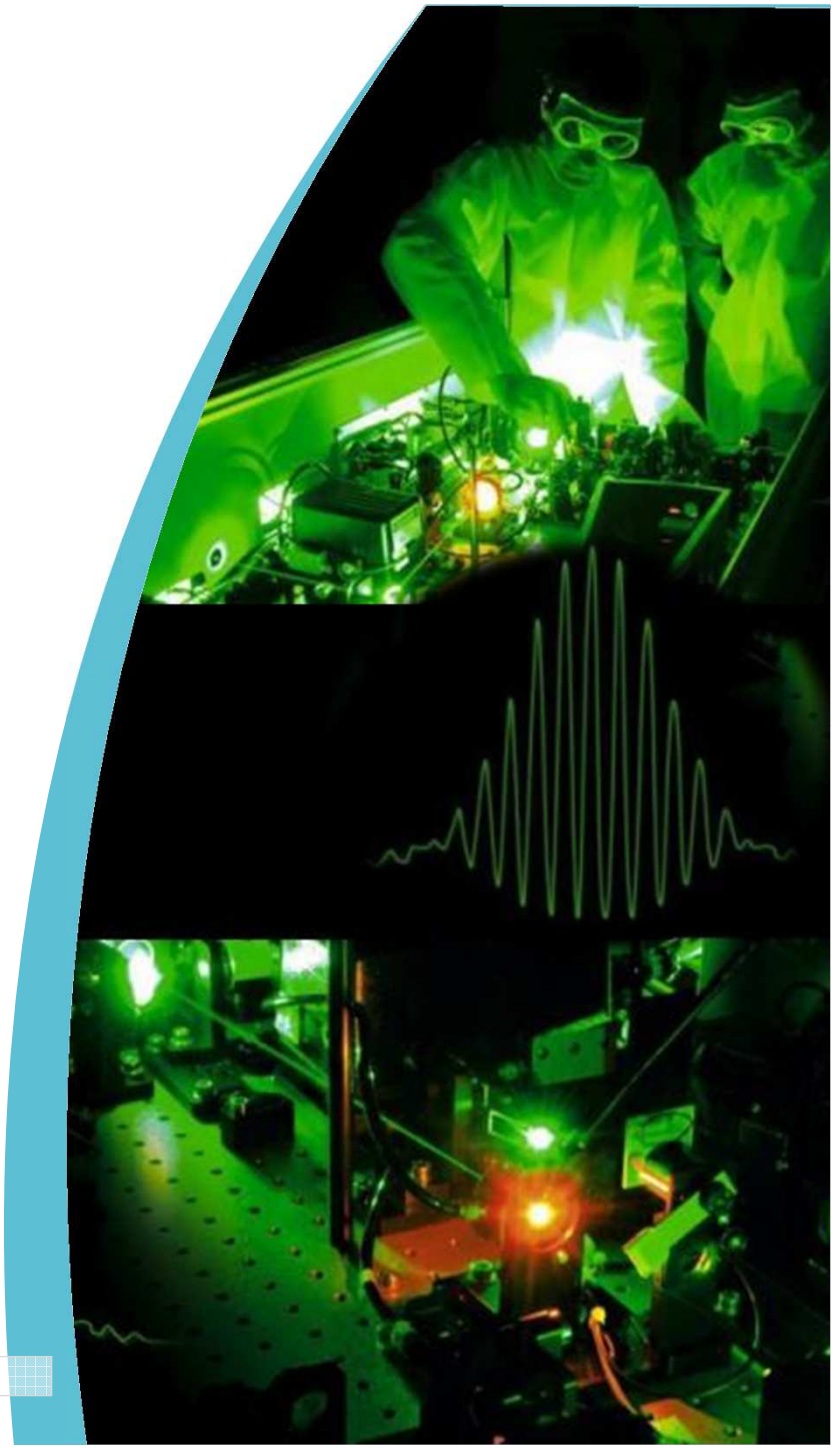
THALES

High average power laser technologies for future accelerators

ALEGRO WORKSHOP

27TH MARCH 2018 – OXFORD

CHRISTOPHE SIMON-BOISSON

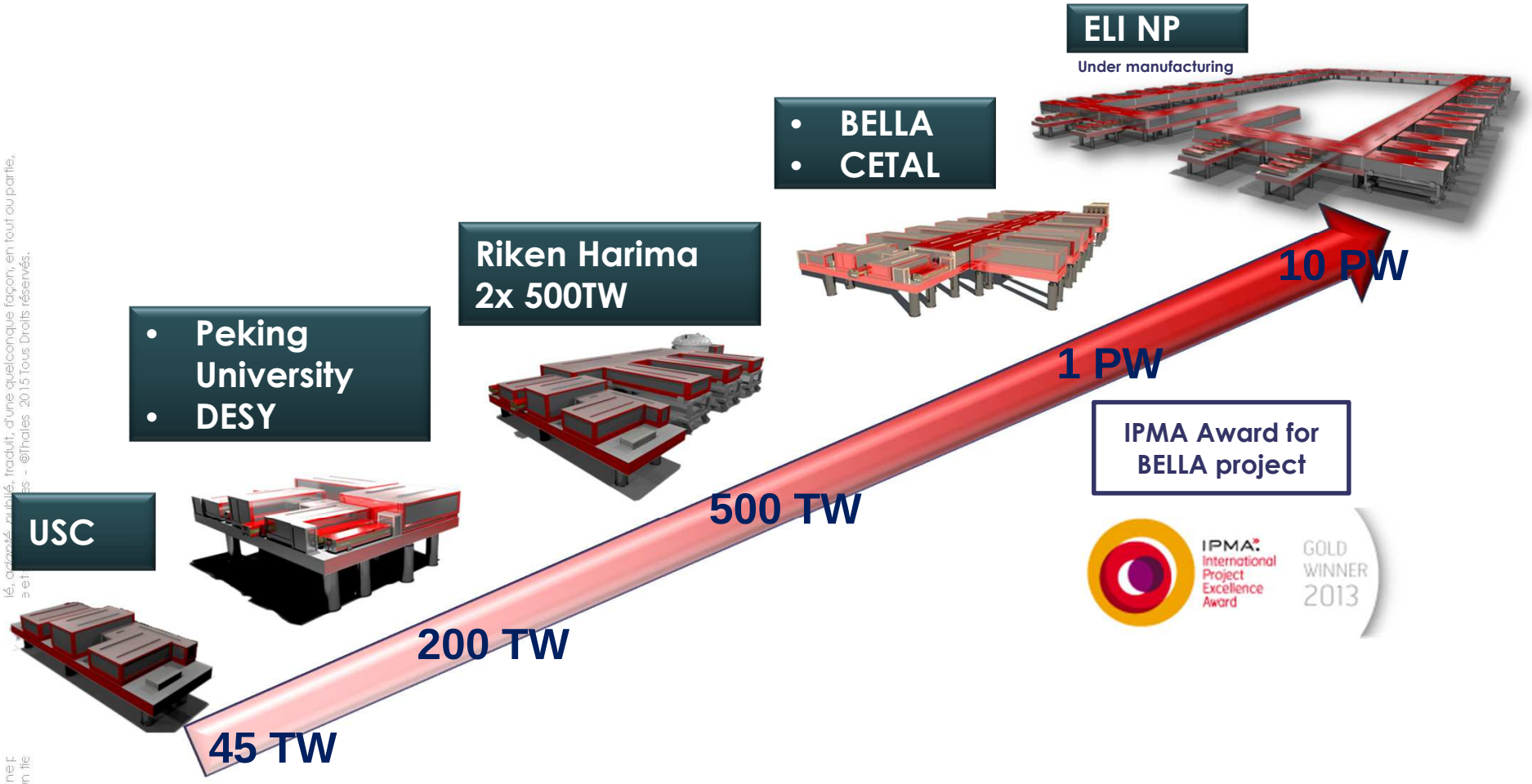


Outline

- Introduction
- Current achievements of lasers for laser plasma acceleration
- Requirements for future accelerators and technologies for high average power lasers
- Coherent combination of fiber amplifiers – XCAN project
- Conclusions

Current achievements of lasers for laser plasma acceleration

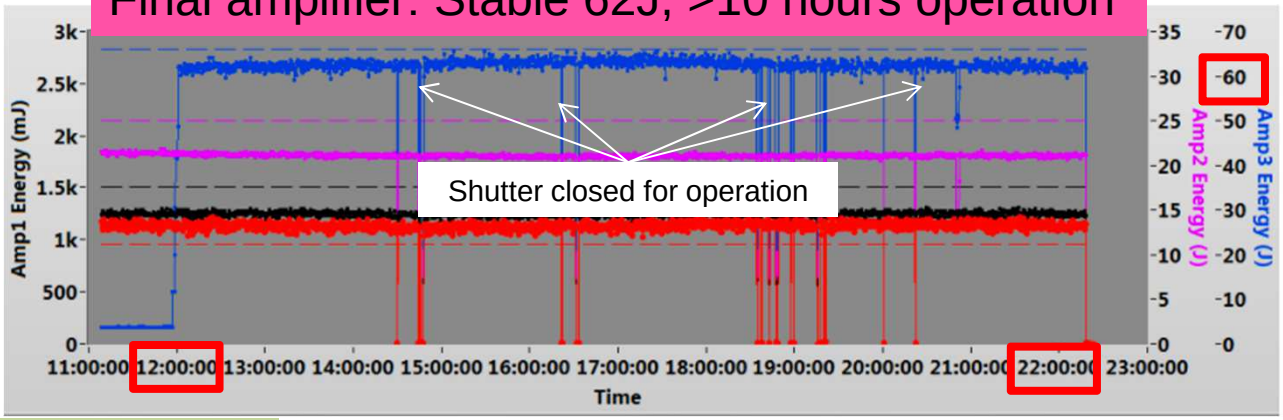
High Peak power laser: From multi TW to multi PW level



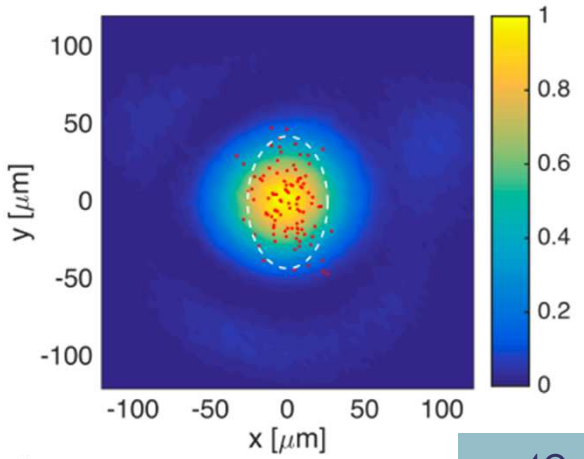
BELLA

BELLA Petawatt Laser: 1 Hz, 1 PW to Realize 10 GeV Class LPA

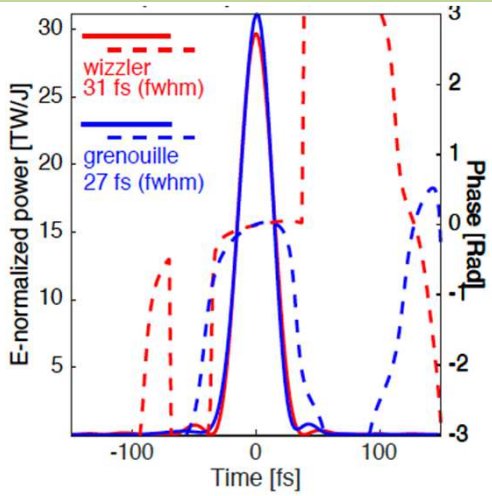
Final amplifier: Stable 62J, >10 hours operation



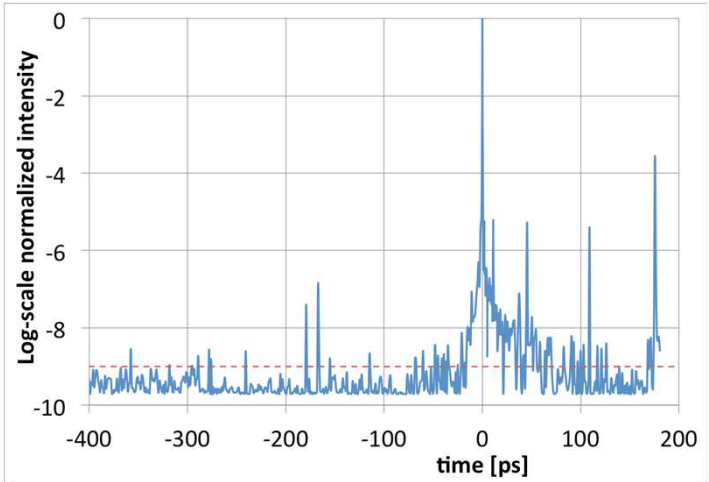
High quality spatial profile
Low pointing jitter



High quality temporal profile



High temporal contrast



49 [J on target] x 25 [TW/J] = 1.2 PW

* K. Nakamura et al., IEEE QE **53** (2017).

Requirements for future accelerators and technologies for high average power lasers

Laser requirements for future accelerators

- **Laser plasma acceleration has allowed to reach more than 1 GeV and is on the way to demonstrate 10 GeV soon**
- **Laser source technology used up to now is pretty mature and commercially available but not suited to future needs of acceleration community because of low efficiency & low average power**
- **There are 2 institutions having established long term roadmaps, defined the laser requirements for these roadmaps and performed analysis of relevant laser technologies for these roadmaps:**
  - Department of Energy (DOE) of US (see W Leemans presentation at this workshop)
  - European Union through EupraXia project (see L Gizzi presentation at this workshop)

Summary of requirements : Eupraxia & DOE roadmap

	Eupraxia Baseline	Eupraxia Target	DoE – 3 kW (k-BELLA)	DoE – 30 kW	DoE – 300 kW
Energy	50 J	100 J	3 J 30 J 30 mJ	3 J 30 J 30 mJ	3 J 30 J
Repetition rate	20 Hz	100 Hz	1 kHz 100 Hz 100 kHz	10 kHz 1 kHz 1 MHz	100 kHz 10 kHz
Pulse duration	60 fs	50 fs	30 fs	30-100 fs	100 fs
Average power	1 kW	10 kW	3 kW	30 kW	300 kW
Peak power	0.83 PW	2 PW	1 TW to 1 PW	0.3 TW to 1 PW	30 TW to 300 TW

Laser technologies for high average power

Indirect CPA

- Titanium Sapphire + 0.5 µm pulsed SSL (bulk /fiber) pump
- Long term : TiSA pumped by cw diodes for 300 kHz – 1 MHz ? (still large quantum defect, efficiency of high power green diode ?)

Direct CPA (diode-pumped)

- Bulk: Ytterbium, Thulium in crystal hosts (YAG, YLF, CaF2)
- Fiber: Ytterbium, Thulium. Requires multiple fibers & combination techniques (this starts from multicore which is the most monolithic setup and goes to less compact schemes). Potential issues for contrast
- No direct CPA scheme compatible with 30 fs operation without post-compressor extension for spectral broadening

OPCPA

- LBO, KD*P. Requires intrinsically a pump laser
- Good for pulse duration, ASE contrast and high average power operation (no energy storage)
- Main issue is the efficiency: indirect scheme (pump laser) + main amplifier extraction efficiency 25% in the best case

Hybrid setups: OPCPA + CPA (or CPA + OPCPA)

Specific considerations

Short pulse duration (30 fs)

- Potential issue with the gratings: gold gratings might be not compatible with kW + operation (even with active cooling) and not easy for MLD gratings to combine in the same time the required bandwidth and high enough LIDT level (must be at least 0.1 to 0.2 J/cm2)
- Except TiSa & OPCPA, no other technique can reach directly 30 fs so that post-compressor devices have to be implemented. State of the art technique might be not scalable in front of a combination of high peak power & high average power

Longer pulse duration (50 fs – 100 fs)

- 50 fs not achievable directly by Ytterbium (bulk or fiber). Significant risk for Thulium at high energy
- 100 fs currently not achievable directly by Ytterbium (bulk or fiber).

Contrast ratio

- ASE-related risk for fiber solutions
- Only few published results
- Will require special attention if wanting to go ahead with fibers

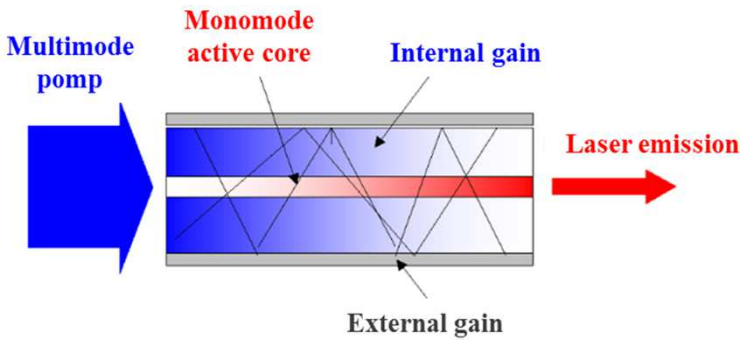
THALES

Coherent combination of fiber amplifiers XCAN project

Fiber amplification

Advantages

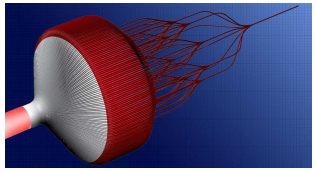
- Excellent beam quality
- Optical efficiency > 80% for Yb doping
- Flexible and monolithic assembly : splicing, combiner
- High surface to volume ratio : very good thermal handling



Fiber geometry : tight confinement of the laser beam

- Non-linear effects : distortion of the temporal pulse profile
- Limited output peak power

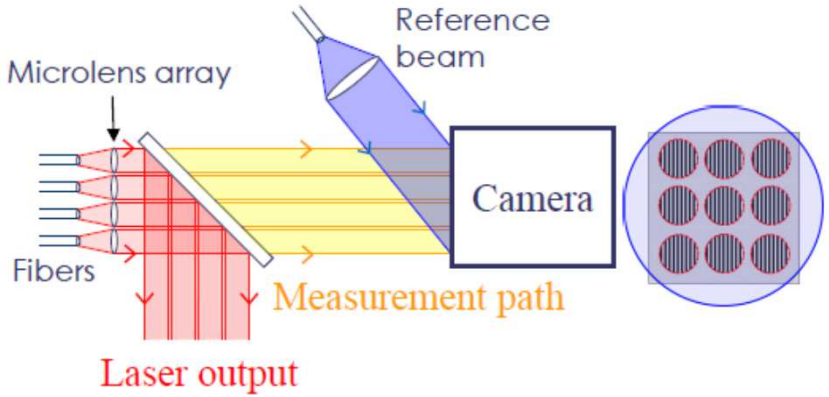
➔ Combining several fibers



Interferometric based CBC in fs regime

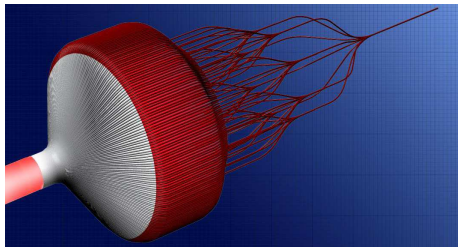
Interferometric phase measurement

> Large fiber number collective measurement



➡ Current achievement :
64 combined fibers (Thales 2011) in CW regime

➡ Foreseen applications require operating in femtosecond regime at high repetition rate



Xcan Coherent Amplification Network POLYTECHNIQUE / THALES Project : CBC demonstrator with 61 fiber amplifiers, 3 mJ, 200 kHz, 300 fs

➔ Intermediate demonstrator in fs regime w/o amplification

➡ **Record number of 19 fibers combined in femtosecond regime**

XCAN project

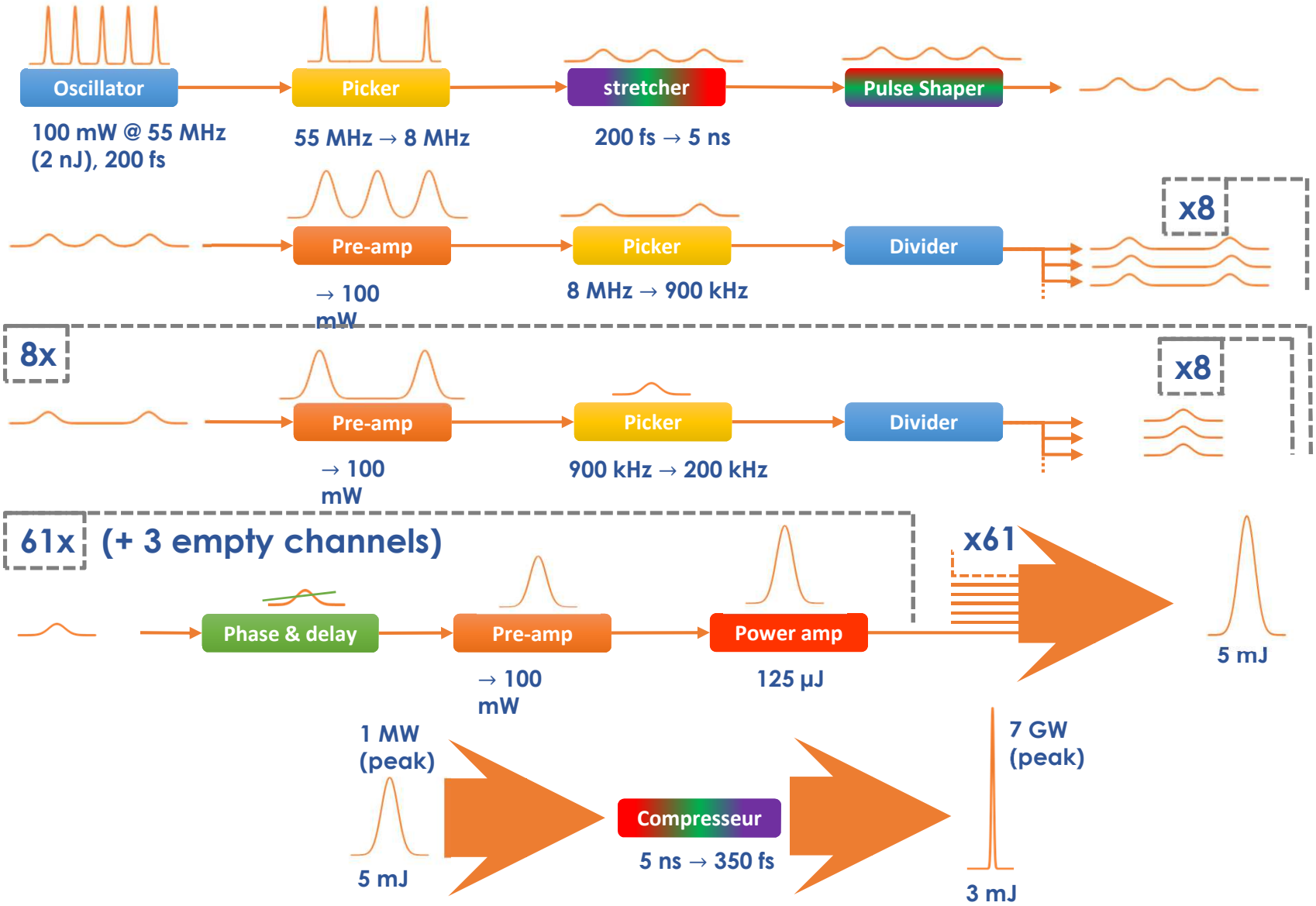
XCAN

- 3 years project: 2015-2018
- Collaboration : Ecole Polytechnique, TRT & TOSA
- Demonstration of the combining of **61 fibers, 3 mJ @ 200 kHz, 300 fs**

Planning of the project

- 2015 – 2017: experimental validation of the main components
  - Tests of the key components
  - Development of intermediate demonstrators (7 fibers active / 19 fibers passive)
- 2017- 2018 : Assembly phase of a 61 fibers demonstrator

XCAN project – Synoptic view



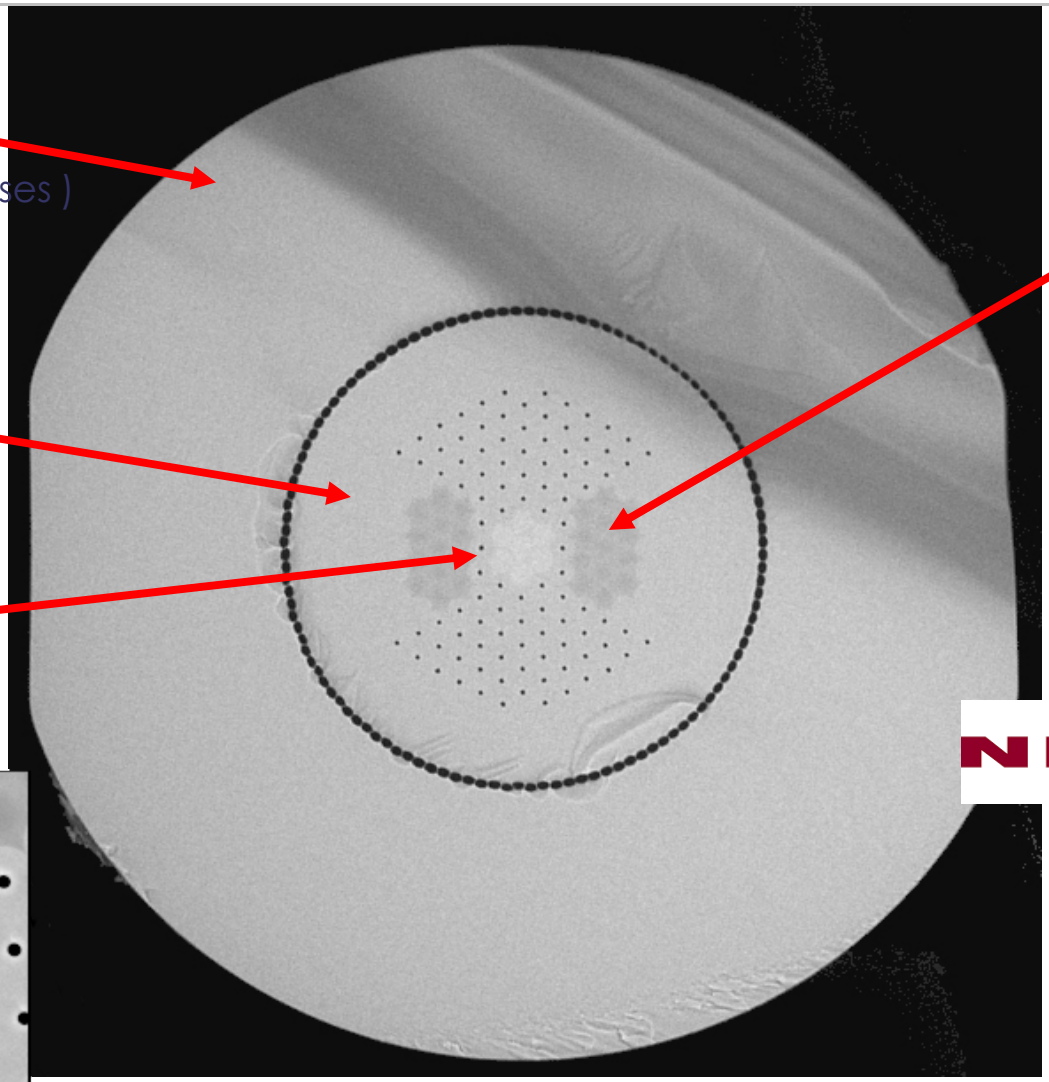
THALES

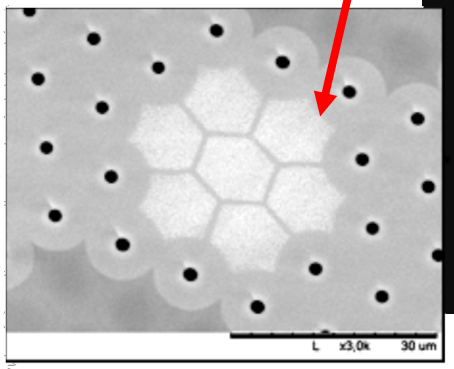
XCAN project – NKT 40/200 PCF fiber for main amplifiers

450 µm diameter
outer cladding
(reduces microbend losses)

200 µm diameter
pump cladding

40 µm diameter
Yb-doped core :
~30 µm mode

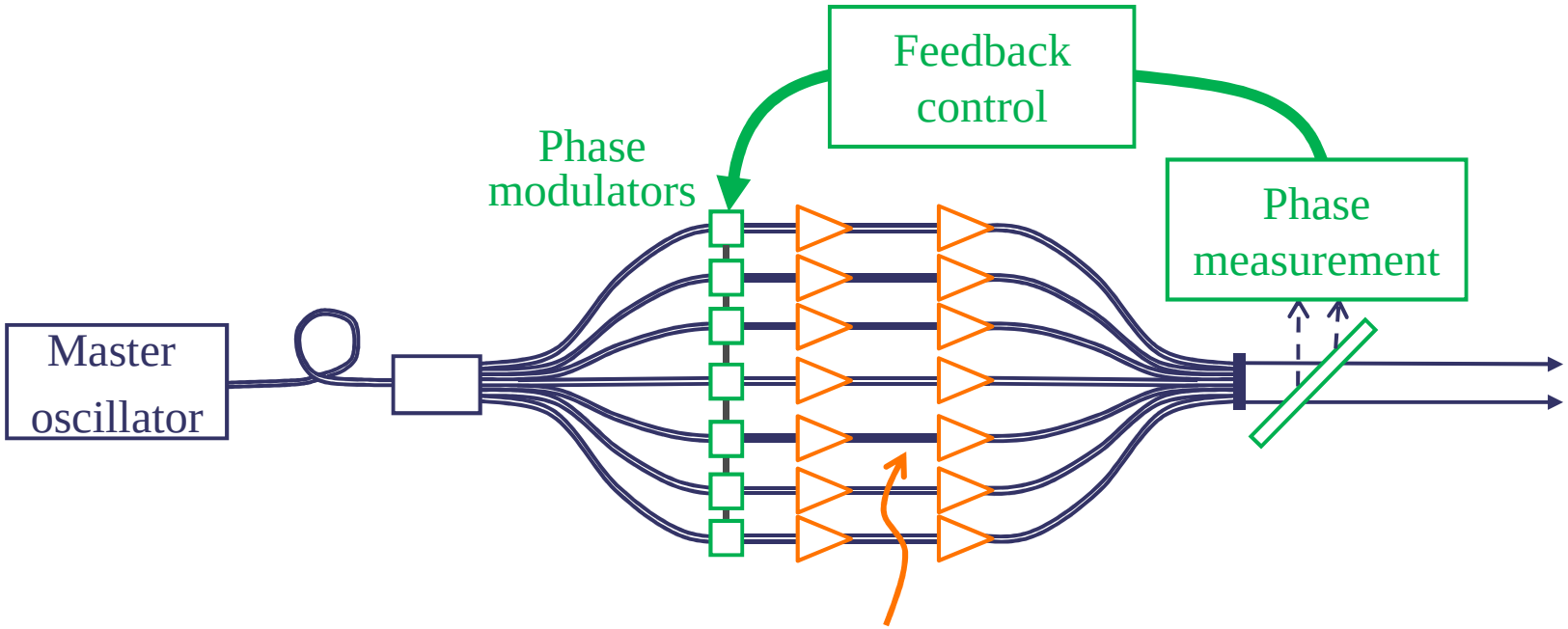




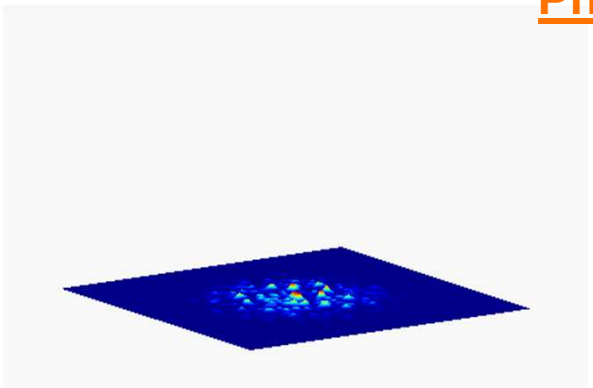
Stress applying parts that create a polarizing waveguide structure, i.e. only one spatial mode with one polarization can propagate.

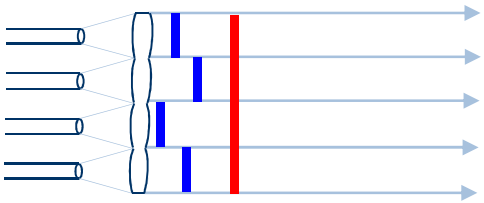
NKT Photonics
the power of light

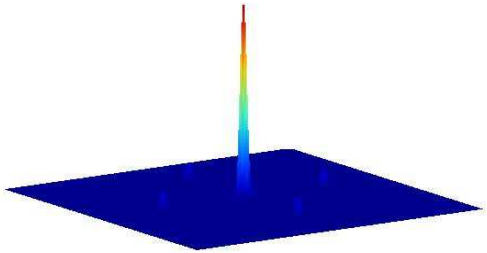
Coherent beam combining (CBC) of fiber amplifiers



Phase perturbations at the kHz regime







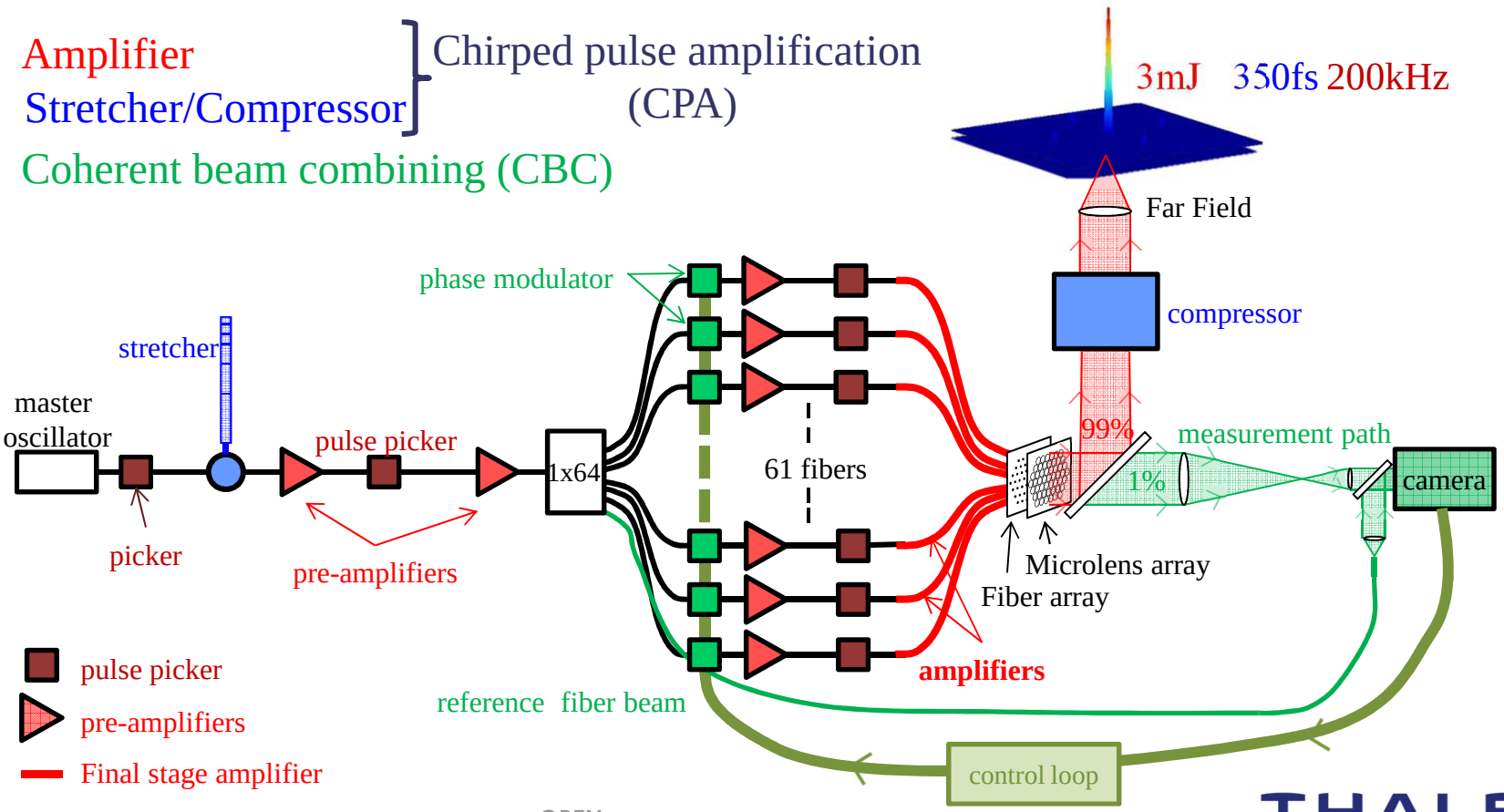
Without control: speckle

With control : in phase

Current architecture of the XCAN demo

Goal

- 61 fibers
- « Small » size : few racks and one optical table

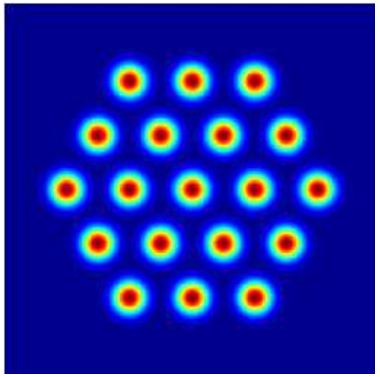


THALES

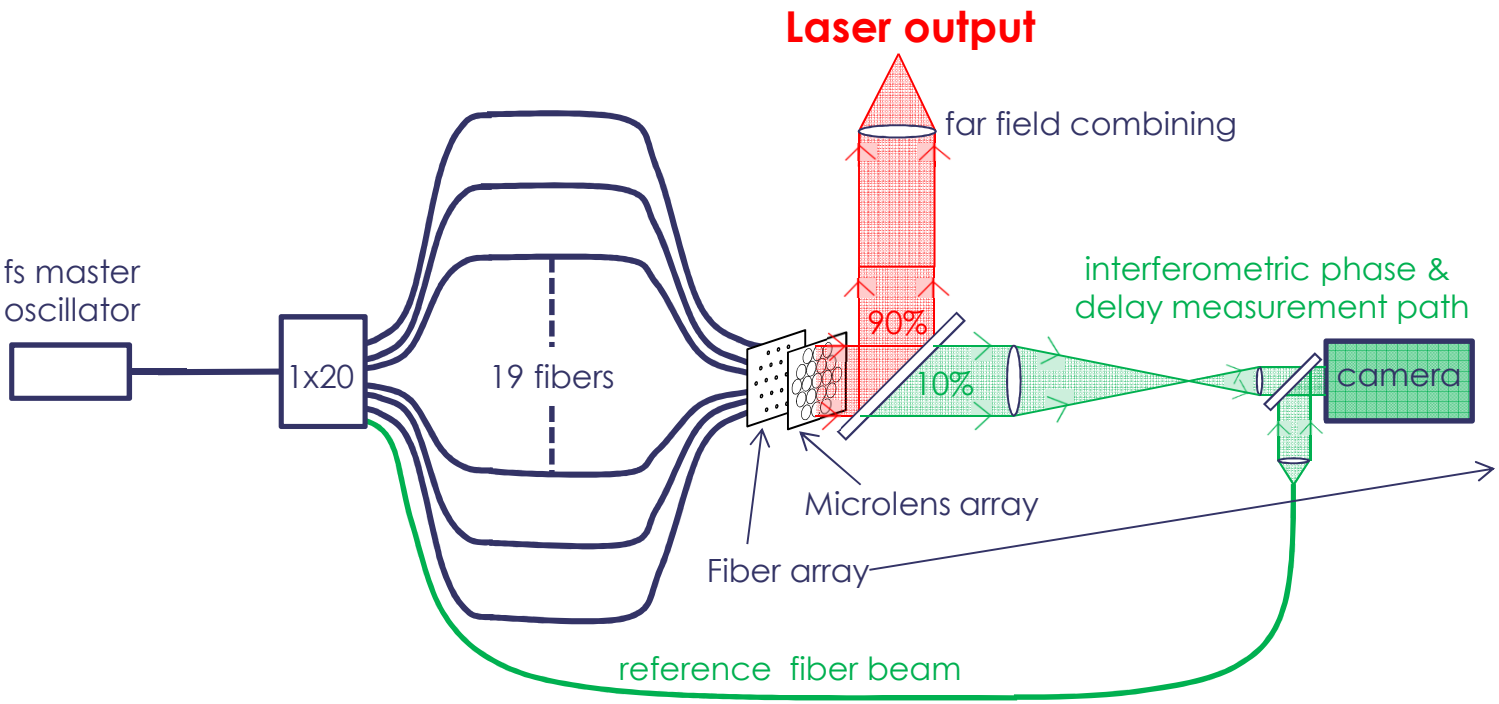
CBC of 19 fibers in the femtosecond regime

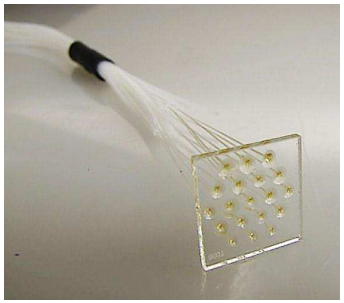
Experimental set-up

- 19 passive fibers arranged in a hexagonal array



J. Le Dortz, et al. "Highly scalable femtosecond coherent beam combining demonstrated with 19 fibers", Opt. Lett. 42, 1887-1890, 2017.





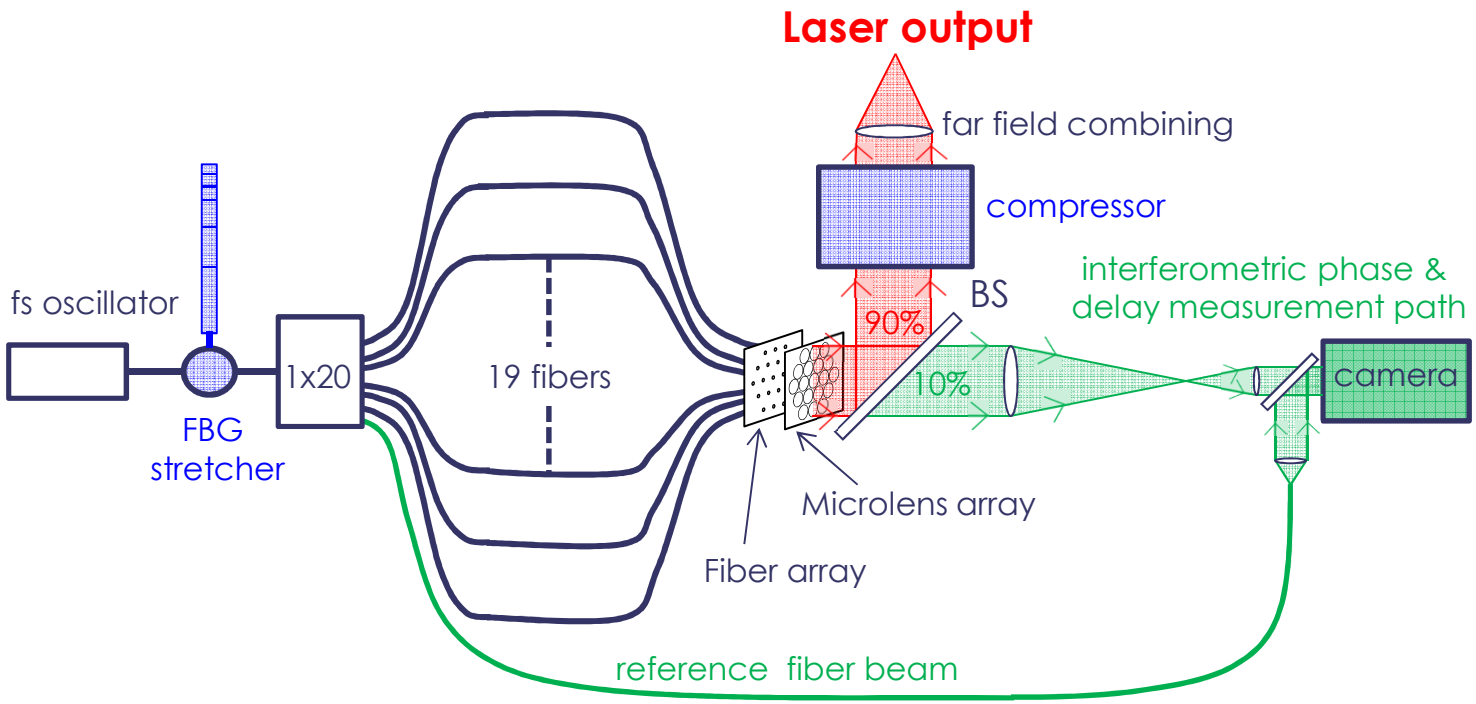
Hexagonal 19 fiber arr

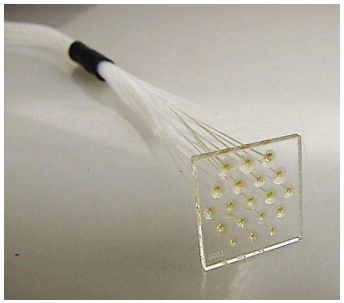
THALES

CBC of 19 fibers in the femtosecond regime

Experimental set-up

- 19 passive fibers arranged in a hexagonal array
- Chirp Pulse system: 300 fs pulses stretched to 200 ps





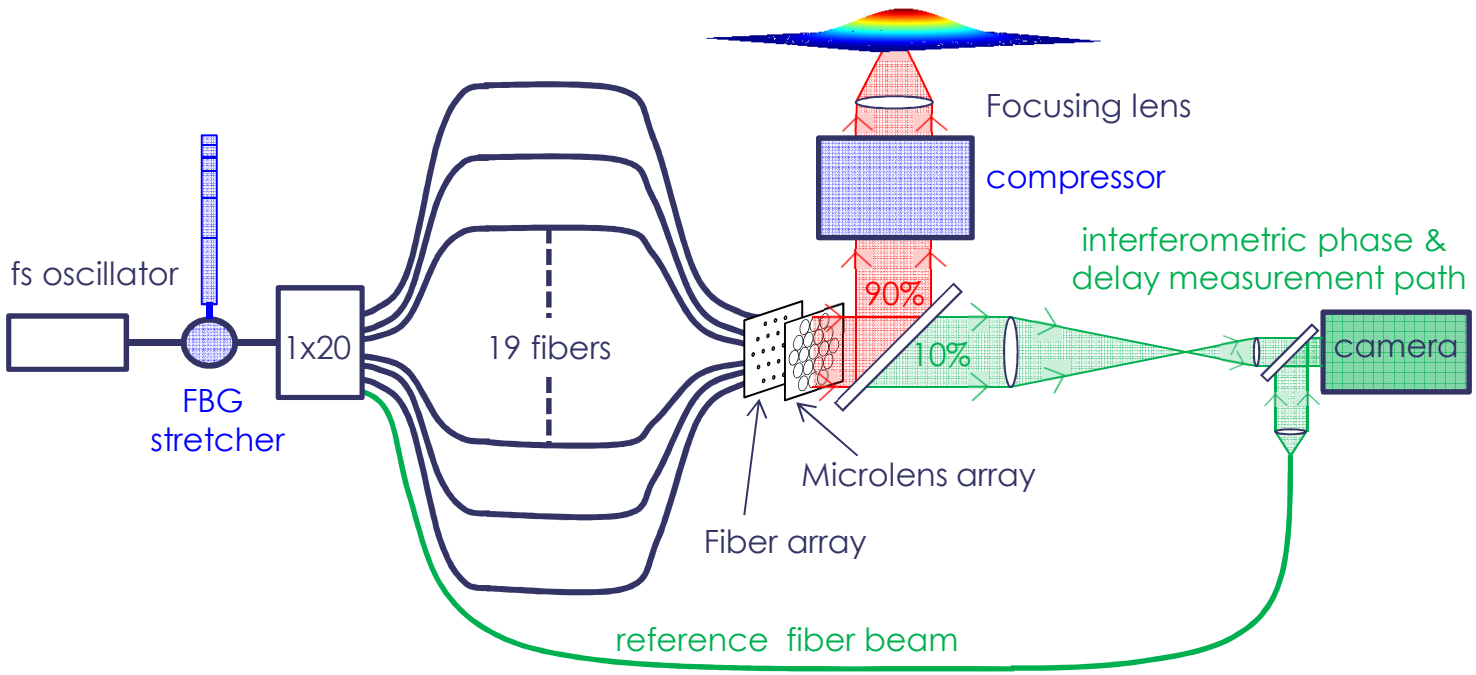
Hexagonal 19 fiber arr

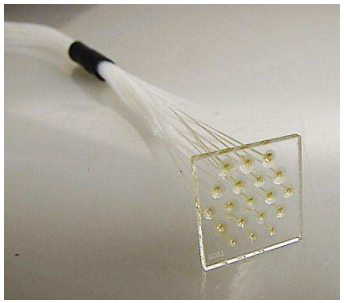
CBC of 19 fibers in the femtosecond regime

Experimental set-up

- 19 passive fibers arranged in a hexagonal array
- Chirp Pulse system: 300 fs pulses stretched to 200 ps

1 - Starting conditions :
No pulse overlap





Hexagonal 19 fibers arr

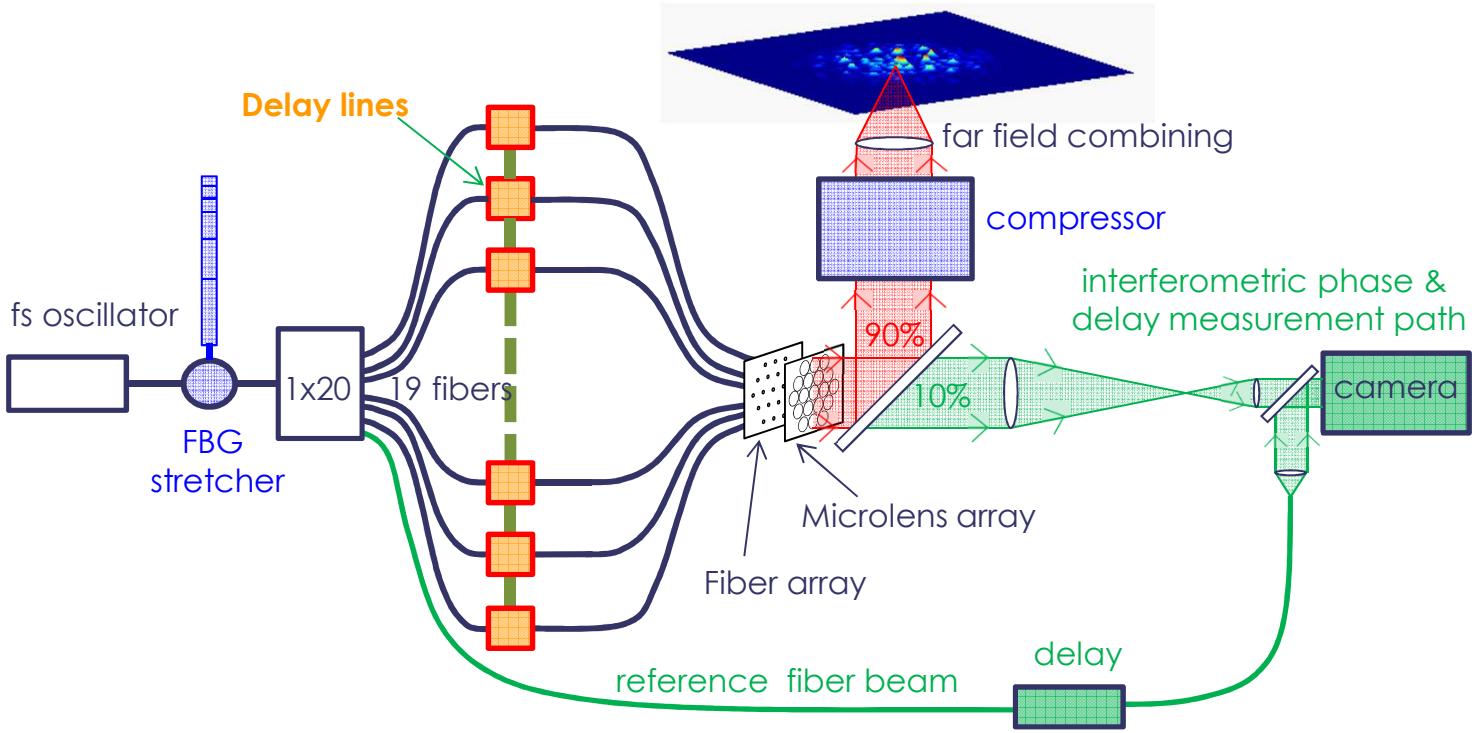
THALES

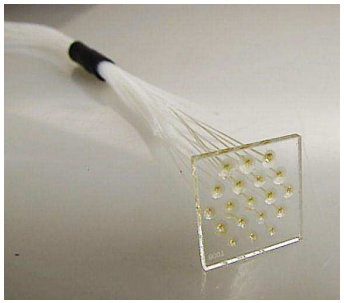
CBC of 19 fibers in the femtosecond regime

Experimental set-up

- 19 passive fibers arranged in a hexagonal array
- Chirp Pulse system: 300 fs pulses stretched to 200 ps
- Variable Optical Delay Lines

2 - Temporal overlap : No phase locking





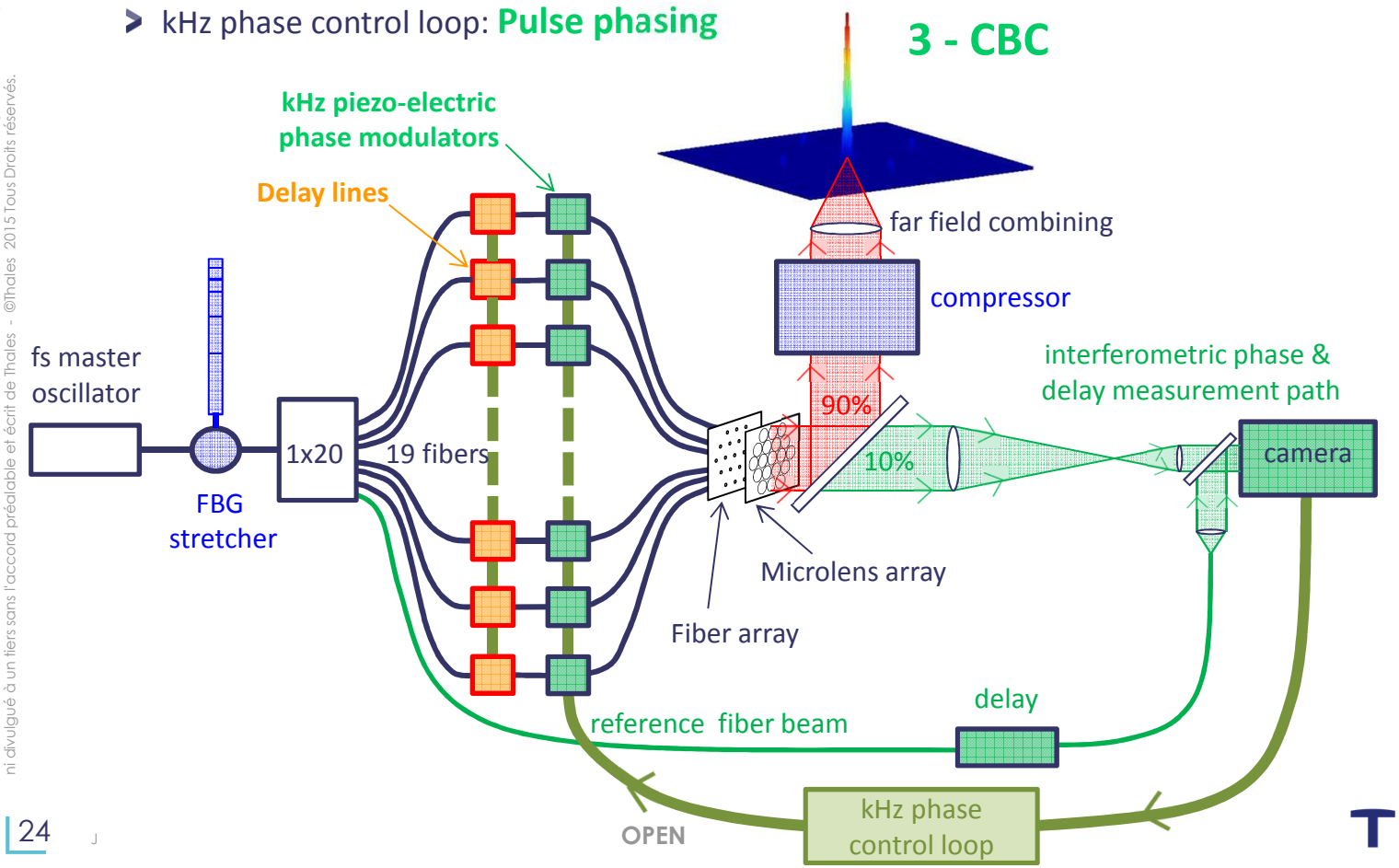
Hexagonal 19 fiber arr

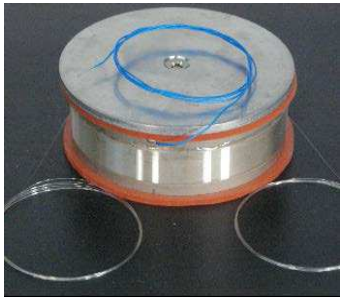
THALES

CBC of 19 fibers in the femtosecond regime

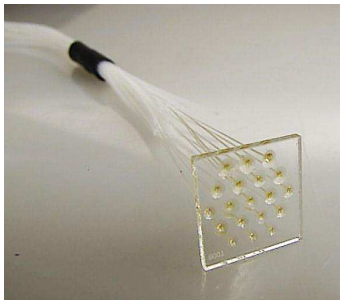
Experimental set-up

- 19 passive fibers arranged in a hexagonal array
- Chirp Pulse system: 300 fs pulses stretched to 200 ps
- Variable Optical Delay Lines: Temporal overlap
- kHz phase control loop: **Pulse phasing**





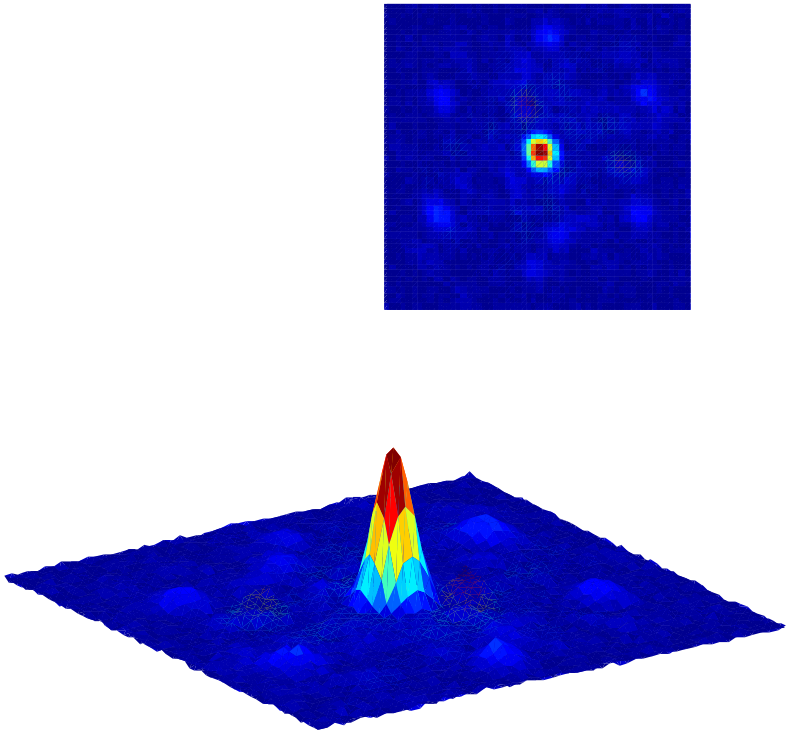
Piezo-electric phase modulators

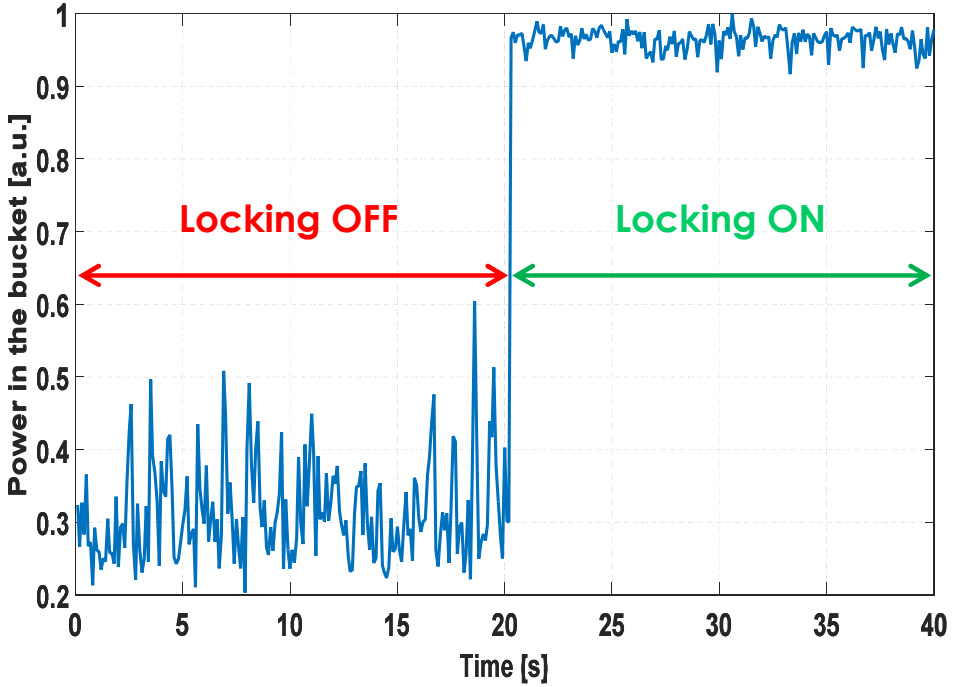


Hexagonal 19 fiber array

THALES

Experimental results

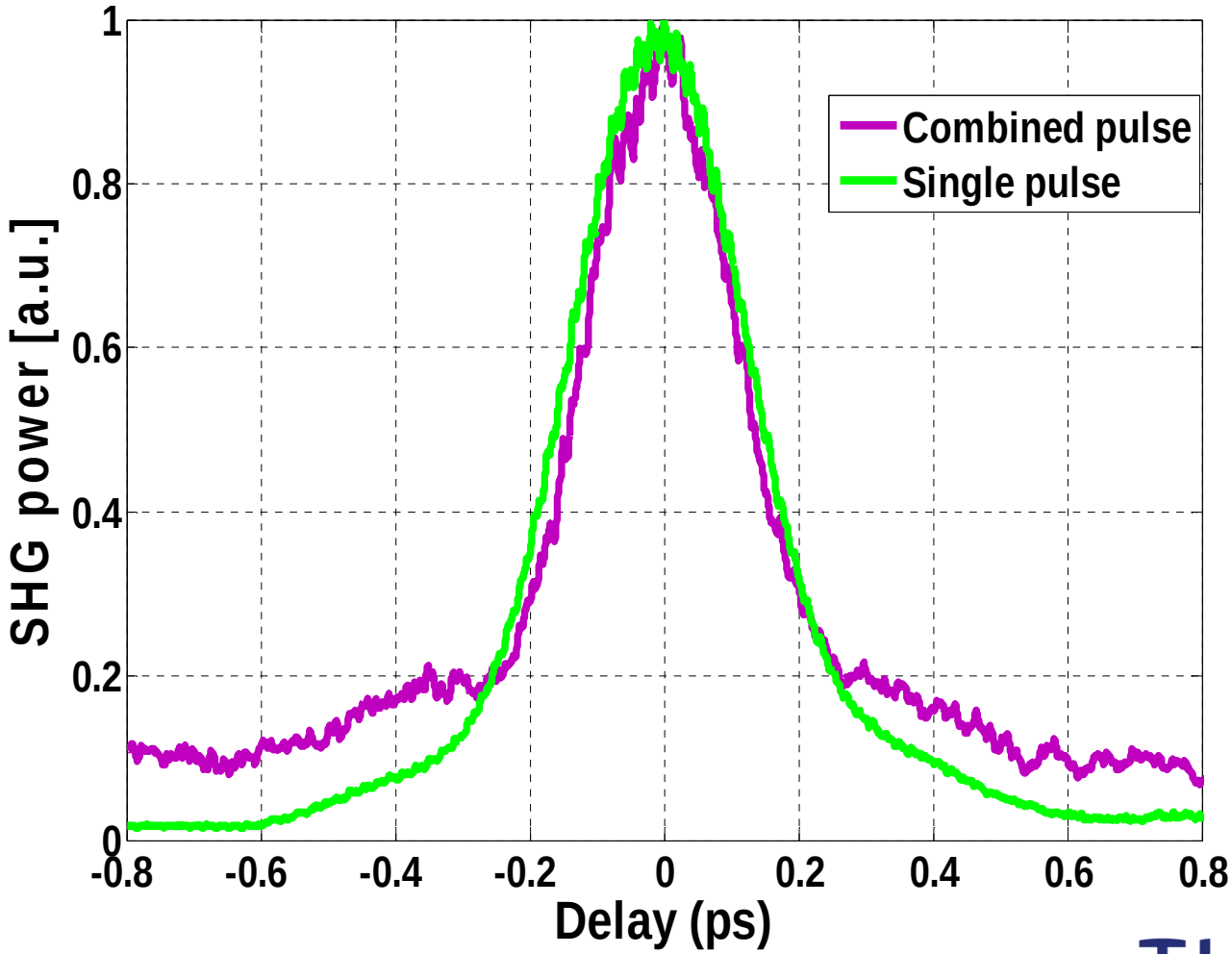




Locking OFF

Temporal profil of the combined pulse after compression

$$\text{FWHM}_{Combined\ Pulse} \cong \text{FWHM}_{Single\ Pulse} < 310\ fs$$



THALES

Conclusions

- There are challenges to scale up the average power of ultra high peak power laser to 1 kW and above
- They are particularly tough when considering 10 kW and above. Laser community is still far from reaching such values
- Laser technology selection will be highly influenced by the requirements on pulse duration and temporal contrast
- Fiber amplification and coherent combination techniques look extremely promising for ultra high average power production if staying on the side of moderate energies (10s mJ to 100s mJ) with ultra high repetition rates (> 100 kHz)
- There are remaining uncertainties for this technology regarding contrast and post-compression

THALES

Thank you for your attention

CHRISTOPHE SIMON-BOISSON
christophe.simonboisson@fr.thalesgroup.com

www.thalesgroup.com