Institute of Applied Physics
of the Russian Academy of Sciences

Nonlinear optics for increasing power and contrast of femtosecond laser pulses

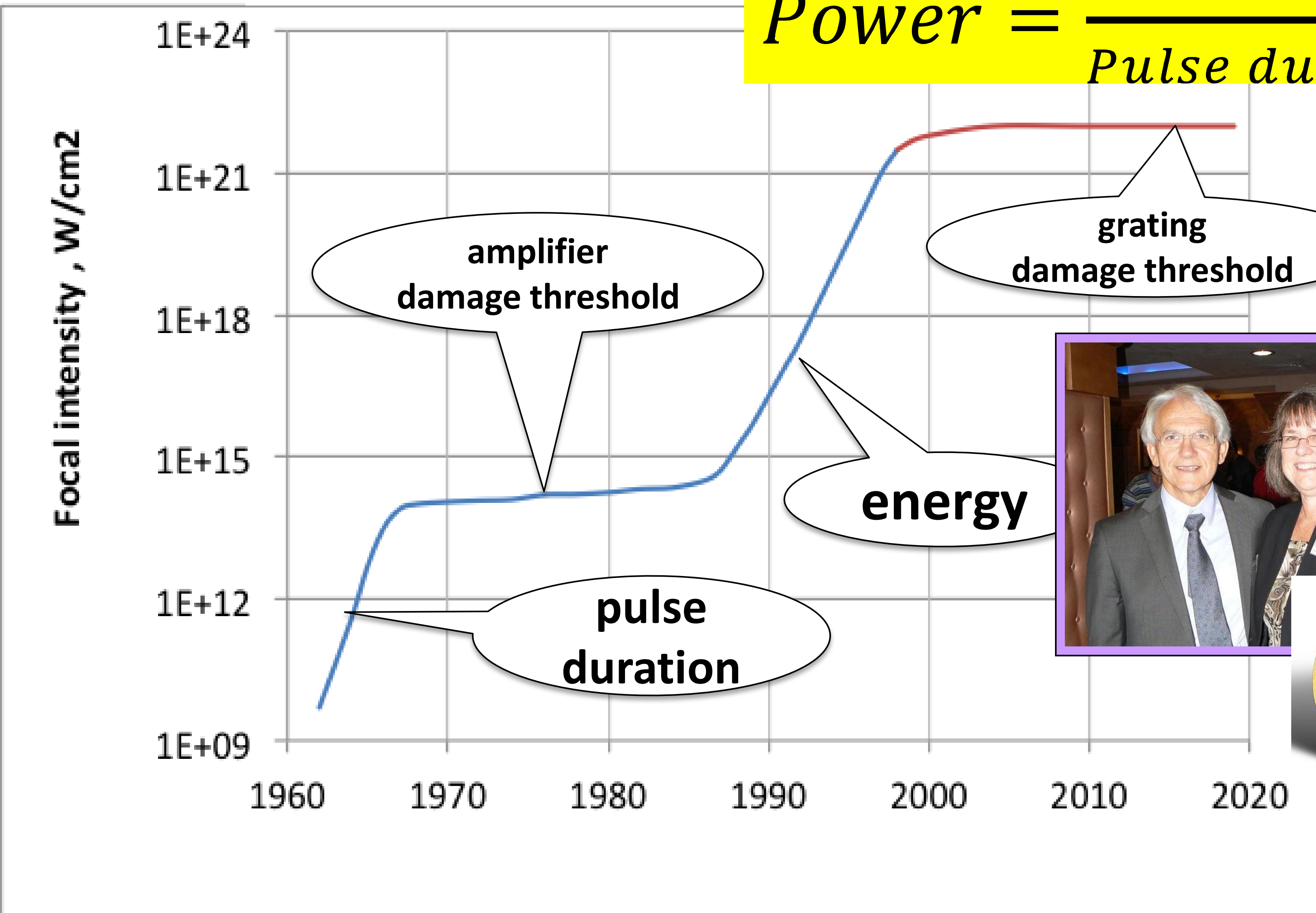
Efim Khazanov

Institute of Applied physics of Russian Academy of Science

- **Motivation**
- **Enhancement of laser pulse power (CafCA)**
- **Enhancement of laser pulse contrast**
- **Conclusions**

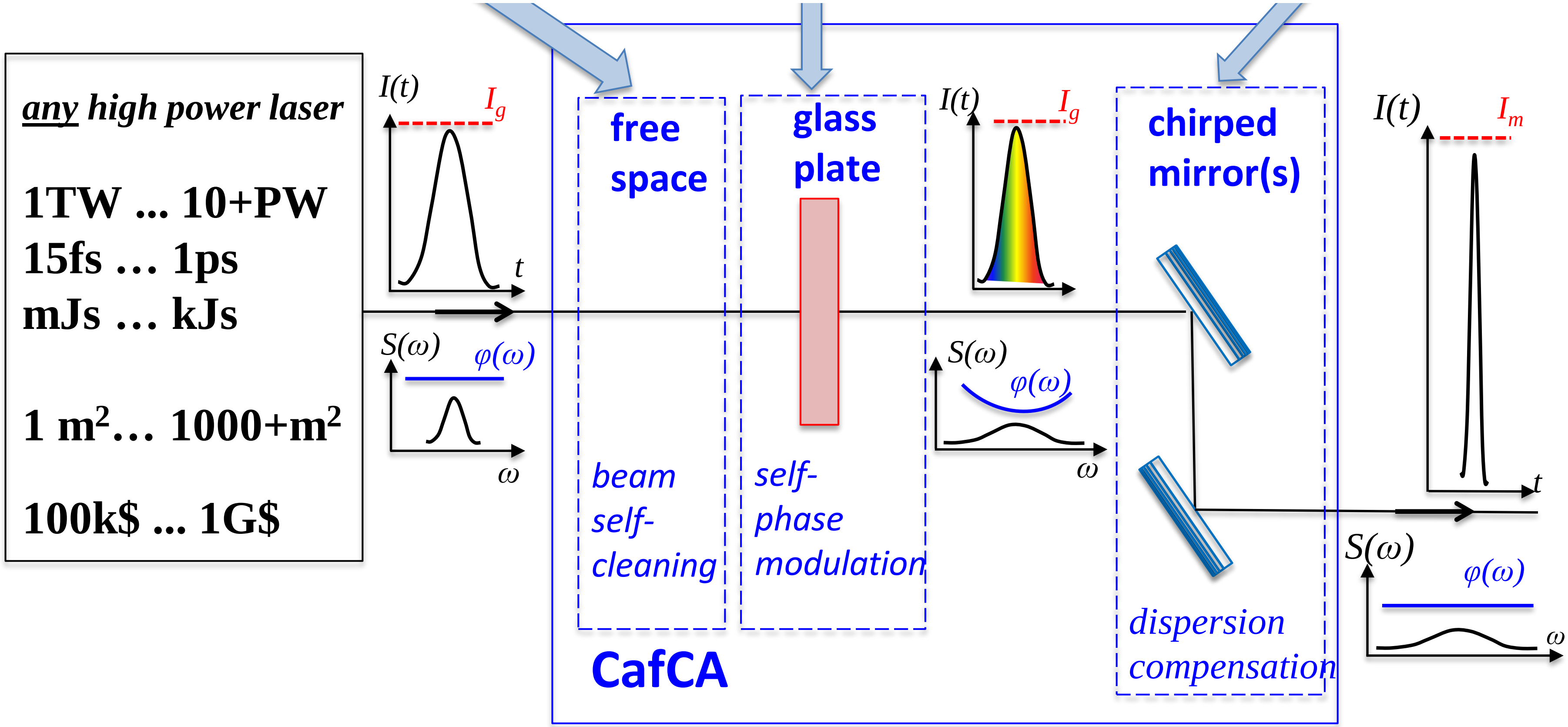
New idea is wanted for the next jump

$$Power = \frac{Energy}{Pulse\ duration}$$



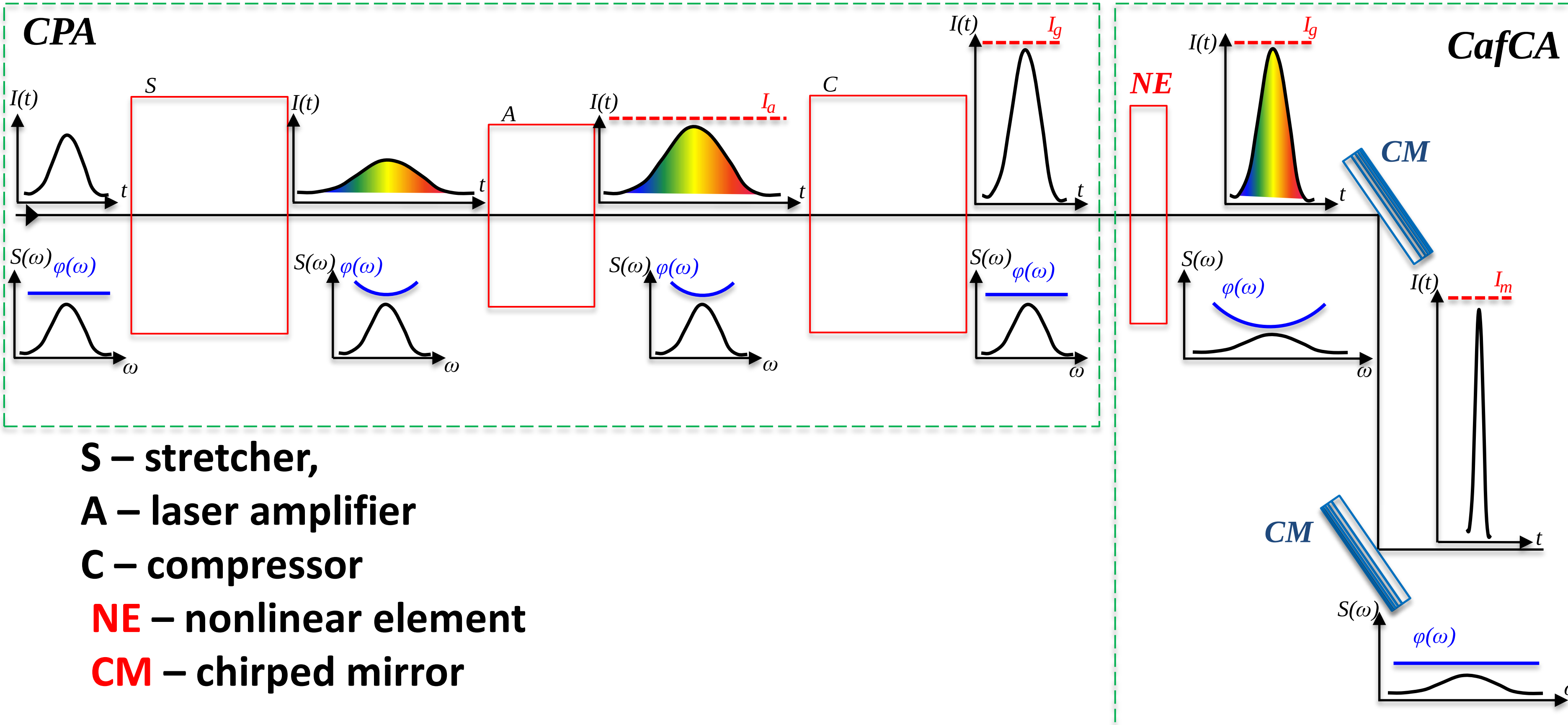
Compression after Compressor Approach (CafCA)

CafCA is simple, robust and cheap recipe: just add free space, glass plate and chirp mirror(s)



R.A. Fisher, P.L. Kelley, T.K. Gustajson, "Subpicosecond pulse generation using the optical Kerr effect" Appl. Phys. Lett 1969
E.Khazanov, S. Mironov, and G.Mourou "Nonlinear compression of high-power laser pulses: compression after compressor approach," Phys. Usp. 2019

CPA + CafCA



S – stretcher,

A – laser amplifier

C – compressor

NE – nonlinear element

CM – chirped mirror

I_a , I_g and I_m– breakdown threshold of the amplifiers, diffractions gratings and chirping mirrors.

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CafCA hystory from nJ to mJ

nJ

Fisher, R.A., Kelley, P.L., and Gustajson, T.K., "Subpicosecond pulse generation using the optical Kerr effect " Applied Physics Letters 14(4), 140-143, 1969.
idea

Laubereau, A., "External frequency modulation and compression of picosecond pulses," Physical Letters 29A(9), 539-540, 1969.
liquid

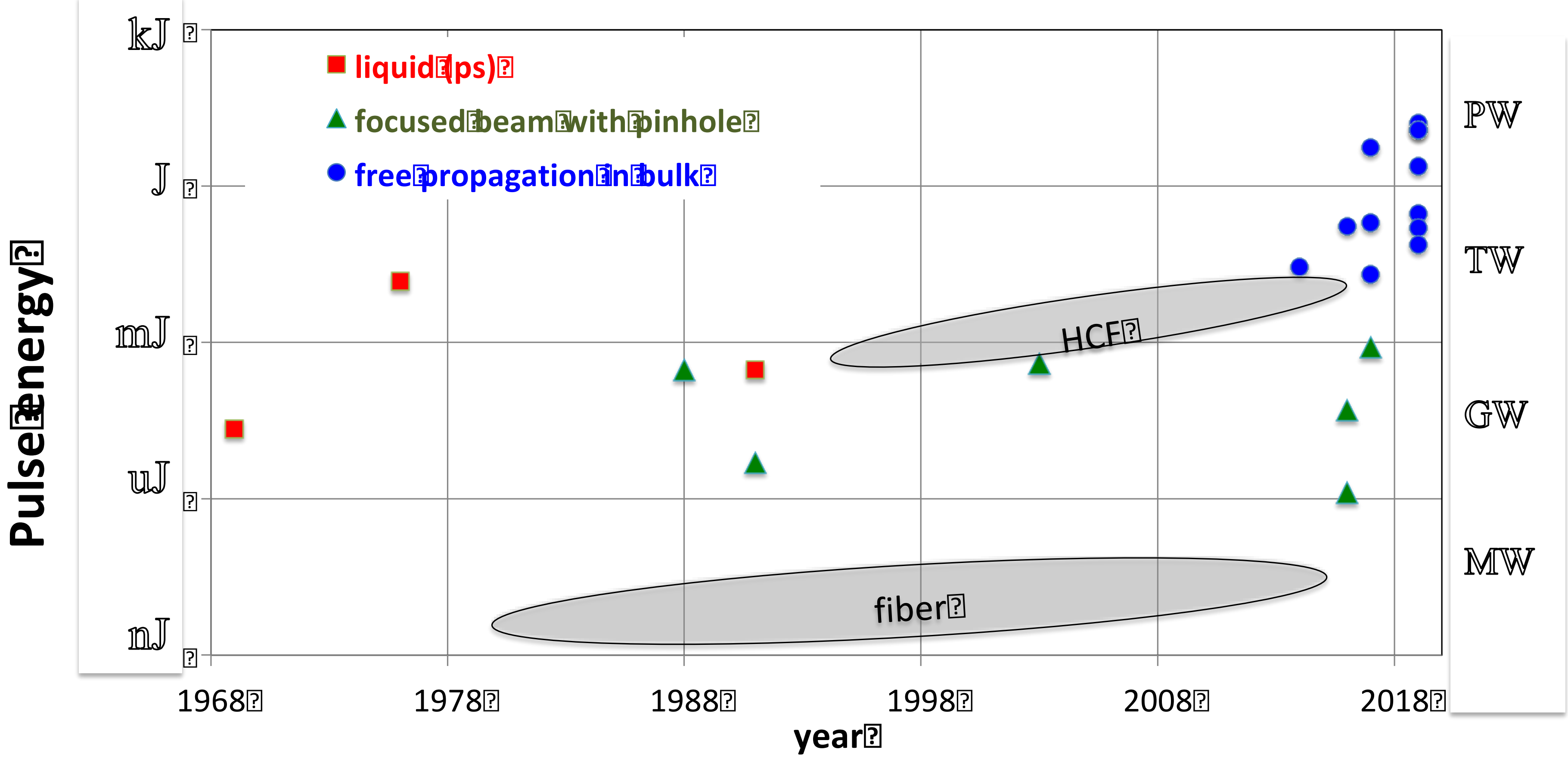
Nakatsuka, H., Grischkowsky, D., and Balant, A.C., "Nonlinear Picosecond-Pulse Propagation- through Optical Fibers arith Positive Group Velocity Dispersion," Physical Review Letters 47(13), 910-913, 1981.
fiber

Rolland, C. and Corkum, P.B., "Compression of high-power optical pulses," Journal of the Optical Society of America B 5(3), 641-647, 1988.
focused beam

Nisoli, M., Silvestri, S.D., and Svelto, O., "Generation of high energy 10 fs pulses by a new pulse compression technique," Applied Physics Letters 68(20), 2793-2795, 1996.
hollow core fiber

mJ

CafCA hystory from nJ to J



CafCA theory basics

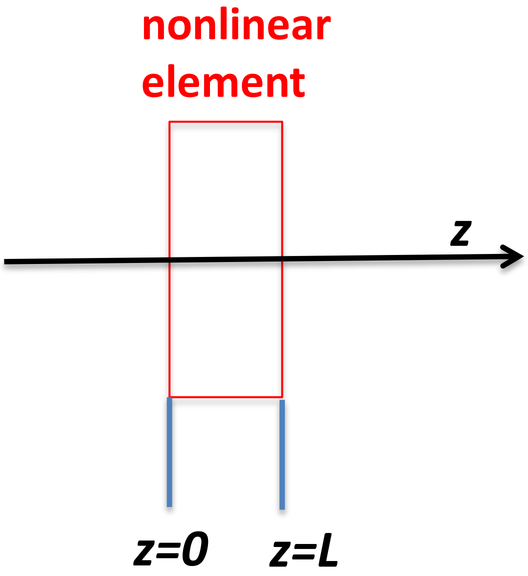
$$\frac{\partial a}{\partial z} - i\frac{D}{2}\frac{\partial^2 a}{\partial \eta} + iB|a|^2 a = 0$$

$a=E(t,z)/E(0,0)$: electric field

$Z=z/L$: normalized distance

$\eta=(t-z/u)/\tau_{pulse}$, : normalized time

τ_{pulse} : pulse duration



$B=n_2IkL=L/L_{nonlinear}$ $D=k_2L(\tau_{pulse})^2=L/L_{dispersion}$

$$F_{power} \approx 1+B/2$$

Small-scale self-focusing limit

$$B < 2\ldots 3$$

$$F_{\text{power}} \approx 1 + B/2$$

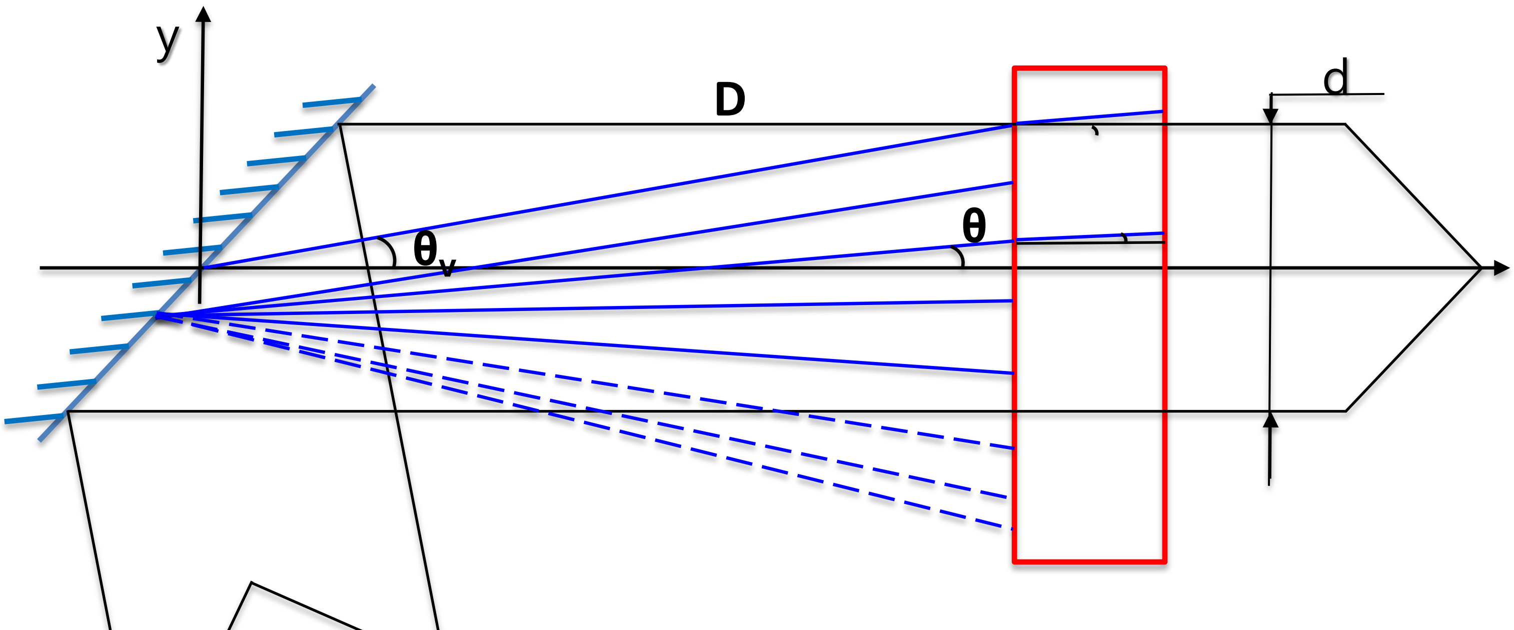
$$F_{\text{power}} < 2\ldots 2.5$$

Beam self-filtering

The technique of beam filtering depends on the intensity level

For ns laser beams intensities I ~ 1÷10GW/cm^2 θ_{max}=0.73÷2 mrad

For fs laser beams intensities I ~ 1÷10TW/cm^2 θ_{max}=20÷50 mrad



Free space propagation leads to beam self-filtering

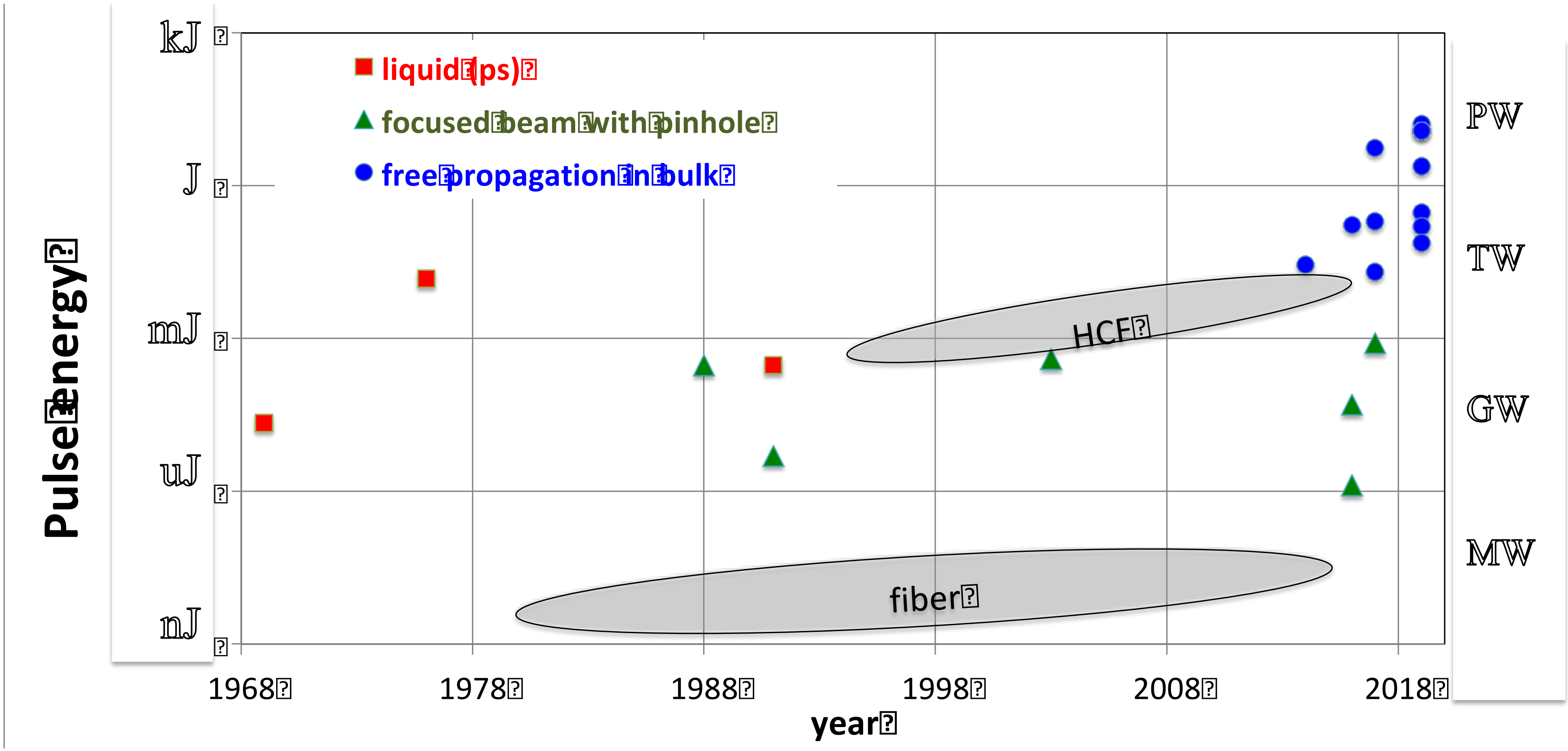
I=1TW/cm^2, d=100mm: the safety distance D>1.6m

$$q_{cr} = 2\sqrt{\frac{gI}{n}}$$

S. Mironov, V. Lozhkarev, G. Luchinin, A. Shaykin, and E. Khazanov, Applied Physics B, 113, 147-151 (2013).

CREMLIN PLUS

CafCA hystory from nJ to J



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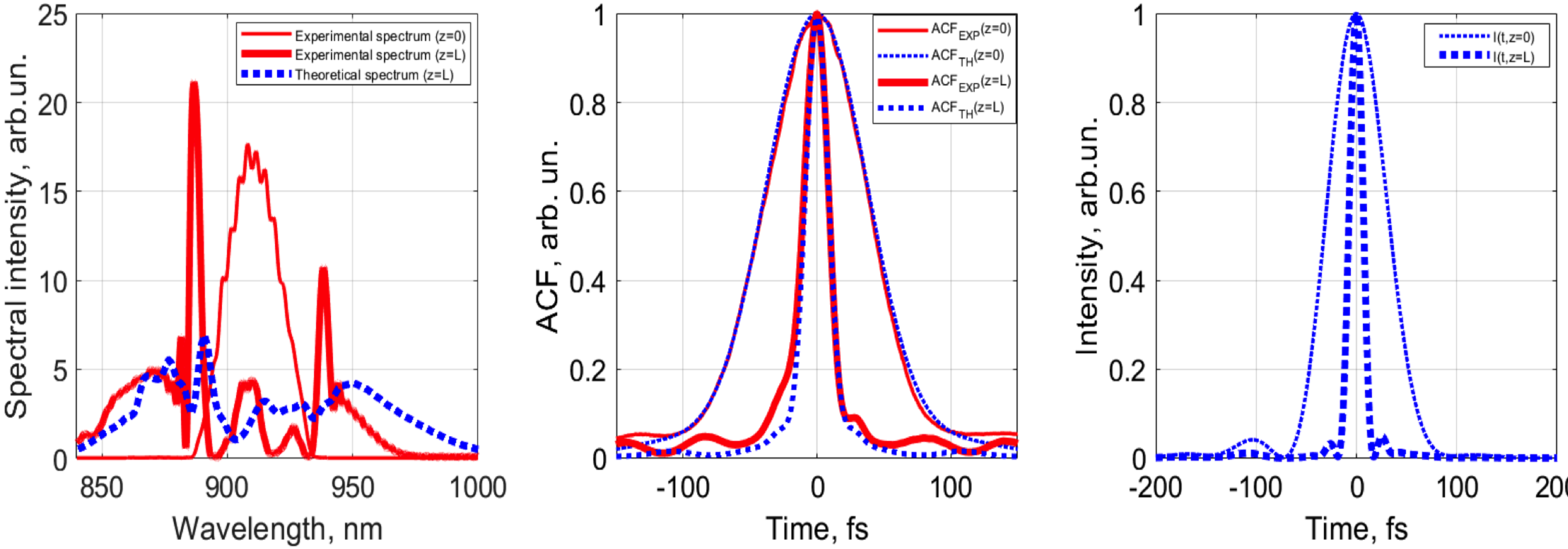
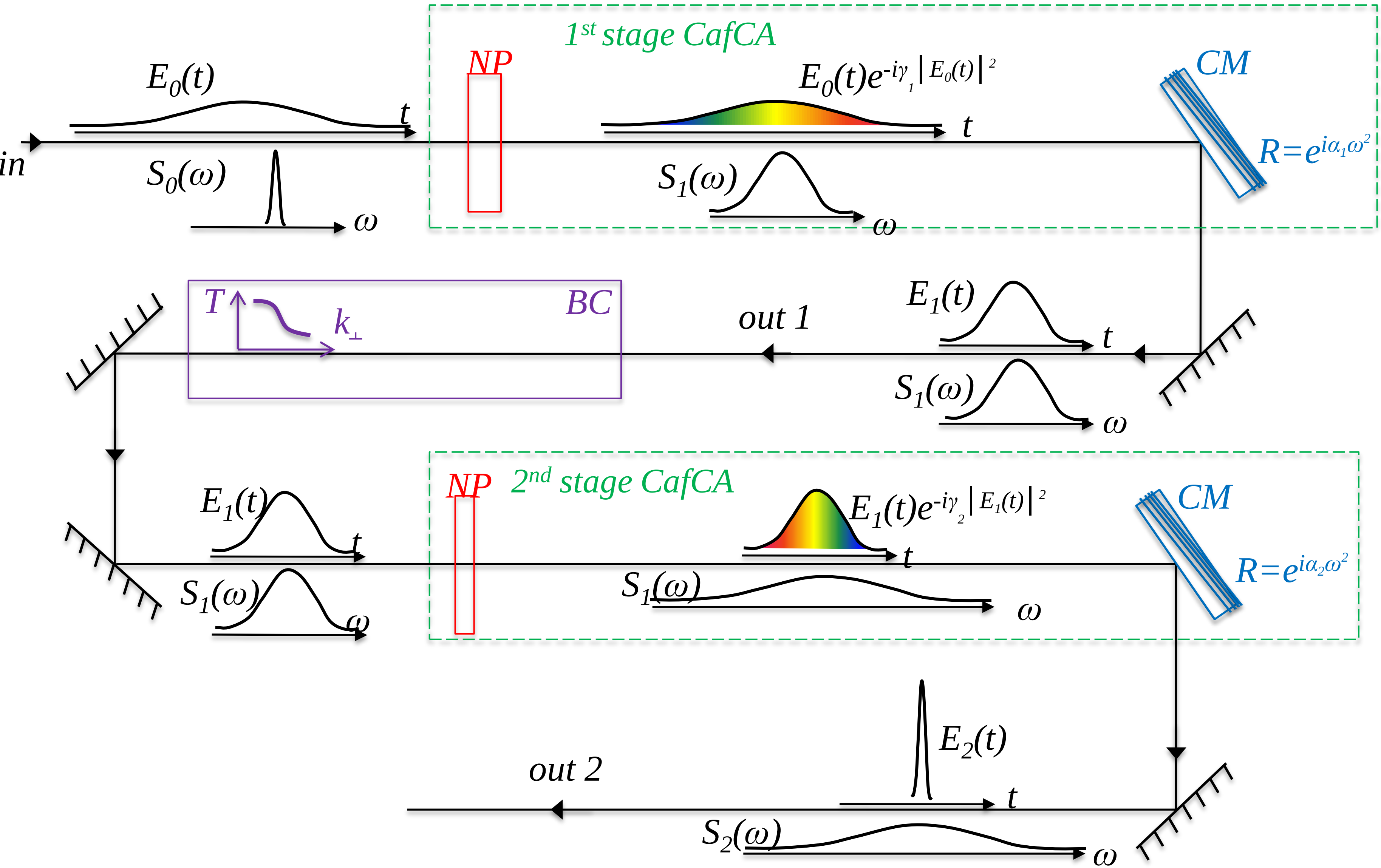
2020 results

<u>Ø 160mm, W=17J,</u> T_{pulse}=70fs -> 14fs, L_{glass}=3 mm, B~7.5



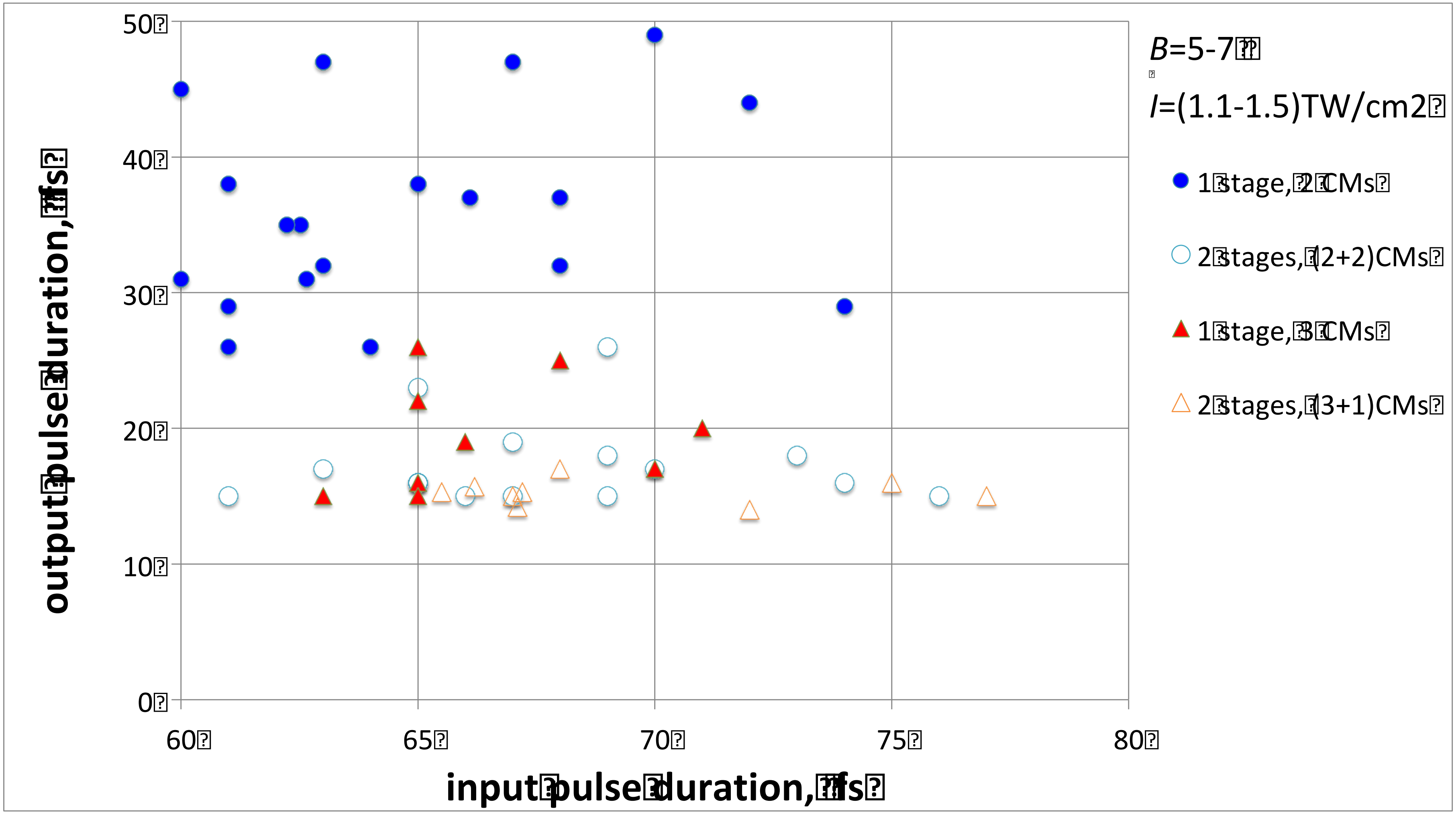
PRA, 101, 013829 2020

CafCA: two-stage



Single-stage vs two-stage

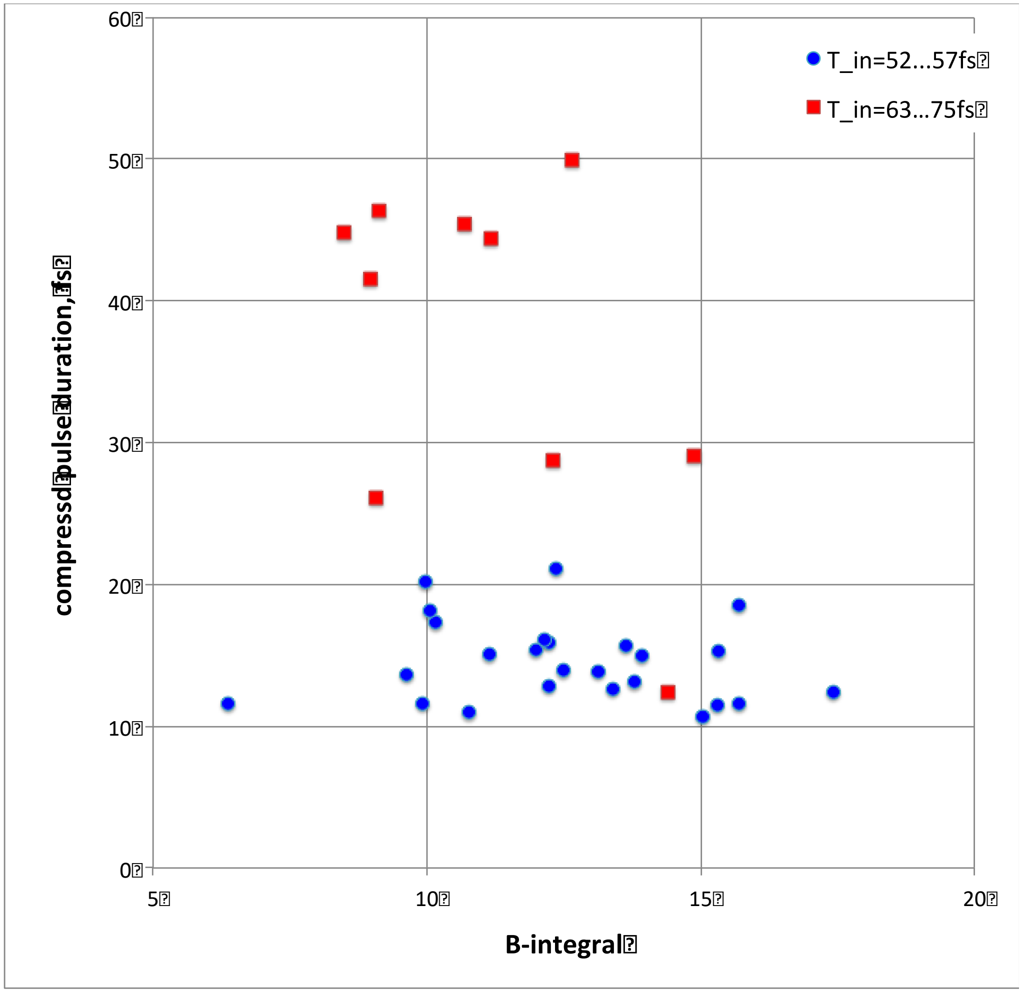
Ø 160mm, W=17J, T_{pulse}=70fs -> 14fs, L_{glass}=3 mm, B~7.5



Quantum Electronics, v.50, p.331–334 (2020)

Fresh new results

Ø 160mm, W=17J, T_{pulse}=55fs -> 11fs, L_{glass}=5 mm, B~15



- **Motivation**
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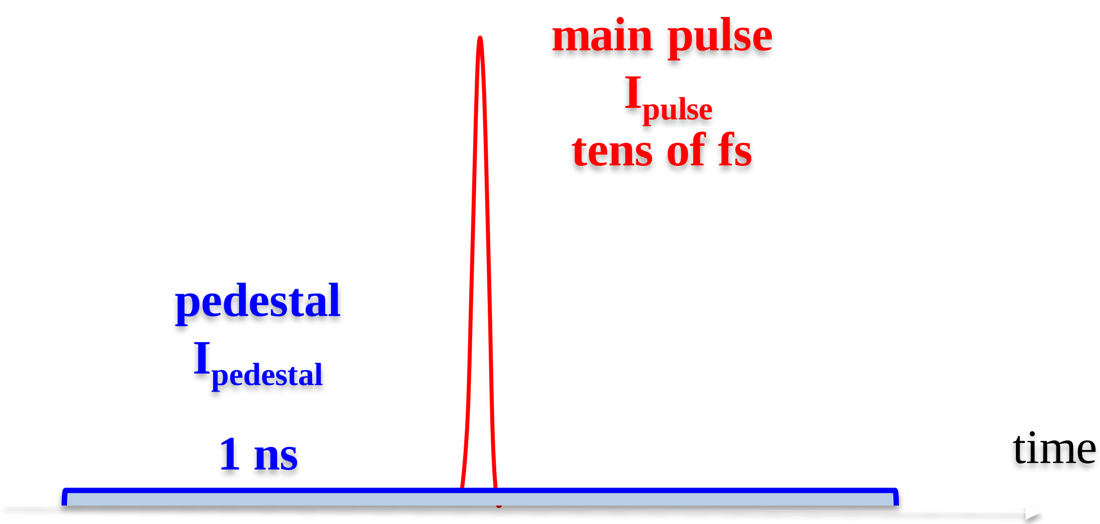
- **Enhancement of laser pulse contrast**
- **Conclusions**

$$C = \frac{I_{pulse}}{I_{pedestal}}$$



Contrast enhancement techniques

- **plasma mirrors**

A. Lйvy, T. Ceccotti, P. D'Oliveira, F. Rйau, M. Perdrix, F. Quйrй, P. Monot, M. Bougeard, H. Lagadec, P. Martin, J.-P. Geindre, P. Audebert Opt. Lett., **32**, 310 (2007)

- **second harmonic generation**

S.Y. Mironov, V.V. Lozhkarev, V.N. Ginzburg, E.A. Khazanov Applied Optics, **48**, 2051 (2009).

- **orthogonal polarization generation (XPW generation)**

A. Jullien, O. Albert, F. Burgy, G. Hamoniaux, J.-P. Rousseau, J.-P. Chambaret, F. Augé-Rochereau, G. Chériaux, J. Etchepare, N. Minkovski, S.M. Saltiel Optics Letters, **30**, 920 (2005).

- **spectral pulse filtering after self-phase modulation**

Buldt, M. Müller, R. Klas, T. Eidam, J. Limpert, A. Tünnermann Optics Letters, **42**, 3761 (2017).
S.Y. Mironov, M.V. Starodubtsev, E.A. Khazanov Optics Letters, **46**, , (2021)

- **spatial spectra manipulation by non-linear wedge**

E.A. Khazanov Quantum Electrinics, **51**, (2021)

- **nonlinear Mach-Zehnder interferometer**

S.Y. Mironov, E.A. Khazanov Quantum Electrinics, **49**, 337 (2019).

- **nonlinear polarization interferometer - this talk**

E.A. Khazanov Optics Eaxpress, accepted (2021)

$\chi^{(3)}$ phenomena

Nonlinear Mach-Zehnder interferometer

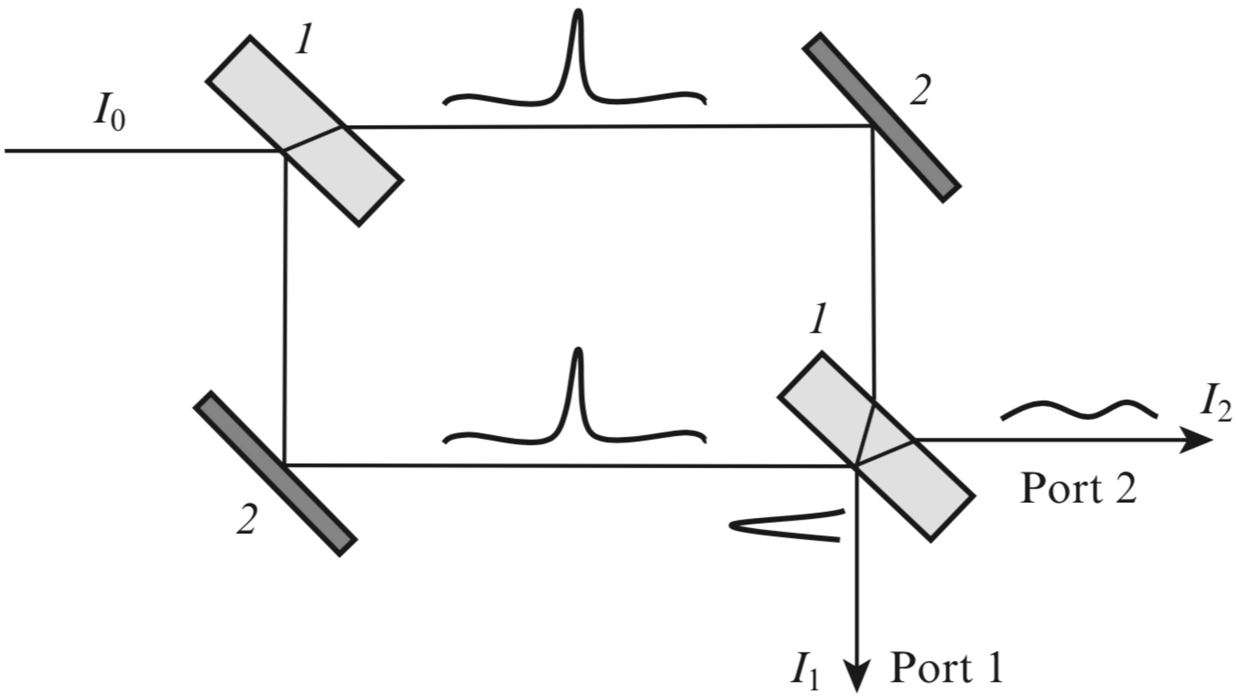
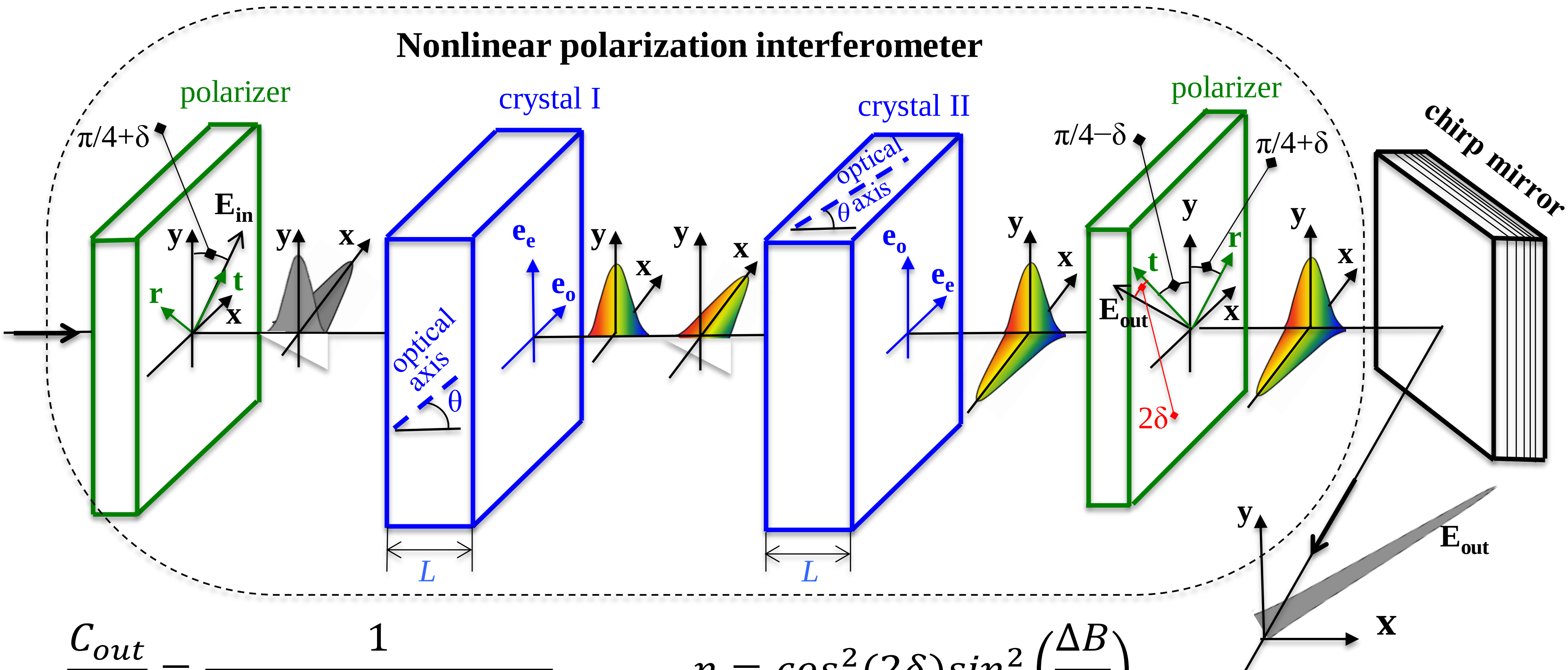


Figure 1. Schematic of a Mach–Zehnder interferometer: (*1*) transmitting optical elements; (*2*) mirrors; I_0 is the initial intensity; I_1 and I_2 are the intensities at interferometer outputs for ports 1 and 2, respectively.

Nonlinear polarization interferometer + CafCA



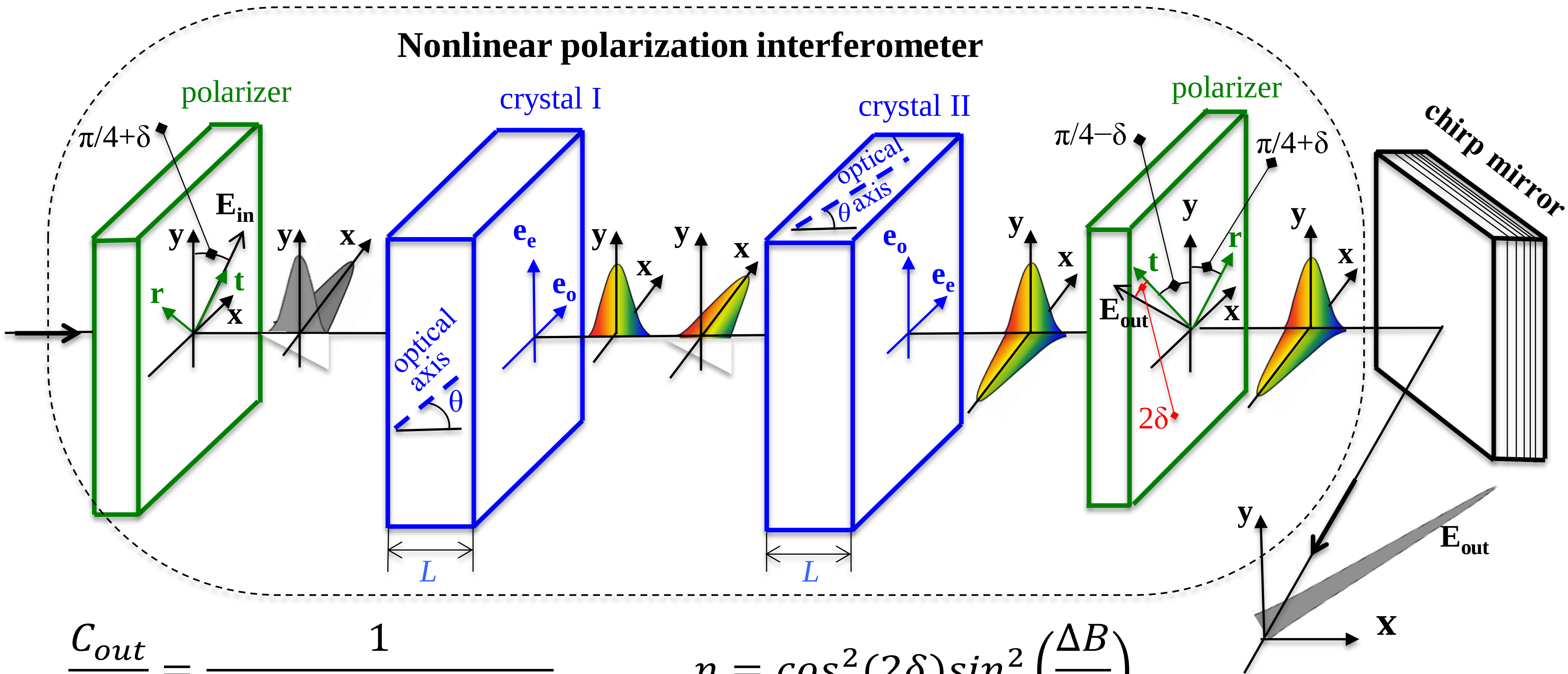
$$\frac{C_{out}}{C_{in}} = \frac{1}{cos^2(2\delta)sin^2(\frac{\Delta\Psi}{2})}$$

$$\eta = cos^2(2\delta)sin^2\left(\frac{\Delta B}{2}\right)$$

ΔΨ – linear phase delay between o- and e-polarizations
ΔB – non-linear phase delay between o- and e-polarizations

ΔΨ=0
ΔB=π

Nonlinear polarization interferometer + CafCA



$$\frac{C_{out}}{C_{in}} = \frac{1}{cos^2(2\delta)sin^2(\frac{\Delta\Psi}{2})}$$

$$\eta = cos^2(2\delta)sin^2\left(\frac{\Delta B}{2}\right)$$

$$\Delta B = B_x - B_y = B_{o,I} - B_{o,II} + B_{e,II} - B_{e,I} \qquad < B >= \frac{B_{o,I}+B_{o,II}+B_{e,II}+B_{e,I}}{2}$$

Nonlinear polarization interferometer + CafCA

$$\eta = cos^2(2\delta)sin^2\left(\frac{\Delta B}{2}\right)$$

$$\Delta B = B_x - B_y = B_{o,I} - B_{o,II} + B_{e,II} - B_{e,I} \qquad \Delta B = \pi$$

i) at anisotropic cubic nonlinearity ($n_{2,I} \neq n_{2,II}$, as n_2 depends on φ), or

ii) at different wave intensities in the x- and y-polarizations ($I_x \neq I_y$, т.е. $\delta \neq 0$), or

iii) when both these cases occur simultaneously

$$h_1 = \frac{\chi_{cccc}}{\chi_{aaaa}} \quad h_2 = \frac{\chi_{aabb}}{\chi_{aaaa}} \quad h_3 = \frac{\chi_{baaa}}{\chi_{aaaa}} \quad h_4 = \frac{\chi_{aacc}}{\chi_{aaaa}} \quad h_5 = \frac{\chi_{aabc}}{\chi_{aaaa}} \quad h_6 = \frac{\chi_{abcc}}{\chi_{aaaa}}$$

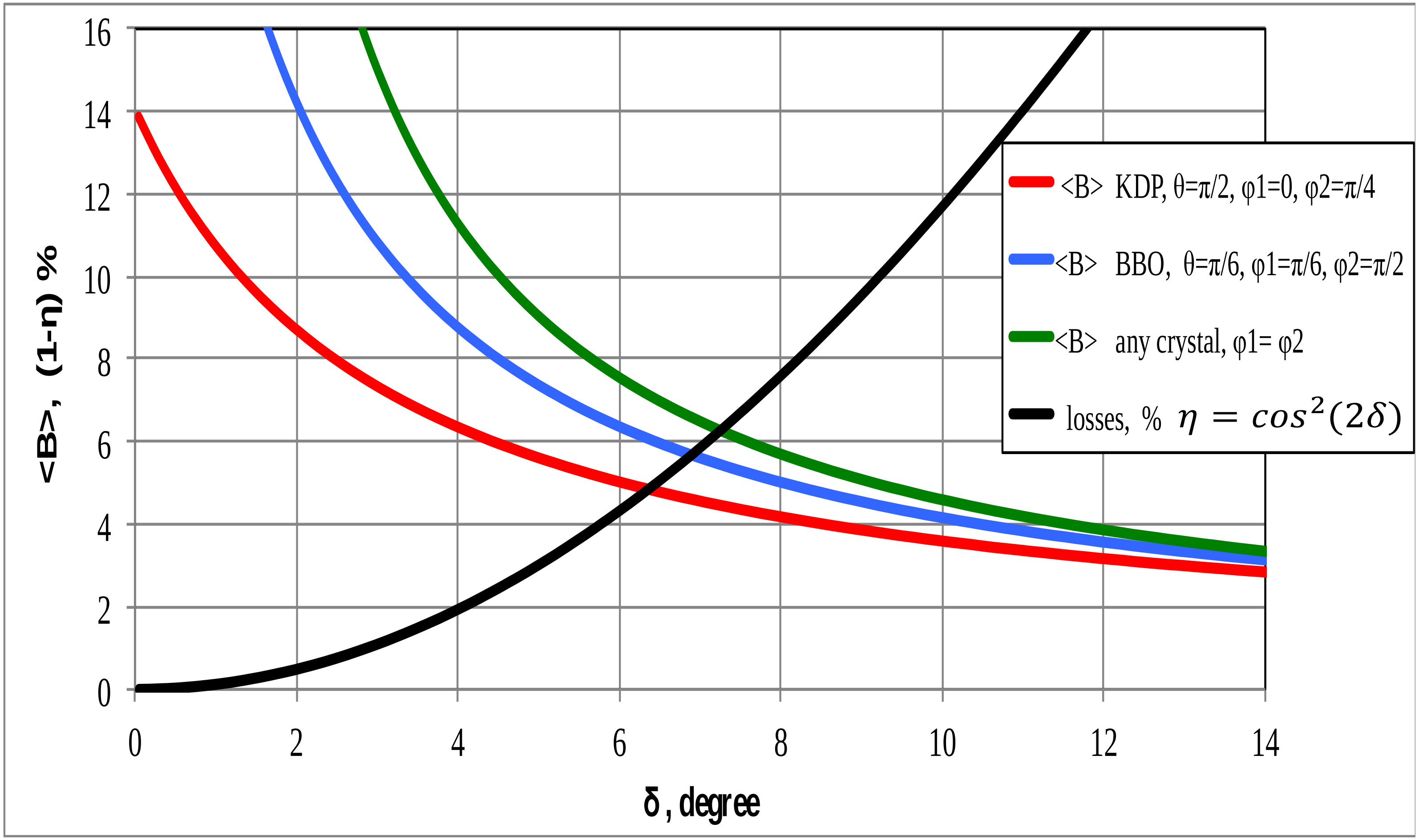
$$n_{2,o} = f(\varphi, h_i)$$
$$n_{2,e} = f(\theta, \varphi, h_1)$$

$$n_{2,o}(\varphi = 0) = \frac{\chi_{aaaa}}{n_o^2}$$

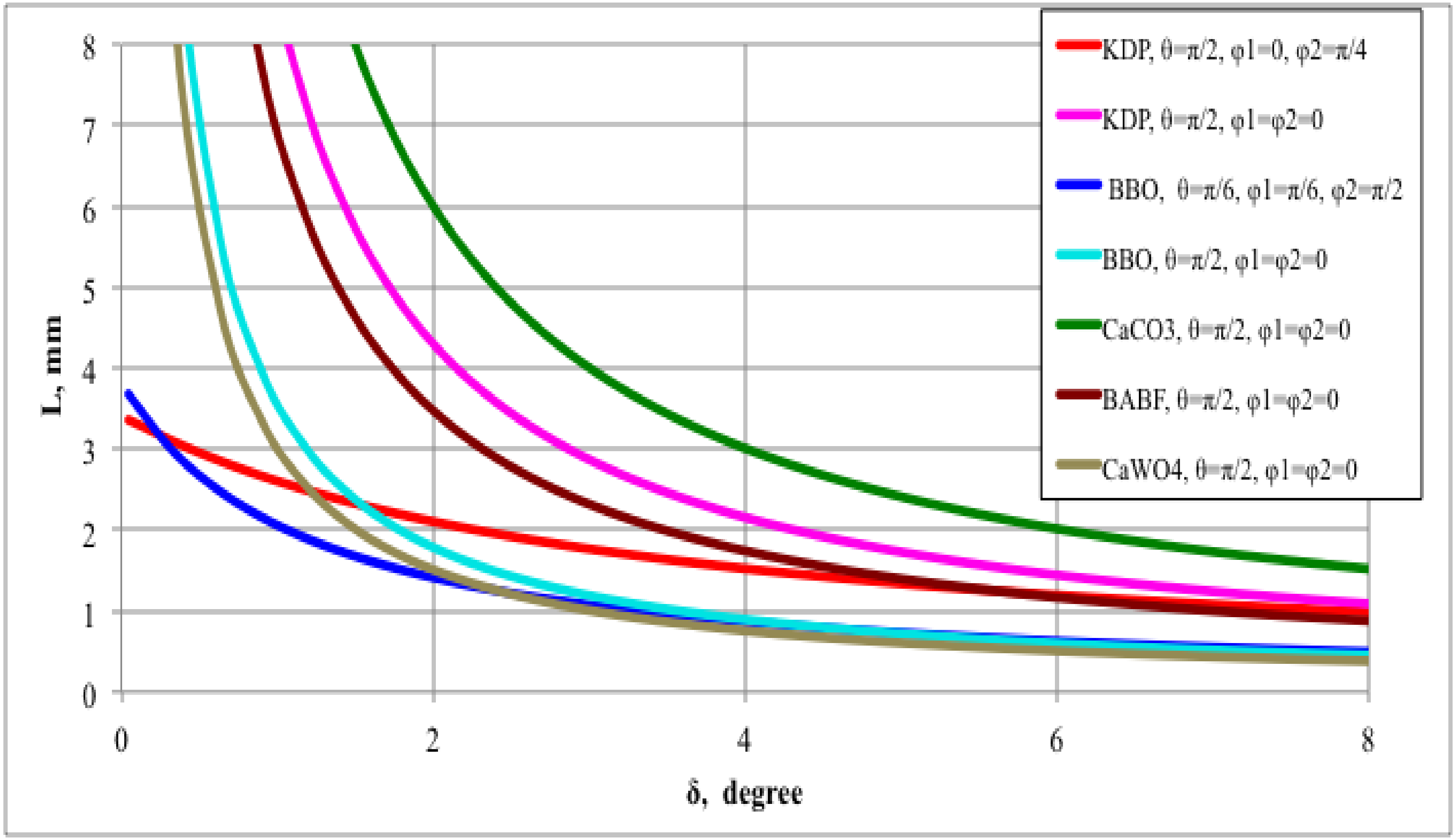
$$B_0 = kL\frac{I_x + I_y}{2} n_{2,o}(\varphi = 0)$$

P.S. Banks, M.D. Feit, M.D. Perry JOSA B, 19, 102 (2002)

Nonlinear phase of the output pulse <B> and losses (1- η)



Crystal length L(δ) for different crystals ($I_x+I_y= 2$ TW/cm^2)



Увеличение контраста C_{out}/C_{in}, длина кристалла *L*, длина разбегания импульсов *l*

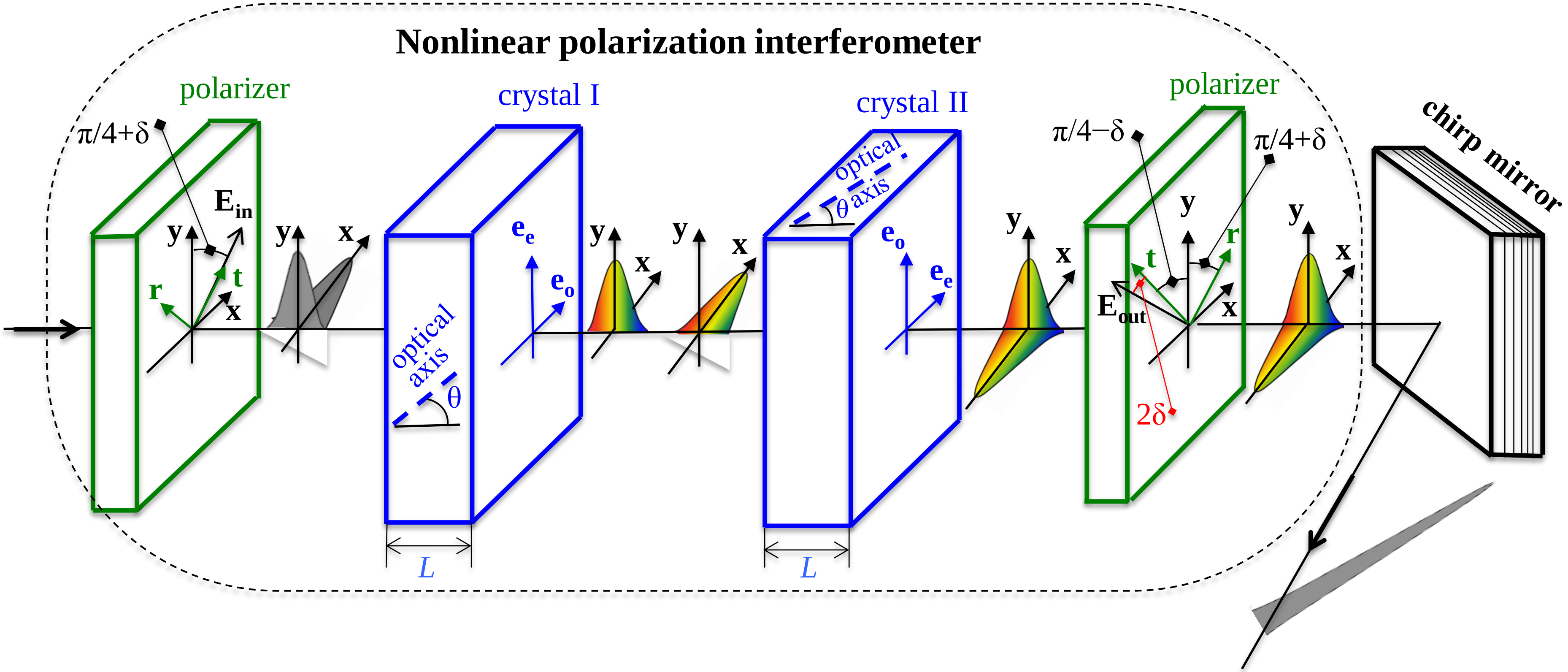
$\langle B \rangle = 14$, $\delta L = \lambda/7$, $I_x + I_y = 2$ TW/cm^2 , $\lambda = 910$nm, $\tau = 30$фс

	θ	φ_1	φ_2	δ, degree	C_{out}/C_{in}	*L*, mm	*l*, mm
KDP	π/2	0	π/4	0	3730	3.4	0.25
	π/2	0	0	3	3730	2.7	0.25
BBO	π/6	π/6	π/2	2	6280	1.4	0.32
	π/2	0	0	3	370	1.1	0.08
$CaCO_3$	π/2	0	0	3	180	3.8	0.05
	π/6	0	0	3	3160	3.6	0.23
BABF	π/2	0	0	3	2780	2.2	0.21
$CaWO_4$	π/2	0	0	3	21500	0.9	0.59

Conclussion

- We have proposed a method for the simultaneous enhancement of the temporal contrast and power of powerful femtosecond laser pulses using a nonlinear polarization interferometer (NPI).
- The nonlinear phase incursion π can be provided both due to the anisotropy of the cubic nonlinearity (n_2 depends on the angle φ), and due to different wave intensities in orthogonal polarizations.
- For the first option, the KDP crystal has suitable properties and for the second option, a wide range of uniaxial crystals.
- The pulse that has passed through the second polarizer is self-phase modulated, which allows it to be compressed by reflection from the chirping mirrors, thereby increasing the peak power.
- The NPI has an in-line geometry that does not require spatial beam separation and can be used at the output of any lasers with TW power and higher, as well as in lasers with double-CPA.

Thank you


Nonlinear polarization interferometer
polarizer
crystal I
crystal II
polarizer
chirp mirror
π/4+δ
π/4−δ
π/4+δ
E_in
E_out
optical axis
θ
L
2δ

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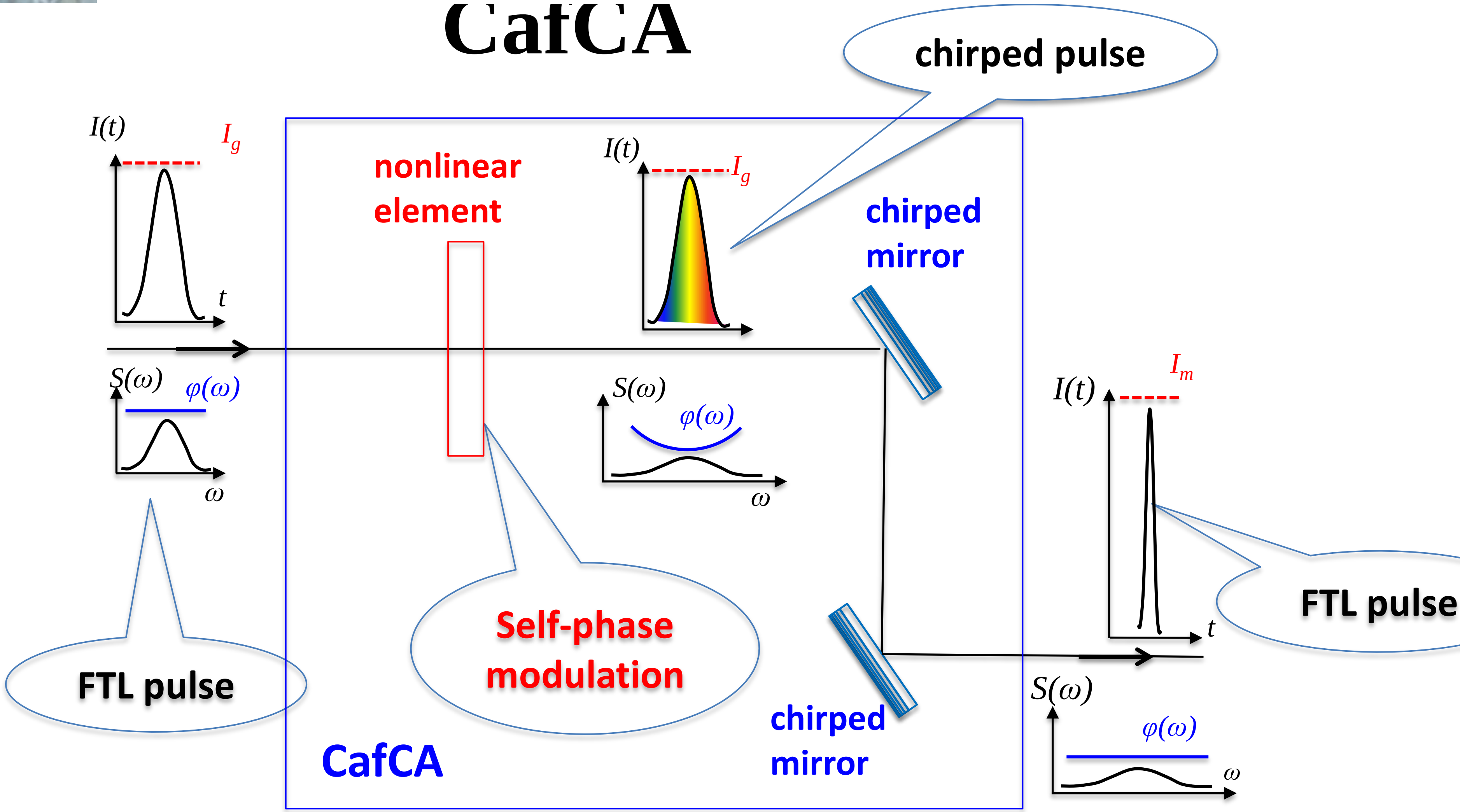
Instead of conclusion

CafCA is simple, robust and cheap recipe:
just add free space, glass plate and chirp mirror(s)

Compression after Compressor Approach

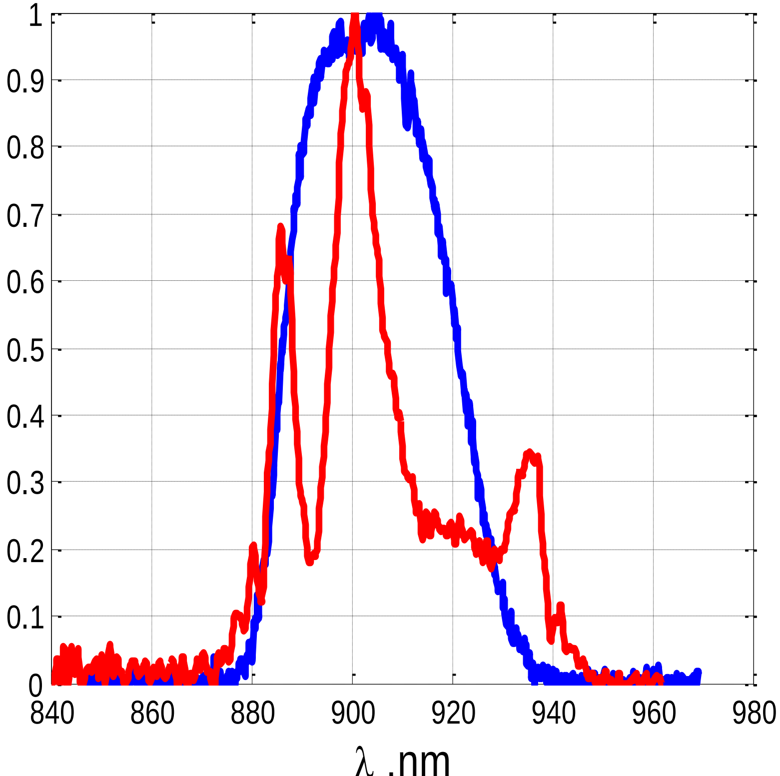
CafCA



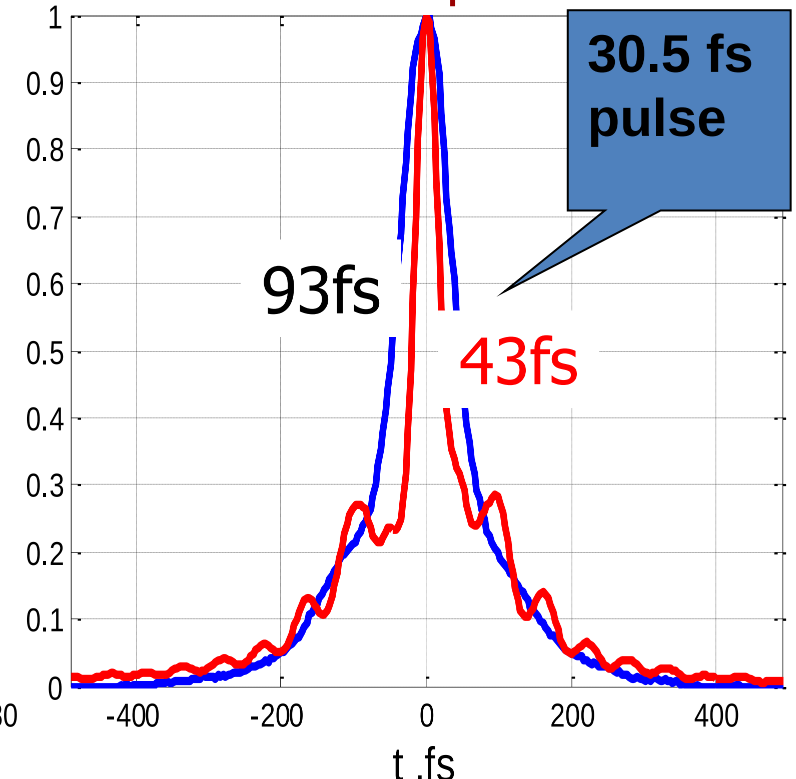
Example 1: at the output of the PEARL front-end

Ø 20mm, W=20mJ, T_{pulse}=66fs -> 30fs, $L_{plastic}$=3mm, B~2

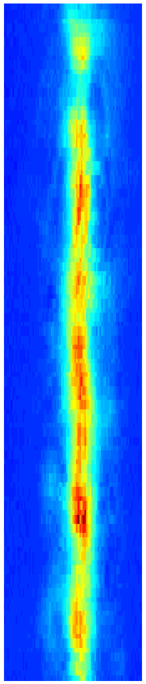
Spectra before and after SPM



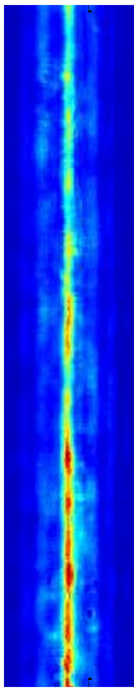
ACF w/o SPM and after SPM & chirped mirrors



ACF



ACF



V. N. Ginzburg, A. A. Kochetkov, I. V. Yakovlev, S. Y. Mironov, A. A. Shaykin, E. A. Khazanov, Influence of the cubic spectral phase of high-power laser pulses on their self-phase modulation Quantum Electronics, 46, 106, 2016

Nonlinear polarization interferometer + CafCA

Crystal Class	**syngony**	**Tetragonal**		**Trigonal**		**Hexagonal**
	symmetry	$4, \bar{4}, 4/m$	$\bar{4}2m, 422, 4mm, 4/mmm$	$3, \bar{3}$	$3m, \bar{3}m, 32$	
	example	YLF, $CaWO_4$, $BaWO_4$, $PbMoO_4$	KDP, DKDP, TeO_2		BBO, $CaCO_3$, $LiNbO_3$	BABF
	h_i	h_1, h_2, h_3, h_4	h_1, h_2, h_4	h_1, h_4, h_5, h_6	h_1, h_4, h_5	h_1, h_3, h_4
	$n_{2,o}(\varphi)$	f(φ)	f(φ)	const	const	const
	$n_{2,e}(\varphi)$	const	const	f(φ)	f(φ)	const
crystals of different orientations: $\theta_1=\theta_2=\Theta$, $\varphi_1=\Phi_I$ $\varphi_2=\Phi_{II}$	**Θ**	π/2	π/2	π/6	π/6	N/A
	Φ_I	$\frac{1}{4}arctg(\frac{4h_3}{1-3h_2})$	0	$\frac{1}{3}arctg(-\frac{h_5}{h_6})$	π/6	N/A
	Φ_{II}	$\Phi_1+\frac{\pi}{4}$	π/4	$\Phi_1+\frac{\pi}{3}$	π/2	N/A
	D	$\sqrt{\left(\frac{1-3h_2}{2}\right)^2+(2h_3)^2}$	$\frac{1-3h_2}{2}$	$\frac{3\sqrt{3}}{2}\left(\frac{n_o}{n_e}\right)^2\sqrt{(h_5)^2+(h_6)^2}$	$\frac{3\sqrt{3}}{2}\left(\frac{n_o}{n_e}\right)^2 h_5$	N/A
	A	$\frac{3}{2}(1-h_2)+2\left(\frac{n_o}{n_e}\right)^2 h_1$		$2+\frac{1}{8}\left(\frac{n_o}{n_e}\right)^2(9+4h_4+h_1)$		N/A
	$\Delta B/B_0$	D+Asin(2δ)				N/A
	<B>	$\frac{\pi}{2}\frac{A+Dsin(2\delta)}{D+Asin(2\delta)}$				N/A
	L	$\frac{\lambda}{n_{2,o}(\varphi=0)I_\Sigma}\cdot\frac{1}{D+Asin(2\delta)}$				N/A
identical crystals: $\theta_1=\theta_2=\theta$, $\varphi_1=\varphi_2=\varphi$	$\Delta B/B_0$	$2\left(1+\frac{n_{2e}(\vartheta,\varphi)}{n_{2o}(\varphi)}\right)\sin(2\delta)$				
	<B>	$\frac{\pi}{2sin(2\delta)}$				
	L	$\frac{\lambda}{n_{2,o}(\varphi=0)I_\Sigma}\cdot\frac{1}{2\left(1+\frac{n_{2e}(\vartheta,\varphi)}{n_{2o}(\varphi)}\right)}\cdot\frac{1}{sin(2\delta)}$				