APPLICATIONS OF NONLINEAR PROCESSES IN THE LASER RESEARCHES IN RFNC-VNIIEF

S.A.Sukharev, RFNC-VNIIEF, Sarov

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The report is based on materials of the following publications:

Ю.В.Долгополов, В.А.Комаревский, и др. Экспериментальное исследование возможностей применения явления обращения волнового фронта при вынужденном рассеянии Мандельштама-Бриллюэна.
ЖЭТФ, том 76, вып.3, стр.908-923 (1979)

А.М.Дудов, С.Б.Кормер, и др. Исследование конкуренции нелинейных процессов в газообразном SF_6 при накачке импульсом длительностью 2 нс.
Письма в ЖЭТФ, том 33, вып.7, стр.363-368 (1981)

С.Б.Кормер, Г.Г.Кочемасов, и др. Применение нелинейных процессов для формирования субнаносекундных высококонтрастных лазерных импульсов.
ЖЭТФ, том 82, вып.4, стр.1079-1091 (1982)

В.И.Анненков, В.А.Багрецов и др. Импульсный лазер мощностью 120ТВт «Искра-5».
Квантовая электроника, т.18, №5 (1991)

R.I.Il'kaev, G.A.Kirillov, et al. HGTF – laser facility for thermonuclear gain investigations.
IAEA Technical Committee Meeting on Drivers for Inertial Confinement Fusion, Paris, France, November, 14-18, Conference Proceedings, pp.191-209 (1994)

G.A.Kirillov, G.G.Kochemasov, et al. HE-pumped iodine laser for plasma and high intensity interactions
12th International Conference on Laser Interaction and Related Plasma Phenomena, Osaka (Japan) 1995 AIP Conference Proceedings 369, part two, pp.866-871 (1996)

S.M.Kulikov, Yu.V.Dolgopolov, et al. Laser with phase conjugation for high intensity interactions.
Laser and Particle Beams, vol.17, no.4, pp.765-772 (1999)

Н.Ф.Андреев, В.И.Беспалов и др. Новая схема петаваттного лазера на основе невырожденного параметрического усиления чирпированных импульсов в кристаллах DKDP.
ЖЭТФ, т.79, вып.4, стр.178-182 (2004)

Г.Г.Кочемасов. О лазерах, ОВФ и плазме. Сборник научных трудов. Саров, РФЯЦ-ВНИИЭФ, с.264 (2004)

С.Г.Гаранин, А.И.Зарецкий и др. Канал мощной установки «Луч» с энергией импульса 3,3кДж и длительностью 4нс.
Квантовая электроника, т.35, с.299-301 (2005)

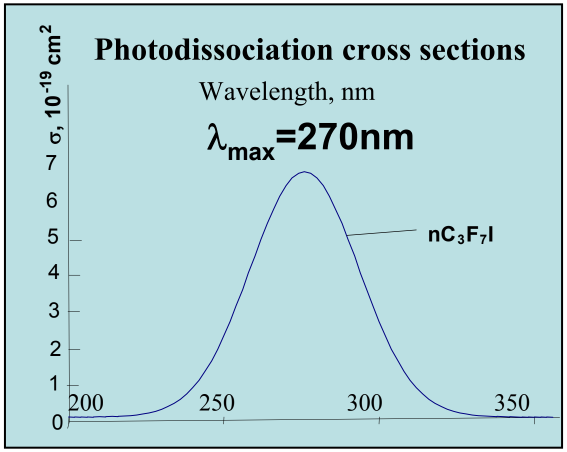
Р.И.Илькаев, С.Г.Гаранин. Исследование проблем термоядерного синтеза на мощных лазерных установках.
Вестник РАН, №6, стр.503-513 (2006)

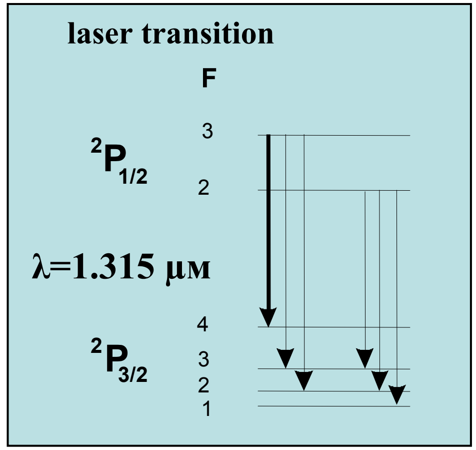
Г.А.Кириллов. Научные исследования. Мощные лазеры.
Атом, т.30, стр.30-32 (2006)

Г.А.Кириллов. Исследования поведения вещества в экстремальных условиях. Монография. Саров, РФЯЦ-ВНИИЭФ, с.310 (2008)

Photodissociation iodine laser

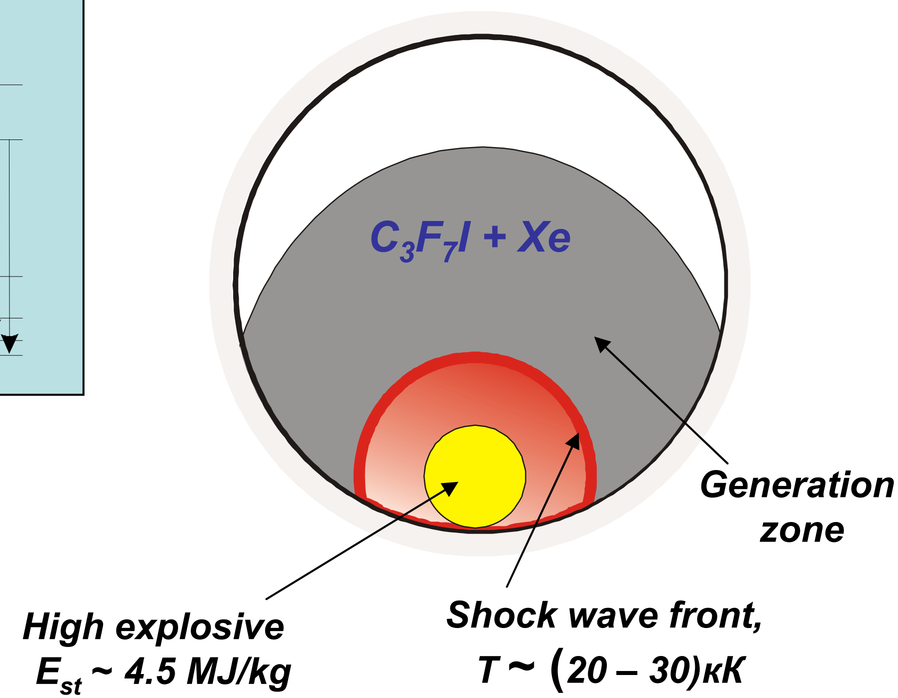
$$C_3F_7J + h\nu_{pump} \rightarrow C_3F_7 + I^*(^2P_{1/2}) \rightarrow I\,(^2P_{3/2}) + h\,\nu_{gen}$$





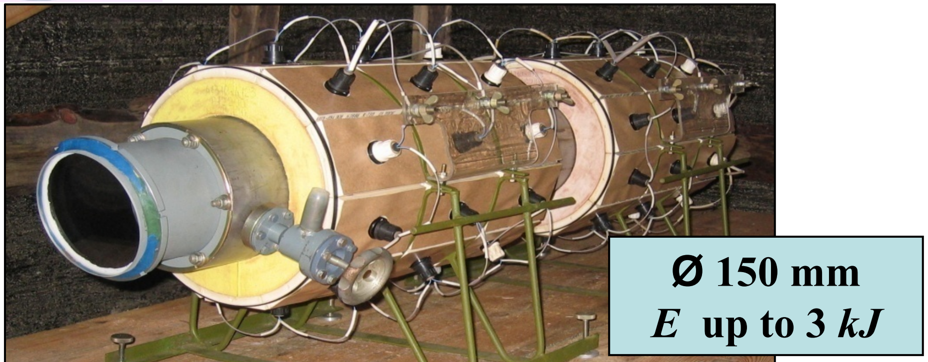
homogeneous EPIL

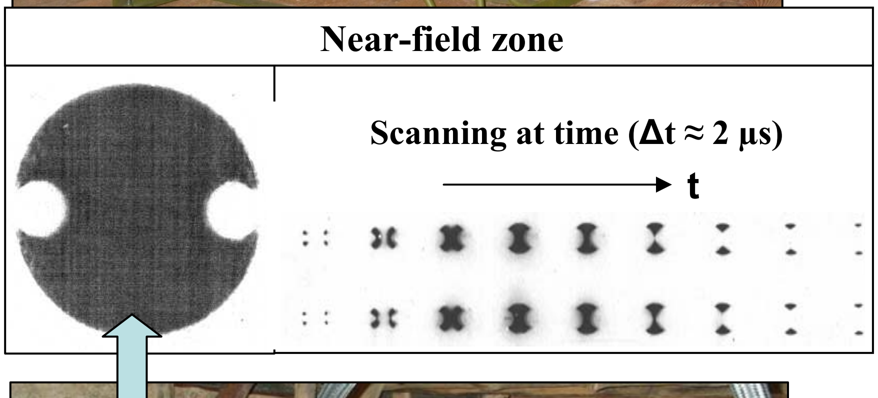
Working mixture :
(2÷25) torr C_3F_7J+(50 ÷700) torr *Xe*

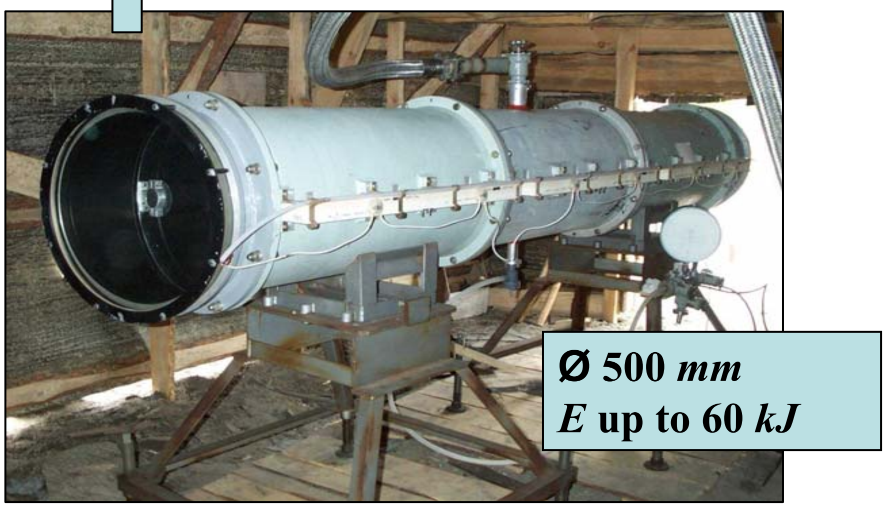


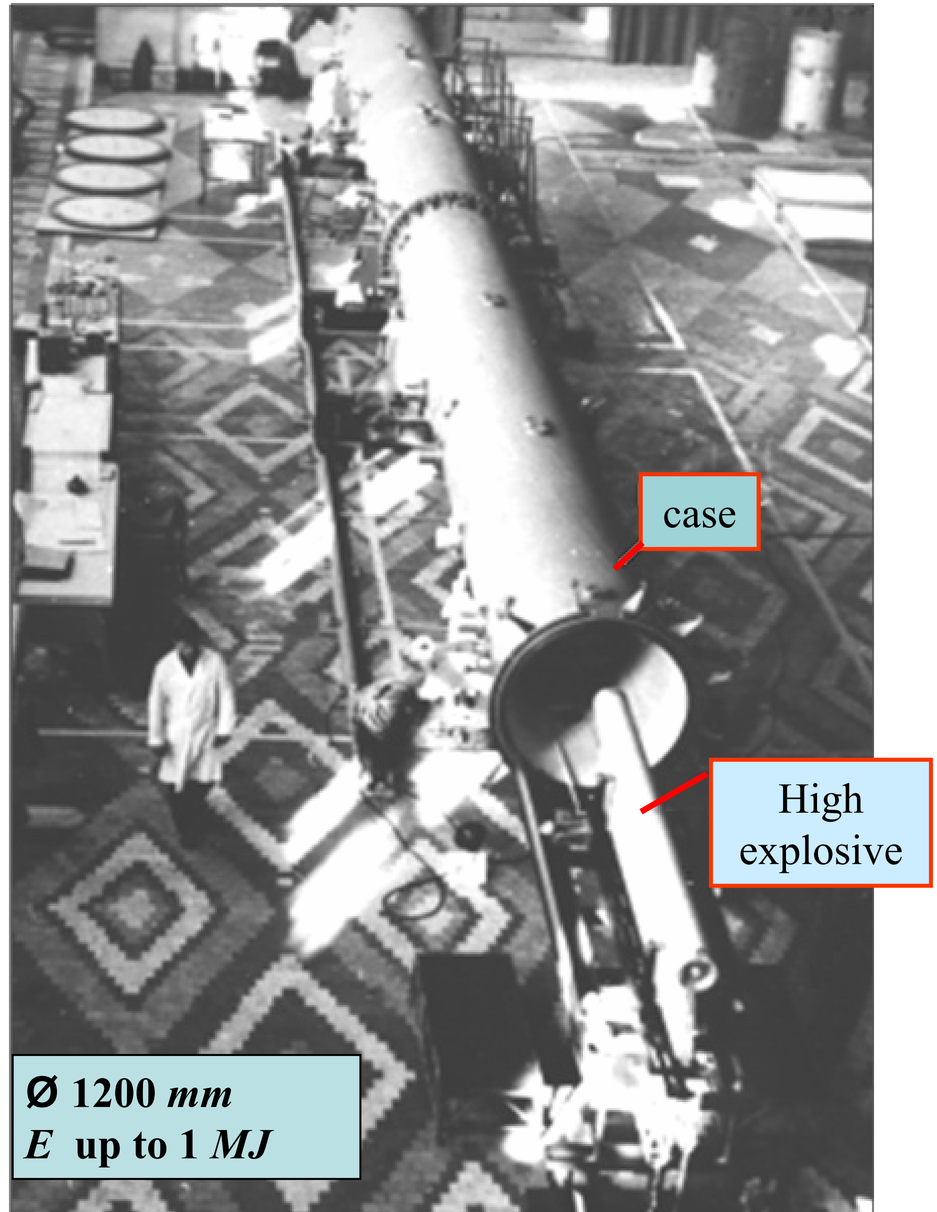
Ø, m	E_{res} (kJ/m)	τ_{gen}, μs
0.15	0.5	10
0.5	3	30
1.3	30	100

High-explosive pumped photodissociation iodine laser (technical realization)

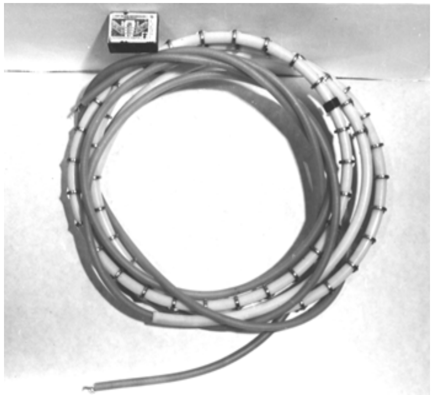






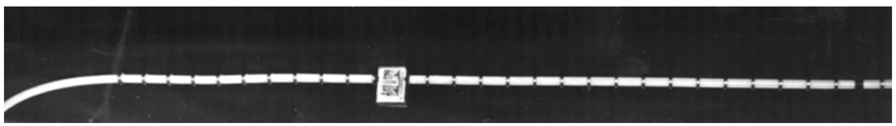


Photodissociation laser – short pulse regime ($\tau \approx 0.1$-10ns)

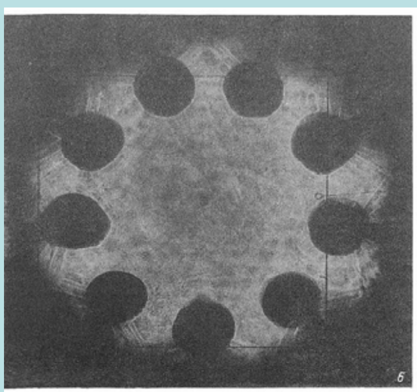


Pumping source	Electric-discharge			Shock wave front		
Laser	"Iskra-3"	"Iskra-4"	"Iskra-5"	"VM-1"	"VM-2"	"Plamya"
∅, cm	40	40-70	70	15	50	130
$E_{channel}$, kJ	0.5	1-2	2.5	0.2	1	up to 6
P channel, TW	0.3	2-10	5-8	0.2	1	up to 6

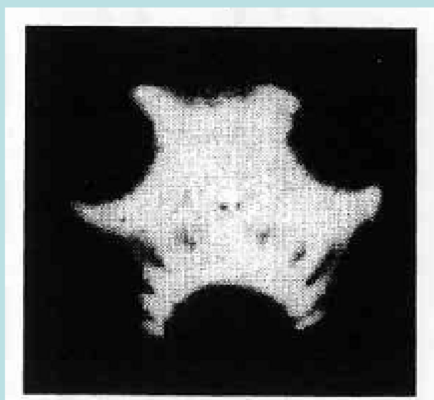
Electric-discharge pumping source ***(more than 200 shots)***



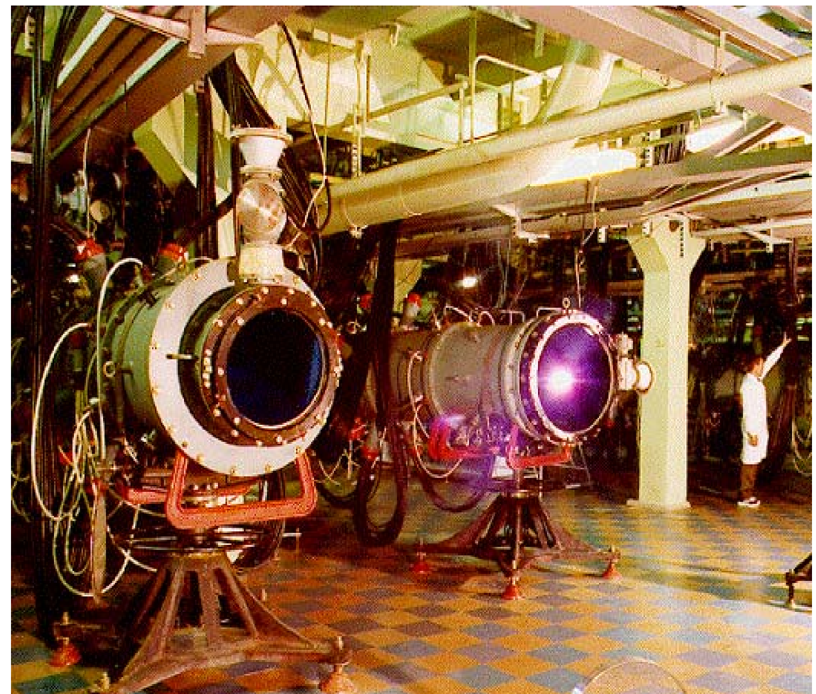
Near-field zone



"Iskra-4"



"Plamya"



"Iskra-5". 12 channels. P_{Σ}=120TW

Converting of iodine laser radiation (λ=1.315mm) to the second harmonic

Nonlinear element – DKDP (>85%)

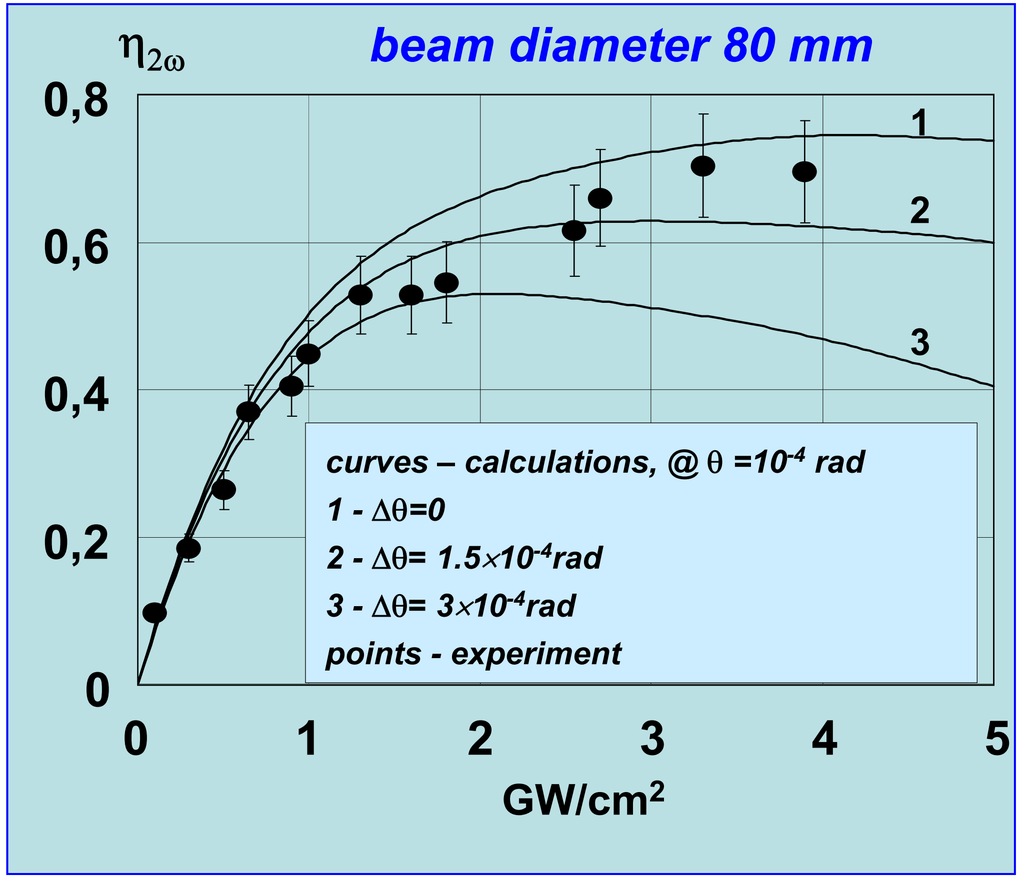
Fast directed growth

210×210×18mm

produced by **IAP RAS**

Experimental results:

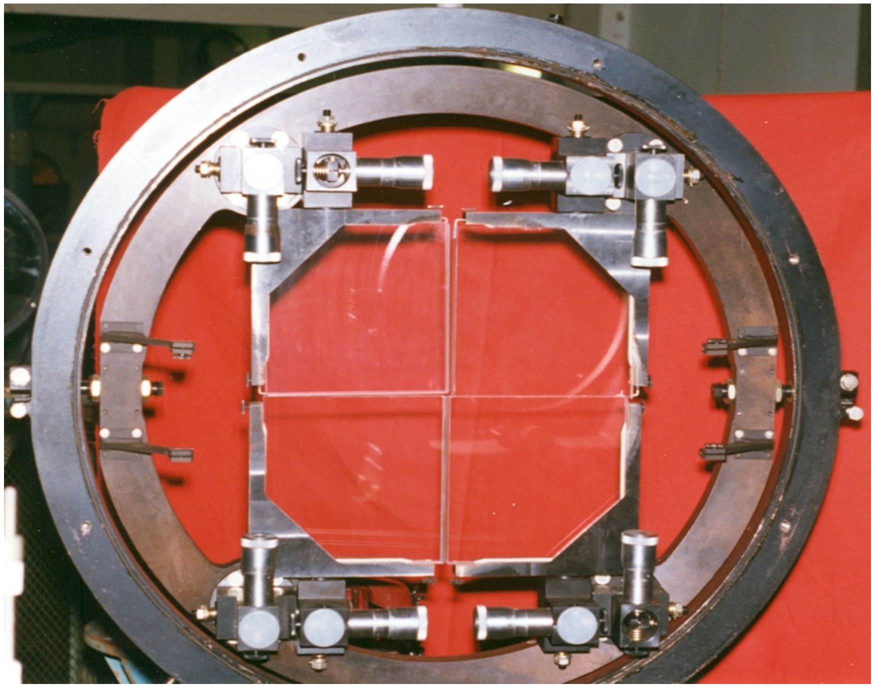
- converting efficiency ~70% @ ~(3-4)GW/cm^2
- simulations and experiments are in good agreement



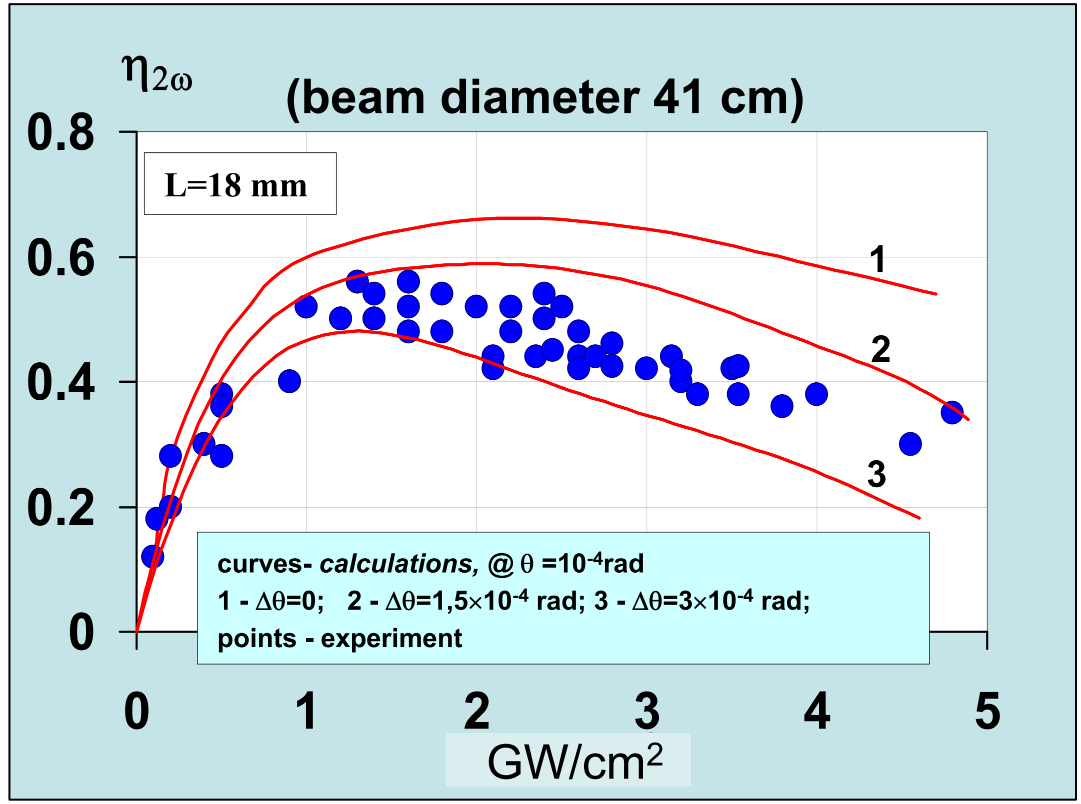
Dependence of experimental converting efficiency on input radiation intensity

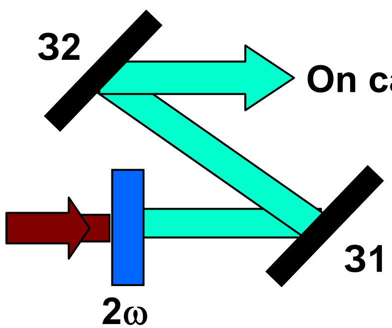
Converting of the «Iskra-4» iodine laser radiation (λ=1.315mm) to the second harmonic

Full-scale experiments with mosaic converters



mosaic converter
2×2 crystals DKDP,
aperture - 42 cm, length - 1,8cm



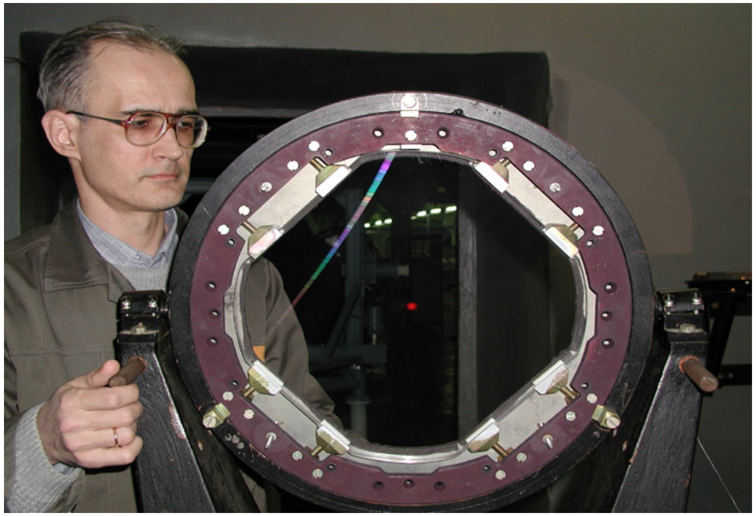


Dichroic mirror:
$R_{2\omega}$>0,95; R_{ω}<0,01

The maximum converting efficiency ≥ 50 %
(is reached at the intensity (1-2.5) GW/cm²)
Maximum energy $E_{2\omega}$ - up to 600J

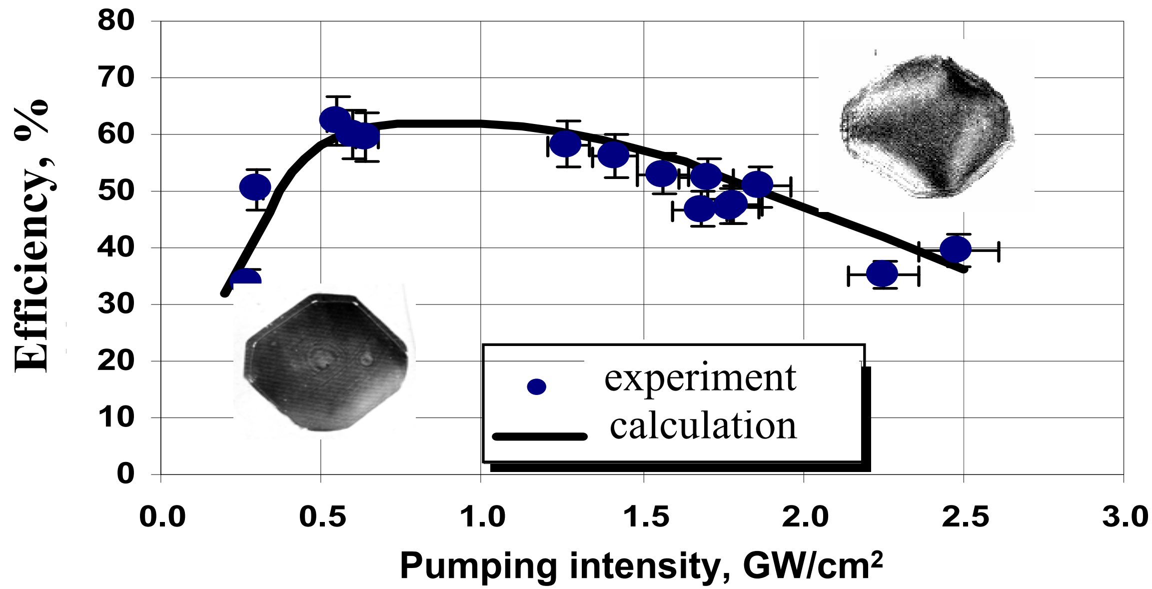
Contrast increase – by 10^4 times

Conversion of the «Iskra-5» facility to the second harmonic operation mode



Crystal DKDP
(aperture 35cm, length 2cm)
produced by IAP RAS

Experimental and calculated converting efficiency to 2nd harmonic vs input radiation intensity



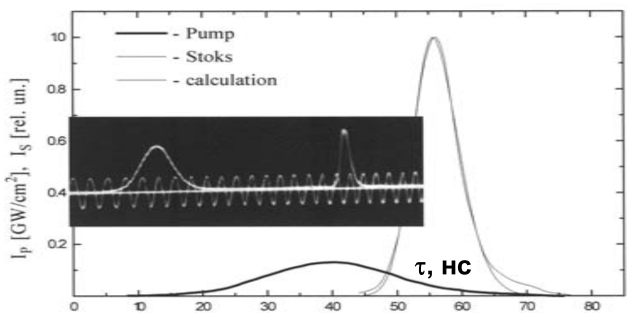
- **The maximum second harmonic conversion efficiency – about 60%**
  (is reached at the intensity (0.5-1.5)GW/cm^2)
- **Total energy in 12-channel's experiments is 3kJ**
  (pulse duration 0.5ns)

Research of the transverse SBS and SRS in anisotropic crystals (KDP and DKDP)

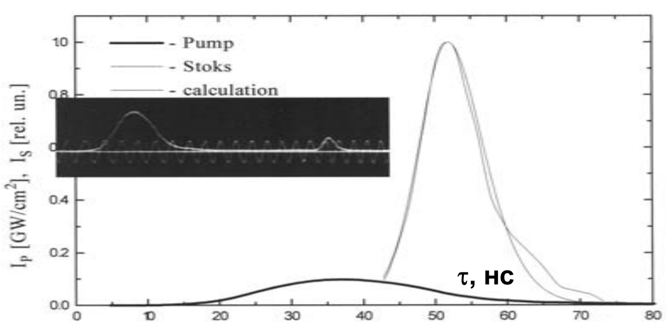
Aim– *experimental definition of stationary small signal gain (g).*

Method – *excitation of induced scattering in the resonator.*

SBS at DKDP



Test (quartz)



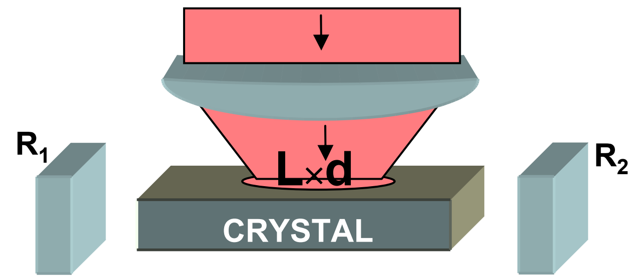
Crystal DKDP

The work is fulfilled under the contract with LLNL
(№B239660, 1997)

E(λ=0.53μm) ≈0.5J

τ_{puls}=25ns

L×d=7×0.4mm



g, cm/GW	4.4±0.4
τ_F, ns	3±0.5
$\Delta\nu_S$, cm^{-1}	0.74±0.03
V_{sound}, km/s	5.7±0.2
[1] g=3.53-5.09 cm/GW	

1. G.W.Faris, L.E.Jusinski and A.P.Hickman. "High-resolution stimulated Brillouin gain spectroscopy in glasses and crystals". J.Opt.Soc.Am.B,v.10,№ 4,p.587 (1993).

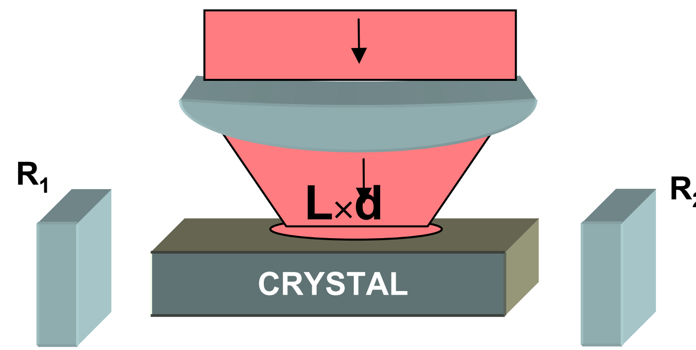
SRS in KDP and DKDP

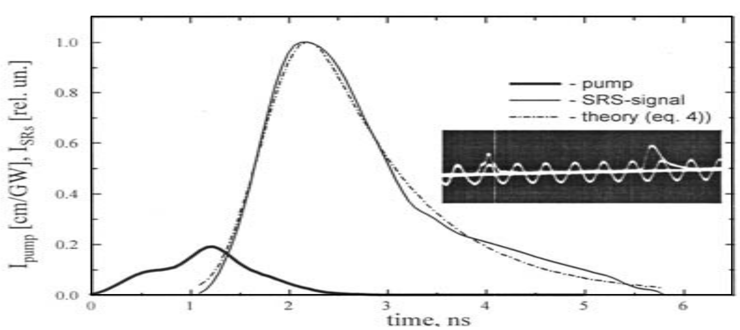
	KDP	DKDP (80%)
g (cm/GW) our measurements	0.29±0.03 λ_p=438nm	0.18±0.05 λ_p=438nm
g (cm/GW) recalculated	0.24±0.03 λ_p=530nm	0.1±0.03 λ_p=353nm
g (cm/GW) data from LLNL	0.21±0.04 λ_p=530nm	0.098±0.07 λ_p=353nm

E(λ=0.438μm) ≈5J

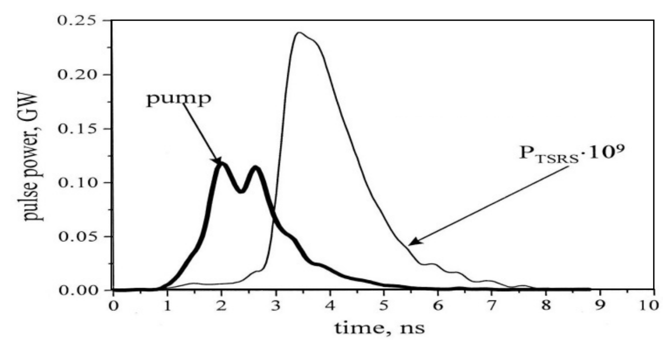
τ_{puls}=(0.5-3)ns

L×d=15×2mm





Test (benzol)



Crystal KDP

The work is fulfilled under the contract with LLNL

(contract №B239661, 1997)

EPIL divergence

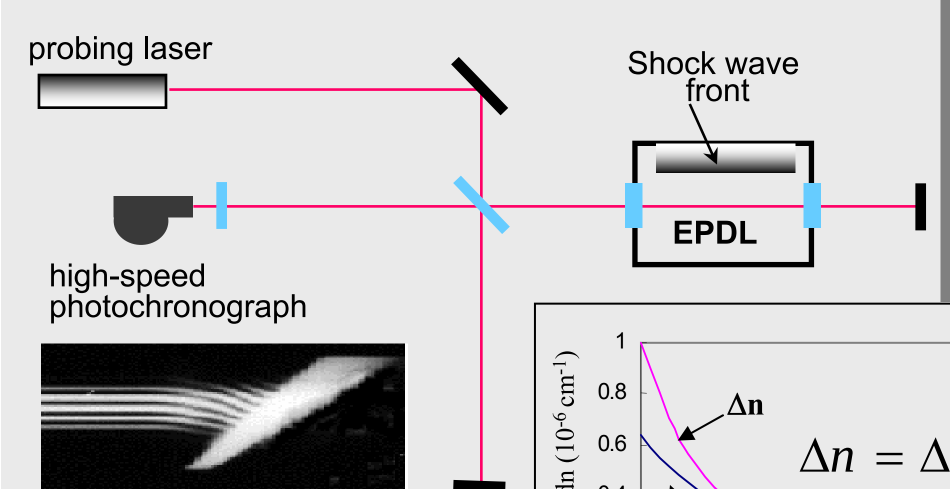
Efficiency $\Rightarrow \left\{ \begin{array}{l} \varepsilon\ [J/cm^2] \\ I\ [W/cm^2] \end{array} \right\} \Rightarrow B \sim \dfrac{E}{\theta^2}\ [J/sr]$ *or* $\dfrac{P}{\theta^2}\ [W/sr]$

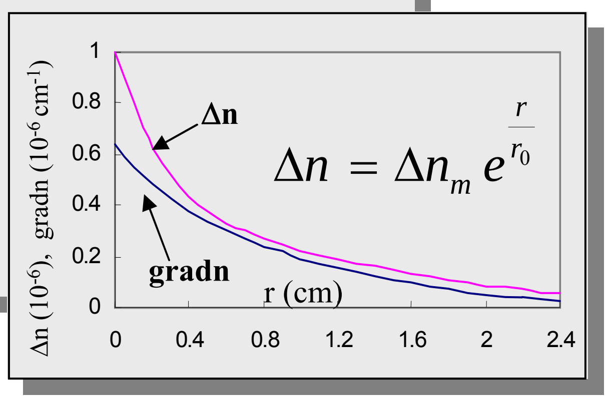
$\theta_{gen} \sim (10^{-2} \div 10^{-3})$ *rad* ⇒ *up to* $\sim 1000\ \theta_{diff}$ $B \approx 10^{10}$ *J/sr* *(for the MJ laser)*

Optimizations of active medium composition

Design of new type resonator

Measurement layout (Michelson interferometer)





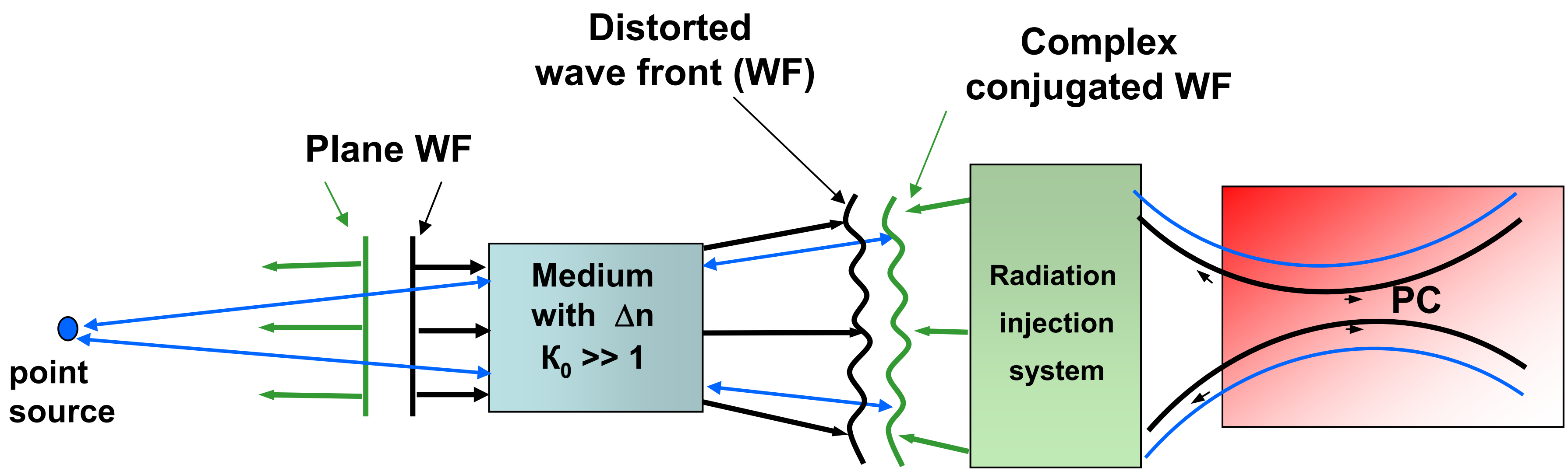
$\Delta n_{max} = 4.6 \cdot 10^{-6}$ ⇒ $\Delta n_{min} \rightarrow 0.4 \times 10^{-6}$

$\theta_{gen} \approx \theta_{ampl} \approx 2\, L_a\, \mathrm{grad}\, n$

$\Theta_{min} \approx (2 \div 3) \cdot 10^{-4}$ rad

$B_{max} \approx 2 \cdot 10^{12}$ J/sr

Phase conjugation (PC)



Key element – PC-mirror ⇐ **SBS in compressed gases($\Delta\nu_S < \Delta\nu_{ampl}$)**

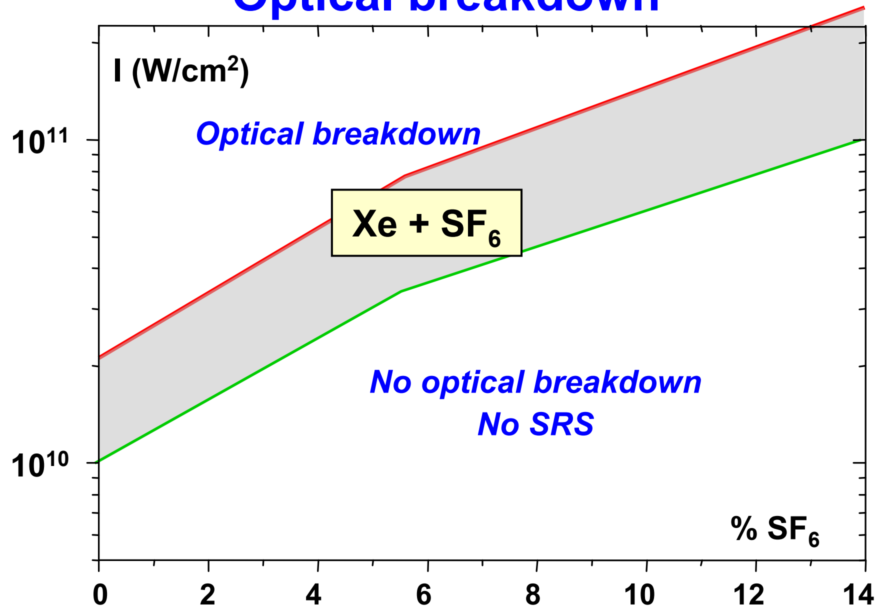
Medium	*P*, atm	*g*, cm/MW	*I*pump, MW/cm²	$\Delta\nu_S$, cm^{-1}
Xe	53	0.06	40-170	0.07
SF_6	17	0.028	1000	0.06

← *Optical breakdown* (Xe)

← *SRS* (SF_6)

PC at SBS and competing processes

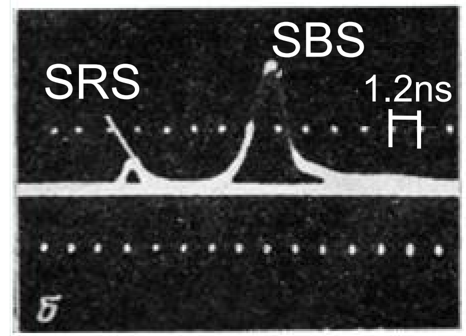
Optical breakdown

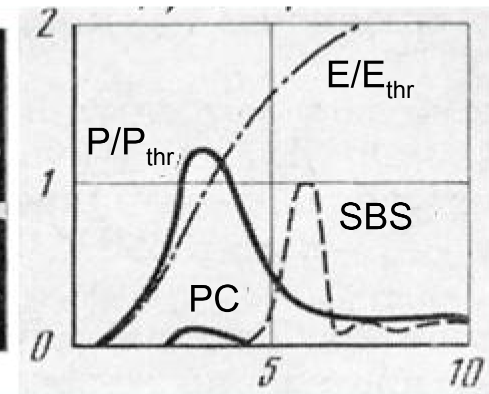


Working medium	Xe + SF_6
Operating pressure	up to 60 atm
Partial pressure	1:0.1
Purification efficiency	99.999%

Competition of SRS and SBS

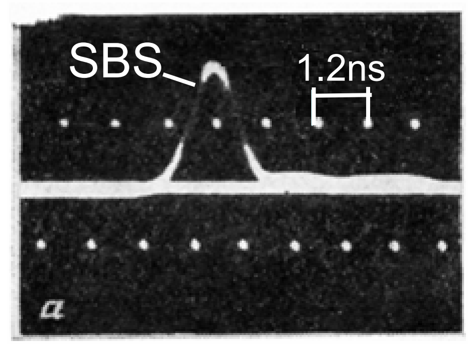
Steep front of pumping pulse





1. $P_{threshold}$ SRS
2. $E_{threshold}$ SBS

Sloping front of pumping pulse



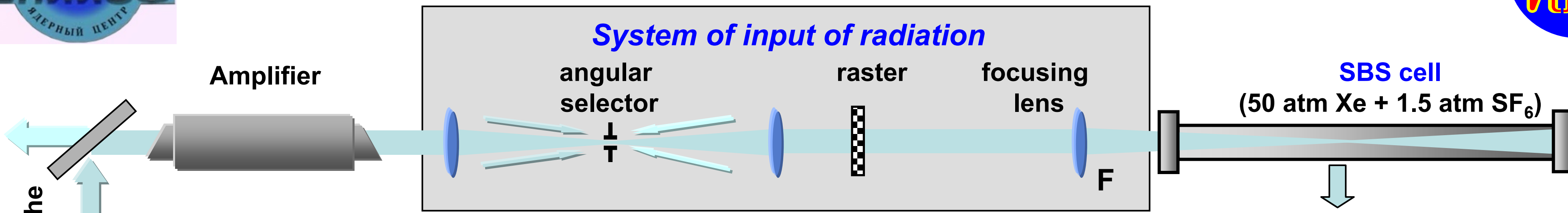
1. $E_{threshold}$ SBS

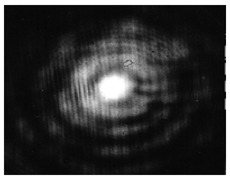
Condition for the production of SBS without SRS

$$\tau_{fr} > G\tau_{P\ SBS} \frac{g_{SRS}}{g_{SBS}}$$

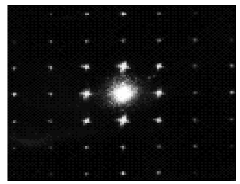
Master oscillator with PC ⇒ «Iskra-4» ⇒ $\tau_{pulse} = 0.1$ ns ⇒ P = 10 TW for one channel

EPIL with phase conjugation

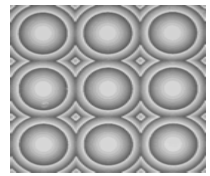




far-field region of output pulse

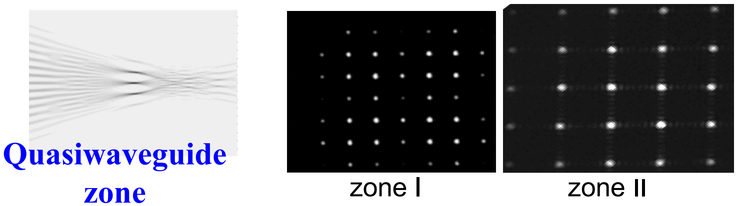


Stokes beam on the angular selector

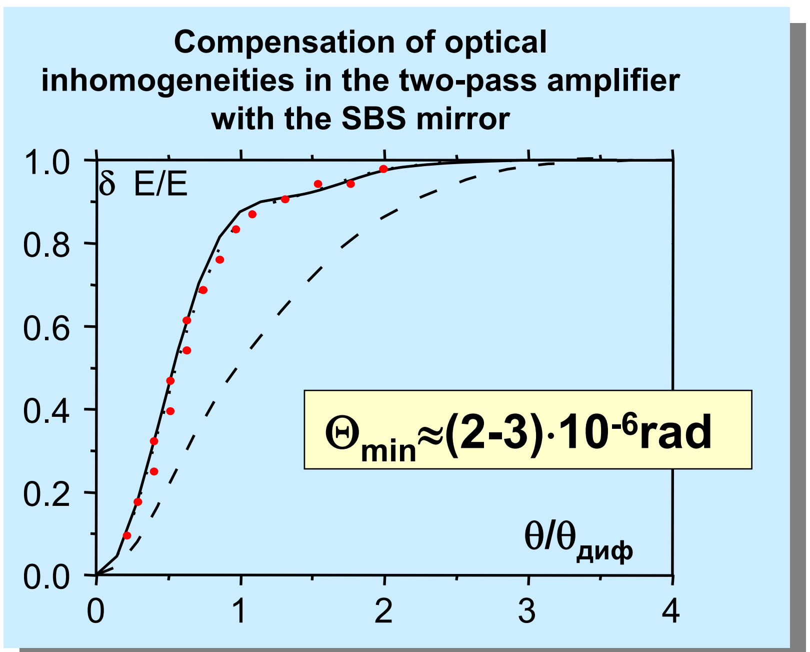


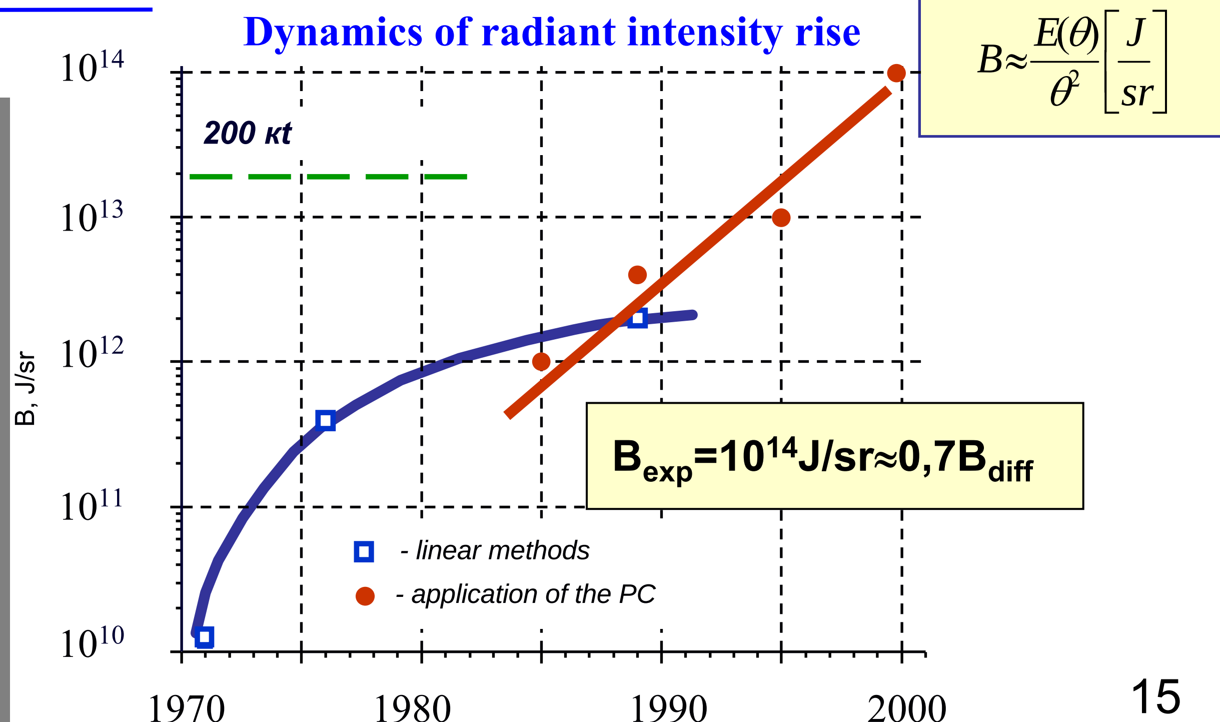
Lens raster (Fragment)

Beam structure in SBS cell



Selection of conjugated component





Production of superstrong electromagnetic fields by means of the EPIL with phase conjugation

TRADITIONAL APPROACH:
reduction of pulse duration
(femtosecond lasers)

→ $\tau \sim (100 \div 10)$fs
$d_f > 10$ μm

→ $I_f \sim$ up to 10^{20} W/cm^2

EPIL with PHASE CONJUGATION:
reduction of focal spot

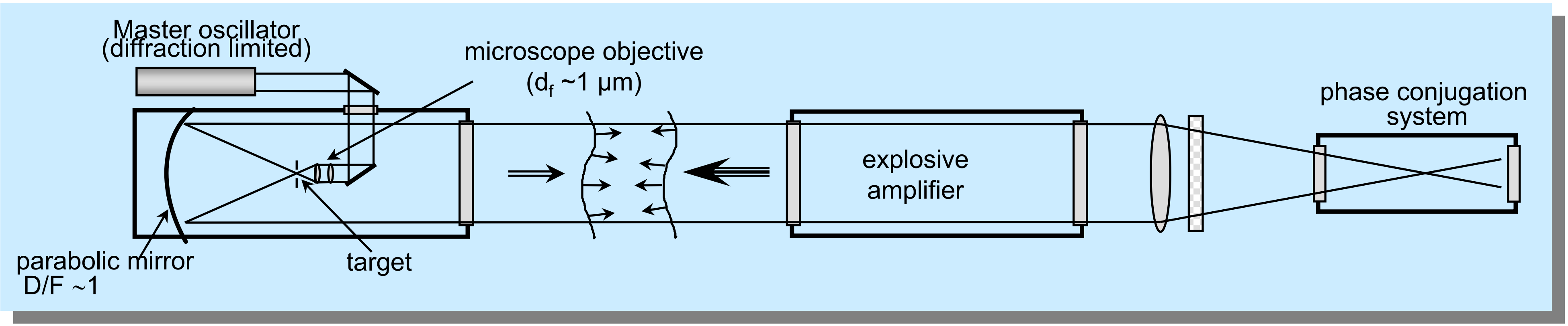
→ $\tau \sim (0.1 \div 1)$ns
$d_f \sim \lambda \sim 1$ μm

→ $I_f \sim$ up to 10^{20} W/cm^2

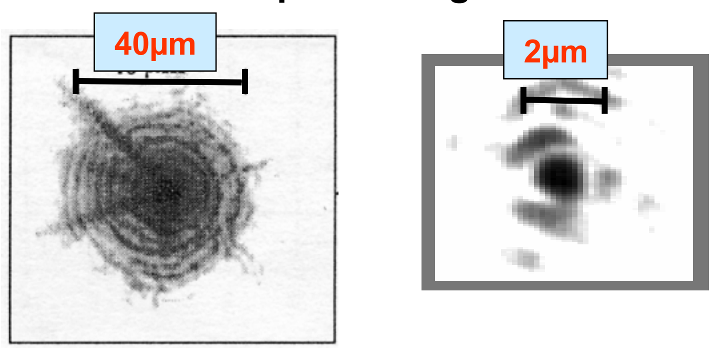
What it gives:

- **possibility to investigate matter behaviour in quasi-stationary fields** ***(as compared to relaxation time of atom)***
- ***possibility of process dynamics observation***
- ***practically monochromatic conditions***

Experiment



Spot on target



without PC   with PC

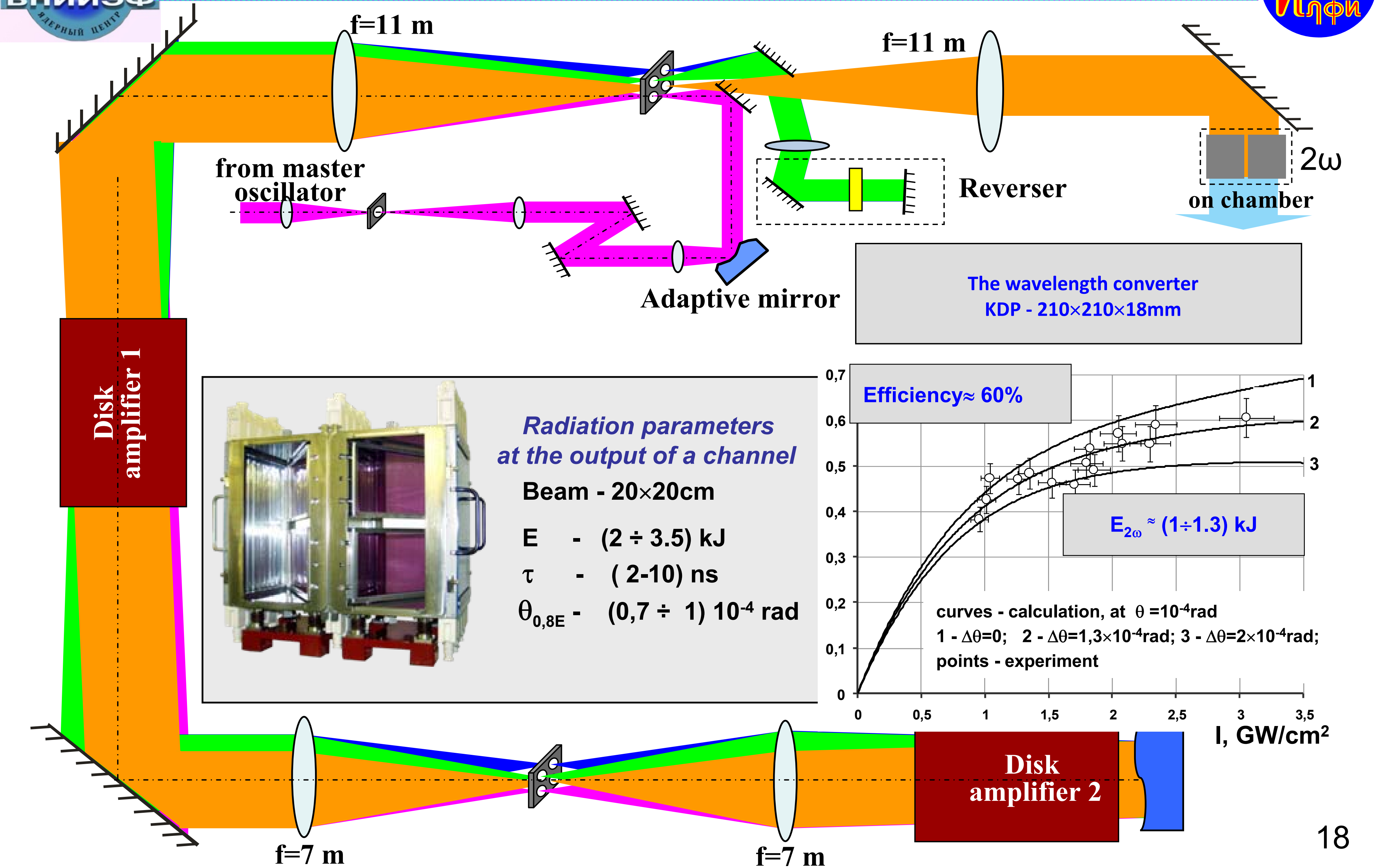
Pulse energy ≈100J

Pulse duration ≈1ns

Intensity on a target ≈10^{18}W/cm^2

Field strength ≈10^{10}V/cm

“Luch” facility. *Wavelength conversion.*



Radiation parameters at the output of a channel

Beam - 20×20cm

E - (2 ÷ 3.5) kJ

τ - (2-10) ns

$\theta_{0,8E}$ - (0,7 ÷ 1) 10^{-4} rad

Petawatt laser system (together with IAP RAS)

Parametric amplification of broadband chirped pulses

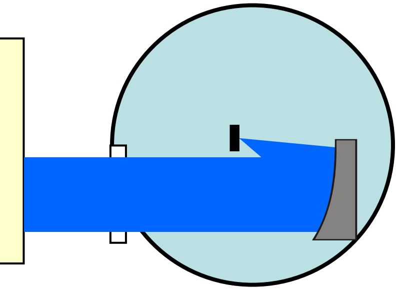
starting system:
MO (50fs),
stretcher,
OPA-1, OPA-2
DKDP
(40×40×75mm)
λ=0.91μм
E=0.1J
τ=0.5ns
f=(1-2)Hz

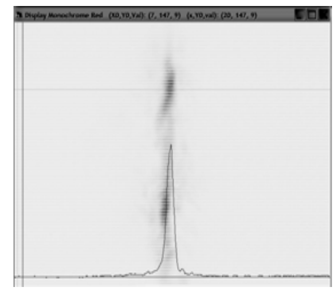
preamplification system
OPA-3
DKDP
(100×100×55mm)
E=10J

output system
OPA-4
DKDP
(300×300×55mm)
E=100J

«Luch» Channel
λ=527nm
E≈1kJ;
τ≈2.5ns

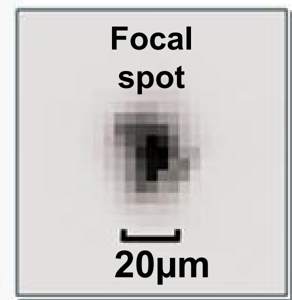
compressor
T≈70%

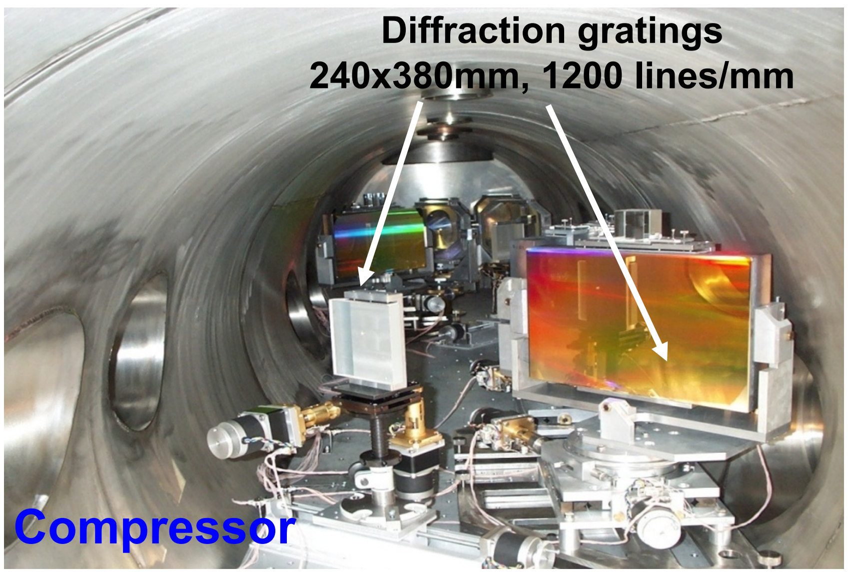




τ=60fs

P=100TW
P=1PW

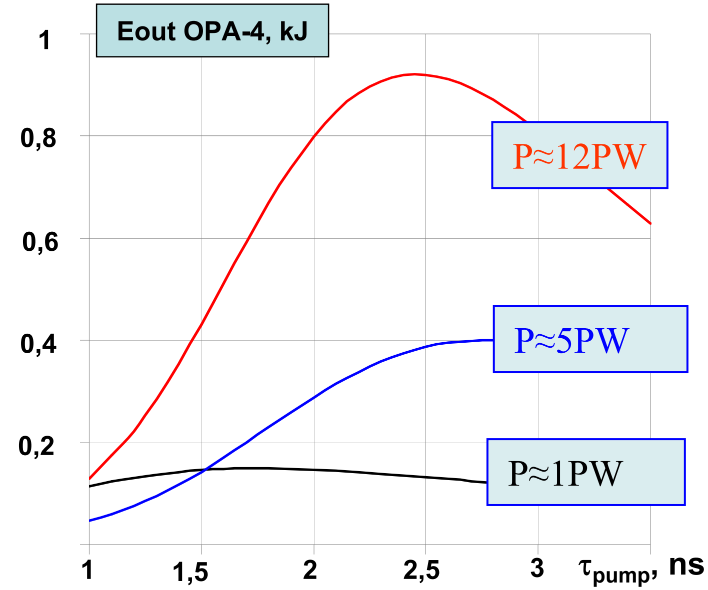




I ~ 10^{19}W/cm²
I ~ 10^{20}W/cm²

Possibility of power increasing

Characteristic	P≈1PW *60J/50fs*	P≈5PW *250J/50fs*	P≈12PW *620J/50fs*
Pumping energy OPA-4, kJ	*1.1*	*1.2*	*1.8*
Pumping pulse duration, ns	*2.8*	*2.5*	*2.5*
Temporal profile of pumping pulse	*Gaussian (n=2)*	*Super-Gaussian (n=6)*	*Super-Gaussian (n=6)*
Chirped pulse energy (J) at the OPA-4 entrance	*1*	*2*	*2*
Chirped pulse duration , ns	*0.42*	*1.5*	*2.5*
Temporal profile of chirped pulse	*Gaussian (n=2)*	*Gaussian (n=2)*	*Super-Gaussian (n=6)*
Beam size of chirped pulse (λ=911nm), cm	*∅18*	*∅18*	*20x20*



Crucial problem:

- low damage threshold of diffraction gratings.

traditional: ≈ 0.5J/cm^2

dielectric: ≈ 2.5J/cm^2

- producing of large aperture DKDP crystals of necessary quality with high damage threshold.

Conclusion

1. **The investigations of phase conjugation effect at the stimulated scattering in compressed gases, including a competition of nonlinear processes (SBS, SRS, optical breakdown) have been done.**

2. **The phase conjugation application to explosive photodissociation lasers had permitted:**

   - to reach record value of light power $B=10^{14}$ J/sr (10^{19} W/sr), and $B_{exp}\approx 0.7B_{diff}$;

   - to focus radiation in a spot with practically diffraction limit size and to receive intensity of radiation $I \approx 10^{18}$ W/cm^2.

3. **The investigations of harmonics generation has allowed to transfer «Iskra-4», «Iskra-5», “Luch" laser facilities to the second harmonic operating mode with efficiency more than 50 % that has raised efficiency of researches.**

4. **Petawatt laser system based on the one channel of “Luch” facility was created. It exploits the principle of parametric amplification and enables to carry out irradiation experiments with intensity up to 10^{20} W/cm^2.**

THANK YOU FOR ATTENTION