The 12th International Organization of Chinese Physicists and Astronomers Accelerator School

Nakhon Ratchasima, Thailand, July. 31, 2025

Ultrafast Laser Technology and Synchronization

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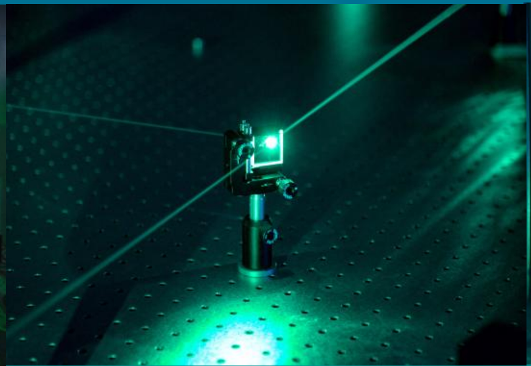
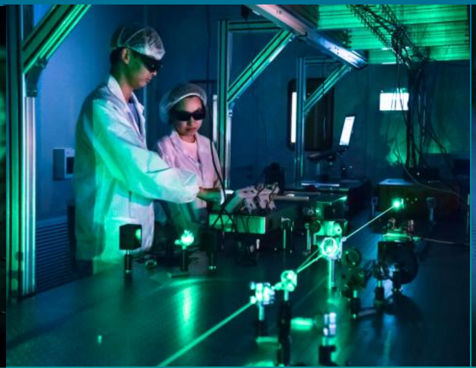
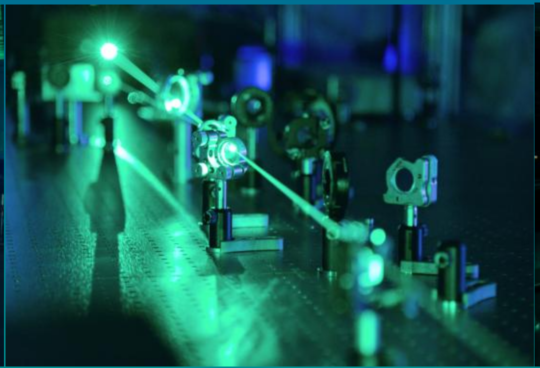




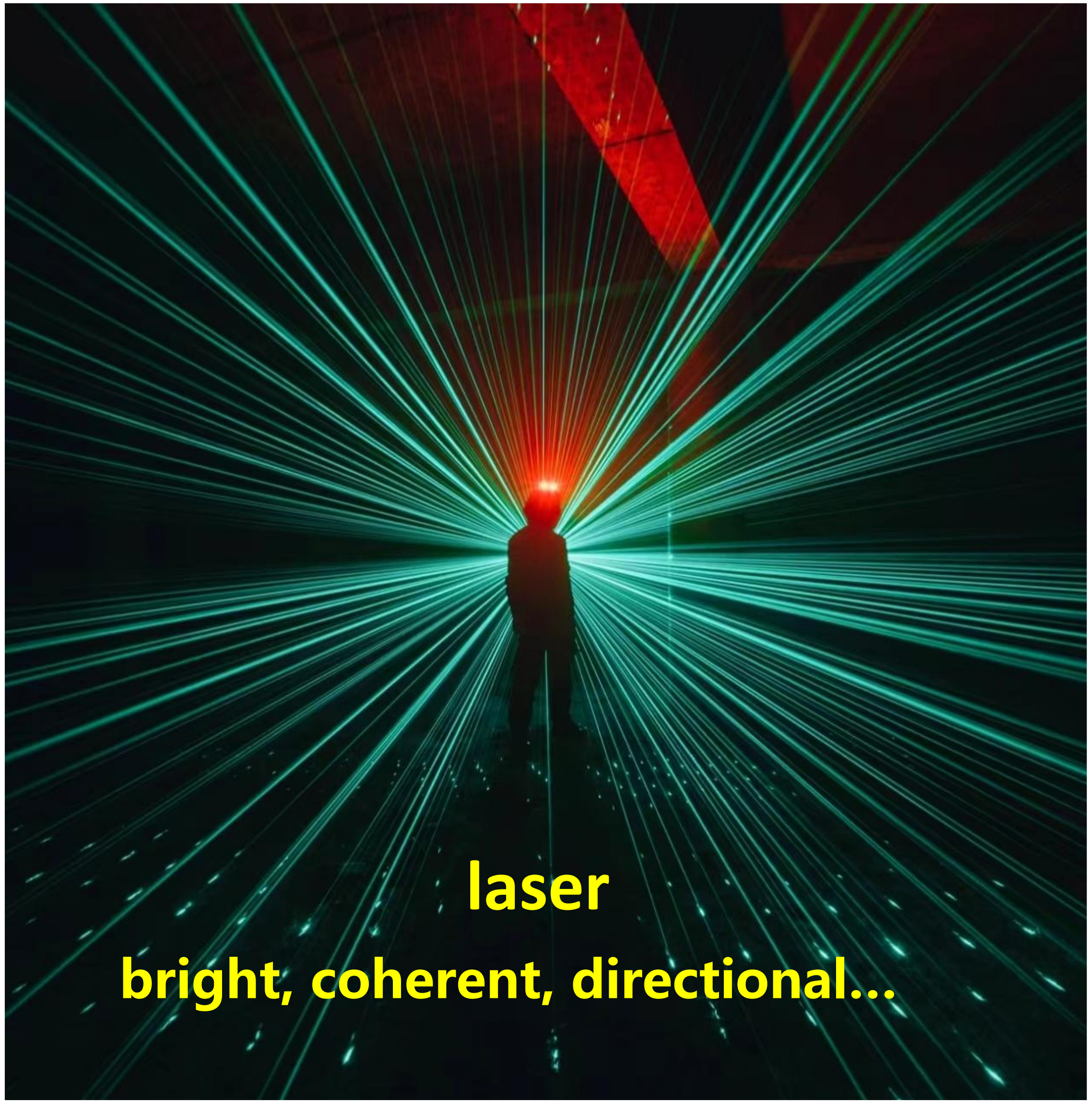

outline

- What is a laser?
- What is an ultrafast laser?
- Mathematic description of an ultrafast laser pulse;
- Ultrafast lasers for S^3FEL;
- Femtosecond timing and synchronization;

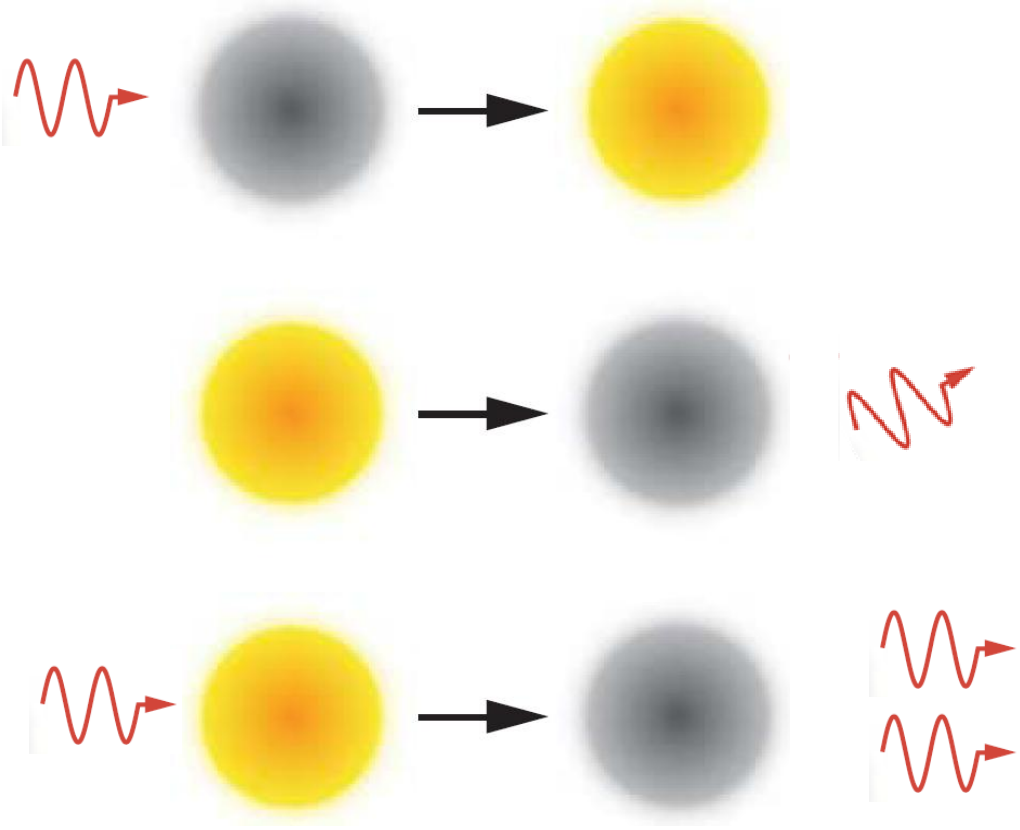
LASER

Light Amplification by Stimulated Emission of Radiation

All kinds of sources of light



The basic principle of laser: interaction of light with matter



Absorption

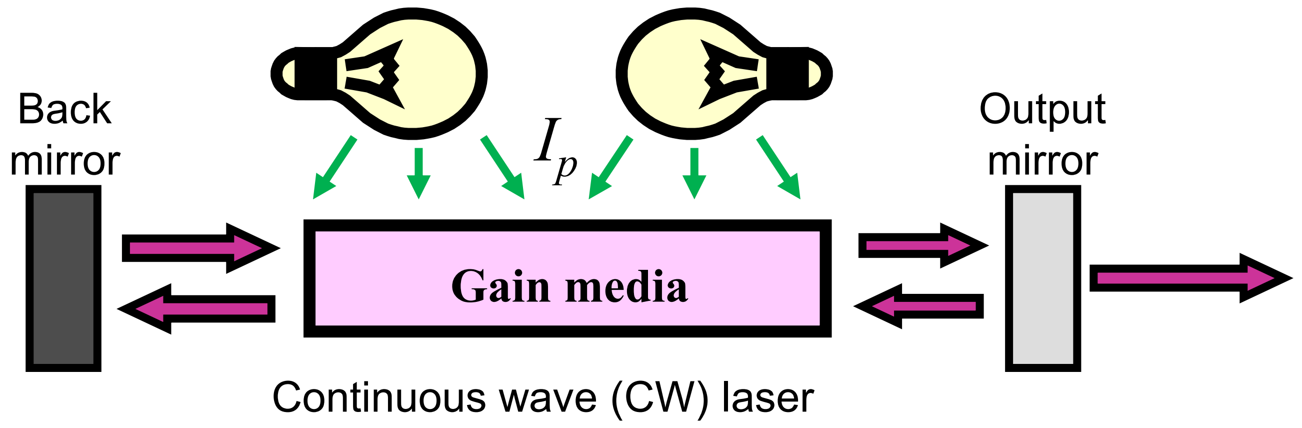
Spontaneous emission

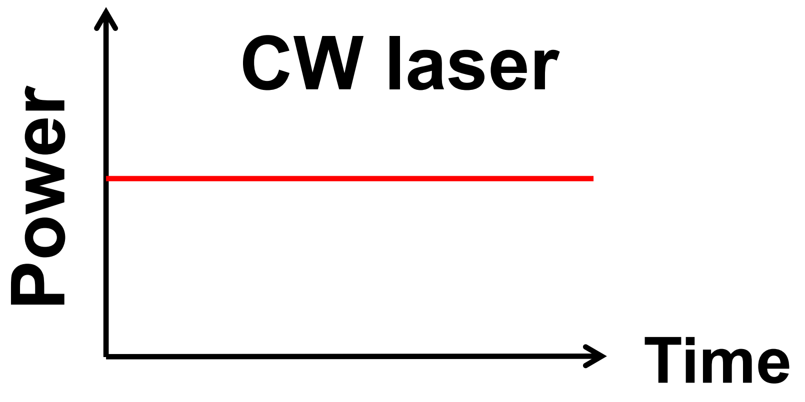
Stimulated emission

1917: *on the quantum theory of radiation* – Einstein's paper

THE LASER

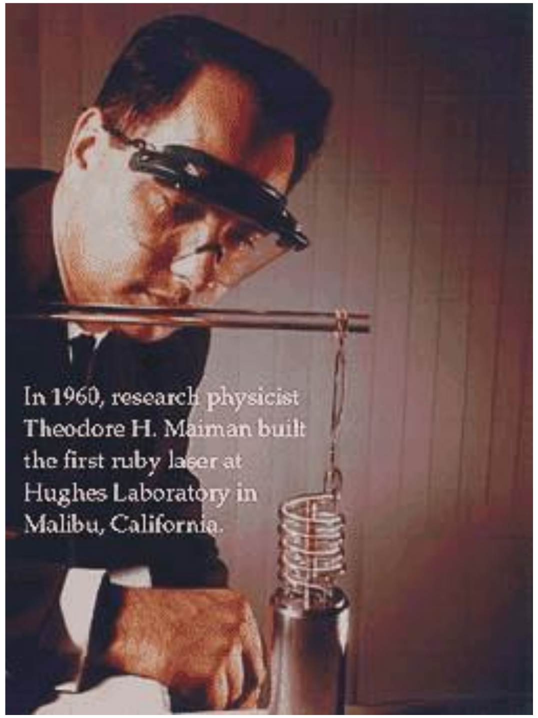
Three key elements to implement a laser

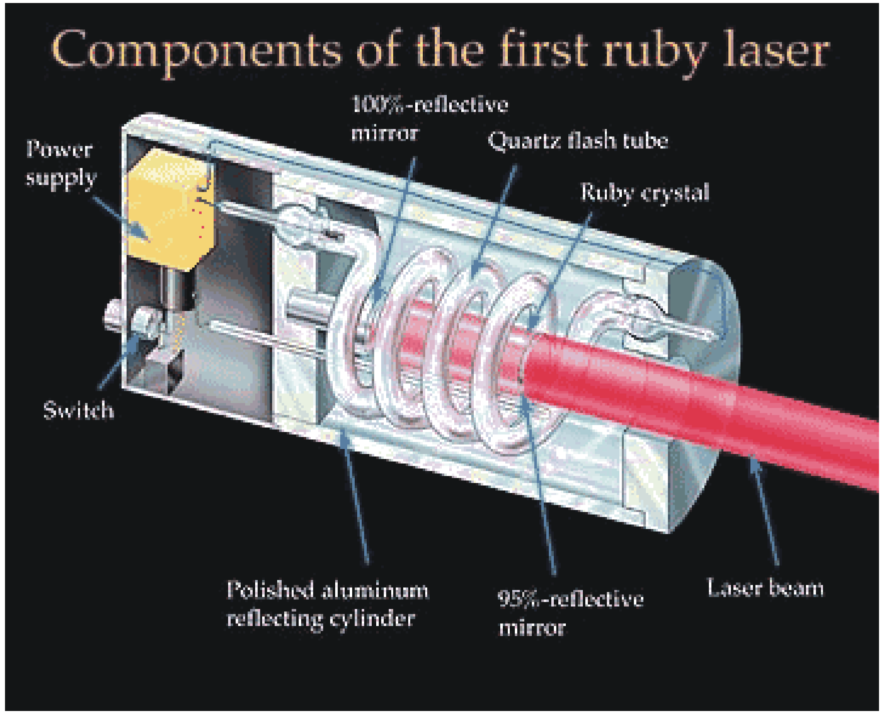




- **PUMP: provide energy;**
- **GAIN MEDIA: storage of the energy provided by pump through population inversion;**
- **RESONANT CAVITY: Light bounces back and forth within a cavity, gaining energy with each pass through the gain medium and transmitting part of the energy out of the cavity in the form of laser.**

Invention of laser





- May 16, 1960: first coherent optical beam generated from the LASER constructed by Theodore Maiman working at Hughes Laboratory.
- Submitted the results to PRL on June 22nd, and got rejected on 24th.
- July 7th, Public demonstration to the press at Hotel Delmonico in New York.

Invention of laser

The most valuable paper ever published in Nature

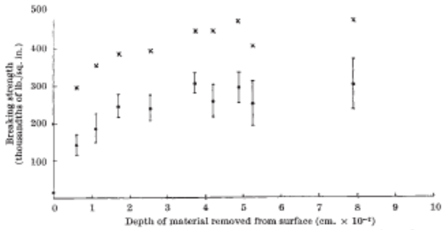


Fig. 1. Breaking strength as a function of depth of material removed from the surface. ×, Highest strength value in one group of rods; ●, mean strength and 95 per cent confidence limits for one group of rods

particular etching solution removes material from a glass surface it is possible to study the strength of etched specimens as a function of the depth of material removed from the surface. Such a study may give some information about the size and nature of the surface imperfections.

Commercially available soda-glass rods, of 6–8 mm. diameter, have been etched and broken in four point bending over a constant bending moment span of 1 in. The rod diameters and loads at fracture were measured and the breaking stresses calculated using the simple bending formula. Groups of rods (containing 16–32 rods) were given different periods of etching, and the depth of material removed from the surface of the rods was calculated for each group.

The variation of the mean breaking strength of these groups of rods, with depth of material removed from the surface, is shown in Fig. 1. Also shown on Fig. 1 are the 95 per cent confidence limits on the mean strength and the highest strength value recorded in each group of rods. Fig. 2 is a histogram comparing the distribution of breaking stresses for a group of rods which have been etched for 40 min. with that for unetched rods. The maximum strengths

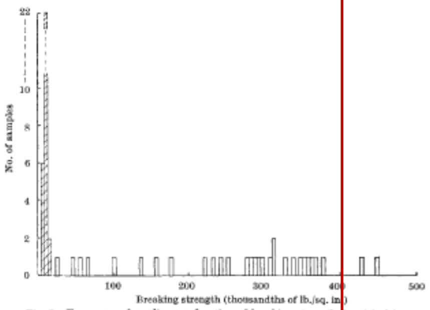


Fig. 2. Frequency of results as a function of breaking strength for etched (unshaded) and unetched (shaded) rods. The former were etched for 40 min.; depth removed from surface = 4·2 × 10⁻³ cm.

obtained with these bulk glass specimens are in the region 450,000–500,000 lb./sq. in. and closely approach the value obtained by Thomas[2] for fine glass fibres.

The glass rod used in these experiments had the following approximate composition by weight (percentages): SiO_2, 69; Na_2O, 16; CaO, 4; Al_2O_3, 3; MgO, 3.

The etching solution contained about 15 per cent hydrofluoric acid, 15 per cent sulphuric acid by weight and the remainder water.

Experiments are being continued to determine the effect on these results of varying the concentration, temperature and nature of the etchant; and of changing the thermal history, size and composition of the glass.

B. A. PROCTOR

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[1] Greene, C. H., J. Amer. Cer. Soc., 39, 66 (1956).
[2] Thomas, W. F., Nature, 181, 1006 (1958); Phys. and Chem. Glasses, 1, 4 (1960).

Stimulated Optical Radiation in Ruby

Schawlow and Townes[1] have proposed a technique for the generation of very monochromatic radiation in the infra-red optical region of the spectrum using an alkali vapour as the active medium. Javan[2] and Sanders[3] have discussed proposals involving electron-excited gaseous systems. In this laboratory an optical pumping technique has been successfully applied to a fluorescent solid resulting in the attainment of negative temperatures and stimulated optical emission at a wave-length of 6943 Å.; the active material used was ruby (chromium in corundum).

A simplified energy-level diagram for triply ionized chromium in this crystal is shown in Fig. 1. When this material is irradiated with energy at a wave-length of about 5500 Å., chromium ions are excited to the $^4F_2$ state and then quickly lose some of their excitation energy through non-radiative transitions to the ^2E state[4]. This state then slowly decays by spontaneously emitting a sharp doublet the components of which at 300° K. are at 6943 Å. and 6929 Å. (Fig. 2a). Under very intense excitation the population of this metastable state (^2E) can become greater than that of the ground-state; this is the condition for negative temperatures and consequently amplification via stimulated emission.

To demonstrate the above effect a ruby crystal of 1-cm. dimensions coated on two parallel faces with silver was irradiated by a high-power flash lamp;

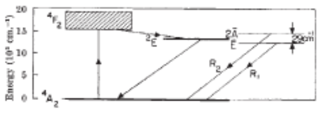

Fig. 1. Energy-level diagram of Cr^{3+} in corundum, showing pertinent processes

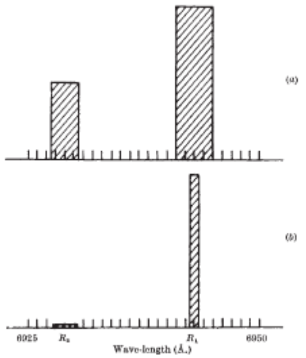

Fig. 2. Emission spectrum of ruby: a, low-power excitation; b, high-power excitation

the emission spectrum obtained under these conditions is shown in Fig. 2b. These results can be explained on the basis that negative temperatures were produced and regenerative amplification ensued. I expect, in principle, a considerably greater (~ 10⁸) reduction in line width when mode selection techniques are used[1].

I gratefully acknowledge helpful discussions with G. Birnbaum, R. W. Hellwarth, L. C. Levitt, and R. A. Satten and am indebted to I. J. D'Haenens and C. K. Asawa for technical assistance in obtaining the measurements.

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[1] Schawlow, A. L., and Townes, C. H., Phys. Rev., 112, 1940 (1958).
[2] Javan, A., Phys. Rev. Letters, 3, 87 (1959).
[3] Sanders, J. H., Phys. Rev. Letters, 3, 86 (1959).
[4] Maiman, T. H., Phys. Rev. Letters, 4, 564 (1960).

METALLURGY

A Simple Method of investigating the Creep of Metals under Simple Shear

DR. K. H. JOLLIFFE and I[1] have investigated the creep of metals under simple shear by the use of a disk of the metal in question, in which is cut a concentric circular annulus, the metal external to the annulus being securely gripped, while that internal to the annulus is subjected to a constant torque. We have shown that the behaviour of the metal in these circumstances is in many ways simpler and more informative than that exhibited by wires or rods under tension.

From the point of view of the industrial study of creep, the method has the disadvantage that the specimens are somewhat troublesome to prepare and measure. To get over this difficulty I have devised a method in which the specimen has the form shown in Fig. 1. In the plate ABCD (Fig. 1a) are cut rectangular grooves MNOP, QRST, as shown in cross-section in Fig. 1b. The metal ABNM, TSCD is securely held, and a force F applied to the metal PORQ in a direction parallel to the grooves. Under these conditions the shear stress distribution in the rectangular plates MNOP, QRST is not strictly uniform, as it is in the disk method, which is clear from the fact that the shear stress over the free ends must be zero. The distribution has been worked out by me[2] and by C. E. Inglis[3].

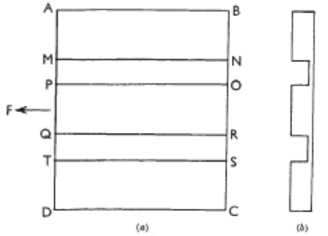

Fig. 1

Mr. D. B. Gilding has been working under my direction on the best form of the plate and has established that if the ratio of MN to NO is in the region of 7, the results on creep obtained with the disposition described correspond closely to those obtained by the method of Andrade and Jolliffe[1]. It seems possible that the new method may be of use in further investigations of creep and may also have applications to the problem of fatigue.

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[1] Andrade, E. N. da C., and Jolliffe, K. H., Proc. Roy. Soc., A, 213, 3 (1952); 254, 291 (1960).
[2] Andrade, E. N. da C., Proc. Roy. Soc., A, 85, 448 (1911).
[3] Inglis, C. E., Proc. Roy. Soc., A, 103, 598 (1923).

An Improvement in the Ductility of Beryllium at High Temperatures

THE outstanding problem in beryllium metallurgy is the lack of ductility exhibited by the metal, both at room temperature and at elevated temperatures. At room temperature, brittleness can be attributed to the ease of cleavage of basal planes of the hexagonal lattice, and to the high yield-strength of the prismatic planes, while at temperatures above 400° C., intergranular failure predominates. A ductility maximum occurs at intermediate temperatures depending on the strain-rate used, tensile specimens failing with

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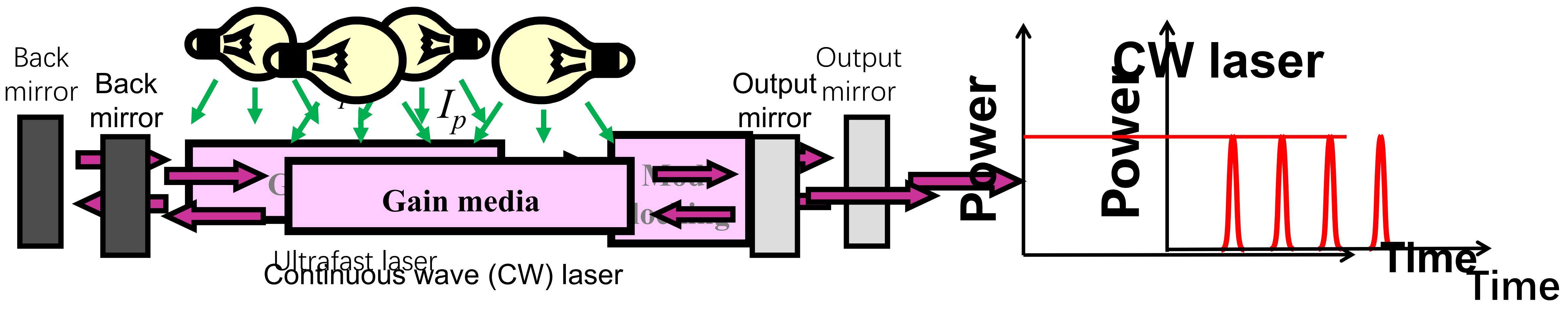
Generation of ultrafast laser pulses: mode locking

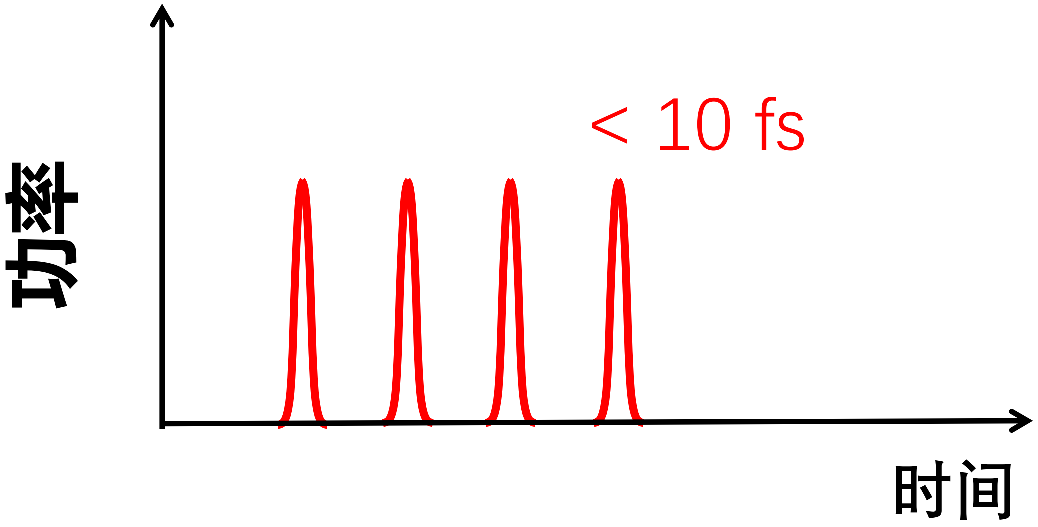


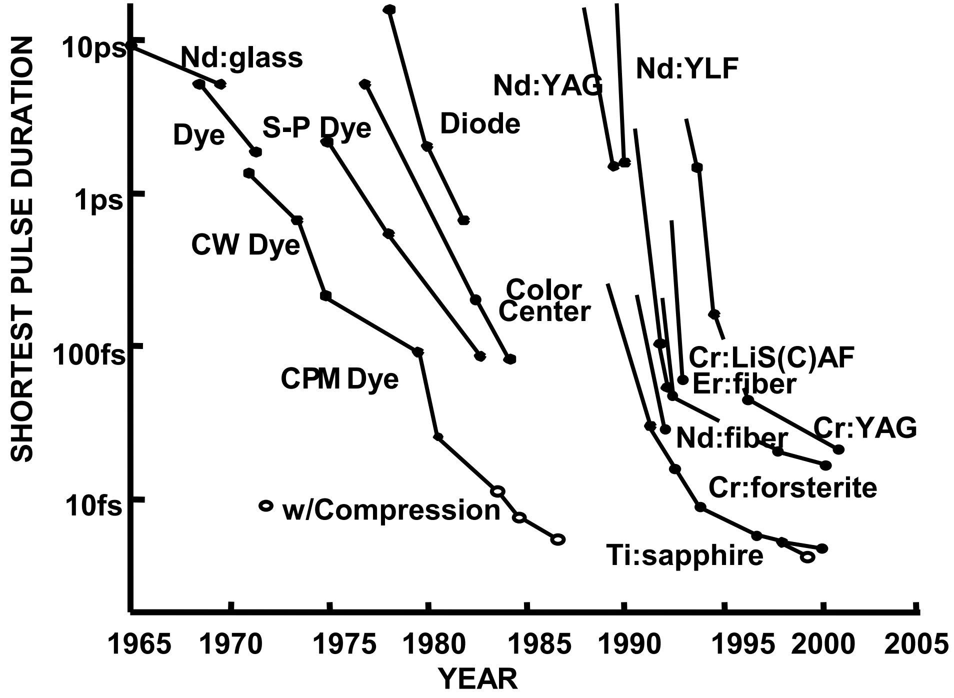
Four key elements to implement an ultrafast laser

- **PUMP: provide energy;**
- **GAIN MEDIA: storage of the energy provided by pump through population inversion;**
- **RESONANT CAVITY: Light bounces back and forth within a cavity, gaining energy with each pass through the gain medium and transmitting part of the energy out of the cavity in the form of laser;**
- **MODE LOCKING: generate phase relation between different longitudinal modes;**

Characters of ultrafast laser pulses:

ultrashort





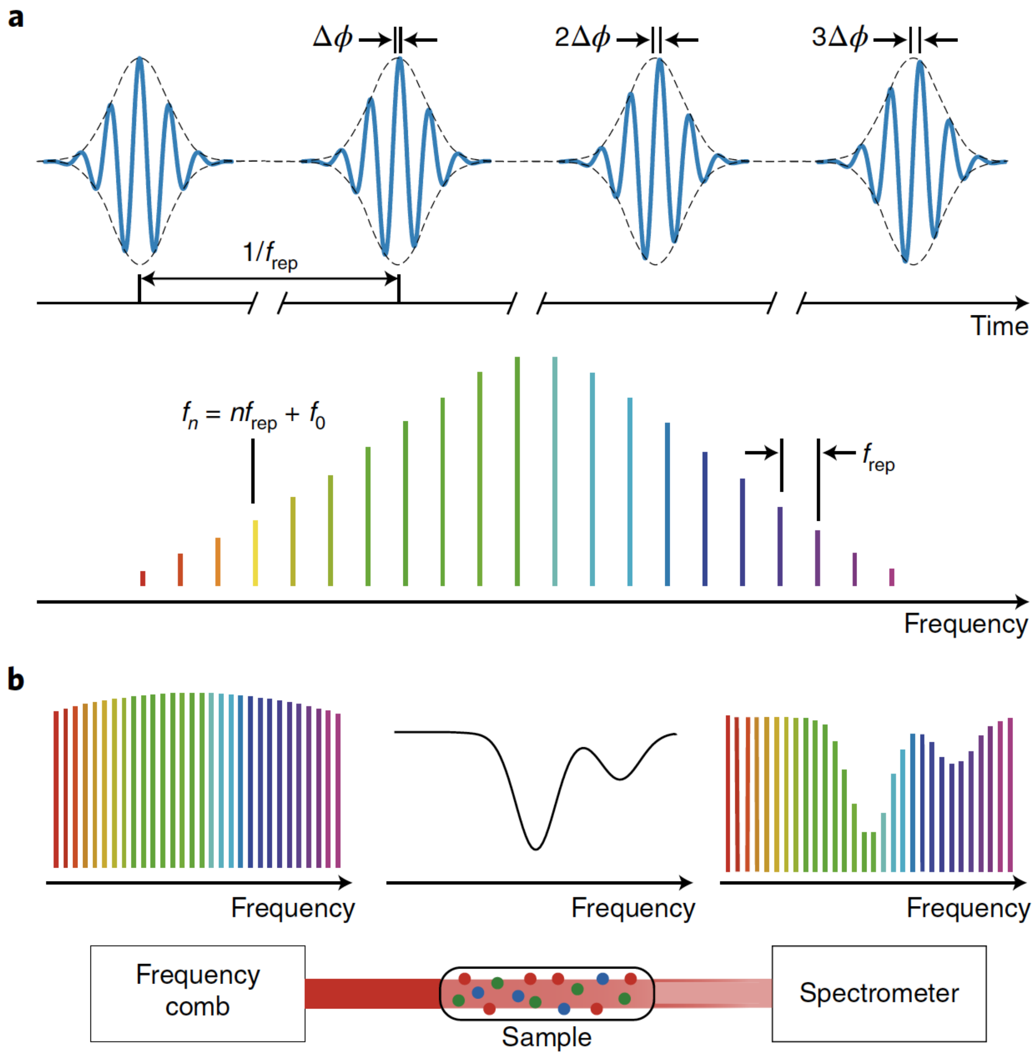
Characters of ultrafast laser pulses:

ultrahigh peak power

SULF petawatt laser from SIOM: 10 PW=1×10^{16} W, (Generation capacity of the Three Gorges hydroelectric station: 23 GW=2.3×10^{10} W)

Characters of ultrafast laser pulses:

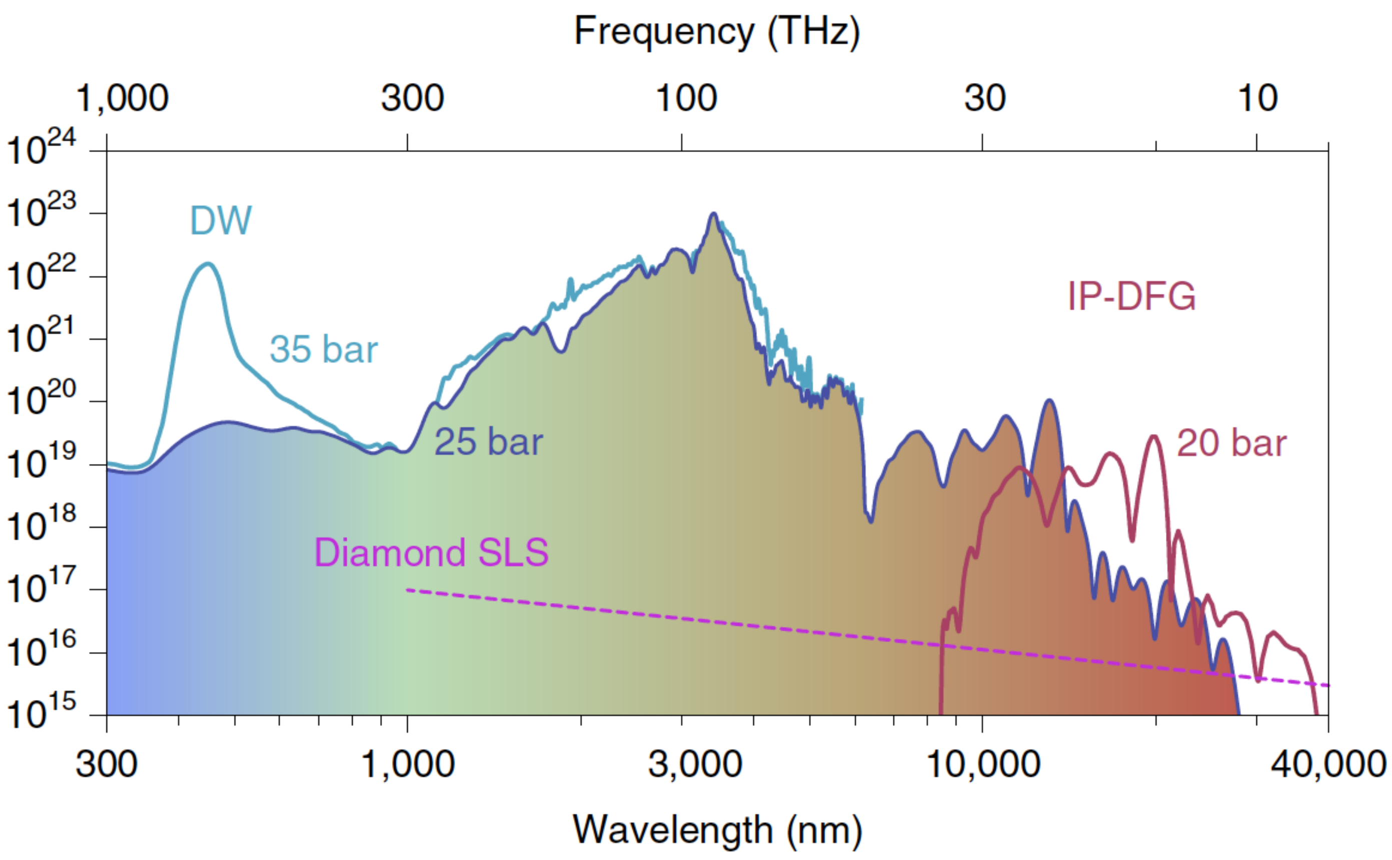
coherence



Nature Photonics **13**, 146 (2019)

Characters of ultrafast laser pulses:

broad spectrum



Nature Photonics **15**, 277 (2021)

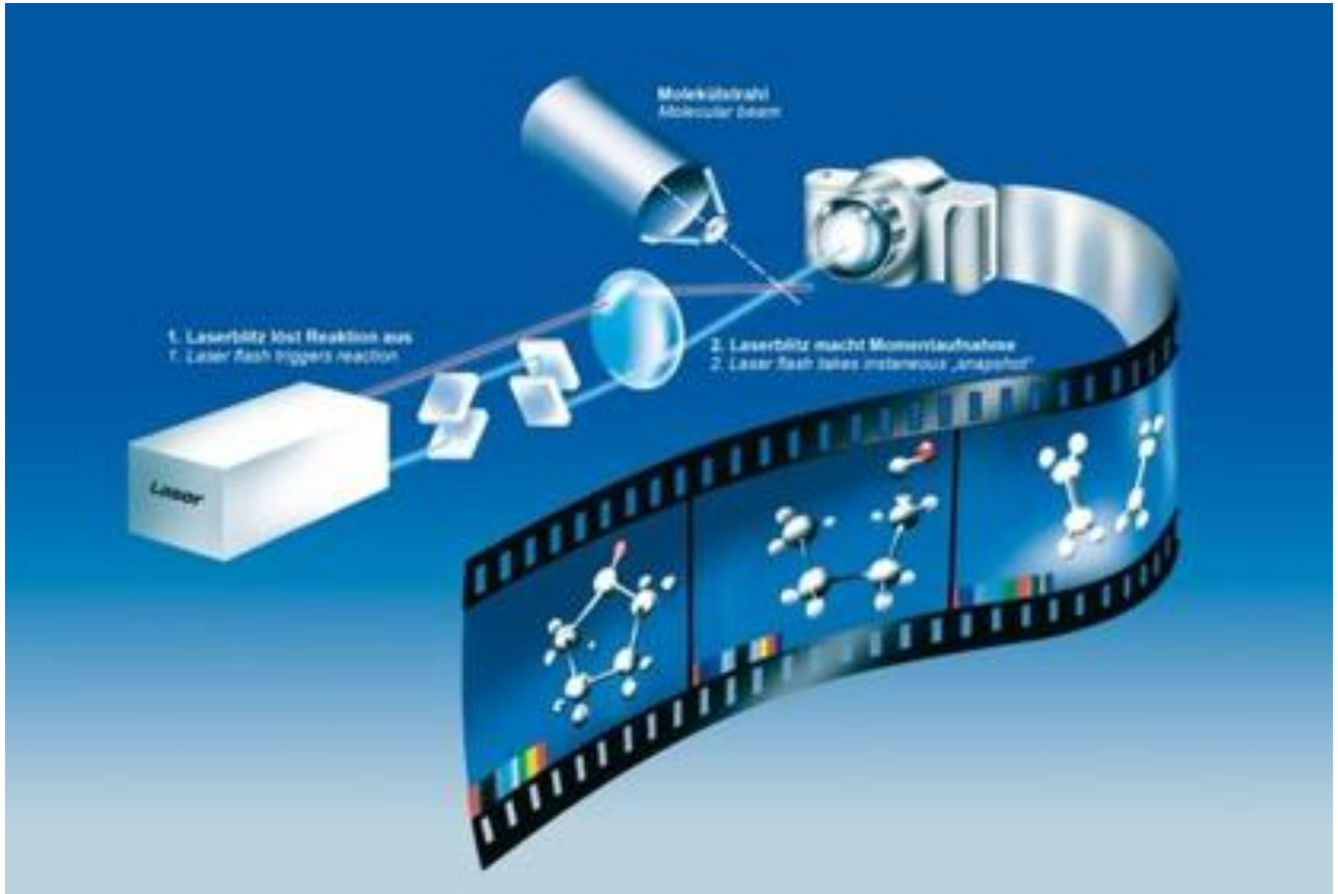
Femtochemistry: molecular "movie"

The Nobel Prize in Chemistry 1999

"for his studies of the transition states of chemical reactions using femtosecond spectroscopy"

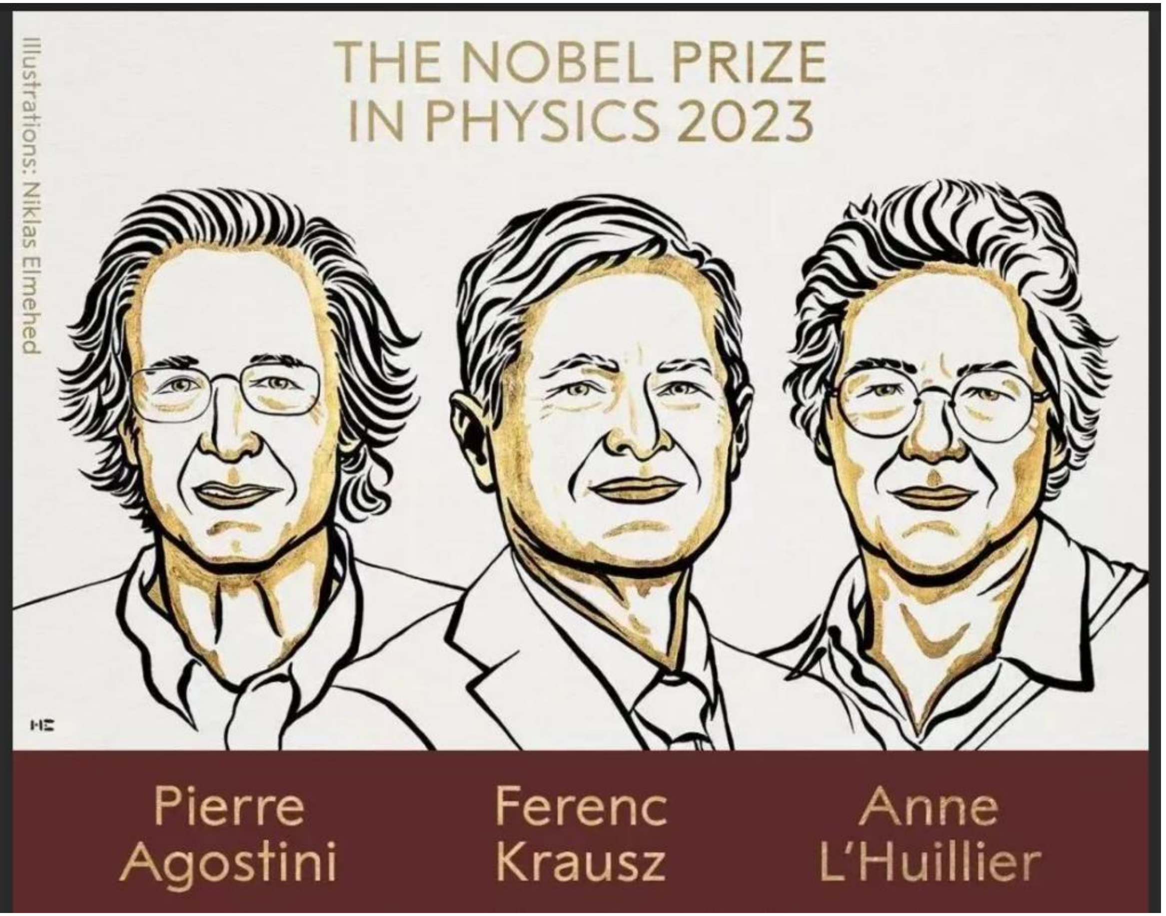
Ahmed H. Zewail

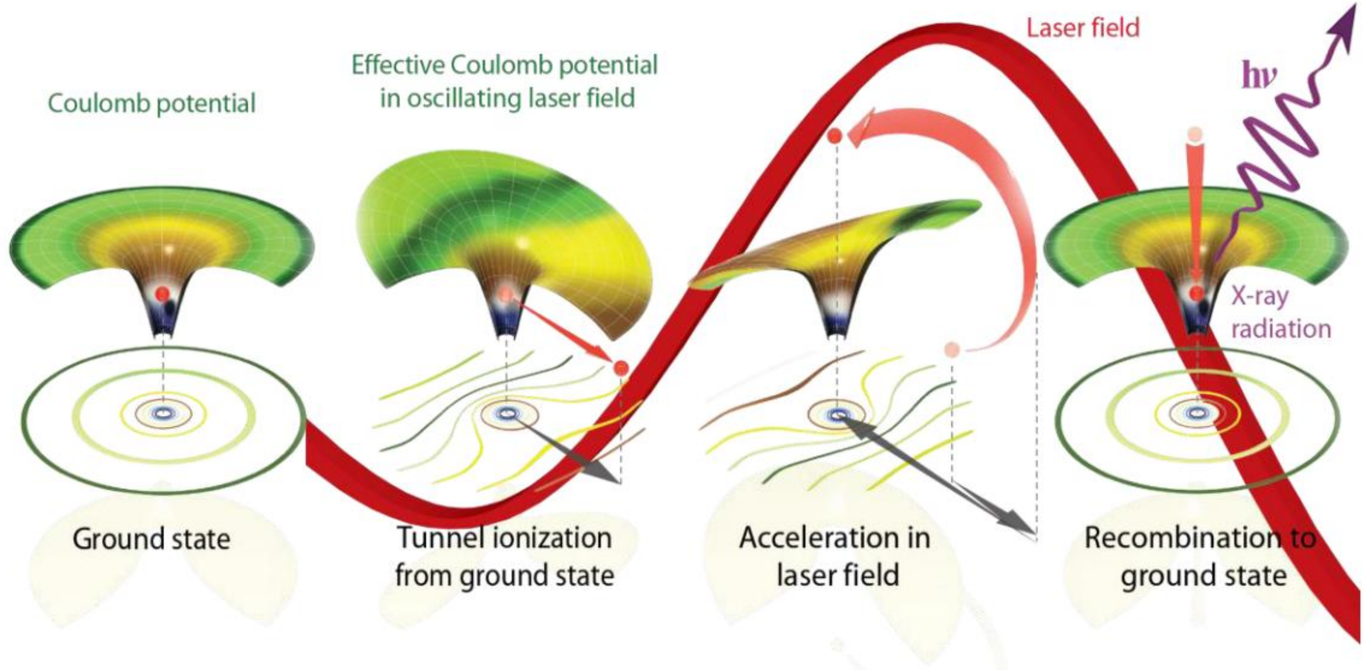
Egypt and USA



Exploiting the ultrashort pulse duration of fs laser pulses

attosecond optics

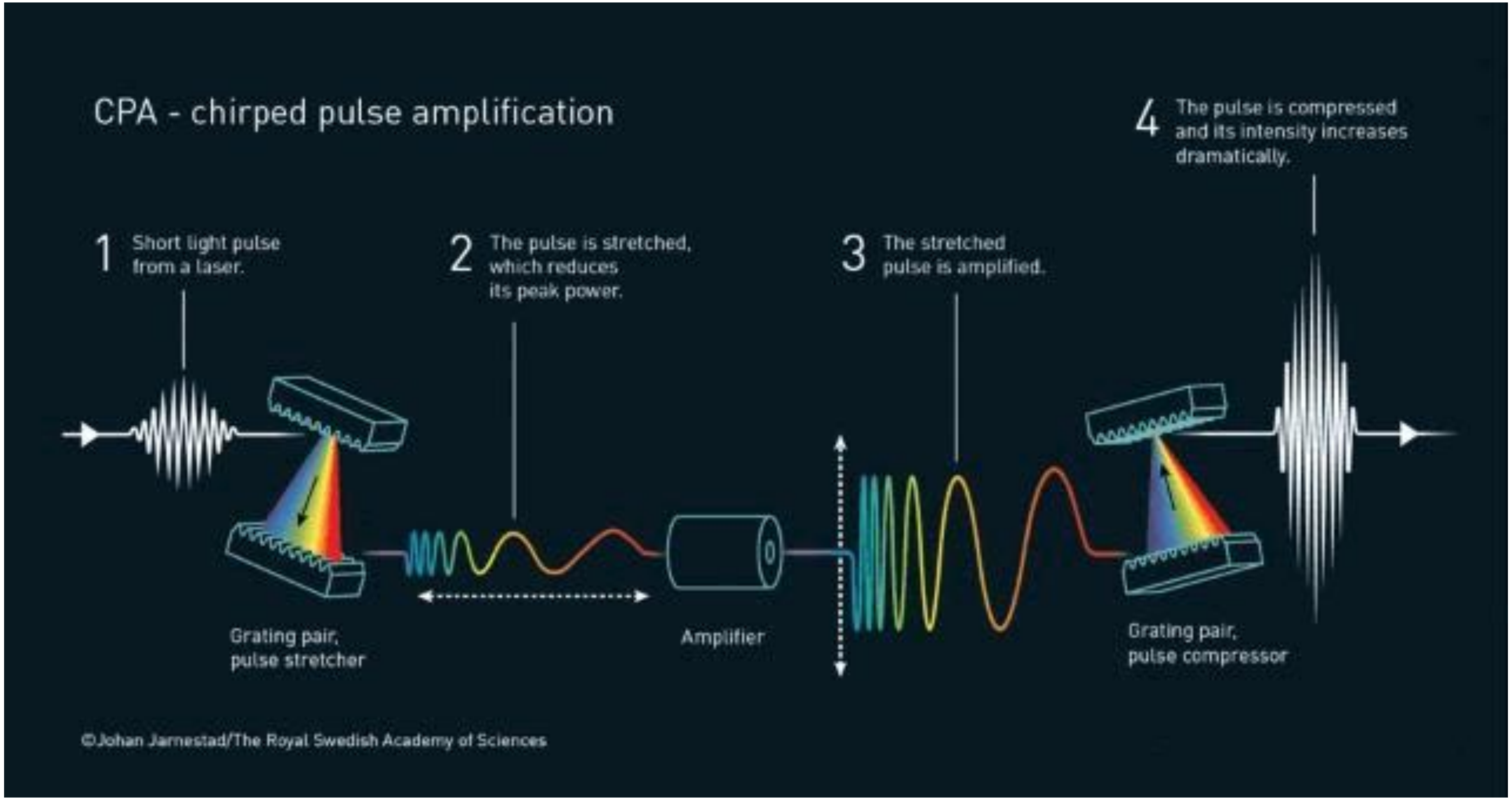


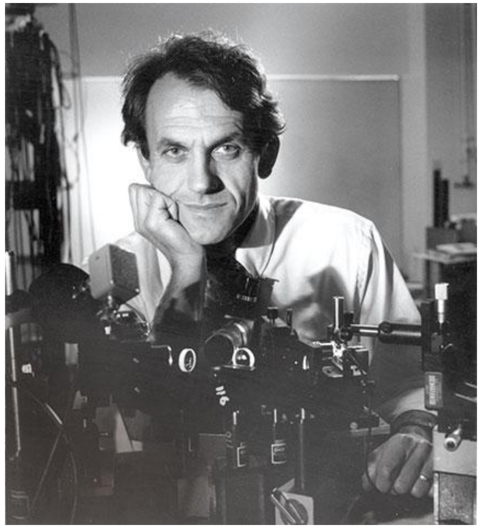


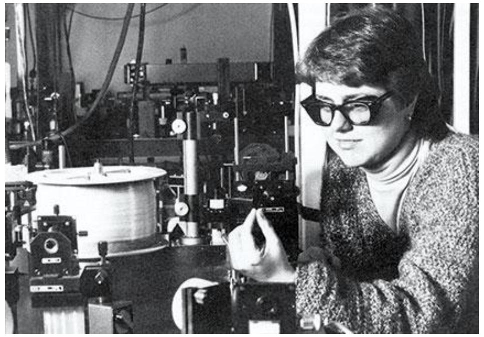
Nat. Photonics **4**, 822 (2010)

the shortest optical pulse ever generated is only 43 attosecond

Pulse energy amplification technology: chirped pulse amplification (CPA)







Nobel prize in physics in 2018

Optical frequency comb

The Nobel Prize in Physics 2005

"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique."

https://www.nobelprize.org/prizes/physics/2005/summary/

Photo: Sears.P.Studio

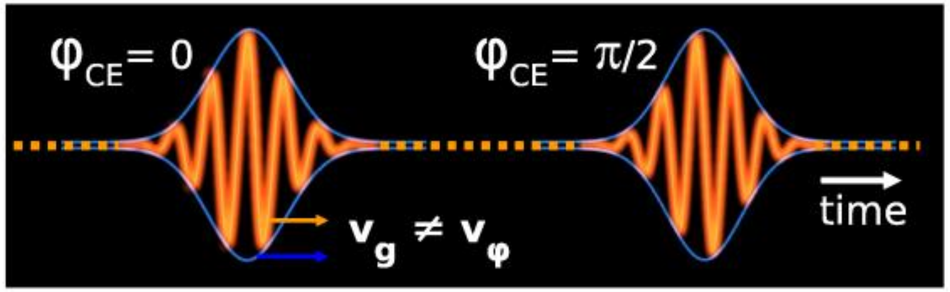
John L. Hall

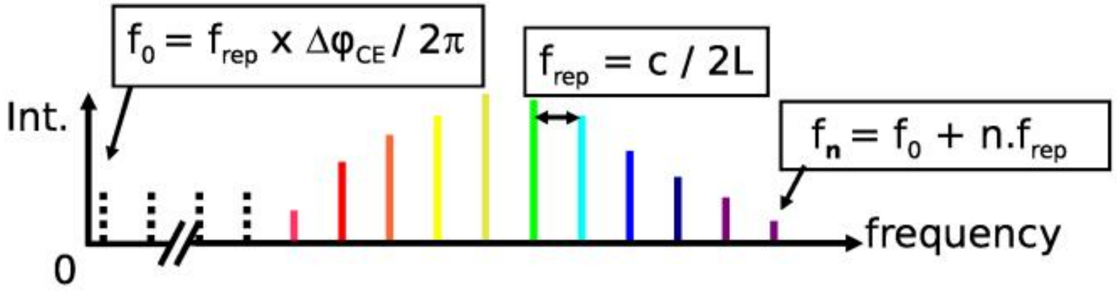
Prize share: 1/4

Photo: F.M. Schmidt

Theodor W. Hänsch

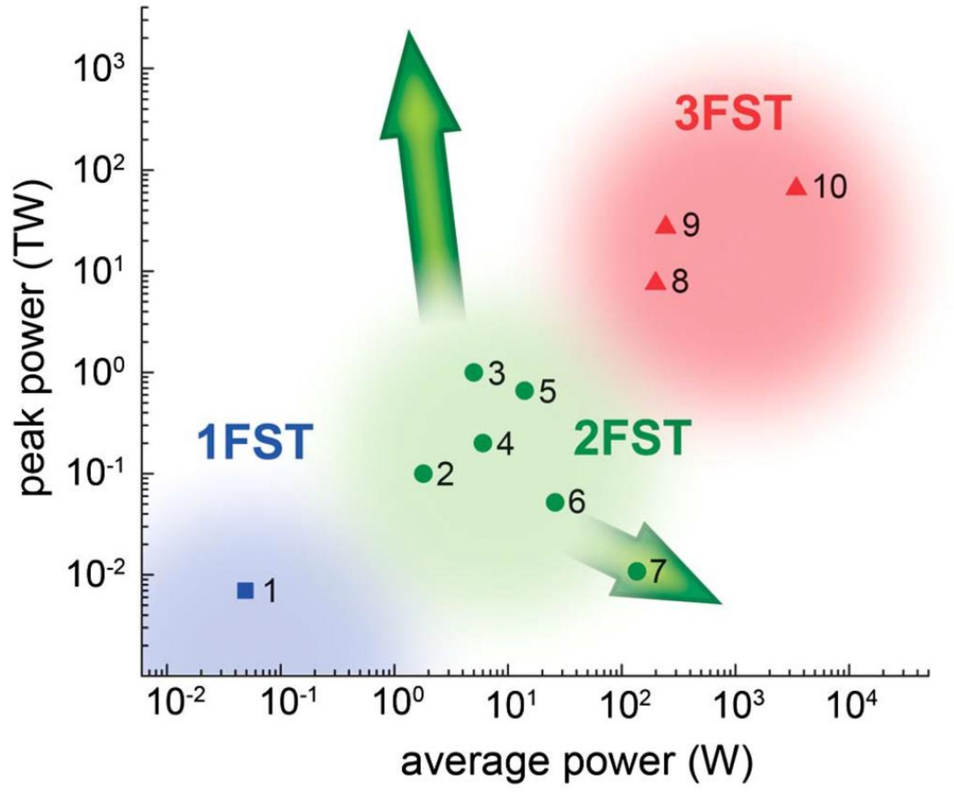
Prize share: 1/4





Exploiting the full coherence of fs laser pulses

Development of ultrafast laser technology



Optica **1**, 45 (2014)

1st	dye laser μJ pulse energy, MW peak power
2nd	CPA based Ti:Sa laser, Yb-doped fiber, slab, disk lasers 10 W average power, PW peak power, or 100 W average power, GW peak power
3rd	Yb-doped lasers + OPCPA or post compression KW average power, TW peak power

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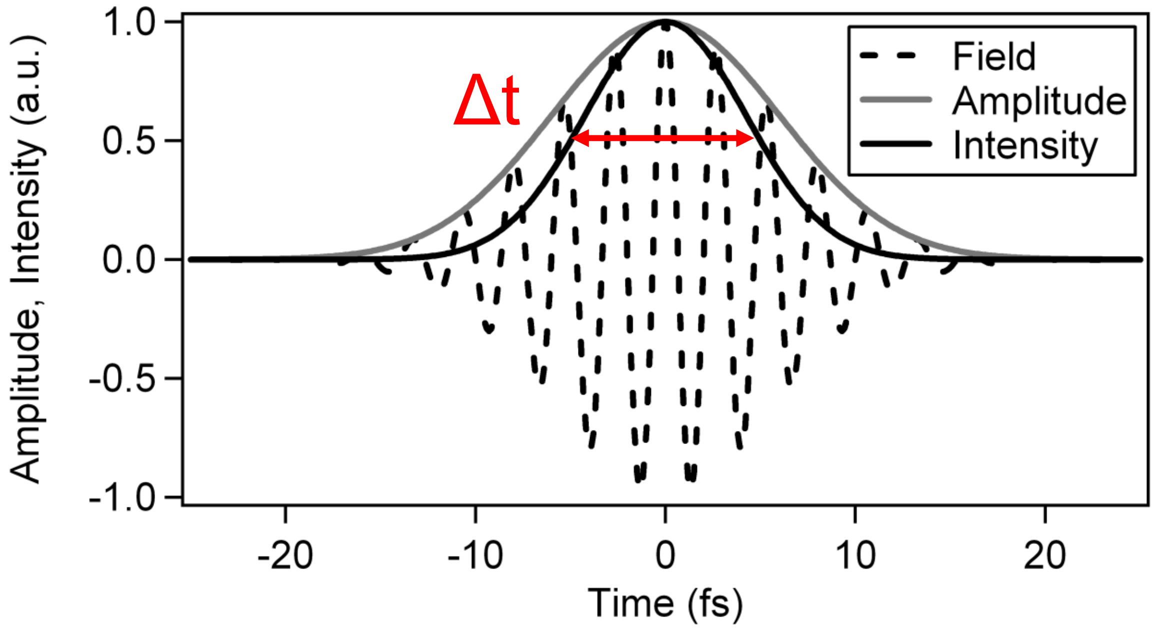
An ultrafast laser pulse: electric field and intensity distributions



$E(t) = \sqrt{I(t)}\cos(\omega_0 t - \phi(t))$ pulse energy $\propto \int |E(t)|^2 dt$

I(t): Intensity profile; Δt: FWHM of intensity distribution;

ω_0: carrier angular frequency; $\phi(t)$: phase in time-domain;

800 nm: 2π x 3.7e10^{14} Hz, T=2.67 fs;

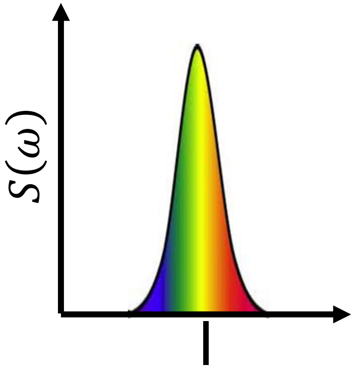
Electric field and spectrum amplitude: the Fourier Transform

Electric field

$$E(t) = \sqrt{I(t)}\cos(\omega_0 t - \phi(t))$$

Spectrum amplitude

$$E(\omega) = \sqrt{S(\omega)}\exp\{-i\varphi(\omega)\}$$



- **Both electric field and spectrum amplitude contains the complete information of the pulse. However, to think about ultrashort laser pulses, the Fourier Transform is essential: always consider things from both perspectives.**

$$\widetilde{E}(\omega) = \int_{-\infty}^{\infty} E(t)\, exp(-i\omega t)\, dt$$

$$E(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \widetilde{E}(\omega) exp(i\omega t)\, d\omega$$

We always perform Fourier transforms on the real or complex pulse electric field.

Continuous vs. ultrashort pulses of light

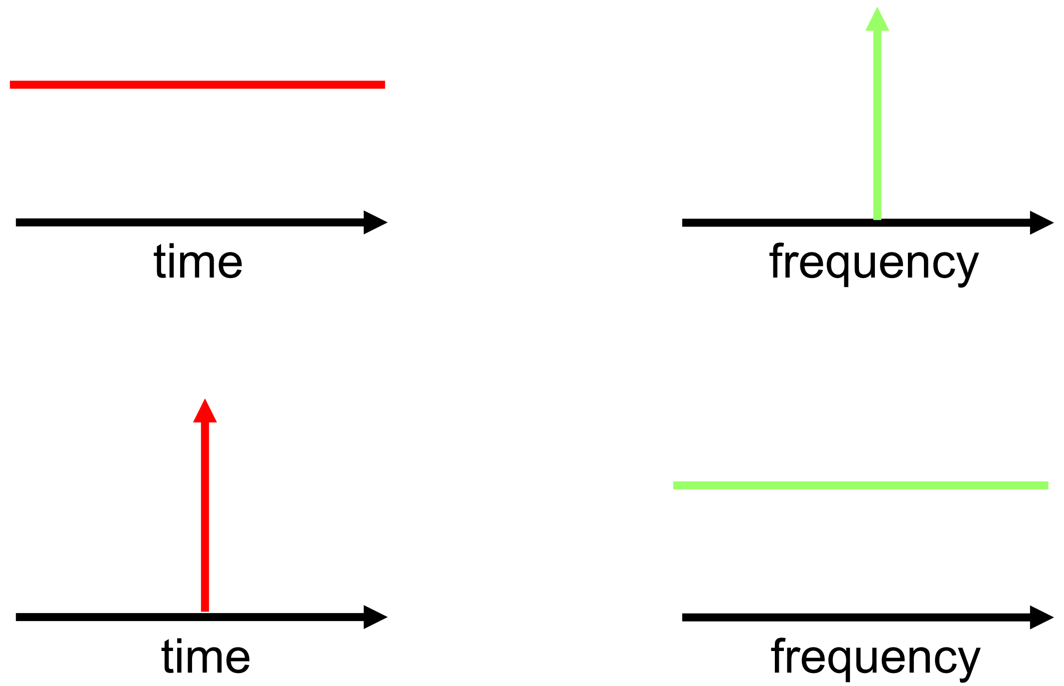
A constant and a delta-function are a Fourier-Transform pair.

Irradiance vs. time

Spectrum

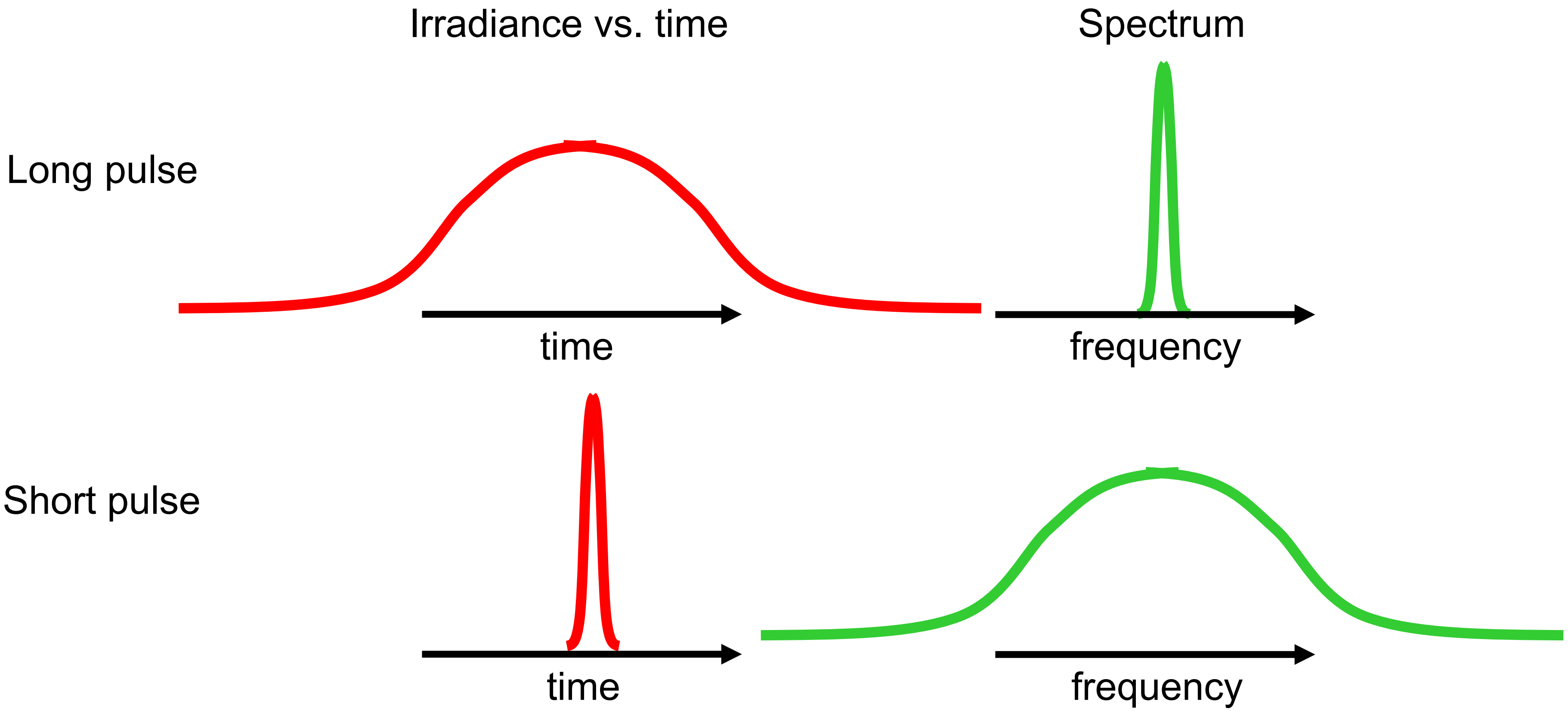
Continuous beam:

Ultrashort pulse:

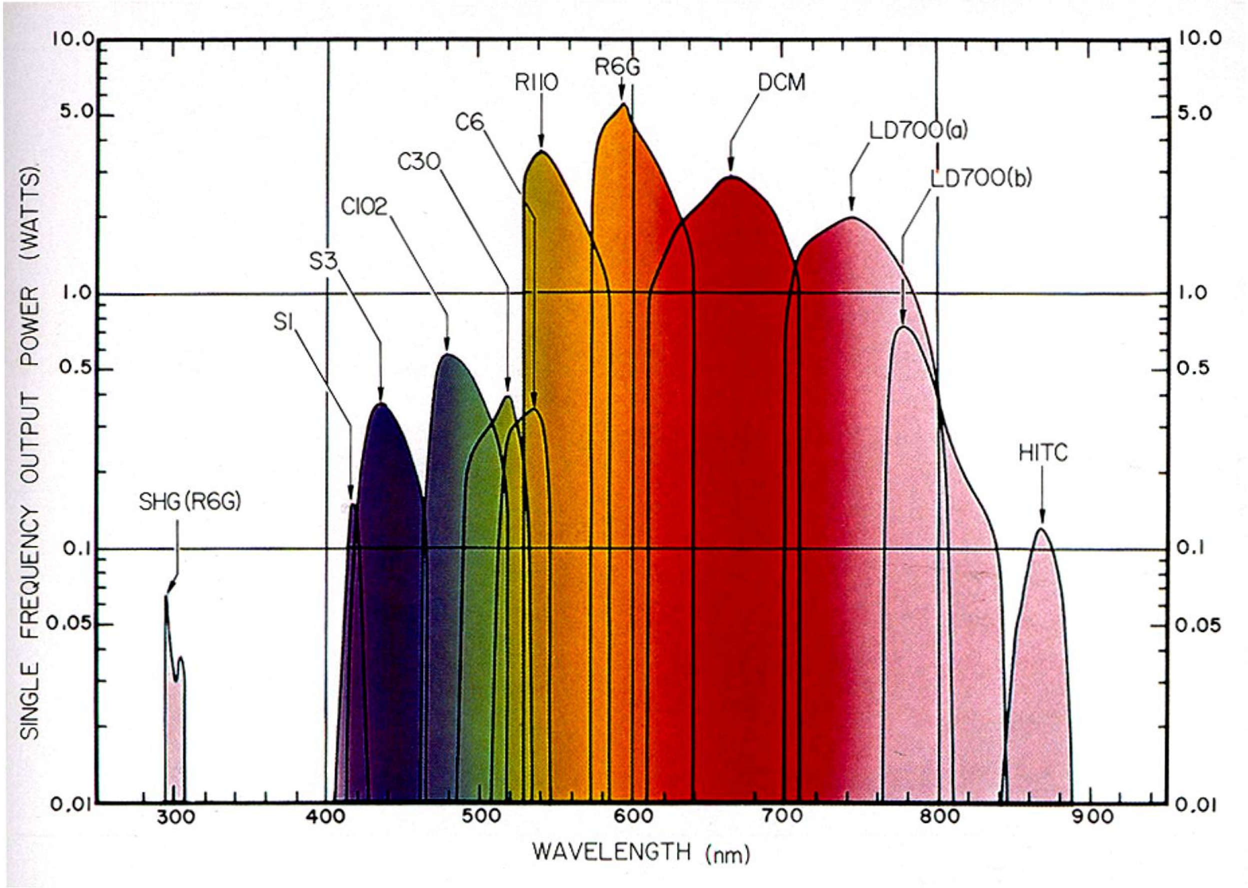


Long vs. short pulses of light

The uncertainty principle says that the product of the temporal and spectral pulse widths is greater than ~1.



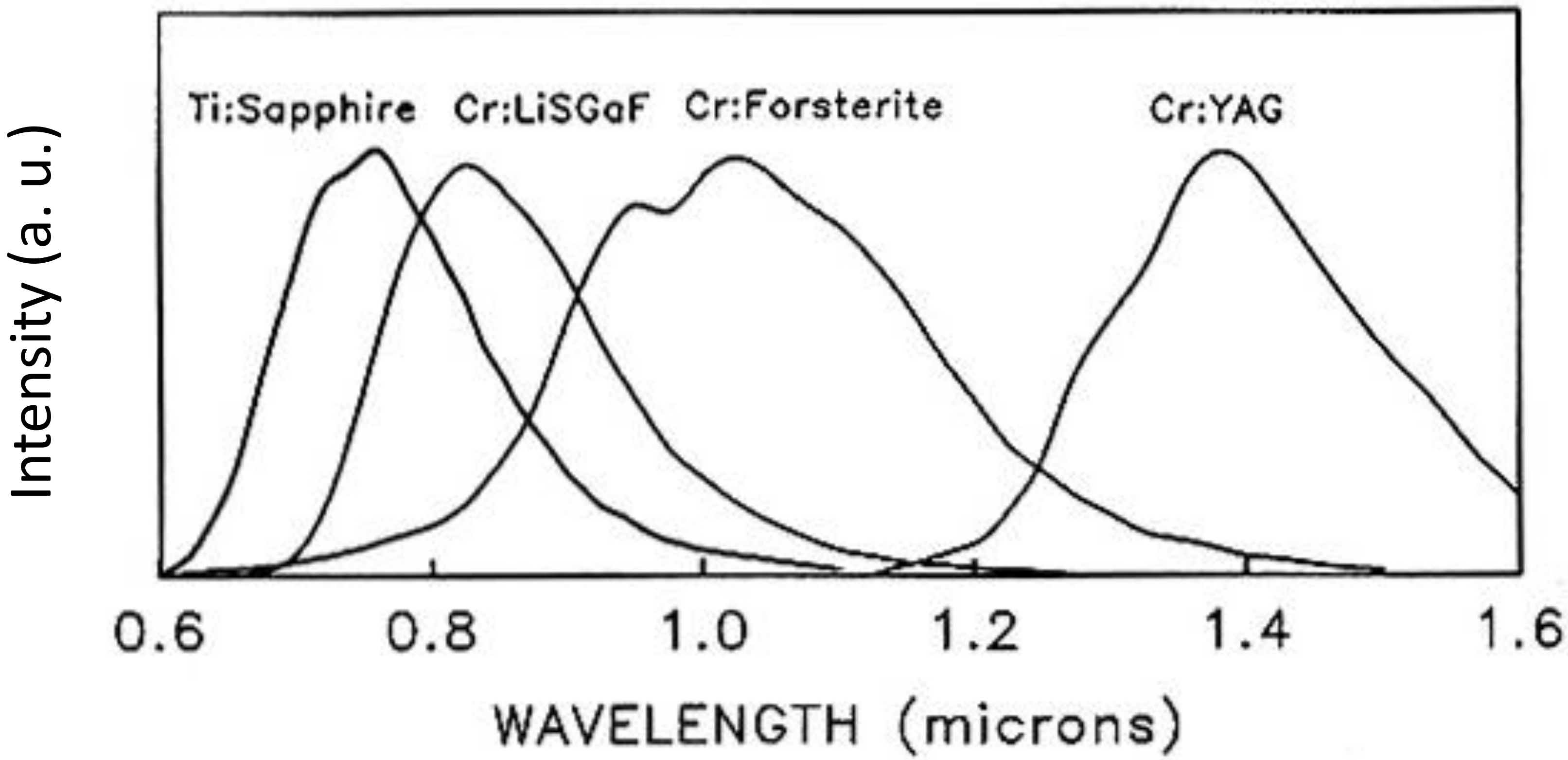
broadband gain media



For many years, dyes have been the broadband media that have generated ultrashort laser pulses.

broadband gain media

Solid-state laser media have broad bandwidths and are convenient.



A little bit more on phase

Electric field and phase

$$\mathscr{E}(\mathrm{t}) = \frac{1}{2}\sqrt{I(t)}\cos(\omega_0 t - \phi(t))$$

Phase Taylor Series expansions:

$$\phi(t) = \phi_0 + \phi_1 \frac{t}{1!} + \phi_2 \frac{t^2}{2!} + \phi_3 \frac{t^3}{3!} + \cdots$$

Spectrum and spectral phase

$$\mathscr{E}(\omega) = \sqrt{S(\omega)}\exp\{-\mathrm{i}\varphi(\omega)\}$$

Phase Taylor Series expansions:

$$\varphi(\omega) = \varphi_0 + \varphi_1 \frac{\omega - \omega_0}{1!} + \varphi_2 \frac{(\omega - \omega_0)^2}{2!} + \varphi_3 \frac{(\omega - \omega_0)^3}{3!} + \cdots$$

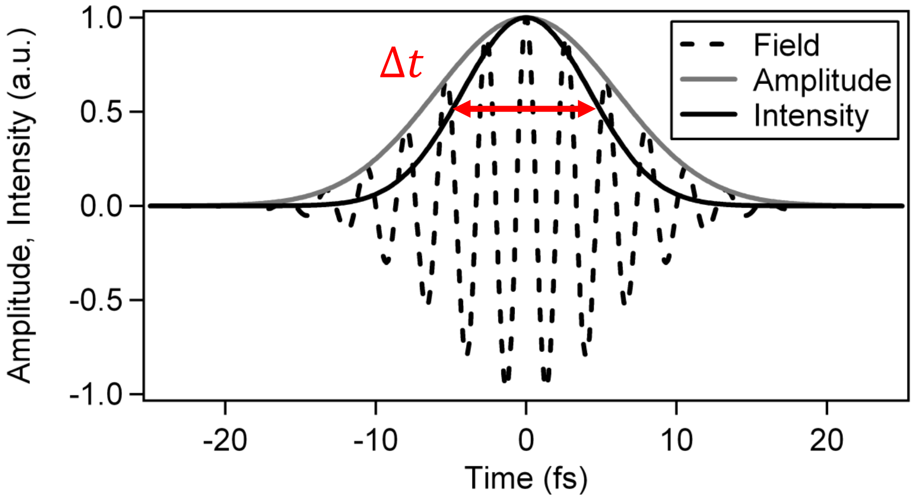
- If $\phi_n(n > 1) = 0$,

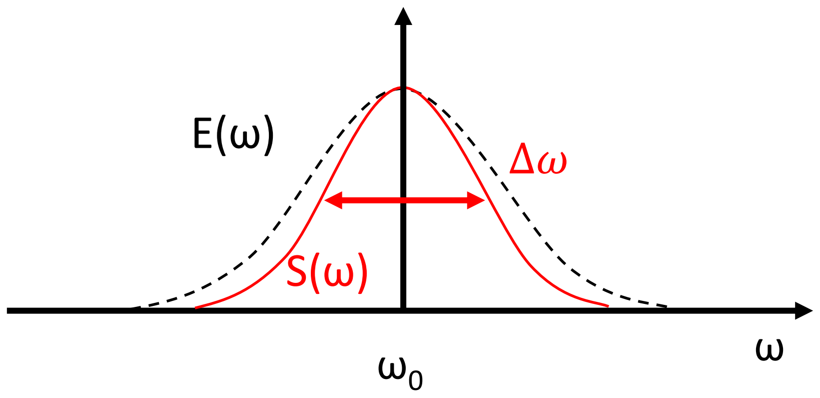
  $$\mathscr{E}(\mathrm{t}) = \frac{1}{2}\sqrt{I(t)}\cos(\omega_0 t - \phi(t)) = \frac{1}{2}\sqrt{I(t)}\cos\{(\omega_0 - \phi_1)t - \phi_0\},$$

  electric field oscillates with a fixed frequency, this pulse is called transform limited, bandwidth-limited, or unchirped.

- **If the second or higher orders derivative of phase are non-zero, oscillation frequency changes within the pulse.** In analogy to bird sounds, this pulse is called a "chirped" pulse.

A transform limited Gaussian pulse and its spectrum





$$\mathscr{E}(t) = \frac{E_0}{2} e^{-2ln2\frac{t^2}{\Delta t^2}} cos(\omega_0 t - \phi_0)$$

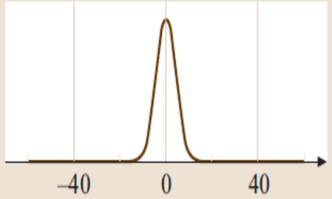
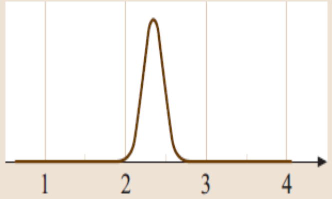
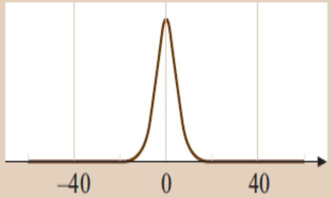
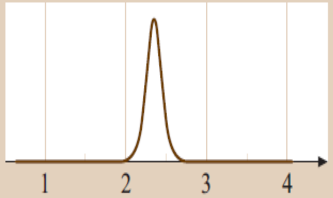
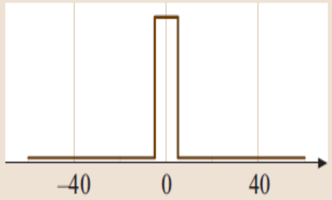
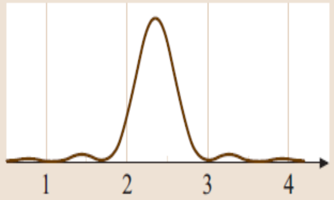
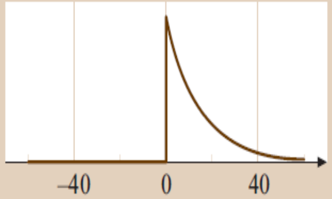
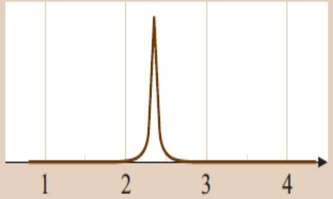
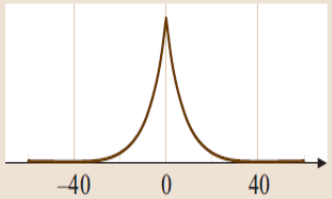
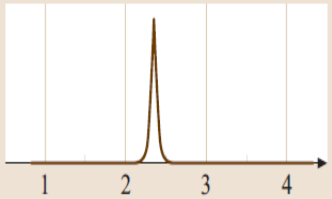
$$E(\omega) = \mathcal{F}\{E(t)\} = \frac{E_0 \Delta t}{2}\sqrt{\frac{\pi}{2ln2}}\, e^{-\frac{\Delta t^2}{8ln2}(\omega-\omega_0)^2}$$

Δt: FWHM of intensity distribution;
Φ_0: carrier to envelop phase;
ω_0: carrier angular frequency;
Δω: FWHM of the spectrum;

$$\Delta t \frac{\Delta\omega}{2\pi} = 0.441$$

For a FT limited pulse of 100 fs, the FWHM of spectrum is 147 cm^{-1}.

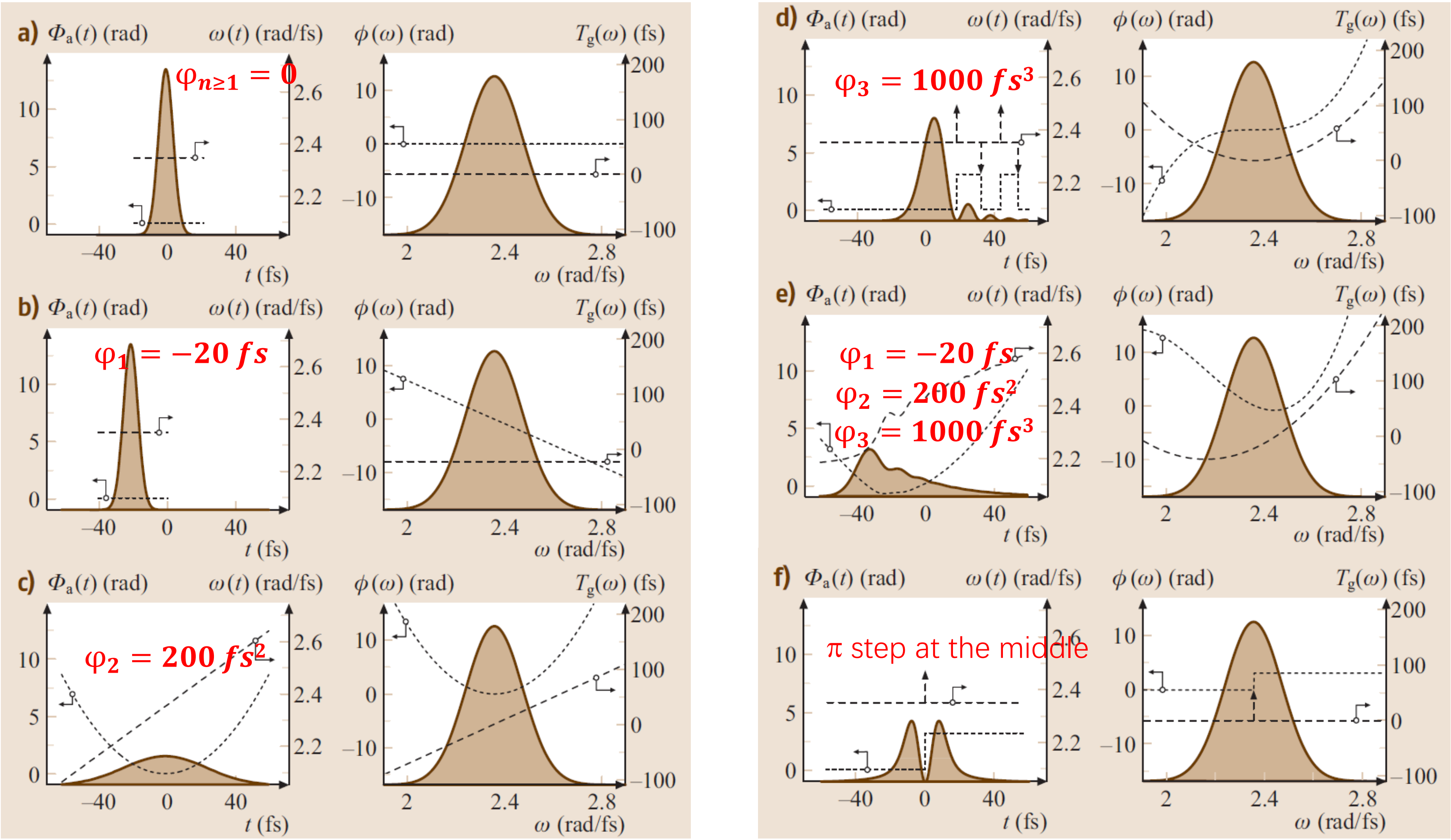
Temporal and spectral intensity profiles and time bandwidth products ($\Delta\nu\Delta t \geq K$) of various pulse shapes

Shape	$I(t)$	$I(\omega)$	$\Delta\nu\cdot\Delta t$	
Gaussian			0.441	$\mathscr{E}(t) = \frac{E_0}{2} e^{-2ln2\frac{t^2}{\Delta t^2}}$ $\mathscr{E}(\omega) = \frac{E_0 \Delta t}{2}\sqrt{\frac{\pi}{2ln2}}\, e^{-\frac{\Delta t^2}{8ln2}(\omega-\omega_0)^2}$
Hyperbolic sechant			0.315	$\mathscr{E}(t) = \frac{E_0}{2} sech[2ln(1+\sqrt{2})\frac{t}{\Delta t}]$ $\mathscr{E}(\omega) = E_0\Delta t \frac{\pi}{4\ln(1+\sqrt{2})} \mathrm{sech}(\frac{\pi\Delta t}{4\ln(1+\sqrt{2})}\omega)$
Square			0.886	$\mathscr{E}(t) = \frac{E_0}{2}\ t \in \left[-\frac{\Delta t}{2}, \frac{\Delta t}{2}\right]$ $\mathscr{E}(\omega) = \frac{E_0\Delta t}{2} sinc(\frac{\Delta t}{2}\omega)$
Single sided exponential			0.110	$\mathscr{E}(t) = \frac{E_0}{2} e^{-\frac{ln2}{2}\frac{t}{\Delta t}}\ t \in [0,\infty]$ $\mathscr{E}(\omega) = \frac{E_0\Delta t}{2i\Delta t\omega + ln2}$
Symmetric exponential			0.142	$\mathscr{E}(t) = \frac{E_0}{2} e^{-ln2\frac{t}{\Delta t}}\ t \in [0,\infty]$ $\mathscr{E}(\omega) = \frac{E_0\Delta t ln2}{\Delta t^2\omega^2 + (ln2)^2}$

Effects of the spectral phase on ultrashort pulses

$\mathscr{E}(\omega) = \sqrt{S(\omega)}\exp\{-i\varphi(\omega)\}$

$$\varphi(\omega) = \varphi_0 + \varphi_1 \frac{\omega - \omega_0}{1!} + \varphi_2 \frac{(\omega - \omega_0)^2}{2!} + \varphi_3 \frac{(\omega - \omega_0)^3}{3!} + \cdots$$

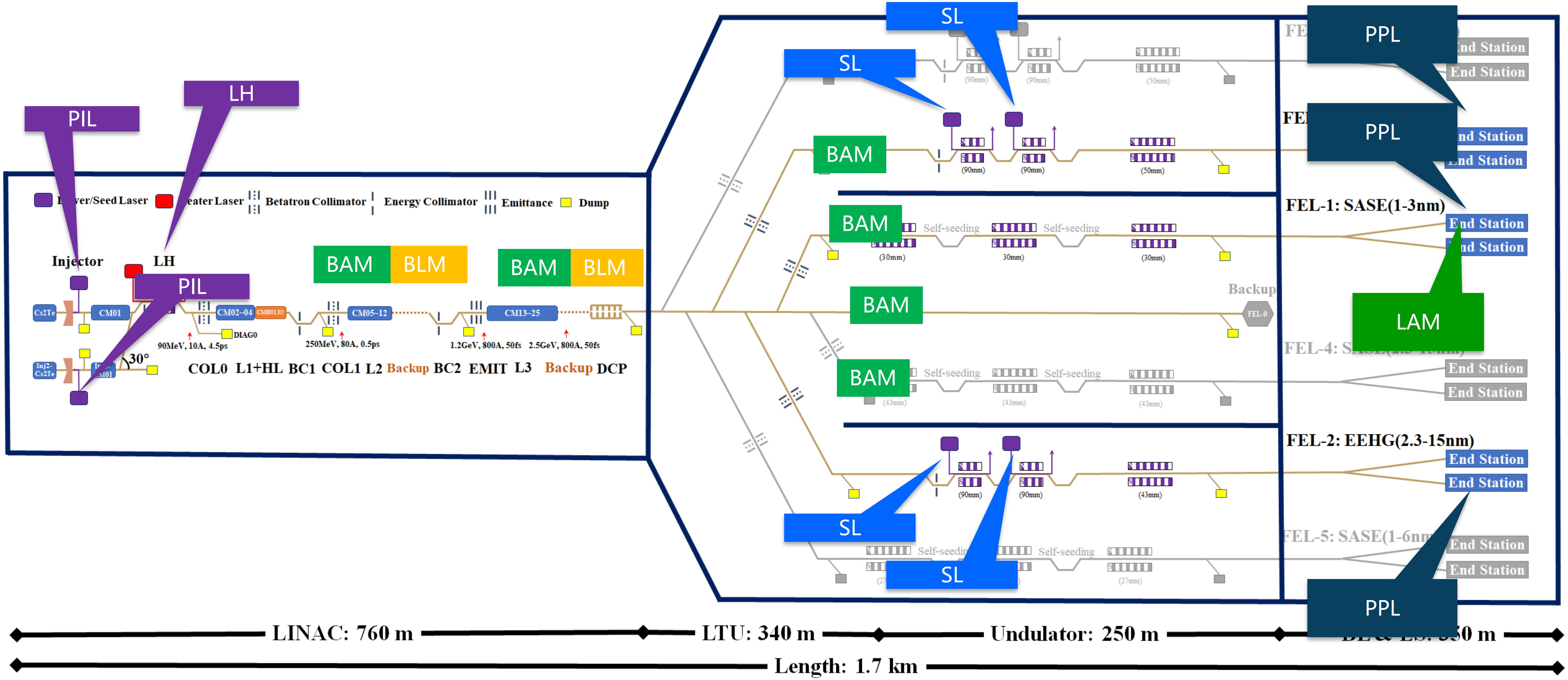


Springer Handbook of Lasers and Optics, Frank Träger (Ed.), 2007, Springer Science+Business Media, LLC New York.

outline

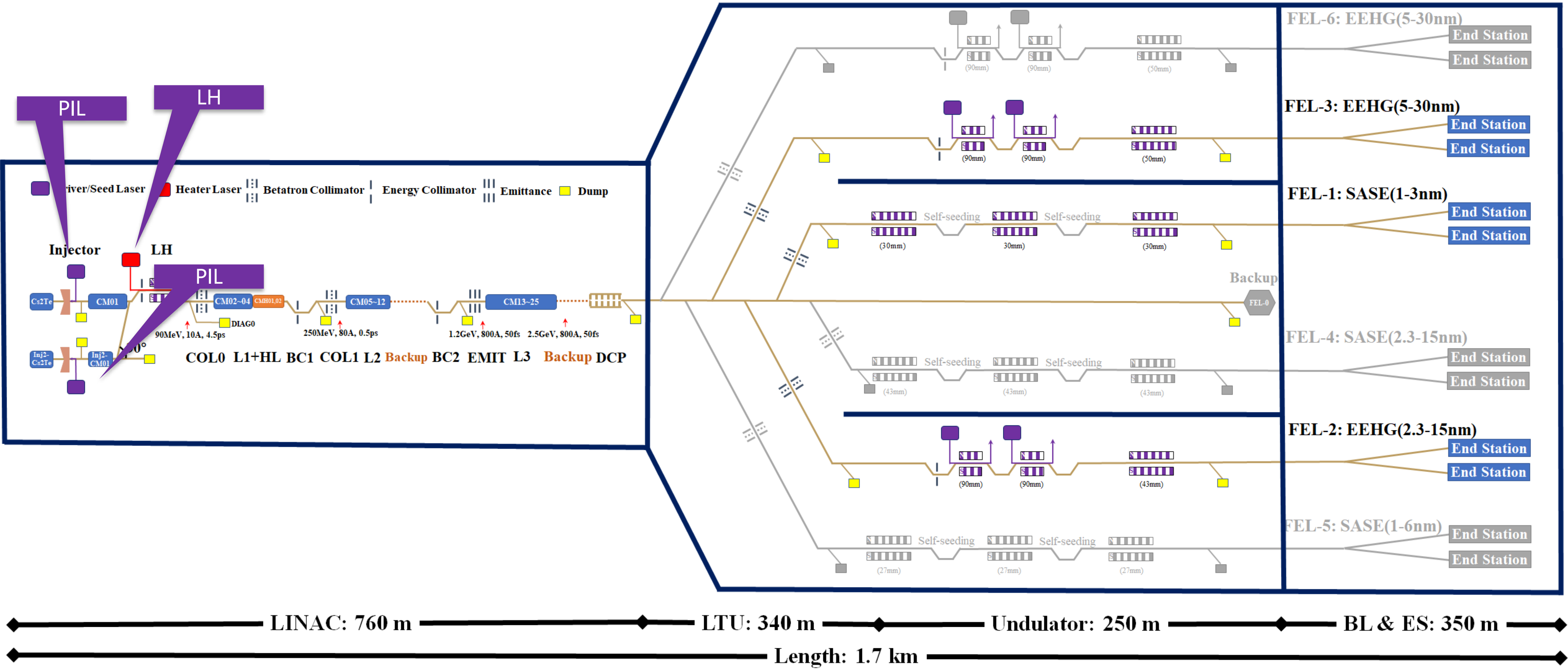
- What is a laser?
- What is an ultrafast laser?
- Mathematic description of an ultrafast laser pulse;
- **Ultrafast lasers for S^3FEL;**
- Femtosecond timing and synchronization

Ultrafast laser systems for Shenzhen Superconducting Soft X-ray FEL (S^{3}FEL)



photoinjector laser (PIL), laser heater (LH), seed laser (SL), pump-probe laser (PPL), beam length monitor (BLM), beam arriving-time monitor (BAM), X-ray arriving-time monitor (LAM), etc.

Photoinjector laser and laser heater



Photoinjector laser and laser heater

Photoinjector laser

Parameter	Value	Unit	Notes
repetition rate	1 – 1 M	Hz	——
Wavelength	257.5±2	nm	——
power	>200	mW	on photocathode
pulse energy stability	<1.5%	--	rms
pulse duration	20 – 60	ps	——
pulse shape	flat-top or expanded Gaussian	——	
beam size	0.2 – 2 (Hard-edge Dia.)	mm	nominal 1.6
beam shape	flat-top		
pointing stability	<10	um	rms

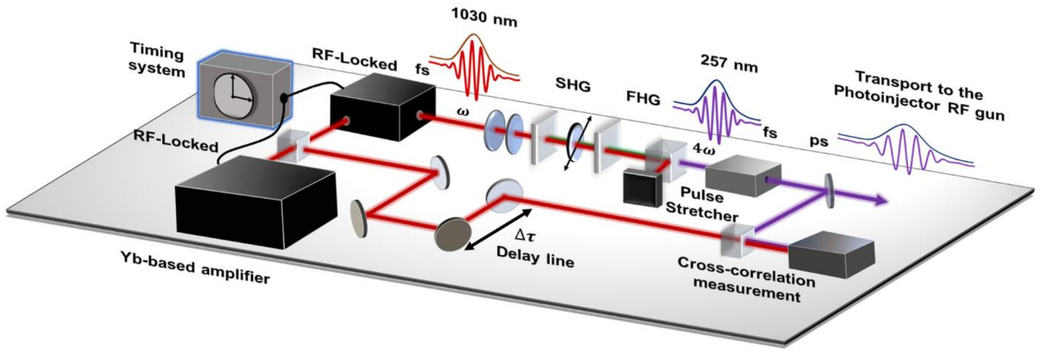
Laser heater

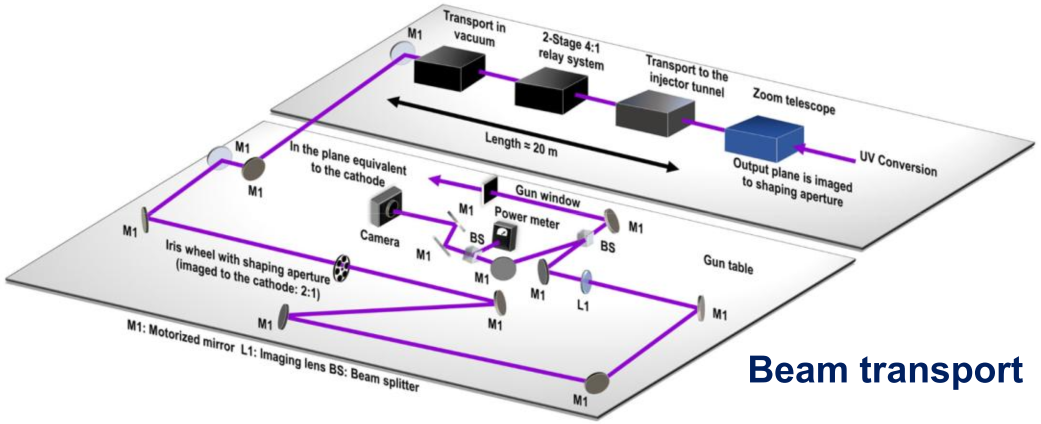
Parameter	Value	Unit
Repetition rate	1 – 1 M	Hz
Wavelength	1030	nm
Pulse energy	Up to 15	μJ
Pulse duration	10 – 30	ps
Beam size	0.2 – 0.8 (FWHM)	mm

PIL and LH share large similarities.

PIL at high rep. rate FEL facilities

LCLS II



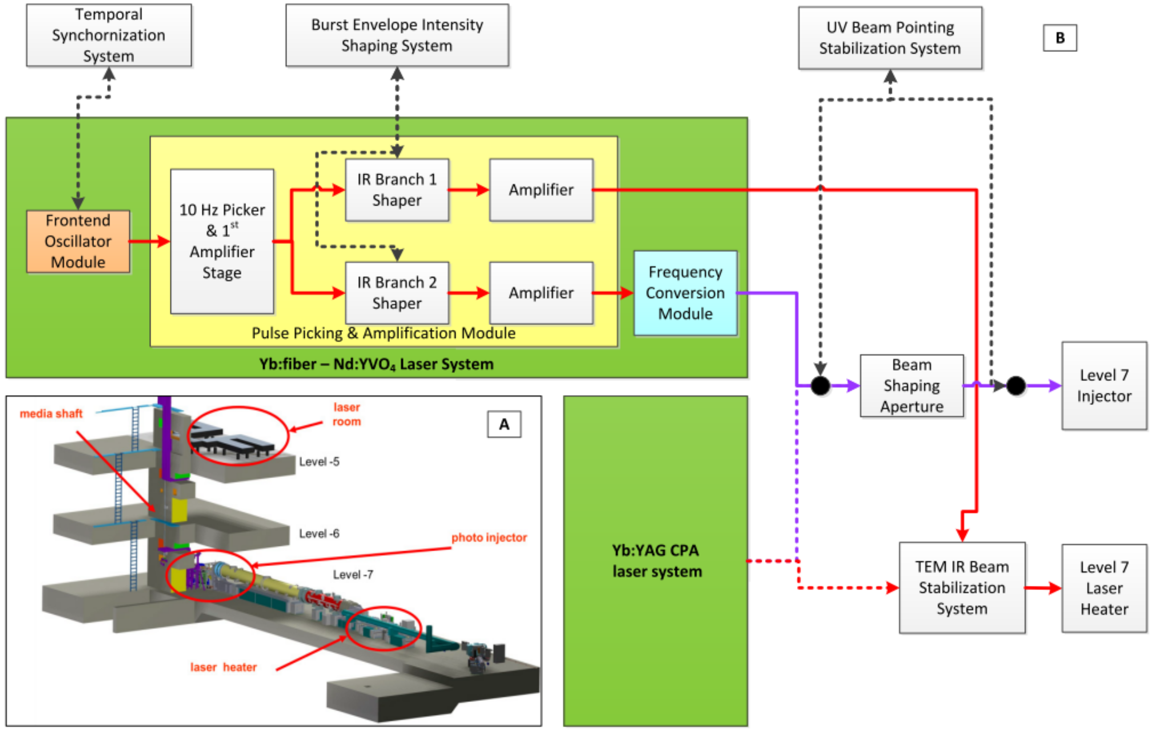


Beam transport

LCLS-II photoinjector laser based on Yb fiber laser

arXiv preprint:2307.12030 (2023).

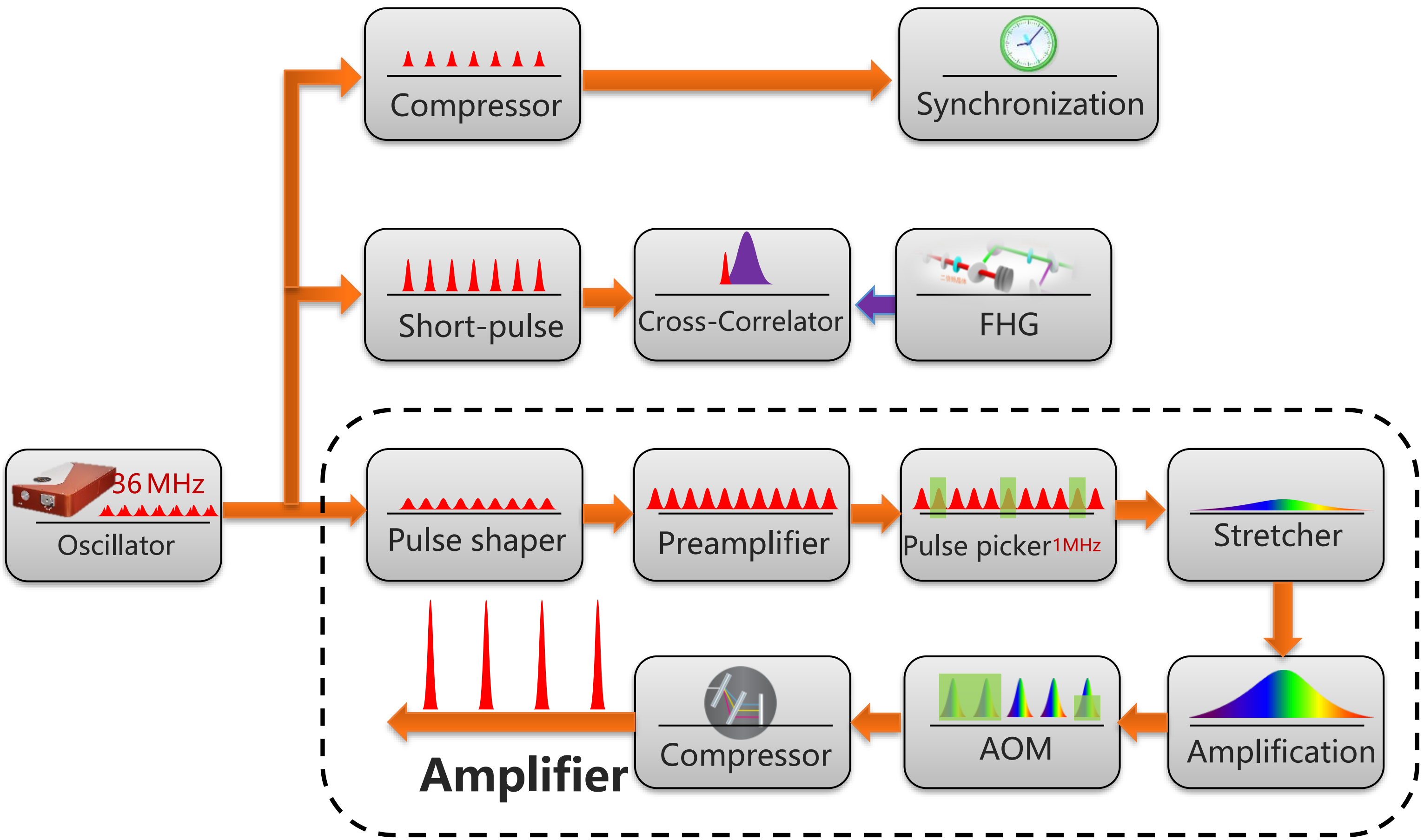
European XFEL



Two laser systems, $Nd:YVO_4$ and Yb:YAG, acting as “hot swap” backups for each other

Proceedings of the International Free-Electron Laser Conference (FEL’19), Hamburg, Germany. 2019.

50 μJ/50 W is sufficient for PIL & LH



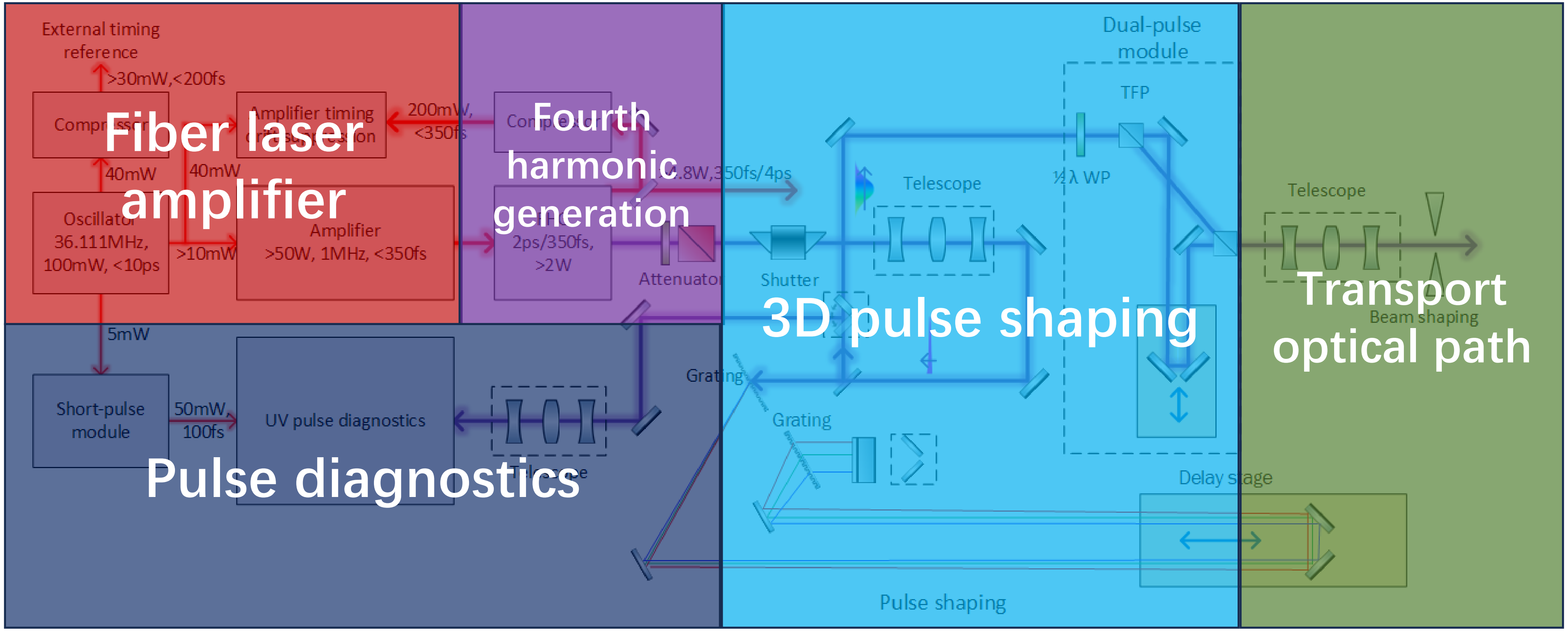
Commercial available ultrafast laser

- **Laser synchronization**
- **Slow drift compensation**
- **Temporal/spatial pulse shaping**
- **Improved pulse energy stability**
- **Stable transportation**
- **…**

- **Multiple industry-grade choices**
- **But a lot of customized upgrades need to be done**

Photoinjector laser system for S^3FEL

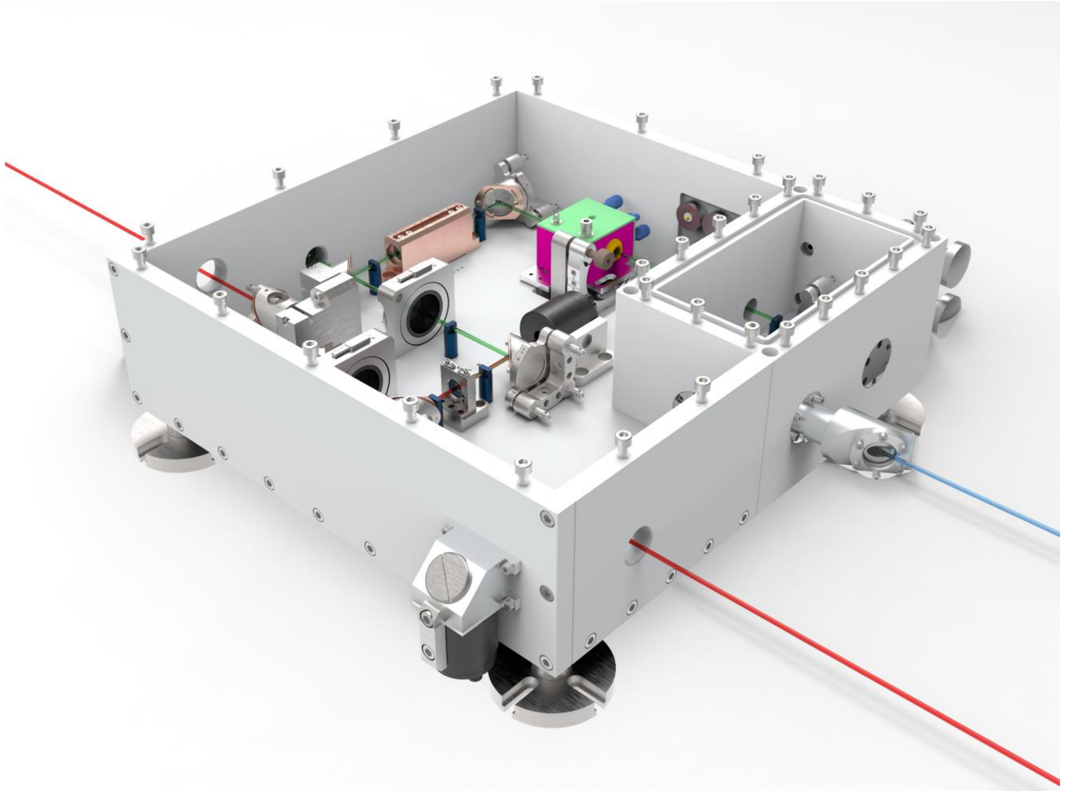
- **High rep. rate(1MHz): matching FEL CW operating mode**
- **High power(>2W): generating sufficient electron beam charge**
- **3D shaping: reducing emittance of electron beams, accelerating the saturation process of FEL**

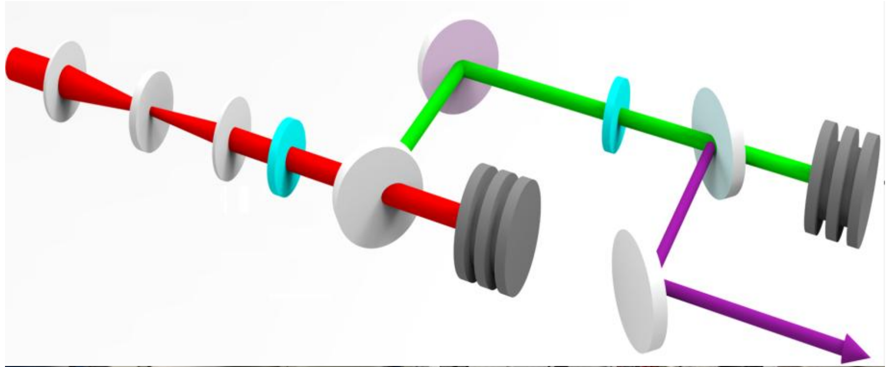


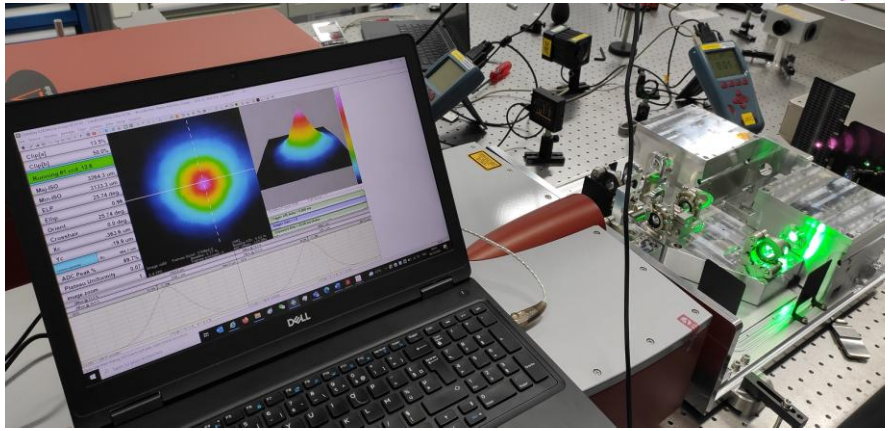
Fourth harmonic generation

Converts infrared fundamental to DUV pulses (257.5 nm)

- 257.5 nm ultraviolet photon effectively extracts electrons from the Cs_2Te photocathode
- Nonlinear conversion efficiency continuously adjustable
- High-quality beam provides a good foundation for beam shaping

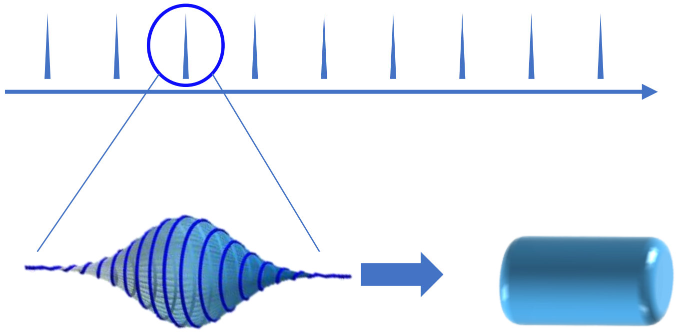




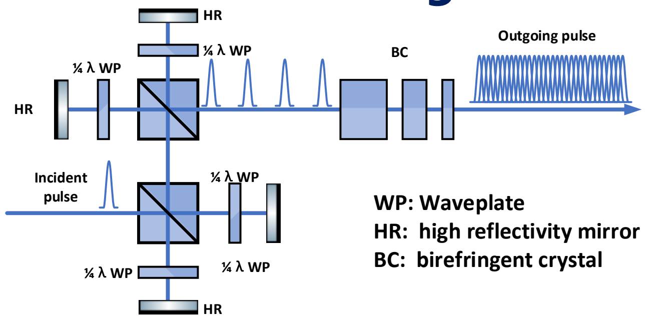


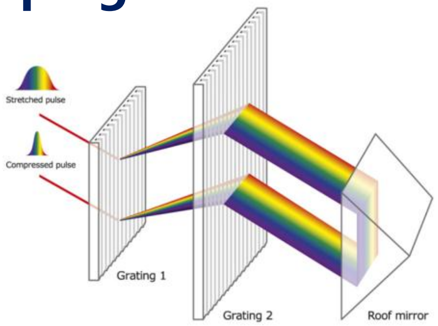
Sophisticated 3D pulse shaping

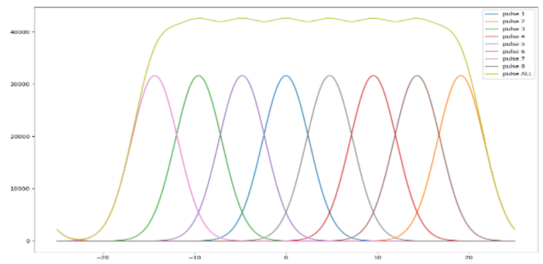
Perform longitudinal and transverse shaping of DUV laser pulses to improve the quality of electron bunches.

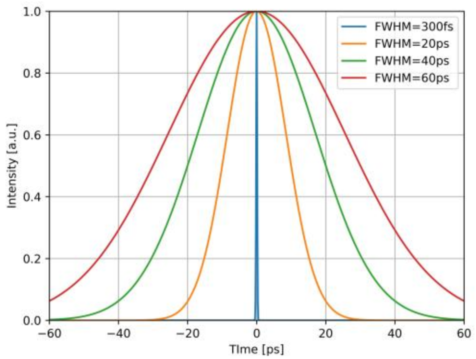


Longitudinal Shaping





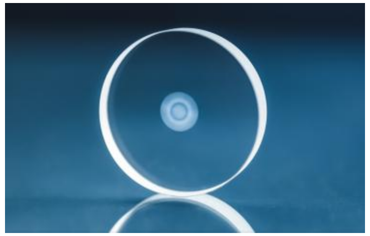


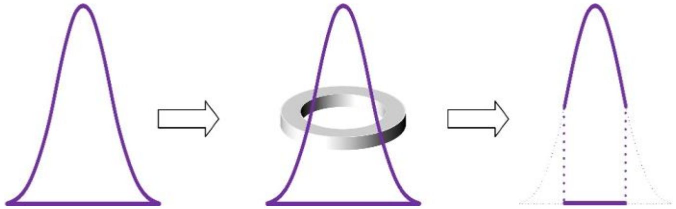


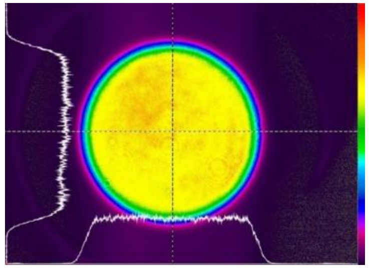
Pulse stacking

Grating pair

Transverse Shaping



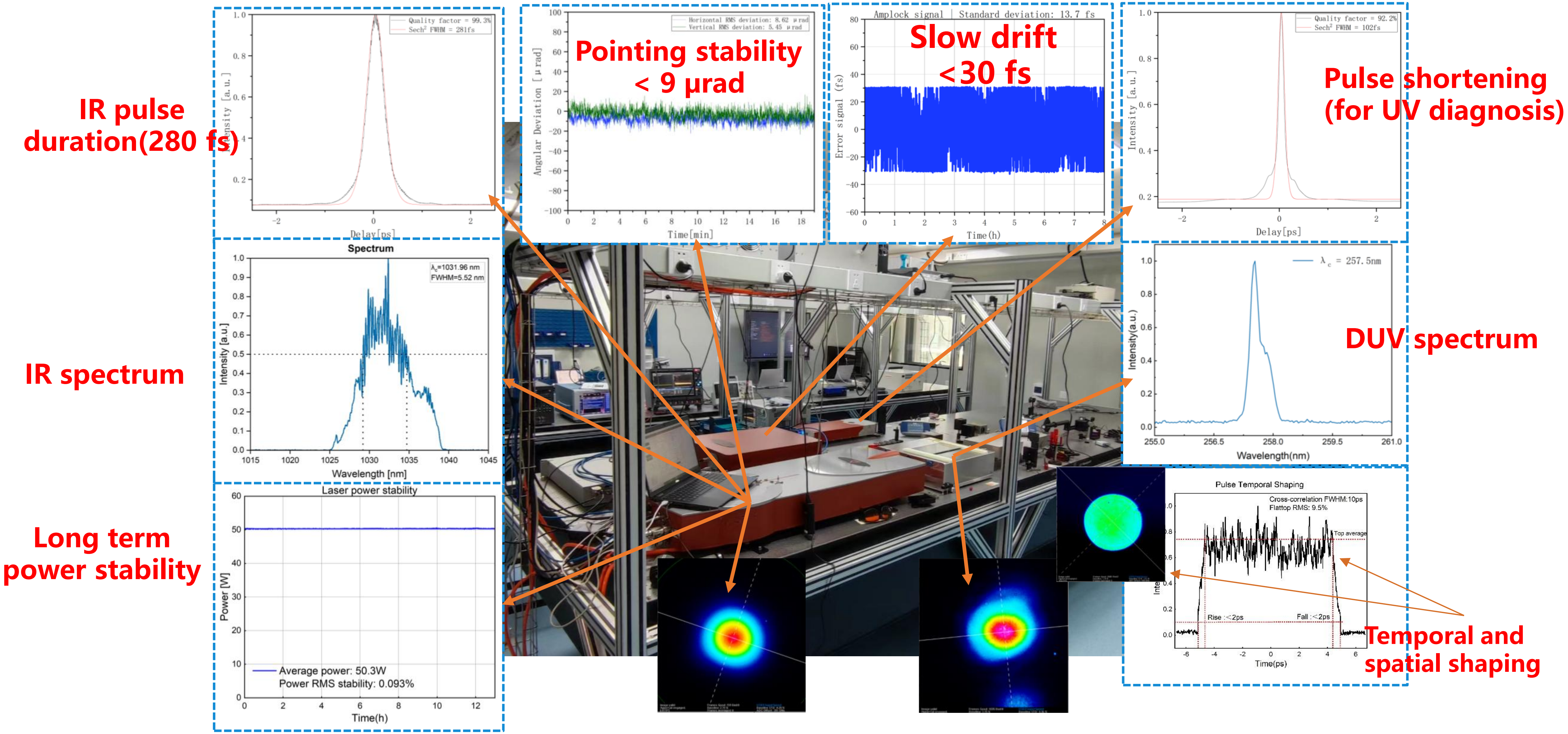




Flat-Top converter

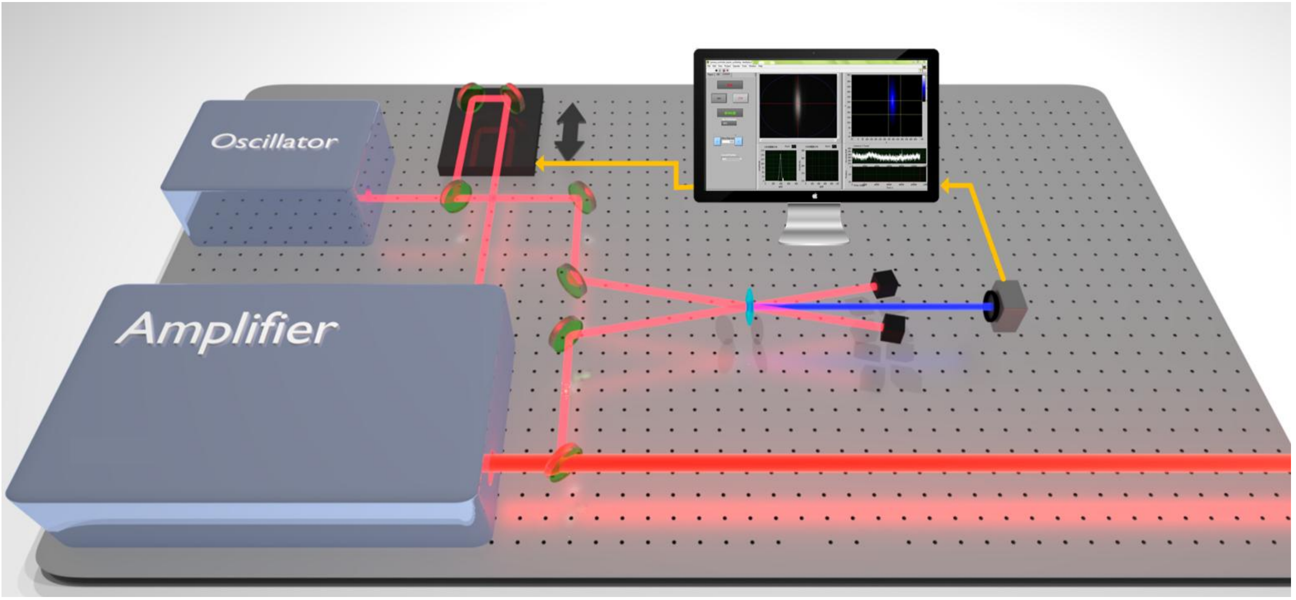
Aperture truncation

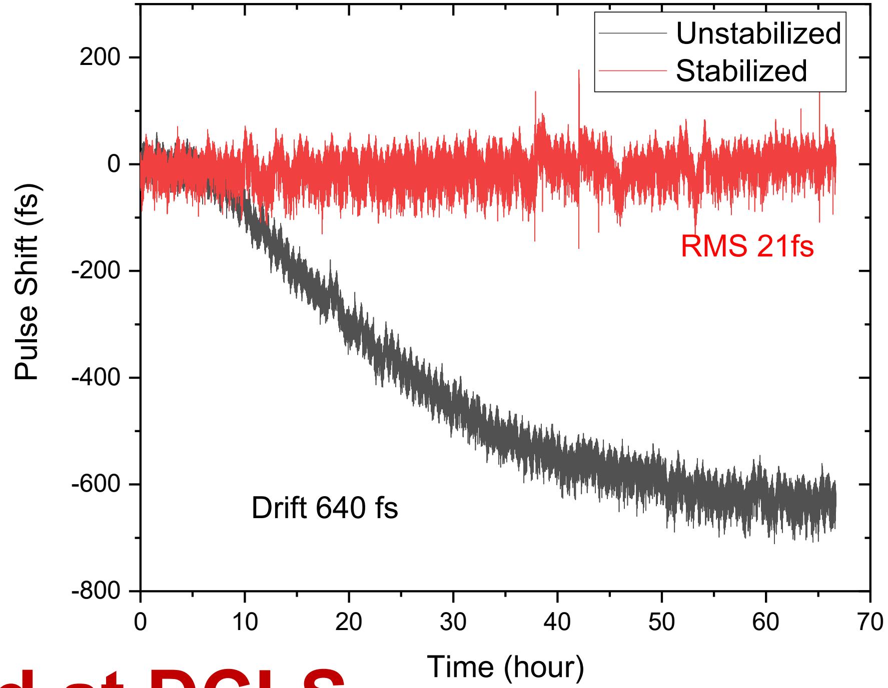
PIL for S^{3}FEL



Amplifier timing drift suppression

- **Suppress the long-term timing drift**
  - **Single-shot cross-correlation technique for measuring temporal jitter and drift;**
  - **Butterworth filter to remove high-frequency noise components;**
  - **PID feedback loop to eliminate long-term timing drift introduced by amplifiers**



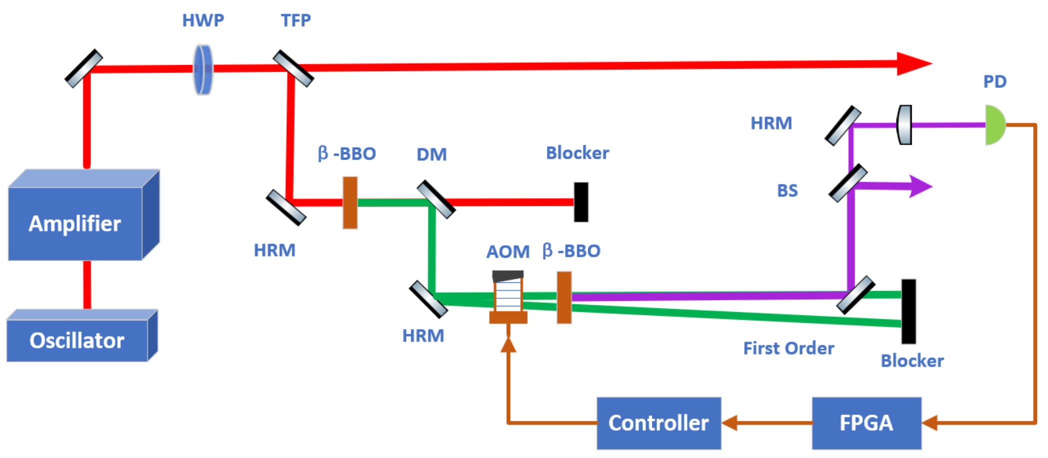


It has been successfully implemented at DCLS.

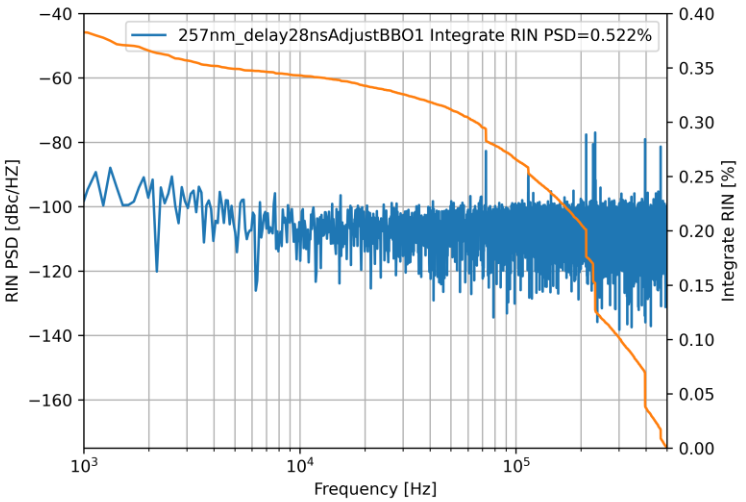
Pulse energy stabilization: from ~2% to 0.5%

Pulse energy stability of PIL is critical to many aspects of S^{3}FEL. We have put lots of efforts to improve it, utilizing both active feedback and passive control techniques.

Active and passive noise suppression



Relative intensity noise of UV laser

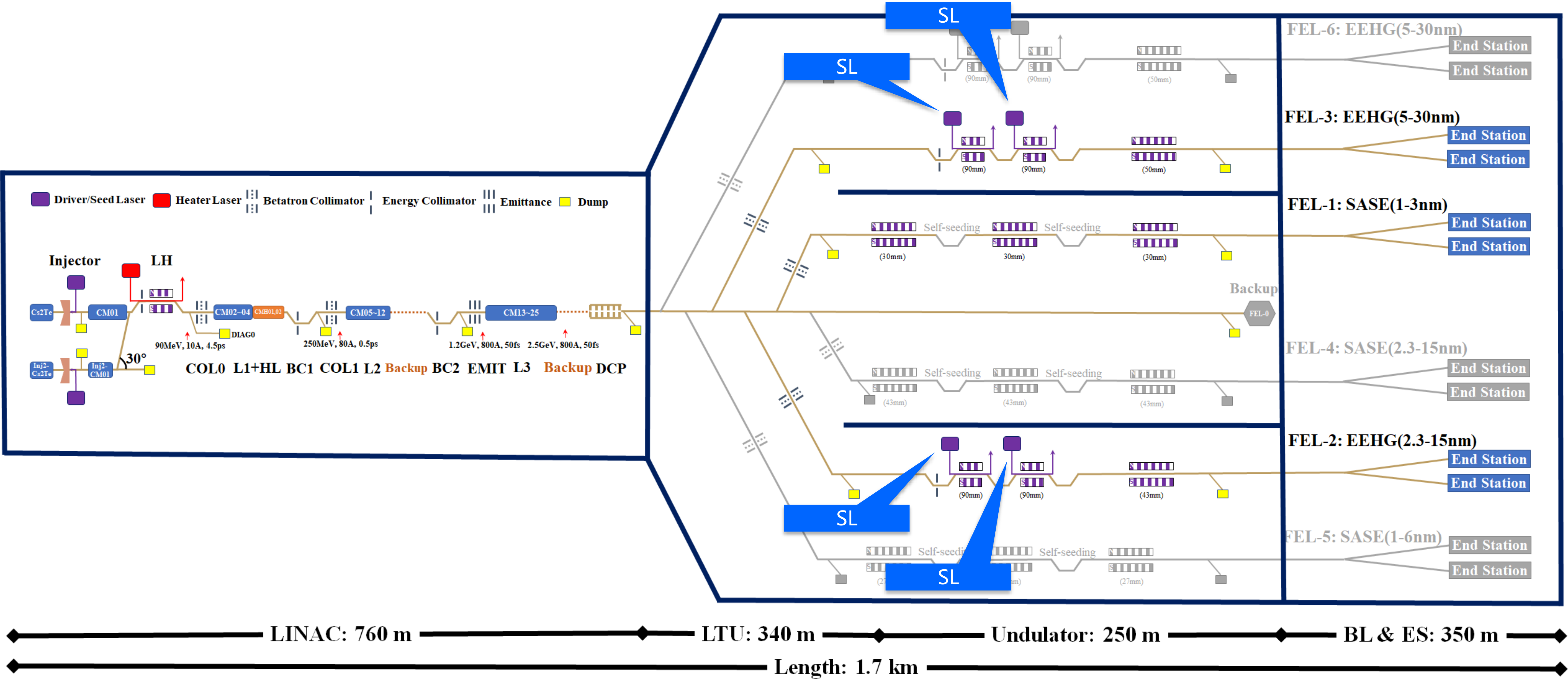


- **Optimizing the Amplifier system parameters**
- **Optimizing the nonlinear frequency conversion process**

- **Active feedback bandwidth of 500 kHz;**
- **Combining feedforward active noise canceling (ANC) with the PID algorithm to maximize control effectiveness**

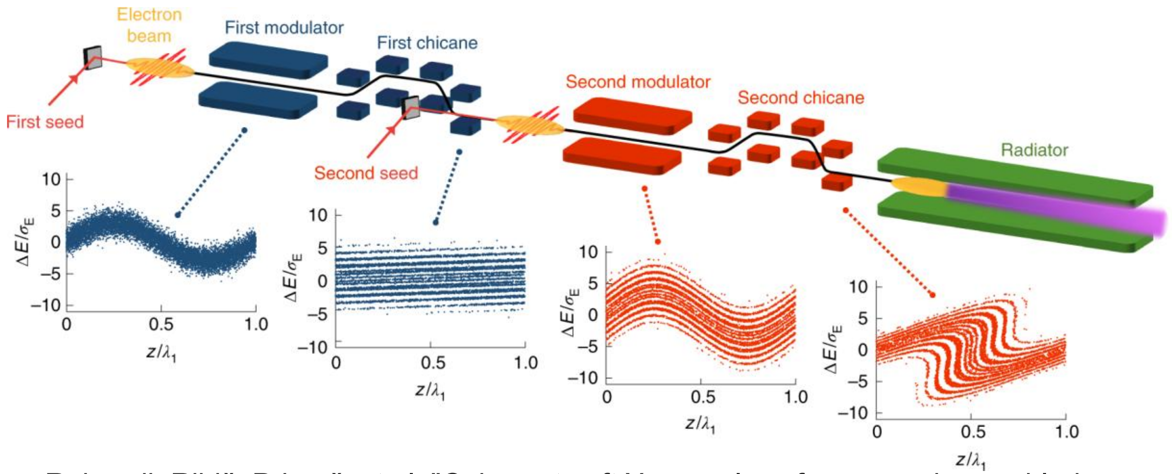
First experimental result of ~ 0.5% rms was just demonstrated.

Seed lasers



SL
SL
SL
SL
Driver/Seed Laser
Heater Laser
Betatron Collimator
Energy Collimator
Emittance
Dump
Injector
LH
Cs2Te
CM01
Inj2-Cs2Te
Inj2-CM01
30°
CM02~04
CM05~12
CM13~25
DIAG0
90MeV, 10A, 4.5ps
250MeV, 80A, 0.5ps
1.2GeV, 800A, 50fs
2.5GeV, 800A, 50fs
COL0 L1+HL BC1 COL1 L2 Backup BC2 EMIT L3 Backup DCP
FEL-6: EEHG(5-30nm)
FEL-3: EEHG(5-30nm)
FEL-1: SASE(1-3nm)
Backup
FEL-0
FEL-4: SASE(2.3-15nm)
FEL-2: EEHG(2.3-15nm)
FEL-5: SASE(1-6nm)
End Station
Self-seeding
(90mm)
(50mm)
(30mm)
(43mm)
(27mm)
LINAC: 760 m
LTU: 340 m
Undulator: 250 m
BL & ES: 350 m
Length: 1.7 km

EEHG seed lasers requirements for S^3FEL

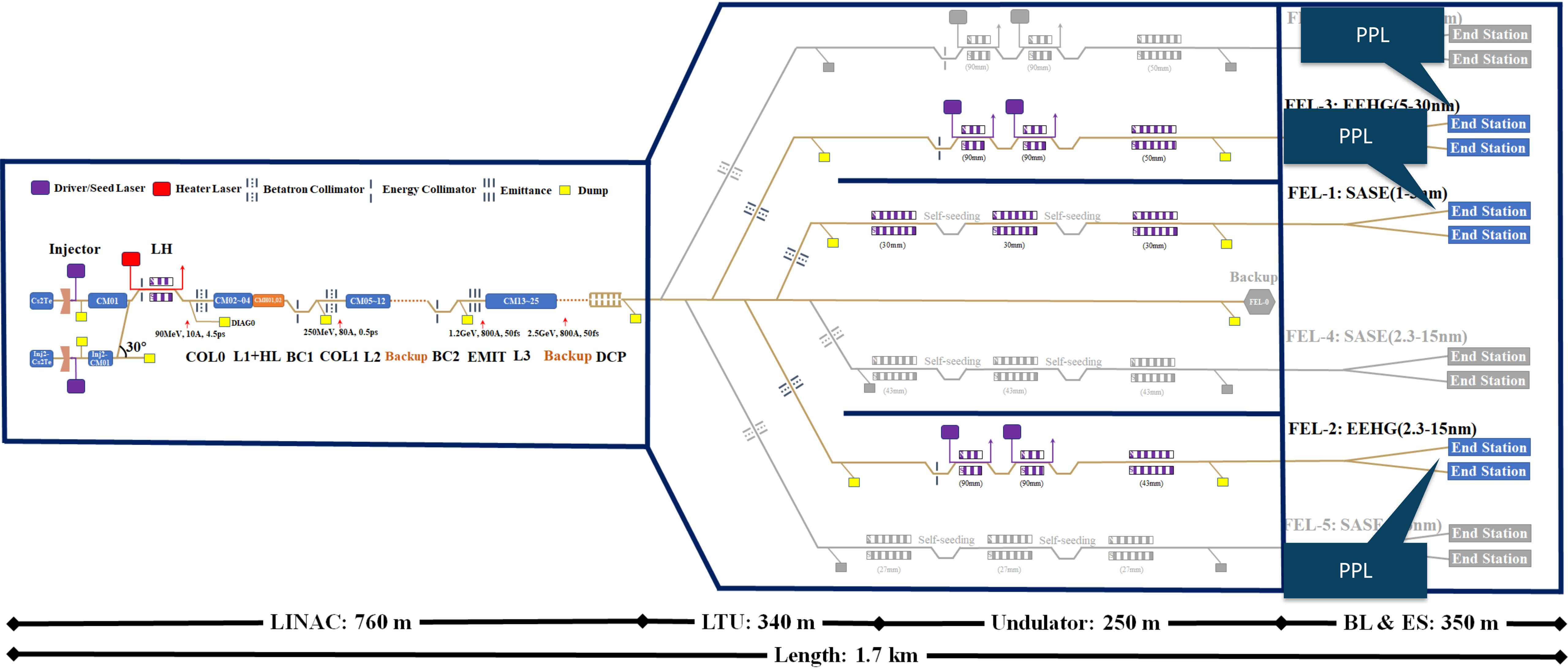


Rebernik Ribič, Primož, et al. "Coherent soft X-ray pulses from an echo-enabled harmonic generation free-electron laser." *Nature Photonics* 13.8 (2019): 555-561.

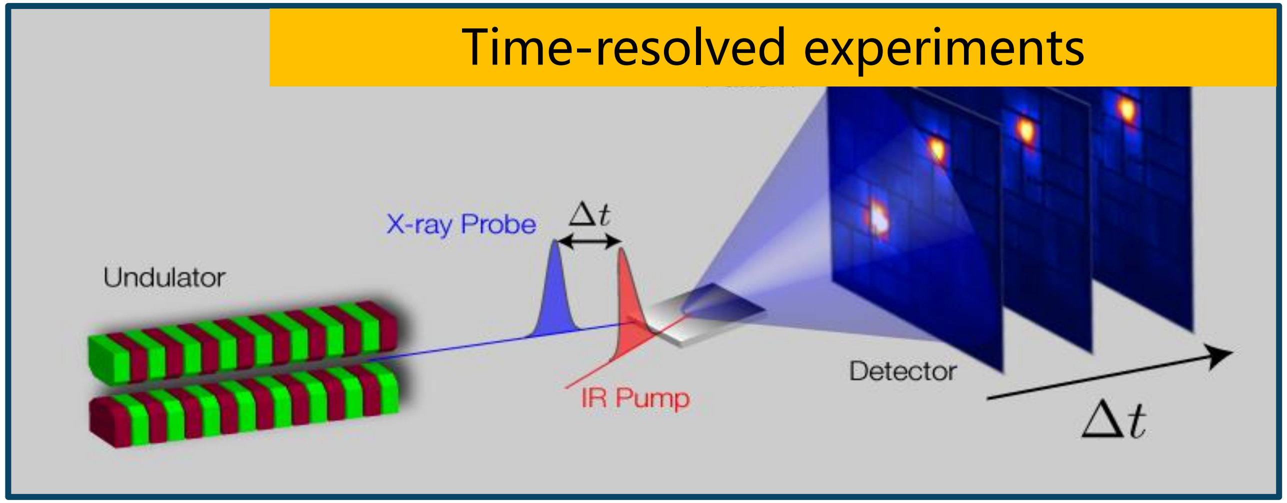
	FEL-3 & 4	
Rep. rate (kHz)	1	
	λ_1	λ_2
wavelength (nm)	267	266-295
Pulse energy (μJ)	20	20
Beam radius (mm)	0.5	
Pulse duration (fs)	100	

- **Nonlinear frequency conversion to the required wavelength range, the pump pulse energy should be in multi-mJ level;**
- **The bottom line: Seed lasers will be running at 1 kHz with mature Ti : Saphire technology;**
- **Advanced seeding schemes are under development with which one to two order-of-magnitudes less pulse energy is required and seeding at 100 kHz is feasible.**

Pump-probe lasers



Pump-probe laser requirements for S^3FEL



- Wavelength: EUV, VUV, UV, visible, IR, THz
- Repetition rate: up to 100 kHz;
- Pulse energy: multi-mJ;
- Average power: 100-1000 W
- Pulse duration: < 50 fs
- Tightly synchronize with X-ray (< 10 fs)

75%

100 kHz

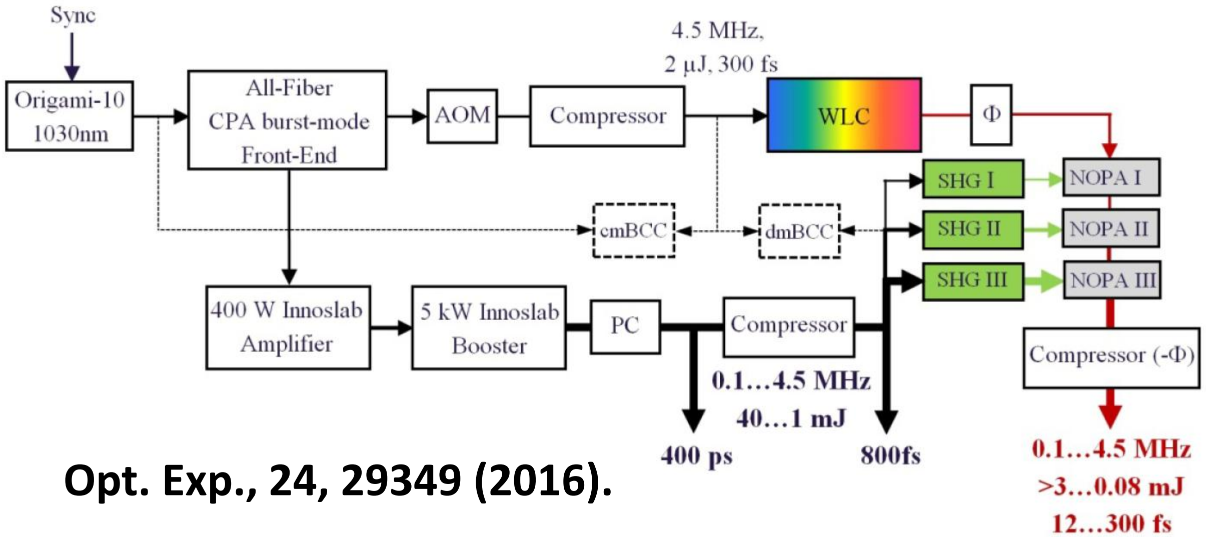
1 mJ

50 fs

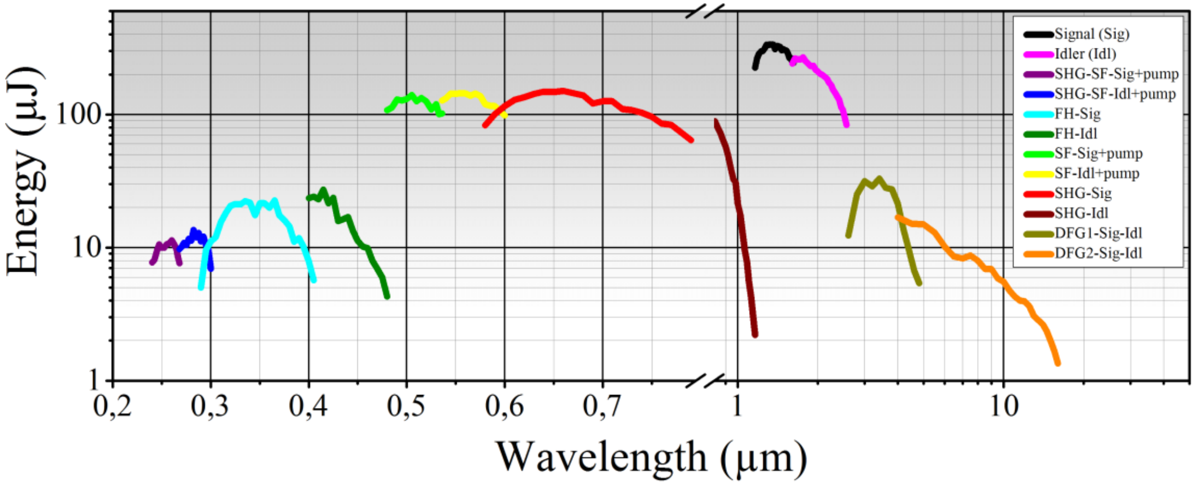
10 fs

Eu-XFEL pump-probe laser (OPCPA)

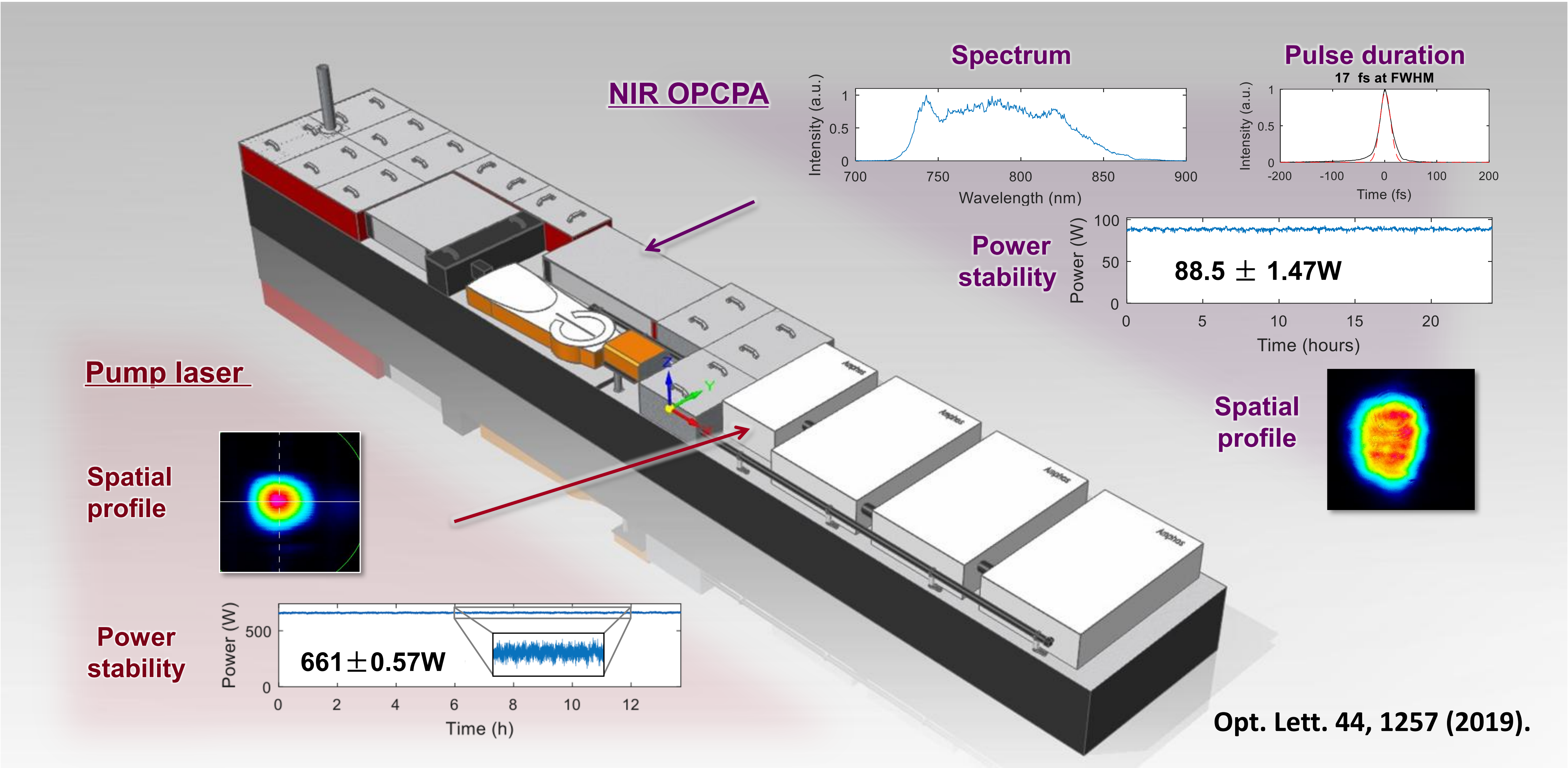
OPCPA: optical parametric chirped-pulse amplification



Opt. Exp., 24, 29349 (2016).



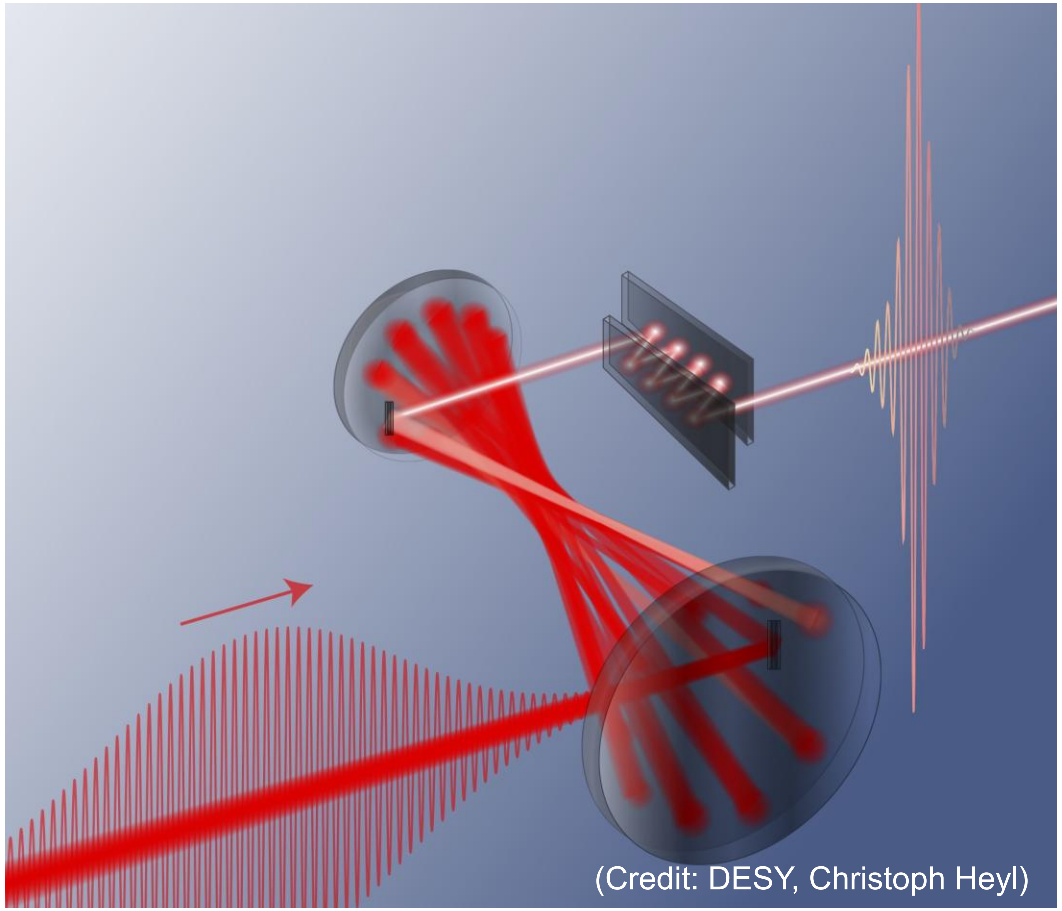
LCLS-II pump-probe laser (OPCPA)



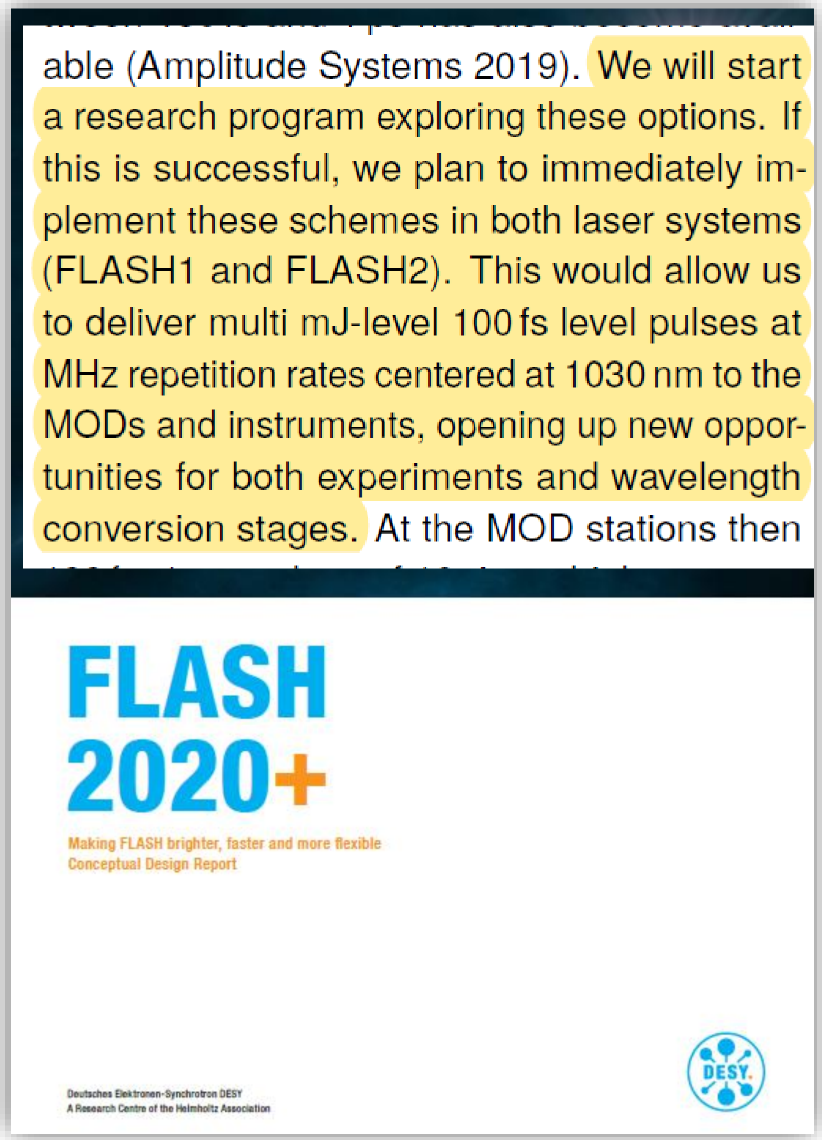
Opt. Lett. 44, 1257 (2019).

A disruptive technology is on the way…

MPC: multi-pass compression with about 10 times higher efficiency



(Credit: DESY, Christoph Heyl)



able (Amplitude Systems 2019). We will start a research program exploring these options. If this is successful, we plan to immediately implement these schemes in both laser systems (FLASH1 and FLASH2). This would allow us to deliver multi mJ-level 100 fs level pulses at MHz repetition rates centered at 1030 nm to the MODs and instruments, opening up new opportunities for both experiments and wavelength conversion stages. At the MOD stations then

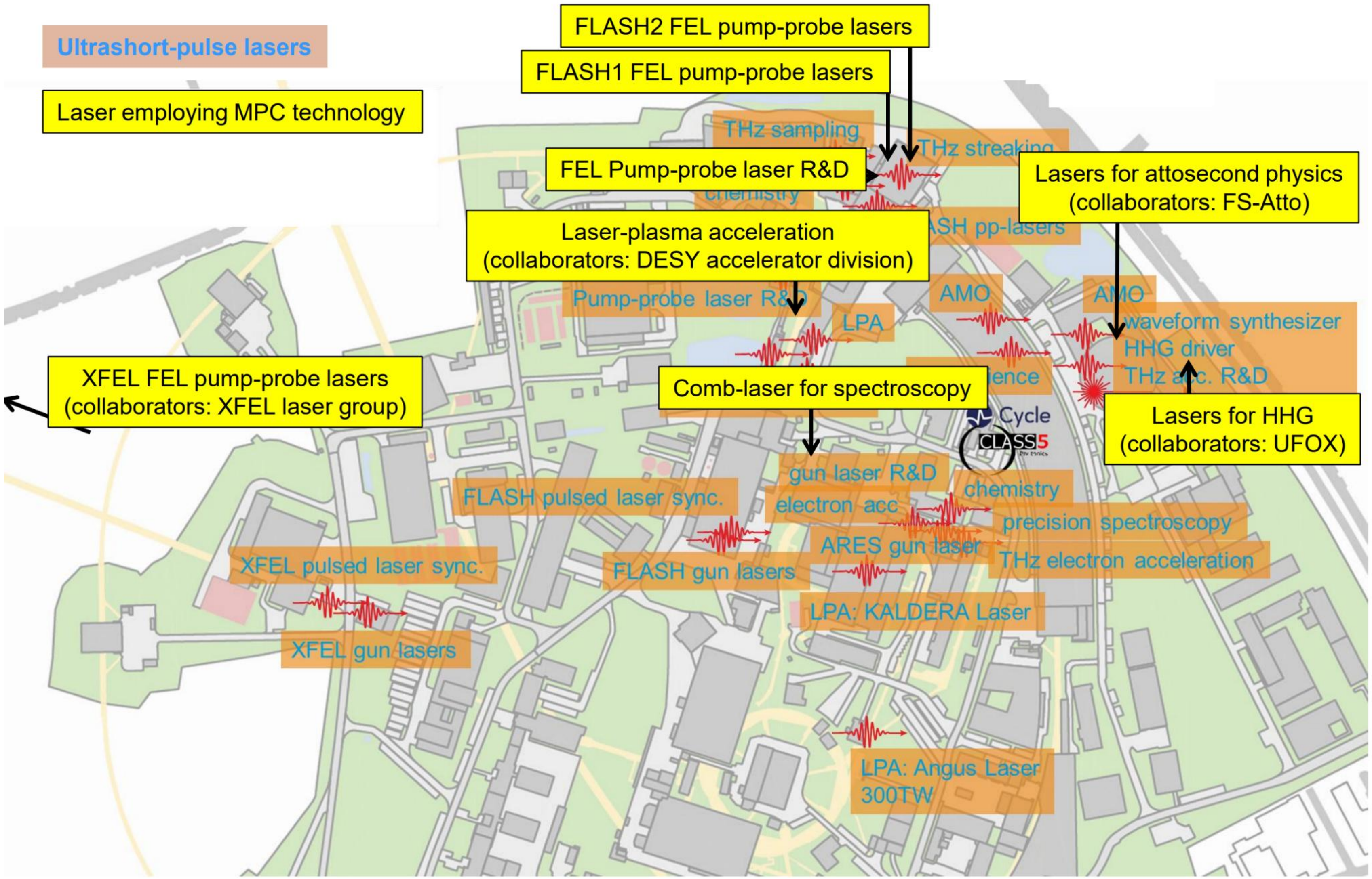
FLASH 2020+

Making FLASH brighter, faster and more flexible
Conceptual Design Report

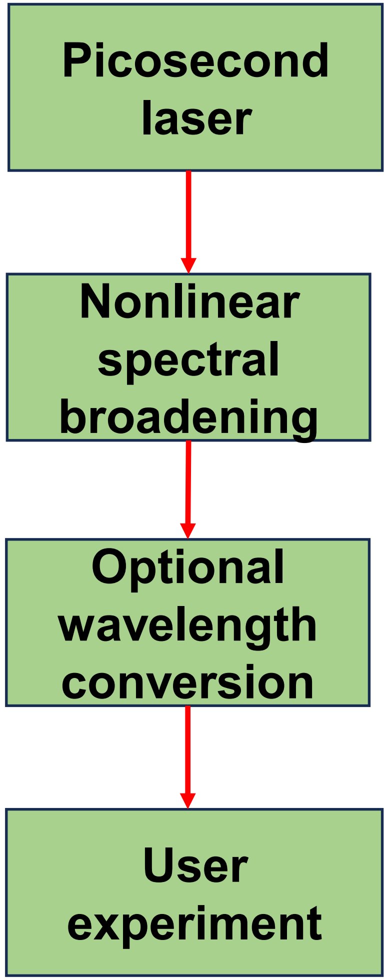
Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

DESY.

MPC widely adopted for lasers of FLASH



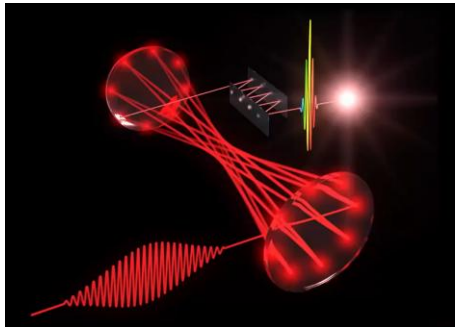
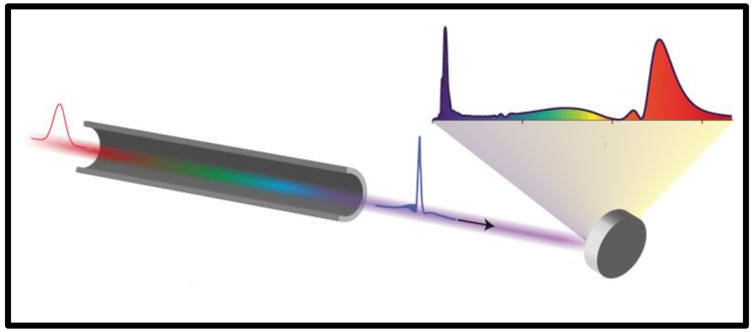
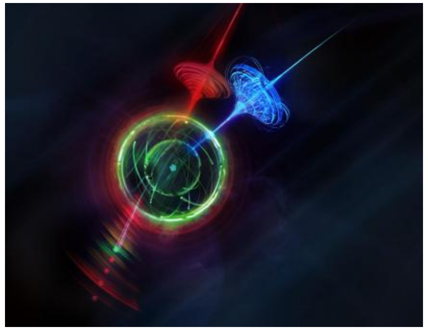
New laser concept currently being implemented FLASH



Our design choice and R&D Strategy

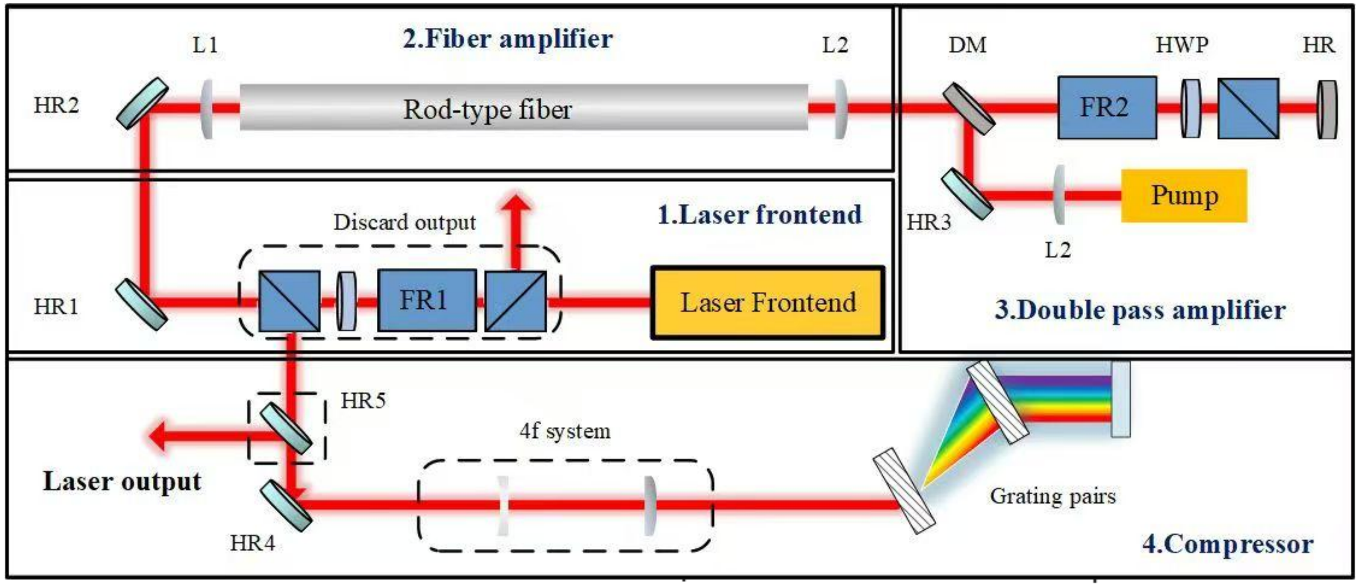
Multi-mJ, high average power: 100 – 1000 W	Short pulse duration: < 50 fs FWHM	Broad λ tunability: THz → EUV	Tight sync.: < 10 fs timing jitter

Yb platform	post compression: multi-pass cell & cascade compression	Commercial OPA, Home-built DWG, HHG	Pulsed laser-based synchronization

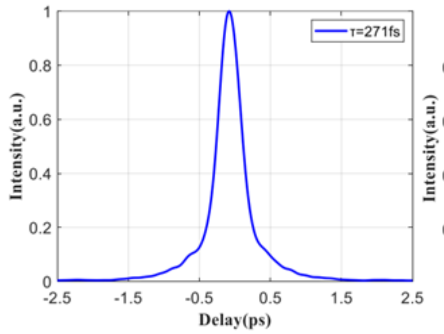





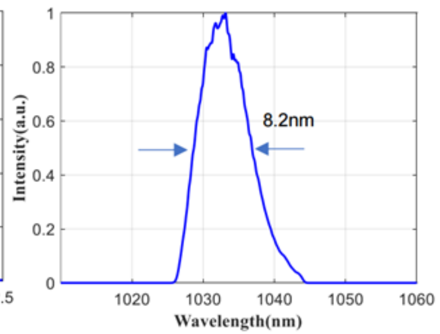
Since most of the solution is not commercially available, we need to put tons of efforts on self-development and engineering

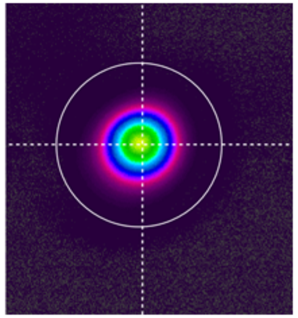
~200W Yb fiber amplifier

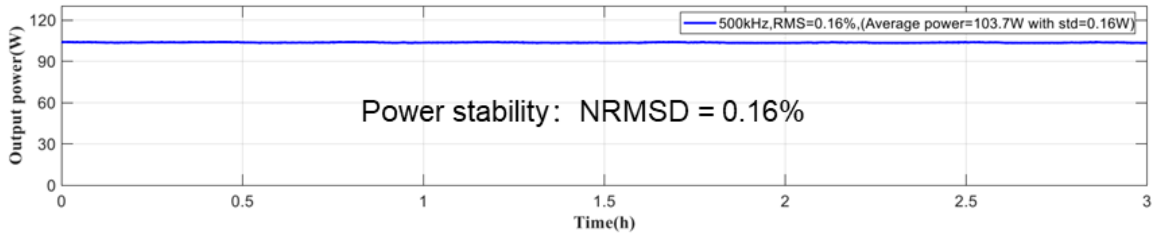


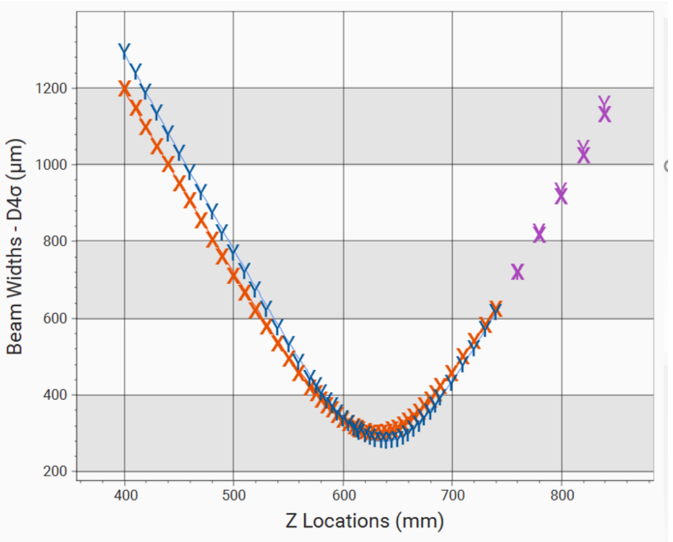
Center wavelength	1034±5 nm
Maximum output power	180 W
Maximum pulse energy	400 μJ
Pulse duration	271 fs
Repetition rate	100 kHz - 1 MHz
Long-term power stability	0.16%
Beam quality, M^2	< 1.2



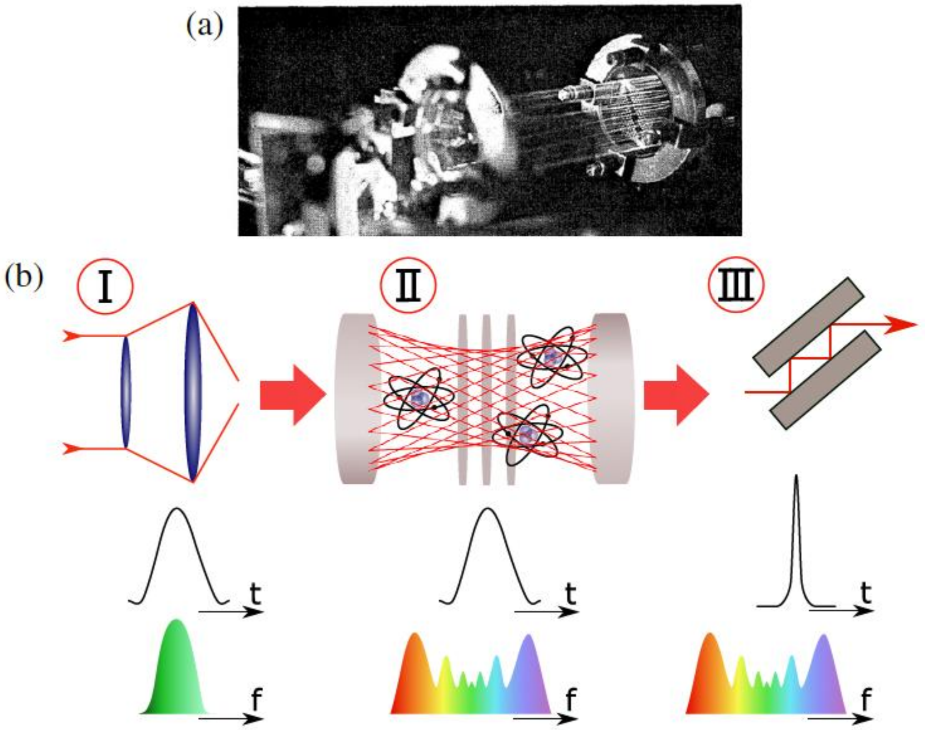


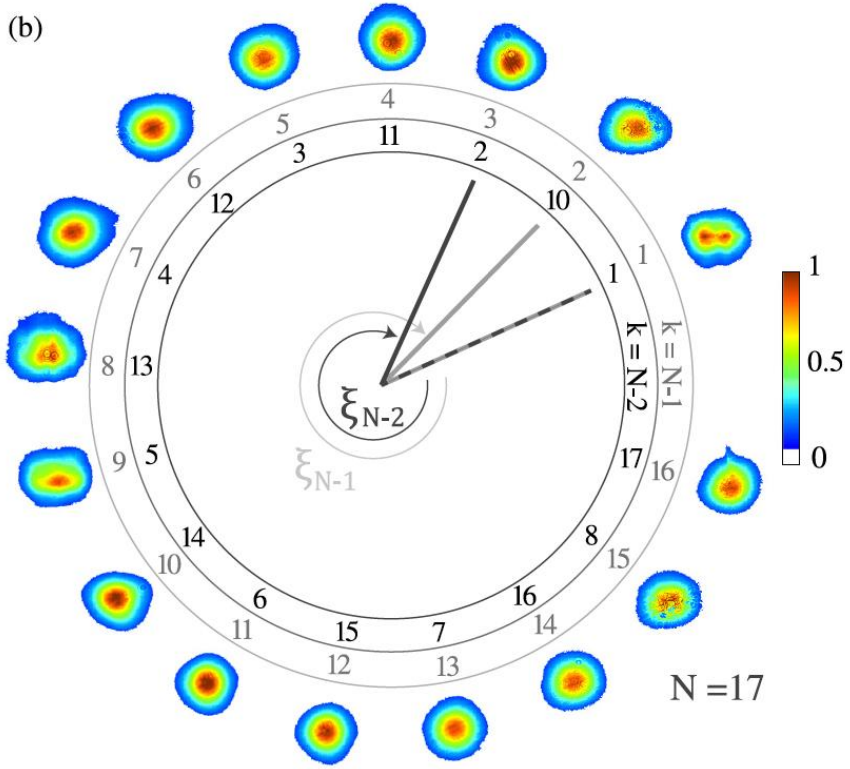






Post compression: multi-pass cell (MPC)





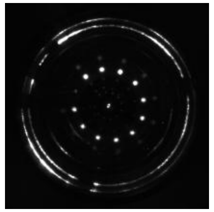
Key features：

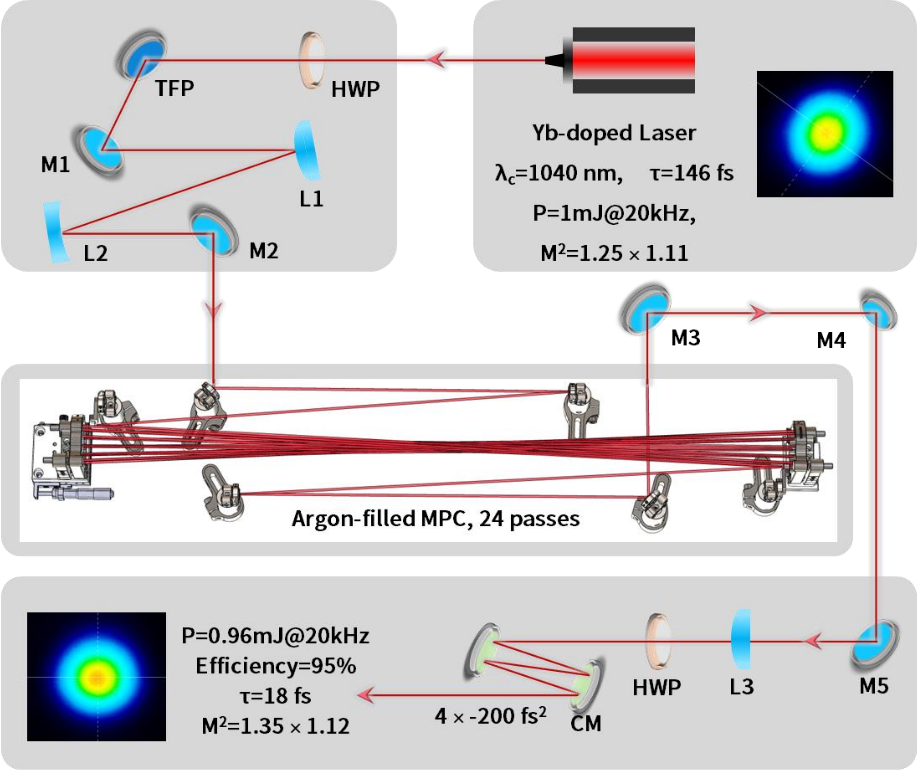
- High power compatibility
- Large compression factors
- High efficiency
- Excellent beam quality
- Compatible with large parameter range
- ……

Optica **9**, 197 (2022)

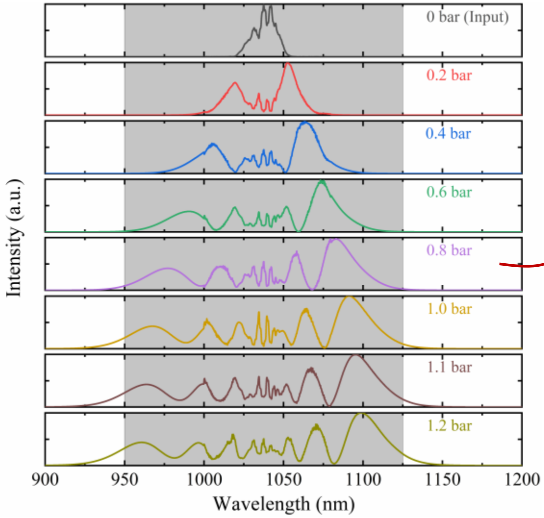
MPC for < 50 fs output

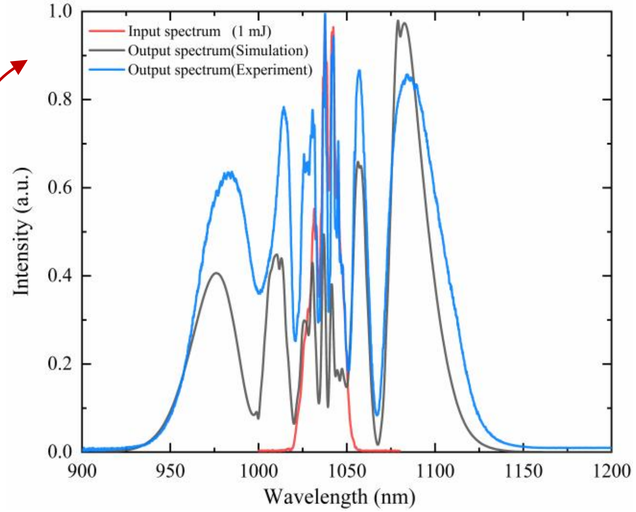
Setup

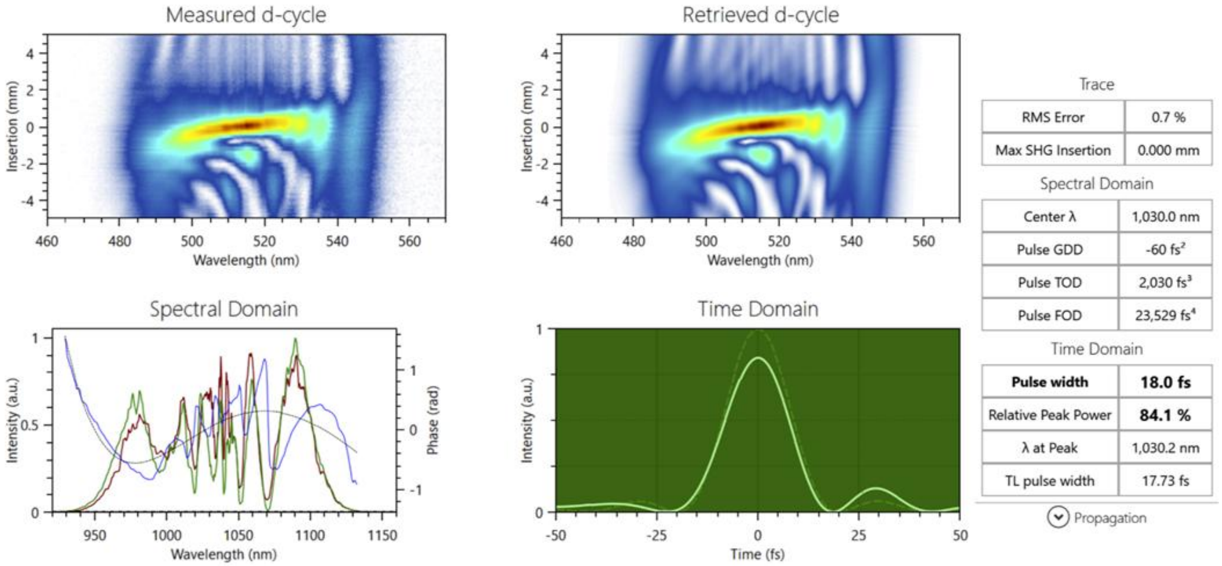




Experimental results





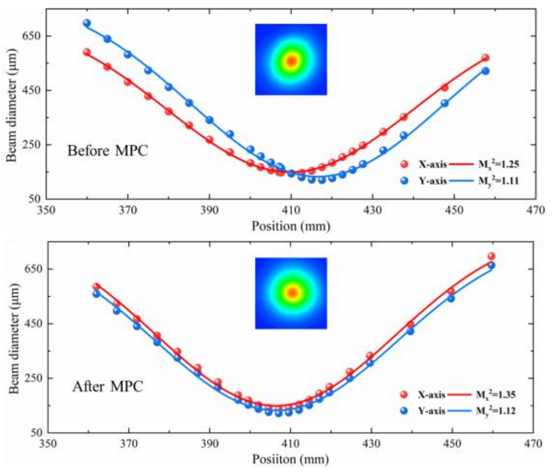


146 fs → 18 fs with 95% efficiency

IEEE PHOTONICS TECHNOLOGY LETTERS, 37, 313 (2025)

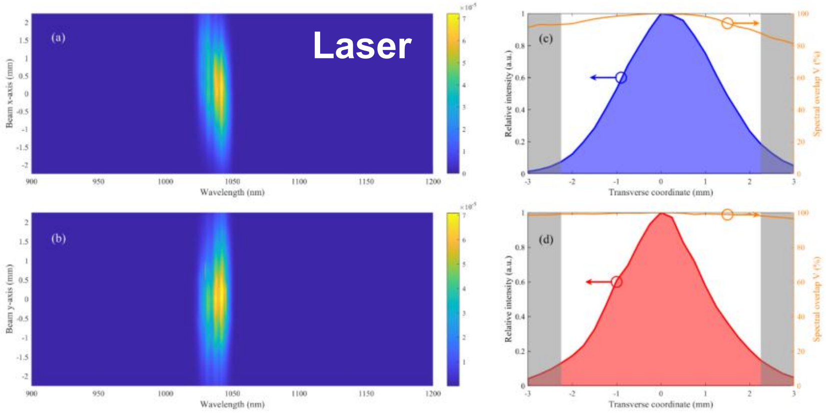
Performance of MPC output

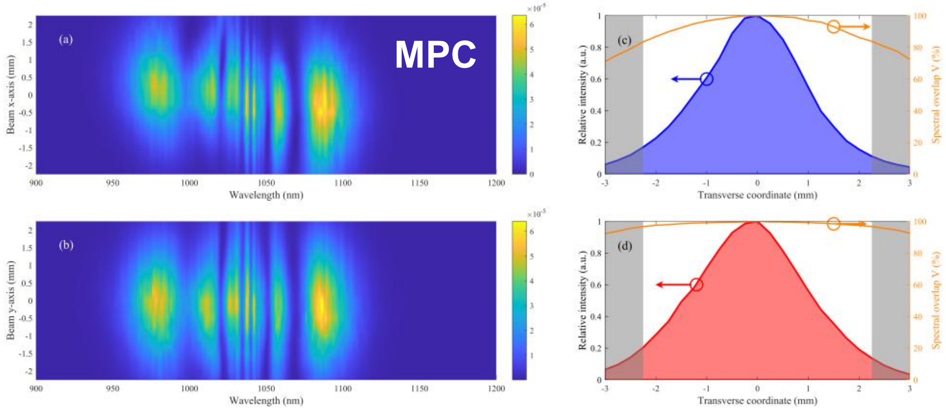
Beam quality M^2



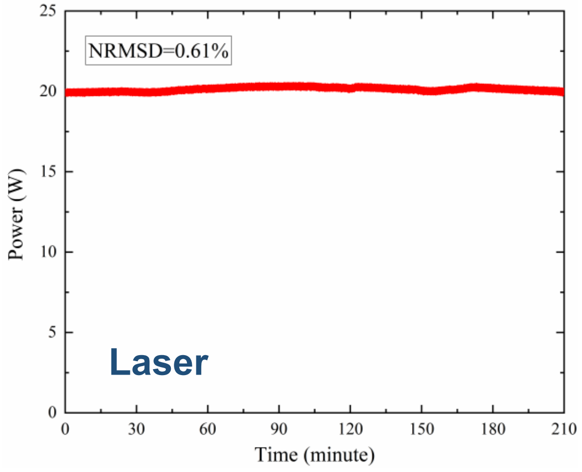
Spatial-spectral homogeneity

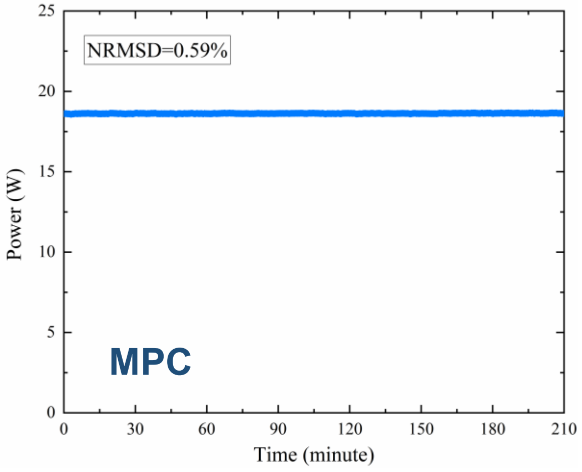
V_X = 95.9%, V_Y = 98.9%



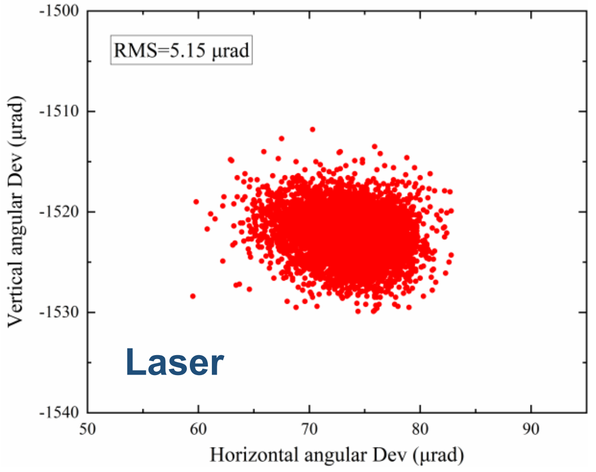


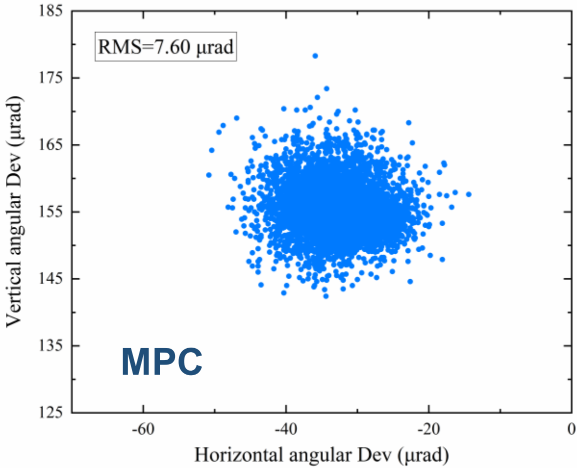
Power stability





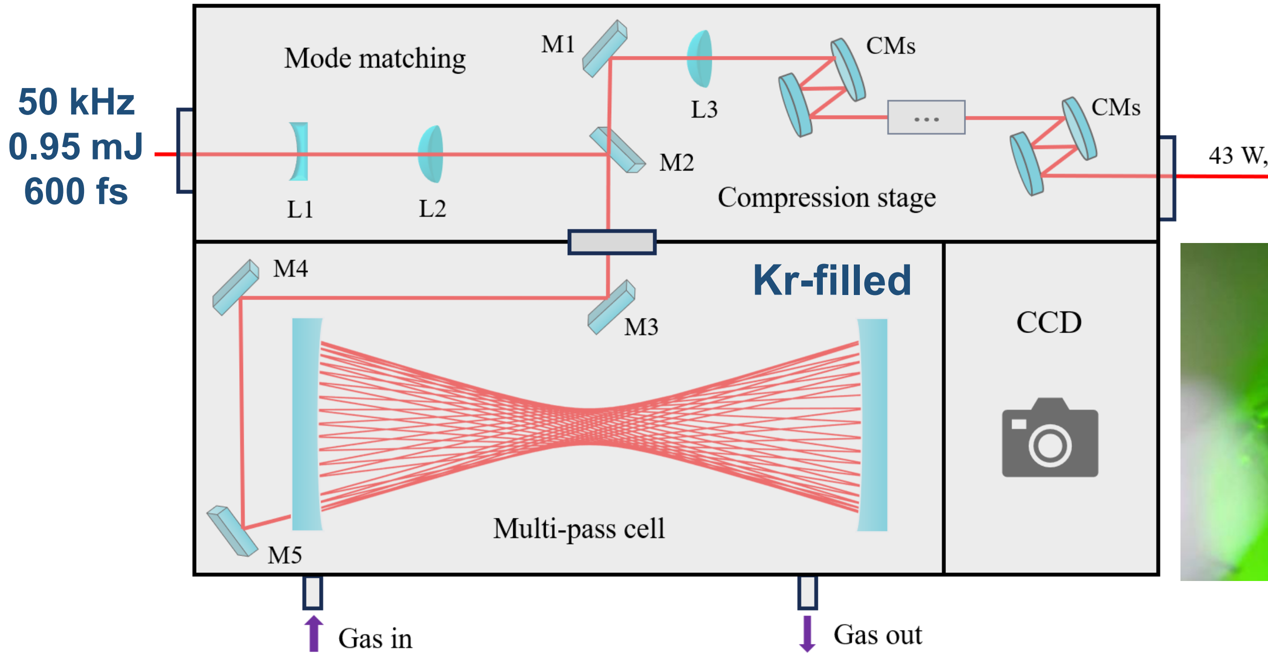
Beam pointing

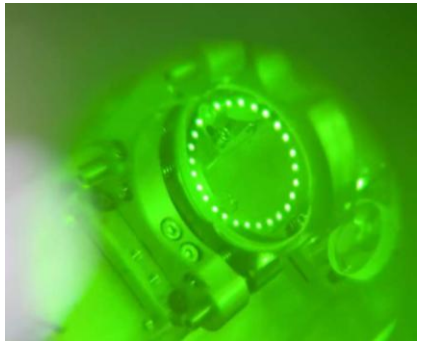


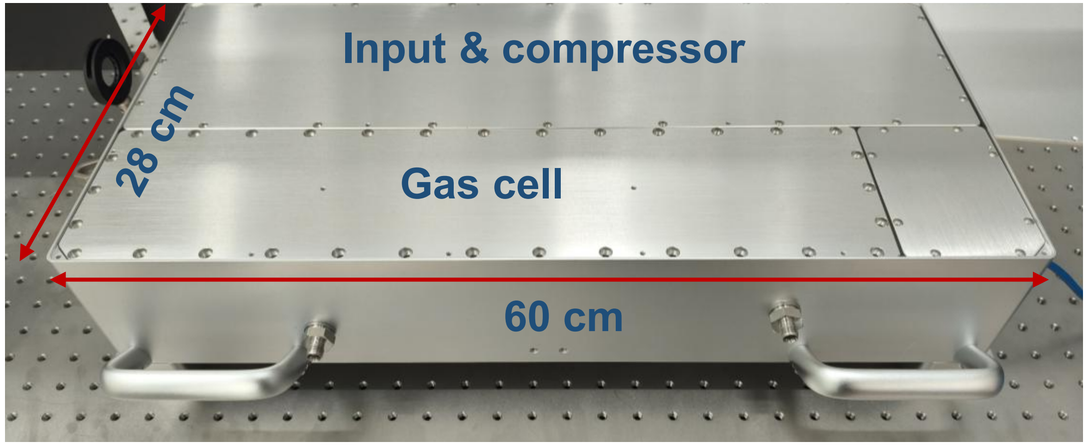


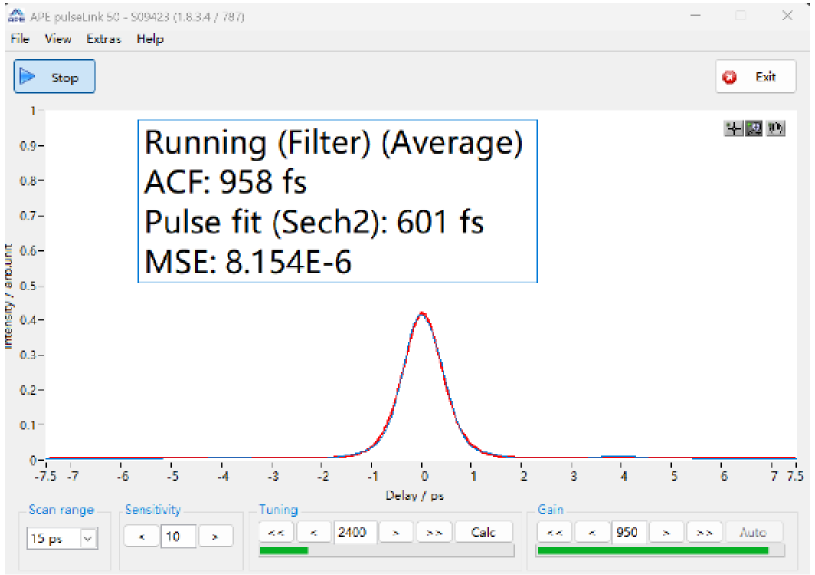
MPC maintains the power stability, pointing stability, beam quality, with homogeneous spectral broadening

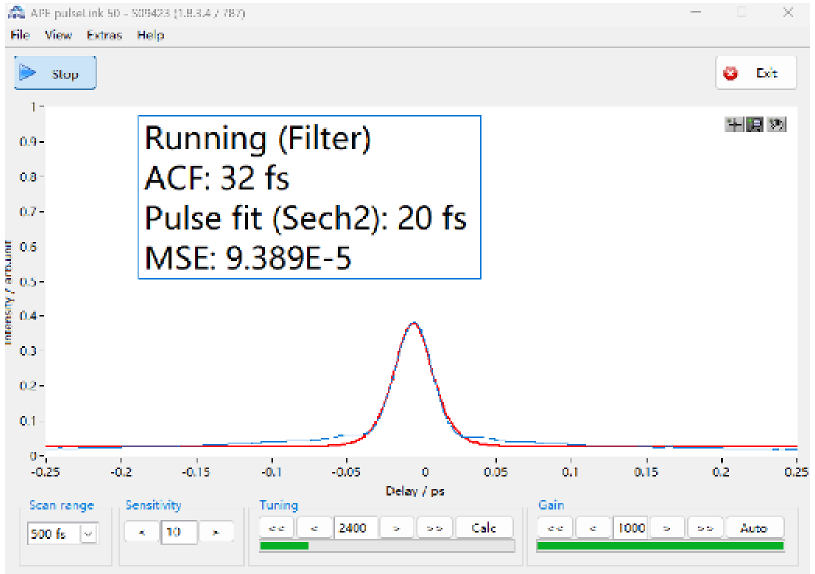
30× compression single-stage MPC system



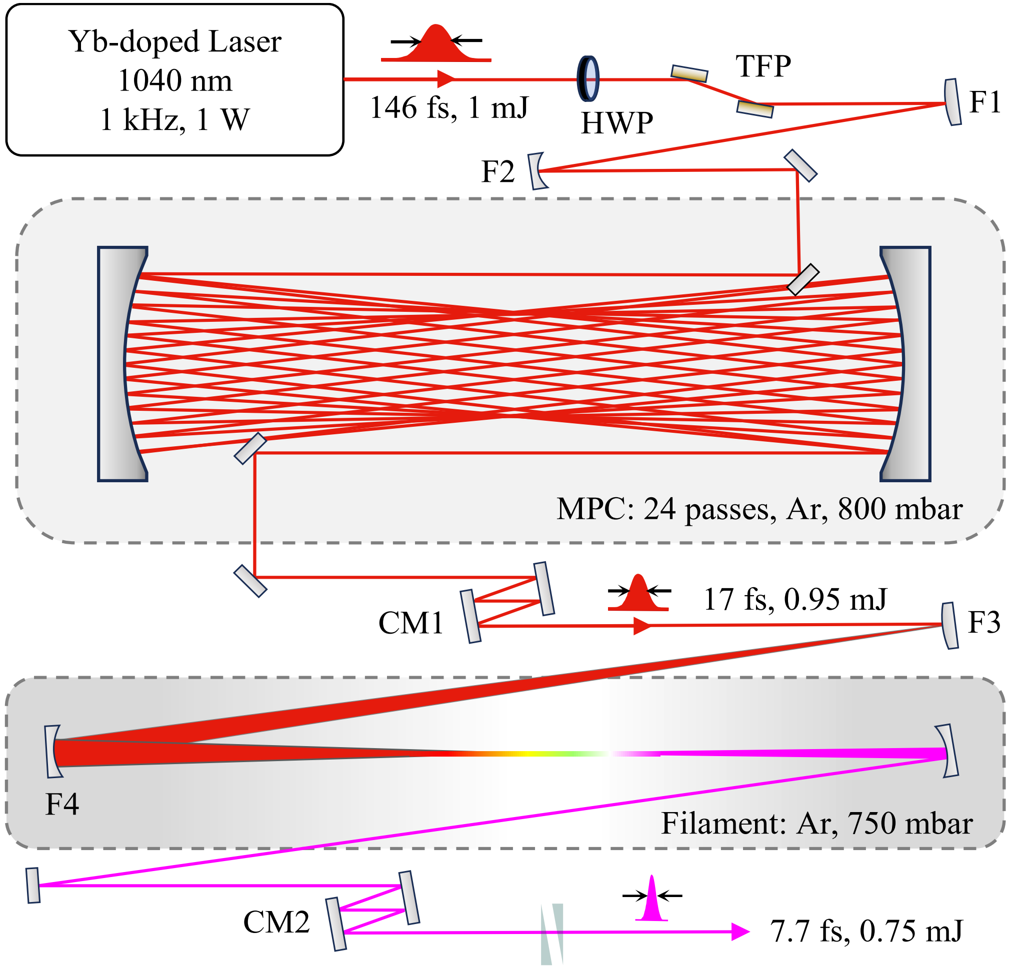


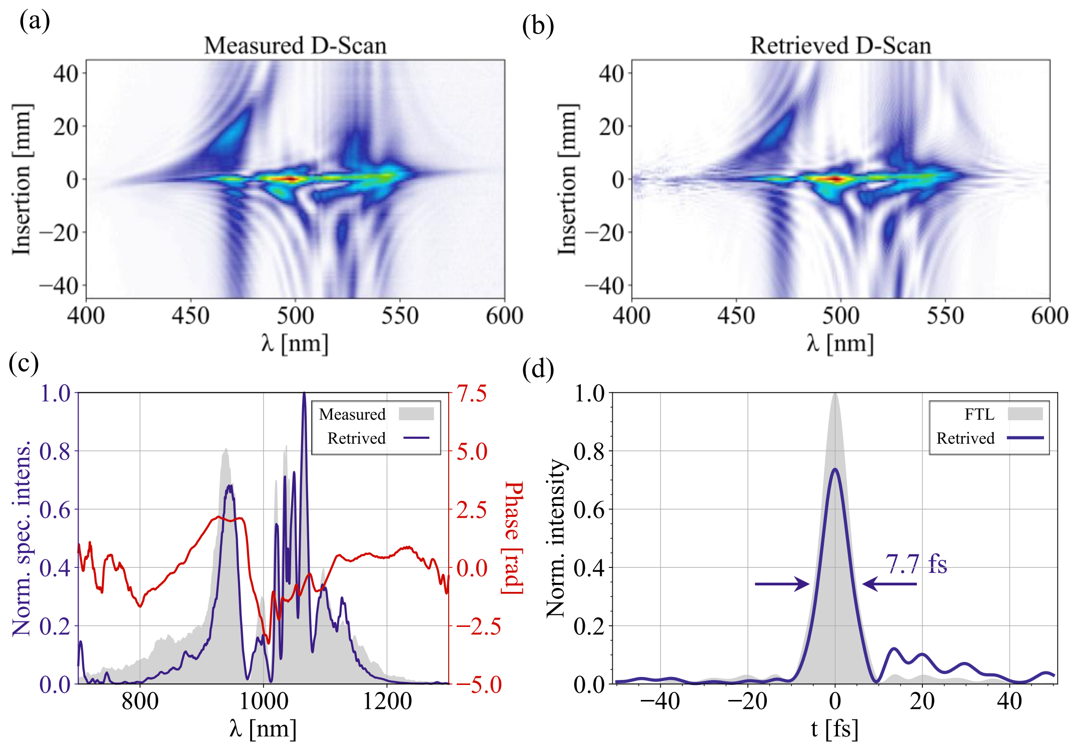






Cascaded post-compression: MPC + filamentation
------ sub 10 fs pulse generation



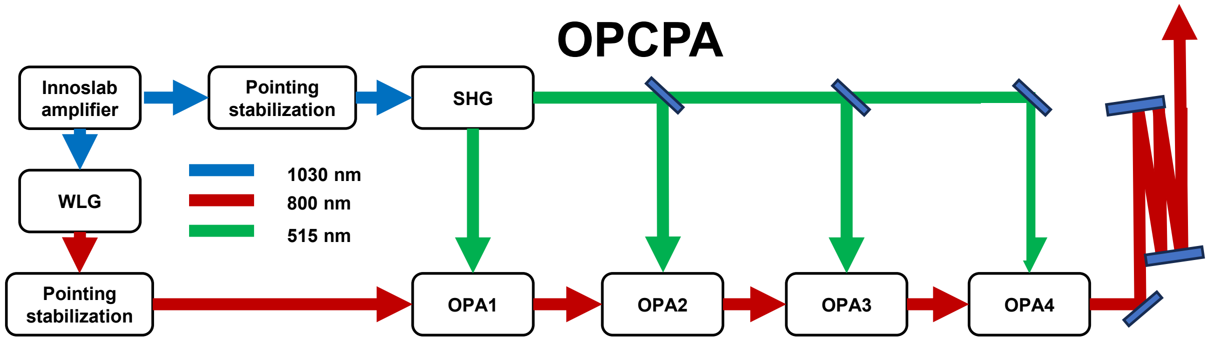


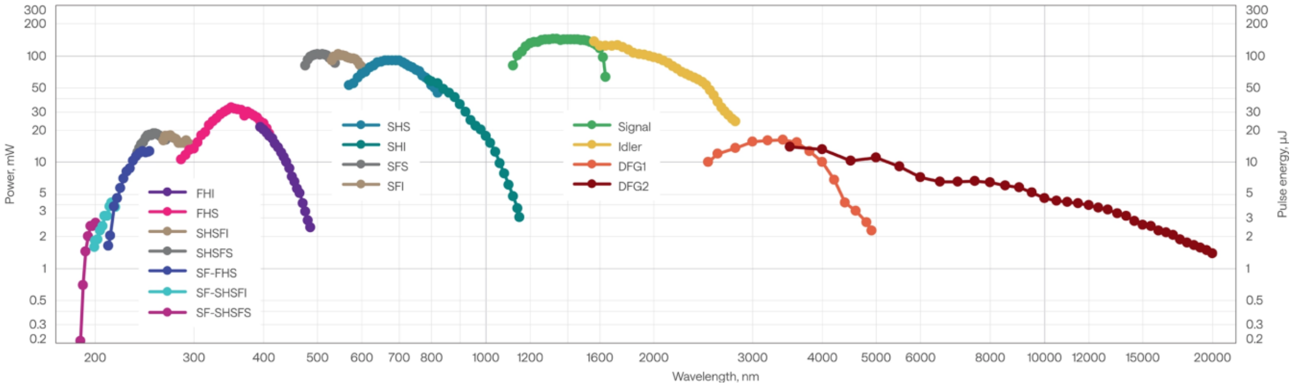
- **Pulse width: from 146 to 7.7 fs;**
- **Pulse energy: 0.75 mJ;**
- **Efficiency: 75 % (total);**

Optical Express, accepted.

Wavelength extension: commercial OPA (down to 200 nm)

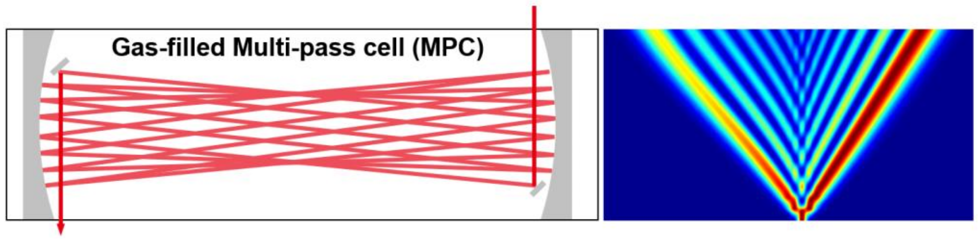
Yb-laser + OPCPA + OPA (800 nm)

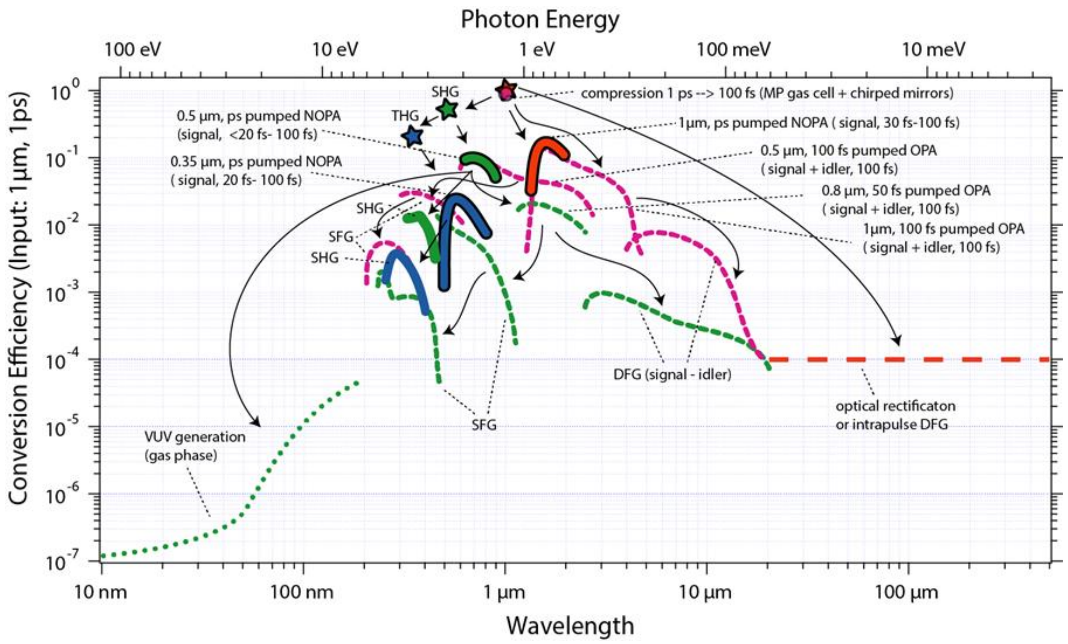




https://lightcon.com/products/topas-prime-opa/

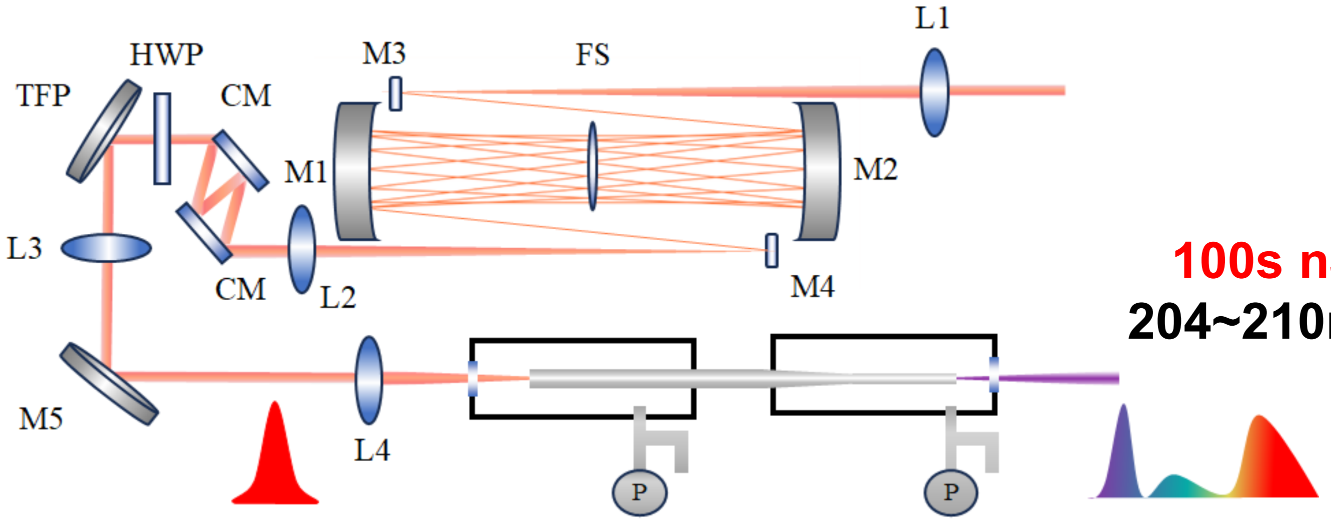
Yb-laser + MPC + OPA (1030 nm)



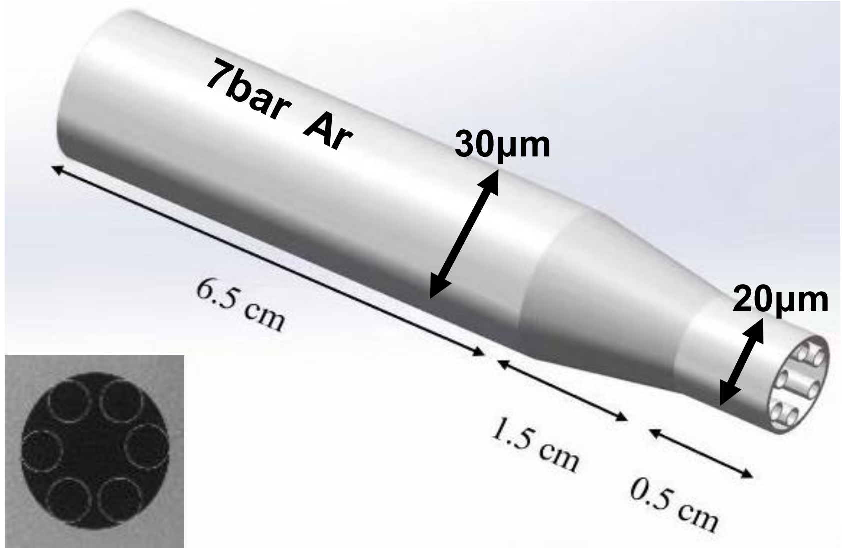


FLASH2020+ conceptual design report. DOI: 10.3204/PUBDB-2020-00465.

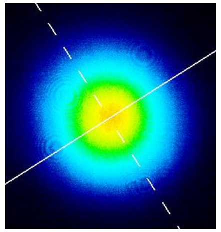
Wavelength extension to DUV (down to 200 nm): DWG with antiresonant PCF

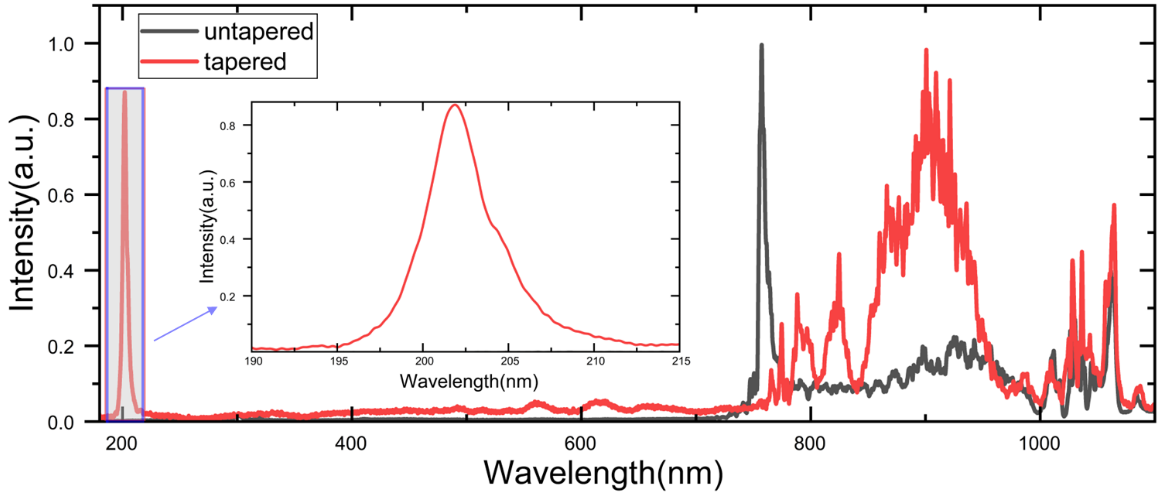


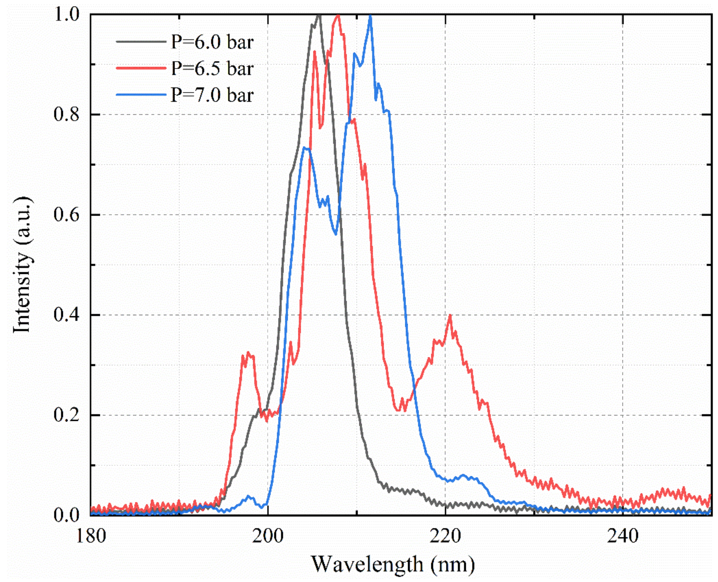
100s nJ
204~210nm



1030 nm 35 fs

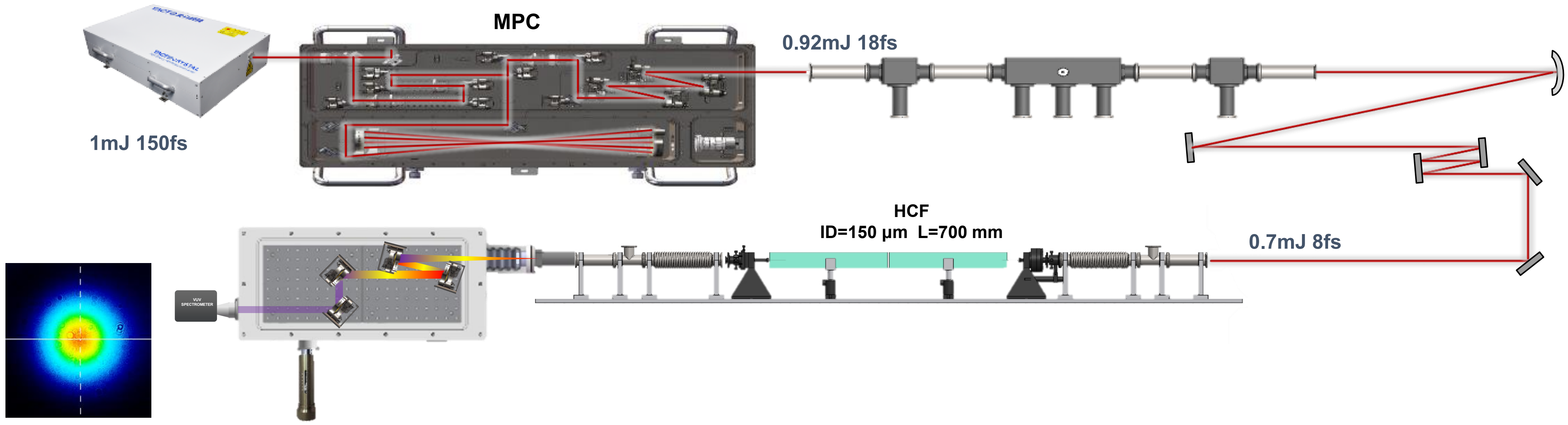




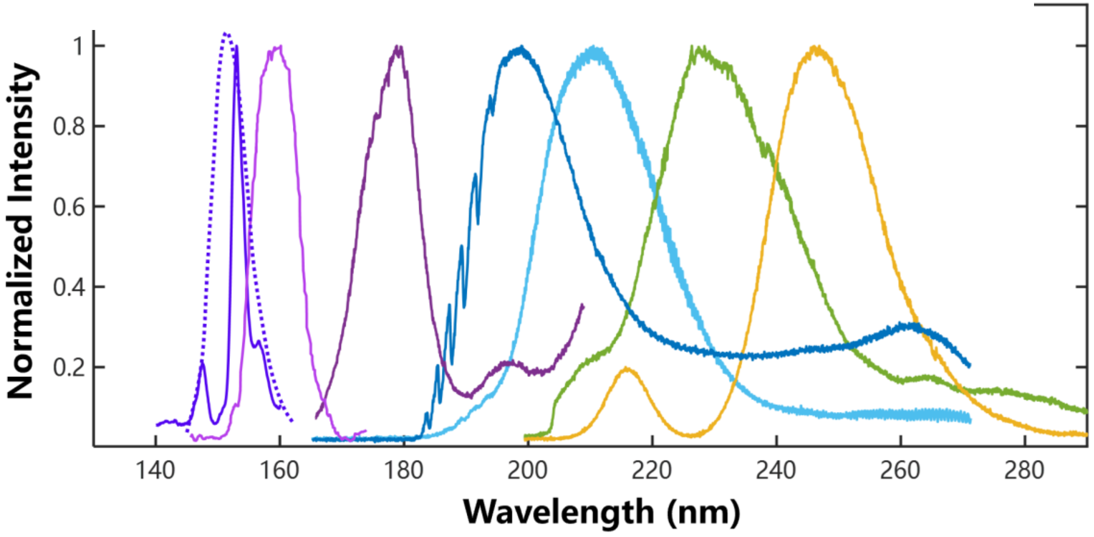


Optics Express, 33, 13796 (2025)

Wavelength extension to DUV & VUV (down to 150 nm): DWG with HCF

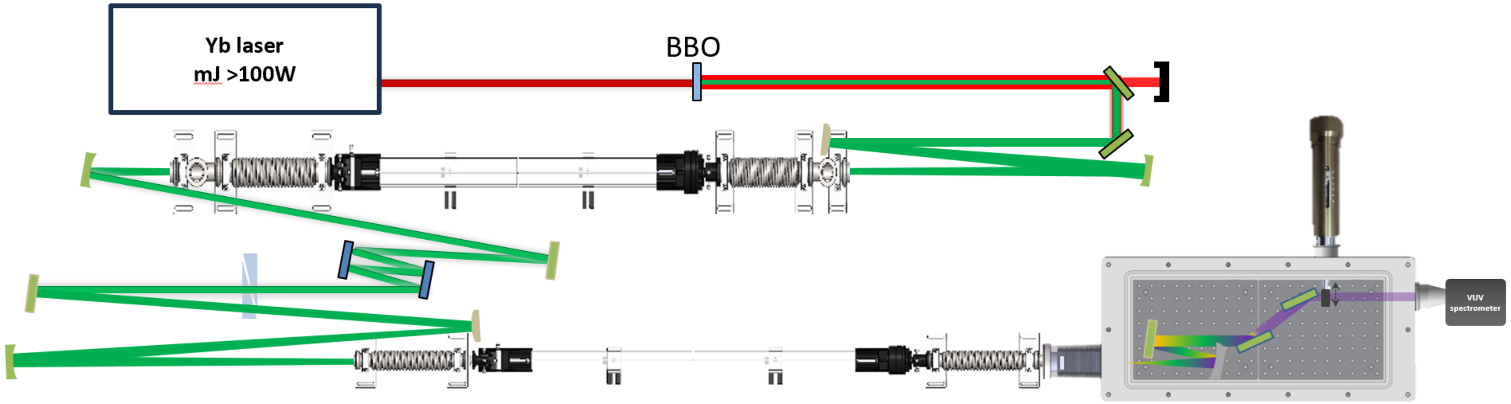


- Table-top ultrashort VUV/DUV source
- Tunable wavelength： 150-250 nm
- Ultrashort pulse （<10 fs）
- High conversion efficiency （0.1-1 %）

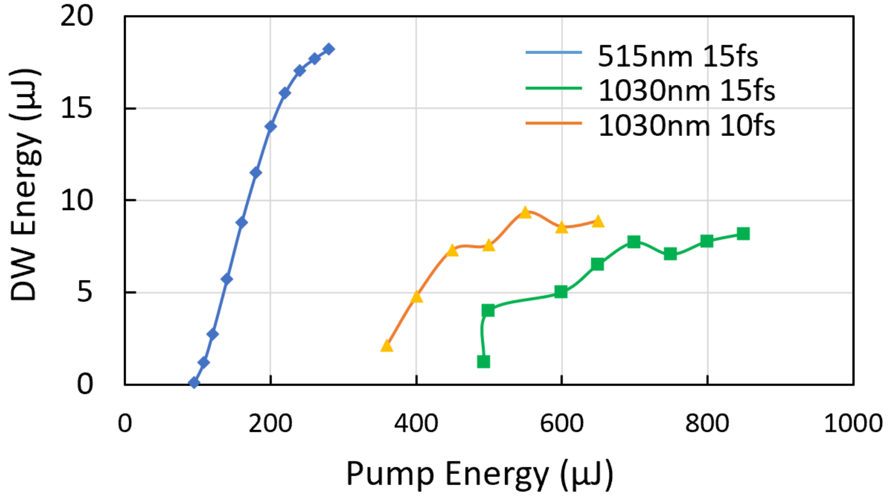


Wavelength extension to 120 nm: DWG with 515 nm pump laser

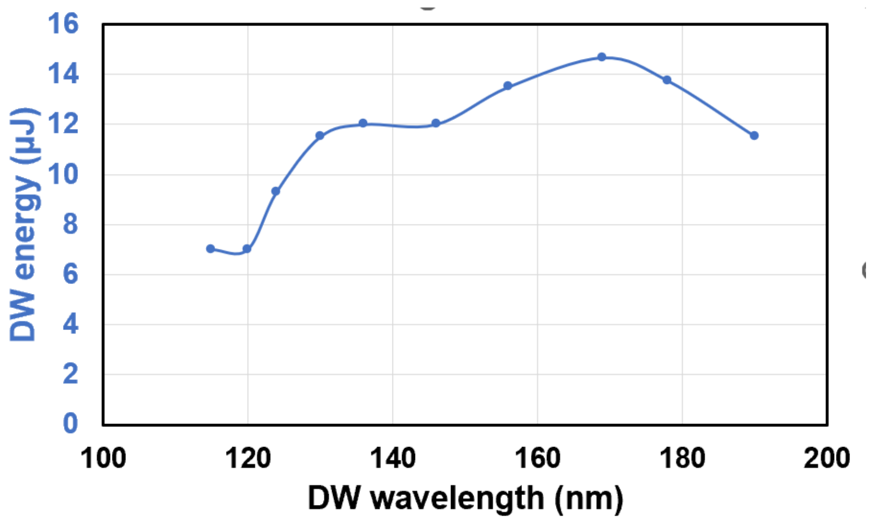
DWG pumped by 515 nm



130 nm generation (simulation)



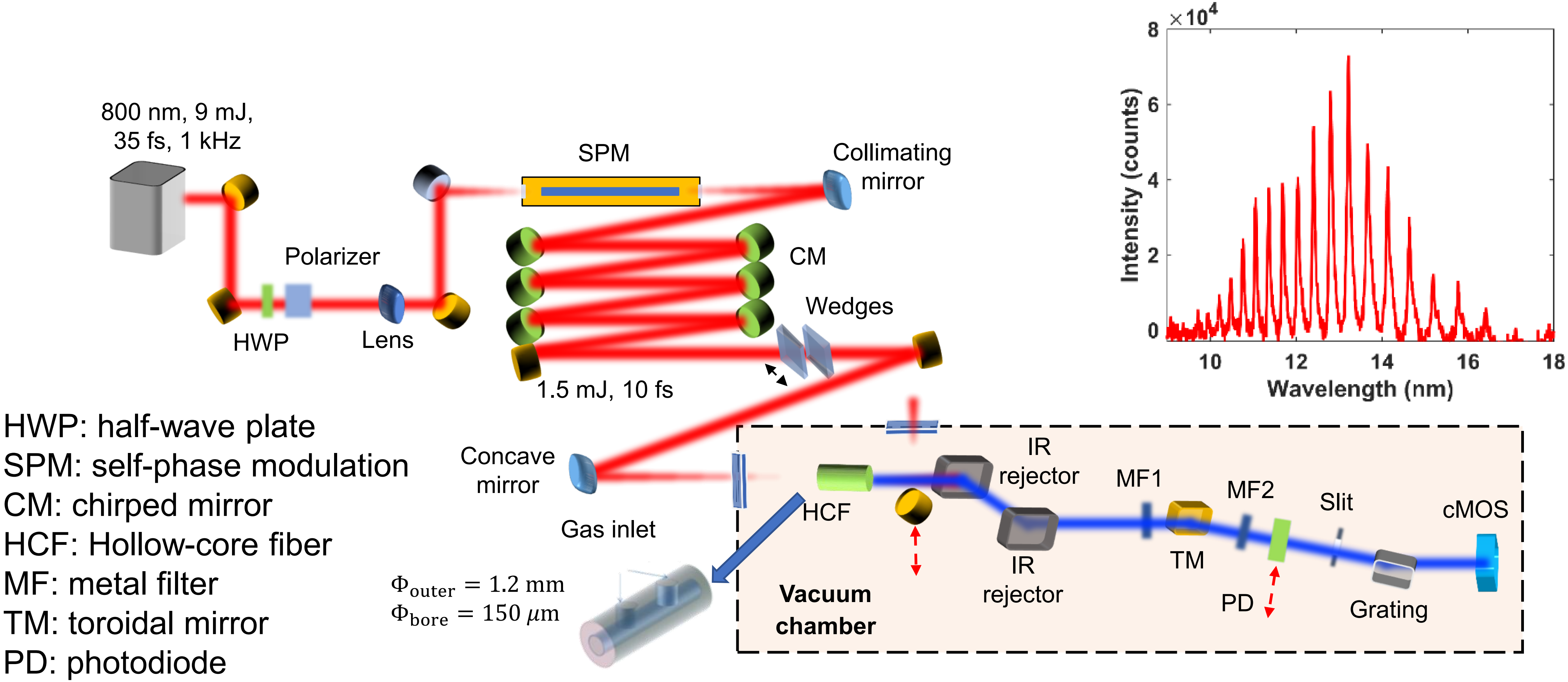
pulse energy of RDW (simulation)



Pumping by green laser pulses:

- Shorter wavelength: ~120 nm
- Ultrashort pulse: < 10 fs
- Higher efficiency: 0.5-1.5%

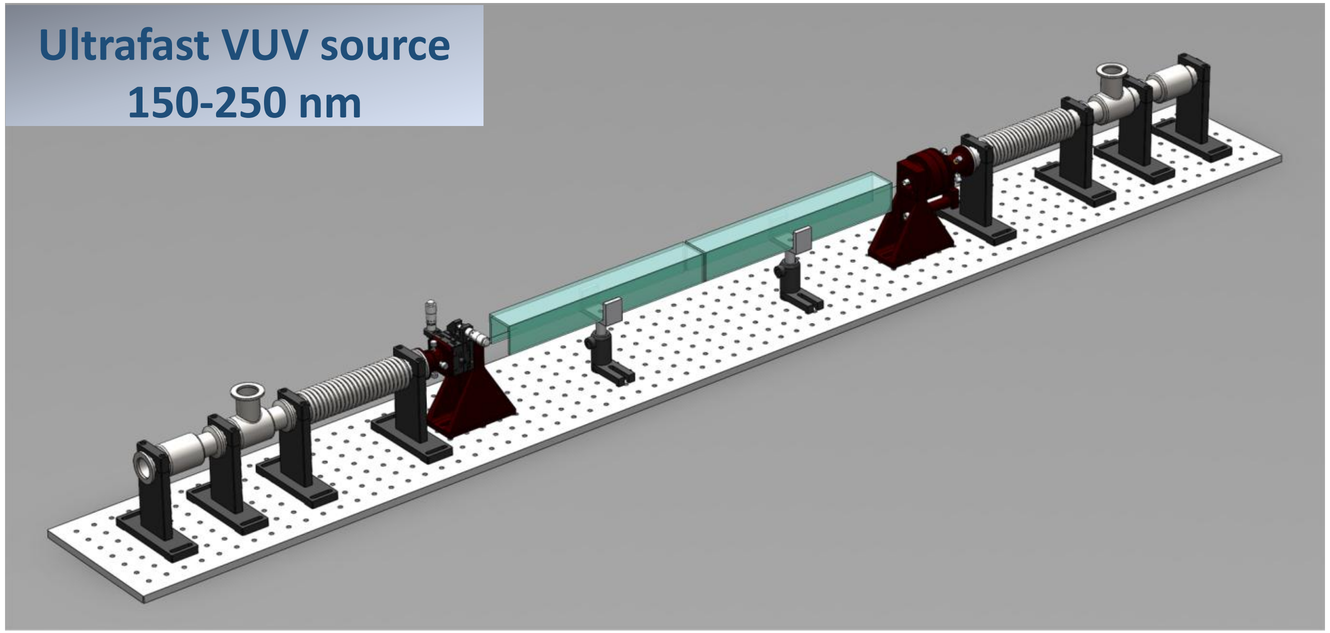
Wavelength extension to EUV：high-efficiency HHG system



Post-compression & capillary HHG

Engineering & Commissioning Progress

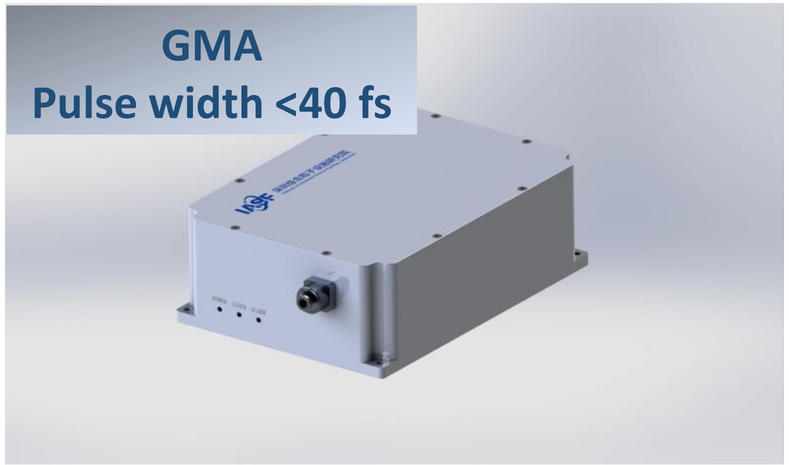
High power ultrafast laser
Up to 200 W



Ultrafast VUV source
150-250 nm

MPC compressor
*shortest pulse width<10 fs

Mid-IR laser
6-20μm tunability



GMA
Pulse width <40 fs

outline

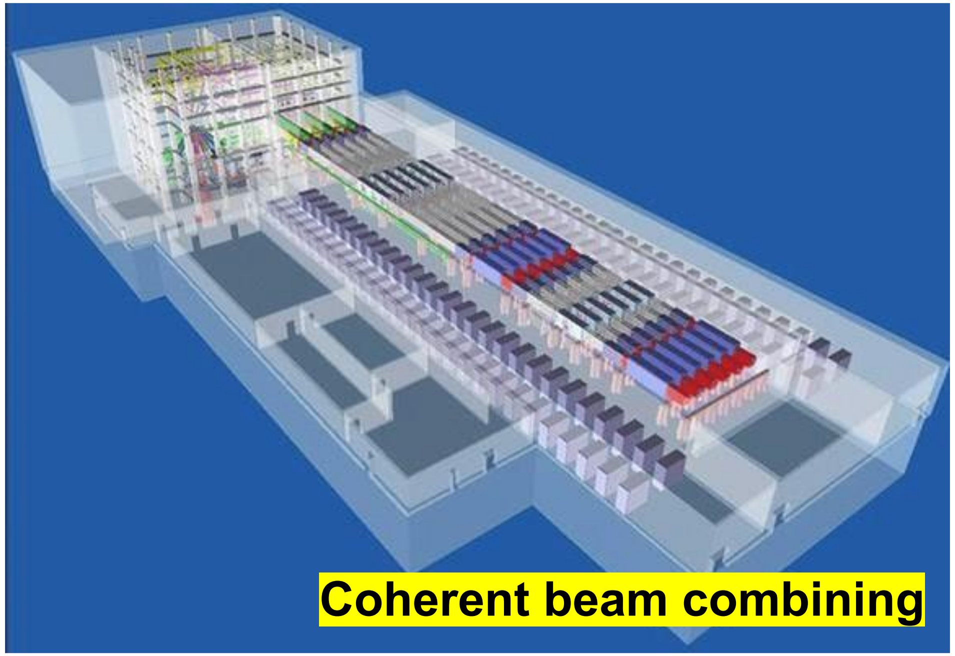
- What is a laser?
- What is an ultrafast laser?
- Mathematic description of an ultrafast laser pulse;
- Ultrafast lasers for S^3FEL;
- **Femtosecond timing and synchronization**

Synchronization

Synchronization is the coordination of events to operate a system in unison [wiki]

High-precision timing and synchronization applications

Radio telescope arrays

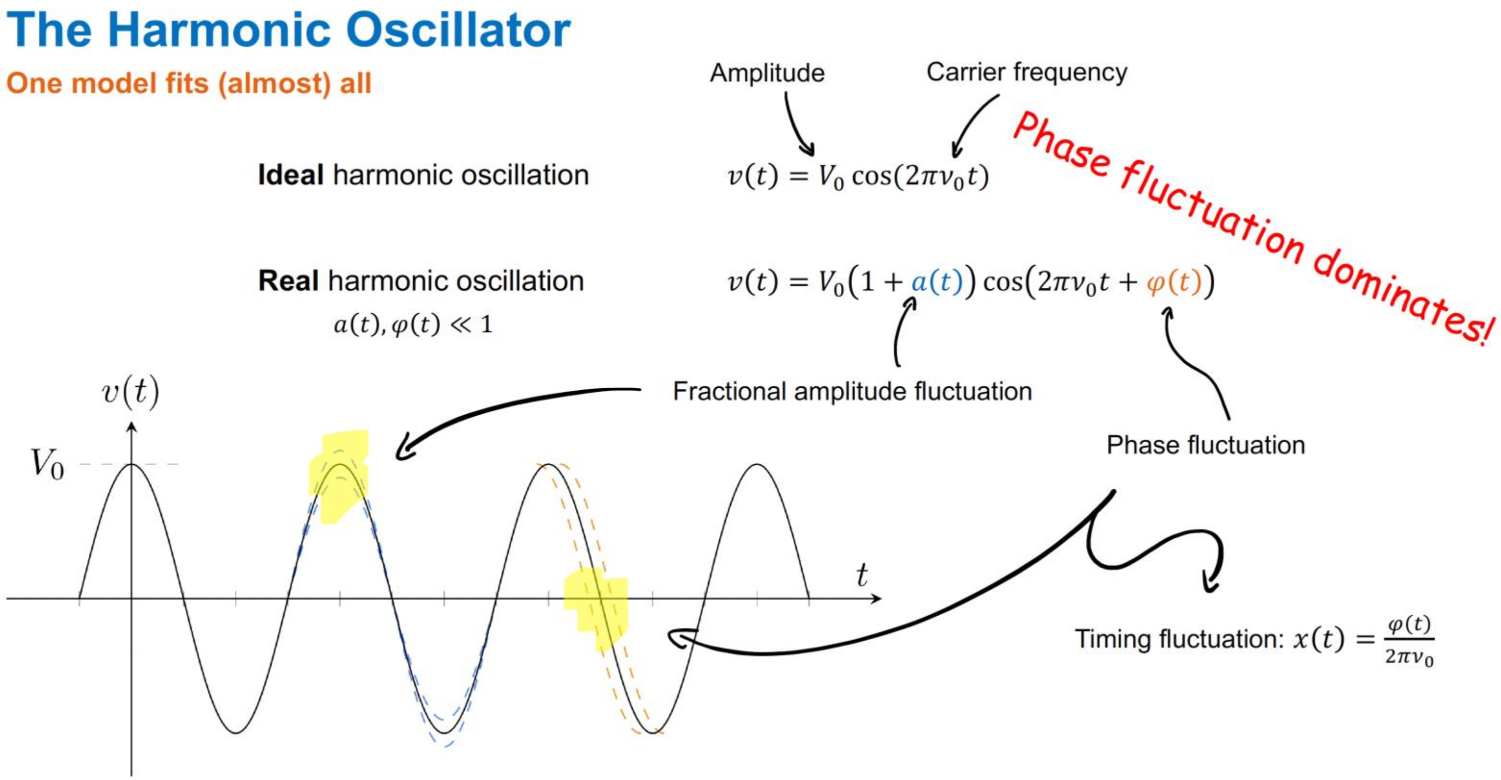


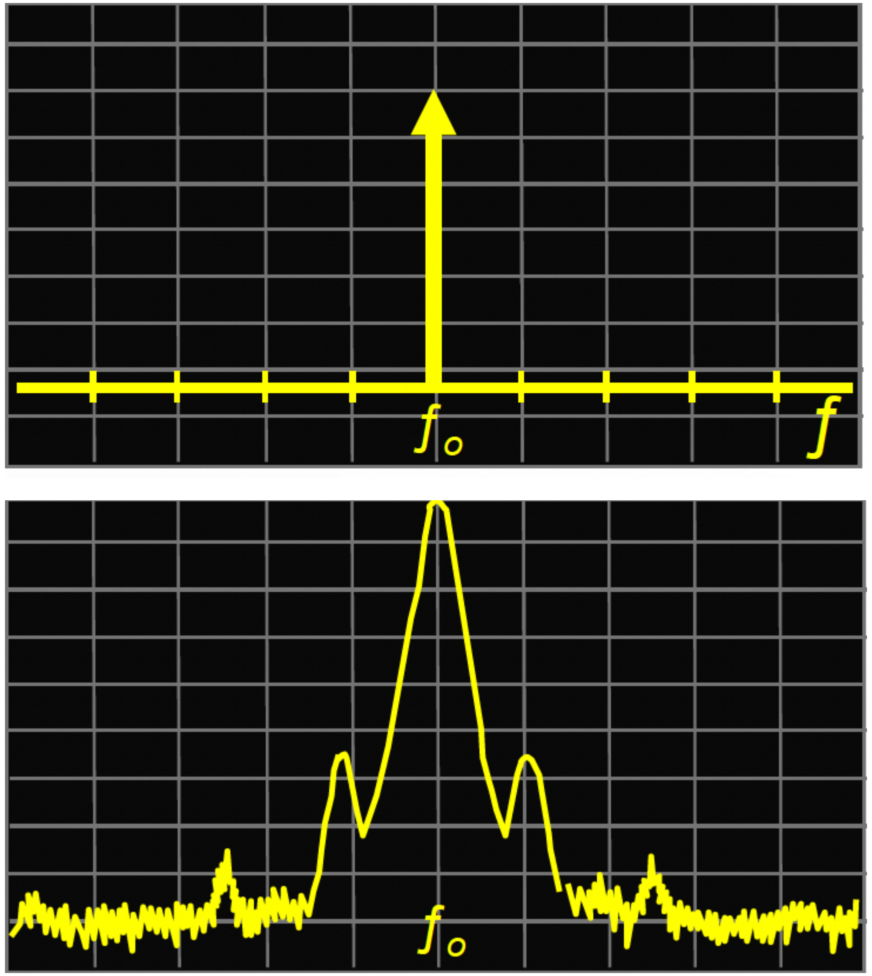
Coherent beam combining

Free electron laser

Phase noise of a real world harmonic signal

Phase noise is generally considered as the **short-term phase/frequency instability** of an oscillator or other RF/microwave component.

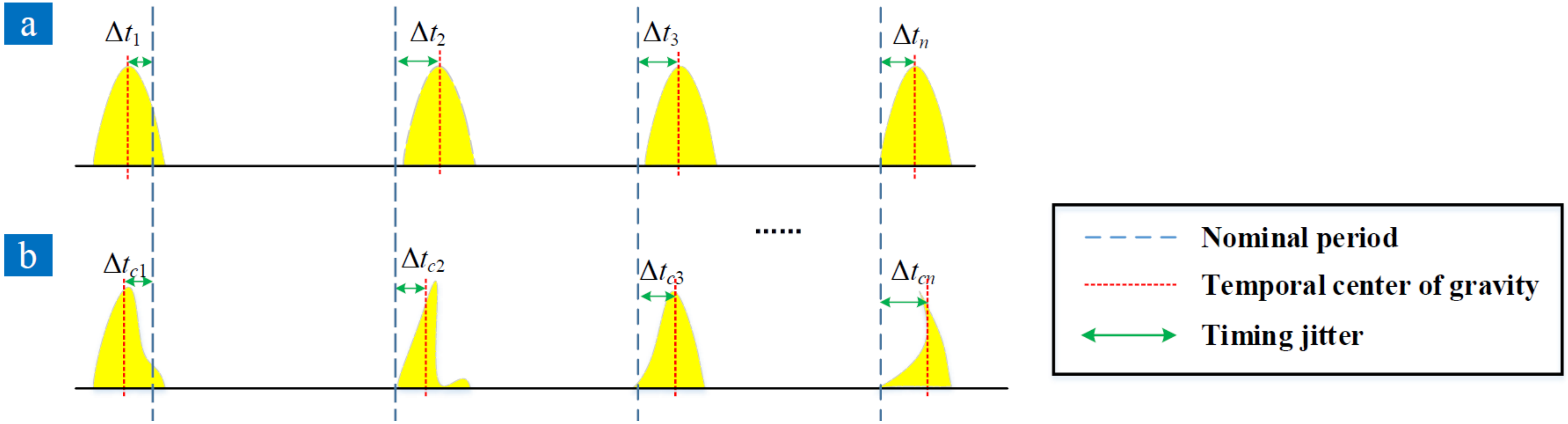




Maximilian Schütte, LLRF Workshop 2024 –
INFN-LNF, Frascati 29th October 2024

Timing jitter of pulsed signal

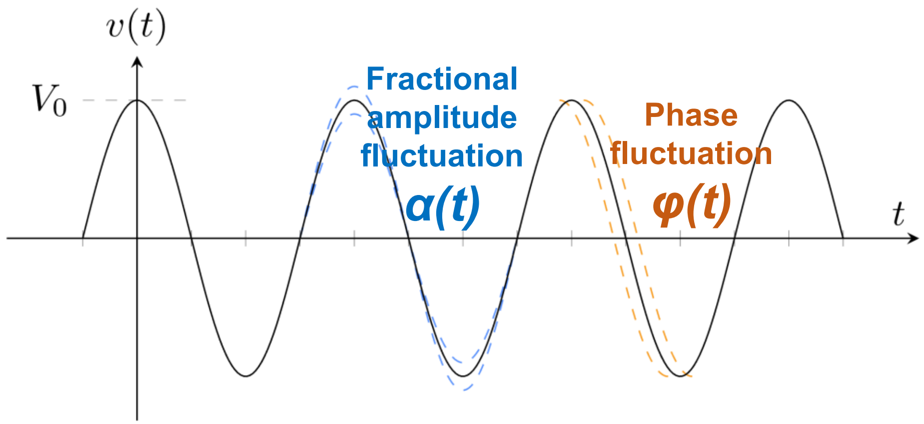
Timing jitter: deviation between the real arrival time of each pulse (timing) and its expected arrival time (nominal period)



$$T_{COG} = \int_{-\infty}^{+\infty} t\,|E(t)|^2\,dt \Big/ \int_{-\infty}^{+\infty} |E(t)|^2\,dt$$

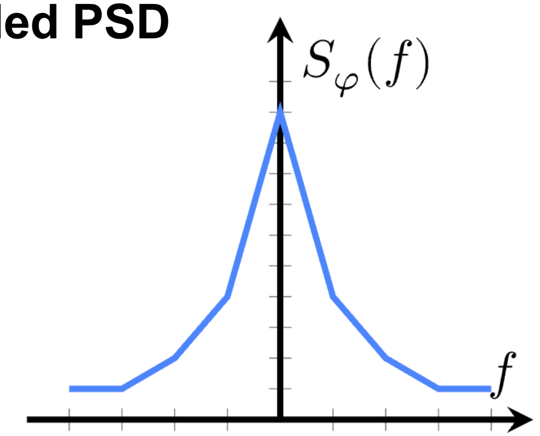
Courtesy Ming Xin (TJU)

Quantitation of timing jitter and phase noise



$$v(t) = V_0\big(1 + a(t)\big)\cos(2\pi\nu_0 t + \varphi(t))$$

Two-Sided PSD



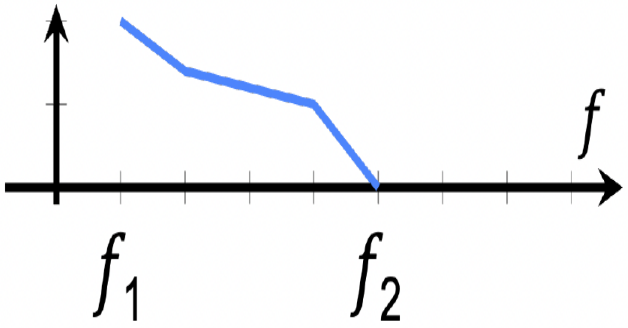
The phase noise power spectral density

$$S_\varphi(f) = \int_{-\infty}^{+\infty} e^{-j2\pi f}\langle\varphi(t+\tau)\varphi(t)\rangle d\tau$$

The timing jitter

$$t_{jitter} = \frac{1}{2\pi f_0}\sqrt{2\cdot\int_{f_1}^{f_2} S_\varphi(f)\,df}$$

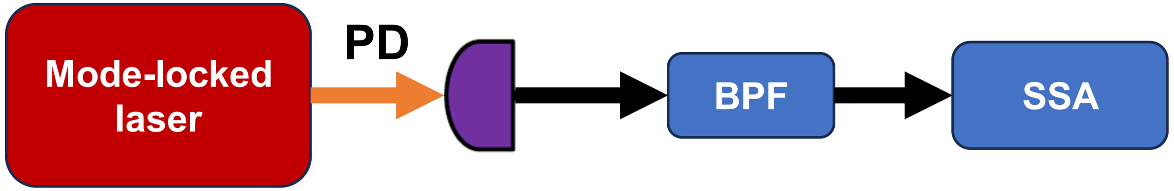
Integrated timing jitter (fs)



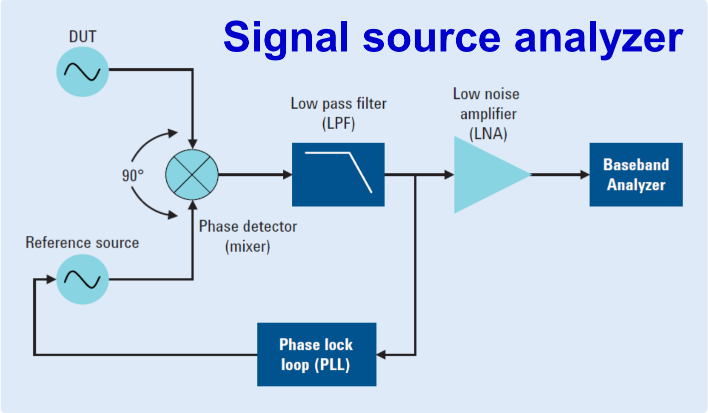
Timing drift is used for timing jitter at very lower frequency range.

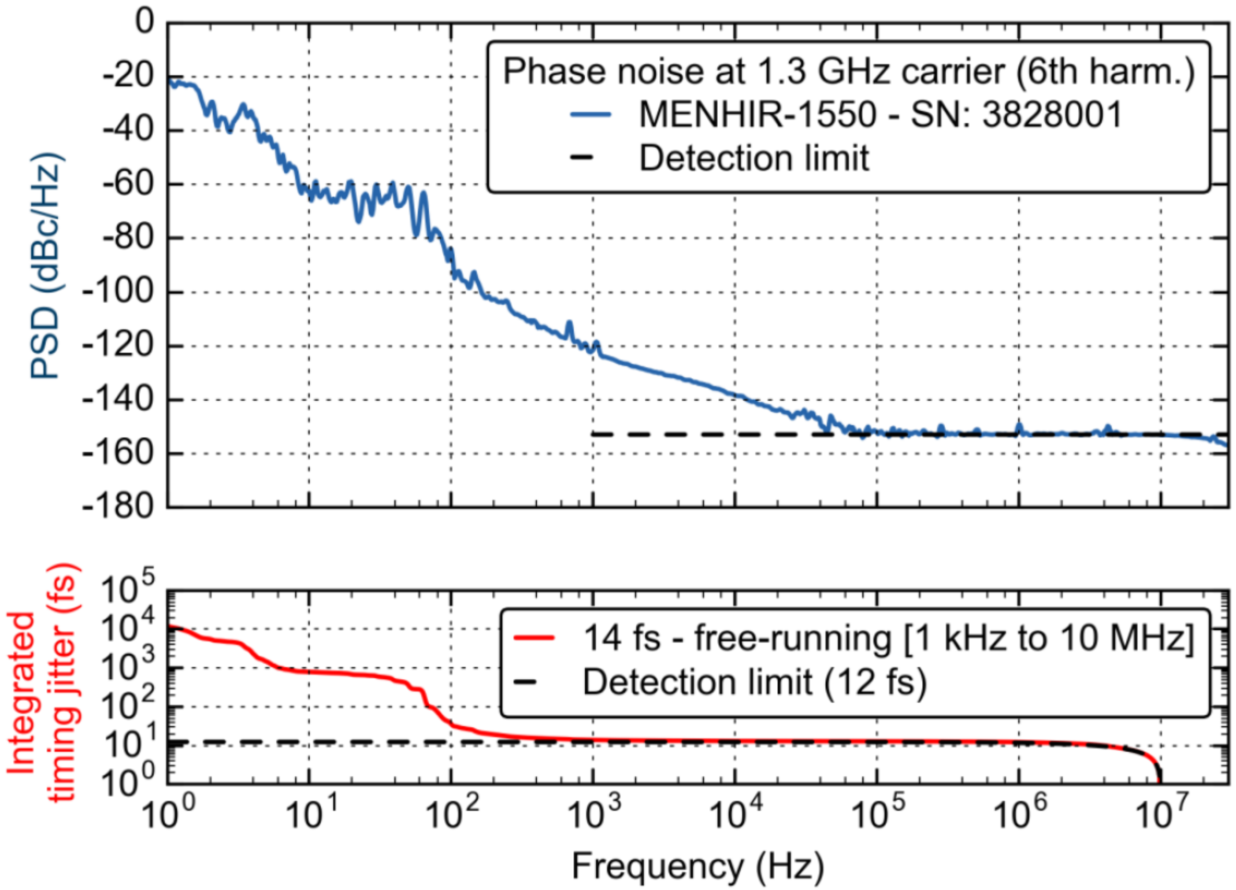
Phase noise and timing jitter detection of optical signal

Direct timing jitter detection



R&S FSWP

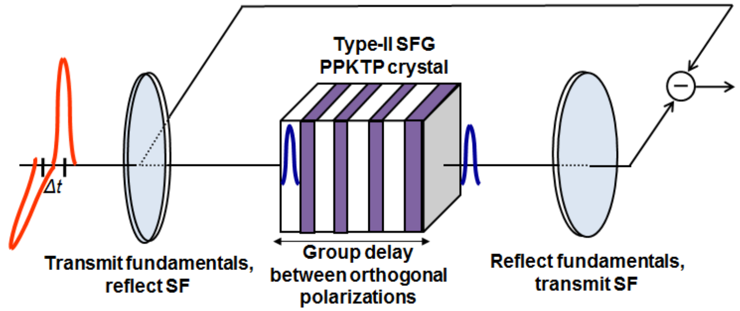




For stable signals, the measurement is limited by AM-PM noise.

Phase noise and timing jitter detection of optical signal

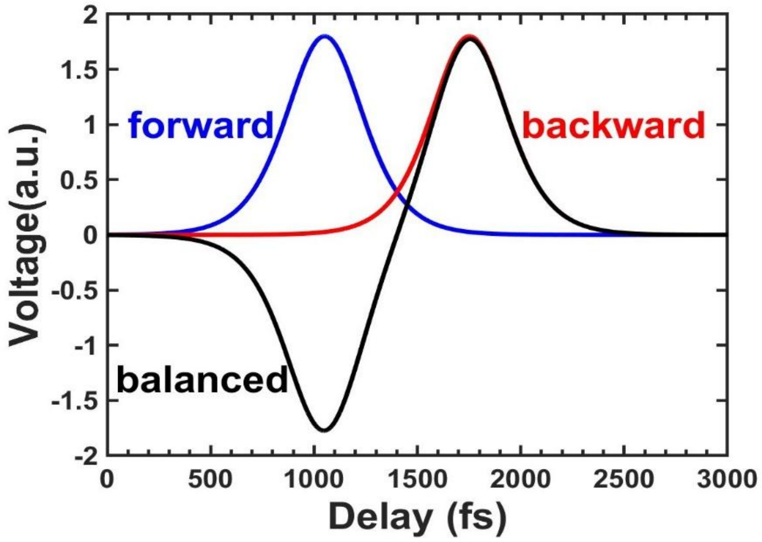
Balanced optical cross-correlator (BOC) between two signals of the same wavelength



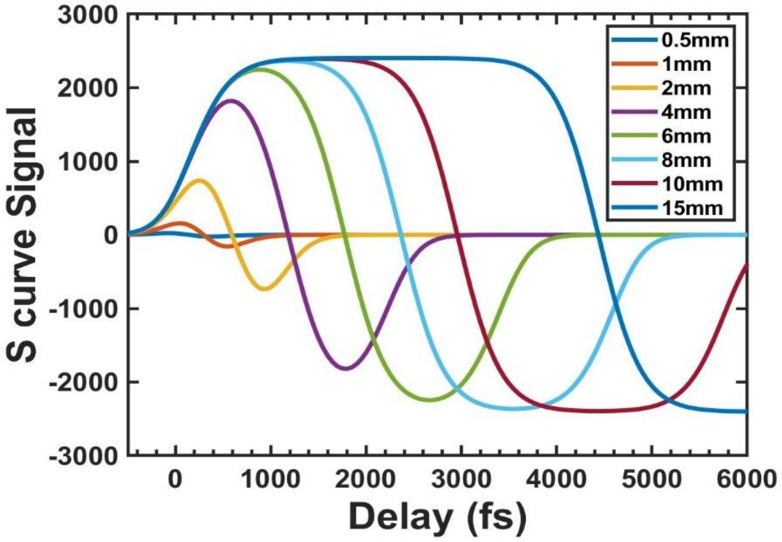
T. R. Schibli, et al., *Opt. Lett.* 28, 947–949 (2003)

- Sum frequency generation
- Type II phase matching
- Quasi-phase matching
- Balanced detection

Highly sensitive balanced detection



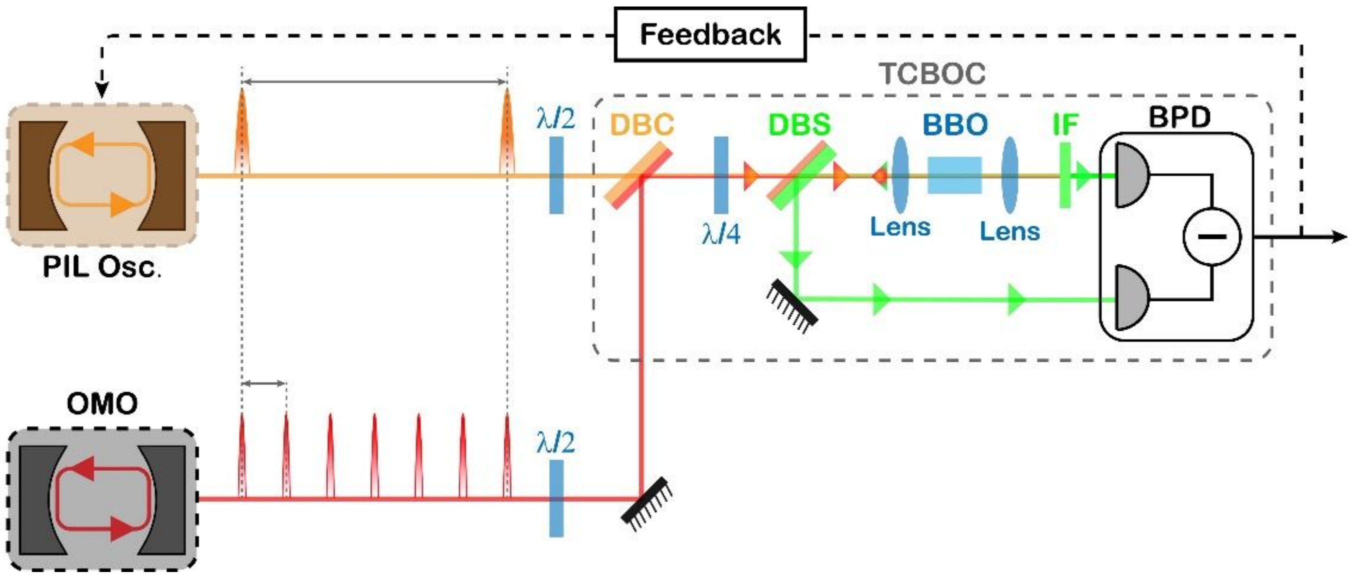
Optimized PPKTP parameter



BOC achieves attosecond-level sensitivity for 1550 nm, 1030 nm and 800 nm.

Phase noise and timing jitter measurement of optical signal

Two color balanced optical cross-correlator (TCBOC) for signals of different wavelengths.

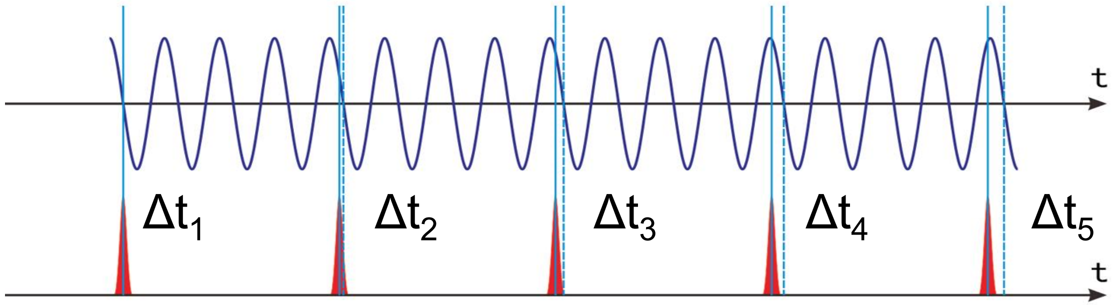


- **Insensitive to laser pulse fluctuations**
- **Sensitivity >10 mV/fs**
- **Approved for solid-state and fiber lasers**
- **Core device of laser synchronization**

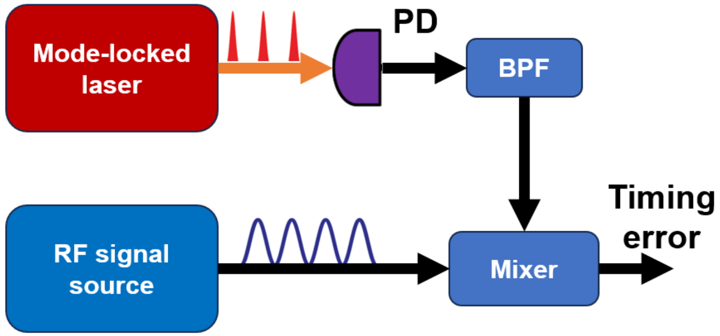
TCBOC achieves sub-fs synchronization for 1030/1550 nm lasers.

Phase noise and timing jitter measurement of microwave signal

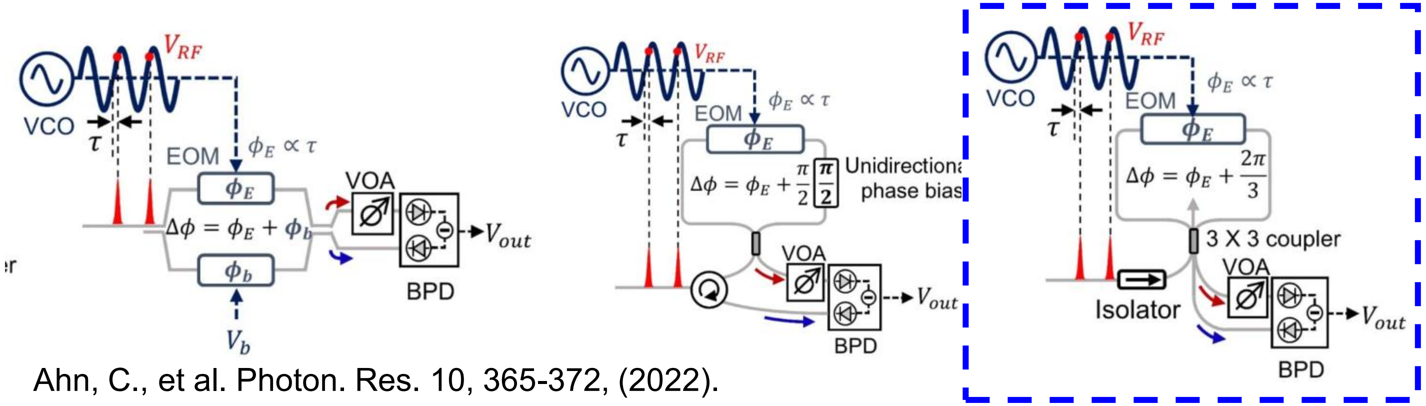
Optical-Microwave



Traditional electronic method



Microwave photonics methods



Ahn, C., et al. Photon. Res. 10, 365-372, (2022).

Limited timing resolution **~50 fs:**

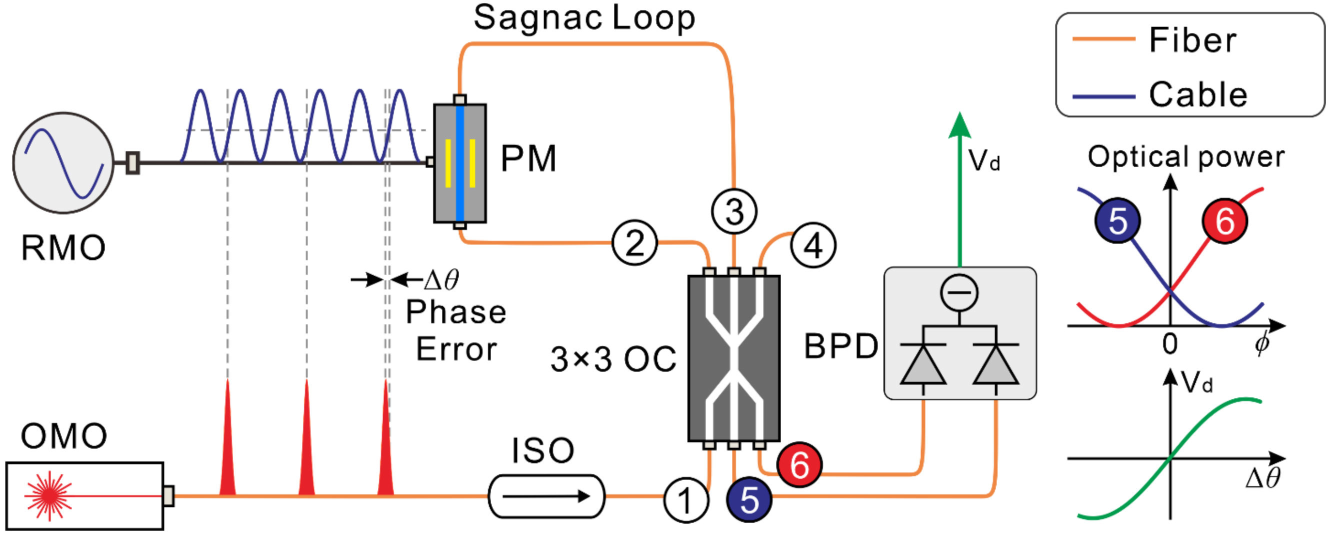
- amplitude-to-phase conversion of photodiode
- phase discrimination resolution of microwave mixer

Precise timing discrimination

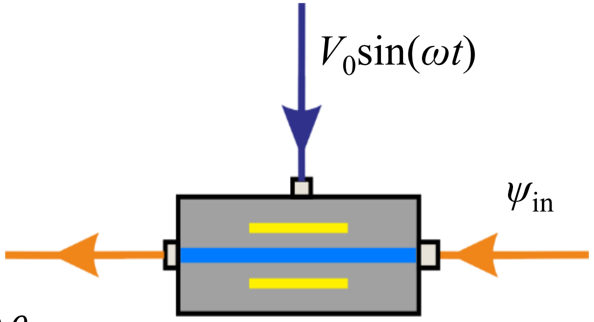
- **sub-fs** timing discrimination
- high amplitude-to-phase suppression ratio by balanced detection

Timing jitter detection of microwave signal

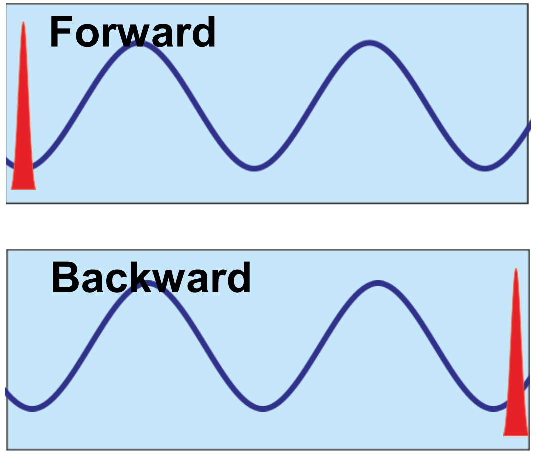
BOMPD: Balanced optical-microwave phase detector



Uni-directional phase modulator



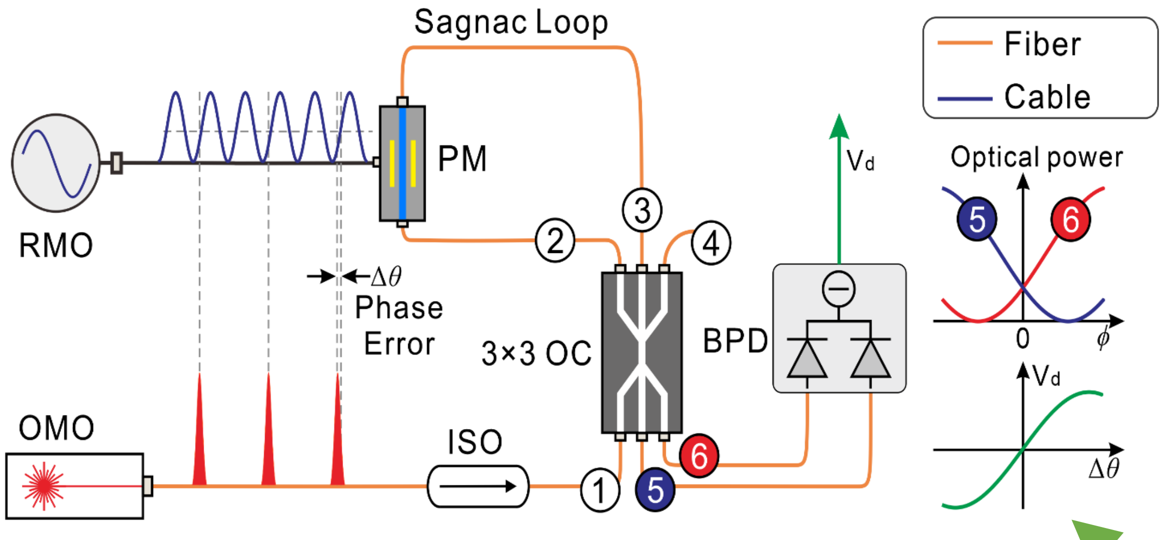
$$\phi \cong \frac{\pi}{V_\pi} V_{RF.amp} \Delta\theta$$



B. Liu et al, NUCL SCI TECH 29:91 (2018)

J. Kim, Opt. Lett. 43, 3997 (2018).

BOMPD



ψ_{1235}: port 1 → port 2 → port 3 → port 5

Interference

ψ_{1325}: port 1 → port 3 → port 2 → port 5

Port 5

$$P_5 = |\psi_{1235} + \psi_{1325}|^2 = \left|\frac{1}{3}\psi_1\left[\exp(i\phi) + \exp\left(i\frac{4\pi}{3}\right)\right]\right|^2 = \frac{4}{9}|\psi_1|^2\cos^2\left(\frac{\phi}{2} - \frac{2\pi}{3}\right)$$

ψ_{1236}: port 1 → port 2 → port 3 → port 6

Interference

ψ_{1326}: port 1 → port 3 → port 2 → port 6

Port 6

$$P_6 = |\psi_{1236} + \psi_{1326}|^2 = \left|\frac{1}{3}\psi_1\exp\left(i\frac{2\pi}{3}\right)\left[\exp(i\phi) + \exp\left(i\frac{2\pi}{3}\right)\right]\right|^2 = \frac{4}{9}|\psi_1|^2\cos^2\left(\frac{\phi}{2} - \frac{\pi}{3}\right)$$

$$V_d = c[P_6 - P_5] = \frac{4}{9}c|\psi_1|^2\sin\left(\frac{\pi}{3}\right)\sin(\phi) \approx \frac{4}{9}\pi c|\psi_1|^2\sin\left(\frac{\pi}{3}\right)\frac{V_{RF}}{V_\pi}\Delta\theta$$

- **Insensitive to laser pulse fluctuations**
- **Sensitivity 0.5 mV/fs**
- **Locking BW~5 kHz**

BOMPD

RF input

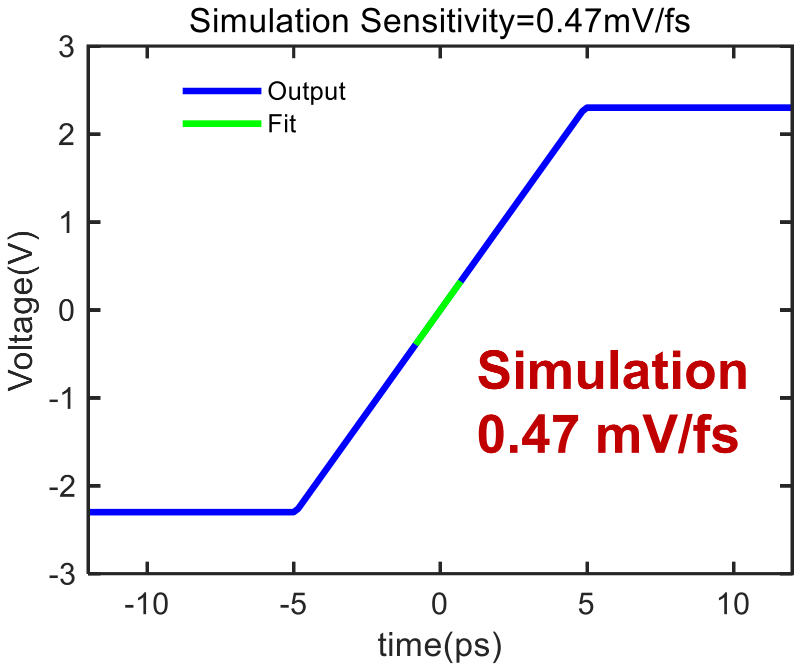
- P = 8.5 dBm
- f = 1.3 GHz

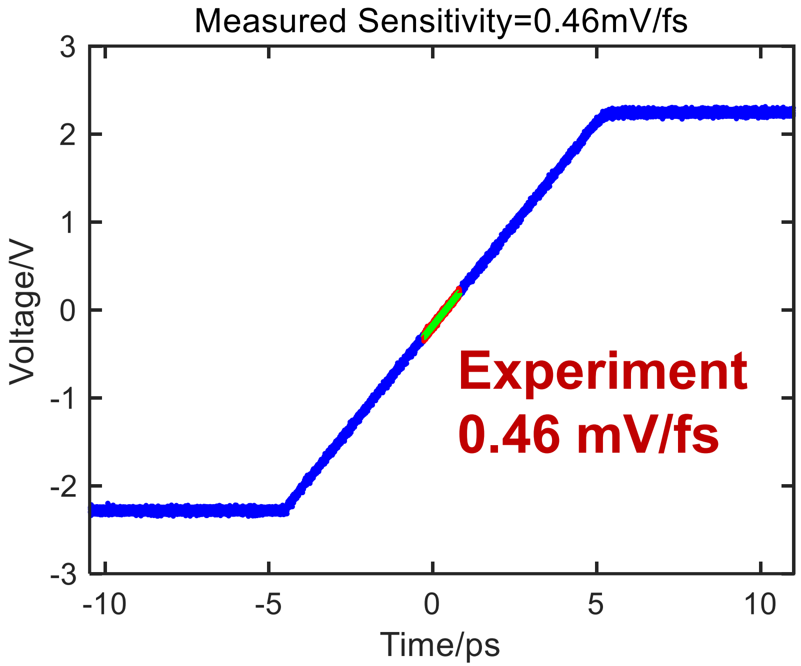
Laser input

- P = 15 mW
- f’ = 216.667 MHz
- λ = 1550 nm

BPD

- Gain = 0.5e5 V/A





Simulation result meets experiment’s very well !

Timing and synchronization system for FEL facilities

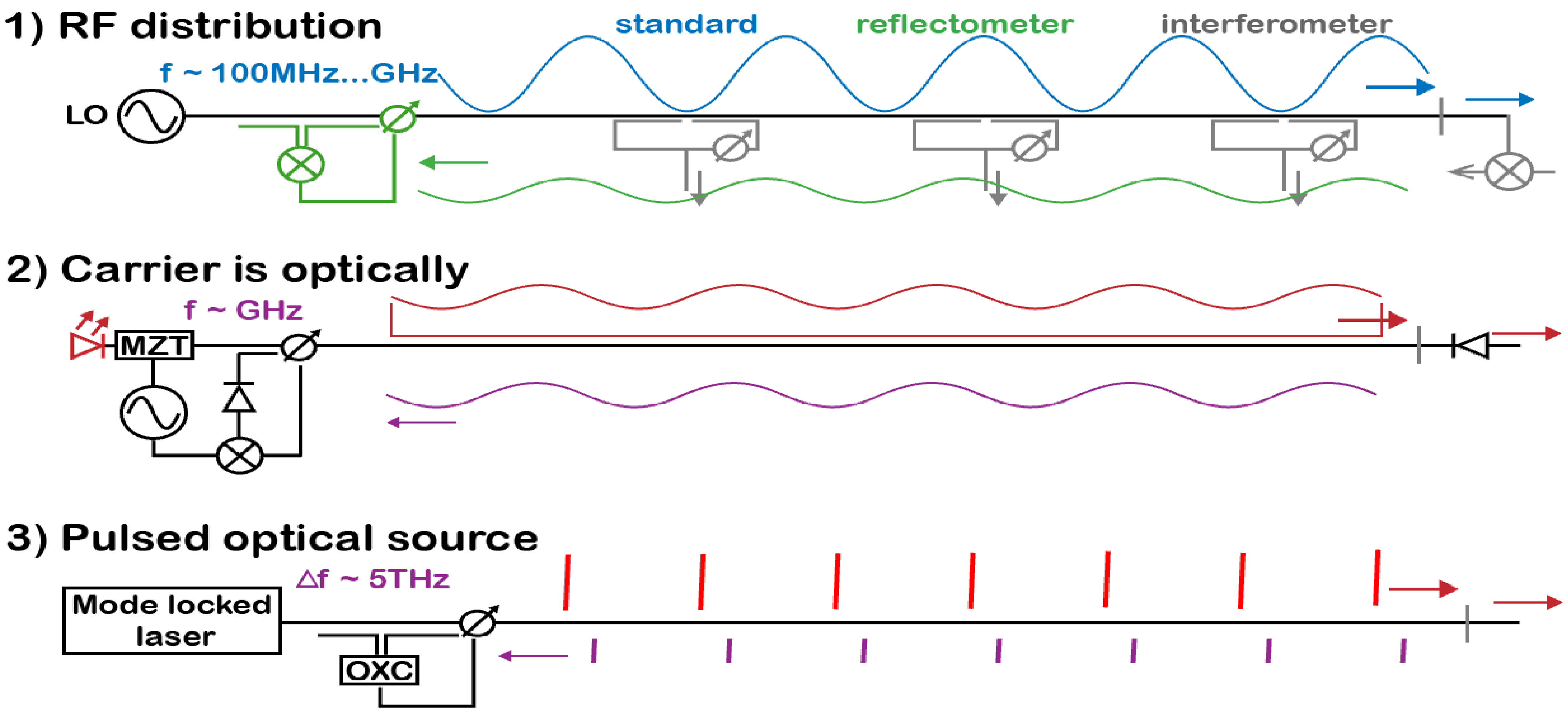
Task:

- Providing femtosecond level stable master clock;
- Distributing fs-level reference signal over the whole FEL facility for slave lasers, LLRF, and diagnostics;
- Tight locking of optical and microwave clients;

Function:

- Stabe operation of FEL;
- Highest time-resolution for diagnostics and pump-probe experiments;

Synchronization methods



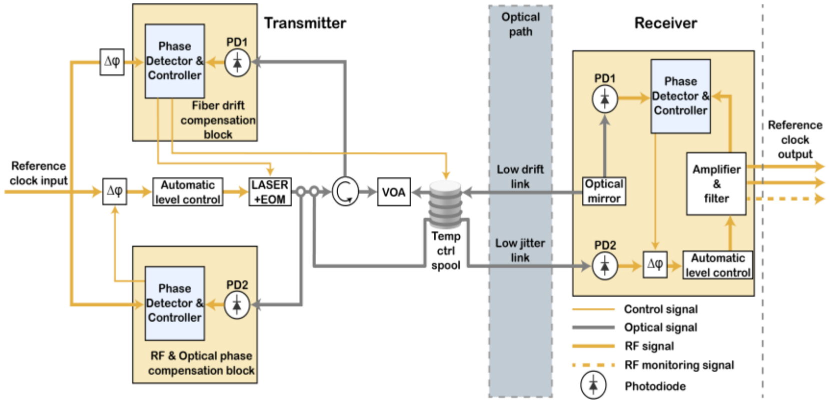
Adapted from Dr. Holger Schlarb slide (DESY)

Synchronization methods

Various synchronization methods have been developed

Approach		Developed by	Jitter fs[10Hz,10MHz]	Drift fs/24h/km	Advantage	Disadvantage
Fiber Link	Pulsed laser + PMF	MIT-CFEL DESY	<0.5	~5	Lowest jitter Drift free Large distance	Expensive
	CW laser + SMF	PSI LBNL	<20	~40	Low jitter Long distance	Certain drift
RF Link	Temperature stabilized RF	PAL SACLA	<10	>250	Stable	Large drift

European XFEL



SwissFEL

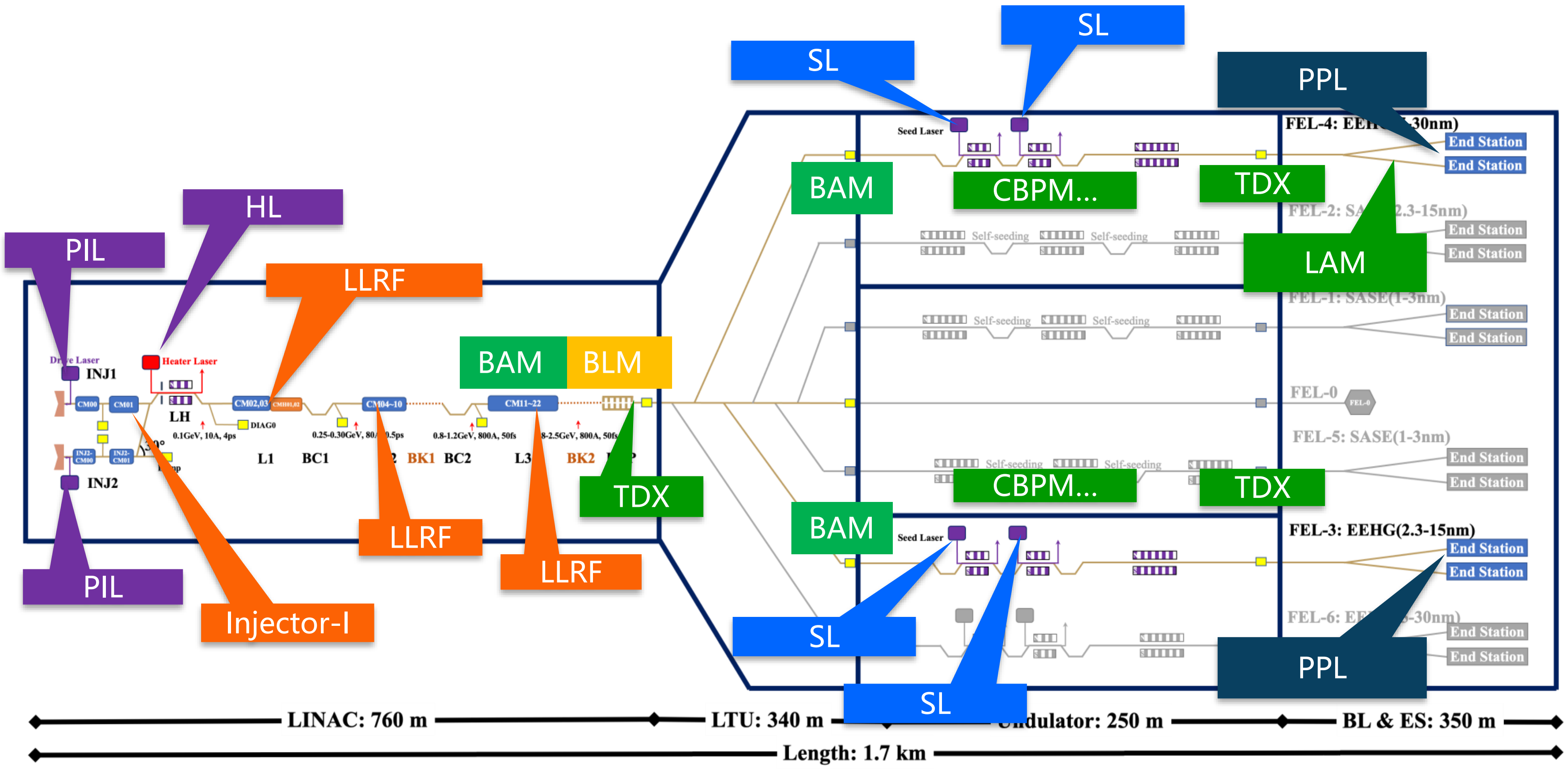
PAL XFEL

Synchronization methods

Hybrid SYN with pulsed laser link as the backbone has become the mainstream design of large-scale FELs.

Facility	RF	CW Laser Link	Pulsed Laser Link
LCLS	●		●
SwissFEL	●	●	●
FERMI	●	●	●
PAL XFEL	●	●	
SACLA	●	●	
SXFEL	●	●	●
DCLS	●		●
LCLS-II	●	●	●
FLASH	●		●
EuXFEL	●		●
SHINE	●		●
S^3FEL	●	●	●
DALS	●	●	●

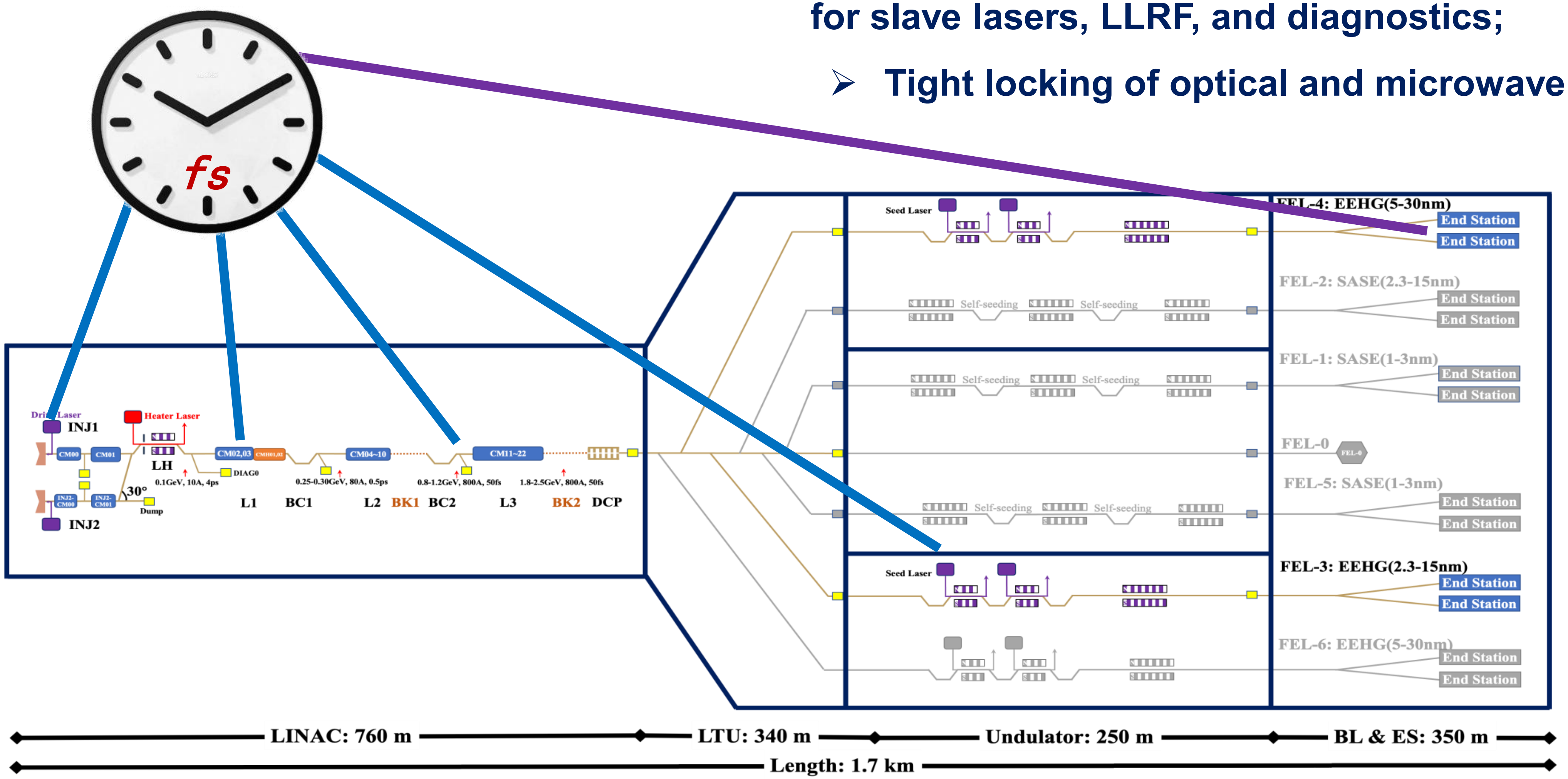
Requirements of Synchronization System for S^3FEL



High-precision, kilometer scale, hundreds clients, robustness

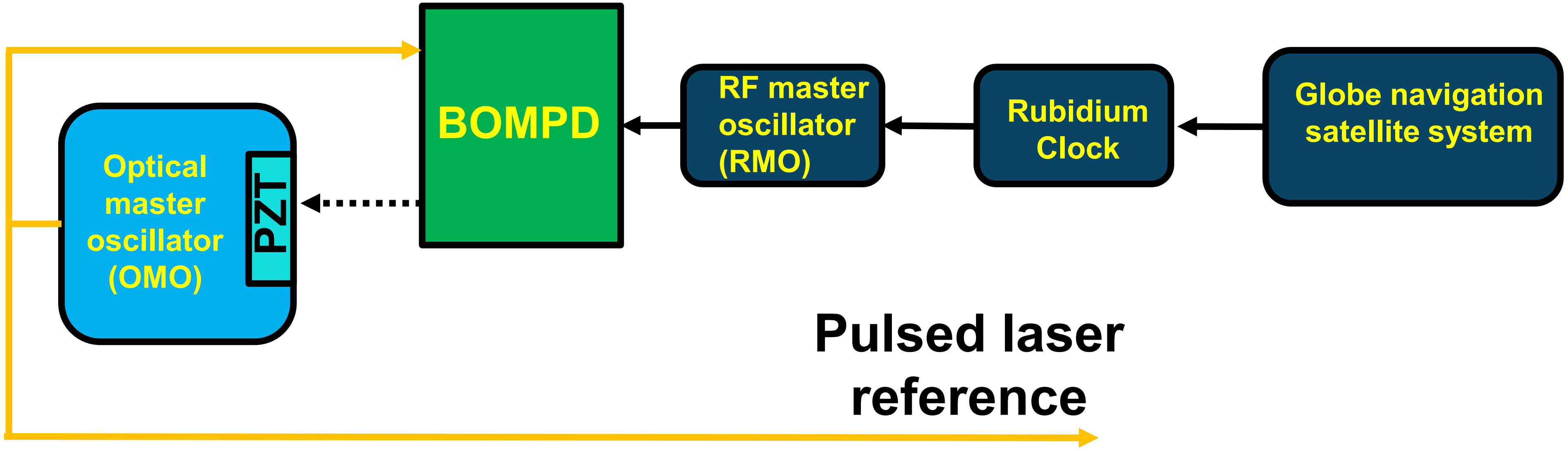
S³FEL Synchronization System

- Providing femtosecond level stable reference signal;
  - Distributing reference signal over the whole FEL facility for slave lasers, LLRF, and diagnostics;
    - Tight locking of optical and microwave clients;



Master Clock

Master clock provides ultra-stable timing reference



Architecture diagram

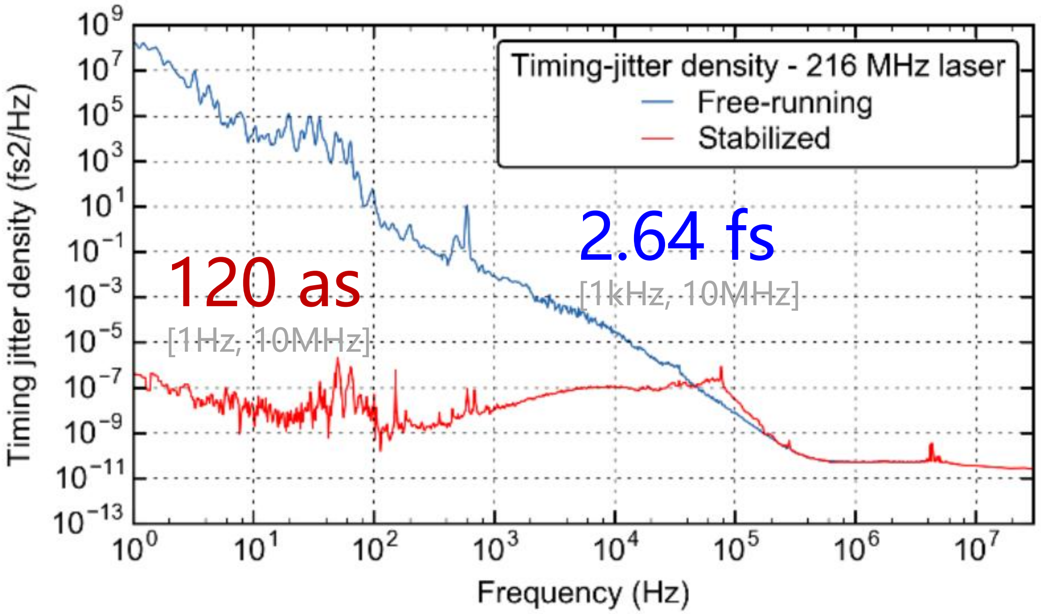
GPSDRO + RMO + OMO → ultra-stable master clock with extremely low jitter and outstanding long-term accuracy.

Master Clock

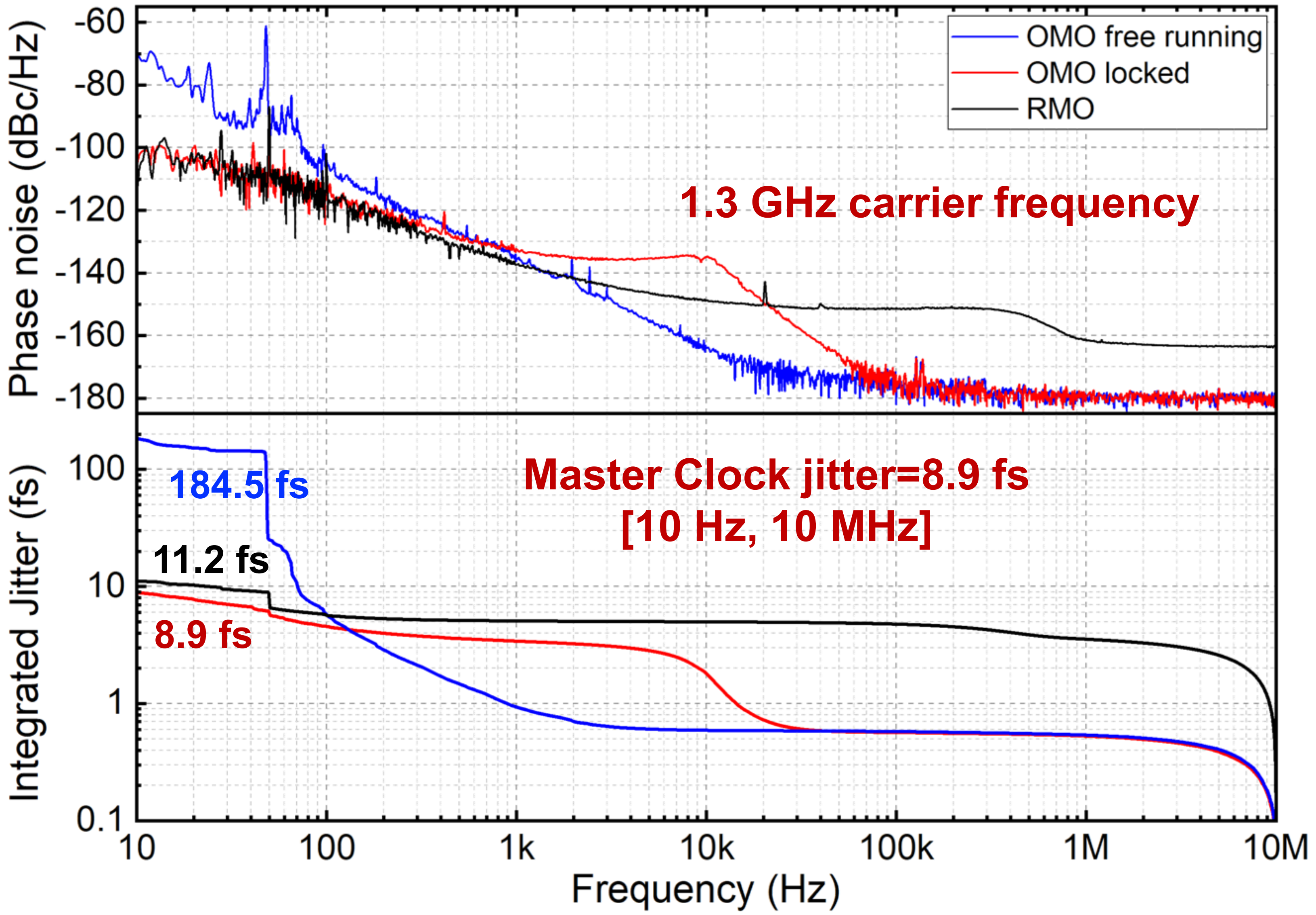
Main components of master clock

GPSDRO + RMO
- Commercial RF signal oscillator
- 1.3 GHz
- Ultra-low phase noise
- 24/7 operation

OMO
- Commercial mode-locked laser
- 216.667 MHz, 1550 nm
- Ultra-low jitter
- 24/7 operation

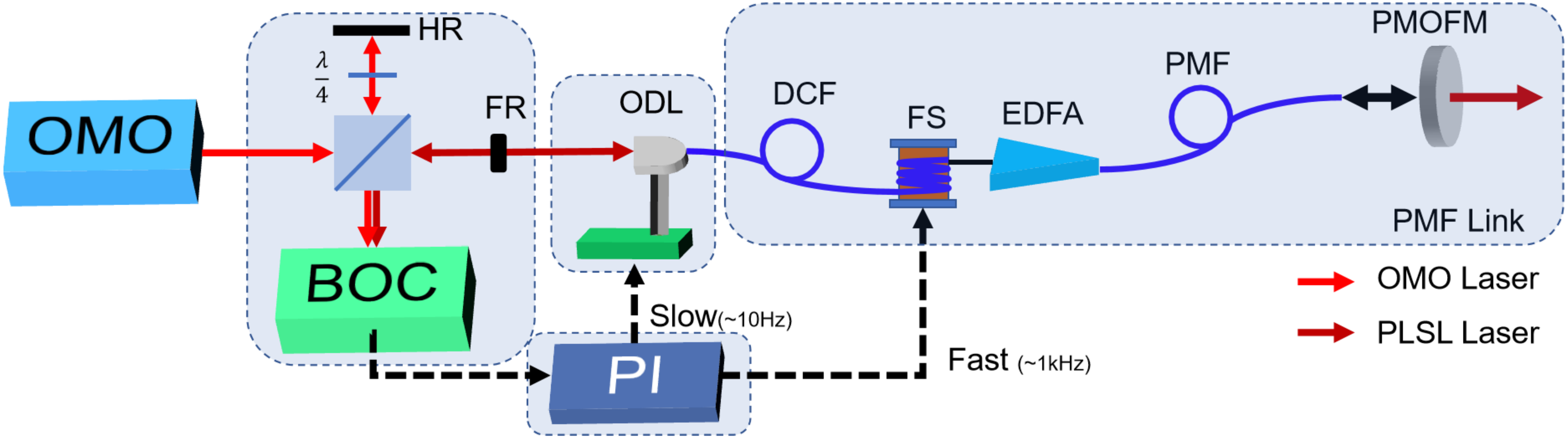


Master clock



Stabilized reference distribution

Pulse laser phase-stabilized link (PLSL) distributes reference signal to laser/ RF clients with sub-fs level additive jitter.



Schematic diagram of PLSL

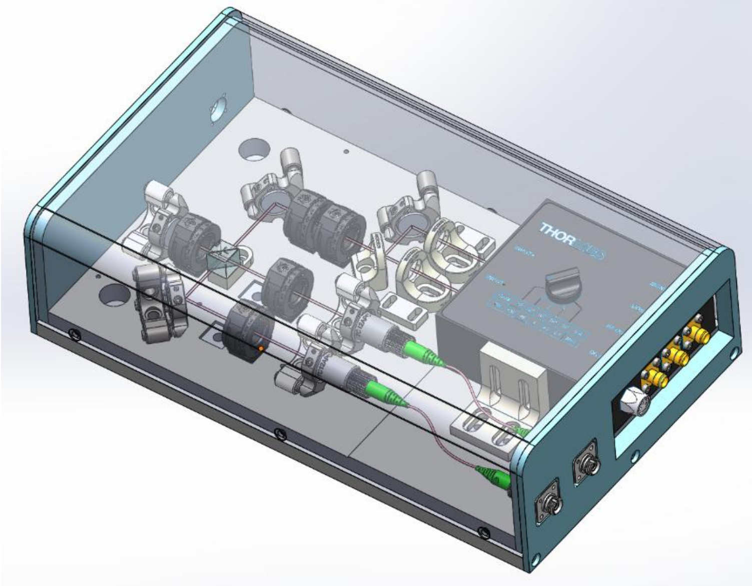
Pulse laser phase stabilized link

Timing detection

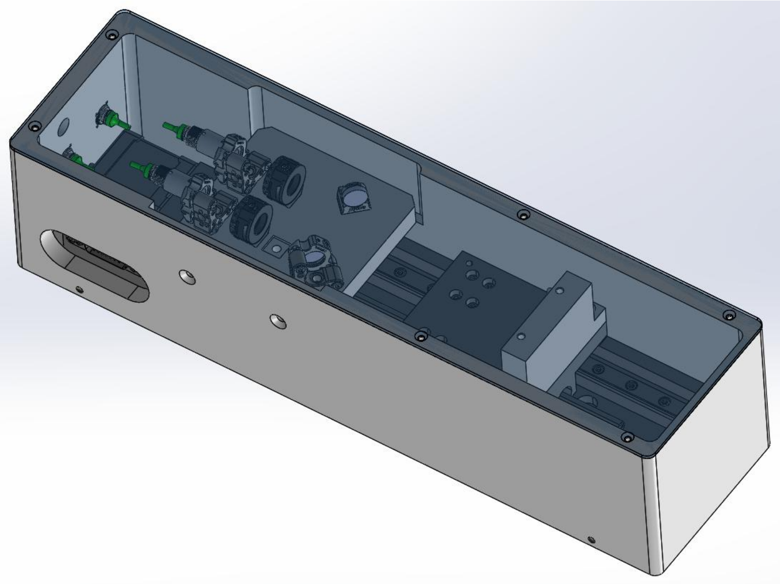
- Balanced optical cross-correlation (BOC)
- Insensitive to laser pulse fluctuations
- Sensitivity 15 mV/fs

Feedback

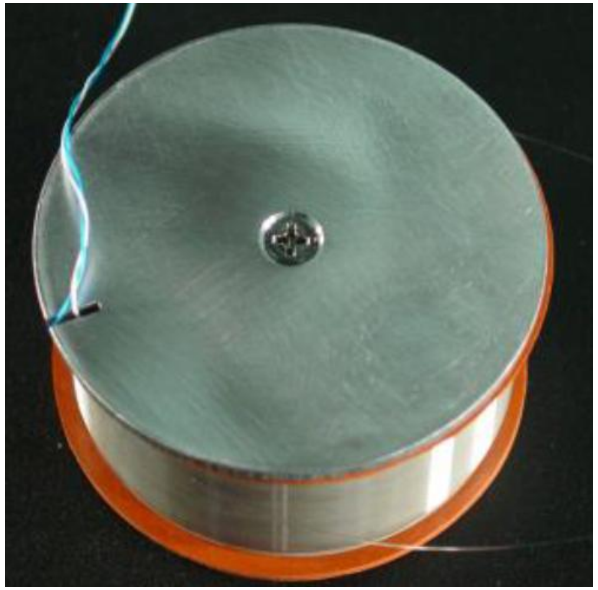
- Fast: Piezo-based fiber stretcher BW~5 kHz
- Slow: Optical delay line ~1.3 ns



BOC-1550 nm



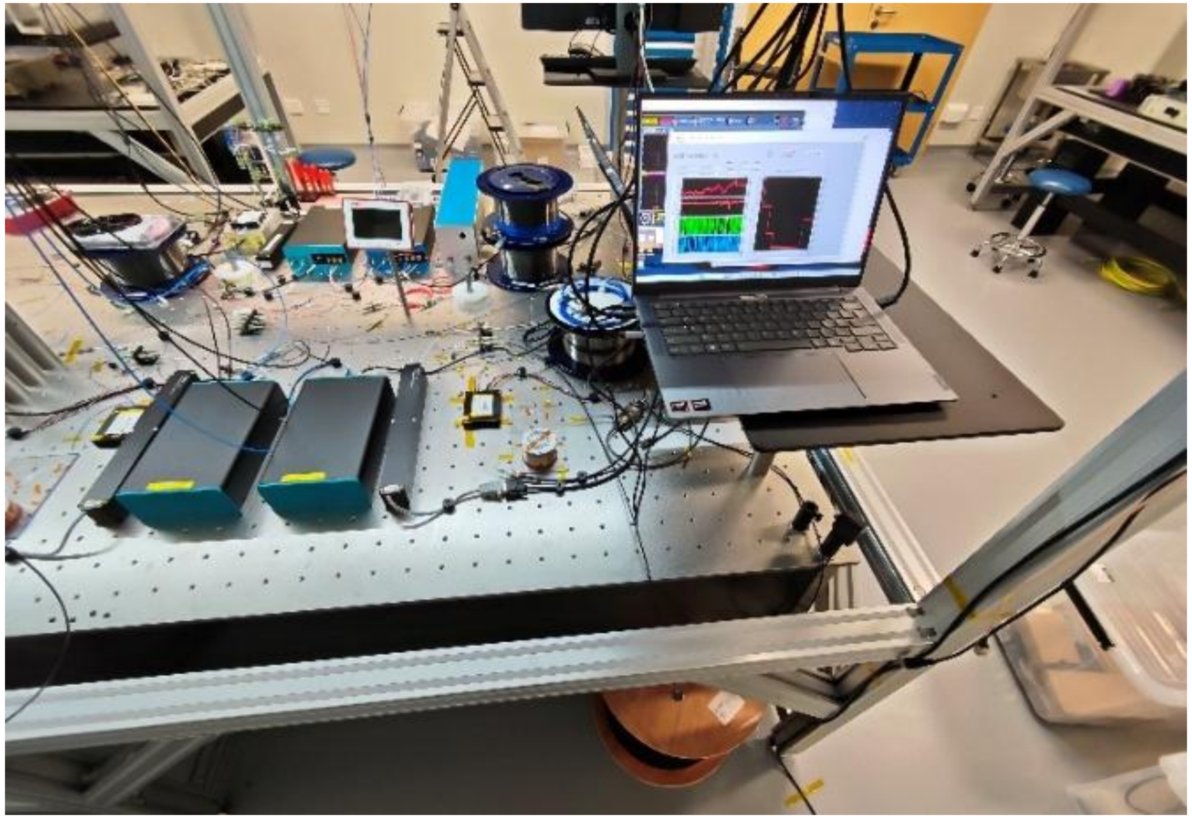
Optical delay line

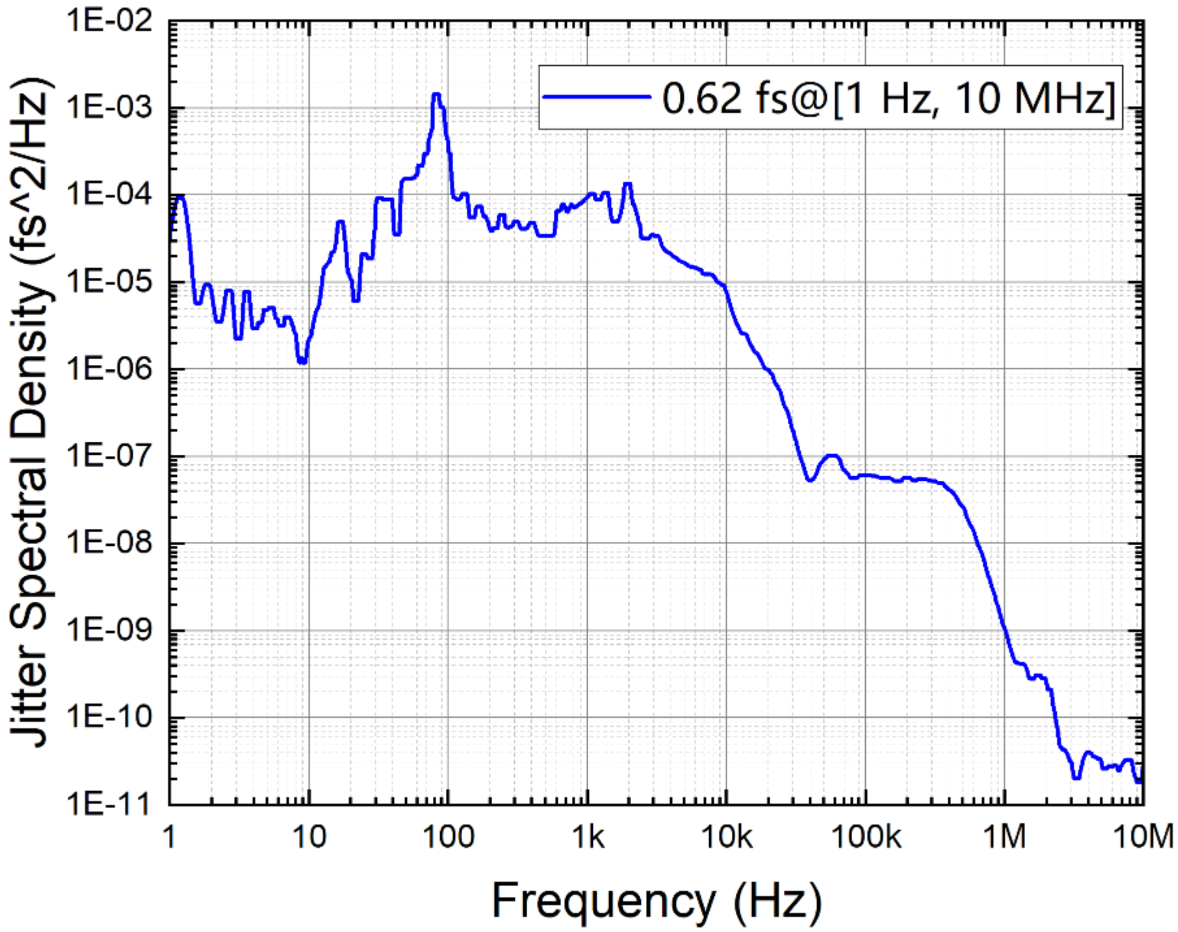


Piezo-based
fiber stretcher

Pulse laser phase stabilized link

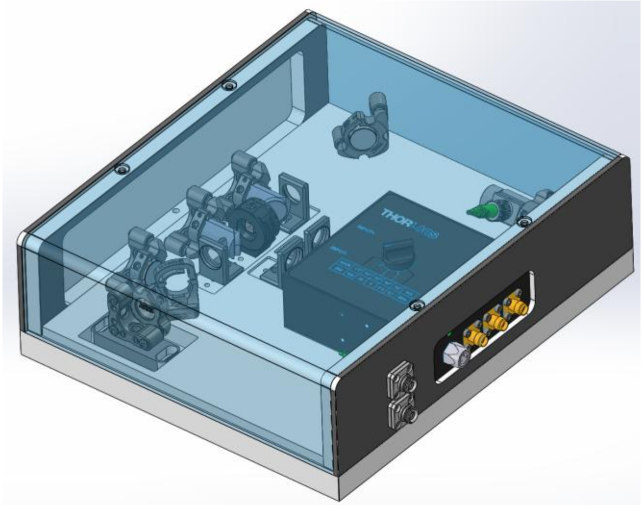
PLSL- 2 km has achieved sub-fs jitter.

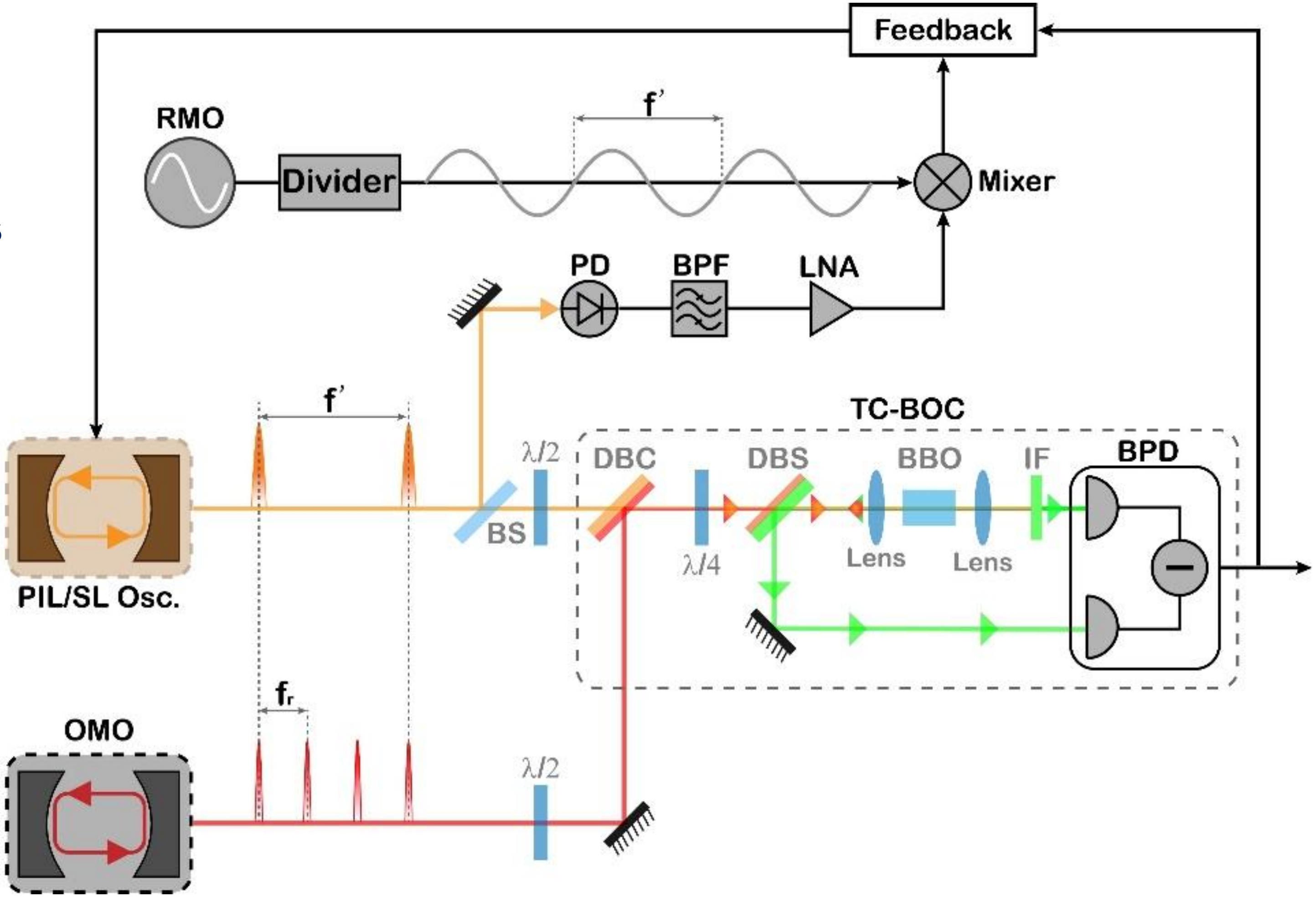




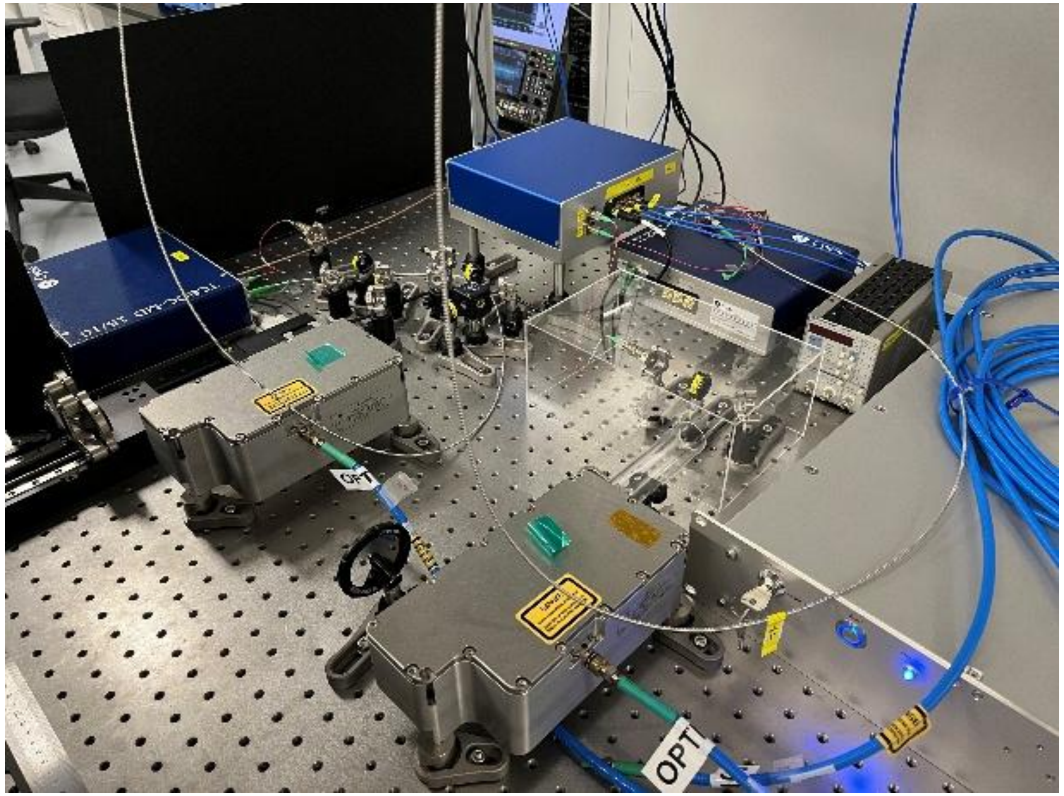
Locking of laser clients

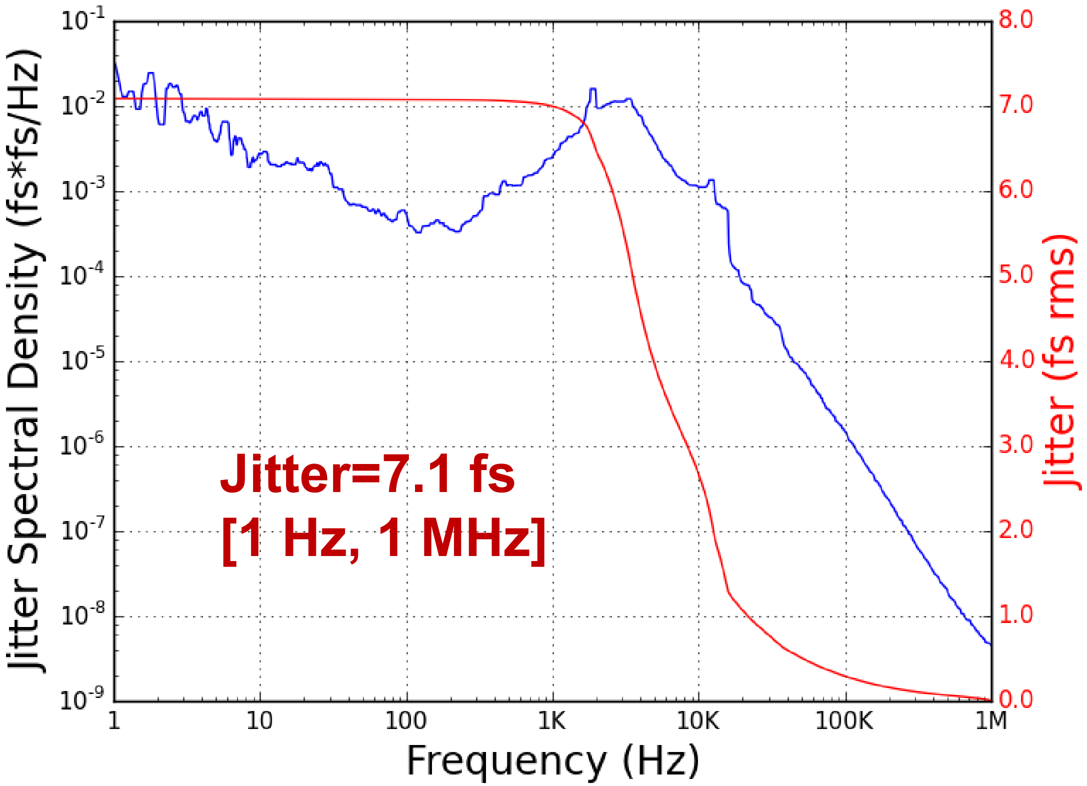
- Two-color balanced optical cross-correlation (TCBOC)
- RF Pre-lock function
- Insensitive to laser pulse fluctuations
- Slope 10 mV/fs
- Piezo-based feedback BW~5 kHz



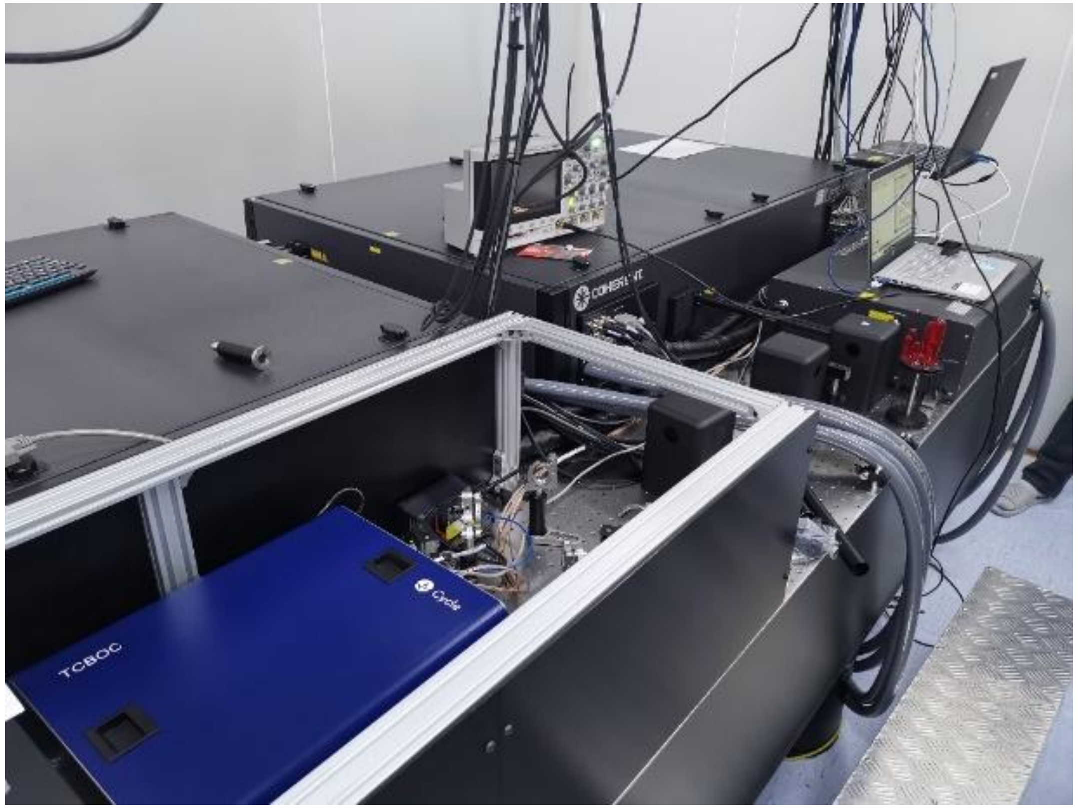


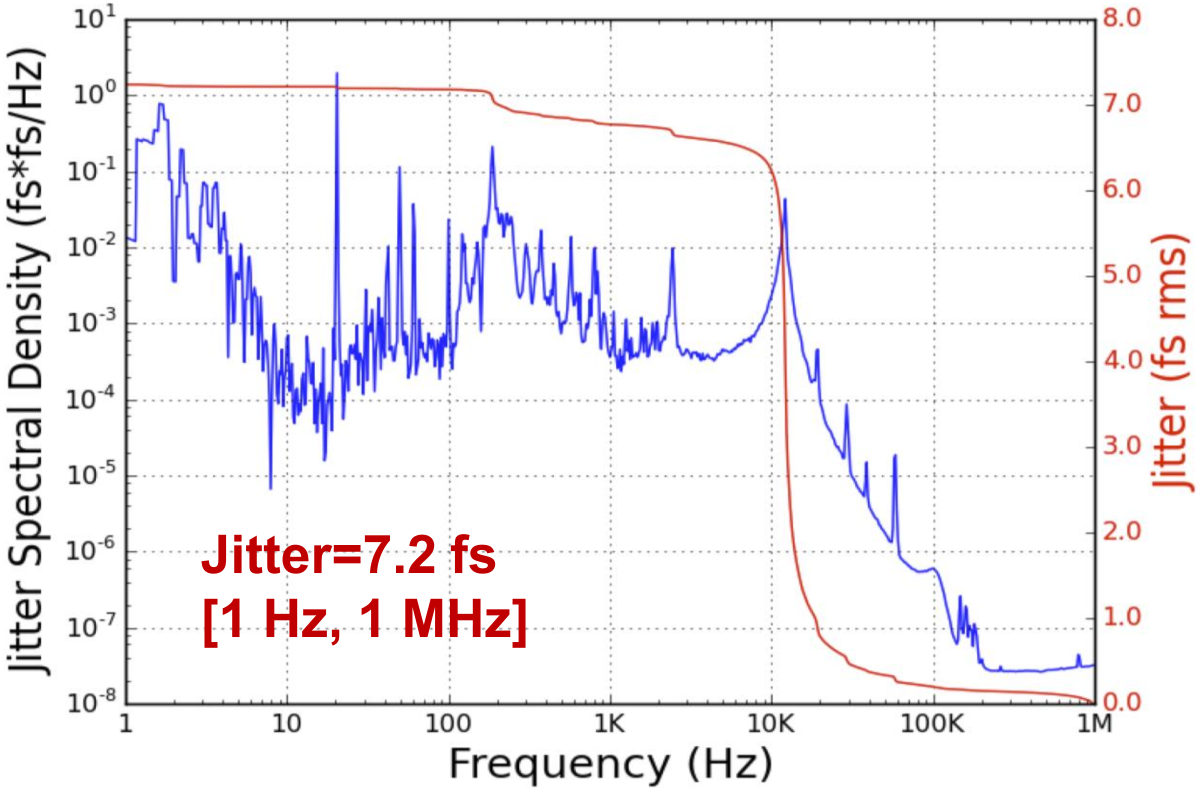
Locking of Yb lasers at 1030 nm





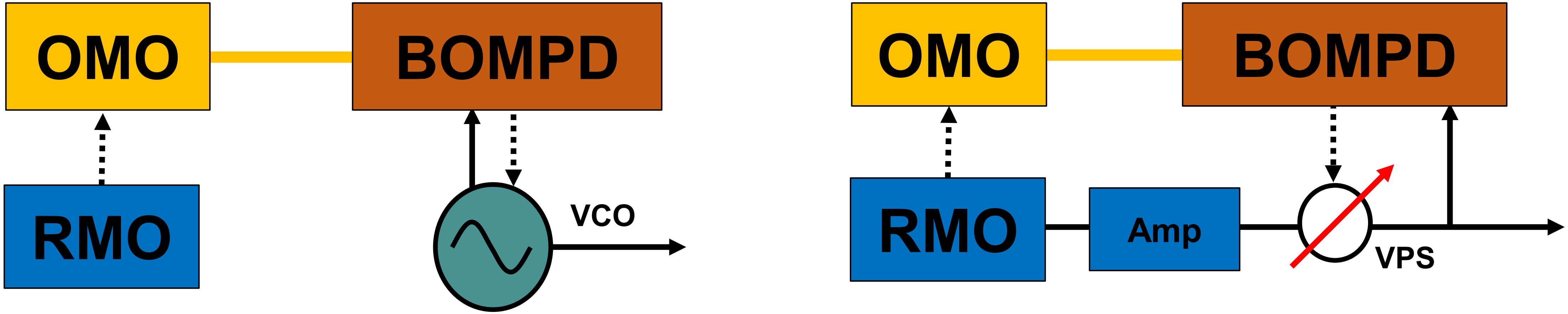
Locking of Ti:Sa lasers at 800 nm





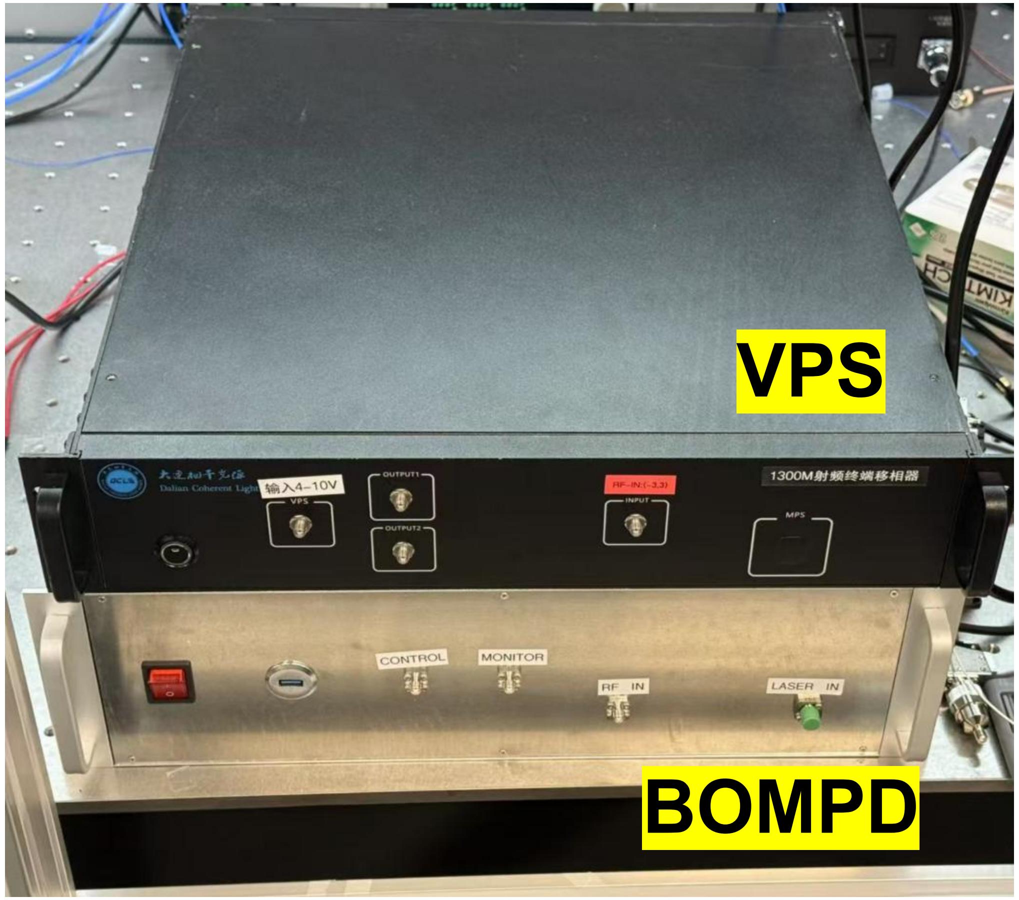
Locking of RF clients

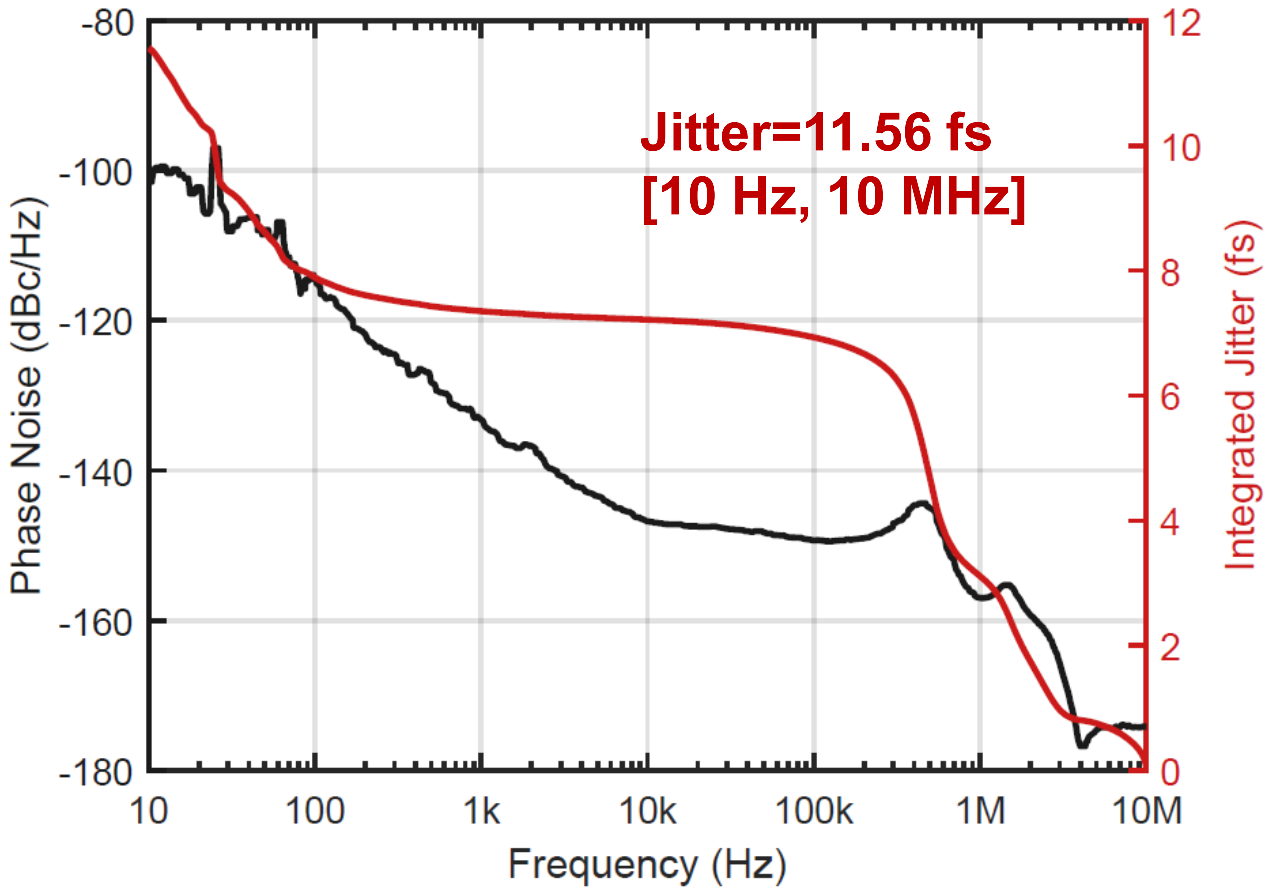
- Balanced optical-microwave phase detector (BOMPD)
- Insensitive to laser pulse fluctuations
- Sensitivity 1 mV/fs
- Locking BW~1 kHz



High performance VCO is embargoed；VPS solution meets FEL requirements.

Locking of RF clients @ 1.3 GHz





Summary

- Ultrafast laser systems and fs timing & synchronization system are critical sub-systems for FEL facilities.

- High R.R. FEL imposes stringent requirements on ultrafast laser systems, especially in achieving high pulse energy and power simultaneously, necessitating cutting-edge laser technologies.

- These systems are required to operate continuously 24/7, with long-term stabilities.

Acknowledgement

Prof. Xueming Yang

Lasers

Dr. Wei Liu
Dr. Zhigang He
Dr. Jiaqi Luo
Dr. Baichao Zhang
Dr. Lifeng Wang
Dr. Yang Liu
Dr. Yanjun Min
Dr. Xincai Diao
Xiaoshen Li
Qi Liu
Zexiu Zhu
Ruirong Qiang
Desheng Zhou

Timing and sync.

Dr. Zhichao Chen
Dr. Tianpeng Hua
Dr. Tao Cao
Dr. Han Ye
Dr. Hao Zeng
Weiyu Lai
He Zhao
Jie Chen
Junsong Ding
Baoqi Xue

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Thanks!