Multiterawatt Ti:Sapphire/KrF laser GARPUN-MTW as a test bench facility for verification of combined amplification of nanosecond and subpicosecond pulses

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Abstract. The possibility of the same large-aperture KrF laser driver to amplify simultaneously both nanosecond pulses for thermonuclear target implosion and picosecond ones for fuel ignition is discussed relative to KrF-based Fusion Test Facility. In this way experiments were performed at hybrid Ti:Sapphire/KrF GARPUN-MTW facility on amplification of subpicosecond pulses. 2-TW, 330-fs pulses were produced with beam divergence 20 µrad in direct double-pass amplification scheme. Peak power as high as 30–40 TW can be achieved in 50-fs pulses, being combined with long pulses (of a few ns to 100 ns) of ~1 GW power.

1. KrF laser as a prospective driver for the Inertial Fusion Energy
A single-shot 1.8-MJ Nd glass National Ignition Facility has been successfully completed and Thermo Nuclear ignition experiments were started at the LLNL, USA [1] whilst the other facility Laser Mega Joule is under construction in France, being scheduled for operation in 2014 [2]. Against this background the research program to produce Inertial Fusion Energy is underway considering Diode Pumped Solid State Laser and e-beam-pumped Krypton Fluoride laser as candidates for rep-rate, highly-efficient and durable IFE drivers [3]. The ongoing research with KrF lasers aims at obtaining ≥3×10⁸ shots in continuous operation with ≥6-7 % overall efficiency at a laser module scalable to 28-kJ energy that is the bench mark for Fusion Test Facility design [4].

To obtain economically attractive IFE power plant two advanced approaches are considered, which allows one to increase TN target gain and to reduce laser driver energy. In a Fast Ignition scheme [5, 6] a powerful tens-ps pulse with intensity \( I \sim 10^{19} \text{ W/cm}^2 \) generates electrons or protons, which off-center ignite the TN fuel preliminary compressed by nanosecond pulse. Simultaneous amplification in the same large-aperture KrF amplifiers stacks of angular-multiplexed nanosecond and picosecond pulses was proposed earlier [7] which seems to be a promising way for the FI IFE. Short pulses of 1 to 20 ps duration can be focused into the same point or distributed over the compressed target [8, 9].

According to the scaling law \( E_e = \left( \frac{I \times (\lambda - 0.5 \mu m)}{10^{19} \text{ W/cm}^2} \right)^{3/2} \) MeV [10] for ponderomotive acceleration of electrons up to energy \( E_e = 1 \text{ MeV} \), which is optimal for electron coupling to the compressed target core...
[11], higher intensity I ~ 2×10^{20} \text{ W/cm}^2 is required for KrF laser wavelength \( \lambda = 248 \) nm. Fortunately, it is easy to achieve due to better beam focusability (~ -\( \lambda^2 \)).

In Shock Ignition scheme [12, 13] hundred-ps final spike with intensity ~ 10^{16} \text{ W/cm}^2, ten times higher than the main part of the pulse, generates a convergent shock wave, which ignites compressed TN fuel in the central spot. Appropriate target design [14] and laser system analysis [15] have shown that, for a short KrF laser wavelength, target gain as high as 140 may be achieved with modest 0.5-MJ driver energy. A required SI pulse shape can be formed in a course of quasi-steady amplification of angularly multiplexed train of input pulses, which should be specially precompensated for heavily saturated amplifier during high-intensity spike [16]. Alternatively, the idea of simultaneous amplification of short & long pulses [7, 8] can be used to combine a complex SI pulse form directly on a target. On the path to its realization we have investigated amplification of subpicosecond pulses in multistage GARPUN-MTW KrF laser facility [8].

2. Amplification of short and long pulses in KrF laser

Particular features of KrF lasers operating at B→X bound-free transitions (see [8] and references therein) are short lifetime of the excited state of the molecule (radiative \( \tau \approx 6 \) ns; with account for collisional quenching it is \( \tau \approx 2 \) ns), large induced emission cross section \( \sigma = 2.5 \times 10^{-14} \text{ cm}^2 \), small value of saturation energy fluence \( Q_s = h\nu/\sigma = 2 \text{ mJ/cm}^2 \) (where \( h\nu = 5 \text{ eV} \) is the energy of radiation quantum), and significant nonsaturable loss in a gain medium (typical ratio of small-signal gain to absorption coefficient \( g_0/\alpha = 10^{-20} \)). Because of rapid recovery time of the population inversion in the gain medium (\( \tau \approx 2 \) ns), each short pulse (with duration \( \tau_{opt} \leq \tau \)) does not affect the subsequent pulse if those follow with time interval \( \Delta t \geq \tau \). Also short pulses will be effectively amplified after termination of a stack of long pulses (with \( \tau_{long} \geq \tau \), typically \( \tau_{long} \approx 5 \) ns), which are amplified in a quasi-steady manner. On the other hand, during quasi-steady amplification at optimal intensity (corresponding to maximum efficiency) \( I_{opt} = I[(g_0/\alpha)^{1/2} - 1] \) the energy stored in the gain medium is not completely extracted. The rest can be used for simultaneous amplification of short pulses, though with less gain \( g = (g_0/\alpha)^{1/2} \). This also might be useful to reduce Amplified Spontaneous Emission, which decreases a contrast of the short pulse.

3. Experimental setup

Hybrid Ti:Sapphire/KrF multiterawatt laser facility GARPUN-MTW combines the previous version of e-beam-pumped multistage GARPUN KrF laser with recently constructed Ti:Sapphire front-end “START-248 M” [8]. The final large-aperture GARPUN amplifier with a gain volume of 12×18×100 cm^{3} is pumped by two counter-propagating 350-keV, 60-kA (50 A/cm^{2}), 100-ns e-beams guided by magnetic field of ~0.08 T. When operating in free-running oscillation mode with Ar/Kr/F\(_2\) gas mixture at 1.4-atm pressure and with specific pumping power \( W_p = 0.7-0.8 \text{ MW/cm}^2 \), it provides up to 100 J in 100-ns pulse. Another 8×8×110-cm^{3} BERDYSH module pumped by a single-side magnetic field-guided 350-keV, 50-kA (50 A/cm^{2}), 100-ns e-beam with \( W_p = 0.6-0.7 \text{ MW/cm}^2 \) produces up to 25 J at 1.8-atm gas mixture. Both amplifiers are synchronized with KrF master oscillator (Lambda Physik EMG TMSC 150 model) producing 200-mJ, 20-ns pulses, which fire laser-triggered switches of HV pulsed power supply of e-beam guns of both Berdysh and GARPUN amplifiers. Frequency tripled Ti:Sapphire front-end “START-248 M” (Avesta Project Ltd.) was designed to generate 10-Hz train of 0.5-mJ, 60-fs pulses at wavelength \( \lambda = 248 \) nm matched with KrF gain band.

The layout of experiments on amplification of short pulses is shown in figure 1 with appropriate equipment for measuring pulse energy, duration, spectral and spatial distribution. A single pulse was cut out of a continuous Ti:Sapphire front-end train and synchronized with KrF amplifiers within accuracy of ±5 ns at the top of 100-ns pumping pulse. Double-pass amplification was used for both preamplifier and final amplifier with a spatial filter placed between them. Initial 8-mm front-end beam diameter was successively expanded by convex and concave mirrors to fit amplifier apertures. The only transmissive optics was CaF\(_2\) amplifier windows inclined to prevent parasitic oscillations.
4. Experimental results and discussion

Figures 2, 3 present experimental dependences of output energy density $Q_{\text{out}}$ on input one $Q_{\text{in}}$ for double-pass amplification in both BERDYSH preamplifier and GARPUN amplifier compared with numerical simulation for various small-signal gain coefficients $g_0$ and nonsaturable absorption $\alpha$ (shown in the figure inserts). Depletion of the gain by the ASE in folded amplifiers was taken into account with corresponding gain profiles along the amplifiers [8].

The preamplifier operating with maximal $Q_{\text{out}} = 0.6$ mJ/cm$^2$ is far from saturation ($Q_s=2$ mJ/cm$^2$) and has a stage gain $G = 70$ ($Q_{\text{out}}/Q_{\text{in}}$). A deviation of experimental dots from calculated curves was probably due to nonlinear absorption of laser radiation in preamplifier windows, which should increase at higher intensities. Total output energy over laser beam cross-section area $S_b=38.5$ cm$^2$ (it is averaged along the amplifier) was $E_{\text{out}} = 23$ mJ with a fill factor $f = 0.6$ (a fraction of $S_b$ relative to the whole amplifier aperture). The final amplifier is saturated by $Q_{\text{out}} = 6.7$ mJ/cm$^2$, which gives total $E_{\text{out}} = 620$ mJ over $S_b = 92.5$ cm$^2$ ($f = 0.43$). Contribution of the ASE in a solid angle of calorimeter ($\sim 2\times10^{-5}$ sr) was $\sim 3\%$. Higher energy up to 1.5-2.0 J in a single short pulse is expected for double-pass amplification in both Berdysh and GARPUN amplifiers after optimization. A train of short pulses can be also amplified or combined with long pulses of few-ns to 100-ns duration [8].

For 0.1-ps input pulse in present experiments, output pulse was time-broadened by group velocity dispersion (GVD) in amplifier windows. Its duration is estimated by using two methods: by interference of two beams being split by a mirror wedge and by a streak camera. In fact a coherence length is measured using the former approach, which gives a lower limit $\tau_{1/2}=0.33$ ps. The latter measurement is limited by a temporal resolution of the camera and gives upper limit $\tau_{1/2} \leq 1$ ps.
Spatial distribution of radiation (see figures 4, 5) was affected by: (i) block-like structure of CaF$_2$ amplifier windows (it is the best material in respect of nonlinear absorption) that introduces phase modulation at block boundaries and (ii) beam filamentation, as pulse power $P \sim 2$ TW $\gg P_{cr} = 3.8A^2/\pi n_2 = 100$ MW, critical power for filamentation of UV ($\lambda=248$ nm) light [17]. For measured ASE contribution and divergence of a short-pulse beam $\Theta_{12}=20\mu$rad (figure 5) the contrast ratios of the short pulse to the ASE can be estimated in the future target irradiation experiments: $CR_{Q} \sim 10^6$ for energy densities and $CR_{I} \sim 10^{11}$ for intensities (short pulse of $\sim 1$ ps was assumed).

A spectral width of amplified short pulse was measured to be $\Delta \nu_{12} \sim 2.3$ nm (figure 6), which enables obtaining pulse duration $\sim 50$ fs if GVD in amplifier windows will be precompensated by initially introduced negative frequency chirp. Then peak power as high as 30–40 TW can be achieved and with improved beam quality the short pulse can be focused into intensities of up to $10^{20}$ W/cm$^2$.

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