The coherent combining of parametric amplified beams locked by optical clock – the way to exawatt femtosecond laser system

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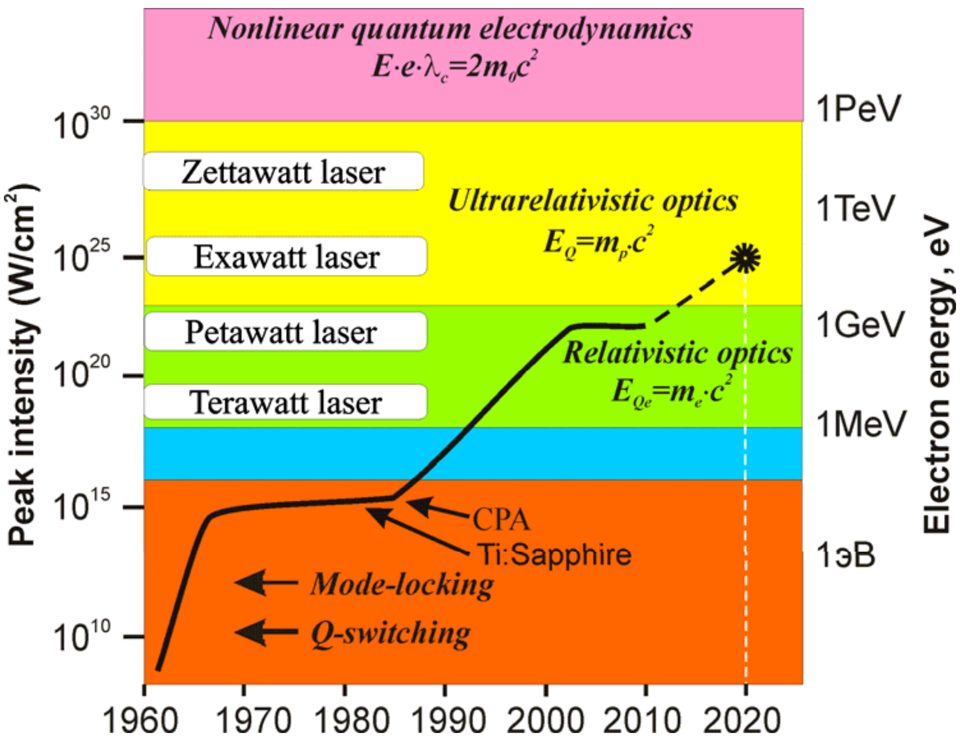
Laser physics of high intensity

Optic&Photonik ,N4, 23, 2010



Ultrarelativistic Optics (Multi Petawatt & Exawatt laser system, $I>10^{23}$ W/cm^2)

- **Relativistic generation of high harmonics and generation soft and hard X-ray radiation,**
- **Relativistic self-focusing and generation attosecond pulses,**
- **Generation quasi-monochromatic electron, proton and ionic bunches and their acceleration,**
- **Extremely states of matter by isochoric heating in superstrong optical fields….**

Record now~2x10^{22} W/cm^2 (Optics Express,v16, 2109, 2008)

Nonlinear Quantum Electrodynamics (Zettawatt laser system, $I>10^{29}$ W/cm^2)

- ***Generation electron-positron pairs,***
- **Scattering of light on light in vacuum,**
- **Nonlinear polarization of vacuum …**

Lasers with ultrarelativistic intensity (declare in projects)

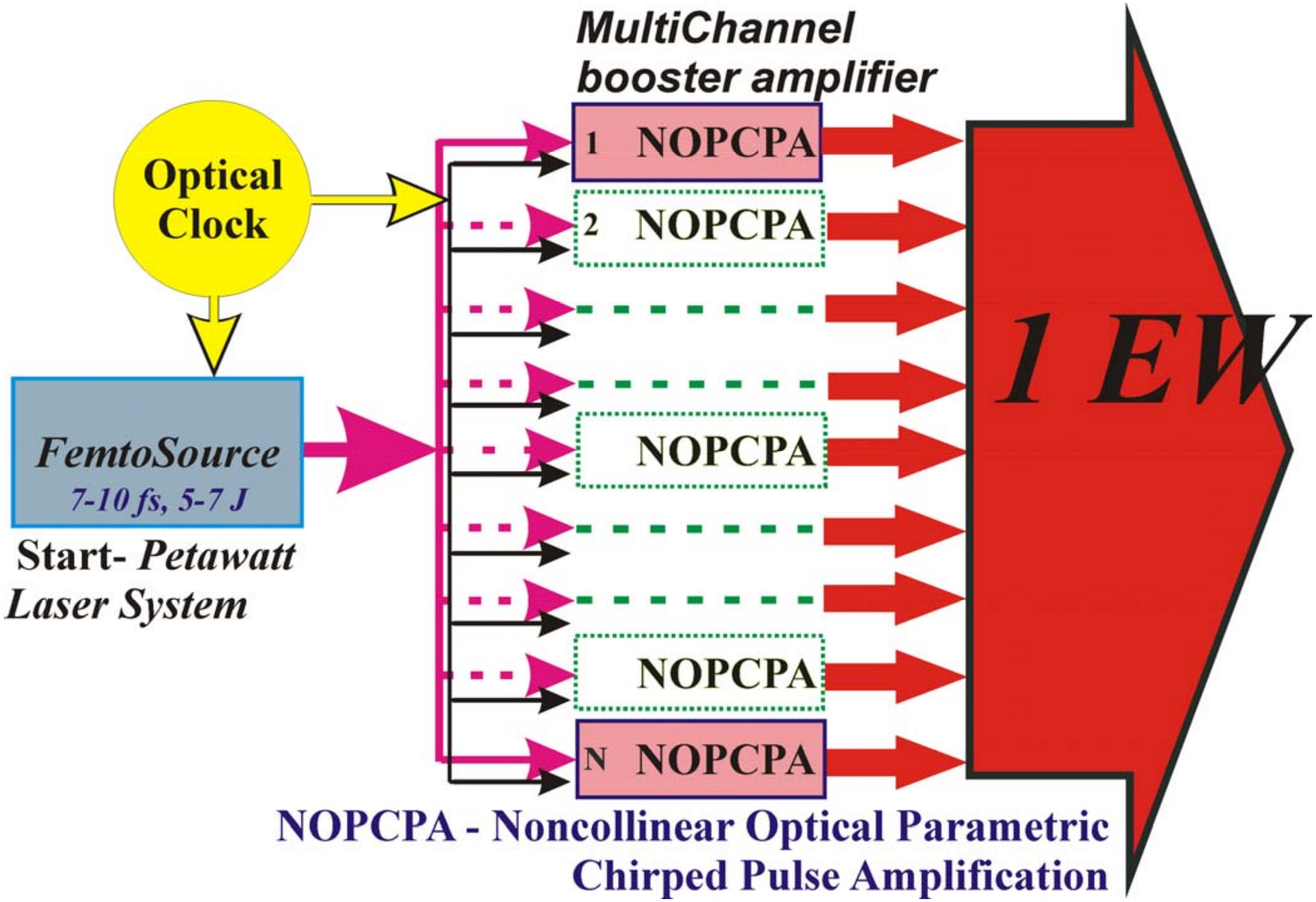
Name, country	Energy, J	Pulse duration, fs	Max.Intensity W/cm2	Rep. rate
Vulcan-10PW U.K.	300	30	*$>10^{23}$*	2 pulses/hour
APOLLON 10P France	150	15	*10^{23}-10^{24}*	1pulse/min.
PEARL-10 Russia	200	20	*$>10^{23}$*	1pulse/min.

Focusing in diameter ~(1-3) μm

The modern approach and basic principles of design for extremely high intensity femtosecond laser systems

- *Multi channel few-cycle femtosecond pulses system, based on ultrabrodband parametric amplification;*
- *Coherent combining of fields of channels;*
- *Phase-controlled generation and amplification of few-cycle pulses locked to optical clock;*
- *Parametric amplification with picosecond pumping;*
- *Precise time synchronization, based on optical clock, between the picosecond and femtosecond oscillators*

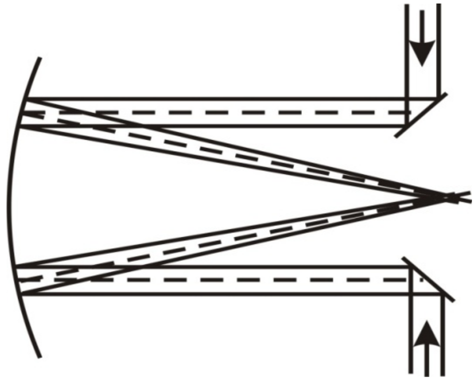
A Conceptual Design for Exawatt Femtosecond Laser System based on Multi-Channel Amplifier and Coherent Field Combining of Amplifier Channels



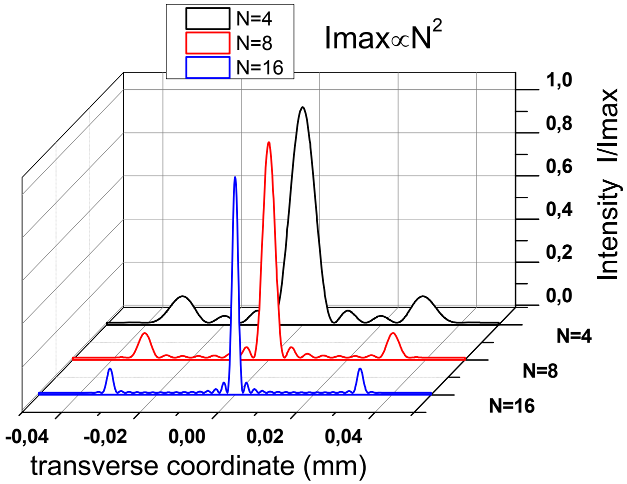
To Exawatt Femtosecond Laser System

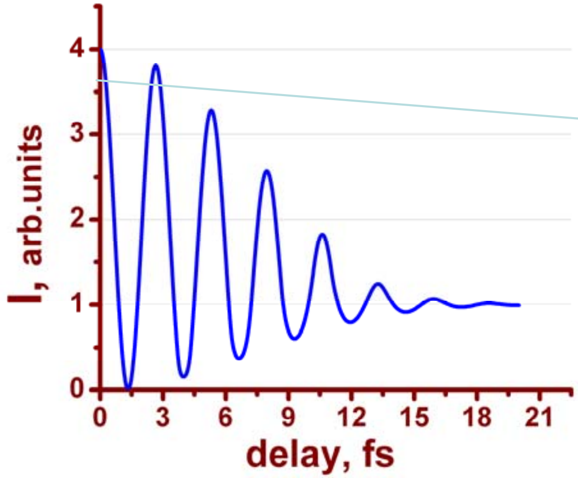
Effective coherent beam combining - jitter <200-400attoseconds

Coherent beam combining

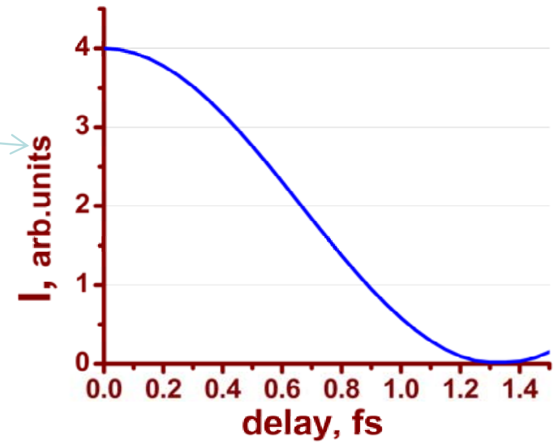


D.Ursescu,L.Ionel,
Proc. SPIE, 750103, 2009





Intensity evolution in the focal region
(pulse duration 10fs)



Effective coherent beam combining
(jitter <200-400ac)

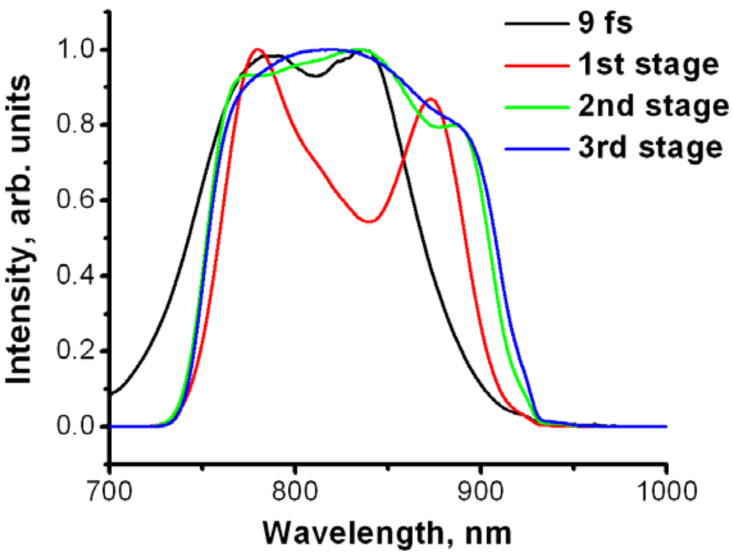
Nonlinear crystal for OPCPA of Ti-Sapphire laser

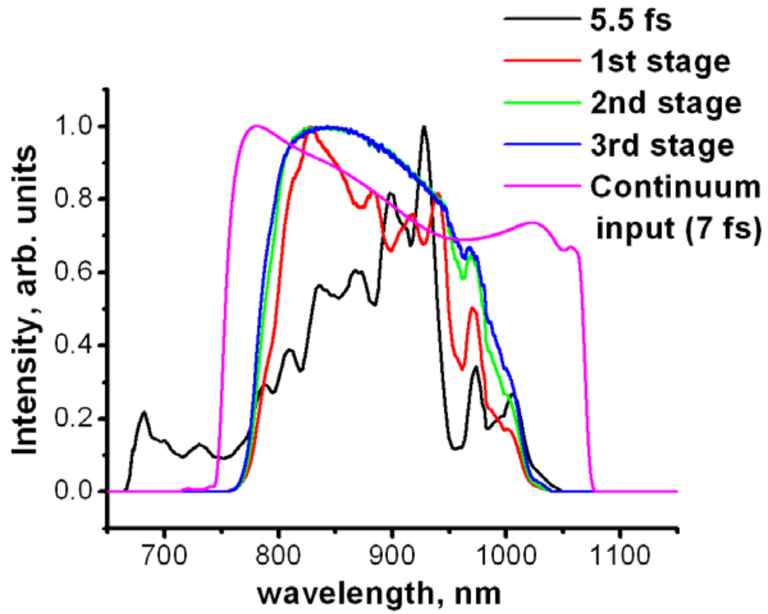
Materials	BBO BaB_2O_4	LBO LiB_3O_5	DKDP KD_2PO_4	YCOB $YCa_4(BO_3)_3$
NLO coefficient d_{eff}[pm/V]	2.1	0.83	0.3	1.03
damage threshold* GW/cm^2	>20	>10	>10	18 (1 ns)
transparency range, nm	190-3500	160-3200	200-1200	220-3500
phase matching angle, [^{o}]	23.83	32.09	36.8	27.5 , XZ
non-collinear angle, [^{o}]	2.26	1.5	0.75	3.45
nonlinear refractive index, n_2, $10^{-16}cm^2/W$	3.65 ($\theta = 29^o$)	2.8	3.5(n_o) 2.5(n_e)	7.4(n_y) 9(n_z)

* For Pulse duration **100 ps**

E.V. Pestryakov, V.V. Petrov, V.I. Trunov, S.A. Frolov, A.V. Kirpichnikov, S.N. Bagayev, A.E. Kokh, Design of high gain OPCPA for multiTerawatt and Petawatt class systems on large aperture LBO crystals, Proceedings of SPIE, v.7994, p.799425-1, 2010

Parametric amplification in BBO and LBO crystals

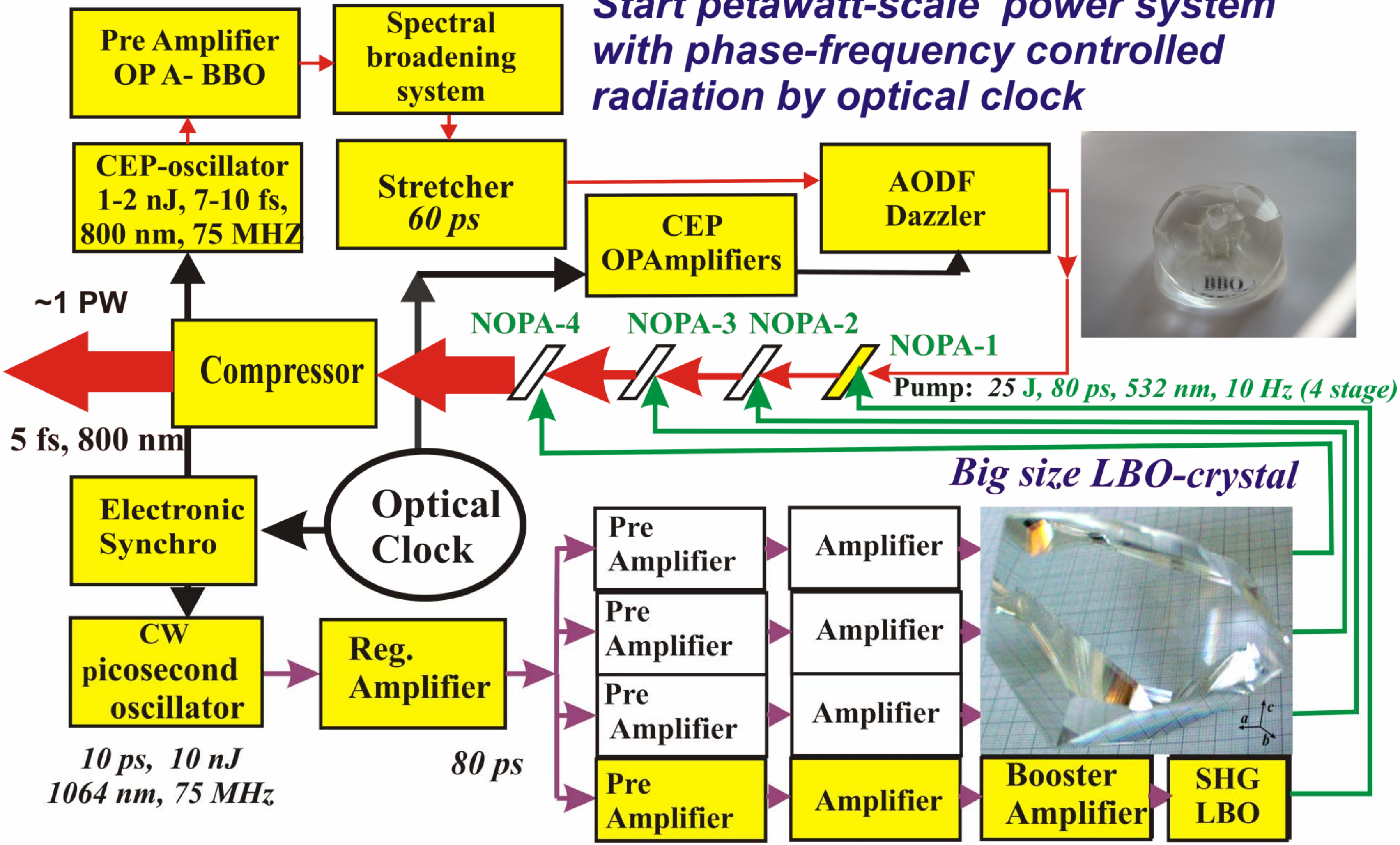




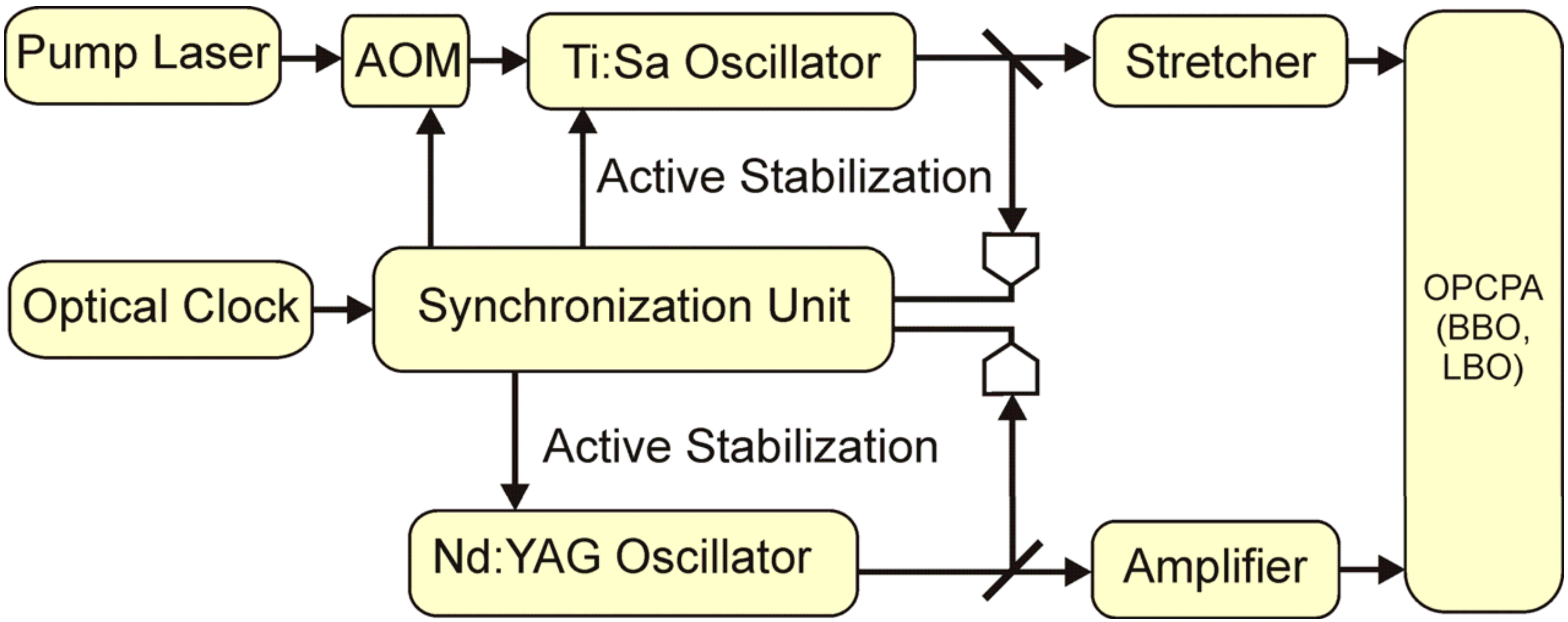
The spectra of amplified pulses for different stages of parametric amplification

Petawatt level can be achieved at LBO Crystals with diameter 100-120mm

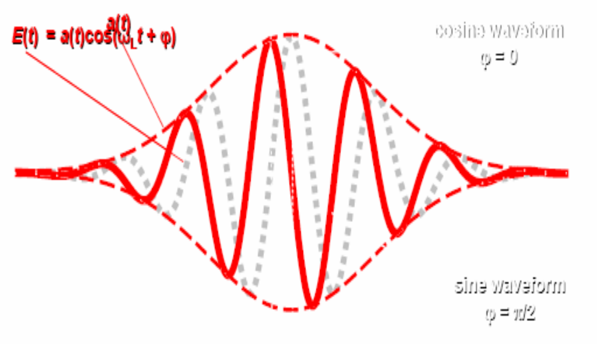
Start petawatt-scale power system with phase-frequency controlled radiation by optical clock

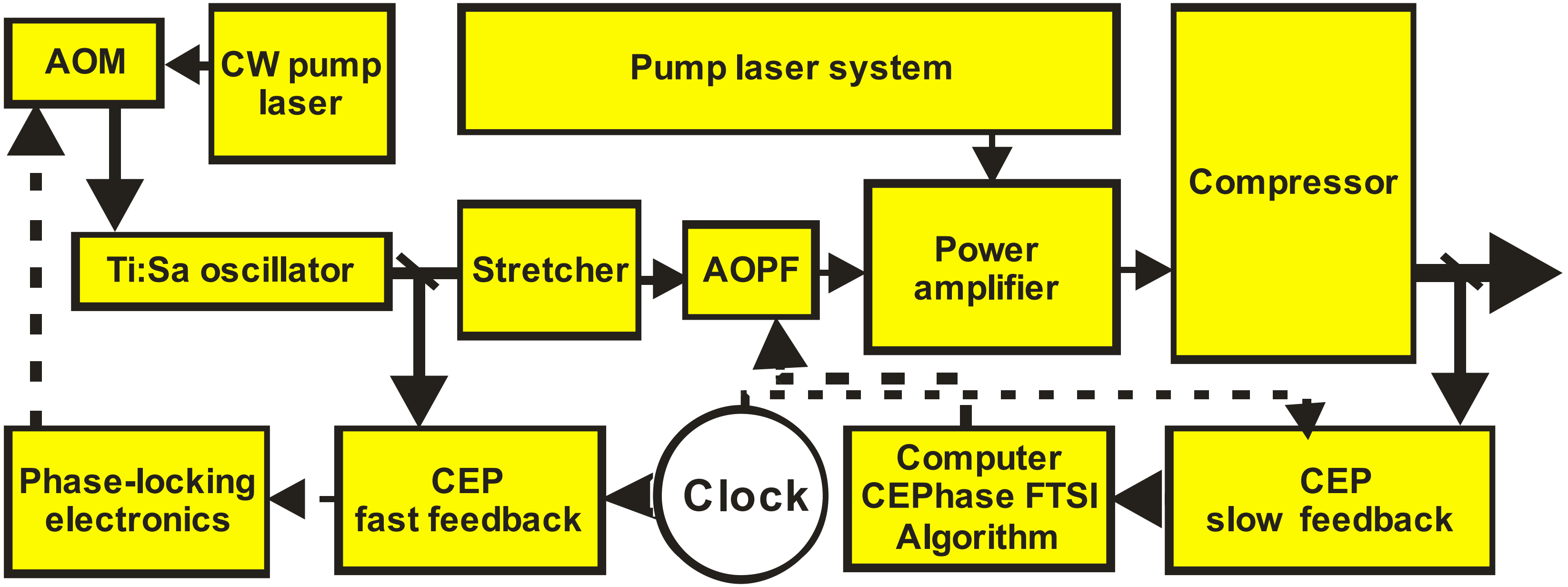


Synchronization principle of CW master oscillators: femtosecond Ti:Sapphire laser and picosecond oscillator for pump channels of OPCPA



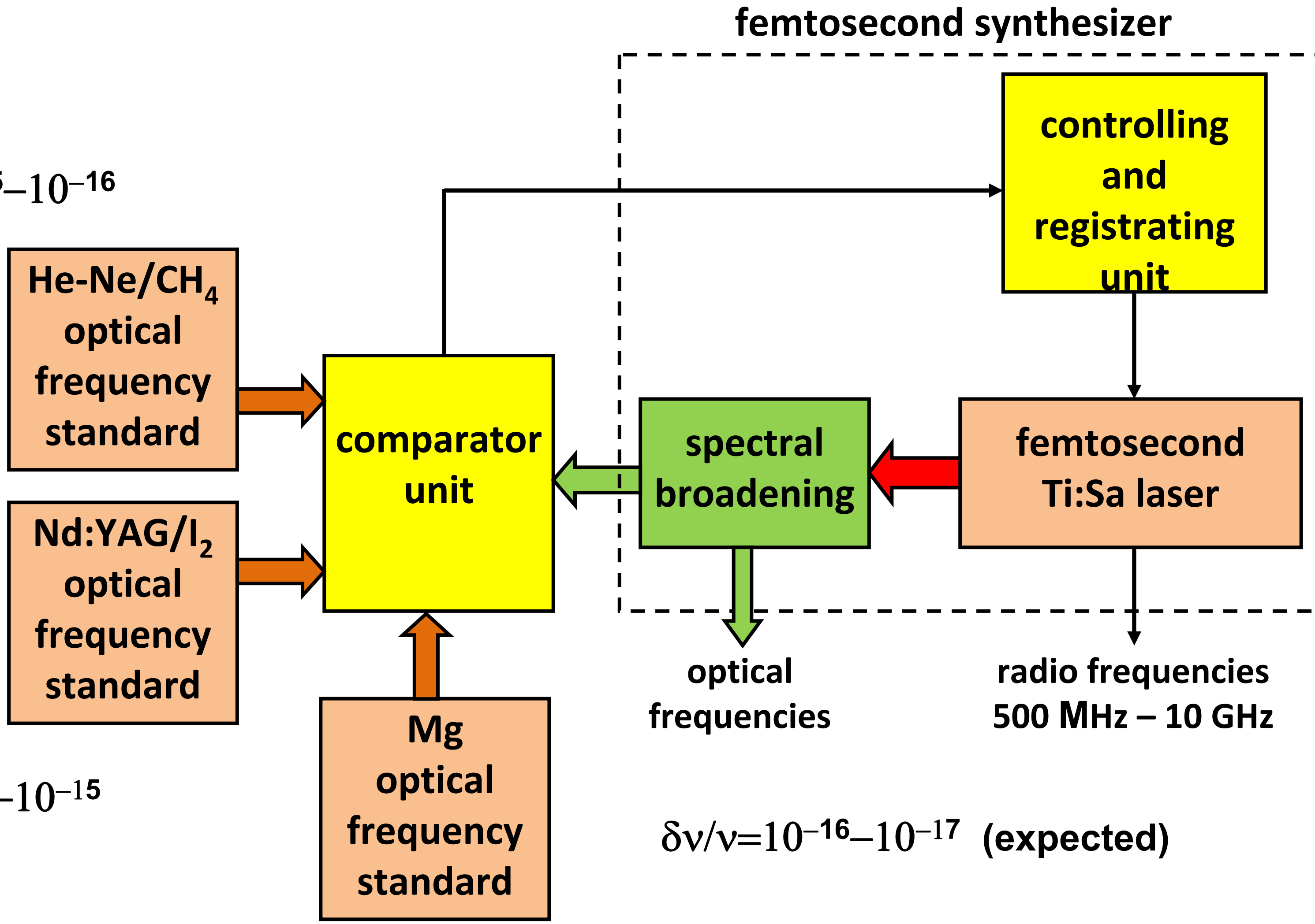
CEPhase Controlled Oscillator and Power Amplifier





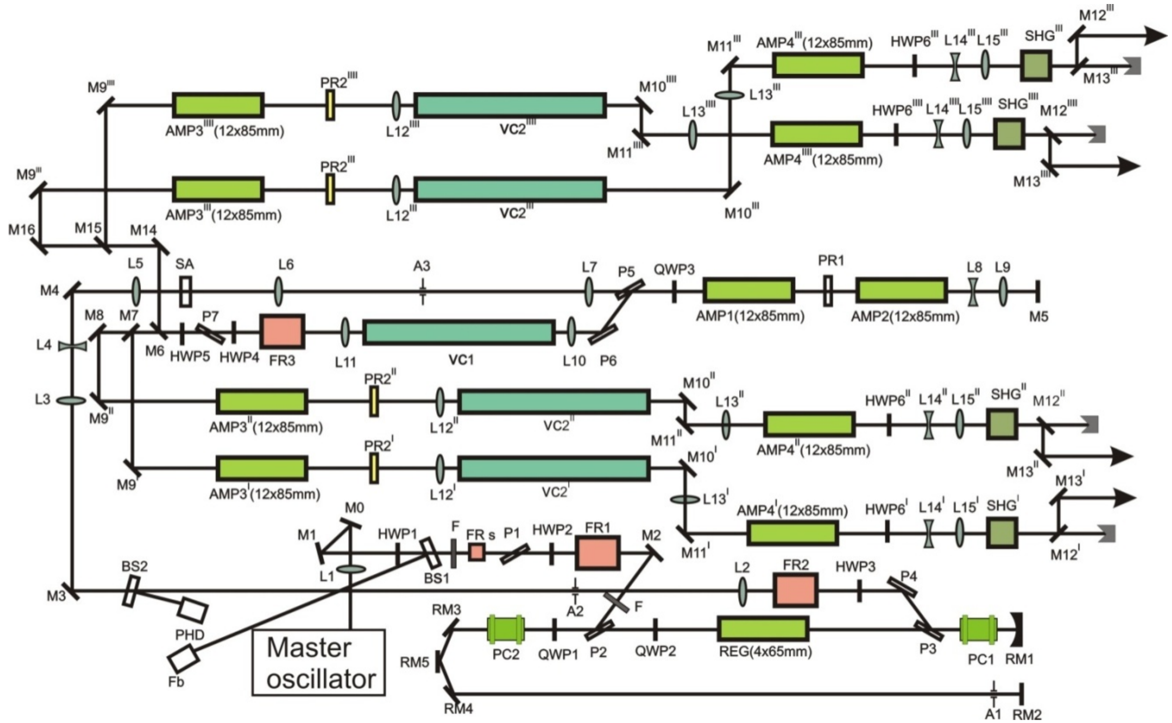
Scheme of universal femtosecond optical clock ILP SB RAS

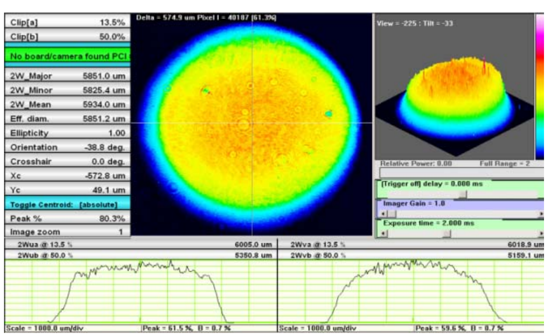
$\delta\nu/\nu=10^{-15}$–10^{-16}



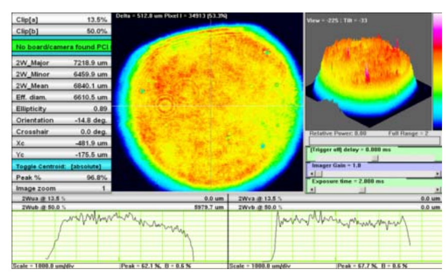
$\delta\nu/\nu=10^{-14}$–10^{-15}

Scheme of 4-channel ps laser for OPCPA pump





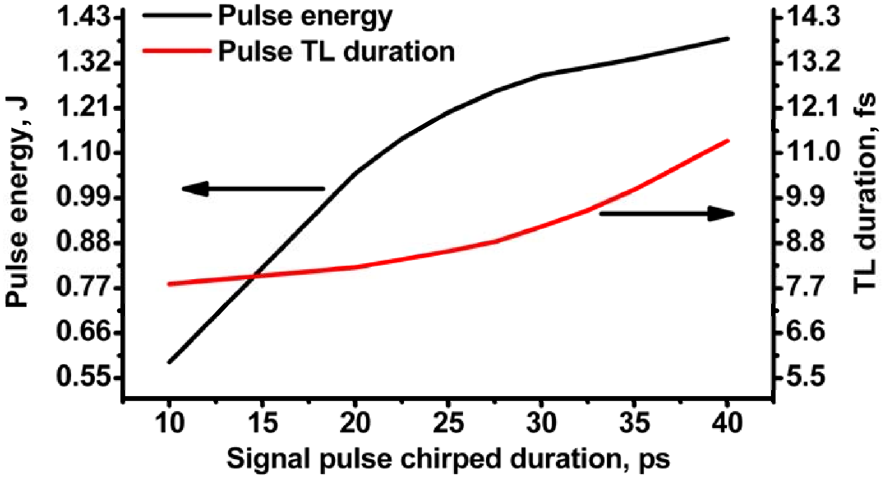
Beam profile at 1064 nm, energy-1.1 J

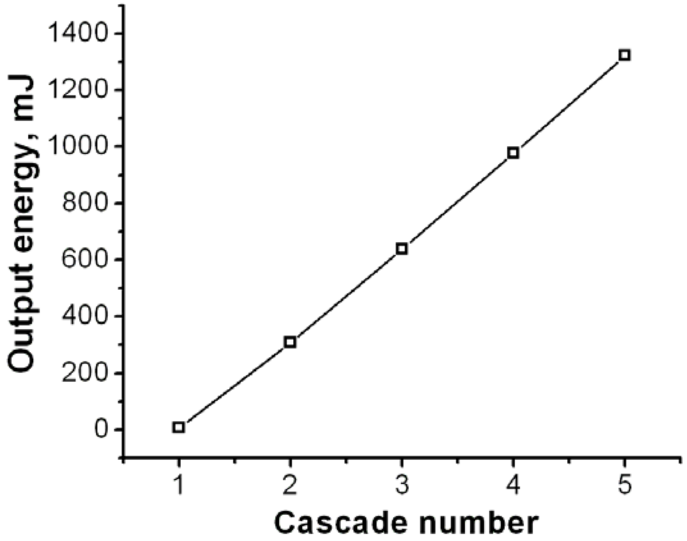


Pulse repetition rate
10Hz

Beam profile at 532 nm, 0.6 J (SHG crystal – DKDP)
Pulse duration-90 picosecond

Optimization of OPCPA in BBO и LBO crystals



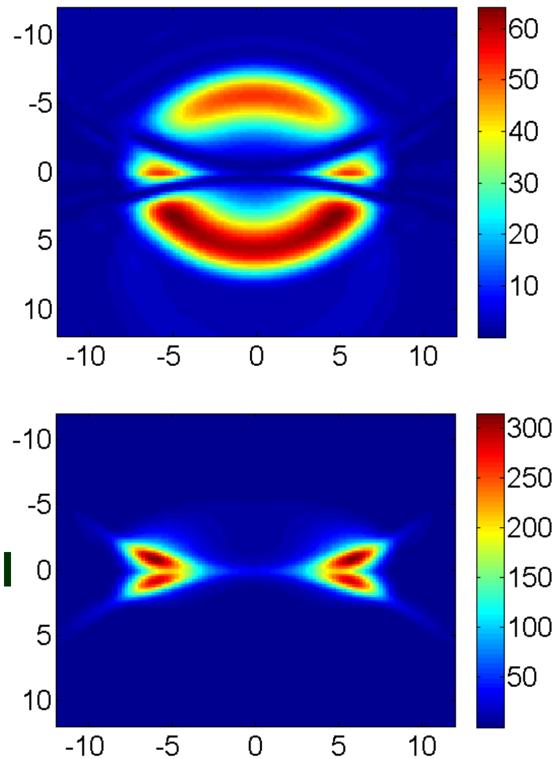


Pump pulse duration - 90ps
Total pump pulse energy – 4 J

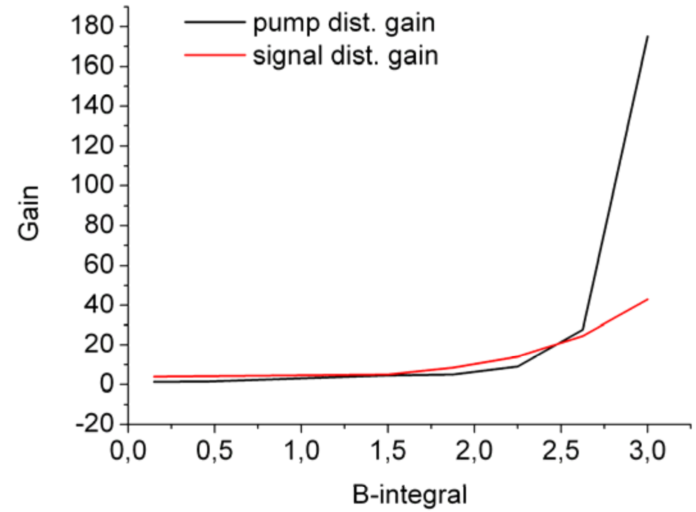
Results of simulation of small-scale self-focusing

pump

signal



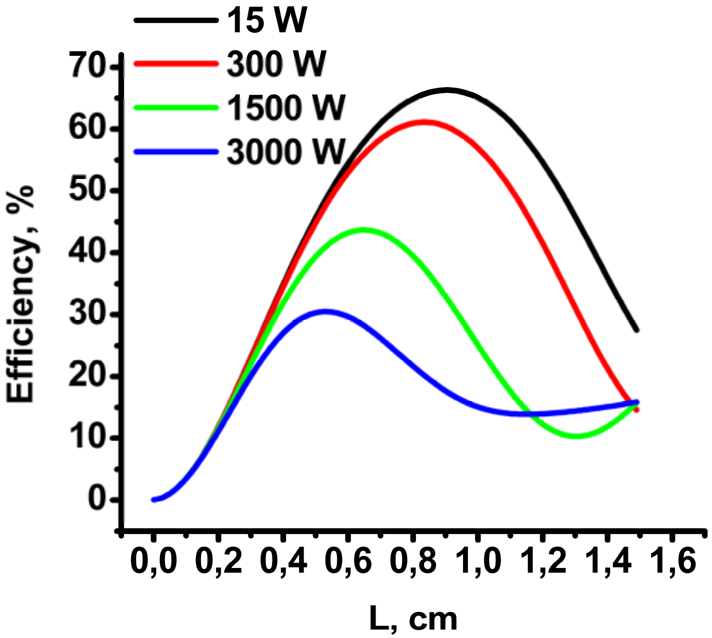
Two cascades disturbance gain vs. angles in mrad for B-integral = 3



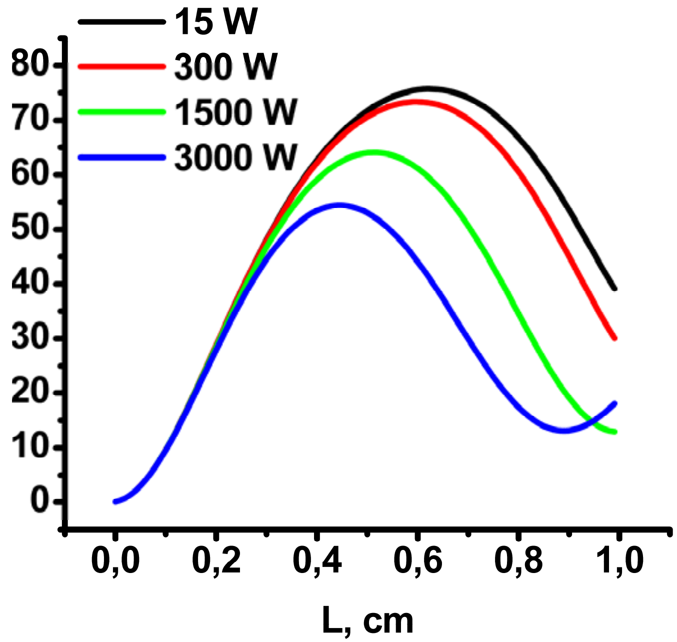
Maximum disturbance total gain vs. B-integral

For B-integral = 3 total gain of disturbances is expected to be about 40 for pump, and 180 for signal.
If we assume I_{th}/I_{av} = 3 this leads to requirement for maximum I_{rms}/I_{av} = 3%.

Influence of the temperature effects on the efficiency of SHG from ps laser



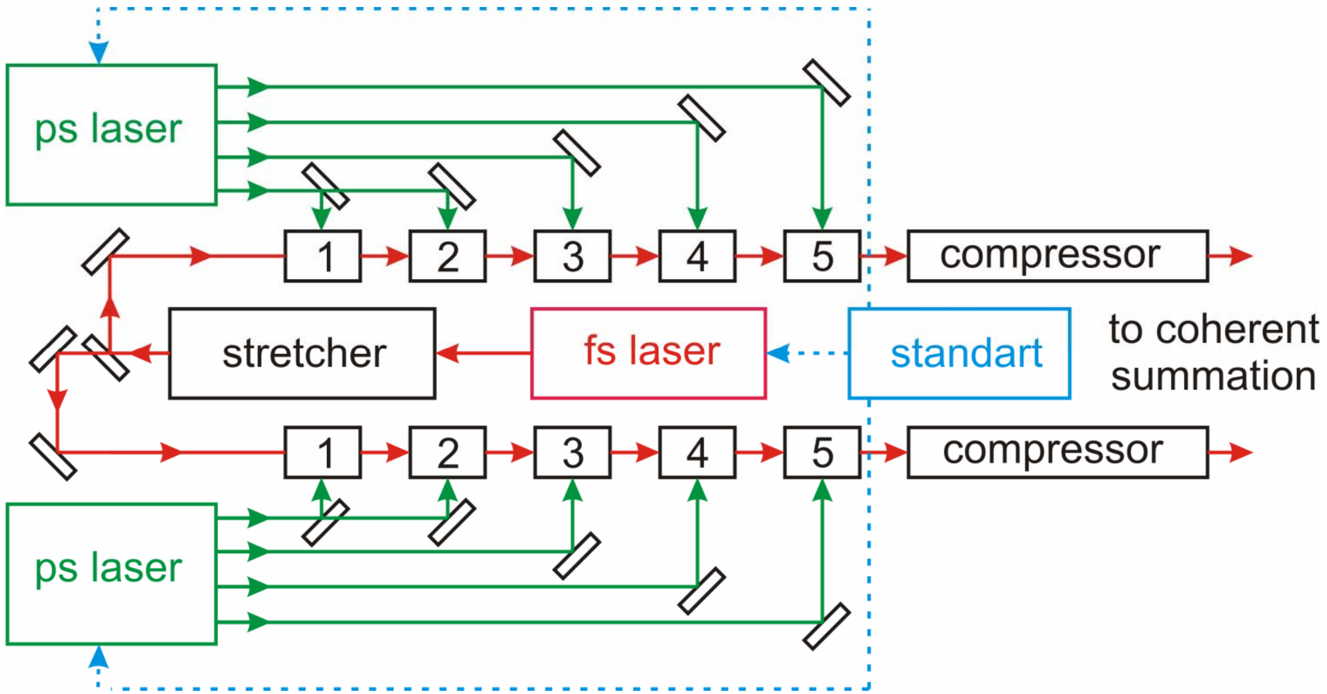
DKDP



LBO

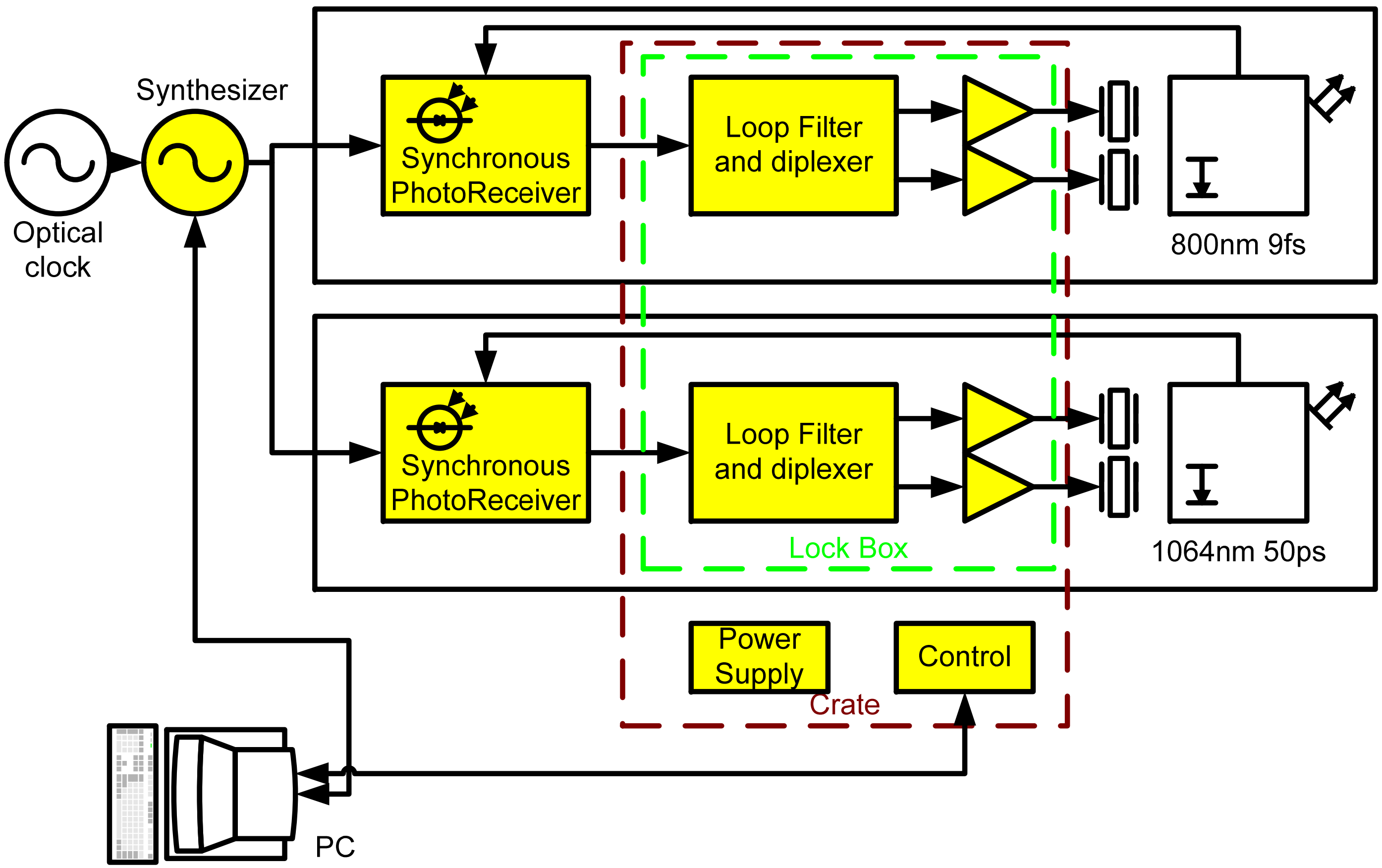
Pulse duration-90ps
Intensity -6GW/cm^2
Pulse energy-1.1J

Scheme of the dual multiterawatt femtosecond laser system with a coherent summation



Creating such a system would certify the basic techniques and tools needed for further scaling of multi-channel principle of construction high-intensity laser systems of multipetawatt and exawatt levels.

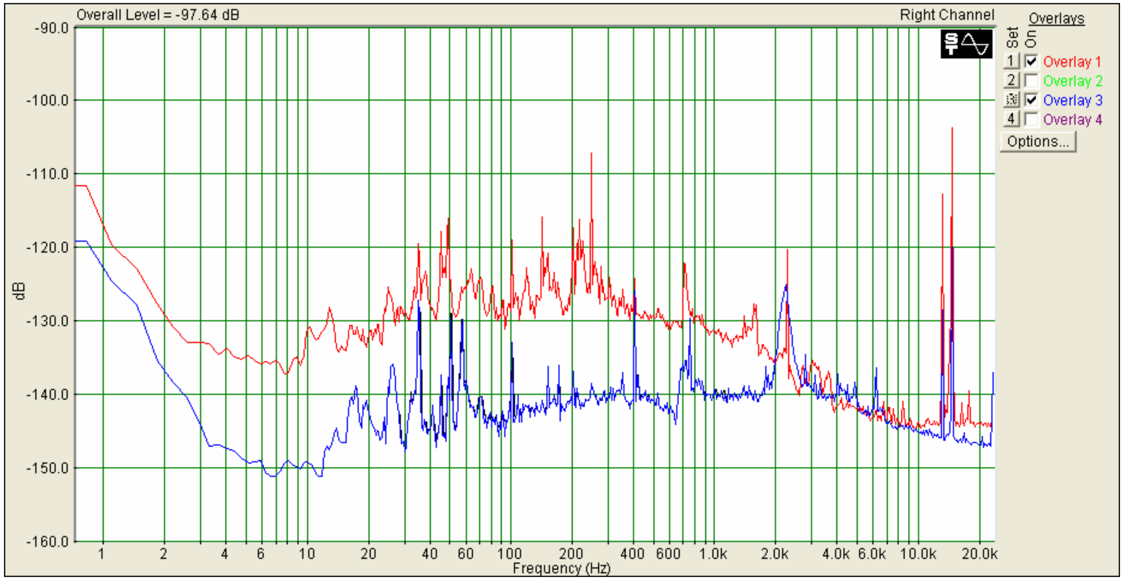
Synchronization with Reference Oscillator: femtosecond oscillator and picosecond Nd:YVO_4 oscillator of pump channel



Block diagram of synchronization based on digital phase detectors

Intrinsic noise – 30fs

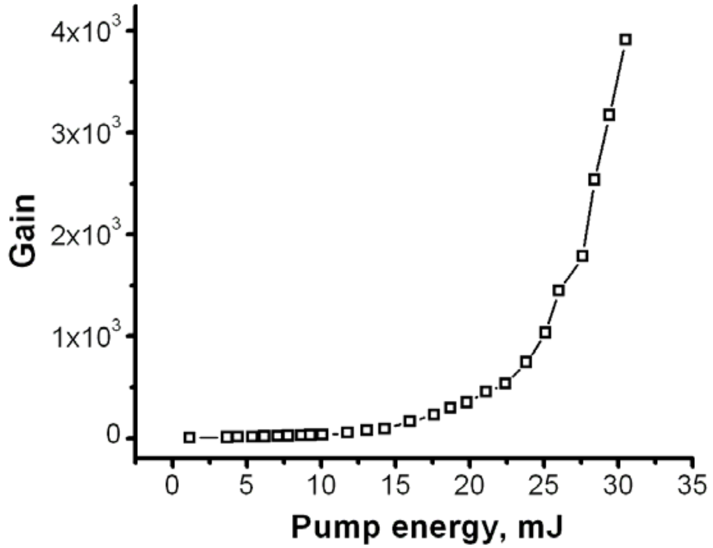
Measuring the relative noise fs and ps lasers



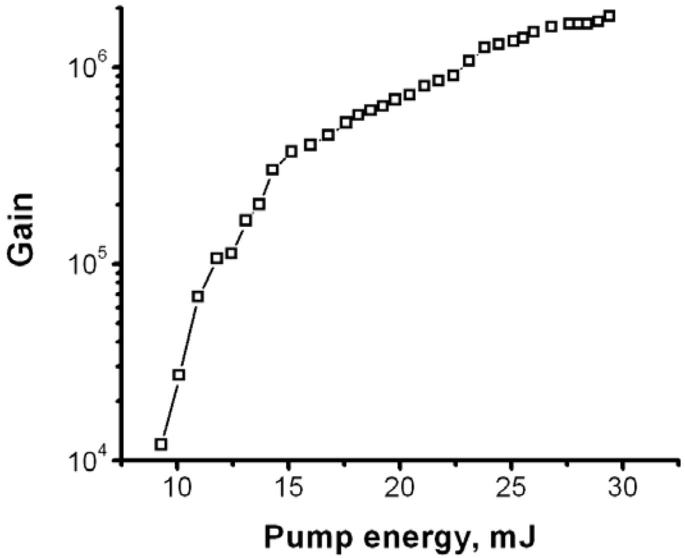
Red relative noise ps-laser oscillator
blue - the relative noise-fs-laser oscillator

Jitter in a band of 1 Hz-20 kHz less than 210fs for the picosecond laser and 150 fs for a femtosecond laser. Relative jitter of femtosecond and picosecond lasers, no more than 250 fs in the band of 1 Hz-20 kHz.

Gain in two pass OPCPA (BBO) with ps pump



first pass gain



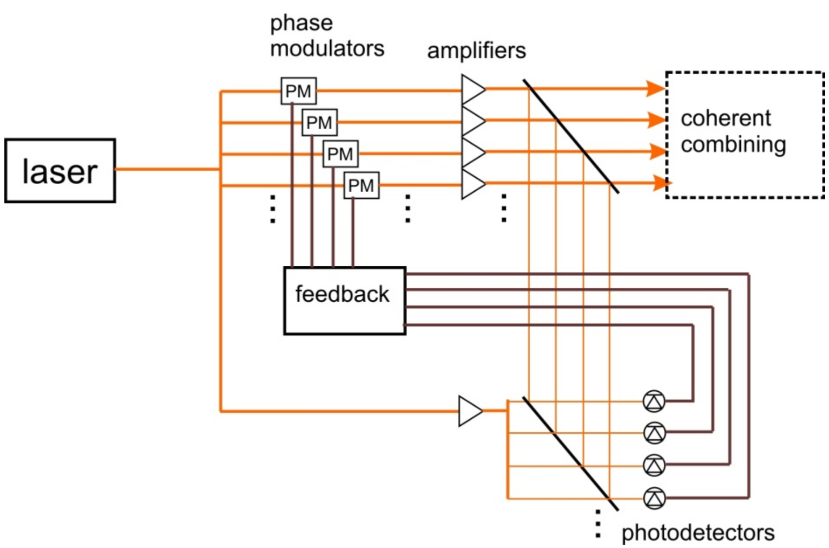
gain after two passes

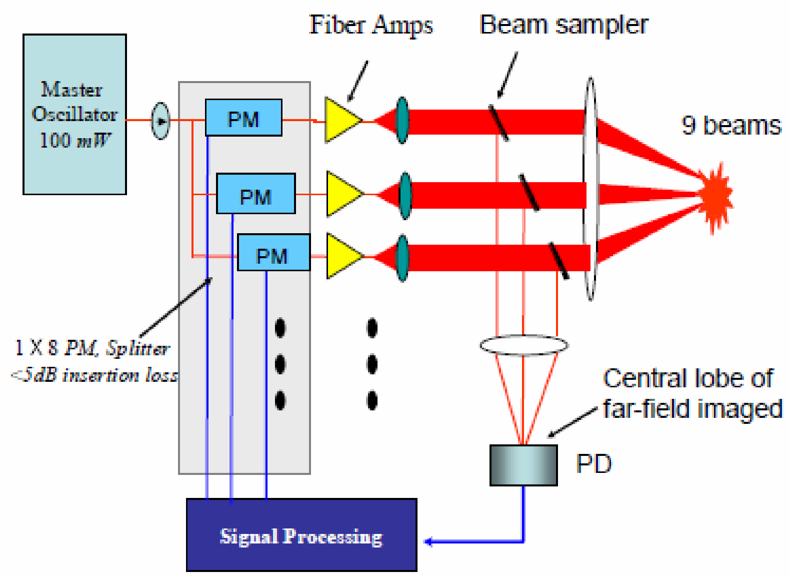
Phase stabilization for realization of coherent beam combining

1. Heterodyne phase detection

Phase detection of beat signal by means of photodiode and phase detector

- **detection of phase difference between reference channel and i-th channel**
- **detection of average phase difference between i-th channel and the others**



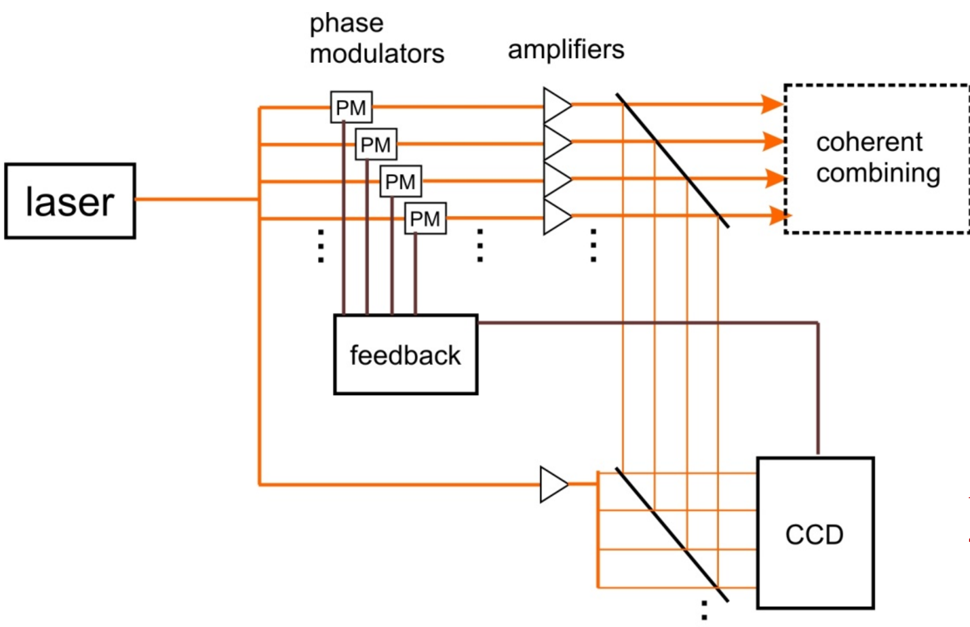


Stabilization scheme

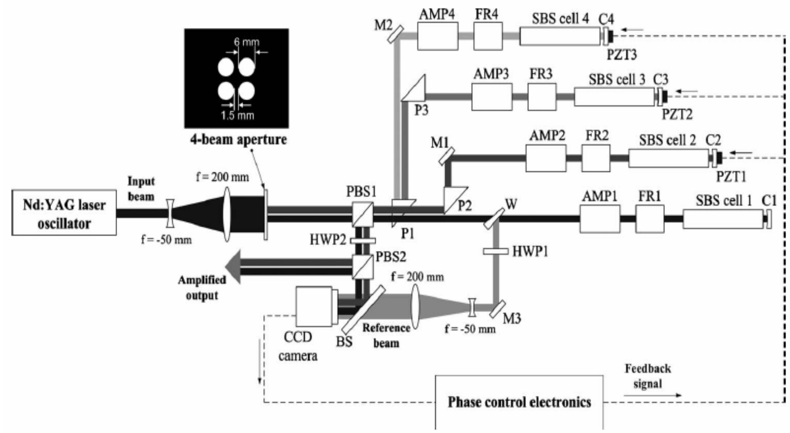
Opt. Express, v14, 12015 (2006)
9 cw channels, phase stability λ/20

Phase stabilization for realization of coherent beam combining

2. Registration of interference pattern of overlapped channels

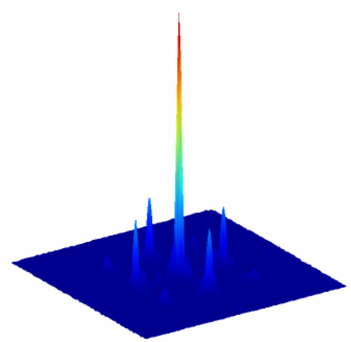


Stabilization scheme



Appl.Phys.Lett.v **96**, 131116 (2010)
4 channels, pulse 10ns, phase stability ~ λ/30

Opt. Express v19, (2011) – 64 channels, phase stability λ/10-λ/13, combining efficiency 80%



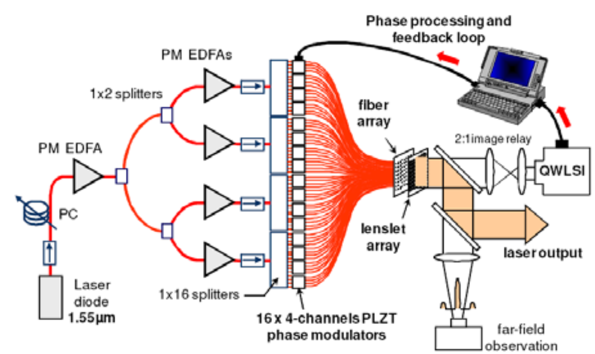
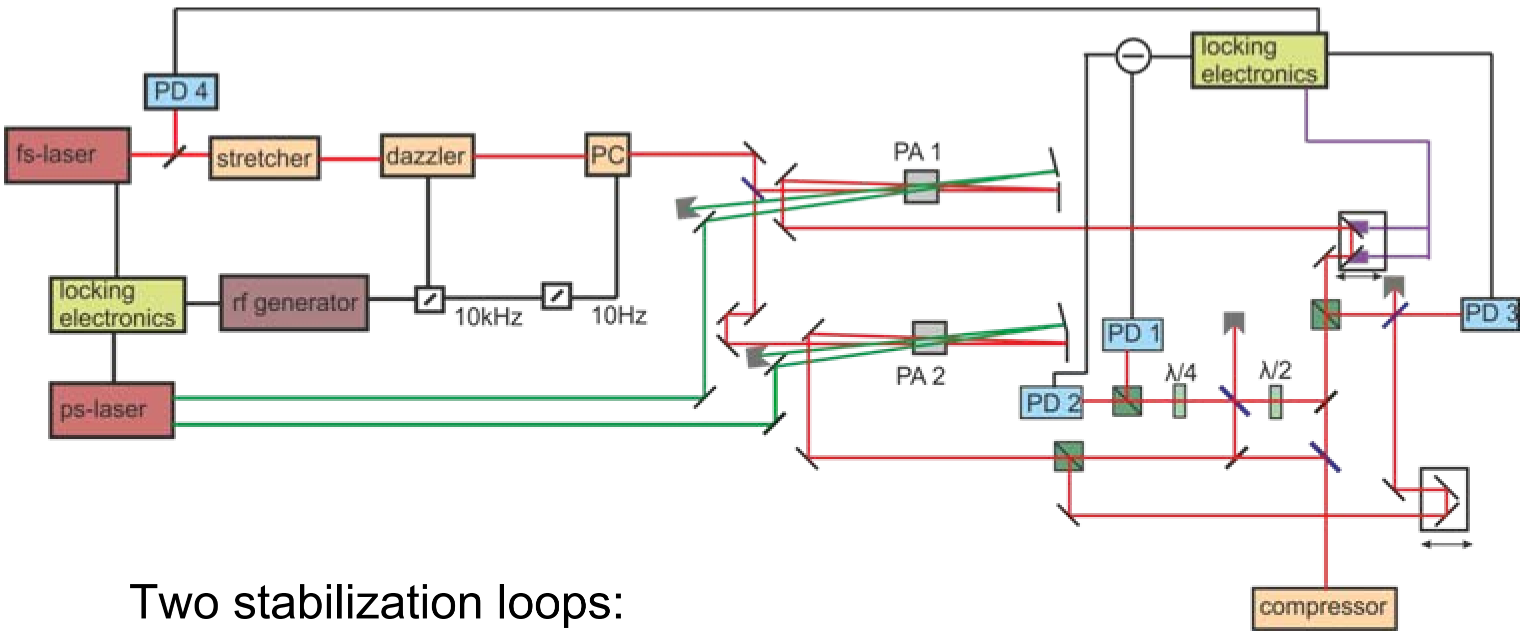


Fig. 1. Experimental setup. PC: Polarization Controller. PM EDFA: Polarization Maintaining Erbium Doped Fiber Amplifier. QWLSI: Quadriwave Lateral Shearing Interferometer.

Beams parameters for coherent combining

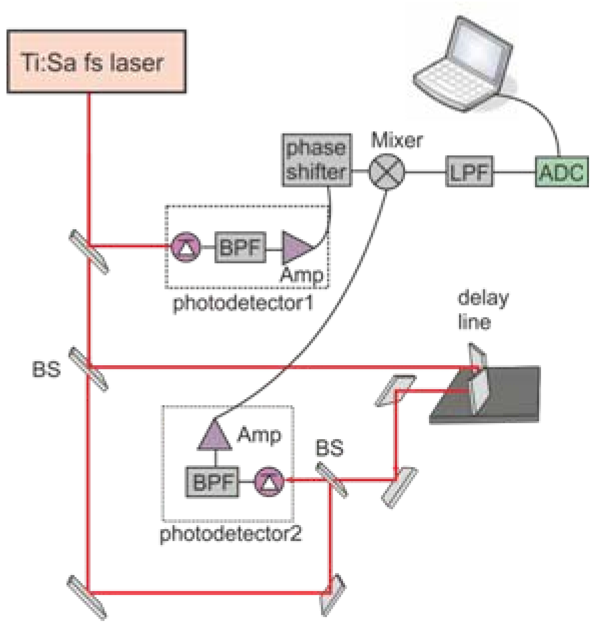
parameter	combining loss 1-η for hypergauss beam profile (m=3)	value for 10% loss	notes
phase variations	σ_{φ}^2	σ_{φ} =0,32rad (18,3 ^{o})	
power fluctuation	$\frac{1}{4}\left(\frac{\sigma_P}{P}\right)^2$	$\frac{\sigma_P}{P}$ =64%	
pulse delay fluctuation	$2\ln(2)\left(\frac{\sigma_t}{\tau}\right)^2$	$\frac{\sigma_t}{\tau}$ =27%	with phase matching (τ – FWHM pulse duration)
polarization angle	σ_{χ}^2	σ_{χ} =0,32rad (18,3^{o})	χ – polarization angle
fractional spot displacement	$6\frac{\Gamma(11/6)}{\Gamma(7/6)}(\ln(2))^{1/3}\left(\frac{\sigma_x}{W}\right)^2$	$\frac{\sigma_x}{W}$ =13%	W – FWHM beam diameter
fractional spot size	$\frac{7}{4}\left(\frac{\sigma_W}{W}\right)^2$	$\frac{\sigma_W}{W}$ =24%	W – FWHM beam diameter
fractional pointing	$2\ln(2)\left(\frac{\sigma_\theta}{\theta}\right)^2$	$\frac{\sigma_\theta}{\theta}$ =27%	θ - FWHM beam divergence
fractional divergence	$\left(\frac{\sigma_\theta}{\theta}\right)^2$	$\frac{\sigma_\theta}{\theta}$ =32%	θ - FWHM beam divergence

Coherent summation in OPCPA

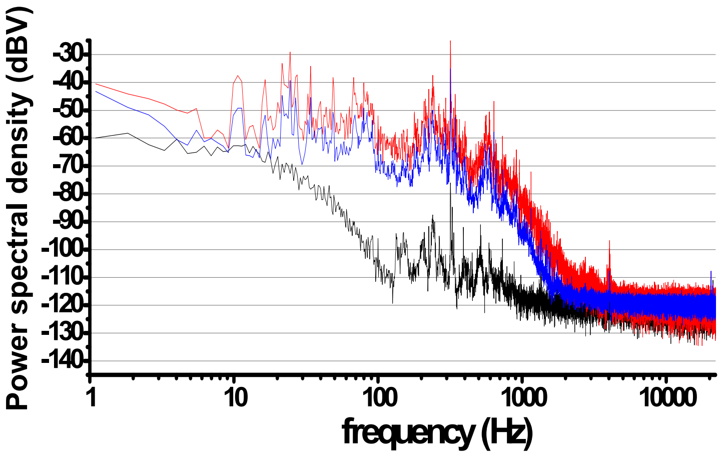


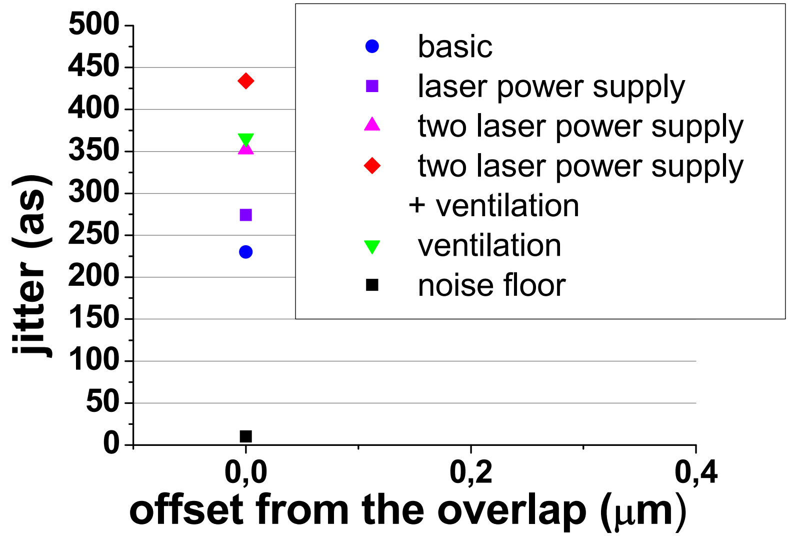
Two stabilization loops:
- Fast
- slow

Relative jitter of two femtosecond pulse trains

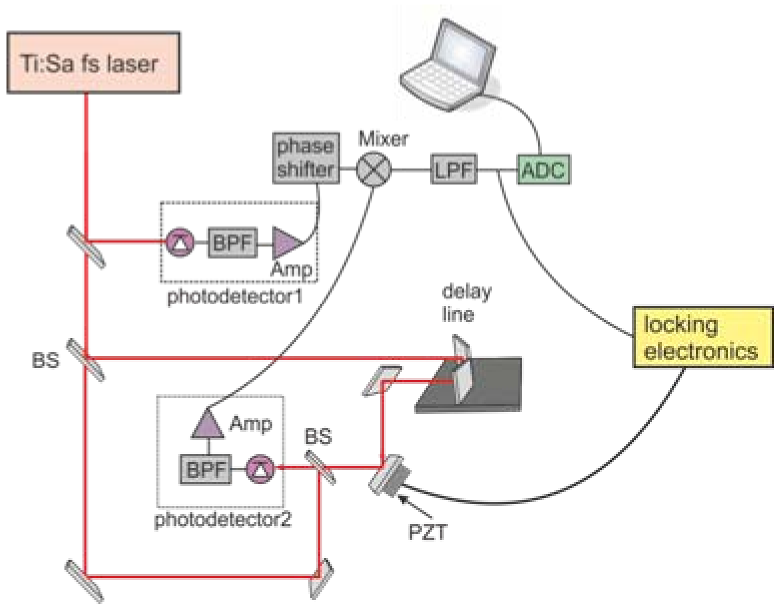


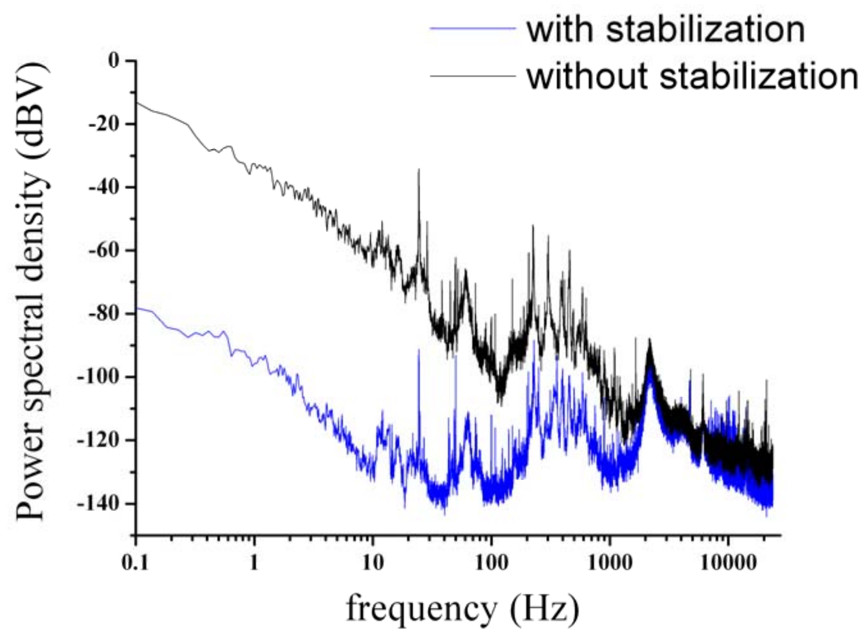
BS – beam splitter, BPF – band pass filter, LPF – low pass filter, ADC – analog to digital converter, Amp – amplifier





Coherent summation of femtosecond pulses with high repetition rate





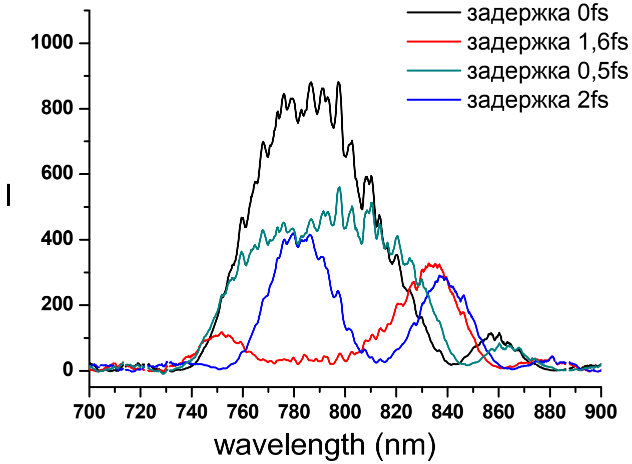
BS – beam splitter, PZT - piezoelectric transducer, BPF – band pass filter, LPF – low pass filter, ADC – analog to digital converter, Amp – amplifier

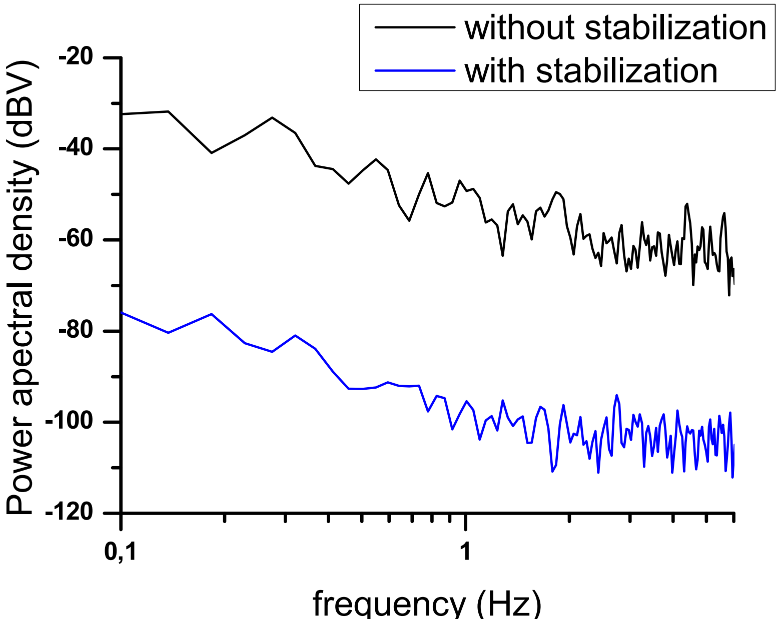
jitter

bandwidth	without stabilization	with stabilization
0,1Hz-20kHz	230as	6,4as
1Hz -20kHz	79as	6,1as
1kHz -20kHz	2as	5,7as

Institute of Laser Physics SB RAS

Coherent summation of femtosecond pulses with low repetition rate



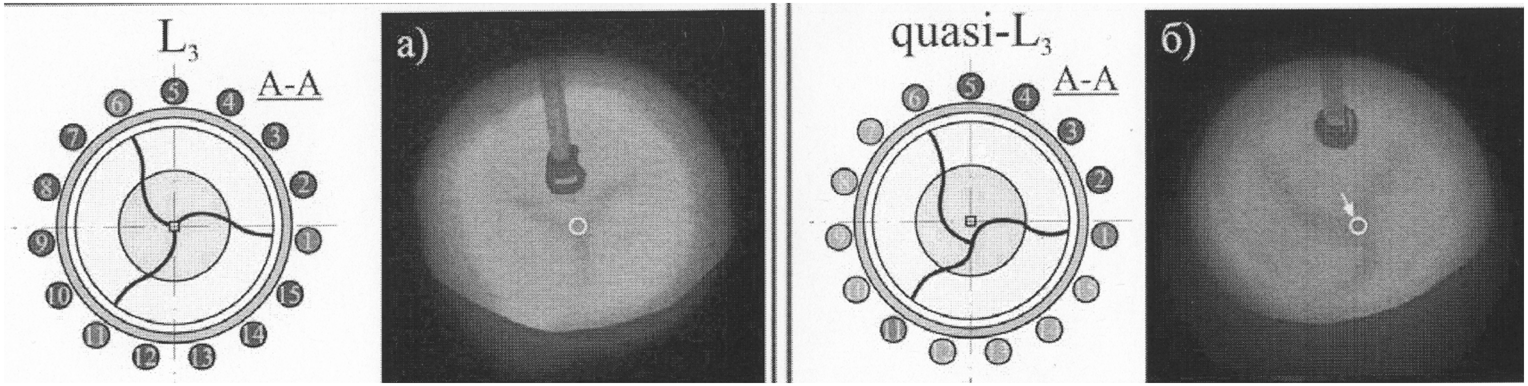


jitter

bandwidth	without stabilization	with stabilization
0,09Hz-5Hz	128as	12as

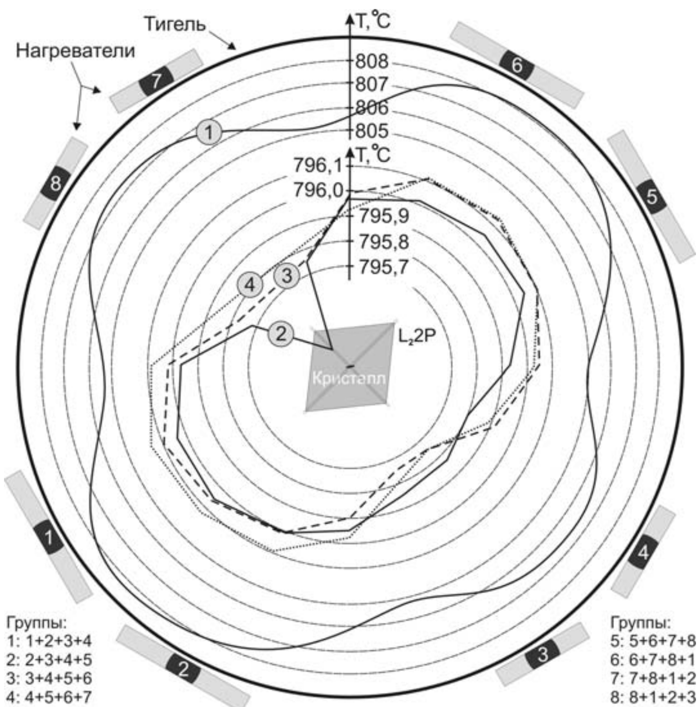
BBO crystal growth in thermal fields with the symmetry axis of the third order L_3

Institute of Geology and Mineralogy SB RAS, Novosibirsk, Russia

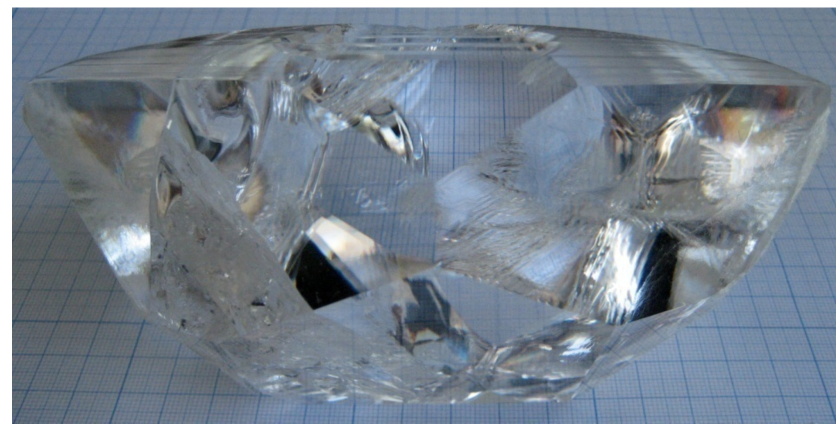


BBO crystal, grown from the fluoride flux, weighing 325 g

Rhombic symmetry of the thermal field and the orientation of the LBO crystal in a growth chamber (a); LBO crystal weighing 1,558 g (b).



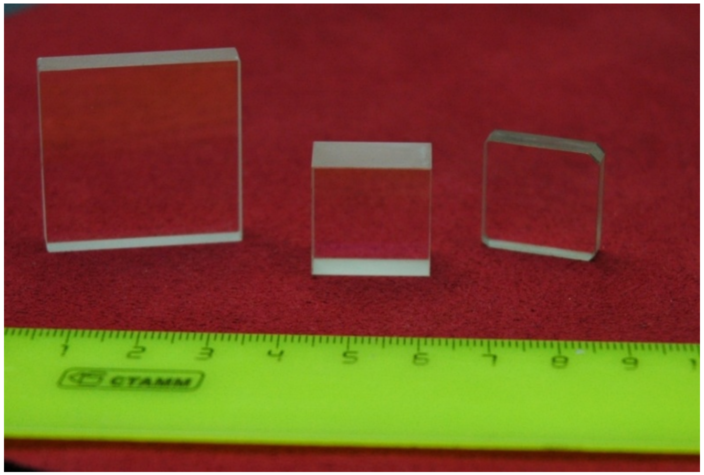
(a)

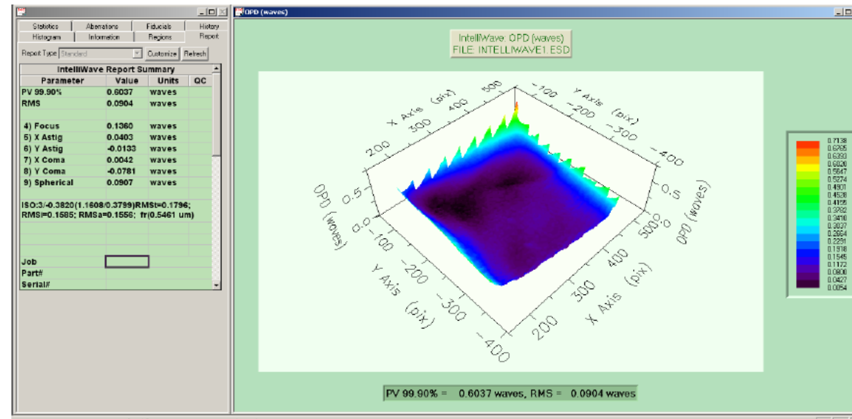


(b)

A.E. Kokh, V.A. Vlezkom K.A. Kokh, “Control over the symmetry of the heat field in the station for growing LBO crystals by the Kyropoulos method”, Laboratory techniques **5, 145-149 (2009).**

BBO и LBO crystals for cascades of parametric amplification



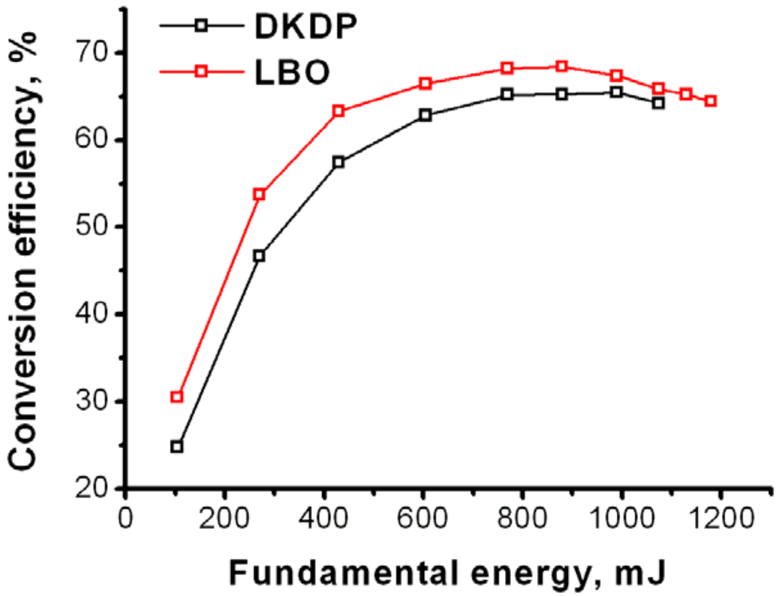


Crystals:
LBO (30x30x6mm, 20x20x9mm)
BBO (20x20x4.6mm)

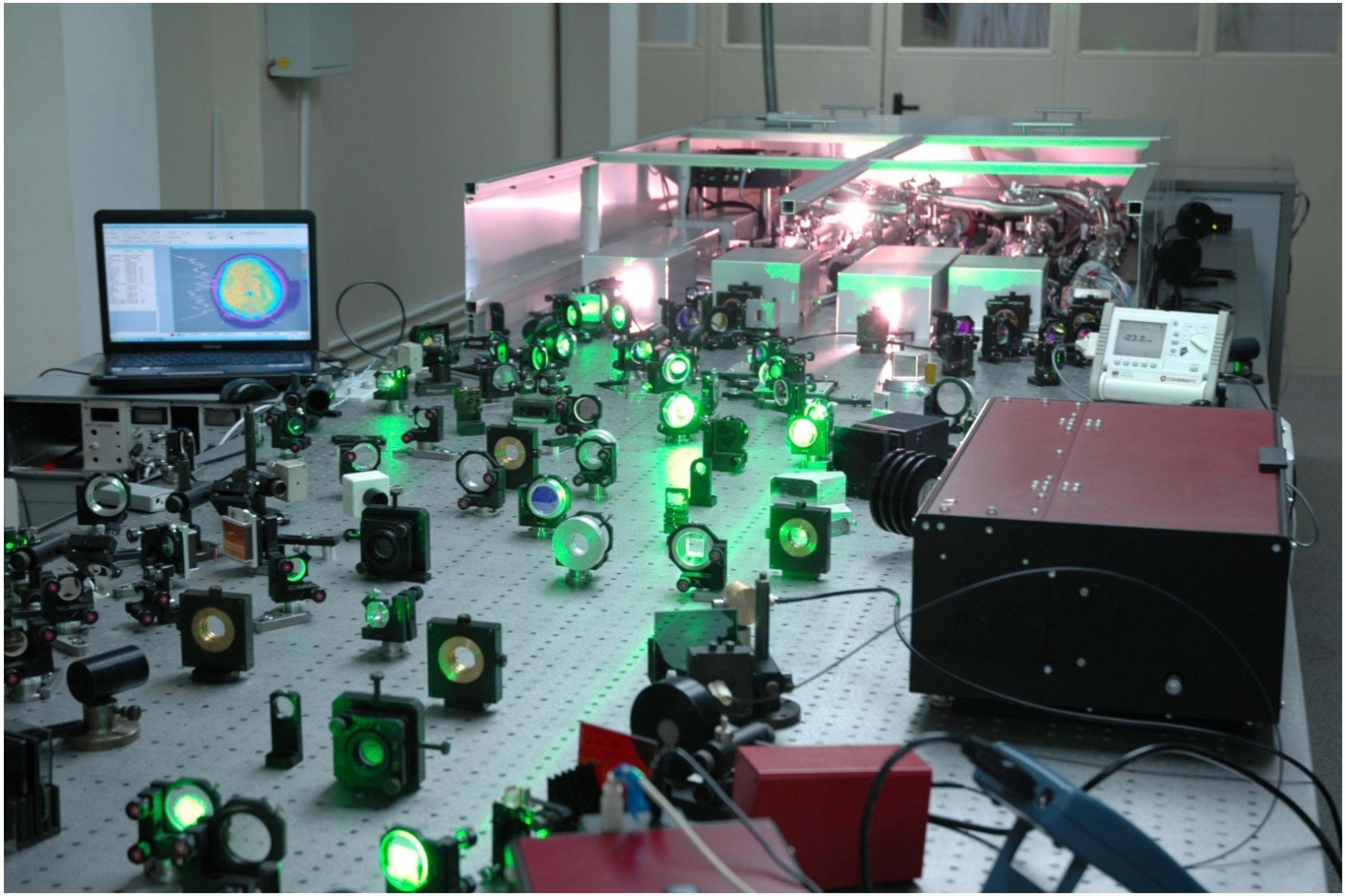
3D map of the optical distortion of the optical element of the LBO crystal with dimensions 30x30x6 mm RMS = 0.09λ

The magnitude of optical losses in the elements of LBO depends largely on the purity of raw materials, but no worse than 10-4 cm-1 at 1064 nm

SHG in LBO and DKDP crystals by ps pulses



Wave front distortion is λ/8 on diameter of 25mm



Front part of powerful femtosecond system
with picosecond pump laser

Research and technical participants:

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A.V. Kirpichnikov , M.N. Skvortsov,

A.E. Kokh, K.A. Kokh,

V.V. Petrov, V.A. Vasiliev ,

V. Vlezkom , N.N.Kvashnin,

I.S. Corel, A. S.Yurkin

Thanks for Your Attention