt hybrid GARPUN-MTW Ti:Sapphire / KrF laser facility combined with several tens of joules in nanosecond pulses. Installation of a 60-cm-aperture DM amplifier at the second phase of PEL Project will allow to increase the energy in a single short pulse up to 18 J and to obtain 4-kJ energy in a 250-ns train of long (nanosecond) pulses. The contrast ratio of short-pulse intensity on a target to the ASE is expected in the range $2\cdot10^8\div3\cdot10^9$.

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