# Final EDP Ti: Sapphire Amplifiers for ELI Project

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## Introduction:

Recently several ultrahigh intensity Chirped Pulse Amplification (CPA) laser systems have reached petawatt output powers [1, 2] setting the next milestone at tens or even hundreds petawatts for the next three to ten years [3, 4]. These remarkable results were reached when laser amplifiers (opposite to Optical Parametric Amplification (OPA) [5]) were used as final ones and from them Ti:Sapphire crystals supposed to be the working horses as well in the future design of these laser systems. Nevertheless, the main limitation that arises on the path toward ultrahigh output power and intensity is the restriction on the pumping and extraction energy imposed by Transverse Amplified Spontaneous Emission (TASE) [6] and/or transverse parasitic generation (TPG) [7] within the large aperture of the disc-shape amplifier volume.

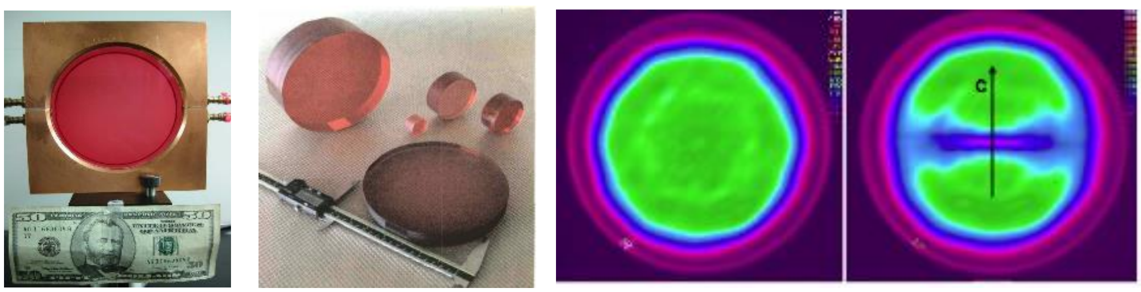

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Fig. 1 **Large aperture Ti: sapphire amplifiers:** a- University of Michigan Hercules laser system's final amplifier (diameter -12 cm) [8] b - Cristal System – 20 cm [9] c – LASERIX laser – parasitic lasing in final amplifier [1]

**TPG is a one of main limitations of output energy.**
The conventional preventive procedure against parasitic generation is to reduce the reflectivity of the side wall of the gain crystals by coating them with an index-matched absorptive polymer layer or liquids. However, the difficulty to introduce exact index matching restricts the diameter of the pump area by few centimeters.

**Two transverse parasitic modes**

Two transverse parasitic modes mainly are developing in the disc-shape amplifier: 1- the generation near two working parallel surfaces due to the maximal population inversion [7] and 2 - the z-pass between these surfaces due to total internal reflection [10]. The latter surpasses the former in large aperture crystals with a high aspect ratio and respectively low crystal doping. The pump fluence is defined for each value of the critical for parasitic generation transverse gain or index matching of the absorber and crystal thickness, so that a crystal with a given aperture fixes the maximum pump fluence. Therefore the product of the crystal diameter and the pump fluence is constant. The product of the pump fluence and the diameter of the pump area of the crystal can be explicitly written as:

$$D \times F_p = K \qquad K = \frac{\gamma_p}{\gamma_{em}} \times \ln G_{pt} \times \frac{zF_s}{n} \text{ for z−pass;} \qquad K = \frac{\nu_p}{\nu_{em}} \times \ln G_{pt} \times \frac{zF_s}{\ln B} \text{ for gain near surface;} \quad (1)$$

where D is the pump area diameter, $G_{pt}$ is the highest transverse gain that would be compensated by an index-matched absorptive coating, z is the crystal thickness, n is the index of refraction of the crystal, $\nu_{em}$ is the emission

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frequency, $v_p$ is the pump frequency, and B is the absorption coefficient for the pump frequency. Further enlargement of the crystal aperture requires reducing the pump fluence. Moreover, because the complete matching is impossible for both polarizations of the transverse modes, the pump fluence will be limited for any crystals and absorbers. In Fig. 2 curves showing the dependence of the pump fluence on the crystal diameter are presented. The purple rhombus-marked curve is an upper bound for 3 cm crystal thickness and was calculated for σ- polarization under the condition of total index matching for π- polarization.

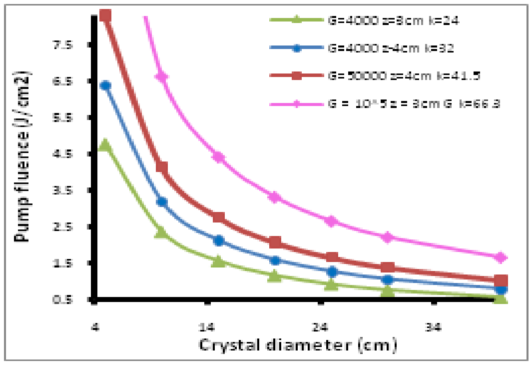


**Fig. 2** dependence of the pump fluence on the crystal diameter for different K-factors ( K=24 – green triangles, K=32 – blue circles, K=42 – brown squares, K=66 boundary curve – purple rhombs)

As one can see from the figure the enlargement of the crystal aperture requires reducing the pump fluence. For example, the maximum pump fluence for the most popular liquid absorber and crystal thickness 4 cm (K=32, blue circles curve) is equal only 0.5-0.7 J/cm$^2$ per crystal side with diameter 15-20 cm, which demonstrates the inefficient amplifier operation.

**TASE is the more strong limitation of the output energy.**

In [6] it was demonstrated that TASE, when losses associated with one pass ASE, places an additional restriction on storing and extracting energy in larger gain apertures. This restriction is even stronger than parasitic lasing because the threshold for the latter can be increased with the development of the new index matching materials for absorbers, while TASE necessarily increases with the aperture size, limiting the maximum stored energy

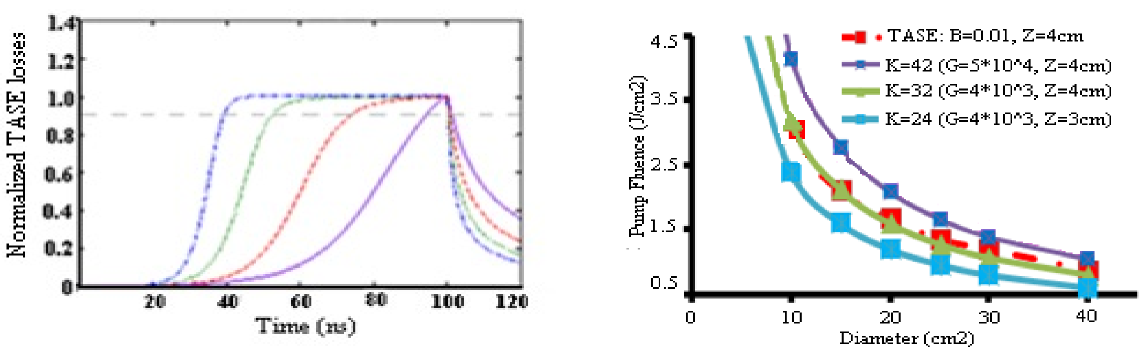


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**Fig. 3** a - evolution of normalized fluorescence of the crystals vs. pumping time for different crystal apertures D: blue-dash-doted curve D=20 cm ($E_{max}$=824 J, $E_{loss}$=590 J), green-dots D=15cm ($E_{max}$=460 J, $E_{loss}$=290 J), red-dashes D=10cm ($E_{max}$=210 J, $E_{loss}$=100 J), and violet-solid D=6 cm ($E_{max}$=74 J, $E_{loss}$=20 J); b - dependence of pump flux on crystal diameter: Solid curves – calculated for. TPG (K=24 - light blue squares, K=32 - green triangles, K=42 - blue squares); dashed curves – calculated for TASE (red squares – B=0.01

Fig. 3a shows the evolution of the gain volume's normalized fluorescence to its maximal value as a function of pumping time for a 100 ns pump pulse given different gain apertures. Here $E_{max}$ is the theoretical maximum of the extracted energy, and $E_{loss}$ the lost energy due TASE. As seen in the plot, ASE grows dramatically after a certain time of pumping (even for a 10 cm gain aperture) and soon approaches the pump energy (flat part of the curves). This means that with further pumping all additional energy will be radiated out of the crystal as ASE. These critical points of "Anomalous" ASE (APs) advance to the beginning of the pumping process with increasing gain diameter. Under these conditions, no more than 30% of the pump energy can be stored in a 20 cm crystal.

From another perspective, we can build the same dependences for the TASE limitation based on the APs (Fig. 3a, crosses with gray dashed line indicating 0.9 of the maximum volume). As seen in the Fig. 3b, the TASE curve for crystals with B=0.01 nearly match the TGP curve with K value of 32. These value correspond to existing absorbers. The main conclusion to be drawn from this correspondence is that there remains no motivation to develop better absorber materials, owing to restrictions of TASE.

According to this discussion we have to conclude that the situation for regular laser amplifiers with large apertures appears bleak, especially with respect to their application as final amplifiers in very high power laser systems.

**Extraction During Pumping (EDP)**

As one can see from the above discussion, suppression of the TASE and TPG is a very important task that has to be solved for the next generation of ultrahigh power laser systems. Most promising solution for this is EDP technology. It was demonstrated that the parasitic losses due to the both TASE and TPG can be significantly reduced using EDP [6, 11, 12].

The conventional amplification process is based on the full energy stored in the upper laser level prior to arrival of the input signal. Nevertheless, as demonstrated above, only limited portion of the energy is able to be stored in the amplifiers with large aperture. It was suggested to change the method of pumping and amplification in the multi-pass laser amplifiers. Pumping only part of the energy before arrival of the input signal and keeping the pumping further after arrival of the amplified pulse we are able to overcome the parasitic lasing limitation as well as the losses connected with TASE. In the other words, the energy extracted during one pass of the amplified pulse through the crystal could be restored by pumping to the parasitic lasing threshold before the next pass.

**Optimization of the EDP Multi-pass Amplifiers [12]**

In the paper [12] optimization of this EDP-technology for presently available large aperture Ti:Sapphire amplifiers was suggested. Frantz–Nodvik solution for the 1-D photon transport equation [13] is broadly applied to describe amplified transmission of pulses through the multi-pass amplifiers. But, in contrast to conventional amplifiers, where this equation is applied iteratively with adjustment of small signal gain for each pass, the solution for EDP amplifiers can be rewritten as a single equation:

$$F_{out} = F_s \ln\left\{1 + \left[\exp\left(\frac{F_{in}}{F_s}\right) - 1\right] \exp\left(N \frac{\nu_{em}}{\nu_p} \frac{F_p}{F_s}\right)\right\} \quad (2)$$

where N is the number of passes, $\gamma_{em}$ is the emission frequency, $\gamma_p$ is the pump frequency, $F_{out}$ is the N-pass output fluence, $F_s$ is the saturation fluence, $F_{in}$ is the incident fluence, $F_p$ is the initial pump fluence (before signal arrives). The main difference between the EDP and the common multi-pass amplification is the restoration of the population inversion, and hence of the small signal gain, for each pass. Therefore to get the output flux after N-passes of amplification we simply introduce a factor of N into the small signal gain expression.

The results of the output fluence calculations for 4-pass amplification with EDP and with conventional amplification for various pump fluences are presented in Fig.4. From this graph one can draw several important conclusions. One of them - the EDP amplifiers possess the ability to produce significantly more energy (up to four times for 4- pass amplifiers) compared to regular ones with the same initial pump fluence, another, that the input fluence for amplification with EDP has to be much higher to make it efficient then that for the regular case. This is clear from comparison of the two green or two blue curves in Fig.4. The process of amplification mimics the case of a high value of the saturation flux ($F_s$), which pushing further theoretical Laser Intensity Limit.

Note that a four-fold increase in the value of the coefficient of small signal gain does not result in a commensurate increase in the total required pump fluence because we only need to replenish the deficit in the population inversion after each pass. It can be demonstrated also that the efficiency of EDP amplifiers is only a few percent lower than that of conventional ones but the problem is that conventional amplifier is not able to be operated at the same initial pump fluence due to parasitic generation.

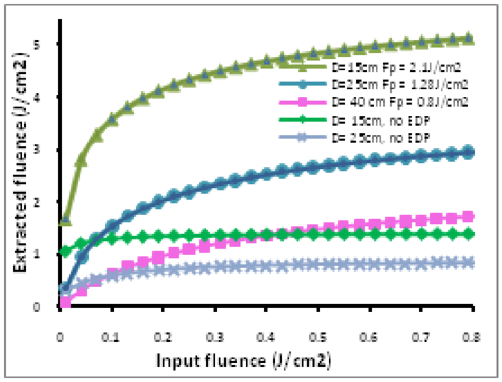


**Fig. 4 EDP vs. Conventional amplifier** -dependence the output flux of the 4-pass amplifier on the input one for several pump fluxes ($F_p = 2$ J/cm$^2$ - two green curves, triangles – EDP amplifier, rhombs – no EDP; $F_p = 1.3$ J/cm$^2$ – two blue curves, circles - EDP amplifier, crosses – no EDP; $F_p = 0.8$ J/cm$^2$ EDP-amplifier – purple squares.

From Fig. 2 and 3 b one can conclude that further, enlargement of the crystal aperture requires reducing the initial pump fluence as well and as result the existence of the optimal crystal diameter. The existence of an optimal diameter for the pump area of the EDP-amplifiers can be demonstrated by introducing into Frantz–Nodvik EDP-formula (2) in place of $F_{in}$ and $F_p$, the ratios $E_{in}$ /A and K/D, respectively

$$F_{out} = F_S \ln\left\{1 + \left[\exp\left(\frac{4E_{in}}{\pi D^2 F_S}\right) - 1\right]\exp\left(N\frac{\nu_{em}}{\nu_p}\frac{K}{DF_S}\right)\right\}$$

where $E_{in}$ is the total incident energy, A is the pump area and K – from formula (1). The relationship between the output energy and the diameter of the pump area, for different K-factor values and incident energies, is presented in Fig. 5. The area on the left of the red dashed line lies above the output fluence damage threshold.

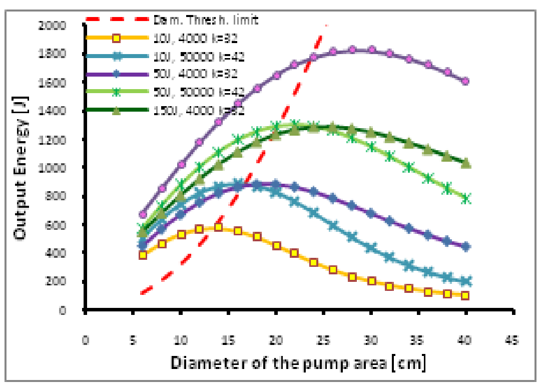


**Fig. 5 Optimal aperture of the EDP- amplifiers.** Dependence the output energy on diameter of pumped area for different input energy and K-factor (10 J input energy – K=32 yellow squares, K=42 blue crosses; 50 J – K=32 blue rhombs, K=42 green asterisks, 150 J – K=32 green triangles, K=42purple circles); dashed red curve – damage threshold flux.

As an example, for a practically available liquid absorber [1] and a crystal with 20 to 25 cm diameter [9], we can calculate the highest output energy for amplification with EDP. The maximum transverse gain this absorber is able to accommodate is 4000, which leads to a value of K=32. From the blue rhombus curve in Fig. 5, we find the output energy of ~800 J, which corresponds to 50 J input energy. Therefore, this discussion demonstrate that amplification with EDP, when operated under optimal conditions, is capable of increasing the extracted energy by up to four times with good efficiency, as compared with conventional amplification of the same initial pump fluence. The existence of an optimal pump aperture for each given index-matched absorber and incident energy was shown. With available index-matched liquid absorbers and large aperture Ti:Sapphire crystals, it is possible to approach kJ level extracted energy by exploiting EDP.

**EDP – experimental results**

The EDP-technology was successfully spread out in the many world class laboratory for application in the ultra-high power laser systems, demonstrated today's world record 2.0 PW output power and here we will exhibit several examples. First time it was used in the 4-pass amplifier of **the HERCULES-300 TW Laser** [8]. Crystal of 4-pass amplifier was cryogenically cooled to 120K to avoid wave-front thermodistortion of the output beam. Cladding of the side surface was prevented because amplifier crystal was located in the vacuum chamber due to avoid surface deposition. Application of EDP increased extracted flux from 0.6 to 1.2 J/cm² [11].

**LASERIX- 4-pass EDP – amplifier [1].** Following [11] the authors have successfully developed a high-energy, high-repetition rate Ti:Sapphire laser system that delivers 33 J before compression at 0.1 Hz. The final booster amplifier was based on a 100 mm diameter Ti:Sapphire crystal (pumped area – 60 mm), pumped with 72 J of energy delivered by frequency-doubled high-repetition rate Nd:Glass lasers. To increase the pump energy staying below TPG threshold, they had seeded the output pulse of 2 J from the front end in the booster amplifier before the end of the pumping pulse. The best temporal delay for efficient amplification with the parameters of that system was in seeding the booster amplifier 20 ns before the maximum of the overall population inversion considering a pump duration of 30 ns FWHM. The system was initially designed to produce 40 J of energy at 800 nm when pumped by 100 J of pump energy, assuming a reasonable 40% extraction efficiency. The good amplification efficiency of 45% with a homogeneous flat-top spatial amplified intensity profile was finally obtained.

The EDP-method has also been applied on several Ti:Sapphire booster amplifiers of petawatt scale, and has allowed output energies in excess of 72 J with the current record power of 2 PW from a single channel [8, 20].

**APRI- South Korea 1.5 PW CPA – laser, 3-pass EDP-amplifier [2]** The team of laser developers reported about the generation of 1.0 PW/30 fs laser pulses at a 0.1 Hz repetition rate from a chirped-pulse amplification Ti:Sapphire laser system. Exploiting the EDP-technology suggested in [11] and developed in [1] the parasitic lasing in final three-pass booster amplifier was suppressed by using an index-matching fluid with an absorption dye and the accurate control of the time delay between the pump and IR pulses. The seed pulse was amplified in the preamplifier and the two power amplifiers such that its energy reached 4.5 J. Before being injected into the final booster amplifier, the amplified laser pulses was upcollimated to a 60 mm diameter optical aperture. The booster amplifier, having a large-aperture Ti:Sapphire crystal with a thickness of 25 mm and an absorption coefficient of 1.2 $cm^{-1}$ had the amplification efficiency limited by TPG. When the Ti:Sapphire crystal was pumped by green laser pulses at an energy of 96 J at 0.1 Hz, the maximum energy of the amplified laser pulse using EDP reached 47 J, giving an amplification efficiency of 44%. Later laser was upgraded up to 1.5 PW by another EDP-amplifier with the maximum output energy of 60.2 J at a pump energy of 120 J.

**Shanghai Institute of Optics and Fine Mechanics, Chinese 2 PW CPA – laser, 4-pass EDP-amplifier [14].** It was demonstrated a 2.0 PW at 800 nm based on the scheme of chirped pulse EDP-amplification using Ti:Sapphire crystals, which is the highest peak power achieved today from a femtosecond laser system. Basing on the EDP-technology developed in [11, 1, 2] and optimized in [12] the authors effectively suppressed the parasitic lasing in the final booster amplifier combining the index-matching cladding technique and the precise control of the time delay between the input seed pulse of 6.5 J and pump pulses of 140 J. The maximum output energy from the final amplifier was 72.6 J, corresponding to a conversion efficiency of 47.2% from the pump energy to the output laser energy. The seed beam was expanded to 82 mm with a uniform profile and is injected to the final four-pass booster amplifier. The Ti:Sapphire crystal with 100 mm in diameter and 30 mm in thickness was used in the final amplifier. The time interval from the seed pulse of the first pass to the front edge of the pump pulse was defined as the time delay. The maximum amplified output energy of 72.6 J was obtained at a time delay of 22 ns. In [12] the simulation for optimal EDP with similar condition was made and ability to reach 90-95 J of the output energy was demonstrated due to requirements of the increasing input fluence up to 0.2 $J/cm^2$. The authors came to the similar tendency in their estimation of the optimal regime. In this case, the optimal time delay for the seed injection of 10 J was 18 ns and output energy was growing up to 81 J.

## EDP –amplifiers for ELI

Extreme Light Infrastructure (ELI) is the ambitious pan-European laser research project. The major mission of the ELI facility is to make a wide range of cutting-edge ultrafast light sources available to the international scientific community. The first purpose of the facilities is to design, develop and build ultra-high-power lasers with focusable intensities and average powers reaching far beyond the existing laser systems. The laser science and technology developments in the facilities will pave the way to intensities above the ultra-relativistic regime. The secondary purpose is to contribute to the scientific and technological development towards generating 200 PW pulses, being the ultimate goal of the ELI project. Between the others EDP technology is looking most promising for reaching these incredible output energy and power.

In the three pillars of ELI, several PW-class lasers have been planned to build. HF PW laser of ELI-ALPS and the L2 laser of the ELI-BEAMLINES with 2 PW peak power, 10 Hz repetition rates and <20 fs pulse duration, while the L4 of the ELI-BEAMLINES as well as the ELI-NP lasers aiming at 300 J / 10 PW lasers. The 200 PW laser facility is on the roadmap of the ELI consortium. ELI will increase the available laser power by at least one order of magnitude in its first three pillars, and by another order of magnitude in its fourth ultra-high-intensity pillar. The establishment of ELI s fourth pillar, planned to push the frontiers of laser power into the sub-exawatt regime.

**ELI-ALPS**

The facility is based on three main ultrashort pulse lasers with duration of a few light periods only, driving a wide range of secondary sources. The laser beam lines will operate in different regimes of repetition rate and peak power. All three primary sources, the high repetition rate (HR), the single cycle system (SYLOS), and the high field laser (HF) will deliver pulses with unique parameters: extreme broad bandwidths, sub-cycle phase control of the generated fields, and as high repetition rate as possible for a given peak power (Fig. 6 a). The high intensity chains (SYLOS and HF) are based on a double-chirped pulse amplification (DCPA) architecture featuring nonlinear XPW filtering and extremely broad pulse bandwidths at high energies which ensures both ultrashort pulse operation and ultra-high temporal contrast. The current Ti:Sapphire technology in combination with modern cooling technologies applied to high average power pump lasers can support the basic requirements of the ELI-ALPS High Field system.

The simulation and optimization of the main parameters for the ELI-ALPS HF final amplifier were made using the methods developed in [6 and12]. It was shown, as the material for cladding of side surface can be used the liquid absorber compensated the transverse gain as large as 4000 and the diameter of the pump area and the crystal are 8 and 9 cm, the output energy is able to achieve 95 J with the pump and input energy – 170 and 10 J respectively. The dependence of calculated TASE losses for this crystal with thickness of 3cm (purple) and 2cm (blue) measured from the moment of the pump arrival are presented in the Fig. 6 b. As visible the losses for the EDP-amplifier can be reduced to less than 10% (compare the green curve with the blue one).

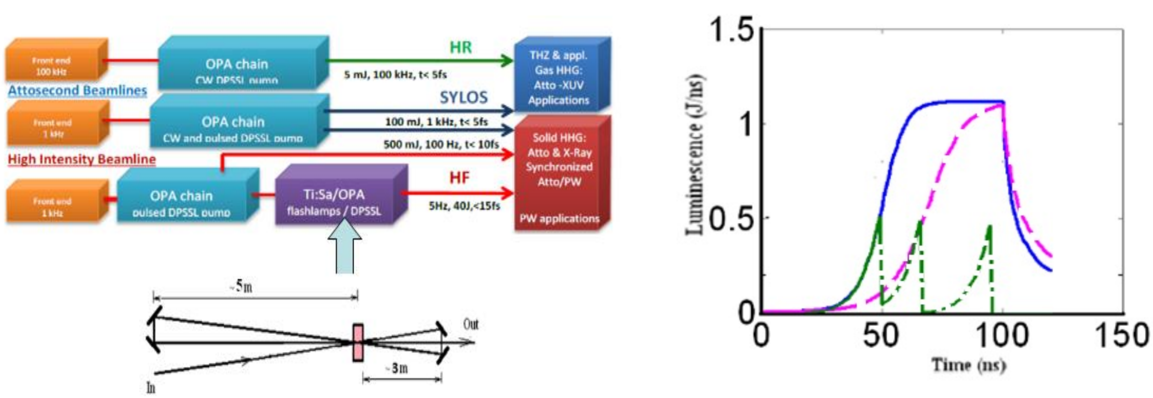


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**Fig.6** a- three pass EDP amplifier as a final amplifier of the ELI-ALPS High Field line; b- dependence of TASE losses for crystal with thickness of 3cm (purple-dashed) and 2cm (blue-solid) and for the EDP-amplifier (green dash-doted curve).

As seen from the curve, the delay between passes 1 and 2 is about 20ns and 2 and 3 – 30 ns, this leads to the construction of amplifier with shoulders 3 and 5 m and with the angle between passes 2 degrees. Three pass EDP amplifier with crystal thickness of 2cm is presented on the Fig. 6 a. The shoulders could be reduced with reduced pump pulse duration.

**ELI-BEAMLINES and ELI-NP**

The ELI-Beamlines will be a modern, cutting-edge laser facility enabling many research and application projects involving interaction of light with matter at intensities that are more than 100 times greater than the values achieved at present. ELI-Beamlines will be delivering ultrashort laser pulses lasting typically a few femtoseconds (10−15 s) and is upgradeable to attain peak intensities of up to 200 PW. The beamline power amplifiers supposed to be based on the OPCPA technique, driven by repetition rate diode pumped solid-state lasers (DPSSL) at a frequency of 10 Hz. Nevertheless, at this moment even few hundred TW output power was not demonstrated with OPCPA-technology, so the fallback solution for the beamline power amplifiers will be Ti:Sapphire technology using as pump systems conventional Nd:YAG flash lamp lasers or DPSSL.

For the ELI-NP facility a very high intensity laser beam are planned where two multi-PW lasers are coherently added to the high intensity of $10^{23}$–$10^{24}$ W/cm$^2$ or electrical fields of $10^{15}$ V/m. The core of the facility is a laser system using Ti:Sapphire technology. The conceptual design will use OPCPA technology at the front-end and Ti:Sapphire high-energy amplification stages. The laser pulses are amplified in the amplification chains to energies of the order of 200-300 J.

As our estimations demonstrate the EDP-technology is able significantly increase these output energy and intensity. The calculated optimal output parameters of ELI-BEAMLINES and ELI-NP final amplifiers for Ti:Sapphire crystals available now [9] are: the diameter of the pump area and crystal - 19 and 20 cm, the pump energy – 960 J, the input and the output energy – 60 and 600 J. The losses with the EDP technology can be made under 5% (Fig. 7).

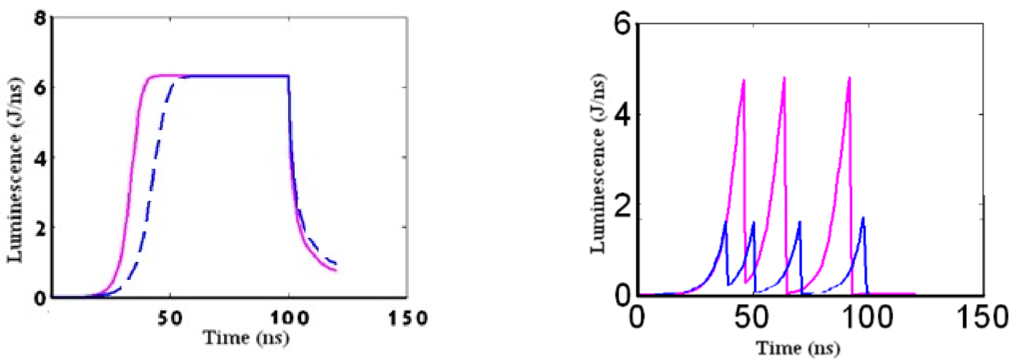


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**Fig. 7** Dependences of losses for 4 (blue-dashed curve) and 3 cm (pink-solid curve) thickness of the crystal: a- conventional amplifier; b- EDP-amplifier

As seen from the Fig. 7 a, the total losses for 4 cm thickness of the crystal is about 70% and for 3 cm – 80% and significant gross begins from 30 and 20 ns of the pump respectively. Dependences of losses for optimal extraction of the 3- pass and 4-pass EDP amplifier with the crystal thickness of 4 cm are demonstrated one the Fig. 7 b. The amplifier similar to the ELI-ALPS could serve as a seed one. As in first case for 3-pass, the delay between passes 1 and 2 is about 20 ns and 2 and 3 – 30 ns, so the construction of the amplifier will be the similar to Fig.8 a, whereas the scheme with delays between passes of the 4-pass amplifier (15, 20, 30 ns) is presented on the Fig.8 b.

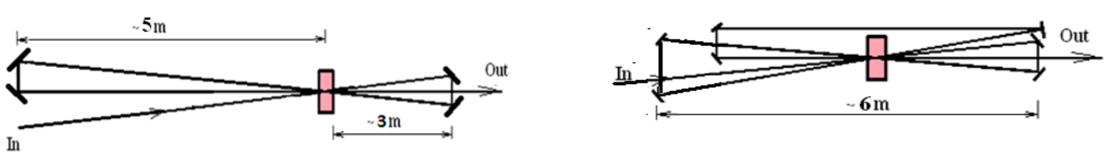


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**Fig. 8 Final 3-pass and 4-pass EDP- amplifier: a-** Three–pass EDP amplifier with a 19-cm-diameter pump area can approach 500-J energy with a 60-J input (100 J losses); b- Four–pass EDP amplifier with a 19-cm-diameter pump area can approach 600-J energy with a 60-J input, when pumped by 960 kJ (28 J losses).

**ELI-ERIC**
As it was mentioned above the secondary and ultimate purpose of ELI project is to contribute to the scientific and technological development towards generating 200 PW pulses. The 200 PW laser facility is on the roadmap now of the ELI consortium.

**EDP- amplifiers: Existing technology**

- As it was demonstrated, the EDP-amplifiers are able to afford 600-700 J.
- Taking in account the compressor transmission efficiency 70% [2], the compressed energy up to 500 J can be expected.
- Output peak power about 30 PW will be reached in one channel with pulse duration 15 fs.
- Seven EDPCPA channels will be enough for approaching 200 PW

**EDP- amplifiers: Limitations of Technology**
How Large can be Large aperture Ti:Sapphire crystal? 40-cm with 6-cm thickness is nearly maximum for EDP amplification due to geometric reasons.

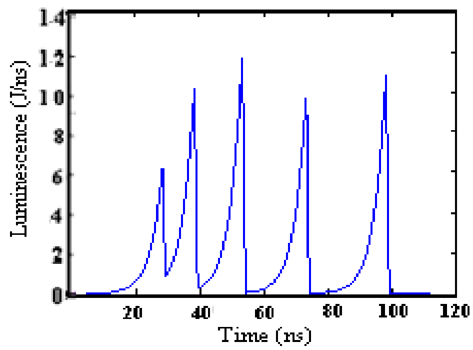


**Fig. 9 Final 5-pass EDP- amplifier:** Ti:Sapphire crystal 40x6-cm, output- 3 kJ/140 PW

The amplifier is able to supply 3 kJ/140 PW with 250 J of seed energy while suffering TASE losses of about 207 J. Two EDPCPA channels will be enough for approaching 200 PW.

## Conclusions:

- We demonstrated that EDPCPA with Ti:Sapphire amplifier is easiest way to reach the required parameters for ELI – pillars. (Higher efficiency, and softer requirements to pump laser, compared to OPCPA; wider spectral emission compared to Nd: glass amplifier).
- With existing index-matched liquid absorbers and the large aperture Ti: Sapphire crystals, it is possible to approach the sub-kJ level of extracted energy by exploiting the EDP method.
- With 70% compressor transmission efficiency and 15 fs pulse duration, 30 PW power level could be reached from a single channel and seven EDPCPA channels will be enough for approach to 200 PW.
- EDP amplifier, when operated under the optimal conditions, is capable of increasing the extracted energy by up to four times and more than ten times reduces the losses connected with TASE and TPG
- The powerfulness of EDPCPA was proved by spreading the method in the other world class laboratories and reaching recently the world record output peak power 2 PW.

  **Next steps in the future**

  - Today's result: ~ 72J/2 PW, pump area – 8.2 cm.
  - Today's technology ability: ~600J/30 PW, pump area – 20 cm.
  - Future's technology: ~3kJ/140 PW, pump area – 40 cm.
  - 30 PW * 7 channels = 210 PW

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