Superatmospheric X-ray preionized TE-CO_2 discharge unit*

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ABSTRACT

CO_2 laser system generating the train of ~ 200 ps pulses with total energy up to 5 J was put in operation in General Physics Institute of Russian Academy of Sciences (IOFRAN) recently. Initial ~100 ps 10.6 μm laser pulse with energy ~ 10 μJ was regeneratively amplified in 5 x 5 x 5 cm^3 discharge volume X-ray preionized TE-CO_2 discharge unit developed and manufactured in D.V.Efremov Scientific Research Institute of Electrophysical Apparatus (NIIEFA) in cooperation with IOFRAN. The results on upgrade of this unit towards obtaining 10 atm volume self-sustained discharge in CO_2:N_2:He mixtures with reasonably high percentage of molecular gases are reported. Owing to this upgrade free running mode laser radiation energy E_l (when the unit was equipped with unstable telescopic resonator) at 6 atm was increased up to 22.2 J, which corresponds to specific energy extraction 5.4 J/l/atm and efficiency 4.5%. The estimated value of E_l from such a laser at 10 atm is 15 J. It corresponds to peak power of regeneratively amplified 2 ps 10 μm pulse formed in master oscillator of laser system ~ 1.5 TW. Prospective of further upgrade of laser system using new 10 x 10 x 100 cm^3 discharge volume 10 atm TE-CO_2 discharge unit which is under construction now in NIIEFA in the network of ISTC Project #1072 is discussed.

Keywords: picosecond pulse, CO_2-laser, high-pressure gas mixture, volume self-sustained discharge

1. INTRODUCTION

The creation of high-power 10 μm picosecond lasers opens new possibilities in fundamental investigations of laser radiation interaction with matter. One of potential and very efficient applications of high power ultrashort λ= 10 μm pulses is laser acceleration of charged particles. It was shown[1] that relative increase of electrons energy after interaction with laser field (averaged over electron bunch) is increased with laser radiation wavelength ~ λ^2. For the duration of laser pulse 10^{-11} s and its power 10^{12} W (laser pulse energy 10 J) the magnitude of accelerating gradient is ~ 1 GeV/m, that is substantially higher than for modern linear accelerators[2].

Another application is generation of high power and high repetition rate γ-beams by backward Compton scattering [3]. The γ-ray is planned to be applied to produce polarized positron beams for Japan Linear Collider (JLC). The temporal structure of e-beam of LINAC which is planned to be used in the experiments is a train of 85 bunches separated by period 1.4 ns. Train of the bunches comes every 6.7 ms corresponding to rep.rate 150 Hz. The estimated energy of the 10 μm laser pulse which will interact with every bunch in the train is 10 J (duration τ= 10 ps). In this case about 10^{10} positron/bunch will be produced necessary for electron-positron experiments in JLC. In order to avoid nonlinear effects under high-intensity interaction it is proposed to divide each 10 J pulse into forty 250 mJ portions . In such a case forty 10 μm pulse trains each consisting of 85 pulses of 250 mJ energy (total train energy ≈21 J) are needed for the experiment.

Therefore for mentioned above experiments on interaction of laser radiation with e-beams an energy of 10 **-** 20 J in 10 ps 10 μm laser pulse or pulse train is needed. 10 ps duration of laser pulse in these experiments is connected with the duration of electrons bunch to be accelerated. At the same time the bandwidth of the high-pressure (~10atm) CO_2 discharge unit (CO_2 – HPDU) which is the principal element of picosecond CO_2 laser system enables to amplify the pulses with duration ~1 ps. In this case an order of magnitude higher power of laser radiation can be achieved in the given laser system.

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To our opinion besides mentioned above and many other fundamental applications high power picosecond 10 μm laser system can find some commercial applications. Between them is development of laser based lightning protection system, mid infrared laser lidars, laser plasma based source of X-ray with controlled temporal and spectral structure for use in microelectronics or medicine etc. Search and development of such an applications is the significant goal of ISTC Project.

At present time the methods of 10 μm picosecond laser pulses generation are well developed and enable production of pulses with τ = 1 - 10 ps duration and 1 - 10 μJ energy [4-7]. In order to amplify these pulses up to energies ~ 10 J one have to utilize many-pass or regenerative amplification (RA) in CO_2 –HPDU with total gain exceeding 10^6 - 10^7 and gas pressure sufficient to provide necessary amplifier's gain bandwidth (≥ 10 atm for 9R or 10 R bands of CO_2 laser). The main factors determining maximum available energy of the amplified 10 μm laser pulse with duration 1 ÷10 ps are: aperture of the amplifier, saturation energy of typical high-pressure gas mixtures (~ 0.4 J/cm^2) , damage threshold of optical windows of the gas chamber (~ 0.7 J/cm^2)[8] and formation of electron density wave due to active medium avalanche ionization at very high intensities of radiation (~ 1 J/cm^2)[7]. Simple estimates show that in order to exceed 1 TW peak power in maximum pulse of the train (containing in our case ≈15% of the total energy) it is necessary to use CO_2 –HPDU with aperture d ≥ 3 cm for τ=1 ps and d ≥ 10 cm for τ=10 ps.

The picosecond CO_2 laser system with output laser beam aperture 4 cm, discharge volume of CO_2 -HPDU 5 x 5 x 55 cm^3 (a prototype of further 10 x 10 x 100 cm^3 CO_2 -HPDU) and short pulse duration 2 ÷ 100 ps (tunable) is under construction now in IOFRAN. The system is intended to generate a pulse train with peak power up to 1.5 TW with present CO_2-HPDU and up to 15 TW with new one. Present status of the set up and the prospective of its upgrade are discussed in given report.

2. LASER SYSTEM CONFIGURATION

The main components of laser system are:

1. 10 μm picosecond master oscillator (MO), which produces a picosecond laser pulse with duration τ_i = 2 ÷ 100 ps (smoothly tunable) and power P = 0.1 - 1 MW by means of choppping a short transient from the 100 ns, 30 mJ radiation pulse of compact TEA-CO_2 laser (method of chopping - semiconductor reflection/transmission switching[4-6]).
2. X-ray preionized CO_2 -HPDU developed and manufactured in NIIEFA under request of IOFRAN with 5 x 5 x 55 cm^3 discharge volume, 6 atm operational pressure and unstable telescopic resonator with aperture d= 4 cm, magnification M=2 and length L= 1.4 m to produce a train of picosecond laser pulses in RA regime.

The construction, principles of operation of MO as well as construction and parameters of CO_2-HPDU (for the case of 6 atm operation) were already reported[9]. The energy of laser radiation to the moment of publication[9] did not exceed 5 J and we were going to carry out the optimization of discharge pumping scheme in order to provide its better matching with the discharge. The results of this optimization will be discussed in the next section.

3. IMPROVEMENT OF CO_2-HPDU OPERATION.

3.1 Increase of preionization level.

In order to amplify 10 μm laser pulses as short as 2 ps it isnecessary to increase the pressure of the gas mixture in CO_2-HPDU up to 10 atm. To solve the problem we had to increase the concentration of initial electrons n_{e0} produced in the active medium of CO_2-HPDU by X-ray preionizer. To realize it we made two independent steps. First, we decreased the distance between the source of X-ray photons (the foil) and discharge gap anode from 13 to 7 cm (taking into account high divergence of X-ray radiation). Second, we increased to the maximum the accelerating voltage U_a on the e-beam vacuum diode (VD) (from 65 to 80 kV) since according to[10] in our case $n_{e0} \sim U_a^{4.2}$.

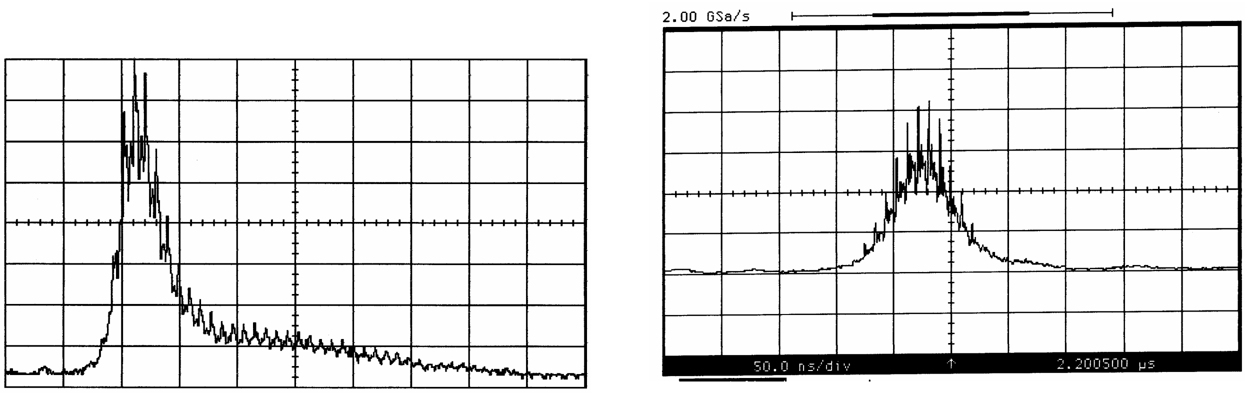
3.2 Optimization of CO_2-HPDU gas mixture for maximum radiation energy extraction.

After increasing of n_{e0} due to mentioned above procedures we considerably increased the stability of volume self-sustained discharge (VSSD) at the previously used[9] CO_2:N_2:He= 2:1:17 gas mix with low ionizing additive (tri-n-propilamine) and got the possibility to use more "hard" gas mixtures that is the mixtures with higher absolute pressure P_m of molecular gases (CO_2 and N_2). Attempts to increase absolute values of pressures of CO_2 and N_2 in the mixture P_{CO2} and P_{N2} while keeping constant $P_\Sigma = P_m + P_{He}$ = 6 atm gave quite different results. In this experiments we controlled not only the volt-ampere parameters of VSSD but also a laser radiation energy in free running mode with the same resonator as in [9].

We did not succeeded to increase P_{CO2} > 0.7 atm (P_{CO2} = 0.6 atm in initial CO_2:N_2:He=2:1:17 mix) with keeping high enough stability of VSSD. For P_{CO2}= 0.8 atm VSSD was very unstable, and practically we obtained very few "shots" without arcing after glow VSSD phase. There is an evident explanation of this - very high cross-section of electrons attachments to CO_2 molecules which probably even more severe for high pressure gas mixtures.

Absolute another picture took place for increase of P_{N2}. The stability of the VSSD was not changed when we increased P_{N2} value in few times, but due to energy transfer from N_2 to CO_2 free running mode energy also increased and reached its maximum 22.2 J for the mixture CO_2:N_2:He= 12:21:67. Such energy corresponds to specific energy extraction 5.4 J/l/atm.. Scaling of radiation energy to full available for radiation area give us laser efficiency η= 4.5 % (relative to the energy ≈ 980 J stored in the capacitors of VSSD pumping generator, PG). Experiments with increasing of P_{N2} value while keeping P_{CO2} = 0.7 atm had shown that an optimum ratio of N_2 and CO_2 in the mix for maximum energy extraction is P_{N2}/P_{CO2} = 1.7 ÷2.5. For higher P_{N2}/P_{CO2} ratios some kind of $N_2 \rightarrow CO_2$ energy transfer saturation may take place.

It is interesting to note that using of mixtures with such relatively high ratio of P_{N2}/P_{CO2} did not cause dramatic growth of the "tail" of laser radiation pulse typical for TEA-CO_2 lasers. The tail was totally absent for initial CO_2:N_2:He=2:1:17 mix while its energy did not exceed 30% of the total pulse energy for the mixtures with P_{N2}/P_{CO2} = 2 ÷2.5 (see Fig.1). It is also seen from the figure that in the case $P_{N2}/P_{CO2} \approx$ 2.4 the duration of pulse was shorter than for P_{N2}/P_{CO2}= 0.5 mixture (35 ns FWHM instead of 50 ns). It means that unlike the case of atmospheric pressure TEA-CO_2 -lasers for high pressure lasers nitrogen transfers the main part of stored energy to CO_2 during first gain switched spike of laser radiation. Dumping of "tail" can be also explained by the decrease of the gain lifetime in the active medium with gas mixture pressure as ~$1/P_\Sigma$. As a result in our case we increased more than in 4 times not only the energy but also a peak power of radiation. It is very promising result from the point of view of getting maximum peak power in the train necessary for generation of hard X-ray photons and high-amplitude currents in laser plasma[11,12].



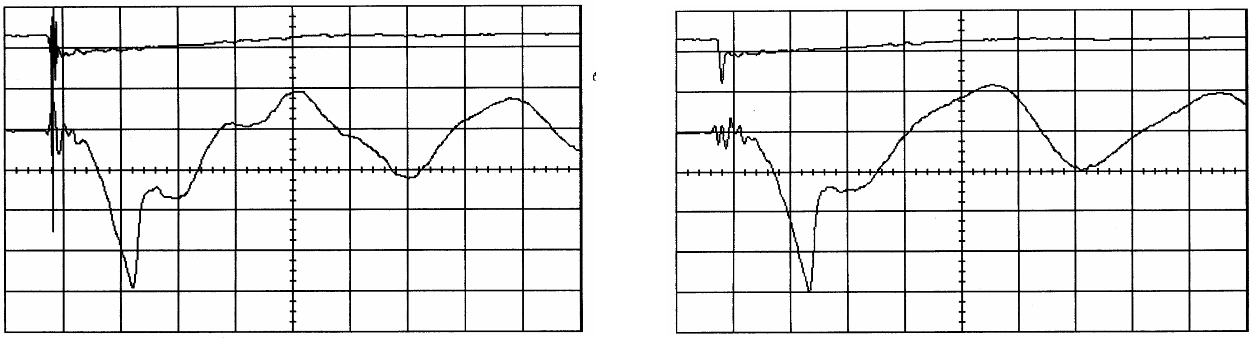
(a) (b)

Fig.1 Oscillograms of free-running mode radiation pulses for mixtures CO_2:N_2:He = 12:28:60 (a) and CO_2:N_2:He = 10:5:85 (b). Total mixture pressure 6 atm. Horizontal scale - 50 ns/div.

3.3 Optimization of VSSD pumping scheme parameters.

3.3.1.The value of separating inductance.

During experiments on optimization of the gas mixture to get the maximum radiation energy we also varied the inductance L_1 which separated 8 -stage Fitch-Gowell generator and low inductance "fast" capacitance located maximally close to the discharge chamber(DC)[9]. Initially L_1 was 9.5 µH and energy 3.5 J on CO_2:N_2:He= 10:5:85 gas mix was obtained with this L_1 value. It turned out that increase of L_1 value lead to some increase of E_l for fixed value of PG charging voltage U_{ch}. The oscilloscope traces of the voltage on the discharge gap $U_g(t)$ for U_{ch} = 60 kV, two values of L_1 and the mixture CO_2:N_2:He= 10:10:80 are shown on Fig.2. It is seen from Fig.2 that increase of L_1 in 3 times did not influence the front of U_g (t) as well as the breakdown voltage. Nevertheless, in the case L_1= 32μH this inductance in higher degree prevents the energy stored in the "fast" capacitance to go back into Fitch-Govell generator. It is illustrated in Fig.2 by the increase of both the duration of quasistationary phase of $U_g(t)$ and total VSSD current duration (interval between the breakdown point and the point where $U_g(t)$ crosses zero line). As a result E_l value increased from 5.5 to 9.5 J. The effect of L_1 increase on E_l is stronger for lower values of U_{ch}. For more "hard" mixtures further increase of L_1 was shown to be efficient. Maximum E_l value 22.2 J was obtained with L_1= 68 μH and U_{ch} = 70 kV on the mixture CO_2:N_2:He= 12:21:67.



(a) (b)

Fig.2. Oscillograms of voltage on the discharge gap $U_g(t)$ (lower traces) for two values of "separating" inductance L_1: 9.5 μH (a) and 32 μH (b). Upper traces are voltage on the vacuum diode $U_{VD}(t)$. Horizontal scale - 1 μs/div.

3.3.2 The delay between X-ray preionization pulse and VSSD start.

Previously in[9] laser system operated with simultaneous triggering of the discharge gaps in PG and generator of pulsed voltages of VD. Such situation is illustrated on Fig.2. However when going to more "hard" mixtures it was established that VSSD stability increases when generator of pulsed voltages of VD was triggered with some delay to PG. This optimal delay value Δt_{VD} (or the range of its variation) depended on the mixture and U_{ch} value. For L_1 =68 μH the duration of $U_g(t)$ front was T_{fr} = 2 ÷ 2.3 μs (depending on mentioned above parameters) and Δt_{VD} was 0.6 ÷ 1.4 μs. The width of the Δt_{VD} range decreased almost to zero when we tried to obtain VSSD at the mixtures with P_{CO2}= 0.8 atm.

While varying Δt_{VD} value we had revealed very interesting fact: when T_{fr} - Δt_{VD} was less than some minimum value (it depended on L_1 and gas mixture, for example 300 ns for L_1 = 32 μH and CO_2:N_2:He= 10:10:80 mix) there were no glow VSSD phase at all (arcing took place just after gas breakdown). This fact corresponds to earlier obtained results on utilization of low-ionization additions in TEA-CO_2 lasers and is connected with significantly higher lifetime of initial photoplasma produced by ionization of organic additives than that produced by ionization of working mix components[13]. Therefore in our case due to the fact that photoplasma recombination rate is much lower that the rate of electrons production by X-ray ionization of tri-n-propylamine we have some kind of accumulation of electrons produced by ionization source.

It is well known that besides production of initial electrons in the discharge gap tri-n-propylamine stabilizes VSSD through depopulation of metastable levels of N_2 responsible for formation of VSSD contraction channels. Another and also very significant roles are: ionization of N_2 molecules via collisions with tri-n-propylamine molecules through Penning ionization process and decrease of E/P_Σ parameter in VSSD causing optimization of electrons energies distribution function for more efficient pumping of laser levels[14]. It is Penning ionization that can explain the fact that at transition from P_{N2}/P_{CO2} = 0.5 to P_{N2}/P_{CO2} = 3.6 mixture (the most "hard" mixture in the experiments with P_{N2} = 2.55 atm and P_m/P_Σ = 54%) the breakdown voltage of the gas mixture increased only twice.

4. PROSPECTIVE OF PICOSECOND CO_2 LASER SYSTEM UPGRADE.

As a first step to 10 atm CO_2-HPDU operation we tried to obtain stable VSSD at P_Σ >6 atm. The measurements were carried out in a condensed version at fixed values of some parameters: 1) energy stored in the PG = 720 J; 2) P_{CO2} = 0.5 atm; P_{N2} = 1.0 atm. As a result we succeeded to obtain VSSD at the mixtures with P_Σ up to 9 atm. At P_Σ =9 atm P_m/P_Σ was 16.7% and W= 57 J/l/atm. In such version of experiment where $W \sim 1/P_\Sigma$ we did not detected any deterioration of VSSD with growth of P_Σ. We did not try to increase P_Σ over 9 atm due to:1) sharp growth of the rate of gas mixture outlet from DC; 2) the fact that earlier at hydraulic tests of DC we observed few times the damage of Al foil at P = 11 – 12 atm.

At present time the new dielectric tube for DC of CO_2-HPDU is manufacturing which will have hermetic enclosure for $P_\Sigma \leq 15$ atm. After new tube manufacturing and reassembling of DC we plan to carry out investigations of possibility to increase the thickness of Al foil used up to 100 – 250 μm in order to make the VSSD investigations at $P_\Sigma \sim 10$ atm more safe.

In conclusion we look with optimism on getting 10 atm VSSD in our CO_2-HPDU but the concrete gas mixture will be determined only in experiments. In such a mixture we'll be able to regeneratively amplify laser pulses with wavelength corresponding to the top of CO_2 molecule 10R band (10.27 μm) and duration down to $\tau \approx 2$ ps. We will not be able to use 9R band of CO_2 laser due to substantial absorption of ≈ 9.3 μm radiation by the tri-n-propylamine.

Let's estimate the expected peak power of the train of 2 ps pulses which we are going to obtain. The temporal structure of free-running mode radiation pulse shown at Fig.1a may be differed by adding 4 atm of He to present gas mixture due to probable dumping of the pulse "tail" at further decrease of small signal gain lifetime with P_Σ. Therefore the expected radiation energy may be about 0.7 x 22 J ≈ 15 J. Our investigations of the temporal structure of the pulse train for $\tau = 200 \div 300$ ps [9] had shown that its envelope well correspond to free-running mode pulse. We can propose that for $\tau = 2$ ps this envelope will not be strongly changed since in both cases $\tau = 200$ and $\tau = 2$ ps the saturation energy densities of the gain medium are close to each other. It means that percentage of energy in the train's maximum pulse will be determined only by duration T_{gen} of free-running mode pulse (FWHM) and $\Delta T = 2L/c$ parameter. For our case $T_{gen} \approx 35$ ns and $\Delta T = 9.3$ ns this percentage may reach 20%. Therefore the expected energy of the maximum train's pulse may be $E_m \approx 3$ J corresponding to train's peak power $P_m \approx 1.5$ TW.

Further increase of E_m and P_m values (approximately on an order of magnitude) may become possible after manufacturing and putting into operation the new 10 x 10 x 100 cm^3 discharge volume CO_2-HPDU which is under construction now in NIIEFA in the network of ISTC Project #1072 (its putting into operation at IOFRAN test bench is planned at the end of 2001). The detailed discussion of the construction of this CO_2-HPDU exceeds the bounds of present report. Briefly, the main features and differences of the new unit relative to present one (except the discharge volume) are:

1. stainless steel body of the DC;
2. low inductance "fast" capacitance in the scheme of PG is an element of DC construction filled with deionized water: such an approach enables to realize minimum possible inductance of the discharge circuit (~ 200 nH) for given discharge volume and to provide the duration of energy input into discharge ~ 200 ns what is quite close to this parameter value of present CO_2-HPDU despite ~ 8 times higher discharge volume of the new unit;
3. the constructive features of the X-ray preionizer enable to realize two modes of its operation:
   - traditional one now used in the present CO_2-HPDU with $U_a = 70 \div 80$ kV, duration of current pulse of a few μs and utilization of $50 \div 100$ μm thick Al foil;
   - nontraditional mode with $U_a = 40$ kV, duration of current pulse ~ 100 ns and utilization of thin ($6 \div 10$μm) foils from materials with high atomic weight, such as Ta, Au etc.

The main idea of the second variant is to use more soft part of the spectrum of X-ray (which is much more efficient for ionization of work gas mix) and to increase to the maximum the current of VD and correspondingly the X-ray flux. This variant may turn out to be more efficient when using gas mixtures without low ionizing organic additives where the mechanism of initial electrons accumulation discussed above will not work.

It will be very interesting to compare the volt-ampere and optical parameters of both CO_2 –HPDU in order to make a conclusions about possibility to scale CO_2-HPDU parameters with active volume (one of the goals of ISTC #1072 Project).

5. CONCLUSIONS.

1. Due to substantial increase of X-ray flux in the discharge volume of CO_2-HPDU we succeeded to dramatically increase percentage of molecular gases in 6 atm mixture (from 15 up to 54%) and free running mode radiation energy (from 5 to 22.2 J). The specific energy extraction reached 5.4 J/l/atm and laser efficiency (relative to the energy stored in the capacitors) reached 4.5%.
2. The optimal range of N_2 and CO_2 partial pressures ratio $P_{N2}/P_{CO2} = 1.7 - 2.5$ was determined which correspond to maximum extraction of radiation energy from CO_2 -HPDU when operating with unstable telescopic resonator.

3. The value of inductance separating Fitch-Gowell generator and "fast" capacitance located close to the DC can be optimized for maximum loading of energy to the discharge volume for given gas mixture and PG charging voltage.

4. Due to substantial more fast $N_2 \rightarrow CO_2$ energy transfer for $P_\Sigma = 6$ atm CO_2 -HPDU relative to TEA-CO_2 lasers increase of P_{N2}/P_{CO2} in the 6 atm mixture from 0.5 to 2.5 did not cause dramatic growth of the "tail" of laser pulse. It means that peak power of laser radiation in our case increased with P_{N2}/P_{CO2}. Moreover relative increase of peak power was close to that of laser radiation energy due to some shortening of laser pulse FWHM.

5. It was revealed that effect of accumulation of initial electrons produced by X-ray preionizer can take place. This effect is more pronounced at the mixtures with high relative concentration of molecular gases. Such accumulation can be associated with the features of photoplasma produced by X-ray ionization of tri-n-propylamine.

6. We have a real prospective to obtain VSSD in our present CO_2-HPDU configuration on 10 atm gas mixture with reasonably high P_m/P_Σ value. The expected peak power of the train of 2 ps pulses obtained in RA regime in CO_2-HPDU with such a mixture is 1.5 TW. As a first step to realization of such a prospective a stable VSSD was obtained at 9 atm 16.7% molecular gases concentration gas mixture and a relatively low specific energy loading density 57 J/l/atm.

7. About an order of magnitude increase of 10 μm 2 ps laser pulse peak power (up to 15 TW) may become possible after putting into operation a new unique 10 l active volume 10 atm CO_2-HPDU now being under construction in the network of ISTC Project #1072.

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