Federal Research Center
Institute of Applied Physics
of the Russian Academy of Sciences

Optimisation of laser-plasma particle acceleration regimes at PEARL facility 

V. N. Ginzburg, I.V Yakovlev, A.A. Kochetkov, A. Kuzmin, I.A. Shaikin, A.A. Shaykin, E.A. Khazanov,
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A.G. Alexandrov, I.V. Galaktionov, V.V. Samarkin, A.V. Kudryashov, (IDG RAS)
M.A. Mart'yanov, I.V. Kuzmin, S.Yu Mironov,
E.A. Perevezentsev, I.B. Mukhin,

Outline:

1- Description of the facility
2- The main results and the main limiting issues
3- Power increase (CafCA - Compression after Compression Approach).
4- Optimisation of the focal spot (linear and nonlinear case)
5- Stability improvement
6- Conclusions

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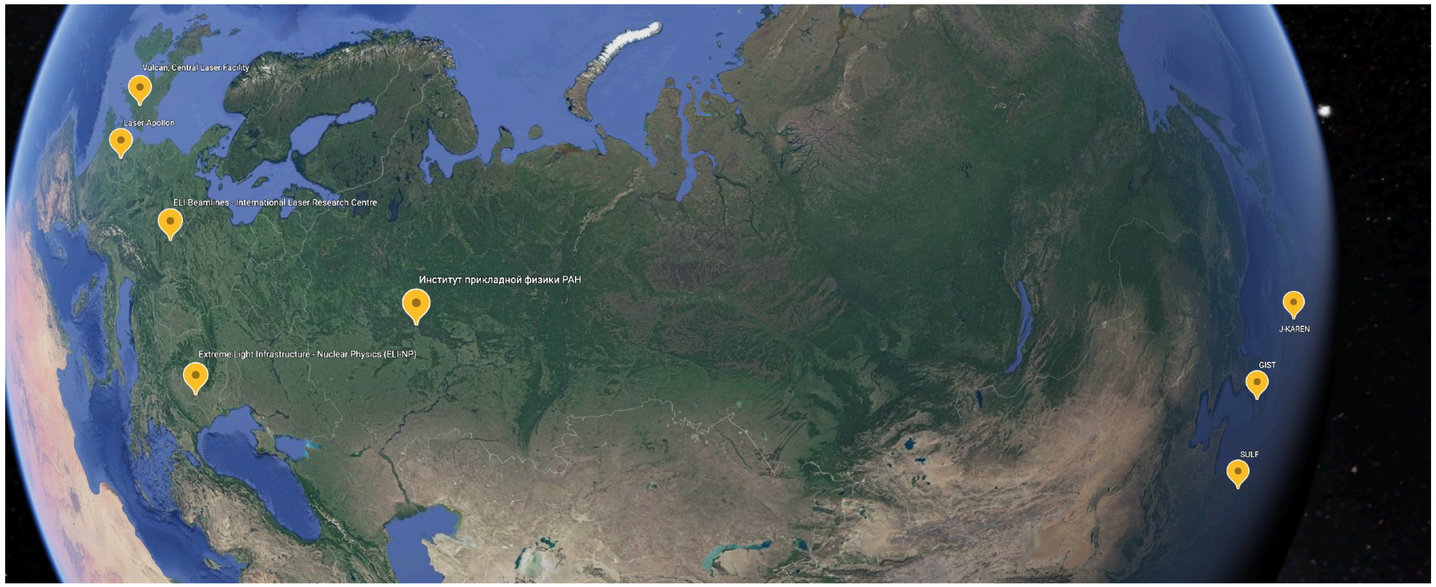
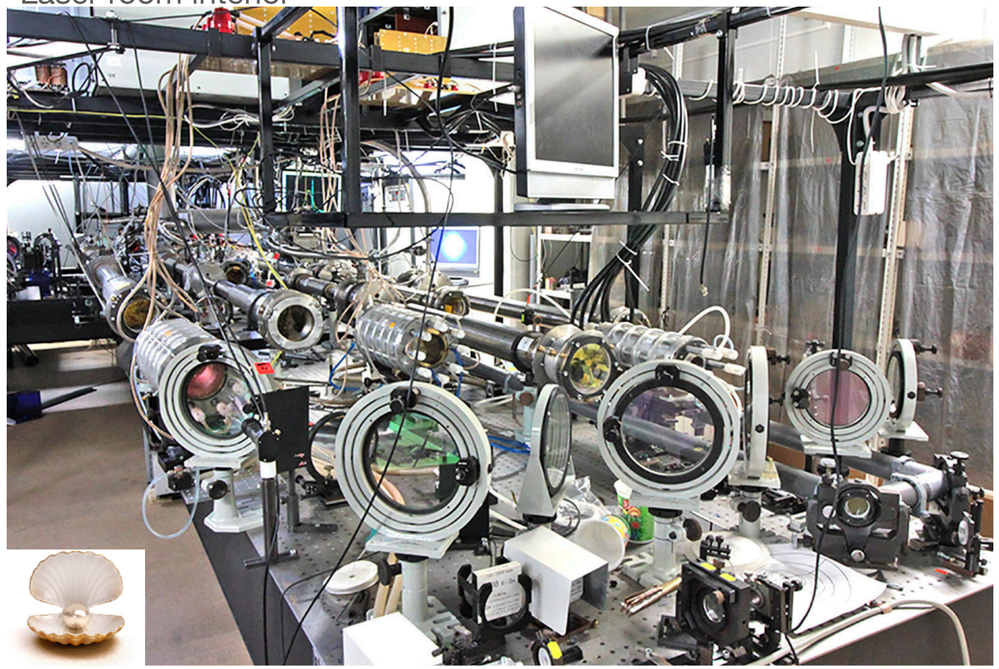
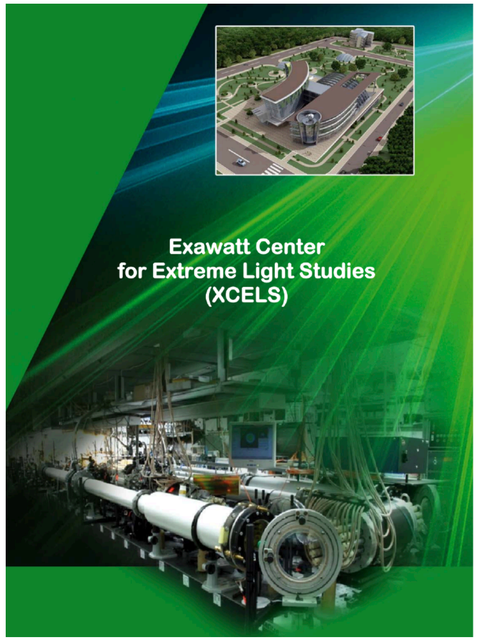


Laser room interior

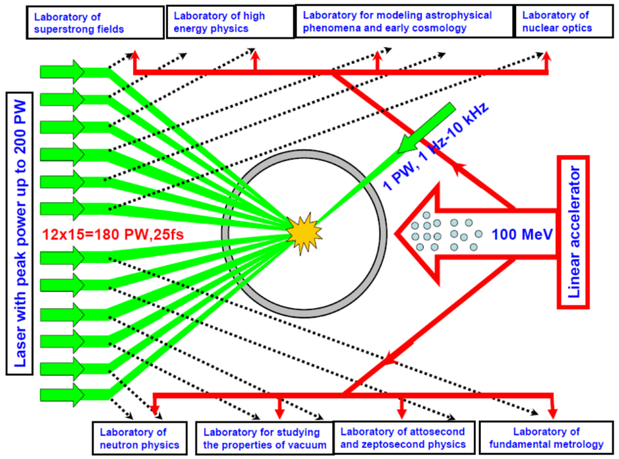


laser system "Luch"
VNIIEF (Sarov)

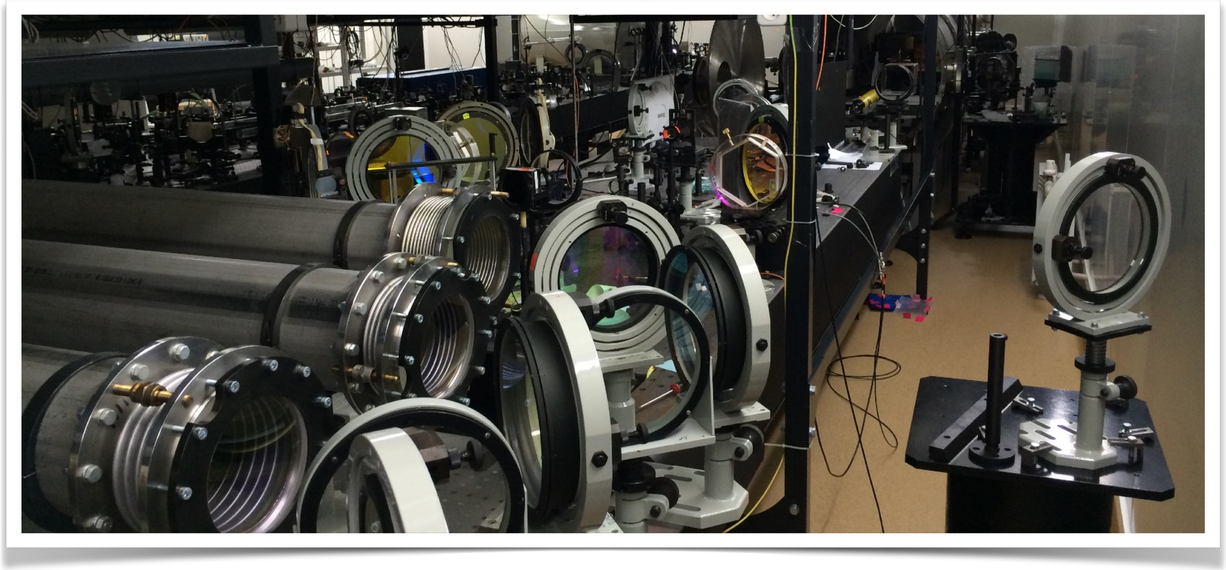
ELF laser facility
MEPhI (Moscow)



https://xcels.ipfran.ru/

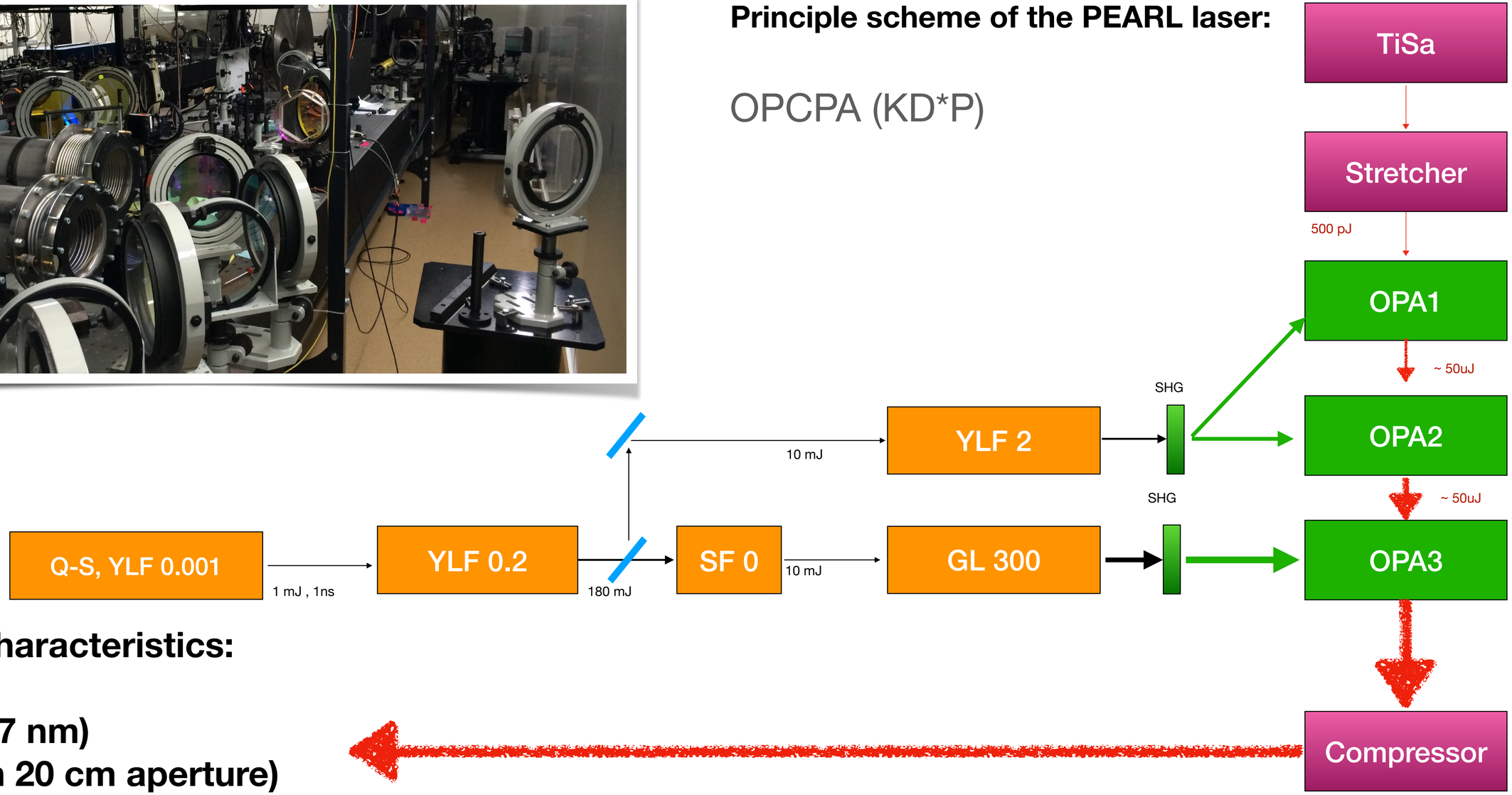


Laser-plasma experimental facility PEARL:



Principle scheme of the PEARL laser:

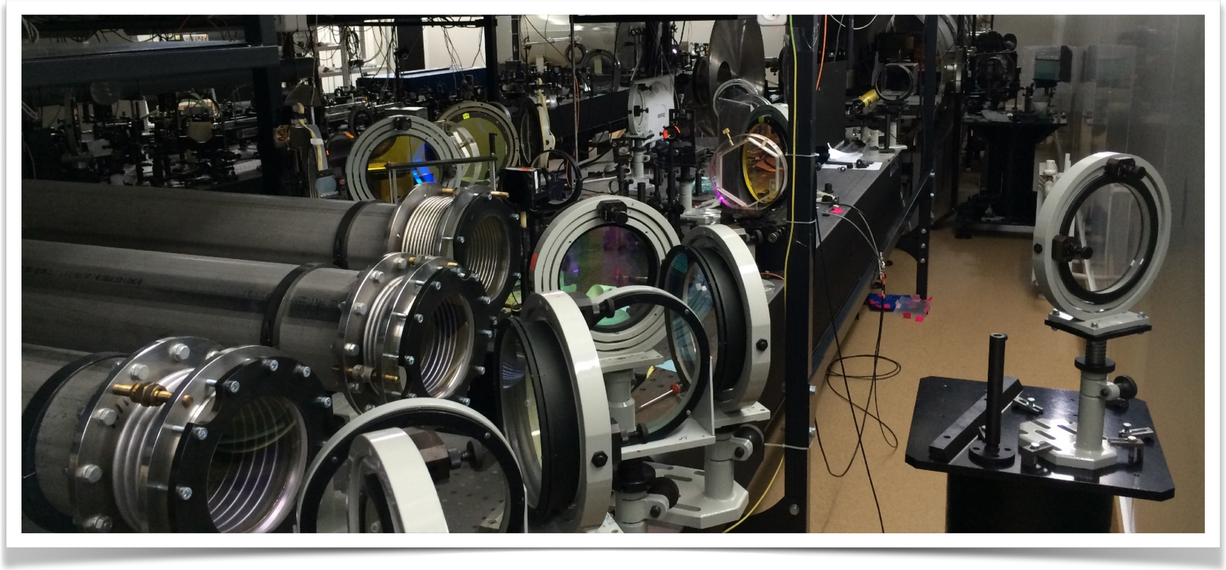
OPCPA (KD*P)



Laser pulse characteristics:

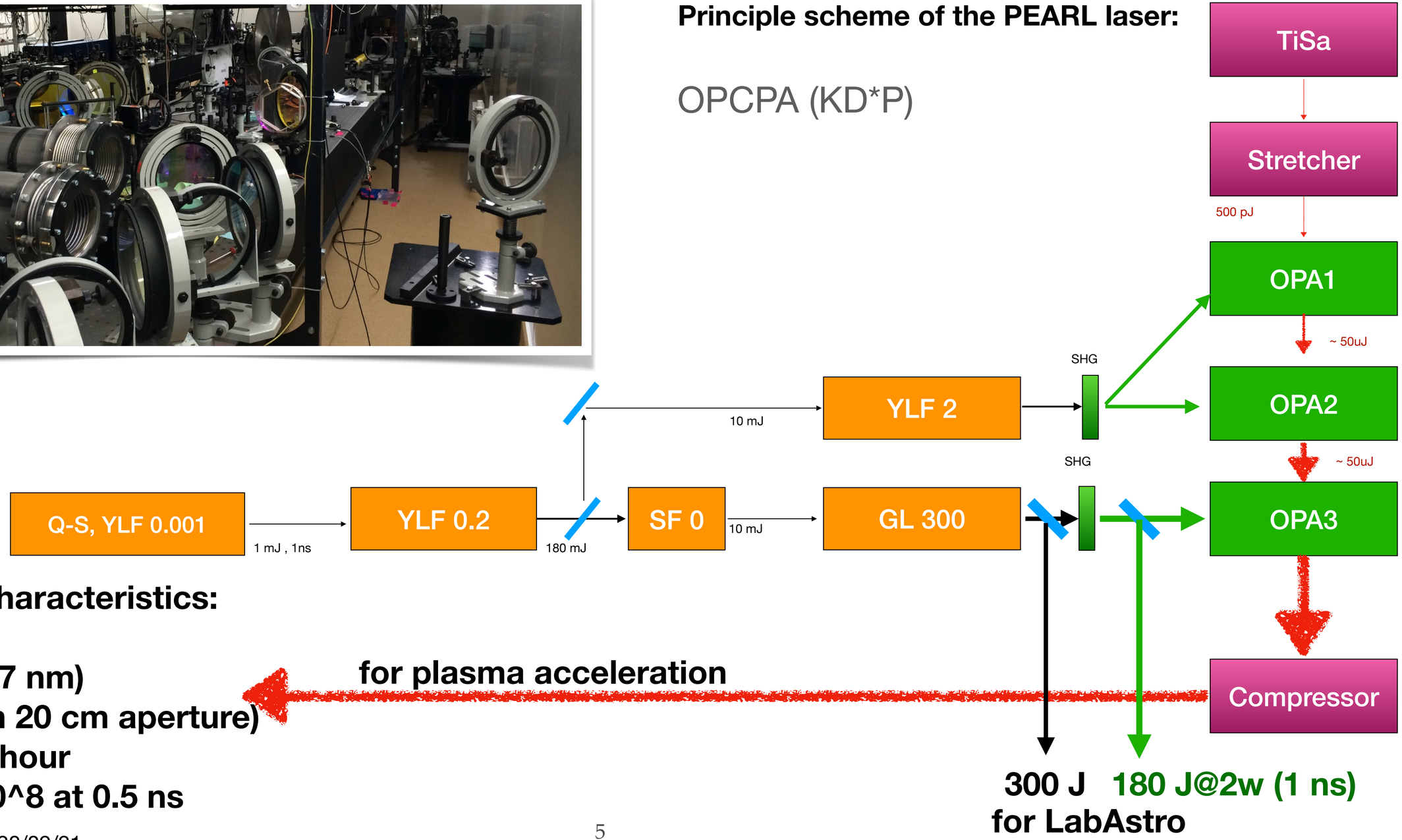
- **50 fs**
- **910 nm (+-17 nm)**
- **up to 20J (in 20 cm aperture)**
- **3 shots per hour**
- **Contrast: 10^8 at 0.5 ns**

Laser-plasma experimental facility PEARL:



Principle scheme of the PEARL laser:

OPCPA (KD*P)



Laser pulse characteristics:

- **50 fs**
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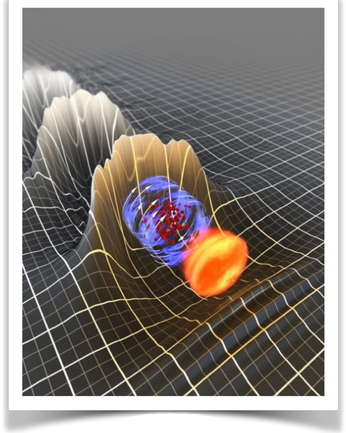
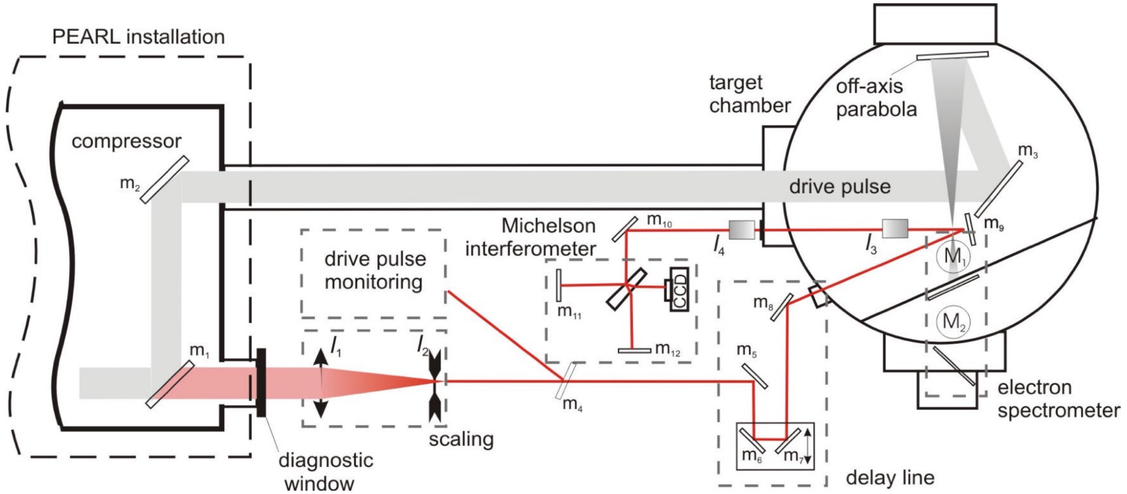
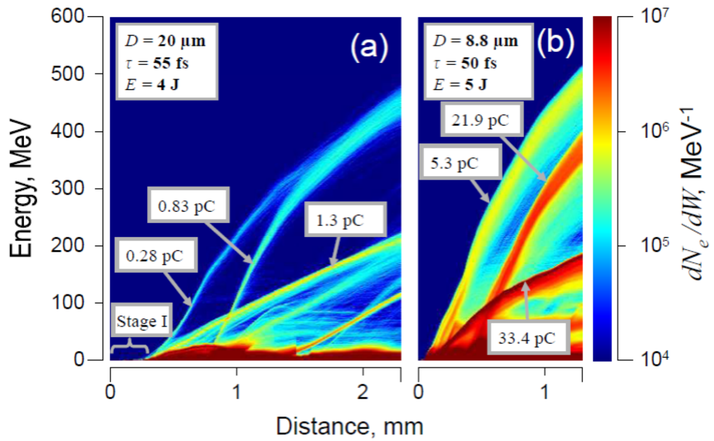
- **up to 20J (in 20 cm aperture)**
- **3 shots per hour**
- **Contrast: 10^8 at 0.5 ns**

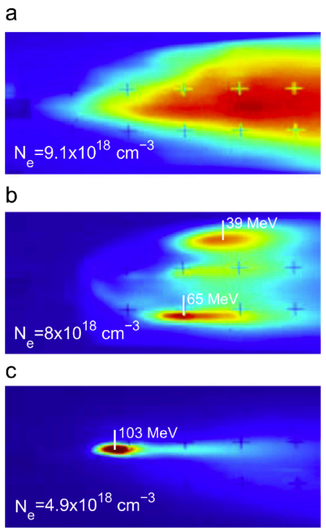
Laser wakefield acceleration (Stage 1): Nozzle

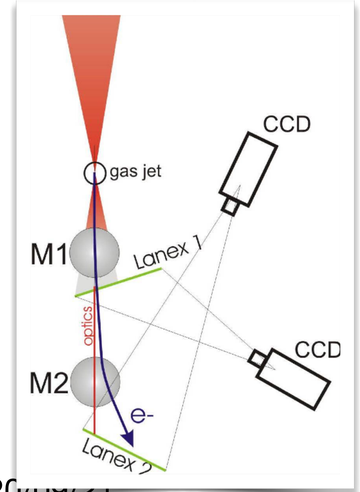


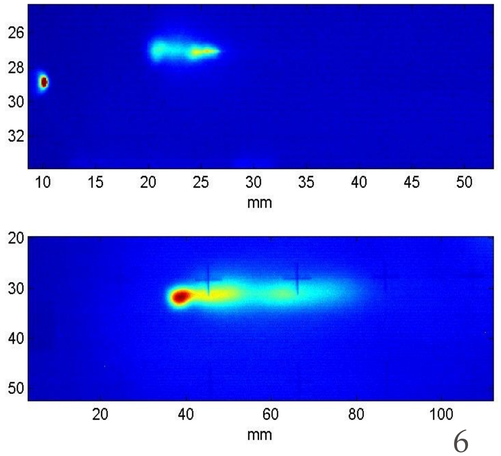
Focusing F/6 and F/15











Launch angle = -0.011

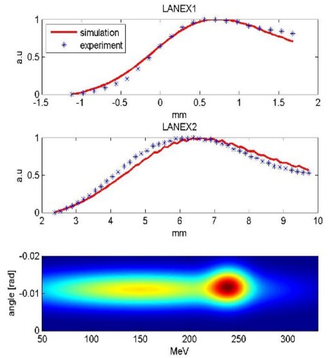
divergence = 4,6 mrad

W = 260 MeV (±20 MeV)

dW = 18 MeV (±10 MeV)

18 pC

Up to 300 pC in some shots

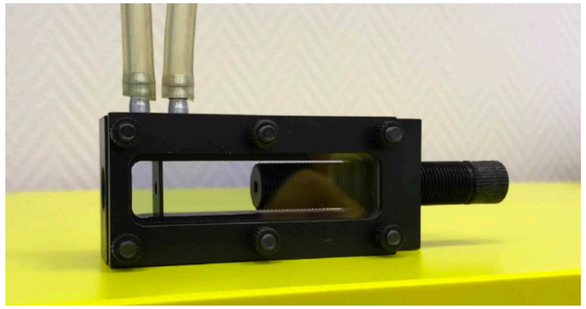


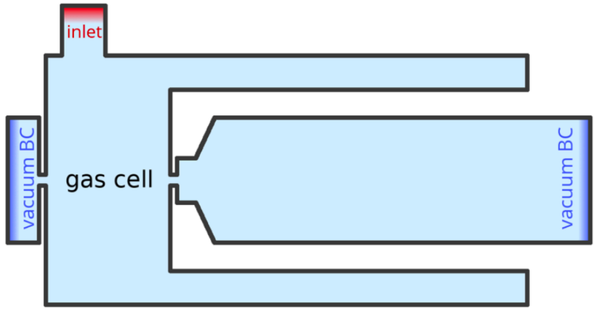
Soloviev et al. *Rev. Sci. Instrum.* **82**, 043304 (2011)

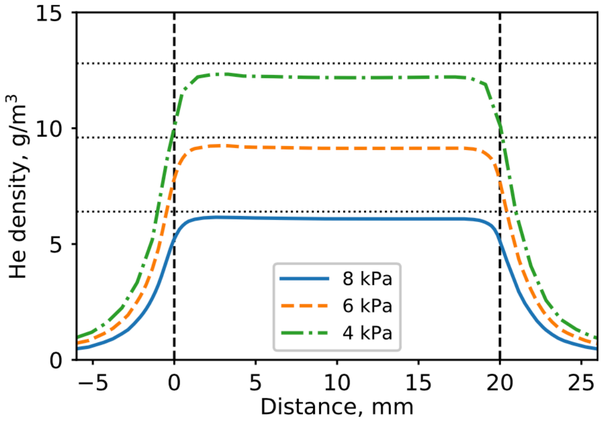
Soloviev et al. *NIMA*, Volume 653, Issue 1, 11 (2011)

Laser wakefield acceleration (Stage 2): Gas Sell

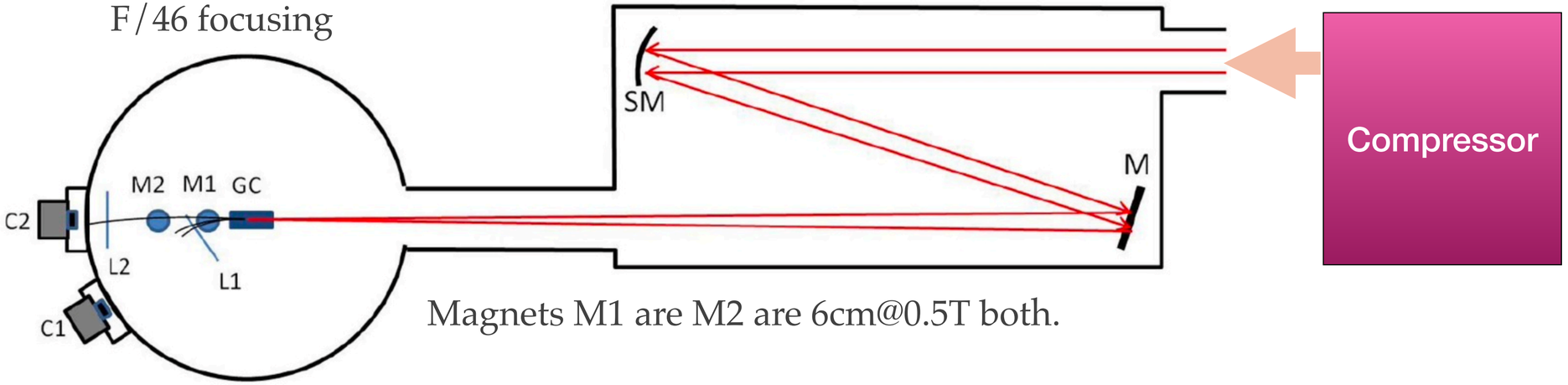
Up to 20J, 50fs@910 nm







F/46 focusing



Magnets M1 are M2 are 6cm@0.5T both.

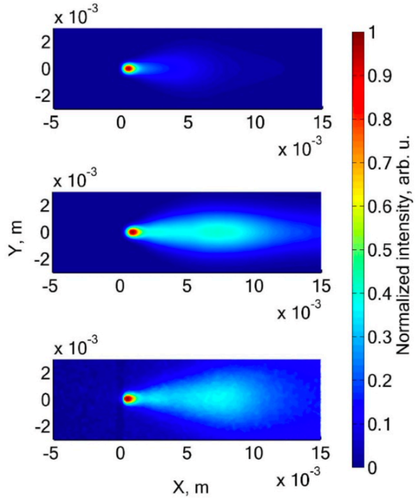
SM – spherical mirror f/40; M – transporting mirror; GC – gas cell; M1, M2 – deflection magnets; L1, L2 – scintillating screens; C1, C2 - CCD cameras.

$$w_m = 2\sqrt{a}\frac{c}{\omega_p}$$ - matched spot size

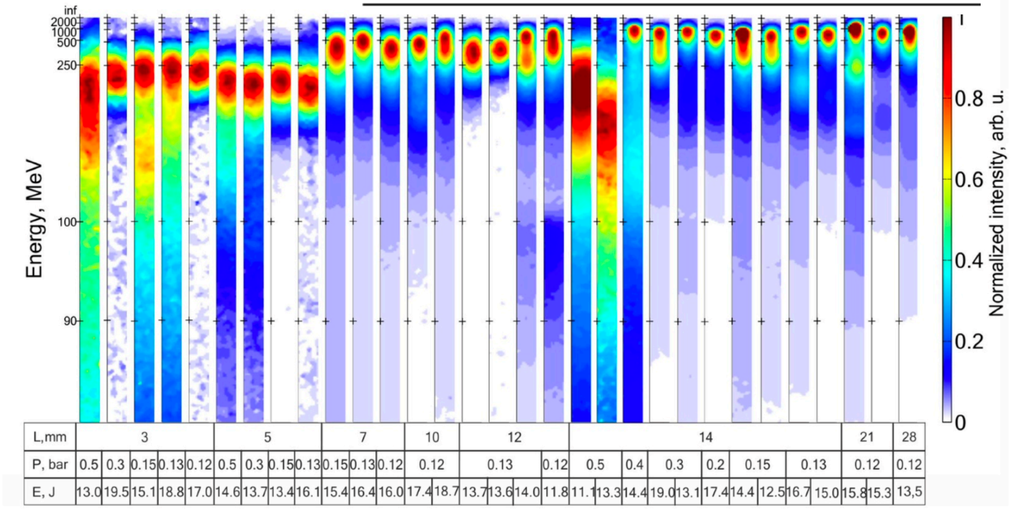
w_0 = 40 um (1/e^2)

w_m = 14 um

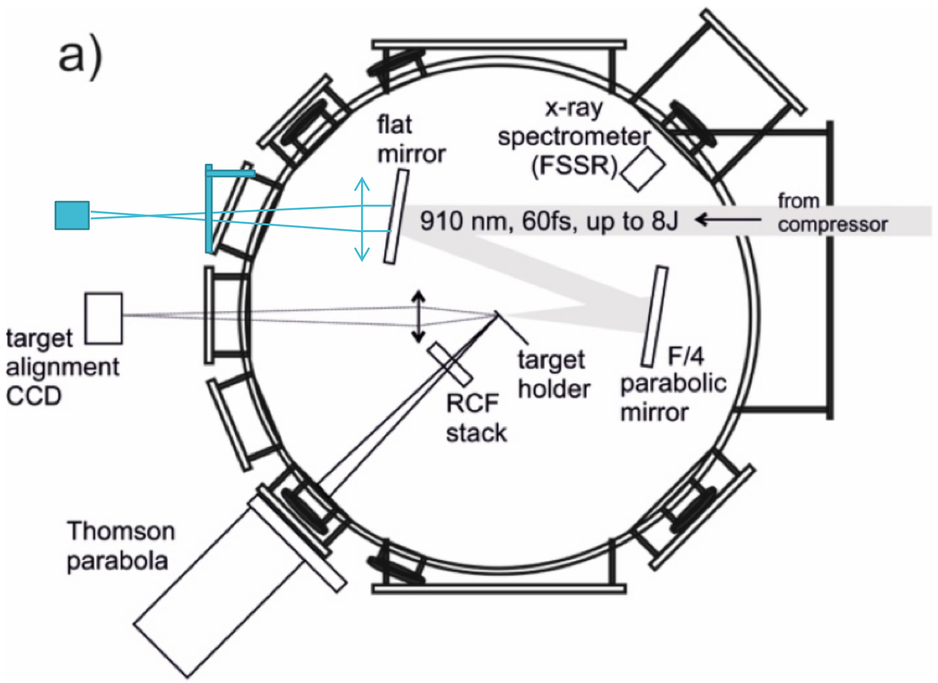
N=1.5 e18 1/cm^3



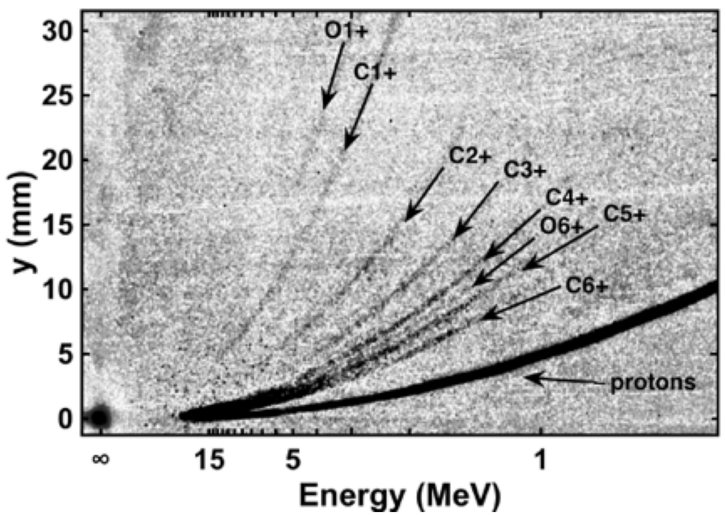
S E Perevalov *et al* Plasma Phys. Control. Fusion **62** (2020) 094004



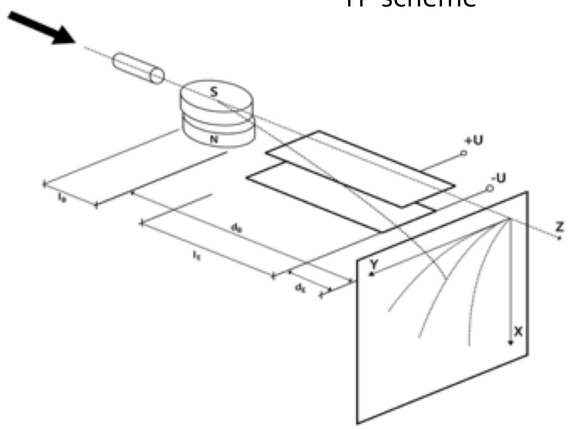
TNSA

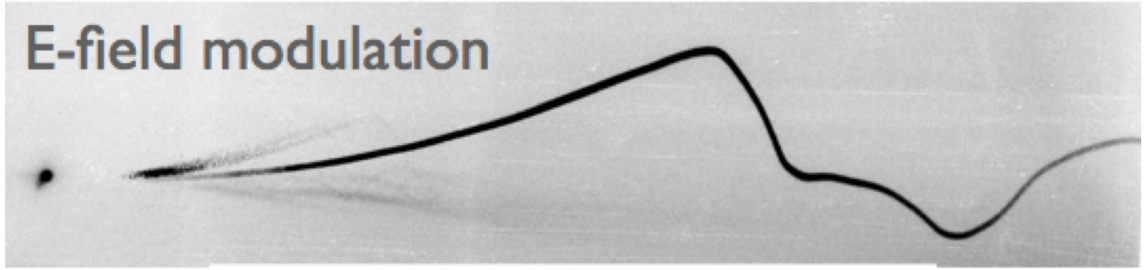


Thomson parabola data:



TP scheme





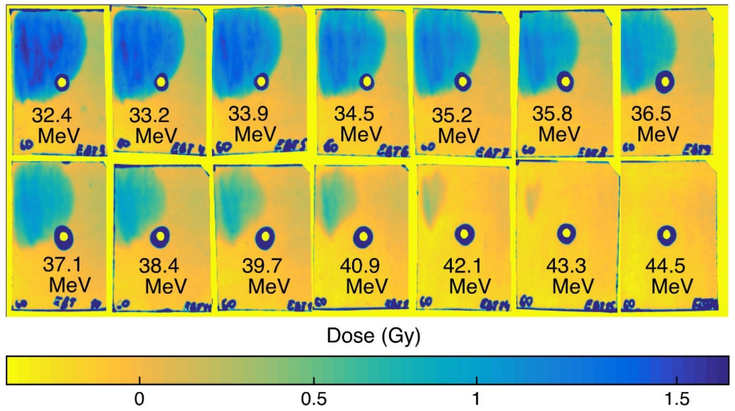
SCIENTIFIC REPORTS | 7: 12144 | DOI:10.1038/s41598-017-11675-2

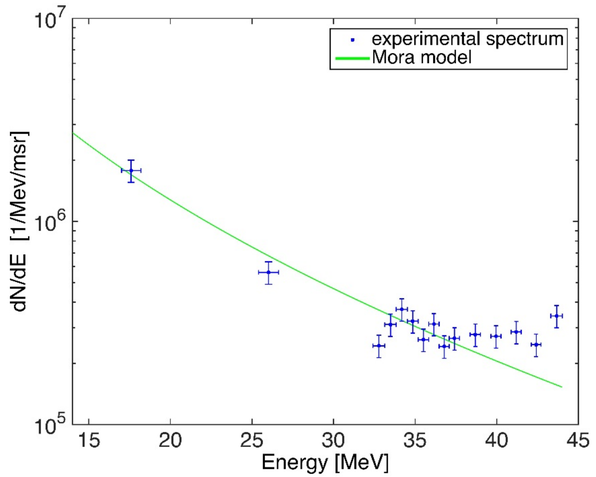
Basic laser parameters:
$\lambda 0 \approx 910$ nm, $\tau \approx 60$ fs,
$E \approx 10$ J,
$P \approx 160$ TW
$D \approx 100$ mm, F/4.2,
$I \approx 3 \times 10^{20}$ W/cm2
$C \approx 2 \times 10^{8}$ (1 ns)
1 Shot/20min

List of diagnostic equipment:
- Thomson parabola
- RCF stack
- FSSR X-ray spectrometer

Proton data: RCF

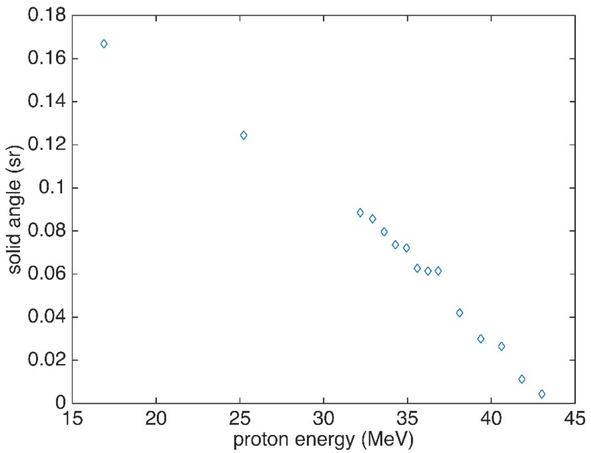
RCF1

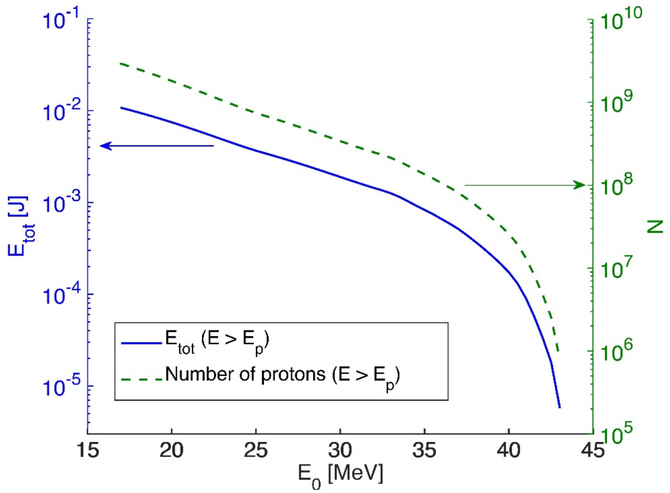




T_h= 3.1±0.3 MeV

P. Mora model: $\frac{dN}{dE} = \frac{n_{e0} c_s t_{acc} S_{sheath}}{(2ET_h)^{\frac{1}{2}}} \times exp\left(-\sqrt{\frac{2E}{T_h}}\right)$

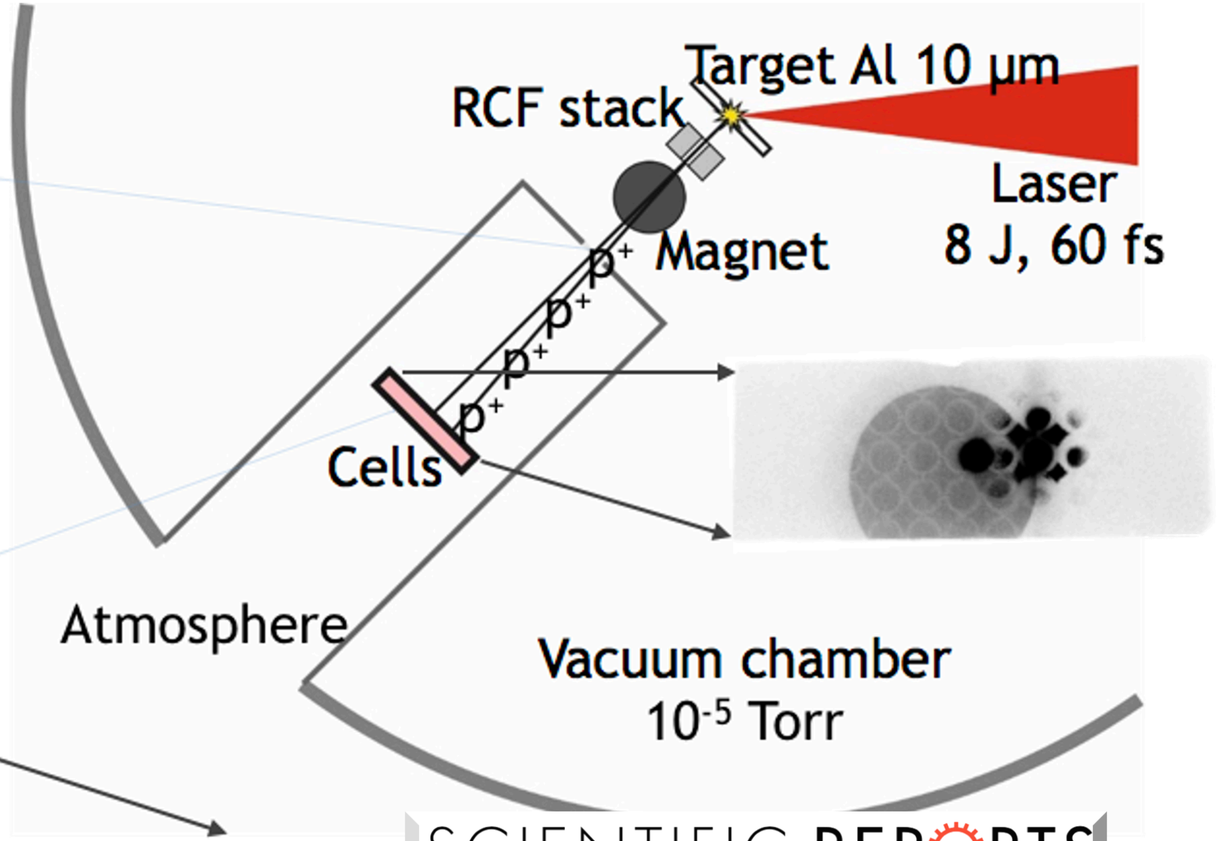


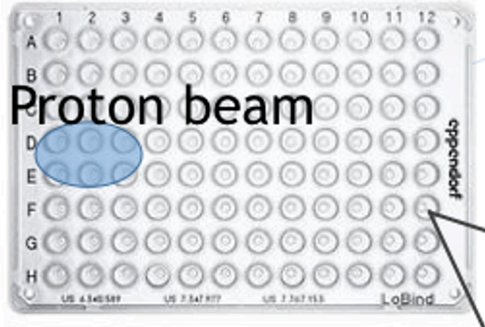


SCIENTIFIC REPORTS | 7: 12144 | DOI:10.1038/s41598-017-11675-2

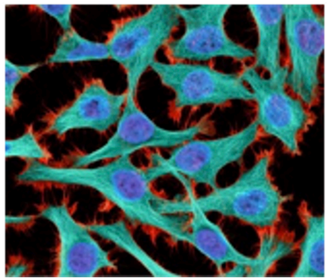
Experiments on bio-objects

Plastic window <100 µm thick
D = 15 mm





Microwell plate for cells



SCIENTIFIC REPORTS

OPEN

Ultra-short laser-accelerated proton pulses have similar DNA-damaging effectiveness but produce less immediate nitroxidative stress than conventional proton beams

Received: 12 May 2016
Accepted: 04 August 2016
Published: 31 August 2016

S. Raschke[1,2,3,*], S. Spickermann[1,*], T. Toncian[1], M. Swantusch[1], J. Boeker[1], U. Giesen[4], G. Iliakis[3], O. Willi[1] & F. Boege[2]

Quantum Electronics **46** (4) 283–287 (2016)

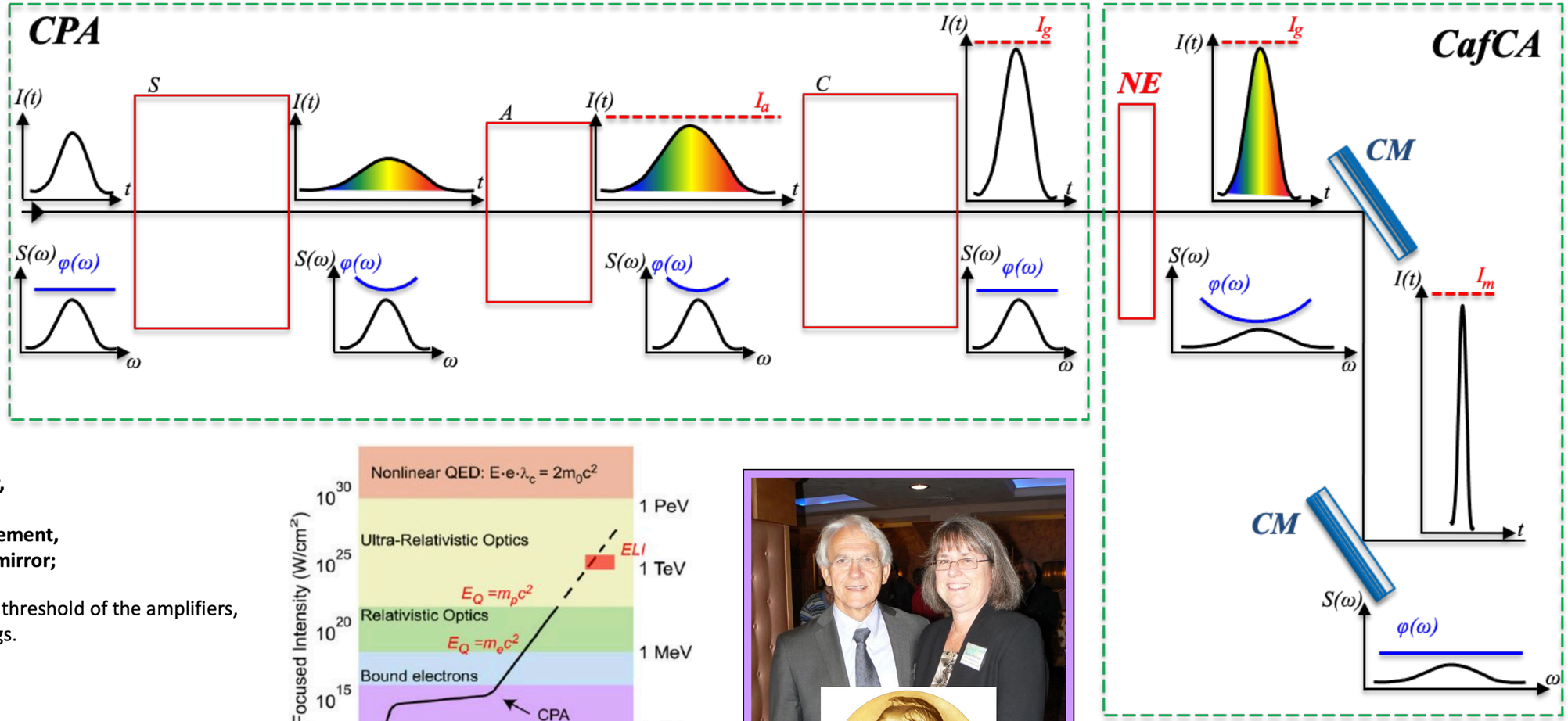
DOI: 10.1070/QEL16043

The experimental results are in good agreement with the experimental results from the community.
Thus we realised, optimisation of the acceleration efficiency is only possible by optimising the laser source.

The main issues:
1. Not enough intensity
2. Focusing is not perfect
3. Low stability

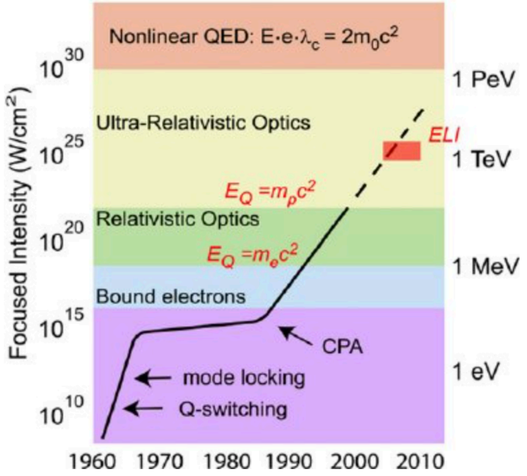
The solution:
1. CafCA (Compression after Compression Approach - peak power increase)
2. Focusing optimisation (linear distortions and nonlinear distortions cases)
3. Optical synchronisation for OPCPA

Compression after Compressor Approach



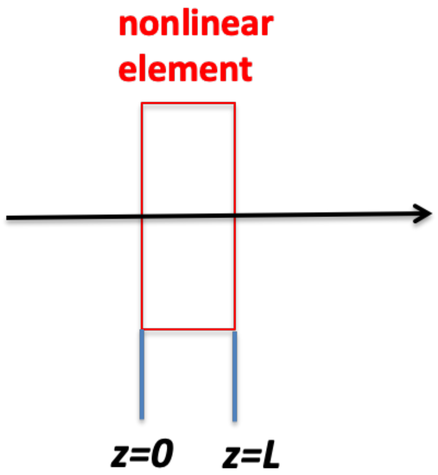
S – stretcher,
A – laser amplifier,
C – compressor,
NE – nonlinear element,
DM – dispersion mirror;

I_a , I_g – breakdown threshold of the amplifiers, diffractions gratings.



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**

η=(t-z/u)/ τ_pulse **: normalized time**

τ_pulse **: pulse duration**

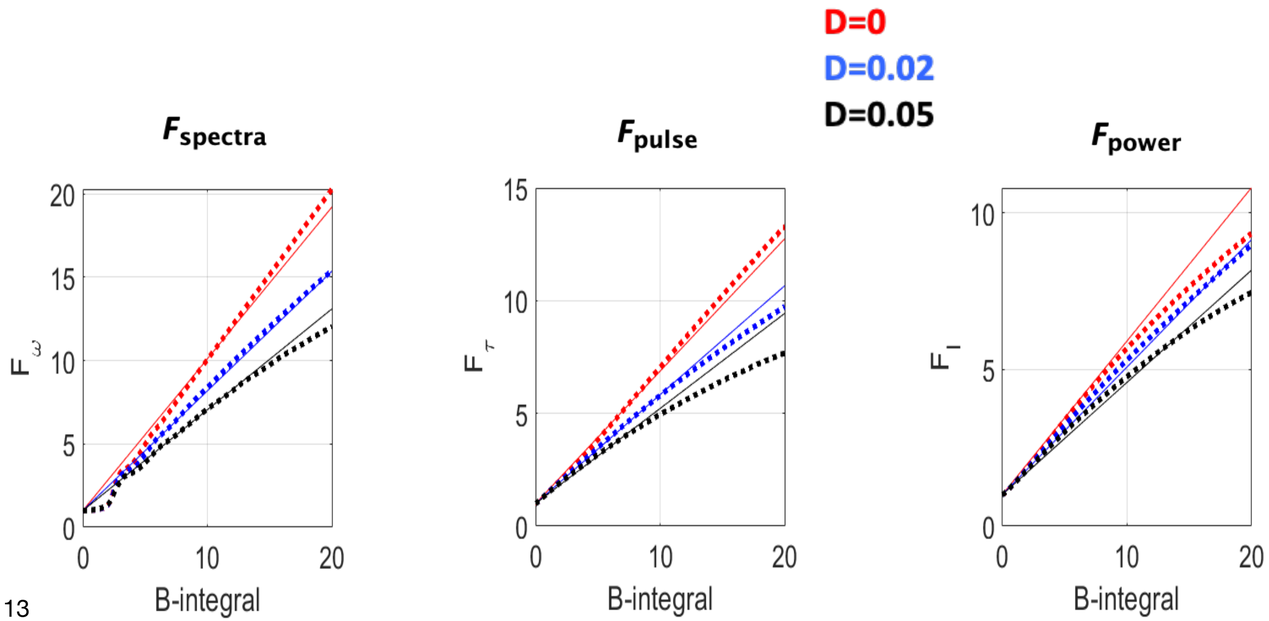
$B=n_2IkL=L/L_{nonlinear}$

$D=k_2L(\tau_{pulse})^2=L/L_{dispersion}<<1$

$F_{spectra}= 1+0.9B(1-1.5D^{1/2})$

$F_{pulse} = 1+0.6B(1-1.25D^{1/2})$

$F_{power} = 1+0.5B(1-1.2D^{1/2})$



V.N. Ginzburg, A.A. Kochetkov, I.V. Yakovlev, S.Y. Mironov, A.A. Shaykin, E.A. Khazanov, Quantum Electronics 46 (2016) 106-108.

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

$$B < 2 \ldots 3 \quad \Rightarrow \quad F_{power} < 2 \ldots 2.5$$

$$B \sim 10 \ldots 16 \quad \Rightarrow \quad F_{power} \sim 6 \ldots 9$$

CafCA scaling problems and solutions

$B=n_2IkL$

Power scaling

Physical problems :

- small-scale self-focusing
- non flat-top beam shape

Solutions:

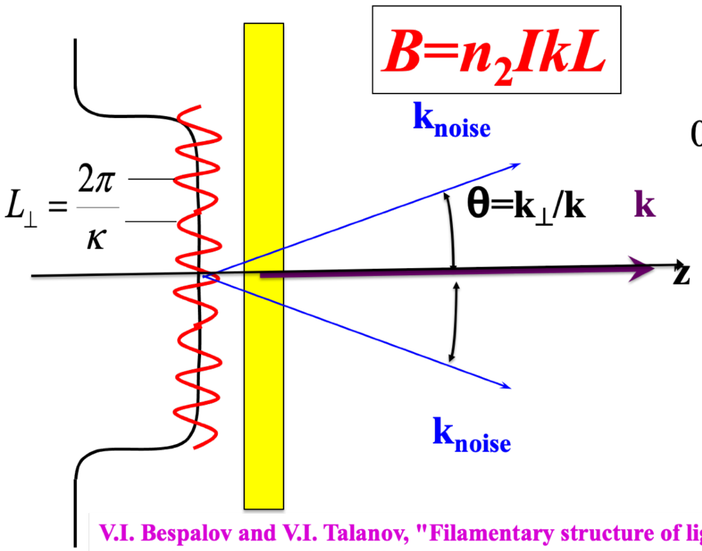
free space beam filtering
negative lens

Technological problem:

- very high aspect ratio 1:100+

Solutions:

plastic instead of glass



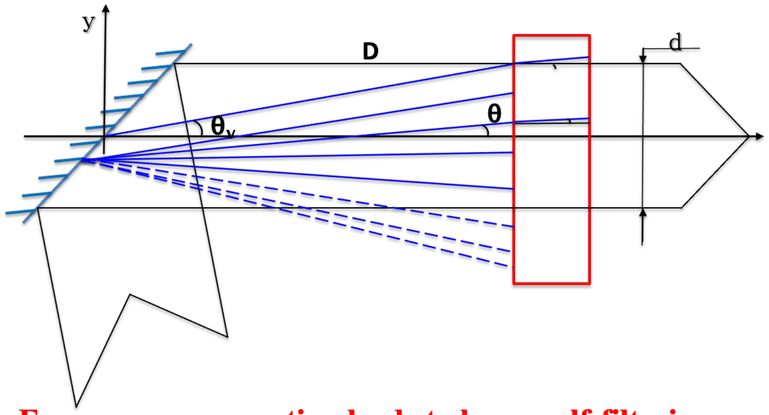
Instability if

$$0 < \theta < \theta_{cr} = 2\sqrt{\frac{\gamma I}{n}}$$

V.I. Bespalov and V.I. Talanov, "Filamentary structure of light beams in nonlinear liquids," JETP Letters, 3, 307-310 (1966).

The technique of beam filtering depends on the intensity level

For ns laser beams intensities I ~ 1÷10GW/cm² θ_{max}=0.73÷2 mrad
For fs laser beams intensities I ~ 1÷10TW/cm² θ_{max}=20÷50 mrad



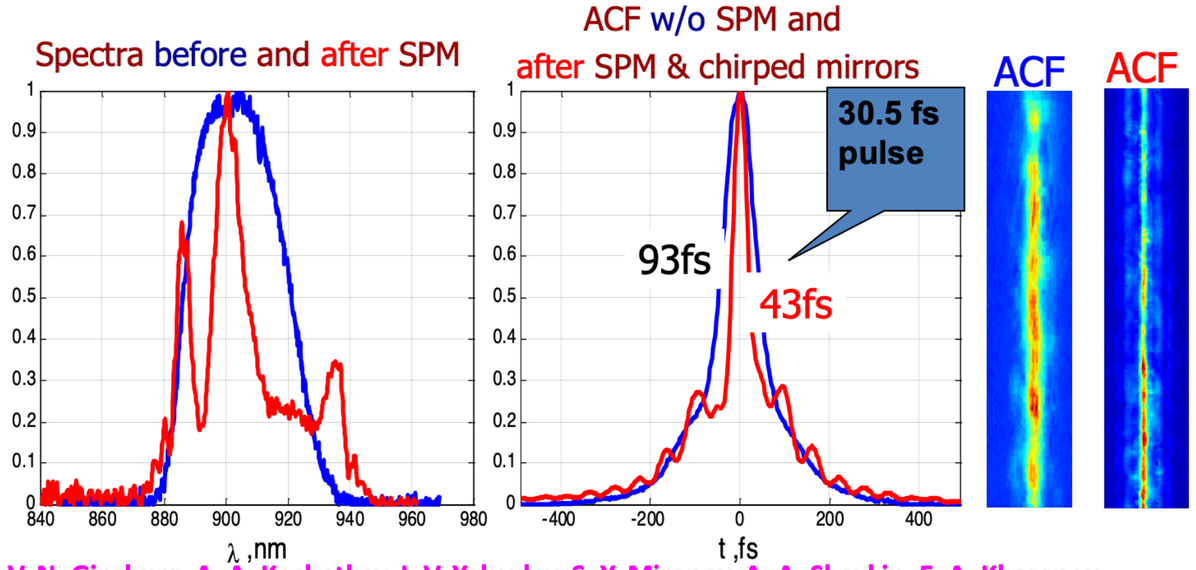
$$\theta_{cr} = 2\sqrt{\frac{\gamma I}{n}}$$

Free space propagation leads to beam self-filtering
I=1TW/cm², d=100mm: the safety distance D>1.6m

CafCA in experiments

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

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



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

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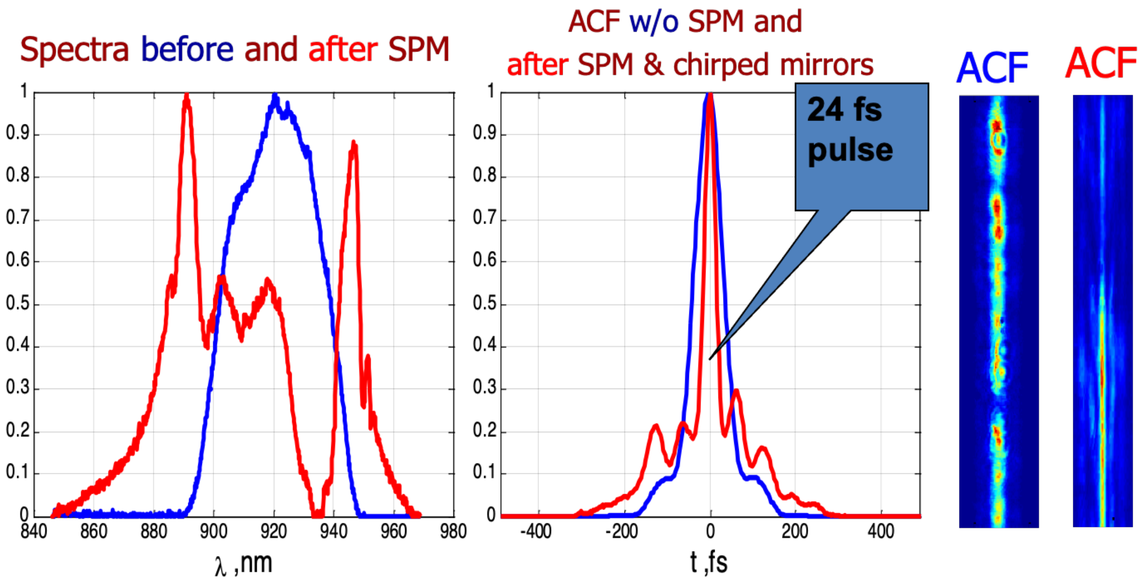
CafCA in experiments

Example 2: at the output of the PEARL

Ø 100mm, W=6J, T_{pulse}=56fs -> 24fs, $L_{plastic}$=0.5mm, B~3



S.Y. Mironov, V.N. Ginzburg, I.V. Yakovlev, A.A. Kochetkov, A.A. Shaykin, E.A. Khazanov, and G.A. Mourou, Quantum Electronics 47, 614-619 (2017).

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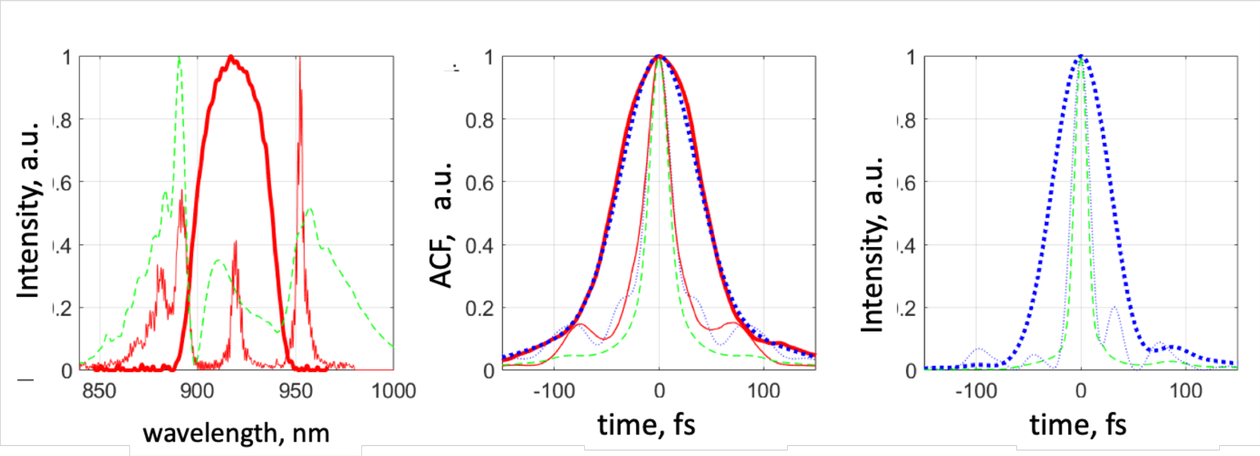
Example 3: at the output of the PEARL

Ø 160mm, W=12J, T_{pulse}=63fs -> 21fs, L_{glass}=3 mm, B~6



V. N. Ginzburg, I. V. Yakovlev, A. S. Zuev, A. A. Korobeinikova, A. A. Kochetkov, A. A. Kuz'min, S. Y. Mironov, A. A. Shaykin, I. A. Shaykin, and A. E. Khazanov, "Compression after compressor: threefold shortening of 200-TW laser pulses," *Quantum Electronics*, 49, 299, 2019.

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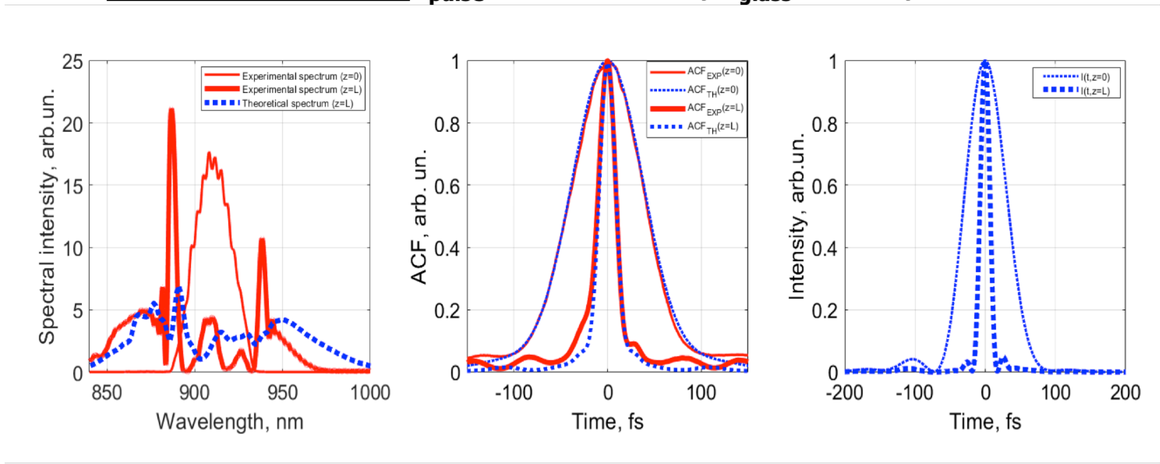
Example 4: at the output of the PEARL

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

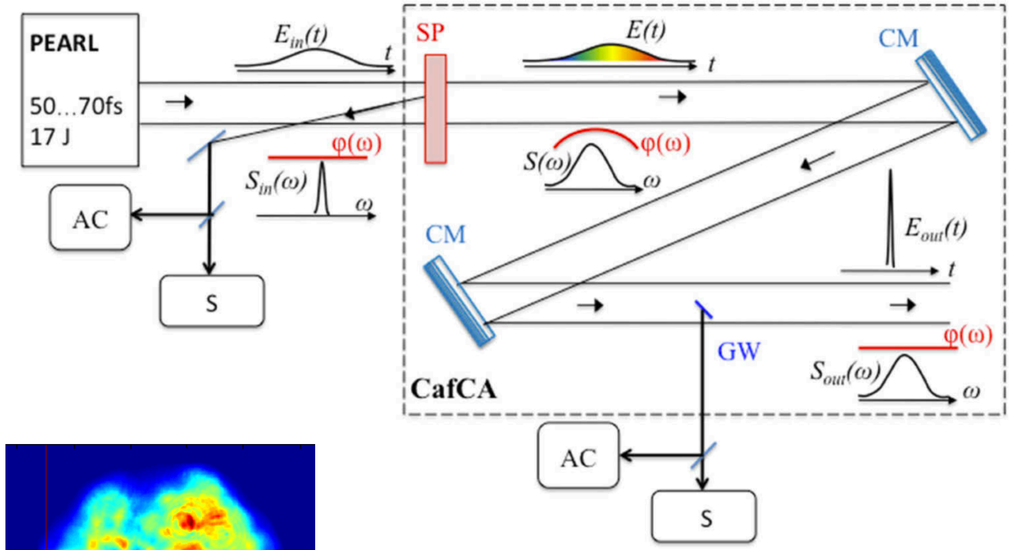


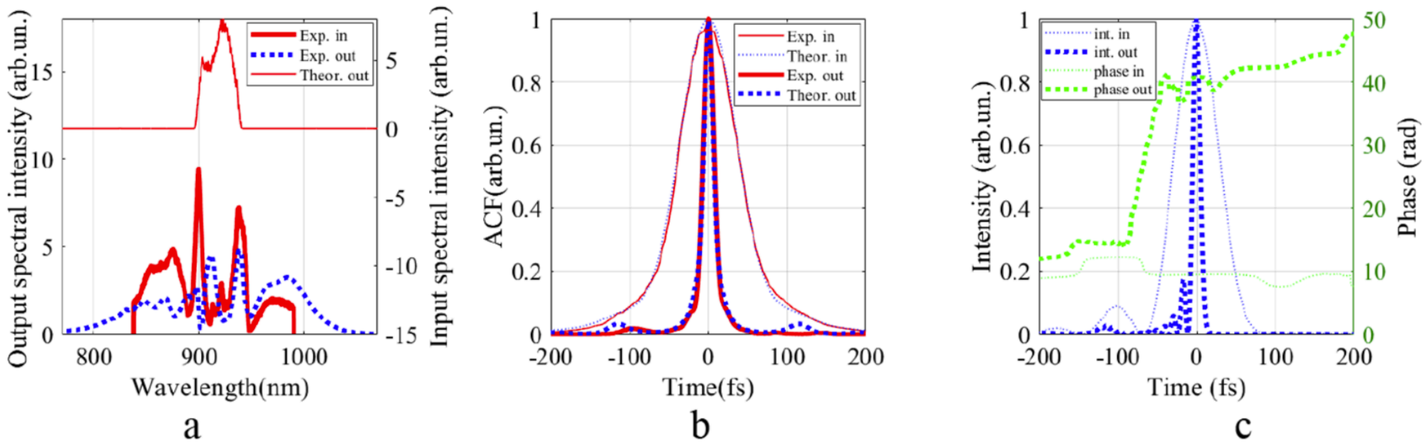
PRA, 101, 013829 2020

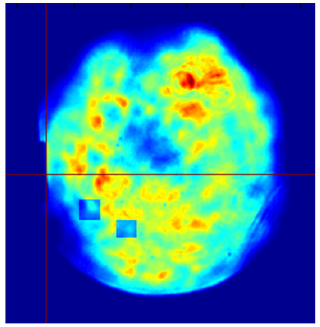
25

Ginzburg, V. *et al.* 11 fs, 15 PW laser with nonlinear pulse compression. *Opt. Express* **29**, 28297 (2021)
https://doi.org/10.1364/OE.434216

Example 5 (the most recent): output of the PEARL







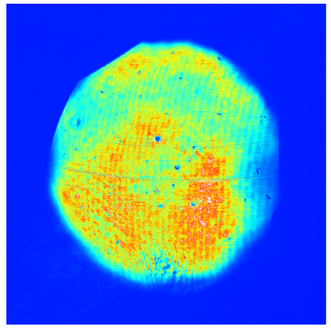
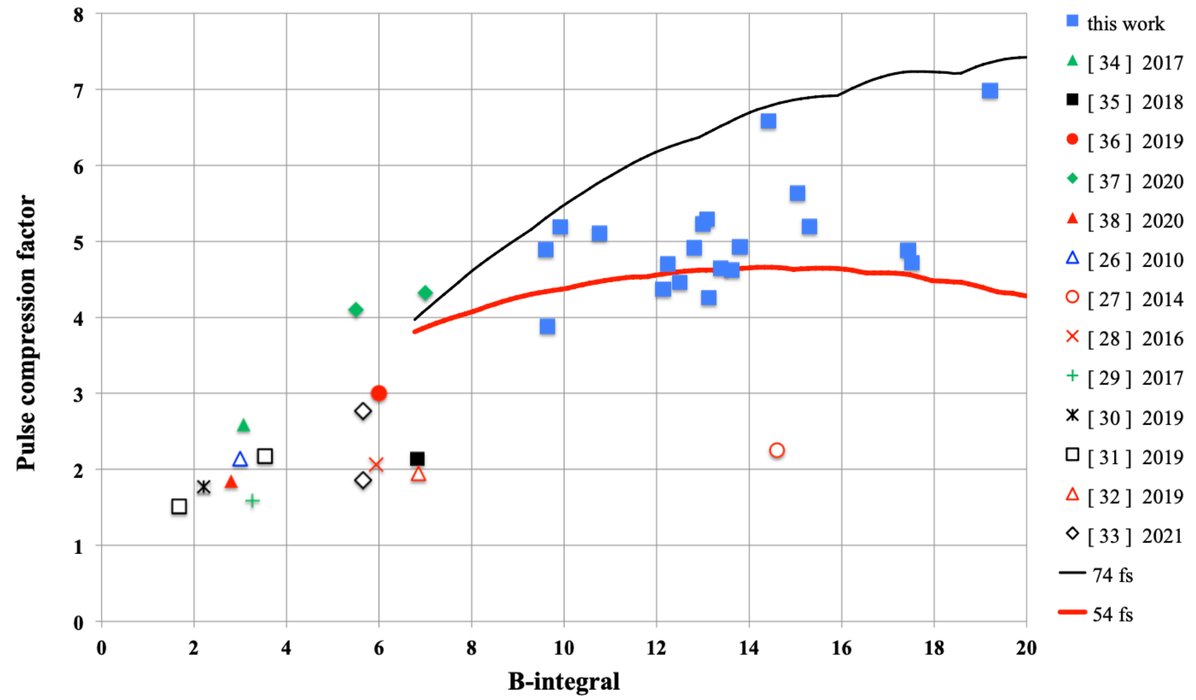
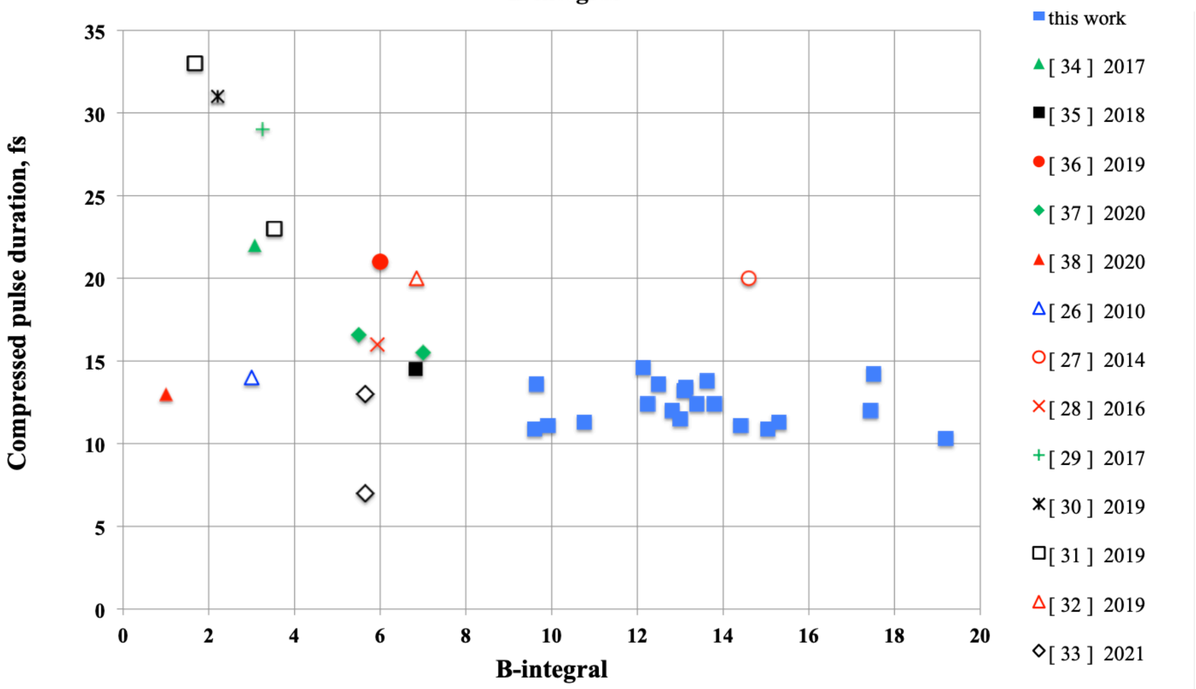


Table 1. Comparison of experimental and theoretical parameters

	Experiment			Numerical study for zero (optimal) TOD of CMs			
B	τ_{in}, fs	τ_{out}, fs	$F_\tau=\tau_{in}/\tau_{out}$	τ_{in}, fs	τ_{out}, fs	$F_\tau=\tau_{in}/\tau_{out}$	$F_i=I_{out}/I_{in}$
9.6	54 ± 5	10.9 ± 1.5	5.0	58	12.3 (9.0)	4.7 (6.5)	4.2 (5.8)
9.9	58 ± 6	11.3 ± 1.5	5.1	58	12.2 (8.9)	4.8 (6.5)	4.0 (5.7)
13	60 ± 6	11.5 ± 1.5	5.2	64	11 (7.9)	5.8 (8.1)	5.0 (7.2)
19.2	72 ± 7	10.3 ± 1.5	7.0	75	10.2 (6.5)	7.4 (10.5)	5.7 (11.3)





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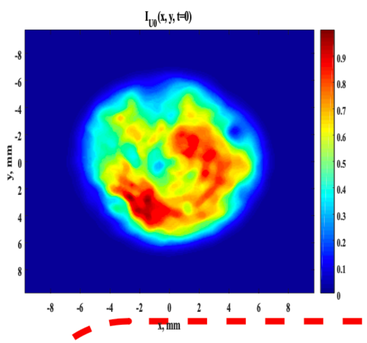
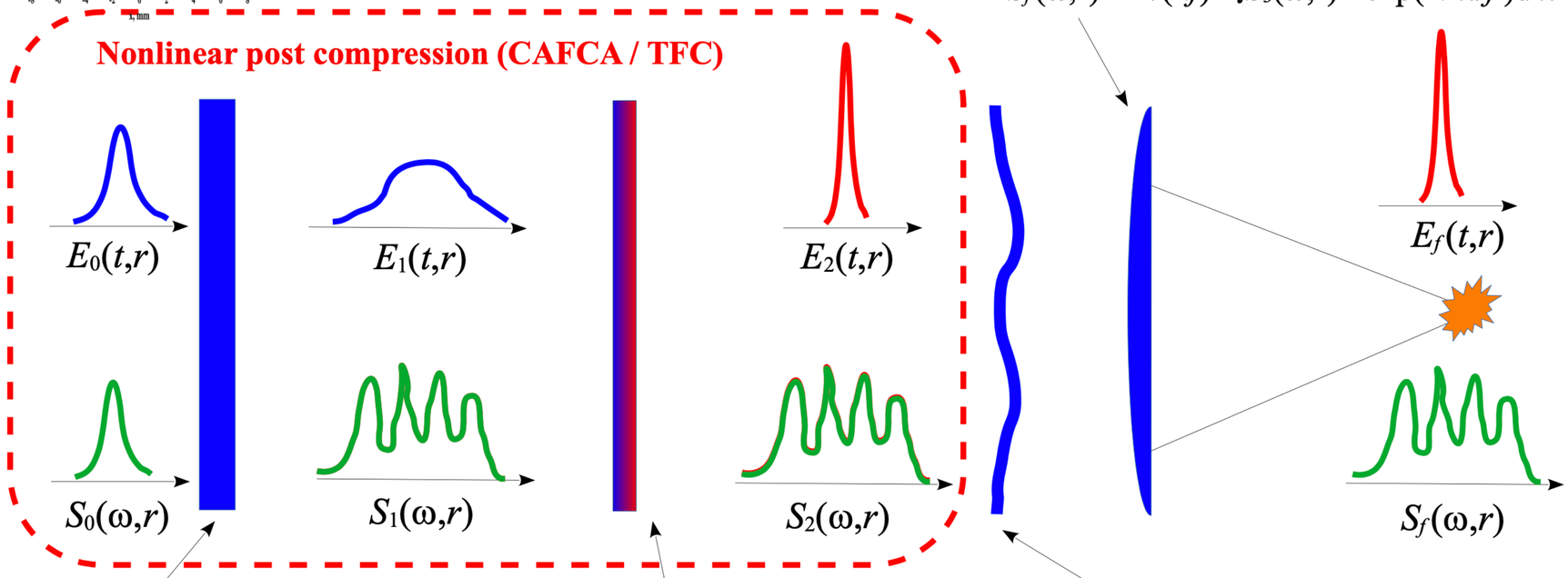
What happens if you focus the pulse after CafCA?



Main challange to employ CAFCA for focusing application:

Nonlinear phase spatial distribution ~ beam intensity distribution!



focusing optics
$S_f(\omega,\boldsymbol{r}) = 1/(\lambda f) \cdot \int S_3(\omega,\boldsymbol{r}) \cdot \exp(ik\boldsymbol{rx}/f)\mathrm{d}^2\boldsymbol{x}$

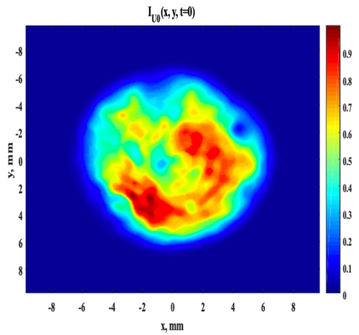
Thin plate with qubic nonlinearity
$n = n_0 + n_2 I$

Intensity $I \sim$ 1-3 TW/cm^2
B-integral ~ 10-20

Self-phase modulation and spectral broadening

Chirp mirrors <=> quadratic spectral phase correction $S_1(\omega,r) = S_0(\omega,r) \cdot \exp(i\beta\omega^2/2)$, pulse compression

adaptive deformable mirror $h(r)$
spatial phase correction
$S_3(\omega,r) = S_2(\omega,r) \cdot \exp(ikh(r))$

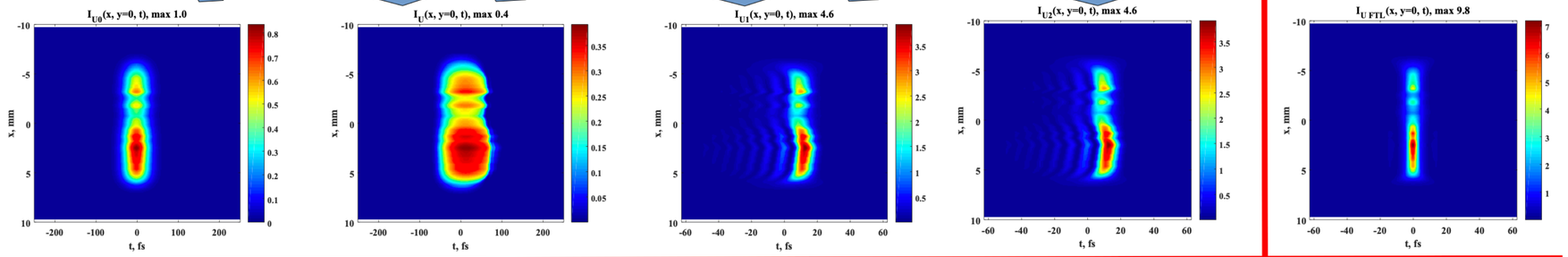


Numerical simulation
Input beam = Spatial distribution A(x,y) x Gaussian G(t)

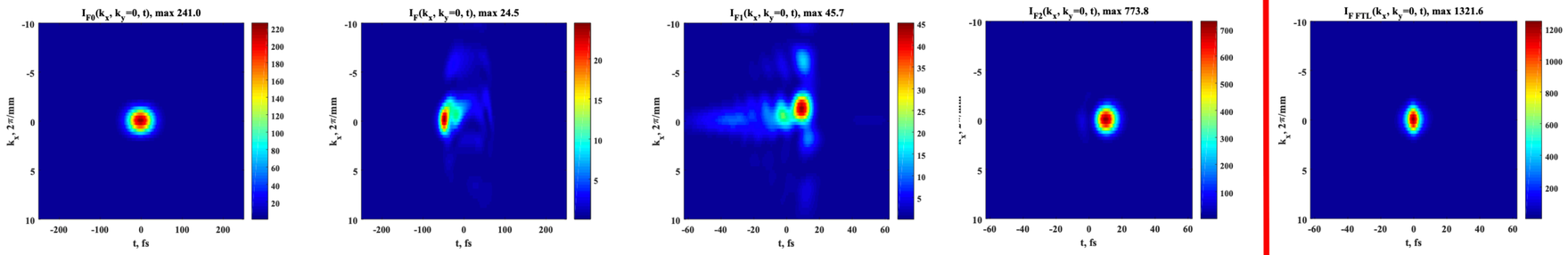
τ_{FWHM} = 50 fs, I = 1 TW/cm², B-integral = 20

Nonlinear propagation | **Pulse compression $\exp(-i\beta\omega^2/2)$ (to maximize pulse power)** | **Spatial phase correction $\exp(-i\varphi(x,y))$** | **FTL for reference**

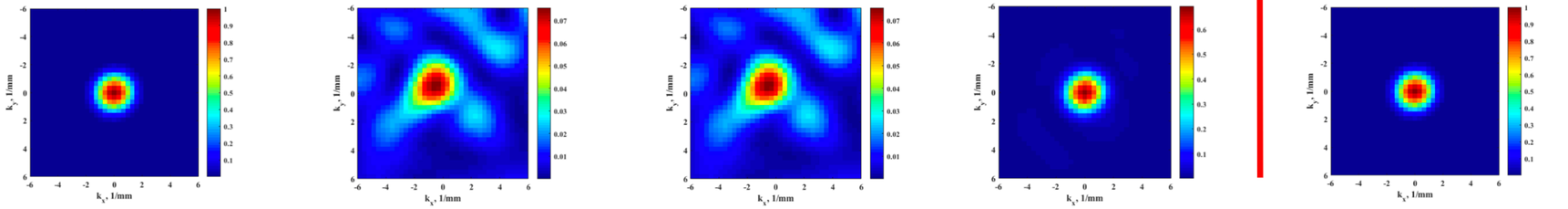
Pulse $I(x,t)$



At focus $I(k_x,t)$



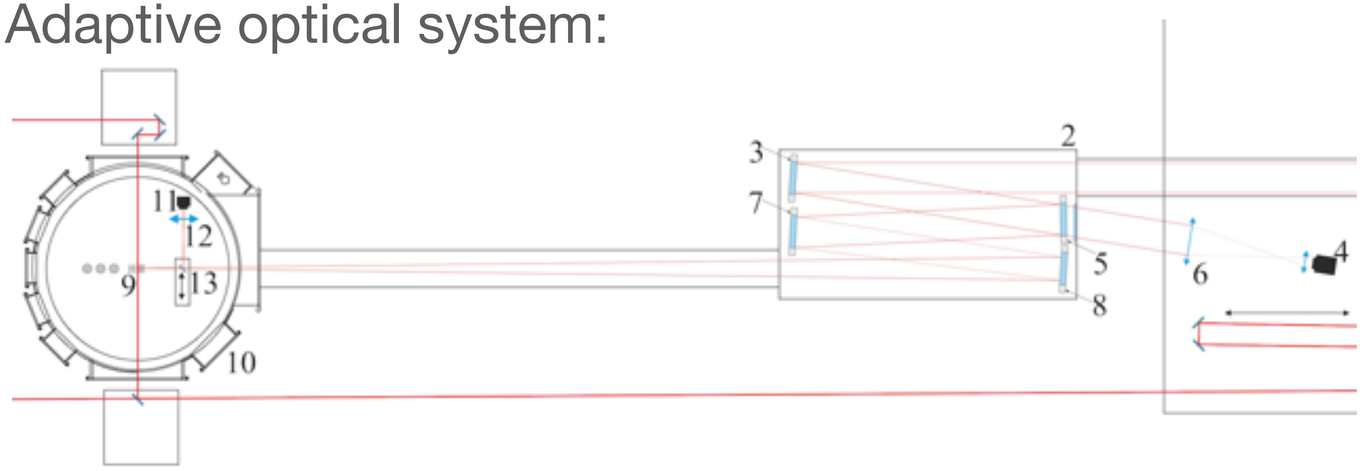
At focus $W(k_x,k_y)$

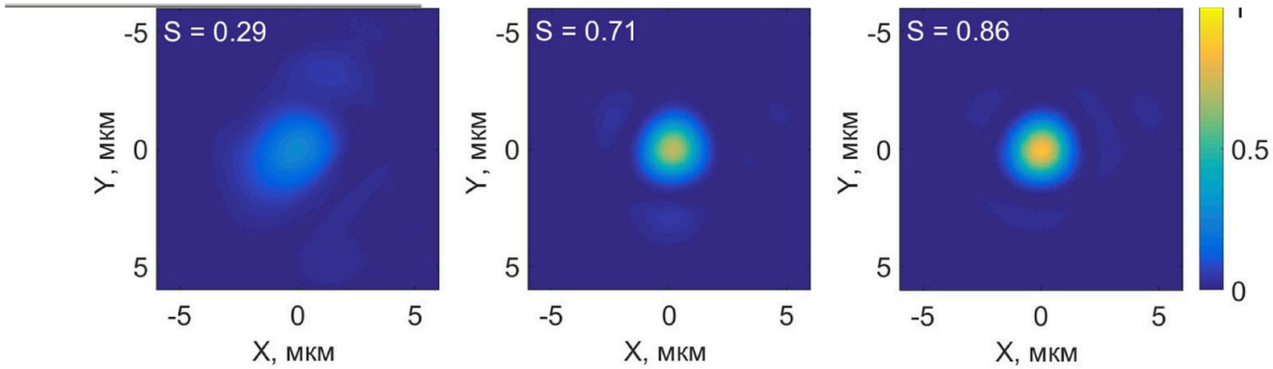


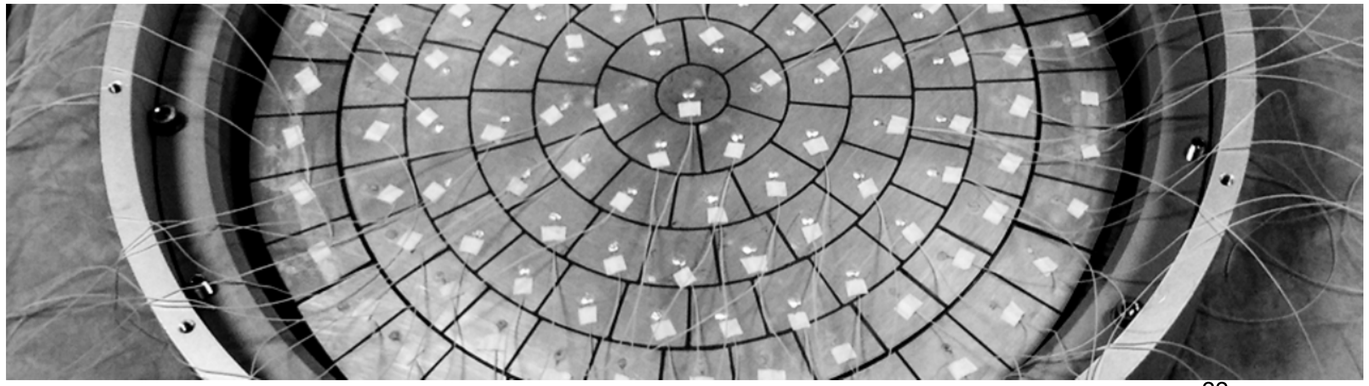
I_{peak} = 1 arb. units	0.1	0.2	3.2	5.5
W_{peak} = 1 arb. units	0.075	0.075	0.7	1
τ_{FWHM} = 50 fs	85	12	12	8

Linear phase distortion correction

Adaptive optical system:







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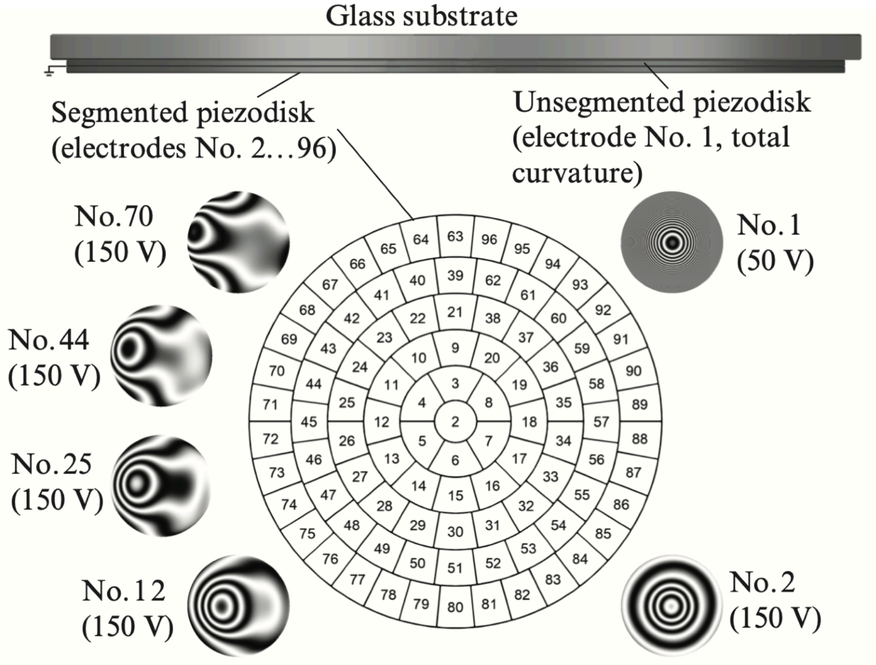
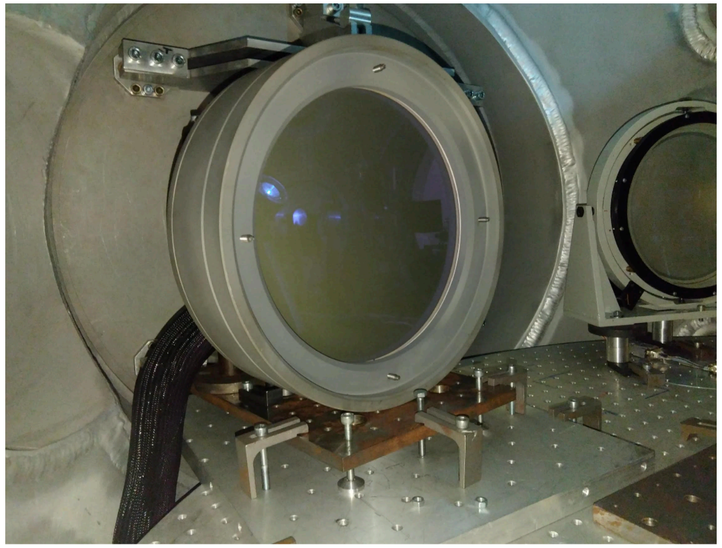
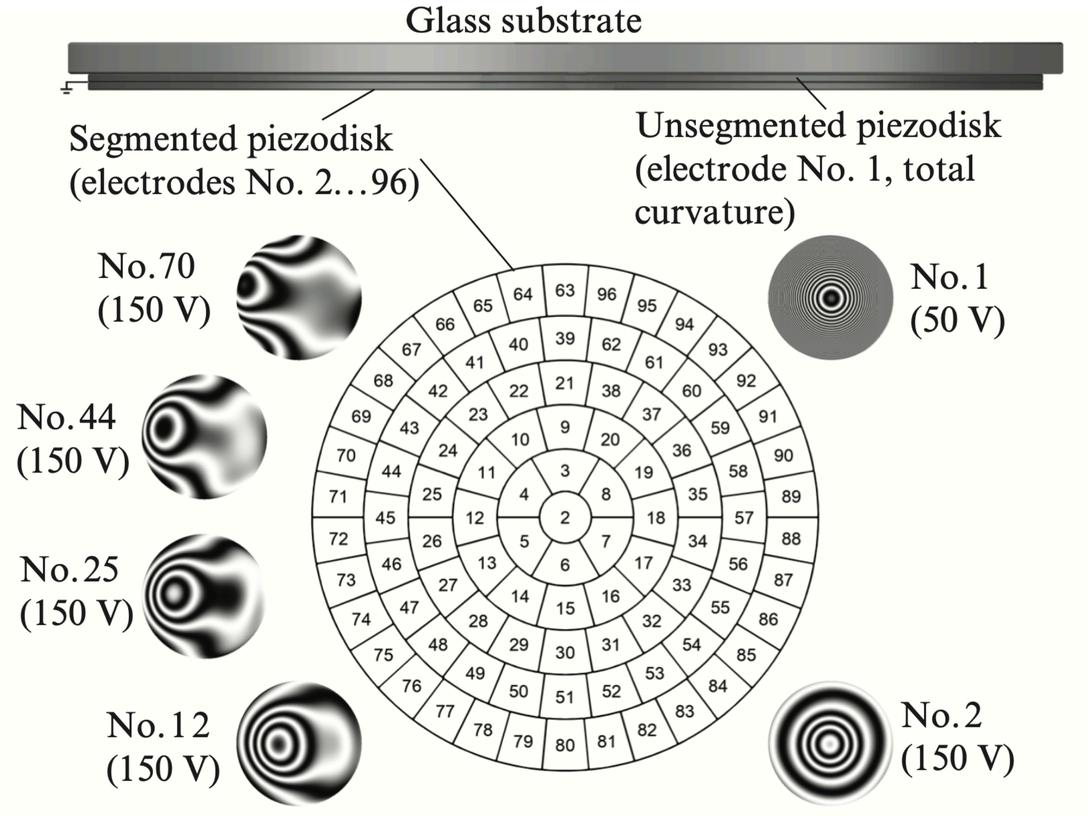
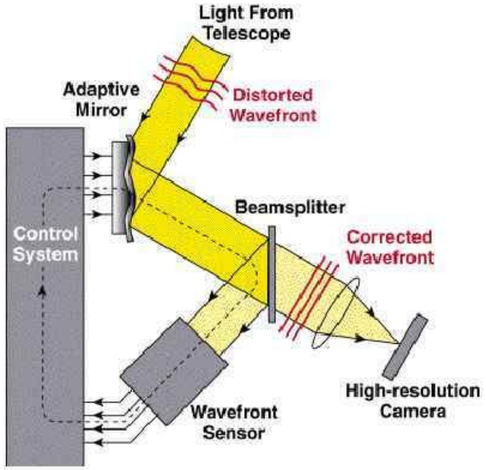
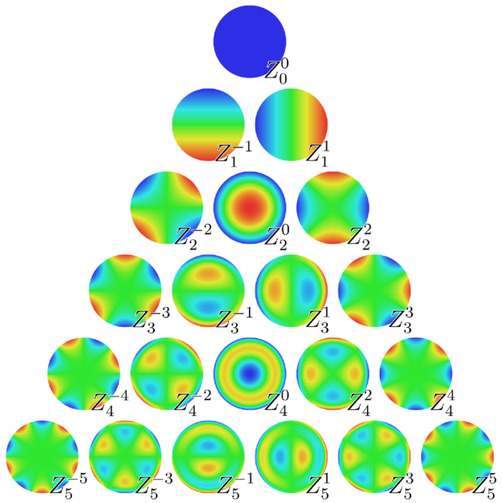


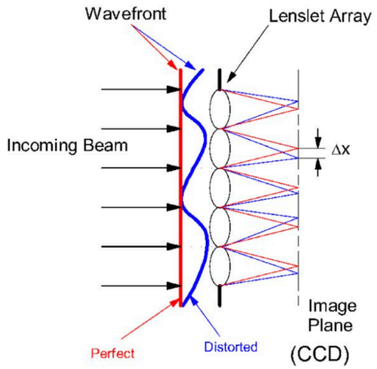


Dynamic optimisation of the reference waveforont

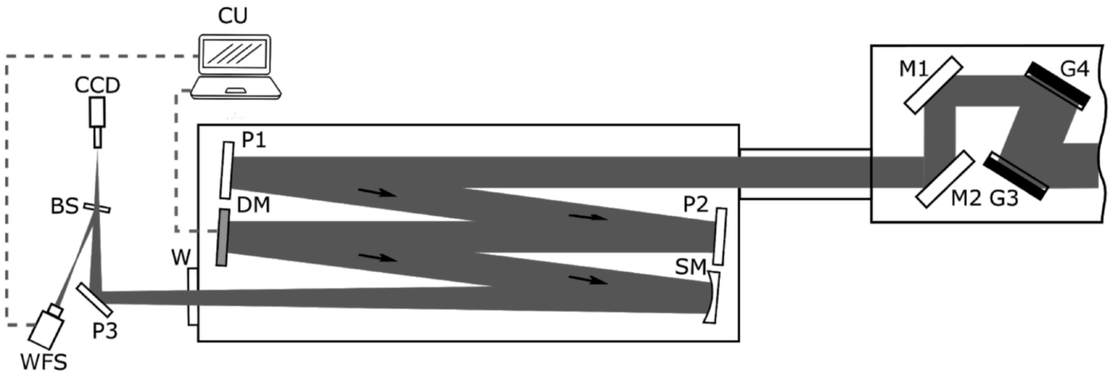








(c) Michael A. Campbell



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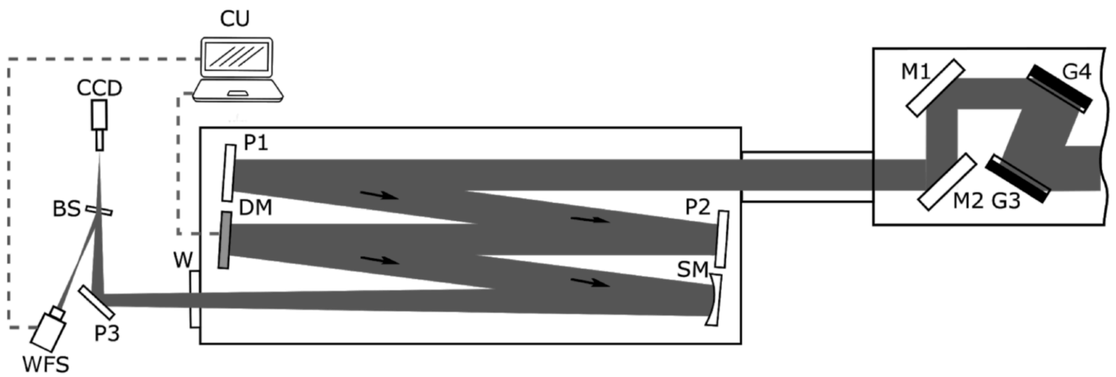
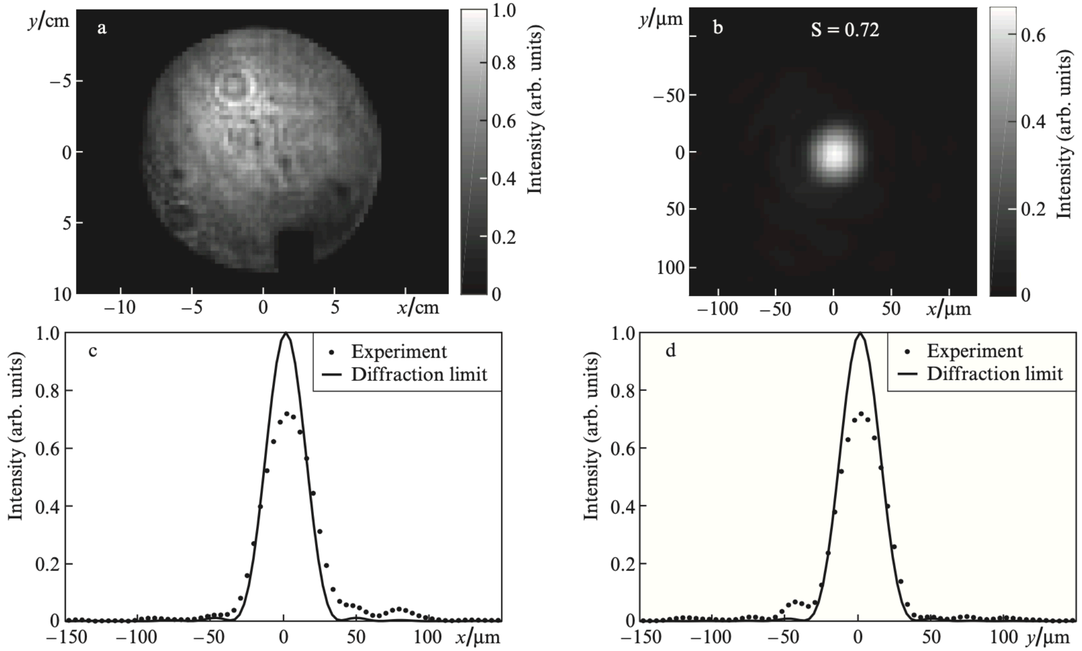
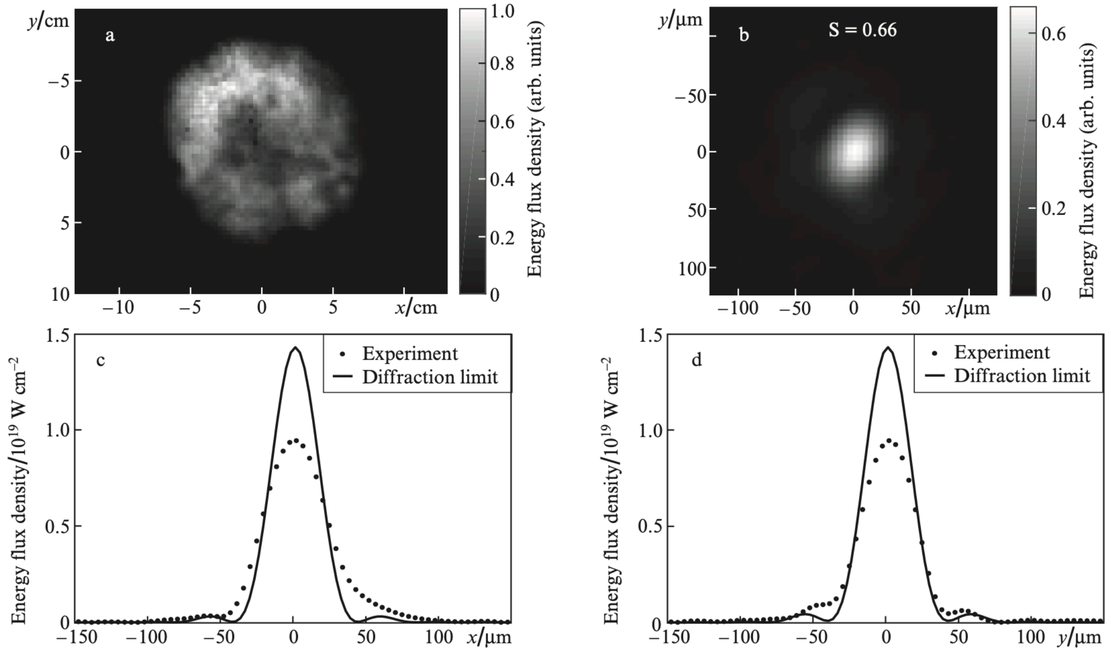
Full energy linear phase correction



CW alignment beam (100 mW)



7J, about 50 fs



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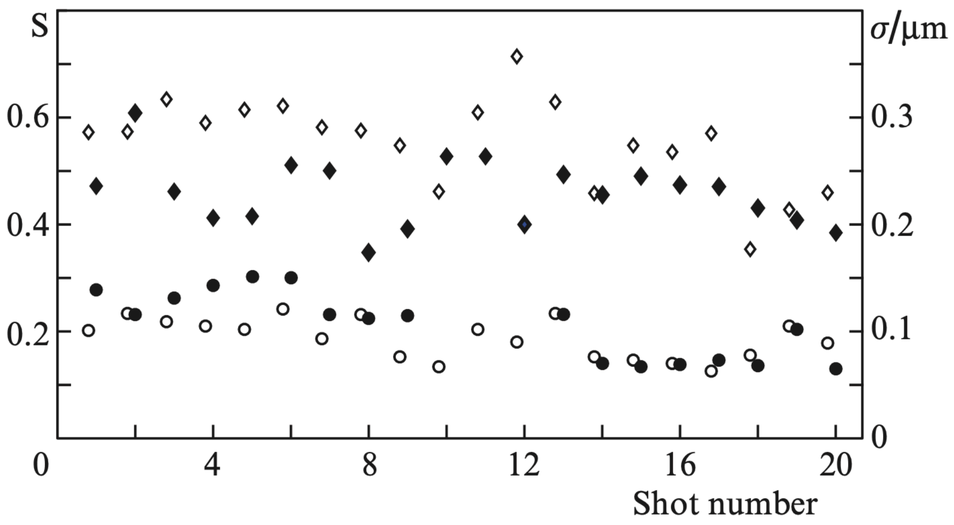

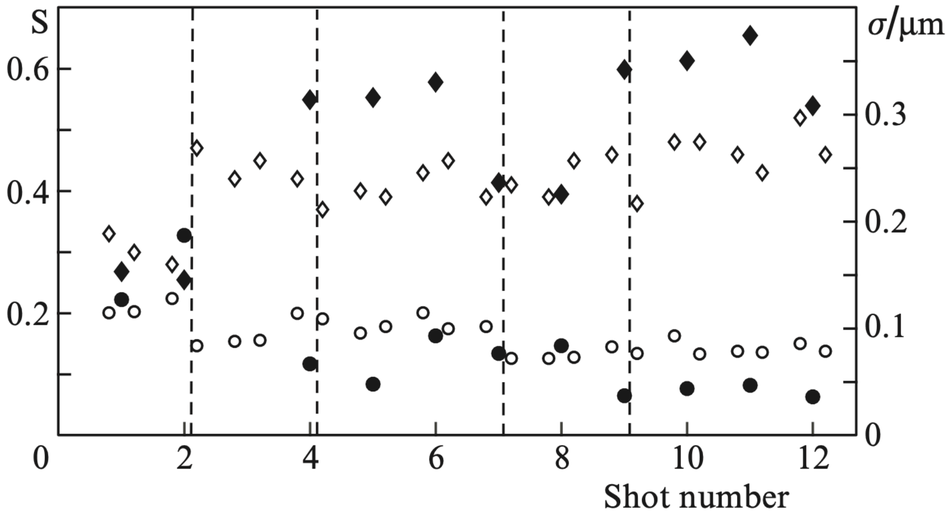

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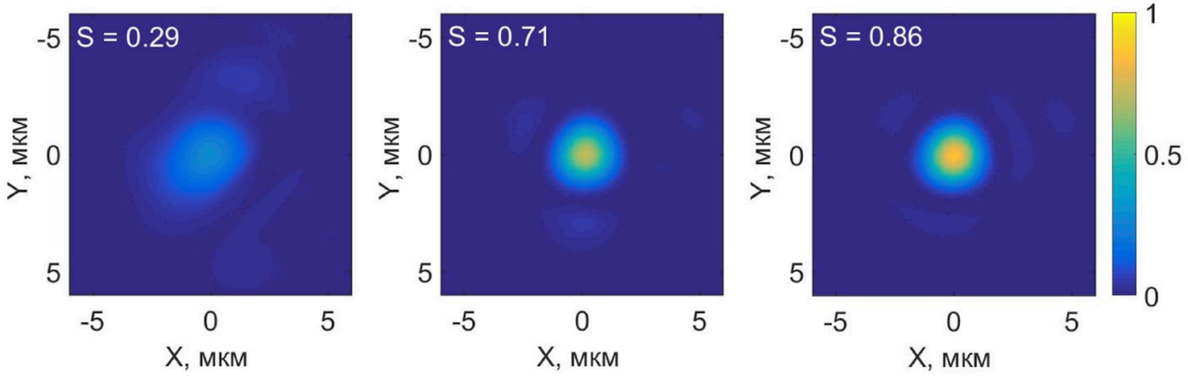
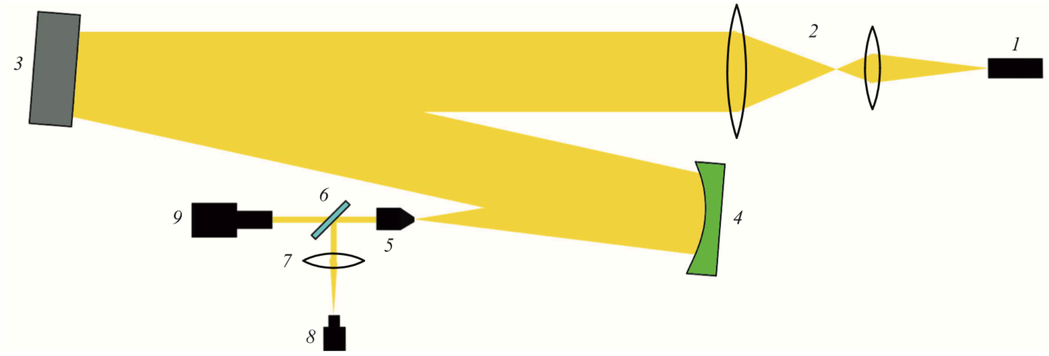


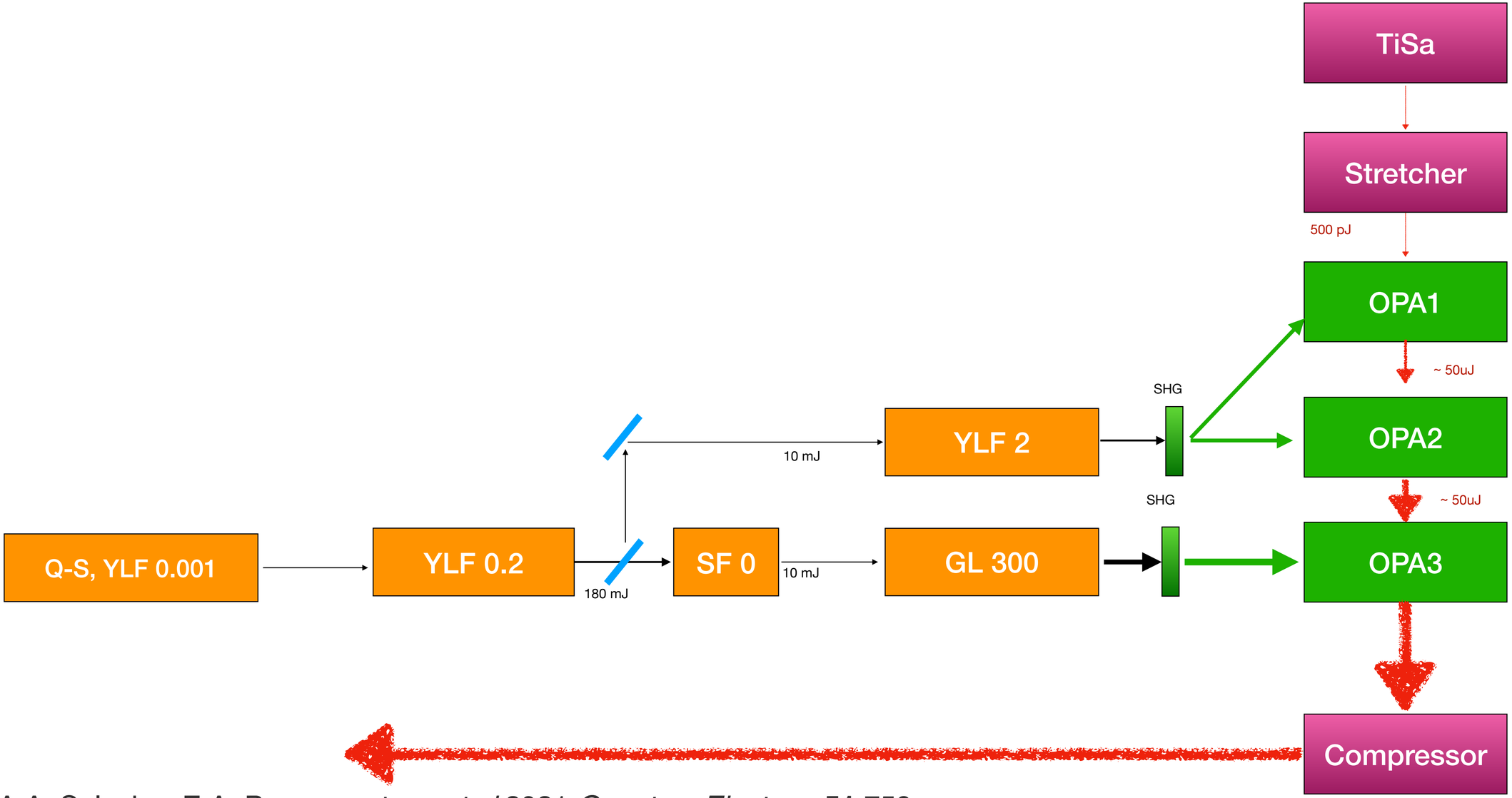


Linear phase correction results:

1. For the alignment beam S=0.72
2. For the full poser beam S is up to 0.66
3. For the alignment beam + dynamic reference S=0.86

Stability improvement:

Principle scheme of the PEARL laser:



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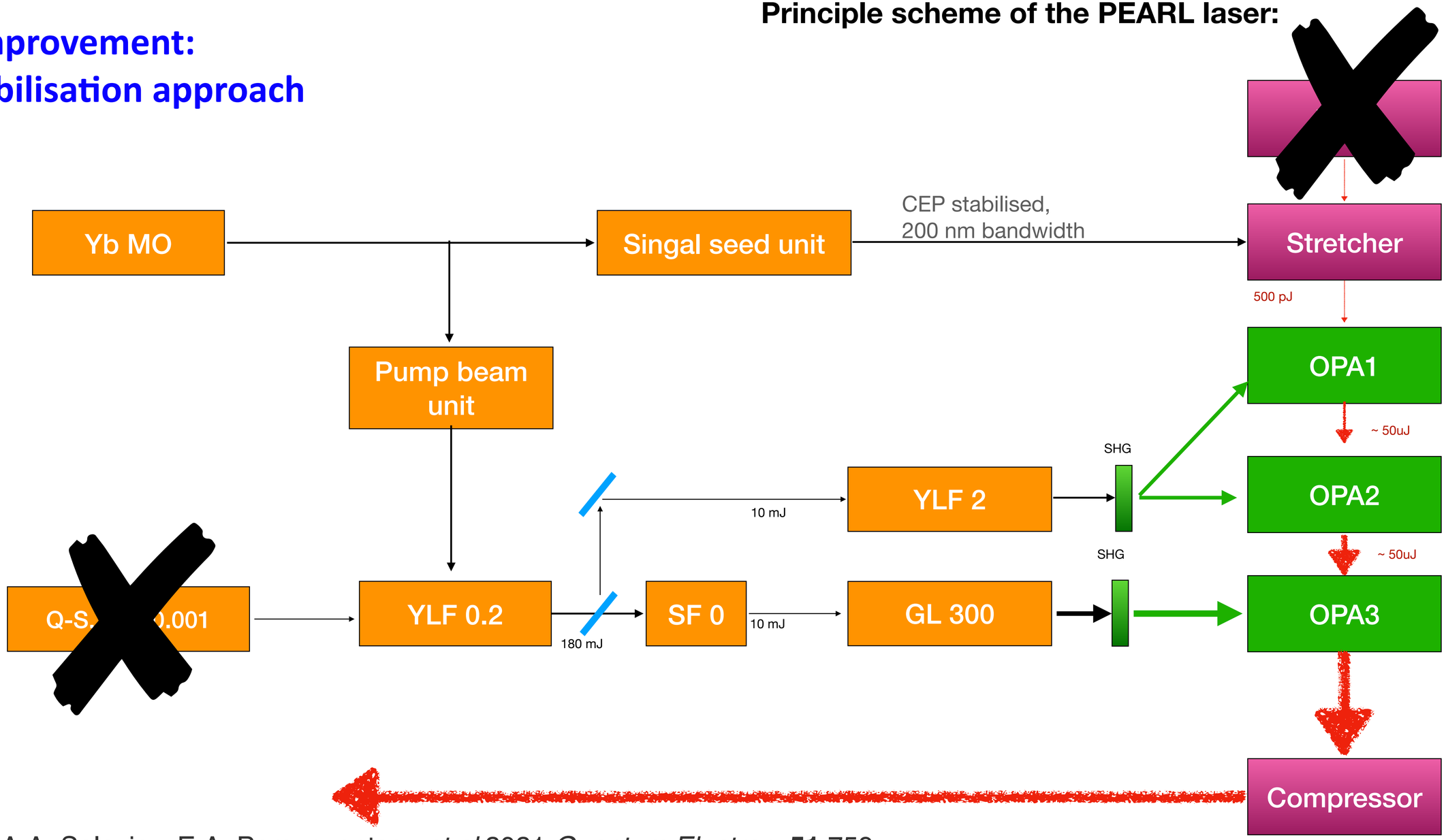
Stability improvement:
Optical stabilisation approach

Principle scheme of the PEARL laser:



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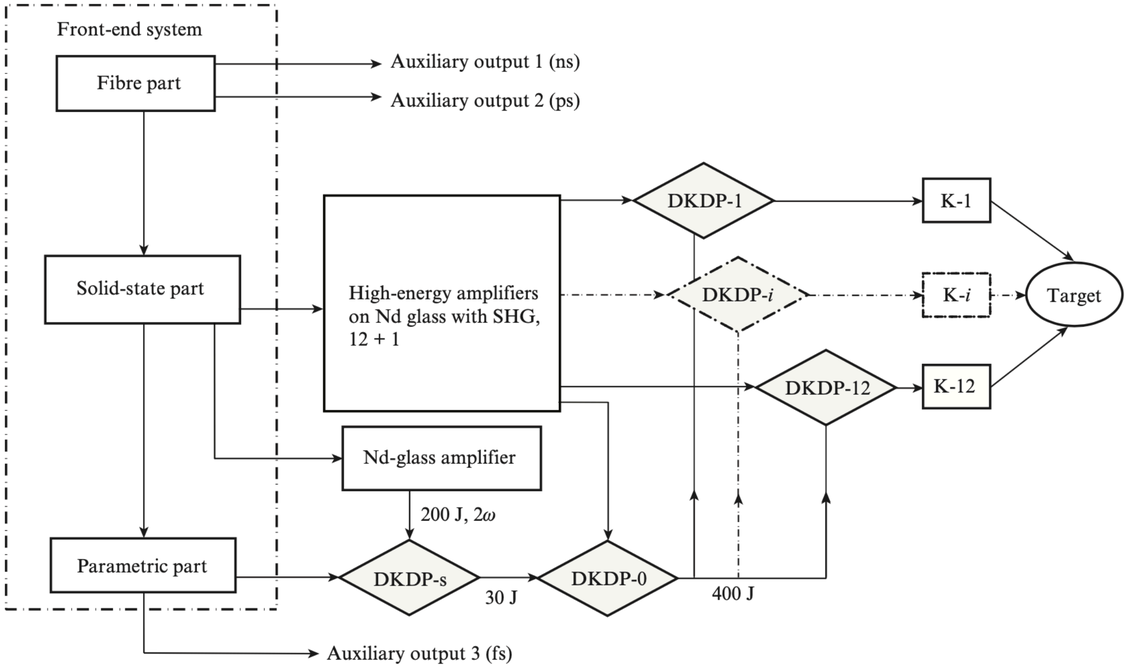
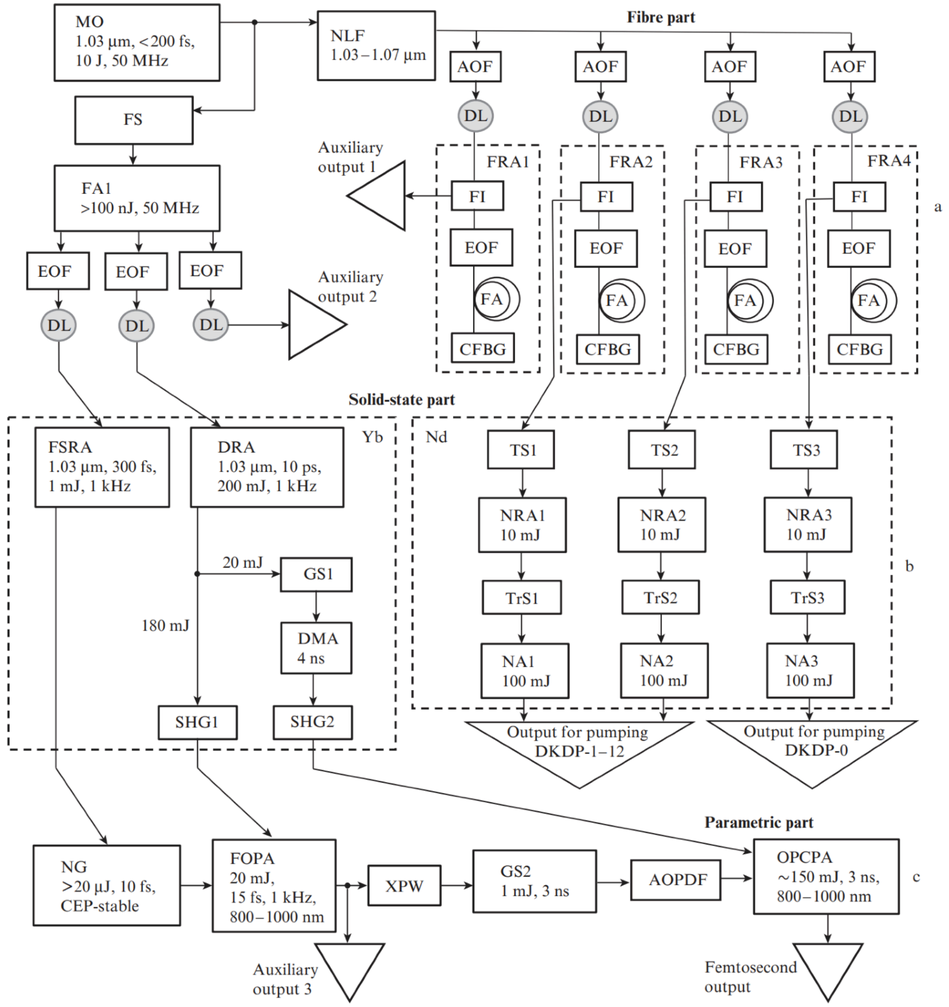
XCELS prototype conceptual design: (based on PEARL)





Functional scheme of the (a) fibre, (b) solid-state, and (c) parametric parts of the front-end system: (MO) master oscillator; (NLF) nonlinear fibre for spectral broadening; (FA) fibre amplifier; (AOF) acousto-optic filter; (EOF) electro-optic filter; (DL) delay line based on a piezoelectric wafer; (FI) Faraday isolator; (CFBG) chirping fibre Bragg grating; (FRA1–FRA4) fibre regenerative amplifiers; (FSRA) femtosecond regenerative amplifier; (DRA) disk regenerative amplifier; (DMA) disk multipass amplifier; (TS1–TS3) pulse time shaping units; (TrS1 –TrS3) laser beam transverse shaping units; (NRA1 –NRA3) neodymium regenerative amplifier; (NA1 –NA3) neodymium rod amplifiers; (NG) unit for nonlinear parametric generation of broadband femtosecond radiation; (SHG1; SHG2) second-harmonic generation units; (FOPA) frequency domain optical parametric amplification unit; (XPW) cross-polarised wave generation unit; (OPCPA) optical parametric chirped-pulse amplification unit; (FS) fibre stretcher; (GS1 –GS2) diffraction grating stretchers; (AOPDF) acousto-optic programmable dispersion filter.

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Conclusions:

- The low intensity of an fs-laser system is not a fundamental limitation.

- Even laser systems with relatively modest parameters can be easily upgraded with CafCA. (Peak power of the PEARL laser has been upgraded up to 1.5 PW / 11 fs)

- Particular importance is attached to improving the stability of the laser system

- Phase distortion becomes non-linear and must be adequately treated

Thanks for your kind attention!