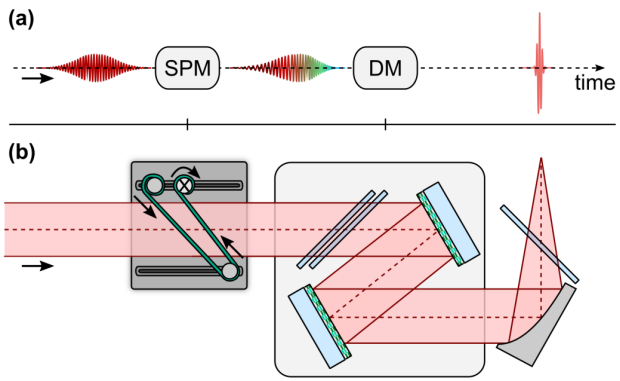
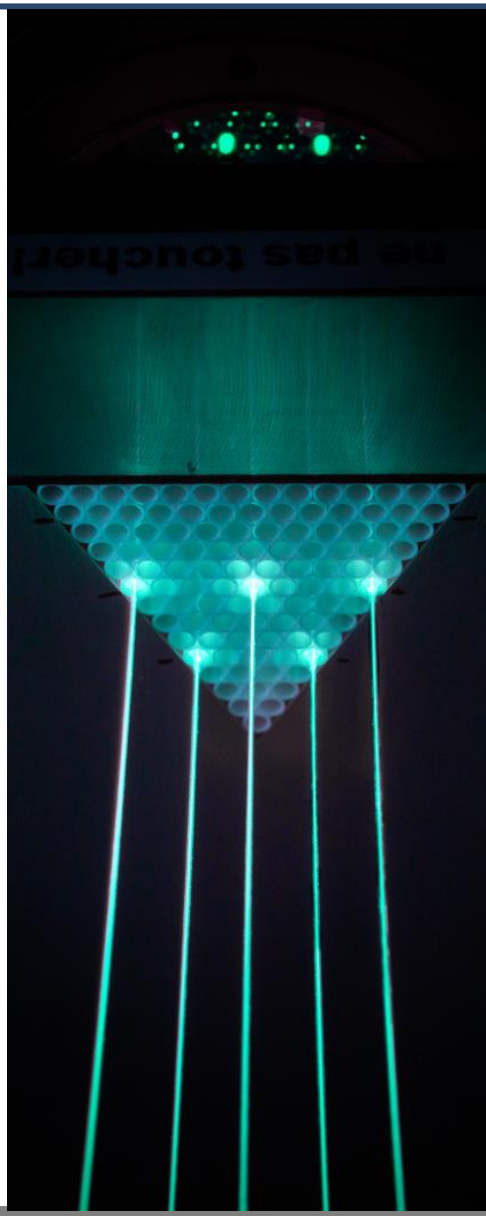
Thin Film Compression and CAN Laser Experimental Results



Jonathan WHEELER
École polytechnique
Palaiseau, France

June 25th, 2019

Coherent Amplifying Network

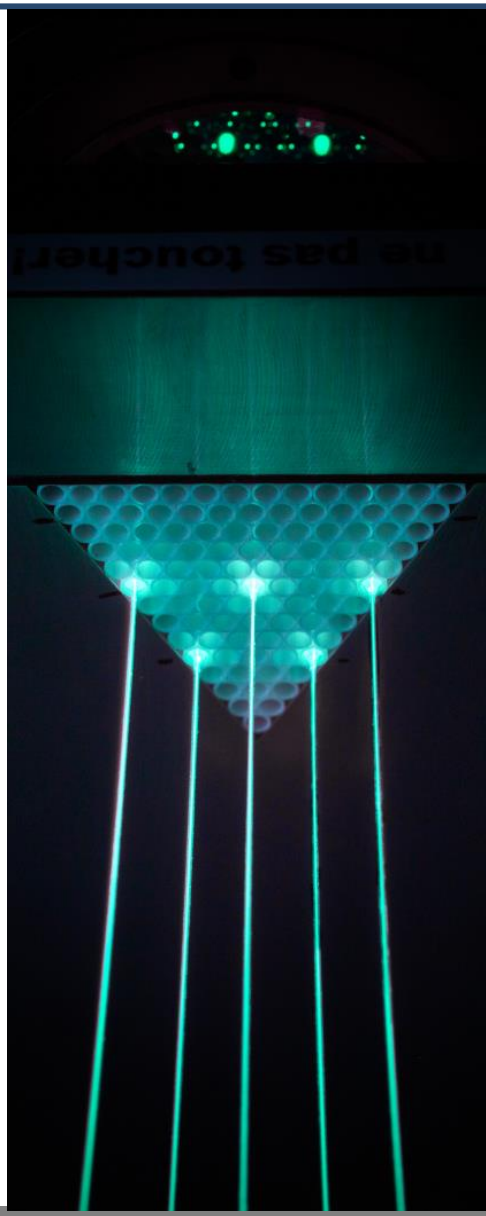


Coherent Beam Combining of femtosecond fiber amplifiers: a path towards high peak and average power lasers

Xcan
Coherent Amplification Network
POLYTECHNIQUE / THALES

J.-C. Chanteloup, A. Heilmann, L. Daniault, I. Fsaifes, S. Bellanger, A. Brignon, J. Bourderionnet, É. Durand, É. Lallier, C. Larat

June 25th, 2019



General context

What about a laser source combining both

High

peak → **Short pulses < ps (few fs)**

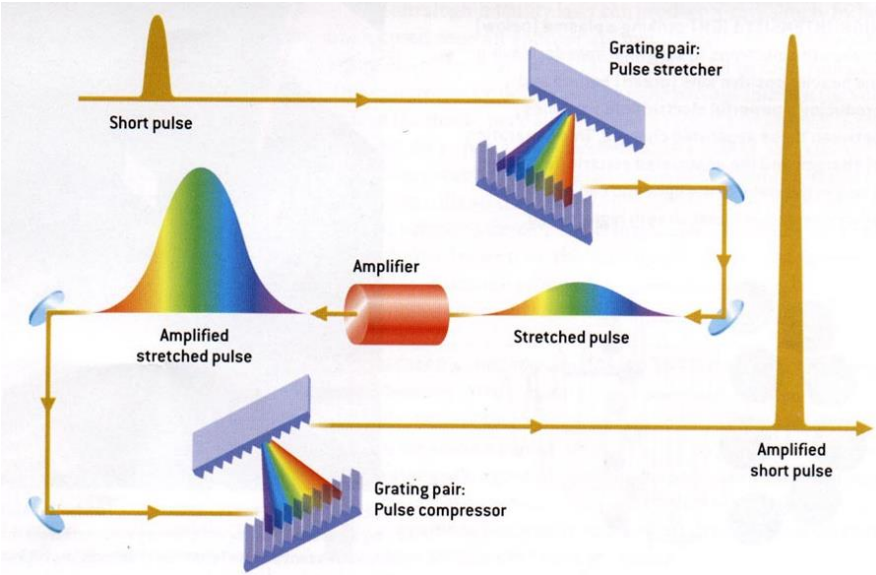
&

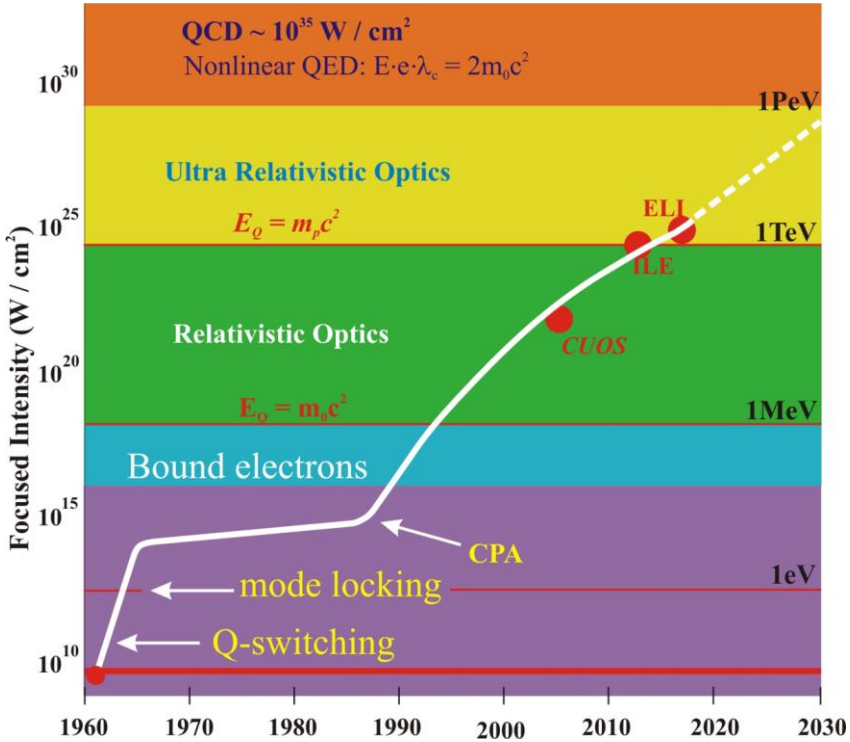
average → **High repetition rate >10 kHz**

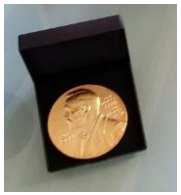
powers ?

Peak Power: Chirped Pulse Amplification (CPA)

Permits amplification of short pulses to high energy







The Nobel Prize in Physics 2018

"for groundbreaking inventions in the field of laser physics"

Arthur Ashkin (Optical Tweezers) /

Donna Strickland & Gerard Mourou (CPA)

Peak Power: The CPA Plateau ?

$$\text{Intensity} \sim \frac{\text{Energy}}{(\text{Time} \cdot \text{Focal Spot})}$$

Focal Volume limit: Lambda–cubed Regime

$$\lambda^3 = \lambda \cdot \lambda^2$$

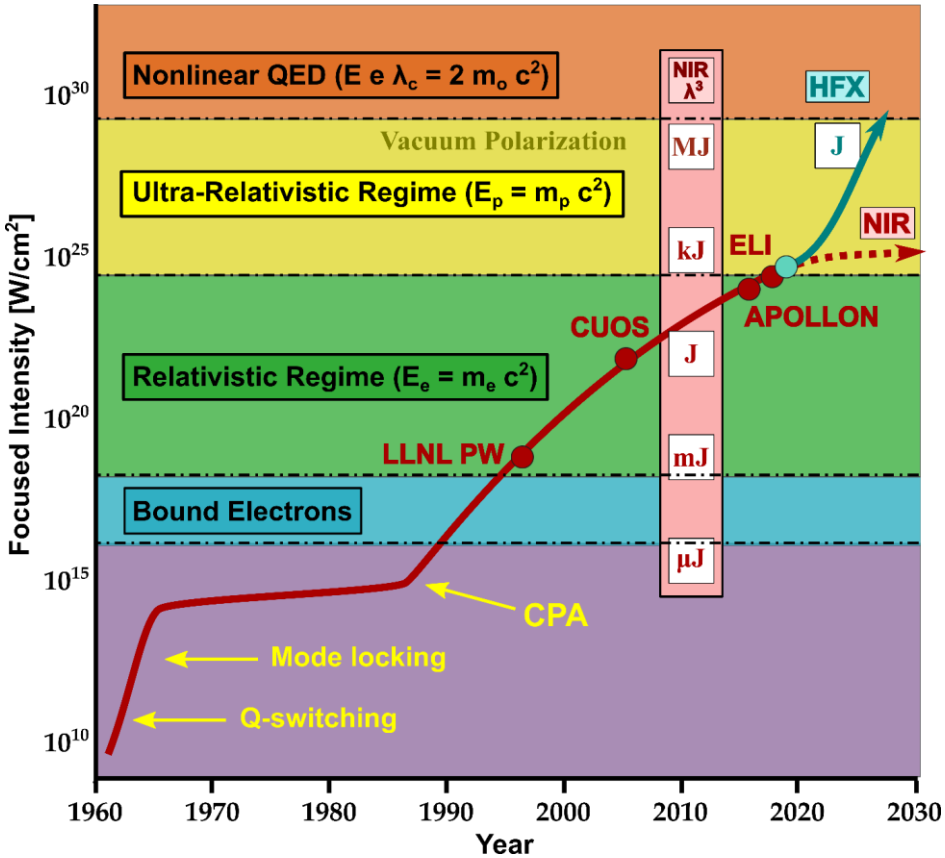
(Time · Focus)

Two Options for continuing the ascent !

1. Increase energy within volume: kJ ⇒ MJ
2. Decrease the wavelength and accessible volume:

NIR ⇒ XUV

	NIR	XUV
ExaWatt		
Energy:	**1 kJ**	**1 J**
Time:	10^{-15} s	10^{-18} s



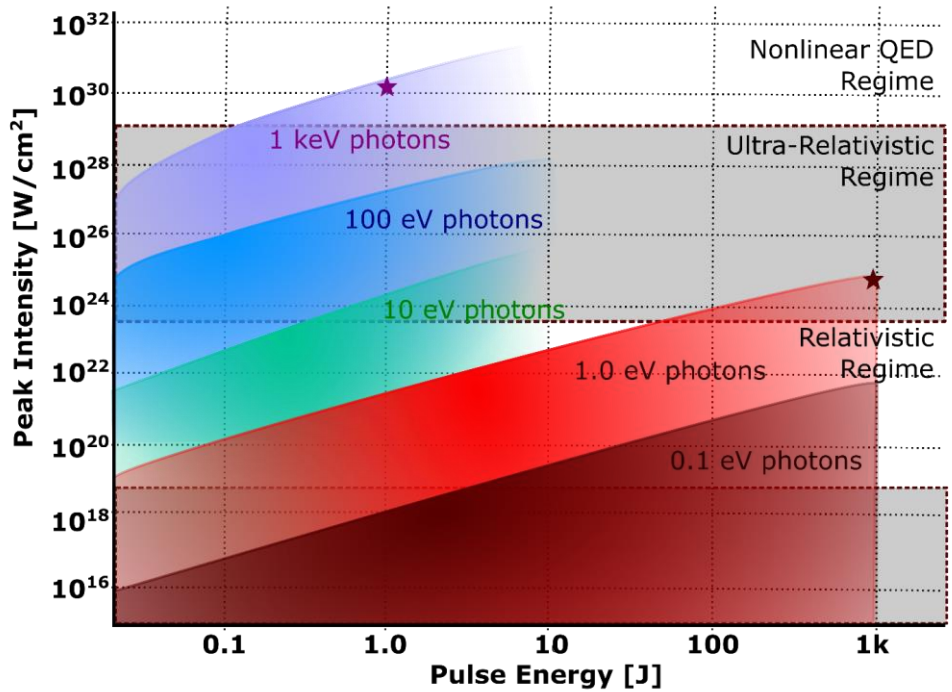
Wavelength Scaling of Peak Intensity

$$\text{Intensity} \sim \frac{c}{\lambda^3} \cdot \frac{\text{Pulse Energy}}{N \cdot M^2}$$

N ≡ Number of cycles
M ≡ Number of wavelengths

λ^3 limit

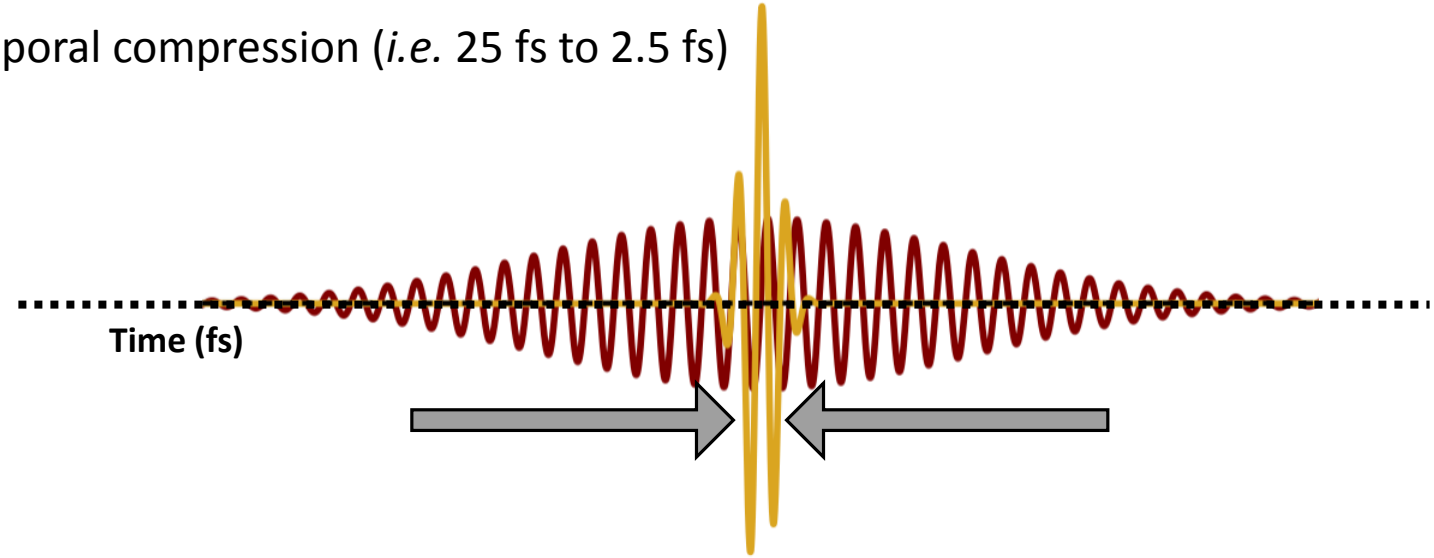
(M, N) → 1

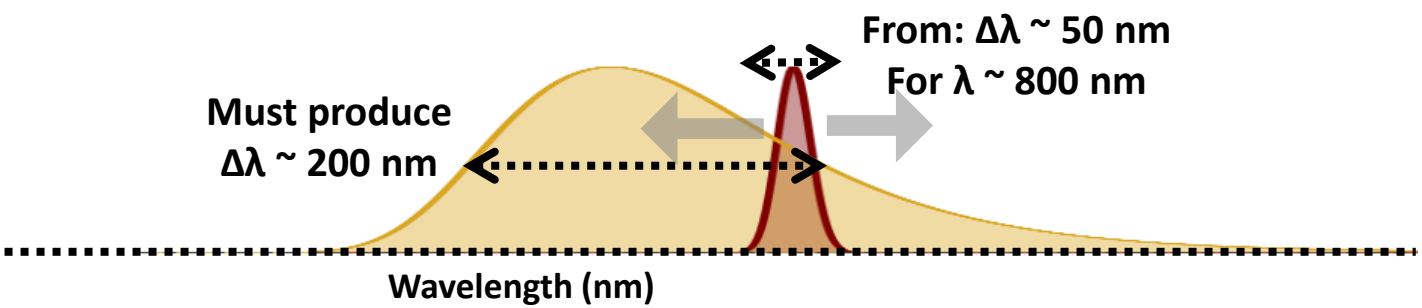


Exawatt Pulse Peak Intensity at 1 eV (★), 1keV (★)

Post-Compression Requirement

Temporal compression (*i.e.* 25 fs to 2.5 fs)

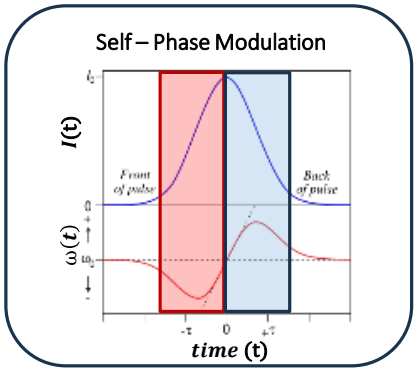


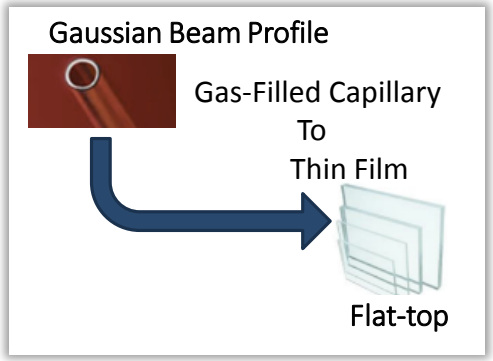


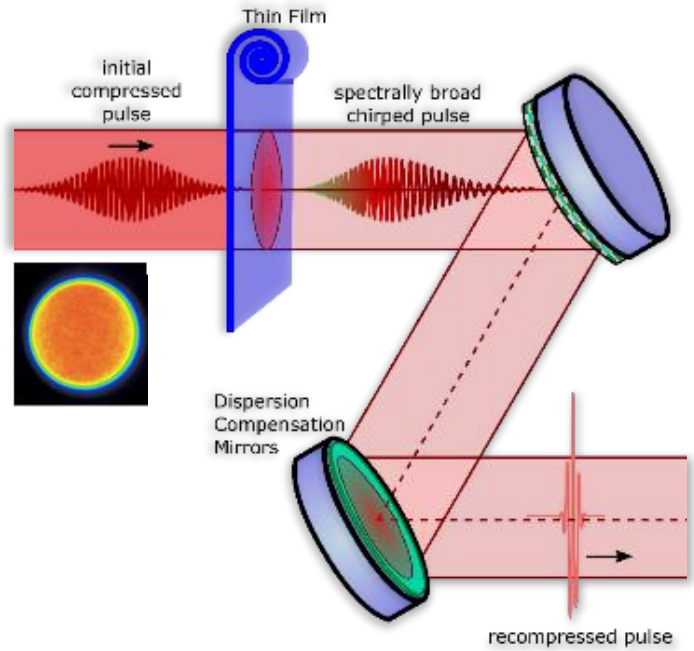
Thin Film Compressor (NIR)

Spectral broadening is produced by Self-Phase Modulation (SPM)

$$n \sim n_o + n_2 \cdot I(x,t)$$







$$\phi_{NL}(z) = \frac{\omega_0}{c} n_2 \cdot I(x,t) \cdot z$$

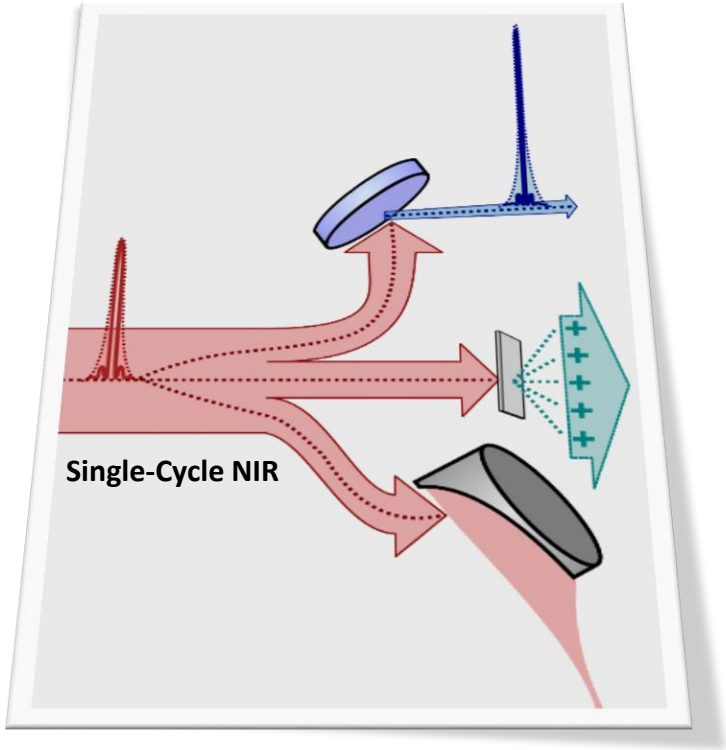
$$\partial\omega = \frac{\partial \phi_{NL}}{\partial t} \sim \quad n_2 \cdot z \cdot \frac{\partial I(x,t)}{\partial t}$$

$n_2 =$ NL Index of Ref.

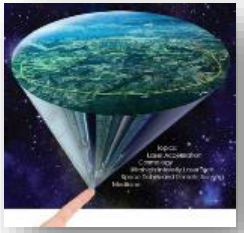
$z =$ material thickness

- G. Mourou, G. Cheriaux, C. Radier, Patent 2009
- A.A. Voronin, A.M. Zheltikov, T. Ditmire, B. Rus , G. Korn, *Optics. Com.*, **291**, 299 (2013).
- Mourou G. et al. *Eur. Phys. J. Spec. Top.* **223** 1181–8 (2014)
- S. Y. Mironov, J. Wheeler, R. Gonin, G. Cojocaru, R. Ungureanu, R. Banici, M. Serbanescu, R. Dabu, G. Mourou, E. A. Khazanov, *Quantum Electron.*, **47**, 173 (2017).

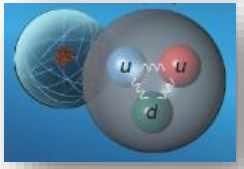
Applications



X-ray Production:
- Exawatt, Attosec. γ-Pulses
- ➢ **TeV/cm WakeField Acceleration**
- ➢ **Short Lifetime Particles (Muon)**
- ➢ **QED Vacuum Physics**
- ➢ **Table Top Cosmos**



Laser-driven Acceleration:
- Energy Enhancement
- Improved Stability/Efficiency
- ➢ **Neutron & Neutrino Sources**
- ➢ **Radio-isotope Production**
- ➢ **Nuclear Waste Treatment**



Direct Use:
- Peak Power Enhancement
- Beam Propagation
- High Energy Plasma Probe

Single-cycle NIR → Coherent X-rays

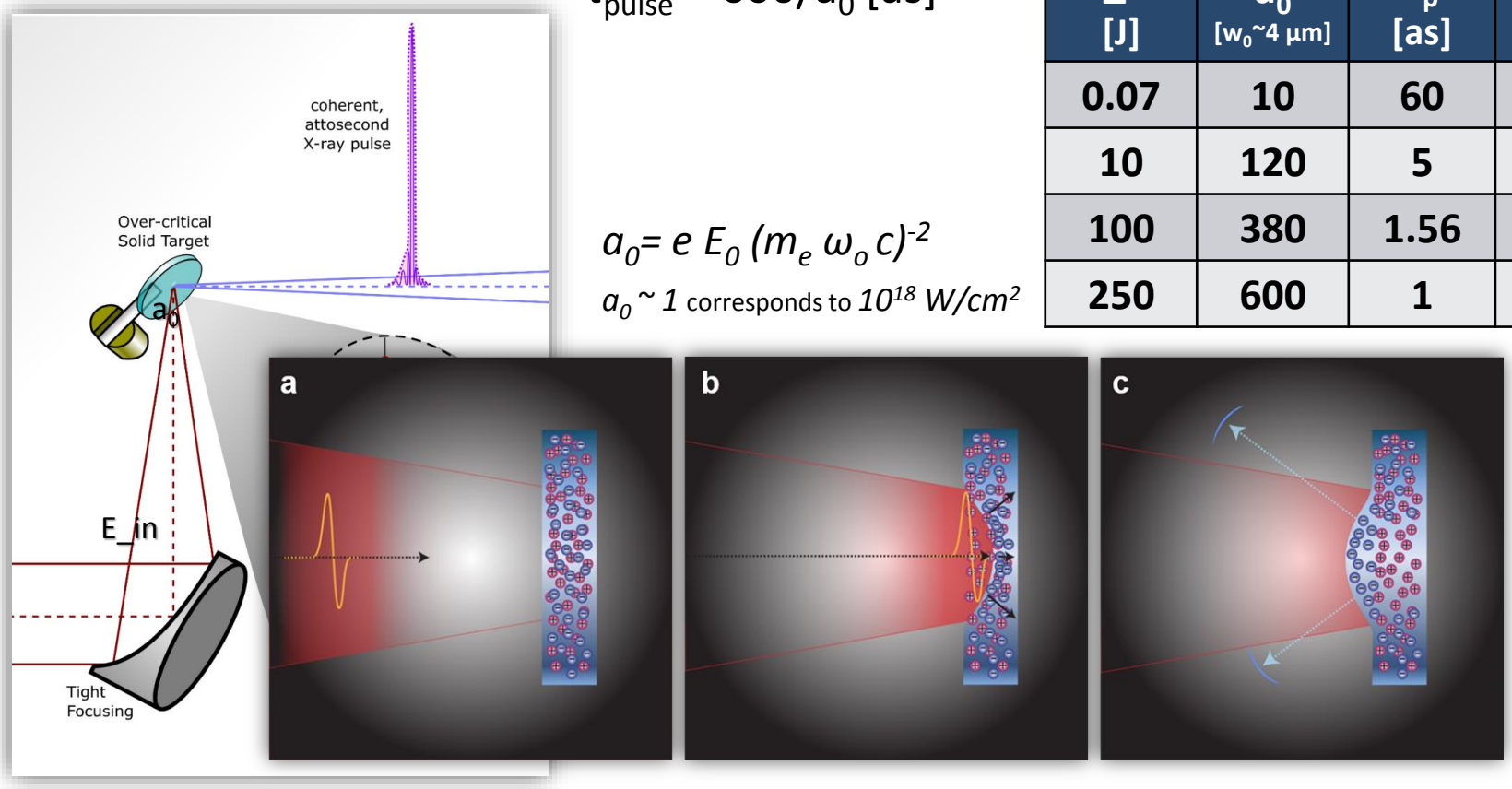
Relativistic Oscillating Mirror (ROM)

$\tau_{pulse} \sim 600/a_0$ [as]

E_in [J]	a_0 [w_0~4 μm]	τ_p [as]	E_ph [eV]
0.07	10	60	65
10	120	5	830
100	380	1.56	2600
250	600	1	4100

$a_0 = e\, E_0\, (m_e\, \omega_o\, c)^{-2}$

$a_0 \sim 1$ corresponds to 10^{18} W/cm^2



N. M. Naumova, et al., Phys. Rev. Lett. 92, 063902-1 (2004).

General context

What about a laser source combining both

High

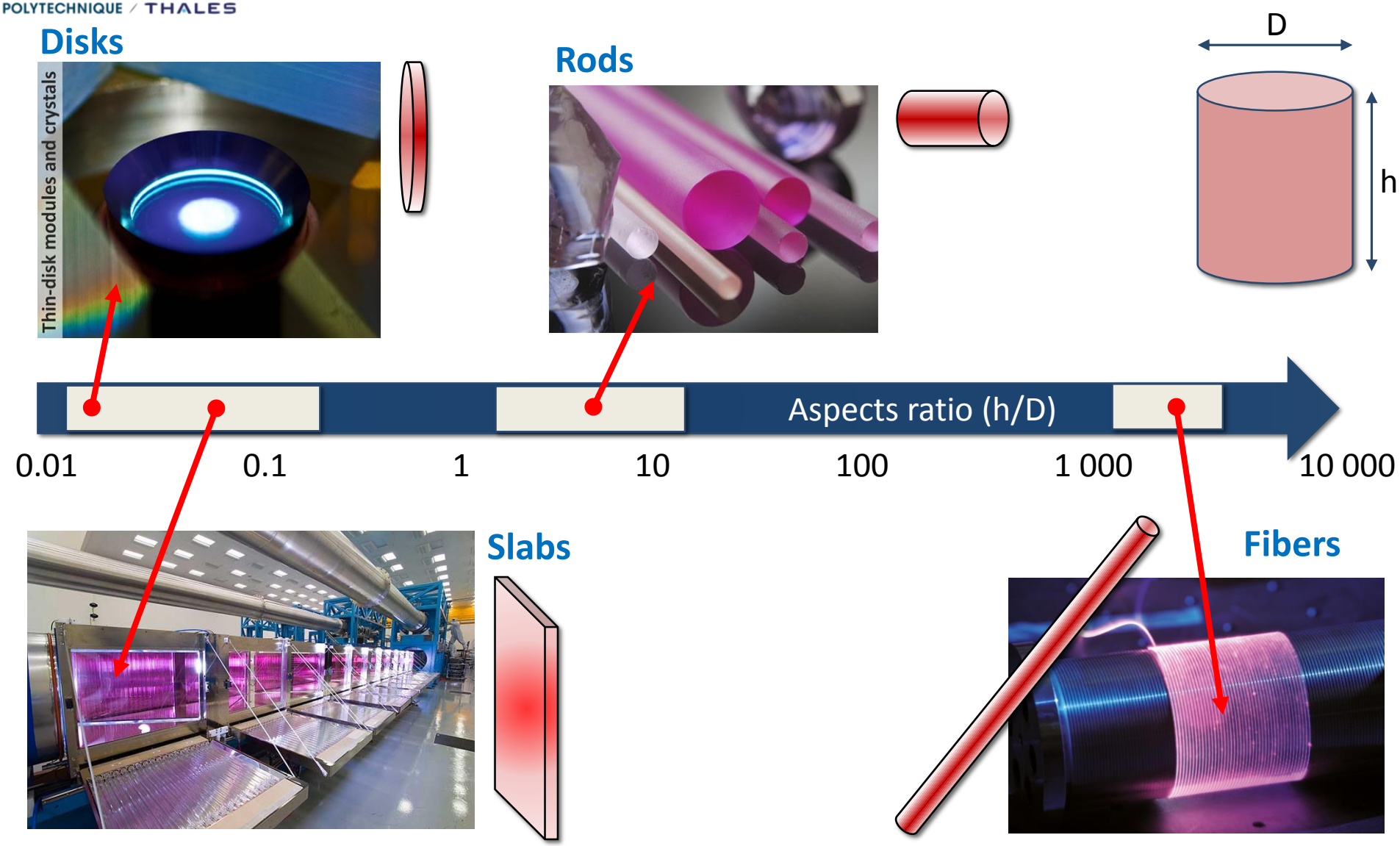
peak → **Short pulses < ps (few fs)**

&

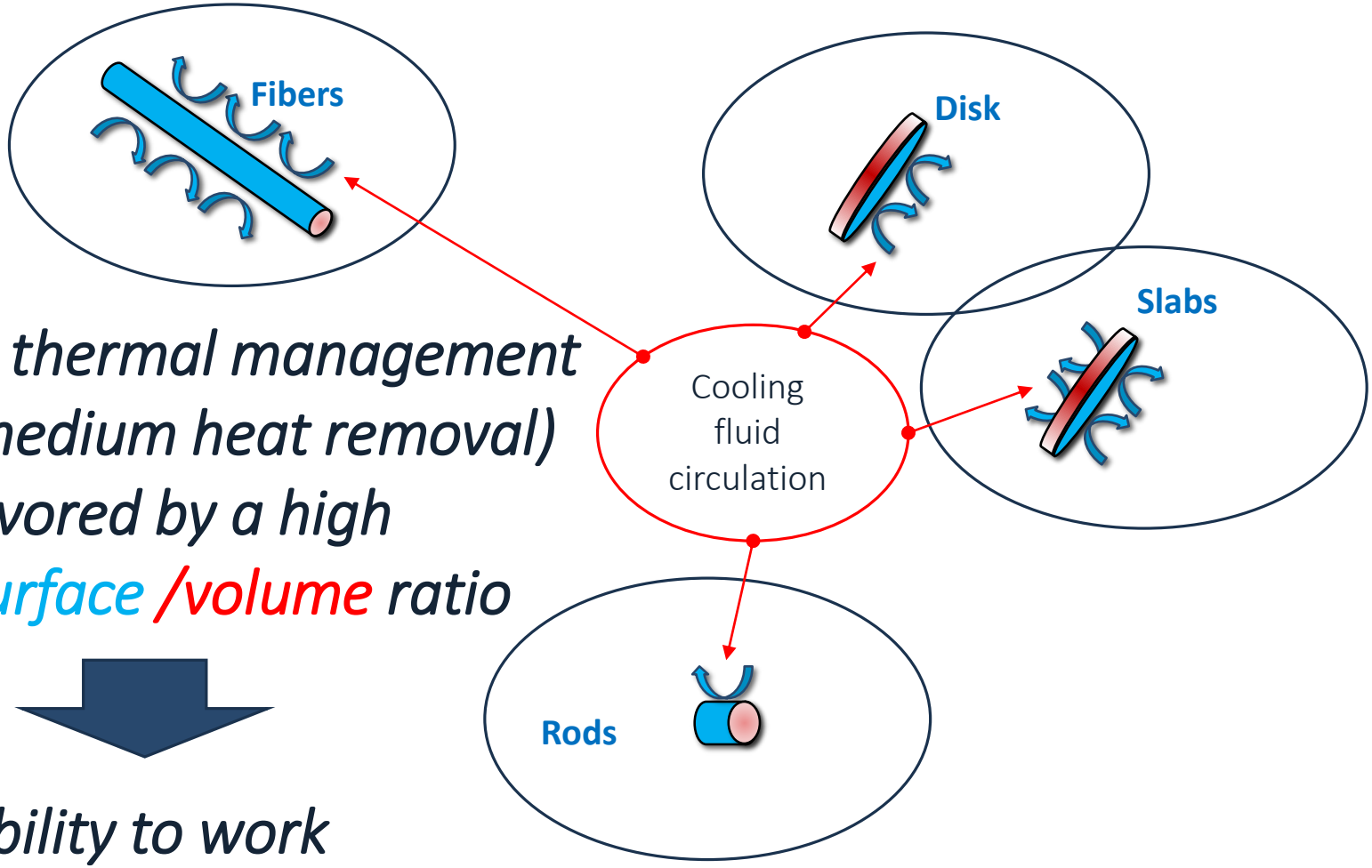
average → **High repetition rate >10 kHz**

powers ?

Solid State laser gain medium geometry



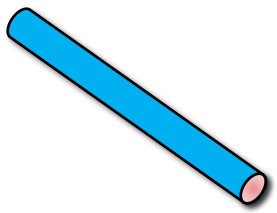
Thermal management of solid state laser gain media



An efficient thermal management (i.e. gain medium heat removal) is favored by a high cooled surface /volume ratio

Ability to work at high repetition rate

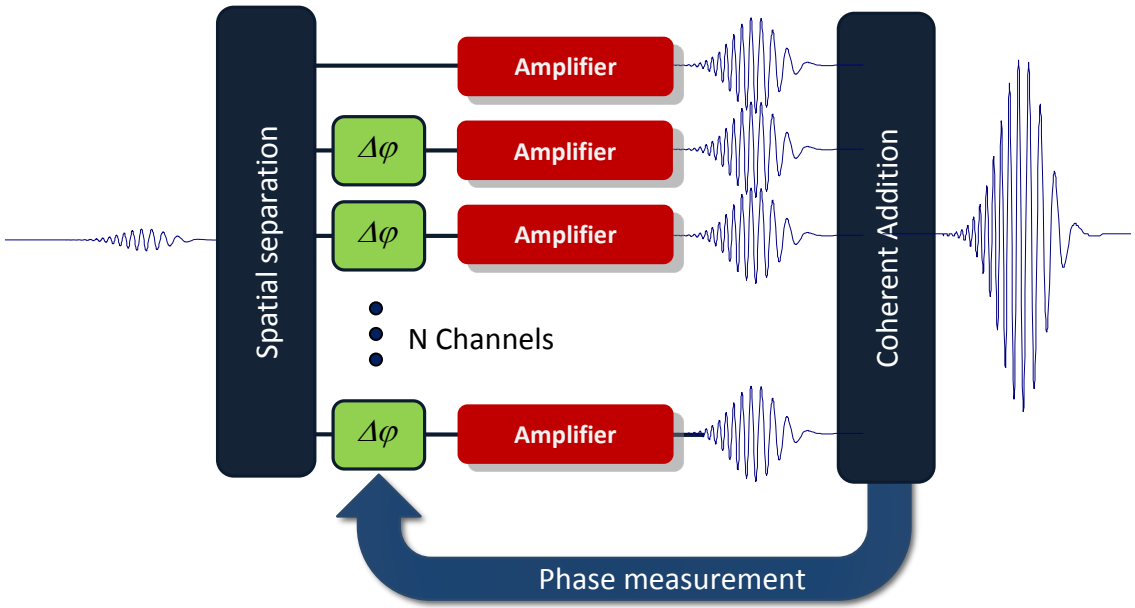
But one fiber does not provide enough energy



Amplify laser pulses
through
a network of fiber amplifiers operated in parallel

Laser pulse train coherent addition

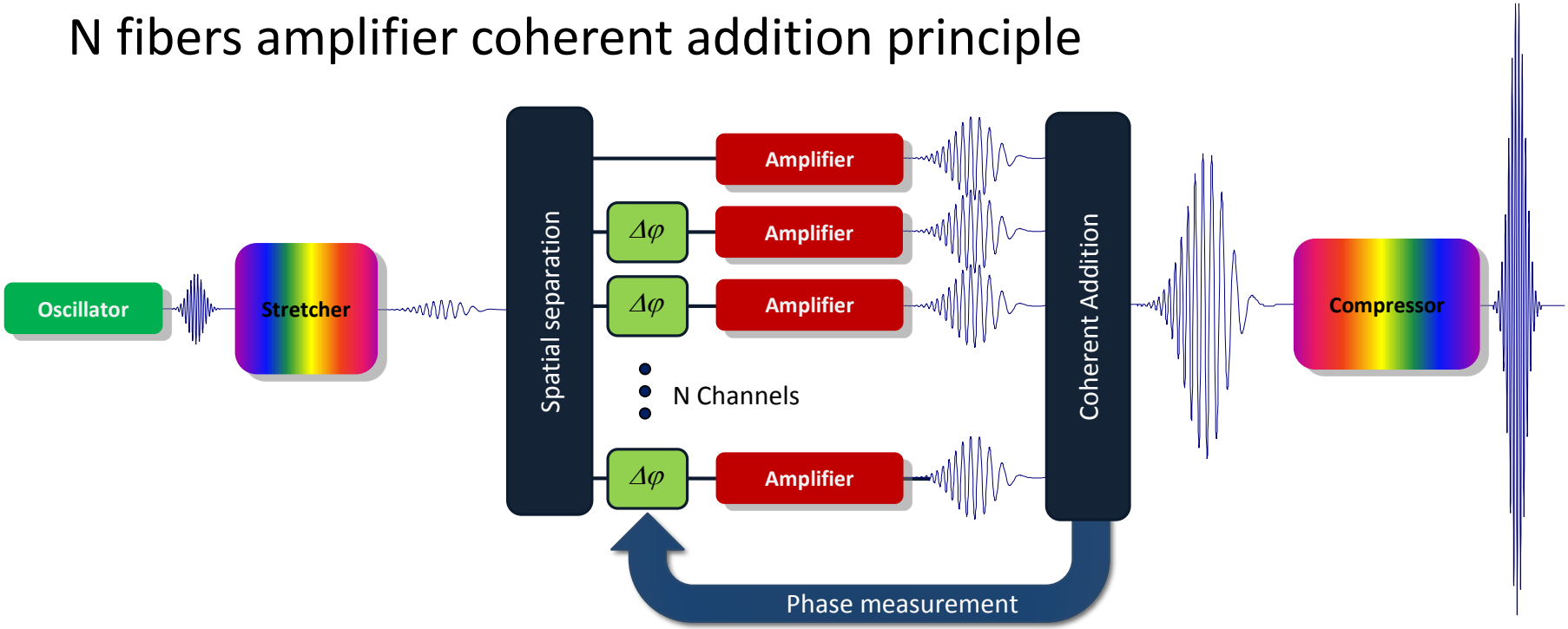
N fibers amplifier coherent addition principle



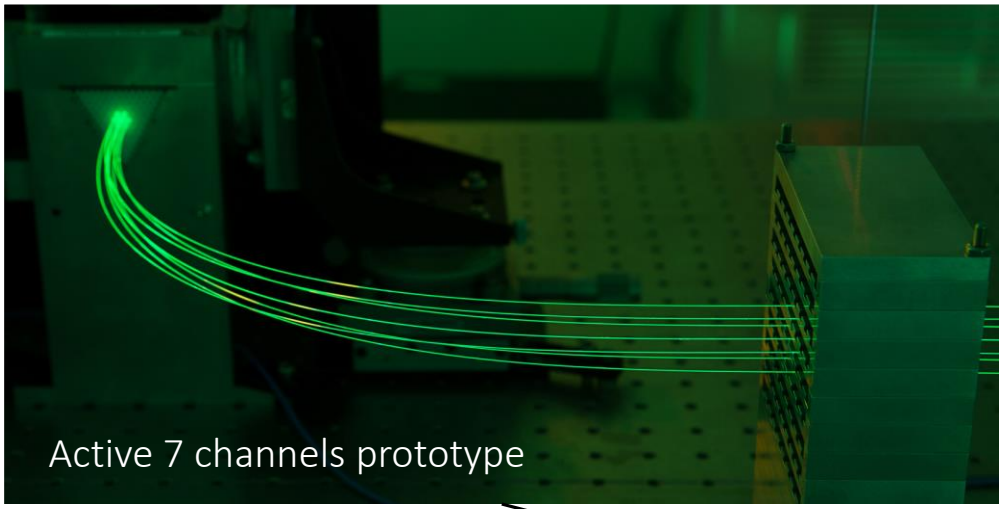
Coherent Amplification Network ➔ CAN

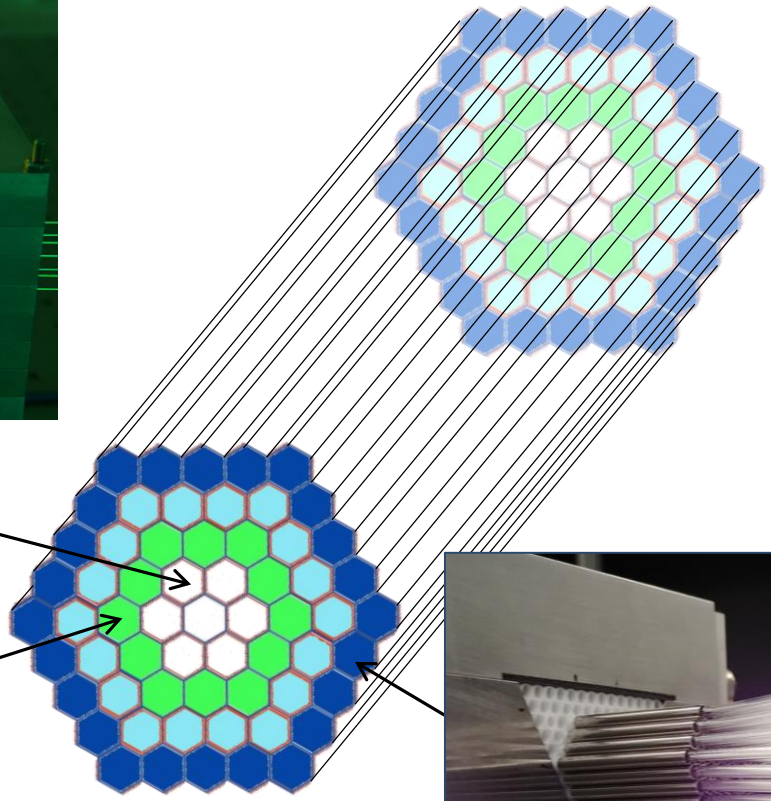
Chirp Pulse Amplification

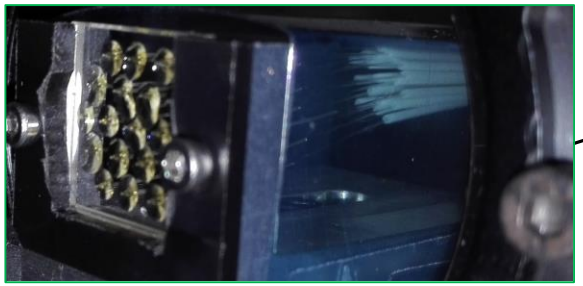
N fibers amplifier coherent addition principle



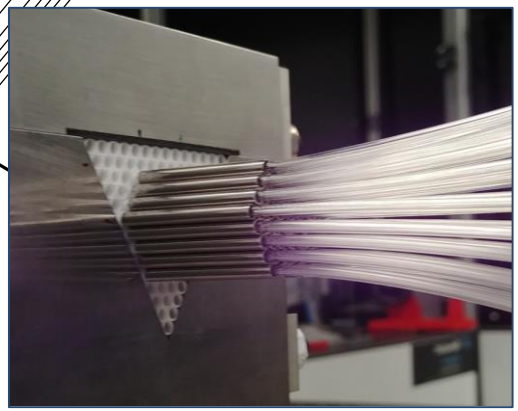
Several prototypes have been developed







Passive 19 channels prototype



61 channels final prototype

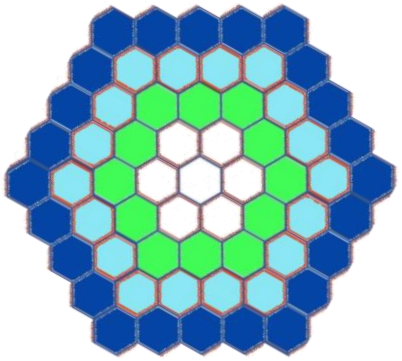
Objective

Designing, integrating and operating a 61 channels prototype

~ 300 fs

~ 3 mJ

~ 200 kHz

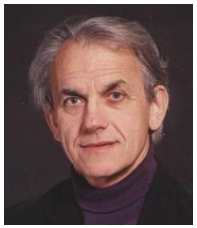


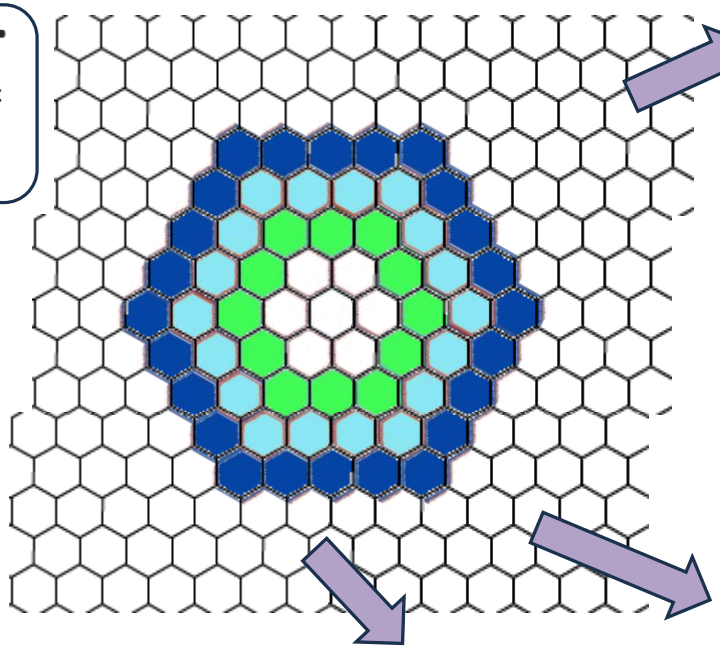
Address key issues at the 61 channels scale…
…and widening the application field

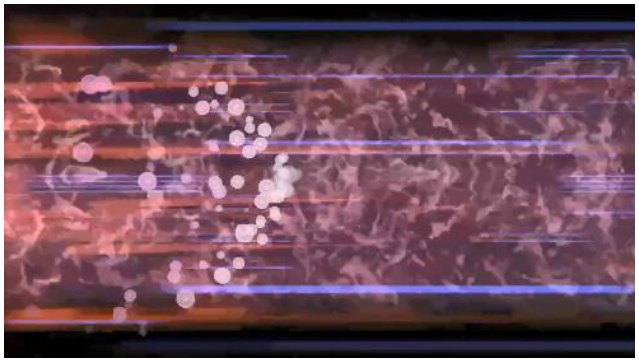
XCAN is an IZEST project

IZEST
International Zeta Exawatt Science Technology

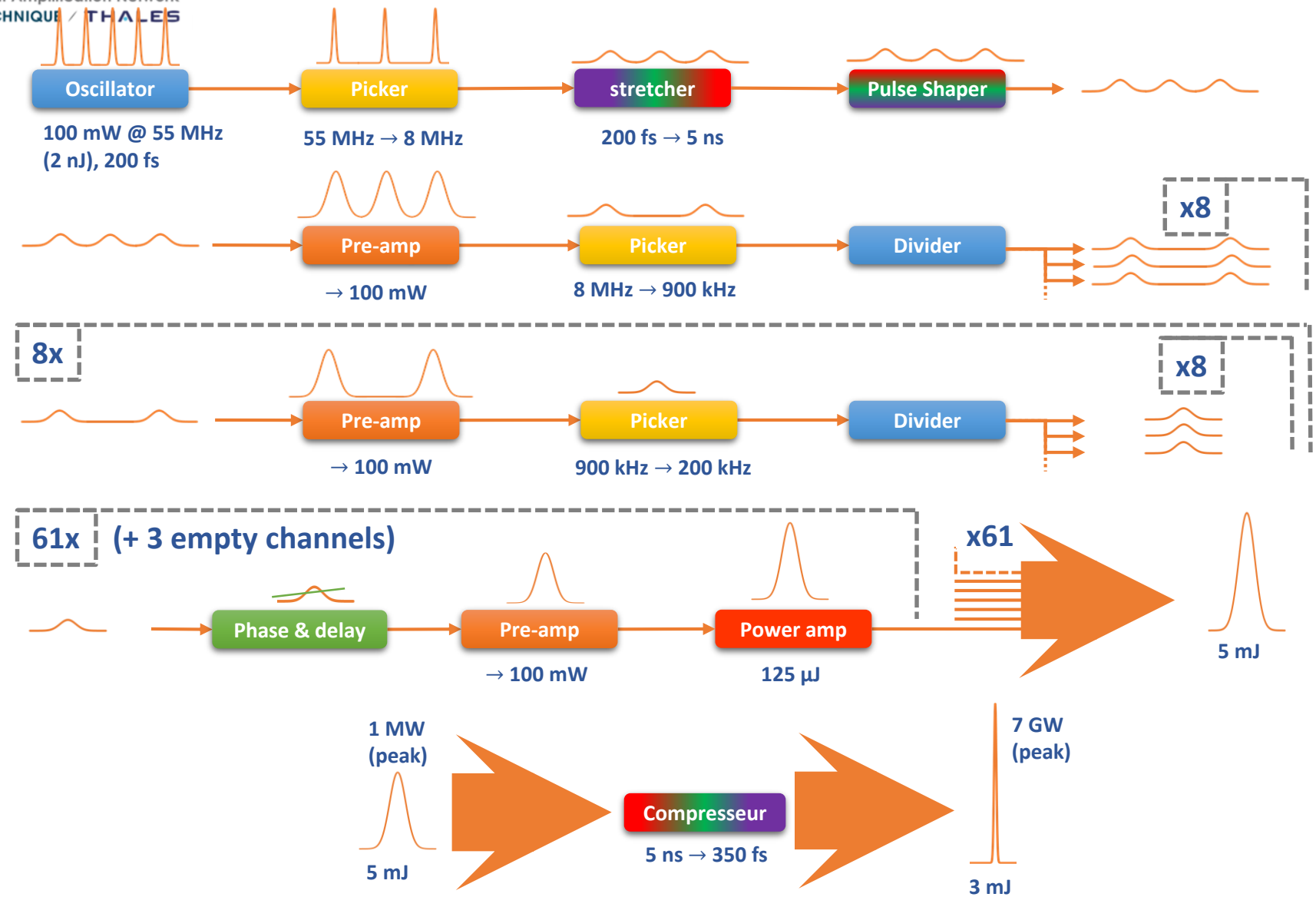
G.Mourou & T.Tajima



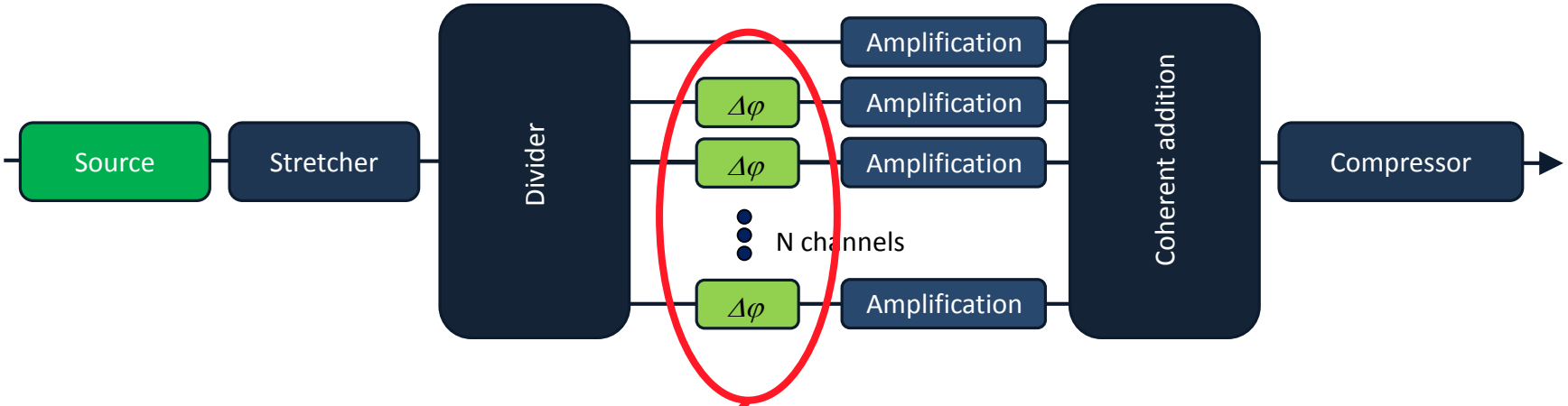




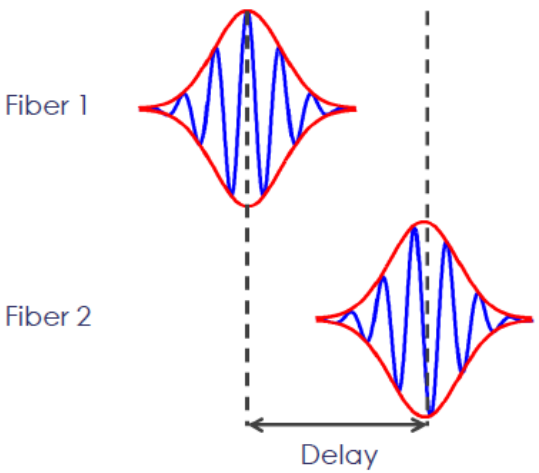
Synoptic view

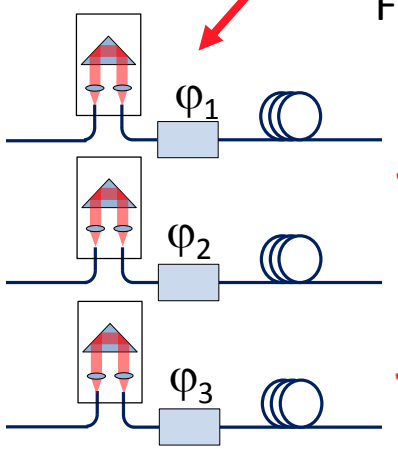


Phase control with two devices

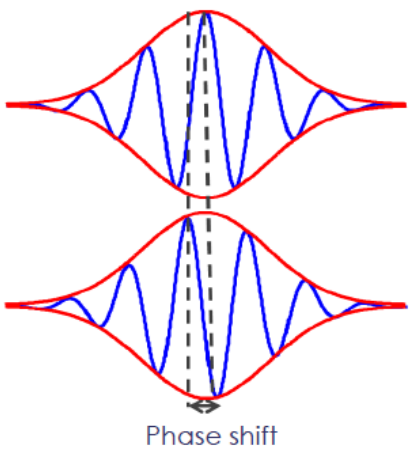


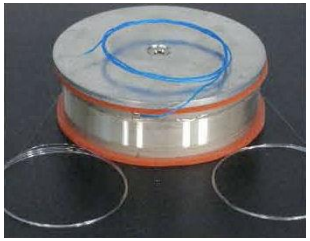
Variable optical delay line





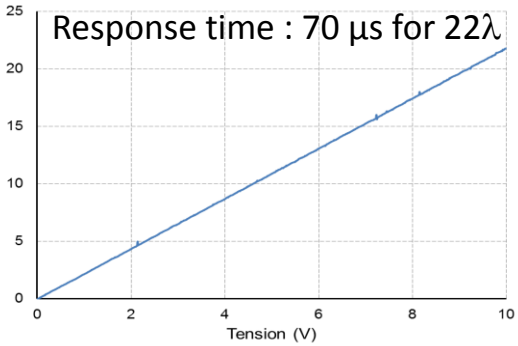
Fiber Stretcher (FS)



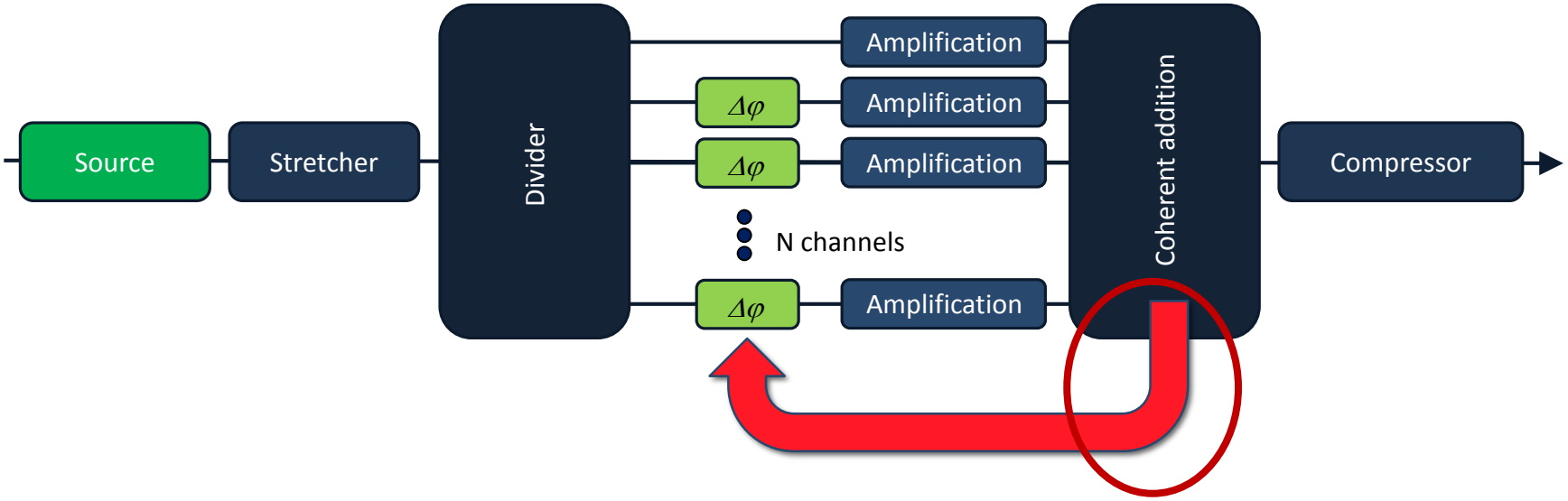


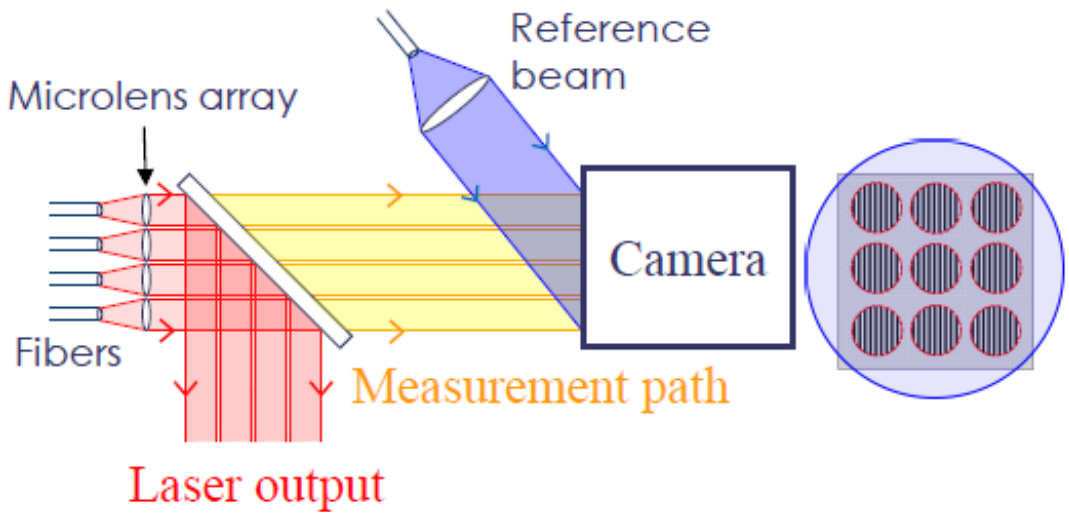
2 λ/V, linear

Response time : 70 µs for 22λ

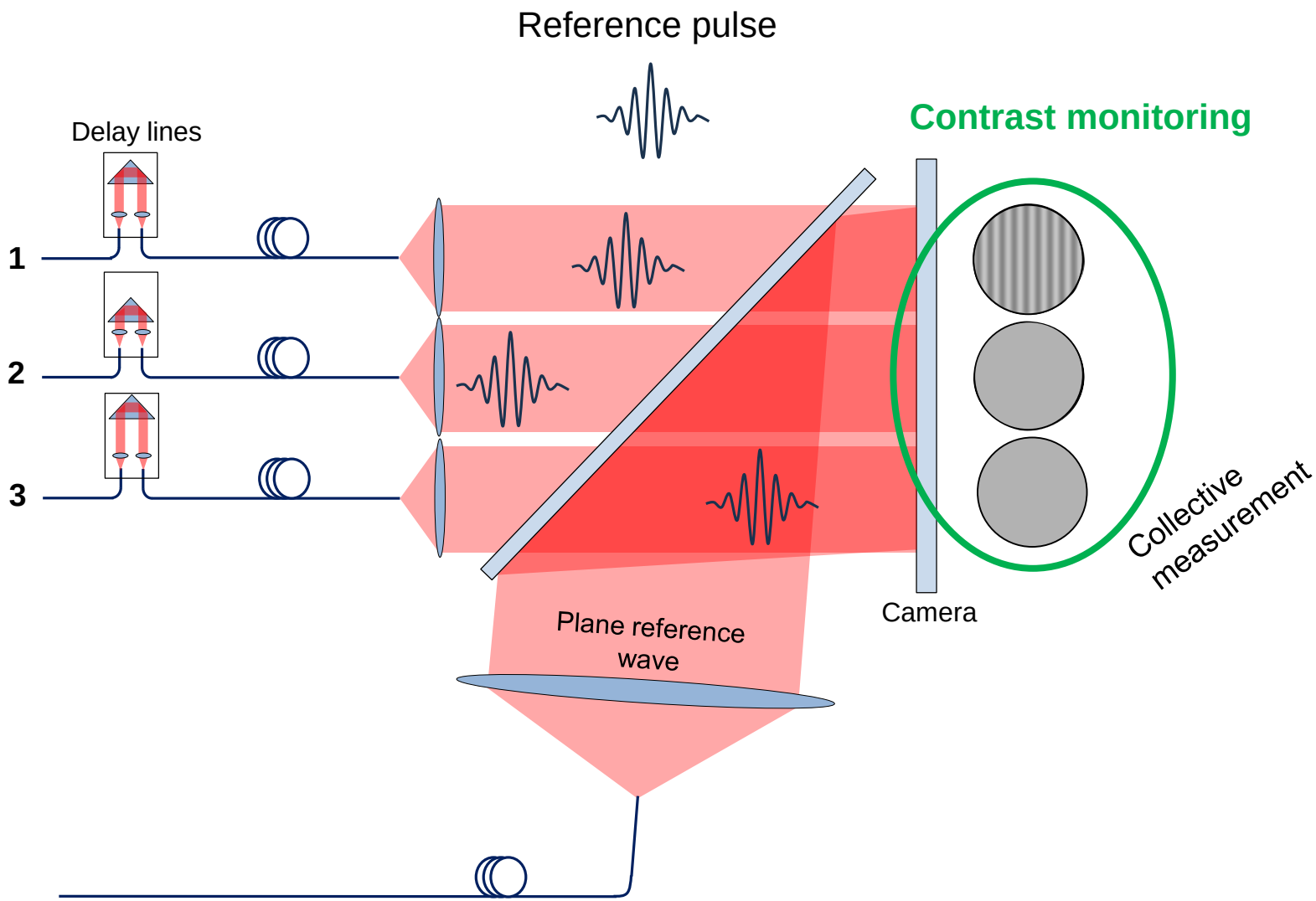


Phase measurement through interferometry

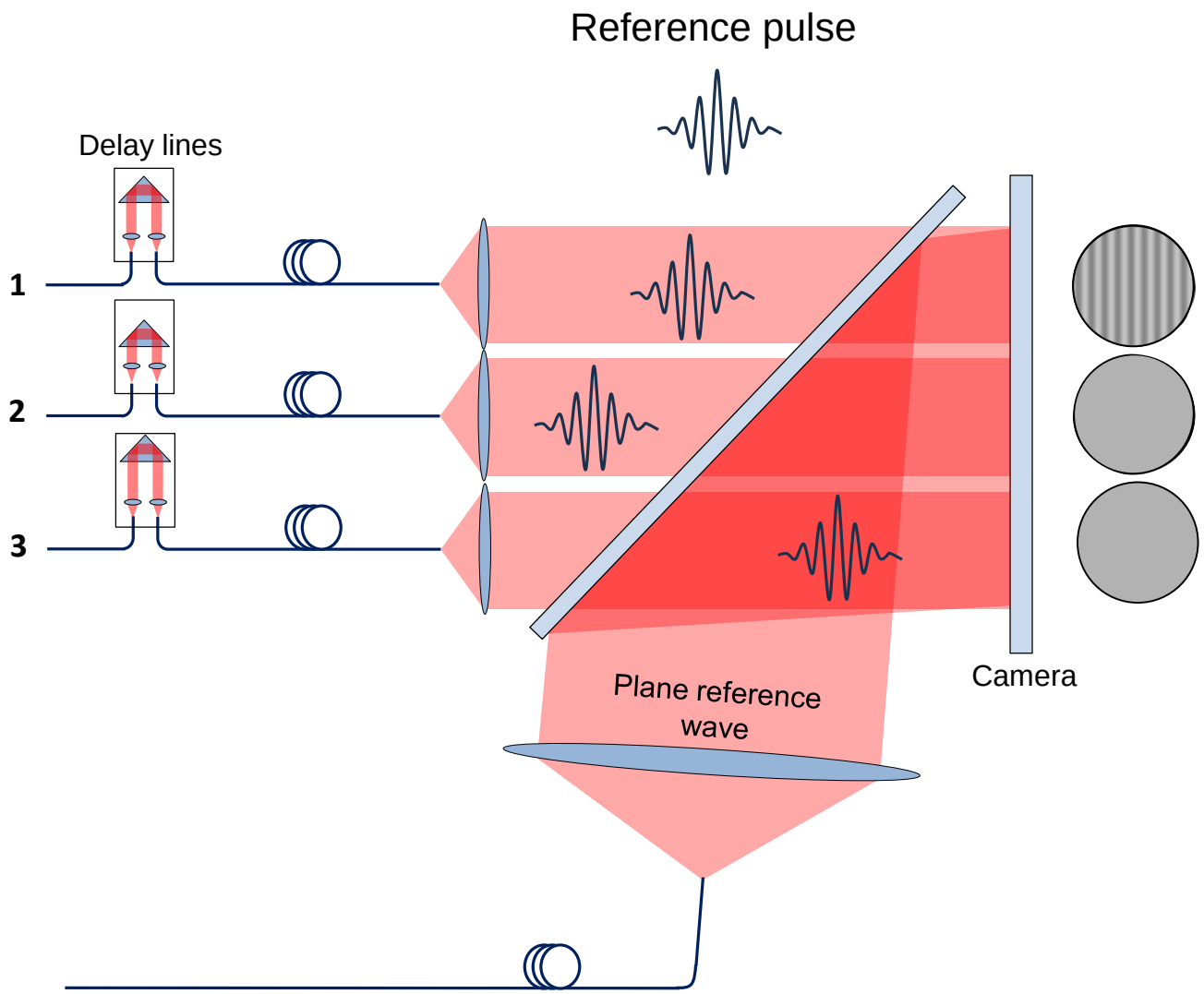




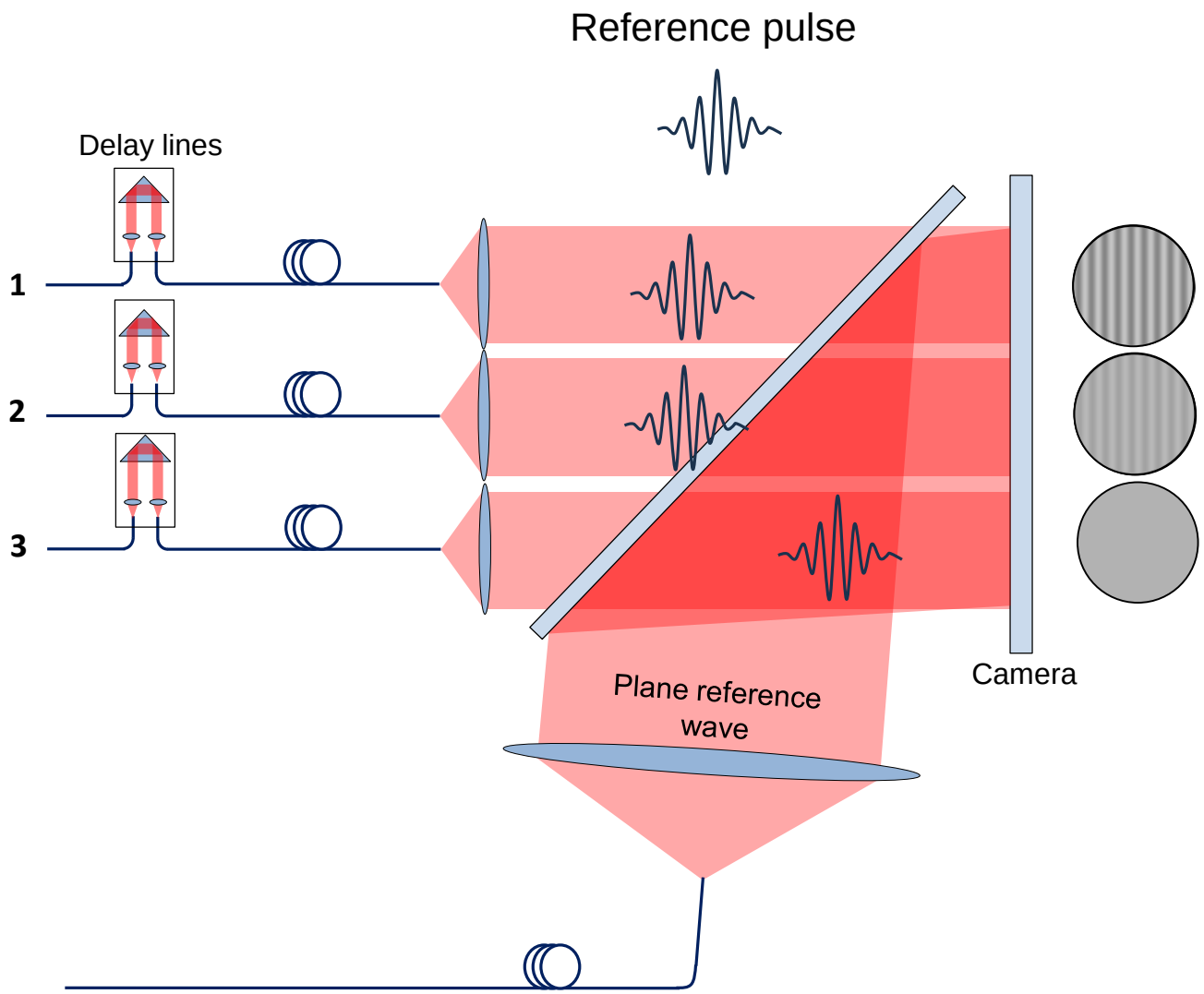
Interferometric temporal synchronization



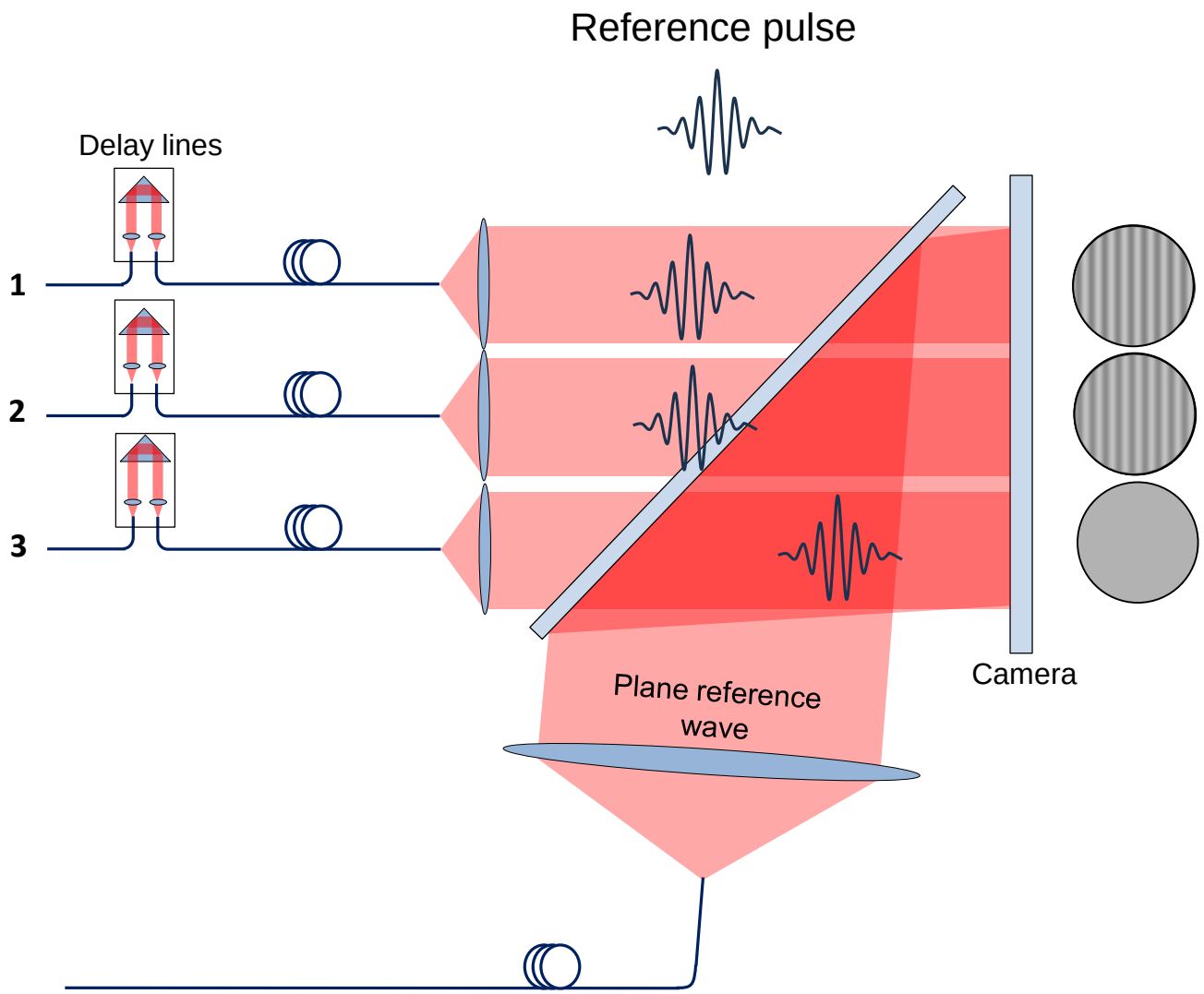
Interferometric temporal synchronization



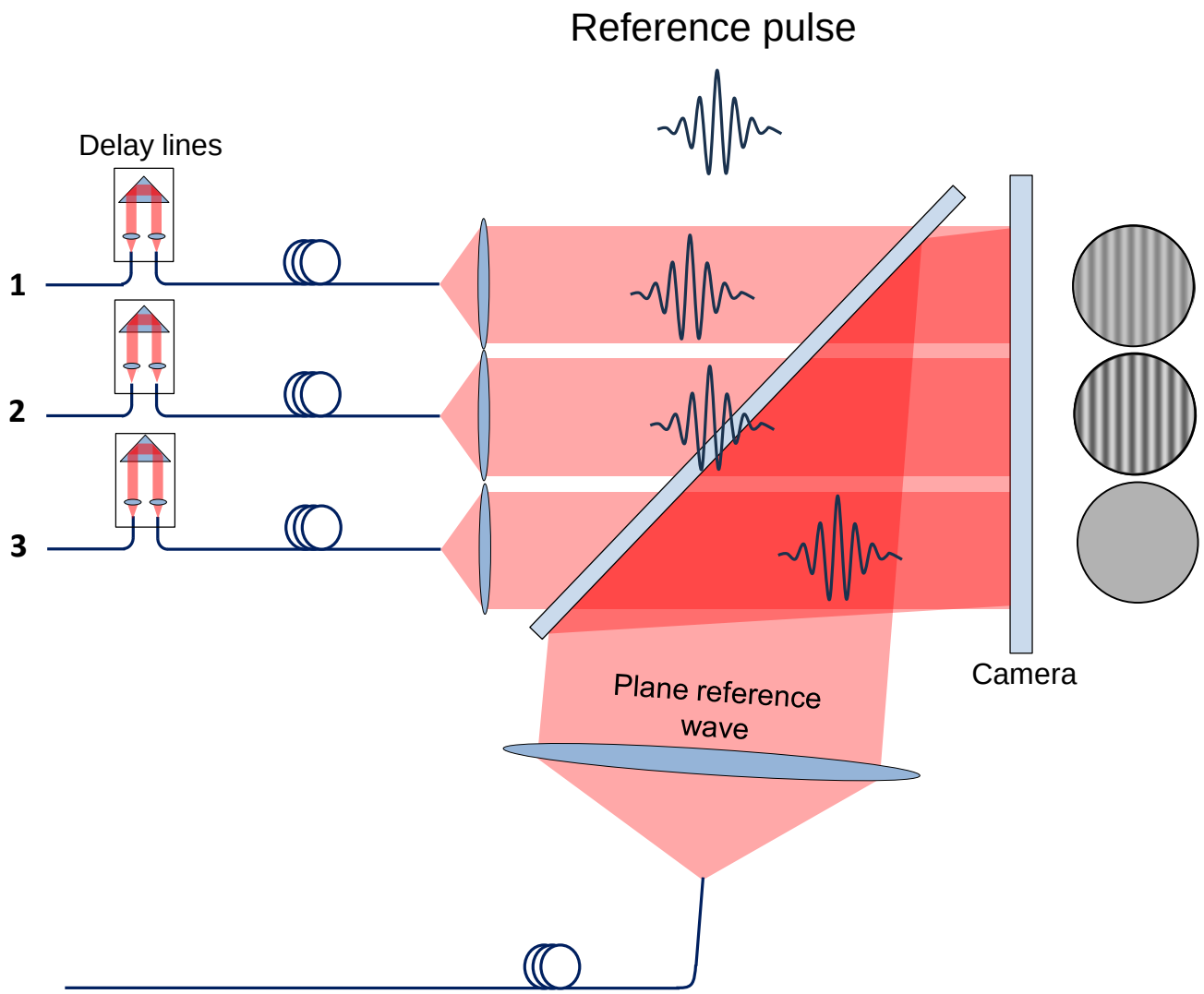
Interferometric temporal synchronization



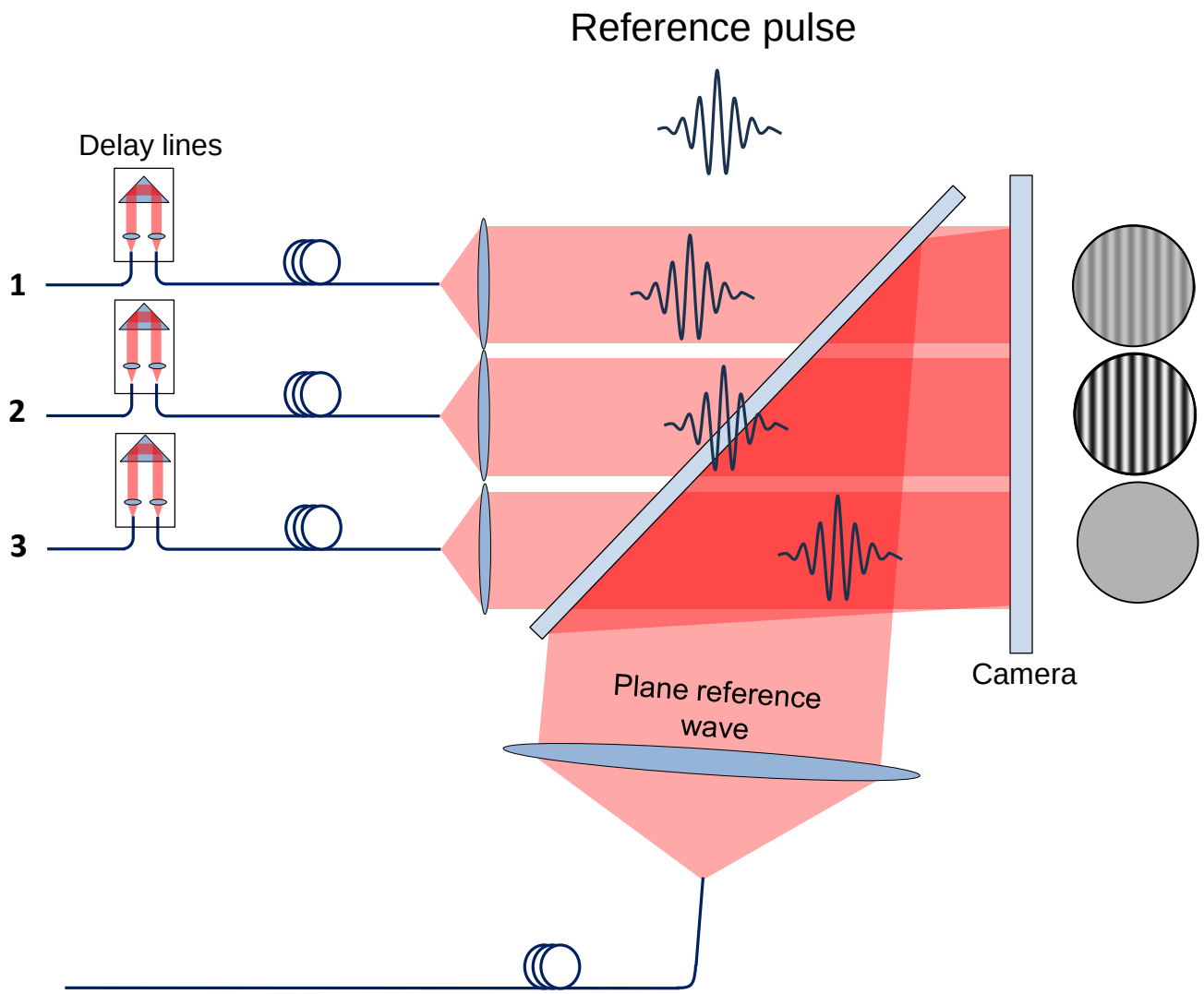
Interferometric temporal synchronization



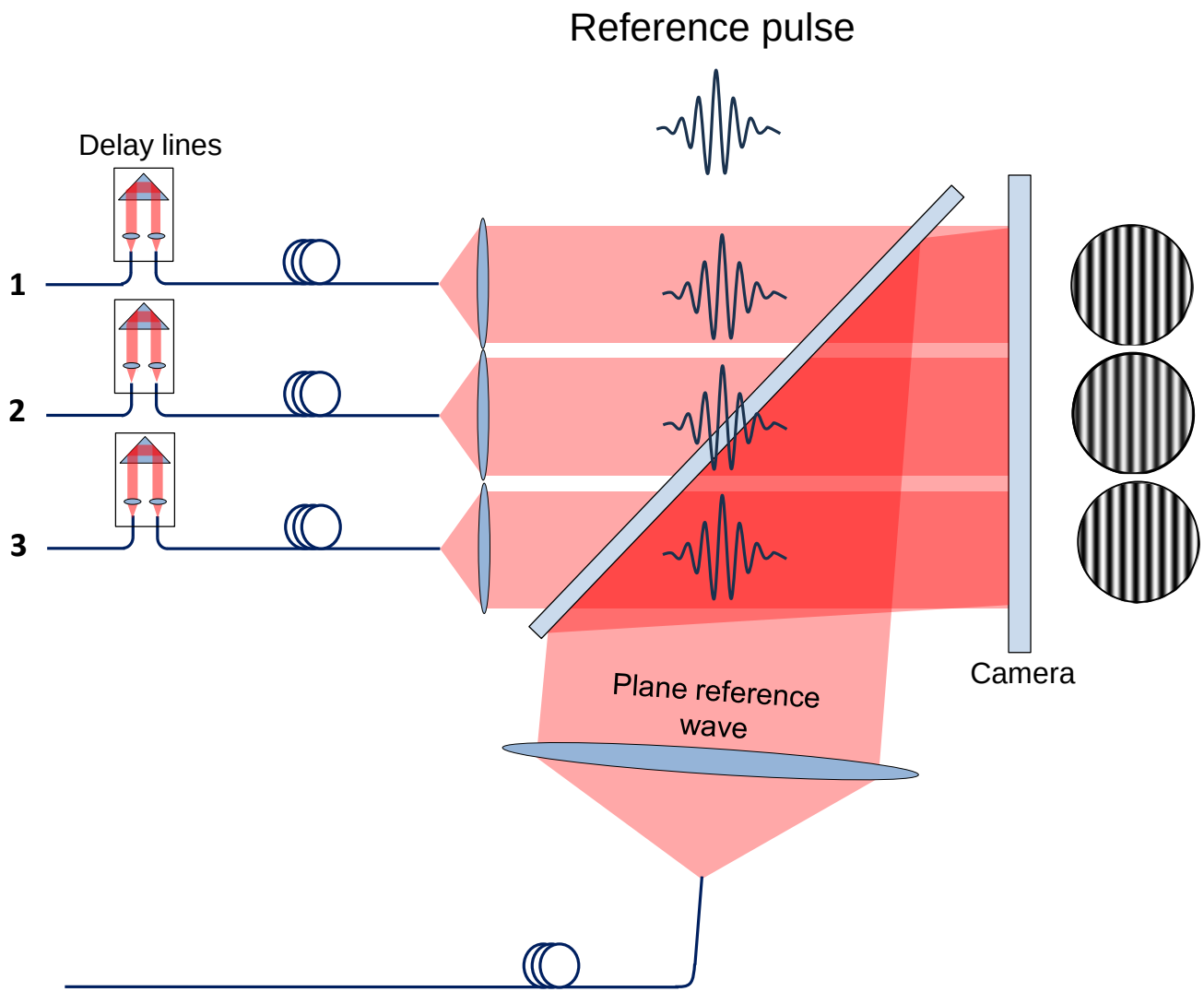
Interferometric temporal synchronization



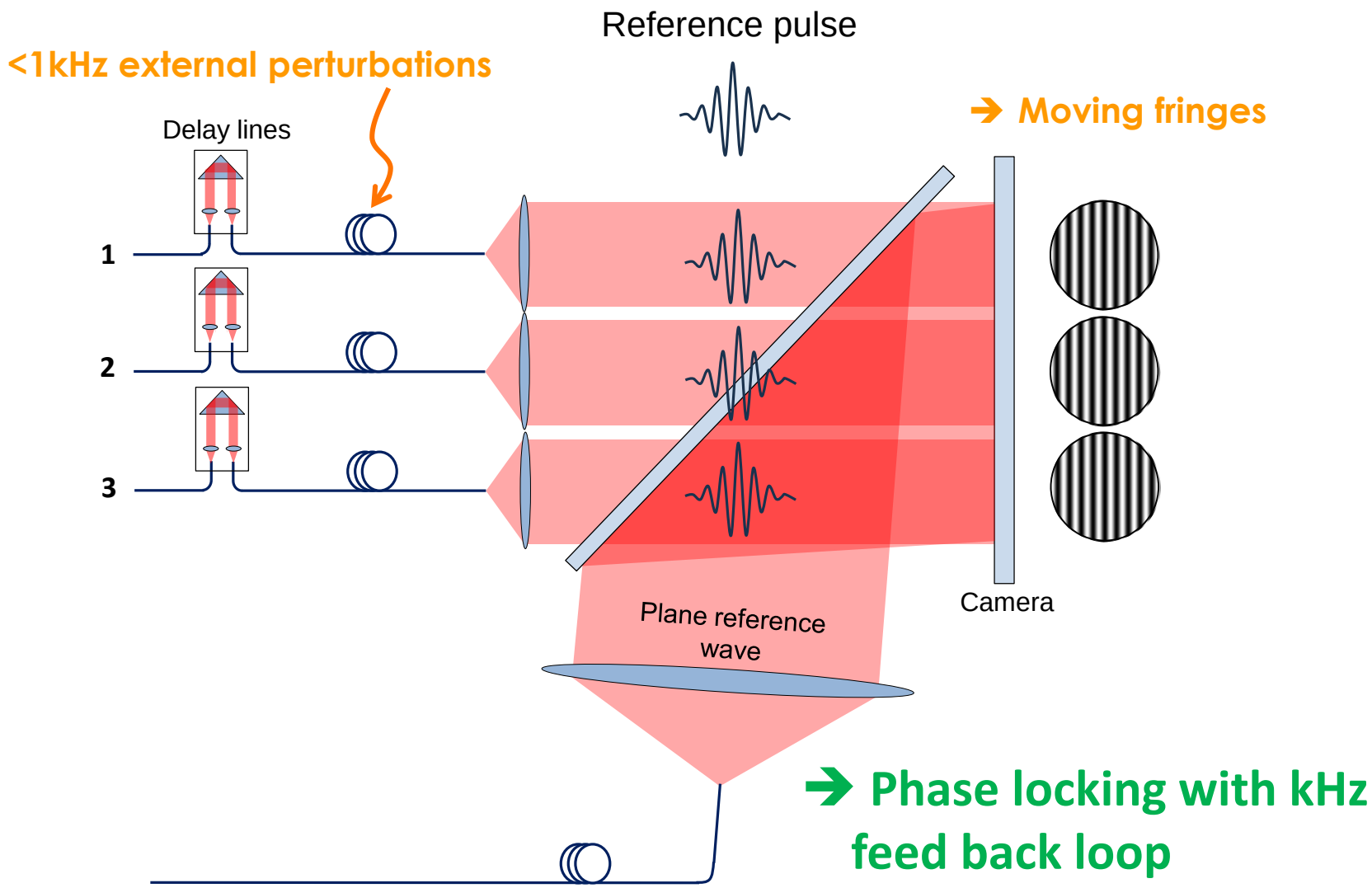
Interferometric temporal synchronization



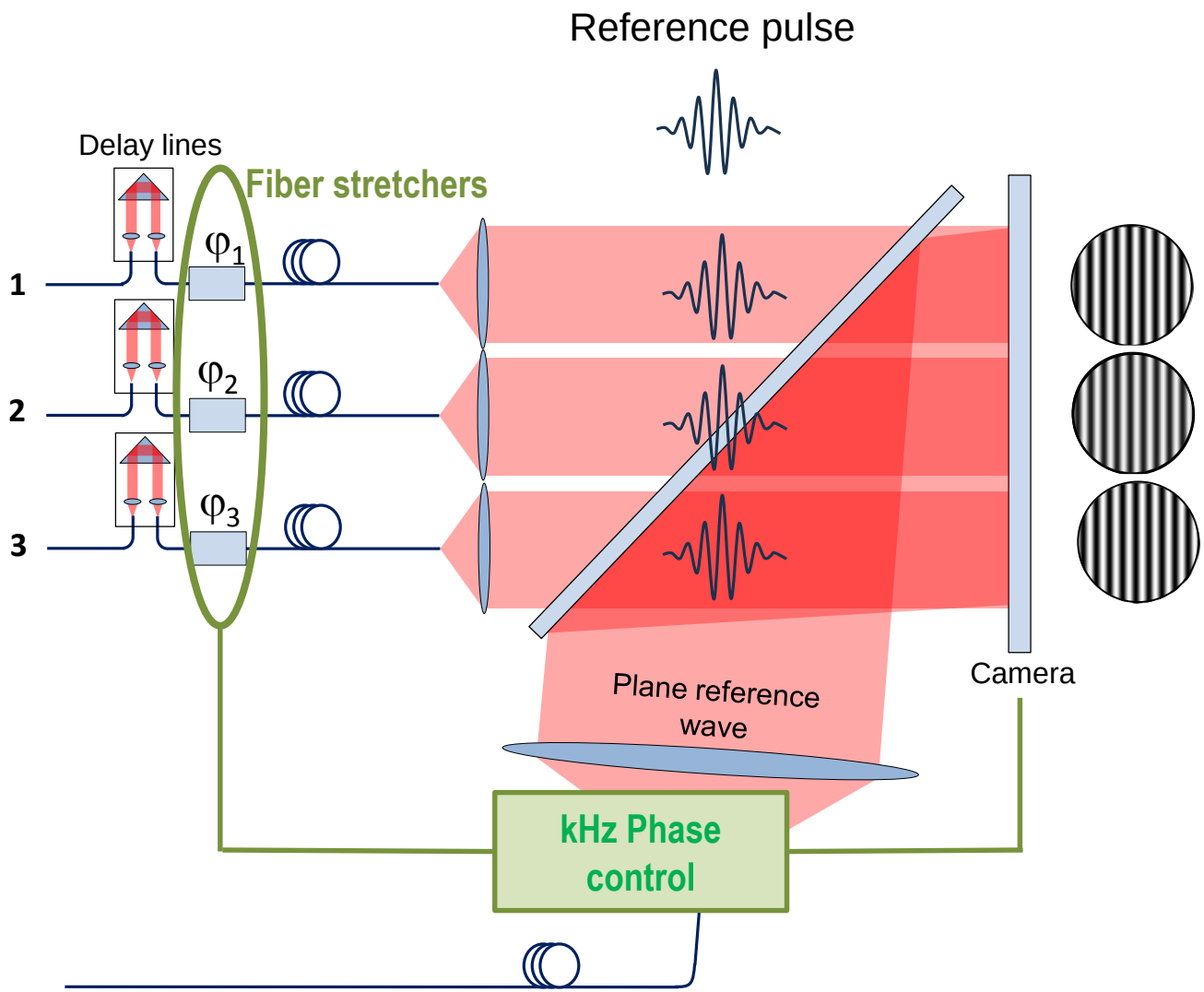
Interferometric temporal synchronization



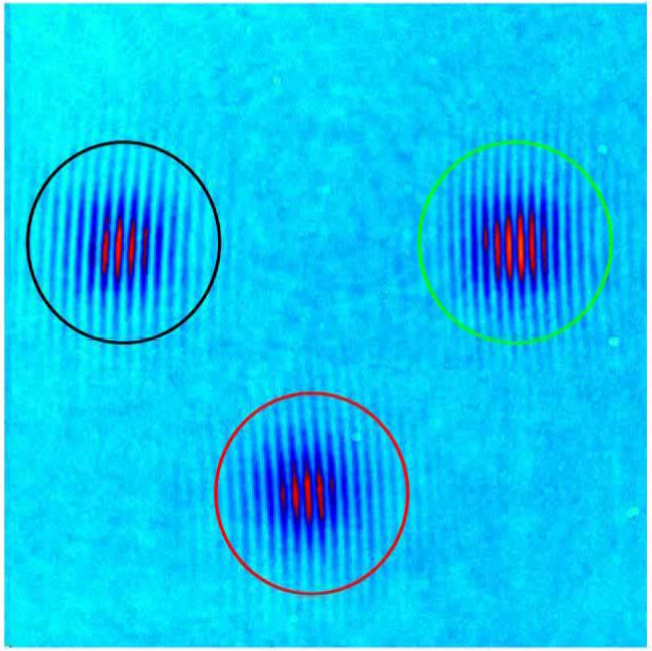
Interferometric temporal synchronization



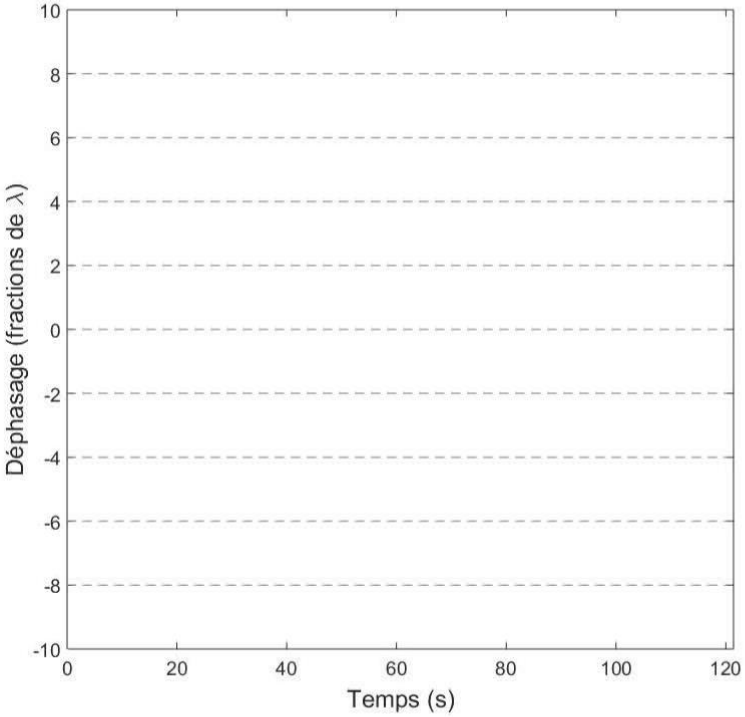
Interferometric temporal synchronization



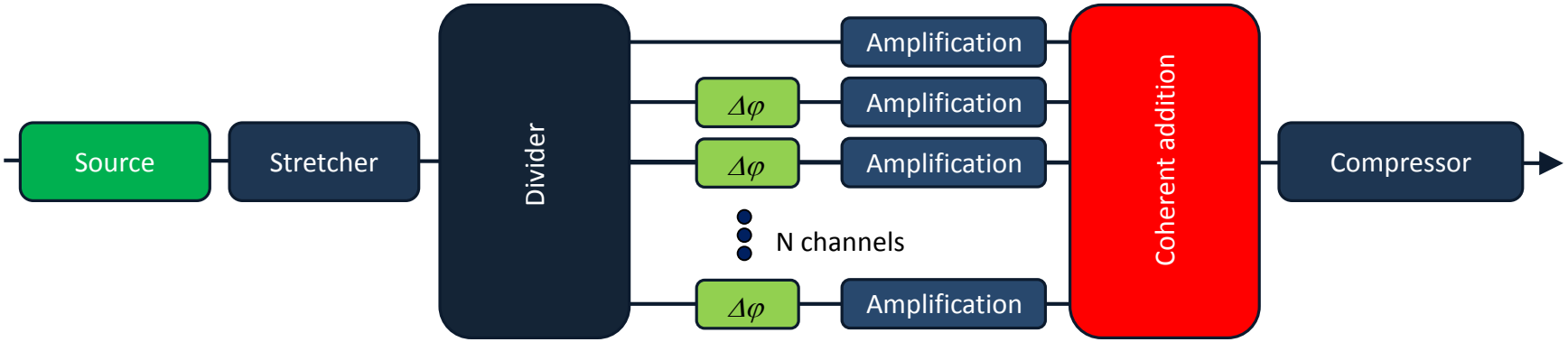
3 fibers co-phasing

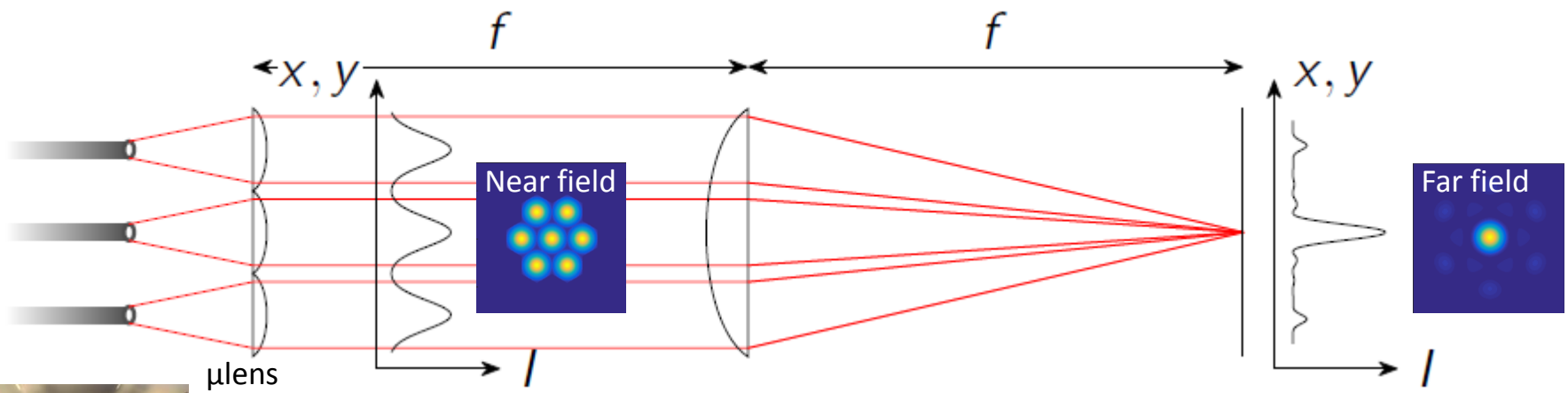


LOCKING OFF

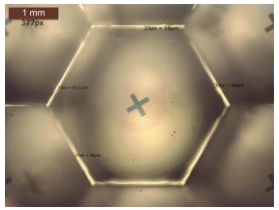


Far field combination for max scalability





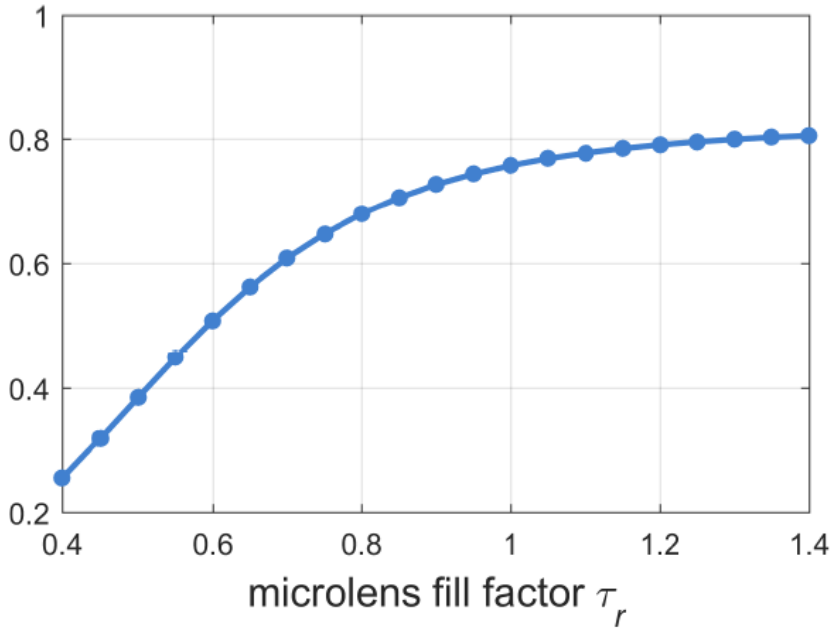
µlens array

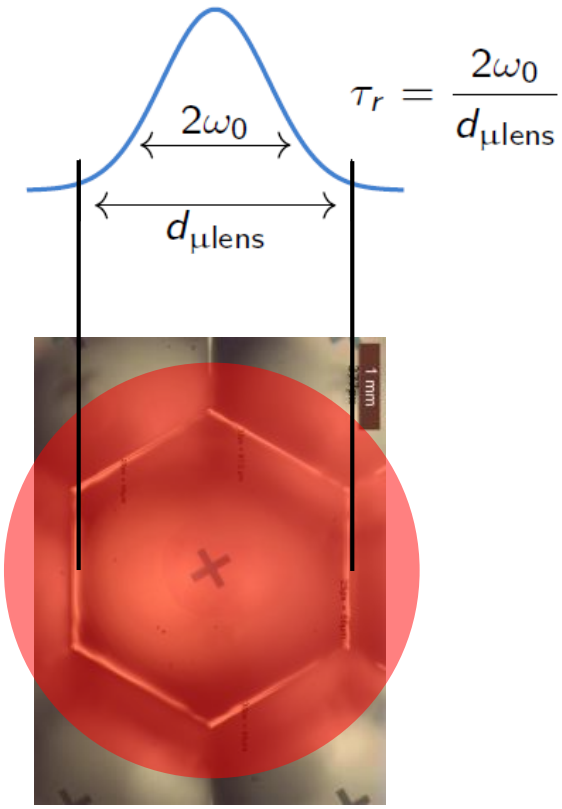


Far field efficiency $\eta_{FF} = \dfrac{\text{power in main lobe of far field pattern}}{\text{overall power in far field}}$

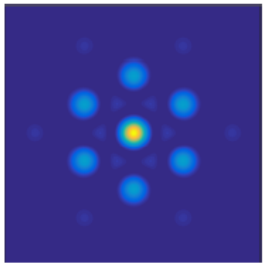
Overall efficiency

Far field efficiency η_{FF}

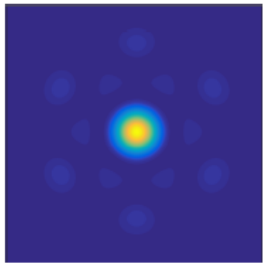




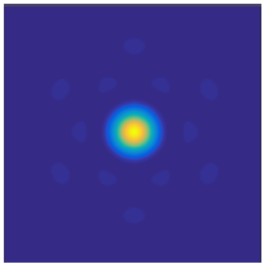
$\tau_r = 0.4$



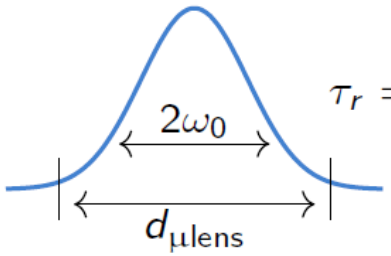
$\tau_r = 0.9$



$\tau_r = 1.3$

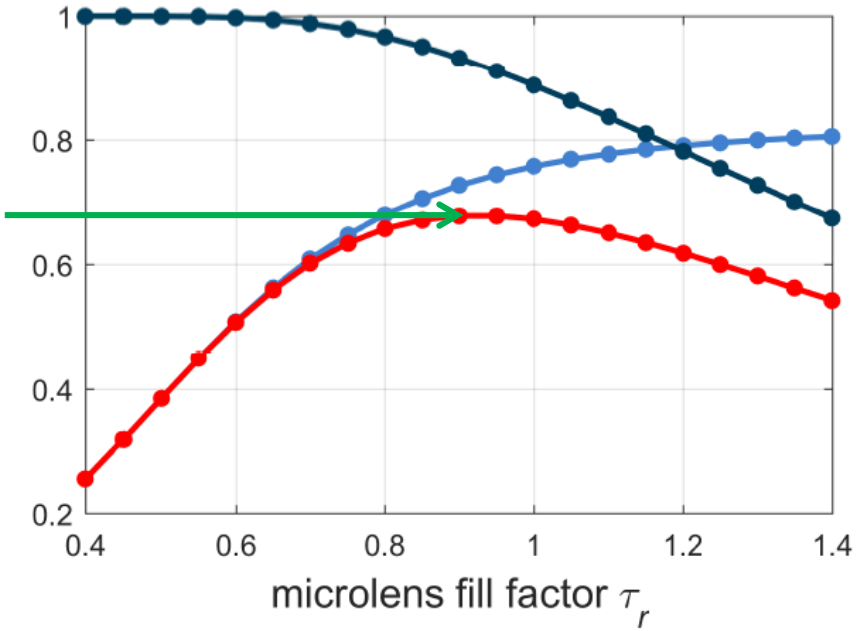


Overall efficiency



$$\tau_r = \frac{2\omega_0}{d_{\mu lens}}$$

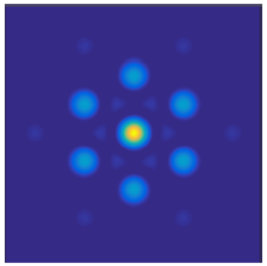
~67%



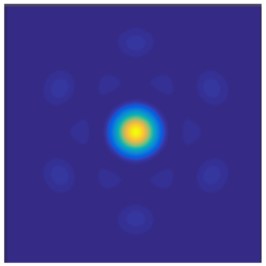
- far field efficiency η_{FF}
- microlens transmission $t_{\mu lens}$
- total efficiency η_{tot}

$$\eta_{tot} = \eta_{FF} \times t_{\mu lens}$$

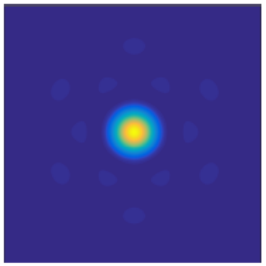
$\tau_r = 0.4$



$\tau_r = 0.9$

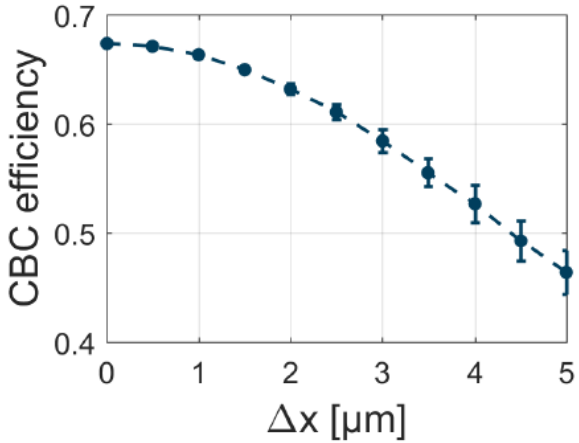


$\tau_r = 1.3$

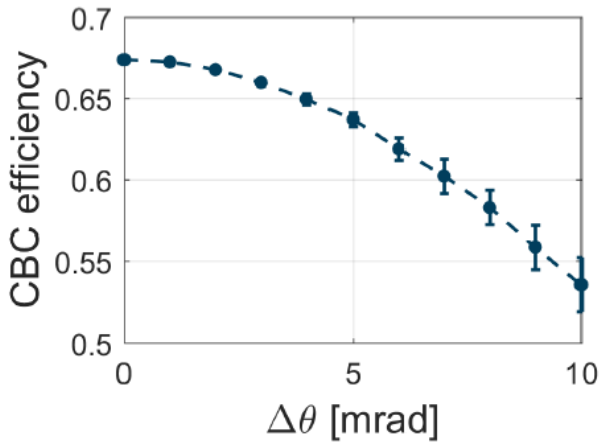


Error tolerances

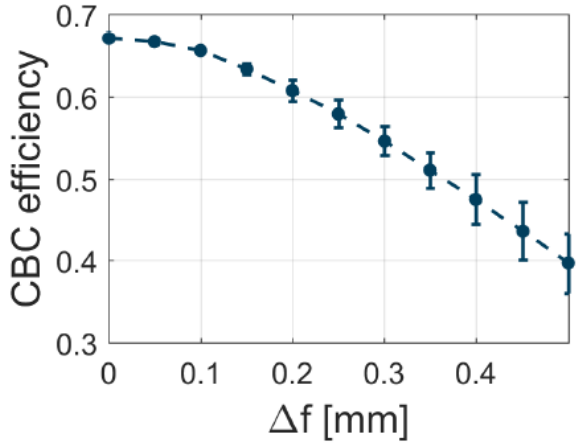
pitch



Beam-to-beam pointing



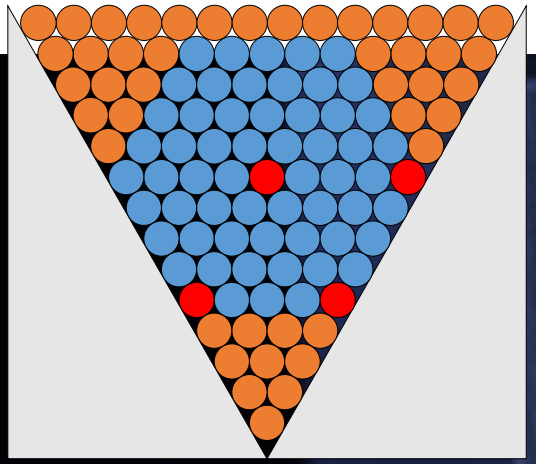
Longitudinal positioning



➔ High (μm/mrad) precision alignment needed

P7 & P61 laser head

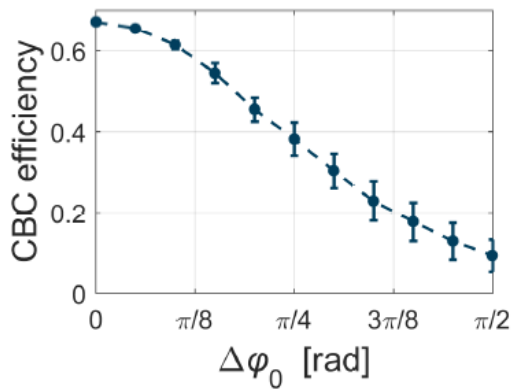
µm/mrad accuracy positioning laser head



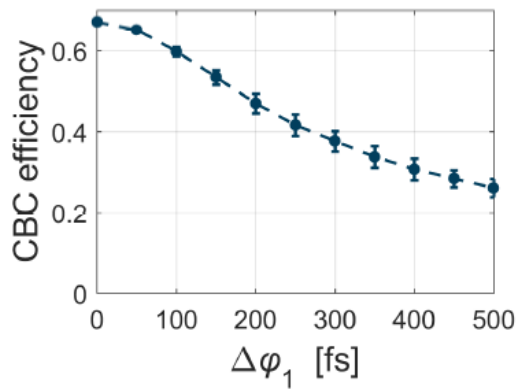
Spectral phase tolerances

$$E(\omega) = E_0(\omega)e^{i\varphi(\omega)} \quad \text{with} \quad \varphi(\omega) = \varphi_0 + \varphi_1\Delta\omega + \frac{\varphi_2}{2}\Delta\omega^2 + \ldots$$

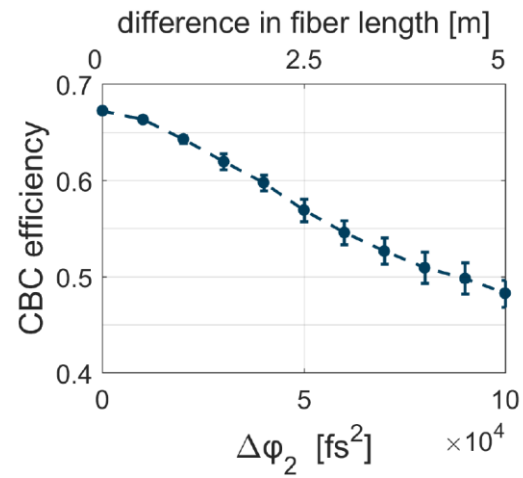
phase



delay



GVD



- Phase stabilization to $\pi/16 = \lambda/32$ rms necessary

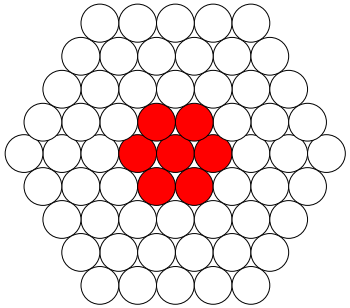
- Delay adjustment to 50 fs
- Optical path length adjustment to 15 µm

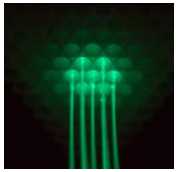
- Group velocity dispersion no problem since all-fiber front end

CBC experiment on 7 channels prototype

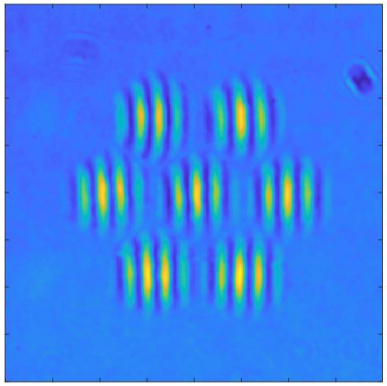
Linear regime	
0.5	ns
20	Watts /channel
55	MHz
<1	µJ/channel

Fibers distribution

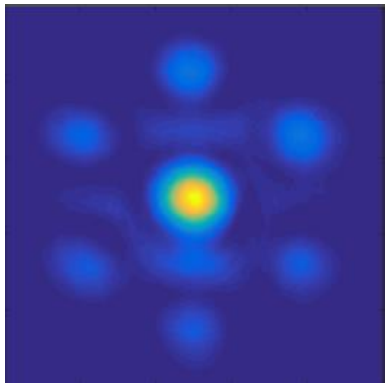


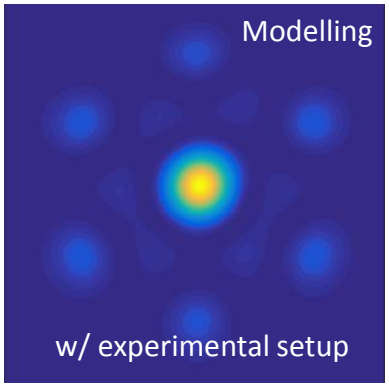


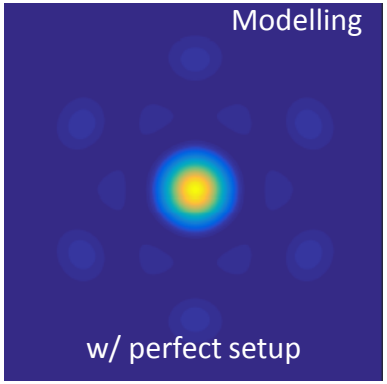
Near-field interferograms



Experimental Far-field

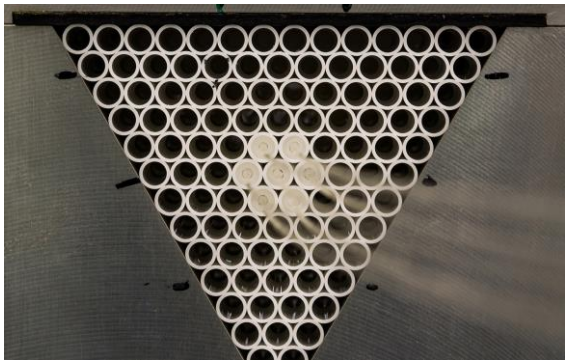




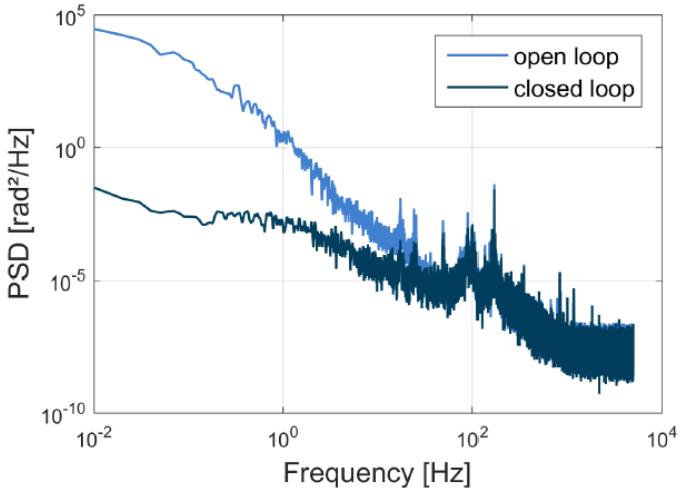


Efficiency	48%	56%	67%
Fraction of the theory		86%	71%

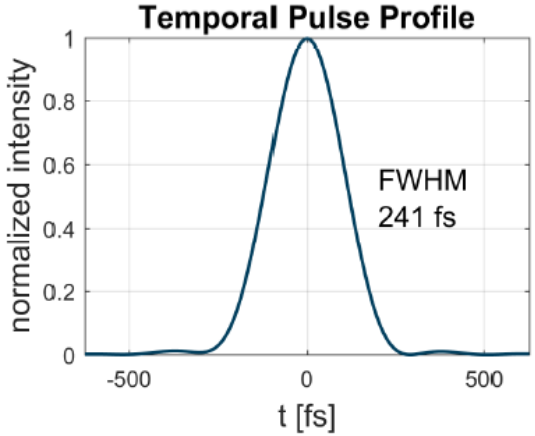
CBC experiment on 7 channels prototype

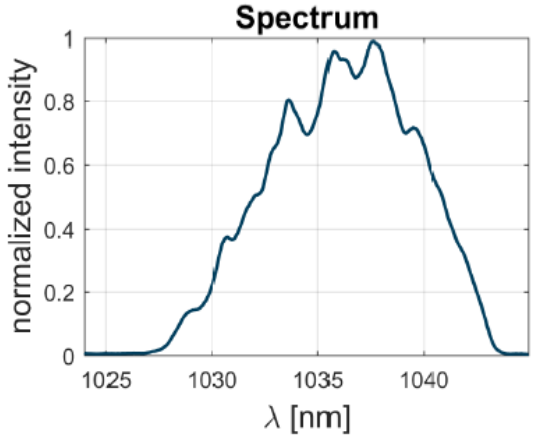


Relative phase noise between two fibers



Residual phase error of $\lambda/38$ rms

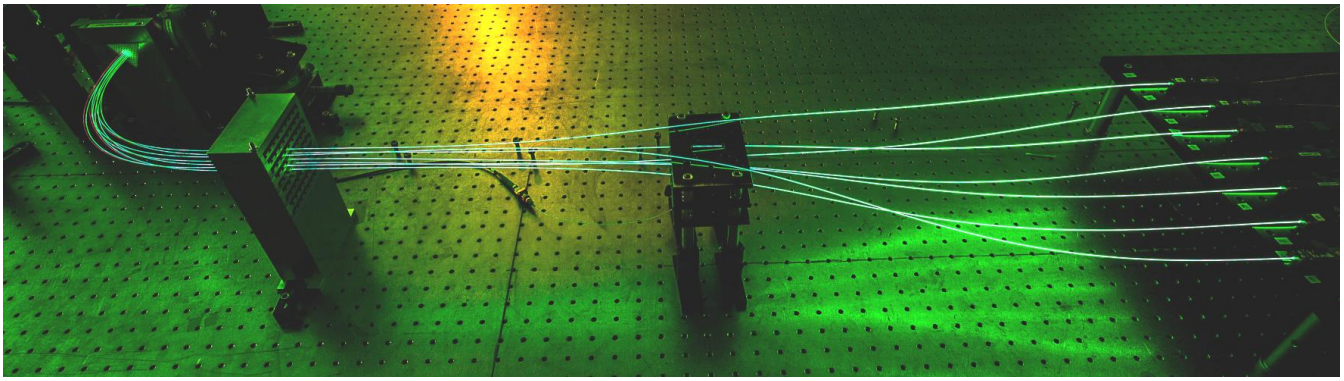




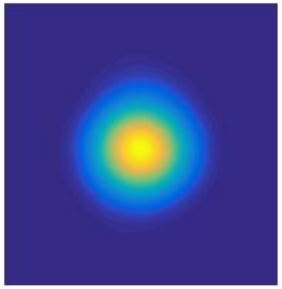
Fourier transform limited 78% efficient compression
47W final output power

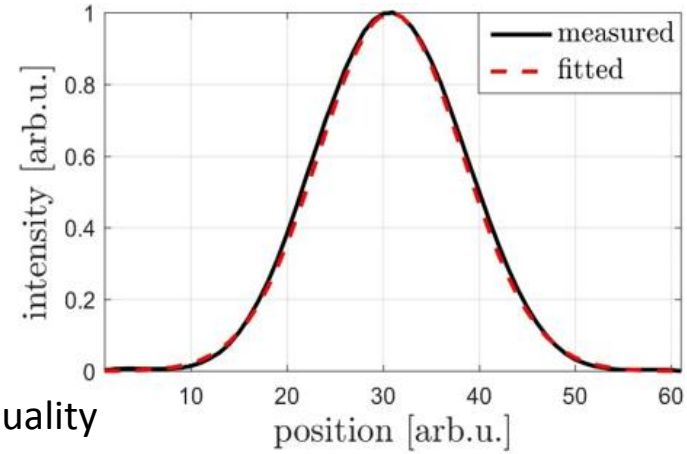
CBC experiment on 7 channels prototype

Coherent Amplification Network
POLYTECHNIQUE / THALES

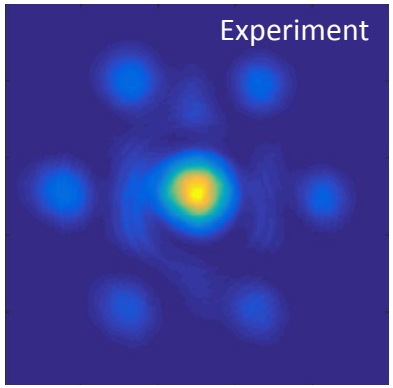


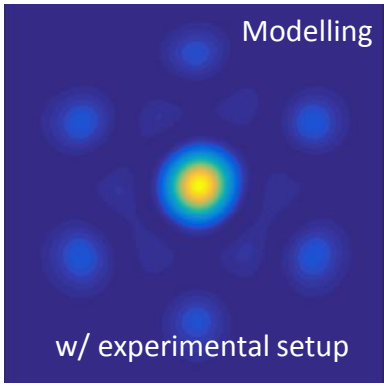
Non Linear regime	
7	channel
0.5	ns
20	Watts /channel
2	MHz
10	µJ/channel
~5	B Integral





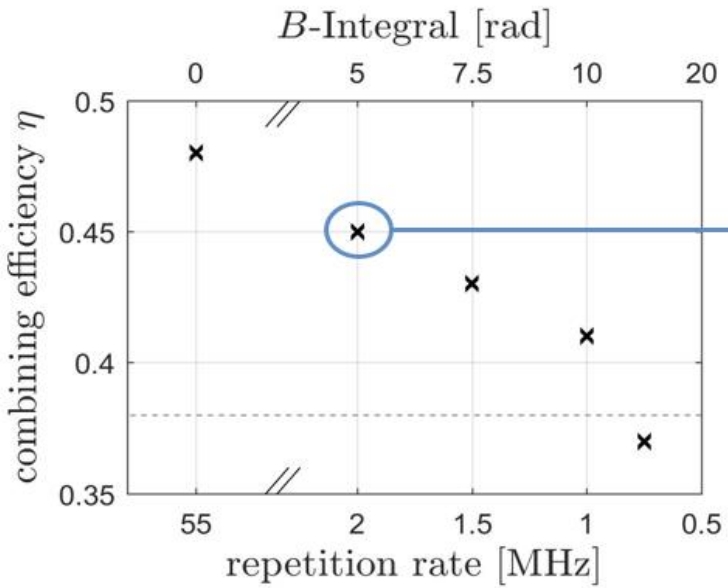
Excellent beam quality

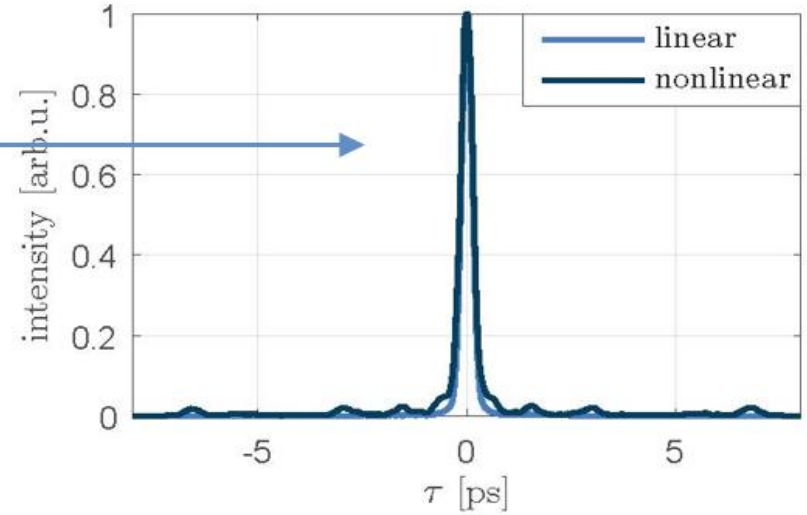


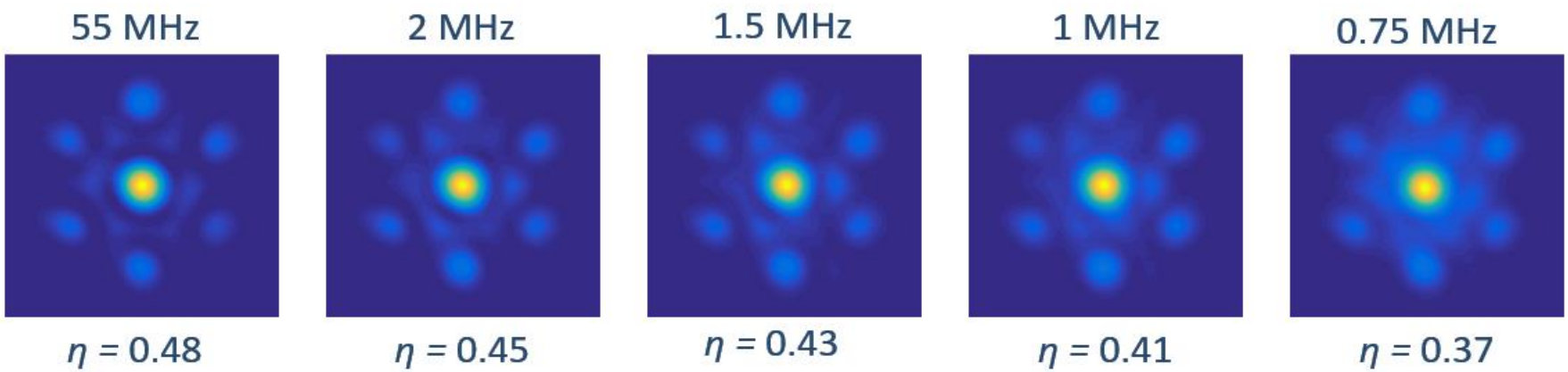


Efficiency	45%	56%
Fraction of the theory		80%

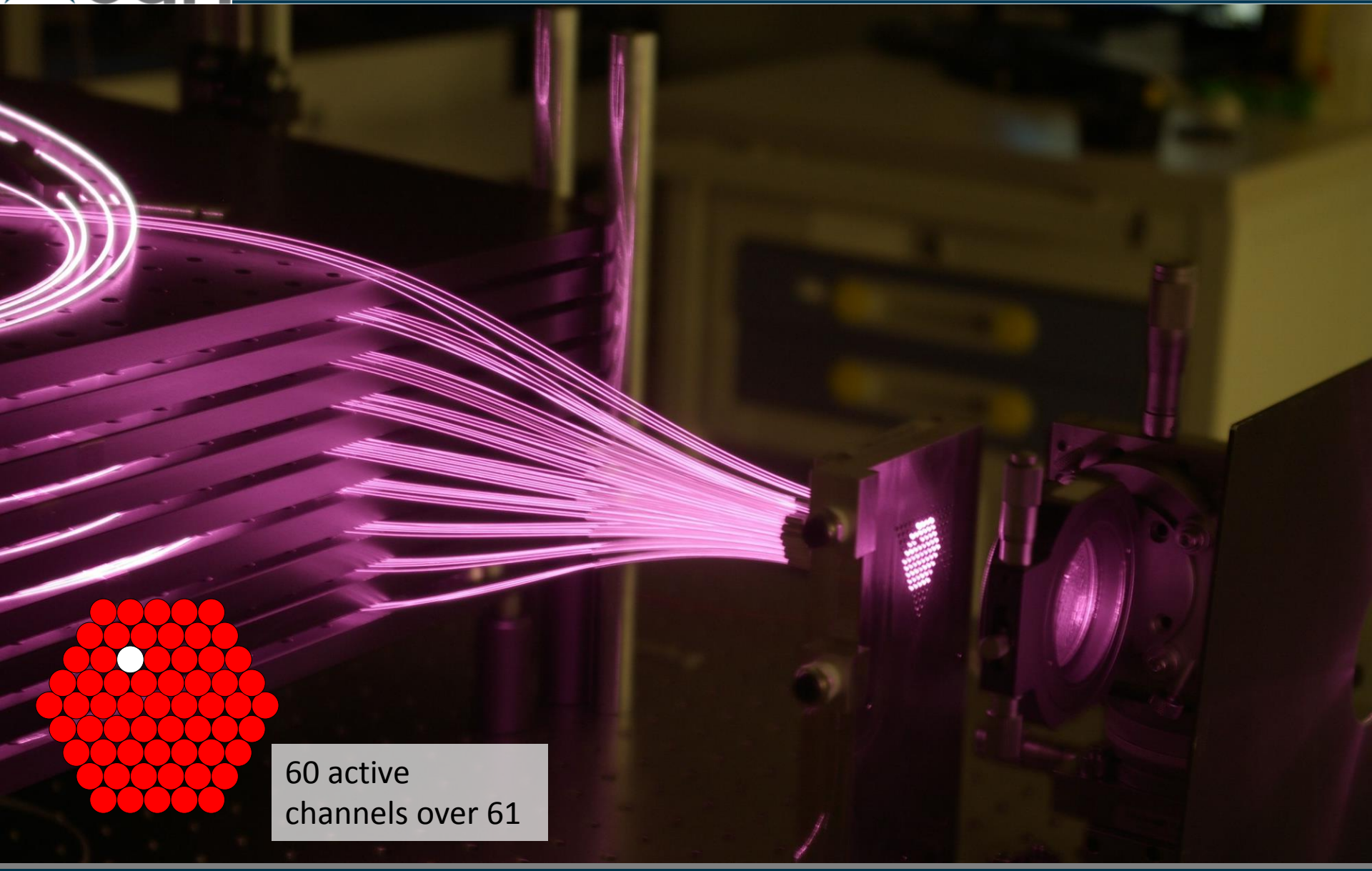
CBC experiment on 7 channels prototype





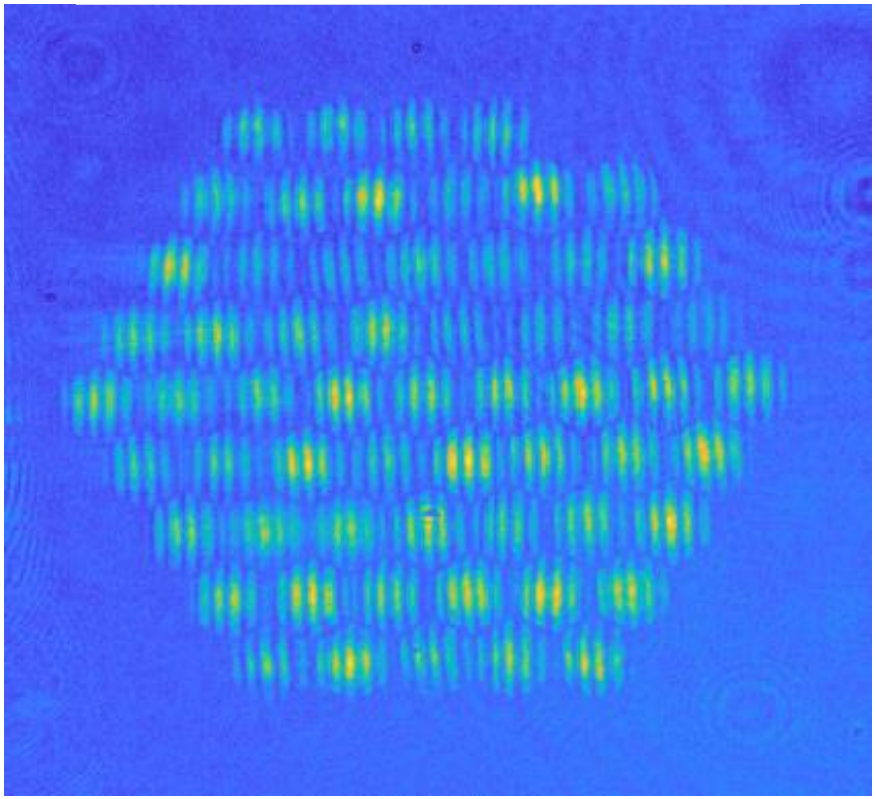


Current status



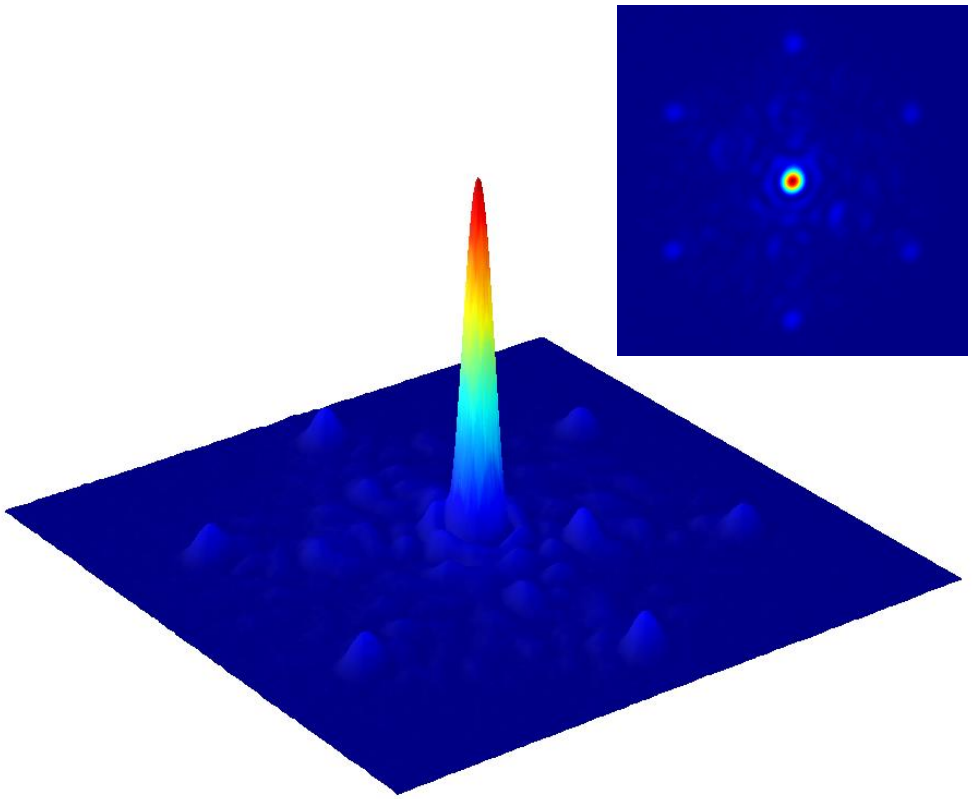
Current status

60 channels interferogram

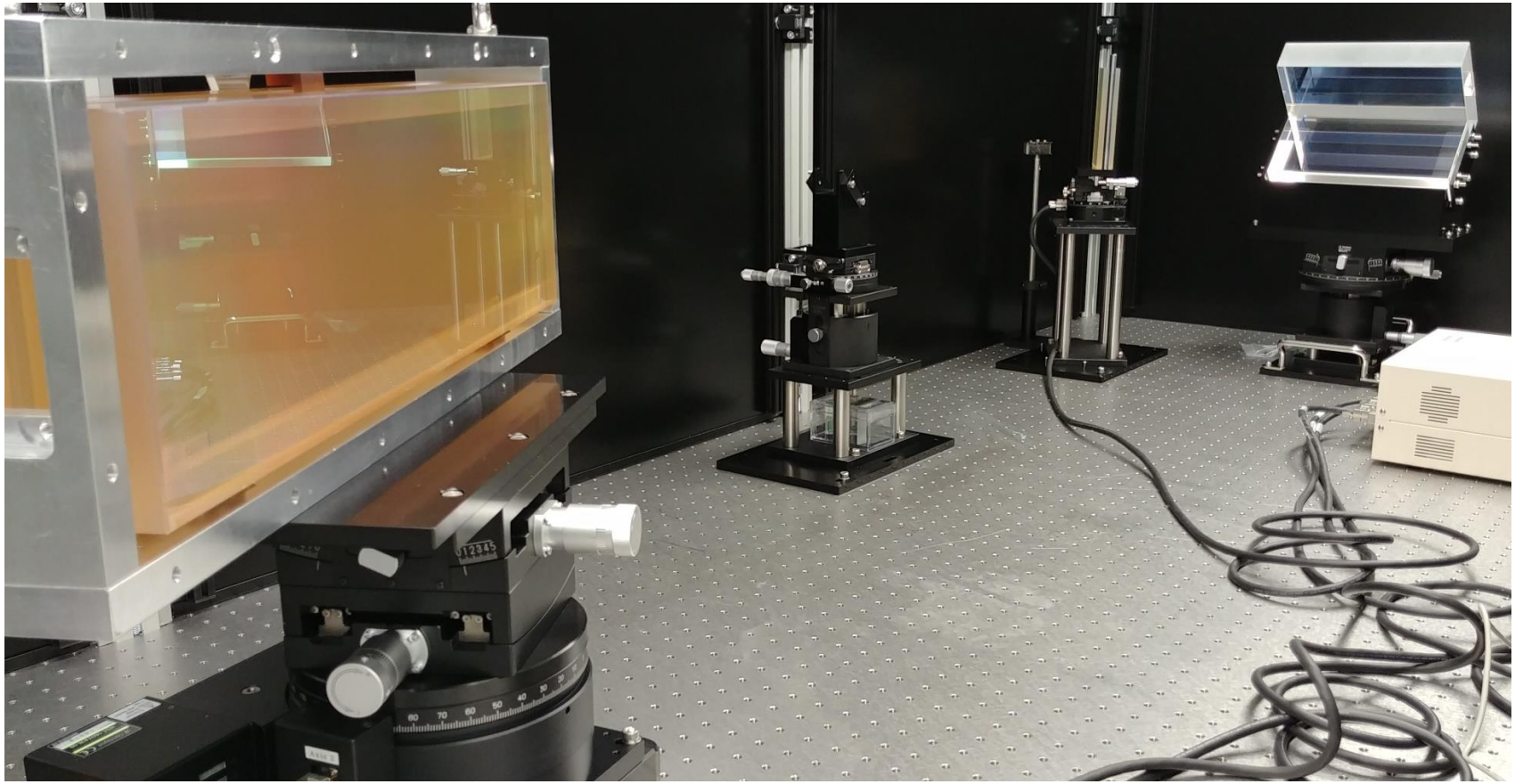


53% efficiency in linear regime

Far field

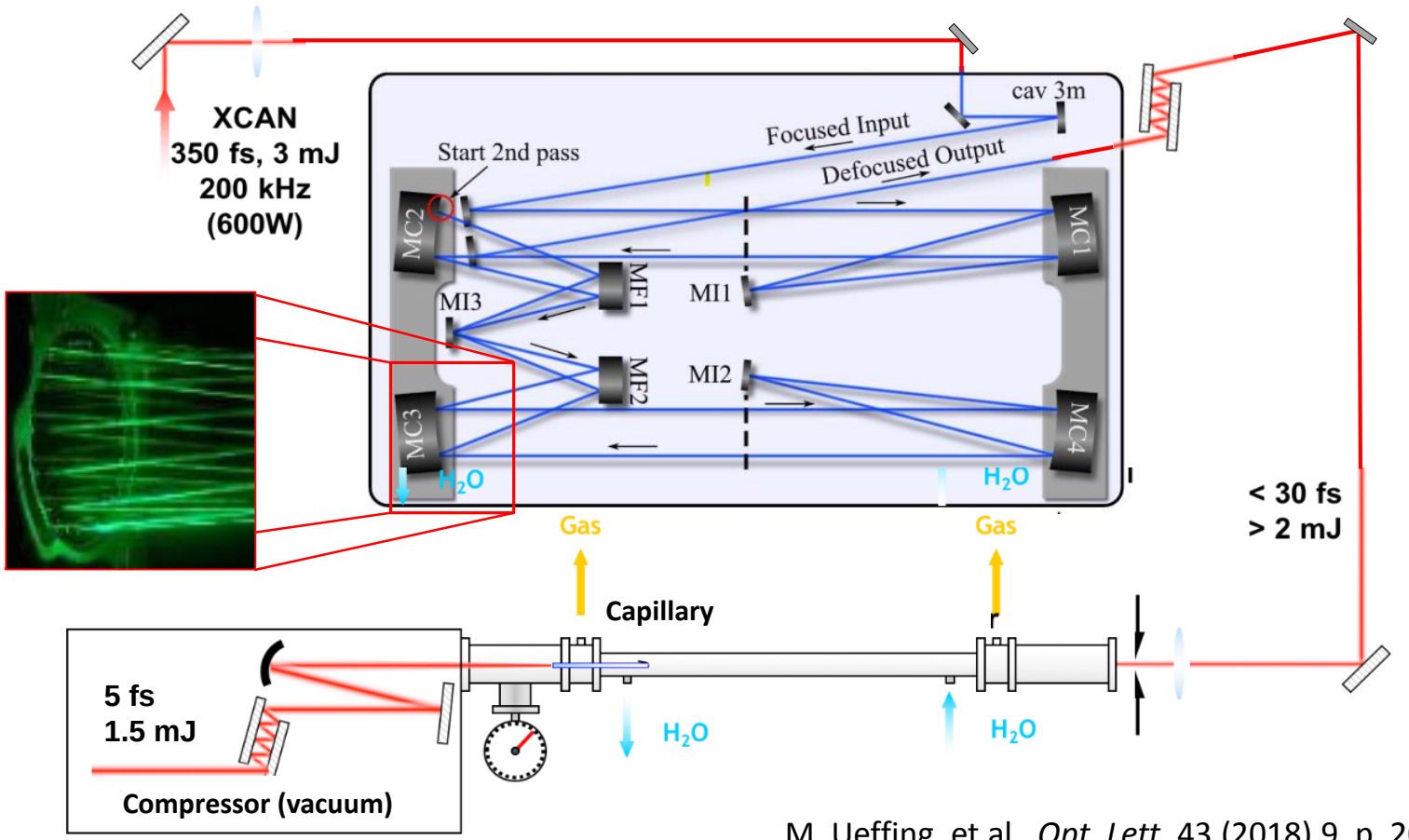


2.5/5ns compressor operational



Perspectives : 300fs ➔ 30 fs ➔ 5 fs

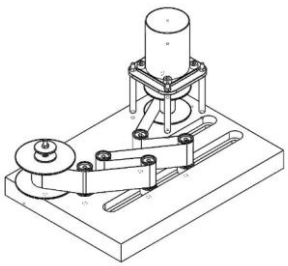
Adding a pair of non linear post compression stages



M. Ueffing, et al., *Opt. Lett.* 43,(2018) 9, p. 2070.

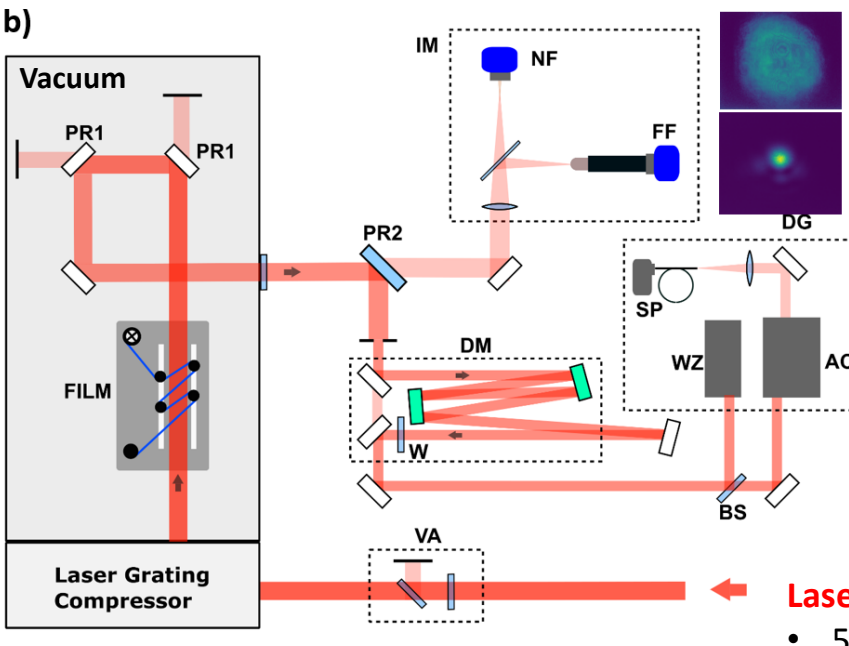
LaserLab Experiment at LASERIX

TFC with 50 fs, 200 mJ pulses



FILM = Cyclic Olefin Polymer (COP; Zeonor)

- 6 x 0.1mm ~ 0.9 mm



IM = Beam Imaging

- Plane of film (NF)
- Focus Spot (FF)

DG = Diagnostics

- FastLite Wizzler (WZ)
- Light Conversion TIPA Autocorrelator (AC)
- Ocean Optics USB spectrometer (SP)

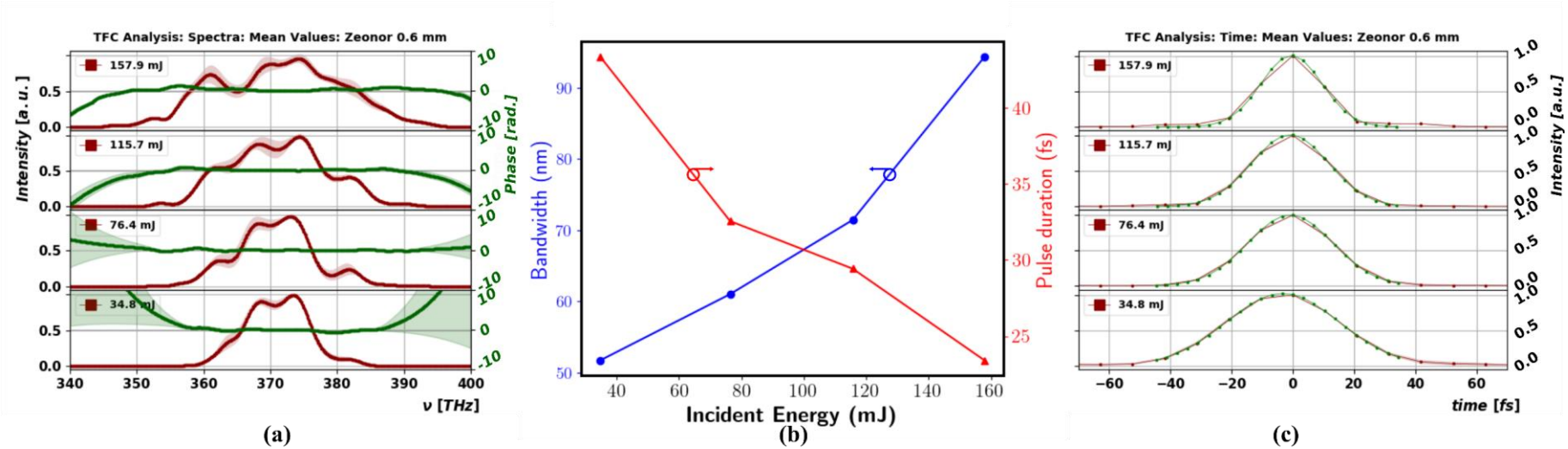
Laser (before compressor)

- 50 to 500 mJ input Energy
- 50 fs; 10 Hz or single-shot
- 1.8 cm diameter

DM = Dispersion management

- 4 bounces on Chirped Mirrors (-250 fs^2/bounce)
- Optional MgF2 windows (W) to optimize compression

Results LASERIX for initial 50 fs pulse

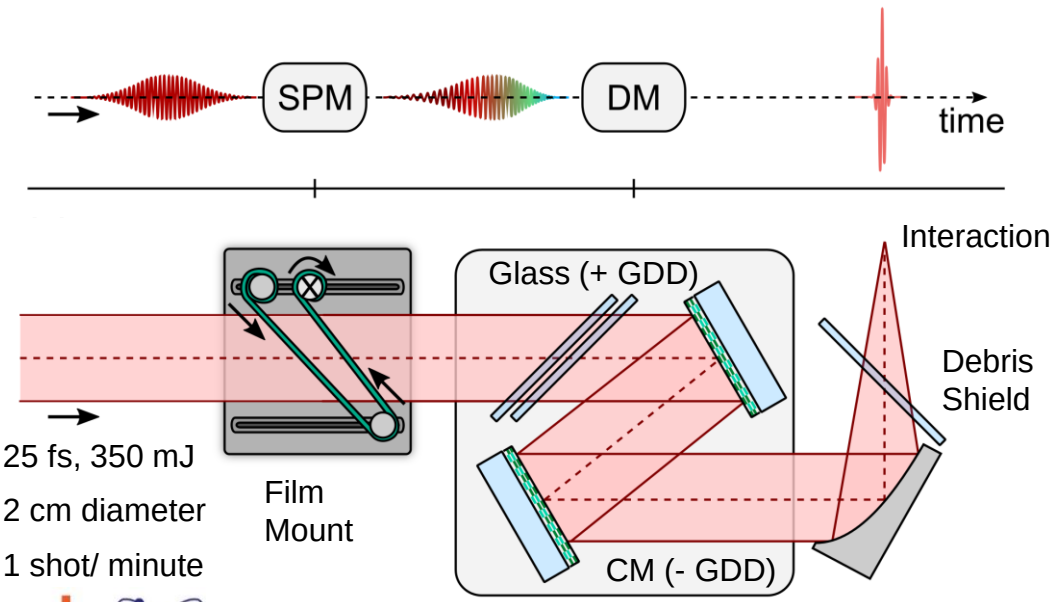


Energy [mJ]	Intensity [TW/cm²]	Δλ [nm]	τp [fs]
35	0.3	51.7 ± 0.6	44.0 ± 1.0
75	0.6	61.7 ± 0.6	32.7 ± 0.8
115	0.9	71.0 ± 2.0	30.0 ± 1.0
160	**1.25**	**94.3 ± 0.6**	**23.7 ± 0.2**

TFC Parameters for PW Probe Lines

Pulse duration for 25 fs input ⇒ 9.5 fs

- Two passes of COP film (Zeonor) with thickness of 0.18 mm mounted on Automatic Roller Machine
- GDD Compensation for SPM and Thin Film Dispersion -70 fs^2
- Additional GDD Compensation for beamline optics (~-1200 fs^2)
- Wedges to compensate and fine-tune of over-correction

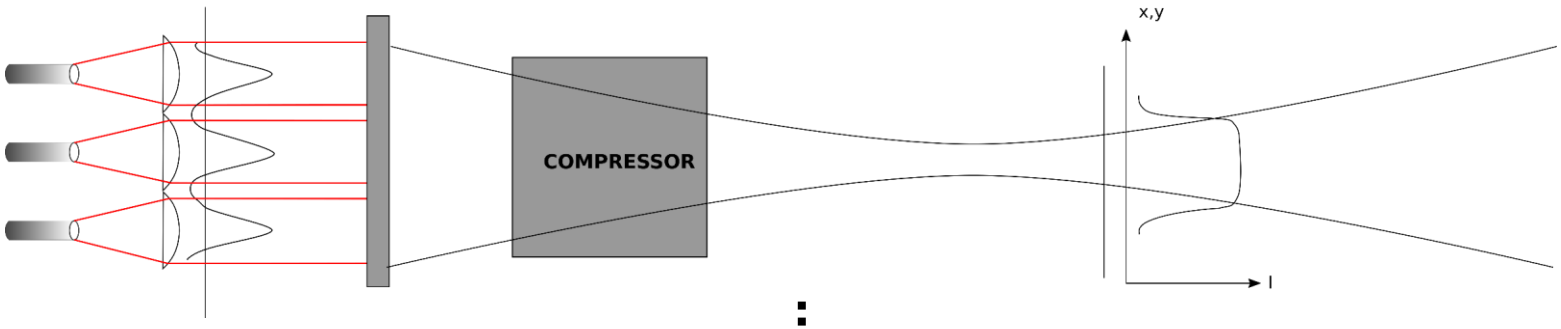


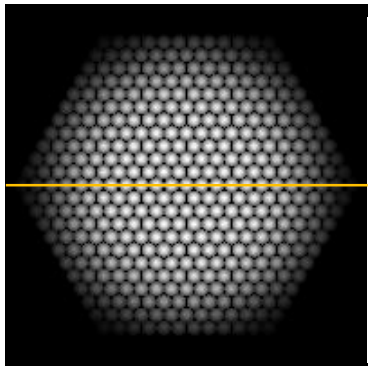
Heuristic Beam Profile: An example

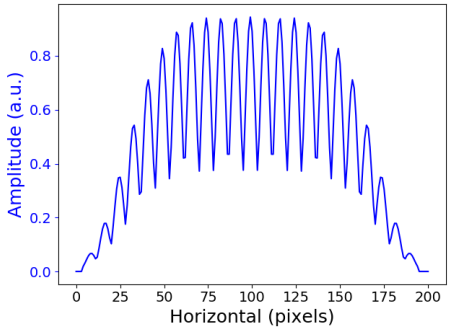
Producing a flat-top profile from an array of Gaussians

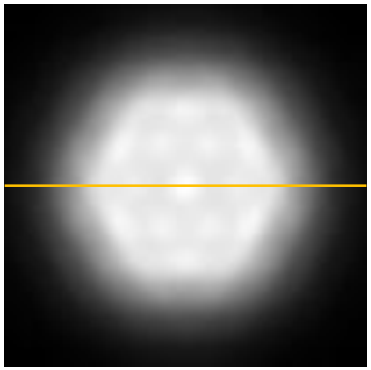
SuperGaussian Mask

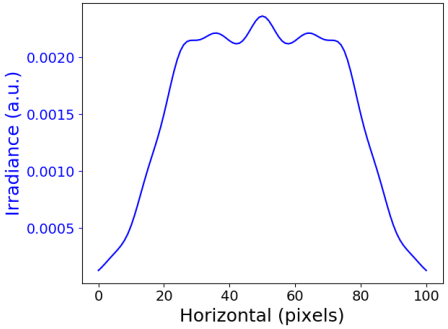
~2 Rayleigh lengths after focus









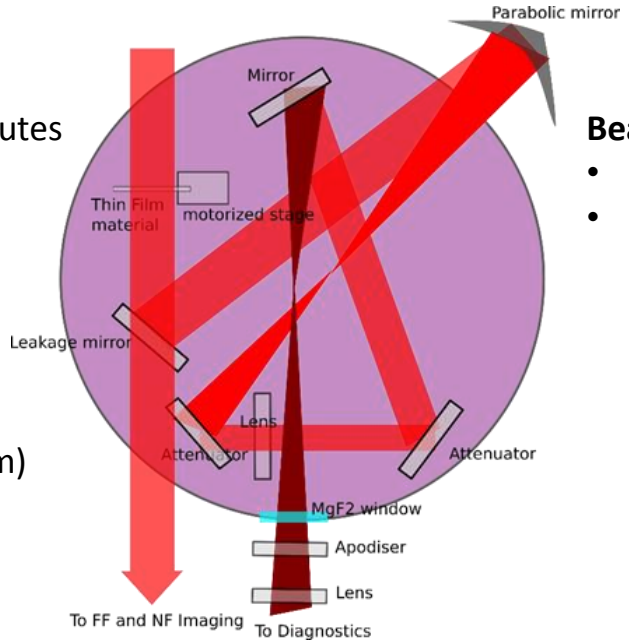


Starting directly from a 300 fs Pulse

ELFIE Facility at LULI (7 J; 300 fs)

Laser (before film)

- 7 J input Energy
- 300 fs; single-shot/20 minutes
- 7.0 cm diameter
- No shot-to-shot stability



Beam Sampling (Resizing and Attenuation)

- Half-coated silver/bare glass Attenuators
- Parabolic Mirror/ lens combination for reduction

"Thin" Films

- Cyclic Olefin Polymer (2 mm)
- Fused Silica (5 mm)

Temporal Diagnostics

- Homebuilt FROG
- Autocorrelator
- Imaging Spectrometer

Beam Imaging

- Plane of film (NF)
- Focus Spot (FF)

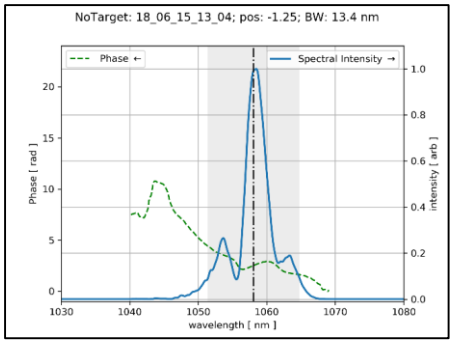
Dispersion management

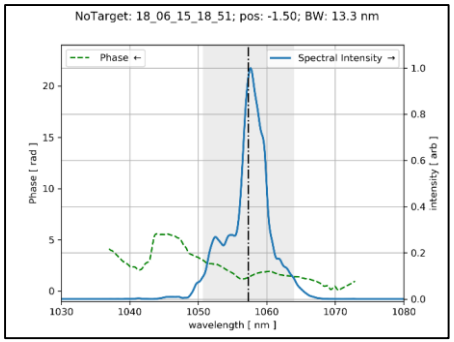
- 6 bounces on Chirped Mirrors (-1000 fs^2/bounce)
- MgF2 windows to minimize additional dispersion

ELFIE Facility at LULI (7 J; 300 fs)

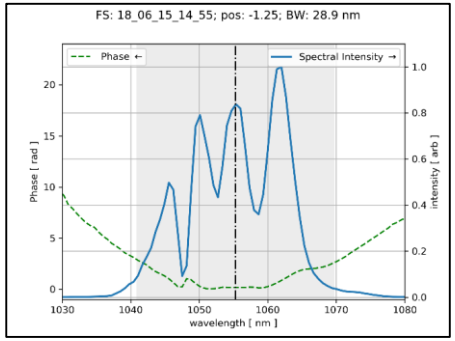
Factor of 2.2 Gain in Bandwidth

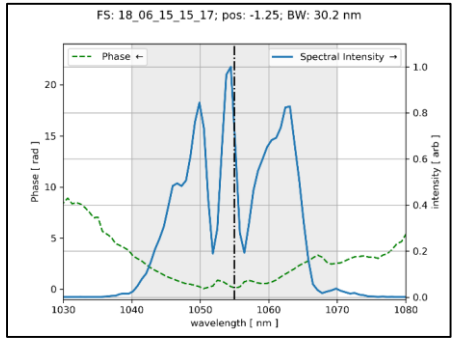
No Film (6x CM) **BW ~ 13.4 nm**



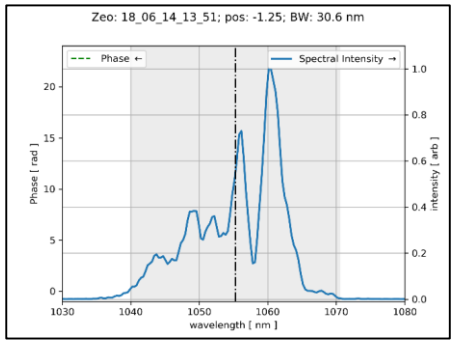


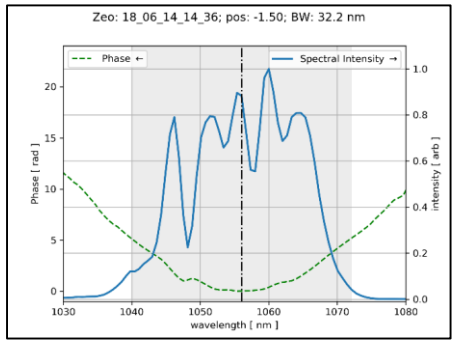
Fused Silica 5mm (6xCM) **BW ~ 29 nm**
2018-06-15 (data) / 2019-04-09 (analysis)





COP 2mm (6xCM) **BW ~ 31 nm**
2018-06-14 (data) / 2019-04-09 (analysis)





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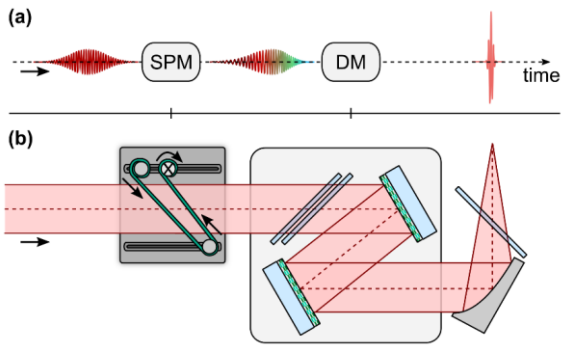
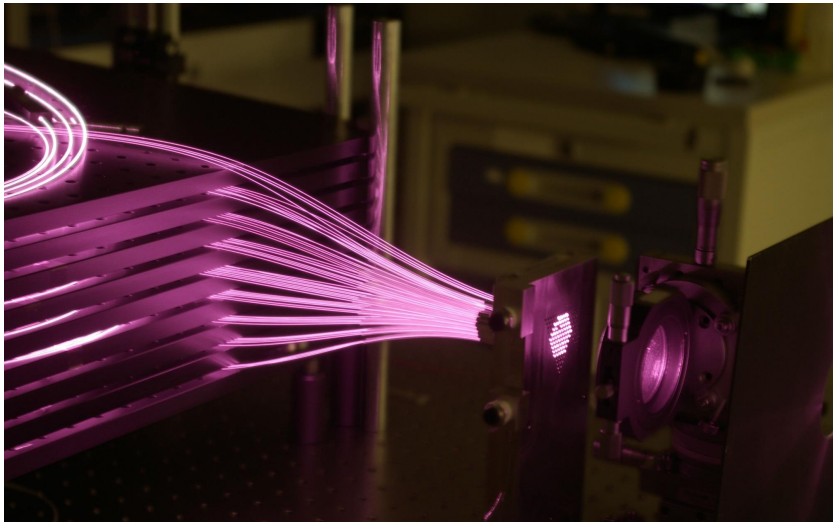
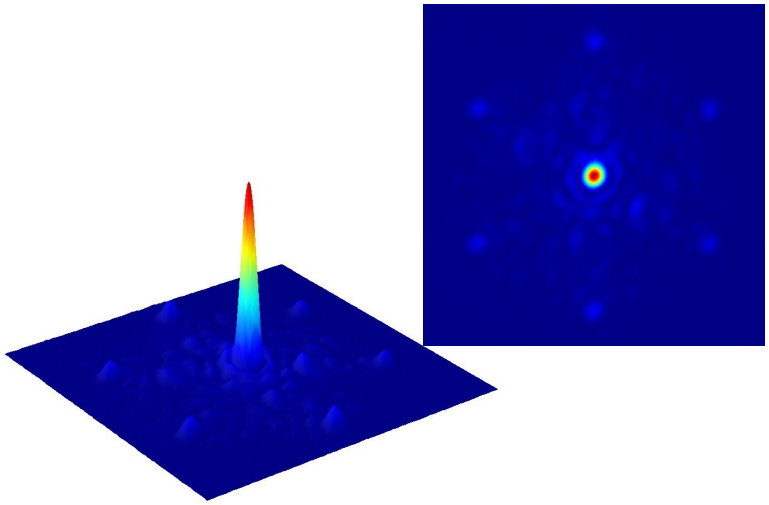
Summary

- Strong motivation for high peak and average power femtosecond pulses.
- The 61-fiber XCAN prototype has been demonstrated in the linear regime with plans with improved efficiencies over the 7-fiber prototype.
- These types of systems will require compression from 350 fs to sub-10 fs via methods such as TFC.



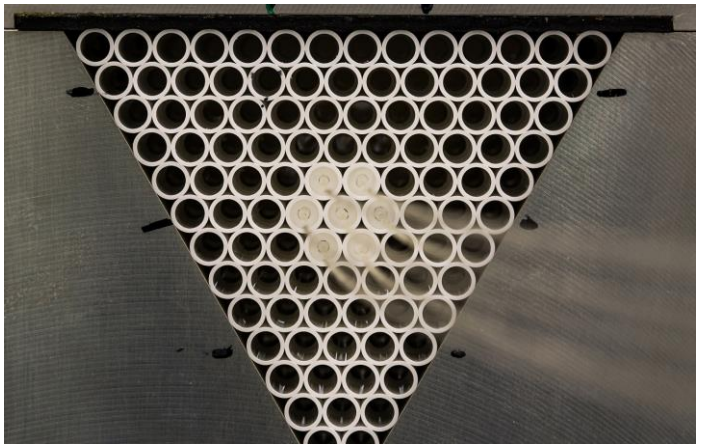




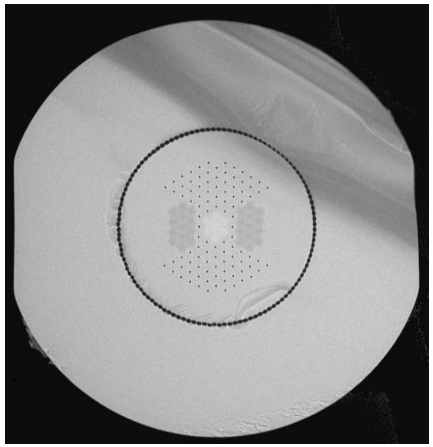
Thank you for your attention

Back-up slides

Scalability



Laser head current pitch : 3 mm
(relying on standard telecom
ferules and sleeves)

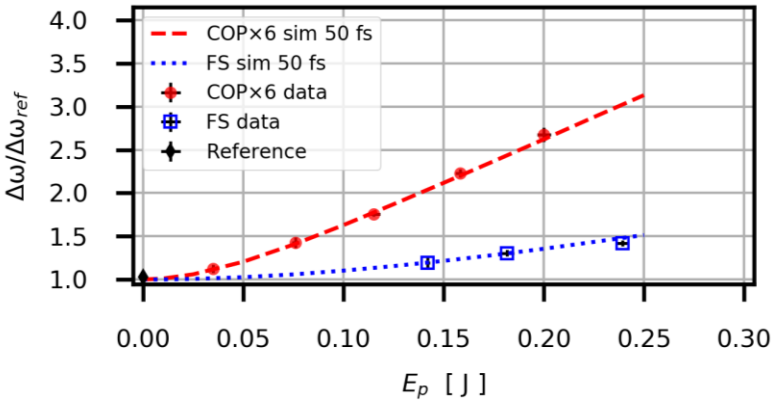


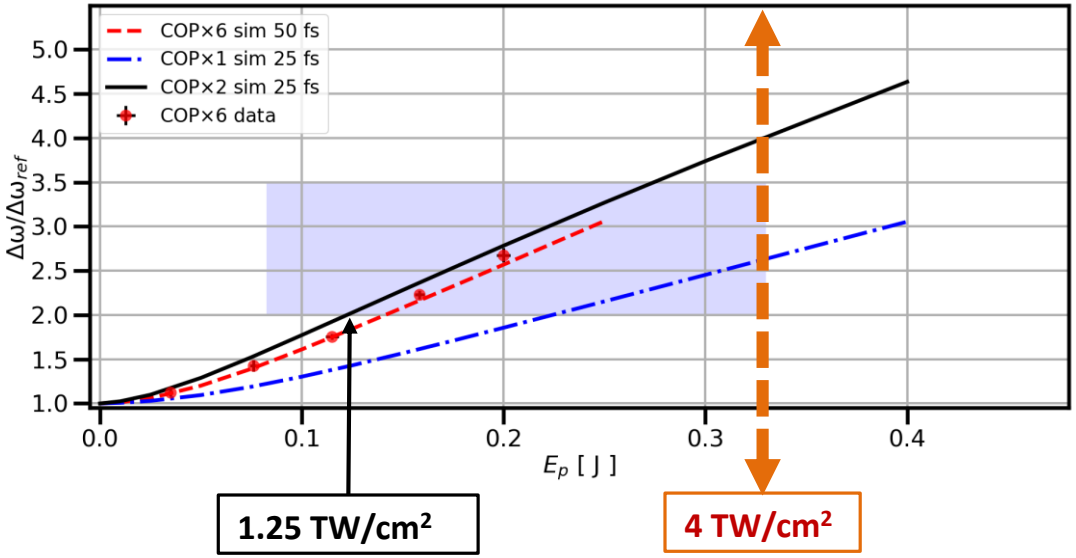
Amplifying fiber diameter : 450 µm

- 2D V-groove (silicon etched) structure with a 700 µm pitch
- 59 rings (10267 channels) ➔117 channel per diameter

} 10K channel, 8 cm diameter composite beam ➔ >100kW

Simulating 25 fs from 50 fs Data





1-D Modeling in pyNLO Python package

- Solves nonlinear Schrödinger equation accounting for GVD, SPM, self-steepening, and Raman effects.
- Required inclusion of **95% transmission for each film** of the series.
- First confirmed results with known Fused Silica, and COP at 50 fs.
- **Modelled expected response at 25 fs pulse conditions of ELI-NP**

Johan Hult. *J. Lightwave Technol.*, 25(12):3770-3775, Dec 2007.