(Ultra) short pulse technologies

Extreme Light Infrastructures Summer School 2023
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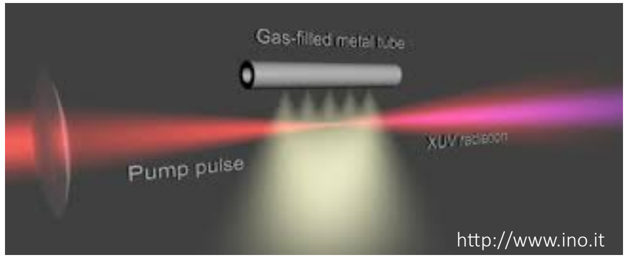
Summary

- High intensity lasers (why short pulses)
- Relevant laser parameters (energy, spectrum, duration, intensity)
- Frequency combs
- Amplification
  - Stimulated emission
  - Parametric processes
  - Chirped pulse amplification
- Post-compression
- Architectures with examples
  - SS CPA
  - OPCPA
  - FCPA and Post-compression

Introduction

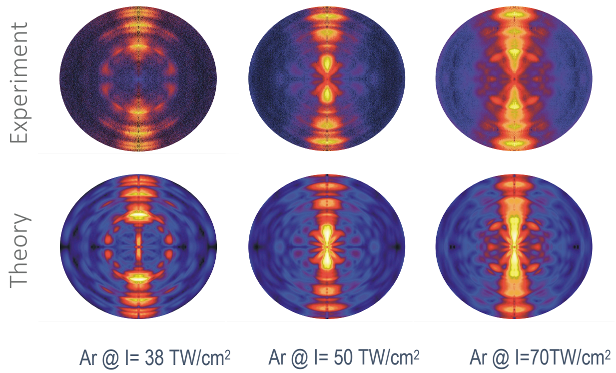
Introduction

High order harmonic generation

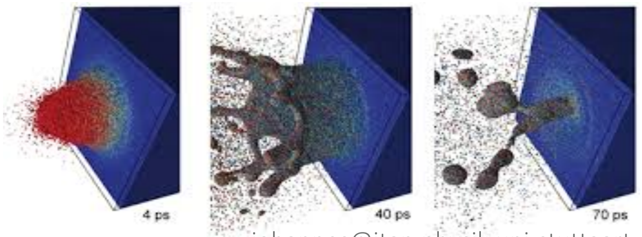


Strong field ionization

Wiehle et al., J. Modern Optics. 50, 451 (2003)



Laser ablation



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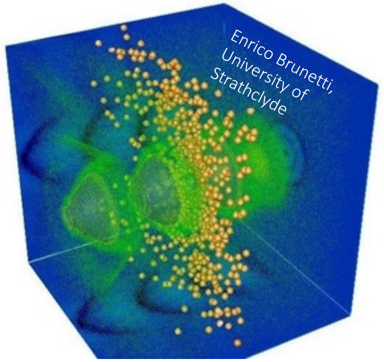
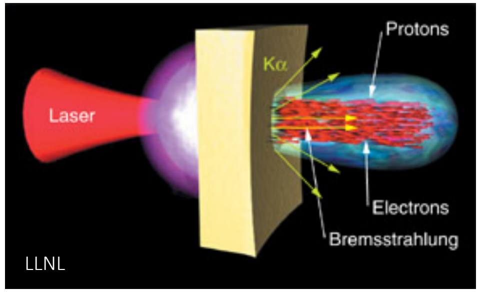
Laser wakefield acceleration



Proton acceleration



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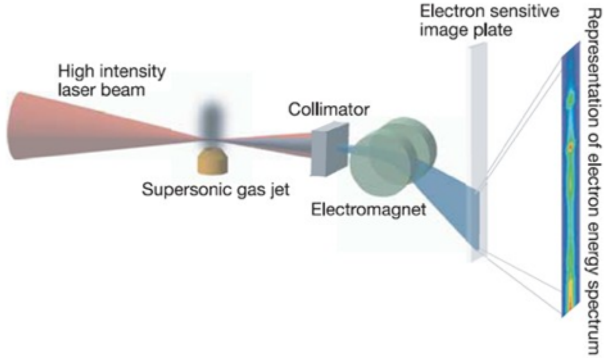
Introduction

Focusing short pulses to get high **intensity**



Intensity (in most cases):

$$I = \frac{E}{S\,\Delta t}$$

J

W/cm^2

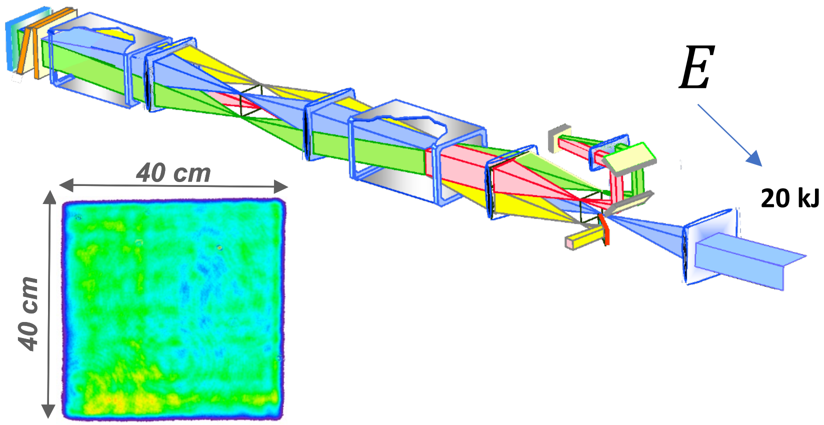
cm^2

fs

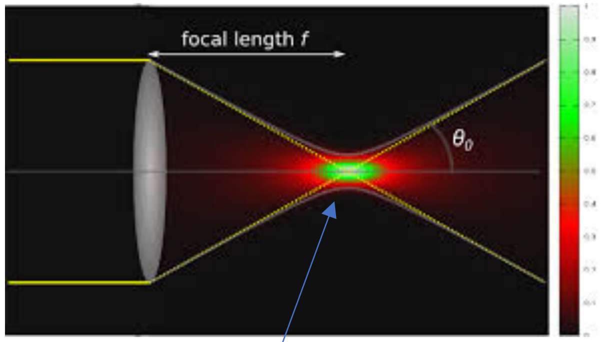
Or (in general):

$$I = I(x,y,z,t)$$

Energy



Spatial



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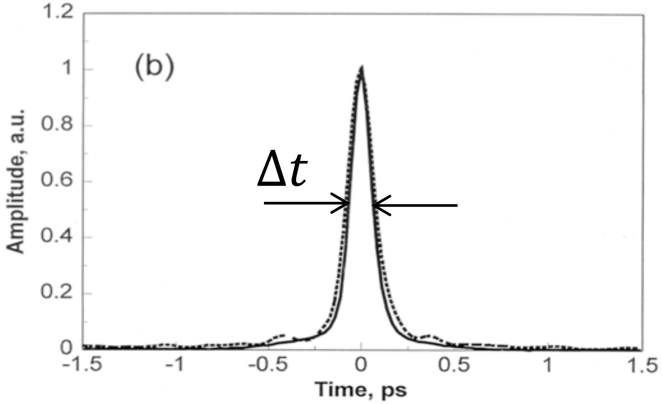
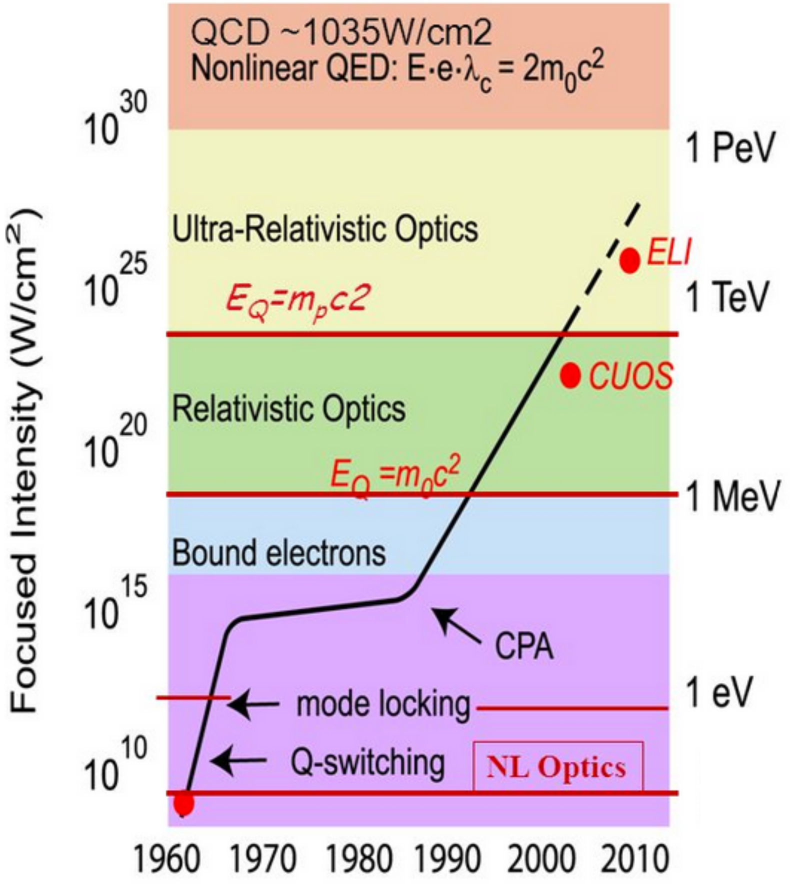
Temporal



Introduction

10^{-1} W/cm^2 : Sun intensity on ground

10^{12} W/cm^2 : Ionization
10^{16} W/cm^2 : Ionization saturation
10^{18} W/cm^2 : Relativistic electrons
10^{25} W/cm^2 : U^{92+}
10^{29} W/cm^2 : Pair creation



Courtesy G. Mourou

Laser parameters

Physical quantities: Energy

- Energy [J]: $\mathcal{W}$
  - 1 J increases the temperature of 1 litre of air by 1° C
  - 4.2 kJ increases the temperature of 1 litre of water by 1° C
  - 1 MJ is delivered by a 1000 W heater in 15 mn
    is used to boil 3 litres of water
    is delivered by MJ/NIF in 4 ns

  - 1 Joule is equivalent to:
    - 1 W in 1 s
    - 1 kW in 1 ms
    - 1 MW in 1 µs
    - 1 GW in 1 ns

$$\mathcal{W} = Pt$$

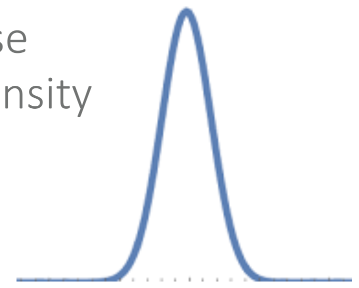
Powers of 10:

Puissance	10^{24}	10^{21}	10^{18}	10^{15}	10^{12}	10^{9}	10^{6}	10^{3}	1	10^{-3}	10^{-6}	10^{-9}	10^{-12}	10^{-15}	10^{-18}	10^{-21}	10^{-24}
Nom	yotta	zetta	exa	péta	téra	giga	méga	kilo		milli	micro	nano	pico	femto	atto	zepto	yocto
Symbole	Y	Z	E	P	T	G	M	k		m	µ	n	p	f	a	z	y

Physical quantities: spectral and temporal

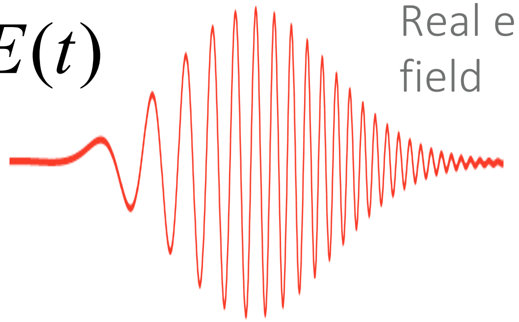
Temporal

Pulse intensity



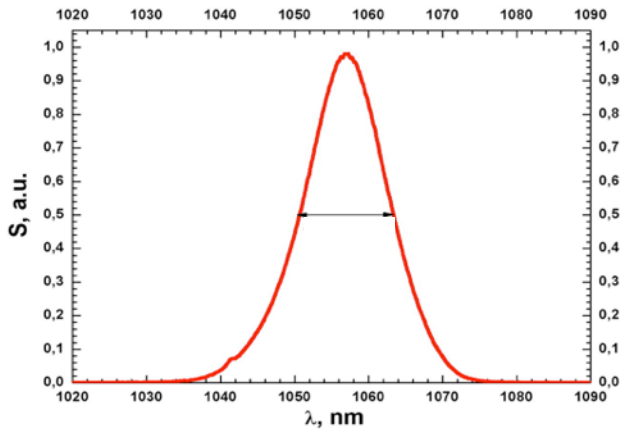
$E(t)$

Real electric field



$$I(t) = |\mathcal{E}(t)|^2 \qquad E(t) = \mathrm{Re}(\mathcal{E}(t))$$

Spectral

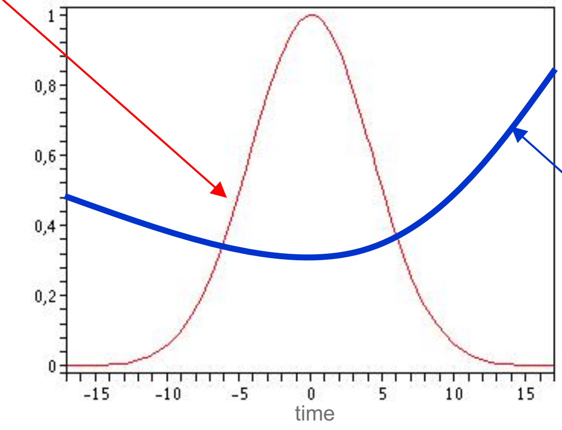


Spectral intensity

$$I(\omega) = |\mathcal{E}(\omega)|^2$$

$$\mathcal{E}(t) = \left|\mathcal{E}(t)\right| e^{i\phi(t)}$$

$|\mathcal{E}(t)|$



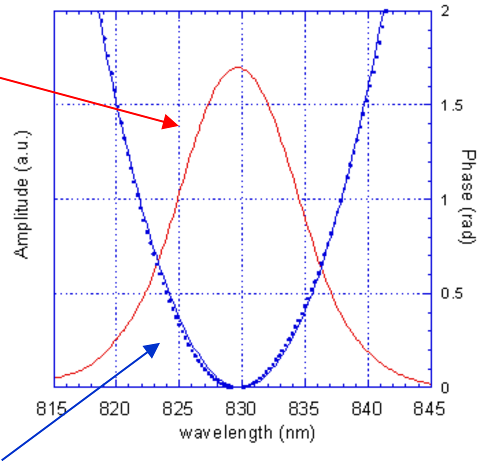
$\phi(t)$

$\mathcal{F}^{-1}$

$\mathcal{F}$

$$\mathcal{E}(\omega) = \left|\mathcal{E}(\omega)\right| e^{i\varphi(\omega)}$$

$|\mathcal{E}(\omega)|$



$\varphi(\omega)$

Physical quantities: Power

- Average power in continuous wave [W]:

$$P_{av} = \frac{\mathcal{W}}{t} \qquad \mathcal{W} = P_{av} t$$

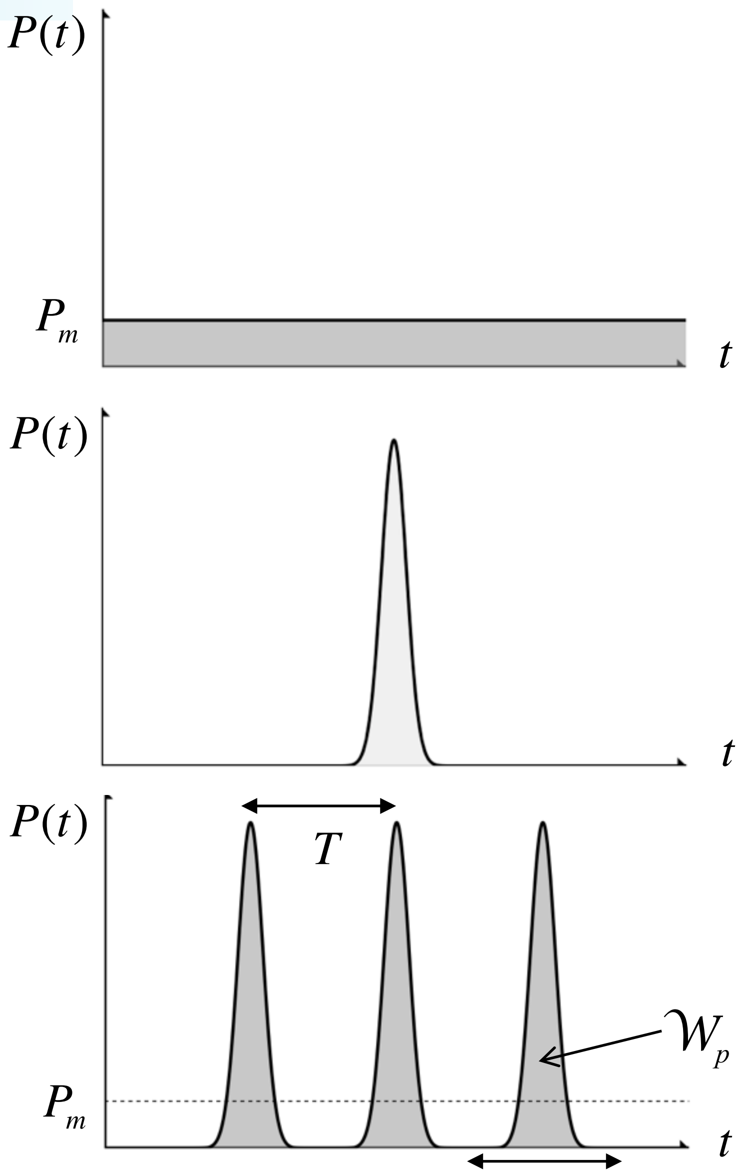
- Instantaneous power [W]:

$$P(t) = \frac{d\mathcal{W}}{dt} \qquad \mathcal{W} = \int P(t)dt$$

- Average power in pulsed regime [W]:

$$P_m = \frac{1}{T}\int_0^T P(t)\,dt \qquad \nu = \frac{1}{T}$$

$$\mathcal{W}_p = \int_0^T P(t)dt \qquad \boxed{P_{av} = \mathcal{W}_p \nu}$$



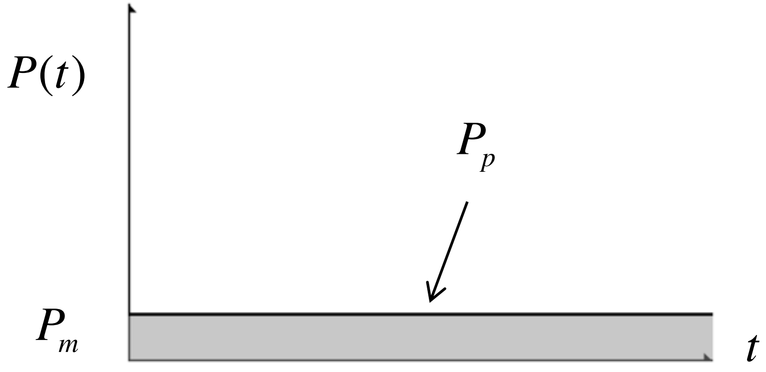
Physical quantities: Power

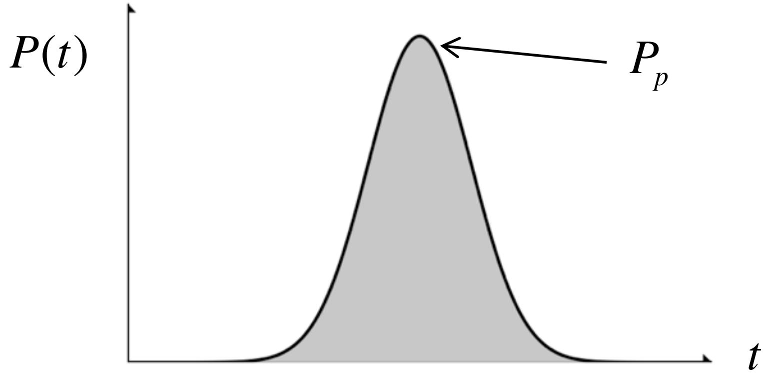
- Peak power[W]:
  - Continus wave (CW)

$$P(t) = P_p = P_m$$

  - Pulsed (Gaussian)

$$P(t) = P_p \exp\left(-\left(\frac{t}{\tau}\right)^2\right)$$

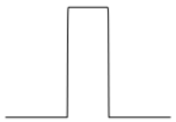
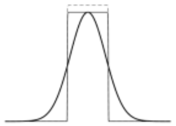
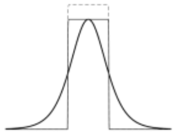
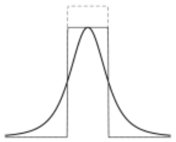


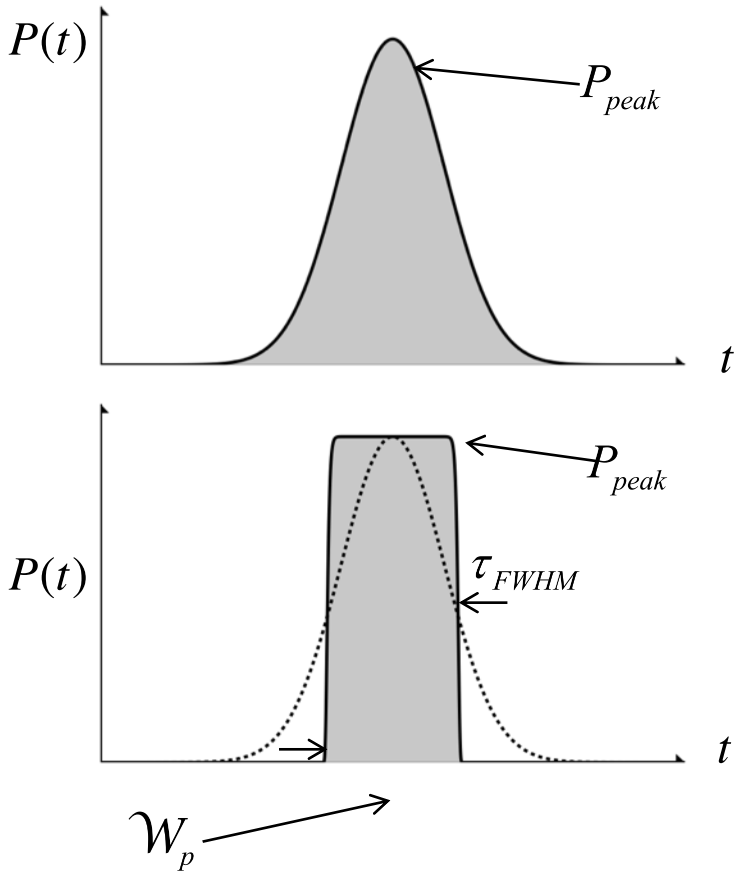


Physical quantities: Power

- <u>Approximated peak power[W]:</u>

$$P_{peak} = C\frac{\mathcal{W}_p}{\tau_{FWHM}}$$

Square	Gaussian	Sech	Lorentzian
			
$C = 1$	C =0.939	C =0.881	C = 0.837



- <u>Relation to the electric field:</u>

$$P(t) = \varepsilon_0 cn \int_A dS \frac{1}{T}\int_{t-T/2}^{t+T/2} E^2(t')dt'$$

where A is the beam cross-section

Physical quantities: Power

Examples:

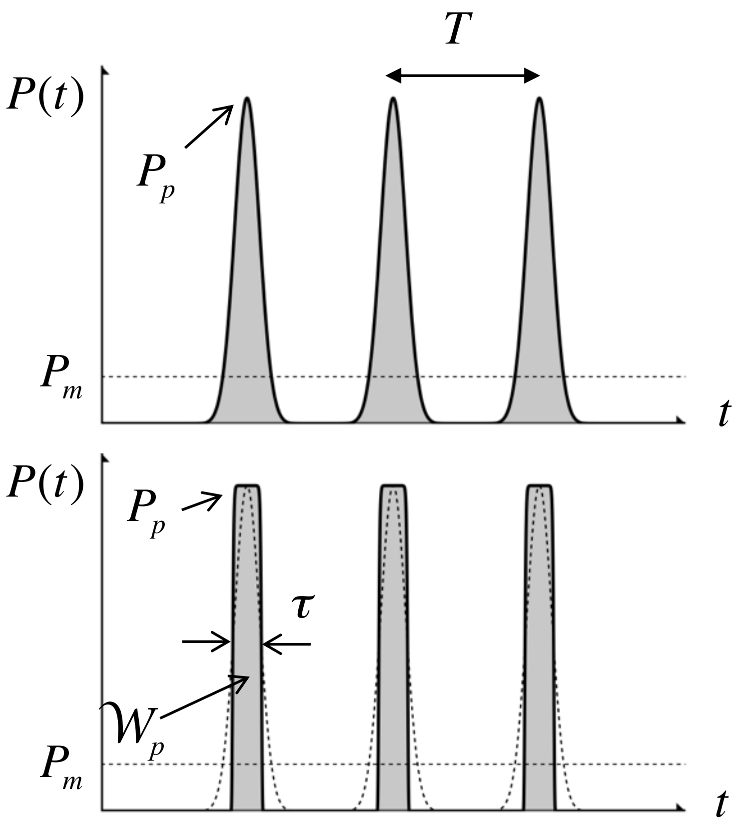
•Pulse energy of a 500 W laser at 100 kHz:

$$P_m = 500\,\mathrm{W}, \quad \nu = 100\,\mathrm{kHz}, \quad \mathrm{E}_i = \frac{500}{10^5} = 5\,\mathrm{mJ}$$

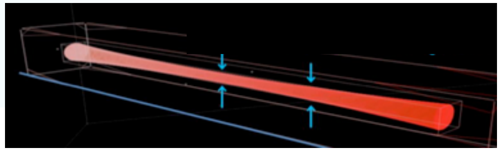
•Peak power delivered by a 15 fs, 30 J pulse:

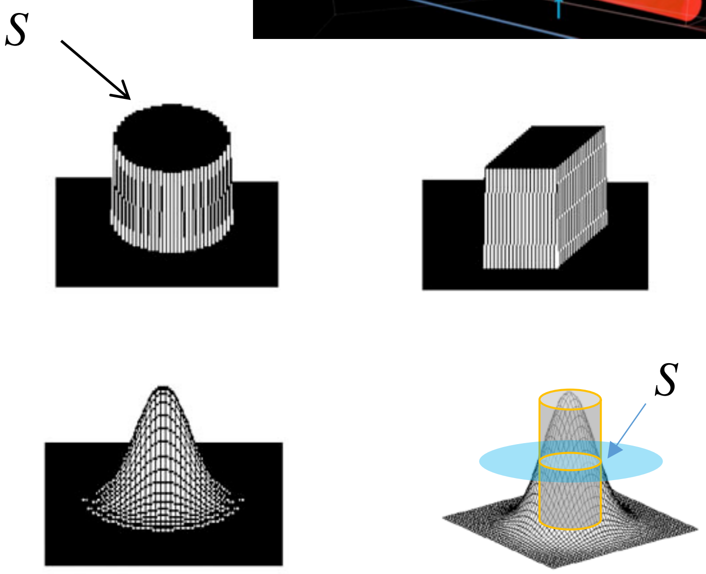
$$E_i = 30\ \mathrm{J}, \quad \tau = 15\,\mathrm{fs},$$

$$P_c = \frac{30}{15\cdot 10^{-15}} = 2\ \mathrm{PW}$$



Physical quantities





- Fluence [J/cm²]:
  - Top hat beam

$$F = \frac{E_i}{S} \qquad E_i = F\cdot S$$

  - Gaussian beam

$$F = \frac{dE}{dS} \qquad E = \int F(s)\,ds$$

- Intensity [W/cm²]:

$$I = \frac{P_c}{S} = \frac{E_i}{S\cdot\tau}$$

Examples:

•Fluence from a 20 mJ pulse focused on 500 µm diameter:

$$E_i = 20\,\mathrm{mJ}, \quad S = \pi(250\cdot10^{-6})^2 = 196\cdot10^{-5}\,\mathrm{cm}^2, \quad F = 10.2\,\mathrm{J/cm}^2$$

•Intensity from a 500 mJ, 30 fs pulses focused on 20 µm diameter :

$$E_i = 500\,\mathrm{mJ}, \quad S = \pi(10\cdot10^{-6})^2 = 3.1\cdot10^{-6}\,\mathrm{cm}^2, \quad \tau = 30\,\mathrm{fs}$$

$$Pc = 16.6\,\mathrm{TW}, \quad I = 5.3\cdot10^{18}\,W/\mathrm{cm}^2$$

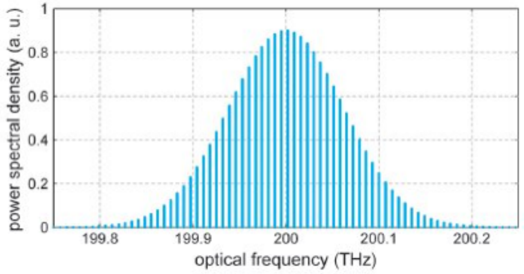
Modelocked oscillators

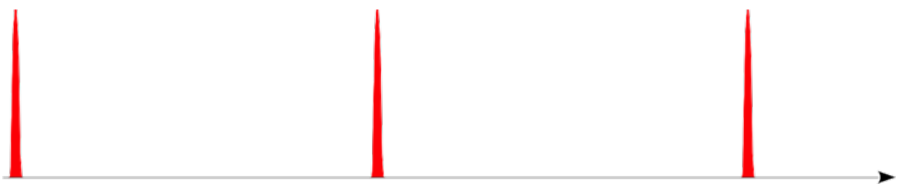
Frequency combs

Time

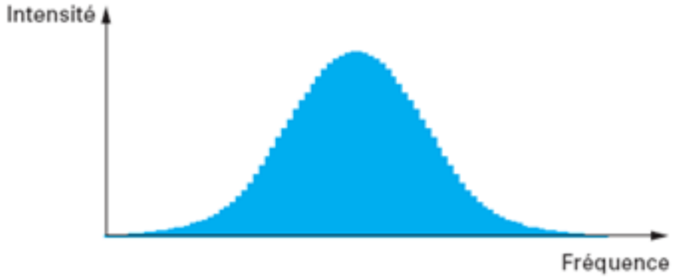
Frequency

ν =10 GHz





ν =100 MHz

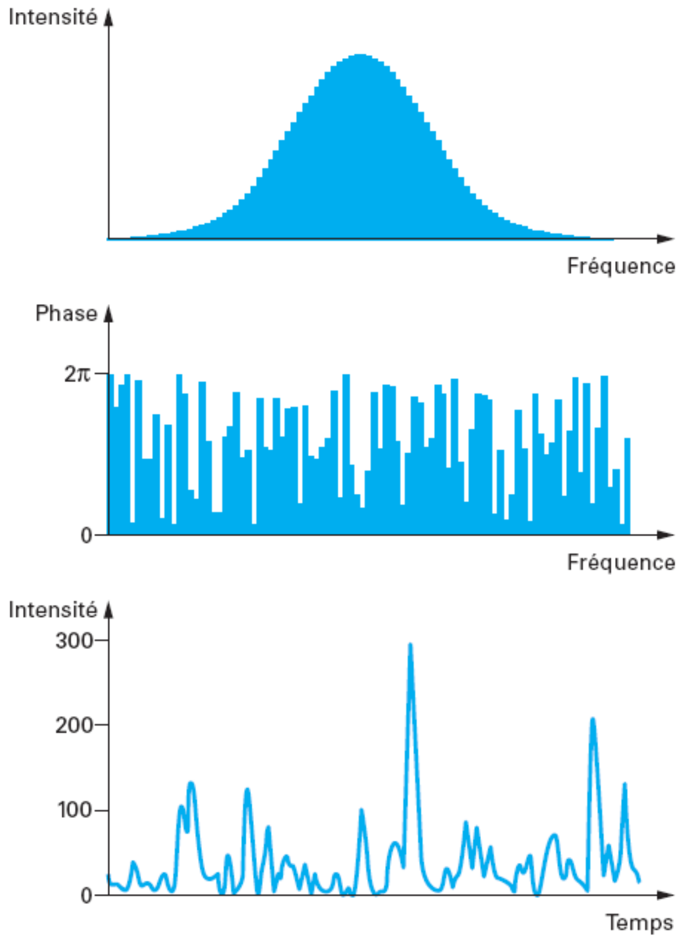


Pulse train

Frequency comb

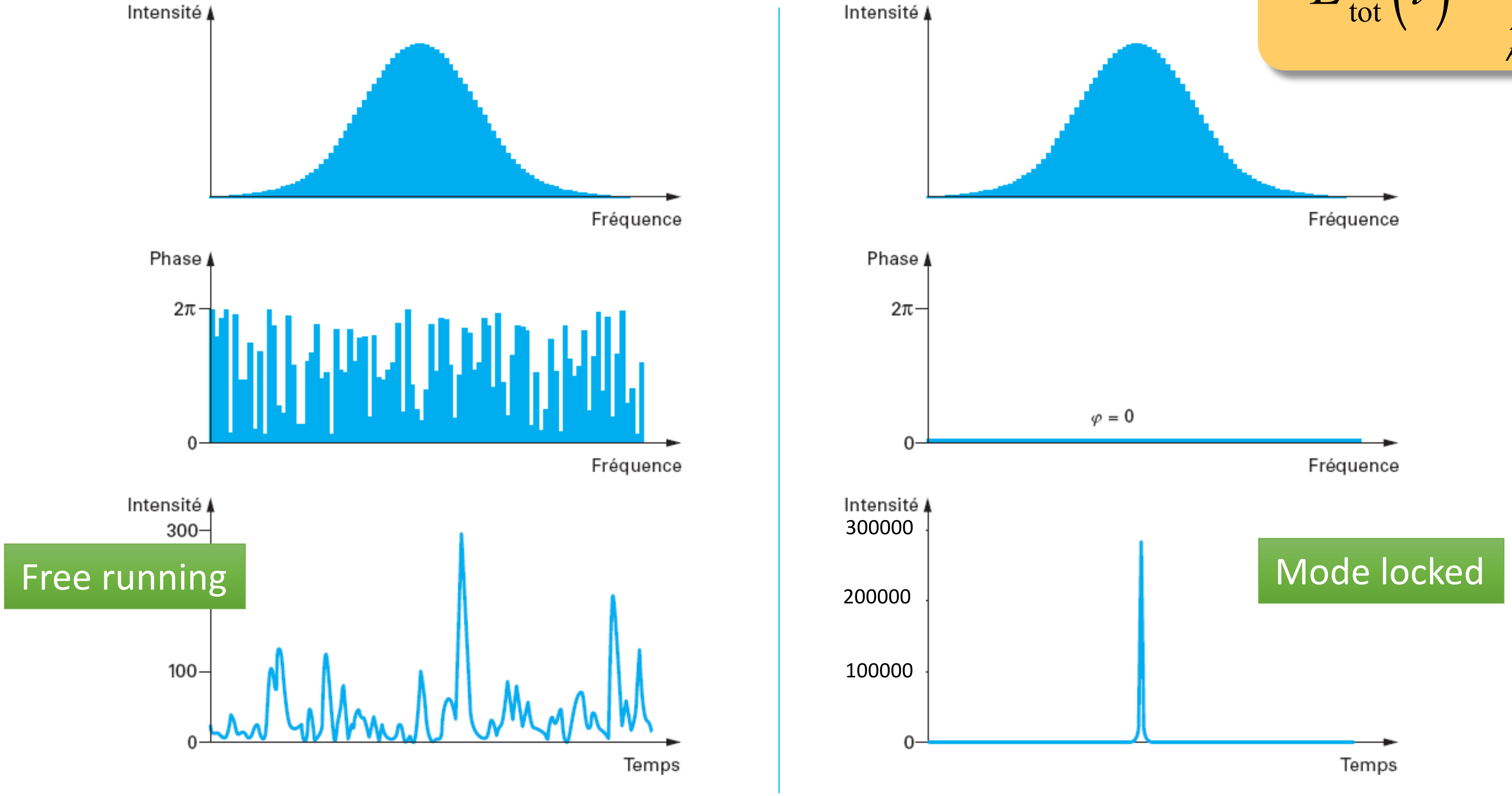
Modelocking

$$E_{\text{tot}}(t) = \sum_{n=p}^{n=p'} E_n e^{i\varphi_n} e^{-i\omega_n t}$$

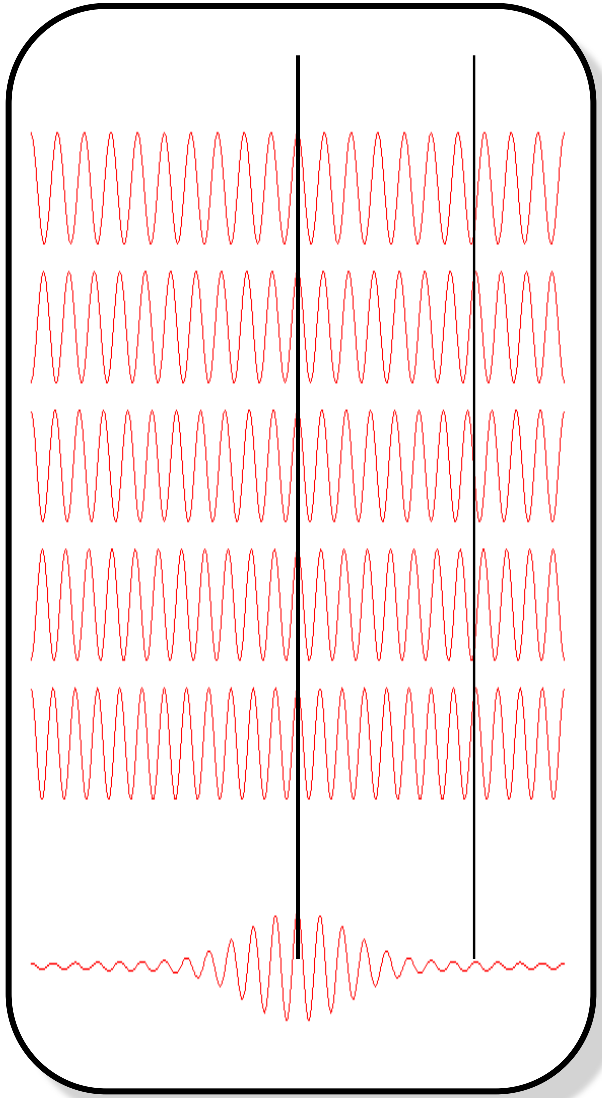


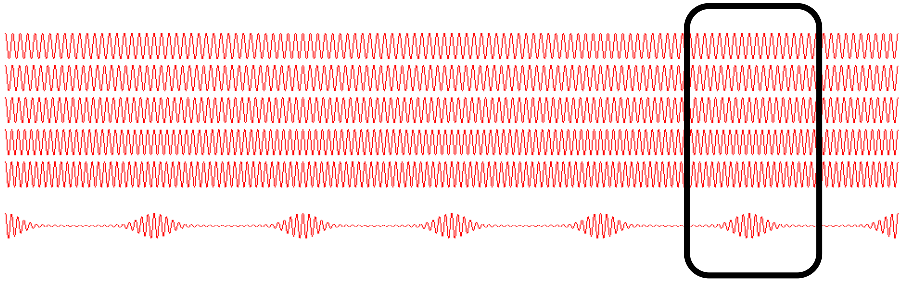
Modelocking

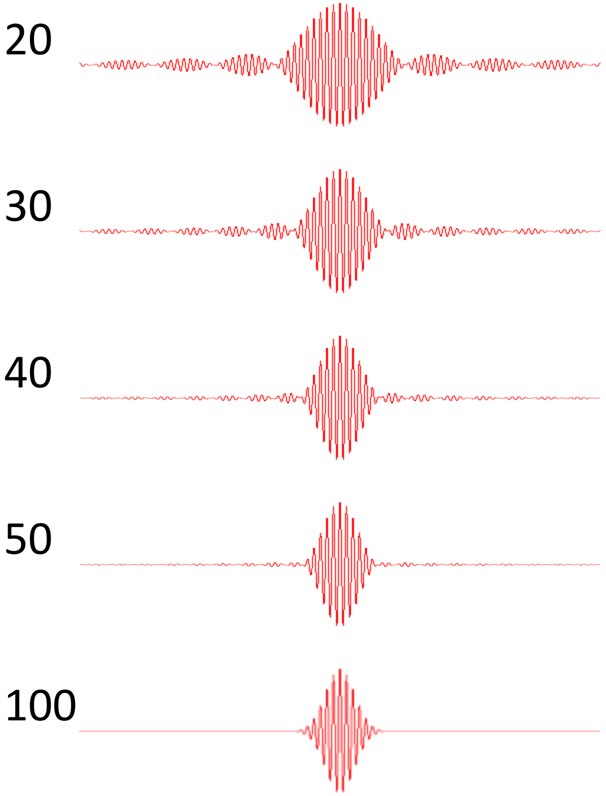
$$E_{tot}(t) = \sum_{n=p}^{n=p'} E_n e^{i\varphi_n} e^{-i\omega_n t}$$



Modelocking

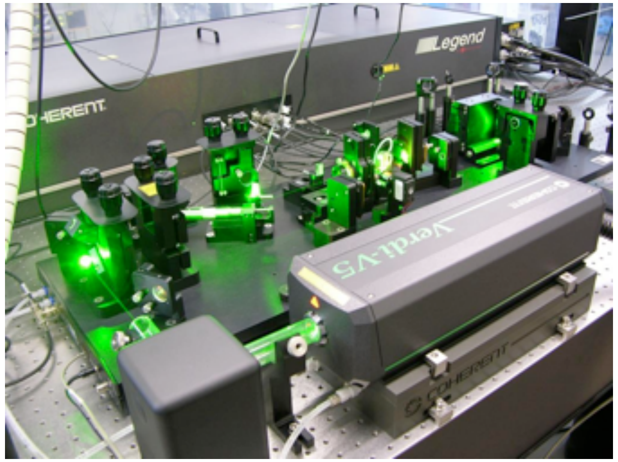


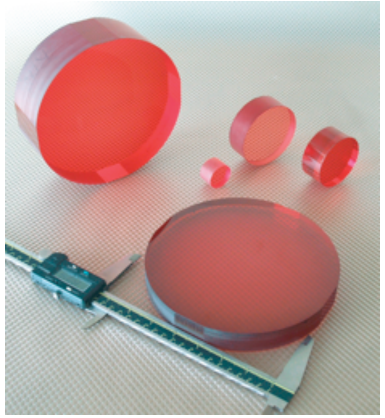


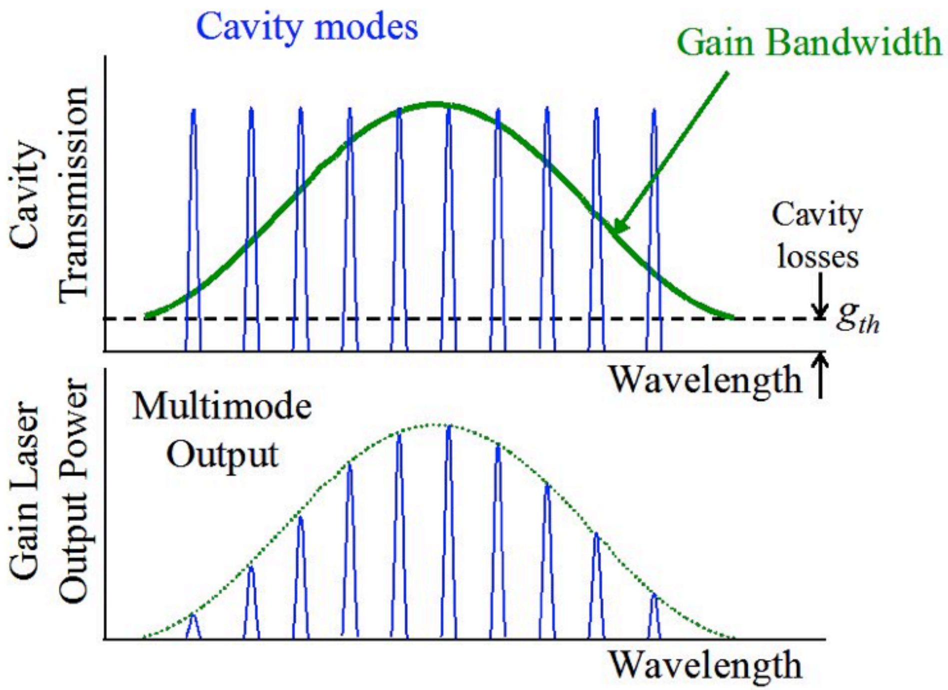


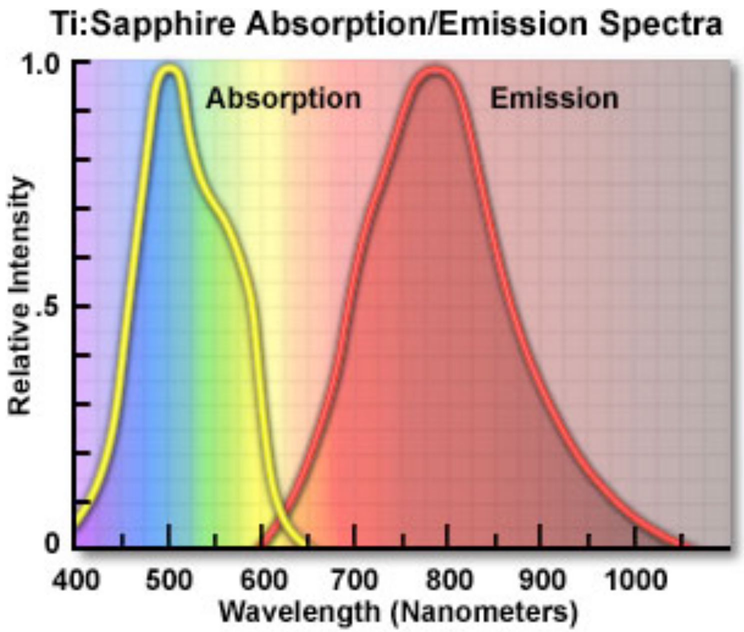
$$E_{\text{tot}}(t) = \sum_{n=p}^{n=p'} E_n e^{i\varphi_n} e^{-i\omega_n t} \approx \left(\int_{-\infty}^{+\infty} \underline{S}(\omega) e^{-i\omega t} \frac{d\omega}{2\pi} \right) \otimes \sum_m \delta\left(t - m t_{\text{rep}}\right)$$

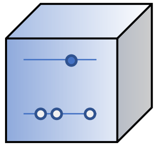
Femtosecond oscillator

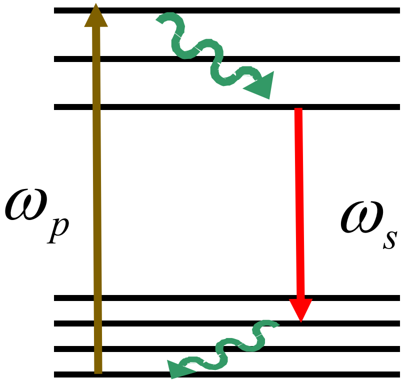






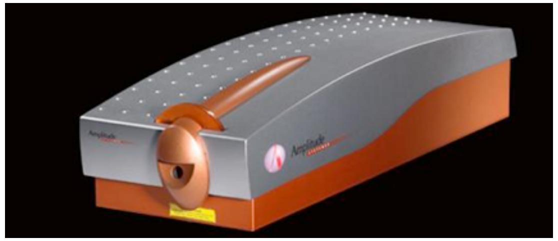




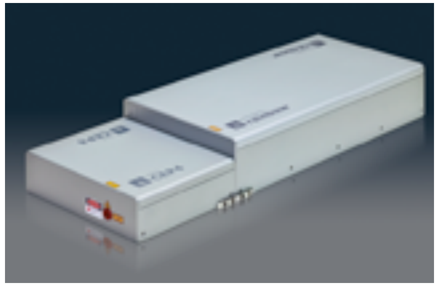


Femtosecond oscillators

T-Pulse: 200 fs @ 1030 nm, 2.5 W

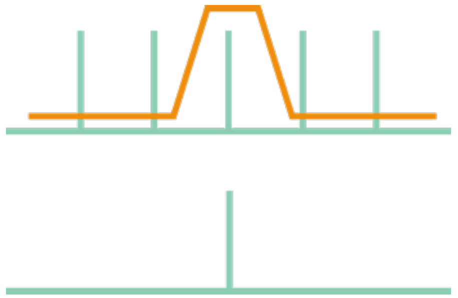


Rainbow 2: 6 fs @ 800 nm, 200 mW



C-fiber: 90 fs @ 1550 nm, 100 mW

Pulse picking



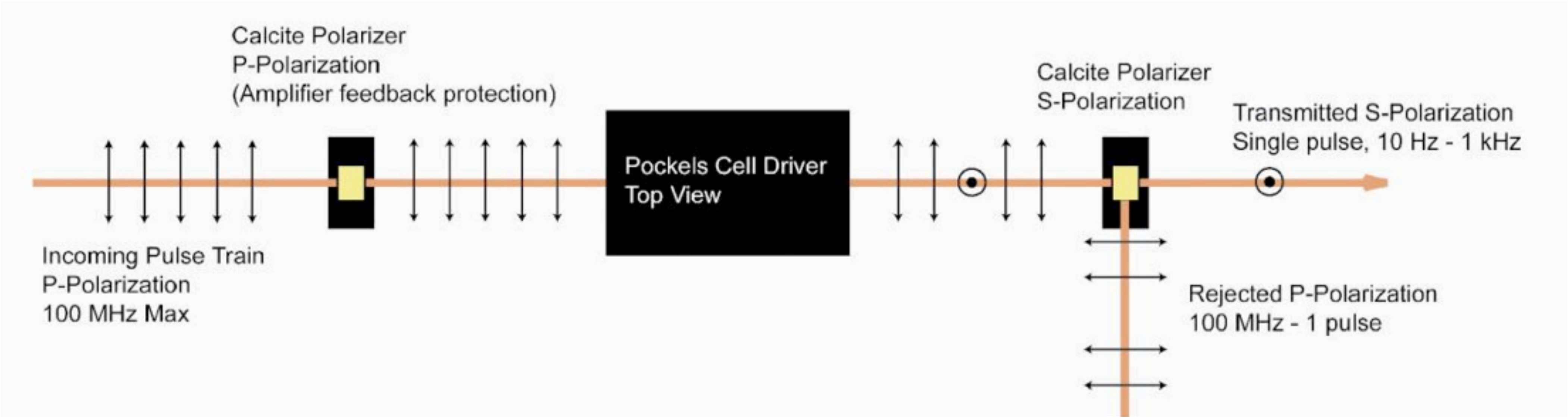
100 MHz

10 Hz

Pockels cell

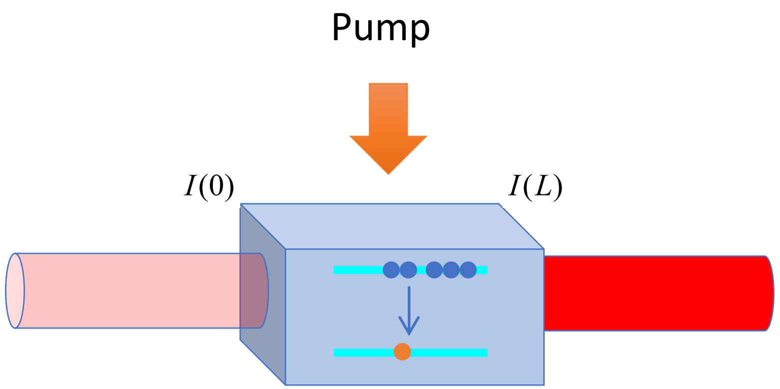
<u>Example:</u>

- Oscillator 100 MHz
- E = 1 J
- P = 100 MW @ 100 MHz !!!!!
- P = 10 W @ 10 Hz



Solid state amplifiers

Amplifier gain: a first approach

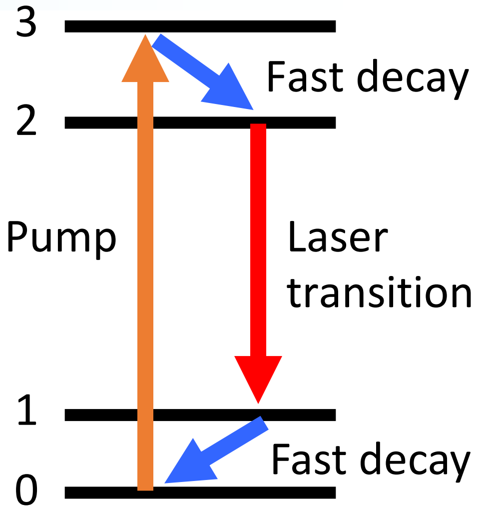


Population inversion

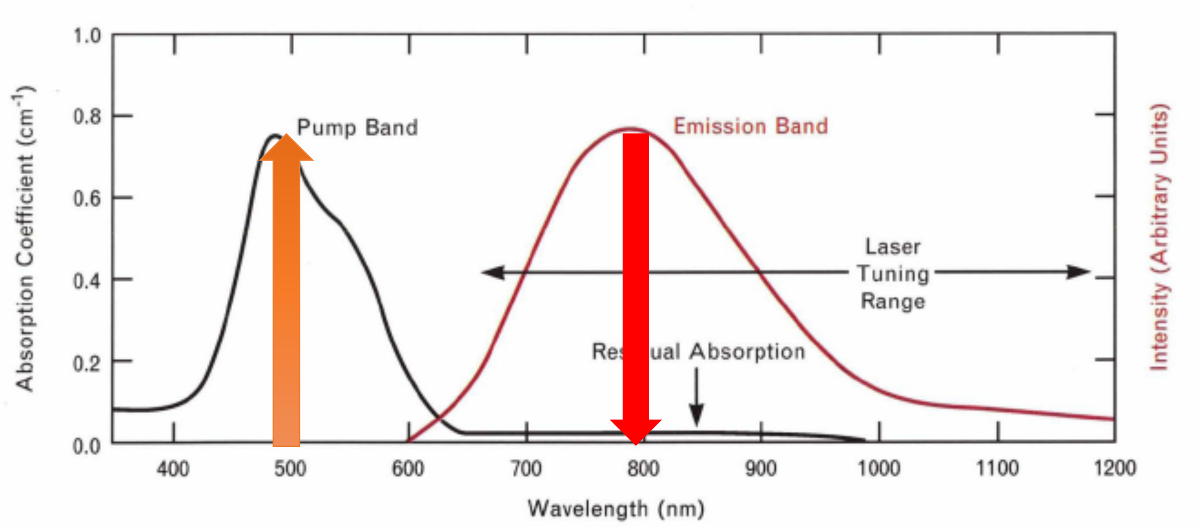
$$G = \frac{I(L)}{I(0)} = \exp\left(\sigma \Delta N L\right)$$

Emission cross section

Length

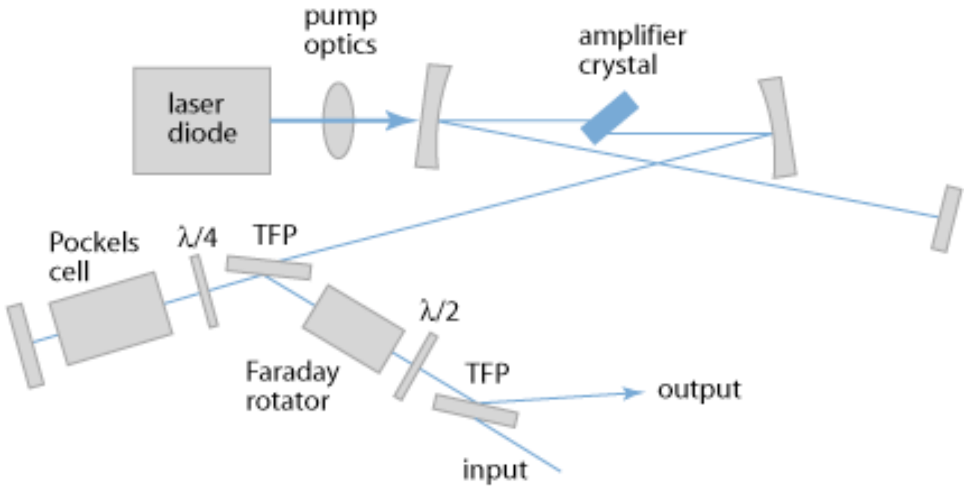


- Small signal gain grows exponentially
- Gain should saturate

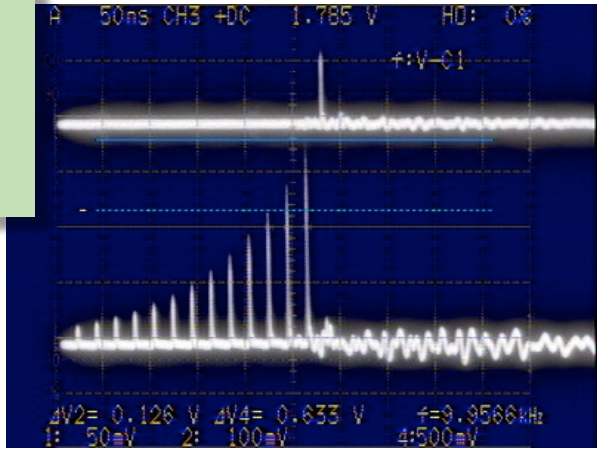


Amplifier architectures

- Regenerative amplifier

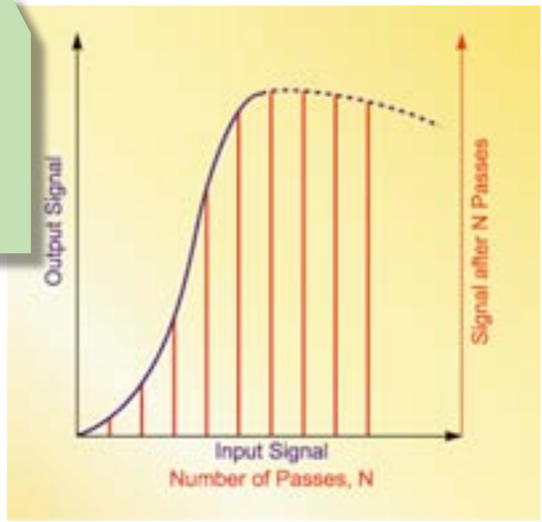


Example:
E_{in} = 2 nJ
E_{out} = 1 mJ
G = 500 000



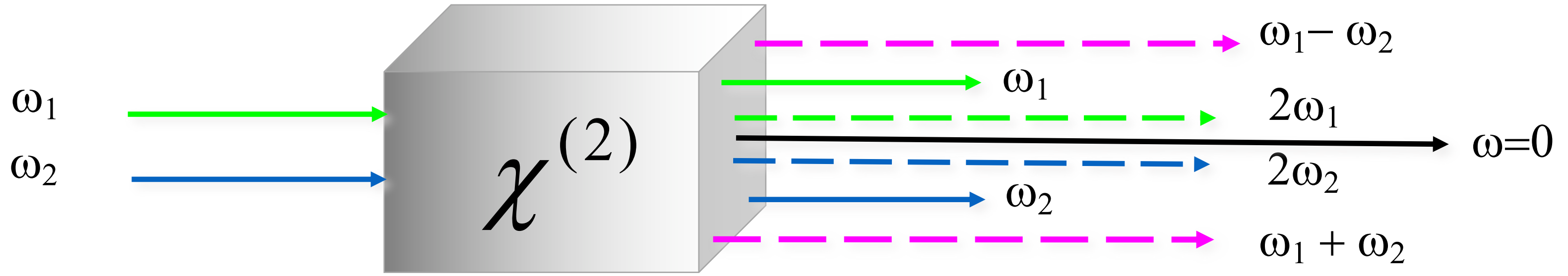
- Multipass amplifier

Example:
E_{in} = 1 mJ
E_{out} = 100 mJ
G = 100



Parametric amplifiers

3 wave mixing



- 2 waves …

$$E(z,t)=E_1(z,t)+E_2(z,t)=A_1(z)\exp(i\omega_1 t-k_1 z)+A_2(z)\exp(i\omega_2 t-k_2 z)+cc$$

$$P^{(2)}(z,t)\propto\chi^{(2)}E(z,t)E(z,t)$$

- … generate more waves

$$\begin{aligned}E(z,t)^2 = {} & A_1^2\exp\left[i(2\omega_1 t-2k_1 z)\right]+cc\\ & +A_2^2\exp\left[i(2\omega_2 t-2k_2 z)\right]+cc\\ & +2A_1A_2\exp\left[i(\omega_1 t+\omega_2 t-k_1 z-k_2 z)\right]+cc\\ & +2A_1A_2^*\exp\left[i(\omega_1 t-\omega_2 t-k_1 z+k_2 z)\right]+cc\\ & +2\left|A_1\right|^2+2\left|A_2\right|^2\end{aligned}$$

Frequency content

$2\omega_1$

$2\omega_2$

$\omega_1+\omega_2$

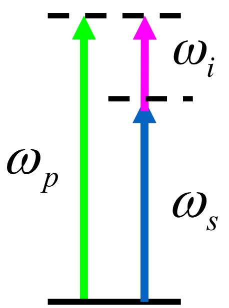
$\omega_1-\omega_2$

0

Conservation laws

- Energy conservation:

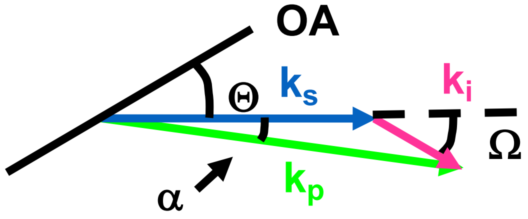
$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$



Instantaneous process + Energy storage free

- Momentum conservation:

$$\vec{k}_p = \vec{k}_s + \vec{k}_i$$



Phase matching conditions

- Manley-Rowe relations

$$\frac{d}{dz}\left(\frac{I_s}{\omega_s}\right) = \frac{d}{dz}\left(\frac{I_i}{\omega_i}\right) = -\frac{d}{dz}\left(\frac{I_p}{\omega_p}\right)$$

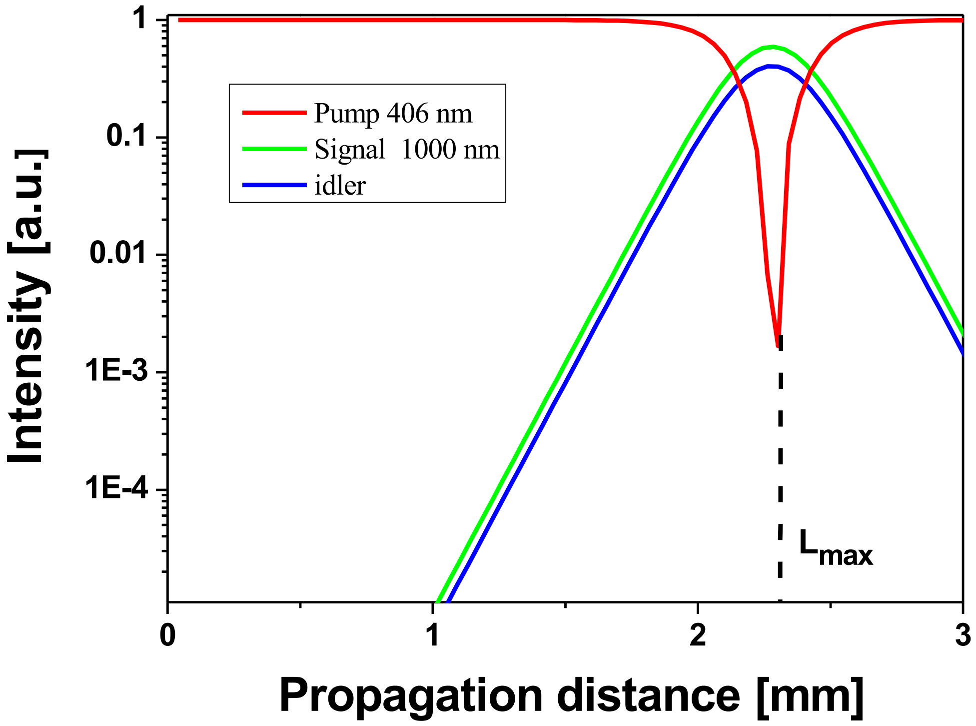
Photon rate conservation

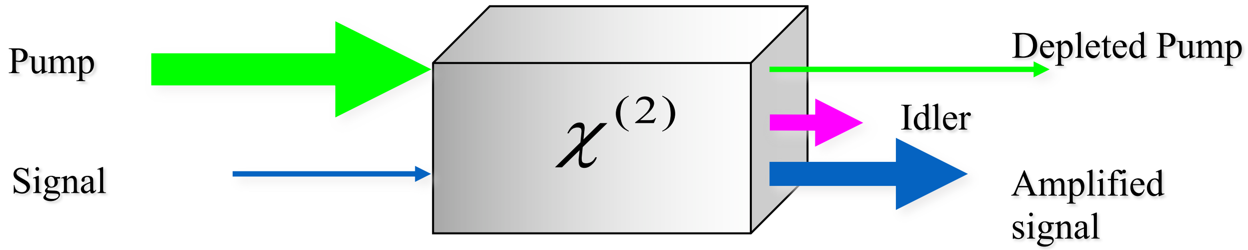
Optical parametric amplifier : OPA

$$\frac{\partial A_s}{\partial z} = -i d_{eff} \frac{\omega_s}{n_s c} A_p A_i^* e^{-i\Delta k z}$$

$$\frac{\partial A_i}{\partial z} = -i d_{eff} \frac{\omega_i}{n_i c} A_p A_s^* e^{-i\Delta k z}$$

$$\frac{\partial A_p}{\partial z} = -i d_{eff} \frac{\omega_p}{n_p c} A_s A_i \, e^{i\Delta k z}$$





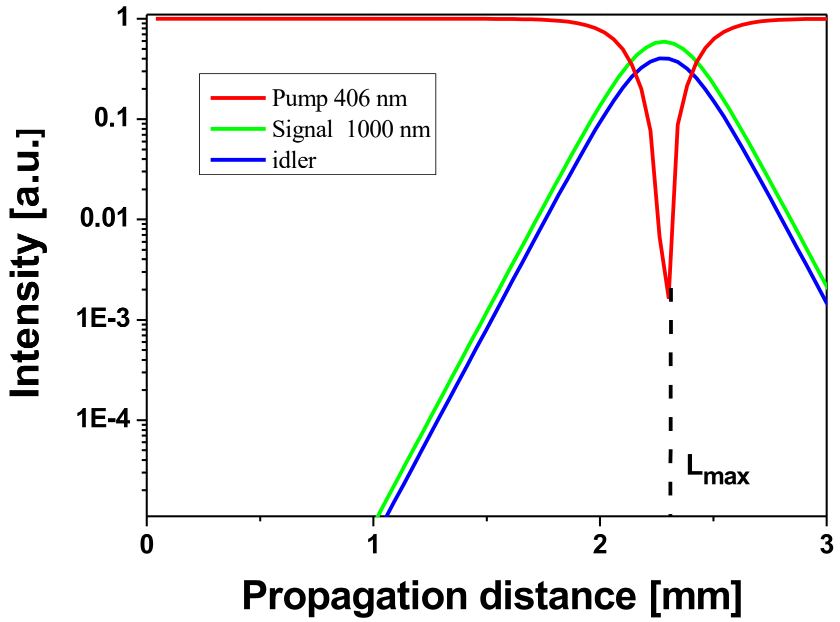
Optical parametric amplifier : OPA

Small signal gain

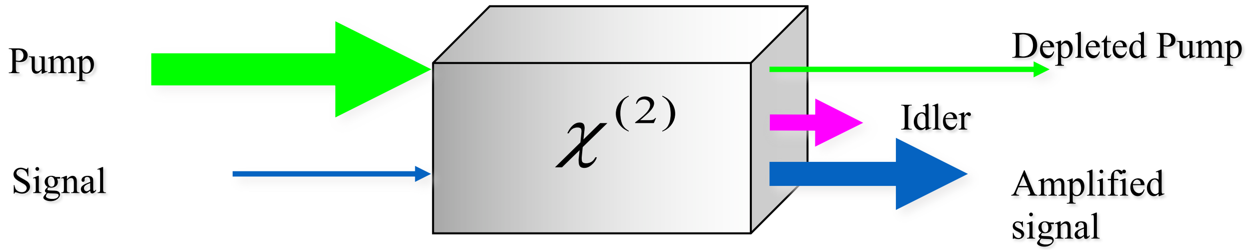
$$G = \frac{I_s(z=L)}{I_s(z=0)}$$

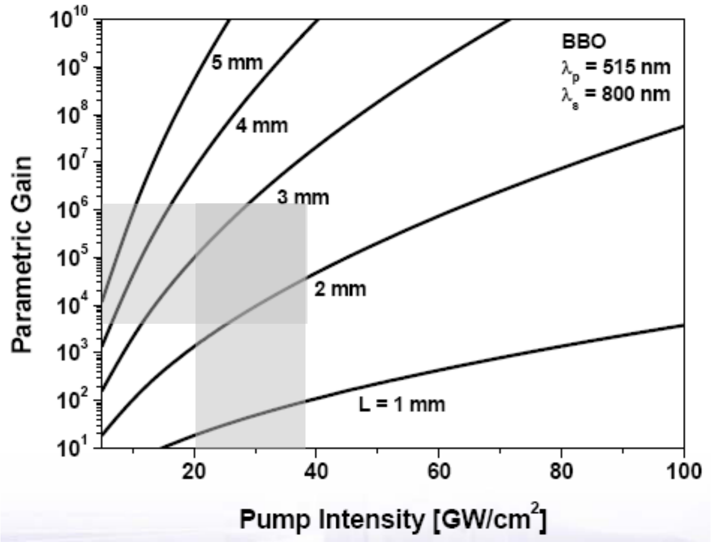
$$G = 1 + \sinh^2\left(\frac{\gamma L_{cristal}}{2}\right)$$

$$\gamma = \frac{d_{eff}}{2c}\sqrt{\frac{\omega_s \omega_i}{n_s n_i n_p} I_p}$$



Parametric gain: 10^4 to 10^6 !!!!





Chirped pulse amplification

Short pulse laser architecture

- Direct amplification

Impossible !!!

2 nJ, 30 fs
P = 0.06 MW

2 mJ, 30 fs
P = 6.6 GW

60 mJ, 30 fs
P = 2 TW

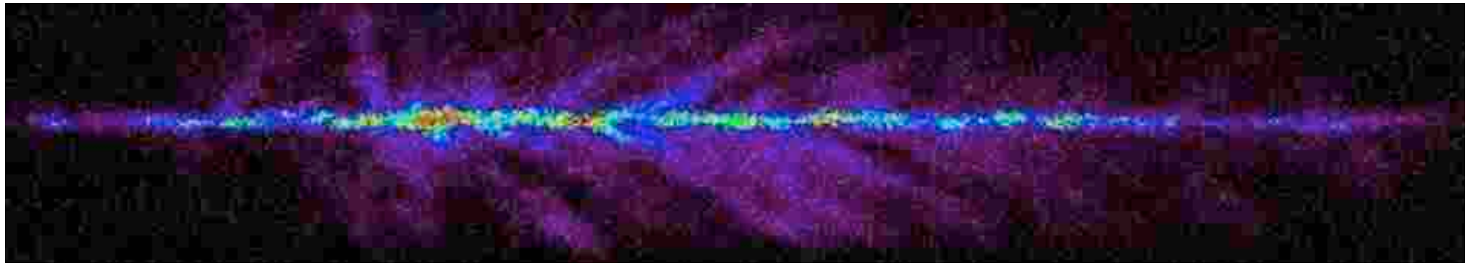
Oscillator → Regen amplifier → Power amplifiers → Output

$$P_c = \frac{0.148\lambda^2}{n_0 n_2}$$

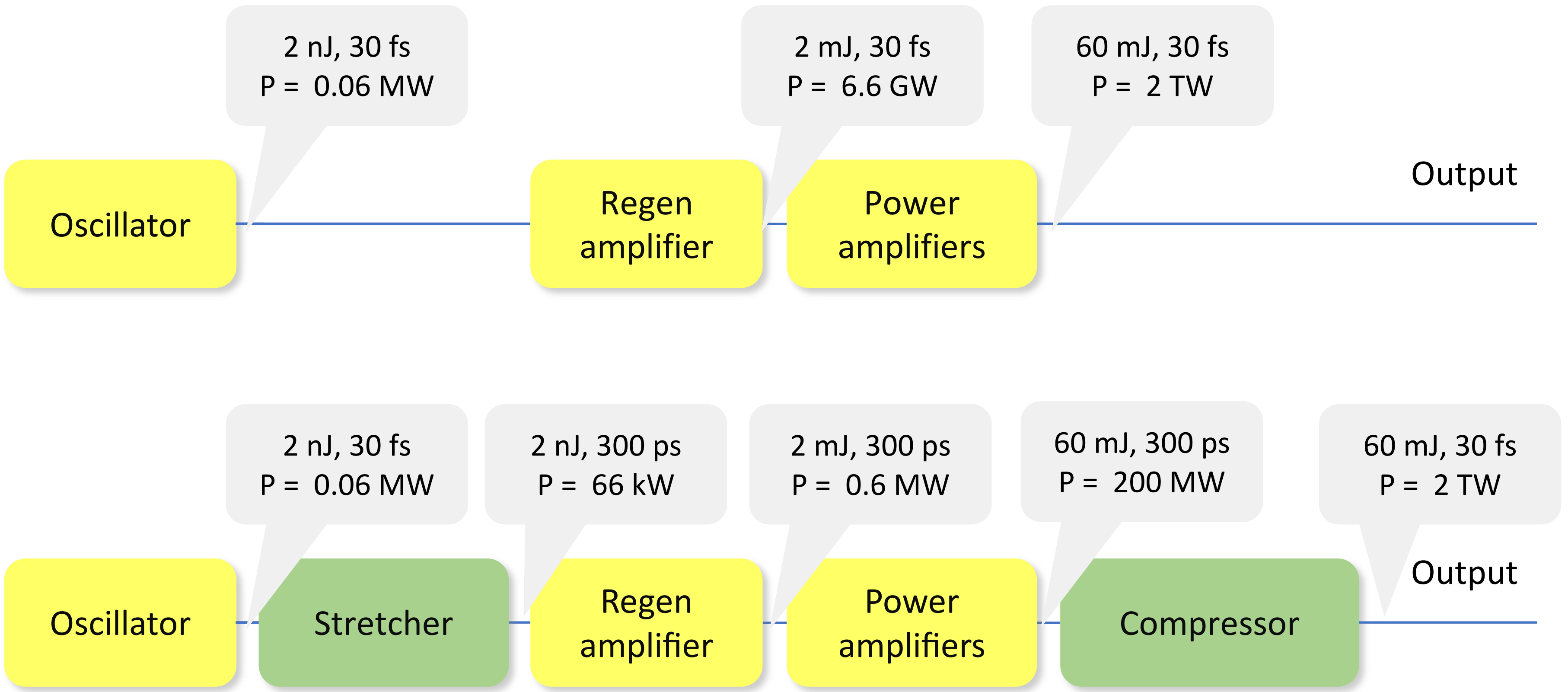
<u>Self focusing limit:</u>

In Sapphire/glass : Pc = 3.2 MW

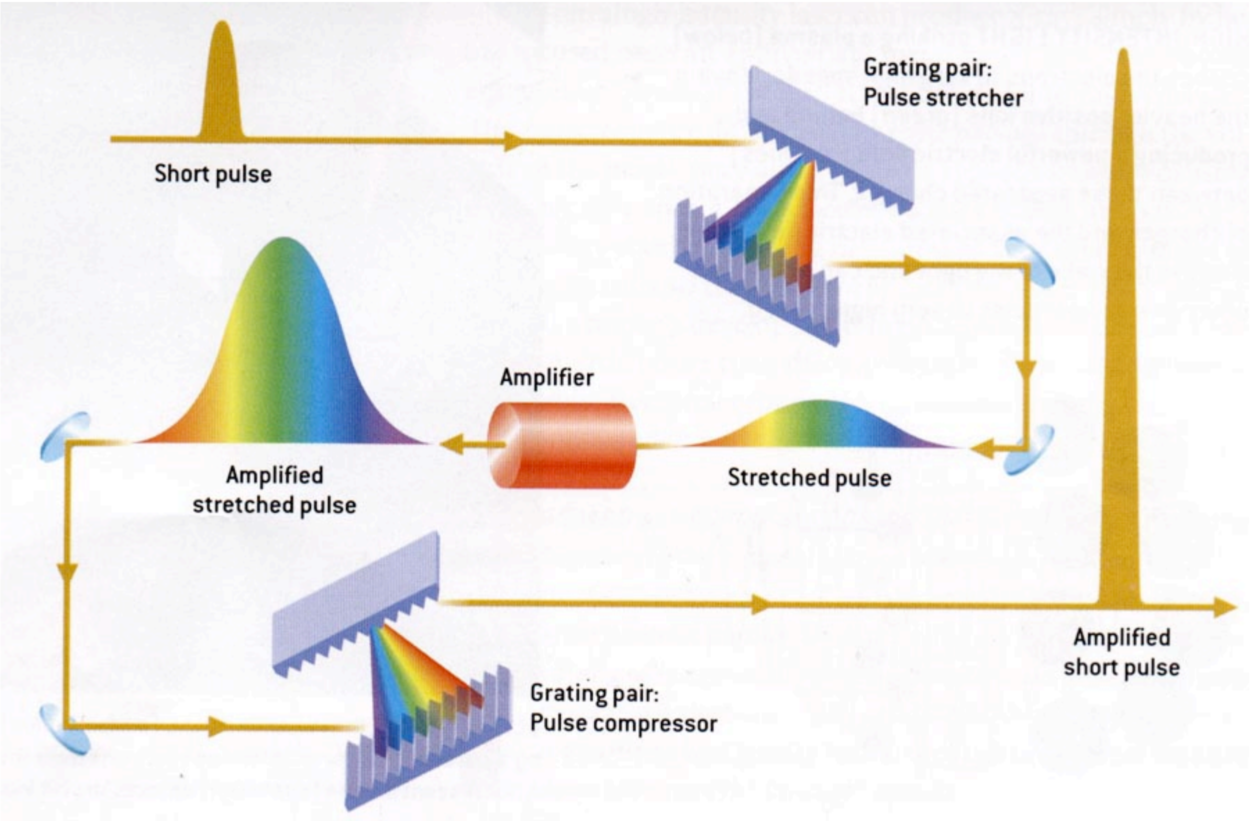
In air : Pc = 3.3 GW



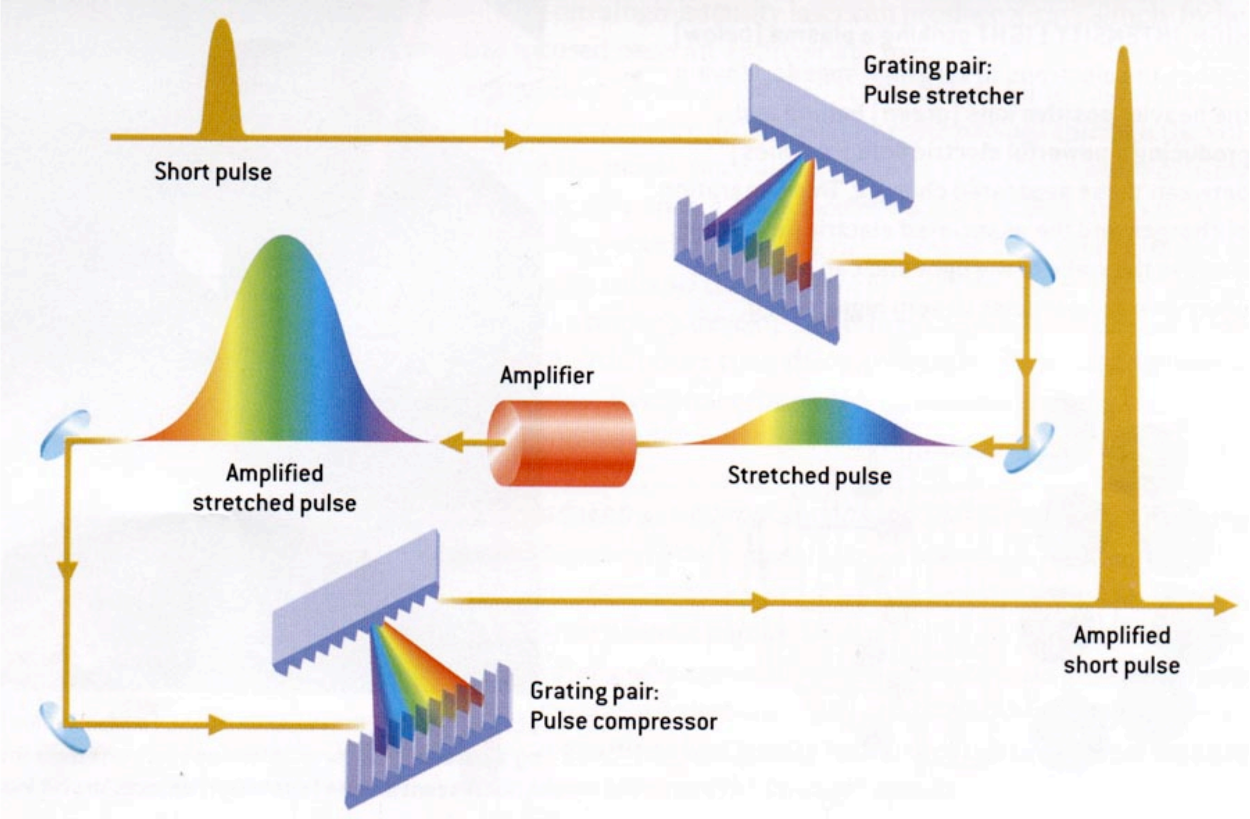
Short pulse laser architecture



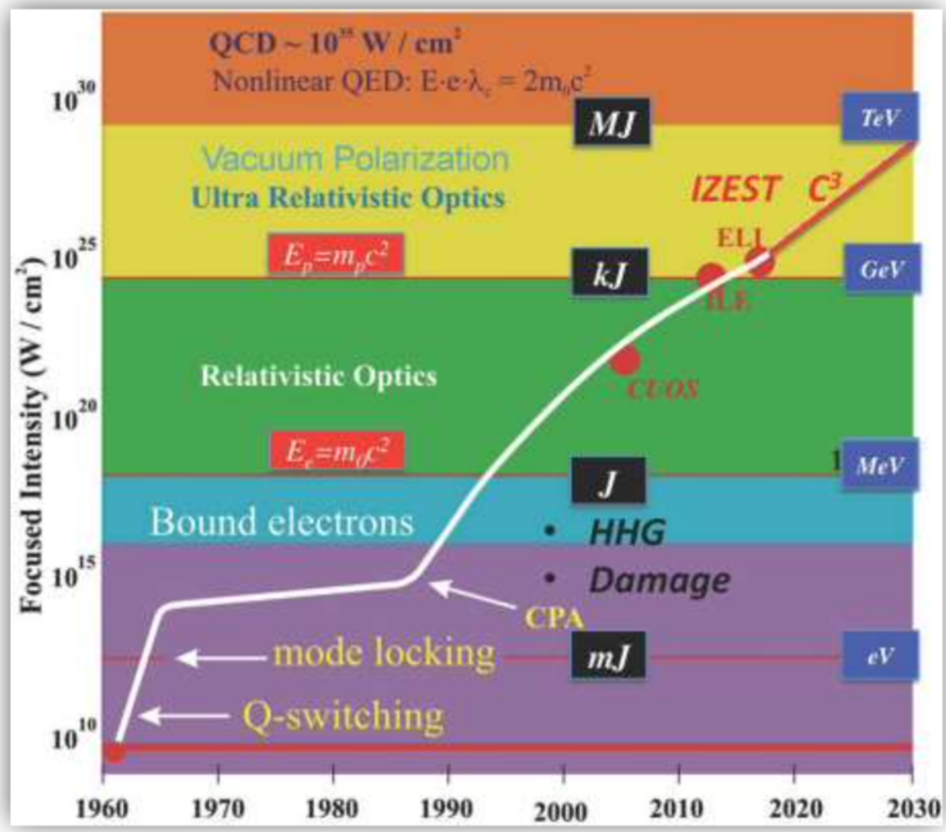
Chirped Pulse Amplification



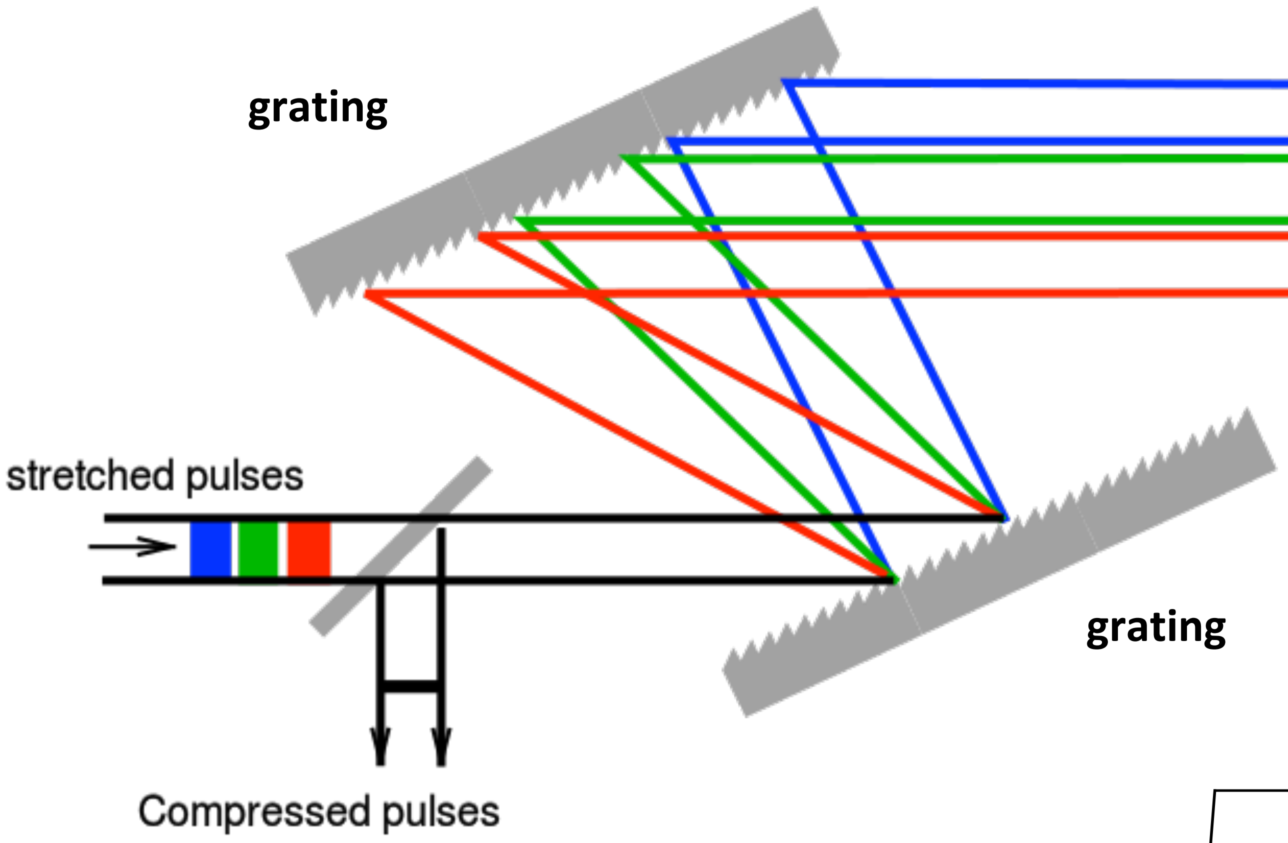
Chirped Pulse Amplification



GERARD MOUROU
& DONA STRICKLAND
(Nobel 2018)



Pulse stretching/compressing

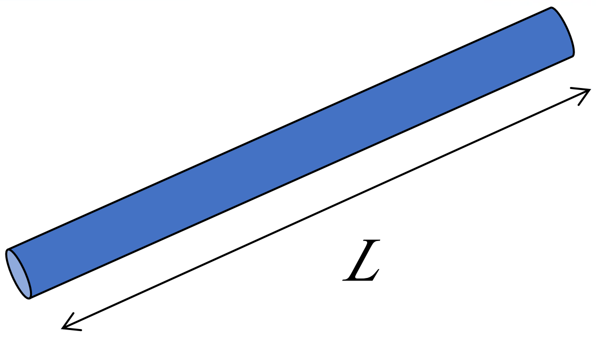


$$\Delta T = \Delta T_0 \sqrt{1 + \frac{16(\ln 2)^2 \varphi^{(2)^2}}{\Delta T_0{}^4}}$$

Post-compression

Self-phase modulation

- Kerr effect in the temporal domain

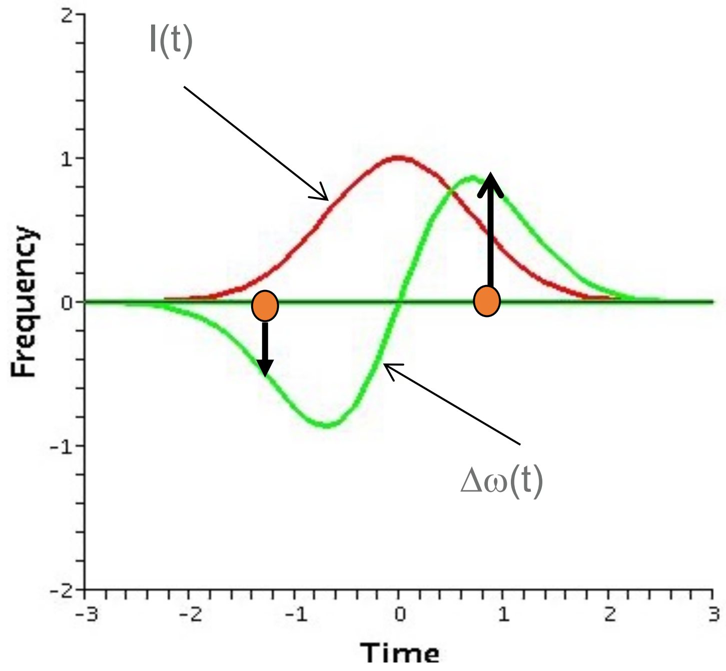


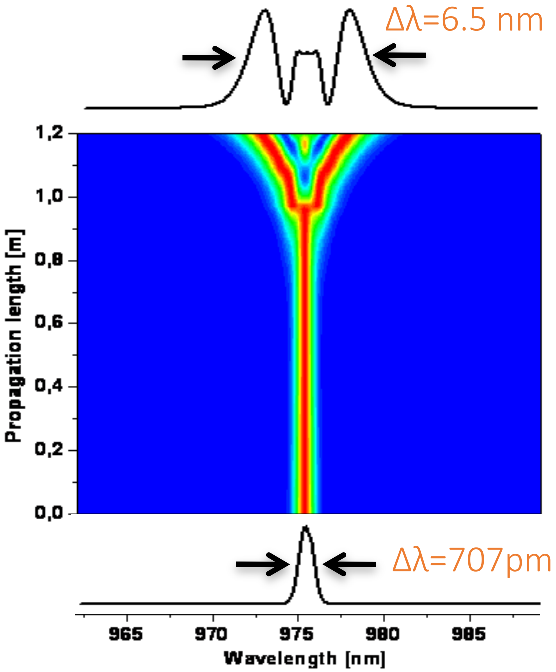
$$n = n_0 + n_2 I(t) \qquad \phi = \beta L = \frac{n\omega}{c} L = \frac{2\pi}{\lambda} n_0 L + \frac{2\pi}{\lambda} n_2 I L = \phi_L + \phi_{NL}$$

$$\phi_{NL} = \frac{2\pi}{\lambda} n_2 I L = \frac{\omega}{c} n_2 I L$$

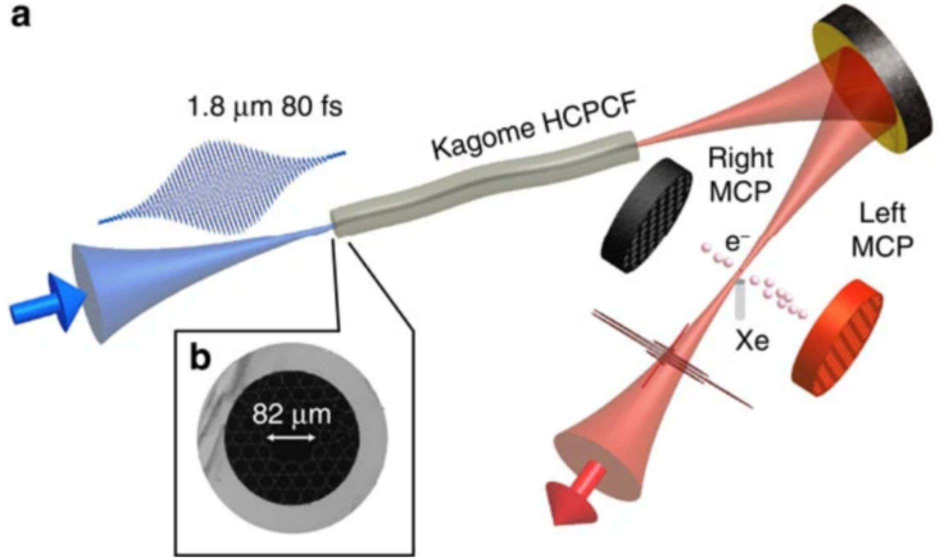
$$\omega_{inst}(t) = \omega_0 - \frac{\partial \phi(t)}{\partial t}$$

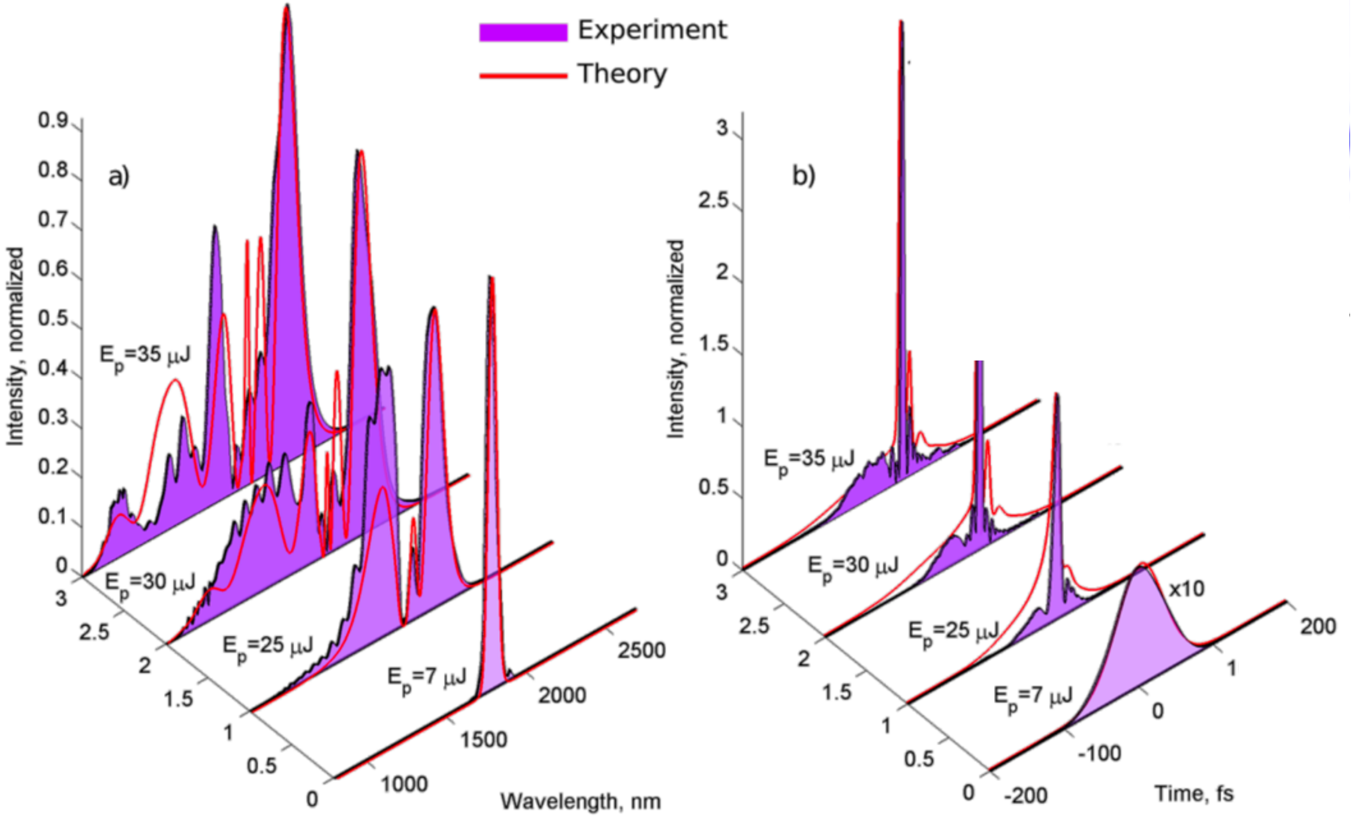
$$\Delta\omega(t) = \omega \frac{n_2 L}{c} \frac{\partial I(t)}{\partial t}$$





Postcompression



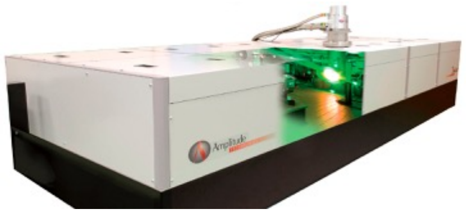


Balciunas, T., *et al.*. *Nat Commun* **6**, 6117 (2015).

Architectures with examples

Ultrashort pulse architectures

Laser material



Ti:Sapphire amplifiers

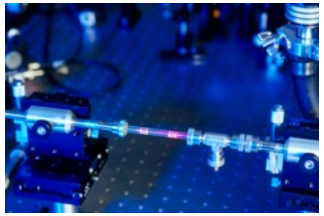
λ = 800 nm
E = 1 mJ – 300 J
$\Delta\tau$ = 15-30 fs
ν = < 1 Hz – 10 kHz
P_{av} < 300 W

χ^2 non-linear material

OPA / NOPA / OPCPA

λ = 600-6000 nm
E = 0.01 – 50 J
$\Delta\lambda$ = octave
$\Delta\tau$ = 2 to 6 cycles

χ^3 non-linear material



Post-compression

λ = 800 - 3000 nm
E = 0.5 – 10 mJ
$\Delta\tau$ = 1.5 – 3 cycles

Ultrashort pulse architectures

Laser material

Ti:Sapphire amplifiers

λ = 800 nm
E = 1 mJ – 300 J
$\Delta\tau$ = 15-30 fs
ν = < 1 Hz – 10 kHz
P_{av} < 300 W

Yb-doped DPSSL

λ = 1030 nm
E = 10 μJ – 1 J
$\Delta\tau$ = 1 – 100 ps
ν = 0.1 – 100 kHz
P_{av} = 700 W

χ^2 non-linear material

OPA / NOPA / OPCPA

λ = 600-6000 nm
E = 0.01 – 50 J
$\Delta\lambda$ = octave
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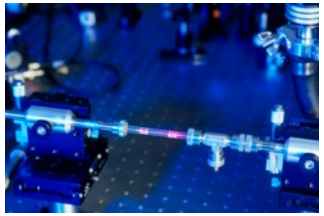
χ^3 non-linear material



Post-compression

λ = 800 - 3000 nm
E = 0.5 – 10 mJ
$\Delta\tau$ = 1.5 – 3 cycles

Ultrashort pulse architectures

Laser material

Ti:Sapphire amplifiers

Yb-doped DPSSL

λ = 1030 nm
E = 10 μJ – 1 J
$\Delta\tau$ = 1 – 100 ps
ν = 0.1 – 100 kHz
P_{av} = 700 W

Yb-doped fiber laser

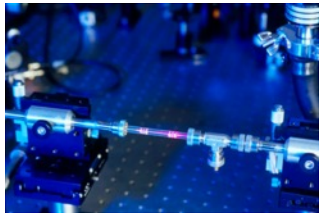
λ = 1030 nm
E = 100 μJ – 5 mJ
$\Delta\tau$ = 200 fs
ν = 50 kHz – 2 MHz
P_{av} = 800 W

χ^2 non-linear material

OPA / NOPA / OPCPA

λ = 600-6000 nm
E = 0.01 – 50 J
$\Delta\lambda$ = octave
$\Delta\tau$ = 2 to 6 cycles

χ^3 non-linear material



Post-compression

λ = 800 - 3000 nm
E = 0.5 – 10 mJ
$\Delta\tau$ = 1.5 – 3 cycles

Ultrashort pulse architectures

Laser material

1

Ti:Sapphire amplifiers

2

Yb-doped DPSSL

λ = 1030 nm
E = 10 μJ – 1 J
$\Delta\tau$ = 1 – 100 ps
ν = 0.1 – 100 kHz
P_{av} = 700 W

3

Yb-doped fiber laser

λ = 1030 nm
E = 100 μJ – 5 mJ
$\Delta\tau$ = 200 fs
ν = 50 kHz – 2 MHz
P_{av} = 800 W

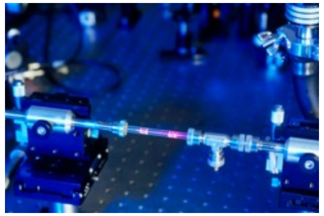
χ^2 non-linear material

4

OPA / NOPA / OPCPA

λ = 600-6000 nm
E = 0.01 – 50 J
$\Delta\lambda$ = octave
$\Delta\tau$ = 2 to 6 cycles

χ^3 non-linear material



5

Post-compression

λ = 800 - 3000 nm
E = 0.5 – 10 mJ
$\Delta\tau$ = 1.5 – 3 cycles

Ultrafast laser architectures

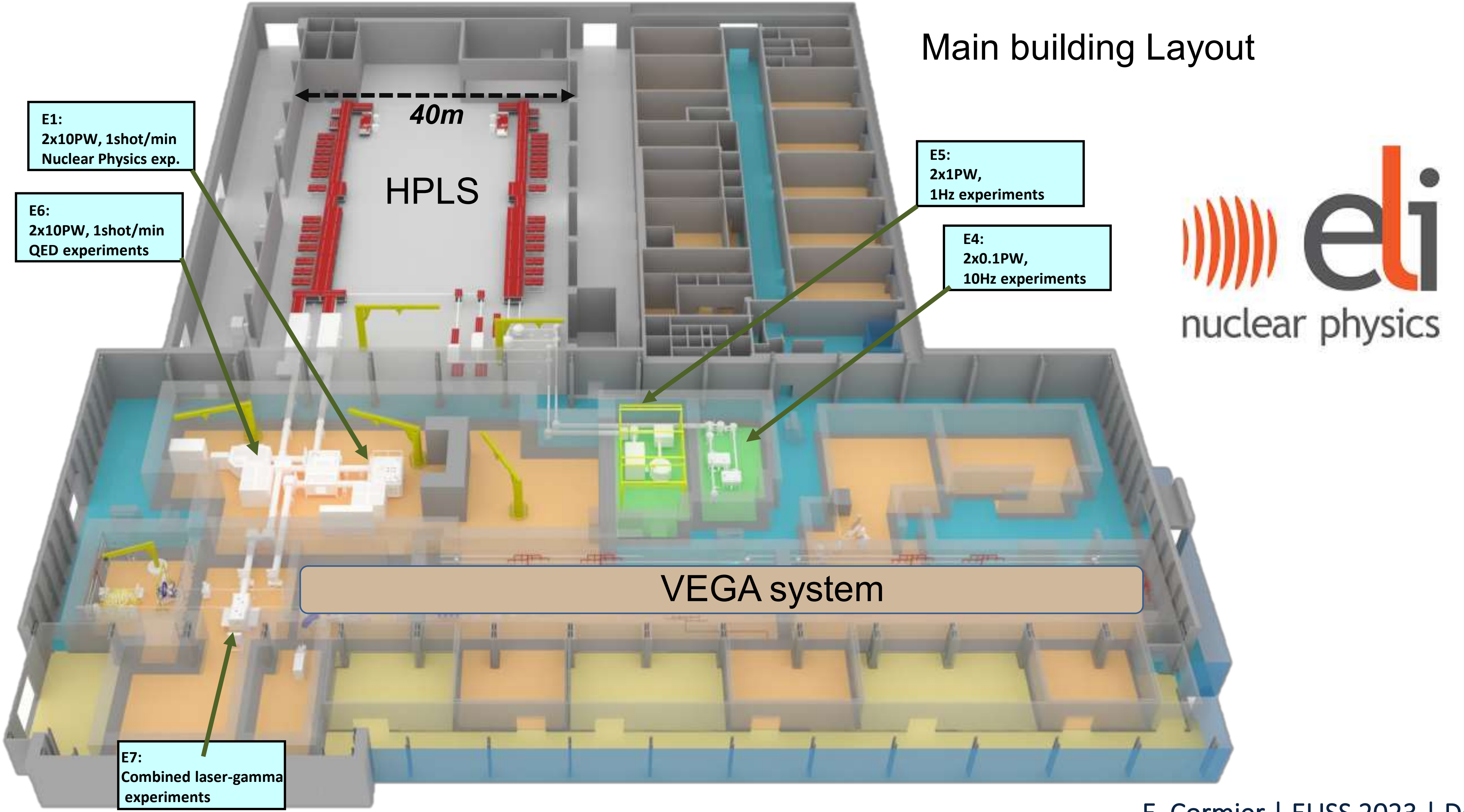
1		• TW and PW lasers (NP, ALPS and Beamline)
2		• Yb:YAG thin-disk and Nd:YAG rods commercial pump system
3	5	• Fiber CPA system + postcompression (ELI-ALPS)
2	4	• 900 nm DPSSL pumped OPCPA (ALPS and Beamline)
2	4	• 3.2 µm DPSSL pumped OPCPA (MIR and MIR-HE @ ALPS)

Ultrafast laser architectures

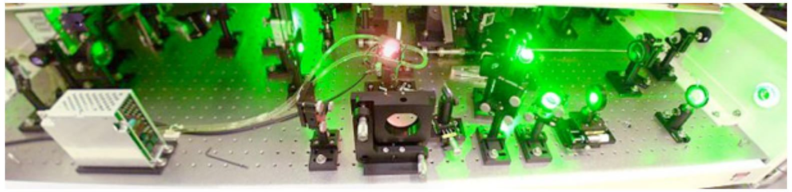
- 1 — TW and PW lasers (NP, ALPS and Beamline)
- 2 — Yb:YAG thin-disk and Nd:YAG rods commercial pump system
- 3 5 — Fiber CPA system + postcompression (ELI-ALPS)
- 2 4 5 — 900 nm DPSSL pumped OPCPA (ALPS and Beamline)
- 2 4 5 — 3.2 µm DPSSL pumped OPCPA (MIR and MIR-HE @ ALPS)

10 PW HPLS @ ELI-NP

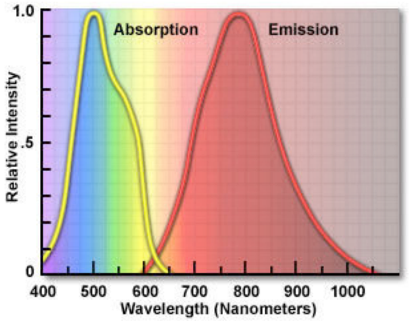
1



10 PW HPLS @ ELI-NP

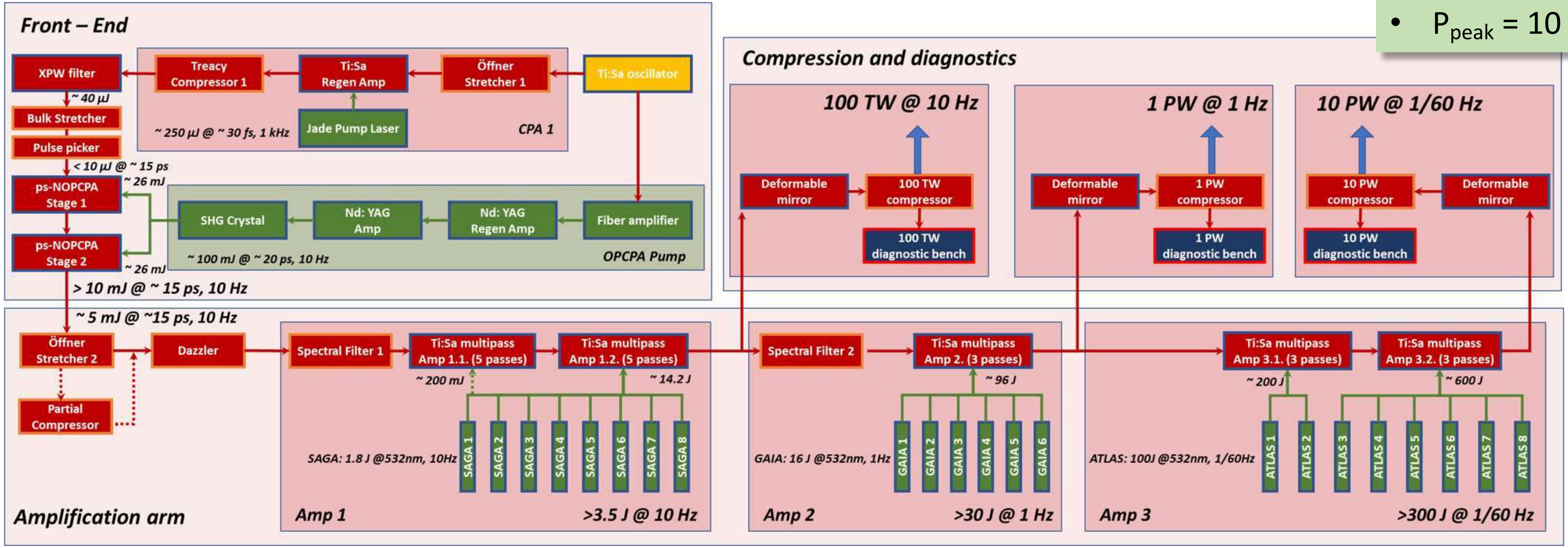


Ti:Sapphire

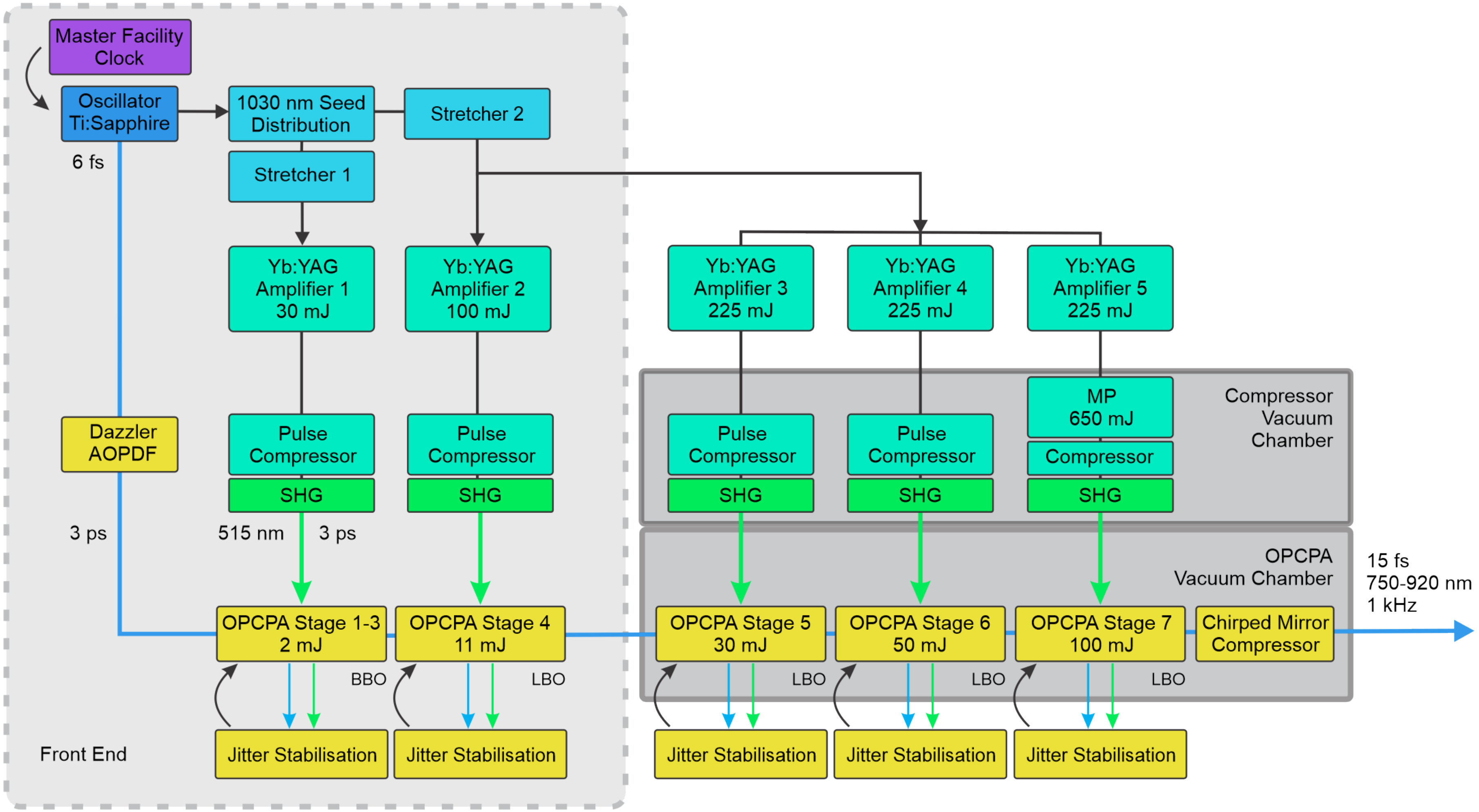


Specifications

- λ = 800 nm
- E = 300 mJ @ 1/60 Hz
- τ = 30 fs
- P_{peak} = 10 PW



L1-Allegra @ ELI-Beamline

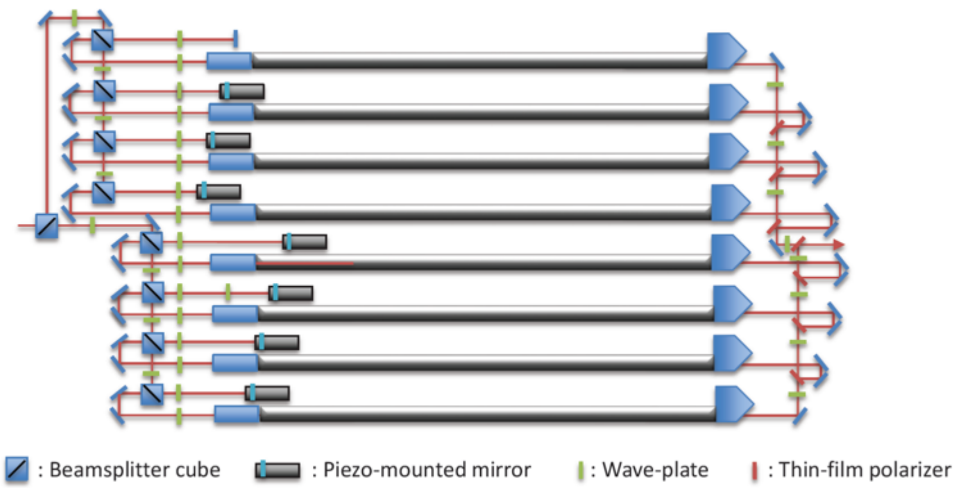


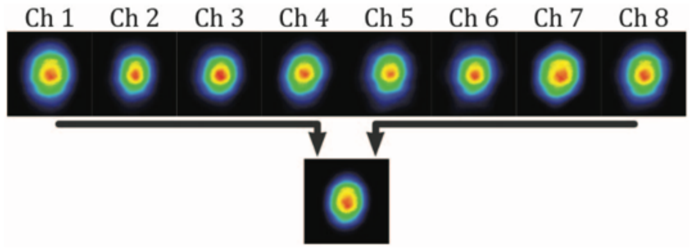
Specifications

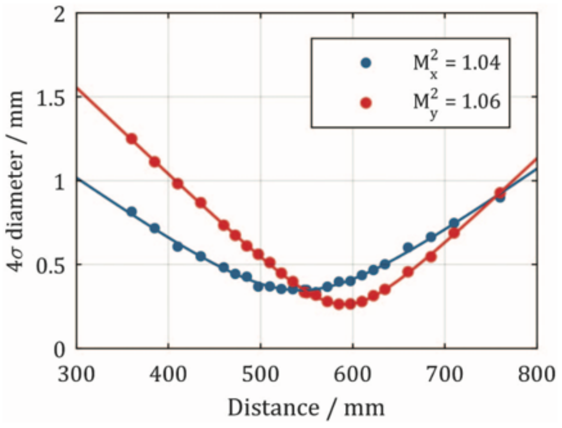
- λ = 800 nm
- E = 30 mJ @ 1 kHz
- τ = 15 fs
- P_{peak} = 2 TW

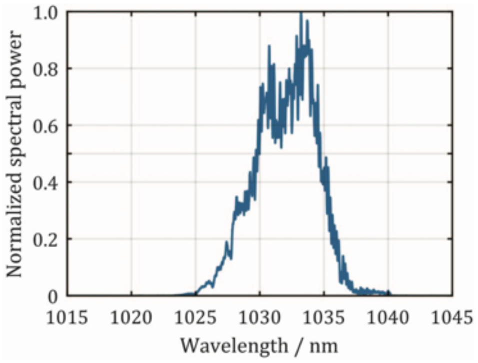
HR1 @ ELI-ALPS

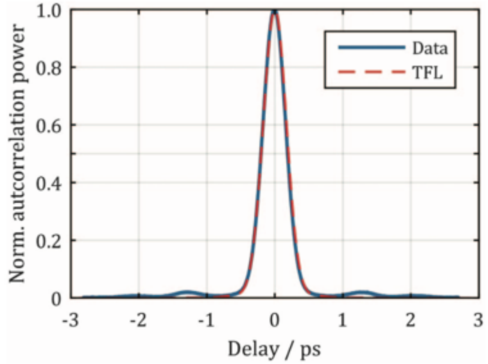
8-channel main amplifier (Yb-doped rod-type LPF) coherent combining







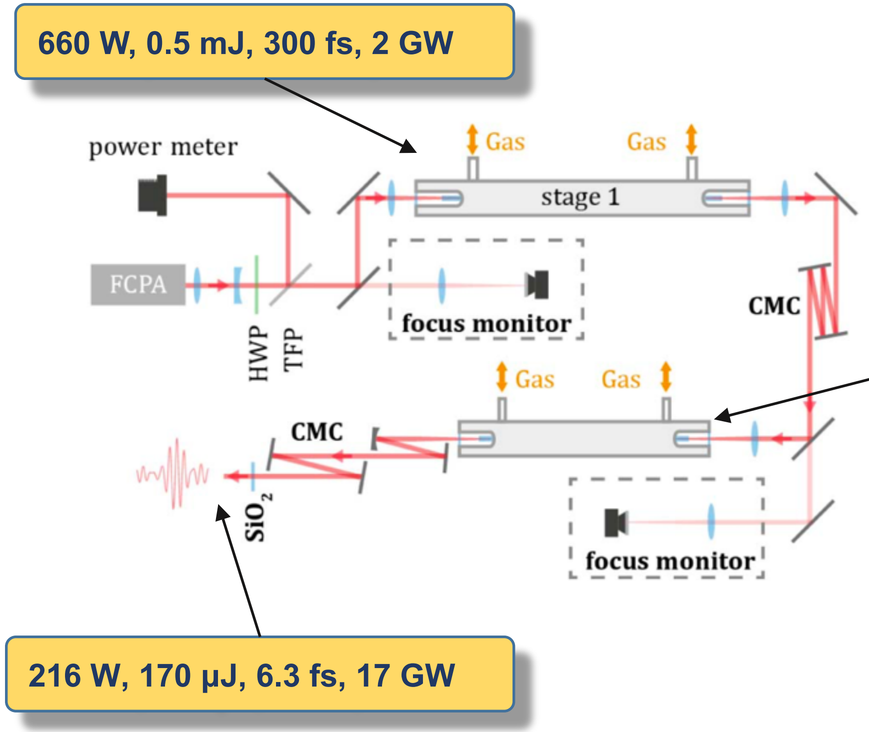




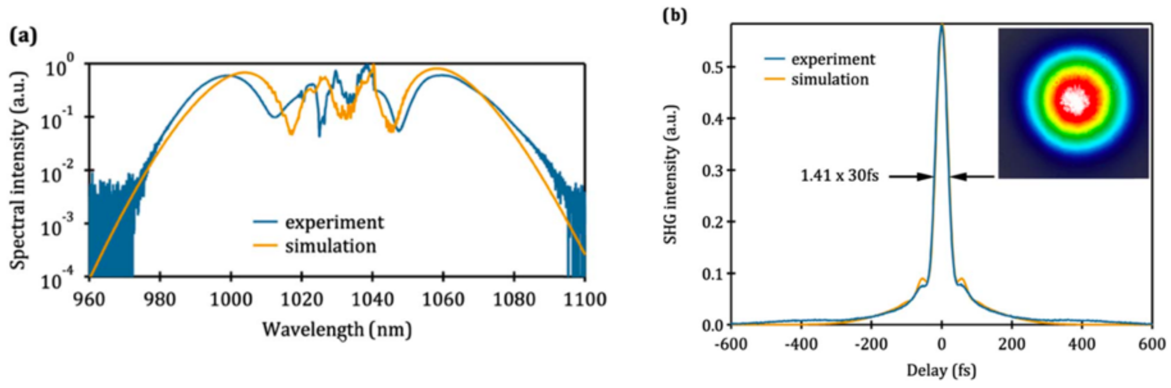
- 1 mJ – 1 kW at 1 MHz
- 3.3 mJ – 870 W at 263 MHz
- Sub 300 fs

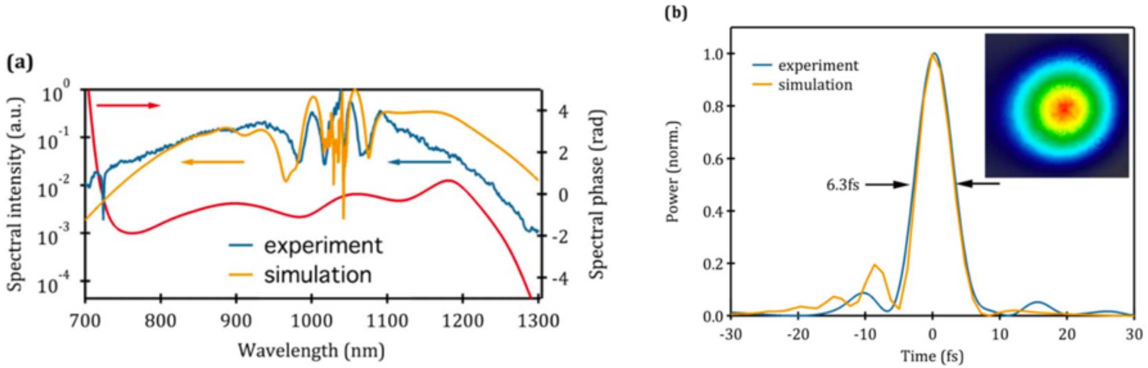
M.Müller, Opt. Lett. 41, 3439 (2016).

HR1 @ ELI-ALPS



408 W, 320 µJ, 30 fs, 10 GW

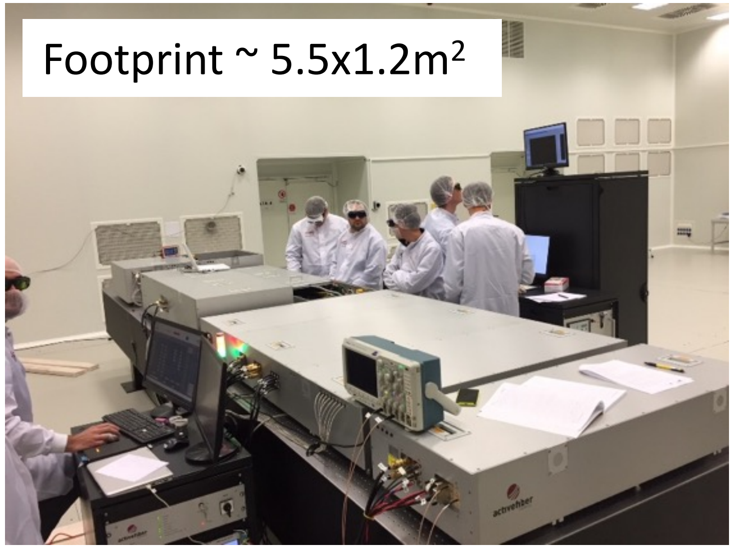




S. Hädrich et al. Optics Lett. 41, 4332 (2016)

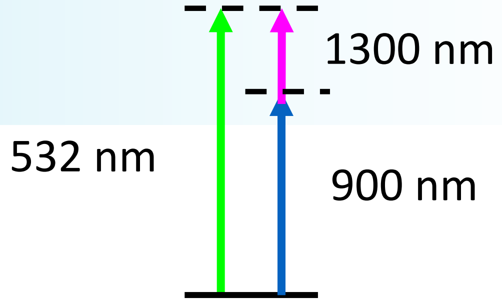
HR1 @ ELI-ALPS

3 5

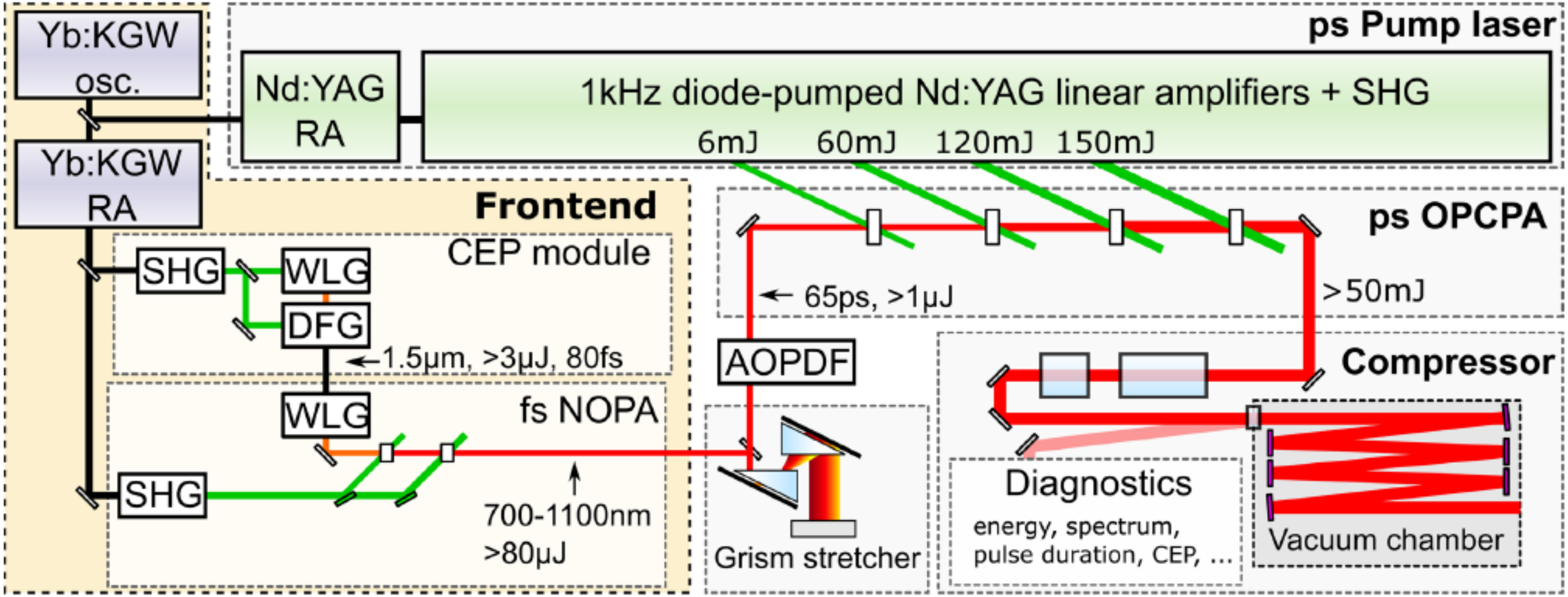


HR 1:1 mJ, < 7 fs (Commissioning in 2017)
HR 2: 5 mJ, < 5 fs (2019)

Sylos @ ELI-ALPS (900 nm)



General architecture

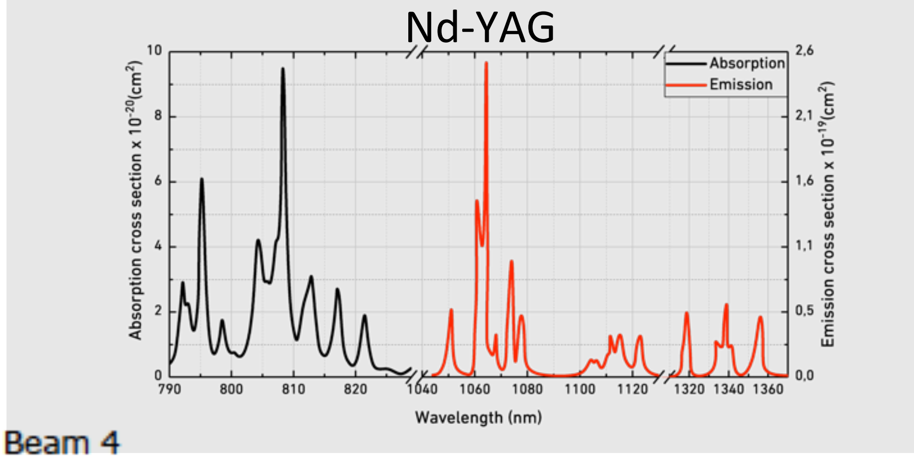


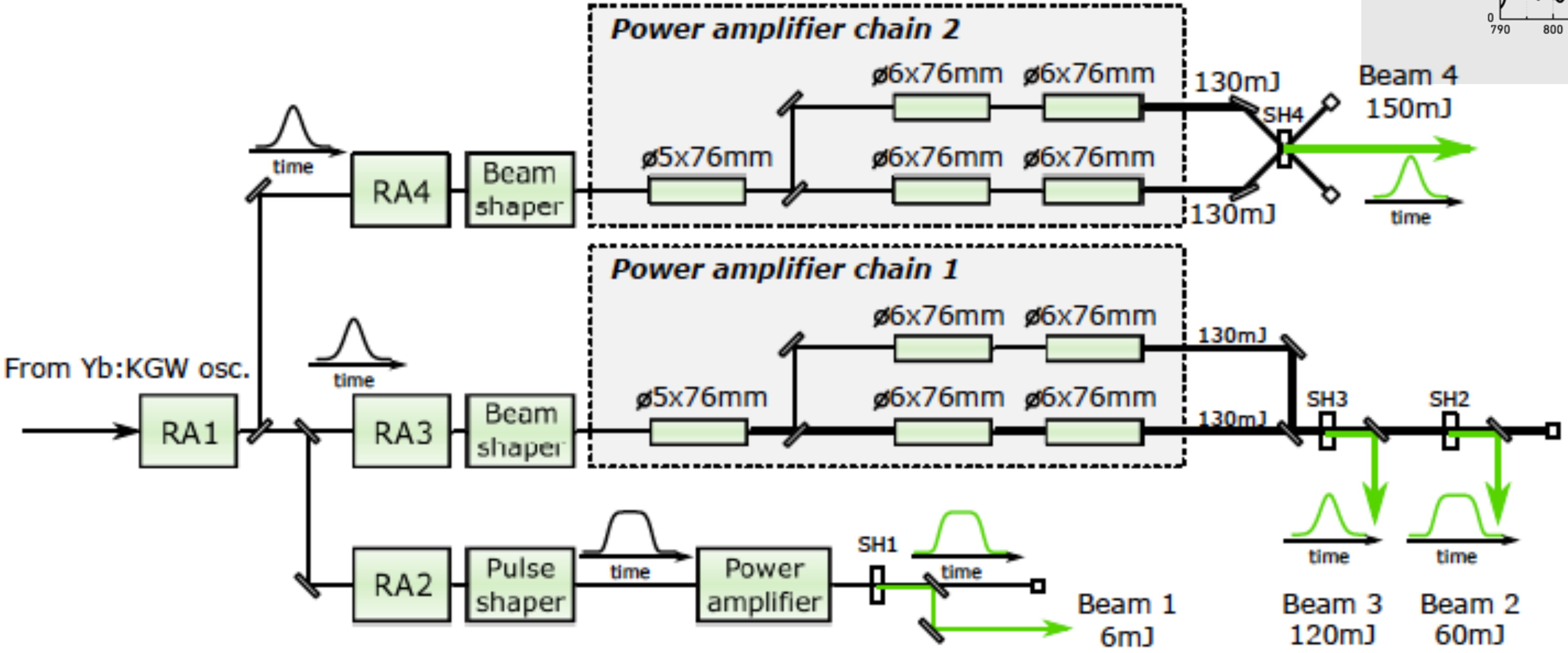
Budriunas *et al.* Optics Express **25,** 5797 (2017)

Sylos @ ELI-ALPS (900 nm)

2 4

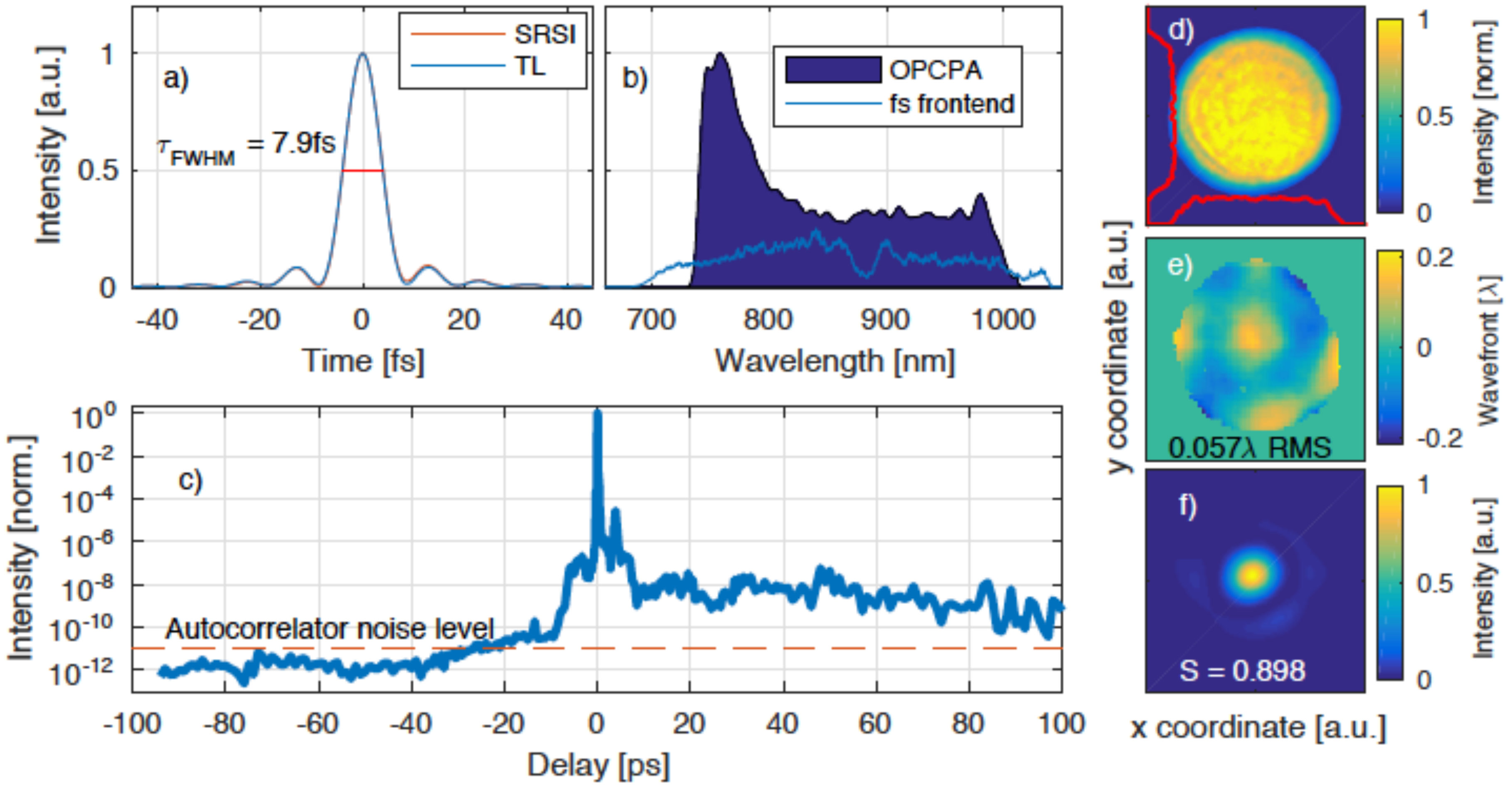
The DPSSL pump laser





Sylos @ ELI-ALPS (900 nm)

2 4



Specifications

- λ = 880 nm
- E = 53 mJ @ 1 kHz
- τ = 8.8 fs (< 3 cycles)
- P_{peak} = 5.5 TW
- $P_{average}$ = 53 W
- CEP = 212 mrad
- Strehl ratio = 0.9
- I > 3.10^{19} W/cm^2

Opening position at ELI-ALPS

eli attosecond

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2. Click on the - Apply - button next to the chosen offer.
3. Sign in! If you have not registered yet, please fill in the fields under - Registration -, and submit your CV.
4. Our colleagues choose the best candidates and will get in touch with them.

RESEARCHER

Research Fellow Laser Sources Division — Apply

Research Fellow positions in the HR Attosources Group and in SYLOS GHHG Attosources Group — Apply

Research fellow — Apply

ENGINEER, TECHNICIAN

Software engineer — Apply

Opening postdoc position at Bordeaux University

Postdoctoral position in Photonics

Development of an ultrahigh GHz to THz repetition rates fs laser source for spintronic applications

Duration : 2 years (24 month) **Starting date** : September 2023

Location : Laboratoire Photonique, Numérique et Nanosciences (LP2N), UMR 5298, IOGS- CNRS-Université de Bordeaux, 33400 Talence, France

Employer : Institut d'Optique https://www.institutoptique.fr

Context

Spectroscopic techniques based on laser-matter interactions allow to probe the vibrational and magnetic degrees of freedom in solids by detecting the associated quantized quasi-particles namely phonons and magnons respectively. These methods rely on the inelastic interaction of light with the object of interest spectrally characterized by Stockes and anti-Stockes sidebands surrounding the light central wavelength. Current techniques are based on laser illumination with either continuous waves or femtosecond pulses. The most advanced commercially available femtosecond lasers deliver pulses at fixed repetition rates around 100 MHz and up to 1 GHz. On the other hand, the characteristic frequencies of phonons and magnons span from tens of GHz up to the THz level. Frequencies being so far apart, spectroscopy in this context remains limited to time-domain Brillouin scattering also referred to as coherent Brillouin scattering hence in a systematic out-of-resonance regime. In the framework of the GigaSpin project (funded by the ANR) we aim at building an instrument implementing a novel spectroscopy approach that relies on tunable optical resonant excitation where the laser repetition-rate can be continuously varied to match any magnonic or phononic eigen-frequencies of the material under investigation. In this context, we are currently developing a femtosecond laser system whose repetition rate is continuously tunable in the range of GHz up to the THz level.

Job description

The researcher will work within the GigaSpin team (5 people) at LP2N in close collaboration with a PhD student on the development of the ultrafast laser source. The topics covered include, but not limited to, fiber lasers and in particular Yb-doped fiber technologies, frequency combs and ultrashort pulses, non-linear propagation in fibers and waveguides, spectral and temporal optical shaping, advanced laser metrology and non-linear optics. She/he will also be involved in the experimental campaigns conducted in collaboration with our partners (IPR Rennes, Lab-Sticc Brest and UMPhy Palaiseau) aiming at characterizing the acoustic and magnetic properties of complex samples on the experimental resonant Brillouin spectroscopy platform driven by the GHz laser source at LP2N. Additionally, the researcher will actively participate to communication activities through peer-reviewed publications, topical meeting and conference presentations where she/he will promote her/his research.

Skills

The candidate must have a Ph.D in photonics, applied physics, optics or a related discipline. Advanced knowledge in fiber laser, non-linear optics, electro-optic modulation, optoelectronics or femtosecond technologies as well as proficiencies for numerical simulations are recommended. A fluent knowledge of English and/or French is a pre-requisite. The successful candidate will be highly motivated, creative, with demonstrated abilities to work in a collaborative environment.

Contacts and application

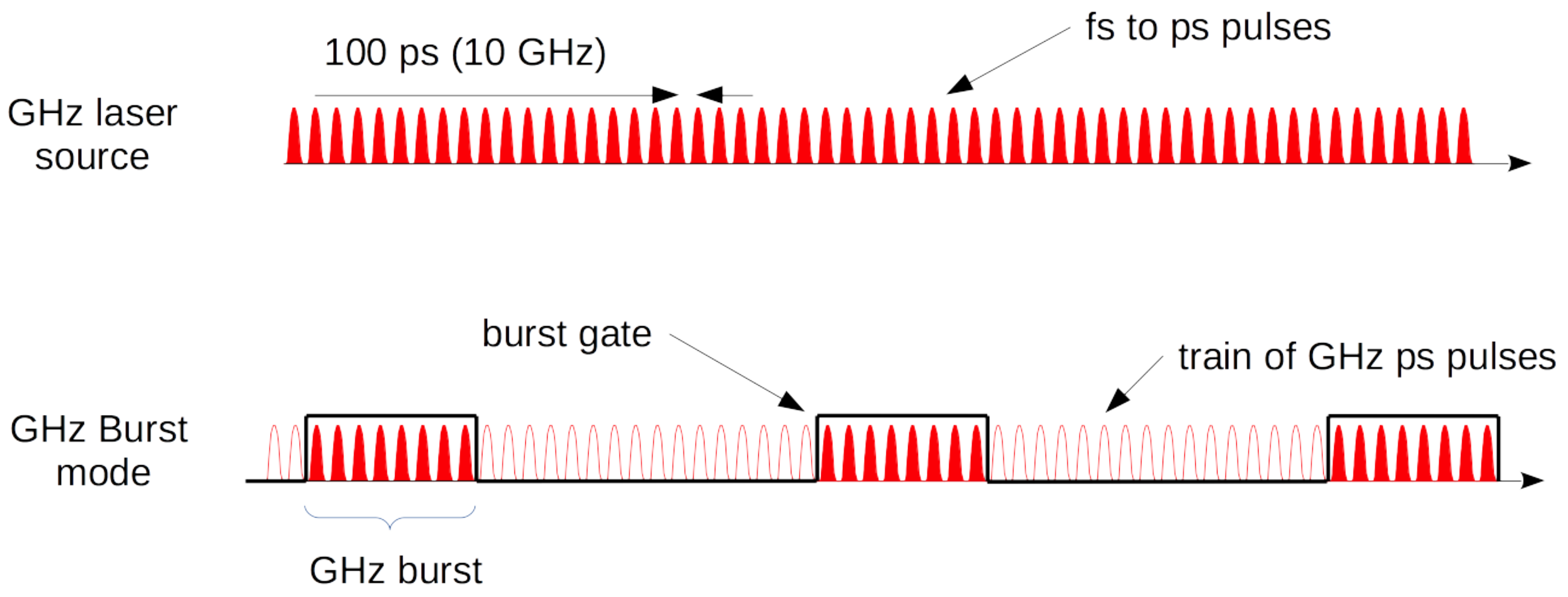
Applications should include a CV, a cover letter, and contact details of 2 professional references.

Prof. Eric Cormier, +33 (0) 5 57 01 72 47, eric.cormier@institutoptique.fr
Dr. Giorgio Santarelli, +33 (0) 5 57 01 72 50, giorgio.santarelli@institutoptique.fr

References

[1] H. Ye *et al.*, *Opt. Express* **28**, 37209 (2020)
[2] O. Kovalenko *et al.*, *Phys. Rev. Lett.* **110**, 266602 (2013)
[3] L. Soumah *et al.*, *Nat. Commun.* **9**, 3355 (2018)

Opening postdoc position at Bordeaux University



- fs oscillator : 100 MHz
- Gigapico : 10 GHz
- Gigaspin : 1 THz

Spintronic | Ultrasonic | Molecular alignement | Plasma waves | • • •

Europhoton 2024

11th EPS-QEOD Europhoton Conference
EUROPHOTON
SOLID-STATE, FIBRE, AND WAVEGUIDE COHERENT LIGHT SOURCE

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Thank you